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Record current density of 344 A mm^{-2} at 4.2 K and 17 T in CORC® accelerator magnet cables

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Abstract

One of the biggest challenges in developing conductor on round core (CORC®) magnet cables for use in the next generation of accelerator magnets is raising their engineering current density J_E to approach 600 A mm^{-2} at 20 T, while maintaining their flexibility. One route to increase J_E could be to add more RE-$Ba_2Cu_3O_{7-\delta}$ coated conductors to the cable, but this would increase the cable size and reduce its flexibility. The preferred route to higher J_E is a reduction in diameter of the CORC® cable, while maintaining the number of tapes wound into the cable. The availability of very thin tapes containing substrates of 30 μm thickness enabled us to wind a 5.1 mm diameter CORC® cable from 50 coated conductors, while maintaining a tape critical current I_c of about 97% after cabling. The cable I_c was 7030 A at 4.2 K in a background field of 17 T, corresponding to a J_E of 344 A mm^{-2}, which is the highest performance of any CORC® cable so far. The magnetic field dependence allowed us to extrapolate the cable performance to 20 T to predict an I_c of 5654 A and a J_E of 309 A mm^{-2}. The results clearly show that rapid progress is being made on overcoming the J_E hurdle for use of CORC® cables in the next generation of accelerator magnets. Further optimization of the cable layout will likely increase J_E towards 600 A mm^{-2} at 20 T in the near future, while further reduction in cable size will also make them even more flexible.

Keywords: CORC cable, high magnetic field, REBCO coated conductor cables, critical current

(Some figures may appear in colour only in the online journal)

1. Introduction

High-field magnets that operate at magnetic fields exceeding 20 T, or at temperatures significantly above the boiling temperature of liquid helium, require the use of high-temperature superconductors (HTS). One of the more challenging magnet applications is the next generation of accelerator magnets that will likely operate at fields up to or even above 20 T, while requiring a cable-bending diameter as small as 40 mm for standard aperture dipoles and quadrupoles. A cable current of around 10 kA is required for accelerator magnets because they need to ramp relatively quickly, while a high J_E, defined as the current over the entire cable cross-section, of around 600 A mm^{-2} at the operating field is required.

Two types of HTS materials are currently being explored for potential use in the next generation of accelerator magnets, being Bi-2212 [1, 2] and RE-$Ba_2Cu_3O_{7-\delta}$ (REBCO) coated conductors [3–6]. Several programs sponsored by the US Department of Energy, Office of High Energy Physics are focused on developing Bi-2212 cables for accelerator magnets following the overpressure processing approach and on conductor on round core (CORC®) cables wound from REBCO tapes [7, 8]. A large collaboration in Europe focuses on developing Roebel accelerator magnet cables wound from

Table 1. Properties of the various REBCO tapes used in this work.

	Substrate (μm)	Width (mm)	Copper (μm)	Thickness (μm)	REBCO (μm)	I_c(77 K) (A)	I_c(76 K) (A)	Zr-doping(%)	Enhanced pinning
1	30	3	5	45	1.6	105	124	7.5	+
2	38	4	5	53	1.2	116	137	7.5	−
3	50	4	5	68	1.2	122	144	7.5	−

REBCO tapes [9–11] within the EUCARD-2 framework [12], which is led by CERN. The main benefit of Roebel cables include the full transposition of the relatively wide cable strands and the potential for a relatively high J_E as long as the magnet design results in the magnetic field being aligned with the plane of the cable. Although Roebel cables have the potential for a high J_E, only data measured at fields up to 9.6 T are currently available [13]. Roebel cables require complex magnet geometries to accommodate the technical challenges that come with bending the cable and providing the preferred magnetic field alignment [14], while their tolerance to mechanical stresses is also an issue.

REBCO tapes that are wound in a helical fashion into CORC® cables have the benefit that they are transposed within each layer, as is the case for filaments in a NbTi or Nb_3Sn wire, significantly reducing the cable magnetization [15, 16]. The relatively short tape twist pitch of between 7 and 25 mm makes CORC® cables relatively flexible, thus minimizing the need for complex magnet structures. The magnetic field dependence of J_E in CORC® cables is determined by the magnetic field angle at which the I_c is lowest, which at 4.2 K is the magnetic field orientation perpendicular to the tape plane. Significant progress to increase J_E at 20 T in CORC® cables has been made over the years, resulting in an increase in J_E at 20 T from 114 A mm^{-2} in 2012 [17] to 217 A mm^{-2} in 2014 [18]. The increase in J_E has been achieved mainly by reducing the cable size from 7.5 mm to 6.0 mm without reducing the number of tapes in the cable and at the same time reducing tape damage during cabling by winding CORC® cables with a custom cable machine. The most recent reduction in CORC® cable size was achieved mainly by winding the cables from tapes with 38 μm thick substrates, compared to the standard 50 μm thickness. The lower substrate thickness reduced the cross-section of the tape, and lowered the winding strain on the superconducting film, allowing for the use of thinner cable formers.

This paper describes the latest effort to further increase J_E in CORC® cables by winding them from tapes with 30 μm thick substrates that are now becoming available from SuperPower Inc. Improved vortex pinning through a further optimization of the doping with 7.5% $BaZrO_3$ (BZO) doping in the tapes in combination with an increased REBCO film thickness from 1.2 μm to 1.6 μm allow for a higher tape I_c at 4.2 K and high fields. We report the results of measurements performed at 4.2 K in fields up to 17 T on a 5.1 mm diameter CORC® cable containing 50 tapes, and show the benefit of these more advanced tapes on the high-field performance of the cable.

2. Experimental

Tapes purchased from SuperPower Inc. with either 30 μm, 38 μm or 50 μm thick Hastelloy C-276 thick substrates were used in this study. The 1.2 μm thick REBCO layer in the tapes with a 38 and a 50 μm substrate, and the 1.6 μm thick layer in the tapes with a 30 μm substrate were deposited on top of the buffer layers by metal-organic chemical-vapor deposition [19, 20]. The coated conductors were then slit from a 12 mm wide tape to their final width of 3 mm or 4 mm. They were surround-plated with 5 μm of copper for electrical and thermal stability, which is the minimum thickness needed to ensure full coverage of the silver cap layer to prevent it from being dissolved into the solder when making cable terminations. The critical current of these 3 mm and 4 mm wide tapes ranged from about 99 A to about 125 A at 77 K in self-field, depending on the tape batch and their width. Table 1 outlines the properties of the various tapes used in this work.

Most superconducting tapes produced by SuperPower Inc. contain a Zr doping of 7.5% to enhance the pinning properties at 30 K and below by forming $BaZrO_3$ nanorods. Extensive study of such tapes using an earlier optimization shows that as much as half the J_c at 4 K in fields up to 20 T is provided by point defects generated by mismatch of the BZO and the matrix [21]. However, SuperPower Inc. has adjusted the processing conditions of the tapes with 30 μm substrates to optimize their performance specifically for operation at 4.2 K and high magnetic fields and claim further advances. These tapes are marked with '+' in the column 'enhanced pinning' in table 1, while tapes optimized for 30 K are market with '−'. The critical current at 76 K shown in table 1 was calculated from I_c at 77 K using an increase in I_c of 18% when the temperature is reduced by 1 K.

2.1. Single-tape CORC® cable construction

The minimum allowable former diameter in CORC® cables depends largely on the applied compressive axial strain in the superconducting film when wound onto the former. The applied compressive strain on the REBCO layer depends on the former diameter d and the thickness t of the substrate according to the following relation:

$$\varepsilon = \frac{-t}{d}. \qquad (1)$$

The former diameter at which irreversible degradation of tapes with 38 μm and 50 μm substrates occurs was determined previously by winding single coated conductors onto

Figure 1. A 3 mm wide superconducting tape wound onto a 2.8 mm diameter former. A 3 mm wide copper tape is wound in parallel to the superconducting tape to ensure a constant winding angle close to 45°.

Table 2. Parameters of the various single-tape CORC® cables investigated.

Former diameter (mm)	α(°)	ε (%) (30 μm)	ε (%) (38 μm)	ε (%) (50 μm)
2.2	46.34	−1.36		
2.4	46.84	−1.25	−1.58	
2.8	43.01	−1.07	−1.36	
3.2	44.13	−0.94	−1.19	−1.56
4	45.74	−0.75	−0.95	−1.25
4.8	46.84	−0.63	−0.79	−1.04

several formers with a diameter ranging from 2.4 mm to 4.8 mm and measuring their critical current at 76 K [18]. Here, we performed similar measurements with the tapes containing 30 μm thick substrate for formers as small as 2.2 mm. The tapes were wound onto the former at an angle α of about 45° to minimize the reversible strain effect on I_c [22, 23]. Any decrease in I_c measured while the REBCO coated conductor was wound onto the former was thus caused by permanent damage to the superconducting film, while the absence of any damage should result in close to 100% retention in I_c of the conductor. Figure 1 shows a 3 mm wide superconducting tape wound around a 2.8 mm diameter former with a 3 mm wide copper tape wound in parallel to the superconducting tape to precisely control the tape winding angle.

Table 2 lists the parameters of the various single-tape CORC® cables made on formers of different diameter, including those wound from tapes with 38 μm and 50 μm substrates, presented earlier [18]. Copper tapes with widths ranging from 1.5 mm to 8 mm were available for winding in parallel to the superconducting tapes, which resulted in the winding angles being very close to 45°, with a maximum deviation of less than 2° as listed in table 2. The maximum winding strain in the superconducting film is also listed in table 2 for each former diameter for all three tape substrate thicknesses. Strains varied from −0.63% for a tape with a 30 μm substrate wound onto a 4.8 mm former, to −1.58% for a tape with a 38 μm thick substrate wound on a 2.4 mm diameter former.

2.2. CORC® cable construction

A CORC® cable containing 50 tapes with 30 μm thick substrates in 20 layers was wound on a solid copper former with a custom cable machine. Availability of only tapes of 3 mm width required the former to be at least 3.2 mm thick. Use of a thinner former would have required 2 mm wide tapes, which were not available at the time that the cable was wound. The CORC® cable was insulated with a 50 μm thick, cryogenically tolerant polyester heat shrink tubing. The cable was about 1.8 m long before the terminations were mounted. A 15 cm long straight section for testing individual tapes was cut from the cable before two 20 cm long terminals were mounted. The cable length was about 1.2 m in between the terminals. It was wound into a 10 cm diameter loop to fit the sample holder for testing at high field (see figure 2). The bottom part of the sample holder consisted of an aluminum mandrel in which a groove was machined. Vacuum grease was used to fill the gaps between the cable and the mandrel after the cable was inserted. Bolting two aluminum shells on the outside of the holder fully enclosed the cable. One of the shells is visible in figure 2. Further details of the sample holder are described elsewhere [17].

3. Results

3.1. Determination of minimum former diameter for tapes with 30 μm substrates

A similar approach to the one described in [18] for tapes with 38 μm and 50 μm thick substrates was used to determine the minimum former diameter onto which tapes with 30 μm substrates could be wound. A single tape was wound at a winding angle of about 45° on formers ranging from 4.8 mm in diameter down to 2.2 mm (see table 2). Figure 3 shows the retention in the critical current at 76 K of the tapes when wound around the different formers. Two samples were prepared for each former diameter. One sample showed significant degradation in I_c at a former diameter of 4.8 mm, but this was likely due to handling of the very delicate tape when wound around the former by hand. No significant change in I_c was measured for any of the other tapes with 30 μm substrates for a former diameter down to 2.4 mm. The first significant degradation in I_c occurred for a former diameter of 2.2 mm, at which point both samples showed a very large degradation in I_c.

The samples containing tapes with 38 μm and 50 μm thick substrates that were measured earlier [18] are included in figure 3 for comparison. Tapes containing 38 μm thick substrates started to degrade when wound onto a 2.8 mm diameter former, while tapes with 50 μm thick substrates started to degrade when wound onto a 3.2 mm diameter former. Table 2 lists the winding strain experienced by the REBCO film for each sample shown in figure 3. All samples, independent of their substrate thickness, showed significant degradation in I_c when the axial strain in the film exceeded about −1.25%. The results clearly show that tapes with

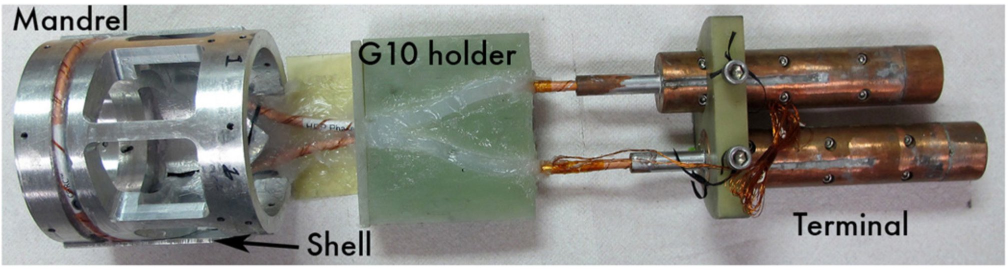

Figure 2. The 5.1 mm thick CORC® cable wound from 50 coated conductors with 30 μm thick substrates mounted in the sample holder for testing at high field.

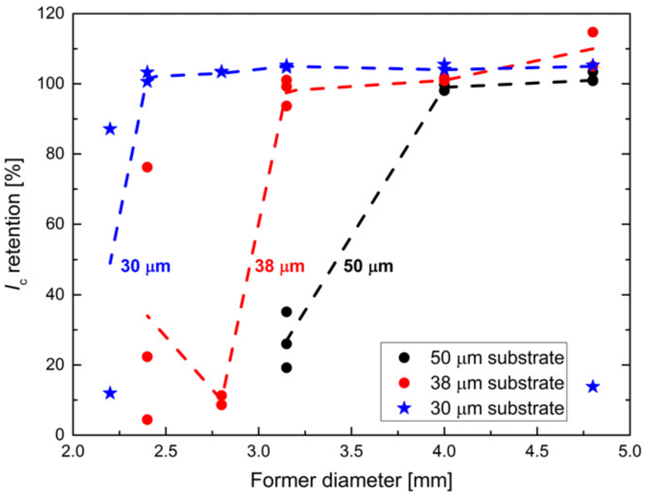

Figure 3. Normalized I_c of the single-tape CORC® cables containing different substrate thicknesses as a function of former diameter. The dashed lines are a guide to the eye.

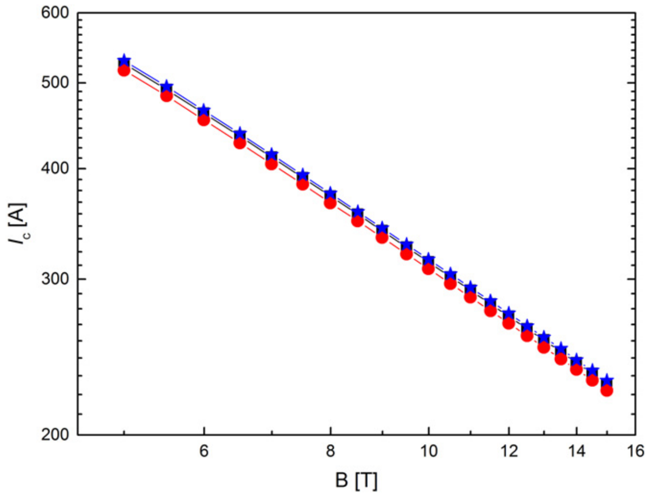

Figure 4. Critical current at 4.2 K as a function of magnetic field for three tapes containing a 30 μm substrate and enhanced-process 7.5% Zr doping.

30 μm thick substrates allow CORC® cables to be wound on 2.4 mm diameter formers, without causing any significant degradation in tape performance, assuming that handling caused the one tape to degrade.

3.2. Performance of tapes with a 30 μm substrate and enhanced 7.5% Zr doping

The processing of the 30 μm substrate tapes from which the 50-tape CORC® cable was wound has been optimized by SuperPower Inc. to boost the tape performance at 4.2 K and high fields, although the Zr-doping remains at 7.5%. Three short tape sections were cut from the 150 m long batch and tested at 4.2 K at fields applied perpendicular to the tape plane between 5 and 15 T. The critical current of the 3 mm wide tapes were within a few percent of each other and ranged from about 520 A at 5 T to about 230 A at 15 T. Figure 4 shows that the magnetic field dependence followed a power-law function, with an average power of −0.75, from which an I_c of about 185 A at 20 T could be extrapolated; the 3-sample average lift factor $I_c(20\,\text{T},\ \text{BIIc},\ 4.2\,\text{K})/I_c(\text{seld-field},\ 77\,\text{K})$ was 1.72. This power law exponent is indeed a little higher than $p = -0.7$ found in earlier detailed study of 7.5% Zr doped SuperPower tapes [21].

3.3. 50-tape CORC® cable characterization in liquid nitrogen

The performance of the CORC® cable containing 50 tapes was measured at 76 K in liquid nitrogen while bent to a 30 cm diameter to fit the nitrogen dewar. The voltage versus current (*V–I*) characteristic measured over the copper terminals of the cable is shown in figure 5, together with a fit to the data to calculate the critical current and the contact resistance using the following equation:

$$U = IR + U_c\left(\frac{I}{I_c}\right)^n + U_0. \tag{2}$$

Here, U_c is the voltage at which the critical current is defined, $1 \times 10^{-4}\,\text{V m}^{-1}$ times the voltage contact length and U_0 is the inductive offset voltage. The voltage contact length was measured along the length of the tapes in the outer layer of the cable and was 1.7 m. The setup was limited to a sample current of about 3900 A at the time of the test, so only the initial part of the superconducting transition could be measured. The current range was sufficient to calculate I_c, which was 4313 A, or 75% of the expected I_c based on the total tape I_c. The contact resistance of both terminals together was 46.4 nΩ at 76 K.

A possible reason for the relatively low retention of 75% in I_c based on the cable test in liquid nitrogen is heating in the terminations at high current, which would cause the

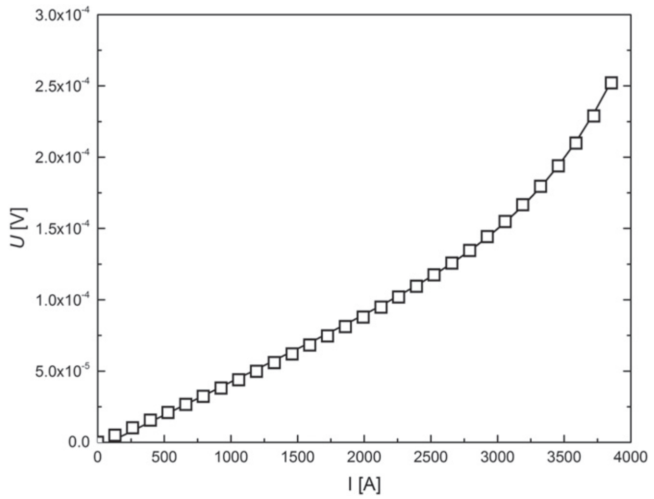

Figure 5. Voltage versus current characteristic of the 50-tape CORC® cable measured at 76 K. The solid line is a fit to the data using equation (2).

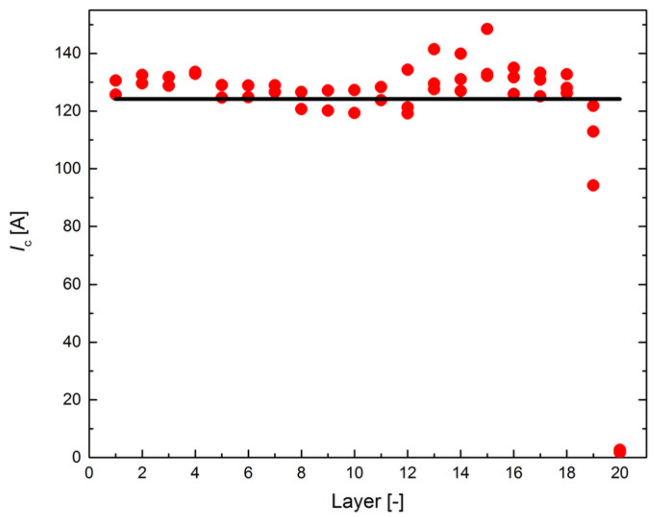

Figure 6. Tape I_c measured at 76 K after the tapes were extracted from a straight section of cable cut from the CORC® cable containing 50 tapes with 30 μm substrates. The solid line is the initial I_c value of the tapes as indicated by the manufacturer, and converted to 76 K. The inner layer is 1 and the outer is 20.

superconducting transition to occur within the terminals and not in the actual cable. The degradation is not expected to be caused by bending the cable to a diameter of 30 cm. The self-field of the cable at these high currents could play a role, although it will be oriented mainly parallel to the tape planes.

The most straightforward method to determine the actual retention in I_c of the tapes in the CORC® cable is to extract the tapes from the cable and measure their I_c individually. For this reason, a 15 cm long straight section was cut from the cable after it was wound. Each tape was extracted from the cable, labeled and visually inspected for damage before their I_c was measured in liquid nitrogen. The labeling was performed for all layers of the cable from inside out. Figure 6 shows the actual I_c at 76 K of each tape as a function of the layer from which the tapes were extracted. Also included in the figure is the expected I_c of the tapes, indicated by the solid line, which was about 124 A at 76 K. The expected I_c at 76 K was calculated by multiplying the I_c at 77 K, as specified by the manufacturer, with 1.18 to take into account the increase in I_c of about 18% caused by the reduction in temperature of 1 K. The results show that except for the outer two layers, none of the tapes showed significant degradation of I_c. The sum of all tape I_c values was 6051 A, or 97.4% of the expected value. This result clearly shows that the very thin tapes remain mostly intact when cabled with the machine. The source of the degradation of the tapes in the outer two layers remains unknown at this moment, but may be related to the heat shrink tubing that was applied to insulate the cable.

3.4. 50-tape CORC® cable characterization at high magnetic fields

The first test of the CORC® cable at 4.2 K, after it was bent to a 10 cm diameter and inserted into the sample holder (figure 2), was performed at the highest field of the large bore resistive magnet at the NHMFL, which was 17 T. The sample current was increased at a constant rate of about 100 A s^{-1}. Multiple voltage spikes were measured that coincided with cracking sounds coming from the sample holder. Indeed the quench detector tripped at about 6000 A due to one of these voltage spikes before the onset of the superconducting transition, rapidly decreasing the sample current to zero. No audible sounds were heard, nor were there any voltage spikes when the current was increased again at 100 A s^{-1} to about 6000 A. Additional voltage spikes and sounds appeared at higher currents, but the quench detector did not trip until the sample current reached about 7200 A. Based on the *V–I* traces, the cable I_c of the initial run at 17 T that resulted in a quench was 7665 A and the contact resistance of both terminals together was 18.4 nΩ. Here, the voltage contact length of the sample is 1 m, which is the length of the superconducting tapes along the cable section located at high field.

The critical current of the CORC® cable was determined for fields between 12 T and 17 T, including several more runs at 17 T. The cable was tested 5 times at 17 T at which point the critical current decreased from 7665 A to 7178 A. The current was ramped each time to the point of cable quench. The sample was quenched 9 more times during voltage versus current measurements at fields all the way down to 13 T, followed by two last measurements at 17 T. The sample current was insufficient to cause a quench at 12 T. After a total of 14 quenches, I_c at 17 T was 7030 A. Three representative *V–I* characteristics measured at 17 T over the cable terminations are shown in figure 7, after the resistive component due to the contact resistance was subtracted. These include the 1st, 5th, and 14th *V–I* curve measured at high field. The slight shift of the *V–I* curve to lower currents due to the slight degradation of the cable can be clearly seen. Surprisingly, the *n*-value of the transition increased from about 12 to about 40 after the multiple quenches. The increase in *n*-value with number of quenches actually caused an increase in I_c when a more sensitive electric field criterion of

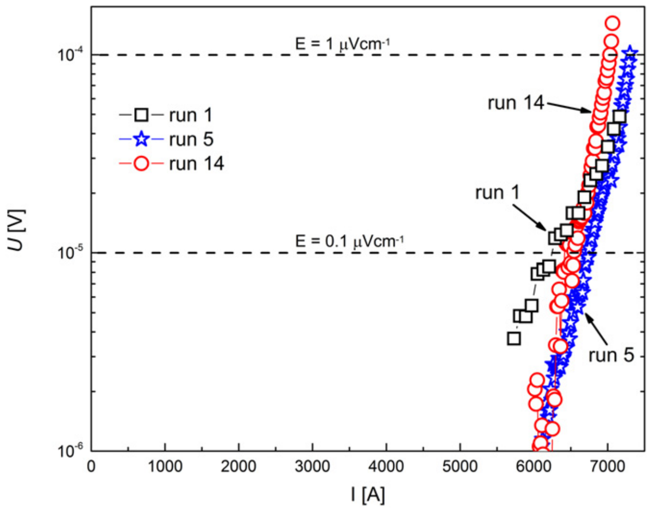

Figure 7. Voltage versus current characteristics measured at 4.2 K and 17 T, after the resistive voltage has been subtracted.

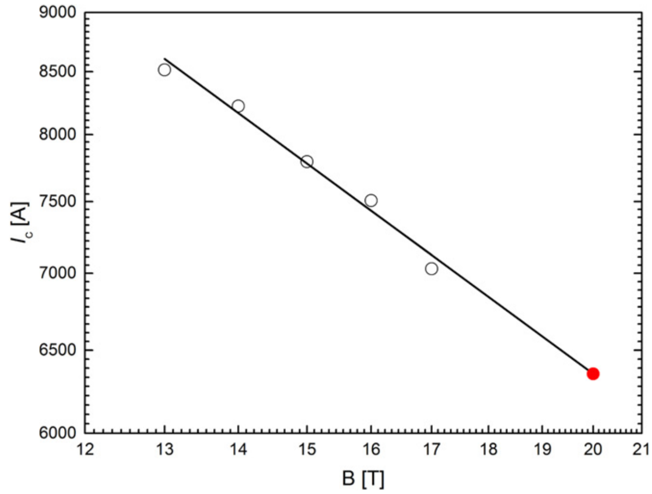

Figure 9. Magnetic field dependence at 4.2 K of I_c of the 50-tape CORC® cable. The solid line is a power-law fit to the data, with an exponent of −0.71. The filled dot is the extrapoloated I_c at 20 T.

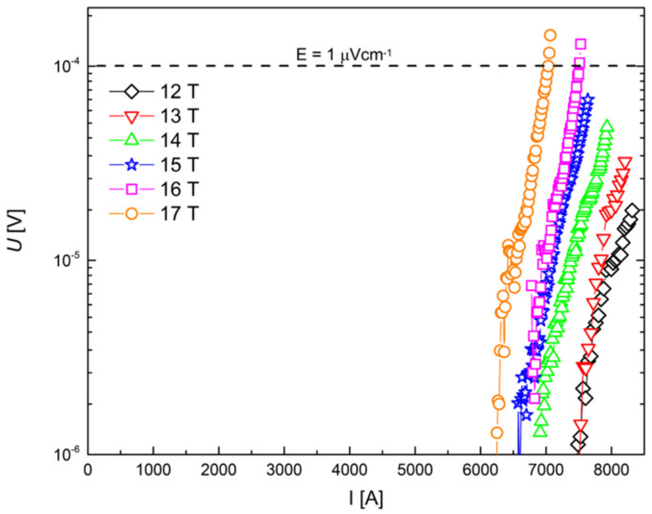

Figure 8. Voltage versus current characteristics measured at 4.2 K for fields between 12 T and 17 T, after the resistive voltage has been subtracted.

$0.1 \times 10^{-6}\,V\,m^{-1}$ would be used instead of the typical criterion of $1 \times 10^{-6}\,V\,m^{-1}$.

The voltage versus current characteristics measured at 4.2 K for fields between 12 T and 17 T are shown in figure 8, after the resistive voltage was subtracted. The highest sample current available was 8300 A, which limited the measurements to a lowest field of 12 T. The magnetic field dependence of I_c is shown in figure 9, including a power-law fit to the data with a power of −0.71, which is slightly lower than measured on the single tapes (figure 4). A critical current of 6354 A at 20 T could be extrapolated from the magnetic field dependence of I_c. The I_c at 17 T used in the fit was the one after 14 quenches ($I_c = 7030$ A), corresponding to a J_E at 17 T of 344 A mm^{-2}. The extrapolated J_E at 20 T was 309 A mm^{-2}, which is a new record for CORC® cables at these fields, almost 50% higher than what we reported earlier this year with a cable utilizing 38 μm substrates where we achieved 217 A mm^{-2} extrapolated to 20 T.

The high-field performance of the 50-tape CORC® cable was slightly lower than what was expected from the single-tape measurements performed at 4.2 K as a function of magnetic field (figure 4). The average I_c of the three tapes measured at 14 T was 235 A, which would suggest a cable I_c at 14 T of 11 750 A. Instead, an I_c of 8224 A was measured at 14 T, suggesting a retention in I_c of 70%, while ignoring the self-field generated by the cable. The cable contained about 150 m of tape, while the three short samples that were tested at high field were cut from a 1 m long tape section located at the end of the batch. A potential variation in chemistry along the length of the conductor could change the pinning and cause a larger variation in I_c at high field over the length of the conductor from which the CORC® cable was wound. Such variations have been seen in other recent SuperPower tapes [24]. Consistent with such pinning center variations, there is indeed a small difference in the power law exponent seen for the short samples shown in figure 4 where α is −0.75 and the cable as whole where $p = -0.71$ (figure 9).

Measurements of the tapes extracted from the cable that was tested at high field were performed to determine their retention of the I_c. A 10 cm long section of cable was cut from the sample loop that was bent to 10 cm diameter and experienced the highest stresses when tested at high field. Figure 10 shows the tape I_c measured at 76 K as a function of tape layer, layer 1 being the innermost layer and layer 20 being the outermost layer in the cable. The solid line in the figure is the expected undamaged I_c at 76 K. Indeed, the I_c of the individual tapes showed degradation. The total tape I_c of all 50 tapes extracted from the cable was 4512 A, suggesting a retention in I_c of 73%, which is similar to the retention of I_c of the CORC® cable tested at high field.

The retention in I_c of a straight section of the 50-tape CORC® cable with 30 μm substrates of 97.4% after cabling, shown in figure 6, is a clear indication that the custom

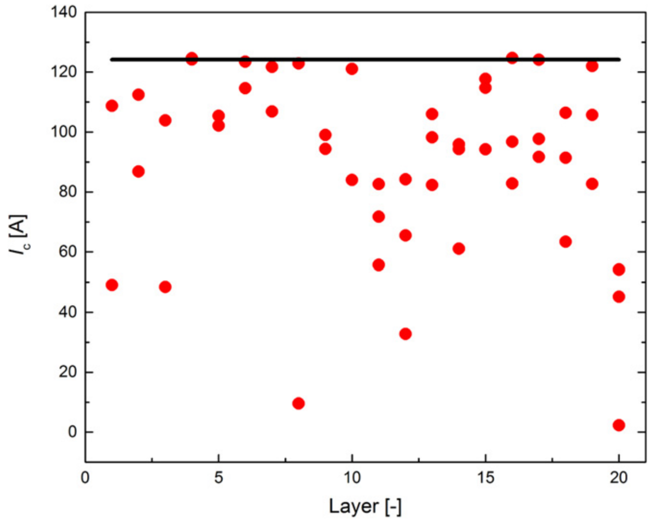

Figure 10. Tape I_c measured at 76 K after the tapes were extracted from a cable section located at high field. The solid line is the initial I_c value of the tapes as indicated by the manufacturer, and converted to 76 K. The inner layer is 1 and the outer is 20.

machine is able to wind these delicate tapes into a CORC® cable without causing any significant degradation. The cause of the additional 25% degradation after the cable was bent into a diameter of 10 cm and tested at high field, including 14 quenches, is likely due to inadequate cable support during high-field testing by vacuum grease alone. The cable I_c degraded from about 7 665 A during the first *V–I* measurement at 17 T to 7030 A at 17 T during the 14th measurement, or a reduction of 8.3%. The voltage spikes and noise suggests cable movement in the probe support. This occurred in the very first 17 T run, which was stopped at 6000 A due to a voltage spike that tripped the quench detector, likely causing even more degradation in the cable. Design of a better sample support that will prevent sample movement is underway. This will allow us to determine the level of degradation at high fields intrinsic to the CORC® cable.

Further improvements of the CORC® cable layout, including the use of 2 mm wide tapes that would allow the use of 2.2 mm diameter formers, offer the opportunity to increase J_E further towards 600 A mm^{-2} at 20 T. This will also reduce the cable size, making them likely bendable to a diameter as small as 40 mm. Such optimization is scheduled for the near future once the narrow tapes are delivered from the manufacturer.

4. Conclusions

Recent availability of REBCO coated conductors containing 30 μm substrates enabled us to significantly increase the performance of CORC® cables. The tapes contained 7.5% Zr doping, while their processing was optimized to increase the critical current at high field at 4.2 K, instead of intermediate fields at 30 K. They also contained 1.6 μm thick REBCO films, which is now the standard thickness the REBCO layer in tapes produced by SuperPower Inc. The combination of enhanced pinning, thicker REBCO layers and thinner substrates resulted in tapes with a very high engineering current density at high magnetic field.

The 30 μm substrate thickness, and the resulting lower winding strain in the REBCO layer, allowed us to wind the tapes into CORC® cables with formers as small as 2.4 mm before any significant degradation in the tape performance occurred. A CORC® cable containing 50 tapes with a 30 μm substrate was wound with a custom cable machine with no significant degradation in tape performance. The cable was tested at 4.2 K in magnetic fields as high as 17 T, where it had an I_c of 7030 A and a J_E of 344 A mm^{-2} after 14 quenches at high field. Extrapolating the cable performance to 20 T resulted in a new record J_E of 309 A mm^{-2}. The results clearly indicate that the last hurdle for CORC® cables for use in accelerator magnets has been overcome and that CORC® cables have now become a key candidate for use in the next generation of accelerator magnets. Further optimization of the cable layout is underway with the goal of putting J_E of 600 A mm^{-2} at 20 T in even thinner CORC® cables within reach.

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