Test Results of High Performance HTS Pancake Coils at 77 K

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***Abstract*—A series of pancake coils using several kilometers of second generation (2G) (RE)BCO conductor has been fabricated as a part of a R&D program to build a large aperture high field solenoid for energy storage application. This paper discusses the preparation of double pancake coils and the test results at 77 K before assembling the final magnet. These tests played an important role in assuring: the quality of conductors, coil winding and assembly, and integrity of splices within the coils.**

***Index Terms*—Critical current, high temperature superconductor (HTS) solenoid, low resistance splice, pancake coil.**

I. Introduction

A HIGH FIELD solenoid (~24 T at 4 K), built with high temperature superconductor (HTS), is currently under construction at Brookhaven National Laboratory (BNL) for a superconducting magnet energy storage (SMES) device [1], [2]. HTS not only generates ultra-high fields and very high energy densities, but also enables a compact design of the whole magnet assembly. This project is funded by Advanced Research Program Agency—Energy (ARPA-E), USA with ABB Corporation, BNL and SuperPower Inc. being the research partners. The prototype magnet consists of two co-axially nested solenoids supported by a suitable mechanical structure [3]. Single pancake coils (SPC) [Fig. 1(a) and (b)], the basic building blocks of this solenoid, are fabricated using surround copper (Cu) stabilized 2G (RE)BCO conductor (SCS12050-AP) from SuperPower Inc. [4]. As a next step, two SPCs are assembled into a double pancake coil (DPC) unit with a splice in spiral geometry placed on the inner-most turn. All DPC units are individually tested at 77 K. These test results form a critical Quality Assurance (QA) check before assembling the final magnet with fourteen DPC units in the inner solenoid and nine DPC units in the outer solenoid.

II. Details of Single Pancake Coils

The ~12 mm wide conductor was co-wound with a slightly wider (~12.3 mm) stainless steel (SS) ribbon (grade 304) to minimize the stress accumulation, to help in quench protection, and to provide turn-to-turn insulation [5]. There are four types of SPC depending on the combination of the conductor and SS ribbon used. More details are provided in Table I. The Table also lists the computed value of fields in a SPC when energized to 100 A. The HTS layer of the conductor faces inward toward the winding bobbin. Both SS and conductor spools were loaded with a relatively low tension during the winding process. The conductor was visually inspected during the coil winding. In order to closely examine the conductor for the presence of possible anomalies, voltage taps were inserted after first 10 and 25 turns and then after every 25 turns of the coil. After winding, both surfaces of the coil were painted with a thin layer of epoxy.

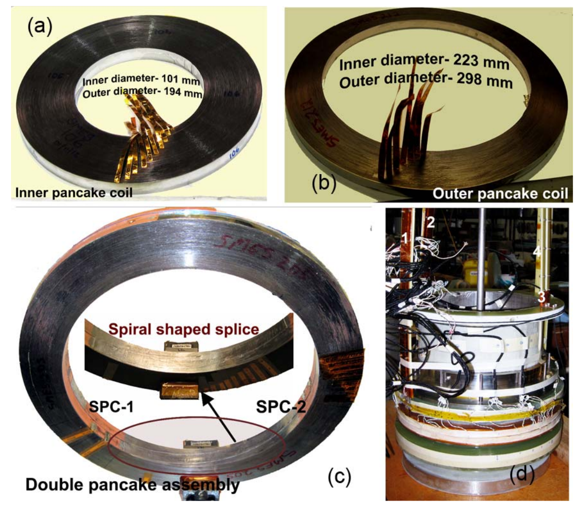

Fig. 1. Representative of the (a) inner single pancake coils and (b) outer single pancake coils built using 2G (RE)BCO conductor from SuperPower Inc. (c) A spiral shaped splice placed on the inner-most coil turn of a DPC assembly. SPC-1 and SPC-2 refer to the companion coils forming a DPC unit. (d) The DPC assembly after attaching the four current leads (labeled as 1, 2, 3, and 4) and after completing the electrical wiring of multiple voltage taps inserted at coil sections. Refer to text for the details.

III. Double Pancake Unit

A. Assembly Method

To provide electrical insulation between a pair of SPC, two pieces of mylar spacer, each with a thickness of ~127 μm, were used. Next, coils were electrically joined by a spiral shaped splice [Fig. 1(c)] using indium based solder. The splice overlap length (L_{sj}) is 15 cm for the inner coils and 20 cm for the outer coils. All splices were prepared using the same methodology as discussed in our earlier work [6]. Voltage taps were inserted about 2 cm away from either end of the spliced section to monitor its resistance (R_{sj}).

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TABLE I
PANCAKE COIL PARAMETERS

Inner coil parameters				
Inner diameter (mm)	~ 101			
Outer diameter (mm)	~ 194			
Coil type	A	B	C	D
Nominal thickness of conductor (µm)	-	~ 120	-	~ 160
Cu stabilizer thickness (µm)	-	~ 65	-	~ 100
Nominal thickness SS ribbon (µm)	-	50	-	50
Nominal length of conductor per coil (m)	-	~ 125	-	~ 100
Nominal number of turns per coil	-	~ 270	-	~ 215
Number of pancake coils	-	4	-	24
Perpendicular field (T) at 100 A		0.24		0.19
Parallel field (T) at 100 A		0.41		0.33
Outer coil parameters				
Inner diameter (mm)	~ 223			
Outer Diameter (mm)	~ 298			
Coil Type	A	B	C	D
Nominal thickness of conductor (µm)	~ 120	~ 120	~ 160	~ 160
Cu stabilizer thickness (µm)	~ 65	~ 65	~ 100	~ 100
Nominal thickness SS ribbon (µm)	25	50	25	50
Nominal length of conductor per coil (m)	~ 211	~ 180	~ 170	~ 149
Nominal number of turns per coil	258	220	208	182
Number of pancake coils	6	4	4	4
Perpendicular field (T) at 100 A	0.23	0.20	0.19	0.16
Parallel field (T) at 100 A	0.30	0.26	0.23	0.21

B. Preparation for the Electrical Test

For thermal conduction, ∼3 mm thick Cu disks were placed on the top and bottom of the DPC unit. A 127 μm thick Mylar spacer electrically isolated the two SPC. To keep the assembly physically intact and to ease the mechanical handling, the whole unit was mounted to an electrically insulated SS tube and then clamped between ∼13 mm thick G-10 flanges. The coil pair was electrically connected in series by attaching the current leads to the outer end of the coil windings. The test rig for the outer pancake assembly provides the flexibility to independently test each of the coils in a DPC assembly [Fig. 1(d)].

IV. EXPERIMENTAL DETAILS

All DPC assemblies were tested in an open mouth vertical dewar. To avoid non-uniform thermal strain on the coils, the whole assembly was cooled down very slowly, initially with nitrogen gas until the coil voltage start dropping at a slow and steady rate. The liquid nitrogen flow rate was then increased gradually. The cool-down process took about 2 hrs. After the test, coils were brought back to room temperature by letting liquid nitrogen vaporize with the help of controlled heat supplied by an electric lamp and, additionally, an electric fan to prevent condensation on the coil surfaces. The coils were energized by a DC power supply (Model-HP 6680) until the electric field in the coil exceeded 1 μV/cm. The voltages developed in different coil sections were monitored simultaneously using a HP 3457A series multi-meter. The critical current of the DPC unit is defined at 0.1 μV/cm, which allows an end-to-end voltage of ∼1 mV to ∼1.27 mV in the inner coils and ∼1.5 mV to ∼2.2 mV in the outer coils. Further, n-value refers to the slope of current-voltage curve when plotted on a logarithmic scale.

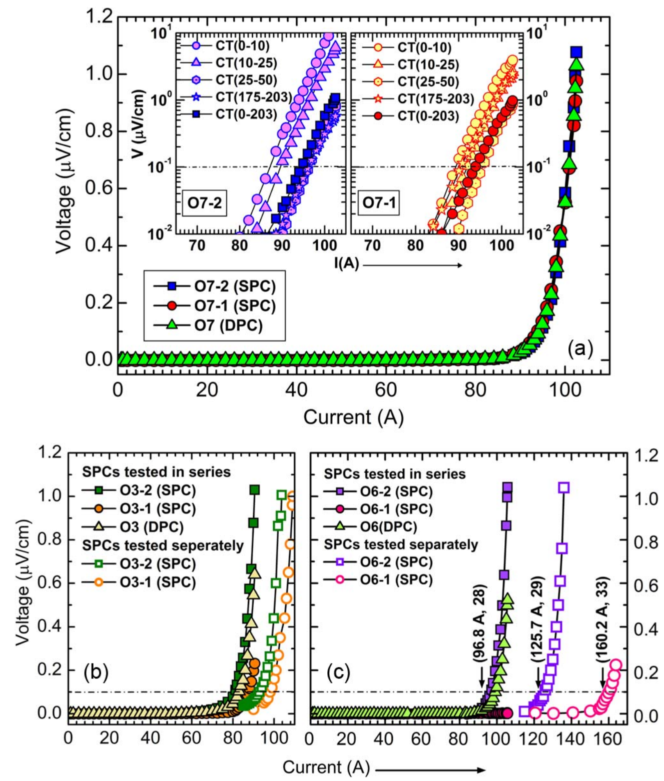

Fig. 2. Electrical characteristics of the representative outer double pancake coil assemblies. (a) Top panel shows the voltage distribution in different coil turn (CT) segments [such as CT(0–10), CT(10–25)] of the companion coils when connected in series as a DPC assembly. (b) and (c) Bottom panel also compare the performance of the single pancake coils when tested separately. The values in parenthesis in (c) indicate the I_c at 0.1 μV/cm and the corresponding n-value. Refer to text for details.

V. RESULTS AND DISCUSSION

A. Critical Current of the Double Pancake Coils

The salient features of the electrical characteristics of the DPC units are depicted in Fig. 2. One scenario is such that the companion coil exhibits almost the same I_c and thereby contributes equally to the overall performance of a DPC unit. A typical example (O7) is shown in Fig. 2(a). Inner DPC units-I2, I5, I8, and I14 also fall into this category [Fig. 3(a)]. In the second scenario, one of the companion coils partly or completely limits the overall current in a DPC unit. An example of former case (O3) is shown in Fig. 2(b). Further, seven inner DPCs (I1, I3, I4, I6, I7, I11, and I13) and two outer DPCs (O3 and O5) show a qualitatively similar behavior (Fig. 3). An example of latter case is shown (O6) in Fig. 2(c). Here, the stand-alone performance of the companion coils (O6-1 and O6-2) and their overall performance in a DPC unit are compared. Three inner DPCs (I9, I10, and I11) and six other outer DPCs (O1, O2, O9, O4, and O8) also show a qualitatively consistent picture as above (Fig. 3). It is important to mention that the O6-1 recorded the highest I_c when tested independently as a

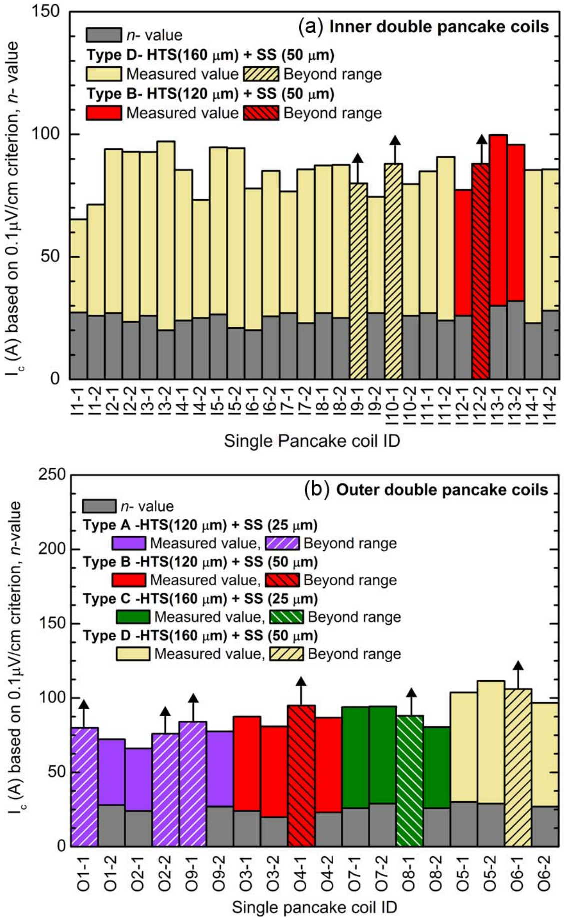

Fig. 3. Critical current (I_c) according to 0.1 μV/cm criterion and the corresponding n-value of (a) inner and (b) outer single pancake coils when connected in series as a double pancake assembly. The arrow above the crossed section indicates that I_c of the coil is beyond the upper boundary of the histogram and is limited by its companion coil. Refer to Table I for the details of four types (A, B, C, and D) of the single pancake coils.

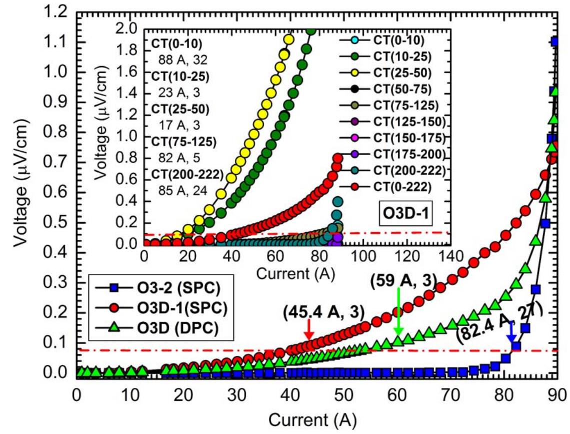

Fig. 4. One DPC assembly (O3D) exhibiting an inferior performance. Inset shows the voltage distributions in the bad coil (O3D-1). I_c at 0.1 μV/cm and the corresponding n-value of the coil sections (CT) are also shown. O3D-1 was subsequently replaced with O3-1. Refer to text for details.

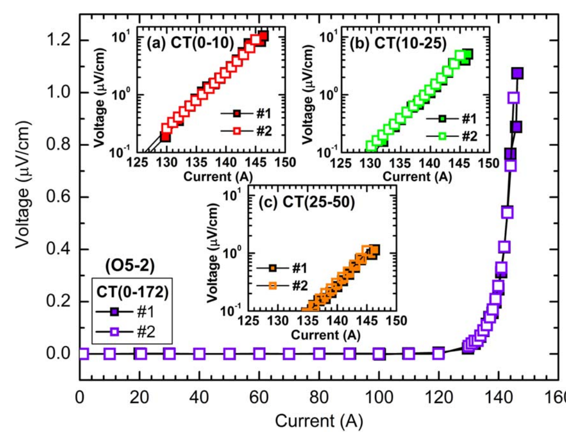

Fig. 5. Electrical characteristic of a single pancake coil, when tested separately as a companion coil of a double pancake assembly (O5-D) (#1) and later on as a part of reassembled double pancake unit (O5) (#2). Inset shows the voltages in the coil turn (CT) segments under similar conditions (#1 and #2).

single pancake coil [Fig. 2(c)]. The major voltage contributions were coming from the innermost 25 turns. This section of coil was made with a conductor having a uniform I_c of $\sim$505 A. Nevertheless, all DPC units mentioned in Fig. 3 exhibit a fairly sharp transition with I_c of companion coils ranging from $\sim$70 A to $\sim$100 A for the inner DPC assemblies [Fig. 3(a)] and $\sim$75 A to $\sim$110 A in the outer DPC assemblies [Fig. 3(b)]. Further, the n-value (between 20 and 32) of all coils remains high down in the electric field range 0.1 μV/cm to 1 μV/cm indicating that these coils have no damaged sections in the winding.

There are two outer DPC units showing peculiar electrical characteristics and thereby making them unsuitable for the final assembly. Fig. 4 shows one of such cases, where the current in an outer assembly (O3D) is limited by one of the companion coil (O3D-1) showing a broad voltage onset spanning a range $\sim$10 A to $\sim$90 A with a relatively low overall I_c at 0.1 μV/cm (45.4 A) and n-value as low as 3, which is an indicator of presence of local defects in the coil. The imperfections on the conductor surfaces such as bubbles, blemishes, small dings and a periodic appearance of long length scratches were noted while winding the coil turn (CT) segments from coil turn number 10 to 175 (10–175). As shown in the inset of Fig. 4, CT(25–50) and CT(10–25) carry very low currents compared to other sections of the coil. The low n-value possibly reflects the presence of local defects consistent with the visual inspection of the conductor in those coil sections. However, two subsequent thermal cycles did not cause any further degradation of the coil. The coil O3D-1 was subsequently replaced with O3-1. The resultant DPC assembly (O3) shows an acceptable performance [Fig. 2(b)].

In the following, we show that the thermal cycling and mechanical handling of the pancake coils during the reassembling process of a DPC unit did not cause any performance degradation. Fig. 5 shows that the electrical characteristics of a good SPC (O5-2) when measured as a part of its original assembly (#1) with a bad companion coil and the reassembled DPC assembly (O5) (#2) with a good companion coil (O5-2). The voltage distributions in the coil sections were also reproducible within the limits of experimental accuracy.

B. *Resistance of Spiral Shaped Joints*

Fig. 6 provides a direct comparison of the resistance of splices (R_{sj}) in the DPC units. Considering the fact that (1)

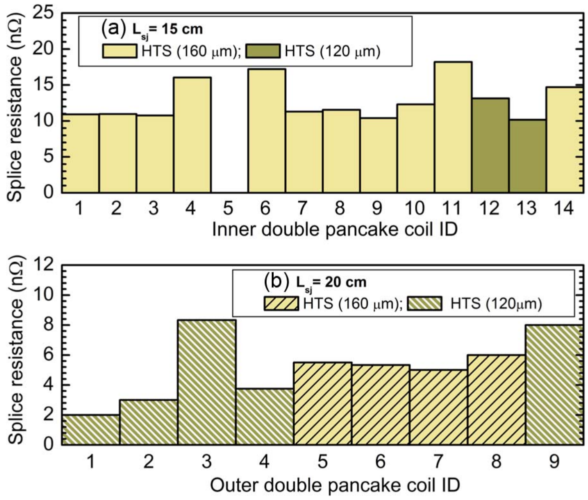

Fig. 6. Total resistance (R_{sj}) of spiral shaped splices at 77 K in the inner and outer pancake assemblies. Conductors with a total thickness 160 and 120 μm contain copper stabilizer of thickness 100 and 65 μm, respectively. This splice configuration contains two splices in total (refer to [6] for details). The splice overlap area was kept the same in both spliced sections. This means resistance per splice can be taken as the half of R_{sj} as plotted in this figure.

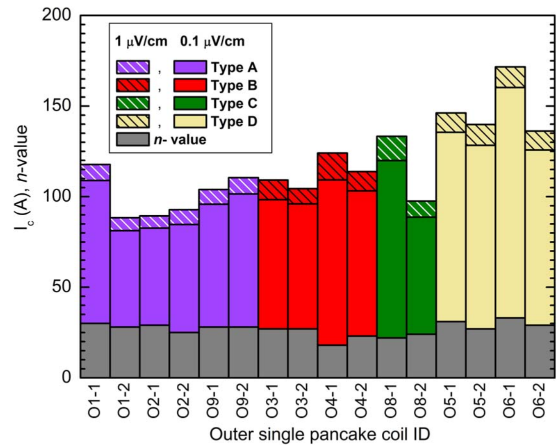

Fig. 7. Comparison of critical currents at 0.1 and 1 μV/cm criterion and the corresponding n-value of a series of outer single pancake coils with four combinations (refer to Table I for details) of conductor and SS ribbon.

all splices have undergone identical preparation conditions as mentioned earlier and (2) the thickness of indium solder in the hand-made splice is kept as uniform as possible within the accuracy of laboratory-scale production, the observed variability in R_{sj} could largely be attributed to factors such as the surface conditions of conductors of different production batches, contact resistance between the silver over-layer and Cu stabilizer layer and the transverse resistance of Cu stabilizer (R_{Cu}). For instance, splices in the eight out of fourteen inner DPC assemblies exhibit R_{sj} of 11 ± 1 nΩ at 77 K of which seven splices are made with conductor of $\sim$100 μm thick Cu stabilizer while one splice has $\sim$65 μm Cu stabilizer in it. In another five such assemblies, R_{sj} falls within the range, 15 ± 1 nΩ with four of them made with conductor of $\sim$100 μm thick Cu stabilizer [Fig. 6(a)]. R_{sj} is found to show no sensitivity to R_{Cu}. This possibly indicates the dominant influence of the extrinsic parameters. Having said so, a reasonable correlation is found to exist between R_{sj} and splice overlap area. Assuming that R_{sj} of 11 nΩ is typical of the series for L_{sj} of 15 cm, it is expected to scale down at least to 8 nΩ for L_{sj} of 20 cm in the outer DPC assembly. Overall, this argument holds well [Fig. 6(b)]. Two splices made with conductor of $\sim$65 μm stabilizer exhibit similar R_{sj}, whereas the other three splices of similar type fall in a still lower range 3 ± 1 nΩ. All four splices made with conductor of $\sim$100 μm thick stabilizer exhibit a similar resistance ($\sim$5 nΩ). The splice in the inner DPC unit #5 showed a comparatively large resistance $\sim$325 nΩ the first time (not shown). R_{sj} dropped to 275 nΩ when the splice was replaced with a conductor from same batch as the original one. This possibly indicates the presence of local defects in the inner turn of the coil(s) spanning the spliced area.

C. Comparison of Electrical Performance of a Series of SPC

It was shown in Fig. 3(b) that I_c of few outer SPCs were beyond the range of measurement when tested together with their companion coils in a DPC unit. In such cases, independent testing of the SPC was helpful. Fig. 7 compares the end-to-end performance of a series of outer SPCs. All coils exhibit a fairly sharp onset voltage with their I_c at an electric field of 0.1 μV/cm and 1 μV/cm differ by $\sim$8 A to $\sim$14 A. Twelve SPCs of this series show a qualitatively similar voltage distribution pattern in the electric field range from 0.1 μV/cm to 10 μV/cm with the largest contribution to the overall coil voltage coming from the innermost 10 turns followed by adjacent section(s) having a progressively reduced contributions. Practically no voltages above 0.01 μV/cm were recorded beyond coil turns $\sim$50 or $\sim$75. A deviation from this typical trend is evidenced in the other four coils (O2-2, O4-1, O4-2 and O5-2). The primary contribution to the overall coil voltage was coming from the intermediate and/or the end sections of these coils. This could possibly be due to the local non-uniformity of the conductor properties and/or the variability in the in-field performance of the conductor sections in the coils.

VI. Conclusion

Forty six pancake coils, including twenty eight inner coils and eighteen outer coils were built. These coils were assembled into twenty three double pancake coil units and tested successfully at 77 K. As envisioned, 77 K tests played a crucial role in the QA process for the prototype $\sim$24 T solenoid magnet for the SMES device. The technology for the low resistance spiral shaped splices has been demonstrated. The detailed diagnosis of the coil sections provides an additional check on the quality of conductors, winding and assembly process of the coils.

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