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High critical current STAR® wires with REBCO tapes by advanced MOCVD

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Abstract

RE–Ba–Cu–O (REBCO, RE = rare earth) symmetric tape round (STAR®) wires of 1.5–2.5 mm diameter have been fabricated with 4–12 strands of symmetric REBCO tape made by advanced metal organic chemical vapor deposition (MOCVD). 1.5 mm diameter STAR® wires made with just four advanced MOCVD tape strands are able to sustain nearly the same critical current (I_c) as 2.5 mm diameter wires made with 12 commercial-grade tape strands. An I_c of 1070 A, corresponding to an engineering current density (J_e) of 597 A mm^{-2}, has been demonstrated at 4.2 K, 30 T in 1.5 mm diameter, four-strand wire at a bend radius of 15 mm. This I_c value exactly matches the I_c expected from the lift factor of the tape strands used in the wire. The 2.5 mm diameter STAR® wires made with 12 advanced MOCVD tape strands exhibit an I_c of 1075 A at 77 K, self-field and sustained currents of 2500–2750 A at 4.2 K, 30 T before burnout, corresponding to a J_e greater than 500 A mm^{-2}. These results show that the cost of STAR® wires can be substantially reduced using fewer tape strands of high-performance advanced MOCVD tapes and that the superior bend performance of STAR® wires can be maintained, even using 12 strands of advanced MOCVD tapes with 4 μm thick REBCO films.

Keywords: STAR®, REBCO, MOCVD, critical current, round wire

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

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1. Introduction

The High Luminosity Large Hadron Collider for high energy physics is transitioning from Nb-Ti dipoles to Nb_3Sn [1] for higher operating magnetic fields. Even higher gains in beam energy and luminosity for the proposed High Energy Large Hadron Collider can be obtained by using high temperature superconductors (HTS) which are the only option for magnetic fields above 20 T [1].

The Canted Cos θ (CCT) design at a smaller winding bend radius is a leading candidate to generate multipole magnetic fields using helical current paths for beam steering magnets. Not only does the CCT design offer good field quality along the entire magnet's straight section and 'ends,' but it also prevents stress accumulation from Lorentz forces.

RE–Ba–Cu–O (REBCO) tapes are an attractive choice for HTS dipoles. Their high yield strength (>700 MPa) is especially beneficial to withstand the intense forces in high magnetic fields. A challenge with REBCO tapes compared to Nb-Ti, Nb_3Sn and Bi-2212 wires is their flat, rather than round, geometry and their wide (~12 mm) profile rather than a multifilamentary architecture. A round wire is mechanically isotropic in bending, which is important in the fabrication of CCT coils. It has been shown by the CORC® method that flat REBCO tape geometry can be converted to a round cable by helically winding the flat tapes on a round core [2]. However, no REBCO wire/cable has been able to meet the stringent bend radius requirement of CCT coils. Lawrence Berkeley National Laboratory (LBNL), that is leading the REBCO CCT effort in the U.S. Magnet Development Program, has stated that an engineering current density (J_e) of 540 A mm^{-2} at 4.2 K, 21 T at a bend radius of 15 mm, is a key requirement for CCT coils [3].

The importance of the minimum bend radius of wire used in CCT coils is evident from the dependency of the dipole transfer function on the tilt angle, which in turn depends on the winding radius. In a CCT coil, the wires are tilted at an angle (θ) with respect to the bore axial direction to cancel the solenoid field components produced by each layer, and double the dipole field in the magnet aperture [3]. The dipole transfer function is proportional to cos θ, and the minimum bend radius is proportional to sin θ [4]. For an HTS wire's minimum bend radius of 25 mm, a large tilt angle has to be used, resulting in a dipole transfer function of only 0.28 T kA^{-1} in a four-layer CCT design, which limits the achievable magnetic field.

If the minimum bend radius of the round wire can be reduced to 15 mm, the tilt angle can be lowered to 30°, and the dipole transfer function can be nearly doubled to 0.48 T kA^{-1} with a four-layer design, and to 0.73 T kA^{-1} with a six-layer design [4]. Clearly, round REBCO wires with high current-carrying capacity at a bend radius of 15 mm or less are vital for CCT coils.

Another HTS accelerator magnet design that is being developed (by Fermilab) is the conductor on molded barrel (COMB). The COMB design requires the HTS wire to withstand sharp bends. Fermilab states that the wire needs to be bendable around 25–30 mm diameter poles with preferably no more than 20% performance degradation [5].

Using specially-made symmetric REBCO tapes where the superconductor film is positioned near the neutral plane, AMPeers and the University of Houston have demonstrated REBCO round wires as small as 1.3–2 mm in diameter [6]. These symmetric tape round (STAR®) wires exhibit excellent tolerance to bend strain and can retain over 95% of their I_c even when wound over a 15 mm bend radius, meeting a key design requirement of CCT as well as COMB coils. A 1.3 mm diameter REBCO STAR® wire reached a J_e of 586 A mm^{-2} at 4.2 K in a background field of 20 T at a bend radius of 15 mm [6]. This J_e meets the design requirement of CCT coils. STAR® wires have been scaled up 23 m with an average I_c of 480 A (1.95 mm diameter) and to 61 m with an average I_c of 370 A (1.84 mm diameter) at 77 K, self-field [7].

Recently, LBNL demonstrated a two-layer subscale CCT dipole magnet with three wire turns in each layer [8]. The magnet used two STAR® wires, electrically in parallel in each layer, and the minimum bending radius was 15 mm at the pole region of the magnet. The magnet showed reproducible current–voltage transitions with a maximum transport current of 8500 A at 4.2 K, with no obvious wire degradation after winding, even at the 15 mm bend radius [8].

The main roadblock to the utilization of STAR® or any other HTS wire/cable in CCT and other magnets for accelerators is its cost. The predominant cost of a REBCO wire/cable by far is the REBCO tape cost. The cost of REBCO tape is particularly important because the greater the number of tape strands used in the wire, the more the cost of every single manufacturing step to fabricate the wire. Note that the quantity of REBCO tape required is about 1.5 times the length of wire because of the 45° wire winding angle.

Our approach in this work was to drastically reduce the cost of STAR® wires by using one third of the number of REBCO strands, utilizing tapes made by advanced metal organic chemical vapor deposition (MOCVD). REBCO tapes made by advanced MOCVD exhibit 3–5 times higher I_c than commercial-grade REBCO tapes [9]. Advanced MOCVD REBCO tapes consist of REBCO films that are 4–5 μm thick compared to ~2 μm in commercial-grade REBCO tapes. Additionally, advanced MOCVD REBCO films consist of nanoscale pinning centers optimized for ultra-high magnetic fields at low temperatures [10, 11]—consequently, they exhibit a lift factor in I_c above 3.5 at 4.2 K, 20 T compared to ~2.15 observed in commercial-grade REBCO tapes. The lift factor is defined as the ratio of the critical current in a magnetic field at a temperature lower than 77 K to the critical current at 77 K, 0 T.

An objective of this work is to evaluate how the thick film advanced MOCVD tapes can be wound to diameters of 0.7–1 mm to fabricate STAR® wires. Another objective of this work was to examine if the high lift factor and critical current of advanced MOCVD tapes persist after the STAR® wire fabrication process.

2. Design

Figure 1 is a flowchart of the fabrication process of STAR® wires. REBCO tapes with ultrathin substrates are slit to narrow widths, copper electroplated to position the REBCO film near the neutral plane and then spiral wound on a former to fabricate STAR® wires. Details of the process steps are provided in the Experiment section.

As shown in the schematic in figure 2, previously, commercial-grade REBCO tapes with 1.7 μm thick REBCO films and ∼22 μm overall thickness were slit to 1.4–2.6 mm wide strands, silver sputter deposited and electroplated with copper primarily on the REBCO film side to produce symmetric REBCO tapes [6]. Twelve strands of these symmetric REBCO tapes, each with an average width of 2 mm and I_c of 75 A at 77 K, self-field and lift factor in I_c of ∼2.15 at 4.2 K, 20 T were wound on 0.8 mm diameter copper former to fabricate 2 mm diameter wires. Such wires can exhibit an I_c of 1730 A at 4.2 K, 20 T when bent to 15 mm radius. A 2.8-fold reduction in the cost of STAR® wire can be achieved by reducing the number of symmetric tape strands used by a factor of three. To achieve the same overall I_c of the wire, we used symmetric REBCO tapes made by advanced MOCVD with three times the I_c of commercial-grade tapes used so far.

In this work, we have replaced commercial-grade tapes used for STAR® wire with tapes made by advanced MOCVD consisting of 4 μm thick REBCO film and Zr or Hf dopant. The thicker REBCO film along with the appropriate (Ba + dopant)/Cu composition can yield both a higher I_c at 77 K, self-field as well as a higher lift factor of ∼3.6 at 4.2 K, 20 T [10]. Together, the I_c of tapes made by advanced MOCVD would be at least three times the I_c of commercial REBCO tapes at 4.2 K, 20 T. So, instead of 12 strands of symmetric tapes needed with commercial-quality REBCO, *we would be able to use just four strands of symmetric tapes with advanced MOCVD REBCO* to achieve the same I_c of 1,730 A at 4.2 K, 20 T. Such a reduction will decrease both the cost and time required to manufacture STAR® wires. Additionally, with fewer layers of tape, the wire will be of smaller diameter (<1.5 mm) which would improve its strain tolerance. Further, with fewer tapes, there will be less likelihood of damage during winding and in handling wires.

3. Experiment

12 mm wide tapes with ∼18 μm thick Hastelloy C-276 substrate, biaxially-textured buffer based on MgO grown by ion beam assisted deposition, and an $LaMnO_3$ cap layer, 4 μm thick (Gd,Y)-Ba-Cu-O film with 5 mol.% Zr addition made by advanced MOCVD [12] were used for STAR® wire fabrication. The critical current of the tape was measured by reel-to-reel scanning Hall probe microscopy (SHPM) at 77 K, 0 T at 1 mm intervals [13]. The lift factor in the critical current of the tape was measured by the physical property measurement system (PPMS) at 4.2 K in magnetic fields of up to 14 T. The 12 mm wide tape was laser slit to 2 mm widths for -strand wire or to widths ranging from 1.5 mm to 2.6 mm for 12-strand wire. Details of the 4- and 12-strand STAR® wire construction are provided in the next section. The laser-slit samples were silver-sputter deposited and copper electroplated primarily on the REBCO film side to position the film near the neutral plane [14]. The critical current of each strand was measured using reel-to-reel SHPM and selected strands were wound on a 1.02 mm diameter copper former for 4-strand wire and on a 0.81 mm diameter copper former for 12-strand wire. The transport critical current of the wires were measured at 77 K, self-field by the four-probe method, both in straight form and in a bent form after bending to a 15 mm radius. Selected wires were measured at 4.2 K in magnetic fields up to 30 T, as described in the next section. Some wires that were damaged after high magnetic field transport current measurements were analyzed by microcomputed tomography (micro-CT).

Micro-CT scans were performed on a Bruker/Microphotonics Skyscan 2214. The STAR® wire was scanned as mounted on the G-10 fixture used during the in-field measurements, in order to avoid any artificial additional damage to the wire beyond that induced during in-field testing. A custom micro-CT sample holder was made for this purpose, in order to accommodate and interface the G-10 fixture to the system mount base. Due to high attenuation of the x-ray-dense wire, an accelerating voltage of 140 kV and a source current of 60 μA were used together with a high voltage tolerant CCD sensor. A total of five frames were collected per angular position for signal averaging (signal-to-noise ratio improvement). In order to increase dynamic range, a 0.5 mm Cu filter was used. The sample was scanned at rotational increments of 0.2° for 180° plus opening of the cone beam. The sample was scanned at 11 mm away from source. The final image pixel size was 0.5 μm.

4. Results and discussion

We began with the fabrication of 25 m long REBCO tapes in a pilot advanced MOCVD tool. Figure 3 shows the critical current measured over a 25 m long tape with 4 μm thick film with a composition (Ba + Zr)/Cu > 0.72, by reel-to-reel SHPM at 77 K, 0 T [13]. The average I_c of the 25 m long tape is 811 A/12 mm and the uniformity (standard deviation/mean) is 5.9%.

The in-field critical current of the tape was measured with short samples using a PPMS at 4.2 K in magnetic fields of up to 14 T. The data shown in figure 4(a) reveals a measured lift factor in I_c @ 4.2 K, 13 T = 4.71 and an alpha value of 0.772. The alpha value is the power-law exponent relating the critical current (or lift factor in critical current) to the magnetic field (B) as $I_c \approx B^{-\alpha}$. Based on the alpha value of 0.772, the projected lift factor in I_c @ 4.2 K, 20 T = 3.41. So, the expected I_c at 4.2 K, 20 T = 2765 A/12 mm. This is 2.86 times

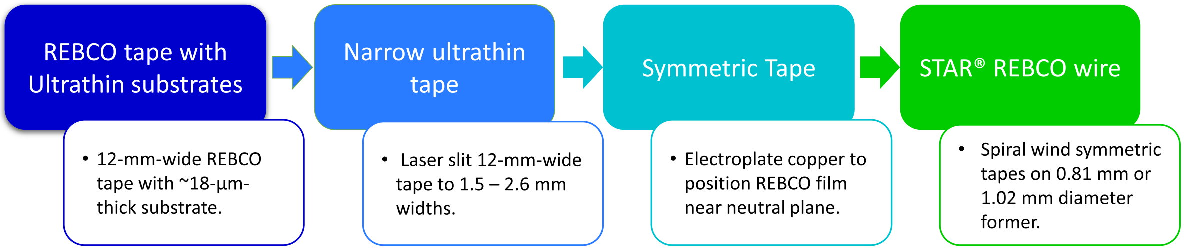

Figure 1. Flowchart showing main steps in STAR® wire fabrication.

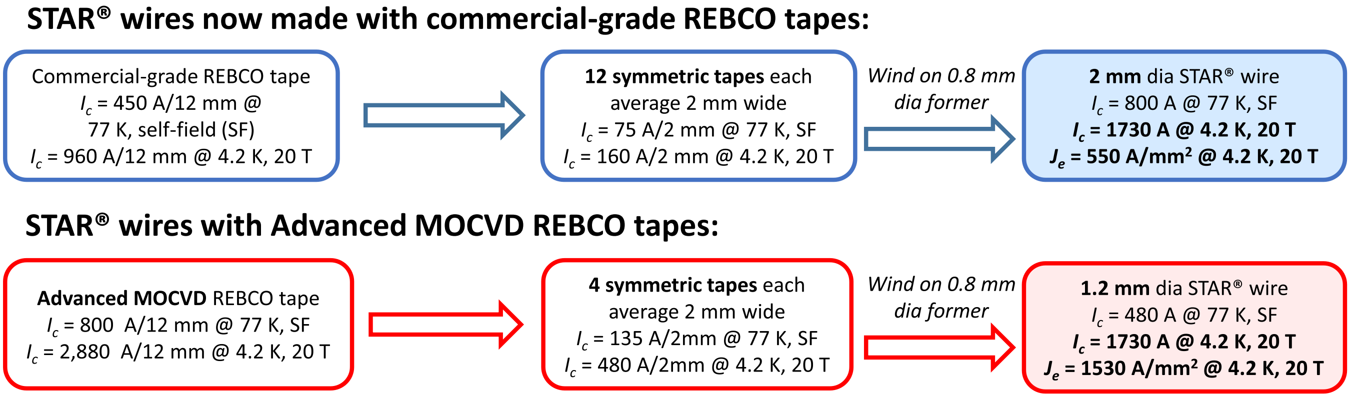

Figure 2. Design scheme of STAR® wires made with advanced MOCVD REBCO tape strands in this work compared to STAR® wires made to date with commercial-grade REBCO tapes.

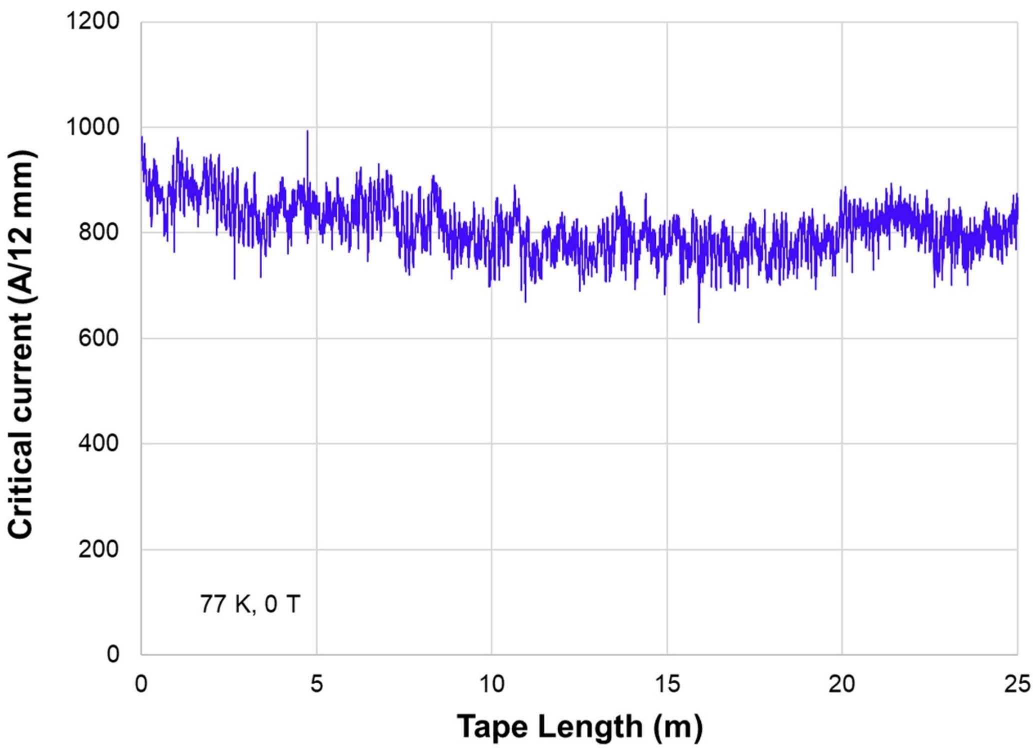

Figure 3. Critical current of a 25 m long REBCO tape with 4 μm thick film made by advanced MOCVD, at 77 K, 0 T.

the I_c of commercial tape at 4.2 K, 20 T. Based on the lift factor of 3.41, the projected I_c of the 25 m long tape at 4.2 K, 20 T is presented in figure 4(b). We have recently successfully scaled up our advanced MOCVD process to 50 meter lengths [15]. One of these 50 m tapes tested at National High Magnetic Field Laboratory, Tallahassee exhibited a critical current as high as 3822 A/12 mm at 4.2 K, 20 T, 38% higher than the I_c of advanced MOCVD tapes used in this work.

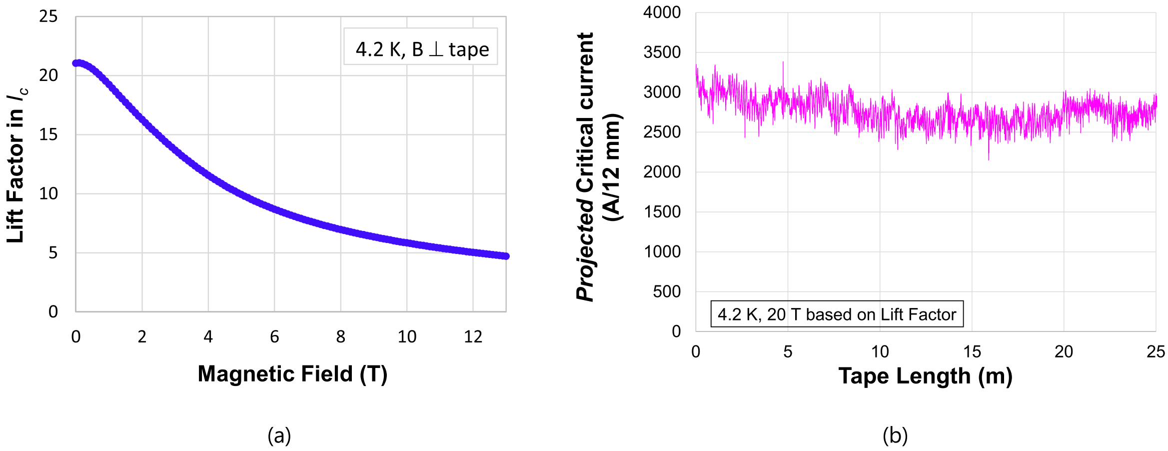

Figure 4. (a) Lift factor in critical current at 4.2 K of a 25 m long REBCO tape with 4 μm thick film made by advanced MOCVD. (b) Projected critical current at 4.2 K, 20 T of the 25 m long tape based on the measured I_c at 77 K, 0 T and scaled according to the measured lift factor and alpha value at 4.2 K.

Figure 5. Photograph of a 1.51 mm diameter round REBCO wire made with four ~2 mm wide tape strands. The tape strands were made with high-performance advanced MOCVD REBCO tape consisting of 4 μm thick film, (Ba + Zr)/Cu > 0.72.

The advanced MOCVD REBCO tapes used for STAR® wire fabrication in this work were ~22 μm thick. The tapes were slit to ~2 mm width and silver and copper deposited to produce symmetric REBCO architecture wherein the film is positioned near the neutral plane [14]. The thickness of the copper stabilizer was determined to ensure good I_c retention when the symmetric tapes are wound on a 1 mm diameter former. Four copper-plated symmetric tape strands were wound on an 18 AWG former (1.02 mm diameter). So, the total tape width of all strands is 8 mm. A photograph of the round REBCO wire is shown in figure 5. The diameter of the wire is 1.51 mm. STAR® wires fabricated in this work were about 20 cm in length.

The STAR® wire made of four REBCO tape strands, with a total strand width of 8 mm, exhibited a critical current of 420 A at 77 K, self-field at a voltage criterion of 1 μV cm^{-1} when bent to a 15 mm radius, as shown in figure 6(a). The n-value was 14. The lift factor in the critical current of the tape strands used in the wire, at 4.2 K in magnetic fields up to 13 T, is exhibited in figure 6(b). The data shown in figure 6 (right) reveals an alpha value (α) of 0.759. Based on the alpha value, the corresponding lift factor in I_c expected at 4.2 K, 30 T is 2.55. So, the expected wire I_c at 4.2 K, 30 T is 1,070 A.

Next, this 1.51 mm diameter wire, made with just four advanced MOCVD tape strands, was tested in the National High Magnetic Field Laboratory, Tallahassee in magnetic fields of up to 30 T at 4.2 K. Because of the very high I_c of the wire and limitations in available power supplies, we could obtain the data only at 30 T and the result is shown in figure 7. The wire I_c and n-value measured at 4.2 K, 30 T were 1070 A and 21 respectively. The I_c value corresponds to a J_e of 597 A mm^{-2}. The measured I_c of wire at 4.2 K, 30 T matches exactly the expected I_c based on the lift factor in the I_c of tapes used in wire as described in the previous paragraph. So, this confirms that the lift factor in the I_c of tapes used in the wire can be used to determine the I_c of the STAR® wire in high magnetic fields. The lift factor in the I_c of tapes used in wire at 4.2 K, 20 T is projected to be 3.46 from the data shown in figure 6. So, the expected I_c of wire at 4.2 K, 20 T is 1,455 A, and the expected J_e is 812 A mm^{-2}. The J_e value is substantially higher than the best J_e of 586 A mm^{-2} achieved in STAR® wires made with commercial-grade REBCO tapes [6]. More importantly, the I_c at 4.2 K, 30 T of STAR® wire made with just four strands of advanced MOCVD tapes, with a total strand width of 8 mm, reaches nearly 90% of the I_c at 4.2 K, 30 T of STAR® wire previously made with 12 strands of commercial-grade tapes with a total strand width of 27 mm [6]. So, this result exhibits the potential of using fewer than three times the I_c tapes to achieve a high I_c and lower the cost of STAR® wires.

Another 1.49 mm diameter STAR® wire was made with only four symmetric tape strands using high-performance

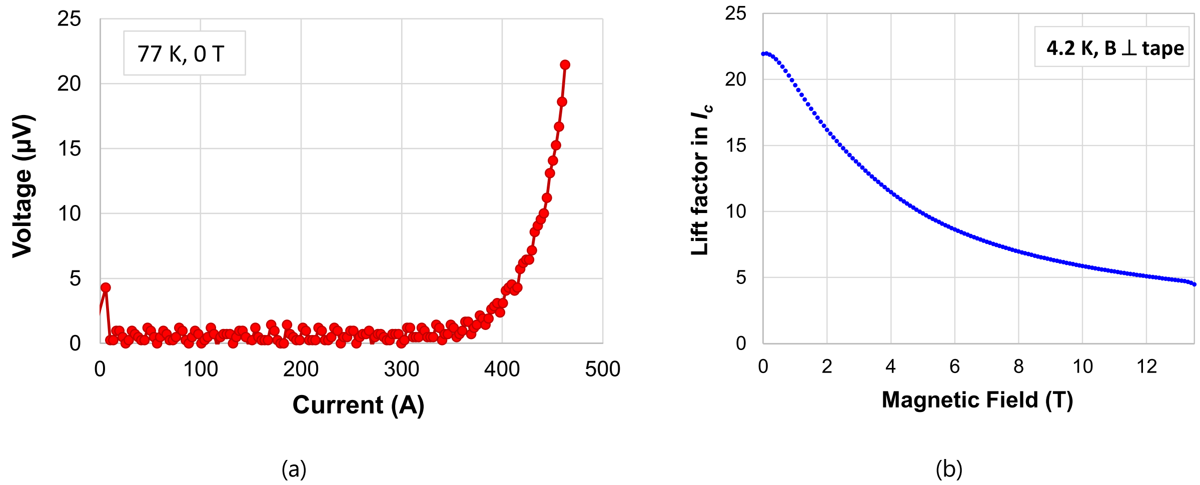

Figure 6. (a) Current–voltage curve of a 1.51 mm diameter STAR® wire fabricated with only four strands of tape, made by advanced MOCVD, at 77 K, self-field. The measurement was done with the wire bent to a radius of 15 mm and a voltage tap spacing of 6 cm. A voltage criterion of 1 μV cm^{-1} was used to determine the critical current. (b) Lift factor in I_c at 4.2 K, up to 13 T of individual tape strands made by advanced MOCVD used in the wire.

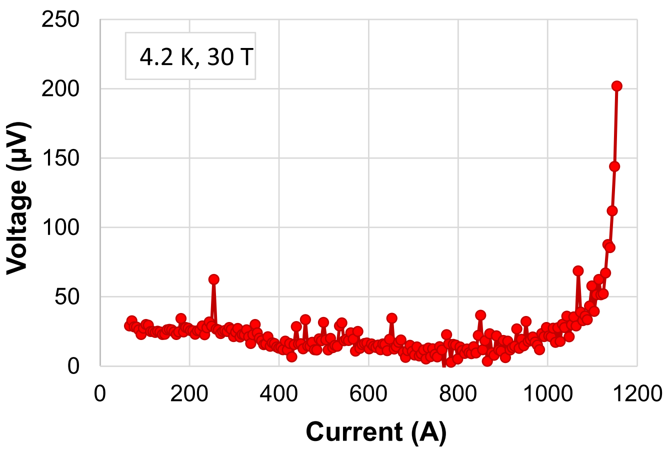

Figure 7. Current–voltage curve of the 1.51 mm diameter STAR® wire fabricated with only four strands of tape made by advanced MOCVD, at 4.2 K, 30 T. The measurement was done with the wire bent to a radius of 15 mm. A voltage criterion of 3 μV cm^{-1} was used to determine the critical current.

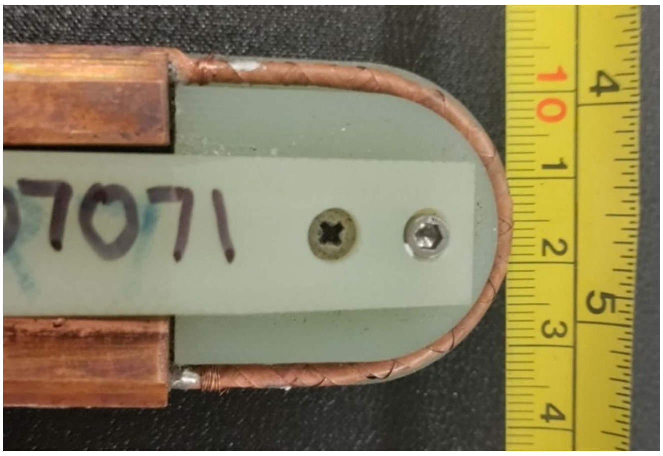

Figure 8. Photograph of a 2.52 mm diameter STAR® wire made with 12 tape strands, bent to a radius of 15 mm. The tape strands were made with high-performance advanced MOCVD REBCO tapes consisting of 4 μm thick film, (Ba + Zr)/Cu > 0.72.

advanced MOCVD REBCO tape, about 22 μm total thickness, consisting of 4 μm thick film, (Ba + Zr)/Cu > 0.72. This wire exhibited an I_c of 506 A at 77 K, self-field when bent to a 15 mm radius. The lift factor in the I_c of the tape strands at 4.2 K, 20 T was 3.88. So, the expected I_c of the round REBCO wire at 4.2 K, 20 T is 1,960 A at a bend radius of 15 mm. The J_e of the wire at 4.2 K, 20 T will be 1,126 A mm^{-2} at a bend radius of 15 mm, which is nearly twice the best J_e of STAR® wires reported to date.

In addition to the ability to use one third of the number of REBCO strands to make STAR® wires at a lower cost, utilization of advanced MOCVD tapes enables STAR® wires with much higher critical current while maintaining a small diameter and superior bend properties. A 2.52 mm diameter STAR® wire was fabricated on 0.81 mm copper former using 12 symmetric tape strands made with high-performance advanced MOCVD tapes. The width of the individual tape strands used in the wire was 1.5, 1.5, 2, 2, 2.3, 2.3, 2.6, 2.6, 2.6, 2.6, 2.6 and 2.6 mm. So, the total width of the tape strands was 27.2 mm. A photograph of the wire tested when bent to 15 mm radius is shown in figure 8.

As revealed in figure 9, the I_c of the 2.52 mm diameter wire in straight form was 1,140 A at 77 K, self-field. The I_c of the wire when bent to a 15 mm radius was 1075 A at 77 K, self-field. This corresponds to a 95% retention in I_c when bent to a 15 mm radius, which confirms that STAR® wires with a diameter of 2.5 mm also maintain superior bend performance. The lift factor in the I_c of tape strands used in the wire was 4.72 at 4.2 K, 20 T. So, the I_c of the 2.52 mm round REBCO wire at 4.2 K, 20 T will be 5,140 A (at 15 mm bend radius), corresponding to a J_e = 1,030 A mm^{-2}.

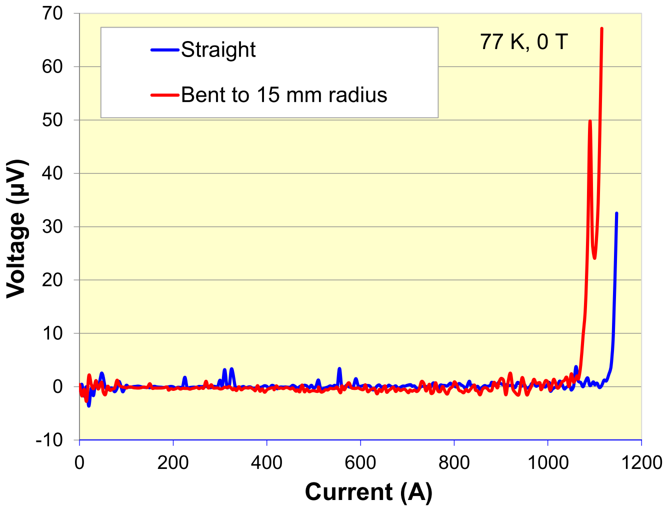

Figure 9. Current–voltage curve of a 2.52 mm diameter STAR® wire fabricated with 12 strands of REBCO tape, at 77 K, self-field, in a straight form and when bent to a 15 mm radius. The tape strands were made with high-performance advanced MOCVD REBCO tape consisting of 4 μm thick film, (Ba + Zr)/Cu > 0.72. Voltage tap spacing was 8 cm. A voltage criterion of 1 μV cm^{-1} was used to determine the critical current.

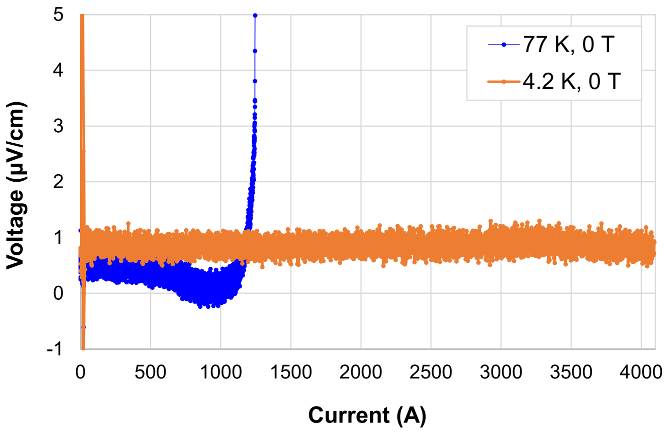

Figure 10. Current–voltage curves of 2.52 mm diameter STAR® wire fabricated with 12 strands of tape made by advanced MOCVD, at 77 K, self-field and 4.2 K, 0 T. The measurements were done with the wire bent to a 15 mm radius. A voltage criterion of 1 μV cm^{-1} was used to determine the critical current at 77 K.

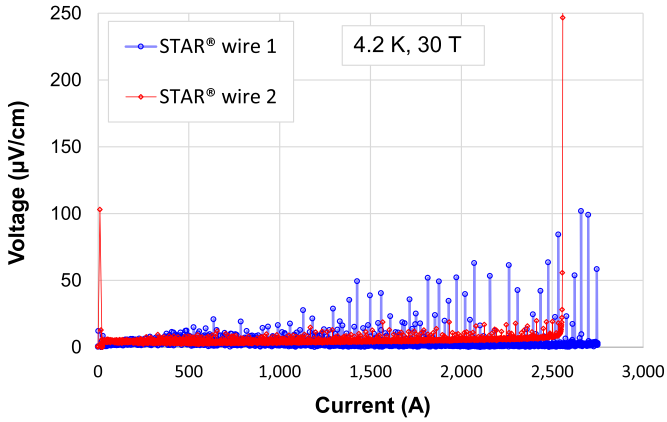

Figure 11. Current–voltage curves of two ~2.5 mm diameter STAR® wires fabricated with 12 strands of tape made by advanced MOCVD, at 4.2 K, 30 T when bent to a 15 mm radius. In both cases, the wires burned out the maximum current.

Figure 12. Photograph of 2.52 mm diameter STAR® wire fabricated with 12 strands of tape, showing burn-out after testing at currents of over 2,500 A at 4.2 K, 30 T.

Three high critical current STAR® wires of ~2.5 mm diameter made with 12 advanced MOCVD tape strands were tested at a bend radius of 15 mm at the European Magnetic Field Laboratory, Grenoble. The wires were filled with Pb-Sn eutectic solder to provide some rigidity to the tape strands. However, as shown later, the solder did not properly penetrate the gaps between the strands. Measurements at 77 K in self-field confirmed a high critical current of 1200 A in the wires, as shown in figure 10. The n-value of the wire displayed in figure 10 was 21. Current ramps up to 2000, 3000 and 4000 A at 100, 150 and 200 A s^{-1}, respectively, were performed at 4.2 K without magnetic field to check the current injection condition. No quench, and no significant temperature increase or voltage noise was observed, as displayed in figure 10.

Then, a maximum field allowed by the 50 mm magnet configuration, i.e. 30 T was applied. The signal was much noisier due to the mechanical vibration induced by the field. The measurement became even more difficult because voltage spikes randomly triggered the current shut-off threshold. These spikes are ascribed to mechanical motions of the tapes in the wire and/or local current redistribution. Nevertheless, by increasing the current target step by step, we were able to inject more than 2500 A in the STAR® wires, which corresponds to a J_e of over 500 A mm^{-2} at 4.2 K, 30 T at a bend radius of 15 mm (figure 11). On all three wires, we ramped up the currents to their limits i.e. burnout in subsequent measurements.

A photograph of one of the wires after burnout during testing at 4.2 K, 30 T is shown in figure 12. The wire was bent to a 15 mm radius and mounted on a G-10 holder for the high field tests. The wire burned out at the bend radius location. To understand the mechanism of quench damage, the

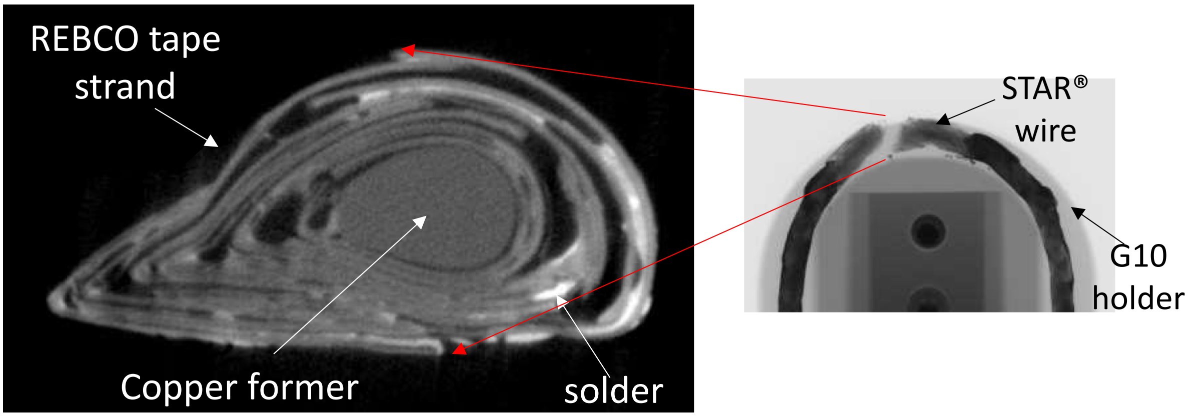

Figure 13. Micro-CT image of the 2.52 mm diameter STAR® wire shown in figure 11, near the burnt-out location. A low-magnification micro-CT image of the wire on G-10 mandrel is shown on the right.

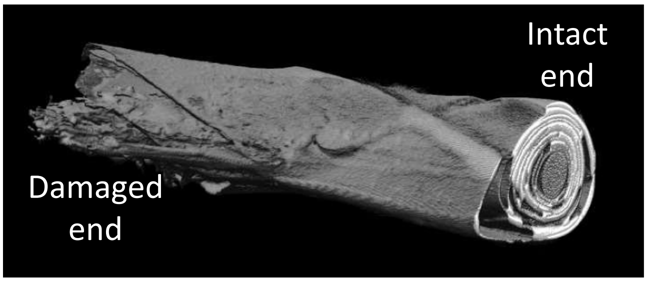

Figure 14. Micro-CT image of 2.52 mm diameter STAR® wire shown in figure 11 near the burnt out location.

wire was examined using micro-CT. Micro-CT is a useful way to nondestructively conduct failure analysis without introducing artifacts in sample preparation [16, 17]. Micro-CT images of the STAR® wire at the damaged location are shown in figure 13 (left). A low-magnification micro-CT image is seen in figure 13 (right), which reveals the damaged area. It is observed that the round copper former has been severely deformed in the damaged area indicating that the copper yielded during damage. Correspondingly, it can be seen that the REBCO tape strands follow the shape of the deformed copper former, squashed towards the left. The bottom part of the wire is in contact with the G-10 holder, so as the wire is pressed down by the high Lorentz force, the bottom part is severely compressed, as seen in the figure.

Figure 14 exhibits a micro-CT image of the wire segment in the vicinity of the damaged region. The left side of the image reveals the damaged area severely flattened while the wire is intact at the other end. In order to observe the progression of damage, we imaged the wire a short distance from the completely burnt out end and the results are shown in figure 15. In this figure, the bottom part of the wire exhibited in figure 11 is now shown on the top side. In figures 15(a) and (b), the copper former is seen to still maintain its round form; however, the REBCO strands are flattened at the bottom part (top side in the figure) due to the wire being pressed down on the G-10 holder. From figures 15(c)–(e), the copper former also deformed. The differences seen in figures 15(a) through (e) must be mainly due to the temperature gradient. This indicates overheating of the wire closer to (e), causing the copper former to soften and deform. Even though the distance from (a) to (e) is small (13 mm), it is possible that the angle between the current and field vectors change, and so does the Lorentz force magnitude. Mechanical stress due to the Lorentz force gradient may have also played some role in the wire deformation. The substantial gaps between the tape strands reveal that the solder did not properly penetrate the wire, and the strands were free to move during testing. Improved impregnation techniques are needed to properly fill the gaps between tape strands and provide better rigidity of the wire during high field measurements.

The fact that the STAR® wires sustained a current as high as 4000 A at 4.2 K, 0 T, as shown in figure 10, without burn out or voltage spikes while they burnt out at currents between 2500 A and 2750 A at 4.2 K, 30 T after many voltage spikes, indicates that mechanical motion of the strands in the wire needs to be avoided. The high current wires need to be secured from mechanical-stress-induced damage in order to properly assess the role of high current density sustained in the tape strands to the damage. Longer, high current density STAR® wires made with advanced MOCVD tape strands need to be tested in a coil form. Current sharing between the high current density strands and with the copper former also needs to be evaluated.

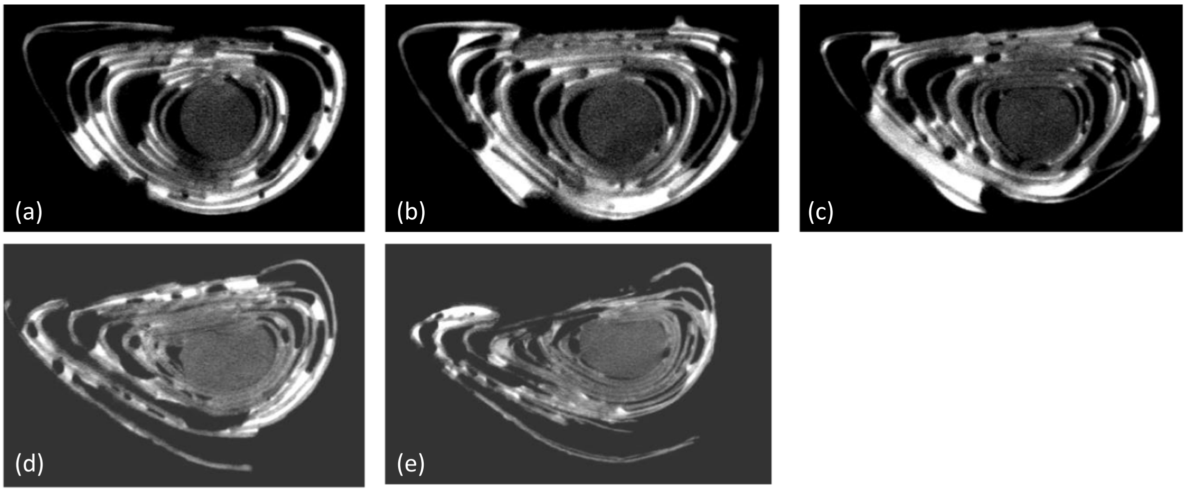

Figure 15. Sequence of micro-CT images of a 2.52 mm diameter STAR® wire shown in figure 13 near the burnt out location. (a) is farthest away from burn out location and (e) is closest to the burnt out location. (a)–(e) are located 20, 17, 15, 10, 7 mm respectively from the completely damaged location. The bright regions between tape strands are solder that was partially filled in the wire prior to testing.

5. Summary

STAR® wires have been demonstrated with high critical current advanced MOCVD REBCO tape strands. Compared to previous STAR® wires made with commercial-grade REBCO tape strands, the new wires use only one third of the number of strands, which greatly reduces the manufacturing cost. Additionally, the new STAR® wires with just four strands are only 1.5 mm in diameter and sustain a critical current comparable to previous wires made with 12 strands that are about 2.5 mm in diameter. The smaller diameter provides more flexibility and can enable more compact coils. A 1.51 mm diameter wire made with four advanced MOCVD REBCO tape strands exhibits a critical current of 1070 A at 4.2 K, 30 T, corresponding to a J_e of 597 A mm^{-2}, when bent to a 15 mm radius. The critical current of this wire at 4.2 K, 30 T matched exactly the critical current expected based on the lift factor in the critical current of the advanced MOCVD tape strands used in the wire, indicating that the performance of the individual tape strands can be used to predict the critical current of the STAR® wire. Accordingly, based on the strand performance, a J_e of 1126 A mm^{-2} is expected at 4.2 K, 20 T in a 1.49 mm STAR® wire made with four advanced MOCVD tape strands. This value is nearly twice as high as the best J_e reported to date for STAR® wires.

The capability of the new STAR® wires was further evaluated with 12 strands of high-performance advanced MOCVD tape. One such wire of 2.52 mm diameter displayed a critical current of 1075 A at 77 K, self-field when bent to a 15 mm radius. Based on the strand performance, a critical current of 5,140 A (at 15 mm bend radius) corresponding to a $J_e = 1030$ A mm^{-2} is expected at 4.2 K, 20 T. The 12-strand wires were tested at currents beyond 4,000 A at 4.2 K, self-field at a 15 mm bend radius, without any problems. However, at 4.2 K, 30 T, these wires burned out at current levels between 2500 A and 2750 A, corresponding to a J_e above 500 A mm^{-2}. Micro-CT imaging of the damaged section of the wire reveals severe mechanical deformation of the copper former and the tape strands.

The potential of using advanced MOCVD high-current tape strands has been demonstrated to substantially reduce the cost of STAR® wires. Additionally, the feasibility of higher current STAR® wires, while maintaining the small bend radius of 15 mm, has been demonstrated using advanced MOCVD tape strands.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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