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journal or publication title	Journal of Physics: Conference Series
volume	1293
page range	012065
year	2019
URL	http://hdl.handle.net/10655/00013153

doi: https://doi.org/10.1088/1742-6596/1293/1/012065

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To cite this article: T A J Meulenbroeks *et al* 2019 *J. Phys.: Conf. Ser.* **1293** 012065

IOP Conf. Series: Journal of Physics: Conf. Series **1293** (2019) 012065 doi:10.1088/1742-6596/1293/1/012065

Observation of a non-uniform current distribution in stacked high temperature superconducting tapes

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Abstract. High Temperature Superconductors (HTS) improve upon low temperature superconductors in many ways and the ability to cope with a non-uniform current distribution might be one of those improvements. To put this to the test, an experimental setup is designed to force a non-uniform current upon a stack of 5 HTS tapes, using a worst case current feeding method. The experiment can help determine the potential of this conductor design and is part of the ongoing effort to develop a non-transposed stacked HTS conductor for the nuclear fusion reactor FFHR. The results clearly show that the conductor sample is able to stably conduct a current equal to its critical current, although at an elevated electric field of roughly 5 mV/m. This means non-transposed stacked tape conductors remain stable, even if a worst case non-uniform current is constantly forced upon them. A hypothesis to explain this abnormally high electric field is formulated on the basis of the results, however additional research is needed to verify it. It states that the electric field is necessary for the tapes to share current and would mean that in a properly engineered application, these losses due to the electric field, would only occur during start-up. Overall it is clear that this experiment proves the excellent stability of non-transposed stacked HTS tapes and their ability to conduct a non-uniform current.

1. Introduction

Traditional Low Temperature Superconductors (LTS) struggle with conducting non-uniform currents and often quench prematurely when exposed to them [1]. Transposition of the conductor is necessary to avoid a non-uniform current distribution and often makes the conductor significantly more complex, especially when using High Temperature Superconductors (HTS) [2]. Besides making the conductor more complex, in some cases, transposition increases the strain in the conductor [3] [4]. This strain can reduce the performance of the superconductor [5].

Research led by the National Institute for Fusion Science (NIFS) has proven that it is possible to build and operate a coil, using a non-transposed stacked HTS tape conductor design called Stacked Tapes Assembled in Rigid Structure (STARS [6]). It is highly likely that, during the test of this coil, it had been subjected to a non-uniform current distribution but did not quench, noting that the increased thermal stability of HTS is the essential key to its success. This has been the inspiration for the main research question of this paper: Are stacked HTS tapes able to stably conduct a worst case non-uniform current? After answering the main research question, the aim is to make an assessment of the applicability of the non-transposed stacked tape conductor design.

IOP Conf. Series: Journal of Physics: Conf. Series **1293** (2019) 012065 doi:10.1088/1742-6596/1293/1/012065

2. Method

The goal of the experimental setup is to force a worst case non-uniform current unto a superconductor sample of 5 stacked HTS tapes. This is done by clamping the ends of the tape stack between copper connection plates and only supplying current to the top plates. It has to be noted that this is not the proper way to feed current to HTS tapes, but is used in this case, exactly because this causes a non-uniform current distribution [7]. The top plates will only be in contact with the first tape, and not with the rest of the tapes, thus the current will prefer to flow through the first superconducting layer to the other side, as all other paths offer more resistance (see Figure 1). All other paths offer more resistance because they cross resistive layers. In Figure 2 it is shown how, in a tape, the resistive layers sandwich the superconducting layer and form the resistive barrier which the current is forced to cross if it is to reach the lower tapes.

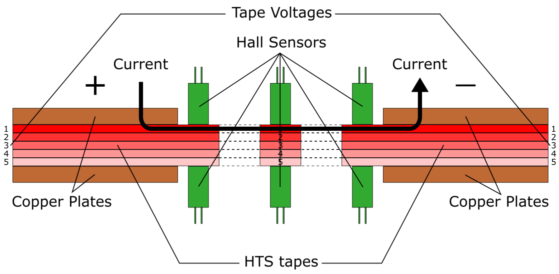

Figure 1: Simplified schematic side view of the experimental setup, showing the HTS tape stack clamped between the copper connection plates at each end. The current is only fed from the top plates, forcing the current to become non-uniform. Additionally the location of the Hall sensors and voltage taps are depicted.

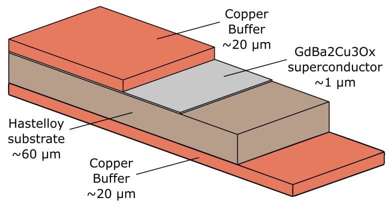

Figure 2: Simplified structure of a single HTS tape used in the experiment. The metallic layers sandwiching the superconducting layer, especially the hastelloy substrate, are the resistive barrier the current has to pass, to get to the next tape.

The tapes that make up the superconductor sample are 4mm GdBa2Cu3Ox tapes produced by SuperOx [8]. Each tape has a minimum critical current of 120 A at 77 K and is 1.7 m long. Five of these tapes are stacked on top of each other to make up the sample, resulting in a total critical current capacity of 600 A. The tapes are stacked with their superconducting layer up, towards the current feeding connection plate so the current does not have to cross the hastelloy layer to reach the first superconducting layer. In addition to the before mentioned copper connection plates, some materials and equipment are added to the experiment to ensure realistic HTS conductor behavior. A copper jacket enveloping the tape stack is added for thermal stability and clamps are added to hold the jacket in place. Additionally the clamps apply pressure to the tape stack, reducing the contact resistance between individual tapes.

The experimental setup also needs sensors to verify whether the current distribution is indeed non-uniform and to detect any thermal runaway processes. The non-uniformity of the current distribution is measured by 3 sets of 2 Hall sensors which are depicted in Figure 1. Each set of sensors is placed perpendicular to the flat tape surface in order to measure the magnetic field generated by the current flowing through the sample. The difference between the sensors can verify whether the current distribution is asymmetric. And non-uniformity can be verified by measuring asymmetry. Two sets of Hall sensors are located at the ends of the copper jacket, as close as possible to the copper connection plates and the final sensor set is located at the middle of the jacket. All sensors are directly touching the stack of tapes via slots carved into the copper jacket to ensure the distance to the tapes is minimal and they are held in place by fiber reinforced plastic blocks to ensure minimal movement between experiments. A possible resistive transition or thermal runaway can be detected by measuring the voltage across each tape. The voltage is measured by voltage taps soldered to the top of each tape at both ends. To make the setup complete, a bakelite support plate was manufactured to minimize movement of the parts and to make insertion into the stainless steel liquid nitrogen bath more convenient. A picture of the entire setup is shown in Figure 3.

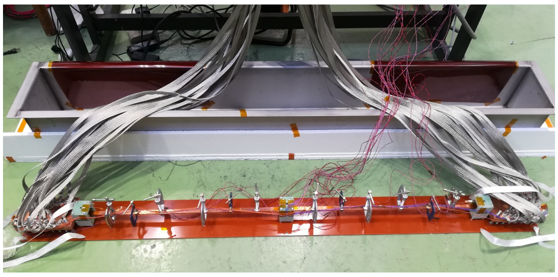

Figure 3: Picture of the experimental setup. In the bottom the copper jacket is visible. It surrounds the stack of tapes and is held together by clamps. The rectangular blocks in the middle and at the ends contain the Hall sensors. In the top the liquid nitrogen bath and the current leads are visible. The stainless steel container is roughly 2 m long.

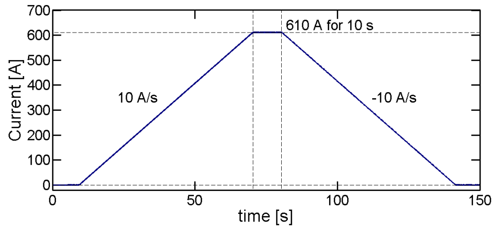

Figure 4: The structure of the current waveform applied to the sample in the 610 A test. The ramp rate and waiting period at maximum current were kept the same during all tests and were chosen as such to reduce transient effects as much as possible.

The experiment is started by lifting the experimental setup described above, into the liquid nitrogen bath and connecting a current source to the top connection plates via current leads. Next the bath is filled, cooling the setup down to 77 K. When the current waveform (Figure 4) is applied, the measurements from the voltage taps are closely monitored and if the voltage becomes unstable or in other words a thermal runaway is registered, the power supply is switched off manually. The maximum current of the waveform is increased step by step until thermal runaway has occurred.

3. Results

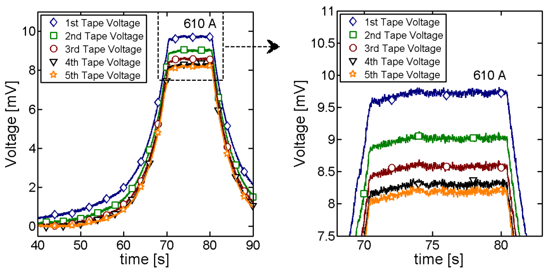

Figure 5: The tape voltage measurement that shows that a current of 610 A was stably conducted (Ic stack = 600 A), although at an elevated electric field of 5 mV/m. Distinct voltage differences between the tapes are visible

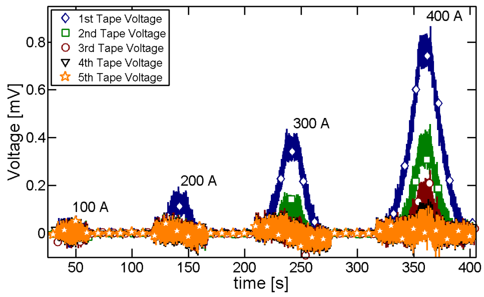

Figure 6: Development of the tape voltages while increasing the maximum current of the waveform. Note as the currents become larger, each tape voltage becomes non-zero in order from top to bottom.

Figure 5 shows that the conductor sample has stably conducted 610 A, which exceeds the minimal critical current of the sample stated in the datasheet. Though, it is important to note that even at low currents, the tape voltages exceed 10 $\mu V/m$ (see Figure 6) and at maximum current, an electric field of 5 mV/m is reached. This electric field far exceeds the threshold of 10 $\mu V/m$, commonly used for determining the critical current. Thermal runaway was verified during all tests of 620 A and more. During the constant current portion of the waveform, distinct differences between the tape voltages are observed. The differences between them become gradually smaller, the further the tape is from the current feeding connection plate.

Another note on Figure 6 is that as the currents become larger, each tape voltage becomes non-zero in sequence.

The results from the Hall sensors show that the current distribution at the negative and positive terminal, close to the connection plates, is non-uniform (see Figure 7). At both terminals, the measured magnetic field of the top sensor is larger than that of the bottom sensor. The result from the middle sensor shows small to no difference between the top or bottom sensors. It is likely that in the middle the current distribution is symmetric.

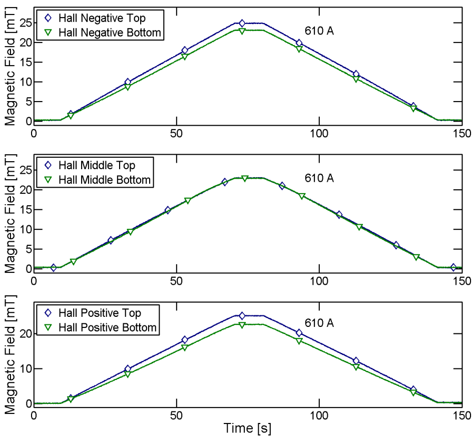

Figure 7: Results that show the current running through the sample at the positive and negative terminal is asymmetric and thus non-uniform. The result from the middle sensors imply that is likely that the current distribution is more symmetrically distributed in the middle.

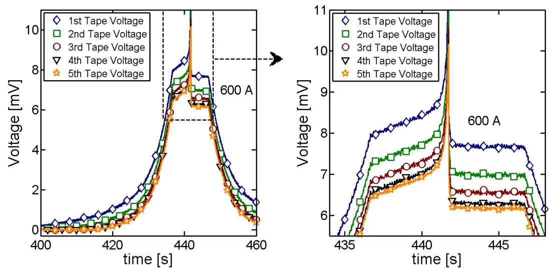

Figure 8: Graph of the recovery phenomena. Note that after the maximum current of the waveform is reached, thermal runaway of the tape voltages occurs for all tapes, followed by a sudden recovery back to a stable regime.

In Figure 8, an example of the recovery phenomena is shown. It was observed several times during tests near 600 A. After the maximum current of the waveform was reached, thermal runaway was detected, followed by an sudden crash back to stability.

4. Discussion

The fact that the sample has stably conducted a worst case non-uniform current, equal to its critical current, proves the excellent stability of non-transposed stacked HTS tapes. The tape voltages at constant current are relatively high compared to the critical electric field criterion (10 $\mu V/m$) but remain stable for 10 seconds and do not show any sign of instability/thermal runaway.

The Hall sensors confirm that the current distribution at the ends of the positive and negative terminals was asymmetric and thus non-uniform (see Figure 7), just as expected by the method. It has to be noted though, that 2D Biot-Savart analysis has shown that the uncertainty of the measurement was relatively high. The maximum deviation in magnetic field, due to the uncertainty of the sensor location was 1.4 mT. The maximum deviation in magnetic field, due to changes in the current distribution was 2.1 mT. Even though those two deviations are similar in size, there is reason to believe the measurement results from the negative and positive terminal are truthful. As pointed out in the methods, theory supports that the current distribution is non-uniform at the terminals because of the way the experiment was constructed. Additionally, it is suggested by theory, that it takes some length along the conductor to share the current between tapes [9]. Both arguments add much to the likelihood that the current distribution at the terminal was non-uniform. Remarkable is the Hall sensor results of the middle sensors. These results imply that it is likely that the current distribution naturally grows towards a symmetric distribution and will redistribute current among the tapes to do so.

Even though it is remarkable that the conductor sample is able to stably conduct a non-uniform current distribution, the electric field has to be addressed. Electric fields that exceed the standard 10 $\mu V/m$ criterion are observed at much lower currents than the critical current of the sample, some as low as 120 A. Although the diagnostic data of this experiment is not enough to explain this phenomena with absolute certainty, in the next section a hypothesis is formed based on the results observed. The hypothesis consists of two parts. The first part describes the dominant mechanism that creates the electric field at low currents (<300 A), and the second part, the dominant mechanism at high currents (>300 A). The hypothesis is built around the idea that the electric field is necessary to distribute the current between the tapes in the stack and thus the electric field is directly connected to the non-uniform current distribution.

The first part states that the electric fields are created, thus the tapes become resistive, because the critical current density is exceeded and that they are forced to share current with the tape below them. If the the total current flowing through the sample is lower than the critical current of one tape, it is likely that the superconducting layer of the first tape conducts almost all current. The paths through the others tapes are much more resistive because those paths have to cross the metallic resistive layers that sandwich the superconducting layer. The combinations of all metallic resistive layers in between two superconducting layers, for convenience sake, is called the Inter Tape Resistance Barrier (ITRB) and is shown in Figure 9. As the total sample current is increased, a point will be reached where the total sample current will exceed the critical current of the first tape and it will become resistive. As the resistance of the first tape increases, the path to the second superconducting layer becomes comparable in resistivity and the first tape will start to share current with the second tape below it. This first part of the hypothesis is supported by the results shown in Table 1 and Figure 5. Table 1 shows that during three tests, the currents at which the first and second tape become resistive, coincide closely with the critical currents of 1 and 2 tapes (120 A and 240 A respectively). Additionally the voltage differences between tapes shown in Figure 5 match with the mechanisms described in the hypothesis. The voltage differences between tapes are caused by the current flowing through the ITRB and as the current becomes smaller and smaller as it goes down the stack, the voltages differences become smaller and smaller as well.

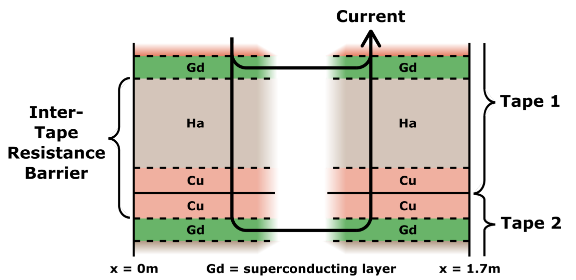

Figure 9: A simplified schematic showing the difference between two possible paths the current can take and their respective resistances. The difference in resistance being twice the Inter Tape Resistance Barrier (ITRB)

Table 1: The currents at which each tape starts its resistive transition for 3 different waveforms. Visible across all waveforms is the similarity between the current at which the first and second tape become resistive and the critical current of 1 and 2 tapes (120 A and 240 A)

Max Waveform Current	600A [A]	550A [A]	500A [A]
Tape 1	122	121	123
Tape 2	237	232	224
Tape 3	347	327	313
Tape 4	389	389	396
Tape 5	406	395	407

The second part of the hypothesis states that at some point, the increase in resistance due to the critical temperature being exceeded, becomes dominant. Note that this effect is caused by the increased resistivity described in the first part of the hypothesis. The combination of the increase in sample current and more superconducting layers becoming resistive, create local heat losses that exceed the cooling by the liquid nitrogen. This could explain the results for tape 3, 4 and 5 in Table 1 and why they occur at lower currents than their respective critical currents, 360 A, 480 A and 600 A. This could also explain the recovery phenomena. As a local hot spot boils off liquid nitrogen at a rapid rate, the nitrogen vapor is pushed outwards, creating a rapid flow that causes flash cooling, bringing the sample back to a stable resistive state. Future research might discover a way to control this phenomena and use it to suppress a thermal runaway, instead of the current approach of protection via shutdown.

If the hypothesis is assumed to be correct, this means that the method used to force the current non-uniform has caused the excessive and premature electric field and thus is the cause of the losses. In other words, to distribute the current between tapes, the electric field has to be present. If no distribution of current is necessary, the electric field would also disappear and the losses with it. This would change the way engineers approach transposition. Transposition would become an option, instead of a necessity. It would become a trade-off between additional losses in AC operation in return for a simplified conductor design and all the benefits that come with it. Moments of AC operation, like the charging and discharging of a coil would be paired with temporary increases in losses and refrigeration, up until the current has distributed itself once more. But as an upside, the manufacturing costs and mechanical performance of the coil would both improve. This opportunity is exactly why it is of paramount importance that future research is focused on verifying or disproving the hypothesis stated in this paper.

5. Conclusion

The experiment described in this paper has proven the excellent stability of non-transposed stacked HTS tapes and their ability to conduct a worst case non-uniform current. The stack of 5 HTS tapes has stably conducted a worst case non-uniform current of 610 A (Ic stack=600 A) at elevated electric fields of roughly 5 mV/m. In this paper, a hypothesis is discussed to explain this abnormally high and premature electric field. The hypothesis states that the electric field is necessary to distribute the current between tapes and that it is directly related to the non-uniform current distribution. Unfortunately, it was not possible to verify or disprove the hypothesis with the data available. If the validity of this hypothesis is confirmed, it would change the way engineers approach transposition. Instead of a necessity, it would become optional to transpose HTS cables. This opportunity is why future research should be focused on verifying or disproving the hypothesis.

Acknowledgements

Special thanks goes to FuseNet for supporting this research.

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