Wind-and-react Bi-2212 coil development for accelerator magnets

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Abstract
Sub-scale coils are being manufactured and tested at Lawrence Berkeley National Laboratory in order to develop wind-and-react $Bi_2Sr_2CaCu_2O_x$ (Bi-2212) magnet technology for future graded accelerator magnet use. Previous Bi-2212 coils showed significant leakage of the conductors' core constituents to the environment, which can occur during the partial melt reaction around 890 °C in pure oxygen. The main origin of the observed leakage is intrinsic leakage of the wires, and the issue is therefore being addressed at the wire manufacturing level. We report on further compatibility studies, and the performance of new sub-scale coils that were manufactured using improved conductors. These coils exhibit significantly reduced leakage, and carry currents that are about 70% of the witness wire critical current (I_c). The coils demonstrate, for the first time, the feasibility of round wire Bi-2212 conductors for accelerator magnet technology use. Successful high temperature superconductor coil technology will enable the manufacture of graded accelerator magnets that can surpass the, already closely approached, intrinsic magnetic field limitations of Nb-based superconducting magnets.

1. Introduction

The magnetic field limit in Nb-based accelerator-type dipole magnets is about 18 T [1]. This magnetic field limitation can be increased to about 21 T by improvement of the high field pinning efficiency in Nb_3Sn [1, 2], but improved pinning has not yet been demonstrated in Nb_3Sn wires. A presently more feasible way to move significantly beyond the Nb-based superconductors' intrinsic limitations is to switch to a new superconductor with an increased effective critical magnetic field (H^*_{c2}). Of the suitable alternative superconductors, only Bi-2212 is commercially available as a round wire, and is therefore, for accelerator magnet technology, the present most suitable alternative to the Nb-based materials. With an H^*_{c2}(4.2 K) of 85 T or higher [3], round wire Bi-2212 opens the possibility to move significantly beyond the magnetic fields that are achievable with Nb-based technology.

Lawrence Berkeley National Laboratory (LBNL), in close collaboration with industry, initiated the development of wind-and-react (W&R) round wire Bi-2212 accelerator magnet technology in 2006 [1, 4, 5]. The Bi-2212 technology is being developed to enable the use of Bi-2212 insert coils in future graded accelerator magnets. The choice of a W&R approach is dictated by the small bending radii of insert coils, in combination with the potential significant irreversible reduction of the critical current with strain [1]. The W&R technology is, however, complicated by the requirement to react the coils after manufacture at temperatures close to 890 °C in pure oxygen. This reaction places stringent demands on the construction and insulation materials used, as well as their compatibility with the Bi-2212 reaction.

Previous coils showed a significant amount of leakage of core constituents from the wires to the environment [4, 5]. The cause of this leakage was initially unclear, but it has now been concluded that the main cause of the leakage is lack of complete integrity of the Ag-alloy sheet around the wire core. The leakage is therefore being addressed at the wire manufacturing level, and significant improvements have been made.

This article reports on new studies that investigate the compatibility of insulation and coil construction materials in a cable clamp that simulates a coil environment [4]. The

article further reports on the manufacture, heat treatment, and test of three new coils that exhibit only minor leakage and a steadily increased critical current. The results demonstrate, for the first time, the suitability of W&R Bi-2212 technology for accelerator magnets.

2. Compatibility studies

Compatibility studies that investigate potential interaction of insulation and coil construction materials with the Bi-2212 reaction is ongoing work that provides basic knowledge on suitable materials. Such studies were, until recently, complicated by the fact that the wires and cables exhibited intrinsic leakage, i.e. not leakage as a result of what is in contact with the conductors. It has become clear that a conductor that is heat treated not in contact with other materials, might give the impression that it does not leak. To detect leakage, however, the conductor needs to be covered with an indicator, such as Y_2O_3. The indicator does not react with the Ag-alloy sheet and therefore does not initiate leakage, but it does react with the core constituents and can therefore be used as a medium to detect leakage [6]. The typical test that has been developed is to coat the conductor with Y_2O_3, which is white, and any leakage that occurs then shows up as blackening of the Y_2O_3 [7].

We performed such leakage tests on wires, extracted strands, and cable sections from LBNL cable 988, which is manufactured from 2007 generation Oxford Superconducting Technology (OST) strand with billet number PMM070420, i.e. a modern wire on which the leakage issues have been addressed. The conductors were coated with Y_2O_3 and reacted using a generic Bi-2212 reaction with an elevated maximum temperature $T_{max} = 900\,°C$ in pure oxygen. No leakage was detected in these tests, indicating that the conductors do not leak when reacted not in contact with other materials.

Next, 0.5 m long sections of insulated cable 988 were clamped in the 0.2 m long INCONEL® 600 LBNL cable clamp that was developed previously to simulate a coil environment [4]. The manufacturer's sizing was removed from the braided sleeve using a 4 h at 825 °C cycle in a constant flow of pure oxygen, before the insulation was placed around the cables in all the tests with the Al_2O_3–SiO_2 braided sleeve. The sizing was not removed prior to insulating the test cable for the pure SiO_2 insulation. The cable sections were clamped with a pressure of about 1 MPa, which is comparable to the mounting pressure that is used in the Bi-2212 sub-scale coils. The cable clamp is placed longitudinally in a tube furnace and the cable sections are long enough, so that the cable ends are below 870 °C when the clamped section is at 900 °C. In this way leakage from the cable ends is prevented. The insulated cable section was placed in contact with shims of INCONEL® 600, stainless-steel 304 (SS 304), or stainless-steel 316 (SS 316). Some of the shims were pre-oxidized at 900 °C for 1 h in air before placement in the clamp. The clamp was then reacted using a generic Bi-2212 reaction with an elevated $T_{max} = 900\,°C$ in a constant flow of pure oxygen. The reaction was identical for all the tests, except in one reaction with non-pre-oxidized INCONEL® 600 shims, in which the heat treatment was modified using an additional, proprietary, oxidation step.

Table 1. Summary of compatibility tests of insulated LBNL cable 988, made from OST PMM070420 strand, in contact with various materials in the LBNL cable clamp structure.

Insulation	In contact	Pre-oxidized?	Leakage and comments
Al_2O_3–SiO_2	INCONEL® 600	Yes	1 spot, clean elsewhere
Al_2O_3–SiO_2	INCONEL® 600	No	6 spots, clean elsewhere
Al_2O_3–SiO_2	INCONEL® 600	During HT	1 spot, clean elsewhere
Al_2O_3–SiO_2	SS 304	Yes	2 spots, red discoloration of insulation, strong adhesion of insulation to SS 304
Al_2O_3–SiO_2	SS 304	No	No leakage, red discoloration of insulation, strong adhesion of insulation to SS 304
Al_2O_3–SiO_2	SS 316	No	Leakage all over contact area
Al_2O_3–SiO_2	SS 304	No	*Test without cable*, no discoloration, no adhesion
Pure SiO_2	INCONEL® 600	Yes	Sizing not removed, no leakage, very clean[a]

[a] Discoloration of insulation occurred outside the cable clamp.

Detailed investigation of the cable sections after reaction highlights the presence of leakage and/or discoloration of the insulation. Leakage was visible in some cases in the form of small black spots on the cable after removal of the insulation. The spots have a typical size of 1–3 mm in diameter, except in the case of the SS 316, for which severe leakage was observed over the entire contact area. The results of the cable clamp compatibility studies performed so far are summarized in table 1.

The following conclusions can be drawn from table 1: (1) INCONEL® 600 has to be oxidized, either before coil manufacture or during the reaction, but appears otherwise compatible. (2) SS 304 does not necessarily introduce leakage, but discolors and bonds to the insulation, which is not a result of a reaction of the SS 304 and the insulation alone, but requires the presence of a cable. (3) SS 316 is incompatible and causes severe leakage. (4) Pure SiO_2 appears the most compatible insulation inside the clamp (it looks cleaner after reaction than the Al_2O_3–SiO_2), but significant discoloration occurs outside the clamp, which is not the case for Al_2O_3–SiO_2.

Overall, the INCONEL® 600 and Al_2O_3–SiO_2 combination provides a workable system, although it has been established that the Al_2O_3–SiO_2 reacts with the Ag [8]. There is also circumstantial evidence that the Cr in the INCONEL® 600 becomes volatile in combination with O_2 and reacts with the Ag, as was suggested in the community [7]. Energy dispersive x-ray spectroscopy (EDX) analysis in a scanning electron microscope (SEM) revealed that some AgCr-oxide crystals were present after reaction inside the HTS-SC08 'island' (figures 1 and 2). The use of pure SiO_2 looks

Table 2. Coils fabricated using OST Bi-2212 round wire.

Coil ID	Cable	Insulation	Sizing	Oxidation	T_{max} (°C)
HTS-SC02	17 strand Ag dummy	Pure SiO_2	Present	Pre-oxidized	N/A
HTS-SC04	17 × PMM051221	Al_2O_3–SiO_2	600 °C/1 h	Pre-oxidized	885.4
HTS-SC06	17 × PMM051221	Al_2O_3–SiO_2	825 °C/4 h	During HT	887.8
HTS-SC08	17 × PMM070420	Al_2O_3–SiO_2	825 °C/4 h	During HT	887.8

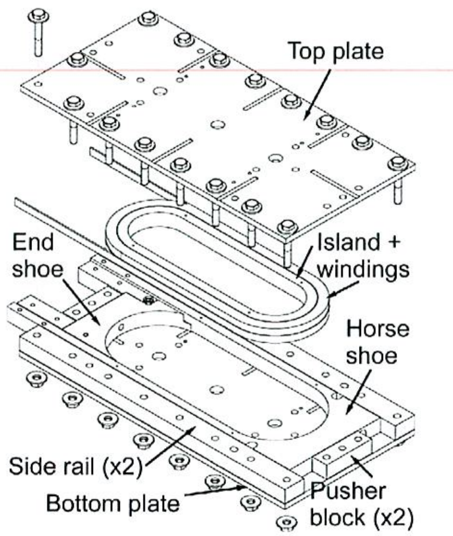

Figure 1. Design of a 2 layer, 6 turn Bi-2212 sub-scale coil in its reaction holder.

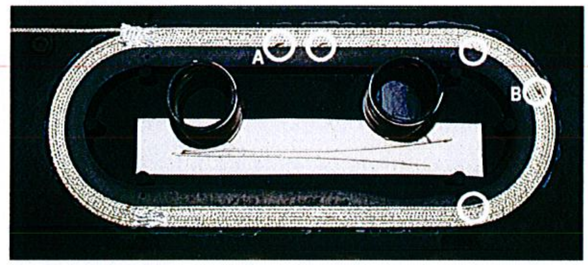

Figure 2. Coil HTS-SC08 and witness barrels and wires after reaction. Leakage spots are indicated by white circles. Spots A and B both contain large amounts of Bi and Sr, and traces of Ca and Cu, indicating that they originate from the wire cores.

promising, but further research is needed in order to deviate from the now more common use of Al_2O_3–SiO_2. The significant discoloration of the insulation in contact with the SS 304, the fact that the SS 304 bonds strongly to the insulation, and the thermal contraction mismatch of SS 304 compared to Bi-2212 [1] renders, for now, INCONEL® 600 a better choice.

3. Coil manufacture and heat treatment

A total of 10 Bi-2212 sub-scale coils have been manufactured at LBNL. Four coils have been manufactured for collaboration with OST. A schematic of the sub-scale coil reaction package is depicted in figure 1. The total length of the sub-scale coil is about 0.3 m. The coils are 2 layer, 6 turn, double pancake racetracks, wound with a 17 strand Rutherford cable with a nominal cross-section of 1.46×7.80 mm^2. The bending radius around the island ends is 39.4 mm.

Ag–2%Au alloy strips were placed in contact with the cable during coil manufacture. These strips sinter to the Ag-alloy of the cable during the coil reaction and act as taps for the voltage connections for coil testing. All Bi-2212 coils use a combination of INCONEL® 600 construction material and Al_2O_3–SiO_2 sleeve insulation. The sizing on the insulation was removed using a high temperature cycle as given in table 2 in a constant flow of pure oxygen, before placing the sleeve around the cable. A summary of the four coils is given in table 2.

Coil HTS-SC02 is a dummy coil, wound from a cable made from Ag wire, and used to optimize the reaction in the furnace. Coils HTS-SC04 and HTS-SC06 are manufactured from LBNL cable 948, which is made from a 2005 generation OST wire from billet PMM051221. HTS-SC08 is manufactured from LBNL cable 988, from 2007 generation OST wire from billet PMM070420. None of the wires are twisted. Cross-sections of cable 988 revealed that in some places the central filament bundle was compromised, due to the use of a non-optimal wire design configuration. This can potentially reduce the cable critical current slightly with respect to a non-compromised witness sample, with a maximum I_c reduction of 14% if the central bundle carries no current.

The side pressure during coil manufacture is controlled by shims around the windings, using pressure versus insulated cable thickness data as determined from 10 stack measurements. The side pressure before reaction amounts to about 2 MPa for coil HTS-SC04 and about 1 MPa for coils HTS-SC06 and HTS-SC08.

Coil HTS-SC04 was reacted using an optimized heat treatment with a $T_{max} = 885.4$ °C, which is just above the sharp rise of the $I_c(T_{max})$ dependence around 884 °C, and therefore potentially too low. Coil HTS-SC06, which is identical to HTS-SC04, was therefore reacted at a slightly increased $T_{max} = 887.8$ °C. The reaction of coil HTS-SC08 was kept identical to the reaction of HTS-SC06, after confirmation of the critical current of a PMM070420 witness sample that was reacted together with HTS-SC06. The estimated temperature homogeneity over the coils during the reaction is ± 1 °C.

Inspection of the coils after reaction revealed only a few small leakage spots, identical as those observed in the compatibility studies. All the spots were located at the cable edges. The sides of the winding packages were clean. All coils showed 6 spots per side on average. An exemplary view of coil HTS-SC08 after reaction is shown in figure 2. The

opposite side, as well as coils HTS-SC04 and HTS-SC06, look comparable. Six small spots can be identified on the top of HTS-SC08. These are located inside the five white circles. Small chips of the insulation were taken from positions A and B and analyzed using SEM-EDX. The EDX analysis identified, next to the expectable elements, large amounts of Bi and Sr, and traces of Ca and Cu in positions A and B. This indicates that the source of spots A and B is indeed leakage from the wire core. It should be noted, however, that spots can in principle also originate from an external contamination on the cable or the insulation.

Two INCONEL® 600 barrels with wires and two straight wire samples are also visible in figure 2. These wires are reacted together with the coils. The wires from the INCONEL® 600 barrels are transferred and soldered to stainless-steel barrels after the reaction for critical current measurements. These are the witness samples for the coils.

Glass-fiber epoxy (G10) plates are inserted in the hollow 'islands' (figure 1) after reaction. The coils are then instrumented by connecting Cu voltage tap strips to the Ag–2%Au alloy flags, after which the coils are vacuum impregnated with CTD-101 epoxy. The coils are then repacked inside a stainless-steel 304 package without the presence of an iron magnetic circuit, and prepared for testing.

In summary it can be concluded that the significant leakage that was observed in previous coils after the heat treatment is virtually eliminated. The remaining few spots (some of which could come from external contamination) are, for now, acceptable if they do not cause shorts in the windings, or reduce the critical current of the coils.

4. Measurements

The critical current and n-value at 10^{-5} V m^{-1} of the witness barrel samples are measured by OST at various applied magnetic fields. The critical currents at 10^{-4} V m^{-1} are calculated from the 10^{-5} V m^{-1} I_c and n-values using $I_c(10^{-4}) = 10^{1/n} I_c(10^{-5})$. The corresponding total magnetic fields on the filamentary volumes in the wires are self-field corrected using a self-field constant of 4.94×10^{-4} T A^{-1} and the 10^{-4} V m^{-1} I_c values. The 10^{-4} V m^{-1} I_c data, combined with the total magnetic field data, provide the 'short sample' limit for the coils.

The voltage tap connections to the coils are schematically depicted in figure 3 and are positioned to provide the critical currents of the total coil, the upper and lower layers, the ramp from the lower to the upper layer, and the inner and outer turns of the upper and lower layers independently. A deviation in the voltage tap layout for coil HTS-SC06 results in the determination of the I_c of the outer two turns of each coil layer and a combined I_c of the ramp (V_r) and layer 2 inner turn, as shown in figure 3. All coils, mounted in a stainless-steel test package, were tested in self-field in boiling helium at atmospheric pressure.

5. Results and discussion

The critical current data for the witness barrel samples is summarized in table 3. The critical current of the witness

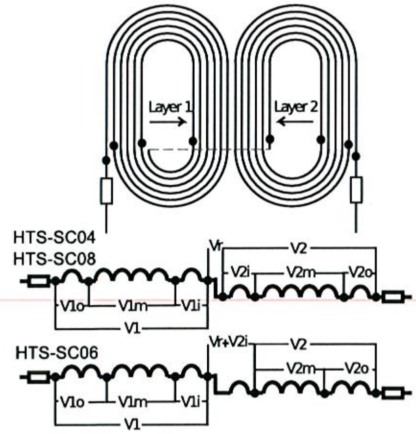

Figure 3. Schematic representation of the voltage tap locations in coils HTS-SC04, HTS-SC06 and HTS-SC08.

sample for coil HTS-SC06 is significantly higher than the witness sample for coil HTS-SC04. This is presumably mainly a result of the increased T_{max} during the heat treatment.

The low n-value for the HTS-SC04 witness sample is indicative for an under-reacted sample, as a result of a too low T_{max}. A T_{max} of 885.4 °C is probably too close to the steep increase of I_c with T_{max} around 884 °C as determined from $I_c(T_{max})$ data. The I_c increases from zero to the maximum I_c within one degree in this temperature region. Any small gradient in temperature in this region will therefore result in a large critical property distribution in the wire, resulting in a low n-value. This suggestion is confirmed by the fact that the I_c and n-value more than double for the witness sample of HTS-SC06, which was reacted at 887.8 °C. The $I_c(T_{max})$ data further indicate that the I_c of the wires varies by about ±25 A in the region where T_{max} is 888 ± 1 °C, thus providing an indication for the uncertainty in the witness sample I_c values for the higher temperature reactions of coils HTS-SC06 and HTS-SC08.

The critical current of the witness sample for HTS-SC08 is approximately double that of HTS-SC06, whereas the reaction for these coils was identical. This increase in the I_c of the HTS-SC08 witness compared to the HTS-SC06 witness is attributed to conductor improvements from the 2005 to the 2007 generation wires.

The electric field as a function of current ($E(I)$) data for the coils are shown in figures 4–6. All the transitions were reproduced at least once after the coils quenched, and reproduced within 10 A of the previous values. This lack of the usual training that is common in high field tests of accelerator-type magnets wound from low temperature superconductors is presumably a result of the low load levels below 2 MPa during the self-field measurements [4].

The quench current of coil HTS-SC06 is, at about 1800 A, about 200 A higher than the quench current for HTS-SC04. The higher reaction temperature causes a significant reduction in the distribution of the I_c values for the different coil sections. The ramp and the inner turns are limiting the coil performance in both coils. This limitation by the inner turns

Table 3. Summary of witness sample I_c values, measured on stainless-steel barrels with the wires soldered to the barrels.

Coil ID	Applied field (T)	I_c at 10^{-5} V m^{-1} (A)	n-value	Total field (T)[a]	I_c at 10^{-4} V m^{-1} (A)[b]
HTS-SC04	0	66	6	0.05	96
	4	29	6	4.02	44
	8	24	5	8.02	37
	12	21	6	12.02	32
	14	21	5	14.02	31
	15	20	5	15.01	30
HTS-SC06	0	181	18	0.10	206
	4	76	14	4.04	89
	6	63	13	6.04	76
	12	53	12	12.03	63
HTS-SC08	6	131	18	6.07	149
	12	110	16	12.06	127

[a] Using a self-field correction of 4.94×10^{-4} T A^{-1} and the 10^{-4} V m^{-1} I_c value.
[b] Calculated from the 10^{-5} V m^{-1} I_c and n-value.

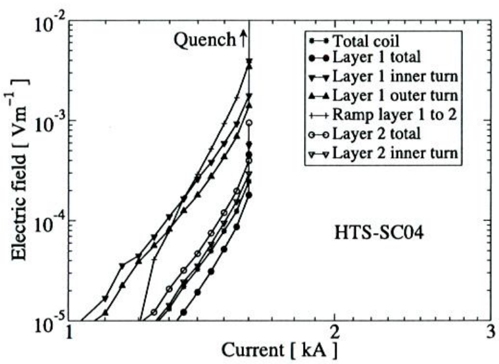

Figure 4. Electric field as a function of current during a DC I_c test of coil HTS-SC04 at 4.2 K.

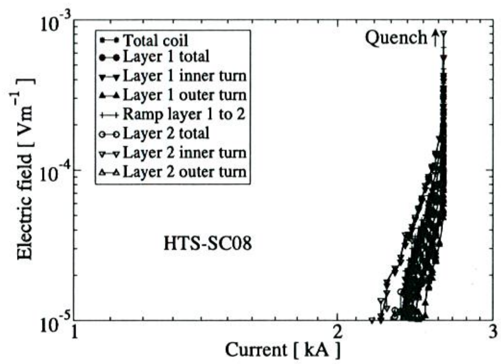

Figure 6. Electric field as a function of current during a DC I_c test of coil HTS-SC08 at 4.2 K.

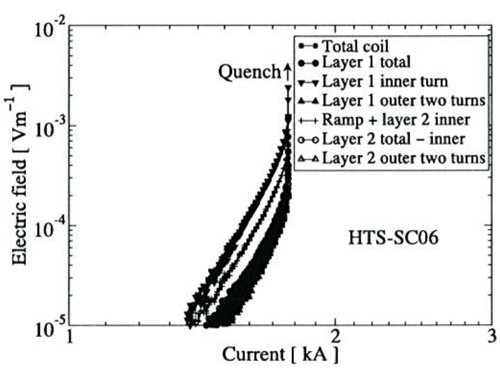

Figure 5. Electric field as a function of current during a DC I_c test of coil HTS-SC06 at 4.2 K.

and the transition is comparable to what was observed in earlier coils [5]. This reduced performance of the inner turns could originate from strain and/or magnetic field gradients across the windings and is the subject of further research. The transitions for coil HTS-SC08 show a substantial improvement of the quench current, I_c, and n-values. The quench current increases from about 1800 A for coil HTS-SC06 to about 2600 A for coil HTS-SC08.

Critical currents and n-values are determined from the $E(I)$ transitions of the coils using an electric field criterion of 10^{-4} V m^{-1}. The resulting data are summarized in table 4. The critical currents of coil HTS-SC08 were only determined for the inner turns and the ramp, since the other sections did not reach the electric field criterion before thermal runaway occurred. From the table it is evident that, with the notable exception of the layer 2 inner turn in HTS-SC04, all coils are limited by the inner turns and the ramp.

It has to be noted that the n-values that are achieved in HTS-SC04 are higher than those for its witness sample. This can be a result of inhomogeneity in the witness sample for HTS-SC04, as a result of its potentially lower T_{max} as discussed before. The relatively high n-values in HTS-SC04 can also be a result of heating, as is suggested by the non-linearity in the upper part of the $E(I)$ transitions, even though the transitions were reversible during the measurement. The coil n-values for HTS-SC06 and HTS-SC08 are roughly comparable to the n-values of the witness samples.

A graphical comparison between the performance of the coils and the witness samples is given in figure 7. Here, the total coil I_c values are used and the coil critical current is divided by 17 (the number of strands in the cable). For coil HTS-SC08 the quench value is used. For completeness, the

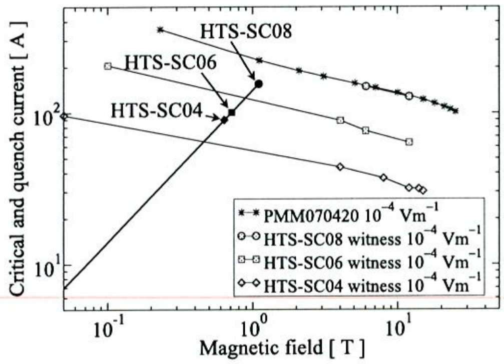

Figure 7. Comparison of coil performance and the witness sample $I_c(B)$ data. The points are measured and the lines are a guide to the eye.

Table 4. Summary of coil I_c values at 10^{-4} V m^{-1} and $T = 4.2$ K.

	HTS-SC04		HTS-SC06		HTS-SC08	
	I_c (A)	n-value	I_c (A)	n-value	I_c (A)	n-value
Total coil	1526	14	1711	17	2636[a]	—
Layer 1 total	1564	16	1702	17	2636[a]	—
Layer 1 inner turn	1290	11	1580	14	2608	23
Layer 1 outer turn	1323	10	1740[b]	19	2636[a]	—
Ramp layer 1 to 2	1319	17	1635[c]	15	2589	24
Layer 2 total	1481	14	1727	17	2636[a]	—
Layer 2 inner turn	1506	14	—[a]	—	2557	18
Layer 2 outer turn	—[d]	—	1738[b]	18	2636[a]	—

[a] Quench value. [b] Outer two turns.
[c] Transition and coil 2 inner turn combined. [d] Open contact.

witness data for coil HTS-SC08 are combined with additional data on the same wire batch. The load-lines for the sub-scale coils are calculated using the maximum magnetic field that occurs on the winding pack, yielding a magnetic field constant of 4.18×10^{-4} T A^{-1} [4].

From the comparison in figure 7 a rough estimate of the coil performance with respect to the witness samples can be made by assuming a comparable magnetic field dependence of the HTS-SC08, HTS-SC06, and HTS-SC04 witness I_c data as the additional PMM070421 data. This leads to a performance of HTS-SC04 that is slightly above the witness sample. HTS-SC06 performs at roughly 70% of the witness sample, and HTS-SC08 performs roughly at 75% of its witness sample. That HTS-SC04 performs better than its witness sample is at first sight suspect, but the recorded inside temperature of the furnace was 884.1 °C compared to the measured coil temperature of 885.4 °C. It is thus very well possible that the witness sample was reacted at a slightly lower temperature than the coil, rendering the comparison to the witness sample unreliable, if the steep increase of $I_c(T_{max})$ around 884 °C, as discussed previously, is accounted for. Coils HTS-SC06 and HTS-SC08 were reacted at substantially higher temperatures, and the comparison will therefore be less dependent on local temperature variations in the furnace on the order of 1 °C.

In summary it can be concluded that the coils achieve roughly 70% of the witness sample I_c with the uncertainty originating from small local temperature variations during the reaction, differences in the strain state between the coils and the witness samples, and the detailed magnetic field dependence of the critical current. Coil HTS-SC08 could carry on the order of 100 A per strand, or 1.7 kA at 15 T, provided that it will withstand the Lorentz loads (which is in itself a large uncertainty). This, combined with the now marginal occurrence of leakage shows that with W&R Bi-2212 technology, graded magnet systems to surpass the Nb-based accelerator magnet systems appear to become a realistic option.

6. Conclusions

From the compatibility studies it can be concluded that the combination of INCONEL® 600 construction material and Al_2O_3–SiO_2 braided sleeve insulation provide a workable system, although it is evident that the insulation reacts with the Ag and it is suggested that the Cr in the INCONEL® 600 might also react with the Ag from the wires.

The now marginal leakage in combination with a coil performance of roughly 70% of the witness sample, and the potential to carry around 1.7 kA at 15 T, mean that the W&R Bi-2212 coil technology is sufficiently developed to show that it is a realistic option for accelerator magnets. Obviously, details and critical current densities will need improvement, but the feasibility of the technology is clearly demonstrated.

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References

[1] Godeke A, Cheng D, Dietderich D R, Ferracin P, Prestemon S O, Sabbi G and Scanlan R M 2007 *IEEE Trans. Appl. Supercond.* **17** 1149
[2] Dietderich D R and Godeke A 2008 *Cryogenics* **48** 331
[3] Trociewitz U P, Schwartz J, Marken K, Miao H, Meinesz M and Czabaj B 2006 *NHMFL Reports 2006* vol 13, p 31
[4] Godeke A *et al* 2008 *IEEE Trans. Appl. Supercond.* **18** 516
[5] Godeke A, Cheng D W, Dietderich D R, Hannaford C R, Prestemon S O, Sabbi G, Wang X R, Hikichi Y, Nishioka J and Hasegawa T 2009 *IEEE Trans. Appl. Supercond.* **19** 2228
[6] Wesolowski D E, Rikel M O, Jiang J, Arsac S and Hellstrom E E 2005 *Supercond. Sci. Technol.* **18** 934
[7] Hellstrom E E 2008 private communication
[8] LoSchiavo M 2009 Processing issues of $Bi_2Sr_2CaCu_2O_8$ round wire involving leakage and alumino silicate insulation *Master's Thesis* Florida State University