High-Field Solenoid Development for Axion Dark Matter Search at CAPP/IBS

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***Abstract*—Construction and test results of a 100-mm-bore solenoid made with the high-temperature superconductor (HTS) producing a peak field of over 10 T are presented. This is the first step toward building a very high field solenoid (35–40 T)—one of the key components of the proposed state-of-the-art facility for dark matter search at the Center for Axion and Precision Physics Research, Institute for Basic Science in Korea. The coils made with HTS are expected to provide a field of ∼25 T, and the coils made with low-temperature superconductors are expected to provide a field of 10–15 T. REBCO HTS tapes were provided by SuNAM along with the measurements at 20 K in 3.5- to 4-T applied field. The Brookhaven National Laboratory measured several samples at 4 K in the applied field of 4–8 T. This paper will present a series of test results of the conductor, six pancake coils, and the fully assembled solenoid.**

***Index Terms*—High-field magnets, HTS, REBCO, solenoids.**

I. Introduction

THE Institute for Basic Science (IBS) Center for Axion and Precision Physics Research (CAPP/IBS) is setting up a major facility in Korea for searching for Axion dark matter with a resonant cavity [1]. Axion dark matter is partially converted to a very weak flickering electric field in the presence of a strong magnetic field. The sensitivity of the detection increases as the square of the magnetic field. In addition to a high magnetic field, a large cavity volume is also important. Since the volume of the magnet dictates the total cavity volume, the key component of this state-of-the-art experiment will be a magnet with high magnetic field and large aperture: 35–40 T and 100 mm. Achieving such high fields requires the use of High Temperature Superconductors (HTS). To reduce cost, it will be a hybrid design with the outer coil made with conventional Low Temperature Superconductor (LTS). LTS coils, likely to be purchased from a commercial vendor, will provide a field of 10–15 T and HTS coils a field of ∼25 T. The Superconducting Magnet Division (SMD) at the Brookhaven National Laboratory (BNL) has recently designed and constructed a REBCO (a second generation HTS) solenoid with a goal of reaching 25 T at 4 K in a 100 mm bore [2] as a part of an R&D module for a Superconducting Magnetic Energy Storage System (SMES). The similarity between the two magnets and the experience of designing and building one forms the basis of this program.

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TABLE I
Major Parameters of the HTS Solenoid

	Quantity	Units
Peak Magnetic Field on the Solenoid Coil	10.8	T
Maximum Field on the Axis	8.6	T
Maximum Current	590	A
Coil Inner Diameter	101.6	mm
Coil Outer Diameter	192	mm
Operating Temperature	4.2	K
Stored Energy	66	kJ
Inductance	0.4	H
Total Number of Turns in the Solenoid	1881	
Number of Single Pancake Coils	6	
Nominal Width of Double Pancake Coil Unit	25	mm
Nominal Thickness of Stainless Steel (SS) Tape	25	μm

II. Magnet Design

Major parameters of the magnet assembled from six pancake coils are given in Table I. The goal of the first phase of CAPP/IBS solenoid program was to demonstrate a peak field of at least 10 T in a 100 mm aperture HTS solenoid with the similar design and technology that was used in the SMES coil [2] and in the proposed Muon Collider solenoids [3].

The maximum current achieved in the CAPP/IBS solenoid was 590 A at 4.2 K. This corresponds to a computed peak field of 10.8 T on the surface of the coil (see Fig. 1) and a field of 8.6 T at the center of the coil, as computed by OPERA [4].

III. Conductor

A. Specifications

CAPP/IBS pancake coils were wound with the 12 mm wide REBCO tape from SuNAM [5]. Major specifications of the conductor are given in Table II. The conductor was delivered from three production runs, each having a minimum length of 140 m without any internal splice. The critical current at 77 K in self-field was high (600 A). The bonding of the copper plating

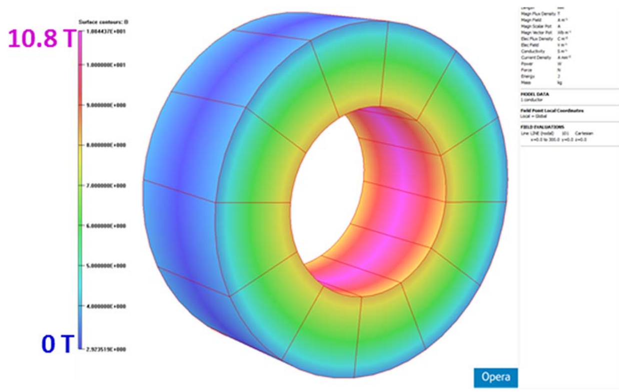

Fig. 1. Computed field contour on the surface of the conductor in the 100-mm-aperture six pancake HTS solenoid built and tested at 590 A.

TABLE II
MAJOR SPECIFICATIONS OF THE HTS TAPE (SUPPLIED BY SUNAM)

	Quantity	Units
Nominal width of 2G HTS Tape	12.05	mm
Nominal Thickness of 2G HTS Tape	100	µm
Nominal Thickness of Copper in HTS Tape	40	µm
Minimum Critical Current (77 K, self-field)	600	A
Minimum Critical Current* (4 K, 8 T), expected	550	A
Thickness of Hastelloy Substrate	50	µm
Minimum Piece Length	140	m
Number of Splices Permitted	None	

any direction (including field perpendicular to the wide face of the tape)

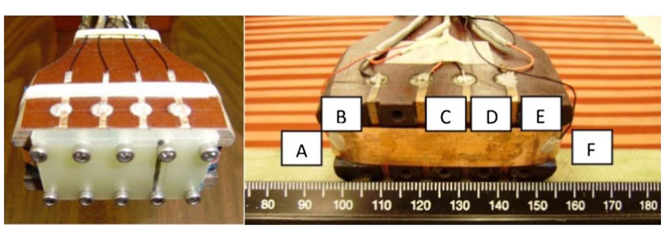

Fig. 2. Sample layout of the BNL test holder. The voltage taps at locations A through F are indicated.

to the conductor was good as it did not delaminate during the coil construction and testing.

B. Conductor Measurements

Measurements of samples of the conductor used in the CAPP/IBS solenoid were made both at SuNAM and at BNL. At BNL, samples of the ends of the coil winding were tested at 77 K and at 4.2 K. Since the solenoid performance is likely to be limited by the critical current of the end coils in field perpendicular to the wide face of the tape, the measurements at 4.2 K were done with field in that direction.

C. Measurement Setup at BNL

The tapes were mounted on a special holder (see Fig. 2 connected to high-current leads capable of carrying 1.5 kA at 4.2 K and can be positioned in a 60 mm bore solenoid that can provide a background field of 8 T. Voltage taps are positioned 10 mm apart from A to F. There are voltage taps to monitor the joint resistance to the HTS leads and across the section that bends around to form the straight section which is in perpendicular field.

TABLE III
CRITICAL CURRENT EXTRACTED FROM THE DIFFERENT SECTIONS

	AB	BC	CD	DE	EF	BE
77 K	10 mm	10 mm	10 mm	10 mm	10 mm	30 mm
I_c, A	681	691	690	685	678	689
n	54	60	63	59	49	60

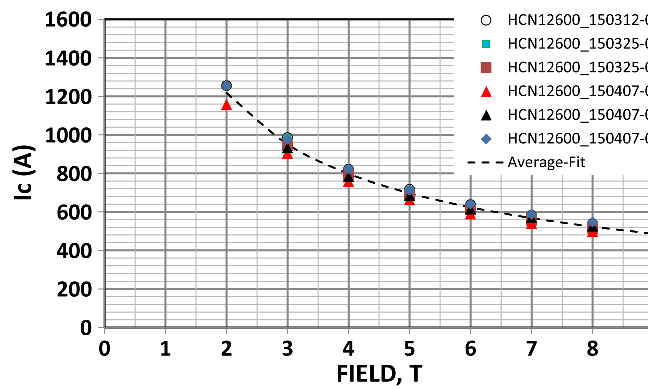

Fig. 3. Critical current at 4.2 K versus field applied perpendicular to the wide face of the tape. The variation between the six samples is quite small.

D. BNL Measurements

The critical current I_c is being reported for a criterion of 1 μV/cm at both 77 K and at 4.2 K. The I_c and n-values are derived from fitting a straight line to a log E vs. log I, where the electric field E is in μV/cm. These data at 77 K for a typical sample are shown in Table III.

The critical current measurements of six samples are shown in Fig. 3. For each sample, the I_c as a function of the external field H is fit to a power law $I_c = AH^{-b}$, where $b = 0.61 \pm 0.015$. The average of the six samples is also given. At 8 T the variation in I_c is ± 19 A, and the lift factor $(I_c(4.2\text{ K}, 8\text{ T})/I_c(77\text{ K, self-field}))$ to 8 T is ~ 0.82.

The I_c measurements of short samples taken from the ends of the spools show that all conductors are fairly consistent with each other. The average I_c at 77 K is 644 A, and in perpendicular field of 8 T, 4.2 K is 526 A with a sigma of 3.6%. From these measurements, the performance of individual coils is expected to be uniform at 77 K and also at higher fields when operated at lower temperatures.

In addition to the measurements performed at BNL, measurements were also made at SuNAM on samples taken from various spools. There the measurements were made at 77 K, self-field, and at 20 K, 3.5 T, and 4 T fields applied perpendicular to the wide face of the tape. SuNAM provided data for eight of the nine spools, whereas BNL measured six of the nine spools of the conductor. From the data summarized in Table IV, one obtains the following ratios between the critical current at 77 K, self-field, to critical current at 20 K, 4 T, to be 0.67 ± 0.03, between 4.2 K, 4 T, and 20 K, 4 T to be 1.84 ± 0.07, and between 4.2 K, 8 T and 4.2 K, 4 T to be 0.66 ± 0.01.

TABLE IV
CRITICAL CURRENT OF SHORT SAMPLES TAKEN AT BNL AND AT SUNAM

Lab	Temp. [K]	Field [T]	Average [A]	σ [A]	σ/Average
SuNAM	77	0	634	36	5.7%
SuNAM	20	4	423	28	6.7%
BNL	77	0	628	51	8.1%
BNL	4.2	4	793	28	3.5%
BNL	4.2	8	524	20	3.7%

Fig. 4. Computer-controlled automatic winder used for winding CAPP coils.

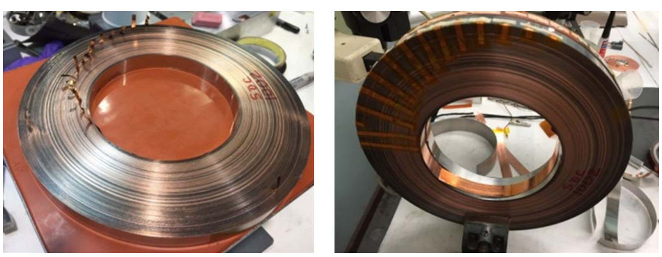

Fig. 5. (Left) Single-pancake coil with voltage taps. (Right) Double-pancake unit made with two single pancakes with a spiral splice joint inside.

IV. CONSTRUCTION

Six single pancake coils were wound with 12 mm wide and 100 μm thick HTS tape from SuNAM with the automatic coil winder (see Fig. 4). Turn-to-turn insulation was 25 μm Stainless Steel (SS) tape, which also helps in quench protection and adds to the support structure [2]. As a part of the Quality Assurance (QA) program, a number of voltage taps were installed (see Fig. 5 left) and removed after 77 K testing of the individual pancake coils. Insulating Mylar sheets of 0.25 mm thickness are installed on either side of the pancakes. A double pancake coil unit is built with a spiral joint at the inner radius of two single pancakes (see Fig. 5 right). Three double pancake units were assembled together with copper discs in between and on either ends to make the CAPP/IBS solenoid. Fiberglass-epoxy and stainless steel band were wrapped under tension on each double pancake to provide radial support structure (see Fig. 6). Voltage taps were placed on the inner and outer radius of each single pancake. Other instrumentation included temperature sensors and a Hall probe. Design and construction techniques were similar to those used in building the SMES coil [2]. The number of turns (which vary because of the thickness in conductor) and the location of various pancakes in CAPP/IBS solenoid are given in Table V.

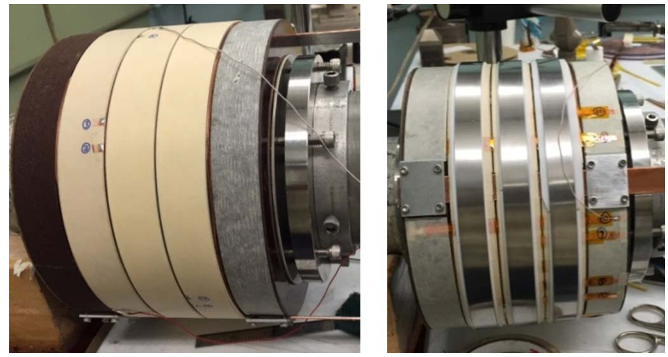

Fig. 6. (Left) Fiberglass epoxy and (right) stainless steel band on each double-pancake unit as a part of the radial support structure.

TABLE V
NUMBER OF TURNS AND LOCATION OF VARIOUS PANCAKE COILS

Pancake Coil	#1	#2	#3	#4	#5	#6
No. of Turns	328	328	308	299	310	308
Location	C	D	E	F	A	B

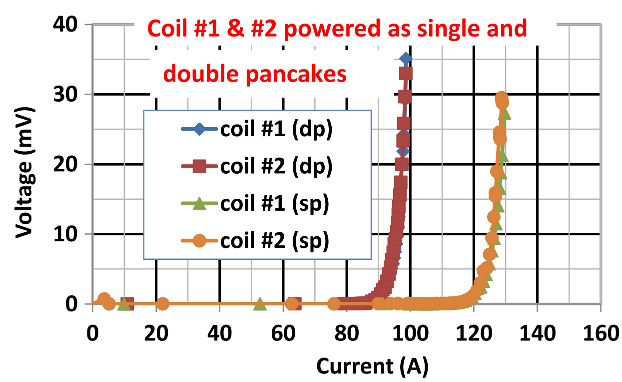

Fig. 7. Measured performance (V–I curve) at 77 K (in liquid nitrogen) of pancake coils #1 and #2 when powered in single-pancake (individually) and double-pancake (together) configurations.

V. TEST RESULTS

All double pancake coil units were tested at ~77 K in liquid nitrogen. Three leads allow testing of individual single pancakes in addition to the double pancake coil test. Fig. 7 (V–I curve) shows the test result of the first unit. The higher critical current in a single pancake coil test as compared to that in double pancake coil is due to the lower field on the coil in the former configuration. Figs. 8 and 9 summarize the performances of all six pancakes in the three double pancake coil tests.

Fig. 10 shows the performance of individual pancakes from "V–I" curve when all six are assembled and powered in series at 77 K. Pancake "A" is at the bottom and "F" at the top (see Table III). As expected, the performance is determined by the pancakes at the two ends ("A" and "F") due to the perpendicular component of the field. Fig. 11 is "V-T" curve when the current is held constant at ~101 A while the HTS solenoid is allowed to warm slowly from 65 K. This method of reaching the critical surface has the lowest inductive voltage noise as the current is held constant. The critical temperature, defined by 1 μV/cm, is reached at 68.3 K. Fig. 12 plots the critical current as a function of temperature. This plot is the summary of several test runs to

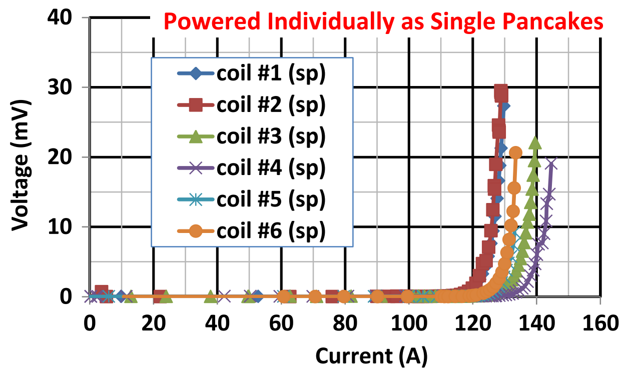

Fig. 8. Measured performance of pancake coils #1 through #6 at 77 K when powered in single-pancake configuration.

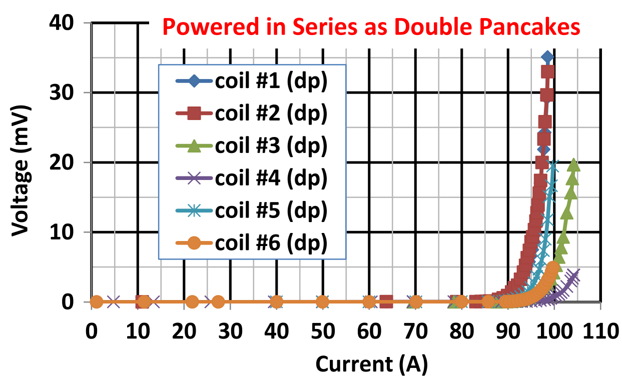

Fig. 9. Measured performance of pancake coils #1 through #6 at 77 K when powered in double-pancake configuration.

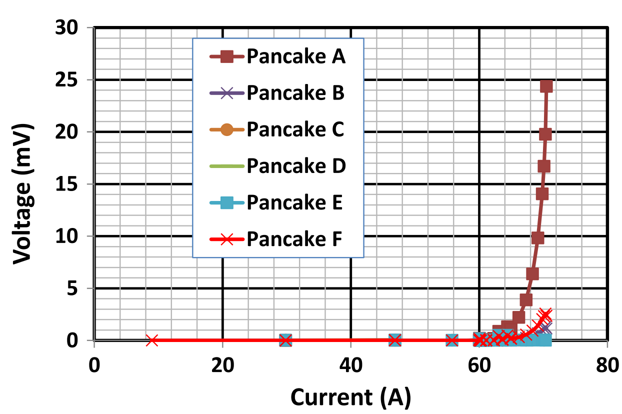

Fig. 10. Measured performance (V–I curve) at 77 K (in liquid nitrogen) of individual pancake coils when all six are powered together in series.

obtain the critical surface as defined by 1 μV/cm criterion. The maximum current the CAPP/IBS solenoid reached was ∼590 A which corresponds to ∼10.8 T peak field on the coil. This exceeds the requirement of demonstrating 10 T peak field.

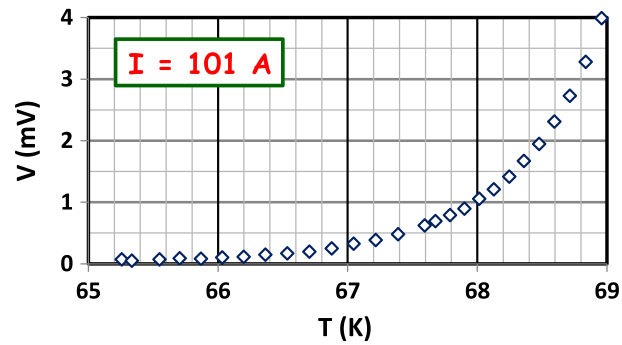

Fig. 11. Measurement of critical temperature of CAPP/IBS solenoid at ∼101 A when the current is held constant and coil is allowed to warm up slowly. The criterion of 1.5 mV or 0.1 μV/cm implies a critical temperature of ∼68.3 K.

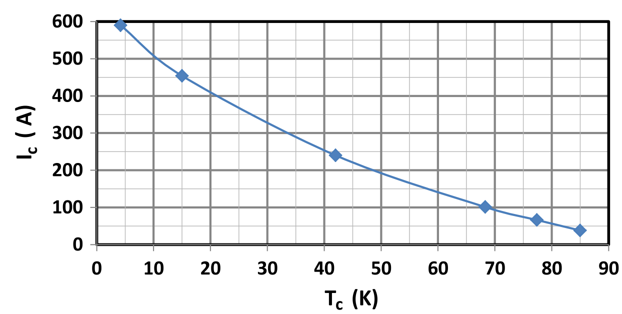

Fig. 12. Critical current as a function of critical temperature for the criterion of ∼1.5 mV over or 0.1 μV/cm over the entire CAPP/IBS solenoid.

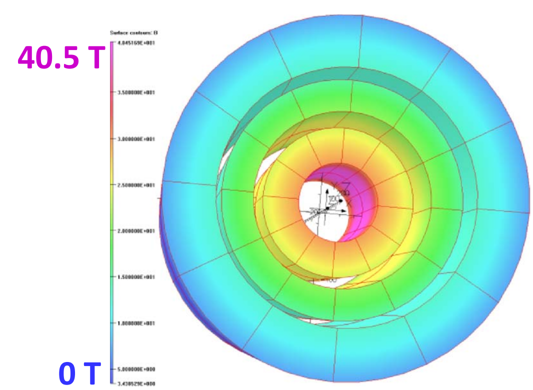

Fig. 13. Magnetic design of a hybrid ∼40-T solenoid. Two inner coils are made with HTS, and the outer coil is made with LTS.

VI. Discussion

The six pancake CAPP/IBS solenoid, which is described in this paper, is similar to the twelve pancake solenoid built and tested as a part of the SMES [2] program. Both have the same inner and outer radius, and used the same construction techniques. The main difference was in the conductor. Whereas the CAPP/IBS solenoid used ∼100 μm thick 12 mm tape from SuNAM having a ∼40 μm thick copper, SMES used ∼160 μm thick 12 mm tape from SuperPower [6]. The performance of pancake coils made with SuNAM conductor was very uniform and the conductor did not have any delamination issue. SuNAM conductor has significantly higher 77 K, self-field critical current but significantly lower lift factor at 4 K and 8 T. Because of this, the maximum critical current reached in the CAPP/IBS solenoid at 4 K was lower than that in the similar SMES inner coil test.

VII. Magnetic Design of a Very High Field Solenoid

A possible magnetic design of a very high field solenoid (∼40 T) is shown in Fig. 13. The inner two layers are made with REBCO and the outer with Nb_3Sn (LTS). REBCO coils create ∼25 T field and LTS ∼15 T. The major challenge in such a magnet will be dealing with very high stresses. Following the design of the SMES [2], the coil is divided in three layers to intercept the stress accumulation.

VIII. Conclusion

REBCO has a potential for producing very high fields as needed for the research at CAPP/IBS. Construction and test results presented here are encouraging. However, significant R&D is still needed given the much higher field and stresses in a 35–40 T, 100 mm solenoid.

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