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# Impact of a *REBCO* coated conductor stabilization layer on the fault current limiting functionality

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## Abstract

Reliability is one of the crucial requirements of conductors used in resistive superconducting fault current limiters. Possible critical current degradation of a *REBCO* coated conductor during the limiter operation restrains broader application of devices based on these conductors. In this article the impact of an electrical stabilization layer on the conductor protection against overheating as well as its effect on electrical current evolution during the limitation period are investigated. For the experimental part of the study, a commercial copper stabilized *REBCO* coated conductor and a modified conductor without copper stabilization are compared. Extensive experimental work complemented by electro-thermal numerical modeling paved the way for studying the electrical and thermal effects separately. The numerical model assuming adiabatic conditions is sufficient to reproduce experimental results and predict the peak temperature for conductors with various stabilization layers in realistic conditions. Reduction of the conductor critical current caused by multiple current limitation pulses was studied using pulses with various durations. It was observed that the degradation due to temperature rise is gradual with the rate depending solely on the peak temperature. It is this quantity through which other parameters like the pulse duration, the thickness of stabilization and the peak current cause the tape damaging.

Keywords: *REBCO* coated conductor, thermal degradation, fault current limiter, critical current degradation

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

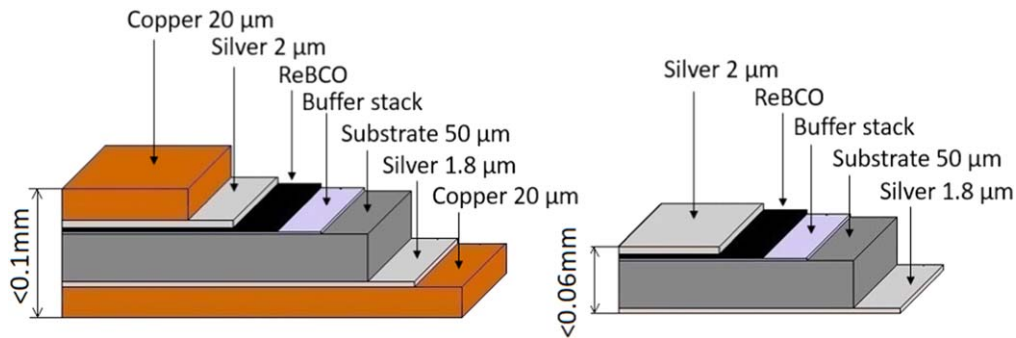
## 1. Introduction

In order to satisfy the population increasing demand for electricity, it is necessary to increase the installed capacity of electricity generating devices—power plants. This causes an

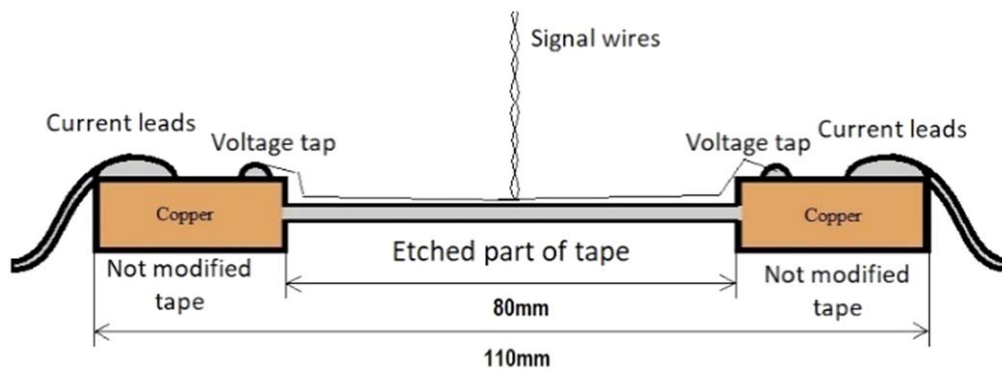
increasing of the short-circuit power level in distribution and transmission networks. Then the potential danger of exceeding the maximum permitted short-circuit current level, which can result in irreversible damage of the network equipment, grows as well. Currently, there are several devices for limiting the short circuit currents such as limiting fuses, series reactors, and high-impedance transformers. However, these solutions may cause other problems, such as loss of power system stability and appearance of additional impedances. This can reduce the voltage stability, along with growing cost



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**Figure 1.** The architecture of the superconducting tape, before (in the left) and after (in the right) process of etching.



**Figure 2.** An arrangement of current leads and voltage taps on the tape without copper stabilization in the active part.

and lower efficiency, which may ultimately lead to a reduction of operational flexibility and reliability [1].

Resistive superconducting fault current limiter (SCFCL) is a device that limits the magnitude of a short-circuit current, due to exceeding the maximum transport capacity determined by superconductors critical current. Some of the advantages of SCFCL over conventional FCLs are fast response to increase of fault current, reduction of peak current causing mechanical stress, low weight and dimensions, and the possibility of installation in the electrical stations without essential changes in internal connection arrangement [2].

During a fault in a system, the current magnitude exceeds the critical current value of superconductor. Produced heat causes the transition of the superconductor to a normal state, which results in a rapid increase of resistivity and thus current limitation.

After the required period for reaction, a conventional breaker interrupts the limited current and superconductor is re-cooled to the operation temperature [1]. The heat dissipated in the current limiter during limitation causes a dramatic increase of temperature. REBCO (*RE* = rare earth, barium copper oxide) coated conductors, which are widely used in SCFCLs, are rather sensitive to overheating and high temperature can cause degradation of superconducting material indicated by a reduction of critical current [3].

In [4] authors investigated the degradation of REBCO coated conductors exposed to pulse current higher than the critical current. They have found out that the level of the tape degradation is not dependent on the initial value of the critical

current, but on the peak value of the reached temperature. Overcurrent testing of superconducting tapes and cables was mainly performed by means of a constant current source for investigating the magnet or cable stability [4–6].

However, in the case of SCFCL conditions are closer to a constant voltage source. Therefore, in our experiment, we keep constant the level of electric field while electric current is limited by the tape resistance. Lower tape resistance causes a higher current in the circuit, which has a greater impact on heat generation.

In this paper, the evolution of the REBCO coated conductor temperature during the limiting process at various amount of released energy delivering pulses with various duration is studied. Effect of stabilizing metallic layer is analyzed by comparing the behavior of copper stabilized conductor and conductor without copper stabilization layer.

Testing conditions resemble the limiting process in DC circuit with parameters linked to FASTGRID project [7].

## 2. Samples description

Commercial REBCO tape produced by SuperPower company has been used. The tape is copper stabilized (thickness  $20\ \mu\text{m}$ , surrounding), 6 mm wide, with the critical current of 131 A [8]. According to the producer's datasheet, the thickness of the Hastelloy substrate is  $50\ \mu\text{m}$  and the silver cap layer is about  $2\ \mu\text{m}$  thick.

**Table 1.** Properties of physical tapes and modeled structure.

Super power SCS 6050	Tape with copper		Tape without copper	
	Experiment	Model	Experiment	Model
Width	6 mm	6 mm	6 mm	6 mm
Substrate thickness	50 $\mu\text{m}$	50 $\mu\text{m}$	50 $\mu\text{m}$	50 $\mu\text{m}$
Silver thickness	2 $\mu\text{m}$	0.9 $\mu\text{m}$	2 $\mu\text{m}$	0.9 $\mu\text{m}$
Copper thickness	20 $\mu\text{m}$	15 $\mu\text{m}$	—	—
Resistance @300 K	0.090 $\Omega \text{ m}^{-1}$	0.088 $\Omega \text{ m}^{-1}$	1.097 $\Omega \text{ m}^{-1}$	1.113 $\Omega \text{ m}^{-1}$

The thickness of the copper layer substantially affects the resistance of the tape, which is of high importance in case of using the tape as a current limiting element. To determine the effect of tape resistance as a current limiting element on the performance of the coated conductor, the resistance of the original tape was modified. This modification was performed by wet etching of the copper stabilizer using ferric chloride which was diluted with distilled water in ratio 1:1. Result of this process is shown in figure 1.

The time required to remove the copper layer was about 20 min at room temperature. The sample ends serving as current leads and voltage taps were protected during the etching to keep the copper stabilization layer there. The sketch of the modified sample finalized for electrical testing is shown in figure 2.

### 3. Experimental methods

#### 3.1. Temperature dependence of the tape resistance

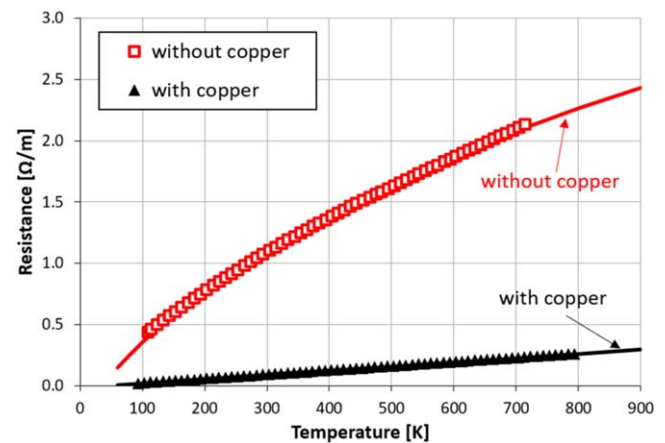
The tape temperature during the limitation cannot be measured by a direct method. The process is so rapid that standard thermometers do not have a fast enough response. Therefore, the tape temperature was assessed from measured tape resistance.

The tape resistance was measured during slow heating up in the temperature range from 100 K to about 800 K with ramp rate of 0.1 K s<sup>-1</sup>. Measured dependence was approximated with help of the model of parallel resistors representing conducting layers of the coated conductor.

The temperature dependences of materials resistivities were taken from available literature [9]. The thickness of the silver and copper layers were modified to fit experimental curves in full temperature range. The difference is probably caused by structure imperfection or higher specific resistance of electrolytically deposited layers while model considers data for pure bulk material. Geometry corrections used in the model with respect to dimensions of the original tape are summarized in table 1.

Figure 3 shows the agreement achieved between calculated (continuous line) and experimental (symbols) curve; lower curves represent tape with the copper while upper curves represent copper-free tape. Etching of the copper layer resulted in around 12 times higher resistance of the original tape at room temperature.

Theoretical model approximates the experiment reasonably well, this allows using them to calculate the temperature of the



**Figure 3.** Comparison of the temperature dependences of the measured tape resistance (symbols) and resistance calculated using a theoretical model (continuous lines).

sample during limitation experiment. However, this method of the temperature evaluation has several limitations: only temperatures, higher than critical one can be evaluated; the model assumes uniform temperature in the whole sample volume.

#### 3.2. Critical current

Critical current of the tape was measured at the temperature of liquid nitrogen by the impulse method. In this experiment, electric current is delivered to the sample from a charged capacitor, triggered by a semiconducting solid-state switch. The electric current rate of change is reduced by the air-core coil connected in series. The typical length of the pulse is 20 ms, the magnitude of electric current pulse is adjusted by the voltage of the capacitor before the pulse. During current pulse, the signal from non-inductive shunt and from the voltage taps on the sample are recorded by the A–D converter with simultaneous sampling. In this way, a complete current–voltage ( $I$ – $V$ ) curve was recorded. An advantage of the impulse method is the possibility to characterize tapes with poor stabilization and a high level of critical current without danger of damage. On the other hand, a drawback is a high noise and the presence of induced voltage in the measured signal, even though, the signal wires were led as close to the tape surface as possible. During the data processing, the residual inductive voltage was compensated in a numerical way. The standard electric field criterion of 1  $\mu\text{V cm}^{-1}$  was used to determine the critical current.

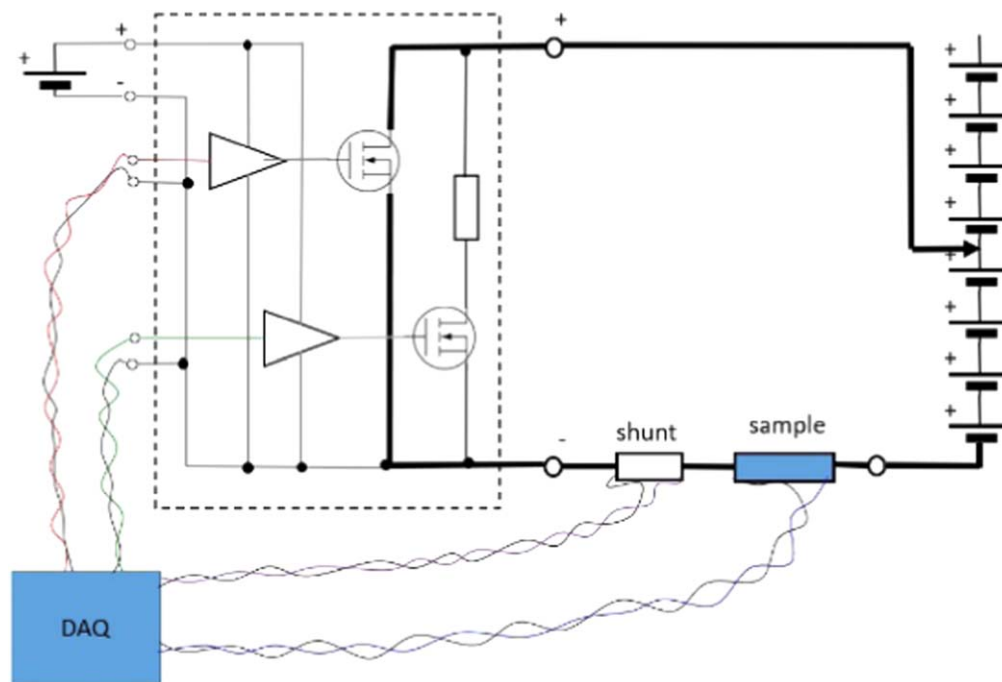


Figure 4. Diagram of testing circuit implementing a solid-state switch.

### 3.3. Current limitation

In typical resistive fault current limiter, the level of dissipated power is in range of tens of kilowatts per meter of tape [10]. Therefore, a representative laboratory testing poses strong requirements on the power supply for current limitation experiments. In our case low-impedance nickel-cadmium accumulators are used, which can deliver high-enough power for short time experiment. The second requirement is the level of electric field, which is set to be about  $100 \text{ V m}^{-1}$ , similar to the specification given in [7]. Actually, the investigated sample length is limited by 10 cm since the maximum voltage range of used A–D converter is 10 V. The sample holder is arranged in the way that the investigated tape is surrounded by liquid nitrogen bath from all sides. Additionally, splitting the return conductor into two leads arranged symmetrically with respect to the tested tape minimizes the Lorentz force experienced by the tape during the current pulse. Current leads and voltage taps were soldered to the tape using standard lead-tin solder. The solid-state switch is based on MOSFET transistors and triggered by a signal from the D–A converter. The principal circuit diagram is shown in figure 4.

Re-cooling time of the tape down to critical temperature can be estimated from impulse measurement of the tape resistance after switching off the limited current. In practice, it is performed by switching auxiliary transistor with a resistor connected in series. The magnitude of the current pulse for resistance measurement is sufficiently low and its duration is sufficiently short to avoid additional heating of the tape. Example of electric current versus time evolution during current limiting experiments with original tape (with copper stabilizer) as well as with modified tape (without copper stabilizer) is shown in figure 5.

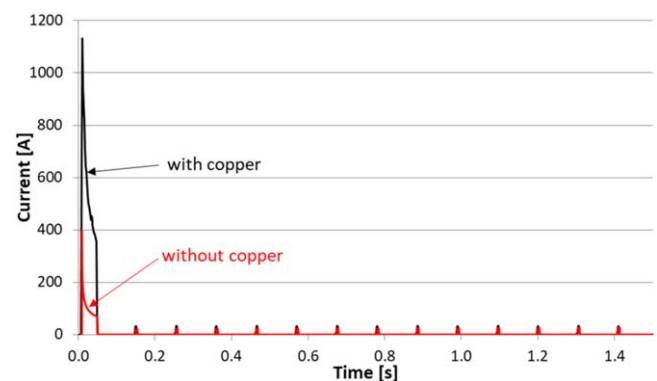
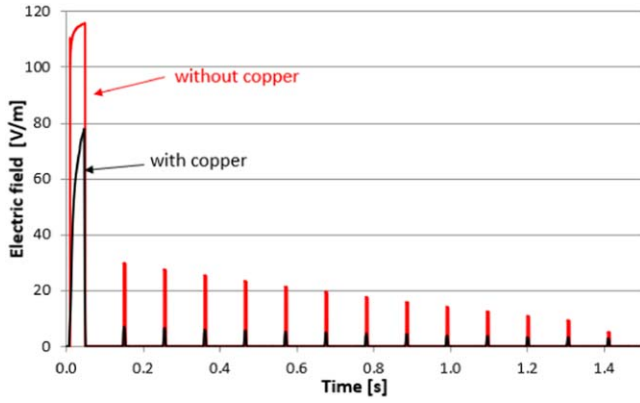
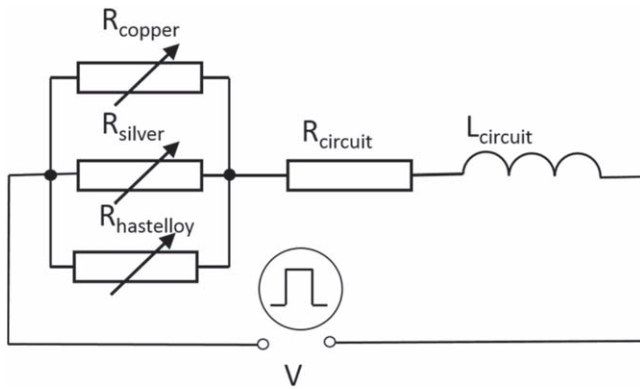


Figure 5. Time dependence of the current during limiting and subsequent cooling period.

The tape is heated up over the critical temperature shortly after an initial steep increase of the current over the critical value. This initial phase takes typically less than 1 ms. After this time, practically all the current flows in metallic parts of the tape. The generated heat causes an increase of the tape resistance and reduction of the current (current limitation) because the setup uses constant voltage source. As a consequence of lower resistance in case of the tape with a copper layer, the magnitude of the peak current and limited current is almost 5 times higher than for the modified tape without copper stabilizer. After the defined time (40 ms) the limited current is switched off by solid state switch. The current pulses applied periodically to measure the resistance of the tape have the magnitude of about 20 A, which is high enough to produce a reasonably strong signal, yet low enough to avoid significant sample heating. Voltages recorded during the experiments are shown in figure 6.



**Figure 6.** Time dependence of electric field during limiting with cooling measurement.



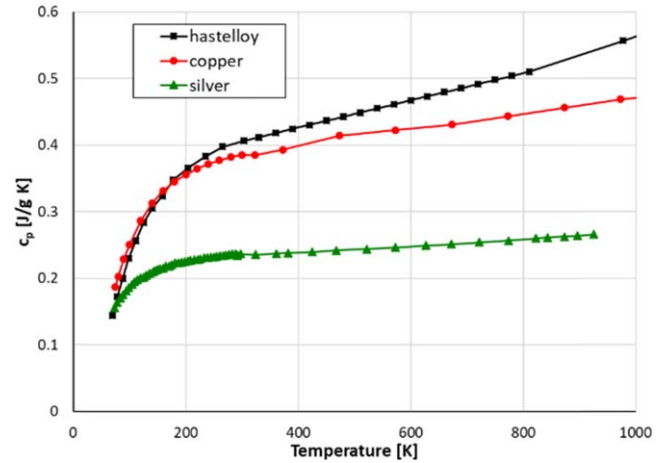
**Figure 7.** Circuit representing the tape in numerical modeling of current limitation.

Even though the same power source in both measurements is used, the electric field on the tape with copper stabilizer is lower. This is caused by voltage drop on the conductors forming the circuit, which is much higher due to the higher current in Cu-stabilized tape. As the tapes cool down after switching off the current, the voltage during current pulses decreases and finally drops to zero when the tape becomes superconducting.

#### 4. Numerical model

For analysis of experimental results, a simplified 1D numerical model based on circuit analysis has been developed. It takes into account the resistance and the inductance of circuit and the resistance of sample depending on the tape temperature (see figure 3). The tape is modeled as a parallel connection of resistive layers forming real tape—hastelloy, silver and eventually copper (figure 7); we completely omit superconductor and its properties in this model. Power source, representing batteries and solid-state switch, creates a rectangular voltage pulse.

The resistance and inductance are considered to be the constant:  $R_{\text{circuit}} = 6 \text{ m}\Omega$ ,  $L_{\text{circuit}} = 5 \text{ }\mu\text{H}$ . The resistance of



**Figure 8.** Temperature dependences of specific heat capacities used in our numerical model.

the sample is represented by parallel connection of temperature dependent resistances.

Electric current  $i$  in time step  $k$  is calculated from the source voltage  $V$ , circuit inductance  $L_{\text{circuit}}$ , circuit resistance  $R_{\text{circuit}}$ , sample resistance  $R_{\text{sample}}$  and electric current in previous step  $i_{k-1}$

$$i_k = i_{k-1} + \frac{(V_k - (R_{\text{circuit}} + R_{\text{sample } k-1})i_{k-1})dt}{L_{\text{circuit}}}, \quad (1)$$

where  $1/R_{\text{sample}} = 1/R_{\text{copper}} + 1/R_{\text{silver}} + 1/R_{\text{hastelloy}}$  and  $dt$  is the length of time step. All these resistances depend on temperature and thus vary between time steps. The current deposits energy by Joule heating of the sample. No heat exchange is considered between the sample and an ambient, therefore the whole deposited energy increases the sample temperature. This assumption is acceptable for a fast heating up process in conditions similar to the operation of a fault current limiter [11]. Change of temperature ( $T_k - T_{k-1}$ ) in time step  $k$  is therefore proportional to the amount of deposited energy and inversely proportional to the total heat capacity of the sample

$$T_k = T_{k-1} + \frac{(R_{\text{sample } k-1} i_k^2)dt}{C_{\text{psample } k-1}}, \quad (2)$$

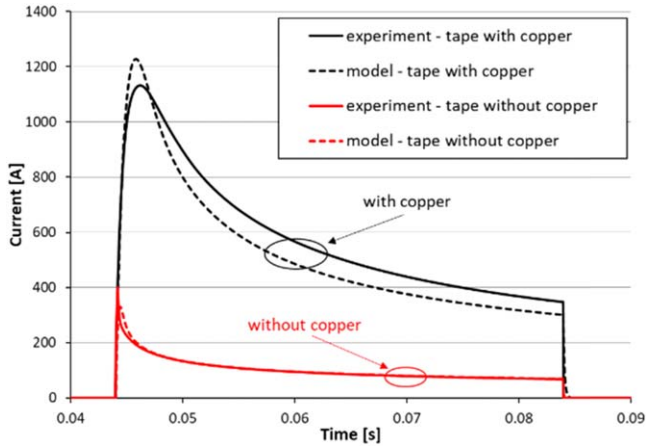
where  $C_{\text{psample}}$  is sum of individual layers heat capacities  $C_{\text{psample}} = C_{\text{phastelloy}} + C_{\text{psilver}} + C_{\text{pcopper}}$ . Where  $C_p$  for each layer is calculated from specific heat capacity  $c_p$ , density  $\rho$ , layer thickness  $t_h$ , and tape width  $w$ :

$$C_p = c_p \rho t_h w. \quad (3)$$

Note that for calculation of heat capacities we used the same layer thicknesses as they are used for resistance calculation—see table 1. Data of the materials specific heat capacities are combined from sources [12, 13] and they are shown in figure 8.

Using the above described algorithm, for each time-step the electric current, temperature and resistance of the sample are calculated. The reliability of the model is tested on the example of current limitation with the applied voltage of 10.2 V (electric field  $127.5 \text{ V m}^{-1}$ ) and duration of 40 ms.





**Figure 9.** Comparison of the current curves for copper and copper-free sample during current limiting.

Figure 9 compares current versus time evolution for both samples (with copper and without copper) recorded during limitation experiment in comparison with the calculated ones.

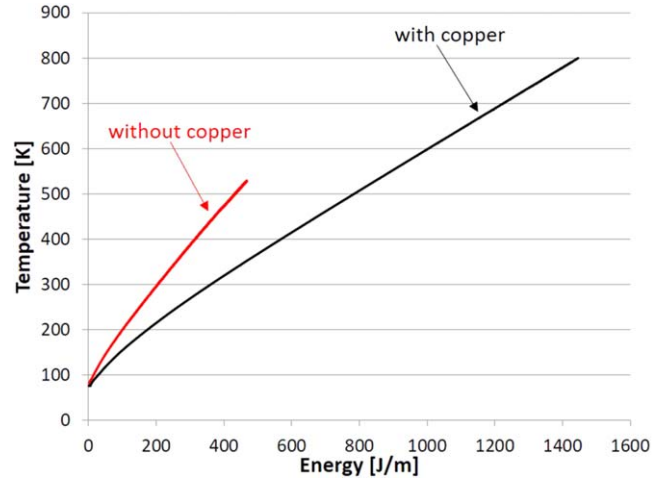
The rate of current increase at the current pulse beginning is mainly given by inductance of the circuit and thus it is the same for both samples. However, in case of the tape without copper, the current rapidly reached the peak and sharply started to decrease. On the other hand, in tape with copper the current continues to increase and reaches about three times higher peak value. Smoother shape of the current pulse is caused by higher heat capacity of the tape with copper. The shape of curve calculated for the sample without copper is smoother than the experimental curve. This might be caused by the fact that our model does not include superconductor. The effect of sharp superconductor transition to a normal state is clearly visible in experiment, while the model cannot reproduce it. On the other hand, the modeled curve converges to experimental curve very fast. For the sample with copper there is difference between the calculated and measured curve that is less than 15%. It probably originates in variance between real material properties and properties included in the model. Especially in the case of copper both the heat capacity and the electric resistivity strongly depend on microstructure and purity of material.

## 5. Peak temperature

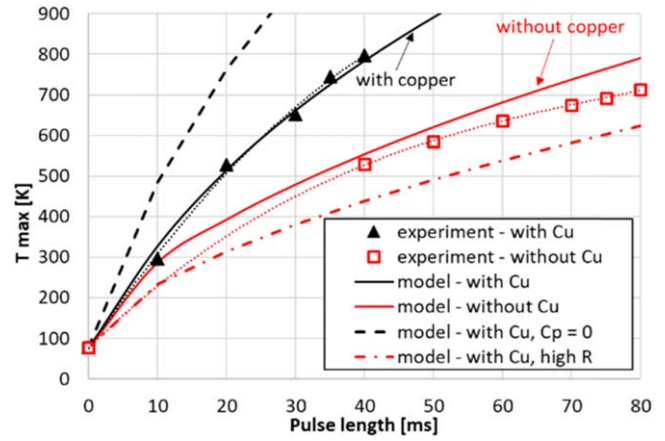
The amount of energy dissipated in tape per unit length from the beginning of limitation to time  $t$  was calculated from experimental values of voltage and current  $V(t)$  and  $I(t)$ , respectively, as:

$$Q = \frac{1}{l} \int_0^t V(t)I(t) dt, \quad (4)$$

where  $l$  is the active length of sample. Temperatures of the samples were calculated using the inversion fit functions of curves shown in figure 3. Comparison of the tape's temperature dependence to the amount of dissipated energy is shown in figure 10.



**Figure 10.** Comparison of the temperature dependence of sample on the amount of energy released.

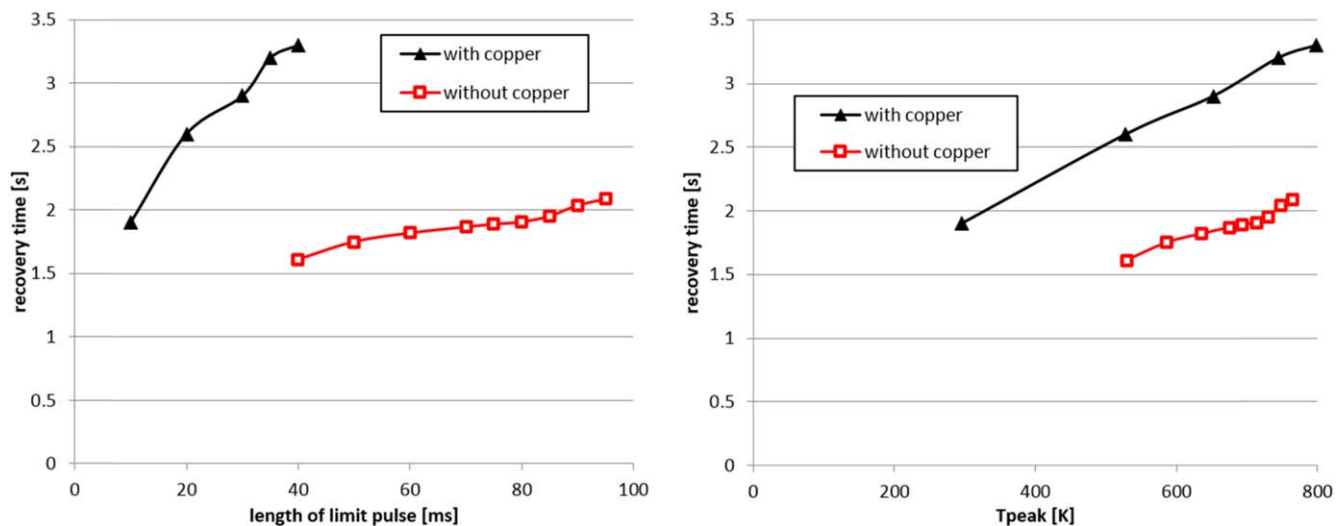


**Figure 11.** Dependence of tape temperature on the pulse duration.

The length of the current pulse in both cases is 40 ms. The total amount of dissipated energy for the tape with copper is significantly higher due to the higher flowing current. For the same amount of released energy, the temperature of the tape with copper reaches a lower value. It is caused by the higher heat capacity due to the presence of additional material—copper layer. Peak temperature  $T_p$  reached during current limitation is directly connected to the amount of energy dissipated in the tape. Naturally, the amount of dissipated energy depends on the length of the current pulse. Dependence of the peak temperature on the duration of the pulse is shown in figure 11.

Due to the higher current in tape with copper (black triangles), more energy is dissipated in shorter period of limitation. For the tape without copper (red squares), the effect of higher electric current predominates over the effect of additional heat capacity. Therefore, the tape with copper heats up to higher temperature at the same pulse duration.

Effect of lower resistance cannot be separated from the effect of additional heat capacity experimentally. However, figure 11 illustrates that such analysis can be performed in



**Figure 12.** Dependence of recovery time on pulse duration (left) and peak temperature (right).

numerical simulation. First, the maximum temperature dependence on pulse duration is calculated for both samples, with copper (black solid line) and without copper (red solid line). The agreement between experiment and model is not perfect, but the model proves that it can be used for rough estimation of peak temperature. In the following calculations, the used material characteristics of copper layer were manipulated. The heat capacity of copper is set to zero while keeping its resistance unchanged. The calculated peak temperature is shown by the dashed black line. If the copper would not contribute to the heat capacity of the tape, temperature rise due to lower resistance in comparison to sample without copper would be even more pronounced. On the other hand, when the resistance is set to be  $10^6$  times higher while keeping its heat capacity unchanged, the temperature rise decreased in comparison to the sample without copper. It can be concluded that for thermal stabilization it would be beneficial to use materials with high electrical resistance and high heat capacity.

Peak temperature defines the maximum possible pulse duration without superconductor degradation. In fault current limiter design it is usually defined to be about 500 K [11] to keep safety margin from degradation temperature. In [14] authors found that superconductor can withstand temperature as high as 720 K during current limitation, but at higher temperatures it starts to degrade.

After switching off the electric current, the superconducting tape starts to cool down. Duration of this process depends on the peak temperature reached during the pulse, the amount of accumulated thermal energy and also on cooling conditions. We have recorded the tape resistance in discrete points during this process using small current pulses—see figures 5 and 6. Real recovery time (when the sample reaches original temperature of 77 K) is difficult to estimate in our experimental arrangement. Therefore, the recovery time is defined as the time from the end of pulse until the sample becomes superconducting (temperature  $\sim 92$  K). Dependence

of recovery time estimated in this way on the length of limitation pulse and peak temperature is shown in figure 12.

Recovery times are shorter for tape without copper for the same duration of limitation pulse. This fact is consequence of several reasons. First, there is a smaller amount of energy dissipated in tape without copper—see figure 10 thus smaller amount of energy should be removed from the sample to ambient to reach the critical temperature. Also, as shown in figure 11, peak temperatures reached in the tape are higher for tape with copper at the same duration of the pulse.

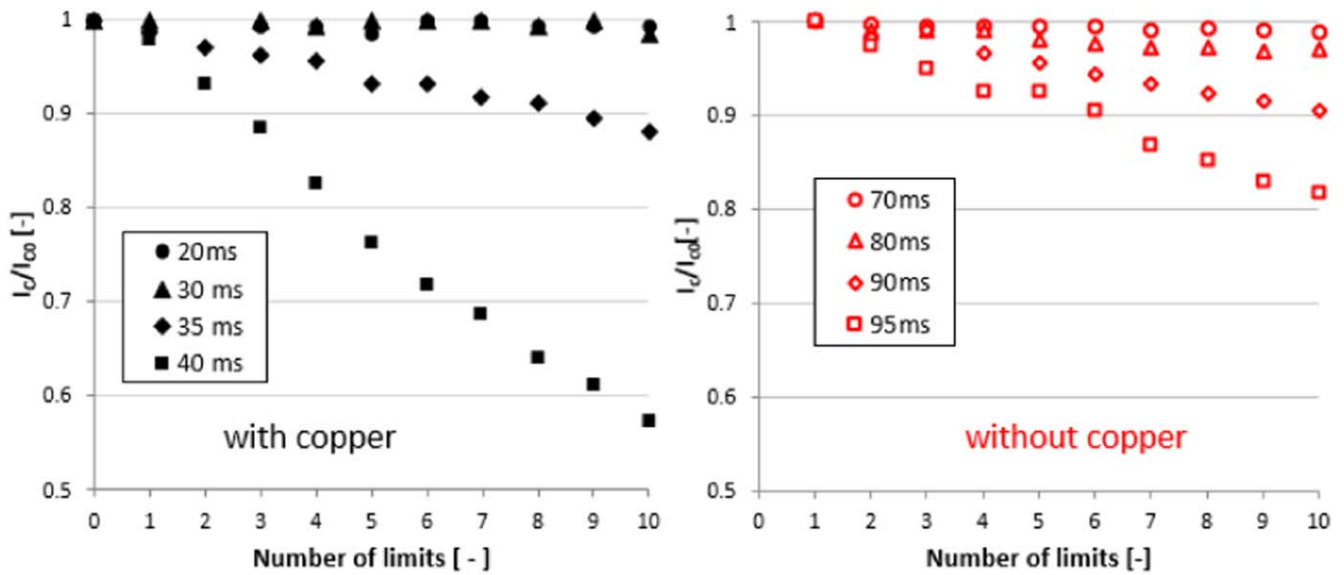
## 6. Critical current degradation

For investigation of critical current degradation in a systematic way, the samples were exposed to multiple limitation cycles with a constant source voltage of 10.2 V. The tape was cooled down to 77 K after each limitation cycle and its critical current was measured utilizing the impulse method as described in section 3.2. The experiment has started with a limitation pulse length of 10 ms. If the sample did not exhibit any significant degradation after the sequence of 10 limitations at fixed pulse duration, it was used for further limitation cycles with longer pulse duration; otherwise, a new sample was being used.

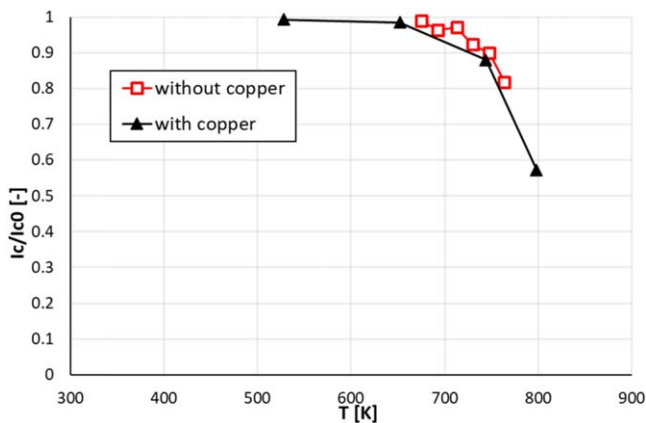
Relative change of the critical current with respect to the critical current of particular tape before a series of limitation cycles is shown in figure 13.

For the sample without copper and for up to 80 ms of limitation pulse duration, no change of critical current was observed. However, the tape with copper had a noticeable gradual degradation of the critical current that started at the 35 ms pulse duration. At these pulse lengths, the temperature reaches 713 K and 744 K for the sample without copper and with copper, respectively. It means that the critical current degradation starts at roughly the same temperature despite the different duration of limitation pulse and the presence of additional copper layer. Critical current degradation roughly started at exceeding 700 K. In the case of the sample without





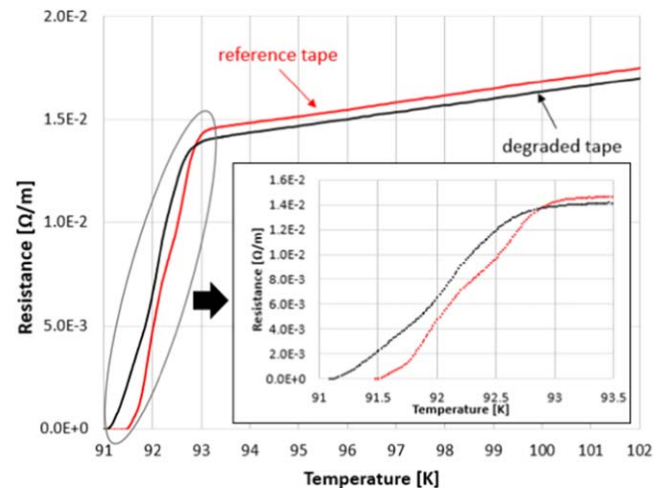
**Figure 13.** Dependence of critical current degradation on the number of limiting pulses repetition with different pulse duration for tape with copper (left) and without copper (right).



**Figure 14.** Dependence of critical current degradation (after 10 limitation pulses) on the peak temperature.

copper, the pulses with length of 80 ms cause only small critical current degradation (about 0.3% per pulse). The maximum temperature for this pulse length is 713 K. Increase of the pulse length to 90 ms causes an increase of maximum temperature to 748 K and a significantly higher rate of degradation, about 1.1% per pulse. Similarly, for the tape with copper, the pulse length of 35 ms results in the temperature of 744 K and degradation rate about 1.2% per pulse, while the pulse length of 40 ms results in the temperature of 798 K and much higher degradation rate of about 4.5% per pulse. The critical current degradation dependence on the reached peak temperature can be observed in figure 14.

The degradation might be caused either by mechanical damage, thermal stress [15] or by oxygen release from the crystal lattice and thus reduction of its content [3]. Oxygen content in REBCO superconductor is closely related to critical temperature  $T_C$  [16, 17]. Therefore, the critical temperature measurement was performed.



**Figure 15.** Comparison of resistance dependence on temperature for reference and degraded tape, respectively, in the temperature range of transition from superconducting to normal state.

In this experiment, two samples with copper stabilization layer were compared. One of these samples was exposed to multiple limitation cycles until the degradation of tape reached approximately 30% of the initial value of  $I_C$ . The second measured tape was an original, non-modified tape with initial properties. Critical temperature measurement was performed by means of transport current of 100 mA. Comparison of recorded resistance is shown in figure 15.

There is only a small shift of critical temperature visible in figure 15. However, as it is shown in [18], change of  $T_C$  with oxygen content is non-monotonous and small change in  $T_C$  cannot be directly related to small change of oxygen content. Moreover, the critical current monotonously decreases with reduction of an oxygen content. In result, dependence of the critical current on a temperature changes

significantly with change of an oxygen content in the crystal lattice. Despite additional experiment, the critical current reduction cannot be clearly attributed to a thermo-mechanical damage of superconducting structure, as it was suggested by [15] or to oxygen release from the crystal lattice [3]. In experiment described in [15], the peak temperature at which degradation occurs was about 600 K. However, it is found that the tape investigated here withstands temperatures as high as 700 K without observed degradation. After exceeding this temperature, the degradation is gradual with the rate increasing with peak temperature reached during the limitation pulse.

## 7. Conclusion

The electrical and thermal behavior of REBCO coated conductor during the current limiting process has been analyzed. The superconducting tapes with and without copper layer have been compared in order to study the influence of a stabilization layer on performance during the current limiting period. Removing the copper layer by etching led to about 12 times higher resistance of the tape at room temperature. The difference between resistances of the tapes with and without copper gave rise to a difference in the peak value of current during limiting period, which is three times higher for the case of the tape with a copper layer. This difference in current magnitude also causes more energy dissipation which leads to more heat release in the copper stabilized tape.

Peak temperature reached during the limiting period is higher for tape with copper stabilizer because of the effect of higher current overweighed the increase of heat capacity. The numerical model confirms this trend and suggests that for good thermal stabilization of coated conductor for fault current limiter it is beneficial to use a material with high electrical resistivity and high thermal capacity.

Measurement of re-cooling time has shown that the cooling of tape with copper stabilization is more than two times slower compared to the copper-free tape. This is caused by higher peak temperature, higher thermal capacity and thus more heat accumulated in the tape with copper stabilization, while the cooling surface is roughly the same.

Although the same peak temperature during the limiting period is reached at different pulse duration, a degradation of critical current starts at temperatures about 700 K for both, sample with copper and that one without copper.

We have found that the degradation process is not abrupt, but it is gradual with the rate dependent on peak temperature.

The critical temperature measurement was performed to identify the main degradation mechanism. Despite only small change of critical temperature the main degradation mechanism cannot be attributed to thermo-mechanical stress between layers of coated conductor, but release of oxygen from the crystal lattice must be considered as probable reason too.

## Acknowledgments

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