Title
Performance correlation between $YBa_2Cu_3O_{7-\delta}$ coils and short samples for coil technology development

Journal
Superconductor Science and Technology, 29(6)

ISSN
0953-2048

Authors
Wang, X
Dietderich, DR
Godeke, A
et al.

Publication Date
2016-06-01

DOI
10.1088/0953-2048/29/6/065007

Peer reviewed

Performance correlation between $YBa_2Cu_3O_{7-\delta}$ coils and short samples for coil technology development

X. Wang, D. R. Dietderich, A. Godeke‡, S. A. Gourlay, M. Marchevsky, S. O. Prestemon, G.L. Sabbi

Lawrence Berkeley National Laboratory, One Cyclotron Road, Berkeley, CA 94720, USA.

E-mail: `XRWang@lbl.gov`

Abstract. A robust fabrication technology is critical to achieve the high performance in $YBa_2Cu_3O_{7-\delta}$ (YBCO) coils as the critical current of the brittle YBCO layer is subject to the strain-induced degradation during coil fabrication. The expected current-carrying capability of the magnet and its temperature dependence are two key inputs to the coil technology development. However, the expected performance is not straightforward to determine because the short-sample critical current depends on both the amplitude and orientation of the applied magnetic field with respect to the broad surface of the tape-form conductor. In this paper, we present an approach to calculate the self-field performance limit for YBCO racetrack coils at 77 K and 4.2 K. Critical current of short YBCO samples was measured as a function of the applied field perpendicular to the conductor surface from 0 T to 15 T. This field direction limited the conductor critical current. Two double-layer racetrack coils, one with 3 turns and the other with 10 turns, were wound and tested at 77 K and 4.2 K. The test coils reached at least 80% of the expected critical current. The ratio between the coil critical currents at 77 K and 4.2 K agreed well with the calculation. We conclude that the presented approach can determine the performance limit in YBCO racetrack coils based on the short-sample critical current and provide a useful guideline for assessing the coil performance and fabrication technology. The correlation of the coil critical current between 77 K and 4.2 K was also observed, allowing the 77 K test to be a cost-effective tool for the development of coil technology.

Keywords: YBCO, coil technology, self field, critical current

Submitted to: *Supercond. Sci. Technol.*

‡ Present address: National High Magnetic Field Laboratory, Florida State University, 1800 East Paul Dirac Drive, Tallahassee, FL 32310, USA.

1. Introduction

The $YBa_2Cu_3O_{7-\delta}$ (YBCO) coated conductor has the potential to enable a new generation of high-field magnets thanks to its high irreversibility field and critical current density over a broad temperature range. The current-carrying capability and available length of the conductor are continuously being improved by several manufacturers around the world [1]. Solenoid applications have been leading the YBCO magnet development; the latest progress is reviewed in [2, 3]. An insert coil made of single YBCO tapes generates 4.2 T in a background field of 31.2 T at 1.8 K [4]. YBCO insert coils that will generate 17 T for a 32 T user magnet are also being developed [5]. The conductor also shows great potential for fusion applications: it enables high-capacity cables [6] and a unique design of a high field, demountable magnet for a compact fusion reactor [7]. The accelerator magnet application is less advanced but several projects are being pursued in Europe [8, 9], Japan [10] and the U.S. [11].

A robust fabrication technology is critical for YBCO coils because excessive strain during coil fabrication and operation can permanently degrade the current-carrying capability of the brittle YBCO layer [2, 3, 12]. Understanding the self-field performance of YBCO coils and its correlation with short samples provides two key inputs for the coil technology development.

The first input is the expected coil performance based on short-sample critical current (I_c). By comparing the expected and actual coil I_c, one can assess and improve the magnet fabrication technology. However, to determine the performance limits in YBCO coils is not straightforward. The coated conductor is available in a tape form with high aspect ratio that features the field angular dependence of the conductor I_c [13]. The magnetic field leads to a non-uniform current distribution in the highly aspected YBCO layer which in turn affects the magnetic field on the conductor [14, 15]. As a result, the classic method to determine the magnet performance limit based on the load line and isotropic conductor $I_c(B)$ is no longer applicable for YBCO coils.

Several models have been proposed to determine the current-carrying capability of YBCO cables and coils in the context of ac loss calculation. The state of the art is reviewed in [16, 17]. In particular, Zhang *et al.* investigated the electric-field distribution inside pancake coils and suggested an optimal electric-field criterion to determine the coil I_c [18]. Zermeño *et al.* developed a self-consistent model to estimate the I_c for various superconducting devices with a high computing speed [19]. Grilli *et al.* demonstrated that simplified fit for the angular dependence is accurate enough to predict the coil performance [20]. Models based on variational principle are also effective to determine the coil I_c as shown by Prigozhin [21] and Pardo *et al.* [17].

While these models, mostly based on finite element analysis, achieve excellent agreement with measurements, they rely on the detailed characterization and accurate fit of the full angular dependence of conductor I_c [22]. To measure the full angular dependence can be challenging and time consuming for the whole conductor spool as part of the conductor characterization. For coil technology development, it is of practical interest to develop an approach that can provide a reasonable performance guideline with a minimum conductor measurement campaign, for instance, the I_c measurement at the field direction that results in the lowest I_c.

The second key input is the correlation between the I_c for coils and conductors at liquid nitrogen and lower temperatures. Compared to the tests in liquid helium, tests of YBCO coils in liquid nitrogen feature less cost and lower risk of quench-related conductor damage. The expected I_c at 77 K can allow the tests in liquid nitrogen a first assessment of the coil quality. If good performance is achieved, one can proceed with the tests at lower temperatures. Furthermore, if the coil I_c at 77 K and 4.2 K can be correlated, the 77 K I_c will be a useful metric to provide feedback to the coil technology development for accelerator insert coils and other applications that operate in liquid helium temperature. While such a correlation was observed on short-sample I_c between 77 K and temperatures down to 20 K [23, 24], similar correlation between 77 K and 4.2 K on short samples and coils is weak [25] or does not exist [26].

In this paper, we report an approach to correlate the self-field performance in YBCO racetrack coils and short samples at 77 K and 4.2 K. The racetrack design offers a simple coil geometry to study the magnetic-field dependence of the current-carrying capability which is the focus of this paper. We study the self-field performance for two reasons. For a stand-alone YBCO magnet, its I_c is determined by the self field. For insert coils, understanding and achieving the self-field performance limit is necessary to reach high performance in background fields. In section 2, we discuss the calculation method, along with the details regarding the preparation of short samples, coils and test procedures. The test results are presented in section 3, followed by the implications from the observations and possible applications of the developed method.

2. Experiments

2.1. Magnetic models

The critical-current density (J_c) of a coated conductor depends on the magnetic field, temperature and strain state of the YBCO layer. Here, we focus on the field dependence at specific temperatures to determine the coil I_c. The magnetic field in the straight section of a racetrack coil is two dimensional (2D), as shown in figure 1. We study the J_c distribution in the conductors as a function of magnetic field on this 2D plane.

The computational approach is based on the work by Babaei-Brojeny and Clem which determines the local J_c in the conductor consistent with the self and applied magnetic fields [27]. The conductors in the coil were discretized into cells. The J_c was constant in each cell but can vary among cells. The calculation had two steps. First, the field at one cell location was determined based on the Biot-Savart law. Second, the cell J_c was determined based on the field from the first step and a given $J_c(B)$. These two steps were repeated for all the cells and were iterated until the J_c distribution converged. The same algorithm was used in earlier work on Bi-2223 tapes [28]. The $J_c(B)$ is the

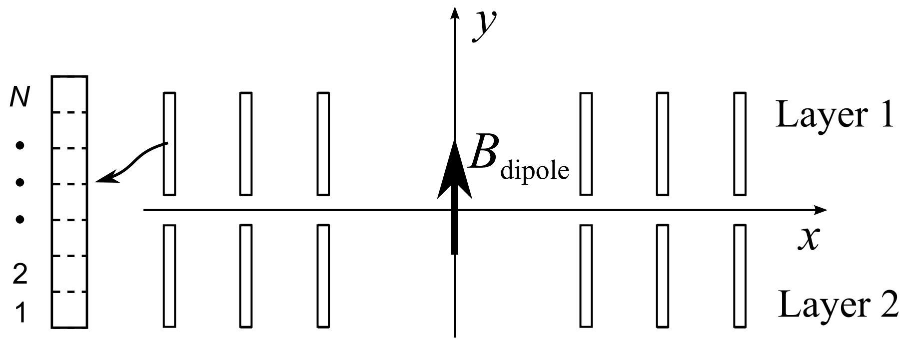

Figure 1. Cross section and coordinate system for the straight section of a racetrack coil. Here a 2×3-turn coil (double layer with 3 turns in each layer) is used as an example. The current perpendicular to the x-y plane generates a dipole field at the coordinate origin. Each conductor is discretized into N cells along the y-axis with uniform current density in each cell.

self-field corrected current density which can be determined from the I_c measured on the short samples [27, 29].

The I_c for each turn was then obtained by summing the current density of all cells in the turn (figure 1), *i.e.*, $I_{\text{turn}} = \sum_{i=1}^{N} J_i\, w\, t/N$, where J_i is the critical-current density in cell i, w is the cell width, t is the thickness of YBCO layer and N is the number of cells in each conductor. When the calculation converged, the lowest current of all turns defined the coil performance limit. It can be demonstrated that this current equaled the critical current as determined by Prigozhin's model where the transport current in each turn can be specified [21]. While the model can take into account the anisotropic $J_c(B)$, only the field component perpendicular to the tape surface, $B_\perp$, was considered here as it limited the conductor performance. We will use this approach to calculate the I_c as a function of magnetic field for a single tape in section 3.1.

2.2. Preparation of short samples

The YBCO coated conductor (SCS4050) was purchased from SuperPower Incorporated in 2008 and was typical of samples of that time frame. The bare tape was 4.0 mm wide and 0.095 mm thick. The conductor was insulated with a 50 μm thick Kapton tape with 30% overlap. The average I_c of the 100 m long conductor measured in self field by the vendor was 170 A at 77 K with a minimum I_c of 154 A. The n value was between 30 and 32. Samples about 8 cm long were cut from the lead and tail ends of the conductor piece used to wind the coil for the I_c measurements at LBNL.

To accurately measure the I_c at 4.2 K, we reduced the sample width from 4 mm to 2.2 mm by machining. The resulting sample had a lower I_c which helped in reducing the Joule heating from the current leads during the transport measurements. The full width sample was first clamped between two Aluminum blocks and the portion of the tape to be removed was exposed for machining. The transverse pressure on the tape surface was about 75 MPa after clamping. The center straight section was 2.2 mm wide and 8 mm long after machining (figure 2).

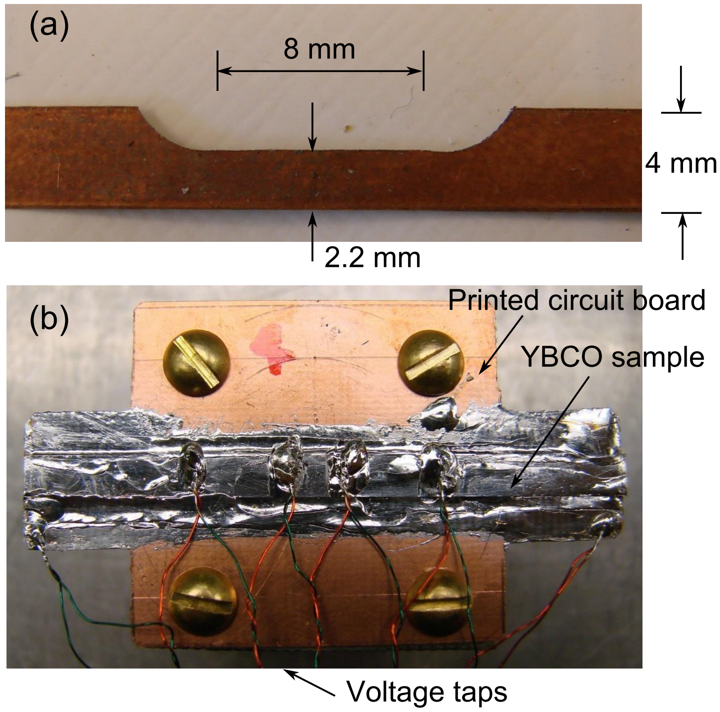

Figure 2. (a) The YBCO sample after being machined. (b) A YBCO sample was soldered to a printed-circuit-board holder.

To measure the $I_c(B)$ at 4.2 K in a superconducting solenoid, we made a sample holder with printed circuit board (PCB). The substrate side of the YBCO sample was soldered to the PCB using Sn60Pb40 solder. Solid Cu instrumentation wires were soldered on the YBCO side of the sample. The center voltage-tap section was 5 mm long. Within this length, the magnitude of the solenoid field varies by 0.02%. Flexible current leads were soldered to both ends of the PCB after it was mounted to the measurement probe. The angle between the solenoid field and the tape surface was $90 \pm 1°$.

2.3. Fabrication of racetrack coils

A series of racetrack coils were wound to develop the coil fabrication technology and to test the coil performance. All coils consisted of two layers but with either 3 turns or 10 turns in each layer. The first three coils were tested at 77 K only to establish the techniques for coil winding and instrumentation. Strong self-field effects were observed with more details reported in [30]. Here we focus on the two latest coils, YC04 and YC05, which were tested at 77 K and 4.2 K. The conductor was continuously wound from one layer to the next around a stainless steel 304 island. The YBCO side of the conductor was facing the island leaving the YBCO layer under compression during the winding.

About 6 cm long section of YBCO conductors were soldered to Cu current leads to make splices (figure 3). Voltage taps were soldered on the edge of the conductor after removing the Kapton insulation.

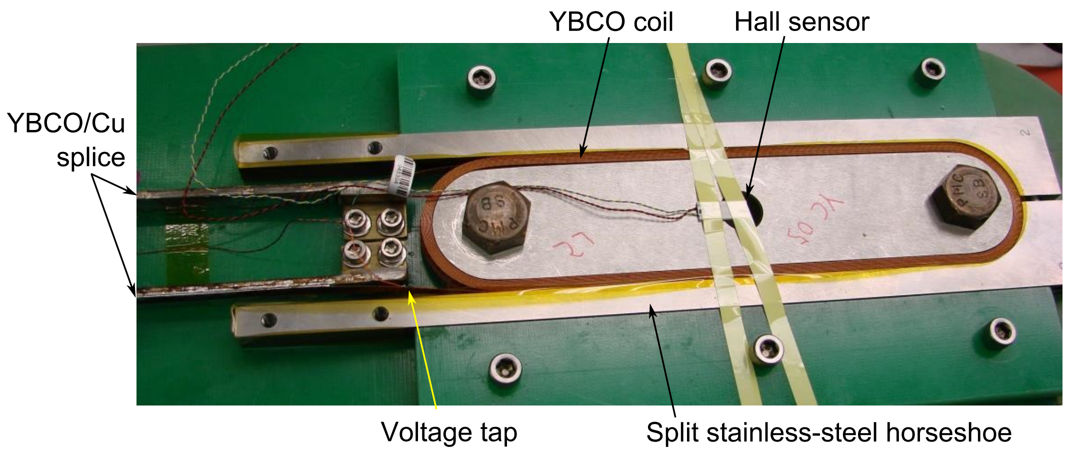

Figure 3. YC05, a 2 × 10-turn coil.

The coils were not impregnated with epoxy to avoid the conductor degradation [31]. For coil YC04, two G10 side bars and waxed strings were used to constrain the winding. A split stainless steel frame ("horseshoe") was used to constrain coil YC05 for future loading test (figure 3). The horseshoe consisted of a pair of guides applied from both sides of the coil and was supported by the G10 side bars. A cryogenic Hall sensor (Lakeshore HGCT-3020) was glued on the surface of the island center with VGE-7031 Varnish to measure the magnetic field generated by the coil.

2.4. Measurement protocol

The I_c of short samples was first measured in liquid nitrogen at 77 K self field and then at 4.2 K with a background field from 15 T to 0 T. Samples were measured again at 77 K after the 4.2 K test and no I_c degradation was observed.

The I_c test used a stair-step current profile. The voltage across the sample was measured by digital multimeters (Keithley 2010 and 2182A) after the current stabilized to minimize the inductive pickup. The instruments and data acquisition were controlled by a PC via a GPIB bus. Samples were submerged in cryogen during the measurement. A similar test protocol was used for racetrack coils. Typical cooldown rate for the coil tests was 6 K/s from room temperature to 77 K and 0.2 K/s from room temperature to 4.2 K.

3. Results and discussion

3.1. Critical current of short samples and expected coil performance

Figure 4 shows the measured $I_c(B_\perp)$ at 4.2 K of a 4-mm wide and a 2.2-mm wide samples. An electric-field criterion of 1 μV/cm was used to determine the I_c. The average ratio between the I_c of the 4-mm wide and 2.2-mm wide samples was 2.1 with a standard deviation of 0.01 based on the 18 data points ($B_\perp = 0$ T and > 0.5 T). The I_c ratio was 15% higher than the ratio between the sample widths, which can be contributed by the possible damage to the YBCO layer during the machining. The ratio was used to scale the calculated I_c from the 2.2-mm wide sample to the 4-mm wide one (solid lines in figure 4).

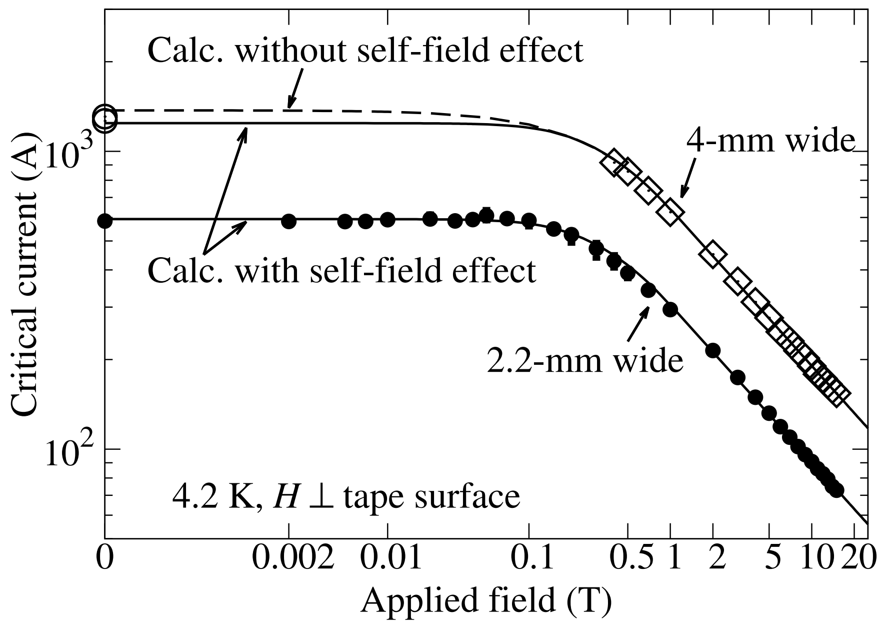

Figure 4. Critical current as a function of applied field perpendicular to the tape surface at 4.2 K. I_c is defined with an electric-field criterion of 1 μV/cm. Solid circles: 2.2-mm wide sample. Open squares: 4-mm wide sample. Open circles at 0 T: two 4-mm wide tapes measured in a different cryostat at 4.2 K, self field. Solid lines: calculated I_c with self-field effect. Dashed line: calculated I_c without self-field effect for the 4-mm wide sample according to (1).

As mentioned in section 2.1, a self-field corrected current density, J_{SFC}, of the YBCO layer is required to determine the self-field performance of single conductors or coils [27, 29]. At low field, we used Kim's model [32] to determine the J_{SFC} from the I_c data. A power law of the applied field was used when the applied field dominated, *i.e.*,

$$J_{SFC}(B_\perp) = \begin{cases} \dfrac{J_0}{1 + |B_\perp/B_0|} & \text{for } B_\perp \le 1 \text{ T}, \\ \dfrac{c}{A}|B_\perp|^\alpha & \text{for } B_\perp \ge 1 \text{ T}. \end{cases} \quad (1)$$

The parameters J_0 and B_0 for the Kim model were fit of the I_c data measured between 0.3 T and 2 T with the least-square method. In (1), A is the cross sectional area of the YBCO layer. Table 1 summarizes the fit parameters.

Given the $J_{SFC}(B_\perp)$ of the short sample, we first reproduced the measured $I_c(B_\perp)$ of single conductors based on the method outlined in section 2.1. The calculation reproduced the self-field effect as shown by the solid lines in figure 4. The good

Table 1. The fit parameters in (1) for $J_{\mathrm{SFC}}(B_{\perp})$ at 77 K and 4.2 K, 4-mm wide sample. The $I_c(B_{\perp})$ at 77 K was provided by the vendor [33].

Temperature (K)	77	4.2	4.2
Field range (T)	0–5	0–1	1–15
$J_c(0)$ (Amm^{-2})	50000	343298	
B_0 (mT)	115	866.2	
α			−0.53
c ($\mathrm{AT}^{-\alpha}$)			305.49

agreement validated the fit parameters, and these were also used to determine the expected coil I_c.

Table 2 presents the performance limits for both 2×3-turn and 2×10-turn coils. The calculation considered the dimensions of the pole island and the insulation thickness for the racetrack coils. Also shown are the lift factors defined as the ratio between the I_c at 4.2 K and 77 K. The expected I_c given in table 2 set an upper bound for the coil performance because the higher magnetic field in the end region of racetrack coils reduces the conductor I_c, which can be considered with a 3D model [34]. With the increasing number of turns in the racetrack coils, the expected coil I_c decreases as the perpendicular field component on the turns in the center of the coil pack becomes stronger.

Table 2. The expected I_c and lift factors for the straight section of the racetrack coils. For comparison, the measured self-field I_c values of a single conductor are also included.

	77 K	4.2 K	Lift factor
2×3-turn coil	156	1078	6.9
2×10-turn coil	121	837	6.9
Short sample	180	1255	7.0

3.2. Critical current of racetrack coils

The coil I_c was defined with an electric-field criterion of 1 μV/cm across the coil terminal; same criterion was used for the short-sample I_c. Coil YC04 was tested three times, the first two at 77 K and the third one at 4.2 K. The coil warmed up to room temperature between each test. The I_c was 141 A at 77 K and 956 A at 4.2 K (figure 5). The normal zone developed inside the YBCO coil based on the voltage signals. The $V(I)$ curves at 77 K before and after the 4.2 K test were identical, indicating no I_c degradation due to thermal cycles or resistive transitions during the tests.

YC05, the 2×10-turn coil, went through the following tests: 1) 77 K with the G10 side rails, 2) 77 K with the horseshoe, and 3) 4.2 K with the horseshoe. Between the

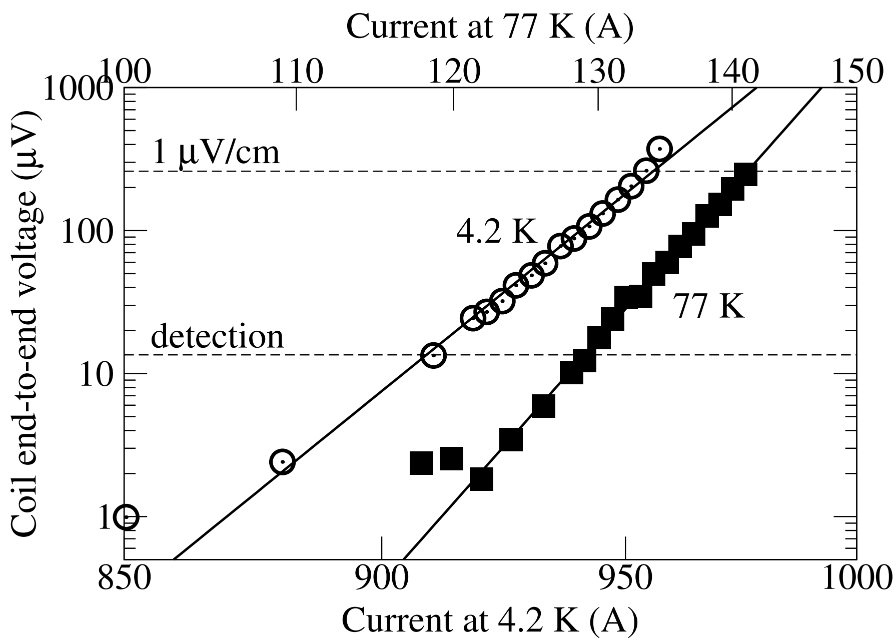

Figure 5. Coil voltage as a function of current for coil YC04 (2 × 3-turn) at 4.2 K (open circles) and 77 K (solid squares), log-log scale. A power-law fit of the data ($V \propto I^n$) is also plotted. n is 32 at 77 K and 59 at 4.2 K. The dashed lines give he voltage levels corresponding to an electric field of 1 μV/cm across the coil and a minimum voltage level that can be used for the detection of resistive transition.

tests, the coil warmed up to room temperature. Both 77 K tests gave identical I_c of 103 A, indicating that no degradation was introduced by either thermal cycles or the horseshoe structure. To prevent thermal runaway at 4.2 K, the current was ramped down when the coil voltage reached about 300 μV. Figure 6 compares the coil voltage as a function of current measured at 77 K and 4.2 K.

Table 3 summarizes the measured I_c of two racetrack coils at 77 K and 4.2 K and the corresponding percentages of the expected performance. While there is room to improve the prediction by considering, *e.g.*, the impact from the magnetic field at the coil end [34] and the local conductor strain [35], at least 80% of the expected I_c was reached at 77 K and 4.2 K for both coils. This indicated that the 2D electromagnetic approach can establish a reasonable coil performance limit to assess the coil technology at least for racetrack coils featuring simple geometry. We note that the calculation was based on the field direction that limited the short-sample I_c, as opposed to the full angular dependence typically used in the calculation [17–20]. While coils of other geometries are needed to further verify the approach, the observation suggested that the I_c characterization at the most I_c-limiting field direction can be sufficient to determine the expected coil I_c which would reduce the cost of the coil technology development.

Assuming a uniform and identical I_c for the conductors used for various coils, the 77 K self-field performance of the coils reported here were about 5% lower than those of two earlier coils reported in [30]. In reality, the conductor I_c variation can play a

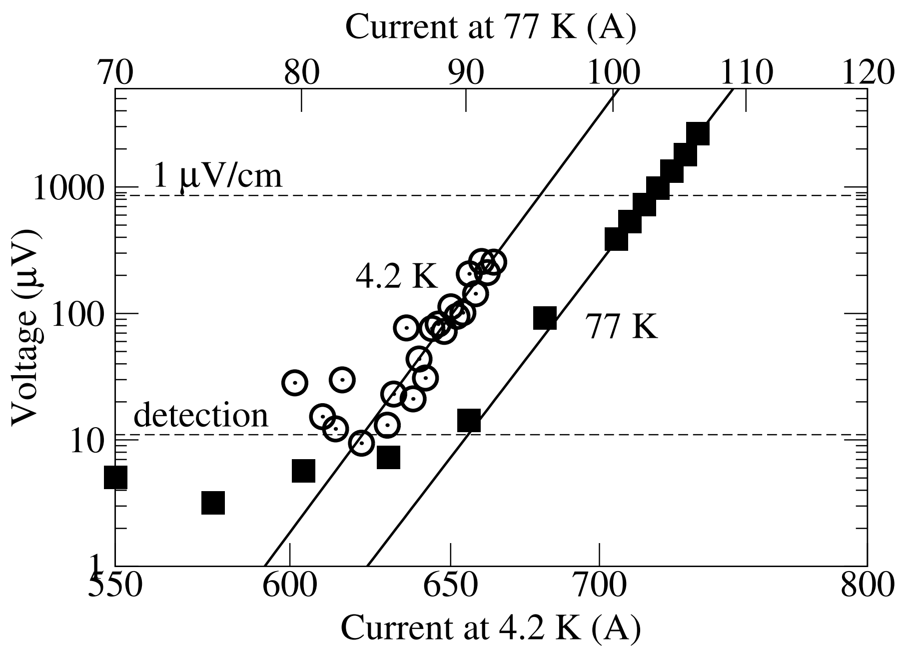

Figure 6. Coil voltage as a function of current for coil YC05 (2×10-turn) at 4.2 K (open circles) and 77 K (solid squares), log-log scale. n is 33 at 77 K and 49 at 4.2 K.

Table 3. The measured I_c for the racetrack coils with 1 μV/cm criterion and its percentage of the expected I_c.

Coil	77 K	4.2 K	Lift factor
YC04 (2×3)	141 A (91%)	956 A (89%)	6.8
YC05 (2×10)	103 A (85%)	680 A (81%)	6.6

role but to draw a conclusion, a detailed I_c characterization along the conductor used to wind the coils is required. The I_c difference between several coils of the same design highlighted the sensitivity of the coil performance on the uniformity of I_c along the conductor length.

Hall sensor output was monitored during the current ramping at both 77 K and 4.2 K (see figure 3 for sensor location). At 664 A, a field of 0.245 T was measured for coil YC05. A transfer function of 0.376 mT/A at 77 K and 0.369 mT/A at 4.2 K were observed, within 2% of the calculated value of 0.375 mT/A.

3.3. Temperature dependence of coil critical current

The temperature dependence of the coil I_c is expressed in the lift factors defined in section 3.1. Since the coil I_c depends on the electric-field criterion, we give the range of the lift factors bounded by two voltage levels: 1) the level corresponding to the 1 μV/cm electric-field criterion and 2) the minimum level that can be used for the detection of the resistive transition during test. Both levels are shown with the dashed lines in figures 5 and 6. The lift factor ranged from 6.8 to 7.1 for YC04 and from 6.6 to 7.2 for YC05, all within 6% of the expectation given in table 2. Thus, the proposed approach can indeed determine the lift factor of the coil I_c based on that of the short sample. While tests of coils with other geometries are needed to confirm the observation, our results indicated that the 77 K self-field I_c can be a useful metric for coil performance. With the expected lift factor, the 77 K self-field I_c can also determine the self-field coil I_c at 4.2 K. This would allow the cost-effective tests in liquid nitrogen to provide fast feedback to the coil technology development. In addition, the comparison between the measured and expected lift factors can help to determine if the cooldown introduces any coil degradation.

We note that the conductor used in our experiments was free of Zr doping which was also evidenced by the measured α as shown in table 1 [36]. For these samples, $B_\perp$ limits the short-sample I_c at 77 K and 4.2 K. Recent coated conductors feature various addition [37, 38] to enhance the $I_c(B_\perp)$ and reduce the angular dependence of $I_c(B)$. In these conductors, $B_\perp$ remains the limiting direction for short-sample I_c at 4.2 K but not for temperatures above 20 K [13, 36–39]. For coils made of these conductors, one needs to consider the actual I_c-limiting direction at 77 K to determine the performance limit and the temperature correlation between 77 K and 4.2 K.

The proposed approach is applicable to other coil geometry that can be reduced to a 2D problem, *e.g.*, pancake coils with rotational symmetry and the straight section of accelerator magnets. The approach presented here can also be applied to coils with larger sizes or numbers of turns from the magnetics point of view. On the other hand, the local conductor stress/strain can increase with the coil size during coil fabrication and operation and detailed analysis is required to consider the local stress/strain state of the conductor in larger coils to better determine the expected coil performance. Feasibility of the proposed approach for the current-carrying capability of a stack of conductors [40, 41] and conductor on round core cable [42] will be studied. The approach can be extended to consider the performance of coil and conductor in a background field by assigning the local background field component to each cell in the magnetic model of figure 1.

4. Conclusion

We presented an experimental and computational approach to correlate the self-field I_c of YBCO short samples and racetrack coils made from single YBCO tapes. The I_c of the short samples was measured with the applied magnetic field perpendicular to the conductor surface which limited the conductor I_c. The critical-current density excluding the self-field effect was determined from the transport measurement as an input to the model. Double-layer racetrack coils with different number of turns were wound and tested at 77 K and 4.2 K. The coil I_c reached at least 80% of the expected performance. The approach provided a reasonable expected coil I_c that is sufficient to develop the YBCO coil technology. A ratio around 7 was observed between the self-field I_c at 4.2 K and 77 K for both racetrack coils and single conductors, within 6% of the calculation. The proposed approach and the observed correlation of the coil I_c between 77 K and 4.2 K suggested that the 77 K self-field test can be a cost-effective tool to provide fast feedback for the development of YBCO coil technology.

5. Acknowledgments

We appreciate the indispensable support from D. W. Cheng for designing the pole island; P. Wong for machining samples; P. Bish, H. Higley, S. King, N. Liggins, and J. Swanson for winding coils and testing short samples and coils; T. Lipton for arranging technical resources; M. Mentink and C. Kozy for instrumentation. This work was supported by the Director, Office of Science, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

References

[1] Obradors X and Puig T 2014 *Superconductor Science and Technology* **27** 044003

[2] Maeda H and Yanagisawa Y 2014 *IEEE Trans. Appl. Supercond.* **24** 4602412

[3] Senatore C, Alessandrini M, Lucarelli A, Tediosi R, Uglietti D and Iwasa Y 2014 *Superconductor Science and Technology* **27** 103001

[4] Trociewitz U P, Dalban-Canassy M, Hannion M, Hilton D K, Jaroszynski J, Noyes P, Viouchkov Y, Weijers H W and Larbalestier D C 2011 *Applied Physics Letter* **99** 202506 (pages 3)

[5] Weijers H, Markiewicz W, Voran A, Gundlach S, Sheppard W, Jarvis B, Johnson Z, Noyes P, Lu J, Kandel H, Bai H, Gavrilin A, Viouchkov Y, Larbalestier D and Abraimov D 2014 *IEEE Trans. Appl. Supercond.* **24** 4301805

[6] Uglietti D, Bykovsky N, Sedlak K, Stepanov B, Wesche R and Bruzzone P 2015 *Superconductor Science and Technology* **28** 124005

[7] Mangiarotti F J, Goh J, Takayasu M, Bromberg L, Minervini J V and Whyte D 2014 *Journal of Physics: Conference Series* **507** 032030

[8] Rossi L, Badel A, Bajko M, Ballarino A, Bottura L, Dhalle M, Durante M, Fazilleau P, Fleiter J, Goldacker W, Härö E, Kario A, Kirby G, Lorin C, van Nugteren J, de Rijk G, Salmi T, Senatore C, Stenvall A, Tixador P, Usoskin A, Volpini G, Yang Y and Zangenberg N 2015 *IEEE Trans. Appl. Supercond.* **25** 4001007

[9] Kirby G, van Nugteren J, Ballarino A, Bottura L, Chouika N, Clement S, Datskov V, Fajardo L, Fleiter J, Gauthier R, Gentini L, Lambert L, Lopes M, Perez J, de Rijk G, Rijllart A, Rossi L, ten Kate H, Durante M, Fazilleau P, Lorin C, Haro E, Stenvall A, Caspi S, Marchevsky M, Goldacker W and Kario A 2015 *IEEE Trans. Appl. Supercond.* **25** 4000805

[10] Amemiya N, Zhang Z, Sano T, Sogabe Y, Ogitsu T, Koyanagi K, Kurusu T, Mori Y, Iwata Y, Noda K and Yoshimoto M 2015 *IEEE Trans. Appl. Supercond.* **25** 4003505

[11] Gupta R, Anerella M, Ghosh A, Lalitha S, Sampson W, Schmalzle J, Kolonko J, Scanlan R, Weggel R, Willen E and Nakao K 2015 *IEEE Trans. Appl. Supercond.* **25** 4003704

[12] Song H, Brownsey P, Zhang Y, Waterman J, Fukushima T and Hazelton D 2013 *IEEE Trans. Appl. Supercond.* **23** 4600806

[13] Xu A, Jaroszynski J J, Kametani F, Chen Z, Larbalestier D C, Viouchkov Y L, Chen Y, Xie Y and Selvamanickam V 2010 *Superconductor Science and Technology* **23** 014003

[14] Polak M, Ušák P and Demencik E 2006 *Physica C* **440** 40–44

[15] Yoo J, Lee J, Lee S M, Jung Y H, Youm D and Oh S S 2009 *Superconductor Science and Technology* **22** 125019

[16] Sirois F and Grilli F 2015 *Superconductor Science and Technology* **28** 043002

[17] Pardo E, Šouc J and Frolek L 2015 *Superconductor Science and Technology* **28** 044003

[18] Zhang M, Kim J H, Pamidi S, Chudy M, Yuan W and Coombs T A 2012 *Journal of Applied Physics* **111** 083902

[19] Zermeño V, Sirois F, Takayasu M, Vojenciak M, Kario A and Grilli F 2015 *Superconductor Science and Technology* **28** 085004

[20] Grilli F, Sirois F, Zermeno V and Vojenciak M 2014 *IEEE Trans. Appl. Supercond.* **24** 8000508

[21] Prigozhin L 1996 *Journal of Computational Physics* **129** 190–200

[22] Hilton D K, Gavrilin A V and Trociewitz U P 2015 *Superconductor Science and Technology* **28** 074002

[23] Selvamanickam V, Xu A, Liu Y, Khatri N D, Lei C, Chen Y, Galstyan E and Majkic G 2014 *Superconductor Science and Technology* **27** 055010

[24] Xu A, Delgado L, Gharahcheshmeh M H, Khatri N, Liu Y and Selvamanickam V 2015 *Superconductor Science and Technology* **28** 082001

[25] Abraimov D, Weijers H W, Markiewicz W D, Santos M, Francis A, McCallister J, Dickey J, Jaroszynski J, Hu X, Lu J, Toplosky V, Jarvis B, Carter S, Sheppard B, Polyanskii A A, Viouchkov Y L and Larbalestier D C 2015 Properties of (Re)BCO conductor for development of 32 T user magnet Tech. rep. National High Magnetic Field Laboratory presentation at 2015 MRS Spring Meeting, San Francisco. http://www.magnet.fsu.edu/library/presentations/NHMFL_Presentation-7968.pdf

[26] Dalban-Canassy M, Trociewitz U P, Hilton D K, Viouchkov Y, Noyes P, Jaroszynski J, Sinclair J W, Markiewicz W D, Weijers H W, Chen P, Craig N, Hellstrom E E,

Jiang J, Matras M and Larbalestier D C 2013 Considerations for quenching HTS coils `https://indico.cern.ch/event/199910/contribution/39`

[27] Babaei Brojeny A A and Clem J R 2005 *Superconductor Science and Technology* **18** 888–895

[28] Däumling M 1997 *IEEE Trans. Appl. Supercond.* **7** 1335–1338

[29] Rostila L, Lehtonen J, Mikkonen R, Šouc J, Seiler E, Melíšek T and Vojenčiak M 2007 *Superconductor Science and Technology* **20** 1097

[30] Wang X, Caspi S, Cheng D W, Dietderich D R, Felice H, Ferracin P, Godeke A, Joseph J M, Lizarazo J, Prestemon S O and Sabbi G 2010 *IEEE Trans. Appl. Supercond.* **20** 368–372

[31] Takematsu T, Hu R, Takao T, Yanagisawa Y, Nakagome H, Uglietti D, Kiyoshi T, Takahashi M and Maeda H 2010 *Physica C* **470** 674–677

[32] Kim Y B, Hempstead C F and Strnad A R 1963 *Phys. Rev.* **129**(2) 528–535

[33] Hazelton D W Continued developments in high magnetic fields enabled by second-generation high-temperature superconductors Presented at 2009 Magnetics Conference, Chicago, IL April 15-16, 2009

[34] Zermeño V and Grilli F 2014 *Superconductor Science and Technology* **27** 044025

[35] Fabbricatore P, Priano C, Testa M P, Musenich R, Kovac P, Matrone A, Petrillo E and Ariante M 1998 *Superconductor Science and Technology* **11** 304–310

[36] Xu A, Delgado L, Khatri N, Liu Y, Selvamanickam V, Abraimov D, Jaroszynski J, Kametani F and Larbalestier D C 2014 *APL Materials* **2** 046111

[37] Selvamanickam V, Yao Y, Chen Y, Shi T, Liu Y, Khatri N D, Liu J, Lei C, Galstyan E and Majkic G 2012 *Superconductor Science and Technology* **25** 125013

[38] Abraimov D, Ballarino A, Barth C, Bottura L, Dietrich R, Francis A, Jaroszynski J, Majkic G S, McCallister J, Polyanskii A, Rossi L, Rutt A, Santos M, Schlenga K, Selvamanickam V, Senatore C, Usoskin A and Viouchkov Y L 2015 *Superconductor Science and Technology* **28** 114007

[39] Braccini V, Xu A, Jaroszynski J, Xin Y, Larbalestier D C, Chen Y, Carota G, Dackow J, Kesgin I, Yao Y, Guevara A, Shi T and Selvamanickam V 2011 *Superconductor Science and Technology* **24** 035001

[40] Takayasu M, Chiesa L, Bromberg L and Minervini J V 2012 *Superconductor Science and Technology* **25** 014011

[41] Bykovsky N V, Fetisov S S, Nosov A A, Zubko V V and Vysotsky V S 2014 *Journal of Physics: Conference Series* **507** 022001

[42] van der Laan D C, Lu X F and Goodrich L F 2011 *Superconductor Science and Technology* **24** 042001