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Introduction of CORC® wires: highly flexible, round high-temperature superconducting wires for magnet and power transmission applications

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Introduction of CORC® wires: highly flexible, round high-temperature superconducting wires for magnet and power transmission applications

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Abstract

Conductor on Round Core (CORC®) technology has achieved a long sought-after benchmark by enabling the production of round, multifilament, (RE)$Ba_2Ca_3O_{7-x}$ coated conductors with practical current densities for use in magnets and power applications. Recent progress, including the demonstration of engineering current density beyond 300 Amm^{-2} at 4.2 K and 20 T, indicates that CORC® cables are a viable conductor for next generation high field magnets. Tapes with 30 µm substrate thickness and tape widths down to 2 mm have improved the capabilities of CORC® technology by allowing the production of CORC® wires as thin as 3 mm in diameter with the potential to enhance the engineering current density further. An important benefit of the thin CORC® wires is their improved flexibility compared to thicker (7 to 8 mm diameter) CORC® cables. Critical current measurements were carried out on tapes extracted from CORC® wires made using 2 and 3 mm wide tape after bending the wires to various diameters from 10 cm to 3.5 cm. These thin wires are highly flexible and retain close to 90 % of their original critical current even after bending to a diameter of 3.5 cm. A small 5-turn solenoid was constructed and measured as a function of applied magnetic field, exhibiting an engineering current density of 233 Amm^{-2} at 4.2 K and 10 T. CORC® wires thus form an attractive solution for applications between 4.2 K and 77 K, including high-field magnets that require high current densities with small bending diameters, benefiting from a ready-to-use form (similar to NbTi and contrary to Nb_3Sn wires) that does not require additional processing following coil construction.

1. Introduction

Several research organizations in fields including energy, healthcare, and defense have called for the development of practical wires made from high-temperature superconductors (HTS) [1-3]. Such wires are advantageous because they allow superconductivity to be achieved under a wide range of conditions, including temperatures in excess of 20 K, and at magnetic fields well beyond 20 T. The high temperature operation of HTS is appealing for applications such as power transmission, power generation, and energy storage because it lessons cooling and maintenance requirements compared to low-temperature superconductors, while the use of HTS to generate very high magnetic fields further the capabilities of scientific and industrial magnets. The development of robust HTS wires has been hindered by their intrinsically weak-linked grain boundaries that require either the elimination of grain boundaries or the extreme alignment of crystallites. This has been achieved by the development of coated conductors like Rare-Earth (RE)$Ba_2Ca_3O_{7-x}$ (REBCO), but results in a non-ideal conductor geometry for many applications.

The high aspect ratio and single filamentary character of REBCO superconductors make them particularly difficult to cable. Three cabling techniques have so far been developed for REBCO tapes to produce suitable conductors for magnet builders, with varying levels of success [4, 5]. The Conductor on Round Core cabling approach consists of the helical winding of REBCO conductors on a round former. The transposition of the tapes within each layer of the cable significantly reduces the cable magnetization while the coaxial and mechanically decoupled arrangement of the tapes enables them to slide when the cable is bent, making them particularly flexible [6]. The tape count in CORC® cables can be varied to suit a range of applications, and engineering current densities (J_e) in excess of 340 Amm^{-2} have been demonstrated at 4.2 K and 17 T [7]. Recently, the availability of REBCO tapes with 30 µm substrate thickness and widths down to 2 mm allows the incorporation of dozens of narrow REBCO tapes into a cross section of less than 5 mm diameter, representing a new breed of CORC® technology. The miniaturization of CORC® cables has produced a flexible, round, multi-filamentary REBCO wire. Figure 1 shows a CORC® wire compared to a typical CORC® cable.

Figure 1 – 7 mm diameter CORC® cable (above) made out of 4 mm wide REBCO tapes with 50 µm thick substrates compared to a 3.6 mm diameter CORC® wire (below) made up of 2 mm wide tapes with 30 µm thick substrates.

Here, prototype CORC® wires were designed, produced, and tested in a reiterative fashion to develop robust, flexible HTS conductors. Critical currents were measured in CORC® wires and in the individual tapes extracted from the wires to determine the limitations of CORC® wires and to identify potential room for improving their properties. The minimum size of the wires is determined by the compressive strain-limit of the superconducting tapes as they are wound around the former that makes up their core. Based on the results of this study, we have designed a 4.8 mm diameter wire that can contain 77 REBCO tapes with a combinedcritical current (I_c) of over 5 kA at 77 K. Further development of REBCO superconductors using thinner substrates and widths will result in even smaller CORC® wires with diameters of 2 to 3 mm and further enhanced flexibility.

2. Experimental

2.1. Conductor properties

Table 1 - Tape properties

Sample name	Tape thickness (µm)	Width (mm)	Average tape I_c (A) [76 K]*	Minimum tape I_c (A) [76 K]*
Wire 1	42	2	60.2	54.3
Wire 2	46	3	99.1	83.8
Wire 3	46	3	76.5	70.8
Solenoid	44	2	61.3	48

*Tape I_c shown was converted from 77 K data to 76 K values by multiplying by 1.18

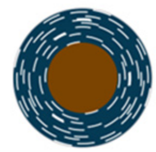
CORC® wires were constructed with tapes purchased from SuperPower Inc. containing a 1.6 µm thick REBCO layer deposited on a 30 µm thick Hastelloy C-276 substrate. The tapes used in this study contained 7.5 % Zr-doping and were surround plated with 5 µm of copper for thermal and electrical stability. Tape properties are summarized in table 1 for each sample constructed. Relatively low-I_c tapes with average critical current between 25 and 28 A/mm-width at 77 K were selected since the aim of this experiment was to determine the extent of degradation with bending, which does not depend on the starting tape I_c.

To determine the minimum allowable former size on which tapes with 30 µm substrates can be wound before I_c is degraded, representative tapes were wrapped at a 45 degree angle around formers with various diameters. Winding the tapes at 45 degrees minimizes the reversible strain effect on I_c [8], allowing accurate determination of the winding diameter at which irreversible degradation occurs. I_c was determined by measuring voltage (V) as a function of current (I) in boiling liquid nitrogen via the standard 4-point transport method using the equation:

$$V = IR + V_c\left(\frac{I}{I_c}\right)^n + V_0 \tag{1}$$

where R is the contact resistance, V_0 is the inductive offset voltage, n is a fitting parameter known as the n-value, and V_c is the voltage contact separation (L) multiplied by the electric field criterion (E_c) of 1 µVcm^{-1}.

Table 2 - CORC® wire properties

Wire name	Purpose of sample	# of SC layers	# of SC tapes	Tape width (mm)	Average twist pitch (mm)	Wire OD (mm)	Nominal wire I_c (A) [76 K]*	Nominal wire J_e (A mm-2) [4.2 K, 20 T]**	Wire cross section***
Wire 1	Flexibility tests on CORC® made with 2 mm wide tapes	6	12	2	5.65	3.3	722	114	
Wire 2	Flexibility tests on CORC® made with 3 mm wide tapes	10	20	3	9.38	3.9	1982	225	
Wire 3	Flexibility tests on optimized CORC® made with 3 mm wide tapes	12	29	3	12.35	5.0	2217	153	
Wire 4	Conceptual high J_e design based on results of wires 1-3	25	77	2	10.52	4.8	6360	481	

*No self-field correction applied. I_c shown was converted from 77 K data to 76 K values by multiplying by 1.18
**Assuming a lift factor of 1.6 from (77 K, SF) to (4.2 K, 20 T)
***From inside to outside: Orange: Cu core, Red: Cu tapes, Blue: SC tapes, Gray: SS and insulation

2.2. CORC® wire construction

Three CORC® wires were constructed in this study with a custom winding machine to evaluate the flexibility of conductors with different layouts. The construction of each wire followed the same basic architecture where superconducting tapes were wound helically in layers around a core that consisted of a solid copper former with several layers of copper tape wound around it. Each tape layer was coated with a polytetrafluoroethylene lubricant. The purpose of the copper tape is to increase the former diameter to a target diameter before adding the superconducting tapes. After winding several layers of superconducting tape, two layers of 50 µm thick stainless steel tape were added on the outside to armor the wires. Finally, polyester heat shrink tubing of 30 µm thickness was added to insulate the wires. Wire 1 was wound from 2 mm wide tapes while wires 2 and 3 were wound from 3 mm wide tapes. Based on the results of the following study, a fourth wire was designed but not tested here. Details of each wire's architecture are listed in table 2. Here, nominal wire critical current is defined as the expected I_c based on the tape manufacturers specified average measured tape I_c multiplied by the number of tapes in the wire. The 77 K data provided by the manufacturer was multiplied by an empirically determined factor of 1.18 to convert to 76 K values for a valid comparison to our measurements.

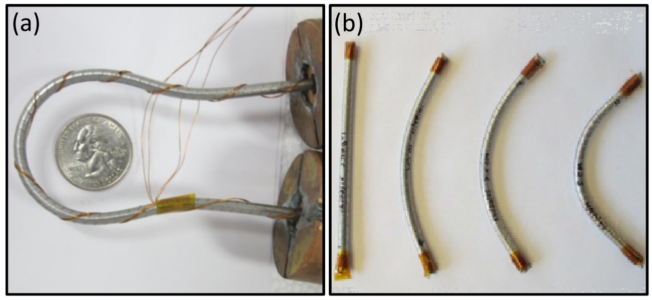


Figure 2 – (a) Section of wire 1 bent to a 3.5 cm diameter hairpin shape prior to full wire V(I) measurement. (b) 7 cm long sections of wire 1 prior to V(I) measurements on extracted tapes.

2.3. CORC® wire bending procedures

Two procedures were developed to determine the effect of bending on the performance of the CORC® wires. The first procedure involved measuring the I_c of long wire sections before and after sequential bending at room temperature into a hairpin shape with diameters of 10 cm, 7.5 cm, 5 cm, and 3.5 cm, respectively. Figure 2a shows wire 1 bent into a 3.5 cm diameter hairpin shape. For these tests, voltage versus current (V(I)) characteristics were measured across tubular Cu terminals that were mounted on either end of wire 1 and wire 2. The insulation and stainless steel tapes were removed at the wire ends prior to soldering into the terminals with eutectic Sn63Pb37 solder. Each tape layer was cut to a different length in a taper to expose each tape to the Cu terminals. Wire 1 had 15 cm long terminals with a 1.27 cm outer diameter (OD) and measured 49 cm between terminals. Wire 2 had 20 cm long terminals with a 0.79 cm OD and measured 30 cm between terminals. The second procedure involved measuring the V(I) characteristics of each individual superconducting tape extracted from short (7 – 10 cm long) sections of wire that were straight or bent to a diameter of 10 cm, 7.5 cm, 5 cm, or 3.5 cm. Figure 2b shows several sections of wire 1 bent to various diameters prior to extracting the tapes.

2.3. High field test of a CORC® solenoid

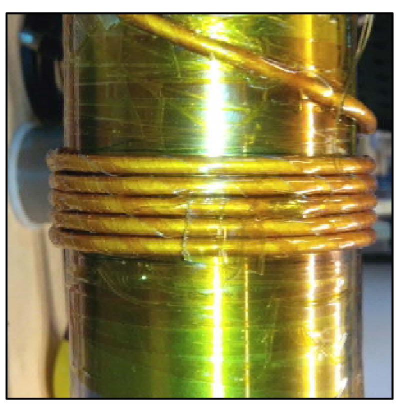


Figure 3 – Five turn solenoid sample (reinforcement wrapping and joints not shown) made from a 3 mm diameter Kapton insulated CORC® wire wound around a 6 cm diameter mandrel as tested at the University of Twente at 10 T, 4.2 K.

For critical current versus magnetic field (I_c (B)) tests, we constructed a wire following the design of wire 1 with a few key differences:

- The thickness of the Cu tapes on the former was reduced from 100 to 50 µm.
- The total former diameter was reduced from 2.4 to 2.2 mm to accommodate two additional layers of REBCO tape.
- The stainless steel tapes were removed and the polyester insulation was replaced with polyimide tape insulation.

The modified version of wire 1 had an outer diameter of 3 mm and was wound around a 6 cm diameter mandrel as seen in figure 3. The sum of the expected tape I_cs in the solenoid add up to a nominal I_c of 981 A at 76 K.

The high field measurements up to 10 tesla at 4.2 K were performed at the University of Twente in collaboration with CERN. The CORC® wire on the mandrel was first taped by a protective layer of Teflon to avoid bonding to resin so the wire could be recovered after testing. A reinforcing wrap of STYCAST resin filled fiberglass tapes was then applied to sustain Lorentz forces and suppress conductor movement. For introducing current, the coil sample was connected to a superconducting transformer and inserted in the bore of an 11 T Nb_3Sn coil testing facility. The facility applies an axial magnetic field on the test solenoid, i.e. a perpendicular magnetic field on the CORC® wire in the coil. Both joint terminals were positioned in the stray magnetic field of the facility with up to 5 T present at the entry tip of each terminal. Critical current measurements were performed in 0 to 10 T background field at 4.2 K. At each run, the current was ramped up in small steps and settled on each plateau for 3 second before the voltage was recorded.

3. Results

3.1. Effect of former size on tape I_c retention

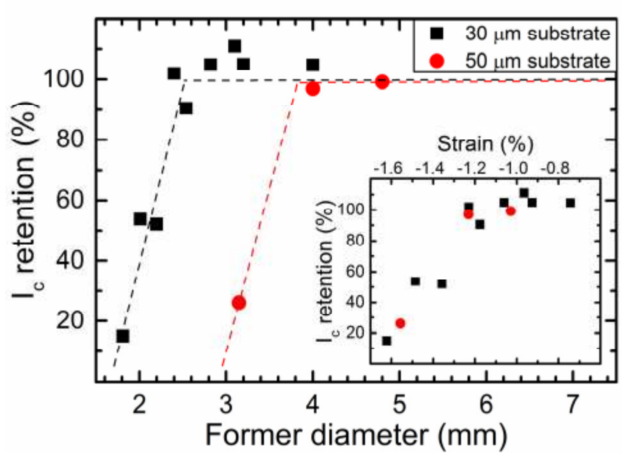


Figure 4 – I_c retention as a function of former diameter at 76 K for helically wound REBCO tapes with 30 and 50 µm thick substrates. Inset is the same data plotted as a function of bending strain in the REBCO layer. Dotted lines are to guide the eye.

There is a limit on the strain that can be applied to the REBCO layer as the coated conductor is bent around a former before irreversible degradation of I_c occurs [9]. The strain (ε) at the YBCO interface can be calculated using the equation:

$$\varepsilon = \frac{-x}{D+x+2t} \quad (2)$$

where x is the substrate thickness, D is the former diameter, and t is the thickness of the stabilizer layer. Since the REBCO is deposited on one side of the substrate, it is advantageous to have the REBCO facing towards the former (putting it under axial compression) and to have the thinnest substrate possible [7, 9]. To illustrate this point, figure 4 shows I_c retention of measured tapes as a function of former diameter for coated conductors grown on 30 and 50 µm thick substrates. The inset shows the same data plotted as a function of bending strain calculated at the REBCO layer as described in reference 10. Little degradation of the tapes is observed until the compressive strain exceeds about -1.23 %, corresponding to a minimum former thickness of 2.4 mm for CORC® wires wound from tapes with 30 µm thick substrates. If the substrate thickness was further reduced to 20 µm, -1.23 % strain would correspond to a 1.6 mm former, allowing the incorporation of 24 additional 2 mm wide tapes in an equivalent cross section of wire.

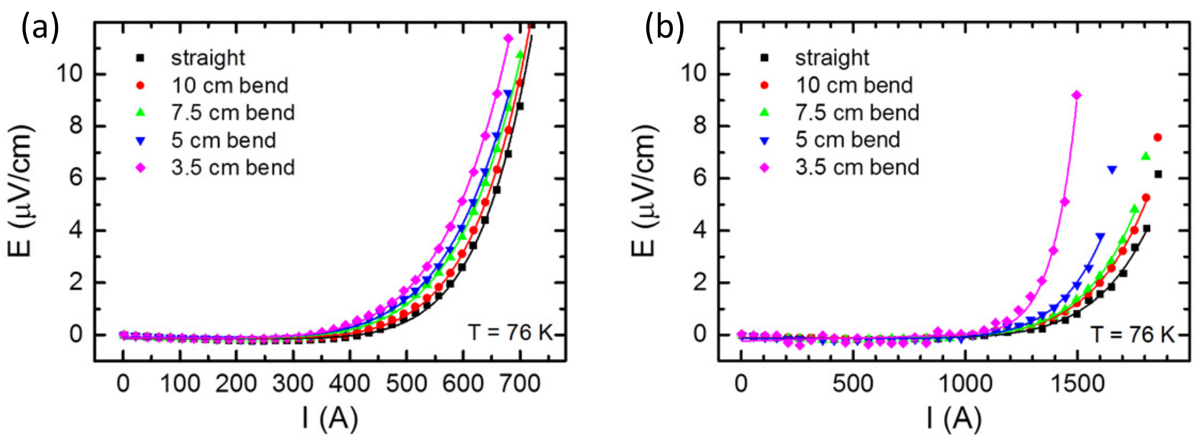


Figure 5 – Electric field as a function of current measured at different bending diameters for (a) wire 1 and (b) wire 2. Solid lines represent the fits used to calculate the critical current density.

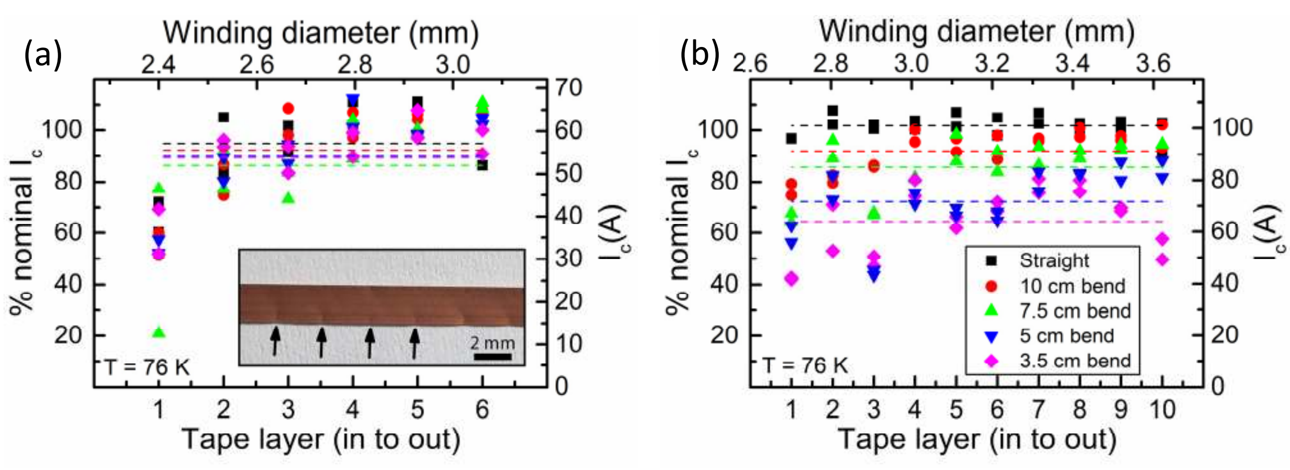


Figure 6 – Extracted tape I_c as a function of tape layer and winding diameter after bending sections of wire to various diameters for (a) wire 1 and (b) wire 2. Dashed lines represent the average I_c for each wire section. Inset to (a) shows a superconducting tape extracted from layer 1 of the straight section of wire 1 with arrows pointing out tape damage.

3.2. Effect of bending on the CORC® wire performance

To determine how the performance of CORC® wires is affected by bending, critical current measurements were carried out on wire 1 and 2 before and after bending to various diameters. Figure 5 shows the electric field E = (V/L) measured on the terminals of wire 1 (figure 5a) and wire 2 (figure 5b) as a function of current at 76 K. The resistive contribution of the terminals (approximately 145 and 82 nOhm for wires 1 and 2, respectively) was subtracted from the data shown. Before bending, wires 1 and 2 had an I_c of 526 and 1500 A, and an n-value of 7.8 and 7.6, respectively. This corresponds to 73-76 % of the nominal I_c, due mostly to self-field effects as discussed in the following section. While wire 1 shows a slight but steady decrease of I_c with decreasing bending diameter by about 1.1 % per cm-bent from 10 to 3.5 cm, wire 2 had a more substantial 10 % drop in I_c when the wire was bent from a diameter of 7.5 cm to 3.5 cm. Interestingly, the n-value decreased slightly as a function of bending down to 5.9 for wire 1, but increased to 10.3 for wire 2 after bending to 3.5 cm. Figure 6a and 6b show the measured I_c of extracted tapes as a function of tape layer and winding diameter for wire 1 and wire 2, respectively, after bending to different diameters. Here, nominal I_c is defined as the average I_c of the tapes that make up the wire, as listed in table 1. For wire 1, the first tape layer (at a winding diameter of 2.4 mm) had more than 20 % degradation even before the wire was bent. A regular pattern of kinks (seen in the inset to figure 6a) corresponds to the gaps in the underlying layer of 100 µm thick Cu tapes. To prevent similar damage from occurring in wires 2 and 3, the underlying layer was changed from 100 µm thick Cu tape to 50 µm thick Cu tape to provide a smoother surface on the former for the superconducting layers to be wound onto. Figure 7a and 7b summarize the above results by plotting total wire I_c as a function of bending diameter. For the extracted tape measurements in figure 7, a summation of all the tape I_cs is used for each bending diameter. The results will be discussed in more detail in the next section.

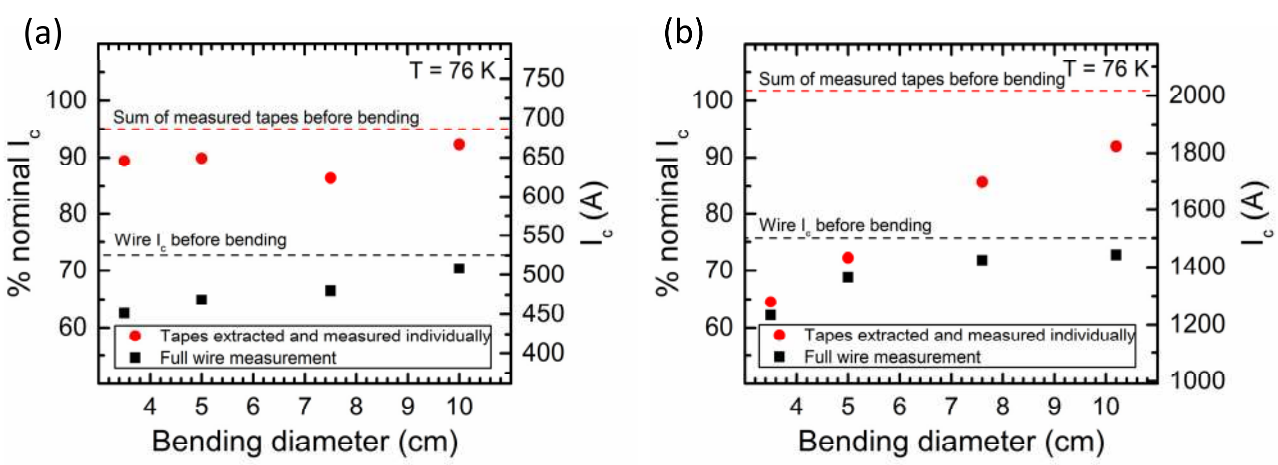


Figure 7 – Total wire I_c as a function of bending diameter for (a) wire 1 and (b) wire 2. Dashed lines represent the critical currents measured on wire sections that were never bent.

The larger decrease in I_c of wire 2 at a bending diameter of less than 7.5 cm was likely due to closing of the gaps between the tapes in some of the layers. Based on the above results, a third wire was manufactured from 3 mm wide tapes with an optimized design (wire 3 in Table 2). The new design included larger gaps between superconducting tapes in each layer. In addition, a larger former was incorporated to test the flexibility of this wire at larger winding diameters than in wire 2. Figure 8 shows the extracted tape I_c as a function of tape layer and winding diameter for a straight section of wire 3, and one bent to 5 cm. Overall, the wire retains about 93 % of the expected I_c without any observed dependence of I_c retention on the winding diameter.

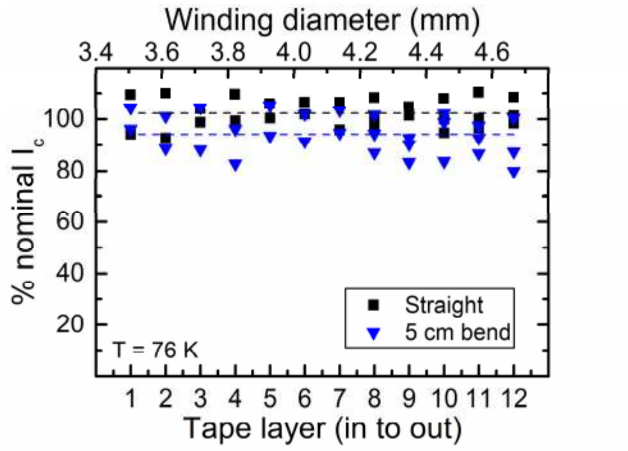


Figure 8 – Percent nominal I_c as a function of tape layer and winding diameter for tapes extracted from sections of wire 3. Dashed lines represent the average I_c for each wire section.

3.3. Effect of applied magnetic field on the CORC® solenoid

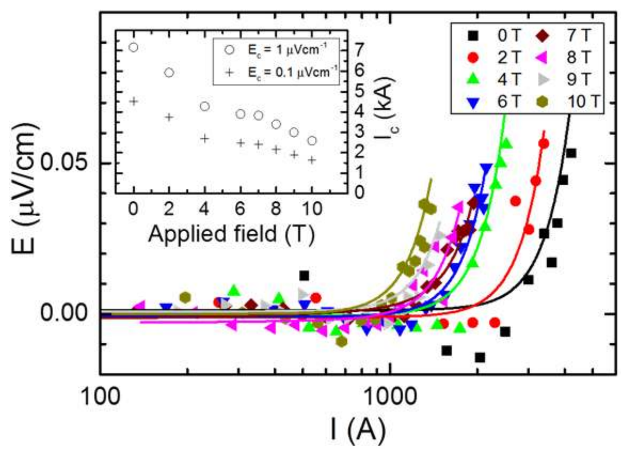


Figure 9 – Electric field as a function of current and external applied magnetic field for the 5 turn solenoid at 4.2 K. Solid lines represent the fits used to calculate the critical current density according to equation 1 with n set to 5. Inset is critical current as a function of applied magnetic field calculated using an electric field criterion of either 1 μVcm^{-1} or 0.1 μVcm^{-1}.

Figure 9 shows the electric field as a function of current at different applied magnetic fields and I_c as a function of magnetic field (see inset) for the 5 turn solenoid taken at 4.2 K. Due to the limited output power of the superconducting transformer and a quench occurring at one of the joints, the data gathered shows just the beginning of the superconducting transition. Uncertainties in extrapolating the data using equation 1 led us to use a conservative voltage criterion of 0.1 μVcm^{-1} instead of 1 μVcm^{-1} to determine I_c. Using the more conservative criterion, at 10 T the solenoid had an I_c of 1625 A, corresponding to a J_e of 230 Amm^{-2}. Assuming a ratio of nominal I_c (77 K, 0 T) to I_c (4.2 K, 10 T) of 2.2, an I_c of 1829 A would be expected for the solenoid at 4.2 K and 10 T, meaning the solenoid carried 89 % of the expected current. However, 1829 A is well below the expected I_c using a criterion of 1 μVcm^{-1} as is shown in the inset to figure 9. Following the high field measurement, tapes were extracted from a 15 cm long section located in the high field region of the solenoid. Figure 10 shows the I_c measured in the extracted tapes compared to a straight sample that was not bent or tested at high field. The extracted tape I_c measurement shows that the wire retained approximately 80 % of its total expected I_c, with most of the degradation located in the innermost two layers that were subjected to excessive compressive strain because they were wound at a diameter between 2.2 and 2.4 mm.

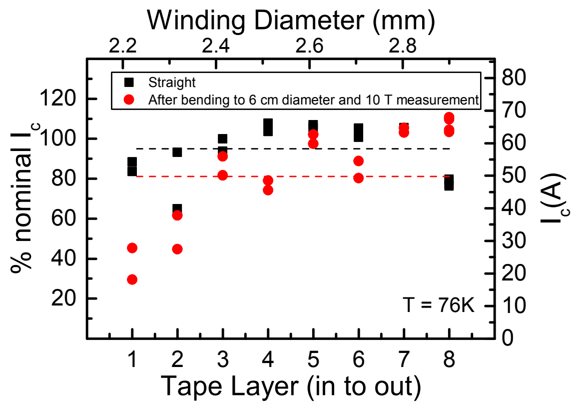


Figure 10 – Percent nominal I_c as a function of tape layer and winding diameter for tapes extracted from a section of the solenoid subjected to bending and high field measurements and a representative sample of a straight section that was not subjected to high-field measurements. Dashed lines represent the average I_c for each wire section.

4. Discussion

The flexibility of superconducting wires vastly affects the complexity and cost of superconducting machines, particularly for magnets. Superconductors such as Nb_3Sn and $Bi_2Sr_2CaCu_2O_x$, that are essentially inflexible in their final form, require wind-and-react manufacturing techniques that have notoriously slowed their development. The aim of this experiment was to determine the level of flexibility that can be achieved in CORC® wires utilizing REBCO coated conductors with the 30 μm substrates that are now commercially available. Unlike solid conductors, in which the superconducting filaments are bound by a matrix, each tape in a CORC® wire is physically decoupled. An important feature of these wires is that gaps are intentionally left between the tapes in each layer. These gaps can be seen in the cross sections in table 2, and allow room for the tapes to slide when the wire is bent; relieving the stress that would accumulate away from the bending radius if the wires were solid. In addition, the gaps, which make up 5 to 12 % of the cross sectional area, form a vast network of transversely intercepting coaxial channels that can be utilized for coolant flow in specialized applications.

Wires 1 and 2 were designed with the minimum former size to produce no more than -1.23 % compressive strain on the innermost superconducting layer of the wire utilizing 2 and 3 mm wide tapes, respectively. The unexpected degradation of the innermost layer of wire 1 in the as-wound conductor resulted in an initial 5 % degradation of wire I_c. This prompted a redesign for the following wires that avoided such degradation by utilizing thinner inner Cu tapes that produced a shallower gap, preventing the superconducting tapes from kinking as shown in the inset of figure 6a.

To interpret the data shown in figure 7, it's important to consider the self-field imposed on the energized wire. While the coaxial arrangement of transversed tapes results in a cancellation of the self-field component perpendicular to the tapes along the center of the wire, the terminations can be particularly sensitive to self-field effects. For this reason, the full wire is not being energized since the quench at 70 to 75 % of the nominal I_c at 76 K is expected to occur in the terminations. This is evidenced by a relatively low n-value measured across the terminals of between 5 and 10, compared to an n-value between 18 and 30 for extracted tapes. For lower temperatures, where flux pinning is better, or in situations where the wire experiences higher field than the terminations, we observe higher n-vales and closer to nominal I_c in CORC® conductors [7].

When the entire wire was measured, wire 1 showed a weak linear dependence of I_c on bending diameter, decreasing by 14 % between being straight and being bent to a 3.5 cm diameter. However, the extracted tape measurement revealed less than 7 % degradation in the same range. Since we believe the superconducting transitions of the full CORC® wires seen in figure 5 are influenced by the terminations to around 75 % of their nominal I_c at 76 K, the observed correlation of I_c vs bending diameter for the full CORC® wire measurement may be caused by something other than bending damage, such as an enhanced self-field effect on the CORC® wire due to the hairpin bend.

For wire 2, the full wire I_c measurement follows nearly the same dependence of I_c vs bending diameter as wire 1. However, the extracted tapes of the unbent sample revealed 100 % I_c retention, but degraded much more significantly to 65 % I_c retention after bending to a 3.5 cm diameter. It's clear that once the wire center was damaged by more than 25 % due to bending, then the full wire measurement followed the extracted wire measurement much more closely. This is because the full wire measurement was limited to 75 % I_c at the terminals. After bending to 3.5 cm, the increase in n-value of wire 2 suggests the wire quenched at the bend instead of within the terminals. For this reason, the best indicator for irreversible damage at 76 K comes from the extracted tape measurements. In figure 6b we see most of the degradation as a function of bending occurring on the inner 7 layers (< 3.3 mm winding diameter) of wire 2. Similar damage is not seen in wire 1, which is made up of 2 mm instead of 3 mm wide tapes, suggesting that the winding diameter is further limited by the width of the tape. Wire 3 was designed to utilize 3 mm wide tapes and avoid such damage by starting at a larger winding diameter. Figure 8 shows that greater than 90 % I_c retention could then be obtained in wire 3 after bending to a 5 cm diameter.

I_c (B) measurements were carried out on a 5-turn solenoid following the design of wire 1, with the modifications mentioned in section 3.3. One of the concerns with winding tapes under compression near the limit determined in section 3.1, is that additional strain imposed by Lorentz forces during high field measurements could be sufficient to exceed the compressive strain-limit and damage the tapes. The additional two layers of tape (at winding diameters between 2.2 and 2.4 mm) were subject to winding-strains exceeding -1.23 %, allowing us to see how I_c is affected by strain approaching and exceeding this limit. While the tapes in these two layers carried less than half of their nominal I_c after the high field measurement, the tapes wound at diameters of 2.4 mm and above had an average I_c of 57 A, or 93 % of the nominal I_c. This is close to the I_c retention expected from bending alone (figure 7a), indicating that the epoxy we used to support the wire was sufficient to prevent detrimental strain due to the additional Lorentz forces imposed by this test.

Based on the above results, wire 4 was designed to obtain high J_e while maintaining high flexibility. 2 mm wide tape was chosen as the coated conductor to minimize the size of the former and to allow for a large number of fine tapes, which will decrease magnetization losses. Assuming a critical current of 35 A/mm-width at 77 K (values that are commercially available [11, 12]), the 4.8 mm diameter wire 4 in table 2 should obtain a nominal J_e of 301 Amm^{-2} at 77 K. This is significant for the development of medical gantries, demountable fusion magnets, rotating machines, power transmission, and generation applications that require low cooling costs or cryocooled operation. With a lift factor (J_e (4.2 K, 20 T) / J_e (77 K, 0 T)) of 1.6, a J_e at 4.2 K and 20 T of 481 Amm^{-2} can be expected. This would exceed the current record J_e in a REBCO cable [7] by over 50 % and is significant for accelerator and detector magnets that require such high in-field current densities.

There are several clear paths to further increase the J_e of CORC® wires by more than a factor of two over the next two years. Closest to fruition, increases in lift factor can be obtained by moving from 7.5 % to higher levels of Zr-doping that further enhance the pinning properties of coated conductors[13-15]. This has already been demonstrated on standard 50 µm substrates by SuperPower Inc. on a pilot scale [16]. Wire 4 made using similar tapes with 30 µm thick substrates will already reach a design J_e of over 600 Amm^{-2} (4.2 K, 20 T) with a lift factor of 2, as expected from tapes with 15 % Zr doping. Independently, an increase of the deposited REBCO layer thickness from 1.6 to 2 µm would similarly allow wire 4 to exceed a J_e of 600 Amm^{-2} (4.2 K, 20 T) assuming a 25 % increase of J_e at a cost of less than 1 % of the cross section of the coated conductor. Additionally, an increased superconducting volume fraction will significantly improve J_e if substrate thickness is further decreased to less than 30 µm. In this case, a smaller former can be used due to the decreased strain state of the inner REBCO layers. Even a minor decrease of substrate thickness from 30 to 25 µm would allow the design of a CORC® wire with a J_e around 600 Amm^{-2} (4.2 K, 20 T) and a smaller diameter of about 4 mm. Presently, the limited tape widths available (2, 3 and 4 mm, for instance) requires the winding angle (α) to be varied for each layer. This affects the efficiency of the wires, both in terms of tape used and in terms of the J_c of each individual layer. The availability to vary the width and keep α constant would allow for an additional increase of J_e and decrease the amount of tape needed in a wire of a given diameter. Figure 11 shows a projection of the impact of just reducing the substrate thickness and optimizing the tape width on J_e as a function of CORC® wire diameter using a lift factor of 1.6. The combination of all the above improvements is sufficient to deliver 600 Amm^{-2} (4.2 K, 20 T) in a wire with a diameter of much less than 3 mm, or significantly higher values in a thicker wire.

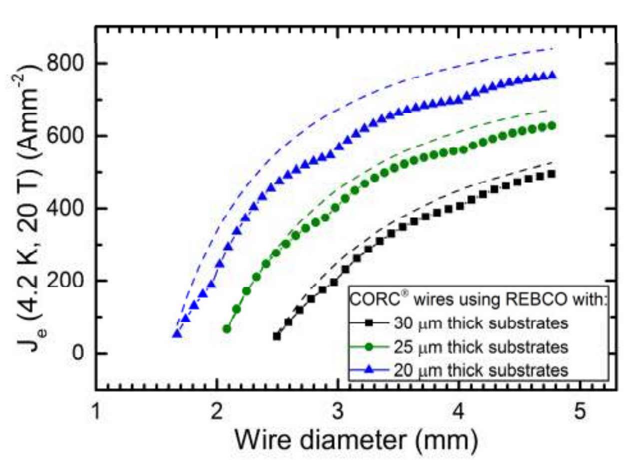


Figure 11 – Projected whole wire critical current density (at 4.2 K and 20 T) at a lift factor of 1.6 as a function of wire diameter for CORC® wires made using REBCO tapes with different substrate thicknesses. Symbols are for wires made from tapes with fixed 2 mm width while dashed lines are for wires made from tapes with variable widths.

5. Conclusion

In summary, the recent commercial availability of REBCO coated conductors with 30 µm thick substrates has enabled the design of thin, highly flexible CORC® wires with expected current densities well beyond 400 Amm^{-2} at 4.2 K and 20 T. Three wires were constructed to verify the flexibility of CORC® wires, which is relevant for compact magnet designs. One wire wound from 2 mm wide tapes showed a weak I_c dependence on bending diameter, retaining over 90% I_c after bending to a 3.5 cm diameter compared to before bending. Similar flexibility was achieved in a 5 mm thick CORC® wire wound from 3 mm wide tapes. I_c dependence on applied field was also measured on a 5 turn solenoid that had a J_e of 233 Amm^{-2} at 4.2 K and 10 T. Based on the rapid progress of coated conductor development, we designed a flexible 77 tape REBCO wire that has the potential to exceed current densities of 600 Amm^{-2} (4.2 K, 20 T) in the near future.

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