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]. The IBS design is based on the no-insulation winding to provide an extra level of protection against local defects [5, 6]. The no-insulation scheme is particularly suitable in this application because of the relaxed field quality (10% field errors allowed) and slow charging requirements (a day allowed).

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II. Magnet Design

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

A. Superconductor

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

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

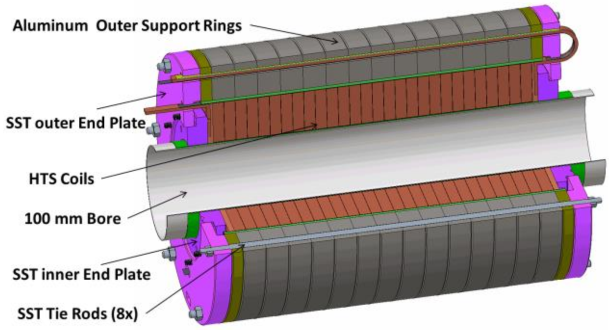

Fig. 1. Major components of the 25 T, 100 mm bore HTS solenoid that BNL is building for IBS.

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.

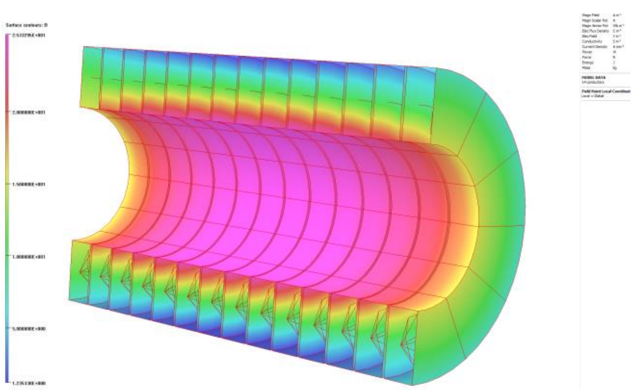

Fig. 2. Magnetic model of the 100 mm bore, 25 T HTS solenoid for IBS with the magnetic field superimposed on the surface of the coil.

C. Mechanical Structure

The basic structure of the magnet is shown in Fig. 2. 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 which will be accurately machined to the desired outer diameter with a nominal thickness of 3 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

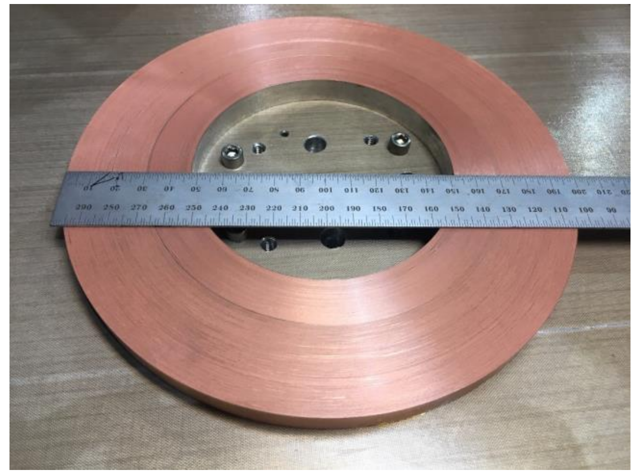

Fig. 3. A single pancake coil with an i.d of 105 mm and o.d. of 200 mm.

500 MPa. Aluminum structure with higher thermal contraction than the coil is chosen to overcome a gap of 0.13 mm between the coil and tube to allow for assembly tolerances. Stainless Steel inner and outer end plates and axial tie rods with thermal contraction similar to the coil form the axial structure.
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 are based on the measurements at SuperPower [11] on the wide face of conductor. The influence of loading narrow face 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 actual conductor used has even lower copper (20 μm).

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

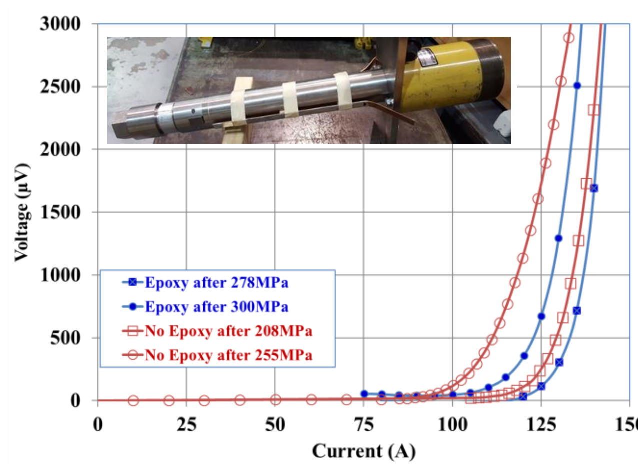

Fig. 4. Influence of loading on the narrow face of HTS tape with 40 μm copper and 50 μm Hastelloy with and without epoxy painted on the surface. A picture of part of the fixture is shown in the inset.

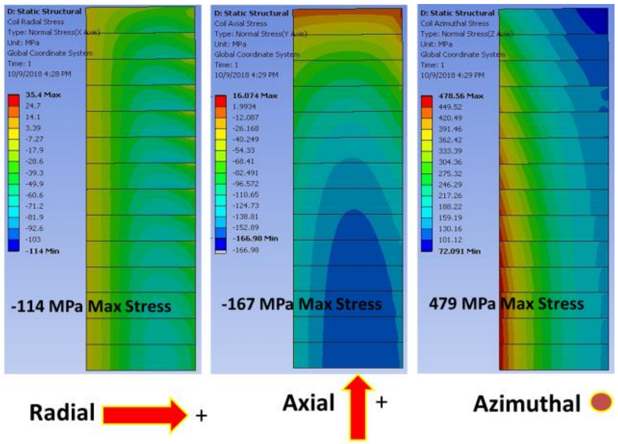

Fig. 5. Mechanical analysis of the 100 mm bore, 25 T HTS solenoid.

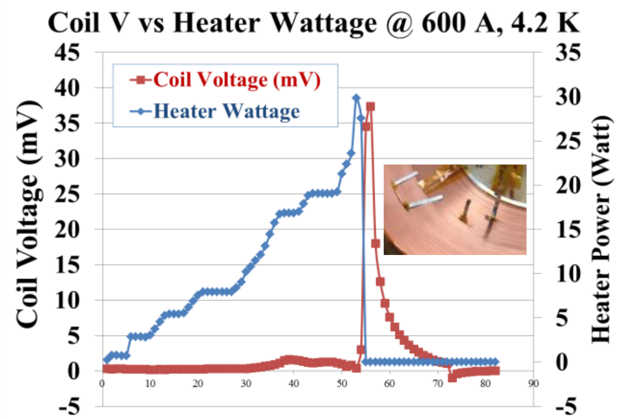

Fig. 7. Coil voltage (red) with heat power (blue) simulating local defects with stainless steel heater strip (see inset).

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 o.d. of 220 mm and a total of 971 turns wound with over 500 meters of 12 mm wide ReBCO tape from SuperPower with 50 µm Hastelloy and 65 µm copper. The single pancakes were wound as per the IBS design parameters given in Table I. A double pancake was made with two single pancakes with an internal splice in between and has a total number of 1250 turns using ~600 meters of conductor.

IV. Test Results

We performed an extensive set of tests at various temperatures at ~77 K with liquid nitrogen, at ~4.2 K with liquid helium and at intermediate temperature in a gaseous helium environment. 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.

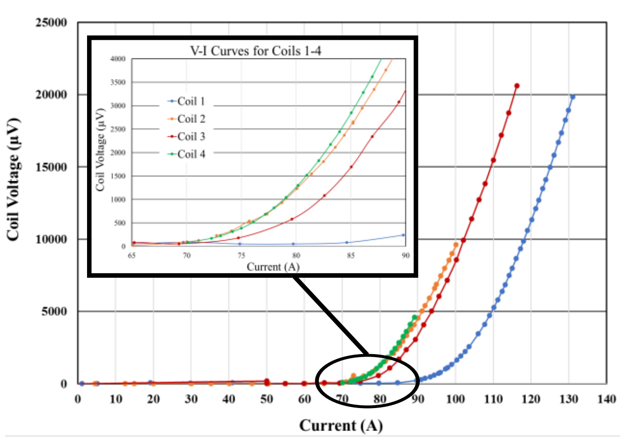

Fig. 6. V-I curves of four single pancake coils tested at 77 K.

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. The local defects were simulated with three stainless steel heaters (Fig. 7, inset) at 600 A. As shown in Fig. 7, the coil kept operating 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 damage in coil performance was observed following such experiments even after the thermal runaway (quench). This demonstrates the tolerance against significant local disturbances or defects even in 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 (radially) rather than circulating (tangentially). Whereas the circulating current creates the field, the sideway flow of current between the turns creates heat. Both the charging/discharging delay and the heating caused by side-

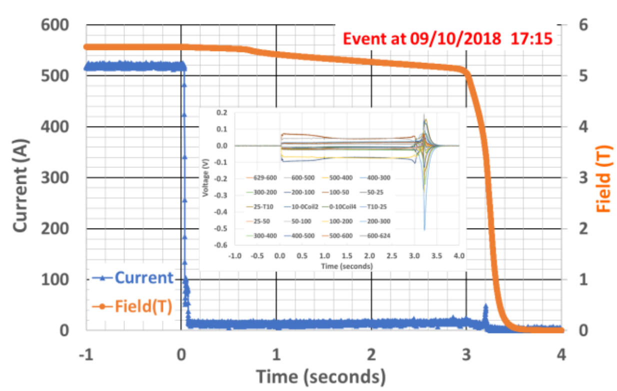

Fig. 8. Shut-off at ~550 A. The field decays slowly first and then rapidly when the coil goes normal after ~3 seconds (see inset).

ways 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 as they remove major concerns associated with the “low quench velocities” in HTS coils. 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 with 200 milliseconds. This implies that essentially the whole coil has become normal in a short period of time. This means that the energy deposition will be spread over the whole coil rather than the spot where 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 pancakes coils had several voltage taps installed in the coil (see bottom picture in Fig. 9). 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

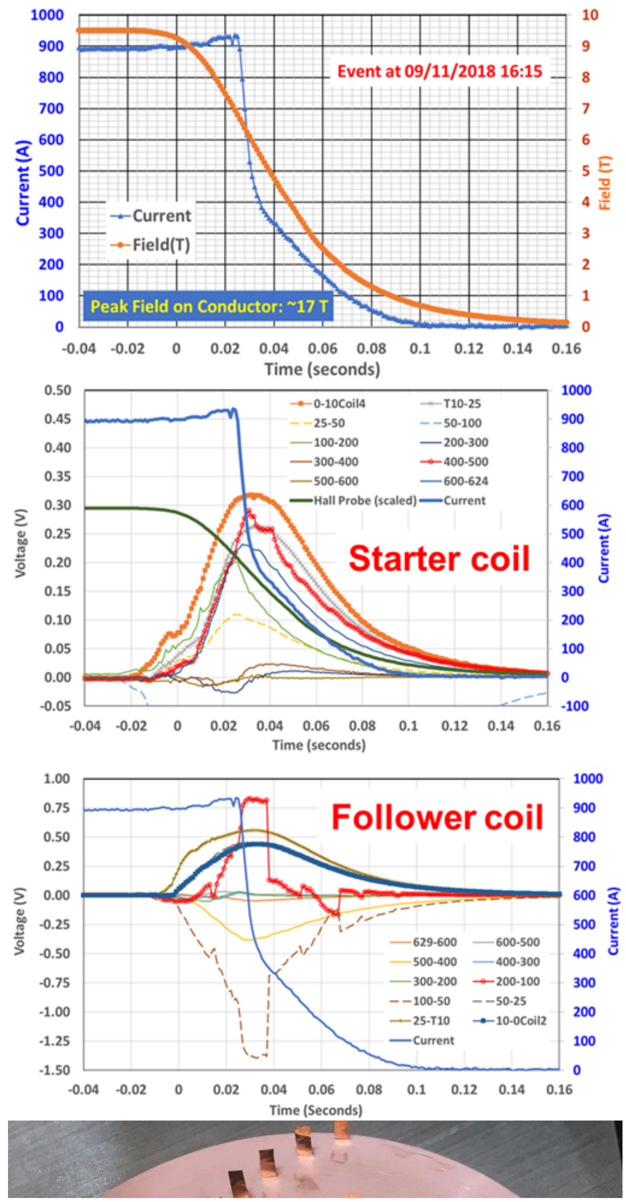

Fig. 9. Thermal runaway (quench) at 4 K in the IBS double-pancake coil. Plot at the top shows how rapidly the field drops, and the middle two plots show how rapidly the quench propagates within each pancake and pancake-to-pancake as measured by voltage taps within the coil (bottom).

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 IBS 25 T, 100 mm bore solenoid. Test results and process discussed in this paper should remove the concern associated with the slow quench propagation. This is particularly important in large no-insulation coils from which it is difficult to extract significant energy. Moreover, the quench spread should be faster than that which can be initiated with conventional quench heaters [13] while allowing a large and variable temperature margin to be present throughout the solenoid.

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