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**Present Status and Recent Developments of the  
Twisted Stacked-Tape Cable (TSTC) Conductor**

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## **ABSTRACT**

High magnetic field performance of a 40-tape Twisted Stacked-Tape Cable (TSTC) conductor made of 4 mm width, 0.1 mm thick REBCO tapes was successfully tested. The critical current was 6.0 kA with the n-value of 35 at 4.2 K with a background field of 17 T. No-cyclic load effect was observed between 10 T and 17 T with the maximum Lorentz load of 102 kN/m. Various issues such as sample length, non-uniformity of termination resistances, soldered joint of a coated tape cable with regards to a TSTC conductor are discussed. Large-scale conductor designs of various scalable TSTC conductors are discussed taking into account current densities and stabilizers.

**KEYWORDS:** 2G cable, stacked tape cable, twisted stacked-tape cable, high-field magnet, fusion magnet, HTS, CICC.

## I. INTRODUCTION

High Temperature Superconductors (HTS) such as BSCCO and REBCO tapes have excellent high-field and high-current performances. Cabling methods for the HTS tapes such as Roebel Assembled Coated Conductor (RACC), Conductor-On-Round Core (CORC), Twisted Stacked-Tape Cable (TSTC) and a few other alternates have been proposed [1]–[8].

The TSTC method consists of a stack of flat tapes, either BSCCO or REBCO, twisted along the axis of the stack. This cabling method is suitable for developing a high current cabled conductor for high-field magnet applications such as fusion and accelerator machines as well as power transmission cables. TSTC conductors have been fabricated by several methods, including sheathing the tape stack with copper strips and embedding the stack in single and multiple helical grooves machined on a circular rod. In the latter configuration, an untwisted stacked-tape cable or a twisted stacked-tape cable can be embedded in each groove [5].

Various REBCO TSTC conductors have been tested in liquid nitrogen and liquid helium in order to evaluate the performance of the twisted cable [9]. 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.

In this paper we will discuss the present status of our TSTC conductor, the termination development work and test results at high fields in liquid helium. High-field tests of various TSTC conductors were performed at the FBI facility at Karlsruhe Institute of Technology (KIT), Germany [10] and at the National High Magnetic Field Laboratory (NHMFL), Florida State University. We will discuss the test results taking into account termination-resistance distribution and transvers-load effects. A soldered joint development for a 2G coated-tape cable will be described. Additionally, scale-up conductor designs for a TSTC conductor will be discussed, to contextualize the applicability of TSTC cabling methods for high current high-field applications, and the industrial feasibility of producing a long TSTC conductor.

## II. HIGH-FIELD TESTS OF TSTC CONDUCTORS

A total six TSTC conductor samples were tested in high fields at 4.2 K. These samples are summarized in TABLE I.

### A. Straight short sample tests

#### 1) *First straight sample*

The first sample of a TSTC cable tested at the FBI, KIT was made of 4 mm width REBCO tapes (SuperPower SCS 4050-AP, 2012). The cable was 1.16 m long including terminations and was composed of 40 tapes stacked between copper strips (0.5 mm thick, 4.8 mm width), and then twisted with 200 mm twist-pitch. It was inserted in a copper sheath of 9.5 mm OD, and filled with 60%Sn-40% Pb solder. Each end of the conductor had demountable REBCO-BSCCO termination [12]. The sample (shown in Fig. 1) was tested at the KIT FBI facility [10]. A cycle test was



performed between 6 T and 12 T. The critical currents measured at  $5 \mu\text{V}/\text{cm}$  are shown in Fig. 2 [11]. The results showed degradations of about 15% at 6 T and 10% at 12 T between the first measurement cycle and the second cycle. After the second cycle no further degradation was observed [11]. Nevertheless, the critical current values were much lower ( $\sim 50\%$ ) than what was expected from single tape data.

After the high-field test at KIT adding a pair of voltage taps for the end section on the sheath without any other modification we examined two sections of the tested conductor, the center section and the end section, at 77 K in self-field. The critical current of the center section, which experienced the highest Lorentz load during the test at KIT, was about 1.7 kA, while that of the end section close to one extremity of the cable was about 2.0 kA. The end section was outside of the high-field zone during the test at KIT, therefore it did not experience large load during the test [13]. Those results showed that the center section was indeed permanently degraded with Lorentz load during the high-field test at KIT by 15% compared with the end section of the unloaded area during the test. Most of the  $\sim 50\%$  degradation observed at the high-field test at KIT might not be permanent degradation and possible explanations for this behavior will be discussed in the next section.

TABLE I  
Samples tested at high magnetic fields.

Sample Name	Sample Holder	Cable Mounting	Tested at KIT/NHMFL (Year)
1 <sup>st</sup> Straight	Cu tube	Soldered in Cu tube	KIT (2012)
2 <sup>nd</sup> Straight	Grooved Cu rod with Cu sheath	Inserted in groove without solder	KIT (2014)
1 <sup>st</sup> Pentagon	Aluminum	Soldered cable	NHMFL (2012)
2 <sup>nd</sup> Pentagon	Aluminum	Stycast	NHMFL (2012)
3 <sup>rd</sup> Pentagon	G10	Soldered, then Stycast	NHMFL (2015)
4 <sup>th</sup> Pentagon	G10	Soldered with braided sleeve, then Stycast	NHMFL (2015)



Fig. 1. 40-Tape TSTC conductor of 1.16 m long, 200 mm twist-pitch cable in 9.5 mm OD solder-filled Cu tube with REBCO-BSCCO terminations fabricated at MIT, and tested using the FBI facility at KIT, Germany.

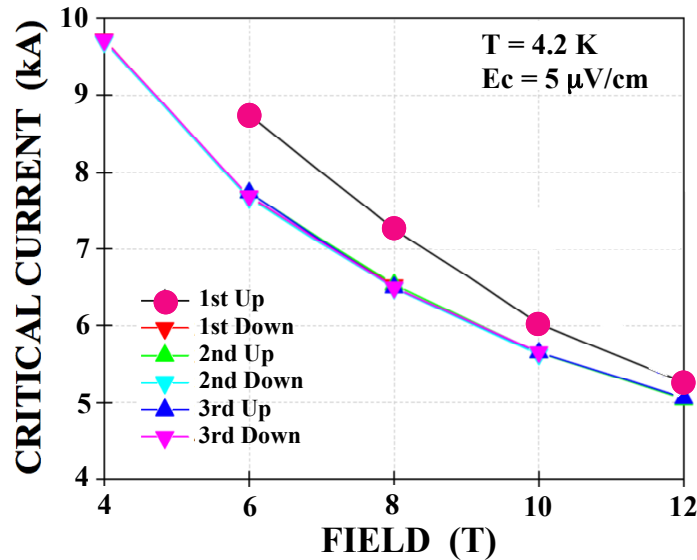


Fig. 2. Test results of the first 1 m 40-tape TSTC conductor tested at KIT. Critical current vs. field for up and down cycles [11].

## 2) Termination resistance effects

Following the results just described, various possible electrical and mechanical effects were investigated to explain the origin of the degradation observed during the high-field tests of the TSTC conductor. Large mechanical degradations have been observed in our mechanical tests, however all of them caused permanent degradations [13]. It is difficult to envision the possibility of a 50% reversible degradation caused by mechanical loads. Electrical origins such as loop currents due to low loop resistances and non-uniform current distributions were considered for the ~50% non-permanent degradation.

In general low termination resistance is preferred. Furthermore, the uniformity of wire termination resistances of a cable is very important, in order to obtain a uniform current distribution in a cable [12]. Additionally, in order to reduce coupling currents in a cable, loop resistances between two tapes in a cable should not be too low to minimize the coupling AC loss and the ramp-rate limitation issues for AC or pulse operations of a magnet.

We have examined loop resistances of two tapes composing the terminations developed: REBCO-BSCCO, REBCO-REBCO [12] and soldered folding-fan. For the REBCO-BSCCO termination the loop resistances of a termination between two BSCCO tapes soldered in a copper tube through a mechanical clamp between REBCO and BSCCO tapes were measured. In this case the loop resistance included both a mechanical contact resistance between REBCO and BSCCO tapes, and the soldered resistances of the BSCCO tapes [12]. For the REBCO-REBCO and folding-fan terminations loop resistances between two tapes in the cable were measured without the contact resistances between REBCO-REBCO tapes. The results are shown in Table II.

TABLE II  
Loop resistances of two tapes measured for three termination methods.

	Termination Methods		
	REBCO- REBCO	REBCO- BSCCO	Soldered Folding Fan
Loop Resistance ( $\mu\Omega$ )	0.416	0.317	0.323
Standard Deviation ( $\mu\Omega$ )	0.070	0.140	0.061

The loop resistances of a termination between two tapes were roughly twice of a tape termination resistance. The present termination resistance and the standard deviation will be further improved by optimizing the termination designs and fabrication methods. Using the loop resistance and an inductance of the loop in a cable one can evaluate the coupling loop current and the time constant, which can affect magnet operations.

Transient electrical currents induce a magnetic field that could generate excess current in superconducting tapes in a cable, and cause the current to exceed the critical currents. Such transient currents disappear with an electrical time-constant given by the ratio of the circuit inductance divided by the circuit resistance. For the short cable we tested the inductances are small (at most a few ten micro-Henry). The induced current should pass through terminations in a cable, which are about  $0.3 \mu\Omega$  as shown in Table II. Therefore the time constant is about a few hundred seconds and this induced loop current in our tested conductors disappears before the critical current is obtained during experimental operation. Therefore we can conclude that the loop current is not an origin of the degradation of the TSTC conductor performance.

Another electrical origin could be the non-uniform current distribution effect in a cable due to non-uniform termination resistance. This effect was previously demonstrated for a 4-tape REBCO cable, which had indicated about 25% performance degradation [14], [15]. We have investigated a cable critical current degradation due to non-uniform termination resistances for a 40-tape cable, based on the 1.16 m TSTC conductor tested at KIT. In our investigation the current distribution during charging has been analytically simulated using a non-uniform termination resistance distribution estimated from our measured termination resistances (shown in Fig. 3). Average and standard deviation of the termination resistances used in the model are given in Table III. An equivalent model circuit for the 40-tape cable is shown in Fig. 4. It is composed of 40 pure-resistances of the terminations at each end. In this model current sharing among the tapes in the cable has been neglected. Current distributions in this circuit were analyzed with the n-value 30 for the V-I characteristic of the REBCO tapes by an iteration procedure using Microsoft Excel<sup>®</sup>.

TABLE III  
Termination tape-resistance statistic estimated for simulation.

Average	Standard Deviation	Maximum	Minimum
529 n $\Omega$	109 n $\Omega$	672 n $\Omega$	254 n $\Omega$

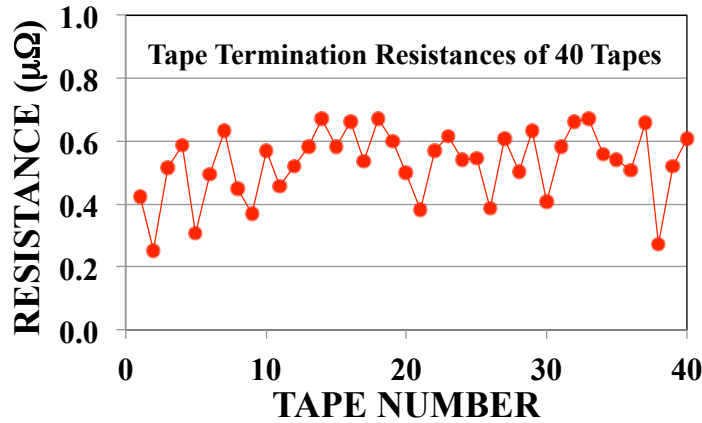


Fig. 3. Estimated termination resistance distribution used for simulation.

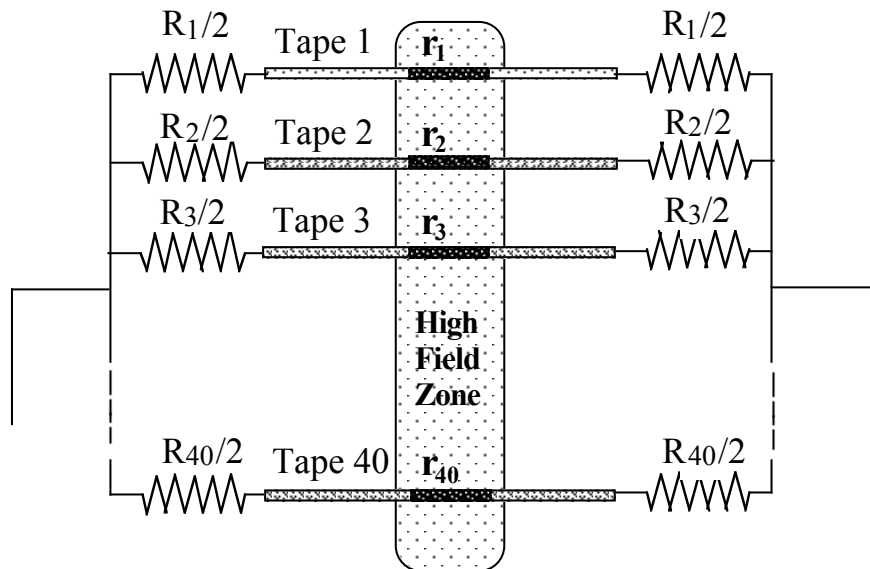


Fig. 4. Model circuit of a 40-tape cable with 40 resistive terminations at each end.

Simulation results of tape voltages and tape currents as a function of the total cable current in the 1.16 m 40-tape cable tested at KIT are shown in Fig. 5(a) and (b), respectively. To ease the visualization of the results, the voltage and current behaviors of only 20 tapes (#1 to #20) are plotted. The uniform high-field zone of the KIT FBI test magnet is about 100 mm length. Therefore the sample length of the cable for the analysis was chosen to be 100 mm since only the high-field section contributed to the resistive transition. As seen in Fig. 5(a), Tape #2 (which has the smallest termination resistance as seen in Fig. 3) is the first to show a voltage increase at about the total cable current of 4 kA since the tape charged quicker than the others as shown in Fig. 5(b). As the resistance of Tape #2 increased, the current of Tape #2 was saturating at its critical value as seen in Fig. 5(b). Similar behaviors are observed for the tapes of the next smallest termination resistance (Tapes #38 (not shown), #5, #9 and so on). During the cable critical-current test the sample voltage was measured on the copper sheath (whole cable), therefore some averaged tape voltages were detected as a cable voltage, and the tape voltages might be affected by current sharing. The actual

V-I curve of the cable measured at KIT is given in Fig. 6 [11]. The critical current was about 5 kA. As seen in Fig. 5(a) the lower termination-resistance tapes reach the criterion of  $100 \mu\text{V/m}$  at much lower current than the cable critical current expected from single tape data ( $\sim 8 \text{ kA}$  at  $12 \text{ T}$  at  $4.2 \text{ K}$ ), therefore we can conclude that the non-uniformity of the joint resistances could be the cause of the performance degradation of the cable observed experimentally.

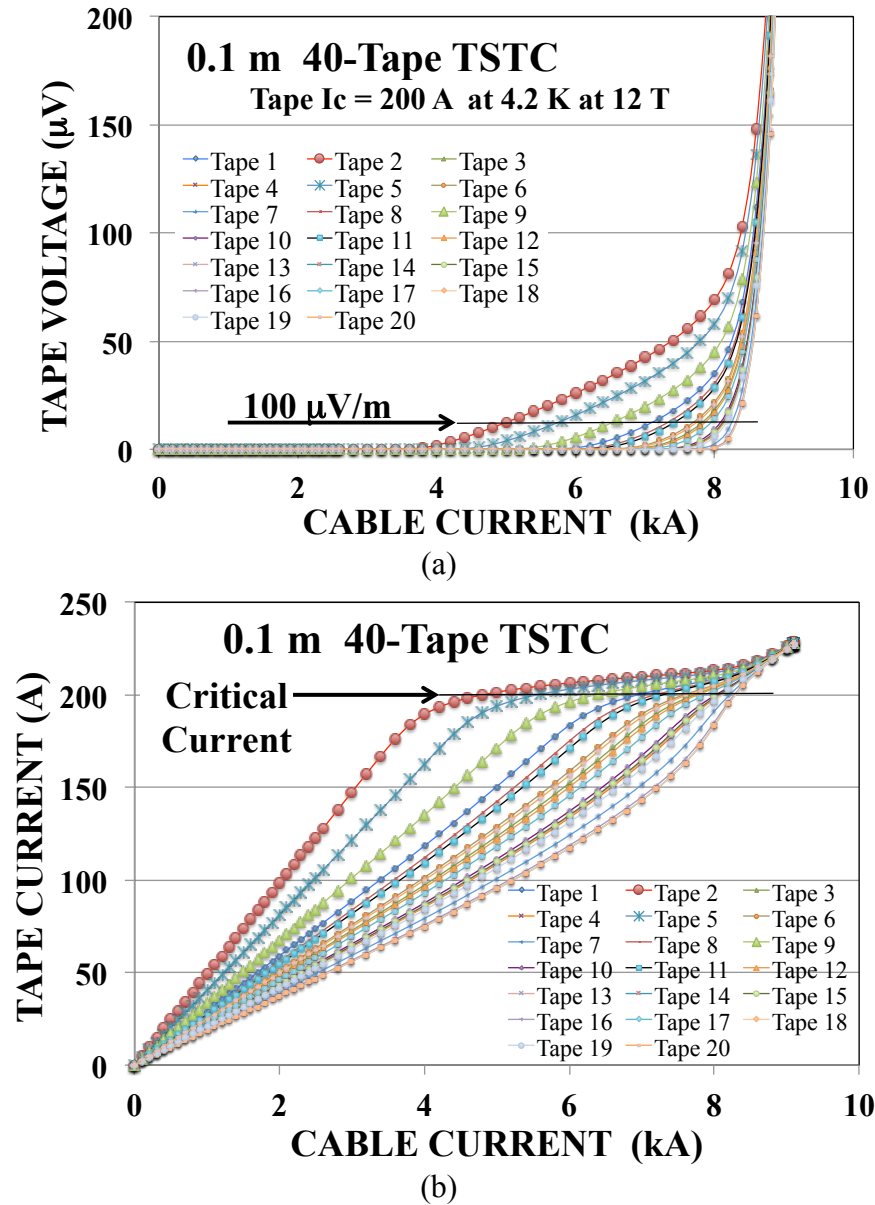


Fig. 5. Simulation analysis results of 40-tape TSTC conductor of 0.1 m high-field zone at  $12 \text{ T}$  and  $4.2 \text{ K}$ . Voltages (a) and currents (b) of 20-tapes among 40-tapes plotted as a function of the total cable current.

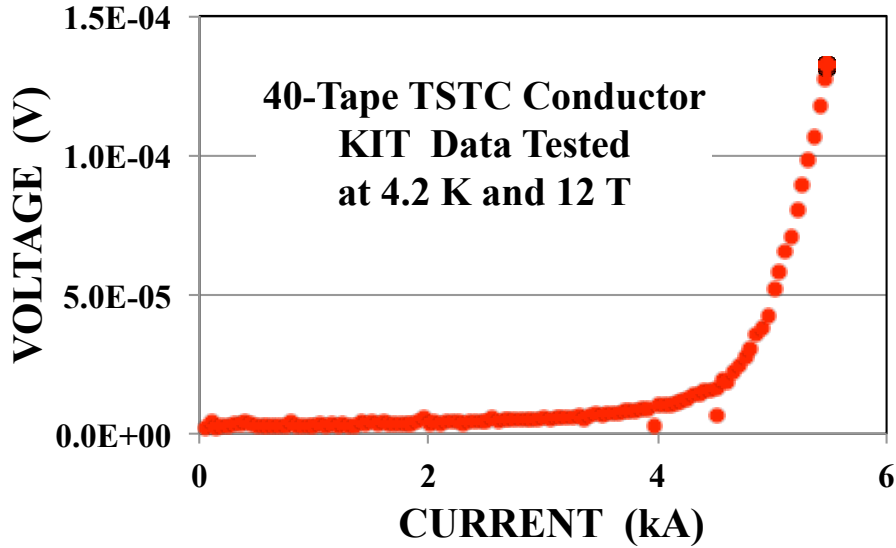
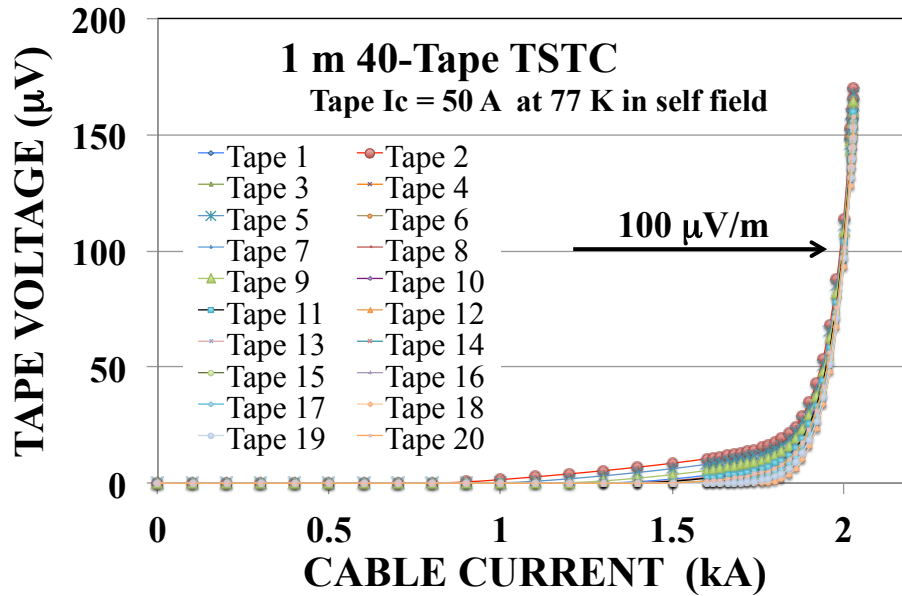


Fig. 6. V-I curve of the first 40-tape TSTC conductor tested at KIT.

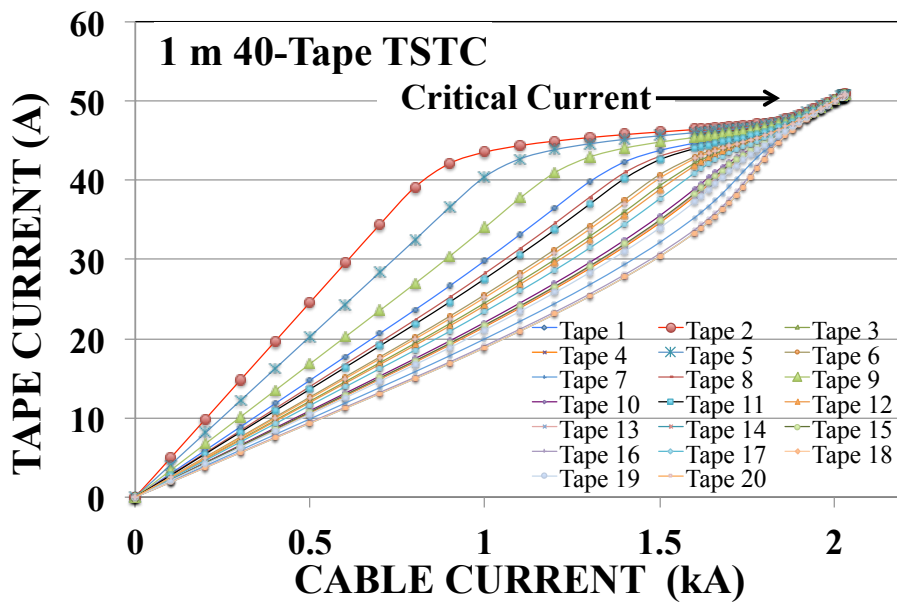
Fig. 7 shows the simulation analyses at self-field and 77 K (using the same termination resistances from Fig. 3 which were used to produce Fig. 5). In this case the sample length is the full length of 1 m and the critical current of each tape is 50 A taking into account the self-field effect at 77 K. As seen in the figure Tape #2 and the other tapes with the lower resistances, show an increase in voltages earlier than the cable critical current which is about 2 kA, however the voltage they develop is much lower than the voltage at the criterion of  $100 \mu\text{V/m}$  (where the critical current of the cable is evaluated) therefore they do not affect the performance of the cable and the overall critical current is the one expected from single tape performance. This was also verified experimentally as the current measured for a 1 m 40-tape cable tested in self-field at 77 K was  $\sim 2$  kA. Therefore in this case the termination resistances and the non-uniform redistribution of the current at the joints did not affect the value of the critical current.

Additionally, as the sample length in the high-field zone becomes longer, the termination resistance and its effect on the performance become less problematic. Fig. 8 shows simulation analyses of a 5 m 40-tape cable at 12 T and 4.2 K using the same termination distribution (Fig. 3). As seen in Fig. 8 the cable critical current is not affected by the termination resistance, as discussed above for the self-field test at 77 K in Fig. 7.

We can conclude that the performance of a longer cable is affected less by termination resistances. At the same time, it is clear that uniformity of termination resistances for a short sample test in a magnetic field is very critical since the high-field zone is usually short.

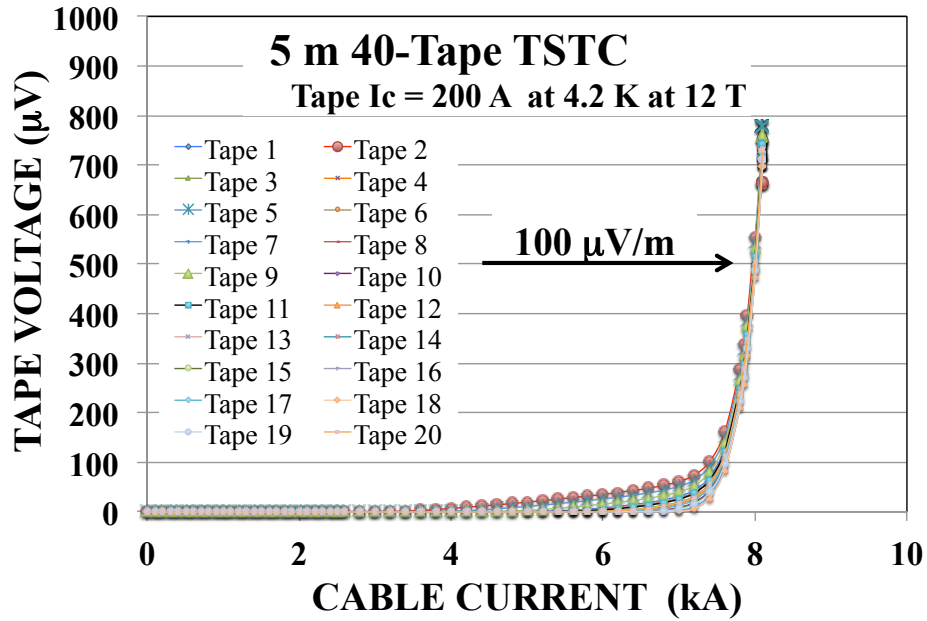


(a)

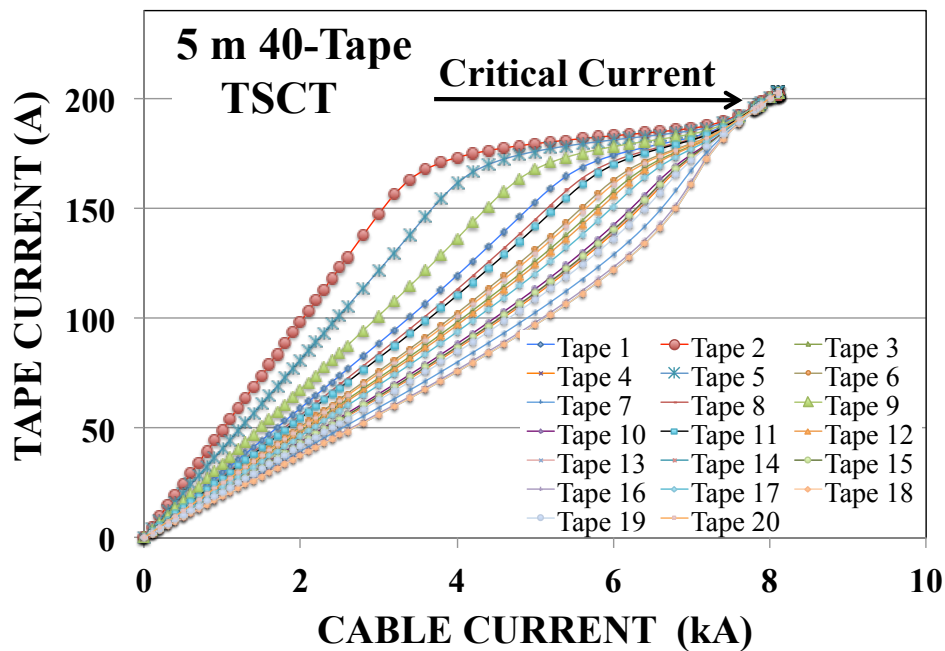


(b)

Fig. 7. Simulation analysis results of 1 m, 40-tape TSTC conductor at 77 K in self-field. Voltages (a) and currents (b) of 20 of the 40-tapes plotted as a function of the total cable current.



(a)



(b)

Fig. 8. Simulation analysis results of 5-m, 40-tape TSTC conductor at 12 T and 4.2 K. Voltages (a) and currents (b) of 20 of the 40-tapes plotted as a function of the total cable current. Long cable is affected less by non- uniform termination resistances.

### 3) Second straight sample with soldered joint

A second straight sample with overall dimension (total length of 1.16 m) as that of the first sample, was prepared and tested at the FBI facility, KIT. The second sample was fabricated in a



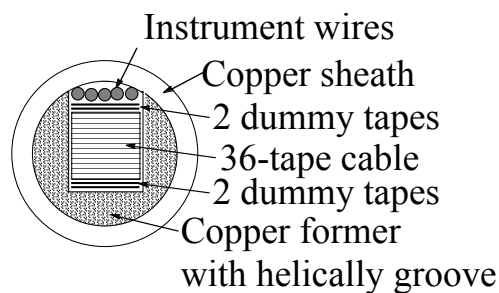
different way. Instead of soldering the twisted stack in a copper tube, the 36-tapes with 4 dummy tapes were mounted in a helical groove with a 200 mm twist-pitch. The helical groove was machined on an OFHC copper rod, as shown in Fig. 9. These tapes were not soldered in the copper rod.

In order to obtain uniform and low termination resistances a soldered joint “folding fan” method was developed. The folding fan joint method will be discussed in the following section. The folding fan joint of the second sample is shown in Fig. 10. To make the termination resistance lower and uniform the fan joint was made longer and BSCCO tapes were used (Soldered REBCO-BSCCO Folding-Fan termination). As shown in Fig. 10(b) one BSCCO tape was inserted between two REBCO tapes of the stacked tapes improving the current redistribution (the electrical resistance of a BSCCO tape is symmetric while the one of REBCO is asymmetric due to the architecture of the tape and the substrate and buffer materials). Details on how the folding fan joint was assembled and prepared are shown in Fig. 10.

Unexpectedly, the measured critical currents of this sample were significantly degraded, and the measured values kept degrading at each current charge even if the test conditions were same, as shown in Fig. 11. For example, at 8 T in Fig. 11 the critical currents decreased from 3.3 kA to below 3 kA, and at 12 T the critical current degraded by about 80% from that expected value from single-tape data. Also the n-values were below 10 as seen in Fig.11. After the critical current test at various fields up to 12 T, a cable tension test was performed.

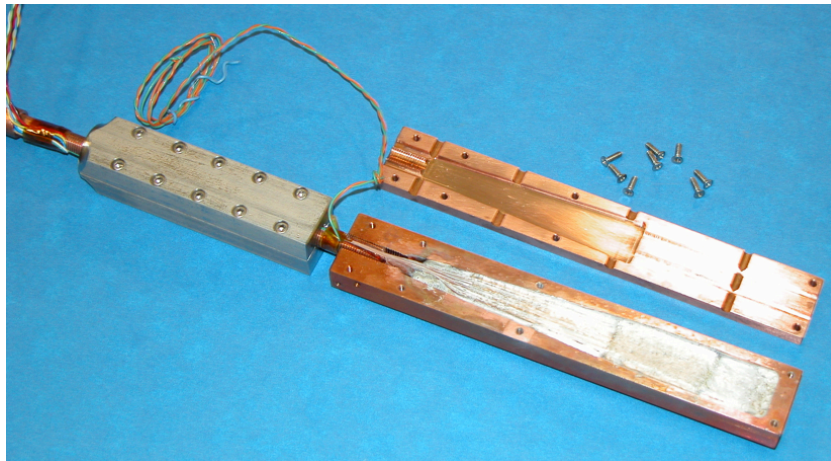


(a)

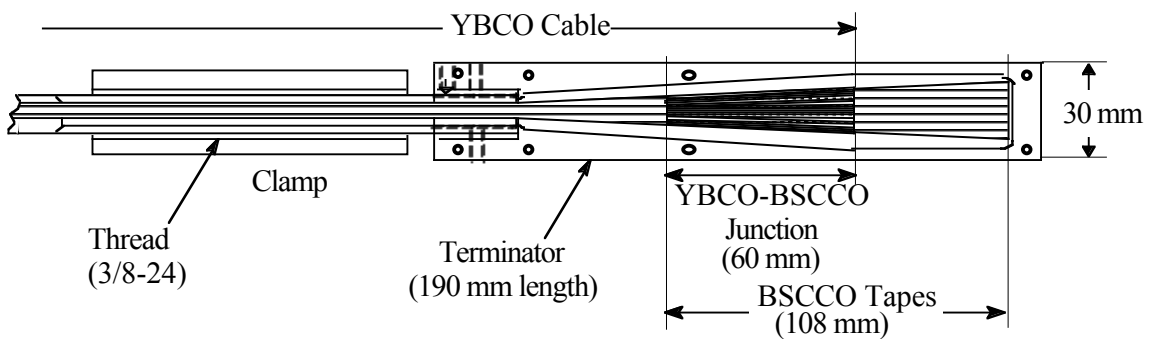


(b)

Fig. 9. (a) 36 tape, SuperPower REBCO in a helical groove of 200 mm twist-pitch on 9.5 mm diameter OFHC rod, before mounting voltage tap wires, but seeing three voltage tap copper tapes. (b) Cross-section illustration of the conductor, sheathed with a copper tube (9.5 mm ID, 12.7 mm OD).



(a)



(b)

Fig. 10 (a) Folding fan joint with BSCCO tapes (soldered REBCO-BSCCO Folding-Fan termination) of the second straight sample tested at KIT. A stainless steel square grip is mounted near the termination for a cable tension test. (b) Illustration of the termination and tension test grip.

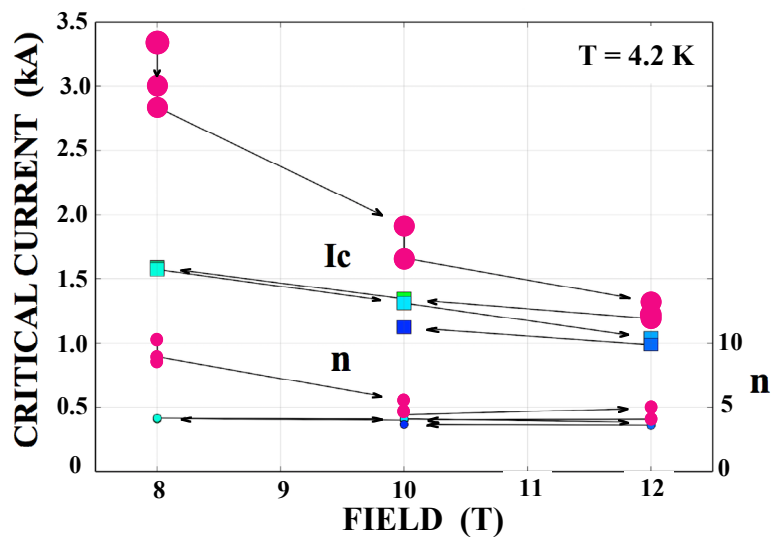


Fig. 11. Results of critical current vs. field of the second sample tested at KIT.

The critical current behavior of this sample is still not well understood. After the high magnetic field tests the cable was diagnosed and tape critical currents were investigated. The tapes were significantly degraded as expected, but it revealed that the degradations were along the entire length of the tapes, and not only at the high-field zone. It is important to notice that the tape degradation might have happened during the tension test that was performed after the critical current measurements. For this set of measurements, it was not possible to determine the origin of the abnormal critical current behavior of the cable.

## B. Coiled Pentagon Sample Tests

In addition to testing straight samples, we have developed a new magnet winding method called the Stacked-Tape Twist-Wind (STTW) technique for a TSTC conductor; suitable for the fabrication of small diameter coils and complicated 3D windings of 2G HTS tape cables [9]. Four samples of REBCO tapes of 2.5-turn pentagonal-shape coils were fabricated and tested at 4.2 K using a 195 mm warm bore Bitter magnet at NHMFL, Florida State University [9].

Sample currents for the first three samples were provided using a 20 kA, 10 MW Bitter magnet DC power supply through a 4.7 m-Ohm stainless-steel tube resistor connected in series with the test sample. The tested cables were 2.3 m length composed of 50 (or 40 for the fourth sample) stacked tapes (SuperPower, 0.1 mm thick and 4 mm width). They were wound using the STTW method on a 165 mm diameter pentagonal cylindrical holder made of aluminum or G10 as specified later.

### *1) First pentagon sample*

The test result of the first sample (the first pentagon sample) showed that the critical current at the criterion of 100  $\mu\text{V/m}$  was 4.0 kA with a low  $n$ -value of 12 at 19.7 T as reported earlier [9]. The cable quenched at 4.7 kA and showed a clear degradation compared to the expected value from single tape performance. The cable itself was soldered between the stacked tapes but it was not well supported in the round groove therefore it was thought that the Lorentz force might have caused the degradation. Unfortunately the sample burned out after the first test run due to an excess in current through the sample.

### *2) Second pentagon sample*

The second pentagon sample was made with the same methodology as that of the first one, but it was not soldered. The conductor was supported with Stycast epoxy in the groove of the aluminum sample holder. The sample carried 10 kA at 4 T without developing any voltage. The critical currents were measured at various fields from 4 T to 20 T. However the critical currents of the sample were degraded by about 50%, showing noticeable resistive component on the V-I curves as the tests progressed. At the end of the measurements and following a careful analysis of the current signal through the sample, it was noticed that a high current spike (with values that were few times the critical current value) was produced at the end of each shot for a few hundred milliseconds when the sample current was dumped (the sample current was provided using a 20 kA, 10 MW Bitter magnet power supply). The over-current could be a possible cause of

degradation of the sample performance.

After the high-field test at the NHMFL the second pentagon sample was tested at 77 K in self-field. The critical current was evaluated in order to investigate sample condition. V-I curves of the 1 m length center section of the coiled sample exposed to the high-fields and a straight current-feeder section of the leg including a 90° bending section clearly showed resistive transitions starting from low current levels. The cable was clearly damaged during the high-field test.

### *3) Third pentagon sample*

The third pentagon coiled sample was wound on a G10 holder, of the same dimensions of the aluminum ones used previously, using the STTW method. This sample was tested in the same way as that of the first and second samples. Unfortunately, at 6 T and at about 10 kA, an accidental manual dump of the 20 kA sample current power supply was performed due to noisy signals and it damaged the cable at the 90° transitions between coiled section and current leads. Both the positive and negative 90° transitions of the cable became resistive ( $\sim 200$  n $\Omega$ ).

Although these three samples might have been damaged due to the over currents of the Bitter magnet power supply, the first and second pentagon samples showed significant degradations of about roughly 50% compared with the critical current expected from the single-tape critical current in perpendicular field (parallel to the c-axis). Therefore, the large Lorentz load ( $\sim 60$  kN/m) experienced by those cables tested at the high-fields was thought to also be one of the possible causes of the degradation and was investigated further with the fourth pentagon sample as described in the next section. It is noted that the sample length of the pentagon coils in the high-field zone was more than 1 m, therefore the termination resistance effect is expected to be minor compared to the case of the straight samples tested at KIT where the length exposed to the high field was only 100 mm.

### *4) Fourth pentagon sample*

The fourth pentagon sample was fabricated with a better cable support method with soldering and Stycast, and reinforcing the 90° bent sections with soldered copper tubes. This sample was tested using small DC power supplies in parallel instead of the 20 kA, 10 MW bitter power supply. The tested cable was made of 4 mm width SuperPower REBCO tapes (SCS4050-AP). Fig. 12 shows the sample fabrication steps. The pentagon sample holder was made of G10. First, braided copper was inserted in the groove, and then a 40-tape REBCO stacked-tape cable was wound on the braided sleeve using the stacked-tape twist-winding (STTW) technique (Fig. 12(a)). The stacked tapes with braided copper were soldered with 52%In-48%Sn solder (Fig. 12(b)). The 90° bent sections were encapsulated in 90° elbow copper tubes and soldered (Fig. 12(c)). The soldered braided cable was glued with Stycast (Fig. 12(d)). Stycast was filled underneath the soldered braided cable to support Lorentz load applied inward during a high-field test.

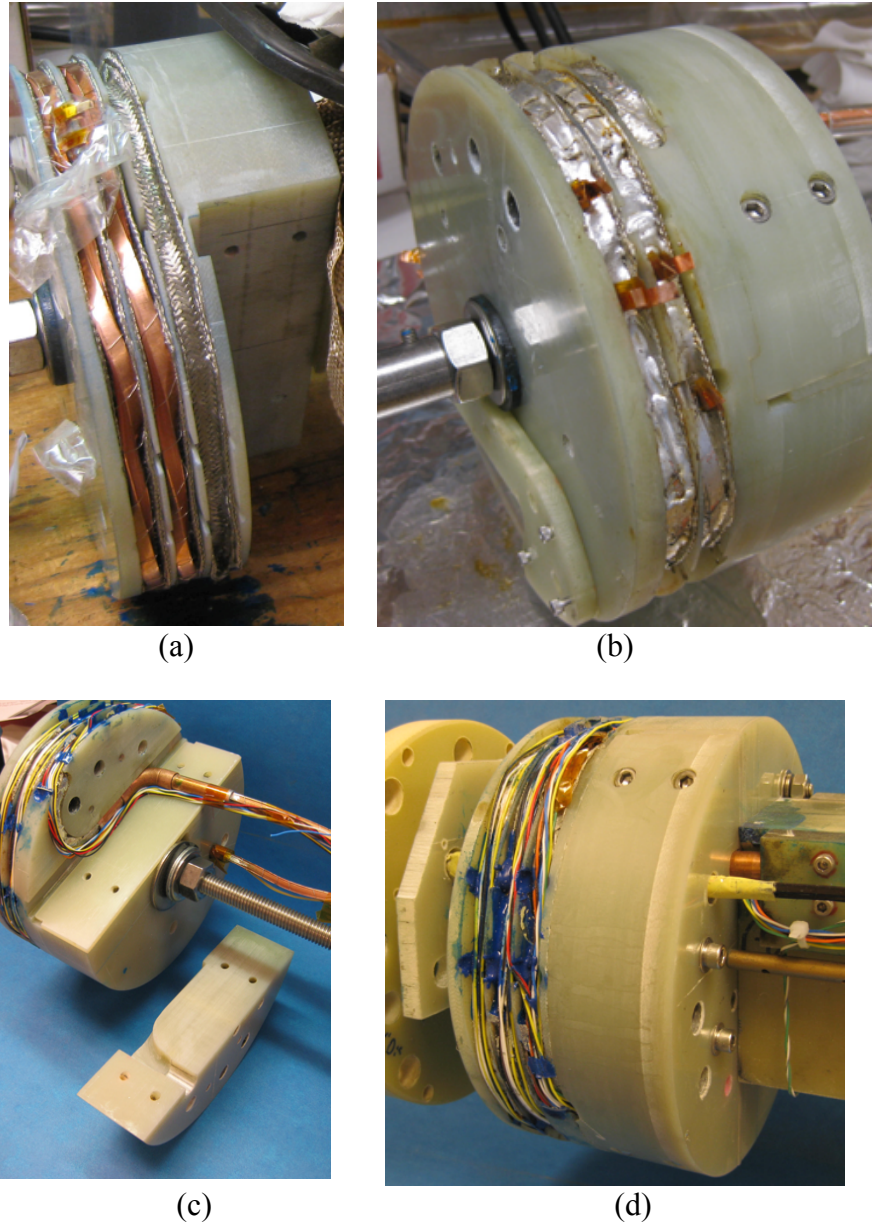


Fig. 12. Sample with instrumentation wires wound in a pentagon G10 holder. (a) 40-tape cable wound on braided copper in the pentagon shape groove. (b) Cable soldered with braided copper. (c) 90° bent sections of the cable in copper tube and soldered. (d) Test sample finished with Stycast on a probe.

Fig. 13 shows the test results of the critical current measured at the criterion  $100 \mu\text{V}/\text{m}$  in liquid helium with background magnetic fields up to 17 T, the maximum field of the test facility. A cyclic load test was performed between 10 T and 17 T. As seen in the figure no cyclic load effect was observed. The critical currents between 10 T and 17 T were degraded by 16% from single tape critical currents measured in perpendicular field. From these results, we can conclude that Lorentz loads up to  $102 \text{ kN}/\text{m}$  ( $17 \text{ T} \times 6.0 \text{ kA}$ ) might not degrade the critical currents since they do not

change with the fields or the Lorentz loads between 10 T and 17 T applied for multiple cycles. Overall engineering critical-current density  $J_e$  was 117 A/mm<sup>2</sup> for the present conductor considering an overall averaged diameter of 8.1 mm. If only the conductor cross-section of 4 mm x 4 mm is considered,  $J_e$  is estimated to be 375 A/mm<sup>2</sup>. If the circular envelop of the TSTC conductor (5.7 mm diameter) is considered, then  $J_e$  is 239 A/mm<sup>2</sup>. The fourth pentagon coiled TSTC conductor was successfully tested. The conductor seemed to be very well supported, however the sample showed quenches similar in behavior to a thermal runaway after 200  $\mu$ V/m criterion. Origins of the quenches are under investigation.

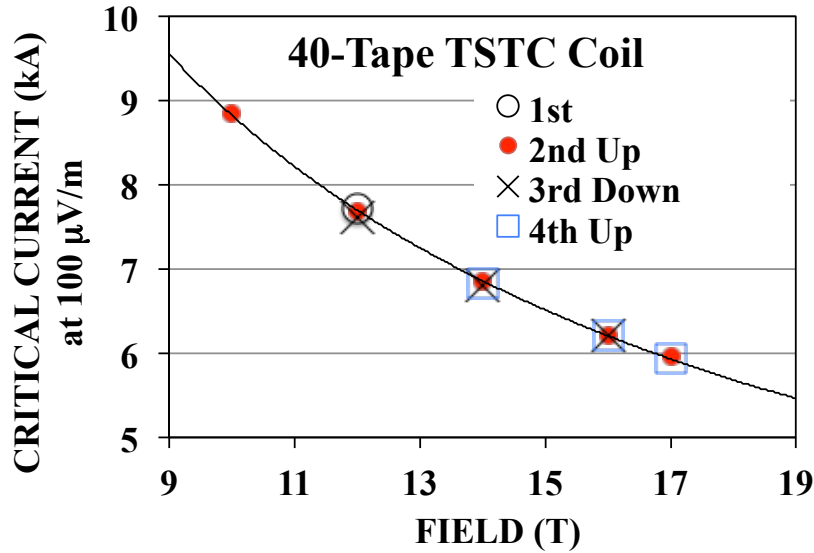


Fig. 13. Measured critical currents of the fourth 40-tape Superpower TSTC conductor sample tested at NHMFL. No cyclic load effect was observed.

### III. SOLDERED FOLDING-FAN JOINT

A soldered compact termination method has been developed for a TSTC conductor. Stacked REBCO tapes (32 tapes) are spread partially to open the stacked tapes in a way of a folding-fan at the cable end to make a joint, as shown in Fig. 14. The stack of tapes, spread circularly, is mounted on a copper termination plate where the superconducting sides are facing the copper plate, so that each tape has a direct surface contact with the copper plate. Both ends of the tape stacks are covered with copper strips to support the stack of tapes. A dummy tape is inserted between the outermost-stacked tape and the copper strip at both far ends of the stack of tapes. In this way, the outermost REBCO tapes (#1 and #32) also have the same surface facing the copper plate as the other tapes. In Fig. 14 the folding-fan terminator is designed so that each REBCO tape has an opened surface of about 20 mm<sup>2</sup> facing the copper plate.



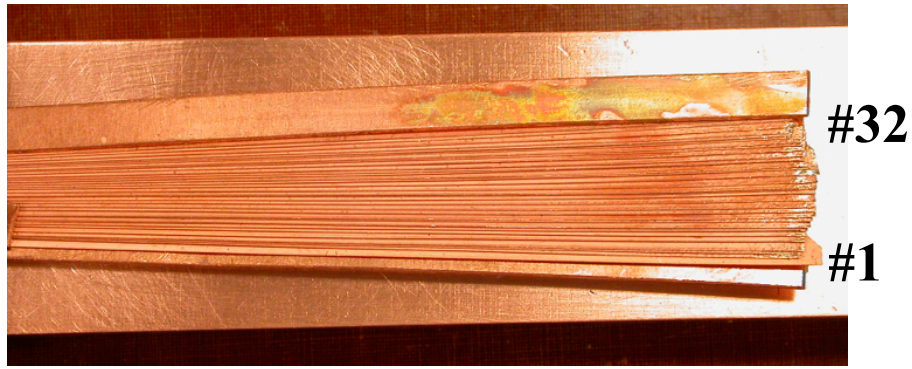


Fig. 14. A photo of spreading REBCO 32-tapes open circularly on a copper plate to fabricate a folding-fan termination.



Fig. 15 A soldered folding-fan termination fabricated.

Fig. 15 shows a fabricated folding fan. A 70-mm length end section of a TSTC conductor was soldered on a 9.5 mm thick copper plate. The copper plate is connected to a copper power cable to supply a current to the conductor. The termination length and the opened surface of each tape will be optimized in the future to obtain proper terminator size and uniform electric resistance.

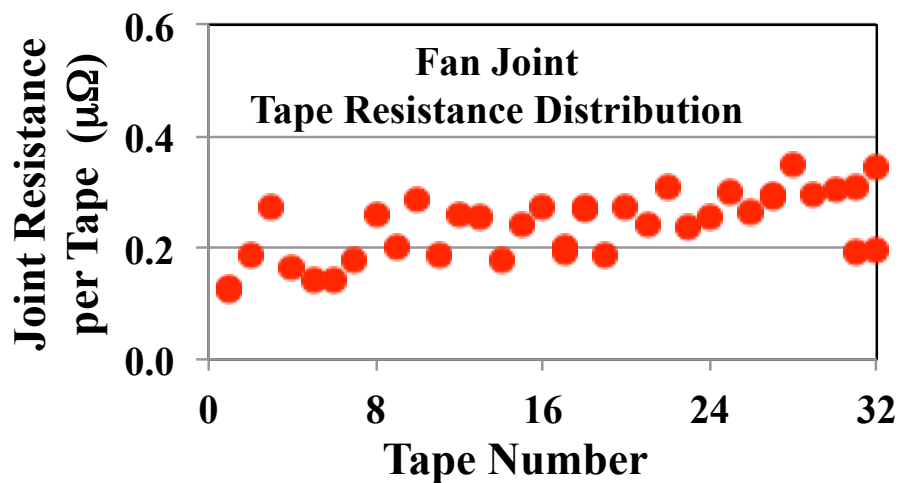


Fig. 16. Termination resistance distribution of a folding fan termination of 32-tape REBCO cable. The average resistance and the standard deviation are 238 n $\Omega$  and 59 n $\Omega$ , respectively.

From the initial linear slope of a measured V-I curve of the folding-fan termination at 77 K the cable-termination resistance was about 6.0 n $\Omega$ . Each tape termination resistance between any tape of the stack and the soldered copper was also measured for this 32-tape folding-fan termination. The test results are shown in Fig. 16. The average termination resistance was 238 n $\Omega$  with a standard deviation of 59 n $\Omega$ . As seen in Fig. 16 the termination resistances slightly increase from Tape #1 toward Tape #32 which was at the far end of the stack of tapes from the copper plate. The soldering and preparation of this joint should be improved to obtain a more uniform resistance distribution as it is very important to reduce joint termination resistances with uniformity in order to establish a uniform current distribution among cable strands.

To summarize our work on joints, we would like to remind the reader the three termination methods for a 2G coated REBCO tape stacked cabled conductor we have developed: 1) REBCO-BSCCO, 2) REBCO-REBCO and 3) soldered folding fan. The REBCO-BSCCO, REBCO-REBCO termination methods have been reported earlier [12]. The folding-fan termination method was a soldered termination developed for a coated 2G-tape cable having asymmetric conductivity. These termination concepts for a 2G REBCO tape cable have been demonstrated. They have shown very good uniform termination results. The folding-fan method will be very useful for a compact soldered termination. A modification of the folding-fan method has also been developed using BSCCO tapes (electrically symmetric HTS tapes) and was used for the second straight sample and discussed in Fig. 10.

#### IV. SCALE-UP CONDUCTOR

The basic TSTC conductor can be made by stacking tapes and then twisting them along the axis of the stack. It is important to keep the tapes free during the twisting process in order to allow slipping of the tapes with respect to each other. To use this conductor for a magnet where the conductor can be exposed to a severe electromagnetic force, the conductor has to be mechanically supported well against the force. Also a conductor should have proper stabilizer to protect from abnormal disturbances such as quenching. For this purpose various conductors have been proposed using copper and aluminum formers [5]-[7].

We have made a single channel copper former to stack 40 tapes in a helical groove on a 9.5 mm diameter copper rod. We have sometimes faced difficulties to uniformly insert 40 tapes in such a deep helical groove without causing unexpected local strains along the length, as mentioned for the second straight sample in Section II A (3). Fig. 17 shows one example where the tapes are dislocated with torsion and they are not stacked correctly. In order to avoid such a problem the stacked tapes can be mounted vertically (tape surfaces are parallel to the side wall of the groove) as shown in Fig. 18. Another method could be to fabricate a TSTC conductor without a former (but inserted in a copper jacket or a braided sleeve), and then mount it in a former, as shown in Fig. 19. In the sample showed in this figure, a 3 mm width, 0.1 mm thick, 30-tape stack was twisted with 200 mm twist-pitch, and enclosed with a braided copper sleeve, and then soldered. The TSTC basic conductor of 6 mm diameter can be mounted in a groove on a copper rod. The groove on the copper rod can be straight or helical. For the latter the conductor can be double



twisted through the conductor twist (twisted stack) and the twist of the conductor within the helical groove.



Fig. 17. Stacked-tapes distorted by twisting in helical groove of former.



Fig. 18. Vertical stack in helical groove where the tape surfaces are parallel to the side wall of the groove.

Fig. 20 shows two other basic conductor fabrication methods with 4 mm-width, 0.1 mm thick tapes. Fig. 20(a) shows a 40-tape conductor which is twisted, braided and then soldered (7.4 mm diameter) similar to the conductor in Fig. 19. Fig. 20(b) shows a square conductor of 40 tapes with a cross-section of 5.8 mm x 5.8 mm which is twisted and soldered to form the square shape of the desired dimensions. The twist-pitch of these TSTC conductors was 200 mm. To follow, we will estimate the possible current and current density of these conductors, and also discuss multi-stage cables based on these basic conductors.

Through our measurements, we have confirmed that a 40-tape, 4 mm width, 0.1 mm thick SuperPower 2G-AP TSTC conductor performs with a critical current of 6.0 kA at 17 T and 4.2 K. It is degraded by 16% from the expected single tape data.

For the following discussion and to estimate the values of critical currents of the TSTC

conductors shown in Fig. 20 and Table IV, measured tape data of  $I_c=235$  A at  $B=12$  T and  $I_c=170$  A at  $B=20$  T at  $T=4.2$  K were used. Stabilizer can be easily added to the conductors in Fig. 20(a) and (b). For our calculation we will assume the fraction of stabilizer respect to the total cross section is 63% for Fig 20(a) and 52% for Fig. 20(b). Table IV also shows the estimated performance of the 3 mm width tape cable shown in Fig. 19.

Possible multi-stage cables made with basic conductors are shown in Table V. Triplet, 3x3 and 3x6 conductors are evaluated based on the basic conductors A and B shown in Table IV. The square conductor shown in Fig. 20 (b) can be mounted on a former having three square channels. The conductors will be rigidly supported by the former. Additional solder or impregnation will be added to properly support the conductors in the former. As shown in Table V a 3x3 round cable is a 50 kA class HTS conductor, and a 3x6 Cable-in-Conduit-Conductor (CICC) cable can carry 100 kA (Fig. 21). The main advantage of a TSTC conductor is that it can be easily scaled up to obtain these conductors designs while providing the appropriate amount of stabilizers in the cable.

TABLE IV  
Two basic conductor performances expected from single tape data at 4.2 K.

	Basic Cable	Critical Current	Overall $J_c$
A	4 mm width, 0.1 mm thick, 40- tapes, 7.4 mm Dia. braided soldered conductor	9.4 kA(B=12 T)	219 A/mm <sup>2</sup> (B=12 T)
		6.8 kA(B=20 T)	158 A/mm <sup>2</sup> (B=20 T)
B	4 mm width, 0.1 mm thick tape, 40-tapes, 5.8 mm x 5.8 mm, square soldered conductor	9.4 kA (B=12 T)	279 A/mm <sup>2</sup> (B=12 T)
		6.8 kA (B=20 T)	202 A/mm <sup>2</sup> (B=20 T)
C	3 mm width, 0.1 mm thick, 30- tapes, 6.0 mm Dia. braided soldered conductor	5.3 kA (B=12 T)	188 A/mm <sup>2</sup> (B=12 T)
		3.8 kA (B=20 T)	135 A/mm <sup>2</sup> (B=20 T)

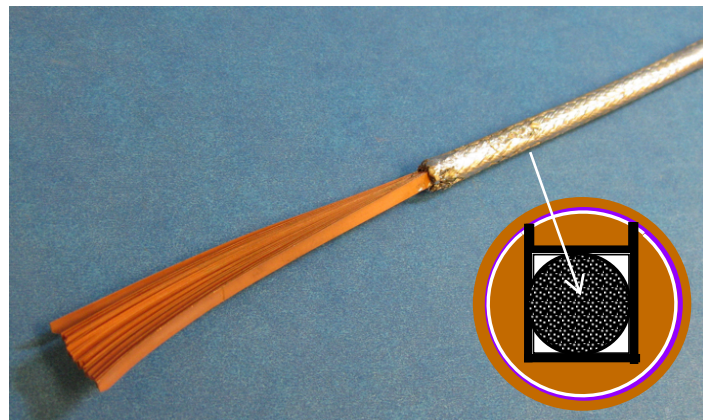


Fig. 19. Mounting TSTC basic conductor in a groove.



(a)



(b)

Fig. 20. (a) 7.4 mm diameter braided soldered 40-tape (4 mm width) TSTC conductor. (b) Square (5.8 mm x 5.8 mm) soldered 40-tape (4 mm width) TSTC conductor.

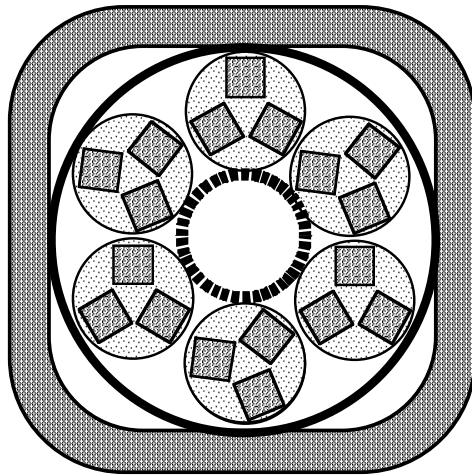





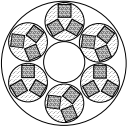


Fig. 21. 3 x 6 CICC (70 mm x 70 mm).

TABLE V  
Multi-stage conductors performances calculated based on single tape data.

Conductors	$I_c$ at 20 T, 4.2 K (kA) [ $J_e$ (A/mm <sup>2</sup> ) ]	Conductor Dimension (mm)	Conductor Cross- Section	Stabilizer Volume ratio Tape/Total
Braided soldered	6.8 [ 158 ]	Dia. 7.4		37%
Triplet	20 [ 101 ]	Dia. 16		24%
3x3 cable	61 [ 99 ]	Dia. 35		
Square soldered	6.8 [ 202 ]	5.8 x 5.8		48%
3-channel basic cable	20 [ 81 ]	Dia. 18		19%
3x6 cable	122 [ 45 ]	Dia. 58		

## V. CONCLUSIONS

We have been investigating Twisted Stacked-Tape Cable (TSTC) conductors made of 2G coated HTS tapes. For high-field applications, various TSTC conductors of 40 to 50 tapes with 4 mm width SuperPower REBCO tapes have been fabricated and tested. Two straight 40-tape TSTC conductors with copper stabilizer have been tested at the FBI facility, KIT, Germany. Additionally, four solenoid coiled TSTC conductor samples of 50 or 40 REBCO tapes wound on a pentagonal shape cylindrical surface using Stacked-Tape Twist-Winding (STTW) method have been tested at the NHMFL, FSU, Florida. These test results provided very useful information on the electromagnetic load effects and termination resistance distribution effects in a TSTC conductor at high fields and high currents.

Our experiences and the incremental knowledge acquired during those tests were discussed, and a successful operation of a 40-tape TSTC conductor of SuperPower 2G-AP tapes was presented. The critical current of this sample was 6.0 kA at 17 T and 4.2 K. A cyclic test was performed between 10 T and 17 T and no cyclic load effect was observed. The measured critical currents

were consistently repeatable. The n-values were as high as 35. The critical currents between 10 T and 17 T were degraded by 16% from the single tape data. However, there was no clear evidence that the cable experienced Lorentz load degradation for electromagnetic loads up to 102 kN/m. It is very important to support a conductor against Lorentz force. For this particular TSTC conductor, it was supported with solder and Stycast. The 90° bent sections of the cable were protected with copper tubes with solder filling.

As discussed with the results obtained with the samples tested at KIT, for tests of a short sample (especially a high-field test with a straight sample, where the sample length in the high field zone is usually short), the non-uniform current distribution in the cable sample is dominated by the termination resistances of the tapes. It is believed that this effect will result in a poor cable performance and a low n-value. It is therefore important to provide uniform and low joint resistances for a short-cable test. Longer termination should be used.

A Twisted Stack-Tape Cable (TSTC) method can be used with various HTS tapes including BSCCO tapes (it is not limited to 2G REBCO tape), and it has the following advantages: simple cabling, high tape usage, good bendability, compact cabling, high current density, easy scale-up for high-current and large conductors, adjustable stabilizer content to provide proper stability and protection [9], [17].

Recently we also have developed an analytical model to evaluate bending degradation of a TSTC conductor [17]. It was found that a perfect slipping model (PSM), where the tapes can slip so that the internal longitudinal axial strain can be released while minimizing the bending strains of a TSTC conductor; properly predicts the experimental behavior observed with a TSTC conductor [18]. It should be noted that a TSTC conductor has good bendability because compressive and tensional stresses of each twisted tape due to bending balance in one full twist-pitch and cancel out over the short length even for a long cable.

Round and square conductor fabrication methods using soldered TSTC were discussed to evaluate their use in developing large CICC conductors suitable for magnets.

A TSTC conductor is very useful, especially for high-field fusion magnets requiring high current cables such as Cable-in-Conduit Conductor (CICC). This conductor could be useful for other applications such as transmission cables, SMES, and other high-field magnet devices.

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