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Letter

Superior critical current of Symmetric Tape Round (STAR) REBCO wires in ultra-high background fields up to 31.2T

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Abstract

Symmetric Tape Round (STAR) wire fabricated with an ultra-thin RE–Ba–Cu–O (REBCO, RE = rare earth) coated conductor has a high engineering current density (J_e) and remarkable flexibility. It is a competitive candidate for future canted cosine theta magnets with smaller winding radii that operate at fields above 20 T at 4.2 K. STAR wires consisting of six or eight REBCO coated conductor layers have been fabricated with an outer diameter smaller than 2 mm. We performed in-field tests of the critical current of STAR wires at 4.2 K in background fields up to 31.2 T. At a 15 mm bending radius, J_e values of 438 A mm^{-2} at 20 T and 299 A mm^{-2} at 31.2 T were obtained. These are the highest J_e values measured in any reported round-geometry REBCO wires at such ultra-high background magnetic fields. This exhibits the potential of STAR wires in future compact accelerator magnets.

Keywords: symmetric tape, round wire, REBCO, 4.2 K, accelerator, magnet, engineering current density

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

Introduction

Superconducting magnets using low temperature superconductors such as Nb_3Sn are generally limited to magnetic fields not exceeding 20 T [1]. For applications that require operation at higher magnetic fields or at a temperature above 4.2 K, high temperature superconductor (HTS) magnets are essential [2, 3]. Applications that can benefit from high-field HTS magnets include high energy physics [4], superconducting magnetic energy storage [5], nuclear fusion [6] and other science and research projects.

For HTS magnets, the primary choices include $Bi_2Sr_2Ca_2Cu_3O_{10+x}$ (Bi-2223) tape, $Bi_2Sr_2CaCu_2O_8$ (Bi-2212) wire and REBCO coated conductors. The fragility of Bi-2223 tape makes it difficult to be reformatted to an isotropic multi-strand cable or directly used in magnets of a complex shape. Using Bi-2212 wire in large magnets is a challenge because of the required wind-and-react process. In particular, it is difficult to precisely control the temperature during reaction of large Bi-2212 coils [7]. In contrast, REBCO coated conductors are an attractive candidate for high-field magnets because of their exceptional mechanical strength and feasibility to wind coils of fully-processed conductors. Recently, substantial progress has been made in enhanced pinning of REBCO coated conductors for high-field performance at 4.2 K [8, 9]. A superconducting 32 T user magnet with REBCO high-field coils has been constructed at the National High Magnetic Field Laboratory (NHMFL) [10].

Drawbacks of REBCO coated conductors for magnets are their planar tape geometry and high aspect ratio. In the past few years, REBCO tapes have been reformatted to cable and wire forms such as Roebel cables, twisted stacked tape, Cross Conductor (CroCo) cables, Conductor on Round Core (CORC®) wire and Symmetric Tape Round (STAR) wire. Twisted stacked tape, which consists of multiple twisted REBCO coated conductors in a rectangular configuration, exhibits a J_e around 280 A mm^{-2} at 4.2 K in 16 T field [11]. CroCo cables are also twisted stacked tape conductors with a modified rectangular cross-section. A J_e of 482 A mm^{-2} at 4.2 K and 12 T has been achieved in CroCo conductors in a straight form [12]. Roebel cables consist of multiple punched strands of REBCO coated conductors with a fully transposed pattern. A J_e of approximately 400 A mm^{-2} has been demonstrated at 4.2 K in a 10 T field [13]. However, the rectangular cross-section structure means these three cable forms are not flexible enough in the hard-bending direction, which poses difficulties for magnet design. REBCO wires of a circular cross-section are mechanically isotropic and are based on the excellent tolerance of REBCO tapes to torsional strain that was first demonstrated in 2005 by the spiral winding of narrow tapes to small twist pitch lengths [14]. Round REBCO wires using flat tapes were first demonstrated by wrapping these tapes on a round core [15]. Since then, HTS cables and wires with round cross-sections have been developed, like CORC® cables/wires and STAR wires which are fully transposed, and isotropic in all bending directions. CORC® cables have exhibited a J_e of 412 A mm^{-2} at 4.2 K in a 10.5 T field, at a bending diameter of 60 mm [16].

One of the main target applications of STAR wire is in canted cosine theta (CCT) coils for compact accelerator magnets [17]. The insert coil requires a compact design to fit into the bore of surrounding magnets. This requires a high J_e at small bending radius. It was pointed out that minimum required J_e is 540 A mm^{-2} at 21 T and 4.2 K, at a bending radius of 15 mm [17].

We previously reported STAR wires with overall diameters of 1.6–1.9 mm with excellent electromechanical performances [18, 19]. Also, STAR wires with a J_e of 454 A mm^{-2} at 4.2 K in a 15 T field at a bend radius of 15 mm were recently reported [20]. Such a superior performance at such a small bend radius makes STAR wires a competitive candidate for CCT coils. In this article, we report results from five STAR wires made with different structures tested at 4.2 K in a background magnetic field up to 31.2 T.

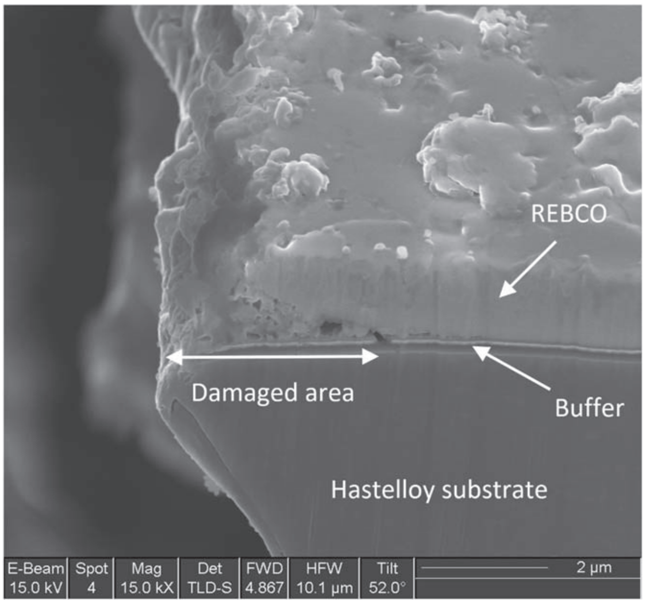

Figure 1. SEM image of the edge of a laser slitted sample.

Experiment

Tape structure

All superconducting tapes used in this work were ultra-thin GdYBCO tapes fabricated at the University of Houston. The tapes consist of a 20–22 μm thick Hastelloy substrate, a 0.2 μm thick ceramic buffer layer and a 1.6 μm thick REBCO layer. The GdYBCO film with 7.5% Zr was deposited by metal–organic chemical vapor deposition on biaxially-textured $LaMnO_3$ on MgO that was grown by ion beam assisted deposition. The nominal critical currents (I_c) of 12 mm wide tape were 490 A at 77 K, self-field and 849 A at 4.2 K, 15 T. The T_c of the tapes was ≈90 K. The original 12 mm wide tape was laser slitted to 2.5 mm in width to utilize copper formers of a small size (about 1 mm in diameter) [17]. Laser parameters were precisely controlled to minimize the extent of damage to the tape. Figure 1 is a scanning electron microscope (SEM) image of the edge of a laser slitted tape. Only a 2–3 μm wide REBCO layer was damaged due to a large thermal gradient. A silver layer was sputtered all around the slitted tape to cover the exposed edges and prevent layer delamination during the cable winding process. The sputtered silver was about 2 μm thick on the REBCO side and 1 μm thick on the substrate side. Afterwards, copper 20–25 μm thick was electroplated on the REBCO side with 2 μm thick copper on the substrate side. This design of the copper stabilizer thickness yields a symmetric tape structure that shifts the REBCO layer closer to the neutral plane. Consequently, the REBCO layer endures much less bending strain when the tape is wound on small-diameter formers compared to a normal REBCO coated conductor [18].

STAR wire construction

Solid oxygen-free high-conductivity copper wire with a diameter of 1.02 mm (18 on the American wire gauge (AWG))

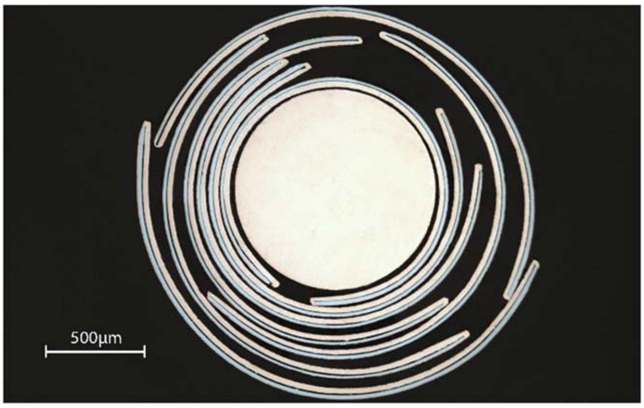

Figure 2. Cross-section view of STAR wire 3. Adapted from [20].

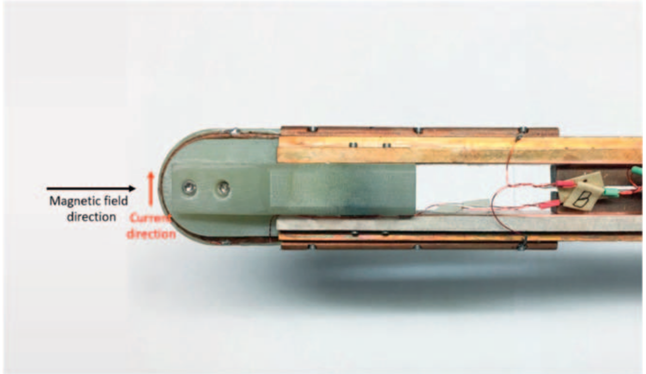

Figure 3. STAR wire mounted on G10 support at a bend radius of 15 mm. The Lorentz force during high magnetic field tests was in the direction pushing the wire against the support.

Table 1. Specifications of STAR wires fabricated and tested in this work.

	Former diameter	Total outer diameter (mm)	Number of layers	Tape width (mm)	Wrap angle (°)	Filled with indium
STAR wire 1		1.69	6			No
STAR wire 2		1.68	6			No
STAR wire 3	AWG 18 (1.02 mm)	1.89	8	2.5	45	No
STAR wire 4		1.96	8			Yes
STAR wire 5		1.97	8			Yes

was selected as the STAR wire former. This size of former provides both axial mechanical strength and transversal flexibility. A custom-made winding machine was used to fabricate round wires. A copper wire former under tension is passed through the center of winding machine at a constant speed. REBCO tapes spooled in winding arms are helically wound around the copper former. By adjusting the ratio of wire former feed rate to winding arm speed, twist pitch and gap between each turn of tape can be precisely controlled. STAR wires 1 and 2 consisted of six layers of HTS tape and STAR wires 3 to 5 consisted of eight layers of HTS tape. In each layer of the wire, one 2.5 mm wide tape was wound with the thicker copper layer facing inward. The winding angle of all tapes was maintained near 45° to minimize the I_c degradation because of the bending strain effect [21]. HTS tape 1.41 m long was needed to wind one layer of 1 m long STAR wire. In each layer, winding of tapes of a fixed width resulted in a gradually increasing gap between each turn with an increasing number of layers. These gaps allowed the tapes to slide when the STAR wire was bent to a small bending radius and prevent excessive strain on the tapes. STAR wires 4 and 5 were filled with indium after bending. The exposed wire between terminals was dipped in molten indium at 169 °C for a short time. Indium filled up gaps and gave outer layers better support under a large Lorentz force. Figure 2 exhibits a cross-section micrograph of STAR wire 3 with eight layers. Table 1 summarizes the specifications of the five STAR wires. In this table, the total outer diameter was measured at the outermost layer of the STAR wire. The diameters of STAR wires 1 and 2 with six layers were 1.68 mm and 1.69 mm respectively and the diameters of STAR wires 3 to 5 with eight layers were 1.89 mm, 1.96 mm and 1.97 mm respectively. The slightly larger diameters of STAR wires 4 and 5 were due to a thin layer of indium on the surface of eighth layer.

Test method

Critical currents of the STAR wire were tested first in a straight form at 77 K, self-field. Afterwards, the wires were bent into a semicircle with a 15 mm radius on a G10 support, as shown in figure 3. The critical currents in a bent form were obtained at 77 K self-field and at 4.2 K in high magnetic fields. The wire length between two copper terminals was 9 cm. Voltage taps, 7 cm apart from each other, were soldered on the outmost layer of the wire. Voltage wires were twisted in pairs and located along the STAR wire to minimize noise. The 4.2 K in-field performance was tested in a 31.2 T solenoid magnet at NHMFL. The central part of the STAR wire was positioned at the center of the magnet coil. The field was perpendicular to the wire and current direction and was arranged such that the resulting Lorentz force pressed the wire against the G10 support, as shown in figure 3. Wax was applied around the STAR wire to prevent movement at high current.

Results and discussion

STAR wire performance in liquid nitrogen

Figure 4 shows the electric field versus current (E–I) characteristics of STAR wires, in both straight and bent forms at

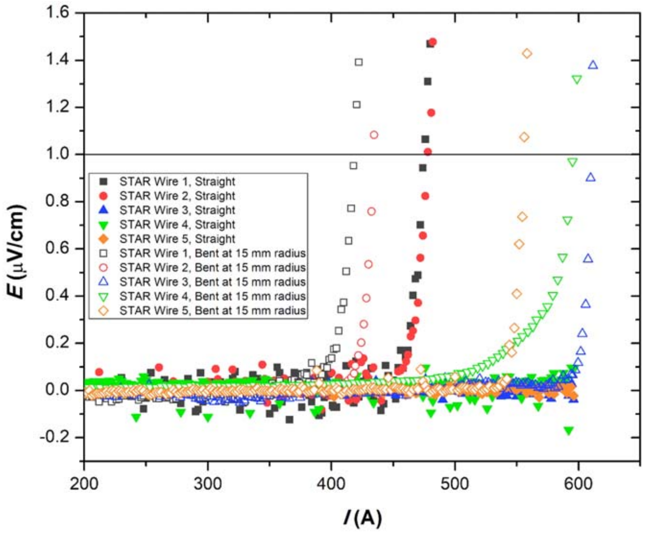

Figure 4. *E–I* plots of STAR wires in both straight form and bent to a 15 mm radius, at 77 K, self-field. The solid line indicates the 1 μV cm^{-1} criterion.

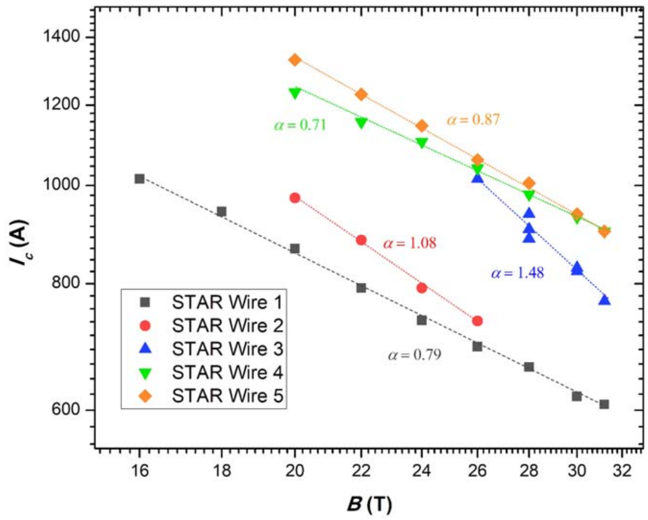

Figure 5. Magnetic field dependence of I_c of STAR wires between 16–31.2 T, at 4.2 K. The dashed lines show fits to the power law. For STAR wire 3, data points used for fitting include multiple tests at same field. A 0.5 μV cm^{-1} criterion was used in all cases.

77 K, self-field. A 1 μV cm^{-1} criterion was used to determine the critical currents. In a straight form, the I_c of STAR wires 1 and 2 were 476 A and 478 A, and the corresponding J_e were 212 A mm^{-2} and 216 A mm^{-2}. After bending to a 15 mm radius, the I_c of STAR wires 1 and 2 became 419 A and 435 A, with corresponding J_e of 187 A mm^{-2} and 196 A mm^{-2}. The slight difference in I_c after bending was possibly because of thickness variation of the tape used to make STAR wires 1 and 2. These results correspond to a critical current retention of 88% and 91% for STAR wires 1 and 2 respectively after bending to a 15 mm radius. As a reference, the allowable bending radius of STAR wires with no degradation in I_c was found to be >25 mm [19]. The symmetric structure of tape used in the STAR wires along with the freedom of the tapes to slide along the gaps resulted in the high I_c retention rate even at a very small bending radius. For STAR wires 3 to 5, because of the current source limitation, a transition could not be reached in straight form. I_c values of 611 A, 595 A and 556 A were measured at a 15 mm bending radius. The corresponding J_e were 218 A mm^{-2}, 197 A mm^{-2} and 182 A mm^{-2}. Because of the slightly larger diameters of the indium-filled structures, STAR wires 4 and 5 yielded relatively lower values of J_e.

STAR wire performance at 4.2 K background magnetic fields

The five STAR wires at a 15 mm bending radius were tested in liquid helium at NHMFL. The applied magnetic field ranged from 14–31.2 T. In fields higher than 18 T, helium bubbles usually form around the sample and are trapped because of the magnetic force. These bubbles obstruct good thermal contact between the sample and liquid helium. Therefore, the magnetic field was ramped down to lower fields than 18 T between each test to release the bubbles. The current ramping rate was 17 A s^{-1}. Pulse current mode was used for all wires at high magnetic fields except for STAR wire 1. In this mode, currents higher than a threshold were not ramped up continuously. Instead, the current was pulsed up to a desired high value, which was increased gradually in each cycle, and then decreased at a lower value between each pulse. This mode allowed the sample to cool thoroughly and prevented overheating. The voltage criterion used to determine critical current in all 4.2 K measurements was 0.5 μV cm^{-1}.

Figure 5 shows the magnetic field dependence of I_c of the five STAR wires between 16–31.2 T. A linear fit of each sample's data is drawn as a dashed line. The relationship can be described by a power-law function as shown in equation (1),

$$I_c(B) = I_c(0)B^{-\alpha}, \tag{1}$$

where B is the magnetic field and α is a power-law coefficient. Due to power source limitation, currents were limited to 1050 A for STAR wires 1 to 3, and 1350 A for STAR wires 4 and 5. For STAR wire 1, the superconducting transition was not reached at magnetic fields lower than 16 T. Its critical currents were 608 A with a corresponding J_e of 271 A mm^{-2} at 31.2 T, and 1015 A with a corresponding J_e of 452 A mm^{-2} at 16 T. $\alpha = 0.79$ was calculated based on the power-law fit. For STAR wire 2, I_c data was measured between 20–26 T. After several repeated measurements at 26 T in pulse current mode, degradation was observed. Measurement at higher fields was abandoned to prevent further damage. At 20 T, its critical current of 972 A corresponds to a J_e of 438 A mm^{-2}. A I_c of 735 A and J_e of 332 A mm^{-2} were measured at 26 T. The α value of power-law fit was 1.08. For STAR wire 3, because of its eight-layered structure, the transition to normal state could be reached only above 26 T. At 28 T and 30 T, measurements were repeated several times in pulse current mode. After three measurements at 28 T, the I_c dropped from 937 A to 886 A, about a 6% decrease. At 30 T, I_c dropped less than 1% after two tests. Due to the multiple degradations observed, the power-law did not fit well for the data of STAR

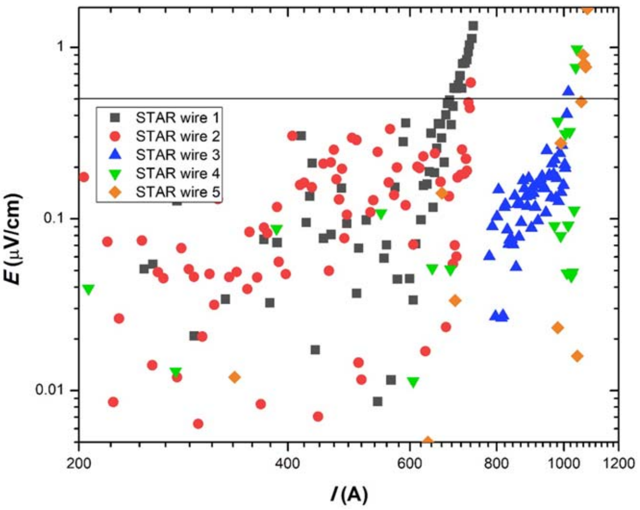

Figure 6. E–I curves of STAR wires at 26 T, 4.2 K. The solid line indicates the 0.5 μV cm^{-1} criterion.

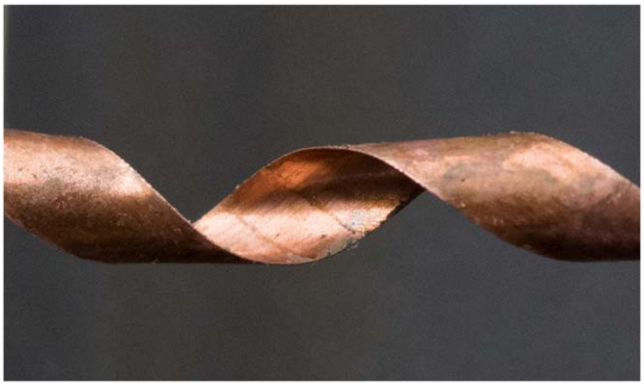

Figure 7. The unwound eighth layer of STAR wire 3 after a 4.2 K in-field test. Imprints can be seen on the inner surface of the tape.

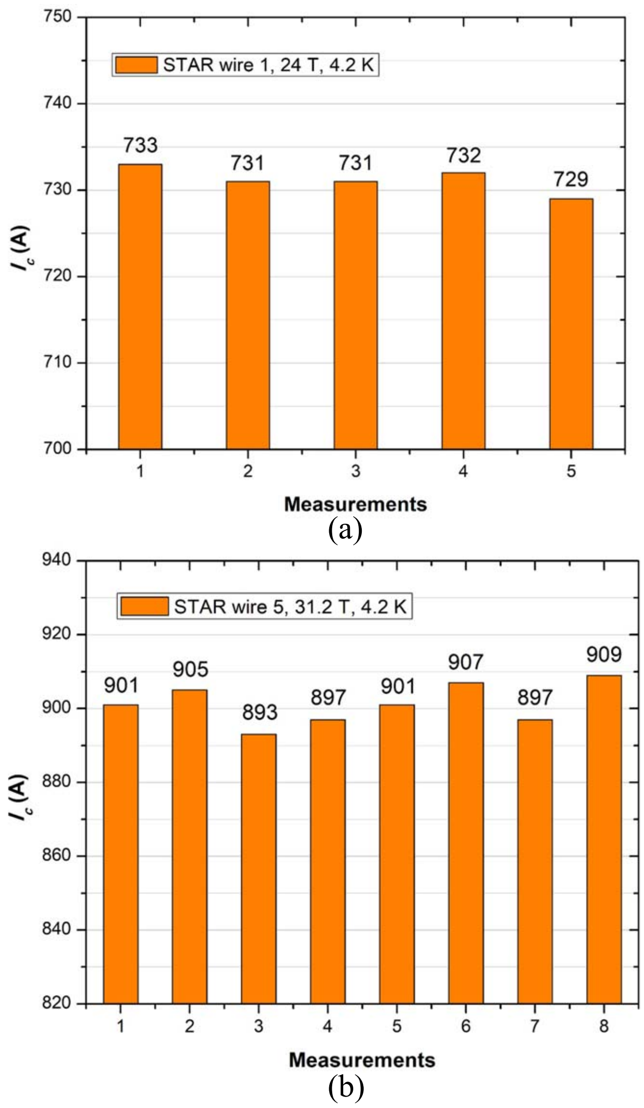

Figure 8 (a) Repeatability test of STAR wire 1 at 4.2 K, 24 T. Data of measurement 1 was taken from the I_c–B curve as a reference. (b) Repeatability test of STAR wire 5 at 4.2 K, 31.2 T. Data of measurement 1 was taken from the I_c–B curve as a reference.

wire 3. Taking all data points into account, an α value of 1.48 was calculated. At 31.2 T, its I_c was 769 A and J_e was 274 A mm^{-2}. At 26 T, its I_c was 1015 A and J_e was 362 A mm^{-2}.

STAR wires 4 and 5 had same eight-layered structure. They were filled with indium and tested with a power supply with a higher current. I_c values were reached from 20–31.2 T. At 31.2 T, both STAR wires 4 and 5 reached a I_c of 901 A, with corresponding J_e values of 299 A mm^{-2} and 296 A mm^{-2}. At 20 T, STAR wire 4 exhibited a I_c of 1236 A with a J_e of 410 A mm^{-2} and STAR wire 5 sustained a slightly higher I_c of 1330 A with a J_e of 436 A mm^{-2}. The α values for STAR wires 4 and 5 were 0.72 and 0.84. These in-field results showed a great improvement towards the required J_e for CCT coils. J_e values of STAR wires have reached about 78% of target J_e of 540 A mm^{-2} at 21 T, 4.2 K at 15 mm bending radius. Figure 6 shows the E–I curves at 26 T, the field at which the transition of all STAR wires were reached. The n-values for STAR wires 1 to 5 were 14.4, 20.9, 31.6, 69.3 and 42.7, respectively.

α values of five STAR wires ranged from 0.71–1.48. This value can be used to estimate I_c at different fields by extrapolation. As an example, at 10 T, STAR wire 5 is predicted to have I_c values of 2489 A, with corresponding J_e of 817 A mm^{-2}. The large α values of STAR wires 2 and 3 indicated their degradation at high fields, which have been discussed. Compared to REBCO tape which is used to fabricate STAR wire, the α values of STAR wires 1, 2 and 5 are close to the tape α value of 0.76. The slight difference could be caused by a different α value along the tape length, or a change in field dependence of the critical current under extreme bending strain. As a reference, the α value of CORC® cables is 0.72 between 11–17 T [22].

The degradation in multiple tests of STAR wire 2 and STAR wire 3 may be due to a decrease in support of the outer layers of the wire stemming from the increased gap. Since tapes with a fixed width of 2.5 mm were used for all layers, the gap between each turn increased as the number of layers increased. While the gradually increasing gap allows tape slide during bending which can relieve the extra stress, it results in decreased support from the inner layer to the outer layer. In a high-field–high-current scenario, such as that experienced by the STAR wires in this work, the Lorentz force might be large enough to press the outer layer inward and leave an imprint on the tape. A typical value of Lorentz force experienced by a single layer is about 30 N cm^{-1} in a 30 T field. STAR wire 3 was unwound after an in-field test to examine for any tape damage. Figure 7 reveals the imprint found on the eighth layer, which was likely caused by the high Lorentz force. This issue can be solved by adding supporting material, like indium in STAR wire 4 and 5, to the increasing gaps. With better support, STAR wires can sustain a large Lorentz force and carry a higher current without degradation. This benefit is also proved by the higher n-values of STAR wires 4 and 5. Another possible reason for degradation is the use of a pulse current mode. Unlike a steady current ramping process, a pulse current mode applies a rapidly-changing Lorentz force to tapes. Such a repeated high impulse force can also cause tape fatigue and degradation.

Additionally, repeatability tests were performed on STAR wire 1 and STAR wire 5. STAR wire 1 reached its critical current four times at 24 T and STAR wire 5 reached its critical current seven times at 31.2 T. The results are shown in figure 8, where the first measurement data was taken from the I_c–B curve in figure 5 as a comparison. After all tests, the critical current values of STAR wires 1 and 5 were 729 A and 909 A, which were within 1% of the original values.

Conclusion

We fabricated five STAR wires with a symmetric structure REBCO tape. Two STAR wires had six layers of tape (STAR wires 1 and 2) and three STAR wires had eight layers (STAR wires 3 to 5). They were tested at 15 mm bending radius in background fields as high as 31.2 T, at 4.2 K. From the straight form to the bending form of 15 mm radius, the two six-layer wires retained 88% and 91% of critical current at 77 K. At 4.2 K, 20 T, STAR wires 2 and 5 exhibited J_e of 438 A mm^{-2} and 436 A mm^{-2} respectively. At the highest field of 31.2 T, STAR wires 4 and 5 exhibited J_e of 299 A mm^{-2} and 296 A mm^{-2} respectively. This is the highest measured engineering current density of any reported REBCO wire with a round format, at these high magnetic fields. Repeatability tests of STAR wires 1 and 5 showed less than 1% I_c degradation after repeated tests at 24 T and 31.2 T. The results exhibit the potential and feasibility of using REBCO STAR wires in ultra-high background magnetic field applications at 4.2 K.

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