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Investigation of HTS Twisted Stacked-Tape Cable (TSTC) Conductor for High-Field, High-Current

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Investigation of HTS Twisted Stacked-Tape Cable (TSTC) Conductor for High-Field, High-Current Fusion Magnets

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Abstract—**The critical currents of a twisted single-tape were measured at 4.2 K in fields up to 17 T. It was confirmed that the critical current of a twisted-tape was similar to that of a flat tape in c-axis fields. Based on the single-tape critical-currents, a 40-tape (4-mm width) twisted stacked-tape cable (TSTC) conductor was experimentally evaluated at fields up to 17 T at 4.2 K. It was found that the Lorentz load degradation of the TSTC conductor was negligible at the end of a cyclic test. The TSTC cabling method has been considered to be suitable for developing a high-field high-current REBCO conductor for magnet applications as well as power transmission cables. A method to fabricate the inner legs of a D-shape toroidal field coil using a TSTC conductor has been discussed. This method allows the conductor to properly resist the transverse Lorentz load and mitigate ac loss issues by adopting a parallel-HTS-tape flat cable configuration where necessary.**

Index Terms—**Fusion magnet, high-field magnet, high-temperature superconductor (HTS), HTS cable, stacked-tape cable, twisted stacked-tape cable (TSTC), coupling current.**

I. Introduction

HIGH Temperature Superconductor (HTS) REBCO tapes could revolutionize large high-current conductors for use in magnets for high field applications such as fusion, high-energy accelerators and SMES. The flat-tape structure, however, remains a challenge for cabling. So far, few cabling methods have been proposed and developed for high field, high current applications [1]–[12]. The Twisted Stacked-Tape Cable (TSTC) conductor is one of the cabling methods under investigation by various groups to develop a high-current conductor with robust structure that can be used in high field applications [5], [7], [11]. The basic concept of the TSTC conductor consists in stacking flat tapes and twisting them along the stacked tapes axis. Although this cabling technique is more complicated than a cable made simply with a stack of tapes without twisting, a TSTC conductor has several mechanical and electrical advantages such easier handling and improved AC performance. We have experimentally examined various TSTC conductors at high fields up to 20 T in liquid helium [9]–[12].

In this paper, we will first discuss details of the experimental results of a 40-tape (4 mm width) TSTC conductor made from SuperPower REBCO tapes which was performed at the National High Magnetic Field Laboratory (NHMFL), Florida State University [9], and then shortly discuss various TSTC conductor options for high field, high current magnet applications.

We will then discuss a method using a TSTC conductor to allow the use of a parallel-HTS-tapes cable at a local segment in the windings of a magnet experiencing high transverse electromagnetic forces during operation, to mitigate the electromechanical degradation of the conductor while limiting the coupling current AC losses. This issue is important as a twisted stacked-tape cable are expected to be less robust against transverse load compared to a non-twisted parallel-tape cable. This can be critical in a high-field tokamak with a magnetic field more than 20 T [13], [14], where a conductor at the inner leg of a D-shape TF coil locally experiences very high Lorentz loads [15].

II. High Field Tests

A. REBCO Tape Tests

The critical current tests of single REBCO tapes were carried out for a twisted tape and a non-twisted tape from SuperPower (SCS4050-AP; 4 mm wide, 0.1 mm thick with 20 μm electroplated copper layer on each side) in various fields at 4.2 K using a high field magnet at NHMFL. The twisted sample was 50 mm long with a 100 mm twist-pitch. The non-twisted sample was tested in c-axis fields. These tapes were mounted on a G10 sample holder utilizing an epoxy glue (Stycast). Fig. 1 shows the test results. The critical currents reported by the manufacturer were 120 A for the twisted tape and 105 A for the non-twisted tape, respectively, at 77 K in self-field. The tapes tested at 4.2 K were obtained from different spools. Even if the critical currents at 77 K differ by more than 12%, the critical currents difference at 4.2 K was less than 3%, as seen in Fig. 1. The deviations of the critical currents correspond to about 10% deviation of the lift-factors Ic(4.2 K, B)/Ic(77 K, self-field) between the two

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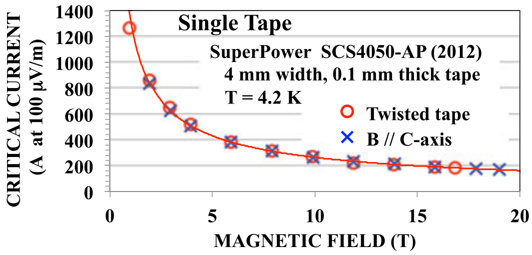


Fig. 1. Critical currents of twisted and non-twisted single-tapes of SuperPower tape (SCS4050-AP) at various fields at 4.2 K. Open symbols are for a twisted tape with a twist-pitch of 100 mm. Cross symbols are for a non-twisted flat tape with fields in the c-axis.

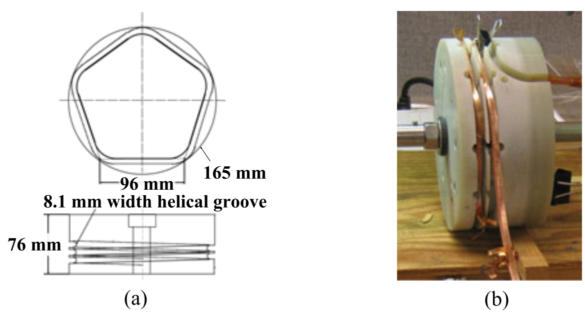


Fig. 2. (a) Dimensions of a pentagon former for a STTW coil. (b) Demonstration of a STTW method for a 40-tape stacked conductor on G10 pentagon sample holder. The sample described in this work is reinforced with copper braid, then solder and stycast.

tapes. The critical current deviations measured could be due to the scatter of the lift-factor which has been reported [16].

B. DC Tests of TSTC Conductor

In order to test a small diameter coiled samples made of a TSTC conductor that could fit the available 17 T Bitter magnet (NHMFL 195 mm warm bore, cryostat cold bore 170 mm), a sample holder was made using a G10 cylinder of a 165 mm diameter on which a pentagon-shaped groove was machined, as shown in Fig. 2(a). A 40-tape stacked-tape conductor was twisted along the straight sides (96 mm length) of the pentagon and bent as a parallel stack at the corners that are about 25 mm in radius using the Stacked-Tape Twist-Wind (STTW) technique [11]. Fig. 2(b) demonstrates the winding of a stacked-tape conductor on the pentagon former using the STTW technique.

The tested cable was 2.3 m long and composed of 40-stacked REBCO tapes (SuperPower SCS4050-AP, 0.1 mm thickness and 4 mm width), stacked between two 0.51 mm thick copper strips. The stacked-tape cable was encapsulated within a braided copper sleeve and soldered. Space between the conductor and the G10 sample holder was filled with an epoxy glue (Stycast) to reinforce the conductor. The 90° bent sections of the sample connecting to the current leads was reinforced with soldered copper tubes. Details of the sample fabrication are found in [9]. Critical current tests were carried out at 4.2 K using the 17 T Bitter magnet at NHMFL with a maximum DC sample current of 9 kA for the cable. This total current was obtained using six small DC power supplies with current capacity between 1.0 kA and 2.4 kA.

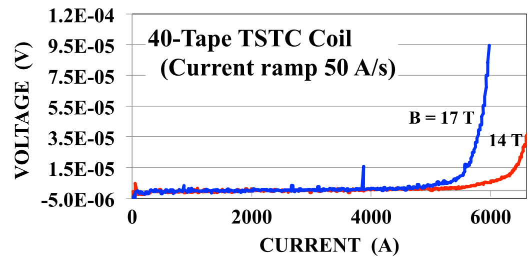


Fig. 3. Measured I-V curves of 0.5 m voltage tap.

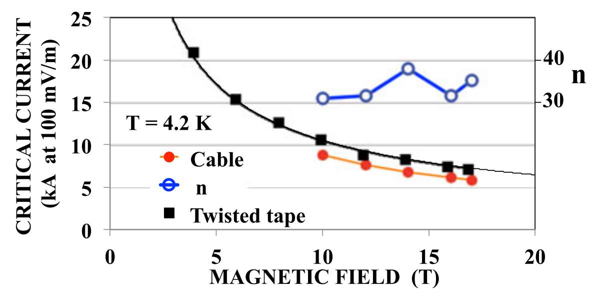


Fig. 4. Cable critical current and n-index value obtained experimentally are compared with the critical current of the twisted single tape.

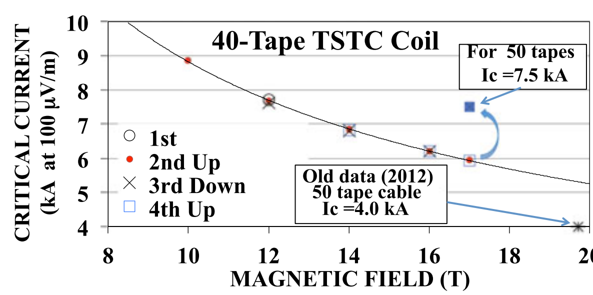
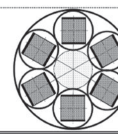


Fig. 5. Measured critical currents of a 40-tape Superpower TSTC conductor sample tested at NHMFL. No cyclic load effect was observed.

Fig. 3 shows I-V curves of 0.5 m voltage tap at the background fields of 14 T and 17 T at 4.2 K. The critical current was 6.0 kA at 17 T and 4.2 K at the criterion of 100 μV/m. The comparison between the cable results and single tape data are shown together with the n-index values of the cable in Fig. 4. The critical-current discrepancies compared to the twisted single-tape critical currents seen in Fig. 1, were uniformly 16% between 10 T and 17 T. Fig. 5 shows additional results of the critical currents measured with background magnetic fields between 10 and 17 T for four different cycles. As it can be seen the critical currents of the cable were repeatable and did not show degradation from the cyclic Lorentz load applied [9]. This indicates that the TSTC conductor was well supported against Lorentz load. The results of 6.0 kA at 17 T for the 40-tape cable corresponds to 7.5 kA for a 50-tape cable, which is a much better performance compared to the 4 kA obtained earlier in a similar TSTC experiment (the star symbol in Fig. 5) [12].

TABLE I
PERFORMANCES AT 17 T OF MULTISTAGE CABLES MADE OF SINGLE-STACKED-TAPE CONDUCTORS OF VARIOUS TAPE WIDTHS, BASED ON THE CRITICAL CURRENT OF 180 A AT 17 T AND 4.2 K FOR A 4 MM WIDTH, 0.1 MM THICKNESS REBCO TAPE

Conductor	Tape width (mm)	Tape current (A)	Number of Tapes	Critical Current (kA)	Cable Diameter (mm)	Conductor Cross-Section
Single-stage	4	180	40	7.2	7.4	
	6	270	60	16.2	11.1	
	12	540	120	64.8	22.2	
Triplet	4	180	120 (40 x 3)	22	16	
	6	270	180 (60 x 3)	49	24	
	12	540	360 (120 x 3)	194	48	
Hexa	4	180	240 (40 x 6)	43	23	
	6	270	360 (60 x 6)	97	35	

From the no-cyclic load effect up to 6.0 kA at 17 T, we can conclude that a Lorentz load up to 102 kN/m (17 T $\times$ 6.0 kA) does not degrade the critical currents for the TSTC cable. The overall engineering critical-current density J_e is 117 A/mm^2 for the present conductor considering an overall averaged diameter of 8.1 mm, while it is 375 A/mm^2 for the conductor cross-section of 4 mm $\times$ 4 mm. The density J_e considering the circular envelop with 36% space around a TSTC conductor (5.7 mm diameter) gives a value of 239 A/mm^2.

C. *High Field and High Current Conductors*

The estimated performance of single-stacked TSTC conductors and its multiple-stage conductors at the magnetic field of 17 T is shown in Table I for various tape widths between 4 mm and 12 mm. The values are estimated considering a tape critical current of 180 A for 4 mm width (450 A/cm) at 17 T at 4.2 K.

As shown in Table I a single stack conductor of 12 mm width, 120 tapes provides the critical current of 65 kA at 17 T and 4.2 K with a diameter of 22.2 mm, while the triplet conductor can get 194 kA with the diameter of 48 mm. A TSTC conductor with a single stack of tapes provides 36% space around the REBCO tapes since they are twisted as mentioned earlier. This space can be used for the stabilizer. A hexa (6-in-1) conductor of six, 6 mm 60-tape conductor carries the critical current of 97 kA with the diameter 35 mm. Given those high currents cables options, a TSTC conductor can provide a very compact cable-in-conduit conductor for fusion magnets and other applications. But a magnet conductor can be exposed to severe electromagnetic forces; therefore the conductor has to be properly supported.

III. METHOD TO MITIGATE COUPLING CURRENTS IN PARALLEL SUPERCONDUCTING-TAPE CABLE FOR A TOKAMAK MAGNET

If REBCO flat tapes can be used in a cable without transpositions, a parallel-tape cable could be desirable in a high Lorentz load environment (high field and high current) as a tape can resist high loads on its wide face [15]. A parallel-tape HTS conductors has been developed for a specially designed helical fusion reactor composed of segmented conductors (STARS; Stacked Tapes Assembled in Rigid Structure) [8].

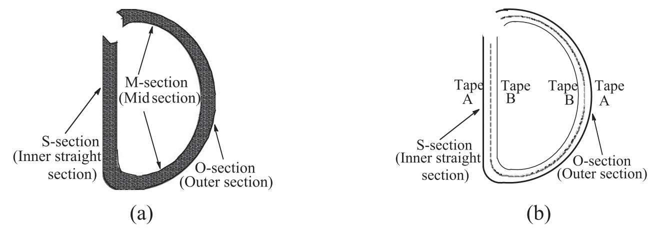


Fig. 6. (a) Illustration of one turn coil of a part of TF magnet. (b) A schematic drawing of a single turn coil of a superconducting parallel-tapes conductor.

For a high-field tokamak, a TSTC conductor can also be modified using the Stacked-Tape Twist-Winding (STTW) method [12] to allow a parallel-HTS-tape cable at the inner legs of a TF coil to provide enough support against Lorentz load and to mitigate AC losses such the coupling current is discussed next.

A. *Conceptual Description*

Fig. 6 shows an illustration of a single turn of a D-shape TF coil, composed of an inner straight section (S-section), an outer section (O-section) and two mid sections (M-sections). If this coil is made of a cable with a stack of tapes without twisting or transposition (parallel-tape) as shown in Fig. 6(b), an outer tape (Tape A) would always be on the outside of the stack while a Tape B would always be in the inside. This configuration would cause significant issues due to magnetic flux coupling. To solve or mitigate this problem the cable is twisted except at the S-section (where the EM load is largest), and the coupling current of the S-section is compensated with coupling currents of the other sections. Two options to compensate the coupling are discussed below: a) Two-turn coil mitigation method and b) Single coil mitigation method.

B. *Two-Turn Mitigation Method*

In the case of a TF coil magnet with multiple turns, the coupling current on a tape can be reduced by canceling it with the coupling current of the same tape on another turn. To make the canceling current in the opposite direction the cable needs to be twisted properly.

A fabrication method of a TF coil is shown in Fig. 7(a), where two turns of a twisted stacked-tape cable using the STTW method are wound, but the tapes at the straight parallel-tapes section (S-section) are not twisted. In the S-section at the first (left) turn in Fig. 7(a), Tape A is at the outermost edge. Then the cable is twisted with an odd number (2n + 1) of half-twists over the other sections, M-sections and O-section, so that Tape A of the cable will be at the innermost edge of the stack at the S-section of the second-turn (Tape B is now at the outermost edge) as shown in Fig. 7(a). The TF coil is wound in this way to change the tape locations from the inner most to the outer most locations alternatively at the S-sections. In this way, the directions of the induced current in each tape in the cable are changed at the first and the next turns, and the coupling currents cancel out and the losses are minimized.

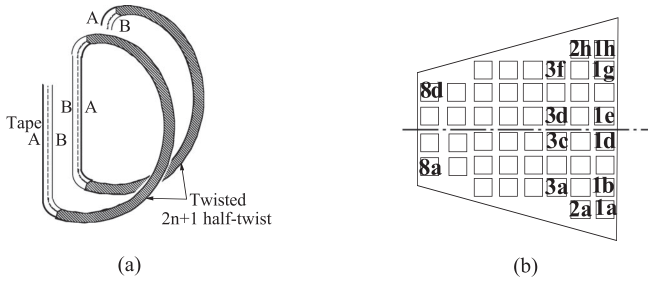


Fig. 7. (a) A conceptual illustration of two-turn coil method to cancel out field-induced coupling currents. The cable of M-sections and O-section is twisted (2n + 1 half-twists). (b) Winding cross-section of an inner leg of a TF magnet, showing coupling flux compensation arrangements from the symmetry of the winding.

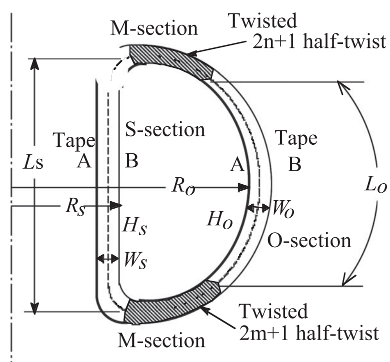


Fig. 8. Single-coil cancelation method to mitigate the field induced current. The cable is twisted between the S-section and the O-section of a coil whose cable is not twisted. Each transition of the stack of tapes in the cable between those sections is twisted by an odd number (2n + 1) of half-twists.

Fig. 7(b) illustrates a cross-section of a TF magnet in a layer winding at the midplane of the S-section. Each square shows a cable cross-section where the tapes are parallel to the winding axis. To achieve a good cancelation of the coupling currents, each layer of a TF coil should be made with an even number of turns as shown in Fig. 7(b), so that the coupling current of the coil turn 1a, for example, is canceled with 1h, located in the symmetric location to 1a. In the same way 1b and 1g, 2a and 2h, 3a and 3f, 3c and 3d, 8a and 8d in Fig. 7(b) make good pairs for current cancelations. In the case of a pancake winding, the paired winding turns should be arranged in the same pancake because the coil turns do not have exactly the same magnetic flux distributions. Therefore, the cancelation requires proper coil design considering the magnetic field intensity and the cable length.

C. Single-Turn Mitigation Method

A method for canceling the coupling currents in one TF coil is illustrated in Fig. 8. A conductor is twisted between the S-section and the O-section of a coil. In the S- and O-sections of the cable, the tapes are not twisted. However, in each transition of the cable between those sections, the stack of tapes is twisted by an odd number (2n + 1) of half-twists. Therefore, Tape A located at the outer in the S-section becomes an inner tape in the O-section. In this way, the induced current of Tape A in the S-section is in the opposite direction of that in the O-section. That is, the induced tape current of each tape cancels out between the two sections.

If the flux crossing-areas of the parallel-tape cable are A_s and A_o at the S-section and the O-section of the conductor, respectively, the condition to cancel the induced tape currents in the S- and O-sections is given by

$$A_s\ H_s\ =\ A_0\ H_0 \tag{1}$$

where H_s and H_o are the magnetic fields at the S-section and O-section, respectively.

Using a rough estimation, the toroidal magnetic fields H_s and H_o at the S-section and O-section in the inner most turn (highest field) follow (2) from Ampère's law,

$$H_s\ R_s\ =\ R_0\ H_0 \tag{2}$$

From (1) and (2), one can obtain

$$\frac{W_o\ L_o}{W_s\ L_s}\ =\ \frac{R_o}{R_s} \tag{3}$$

here, W_s and W_o are the widths of the S-section and O-section facing the magnetic flux, and L_s and L_o are the lengths of these sections.

To satisfy the condition given by (3), the width W_o times the length L_o ($W_o \cdot L_o$) for the O-section needs to be designed larger than $W_s \cdot L_s$, since the ratio of R_o/R_s is larger than 1. If the cable has a uniform cable width ($W_o \approx W_s$), it will be difficult to satisfy the condition in (3) only adjusting the lengths of L_o and L_s. However, if the width W_o can be varied and made larger than W_s, it will be possible to satisfy (3). This can be done by selecting the proper thickness spacers between tapes in the parallel-tape segment at the O-section. This single-turn method may be a useful method for a short coil such as a segmented coil or a demountable coil [14].

IV. Conclusion

The critical currents of a twisted single-tape sample with the twist-pitch of 100 mm were measured at 4.2 K in fields up to 17 T, and it was compared with the critical currents of a flat tape in c-axis fields. Both samples (SuperPower REBCO tapes SCS4050-AP) showed very similar critical current behavior within 3% deviation at 4.2 K over a wide field range between 2 T and 17 T, although those critical currents at 77 K differed by more than 12%.

We have successfully achieved 6.0 kA (for a 100 μV/m criterion) at 17 T and 4.2 K with a 40-tape (4 mm width) TSTC conductor made from SuperPower REBCO tapes. The n-index value was as high as 35. This indicates that the cable terminations were well fabricated with reasonably uniform joint-resistances.

The cable performance was compared with the critical currents of the single tape samples. From a simple comparison, the cable was degraded ~16% from the expected single tape critical currents in fields between 10 T and 17 T. However, no degradation of the critical currents with cyclic loading was observed in this field range. Those results indicate that the degradation due to the Lorentz load up to 102 kN/m (17 T × 6.0 kA) was not significant. Origins of the cable degradation of ~16% are still not clear. Further investigation will be required to understand the critical current discrepancy between the cable and the single tape performance. For high-field magnet applications, it is very important to evaluate the conductor performance in a Lorentz load environment representative of the conditions experienced in real operations (high fields and high currents) and the performance achieved so far is very promising for the future uses of the TSTC conductor in high-field high-current magnet applications. Nevertheless, more experiments in high-field conditions are necessary to reach even higher Lorentz loads.

A method to mitigate the flux coupling AC loss, if a parallel-tapes superconducting cable conductor is used in a Toroidal Field (TF) tokamak magnet, was discussed using a variation of the TSTC conductor and the STTW method. The method discussed allows a parallel-HTS-tape flat cable at the inner legs of a D-shape TF coil to make the conductor rigid against the transverse Lorentz load and to mitigate the coupling currents issue. Applicability and modifications of this method should be considered depending on the winding methods (layer or pancake windings) and the size of the magnet to be built together with its operational conditions such as intensities and ramp rate speeds of the magnetic field.

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