

The Construction and Testing of YBCO Pancake Coils for a High Field Solenoid

Y. Shiroyanagi, A. K. Ghosh, R. Gupta and W. B. Sampson

Abstract— Pancake coils are being fabricated using second generation (2G) High Temperature Superconductor (HTS) for a prototype 10 T solenoid. The length of conductor in each coil is 100 m and the inner diameter of the coil is 101 mm. The critical current of each coil was measured at 77 K in liquid nitrogen and down to ~20 K in helium gas. It has been observed that the effect of thermal shock during cool-down may cause coil performance to degrade irreversibly. The detailed results and the improvements to achieve 10 T will be discussed.

Index Terms—2G HTS solenoid, pancake coil, critical current, thermal degradation

I. INTRODUCTION

VERY high field solenoids (~30T) are needed in the Muon Collider. YBCO conductors hold considerable promise for this application. Pancake coils that can be assembled into a solenoid have been wound and individually tested at BNL as part of a program with Particle Beam Lasers Inc. (PBL) to build a prototype 10 T magnet. Seventeen single pancake coils made with YBCO from SuperPower (SP) have been wound and tested at 77 K. In addition, two double pancake coils have been tested in the temperature range between 20 K and 80 K. These coil elements will be assembled into a 10 T solenoid which will have a total of 28 coils. This magnet will be used as the outer coil for another solenoid in developing the technology for very high field magnets [1].

II. DESIGN AND CONSTRUCTION OF TEST SETUP

The major parameters of the solenoid design are shown in Table I. The inner diameter of the coil is 101 mm and the outer diameter is ~160 mm. Each pancake coil is wound from 100 m long, 4 mm wide 2G tape which is co-wound with 0.0254mm thick stainless steel tape serving as turn-to-turn insulation. The double pancake coil assemblies are sub-units of a ~10T solenoid that will be made up of 14 such coils. The double-pancake is clamped between two copper plates for conduction cooling and then placed between thick micarta

flanges. For a nitrogen test, the coil assembly is immersed in liquid nitrogen (LN_2) so the temperature in the coils is 77K. When the magnet is tested at lower temperatures, the coil assembly is inserted in an open cryostat and helium gas flows through the copper tubing attached to the copper plate. Temperatures are controlled by helium gas flow rate. Fig.1 is a photograph of the coil assembly. A double coil, copper plates and tubing and magnet leads are shown.

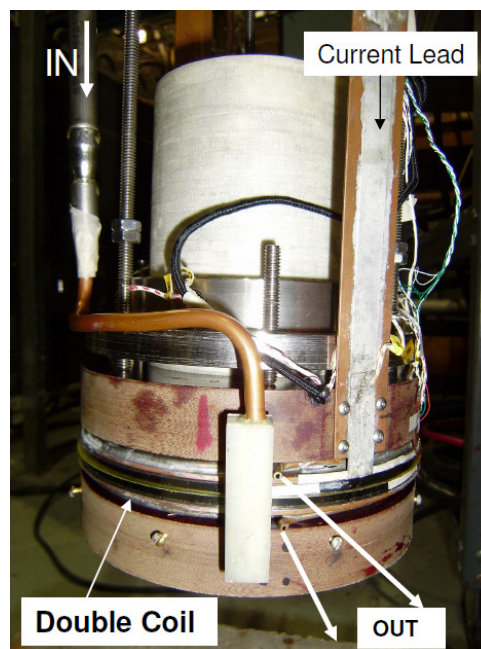


Fig. 1: Fixture to test pancake coils. A double coil between copper plates is placed between two 2.54 cm thick micarta flanges. One of current leads are shown. Helium gas enters from the top and flows through two sets of copper tubing and comes out at the outlets. 8 coils can be accommodated by this set up.

Coils were energized by a high current power supply. The voltage across the coils was measured by a digital multi-meter. The critical current of each coil assembly is defined at 0.1 $\mu V/cm$ which allows 1 mV per coil (each single coils has 100 m conductor). The manufacturer also provides I_c for each conductor which is defined at 1 $\mu V/cm$ as a short sample and self-field. We use a more stringent criterion for defining coil I_c compared to that use for conductor I_c by the vendor. Conductors used in this paper are categorized by I_c from the vendor. In the followings, a low I_c conductor refers to a conductor with $I_c \sim 90$ A, a medium I_c conductor refers to a conductor with $I_c \sim 115$ A and a high I_c refers a conductor with $I_c \sim 160$ A.

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TABLE I: DOUBLE PANCAKE COIL PARAMETERS

Inner diameter (mm)	101
Outer diameter (mm)	~160
Length (mm)	9
Number of turns	480
Total conductor length (m)	200
Field perpendicular (T) at 40A	~0.3
Field parallel (T) at 40A	~0.5

III. TEST RESULTS

A. Single Pancake Tests in LN₂



Fig. 2(a) Photograph of single coils: Fourteen single coils were wound and tested in LN₂. Voltage taps are attached every 50 turns. No indication of local defect was observed in their V-I curves.

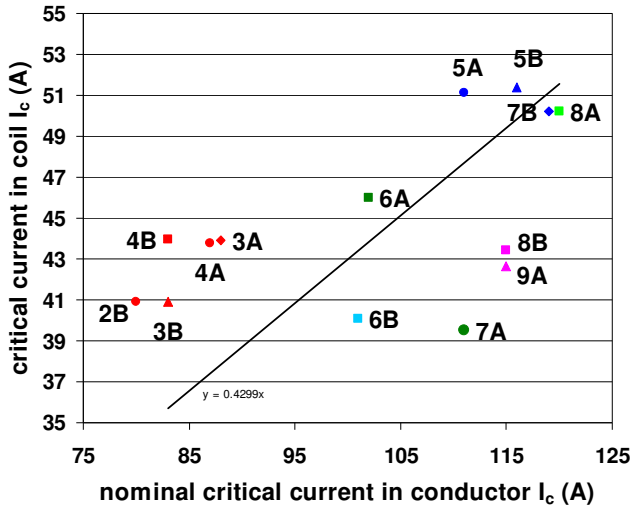


Fig. 2(b) Correlation between measured critical current of a single coil and the minimum critical current of each conductor given by manufacturer

When energized pancake coils behave just like test samples of conductor and a voltage-current curve can be measured and analyzed in the usual way to give an “n” value and a “critical current”. Because of inductive effects, power supply ripple limits the minimum dc voltage that can be resolved.

V-I curves of each single coil were measured in LN₂. The purpose of this test is to establish the baseline of each coil. In order to screen for possible local defects, voltage taps were attached every 50 turns to monitor sectional voltages. Fig. 2(a) is a photograph of single coils. Fourteen single coils were wound and measured in LN₂. The standard method of cooldown takes about 2 hours with the warm magnet in a bucket dewar which is then slowly filled with LN₂ from a

storage vessel. Warm up takes place by letting LN₂ vaporize overnight so that it takes ~ 24 hours to warm up.

Fig. 2 (b) shows the measured critical current of each single coil versus the nominal critical current of conductors which is provided by the manufacturer. There is a weak correlation between these critical currents. Partly, it is because manufacturer’s critical current data includes only the self-field measurement and not the in-field performance. Some conductor may be more sensitive to magnetic fields. The correlation might be better at low temperatures and high fields according to SuperPower Inc. [2]. Coils with similar critical currents were chosen to be double pancake coils.

B. Double Pancake Tests in LN₂

Two double pancake coils were assembled from medium I_c conductor tested in LN₂. One is a combination of coil 7B and 8A, which are matched coils from different batches of conductors. The other is a combination of coil 8B and 9A which are from the same 200 m spool of conductor. The V-I curves of each single coil and the voltage across each coil in the double pancake coils of 7B and 8A are shown in Fig. 3 (a).

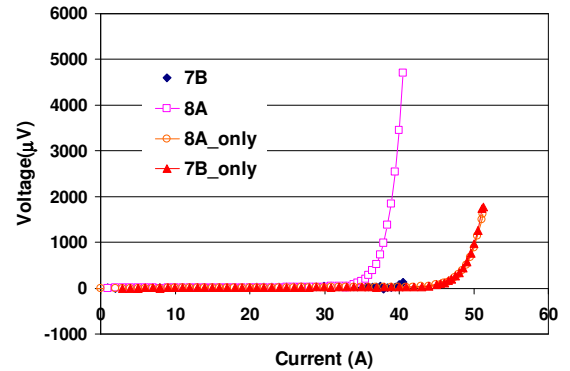


Fig. 3(a) Voltage-current curve of coil 7B and 8A at 77 K made from a different batch. Solid triangles and open circles indicate a single coil performance. They show very similar behavior. The open squares and solid squares indicate performance in the double coil. When the voltage across 8A reaches to 1 mV at 38 A, the voltage across 7B still remains at 0.1 mV. I_c of 7B is extrapolated to be 43A.

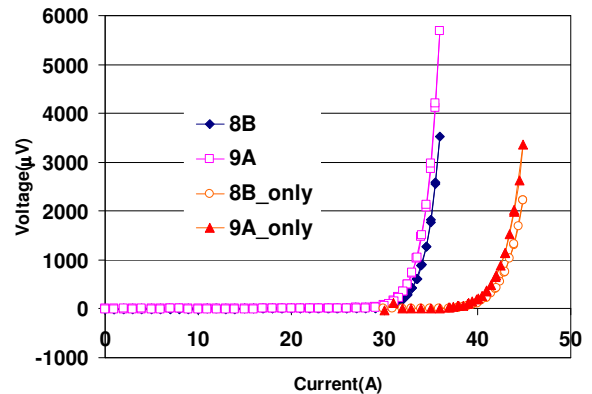


Fig. 3(b) The voltage- current curve at 77K of coil 8B and 9A which are made from the same batch. The red solid triangles and open circles indicate single coil performance. The open squares and solid squares indicate performance in the double coil. These coils behave similarly as single coils and in the double coil.

The V-I curves of 8B and 9A are shown in Fig. 3(b). Although coil 7B and 8A are from different batch, both of

them have critical current of 50.2 A as single coils. However, the measured critical current within the double coil was quite different. The critical current for coil 7B was 38.0 A. The critical current for coil 8A was extrapolated to be 43.0 A.

Coil 8B and 9A also behave similarly as single coils. The critical current of 8B is 43.5 A and 9A is 42.7 A. The voltage across each coil in the double coil is also similar as expected. A critical current was 34.1 A for 8B and was 33.4 A for 9A. From these results, we learned that single coil performance may not necessarily be reflected in double coil performance. The double coil from the same spool is the best matched combination.

C. Sensitivity of HTS Coils to Cooldown

The reason for the slow cooldown is based on experience from earlier tests. A rapid cooldown can induce thermal stress in the conductors. These effects are avoided by 2 hour slow cooldown. Initially, a rapid method of cooldown (about 15 min) with LN₂ sprayed directly on the warm magnet from a storage vessel. An example of this thermal degradation is illustrated by coils 2A and 2B wound from low I_c conductor.

The V-I curves for the initial energization is shown in Fig. 4(a). The coil voltage was monitored every 25 turns with additional voltage taps. The n-value for 2A is ~ 25 and for 2B is ~ 27. The V-I curves for each 25 turn section of coil 2B are in Fig. 4(b). The innermost 25 turns where magnetic field strength is maximum show the largest voltage. The voltage decreases for turns 25-50, 50-75, 75-100 etc.

Several 15 min cooldowns did not change the V-I curves for these windings but plunging the coil assembly into a cryostat filled with LN₂ did alter the V-I curve of coil 2A. The section affected was between turns 175 to 200. These turns also exhibited hysteretic behavior.

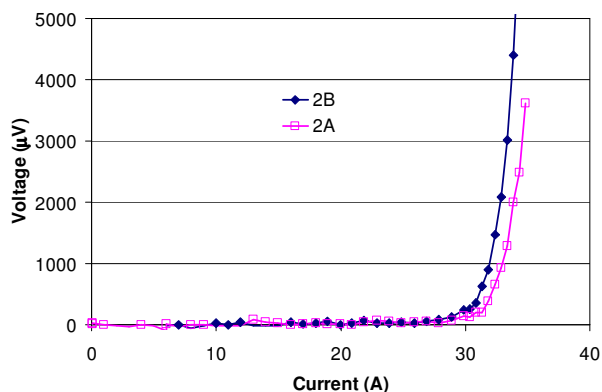


Fig. 4(a) V-I curve of two coils from the low I_c sample. The open squares represent 2A and the solid circles represent 2B. The n-value for coil 2A is 25 and for coil 2B is 27 as expected.

When the magnet was warmed up overnight and re-cooled the next day the voltage-current curve for coil 1B showed higher voltage. After a number of thermal cycles the performance degraded significantly.

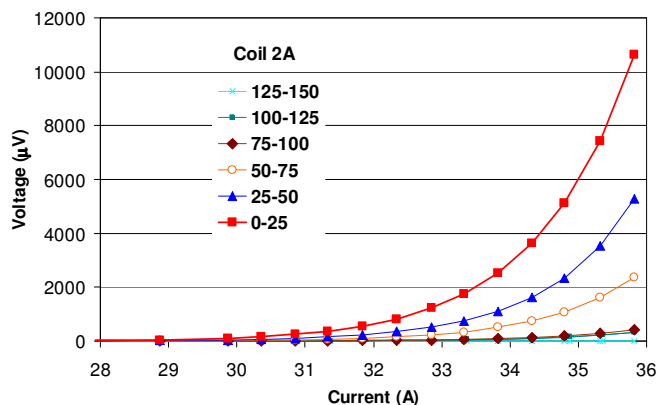


Fig. 4(b) Sectional voltages of low I_c coil (coil 2A). A sectional voltage is at maximum at the first 25 turns and gradually decreases toward outer turns. Sectional voltages at turns 100-125, 125-150, 150-175, 175-200, 200-240 are not distinguishable.

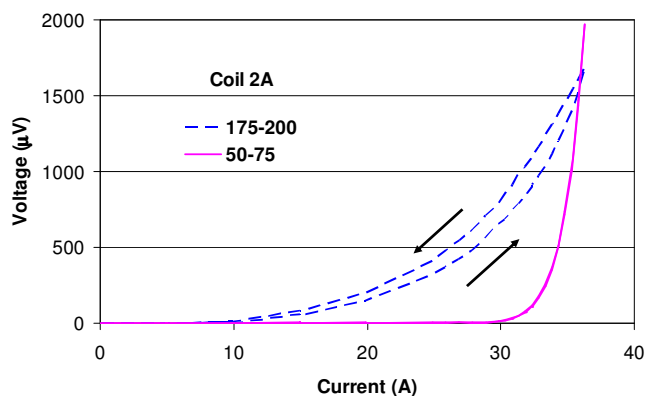


Fig. 5 Voltage-current curves of the coil 2A (low I_c) after plunging to LN₂. Dashed curve indicates 175-200 turns which is a damaged section. This section was indistinguishable before plunging (Fig. 4(b)). Solid curve indicates 50-75 turns which is normal.

The current corresponding to 1 mV decreased from 39 A in the first test to 22 A in the last test. The other indication of degradation is a hysteretic behavior as shown in Fig. 6. The voltage across coil 1B at increasing current is significantly lower than the voltage for decreasing current. Coil 1A and 1B were probably damaged on the first cooldown since they had much lower n values (~10) than expected.

Since we know what defective behavior looks like (low n-value, hysteretic behavior, increase of sectional voltage in the middle section), we also decided to monitor sectional voltages in every test.

With the standard 2 hour cooldown, none of the single coils exhibit indications of thermally induced defects such as hysteretic behavior or unusually high sectional voltages.

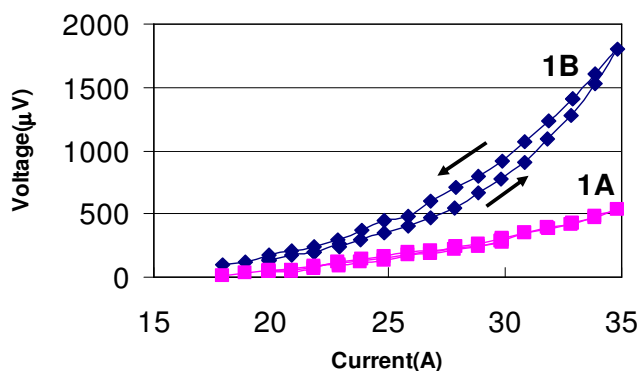


Fig. 6 Coil 1B shows “hysteretic” behavior as an indication of degradation. An upward arrow represents the voltage with increasing current and a downward arrow represents the voltage with decreasing current.

D. Double Pancake Tests in Helium Gas

Two double pancake coils were tested at lower temperatures using helium gas cooling. A technique used earlier in FRIB coils [3]. One is a combination of coil 2A and 2B, made from low I_c conductor and included 2A which had been exhibited the thermal stress damage as discussed earlier. We call this combination double coil #1.

The other consisted of coil 8B and 9A which are made from a single batch of medium I_c conductor. We call this combination double coil #2. Neither coil 8B nor 9A developed defects in the nitrogen test. Fig. 7 shows critical current versus temperature curves for each coil. Critical current is defined here as $0.1\mu\text{V}/\text{cm}$ (1mV per coil). The damaged coil 2A shows significant degradation at low temperatures. An extrapolation was used to obtain I_c of 9A at higher currents. These values are indicated as open triangles in Fig. 7.

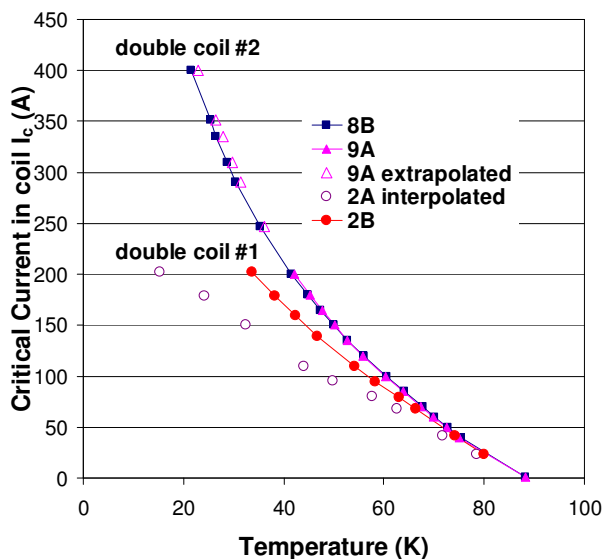


Fig. 7 Voltage-current curves of the double coils in helium gas. Below 40K, the voltage across 9A did not reach 1mV ($0.1\mu\text{V}/\text{cm}$) without risking 8B. So I_c is extrapolated. Voltage across 2A was always significantly higher than 1mV due to the defect from nitrogen test. So interpolation was used to obtain the values displayed.

I_c difference between coil 8B and coil 9A are much smaller than the difference between coil 2A and coil 2B as shown in Fig. 8. The I_c of 2A is 150A which is 50A lower than I_c of 2B at 30K . On the other hand, the I_c difference between coil 8B and 9A was within a few amps. 8B and 9A also shows higher critical current than 2A and 2B combination in all temperatures. For instance, I_c of 8B and 9A is 300A at $\sim 30\text{K}$ which is much higher than 150A of 2A and 2B combination. That is consistent with wire critical current data since 2A and 2B has $I_c \sim 90\text{A}$, and 8B and 9A has $I_c \sim 115\text{A}$. This suggests that the correlation between I_c in conductor and I_c in windings would be stronger in low temperatures. For coil 8B and 9A, the voltages across the innermost 50 turns were the largest which means no defect in the coil. Although the voltage across coil 9A is higher at 77K which means lower T_c , the voltage across 8B becomes higher as current increases above 135A . Lastly, the measurement was continued below 20K . However, significant degradation occurred at 400A (n-value suddenly became lower), thus, data below 20K are not shown.

IV. CONCLUSION

The correlation between I_c in coils and I_c in the conductors appears to be stronger at low temperatures than at 77K . A 10T solenoid has to be designed carefully to avoid thermal shock due to uneven temperature distribution within the coil. Since each coil has different critical currents, the critical current of a whole system is limited by the worst performance coil. So when these 14 coils are assembled into the system, the distribution of coils should be carefully considered. An advanced quench detection and protection system is under development which would be able to detect even smaller defects and protect the coil from possible damage and degradation [1], [3].

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