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REBCO coil with robust behavior against local defects wound using two-tape bundle

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Abstract—REBa₂Cu₃O_{7- δ} (RE: rare earth/Y) coated conductors have good critical current characteristics under high magnetic fields. Their application to superconducting magnets generating above 25T is under active study. However, performance inhomogeneity along their length may cause damaging hotspots. Adapted winding technologies are needed to mitigate this phenomenon. One of such winding techniques is the two-tape bundle co-winding method, where two REBCO tapes are co-wound along with an isolating tape to form the conductor. To test this solution, a double pancake coil was wound with one of the pancakes having an artificially degraded short section on one of the tapes, where the critical current is close to 0. The I - V characteristics of both damages and undamaged pancakes are compared and analyzed based on critical current density $J_c(T, B, \theta)$ data, in terms of operation margins. At low voltage levels, similar I - V characteristics for damaged and undamaged pancakes are observed. The behavior is found similar to the expected behavior of a coil whose critical current I_c is locally reduced by 50 %, demonstrating the effectiveness of two-tape bundle for current redistribution in case of local defect, even under high current density.

Index Terms—HTS coil, local defect, REBCO, two-tape bundle co-winding coil.

I. INTRODUCTION

Rare-earth-based coated conductors are suitable to design high field magnets (25 T and more) thanks to their high critical current densities in high magnetic fields. The development of reliable REBCO magnets for high field has been the subject of many studies recently all over the world. The High Field Laboratory for Superconducting Magnets has an ongoing project to develop a 30 T cryogen-free superconducting magnet (CSM) using REBCO insert coil [1]. It is also well established that REBCO tapes are susceptible to local defects which can cause localized hot spots and become the starting point for thermal runaway. To mitigate the effect of local defects, winding techniques that are robust to local defects, such as no insulation (NI), metal as insulation (MI) and partially insulated (PI) coils were proposed [2-4]. However, these methods have drawbacks, such as excitation delay and uncontrolled current loops when turn-to-turn current exchanges occur. Our group suggested to

retain a classical insulated coil approach but using the two-tape bundle technique [1, 5, 6]. The two-tape co-winding idea (Fig. 1) is that at any point the current can distribute between two tapes through their respective copper layers that are in contact. Chances for a local defect to exist at the same location in the two tapes are very low, so the current carrying capability of the bundle as much less variation along the length than that of single tape, improving the reliability. This concept was used successfully in previous studies focusing on mechanical strength and electro-magnetic behavior [6]

The aim of this study is to evaluate the behavior of a coil wound using this concept in case of an actual major local defect. For that a two-tape co-winding double pancake coil was wound. On one of the pancakes, an artificial local defect was created on one of the two co-wound tapes. After introducing the experimental method, we will present the results obtained with this coil in terms of I - V characteristics and thermal stability, then discuss the results with the help of numerical modelling.

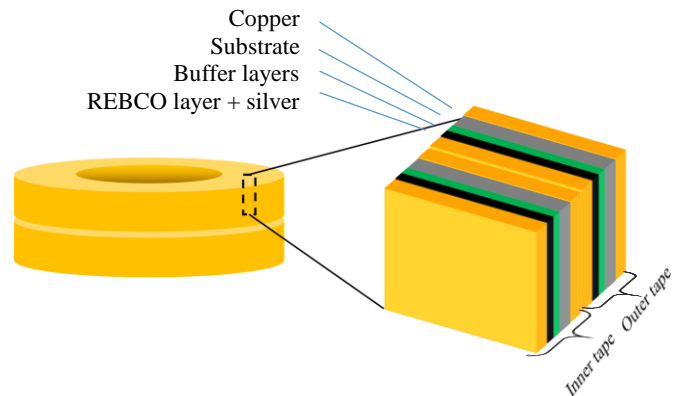


Fig. 1. two-tape bundle co-winding concept

II. EXPERIMENTAL METHOD

A – Test coil specifications

The coil was wound with REBCO tapes produced by Fujikura Ltd. (FESC-SCH04, APCs). The specifications of the REBCO tape and of the coils are summarized Table I. The conductor for this coil is made by bundling two REBCO tapes aligned in the same direction (face-to-back). The two tapes are

Table 1. Properties of REBCO tape and REBCO coil

REBCO tape	
Tape width	4 mm
Tape thickness	0.11 mm
REBCO thickness	2.5 μm
Hastelloy [®] thickness	50 μm
Copper thickness	20 μm
I_c (4mm, 77 K, s.f.)	213.5 A
Double pancake coil	
Turn number	101 turn x 2 layer
Inner diameter	40.0 mm
Outer diameter	94.0 mm
Winding condition	Two-tape bundle face-to-back co-winding
Winding tension	5 kgf
Position of a defect	55th turn of outer tape of bottom pancake
Coil constant	3.78 mT/A

wrapped together in insulation made of fluorine-coated polyimide. The conductor is wound with a tension of 5 kgf to have a tight contact. The pancakes are pressure-impregnated with epoxy resin together with their thin FRP flanges. A high-purity aluminum sheet is bonded in between the two pancakes also with epoxy resin for conduction cooling. The top and bottom coils are connected at the innermost turn by oxygen-free copper plate soldering. An artificial local degradation (defect) was introduced on the 55th turn of the local pancake, by damaging the outer tape of the bundle. Details of the damage method and effect are presented below.

B – REBCO tape and local defect properties

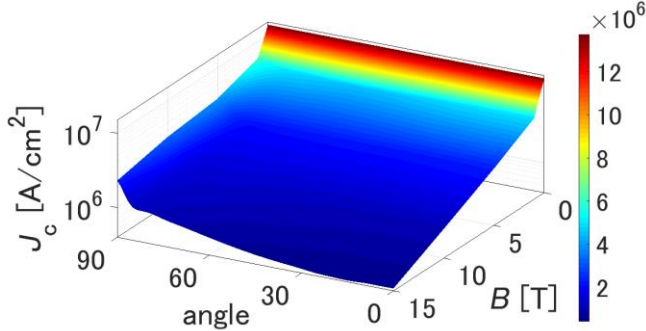


Fig. 2. Critical surface of the short sample of RBCO tape (Fujikura FESC-SCH12) at 50 K.

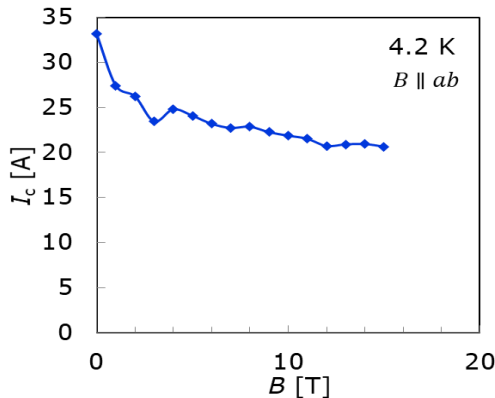


Fig. 3. I_c - B of the degraded 4 mm width tape at 4.2 K. REBCO layer is significantly degraded.

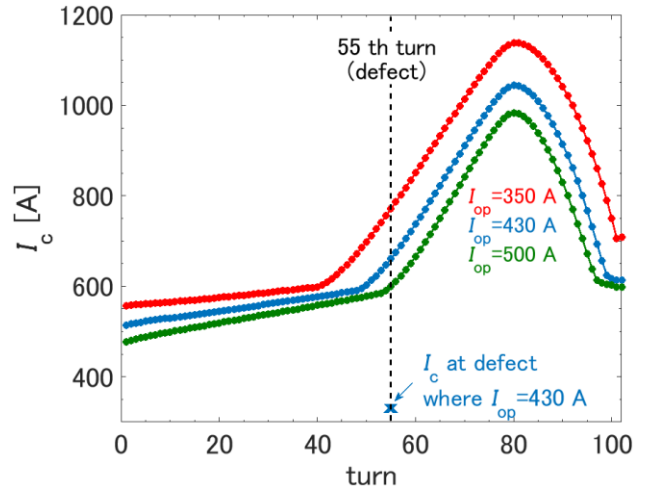


Fig. 4. I_c distribution in the coil at 50 K. The larger the current flow, i.e., the larger the generated magnetic field, the smaller I_c becomes overall. $I_{op}=430\text{A}$ is experimental upper limit .

The critical surface of the tape used in this coil was obtained on a short sample. For the measurement of the sample critical surface $J_c(T, B, \theta)$, a magnetic field was applied with a background magnet (20T-CSM at HFLSM). The temperature was controlled by the He gas flow in the VTI. The current was swept while controlling the angle on a stage rotation probe with a stepping motor. The voltage was measured by four-point method as in [7]. Fig. 3 shows the critical surface at 50 K.

The local degradation introduced on one of the tape in the bottom pancake was produced by double bending process, with a bending radius of 6 mm. This degradation method was also tested on short samples: I_c at 77 K, s.f. was 213.5 A before bending and decreased to 1.7 A (<1% of original I_c) after bending process. Fig. 4 shows the magnetic field dependence of the degraded tape I_c at 4.2 K. The I_c of that sample after bending process is about 32 A at 4.2 K for $B//ab$. This is also no more than a few percent of the original tape I_c mentioned in [7] in the same operation conditions. Therefore, we can assume that the I_c of the degraded part of the two-bundle conductor will be at best 50% of the original in damaged area if the current can redistribute freely from one tape to the other.

Based on the tape critical surface and damage characteristics, we can then establish the expected critical current turn by turn in the pancakes, as a function on the operating current (Fig. 4)

C – Experimental setup

The coil was tested in self field at various temperatures using an existing variable temperature cryostat with current leads rated at 500 A (Fig. 5). Conduction-cooling is made by a 2-stage GM cryocooler (SHI RDK-408D2). In our experiment, the lowest operating temperature achieved was 10 K for the superconducting coil, but the 500 A current limit restricted the study to the 45 – 77 K range where onset of dissipation could be observed.

For the I - V measurements, voltage taps were placed at the extremities of each pancake and on the current leads to obtain the voltages on both top and bottom pancake windings as well as the voltages across the current leads connections and the inner joint between the two pancakes. A pickup coil with sufficient number of turns was placed close below the test coil to enable the compensation of inductive voltage, making it possible to measure the dissipation level and protect the coil even during transient phases following [8].

III. EXPERIMENTAL RESULTS

A- I - V characteristics

As an example of test procedure, the time variation of measured voltage signals is given in Fig. 6 for operation at 50 K. The total dissipation voltage is the voltage across the whole coil (two pancakes + inner joint), whose inductive component was compensated using the pick-up coil. As expected, a significant resistive component exist on this signal, which includes not only the inner joint but also the current leads up to the cryostat

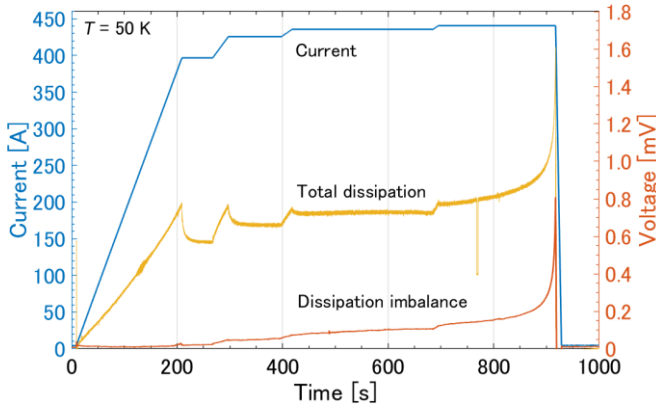


Fig. 6. Operating current and imbalance voltage and total voltage of the double pancake coil at 50 K.

terminals. The imbalance voltage is obtained by subtracting the top and bottom pancake voltages, and is thus a good image of the defect present on the bottom pancake.

Up to 430 A, the current could be maintained in a stable state, but when the current was raised to 440 A, the dissipation increased nonlinearly with time under constant current, indicating the onset of a thermal runaway. Thermal runaway can be observed clearly on both total dissipation and voltage imbalance signal, showing clearly that it originates in only one of the pancakes and not on both pancakes. This was expected considering the existence of the defect in bottom pancake. The local heat generated by the defect may cause a local decrease in the value of I_c , but the discussion assumes that the heat generation in stable state is negligible.

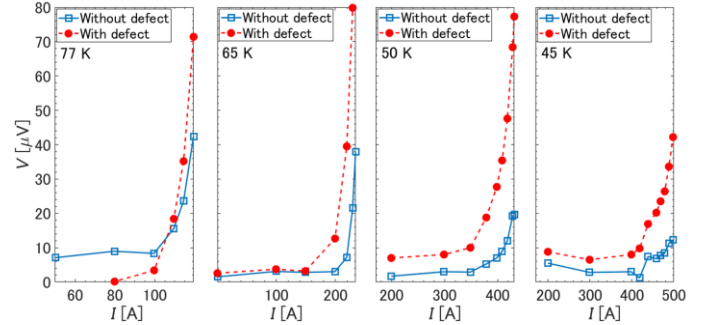


Fig. 7. I - V property of the coil with and without defect measured during current plateau

Fig. 7 shows the voltage levels across the two pancakes (with and without defects) at low dissipation levels where stable operation (and thus sensitive voltage measurements) could be achieved. These values were obtained by direct measurement of the coil voltages during long current plateau. The operating temperature was lowered from 77 K down to 45 K. At 45 K, the maximum operating current of the cryostat was reached. At 40 K and below, no significant voltage could be measured on either coil at 500 A.

B- I^* , safe maximum operation current

At first glance, there is not a large difference in I - V characteristics between coils with and without defects. Using a low threshold voltage criterion, 0.1 mV, we can then derive a safe maximum operation value, I^* for the two pancakes (Fig. 8). The temperature dependence of that maximum operating current is shown in Fig. 8. Note that on Fig. 8 some of the values exceed 500 A at low temperature. They are predicted from extrapolation of the data present Fig. 7.

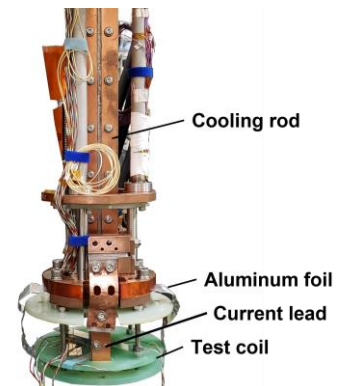


Fig. 5. Set up for coil test. Test coil was cooled by conduction cooling.

The difference in I^* between the pancakes with and without defect is limited: The ratio I_{bottom}^*/I_{top}^* varies from 0.96 at 77 K, down to 0.92 at 45 K. Practically this means that the pancake with local defect can be operated safely at current values very close to the undamaged one, even though the current densities were high in some of the experiments (up to 500 A/mm² averaged in both tapes).

IV. RESULT DISCUSSION

A – Relation between I^* and the local I_c

The maximum operation current is of course related to the local I_c distribution in the coil, but the relation is not straightforward. As an example, Fig 9 summarizes the expected critical current of the pancakes as a function of the operating current

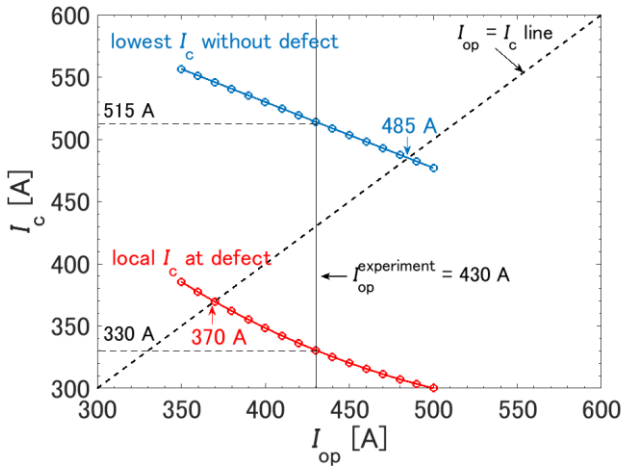


Fig. 9. The blue line with open circle symbol represents the minimum value of I_c per turn. The red line with open square symbol is the half of 55th turn I_c .

for operation at 50 K. In blue (top curve) for the pancake without damage, in red (bottom curve) at the defect position, where a 50 % I_c reduction is assumed. Because I_{op} is proportional to the self-magnetic field, Fig. 9 corresponds to the coil load line. On this load line, the maximum operating current for the coil without damage should be 485 A, and should be limited to 370 A considering the defect. The vertical line corresponds to the maximum stable operating current that was reached experimentally, 430 A, significantly above the expected limit. At that point, the critical current at the defect is reduced to 330 A, while the critical current of the pancake without damage is 515 A.

The problem to compare these estimations to experiment is that the local I_c is not accessible from measurement in general, as the length of the dissipating area is generally unknown. Fortunately, in our case, the two pancakes being identical save for the defect area, subtracting the voltage measured on the undamaged pancake to the voltage measured on the damaged one yields the voltage of the defect area, whose length is known (1.8 cm). Then, considering the standard criterion of 1 μ V/cm, we can obtain the local critical current in the defect area at various temperatures (Fig. 10). It is estimated at 346 A for 50 K, in good agreement with the 330 A estimated at the local defect.

The good agreement between the estimated critical current at the defect in experiment, and the expected value assuming a local 50 % I_c reduction at the defect demonstrates that from dissipation point of view, the bundle behave as a single conductor. The current can indeed redistribute from one tape to the other in the bundle well enough to mitigate local defects. This is true even under high current densities (500 A/mm² in self field

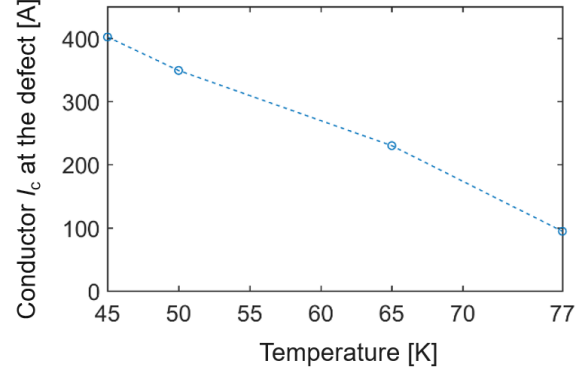


Fig. 10 Critical current of the conductor at the defect location

equal to 1.6 T) and even though the two tapes are not soldered together and placed face to back. The small difference of I^* between the damaged and the undamaged coils is due to the effective length of the dissipation area in both pancakes. In the case of the damaged one, only a small additional length is added (that of the defect).

B – Thermal runaway

We already established that the dissipation level in the two-tape bundle coil with a sharp defect on one tape is similar to that of a single conductor with a local I_c reduction of 50 % over the defect length. The question that is left is if the thermal stability is also similar. The experiment presented Fig. 6 is the only one in which we let a thermal runaway occur for a few seconds before discharging the coil. In this test at 50 K, the current was raised to 440 A, and maintained until the protection discharge

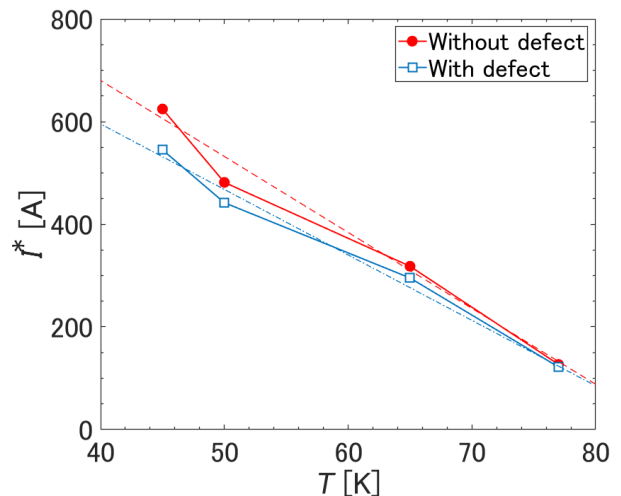


Fig. 8. Experimental temperature dependence of I^* for coil with and without local defect.

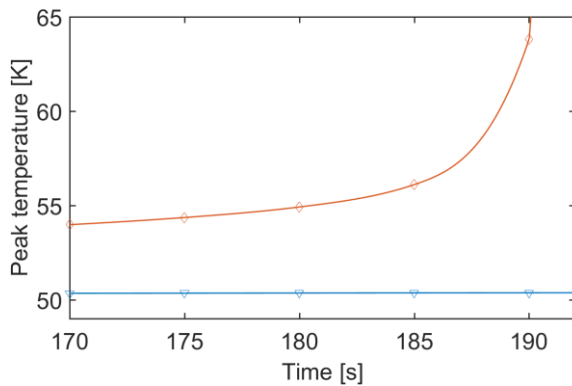


Fig. 12 Simulated peak temperature evolution of damaged (red, diamonds) and undamaged (blue, triangles) and undamaged pancakes during the thermal runaway final phase

was triggered. At that point the dissipation voltage had increased by about 0.85 mV from the value in stable state at 430 A (0.75 mV). The discharge was completed sufficiently early that no damage occurred. In previous works, we introduced a thermal runaway model taking into account local I_c distribution [9] and applied it to the case of coils with localized defects for protection design purpose [10]. This model was used to reproduce the thermal runaway behavior in the experiment at 50 K (Fig. 6). In the model, the bundled conductor is homogenized, with the local defect being represented by a zone with 50% reduction of I_c . The model assume adiabatic condition for the whole double pancake. After a slow ramp (10 A/min) up to 440 A, the current is maintained as in the experiment.

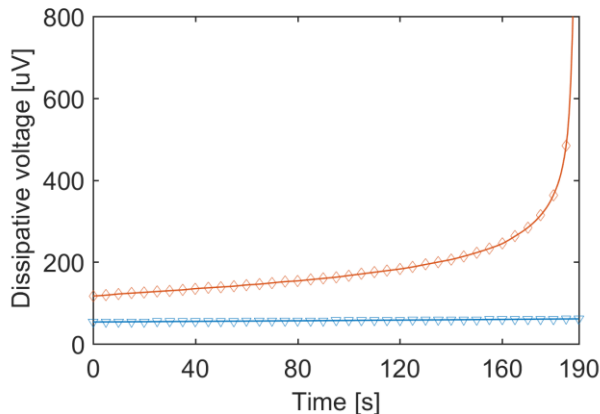


Fig. 11 Simulated voltage evolution of damaged (red, diamonds) and undamaged (blue, triangles) pancakes. Inset is a focus on the last 20 seconds, with a higher scale in vertical axis.

Fig. 11 shows the simulated dissipative voltage in damaged (red, diamonds) and undamaged (blue, triangles) pancakes during the current plateau, while Fig. 12 show the temperature of their respective hottest point. Time reference is set at the beginning of the plateau. As in the experiment, thermal runaway is observed only in the damaged pancake, even though steady dissipation exist in the undamaged pancake. Indeed, even though the undamaged pancake operates below its critical current, estimated at 515 A, a non-negligible electrical field does exist at 440 A, which is only 15 % below. For the damaged pancake, the evolution of the voltage during the plateau is continuous,

but its drift gets noticeably faster above 300 μ V, after 172 s of slow rise. At $t = 172$ s the hottest temperature reaches 54 K, while in the experiment it takes about 500 s to reach 1.5 mV. At that time (t = 190 s) the undamaged coil can still be discharged. From that point it would not spot to exceed 290 K if the current was maintained.

Overall, the simulation are in good agreement with the experiment. The thermal runaway occurs 190 s after the current is stabilized at 440 A, while in experiment (Fig. 6) it took a bit longer: 210 s approximately. This can be understood as the simulation assume adiabatic conditions, while in the experiment a small cooling power is available. The dynamic of thermal runaway after the voltage reaches 300 μ V is well described, it takes 15 s in simulation, against about 12 s in experiment.

During all the plateau, the dissipative voltage of the undamaged coil increases very slowly. It must be noted that the voltage drift in the undamaged pancake is much lower than in the damaged pancake, even for a similar level of dissipation. This can be understood as in the former the dissipation is distributed, while in the latter it is localized.

C – Validation of two-tape bundle behavior and practical applications

The results presented above illustrate that the behavior of a coil wound with a two-tape bundle conductor with a local sharp defect on one of the tape matches very well with the expected behavior of a single conductor coil with a local defect where I_c is only reduced by 50 %. This is verified from the point of view of local I_c estimation (IV – A), as well as from the point of view of thermal stability (IV – B). This means that the electrical contact between the two tapes of the bundle is sufficient to ensure current exchanges in case of local defect, so that the bundle operates practically as a single conductor from the dissipation point of view.

The benefit in term of reliability is significant, as the inhomogeneities in REBCO tape performances typically follow statistical distributions [11, 12], so that statistical chance of having a sharp I_c drop for two tapes in parallel carrying a given current is significantly lower than for a single tape carrying the same current. The robustness against local stress-induced defect will be similarly improved.

Even though these results were only obtained down to 45 K, the current density reached up to 500 A/mm², well above the design value for upcoming very high field magnets [13]. It is therefore expected that the two-tape bundle technique will show similar positive effect in such kind of application, even though the operating temperature will likely be lower (10-20 K range). At such high current densities the local dissipation is intense, and the sensitivity requirements to detect a thermal runaway in time for effective protection are understandably stronger, in the mV range in the thermal runaway observed here, compared to 10 mV or more in studies at lower current densities [10, 14].

For protection purpose, it is important to point that at low level of dissipation the behavior with and without sharp defect is very similar, as illustrated by the close I^* values. It further emphasize the benefit of defining low thresholds for thermal runaway detection, as first mentioned in [14], even at the cost of slower reaction time due to filtering and signal analysis, so that the defined thresholds are valid for any kind of cases including sharp local defect.

V. CONCLUSION

We tested a coil wound using the two-tape bundle concept including an artificial local defect. The coil consist of two pancakes. In one of them a 1.8 cm defect was created where the local critical current of one of the tape was decrease to close to 0. The I - V characteristics of both pancakes where measured in self field at temperatures ranging from 77 K down to 45 K. Both pancakes could be operated up to high current density: 500 A/mm², the damaged coil showing only slightly higher voltage level. Results demonstrate that current redistribution in two-tape bundle conductor is effective, the coil behaving practically like a single conductor coil with local critical current degradation of only 50 %. Protection against thermal runaway could be achieved with a sensitive voltage detection (1 mV range) even on such unfavorable case. All in all this validates the benefits of two-tape bundle concept to make REBCO coils with better reliability, offering promising prospect for future robust high field magnets.

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