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Introduction of the next generation of CORC® wires with engineering current density exceeding 650 A mm^{-2} at 12 T based on SuperPower's ReBCO tapes containing substrates of 25 μm thickness

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Abstract

Next generation particle accelerators and fusion machines will greatly benefit from the development of low-inductance magnets capable of generating magnetic fields in excess of 16 T. Such magnets require high-temperature superconductors capable of carrying very high currents exceeding 5 kA at current densities of 400–600 A mm^{-2}, such as Conductor on Round Core (CORC®) cables and wires wound from RE-$Ba_2Ca_3O_{7-\delta}$ (ReBCO, Re = rare earth) coated conductor tapes. CORC® wires containing ReBCO tapes with 30 μm thick Hastelloy® substrates have previously been demonstrated as a viable high-field magnet conductor that can be produced at long lengths. Further improvement of the performance and flexibility of CORC® wires would benefit from the development of ReBCO tapes with even thinner substrates. SuperPower Inc. recently demonstrated ReBCO tapes based on 25 μm thick Hastelloy® substrates that allow the development of thinner and more flexible CORC® wires that meet the stringent performance requirements of high-field magnets. Several tapes containing 25 μm thick substrates were produced and analyzed, exhibiting critical current and cabling performance in-line with the current production level tapes with 30–50 μm thick substrates. Tape critical current was measured at 4.2 K and applied magnetic fields up to 31.2 T. Several CORC® wires incorporating these tapes were manufactured by Advanced Conductor Technologies using similar winding procedures that previously resulted in high-quality magnet-grade CORC® wires based on tapes with 30 μm thick substrates. The CORC® wires were tested in an applied magnetic field up to 12 T after bending to a 63 mm diameter. A critical current as high as 6231 A (12 T, 4.2 K) was measured with an engineering current density (J_e) of 678 A mm^{-2}, which extrapolates to over 450 A mm^{-2} at 20 T and is the highest current density reported in a CORC® conductor to date. The combination of ReBCO tapes produced using 25 μm thick substrates and the ability to wind them into long-length, high-quality CORC® magnet wires brings the development of low-inductance accelerator and fusion magnets that operate at magnetic fields exceeding 20 T closer to fruition.

Keywords: CORC, HTS cable, REBCO

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

1. Introduction

While the development of second-generation high-temperature superconductors (HTS) has led to a transformative evolution of more efficient and compact magnets for various applications, their very high current densities and ability to operate at temperatures well above 4.2 K make them an enabling technology for fusion and accelerator applications that have a crucial need for the generation of very high magnetic fields [1, 2].

Several companies are now producing coated conductors in the form of a tape that consists of a ReBCO superconducting layer deposited on a strong (e.g. Hastelloy®) substrate and then surround coated in a stabilizing metal such as Cu or Ag. For low inductance magnets, such as those used in fusion and accelerator machines, several such tapes must be bundled or cabled into a high-current conductor.

Multiple cable layouts incorporating ReBCO tapes have been proposed and prototyped for high-field applications including conductor on round core (CORC®) [3–5], Roebel [6, 7], and several variants of stacks of tape [1, 8–11]. Of the three geometries, CORC® is unique in that it requires a core (or former) onto which the ReBCO tapes are wound. A high conductivity former is typically chosen to serve as a normal-state electrical stabilizer for the superconducting layers thus allowing a decrease in the copper plating thickness on each tape. Several studies are currently exploring and quantifying the level of current sharing within different CORC® architectures [12, 13].

While a decrease of substrate thickness benefits any cable design by increasing the engineering critical current density (J_e) through a reduction in overall area, it is particularly beneficial for CORC® conductors because it allows the use of a much smaller former since the tapes can be bent to smaller diameters without adversely affecting I_c [14]. This greatly reduces the outer diameter (OD) of a CORC® wire with a given number of tapes. In 2016, Superpower Inc. introduced ReBCO tapes with 30 μm thick substrates[15] that allowed the introduction of 3–4 mm diameter CORC® wires by Advanced Conductor Technologies (ACT) with enhanced flexibility and in-field critical currents (I_c) and J_e as high as 9.3 kA and 590 A mm^{-2} (4.2 K, 10 T), respectively [14, 16].

Record in-field performance in multi-tape ReBCO conductors is often demonstrated with short-sample tests based on highest performing ReBCO conductors. For instance, the previous record J_e of 423 A mm^{-2}, extrapolated to 20 T achieved in a 4.5 mm thick CORC® wire containing 50 tapes with 30 μm substrates contained such a high number of tapes that it was relatively inflexible and had a retention in tape I_c of about 72% after being bent to a diameter of 63 mm [3]. This CORC® wire would be highly suitable for magnet applications that do not require such tight bends, but magnets with more stringent bending requirements will likely be wound from thinner CORC® wires with a lower tape count of around 30. High-field magnets also require large quantities of tape wound into long-length CORC® conductors. As a result, the actual in-field performance tends to be an average of industrially produced tape that is below the record values achieved in short CORC® samples wound from tapes with above-average performance.

The requirement of single CORC® wire piece lengths exceeding 20–25 m over which the conductor quality and flexibility needs to be maintained adds another level of complexity to producing magnet-grade CORC® wires. Tape winding tension is a critical parameter in long-length CORC® conductors because it prevents tapes from shifting during winding, while it increases the friction between tapes that affects CORC® conductor flexibility. Advanced Conductor Technologies was successful in developing long-length magnet-grade CORC® wires containing 16–29 ReBCO tapes with 30 μm thick substrates by applying sufficient winding tension to avoid tape movement while also maintaining sufficient conductor flexibility. Such optimization needs to be performed each time the tape dimension changes, such as when even thinner substrates or narrower tapes become available.

The ability to wind long-length CORC® wires into accelerator magnets was demonstrated recently within a collaboration with Lawrence Berkeley National Laboratory (LBNL) to develop prototype canted-cosine-theta (CCT) accelerator magnets based on CORC® wires [17, 18]. A 4-layer CCT magnet demonstrated a 2.9 T dipole field at 4.2 K [19]. The magnet was wound from 80 m of CORC® wire containing 29 tapes with 30 μm substrates (about 4.5 km of ReBCO tape).

The CCT magnet development using CORC® wires is a clear example of how the actual performance of flexible, long-length CORC® wires deviates from the latest performance record. The lower tape count needed to maintain the CORC® wire flexibility and the actual in-field tape performance averaged over many production batches, resulted in a J_e of about 60%–70% of the highest short-sample value. CORC® wires with even higher J_e values need to be developed to reach a goal of J_e 400–600 A mm^{-2} at 20 T in long-length magnet conductors, while maintaining at least 80%–85% of the tape I_c after magnet winding and high-field operation.

This paper describes the development of ReBCO tapes containing substrates of 25 μm thickness produced in production scale equipment by SuperPower Inc. that would enable high performing and flexible CORC® magnet wires required for high-field magnet applications. It outlines the tape performance characterization at 77 K in self-field and at 4.2 K in magnetic fields up to 31.2 T. The development of the magnet-grade CORC® wires from these ReBCO tapes with thinner substrates is described, specifically for use in accelerator magnets that require operating currents of 5–20 kA and current densities of initially 350–450 A mm^{-2} and eventually 450–600 A mm^{-2} at 4.2 K and 20 T. The performance of the next generation of CORC® wires is characterized at 4.2 K in magnetic fields up to 12 T, demonstrating that these technical achievements present a clear step towards practical CORC®-based HTS accelerator magnets operating at magnetic fields exceeding 20 T.

2. Experimental methods

All current transport measurements use a standard fit of electric field versus current to determine I_c and N-value using the following equation:

$$E = I\left(\frac{R}{L}\right) + E_c\left(\frac{I}{I_c}\right)^N - E_0,$$

where E is the electric field (measured voltage divided by L, the distance between voltage contacts), E_c is the electric field criterion of 1 μV cm^{-1}, R is the contact resistance, and E_0 is an electric field offset. The N-value is a fitting parameter that quantifies the sharpness of the superconducting transition, with typical values of pristine SuperPower tapes being 25–30 at 77 K, and 40–60 at 4.2 K [20].

2.1. ReBCO tape production

SuperPower's HTS tape is based on ion beam assisted deposition (IBAD) and metal organic chemical vapor deposition (MOCVD) technology. For the tape with 25 μm thick substrate, the architecture is essentially the same as used for tapes containing 30 and 50 μm thick substrates. The thinner 25 μm Hastelloy® based REBCO tape development encountered several production challenges that were predominantly tape handling related, requiring more stringent handling procedures than for the more standard 30 and 50 μm based REBCO tapes [15]. Most of the processing steps used at SuperPower are reel-to-reel, requiring the tape to translate across multiple rollers and helix configurations in tasks that become more difficult for thinner and narrower tapes.

The production of the Superpower tape begins with 12 mm wide Hastelloy® C-276 substrate with 25 μm starting thickness that is electropolished, during which process its thickness is reduced by 2–3 μm. This is followed by the deposition of a buffer stack (about 0.2 μm thick) that consists of 4 layers deposited by sputtering, and a critical MgO texture layer deposited by IBAD. Next, a ReBCO layer (about 1–1.6 μm thick) with 7.5% Zr doped precursor is deposited in a MOCVD reactor, after which it is annealed in oxygen. The 12 mm wide tape is then surround coated with Ag by cylindrical magnetron sputtering, annealed again, and mechanically slit into several narrower tapes. Finally, the slit tapes are surround coated with Ag (about 2 μm thick) to seal the slit edges and Cu electroplated (about 5 μm thick) layers. The Ag and Cu provide good current transfer and electrical stabilization during operation and quench conditions. About 400 m of 2 mm wide ReBCO tape containing 25 μm substrates was delivered to Advanced Conductor Technologies for various performance verification tests and CORC® cabling trials. The three different types of tape outlined in table 1 were used to manufacture high-quality CORC® magnet wires. Tape thickness was measured using a Mitutoyo ball micrometer.

2.2. CORC® wire production

Two CORC® wires, CORC®-01 and CORC®-02, containing 30 and 32 tapes, respectively, were designed and wound by ACT using a custom winding machine. Similar winding procedures as developed for cabling tapes with 30 μm substrates were applied, while some of the winding parameters were optimized for the thinner tapes with 25 μm substrate, to maintain the CORC® wire flexibility and ensure high-quality, long length CORC® magnet wire production. Each wire contained a 2.04 mm diameter C101 annealed copper former. ReBCO tapes with 25 μm substrate thickness were used on the innermost 8 layers, while tapes with 30 μm substrate thickness were used on the outer layers. CORC®-01 is similar in layout to the CORC® wire developed for a 3 T CCT accelerator magnet demonstrator at LBNL [17, 19], but given the smaller former and slightly thinner tapes, it had an OD of 3.2 mm instead of 3.7 mm. CORC®-02 had a similar layout, but switches from 2 mm wide tapes to 3 mm wide tapes on the outer 6 layers of the wire to take advantage of an increase in I_c, but likely at the cost of bending flexibility. Polyester of approximately 30 μm thickness insulates each CORC® wire and is included in the J_e calculation. Sample details are listed in table 2.

2.3. Tape characterization

Prior to cabling, tape I_c was measured by SuperPower at 77 K using a reel-to-reel transport measurement system as well as a non-contact TapeStar magnetization measurement system.

To verify the flexibility of the new SuperPower tape with 25 μm substrate thickness, several 20 cm long pieces were wound by hand around formers of various diameters ranging from 1.64 to 2.37 mm at an angle of 45° with the ReBCO layer facing the former. I_c was then measured in LN_2 at 76 K, which is the boiling point of nitrogen in Boulder, Colorado, where the bending measurements were performed. To evaluate the in-field performance of the SuperPower tapes, several pieces were sent to the Applied Superconductivity Center at Florida State University and I_c was measured as a function of magnetic field at 4.2 K in a 15 T Oxford superconducting magnet and from 4 to 31.2 T in a resistive magnet at the National High Magnetic Field Laboratory with field applied perpendicular to the tape surface. Cross-sections of tapes were analyzed using an Olympus microscope and Stream image analysis software.

2.4. CORC® wire characterization

Tube-type terminations were installed on 1.1 m long sections of the CORC® wires following procedures described elsewhere [3, 21]. The terminations each had a length of 21 cm and an OD of 6.35 mm. After mounting terminations, the CORC® wires were bent into a hairpin shape on a sample holder that had a radius of 31.5 mm (see figure 1). Voids were then filled with Stycast 2850 epoxy before testing in a 12 T Oxford superconducting magnet with an 86 mm bore at 4.2 K. Voltage contacts were installed 10 cm apart in the high-field region of the hairpin. For each I_c measurement, the field was kept constant while the current was ramped at a rate of 500 A s^{-1}. For sample CORC®-01, the measurements at 12 T included additional cycling of the current to at least 90% I_c 56 times to expose the conductor to cyclic electromagnetic forces before an additional I_c measurement was performed. Due to a

Table 1. Properties of the SuperPower tapes.

	Unit	Tape 1	Tape 2	Tape 3
SuperPower batch #	—	M3-1347-5	M4-479-3	M4-406-5
Nominal width	mm	2	2	3
Initial substrate thickness	μm	25	30	30
Nominal stabilizer layer thickness	μm	7	7	7
Measured thickness	μm	36	41	41
Non-stabilizer to stabilizer ratio		1.0 : 0.4	1.0 : 0.3	1.0 : 0.3
Average I_c (77 K, SF)	A	61	59	101
Average I_c (4.2 K, 12 T)	A	159	200	345
Average J_e (4.2 K, 12 T)	A mm^{-2}	2208	2439	2805

Table 2. Design properties of the CORC® wires.

	Unit	CORC®-01	CORC®-02
Former OD	mm	2.04	2.04
CORC® wire OD[a]	mm	3.33	3.42
# of layers		15	16
# of tapes		30	32
Tape width	mm	2	2, 3
Pitch	mm rev^{-1}	6.8–5.4	6.8–9.3
Non-stabilizer to stabilizer ratio		1.0 : 1.0	1.0 : 1.1
Estimated wire I_c at 77 K[b]	A	1765	2422
Estimated wire I_c at 4.2 K, 12 T[b]	A	5374	7677
Estimated wire J_e at 4.2 K, 12 T[b]	A mm^{-2}	619	836
Extrapolated wire J_e at 4.2 K, 20 T[b]	A mm^{-2}	407	556

[a] Includes ~30 μm thick insulation.
[b] Neglecting self-field effects and based off sum of single tape I_c measurements.

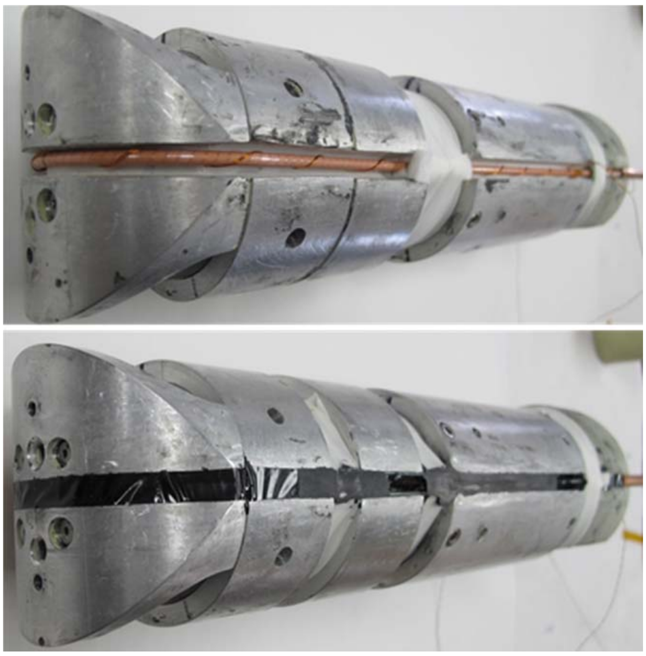

Figure 1. Sample CORC®-01 mounted on the sample probe before and after filling voids with Stycast epoxy.

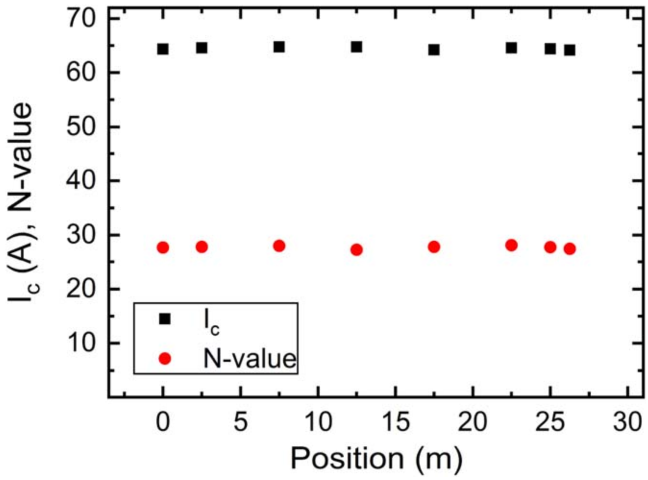

Figure 2. Transport I_c (77 K, self-field) as a function of position of a 26 m length of the 2 mm wide SuperPower tape with 25 μm substrate thickness. Each data point represents the measurement results over a 5.1 m test length.

shortage of liquid helium available following a quench of the 12 T magnet, electromagnetic cycling was not performed on sample CORC®-02.

3. Results

3.1. Characterization of ReBCO tapes containing 25 μm thick substrates

The 25 μm tapes were processed using standard deposition procedures that were slightly modified after some initial optimization runs. While initial production yields were lower than for tapes with 30 and 50 μm thick substrates, several high-quality 2 mm wide tapes with lengths in excess of 25 m were produced. Figure 2 shows I_c as a function of position measured using SuperPower's reel-to-reel transport measurement system for one of the lengths of tape.

To analyze the geometry of the SuperPower tape with 25 μm substrate thickness, three samples were evaluated using optical microscopy. The thickness of the substrate and stabilizer layer (Ag + Cu) was then measured at 5 locations across the width of each cross-section. Figure 3 shows a

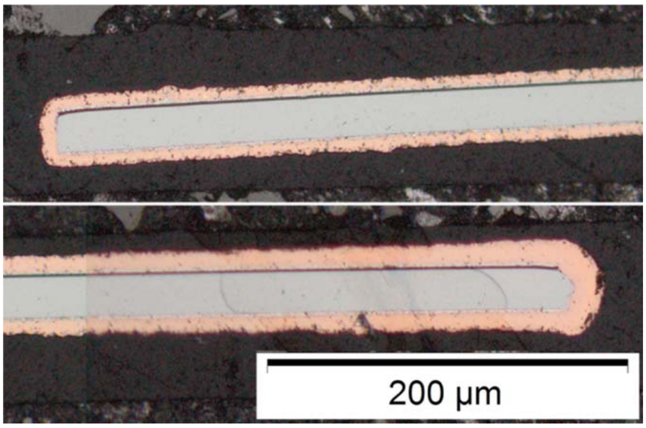

Figure 3. Micrograph of either edge of a 2 mm wide SuperPower tape with 25 μm substrate thickness.

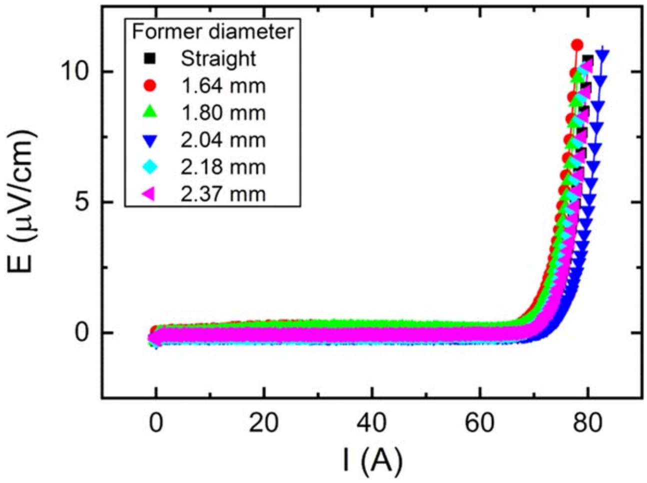

Figure 4. Electric field as a function of current for 2 mm wide SuperPower tapes with 25 μm substrate thickness wound around formers of various diameters at 76 K. Lines are fits to the data to determine I_c and N-value.

micrograph of either edge of one of the tapes. The substrate thickness was measured to be 22.9 μm thick (standard deviation of 0.4 μm), slightly thinner than the substrate starting thickness due to electropolishing. The total stabilizer thickness varied across the width of the tapes somewhat with an average thickness of 9.9 μm (standard deviation of 1.9 μm).

To evaluate the flexibility of the SuperPower tape with 25 μm thick substrates, 2 mm wide tapes were wound by hand around formers of various diameters. The diameters chosen were around 2 mm, which is expected to be the minimum bending diameter of the ReBCO tape before irreversible degradation occurs based on previous work [4, 14]. The I_c and N-values of the bent tapes were derived from the superconducting to normal transition (figure 4) for the bent tapes and are summarized in table 3. I_c and N-value did not decrease significantly, even when wound around a 1.64 mm former.

Figure 5 shows the magnetic field dependence of the critical current for representative samples from each batch of

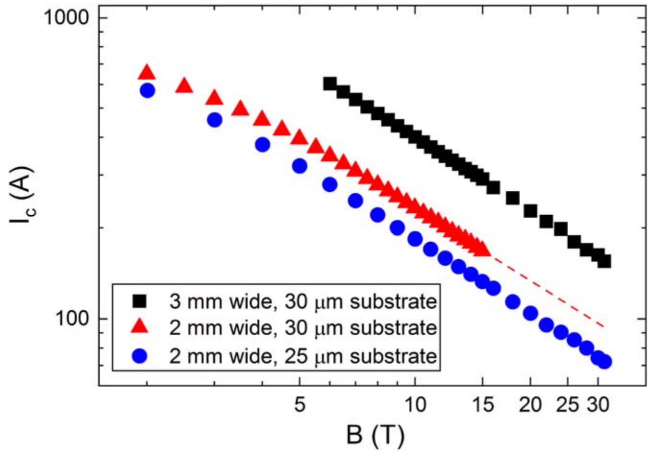

Figure 5. I_c as a function of magnetic field applied perpendicular to the tape surface at 4.2 K for samples from each tape batch used to construct samples CORC®-01 and CORC®-02. Dashed line is an extrapolation.

Table 3. Performance of tapes with 25 μm thick substrate as a function of bending.

Former diameter (mm)	ε (%)[a]	I_c (A) (76 K)	N-value	$I_c/I_c^{\text{straight}}$ (%)
n/a (straight)	0.00	72.7	24.9	100.0
2.37	−0.96	72.9	25.3	100.2
2.18	−1.03	72.4	25.4	99.5
2.04	−1.12	75.2	25.3	103.3
1.8	−1.24	71.5	25.8	98.3
1.64	−1.39	70.9	25.0	97.4

[a] Axial tensile strain calculated assuming 23 μm substrate thickness using equation from [14].

SuperPower tape from which the CORC® wires were wound (see table 1). Despite having the same 2 mm width, and very similar I_c at 77 K, the tape with 25 μm substrate thickness carried about 20% less current than the tape with 30 μm substrate thickness at the maximum applied fields. However, it is well known that the critical current of manufactured tapes can vary from batch to batch due to differences in pinning properties, ReBCO layer thickness, or slitting damage. For production level SuperPower tapes, the I_c of 66.5 A mm^{-1}-width measured at 4.2 K and 15 T for the tape with 25 μm thick substrate is about average, while the I_cs of the two tapes with 30 μm substrate thickness are above average [22].

3.2. Characterization of CORC® wires from tapes with 25 μm substrates

The electric field as a function of current is plotted for samples CORC®-01 and CORC®-02 in figures 6 and 7, respectively, along with the derived field dependence of I_c. At 12 T, both CORC® wires had approximately 81% of the expected critical current if a summation of tape $I_c(B)$ data shown in

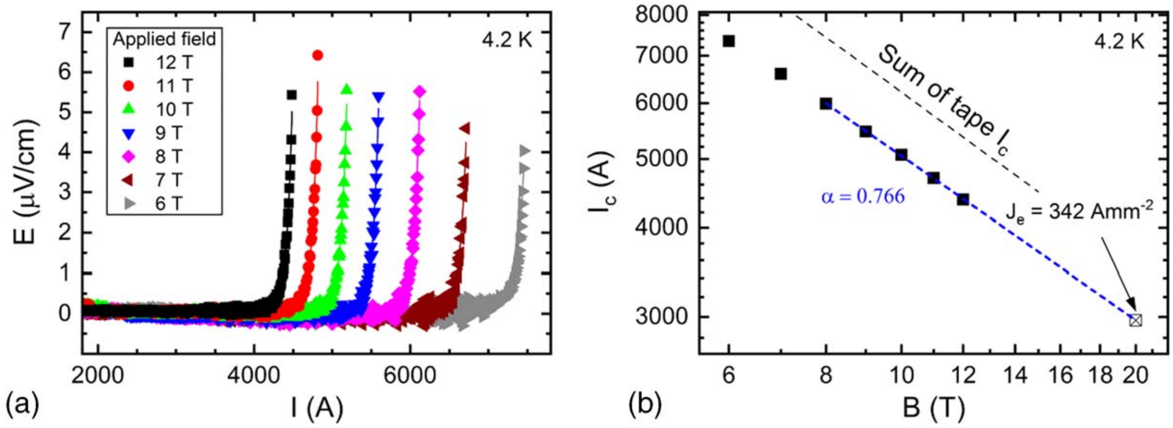

Figure 6. (a) Electric field as a function of current of sample CORC®-01 at various applied fields. Lines are fits to the data used to determine I_c and *N*-value. (b) I_c as a function of applied magnetic field for sample CORC®-01 compared to that expected from the individual tape measurements. The blue dashed line is the power-law fit used to extrapolate to 20 T.

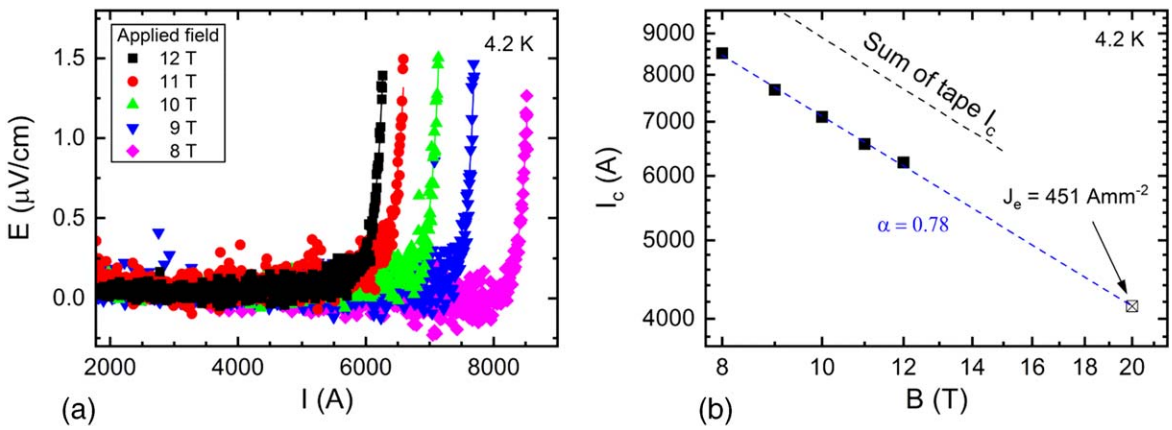

Figure 7. (a) Electric field as a function of current of sample CORC®-02 at various applied fields. Lines are fits to the data used to determine I_c and *N*-value. (b) I_c as a function of field for sample CORC®-02 compared to that expected from the individual tape measurements. The blue dashed line is the power-law fit used to extrapolate to 20 T.

figure 5 is considered. Above 8 T, the magnetic field dependence of I_c for each sample follows a power-law fit of $I_c \propto B^{-\alpha}$ with an α that is nearly identical to that of the individual tapes. A fit is presented for each dataset allowing extrapolation to 20 T, where sample CORC®-01 would have a J_e of 342 A mm^{-2} and sample CORC®-02 a J_e of 451 A mm^{-2}. This is not only a new performance record in CORC® wires, but more importantly, it is a new record in a highly-flexible magnet-grade CORC® wire based on average tape performance and at an I_c retention of more than 80%. Table 4 summarizes the I_c, J_e and *N*-values as a function of field.

For sample CORC®-02, a limited evaluation of conductor performance following electromechanical cycling was performed. After an initial I_c measurement at 12 T and 4.2 K, the current was cycled from 0 to 4000 A repeatedly. The maximum $I \times B$ of the conductor was approximately 50 kN m^{-1}, which is well below the critical transverse compressive load for CORC® wires and cables tested without bending [23]. Following 57 cycles, I_c was measured again and remained unchanged as seen in figure 8.

4. Discussion

The minimum allowable bending diameter at which ReBCO tapes can be wound within a CORC® wire before degrading irreversibly depends on the location of the ReBCO layer with respect to the neutral bending axis of the tapes [4]. The production of thinner CORC® magnet wires with enhanced flexibility and J_e in excess of 600 A mm^{-2} at 20 T thus relies on the commercial production of high-quality, long-length ReBCO tapes with decreased substrate thickness since this enables the use of smaller formers to produce a more compact wire [14]. Asymmetrical stabilizer plating has also been proposed to move the ReBCO layer closer to the neutral axis [24], but best results still require substrate thickness below 25 μm that are not commercially available [25]. There is also a reversible effect of I_c due to strain that is mostly non-existent when bending near 45° to the tape's axis, as is the case in a CORC® wire [26, 27]. It has been shown that a reduction of substrate thickness from 30 to 25 μm should correspond to a decrease of the minimum winding diameter of a tape before it begins to degrade irreversibly from 2.4 to

Table 4. Superconducting properties of samples CORC-01 and CORC-02 as a function of magnetic field at 4.2 K.

	CORC®-01			CORC®-02		
B (T)	I_c (A)	N-value	J_e (A mm^{-2})	I_c (A)	N-value	J_e (A mm^{-2})
6	7344	86	846	—	—	—
7	6597	83	760	—	—	—
8	5987	76	689	8503	63	926
9	5469	72	630	7662	70	834
10	5067	71	584	7097	55	773
11	4700	71	541	6566	43	715
12	4379	67	504	6231	46	678
20[a]	2967		342	4147		451

[a] Extrapolated value.

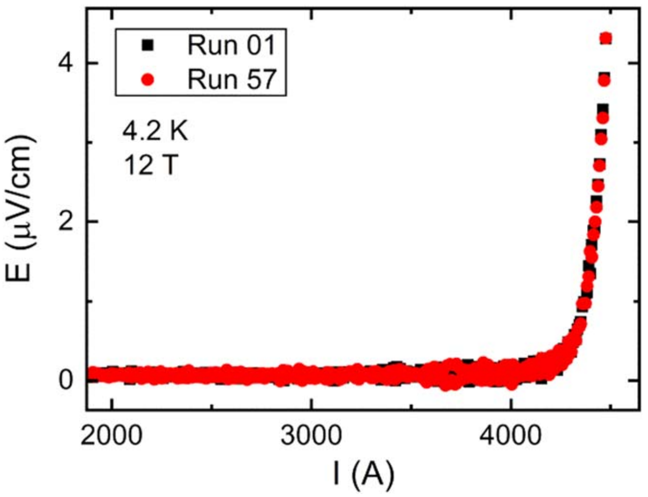

Figure 8. Superconducting to normal transition of sample CORC®-01 at 4.2 K and 12 T before and after cycling to at least 90% of I_c 57 times.

2.0 mm [14]. To evaluate that the relationship holds for the new SuperPower tape with 25 μm substrate thickness, tapes were wound by hand around formers of various diameter at 45° and then I_c was measured in LN_2. I_c only decreased by a few percent even when wound around the 1.63 mm diameter former, which corresponds to −1.39% compressive strain at the ReBCO layer when the measured substrate thickness of 23 μm is considered. A 2.03 mm OD former size was used to build the CORC® wires, while providing some margin away from the irreversible strain limit, previously identified to be around −1.2% compressive strain [3, 14], since the tapes experience additional strain due to CORC® wire bending and testing in-field [28].

Figure 5 shows I_c as a function of magnetic field applied perpendicular to the tape surface. This orientation of field with respect to the tape is near the minima of the tape's angular field dependence of I_c at 4.2 K and is most relevant to compare to CORC® wires because the helical arrangement of tapes results in their exposure to all field orientations. While J_e is lower than could be achieved in a non-twisted stacked tape conductor configuration, where all tapes are aligned parallel to the applied field, it has the benefit of making the conductor macroscopically isotropic, which eases the design and manufacture of magnets. It also allows for a higher degree of current sharing between tapes, which is highly beneficial in case of a quench. Both CORC® wires performed at about 81% of the I_c expected at 4.2 K and 12 T based on the sum of the tape I_cs. The lower performance of the CORC® wires is likely due in part to the self-field generated by the cables that may locally increase the peak-field seen by the conductor beyond the applied field. Other potential causes include some reversible effects of tape I_c on strain due to layers wound at angles other than 45°, or bending related tape degradation. A lack of statistics on pinning variations as a function of tape length for the tapes measured also imposes an uncertainty in how accurate the expected I_c based on these few tape measurements may be.

An important benefit of CORC® conductors for use in high-field magnets is the fact that they will not need to be reacted into the superconducting state after the magnet has been wound, which is the case for other HTS conductors for high-field accelerator magnets such as $Bi_2Sr_2CaCu_2O_x$ (Bi-2212) wires. This important feature of CORC® conductors allows a simplified magnet fabrication process and more flexibility on the choice of conductor insulation, which can result in significant increase on the performance/cost ratio of HTS magnets. CORC® conductors are mechanically much stronger than Bi-2212 wires and even Nb_3Sn cables, easing the requirements for external support and potentially allowing for use of standard tooling during magnet winding [23, 29]. The effect of transverse and axial stress on CORC® cable and wire performance was recently published including both monotonic and cyclic fatigue measurements [3, 23, 29]. Because of the hairpin orientation of the CORC® wires tested in-field, little stress in the axial direction of the wire is expected due to Lorentz forces. Instead, the CORC® wires tested here experience mostly transverse compression. While the peak $I \times B$ imposed load is around 50 kN m^{-1} for CORC®-01 at 12 T, which is well below the critical load where degradation begins in straight samples, it is unclear how the addition of CORC® bending imposed stresses may affect I_c retention. In the case of straight samples under transverse loading, once I_c has decreased by more than 5%–10% it continues to degrade gradually with cyclic loading. For sample CORC®-01, no I_c reduction was observed after cycling 57 times despite the initial I_c being 81% of the expected I_c. It is a positive result that any damage that may have occurred on individual tapes due to CORC® wire bending was not exasperated by cyclic loading. However, additional electromechanical testing of CORC® wires as solenoids that experience large Hoop stresses will be valuable.

In any superconductor design, J_e, stabilizer fraction, and strength must be balanced. Here, we have demonstrated the in-field performance of a round, isotropic, and flexible 3.4 mm diameter CORC® wire that was capable of carrying over 6 kA in a background field of 12 T at a current density of over 670 A mm^{-2}. In addition, the reduction of substrate thickness enables the use of a smaller former that encompasses less than 40% of the total conductor cross section. The use of a smaller former brings the total stabilizer to non-stabilizer ratio close to 1:1, with the added benefit that the former material could be easily modified in future layouts to alter the conductor properties in terms of strength or normal-state resistivity.

The development of ReBCO tape with 25 μm substrate at industrial length scales is the most straightforward route to develop long-length magnet-grade CORC® wires with current densities of more than 400 A mm^{-2} at 20 T that are flexible enough for use in accelerator magnets. The initial batch of high-quality tape on 25 μm thick substrate, but with slightly below average I_c performance, already allowed us to reach a new record performance in CORC® wires. More importantly, it allowed us to reach the performance in a magnet-grade conductor that operated above 80% I_c retention after bending to 63 mm diameter and operating at high current and magnetic field. The tapes with thinner substrates thus increased the performance of typical long-length CORC® wires from 250–300 A mm^{-2} at 20 T to 400–450 A mm^{-2}, an increase of 50%.

5. Conclusion

Future magnet systems, such as those desired for accelerator and fusion applications, require HTS to operate at high fields in excess of 16 T and/or temperatures of 20 K or more. Such magnet systems will require strong and robust high-current conductors. SuperPower has successfully manufactured HTS tapes using 25 μm substrates, which are currently the thinnest produced by any commercial supplier. These tapes offer improved current density and allow the production of CORC® wires with significantly smaller formers. Two CORC® wires incorporating the tapes were manufactured by Advanced Conductor Technologies and measured in background magnetic fields up to 12 T. A peak I_c of 6231 A (12 T, 4.2 K) was measured with a J_e of 678 A mm^{-2}, or 451 A mm^{-2} when extrapolated to 20 T. This was approximately 81% of what was expected based on the sum of individual tape measurements. One CORC® wire was cycled electromechanically at 12 T and showed no sign of further I_c reduction. These results demonstrate the feasibility of producing high I_c and J_e CORC® wires based on commercially produced ReBCO tapes with 25 μm substrate thickness for future magnet systems that require operation at high fields and elevated temperatures. An increase of in-field performance of about 50% was achieved in magnet-grade CORC® wires that are flexible enough to be wound at 63 mm diameter. Further Improvement of in-field tape I_c of only 35% would result in long-length CORC® wires with J_e of 600 A mm^{-2} at 20 T.

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