

# Insulation effect on thermal stability of Coated Conductors wires in liquid nitrogen

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**Abstract.** Superconducting wires are not perfectly homogeneous in term of critical current as well as stabilization. In resistive fault current limiter applications this could lead to hot spots if the fault current is only slightly above the nominal current of the device. Increasing stabilization by using thicker silver coating for example may prevent this problem but this method implies longer wire length to maintain the same impedance during a fault. Very efficient cooling in another way to prevent hot spots, this can be achieved in nucleate boiling regime. Optimal insulation can be used to prevent film boiling regime, staying in nucleate boiling regime in a much broader temperature range. In this work a novel technique is used to monitor in real time the temperature of the wire during the quench. Using this method several increasing insulation thicknesses are tested, measuring for each the heat exchange rate to the nitrogen bath. Exchange rate measurements are made in quasistatic regime and during the re-cooling of the wire. SuperOx wires provided with different insulation thicknesses exhibit an excellent stability, far above a bare wire. On the other side, for very thick insulations the stability gain is lost. Re-cooling speeds dependency on insulation thicknesses is measured too.

## 1. Introduction

THE protection of a power grid can be achieved using different kind of superconducting fault current limiters (SFCL), we focus here on resistive type SFCL (RSFCL). 2G High-Temperature superconducting wires are often used in such devices because they provide a high critical current and are able to change rapidly between a superconducting state and a high resistive state. The efficiency and durability of such devices depend on numerous factors, such as dimension, structure and surface treatment [1]. All these factors have an impact on the heat flux between the wire and the liquid nitrogen bath it is immersed in. When the power grid operates normally, the limiter does not affect the current flow. However when a fault current occurs, the line current reaches the critical current ( $I_c$ ) of the HTS wire and the RSFCL starts limiting the current and protects the installation. The type of fault current triggering the RSFCL also affects the stability of the device. If the fault is perfect, that is, way above the  $I_c$  of the wire, every part of the conductor will quench simultaneously, resulting in a safe limitation. On the other hand, HTS wires are not perfectly homogenous and their  $I_c$  can vary up to 20% along their length [3]. This means that a fault current close to the  $I_c$  may provoke a quench of the weak points of the wire without triggering the RSFCL, this is the case in the so called high impedance fault. It is therefore important to maximize the heat flux between these weak points and the LN<sub>2</sub> in order to avoid damaging



the wire.

The elaboration of theoretical models for boiling heat fluxes as a function of wall superheat has been described as a difficult task due to the complexity of the process and the amount of interacting variables [4]. Experimental data is therefore valuable to help develop temperature profiles and provide insight on heat flux mechanism around the weak spots of a RSFCL device.

This paper builds upon the previous experimental study conducted by the authors [5]. This time, HTS wires have been studied in order to determine an optimal insulation thickness. The amount of heat flux is precisely measured for each experimental condition and the impact of LN<sub>2</sub> can be quantified.

Surround polyimide coating was originally developed by SuperOx for the purpose of electrical insulation of 2G HTS wire. At the same time, this coating has all desired characteristics for the present study: a relatively low thermal conductivity and a very small layer thickness that can be controlled precisely. By preparing a set of samples with varying polyimide layer thickness we intended to vary the heat transfer rate from a hot spot in the wire across the polyimide layer. As the low thermally conducting polyimide layer becomes thicker, the higher amount of heat is expected to dissipate from the hot spot along the silver coating and the smaller amount across the polyimide layer. This should affect the nitrogen boiling regime, and at certain polyimide layer thickness level an optimum regime is expected.

## 2. Experimental Setup

### 2.1. HTS material, insulation and wire length

A 4 m length of regular 4 mm wide SuperOx 2G HTS wire is used in this study. The wire is based on a 60 micron thick Hastelloy C276 substrate, the thickness of the buffer layer stack is about 250 nm and the thickness of the GdBCO HTS layer is about 1.5 microns. The surface of the HTS layer is coated with 2 microns of silver and the back (substrate) side of the wire is coated with a 1 micron thick layer of silver. A detailed description of the wire architecture and fabrication processes can be found in [6]. The wire's original critical current at 77 K in self-field was 100 A. The superconductivity of the wire is suppressed by reducing the oxygen content in the GdBCO layer by a 1 hour anneal at 400°C in 1.5\*10<sup>-5</sup> mbar of residual air. Samples with suppressed superconducting properties were preferable for this experiment, in order to measure exchange power at low power and thus keep the signal to noise ratio reasonable.

Surround polyimide coating is deposited onto pieces of the 2G HTS wire with artificially suppressed superconductivity. The description of the polyimide deposition process by dip-coating modified with electrophoresis is provided in [7]. A series of samples with different thickness of polyimide coating is prepared. The polyimide layer thickness was varied by varying the electrophoresis voltage. Finally, a set of 7 samples with polyimide layer thicknesses of 0, 10, 15, 20, 25, 35, and 65, each 14 cm long, is prepared for measurements. For electrical contact, polyimide layer is removed with water solution of sodium hydroxide and diethylenetriamine at 1 cm at each end of each sample.

### 2.2. Measurements

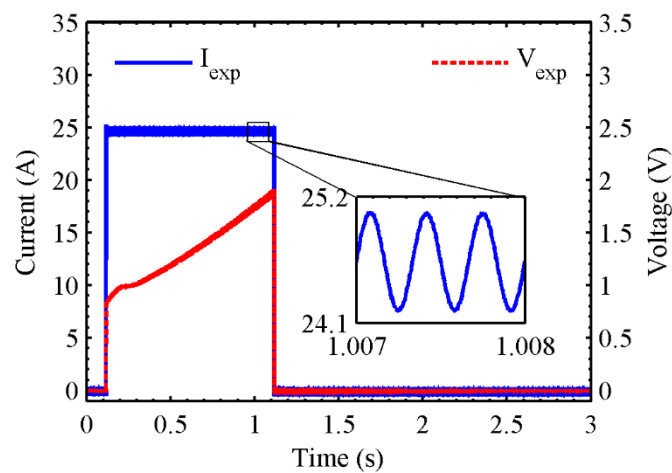
A first set of measures is required in order to obtain the correlation between the resistance and the temperature of each sample. This process is detailed in [5].

The measures were carried out by applying constant current pulses along the HTS wire. For each wire sample, the duration of the pulse was set to 1 second. These pulses act as a carrier signal on top of which a sinusoidal wave is added. This sinusoidal wave acts as a modulation signal and is needed in order to retrieve the electrical resistance before, during and after the pulse.

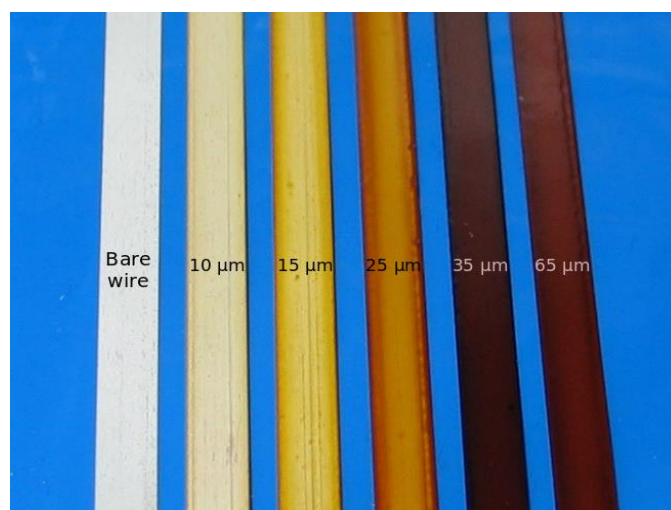
These two signals are transmitted to a voltage-to-current converter. The converter is powered by adjustable voltages between ±12V and ±24V. For each sample wire, the current pulse was gradually increased from 2 A up to 38 A. Current and voltage are digitized at a sample rate of 0.5 Ms/s and a dynamic of 18 bits. A diagram of the circuit is shown in [5]. The wire is mounted on a 4 wires setup.

Data collected by the analog to digital converter is treated by extracting their DC and RMS components at 3 kHz. The resistivity of the wire is then determined using the modulation signal as the ratio of the RMS amplitudes of the voltage over the current. This value is averaged on  $n$  cycles. The value  $n = 2$  has been used generally in this experiment. This corresponds to a time resolution of 6.6 ms for temperature and power measures.

The power generated inside the wire is calculated using DC components of current and voltage values. In order to avoid damaging the wire, a threshold in the voltage measurement is used to interrupt the current pulse. This ensures that no overheating of the wire occur whichever the measuring parameters.



**Figure 1.** Example of measured current and voltage on the wire. In this case, the sample wire is surrounded by a 2 micron polyimide insulation.



**Figure 2.** Sample wires insulated with layers of polyimide film applied directly on the silver surface.

### 3. Results and Discussion

#### 3.1. Evaluation of the stored energy

The resistance is known at each experiment time step and therefore the temperature can easily be deduced using the previously measured resistance-temperature curve. Using this fact, it is possible to evaluate the power corresponding to the energy stored inside the tape during the pulse. Fig. 3 shows the tape power balance according to the following equation:

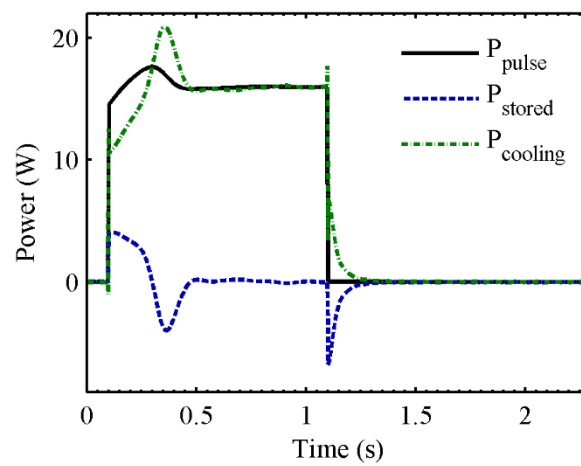
$$\int_{t_k}^{t_{k+1}} \underbrace{(V_{exp} \cdot i_{exp}) dt}_{P_{pulse}} = \int_{T_k}^{T_{k+1}} \underbrace{C p_{HTS}(T) dT}_{P_{stored}} + \underbrace{q}_{P_{cooling}}$$

The left term of this equation is the power provided by the pulse ( $P_{pulse}$ ) and dissipated inside the tape, the first right term is the power corresponding to the stored energy ( $P_{stored}$ ) that will induce a temperature increase of the material, and the last term,  $q$ , is the difference between  $P_{pulse}$  and  $P_{stored}$ . It corresponds to the cooling power ( $P_{cooling}$ ) of the bath.

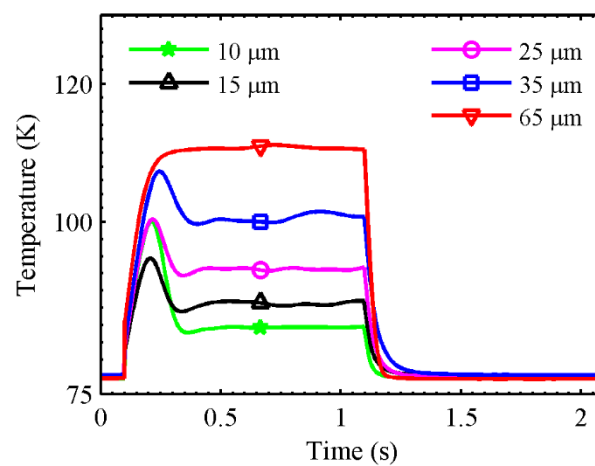
It can be seen that the wires used for this experiment provide a better cooling performance as they are able to release some of their stored energy before reaching an equilibrium temperature. This behavior can be particularly beneficial in certain situations, such as recovery under load [8].

#### 3.2. Impact of the polyimide insulation

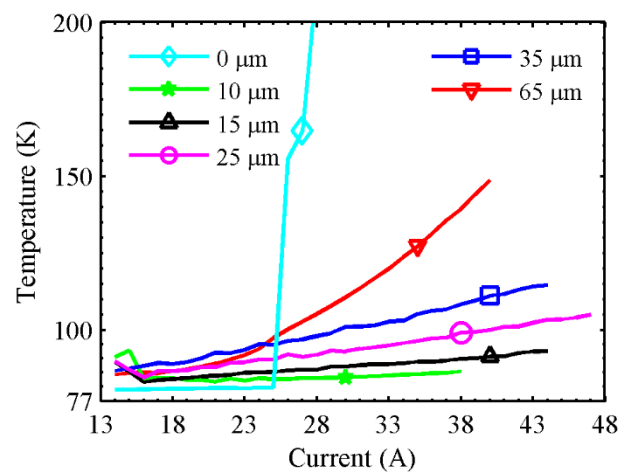
As shown in other studies [1], layers of polyimide film have a significant impact on the cooling process of the HTS wires. Fig. 4 shows the temperature of the samples with different layer thickness for a current of 30 A. At this amplitude, all of them demonstrate a quasistatic regime and stabilize at a certain temperature plateau. Fig. 5 shows the average of this plateau value (between 0.8 and 1.2 s) for all the current amplitude in the experiment. In general, the samples with thinner polyimide coating become rapidly unstable as the amplitude of the current is increased. However, the plateau value of these wires is also lower for the sample with thicker insulation.



**Figure 3.** Generated power, stored power and cooling power in the current study.



**Figure 4.** Temperature of the sample for different insulation layers with a current pulse of 30 A.



**Figure 5.** Average value of the plateau for different insulation layers.

### 3.3. Recovery speed

The recooling speed calculations are done by fitting the temperature curve after the end of the pulse. The time range of these curves is typically between 0.2 and 0.4 seconds. The temperature evolution is simply fitted with an exponential decay law,

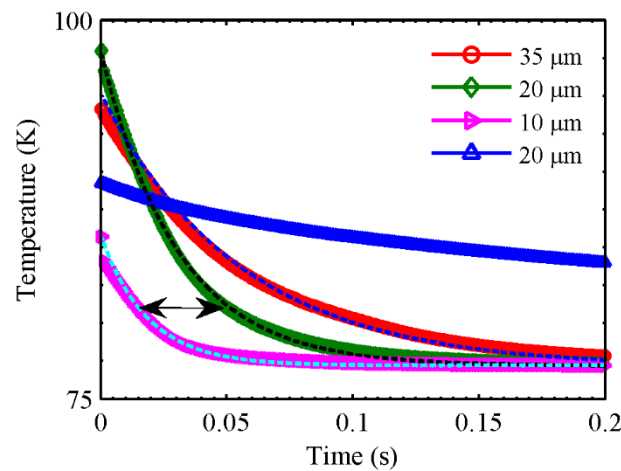
$$f(t) = Ae^{-kt} + B$$

where  $k$  represents the damping factor. Most of the recooling is done during the nucleate boiling phase, where the heat exchange between the wires and the liquid nitrogen is maximum. The initial temperature is always normalized to 1 before the fit in order to obtain comparable damping factors. An example of this fit is shown Fig. 6, the 3 first curves are in nucleate boiling regimes with very high absolute values of the damping factor of 18 for the 65  $\mu\text{m}$  insulation, 32 for the 20  $\mu\text{m}$  insulation and 53 for the 10  $\mu\text{m}$ . The fourth one did not reach nucleate boiling during the pulse and is therefore in conduction regime, the damping factor being much lower at approximately  $1 \text{ s}^{-1}$ . The double arrow shows the difference in the damping factor between two of the curves. The damping factors for different insulation layers are presented Fig. 7. Several observations can be made on this graph:

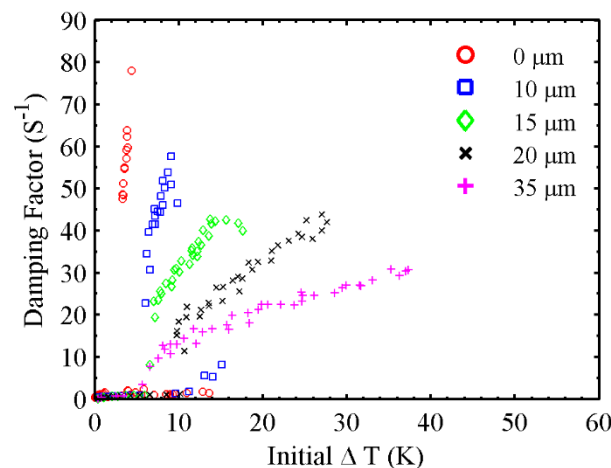
1. All curves start with a low damping factor (between 1 and  $2 \text{ s}^{-1}$ ) corresponding to conduction cooling.
2. All insulated wires show high damping factors (between 10 to  $60 \text{ s}^{-1}$ ) ; meaning an excellent recooling through nucleate boiling.
3. Higher insulation thickness induces lower cooling speed.
4. Small thicknesses (0- 15  $\mu\text{m}$ ) reach film boiling with low damping factor again at relatively low  $\Delta T$
5. Wires with 20 and 35  $\mu\text{m}$  are stable in nucleate boiling up to a higher  $\Delta T$ .

Measurements show that all wires with different polyimide thickness start with conduction cooling, and therefore a very low damping factor. As soon as  $\Delta T$  is high enough to be in nucleate boiling, damping factors are much higher. When  $\Delta T$  reach a higher value, film boiling regime occur and damping factor become again very low as it can be seen in Fig.7. This figure clearly shows that insulation greatly extend the domain (in  $\Delta T$ ) where high damping factors are present, ensuring a much higher thermal stability.

Previous work [5] presented results for handmade insulations, this paper presents measurements on insulations made by manufacturer, here SuperOx. Effective stability gain for these tapes is much better.



**Figure 6.** Exponential fit on the re-cooling part of the curves for different insulation layers and cooling regime.



**Figure 7.** Damping factors measured during re-cooling. The initial  $\Delta T$  temperature is the first point after the end of the pulse.

#### 4. Conclusion

The power exchanged to the nitrogen bath was measured for a bare wire and for several wires surrounded by polyimide coating of different thicknesses made by SuperOx. Optimal insulation thickness allows maintaining nucleate boiling at tape surface. The wires surrounded by polyimide coating are more stable than bare wires, as dissipation factors up to 800 W per meter have been measured in quasistatic regime. The wires surrounded by a 25  $\mu\text{m}$  insulation are stable at 98 K.. This exchanged power generally decreases for lower or higher insulation thicknesses. Recooling speeds were also measured and found to be higher in the nucleate boiling regime which occurred due to the presence of polyimide insulation.

This work definitely assesses that an optimized insulation, like the one made by SuperOx, can greatly enhance tape stability, protecting it against hot spots and irreversible damages at fault currents near or slightly above the critical current.

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