Status of the 25 T, 100 mm Bore HTS Solenoid for an Axion Dark Matter Search Experiment

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***Abstract*—This paper presents the design and test results of the pancake coils for the 25 T, 100 mm bore solenoid that Brookhaven National Laboratory (BNL) is building for the Institute for Basic Science (IBS) in Korea for an Axion dark matter search. The design is based on second-generation (2G) high-temperature superconducting (HTS) tape with no-insulation winding. The major challenges in the high-field, large aperture solenoid are the large stresses and the quench protection. Moreover, the design should be robust for reliable operation in a user facility environment. The paper will also present the construction and test results of two ∼100 mm bore double pancake coils creating a peak field of up to ∼17 T and similar hoop stresses as will be in the 25 T solenoid. The coils were subject to several severe tests, including the simulations of large defects and extended quench studies at ∼4 K. The most striking part of these studies was the demonstration of how fast (a few hundred milliseconds) these coils can turn from the superconducting state to the normal state (quench or thermal runaway). This removes the past concerns of protecting high-field HTS coils because of the low quench propagation velocities.**

***Index Terms*—High field solenoids, HTS coils, very high field magnets.**

I. Introduction

A KEY component of the proposed state-of-the art experimental facility at the Center for Axion and Precision Physics (CAPP) at the Institute for Basic Science (IBS) [1] in Korea for the Axion dark matter search will be the 25 T, 100 mm bore HTS solenoid that Superconducting Magnet Division at Brookhaven National Laboratory is building. Axion dark matter may be partially converted to a very weak flickering electric field in the presence of a strong magnetic field applied in a resonant cavity. A high field, large volume magnet is important as the sensitivity of the Axion detection increases with the product of the square of the magnetic field and the volume. Initial design is based on the experience with HTS R&D solenoid that BNL designed and built for a Superconducting Magnetic Energy Storage (SMES) application [2] with stainless steel insulation between the turns [2]–[4]. While IBS solenoid needs very high fields in a large aperture, its requirement on field quality (up to 10% field errors) and on time to energize the magnet (up to one day charge time) are much relaxed [1]. This makes the no-insulation winding [5], [6] viable which provides an extra level of protection against local defects as compared to the conventional insulation or the metallic insulation.

TABLE I
Major (Nominal) Parameters of the HTS Solenoid for IBS

	Quantity	Units
Maximum Field on the Axis	25	T
Cold Bore	100	mm
Length of Good Field Region	>200	mm
Operating Temperature	4.2	K
Coil Inner Diameter	105	mm
Coil Outer Diameter	200	mm
Number of Pancakes	28	
Nominal ReBCO Tape Width	12	mm
Nominal Tape Thickness	75	µm
Conductor per Pancake	300	m
Operating Current	450	A
Current Density in Coil	490	A/mm^2
Stored Energy	1.3	MJ
Inductance	13	H
Maximum Hoop Stress	480	MPa
Maximum Axial Stress	180	MPa
Thickness of Support Ring	40	mm
Total Coil Length	343	mm

II. Magnet Design

Major parameters of the design are given in Table I and the basic structure is shown in Fig. 1. The major components of the de-sign are discussed in the following sub-sections.

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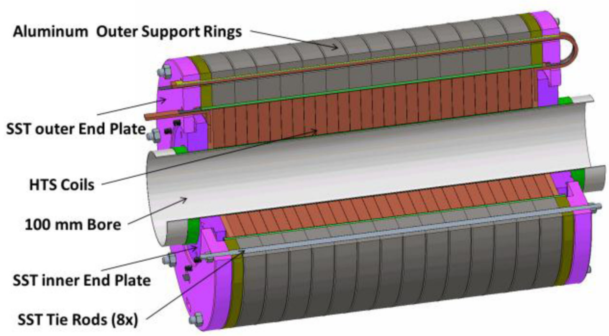

Fig. 1. Major components of the 25 T, 100 mm bore HTS solenoid that BNL is building for IBS.

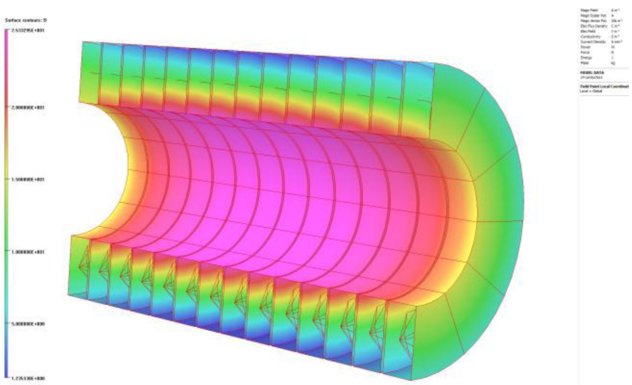

Fig. 2. Magnetic model of the 100 mm bore, 25 T HTS solenoid for IBS with the magnetic field superimposed on the surface of the coil.

A. Superconductor

The choice of the conductor is dictated by the presence of the high field and large stresses in the design. The second generation (2G) Rare-earth Barium Copper Oxide (ReBCO) tape from Super-Power [7] with 50-micron Hastelloy substrate, 20-micron copper and the Advanced Pinning (AP) composition offers the most design margin. The magnet will need a total length of 8.4 km of 12 mm wide tape. Super-Power has already supplied about 4 km.

B. Magnetic Design

The magnetic design is based on the 14 double pancakes to produce a field of 25 T at the center of the magnet. The field must be within 10% of it over a minimum length of 200 mm. The coil inner diameter (i.d.) is 105 mm and outer diameter (o.d.) 200 mm. Fig. 2 shows a cutout of the coil with magnetic field superimposed on the surface as computed by OPERA 3d [8]. The peak field on the coil is ∼25.3 T with the maximum value of the perpendicular component being ∼10 T.

C. Mechanical Structure

The basic structure of the magnet is shown in Fig. 1. Double pancake coils are formed from two single pancake coils with an internal splice spanning almost all of the inner surface of the coils. Fourteen double-pancake coils are installed on a tight-fitting tube having a 100 mm inner diameter and 1 mm wall thickness with fiberglass insulation over it. The insulation between two single pancakes and between double pancakes is 0.25 mm thick and consists of two Nomex sheets [9]. The double pancake will be overwrapped with fiberglass epoxy insulation (with a nominal thickness of 3 mm) will be accurately machined to the desired outer diameter of 206 mm. The primary structure to contain the large hoop stresses over each double pancake will be 40 mm thick outer support rings made of high Strength 7075-T651 aluminum which has a yield strength of 500 MPa. A nominal gap of 0.13 mm between the coil and tube is left in the design to allow for assembly tolerances. Aluminum structure with higher thermal contraction than the coil will eliminate this gap when cold. Stainless Steel inner and outer end plates and axial tie rods with thermal contraction similar to the coil form the axial structure.

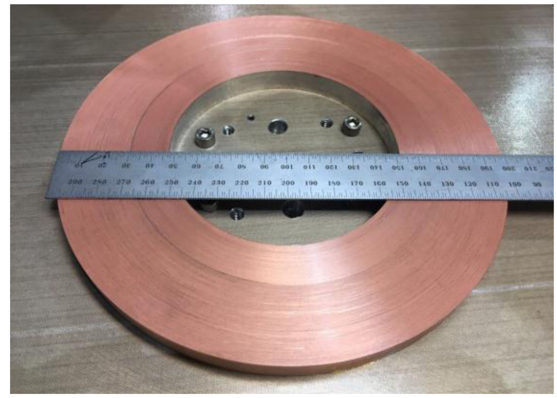

Fig. 3. A single pancake coil with an i.d of 105 mm and o.d. of 200 mm.

Mechanical structure analysis is performed with ANSYS [10] using 2-D axi-symmetric model of ¼ of the structure. Lorentz forces from Maxwell are mapped to the ANSYS static structural model where appropriate boundary conditions, material properties, contacts, and thermal conditions are applied. All contacts are assumed to be frictionless except G-10 overwrap which is bonded to the O.D. of the double-coil pancakes. Mechanical properties of the conductor (tape) are based on the measurements at SuperPower [11] on the wide face (12 mm side bearing azimuthal stress) of conductor. The influence of loading the narrow face (75 μm side bearing axial stress) of conductor was obtained through measurements at BNL with a fixture specifically designed and built for this purpose [12].

Fig. 4 shows the V-I measurements on a small coil made with 40 μm copper and 50 μm Hastelloy. The conductor used has less copper (20 μm) and hence can tolerate more stresses. Painting the top and bottom surfaces of the coil with epoxy reduces the point load on the narrow face of the tape.

The computed radial, axial and azimuthal (hoop) stresses are shown in Fig. 5. All stresses are well within acceptable limits [11].

III. Coil Construction

One R&D double pancake and six single pancakes (see one in Fig. 3) with no-insulation have been wound for IBS. The double pancake R&D coil had an i.d. of 100 mm and an outer diameter of 220 mm and a total of 971 turns wound with over 500 meters of 12 mm wide ReBCO tape from SuperPower with

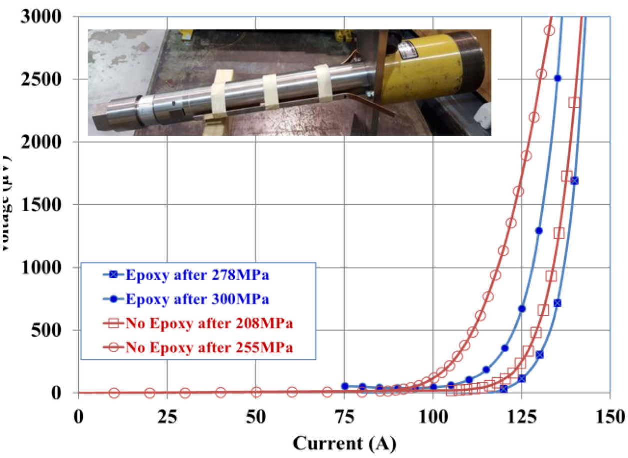

Fig. 4. Influence of loading on the narrow face of HTS tape with 40 μm copper and 50 μm Hastelloy with and without epoxy painted on the surface. A picture of part of the fixture is shown in the inset.

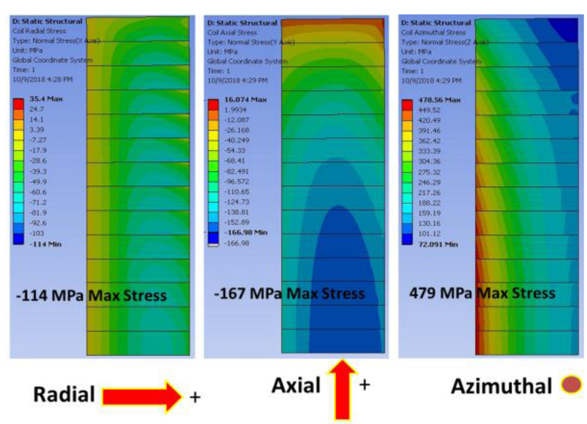

Fig. 5. Mechanical analysis of the 100 mm bore, 25 T HTS solenoid.

50 μm Hastelloy and 65 μm copper. Single pancakes for the IBS solenoid were wound with the parameters given in Table I. A double pancake was made with two single pancakes with an internal splice and a total number of 1250 of turns.

IV. Test Results

We performed a series of tests at various temperatures: (a) at ~77 K with liquid nitrogen, (b) three at ~4.2 K with liquid helium to ~850 A, and (c) several at intermediate temperature in a gaseous helium environment. Several voltage taps were installed within each pancake to monitor the coil performance. No significant degradation in performance was observed after these quenches (which should be called thermal runaways). We will discuss only a few selected cases, highlighting significant outcomes.

A. Measurements With Liquid Nitrogen at ~77 K

Fig. 6 shows the V-I curve of the first four production coils. One can see the variation in coil performance. Two pancakes with performance close to each other were chosen for making the first double pancake and performing the 4 K test.

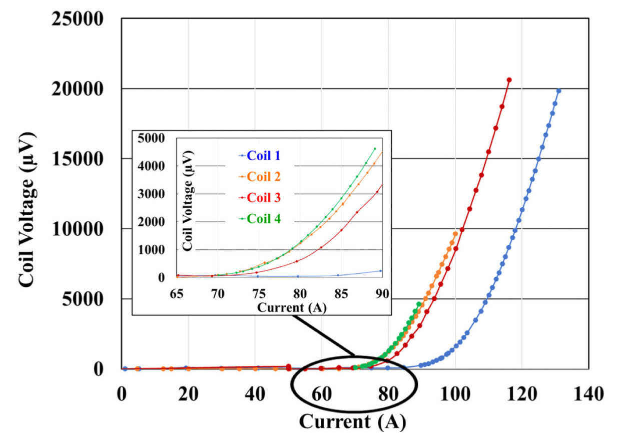

Fig. 6. V-I curves of four single pancake coils tested at 77 K.

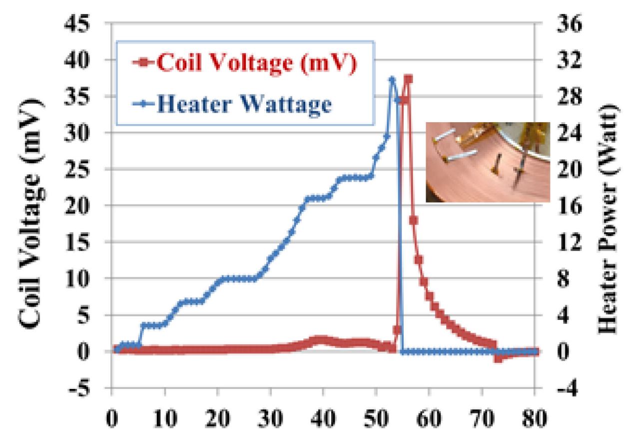

Fig. 7. Coil voltage (red) with heat power (blue) simulating local defects with stainless steel heater strip (see inset).

B. Defect Simulation in Large No-Insulation Coils at ~4 K

Early R&D double pancake coils having 100 mm i.d. were wound with over 500 m of HTS tape having 65 μm copper and 50 μm Hastelloy to examine the tolerance for dynamically controlled local defects at high currents in a no-insulation coil with significant size. Three stainless steel heaters are installed to simulate local defects (see Fig. 7, inset) and not for quench protection. As shown in Fig. 7, the coil kept operating at ~4 K (in liquid helium) at 600 A and didn't runaway (quench) despite a significant local defect (< 30 W) simulated with the heater. The coil turned only partially resistive (~40 mV across the coil) with 30 W. The coil recovered immediately after the heater was turned off. No consequential change in in coil performance (as observed by voltage taps) was observed in the subsequent test runs. This demonstrates the tolerance against significant local disturbances or defects even in such a large no-insulation coil operating at high current.

C. Shut-Off Test in Large No-Insulation Coils at ~4 K

Shut-off experiments were performed at various currents and temperatures. Just as the field doesn't rise immediately with current in no-insulation coil, it may not fall off immediately either. The delay is caused by some of the current traversing sideways

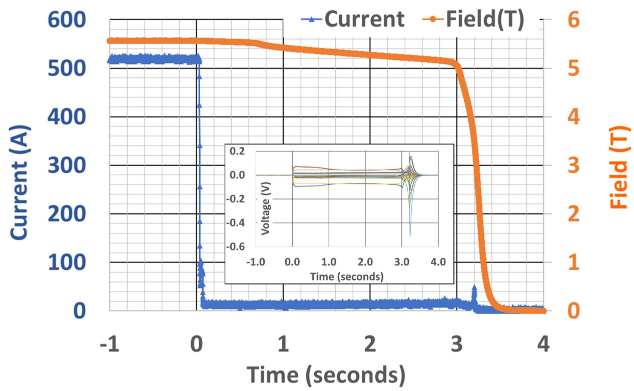

Fig. 8. Shut-off at ~550 A. The field decays slowly first and then rapidly when the coil goes normal after ~3 seconds (see inset).

(radially) rather than circulating (tangentially). Whereas the circulating current creates the field, the side-way flow of current between the turns creates heat. Both the charging/discharging delay and the heating caused by sideways current depends on the contact resistance between the turns. At high enough currents, this heating may be sufficient to turn the coil normal. One such case is shown in Fig. 8 at 550 A with shut off at $t = 0$. When the power supply is shut-off the field starts decaying slowly through the internal contact resistance within the coil. This causes enough heating in about three seconds to drive the coil normal. The inset shows a rapid voltage rise and fall-off at about 3 seconds after which the field falls of rapidly. A significant point to be noted is that once sufficient voltage starts to build up, the whole coil goes normal in a short time (only 200 milliseconds). It may be pointed out that when the current is raised slowly (to make sure that sideway currents, and hence local heat generated remain low), the coil fully recovered for a current up to 400.

D. Quench Propagation in Large No-Insulation Coils at ~4 K

Fig. 9 shows the case when quench (thermal runaway) occurred when the current was being raised slowly to get to the maximum field possible. The field at the center of the magnet became ~9.6 T and the computed peak field ~17 T in this 105 mm aperture coil when the current through the power supply approached 900 A.

The test results shown in Fig. 9 are significant in light of the concerns associated with the "low quench velocities" in HTS coils [13]. If the quench doesn't spread fast enough, the conductor and the coil would be damaged locally over time due to the high hotspot temperature. This is particularly critical in high field, large aperture magnets with large stored energy. The plot shown on the top of Fig. 9 shows that not only the current from power supply, but the field has also become essentially zero within 200 milliseconds. This implies that essentially the whole coil with ~600 meters of conductor became normal in <200 msec. This is to be compared with the typical quench propagation velocities in magnets with conventional insulation, which is <1 cm/sec [13]. This means that the energy deposition will be spread over the whole coil rather than the spot where

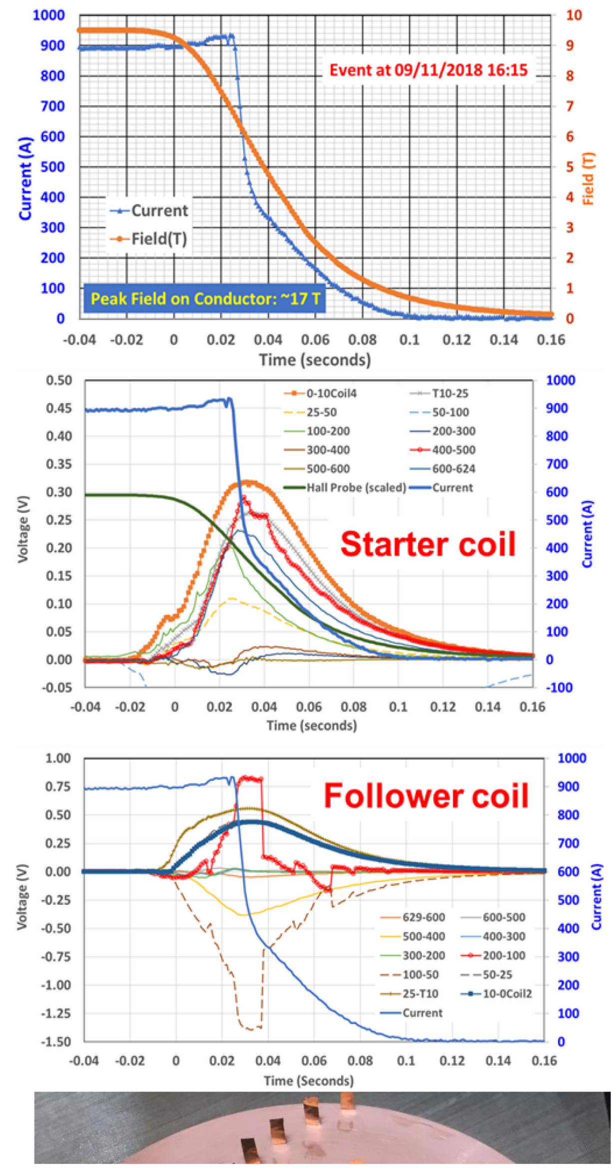

Fig. 9. Thermal runaway (quench) at 4 K in the IBS double-pancake coil. Plot at the top shows how rapidly the field drops, and the middle two plots show rapidly the quench propagates within each pancake and pancake-to-pancake as measured by voltage taps in the coil (bottom).

the quench initiated, which in turn means, that the local hot spot temperature should not become too high. The process and the likely mechanism are explained below.

Each of the two single pancakes in this double pancake coils had several voltage taps installed in the coil (see bottom picture in Fig. 9) to monitor any degradation. The middle two plots in Fig. 9 shows the spread of voltage as a function of time in the pancake where the quench initiates and in the pancake where it follows. One can see the voltage across the set of turns spread rapidly within each pancake (as fast as 10–20 milliseconds between two sets) and also between pancake-to-pancake (as fast as 10–20 milliseconds) after the start of the rapid rise in voltage. The maximum voltage itself could become 500 mV across the double pancake (much higher than what was allowed in HTS coils before).

The individual pancake becomes normal rapidly because of the significant heat generated in the no-insulation winding when the current starts flowing sideways (radially) between turns. This is also reflected in the rapid decrease in field as measured through Hall probes. Since the two pancakes are strongly coupled inductively, a rapid change in local field in one cause a similar change in other. This in turn causes local heating and initiation of a quench which spreads rapidly across that pancake. The spread of quench between pancake-to-pancake should be scalable to 28-pancake structure of the IBS solenoid, as all pancakes are inductively coupled to each other.

V. Conclusion

The paper described the design and latest test results of the double pancake coils for the IBS 25 T, 100 mm bore solenoid. The test results show that the quench in these large no-insulation coils spread faster than a quench that can be initiated with conventional quench heaters [14]. The coil survived several quenches in a high field, large stress environment with no significant degradation observed based on several voltage taps installed within the coil.

References

[1] Y. Semertzidis, "Applications of superconductivity in the detection of axions".

[2] R. Gupta *et al.*, "Design, construction and testing of a large aperture high field HTS SMES coil," *IEEE Trans. Appl. Supercond.*, vol. 26, no. 4, Jun. 2016, Art. no. 5700208.

[3] R. Gupta *et al.*, "High field solenoid development for axion dark matter search at CAPP/IBS," *IEEE Trans. Appl. Supercond.*, vol. 26, no. 4, Jun. 2016, Art. no. 4100705.

[4] R. Gupta *et al.*, "High field HTS solenoid for a muon collider – demonstrations, challenges and strategies," *IEEE Trans. Appl. Supercond.*, vol. 24, no. 3, Jun. 2014, Art. no. 4301705.

[5] S. Hahn, D.K. Park, J. Bascunan, and Y. Iwasa, "HTS pancake coils without turn-to-turn insulation," *IEEE Trans. Appl. Supercond.*, vol. 21, no. 3, pp. 1592–1595, Jun. 2011.

[6] S. Choi, H. Jo, Y. Hwang, S. Hahn, and T. Ko, "A study on the no insulation winding method of the HTS coil," *IEEE Trans. Appl. Supercond.*, vol. 22, no. 3, Jun. 2012, Art. no. 4904004.

[7] [Online]. Available: www.superpower-inc.com/

[8] [Online]. Available: http://operafea.com/

[9] [Online]. Available: http://www.dupont.com/products-and-services/electronic-electrical-materials/electrical-insulation/brands/nomex-electrical-insulation.html

[10] [Online]. Available: www.ansys.com/

[11] Y. Zhang *et al.*, "Stress–strain relationship, critical strain (stress) and irreversible strain (stress) of IBAD-MOCVD-Based 2G HTS Wires Under Uniaxial Tension," *IEEE Trans. Appl. Supercond.*, vol. 26, no. 4, Jun. 2016, Art. no. 8400406.

[12] S. Joshi, W. Sampson, and R. Gupta, "Axial compression fixture and conductor test report on the HTS tape required for 25 T, 100 mm IBS solenoid," BNL Magnet Division Internal Note no. MDN-681-48, Jan. 2018, unpublished.

[13] R. H. Bellis and Y. Iwasa, "Quench propagation in high Tc superconductors," *Cryogenics*, vol. 34, no. 2, pp. 129–144, 1994.

[14] H. Weijers, P. Noyes, W. Sheppard, and E. Stiers, "Performance of the NHMFL 32 T superconducting magnet".