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Erratum: Symmetric tape round REBCO wire with J_e (4.2 K, 15 T) beyond 450 A mm^{-2} at 15 mm bend radius: a viable candidate for future compact accelerator magnet applications (2018 *Supercond. Sci. Technol.* 31 04LT01)

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Due to an error in the production process, the title of this article should read 'Symmetric Tape Round (STAR) REBCO wire with J_e (4.2 K, 15 T) beyond 450 A mm^{-2} at 15 mm bend radius: a viable candidate for future compact accelerator magnet applications'. Furthermore, all references to 'symmetric tape round wires' should be 'Symmetric Tape Round (STAR) wires'.

In the 'Tape preparation' subsection 'The REBCO tape was then slit from a width of 12–2.5 mm using a reel-to-reel laser slitting machine…' should read 'The REBCO tape was then slit from a width of 12 to 2.5 mm using a reel-to-reel laser slitting machine…'.

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Letters

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Letter

Symmetric tape round REBCO wire with J_e (4.2 K, 15 T) beyond 450 A mm^{-2} at 15 mm bend radius: a viable candidate for future compact accelerator magnet applications

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Abstract

Round REBCO (RE = rare earth) wires of 1.6–1.85 mm diameter have been fabricated using ultrathin REBCO tapes where the superconductor film is positioned near the geometric center. Such symmetric tape round (STAR) wires exhibit excellent tolerance to bend strain with a critical current retention of more than 97% when bent to a radius of 15 mm. A 1.6 mm diameter REBCO STAR wire made with six 2.5 mm wide symmetric tapes reached an engineering current density (J_e) of 454 A mm^{-2} at 4.2 K in a background field of 15 T at a bend radius of 15 mm. Such superior performance at a small bend radius can enable fabrication of future accelerator magnets, operating at magnetic fields above 20 T.

Keywords: REBCO, round wires, bend radius, accelerator magnets, engineering current density

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

Introduction

High field superconducting accelerators magnets are now transitioning from use of Nb–Ti to Nb_3Sn conductors [1, 2] to achieve higher operating magnetic fields for circular colliders such as the High Luminosity Large Hadron Collider (HL-LHC) [3]. For the HL-LHC, about 30 Nb_3Sn quadrupoles with peak fields above 12 T and 20 Nb_3Sn dipoles with peak fields in excess of 11 T will be produced. Even higher gains in beam energy and luminosity for the proposed High Energy LHC can be obtained by using high temperature superconductors (HTSs) which are the only option for field strengths in the vicinity of 20 T [1, 4].

There are two choices for HTS materials for use in accelerator magnets. In the US, the predominant focus has been on $Bi_2Sr_2CaCu_2O_8$ (Bi-2212) wires. The main benefits of Bi-2212 are its round form and multifilamentary architecture. Recently, overpressure processing has been developed to consistently improve critical current (I_c) performance of short conductors [5] and racetrack coils [6]. Nevertheless, since Bi-2212 coils have to be fabricated by a wind and react approach, there are technical challenges to implement this technology in manufacturing of large accelerator magnets, as they have to be subjected to long heat treatments at around 900 °C and pressures of 100 bar. Additionally, with more than 60% of the wire being comprised of mint-grade silver, its cost may be out of reach for large accelerator magnets.

A viable HTS alternative are RE-Ba-Cu-O (REBCO, RE = rare earth) coated conductors that are fabricated by a reel-to-reel thin film process [7]. In these coated conductors, a

Table 1. Performance summary of various high J_e tape stacks, cables/wires for accelerator applications developed so far along with their minimum bending radius [18].

Cable/wire concept	J_e (A mm^{-2}) at 4.2 K, B (T)	Max. J_e (A mm^{-2})	Min. bend radius (mm)	Comment
Twisted stacked tape	273 (16 T) [19]	300–400	>140 mm	Partially transposed
Helically twisted stacked tape	100 (12 T) [20]	≈100	Sensitive to bend	Partially transposed
Conductor on round core (CORC®) cable	344 (17 T) [21]	≈344	50	Transposed
Conductor on round core (CORC®) wire	412 (10 T) [22]	≈412	30	Transposed
ROEBEL	400 (10 T) [23]	≈500	>20	Transposed

typical superconductor thickness in the order of 1 μm results in very high critical current densities of about 5 MA cm^{-2} at 77 K, self-field. The rest of the conductor is comprised of inexpensive nickel alloy and copper. Additionally, coated conductors are fabricated by a reel-to-reel continuous process that is amenable to low-cost manufacturing. In the past few years, insert magnets made with coated conductors have been demonstrated with record-high magnetic fields of about 35 T in a background field at 4.2 K [8]. Based on this achievement, a 32 T all-superconducting magnet using a REBCO coated conductor-based insert magnet has been constructed at the National High Magnetic Field Laboratory [9]. The high yield strength (>700 MPa) of REBCO coated conductors is especially beneficial to withstand the intense forces at these high magnetic fields.

Two challenges with REBCO coated conductors as compared to Nb–Ti, Nb_3Sn and Bi-2212 wires are associated with their flat rather than round geometry and a wide (~12 mm) profile rather than a multifilamentary architecture. To address these issues, globally, there have been recent efforts on high-current multi-strand REBCO cable configurations for accelerator applications such as ROEBEL cables in a rectangular structure [10–12], twisted stacked tape cables [13, 14] and conductor on round core (CORC®) cables/wires [15–17]. The rectangular-structured cable configuration can yield a high J_e at a small bending radius but only along the easy-way bend direction which can be a limitation for magnet design and fabrication. Table 1 shows a performance summary of various high J_e tape stacks, cables/wires for accelerator applications developed so far along with their minimum bending radius [18–23]. The round wire configuration, on the other hand, is mechanically isotropic and makes use of the excellent tolerance of REBCO tapes to torsional strain that was demonstrated by spiral winding of narrow tapes to small twist pitch lengths [24]. While round REBCO wires have been demonstrated by wrapping flat tapes on a round core [15, 17, 25], high J_e needs to be demonstrated at a small bending radius for specific magnet designs such as the canted-cosθ concept [26]. We had previously reported fabrication of round REBCO wires of diameter as small as 1.6 mm with excellent critical current retention using ultrathin REBCO tapes [27, 28]. In this article, we report substantially improved performance of these round wires when bent to a radius of 15 mm as well as their critical currents at 4.2 K in magnetic fields up to 15 T.

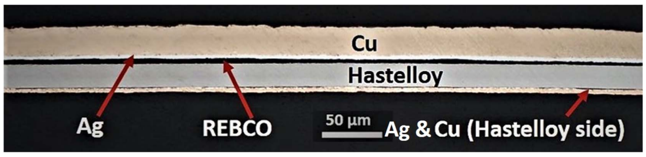


Figure 1. In-house prepared thin symmetric REBCO tape with total thickness of 25 μm before copper plating, and 22 μm thick Hastelloy substrate. The REBCO film is positioned near the geometric center of the tape by incorporating appropriate copper stabilizer thicknesses on the film side and substrate side.

Tape preparation

Ultrathin REBCO tapes of total 25 μm thickness consisting of a 22 μm thick Hastelloy substrate were fabricated. This tape consists of ~0.2 μm thick oxide buffer layer stack and a 1.6 μm thick REBCO layer. A silver cap layer, 2 μm thick on the top of REBCO layer and 1 μm thick on the back of the substrate was deposited using DC magnetron sputtering. The REBCO tape was then slit from a width of 12–2.5 mm using a reel-to-reel laser slitting machine [27]. After slitting, the REBCO layer is exposed along the edges of the tapes and can be susceptible to delamination during the winding process. A 0.5 μm thick silver layer was therefore deposited on the edges of the tape to cover the exposed REBCO layer at edges. Then, a 20–25 μm thick copper layer on the REBCO side and a 3 μm thick copper layer on Hastelloy side were deposited using reel-to-reel Cu electroplating. The final REBCO tape overall thickness varied from 45 to 60 μm. A cross-sectional microstructure of the completed tape is shown in figure 1. As seen in the figure, this architecture provides a symmetric arrangement of the metallic content resulting in the REBCO layer positioned near the geometric center of the tape, which then experiences significantly reduced bending strain during winding [28]. REBCO tapes with this symmetric architecture exhibit exemplary electromechanical properties with nearly 100% critical current retention even at a bend diameter of 0.81 mm, which is believed to be due to the REBCO film being positioned near the neutral plane [28]. Such REBCO tapes were used to fabricate round wires, henceforth called symmetric tape round (STAR) wires.

Fabrication of REBCO STAR wire

A 1.02 mm diameter copper wire (18 AWG) was selected as the former of the STAR wire. It is strong in its axial direction

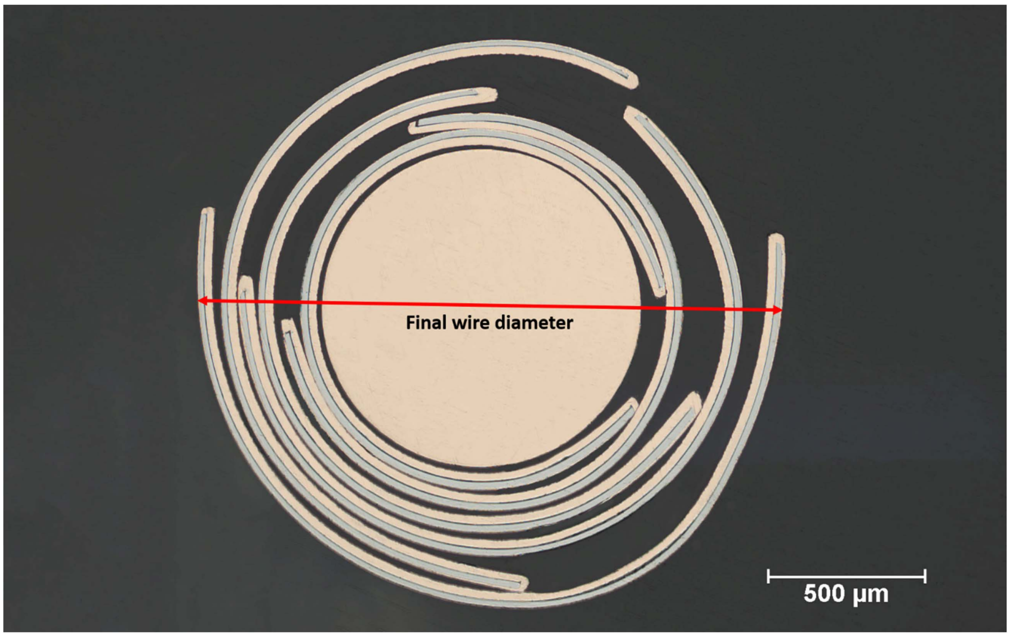


Figure 2. Cross-sectional view of a STAR wire.

Table 2. Specifications of REBCO STAR wires made.

Round REBCO wire	Former diameter (AWG, mm)	Tape width (mm)	Total tape width (mm)	No. of layers	Total length (cm) including copper ends	Wrap angle	Final STAR wire diameter (mm)
STAR Wire-1	18 (1.02 mm)	2.5	15	6	25	45°(constant)	1.85
STAR Wire-2	18 (1.02 mm)	2.5	15	6	25	45°(constant)	1.66

while flexible enough for bending the STAR wire to a small diameter. The former was without any insulation layer to provide current sharing ability. Two STAR wires (STAR-1 and STAR-2) of 1.85 and 1.66 mm final diameter respectively were made by winding six layers of 2.5 mm wide tapes on the Cu former, with the thicker electroplated copper layer on the REBCO film facing inward. We have used six pieces of 2.5 mm wide, 1.41 m long tape to fabricate 1 m of STAR wire. A cross section of the STAR wire is shown in figure 2. The terminals of the wires were made using indium-solder-filled copper tubes. The specifications of the STAR wires are summarized in table 2. The difference in the final diameter of the round wires is due to different process parameters of the wire-winding systems to obtain best configuration of the STAR wire.

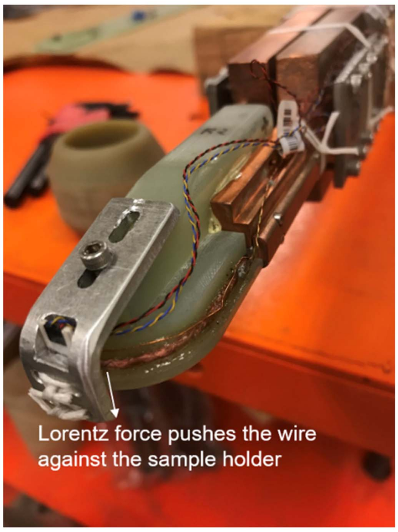
Experimental

The critical current of the STAR wires was measured at 77 K, self-field first in a straight form without bending and again after bending on a G10 fixture at 15 mm bend radius, as shown in figure 3(a). Subsequently, the critical current of the wires was measured at 4.2 K, in field with the wire bent on the G10 fixture. All three sets of measurements used the same voltage taps on the outermost tape layer, positioned 9 cm apart on the wire i.e. 15 cm tap distance on the flat tape. The in-field performance of two STAR wires was tested at 15 mm bend radius at 4.2 K in magnetic fields up to 15 T at Lawrence Berkeley National Laboratory. The central part of the bent wire (figure 3(a)) was located at the center of the solenoid magnet that provided the background field. Thus, the central part of the bent wire determined the wire performance. STAR Wire-1 was tested as is, at 4.2 K in field. Solder flux was applied around the STAR Wire-2 only to prevent the tape from moving during measurement. The current polarity was arranged such that the Lorentz force pressed the wire against the G10 support structure during measurements (figure 3(b)). This arrangement minimizes movement of the wire during the in-field test.

Results and discussion

Figure 4 shows the electric-field-current characteristics (E–I) plot of the STAR wires at 77 K, self-field in a straight form without bending and after bending to a 15 mm bend radius. The critical current (I_c) values of the wires were obtained using a 1 μV cm^{-1} criterion and are shown in table 3. Before bending, the I_c of STAR Wire-1 was measured to be 513 A, corresponding to an engineering current density (J_e) of 193 A mm^{-2} at 77 K, self-field. Here, J_e is defined by the I_c/whole cross-sectional area of the STAR wire. To get the final diameter of the STAR wire (with 18 AWG core and all

a



b

Figure 3. (a) REBCO STAR wire mounted on a G-10 fixture, bent at 15 mm radius along with its copper terminals, (b) side view of the sample holder along with its support structure during in-field test.

six layers), we have measured the STAR wire diameter at different locations in the most outer layer using a micrometer to obtain average diameter. The I_c of STAR Wire-2 before bending was measured to be 482 A, corresponding to a higher J_e of 223 A mm^{-2} at 77 K, self-field because of its smaller overall diameter of 1.66 mm. The critical currents of the STAR wires in bending form were measured at 77 K, self-field when bent to a 15 mm radius as shown in figure 3(a).

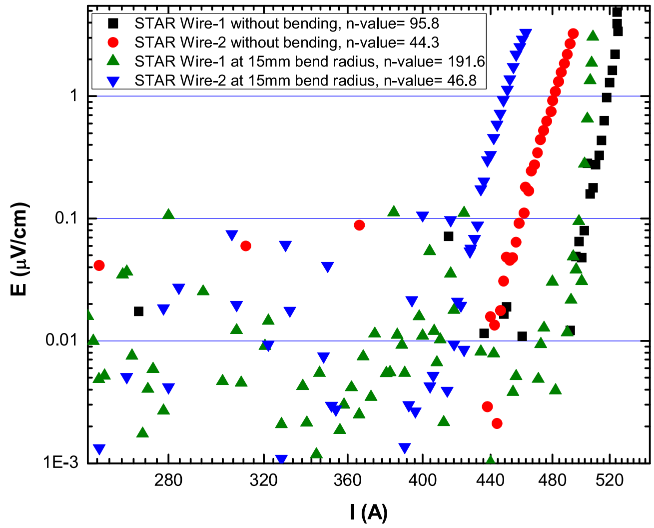


Figure 4. *E–I* plots of REBCO STAR wires without bending and at 15 mm bend radius in 77 K, self-field.

Figure 4 exhibits the *E–I* characteristics of the two STAR wires at 15 mm bend radius and the critical current values are displayed in table 3. It is seen that the STAR Wire-1 retained nearly 98% of its I_c in a bent state yielding I_c and J_e of 506 A and 188 A mm^{-2} respectively and the STAR Wire-2 retained 93% of its I_c in a bent state yielding I_c and J_e of 448 A and 207 A mm^{-2} respectively. Such high values of I_c retention even when bent to a small radius of 15 mm are likely due to the symmetric tape architecture used to construct the STAR wires.

Figure 5 shows the J_e of STAR Wire-1 at 4.2 K. At the 15 mm bend radius, it is observed that STAR Wire-1 exhibits J_e values of 376 A mm^{-2} at 4.2 K, 10 T and 293 A mm^{-2} at 4.2 K, 15 T. A magnetic field dependence of H^{α} where $\alpha = -0.56$ is observed for field values above 4 T. Based on this scaling, a J_e of about 253 A mm^{-2} at 20 T is extrapolated. STAR Wire-1 was measured five times at 4.2 K, 15 T. The J_e was found to be 329 A mm^{-2} in the first measurement and then drop to about 293 A mm^{-2} in the subsequent four measurements. The initial drop in the J_e value could be due to the movement of individual tapes under high Lorentz forces. To prevent the tape movement, solder flux was applied to STAR Wire-2 before the 4.2 K test.

Figure 6 shows the magnetic field dependence of J_e of STAR Wire-2 at 4.2 K. At 15 mm bend radius, STAR Wire-2 exhibits J_e values of 613 A mm^{-2} at 4.2 K, 10 T and 454 A mm^{-2} at 4.2 K, 15 T respectively. No degradation in the transport performance was observed during the multiple tests at the same field. These values of J_e are the highest reported values so far for any round REBCO wire. STAR Wire-2 shows a magnetic field dependence of J_e of H^{α} where $\alpha = -0.69$ for magnetic fields above 5 T. Based on this scaling, a J_e of about 375 A mm^{-2} at 20 T is extrapolated. Such high J_e values for a round REBCO wire are likely because of the excellent tolerance of the symmetric tape geometry that imposes less strain on the REBCO film. It is observed that STAR Wire-2 exhibits 55% higher J_e than

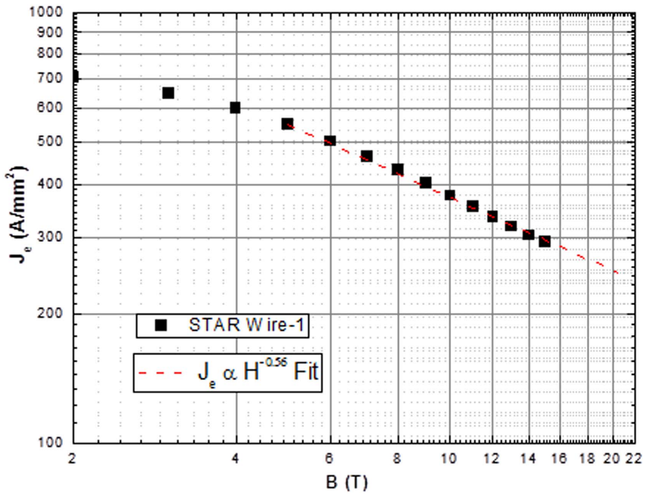


Figure 5. Magnetic field dependence of J_e of the REBCO STAR Wire-1 at 4.2 K. The dashed line is a power-law fit to the data above 4 T, with an exponent of −0.56. The filled dot is the extrapolated J_e at 20 T. Self-field of the wire is not considered.

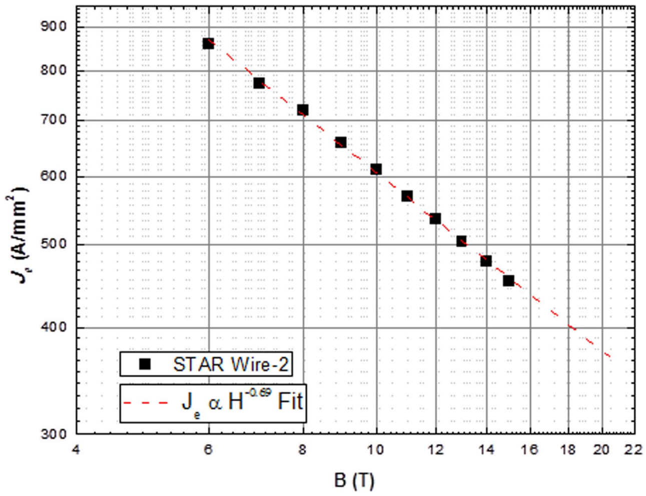


Figure 6. Magnetic field dependence of J_e of the REBCO STAR Wire-2 at 4.2 K. The dashed line is a power-law fit to the data above 5 T, with an exponent of −0.69. The red line is the extrapolated J_e at 20 T. Self-field of the wire is not considered.

Table 3. I_c and J_e values at 77 K, self-field for the REBCO STAR wires tested in a straight form and at a 15 mm bend radius.

REBCO STAR wire	I_c (A) in straight form	J_e (A mm^{-2}) in straight form	I_c (A) at 15 mm bend radius	J_e (A mm^{-2}) at 15 mm bend radius	Retention of I_c (%) at 15 mm bend radius
1	518	193	506	188	97.7
2	482	223	448	207	93.0

STAR Wire-1 at 15 T, 4.2 K because of 24% higher I_c and 20% smaller cross section.

Conclusions

We have fabricated REBCO round wires of 1.66–1.85 mm final diameter using six tapes 2.5 mm in width, helically wound on a 1.02 mm copper core (18 AWG). These tapes are only about 25 μm in thickness before copper plating and have additional 20–25 μm thick copper layer on REBCO side and a 3 μm thick copper layer on substrate side. This symmetric arrangement of the metallic content in the tape strategically positions the REBCO film near the geometric center. Such STAR wires exhibit exemplary performance at small bend radius of 15 mm. Two REBCO STAR wires show critical current retention of 93% and 97.7% when bent to 15 mm radius from a straight form. At this bend radius of 15 mm, the 1.85 mm diameter and 1.66 mm diameter REBCO STAR wires exhibit J_e of 293 and 454 A mm^{-2} at 4.2 K, 15 T which is the highest performance of any REBCO round wire reported so far. Given the remarkably high engineering current density of REBCO coated conductors in high magnetic fields at 4.2 K, REBCO STAR wires of ultra-small diameters (∼1–2 mm) show great promise for the development of high-field compact REBCO accelerator magnets operating in fields above 20 T.

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