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LETTER

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Letter

Next-generation highly flexible round REBCO STAR wires with over 580 A mm^{-2} at 4.2 K, 20 T for future compact magnets

Soumen Kar[1,2], Jithin Sai Sandra[1], Wenbo Luo[2], Mehdi Kochat[2], Jan Jaroszynski[3], Dmytro Abraimov[3], Goran Majkic[2] and Venkat Selvamanickam[2]

[1] AMPeers LLC, Energy Research Park, University of Houston, Houston, TX 77023, United States of America

[2] Department of Mechanical Engineering, Advanced Manufacturing Institute, Texas Center for Superconductivity, University of Houston, Houston, TX 77204, United States of America

[3] Applied Superconductivity Center, National High Magnetic Field Laboratory, Florida State University, Tallahassee, FL 32310, United States of America

E-mail: skar2@uh.edu

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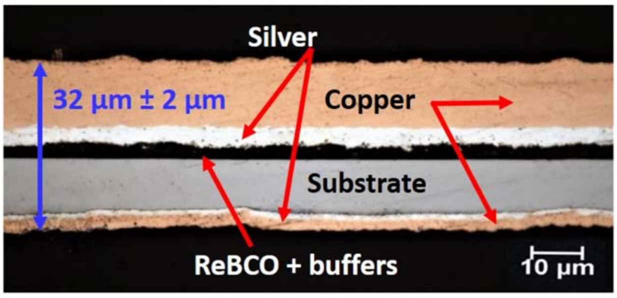
Abstract

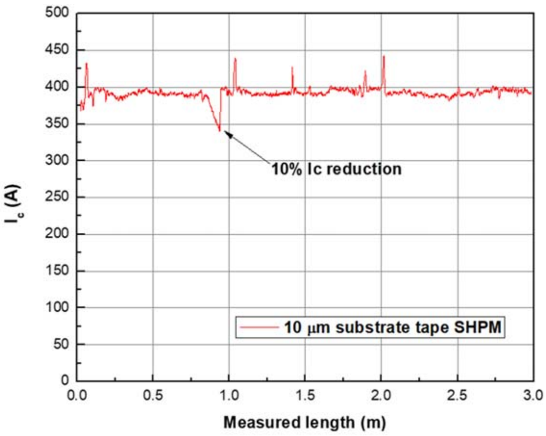
We report the latest developments of next-generation flexible round RE–Ba–Cu–O (REBCO, RE = rare earth) wire, driven by the needs of compact accelerator magnets requiring round isotropic wire with an engineering current density (J_e) of 600 A mm^{-2} at 4.2 K, 20 T at a bend radius of 15 mm. We have developed a Symmetric Tape Round (STAR) REBCO wire using multiple layers of REBCO tapes specifically developed for this architecture, featuring a mechanically symmetric geometry with a 10–18 μm thick substrate wherein the superconductor film is positioned near the tape's neutral plane for superior bend strain tolerance. Furthermore, each layer of REBCO tape is individually optimized for maximum bend strain tolerance. These ultra-thin substrate REBCO symmetric tapes enabled us to fabricate next-generation isotropic round wires of just 1.3 mm diameter and a critical current equivalent to commercial 12 mm wide REBCO tapes. The in-field performance of STAR wires of several configurations has been tested at National High Magnetic Field Laboratory to identify the most suitable architecture to meet the needs of high-field compact accelerators. At a bend radius of 15 mm, a six-layer STAR wire exhibits critical current of 778 A at 4.2 K in 20 T background field, which equals J_e of 586.4 A mm^{-2} at a Lorentz force (F_L) of 15.5 kN m^{-1} which is the highest reported J_e value for REBCO wire in round geometry at this magnetic field. Similarly, a 12-layer STAR wire shows an I_c of 1156 A at 31.2 T, 4.2 K which corresponds to a Lorentz force of 36 kN m^{-1}. Multiple tests of STAR wires at high magnetic field confirm a <0.1% variation in measured I_c. This level of reproducibility of the high performance of STAR wire in high magnetic fields at 4.2 K and small bend radius underscores the potential of STAR REBCO wire for use in compact accelerator magnet and related applications.

Keywords: REBCO, round wire, high magnetic field, engineering current density, Lorentz force, symmetric tape

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



(a)



(b)

Figure 1. (a) Cross-section of symmetric REBCO tape with 10 μm Hastelloy substrate, (b) I_c distribution over 3 m long, 12 mm wide, 10 μm substrate REBCO tape before Cu plating.

Introduction

Utilizing REBCO coated conductors in high-field applications above 20 T started in the mid-2000s [1]. Since then, many demonstrations of high-field HTS magnets have been made [2, 3]. Currently, magnets utilizing REBCO are under development worldwide in high magnetic field laboratories [4, 5]. Compared to the Bi-2212 wire and the Bi-2223 tape, the REBCO coated conductor is attractive because of its superior mechanical strength and improved in-field performance as a result of recent achievements in improved flux pinning [6, 7]. To accommodate magnets that need small bending radii and high J_e, such as the canted cosine theta (CCT) magnet [8], reshaping REBCO tapes into a flexible, isotropic and round wire appears to be the most viable option.

In recent years, several concepts of REBCO cable and wire have been developed, such as Twisted Stacked tape [9], ROEBEL cable [10], Symmetric Tape Round (STAR) wire [11, 12] and Conductor on Round Core (CORC®) wire [13]. It is worth noting that STAR wire differs from Stacked Tapes Assembled in Rigid Structure (STARS) conductor [14], where STAR wire is a small-size, ultra-flexible REBCO wire wound on a round former whereas the STARS conductor is a mechanically rigid REBCO conductor that has high cryogenic stability.

Cables with rectangular cross-section like ROEBEL and Twisted Stacked tape are not uniformly flexible in all bending directions. This drawback makes these cables suitable only for magnets of certain shape. In contrast, wires of round cross-section are based on spiral winding of flat REBCO tapes and wrapping of REBCO tapes on a round core, both first demonstrated in 2005 [15, 16]. This structure is naturally isotropic and takes advantage of REBCO tape's mechanical strength. Therefore, round cross-section REBCO wires should achieve the same bending and in-field performance in every direction. On the other hand, the fill factor of the round wire is lower than that of cables with rectangular or square cross-sections because of the use of a cylindrical former.

For CCT coils, at a bending radius of 15 mm, wires that have a J_e of 540 A mm^{-2} at 21 T, 4.2 K are needed [8], which necessitates improvement of J_e and minimum bending radius. In 2018, STAR wire's excellent in-field performance with a J_e of 454 A mm^{-2} at 4.2 K, 15 T and 438 A mm^{-2} at 4.2 K, 20 T was reported [17, 18]. In this paper, we report on progress in development of next-generation highly flexible STAR wire of much smaller diameter towards meeting the above-mentioned requirements, in particular critical current (I_c) performance at 77 K, self-field and 4.2 K in magnetic fields up to 31.2 T in both straight and 15 mm bend radius configurations. The repeatability of performance after the wires have undergone cycling of the large Lorentz force in operation is discussed as well. Finally, the progress of STAR wire development over the last year is presented and summarized.

Tape preparation

AMPeers and its research institution partner University of Houston jointly developed an innovative approach to fabricate ultra-thin substrate REBCO tapes with a symmetric structure which shifts the neutral plane close to REBCO layer [17]. The 22 μm thick Hastelloy substrate symmetric REBCO tape architecture along with the specifications of the STAR wires using 1.02 mm (18 American Wire Gauge (AWG)) copper former have been reported in our previous publications [17, 18]. In order to maximize J_e and further reduce the former diameter, STAR wires with symmetric REBCO tapes of total thickness $\leqslant$50 μm, wound on AWG 20 and 22 copper formers (0.81 and 0.51 mm diameter, respectively) are needed. For this purpose, 12 mm wide REBCO tapes with 10–18 μm Hastelloy substrates were developed in-house.

In order to utilize smaller copper formers, the original 12 mm wide ultra-thin substrate REBCO tapes were laser slit to 1.4–2.6 mm widths. Hereafter, silver layers of 2–3 μm thickness on the REBCO side and 1 μm on the substrate side were deposited by reel-to-reel magnetron sputtering to facilitate electrodeposition of copper stabilizer. Appropriate shielding was employed in the reel-to-reel copper electroplating tool to minimize the dog-boning electroplating effect on the tapes [19]. We have developed optimal shields to deposit copper stabilizer primarily on the REBCO film side so as to position the superconductor film near the neutral plane. Since the yield strength of the copper stabilizer is substantially lower than of the Hastelloy substrate even after severe cold-working during winding on small diameter formers, the neutral plane shifts in position during the plastic deformation experienced during winding. In addition, the yield strength of Hastelloy can also be exceeded at very small bending radii, further contributing to the shift. We recently reported a result from an elasto-plastic model on shifting of the neutral plane with applied strain in tapes used in our STAR wires [20]. The model takes into account the plastic deformation of metallic layers, which is crucial for accurate representation of the stress states in the wire. The thickness of the electroplated copper stabilizer is individually adjusted for *each* tape layer in order to minimize bending strain as a function of layer radius.

Taking in account information in [20], a cross-section of a 10 μm thick substrate tape is shown in figure 1(a) where the positioning of the REBCO layer near the neutral plane is evident. It should be noted that the neutral plane is generally not at the geometric center, both for reasons of different elastic moduli of individual layers within a tape, as well as due to the mentioned shift during plastic deformation experienced during winding to the target bending radius. As seen in figure 1(b), the critical current profile of a 3 m long, 12 mm wide, 10 μm substrate tape shows $\leqslant$10% reduction in I_c over the length. In our previous report, we observed that the thickness of the copper stabilizer has to be tailored to the substrate thickness to position the REBCO film near the neutral plane [12]. Our next-generation STAR wire is based on the findings from our full elasto-plastic model to determine the location of the neutral plane in the REBCO tape as a function of bending radius, i.e. former diameter and layer number [20].

Next-generation STAR wire fabrication

Four STAR wires with different configurations were fabricated using multiple layers of symmetric REBCO tape wound on oxygen-free high-conductivity copper wires as the formers. Both 0.81 and 0.51 mm (20 and 22 AWG, respectively) former diameters were used, in order to evaluate the feasibility of using smaller former diameter for a higher REBCO-to-copper ratio. In order to achieve this goal, the width and thickness of the symmetric tapes were varied in each layer in order to further optimize the mechanical properties, as illustrated in figure 2 for STAR wire #4 configuration. Tapes with thinner substrates and narrower widths were wound in the inner layers of the wire, while the tapes with 18 μm thick substrates and 2.6 mm widths were wound in the outer layers. This is a significant departure from the first-generation STAR wire where constant tape geometry was used in each layer [17, 18]. This new key feature of the next-generation STAR wire that has enabled significant improvements in electric and mechanical performance.

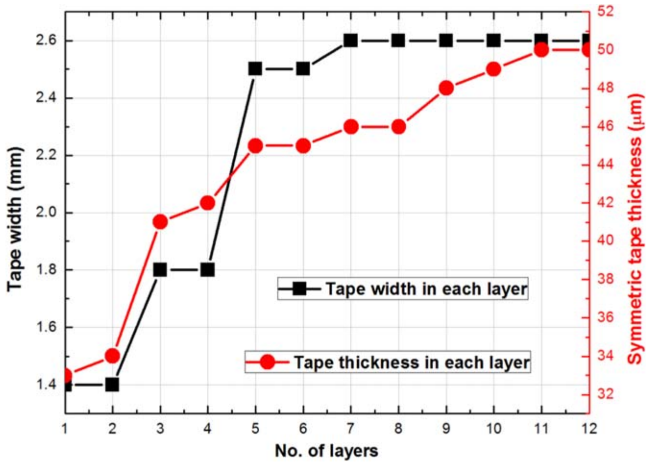


Figure 2. Width and thickness distribution of symmetric REBCO tapes used in REBCO STAR wire # 4.

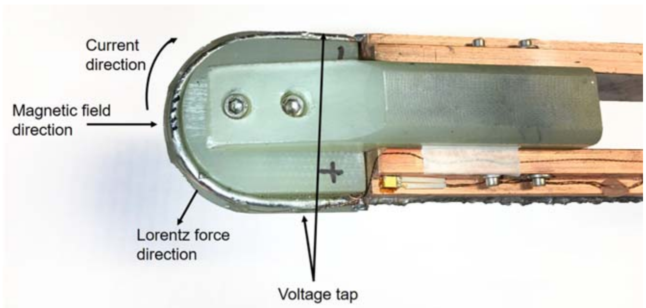


Figure 3. G-10 sample holder of 15 mm bend radius with soldered STAR wire # 4 mounted.

The specifications of the fabricated and tested STAR wires are listed in table 1. In addition to former diameter and tape geometry, the number of REBCO tape layers was varied as well. In particular, STAR wire #4 was wound with 12 instead of six layers, in order to evaluate the feasibility of employing a larger number of layers. All STAR wires were made with one tape in each layer except STAR wire #2, where the first eight layers were made with single tape per layer while the last ninth layer had two tapes of 2 mm width co-wound in parallel. All wires were fabricated using a custom-built winding machine built purposely for winding of STAR wires with high level of accuracy. The tapes were wound with the thicker copper stabilizer on REBCO side facing inward, with a wrap angle of 45°. The gap between turns was increased progressively with tape layer number, in order to increase the cooling efficiency and transversal flexibility of STAR wire, allowing them to be bent to a small radius. The downside is that increasing gap size reduces tape support, making outer layers more susceptible to deformation due to Lorentz force.

Experimental

The STAR wires were first measured in a straight form for I_c at 77 K, self-field. The wires were then bent into a 15 mm radius half circle using a G10 mount. The I_c values in the bent form

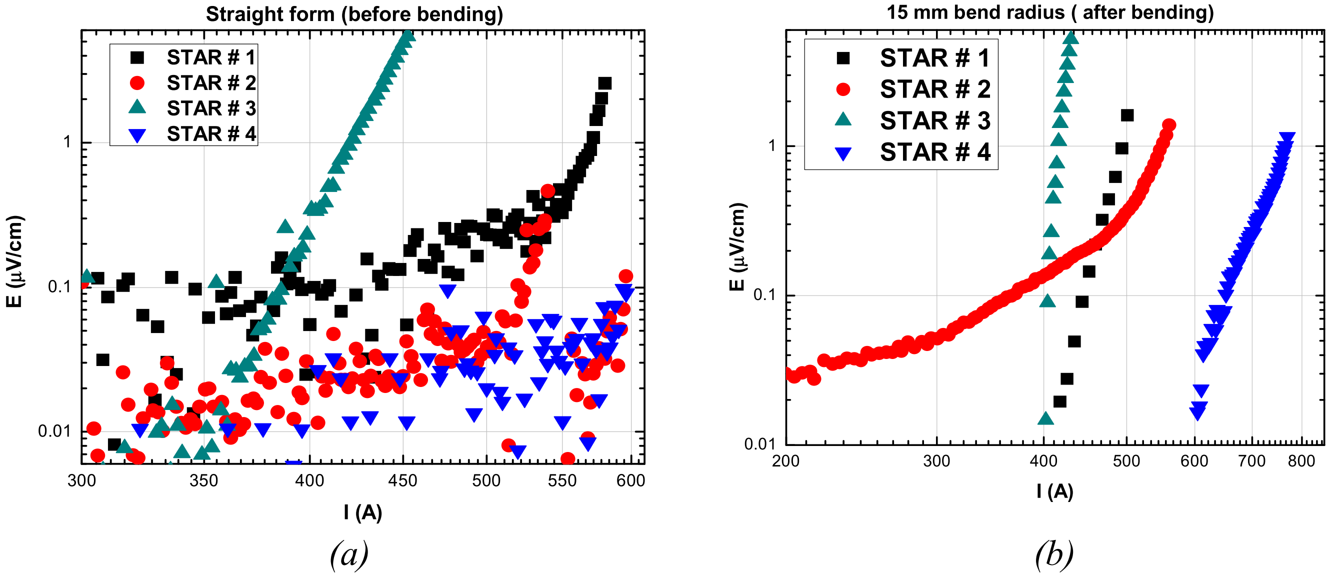


Figure 4. E–I characteristics of the REBCO STAR wires at 77 K, self-field, in (a) straight form, and (b) 15 mm bending radius.

Table 1. Specifications of STAR wire.

STAR #	Former material	Former diameter (AWG)	Tape width in each layer	Tape thickness	Total number of layers (tapes)	Total tape width	Final STAR wire diameter
1	OFHC Copper	0.81 mm (20)	2 mm × 2, 2.5 mm × 6	≈50 μm for each layer	8 (8)	19 mm	1.75 mm
2		0.81 mm (20)	2 mm × 2, 2.5 mm × 6, 2 mm × 2 (2 tapes in 9th layer)		8 (9)	23 mm	1.98 mm
3		0.51 mm (22)	1.4 mm × 2, 1.8 mm × 2, 2.5 mm × 2	Variable in all layers	6 (6)	11.4 mm	1.30 mm
4			1.4 mm × 2, 1.8 mm × 2, 2.5 mm × 2, 2.6 mm × 6		12 (12)	27 mm	2.04 mm

were obtained at both 77 K, self-field and 4.2 K in-field. Figure 3 shows the G-10 sample holder assembly with the STAR wire #4 installed for bend test after solder filling, with wire length of 9 cm between the two copper terminals and voltage taps at 7 cm distance. All 4.2 K tests were performed in a 31.2 T, 50 mm bore magnet at NHMFL. The magnetic field was perpendicular to the middle part of sample, which was positioned at the magnet center. The field distribution of the magnet ensured less than 3% variation of field strength along the bore axis in a range of ±10 mm. The current polarity was selected such that Lorentz force applied on the wire was against the G10 mount.

Results and discussion

Figures 4(a) and (b) show the E–I characteristics at 77 K, self-field of STAR wires in its straight form and at 15 mm bend radius, respectively. As the DC current source was limited to a maximum of 600 A, the transition (at 1 μV cm^{-1} criterion) is not observed for some of the STAR wires with ⩾8 layers. As the I_c of the symmetric tapes used for fabrication of STAR wires was in the range of 30–38 A mm^{-1}, the results reveal 90%–95% of I_c retention after the incorporation of the tapes into STAR wires. The measured I_c values (1 μV cm^{-1}) of the REBCO tapes and STAR wires in straight form and in 15 mm bend radius are summarized in table 2.

In the straight form, STAR wires #2 and #4 did not show a transition because of the current source limitation whereas STAR wires #1 and #3 showed an I_c of 571 and 422 A, respectively. The overall J_e values for the whole round wire are 237 and 318 A mm^{-2} for STAR wires #1 and #3, respectively, where the copper former reduces the J_e of the REBCO tapes approximately by only a factor of 1.3 due to the small former diameter.

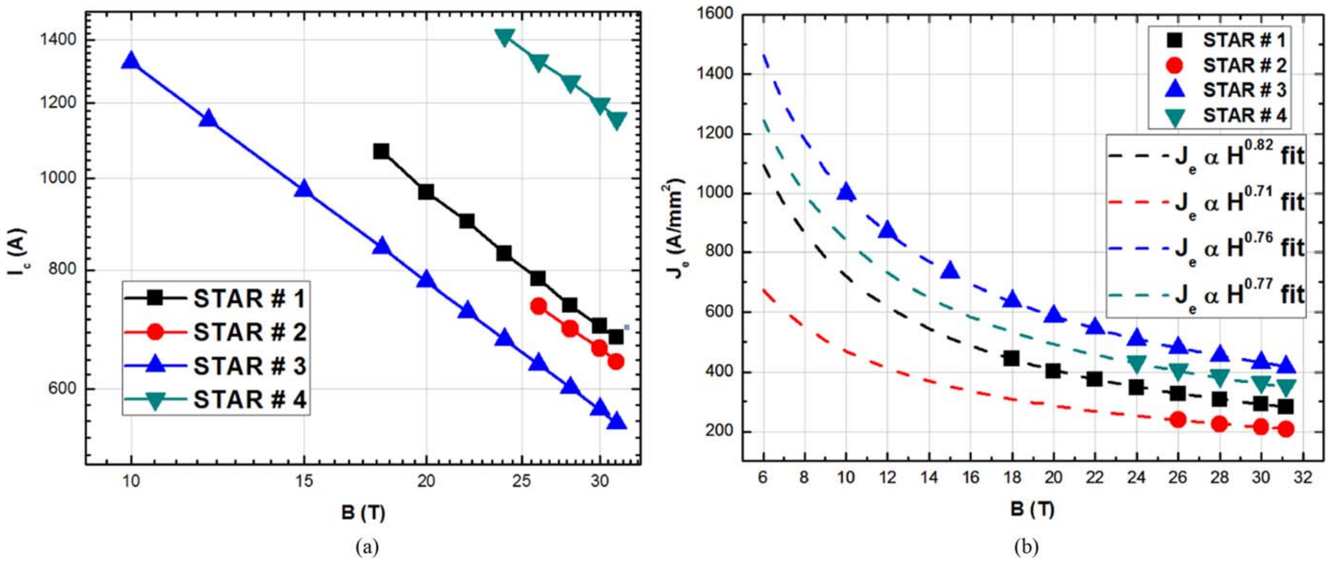


Figure 5. (a) Magnetic field dependence of I_c (0.5 μV cm^{-1} criterion was used for STAR wires #1 and #2, 1 μV cm^{-1} criterion was used for STAR wires #3 and #4) and (b) J_e at different magnetic fields of STAR wires. (Dashed lines are a power-law fit to the data from 10 to 31.2 T.)

Table 2. Critical currents of STAR wires at 77 K, self-field in straight form and at 15 mm bend radius.

STAR #	Tape I_c SUM (A)	I_c (A) in straight form	I_c retention (%) after making STAR wire	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	634	571	90.1	237.5	494	205.8	86
2	858	>600	NA	>195	548	178.1	N/A
3	430	422	98.1	318.3	400	301.5	95
4	953	>600	NA	>183.6	766	234.5	N/A

STAR wires #2 and #4 had higher equivalent tape width due to higher number of layers, as outlined in table 1, resulting in the highest I_c values, exceeding the 600 A current source limit.

When STAR wires were bent to 15 mm radius, the I_c retention was in the range of 86.5%–94.8%. STAR wire #3 showed an I_c retention of 94.8% and a corresponding J_e of 301.5 A mm^{-2} at 77 K, self- field which is the highest reported value so far for REBCO wires with round geometry. STAR wire #2 had a low n-value of 14.7 which indicated damage during bending. For STAR wires #3 and #4, by using a gradually increasing tape thickness with layer number, the average strain on each layer was maintained nearly constant with an increase in wire diameter. For STAR wire #3, this resulted in higher I_c retention of the straight wire even using a 0.51 mm former diameter and during bending to 15 mm radius.

STAR wire performance at 4.2 K, in-field

After the 77 K measurements, all wires were tested in bent form (15 mm radius) at 4.2 K. The applied magnetic field ranged from 10 to 31.2 T. STAR wire #2 was measured in an increasing field from 26 T. Other STAR wires were tested first at 24 T, then measured from the highest field of 31.2 T towards the low fields. The maximum current limit was 1400 A. In certain measurements, pulse current mode was used to avoid overheating of the sample. STAR wire #2 was burned after three measurements due to thermal runaway during fast current ramping before starting the pulsed-current mode.

For the 4.2 K measurements, shown in figures 5(a) and (b) are the magnetic field dependence of I_c and J_e, respectively. A voltage criterion of 0.5 μV cm^{-1} was used for STAR wires #1 and #2 whereas 1 μV cm^{-1} was used for STAR wires #3 and #4 in order to have a clear transition with two to three data points above the criterion. The dashed lines shown in the figure 5(b) are power-law fits to the data according to

$$J_e(B) \propto B^{-\alpha}, \quad (1)$$

where $J_e(B)$ is engineering current density at a magnetic field B ($\geqslant$6 T) and α is the power-law exponent. As shown in figure 5(b), STAR wires #3 and #4 had the highest J_e over the entire range of fields because of the smaller former diameter, good I_c retention due to variable tape thickness in each layer and variable twist pitch that allows tape sliding during bending. The α values of all four wires are comparable, ranging from 0.71 to 0.82, with the most reliable estimates for STAR wires #1 and #3 due to the highest number of data points (0.82 and 0.76, respectively).

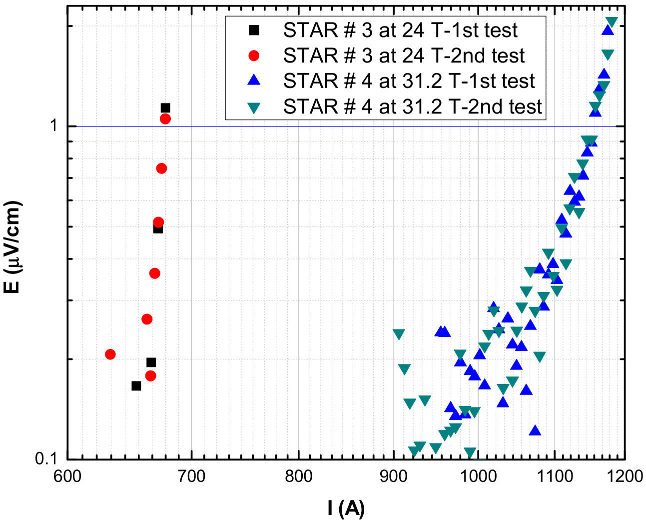


Figure 6. E–I plot of STAR wire #3 at 24 T ($F_L = 16.2$ kN m^{-1}) and STAR wire #4 at 31.2 T ($F_L = 36$ kN m^{-1}) for two times measurement at same field.

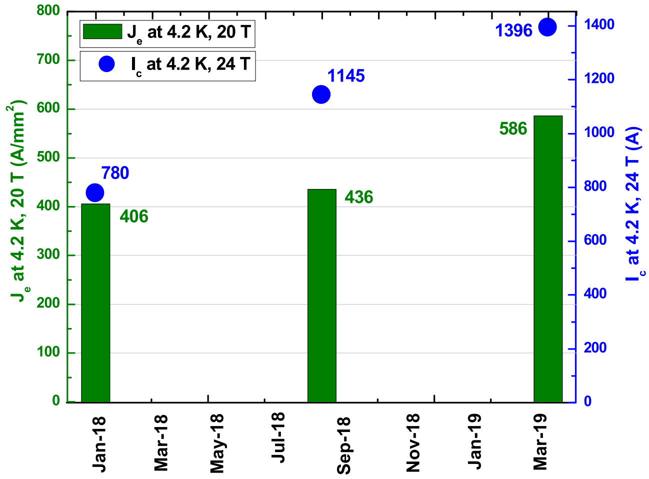


Figure 7. Progress in J_e and I_c of STAR wires tested at NHMFL from January 2018 to March 2019.

At 20 T, STAR wire #3 exhibited a J_e of 586 A mm^{-2}, which is highest reported data so far for REBCO round wires. As a comparison, STAR wire #1 sustained a J_e of 402 A mm^{-2}, whereas STAR wire #2 had a J_e value of 208.5 A mm^{-2}. STAR wire #2 exhibits a lower J_e due to increased transverse load on the wire with almost no gap in the last layer. At 31.2 T, STAR #3 shows a J_e of 416 A mm^{-2} and STAR # 4 shows a J_e of 353.8 A mm^{-2}.

High I_c is desirable for CCT coils at $\leqslant$15 mm bend radius with a dipole transfer function of 0.5 T kA^{-1} [8]. As a comparison, STAR wire #1 sustained an I_c of 966.5 A at 20 T whereas STAR wire #3 shows an I_c of 778 A at 20 T. At 26 T, STAR wire #2 had an I_c value of 734 A with total 23 mm of tape width whereas STAR wire #4 with total 27 mm tape width had an I_c value of 1331 A at 26 T. In terms of total I_c, STAR wire #4 exhibited by far the highest values, exceeding 1100 and 1300 A at 30 and 23 T, respectively.

In addition to the high I_c and J_e performance of the next-generation STAR wires, STAR wire #3 sustained a Lorentz force of 15.5 kN m^{-1} at a J_e of 586 A mm^{-2} without any degradation. Figure 6 shows the E–I plot of STAR wire #3 at 24 T ($F_L = 16.2$ kN m^{-1}) and STAR wire #4 at 31.2 T ($F_L = 36$ kN m^{-1}). For two times measurement at same field, magnetic field is ramped up to the desired field level and then ramped down to 18 T before the second time ramp which helps to avoid formation of helium bubbles in the cryostat due to warm up of the resistive magnet. Both of these STAR wires showed <0.1% variation in the measured I_c between the two tests under huge Lorentz forces and with no trace of damage or thermal runaway.

From the above results and our previous reports, the progress in the J_e and I_c of STAR wires over the past 14 months is shown in figure 7. It is seen that the J_e of STAR wires has been increased by 30% compared to the J_e of STAR wires tested a year ago. The I_c of STAR wires tested in March 2019 has reached nearly 1400 A at 4.2 K, 24 T which is nearly a factor of 1.8 higher than the I_c of STAR wire tested a year ago.

Conclusions

STAR wires with different structures were fabricated to develop a next-generation architecture. We used 20 AWG (0.81 mm diameter) and 22 AWG (0.51 mm diameter) copper wires as formers and wound six to twelve tapes of different width and thickness on the formers. STAR wires were tested at 77 K in straight form and at 15 mm bending radius. The corresponding I_c retention was between 86.5% and 95%. Afterward, STAR wires bent to 15 mm radius were tested in background fields from 10 to 31.2 T at 4.2 K. STAR wire #3 exhibited a J_e of 586.4 A mm^{-2}, with corresponding I_c of 778 A at 4.2 K, 20 T.

In general, STAR wires on 22 AWG former performed better than STAR wires on 20 AWG former due to variable tape width and thickness in each layer which reduces transverse load on the STAR wire. The maximum calculated Lorentz force applied on STAR wire #4 was 36 kN m^{-1} and reproducible performance was observed in two times measurements. J_e of STAR wires has been increased 30% higher than the J_e of STAR wires tested an year ago. The obtained results meet almost 97.5% of the CCT coil requirements and makes the next-generation highly flexible STAR REBCO wires a potential candidate for the use in compact accelerator magnet applications.

Acknowledgments

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ORCID iDs

Soumen Kar https://orcid.org/0000-0001-5550-6859
Mehdi Kochat https://orcid.org/0000-0002-2928-0718
Jan Jaroszynski https://orcid.org/0000-0003-3814-8468
Goran Majkic https://orcid.org/0000-0003-0168-0856
Venkat Selvamanickam https://orcid.org/0000-0001-6618-9406

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