Critical aspects in the measure of the quench propagation velocities on HTS tapes

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Abstract. This paper concerns the investigation of the quench propagation phenomena in High Temperature Superconducting HTS tapes. In particular the determination of the Normal Zone Propagation Velocity NZPV, is based on the measure of the time propagation of the normal zone by reading the rising voltages detected by voltage taps placed at known distances. Several experimental aspects related to the measured times and voltages with their dependencies on temperature have to be considered. In particular, the rise up of the temperature determines a time limit that has to be considered to avoid the damage of the tape. Based on our measures of NZPV and in agreement with the results of a numerical model developed for our experimental environment, it is shown that the time limit of the measures is set by the value of the bias current. The tape length traveled by the normal zone front wave is related to this measure time and depends on the value of the NZPV that have to be measured. Adopting a simplified approach, it is possible to forecast the values of the tape length that may be used for the NZPV measurements and how its value may change as a function of the bias current.

1. Introduction
Superconducting wires and tapes are nowadays widely used to realize technological devices [1-4]. Technological superconductors can be divided into two types, according to the temperature below which the material becomes superconductor [5]. The niobium based Low Temperature Superconductor or LTS are mainly used to fabricate high field magnets and are typically in shape of wires, while the novel rare earths based High Temperature Superconductor or HTS are preferred, when possible, because of their higher stability and better superconducting properties. The HTS tapes are commonly distinguished into two generations and, for the purposes of this paper we will focus our attention on second generation HTS. These tapes have composite nature because in addition to the superconducting layer there is a metallic substrate and, in order to improve their stability, a normal metal coating.

During ordinary operation, in their superconducting state, these materials are able to carry high current densities ideally with no dissipation [6]. This current has to be always lower than a maximum value known as critical current $I_c$. Due to several mechanical or electro-magnetic phenomena, an abrupt transition to the normal state, called superconducting quench, can occur. The quench starts as a local event, when a certain region of the superconductor switches to normal state. During the quench, the normal zone enlarges and, due to dissipative effects, increases both in temperature and voltage. Due to the thermal heating the normal zone propagate along the tape with a proper velocity known as Normal Zone Propagation Velocity or NZPV. In LTS, because of their high NZPV values, the thermal energy...
available from the Joule heat, due to the dissipation of the transport bias current, will distribute quickly inside a large part of the superconductor, leading to a limited rise of the temperature. On the other hand, HTS with lower NZPV values confines the Joule heat into a short length. The concentrated heat may lead to a temperature raise that is high enough to locally destroy the superconductor.

In this framework, many efforts have been done in order to study the NZPV and search a way to improve these values. With this purpose, several groups developed different experimental techniques to measure the NZPV, trying to overcome different measurement problems [7-9]. One of these problems is the measure of NZPV too near the hot spot. As reported in 0, the values of NZPV near the hot spot is not constant and is different from its asymptotic value.

In this paper after a brief description of the NZPV measurement methods, a model able to describe the time dependent temperature behavior of NZPV and the relationship of the maximum traveled length of the normal zone as function of the steady transport bias current is presented.

2. The NZPV experimental determination
A typical experimental setup for NZPV measurement foresees a cryostat to cool down the tape sample below its critical temperature, an insert where the tape is fixed to be placed inside the cryostat, a certain number of voltage taps that are welded in an equally spaced configuration along the tape and an heater is glued in the middle of the tape to induce the quench. The tape is current biased by an external bias current $I_0$ while it is in its superconducting state. Once the heater is turned on, a certain amount of heat is locally delivered to the tape, leading to a local temperature increase that reduces the local temperature dependent critical current $I_c(T)$. At temperatures where $I_c(T) < I_0$ the superconducting layer remains into the superconducting state and transports only the actual $I_c(T)$. The difference $I_0 - I_c(T)$ will flows in the normal layer. The mechanism that splits this current is known as Current Sharing. Within the current sharing regime only the current $I_c(T)$ will flow in the superconductor until it goes to zero and all the current will flow only in the normal metal. The excess current, flowing in normal parts, generate a local heating that enlarge the normal region leading to the normal zone propagation which induces a voltage difference $V(t,I_0)$ along the tape 0.

The measure of NZPV is done by placing on the tape at least two couples of voltage taps. During the quench the voltage trace for each tap is recorded. Later on, during data analysis a fixed voltage threshold is chosen and the NZPV value is computed as the distance between two consecutive taps divided by the time interval needed by the taps voltages to reach the voltage threshold. More details on experimental procedure and materials can be found elsewhere 0.

Fig. 1 shows two $V(t,I_0)$ curves acquired on the same tap couple with different bias current. In the black curve, the Joule heating is not sufficient to trigger the normal zone propagation. On the red curve the bias current is sufficiently high to generate a quench. On this latter curve, it is possible to notice the quench generation and its propagation inside the voltage taps. In this figure, the red line in the region between the dashed lines corresponds to a fully normal state of the tape between the voltage taps. In this region the slow increase of the voltage $V(t,I_0)$ is caused only by the temperature increase.

3. The quench model
Quench propagation phenomena can be investigated experimentally and also by means of simulations and analytical approaches. One of the first quantitative model, able to predict some experimental findings, was developed by M. Wilson [1]. Later Iwasa 0, developed a more accurate model, based on one-dimensional differential general heat balance equation. All models developed so far deal with a complete analysis of the quench phenomena and for this reason are quite complex. Some models use non-linear differential equations with numerical solutions and FEM computation 0.

The proposed model analyzes the behavior of a tiny length of a tape after its complete transition in the normal state. In this condition further raising of the temperature, is only due to the Joule heating of the normal coating. On this region the thermal heating energy $E_j$ due to the Joule effect and the corresponding temperature increase $\Delta T$ can be simply equated:
Figure 1. Experimental representation of $V(t, I_0)$ for an HTS YBCO tape. Curves were acquired on the same tap with different bias current. In the curve, on the bottom of the figure, the energy is not sufficient to sustain the quench, while in the curve on the top the quench propagates along the tape.

$$E_j = V(t, I_0) I_0 t = c_p m \Delta T$$  \hspace{1cm} (1)

Where $c_p$ is the averaged specific heat, assumed constant, and $m$ the mass of this chunk of tape. The general dependence of the voltage $V(t, I_0)$ is quite complex but, in the region bounded by the two dashed lines of Fig.1, the tape between voltage taps is normal and is possible to assume a linear time dependence. We also assume, a power law dependence of the voltage versus bias current $I_0$ such as:

$$V(t, I_0) = K_V I_0^{\alpha} t$$  \hspace{1cm} (2)

Where $K_V$ is a proportionality coefficient and $\alpha$ is the exponent of this power law. By substituting the Eq. 2 into Eq. 1 and, solving with respect to the temperature variation the following result is obtained:

$$\Delta T = \frac{K_V I_0^{\alpha+1}}{c_p m} t^2$$  \hspace{1cm} (3)

This model neglects the time dependence of the heat diffusion along the tape after its local generation. This because the neighboring areas also dissipate by their own with an increasing temperature but this overall heating, keeps only a small linear time dependent temperature gradient. Unfortunately, the result obtained on Eq.3 is not easily verified experimentally. The measure of the temperature without perturbations with a thermometer fast enough to react in a fraction of seconds is not an easy task. In order to overcome this problem it has been decided to make a comparison of the finding of Eq.3 with the temperature obtained as a result of a simulated model of this tape, already published 0. The result of this comparison is shown on Fig.2 where, a second order polynomial, representing Eq.3, well fits all the points obtained by the numerical computation. The Eq.3 shows that the time needed to measure the NZPV cannot be arbitrary long. If $T_{\text{MAX}}$ is the maximum temperature before the tape damage, the maximum time $t_u$ allowed for making the measure is the following:

$$T_{\text{MAX}} = \frac{K_V I_0^{\alpha+1}}{c_p m} t_u^2$$ \hspace{1cm}$$t_u = \frac{c_p m T_{\text{MAX}}}{K_V I_0^{\alpha+1}}$$  \hspace{1cm} (4)
Another result, which can be obtained from this model, is an estimation of the maximum length $\Delta S$, traveled by the normal zone front wave during the measure. This can be done because it is possible to consider an approximate proportional dependence of the normal zone velocity $V_{NZ}$ on the transport bias current [1], or more explicitly, by writing $V_{NZ} = K_{NZ} I_0$ where $K_{NZ}$ is a suitable constant. At this point, the length $\Delta S$ versus $I_0$ can be explicitly determined from Eq.4 as follows:

$$\Delta S = V_{NZ} t_u = K_{NZ} I_0 t_u = K_{NZ} \frac{c_p m T_{MAX}}{K_V} I_0 \left(1 - \alpha^2\right)$$

(5)

**Figure 2.** Comparison of the numerical computed temperatures with a second order polynomial representing the Eq.3. The data are computed with a bias current $I_0 = 50 A$ and the temperatures are taken as the maximum value of the thermal front wave along the tape, as shown in Fig.3 of 0.

4. The role played by alpha

The value of $\Delta S$ it is important for the optimal voltage taps distribution on the tape. Wider separations, will improve the amplitude of the measured $V(t, I_0)$ signal with a better voltage to noise ratio. More couples may lead to a better measures of NZPV along the tape for which, at least two couples are needed. Moreover, voltage taps have to be placed far from the hot spot region in order to avoid its influence on the asymptotic NZPV value 0. All these requirements are in contrast with the finite value of the length $\Delta S$ that limits the maximum available space. The Eq.5 indicate how, within this model, the limiting length $\Delta S$ is related to the bias current $I_0$ through the value of the parameter $\alpha$ that can be experimentally determined as shown on Fig.3. In this figure the measured voltages $V(t, I_0)$ taken from our experimental data has been drawn as a function of the time for several values $I_0$ in the time interval where a thermo resistive behavior is observed (i.e. the region between the dashed lines in Fig. 1). All lines on Fig.3 have been translated to a common origin by setting, for all of them, the time of beginning of the fully resistive data range and the corresponding voltages to zero. From Eq.2, it is possible to observe that the slopes are proportional to $I_0^\alpha$. In this way, the $\alpha$ value may be determined by using the experimental slope coefficients of those straight lines as function of the bias.
In fact, reporting on a log-log plot the $V(t, I_0)$ slope coefficients $K_V I_0^\alpha$ as function of the bias current $I_0$ it may be possible to determine the best $\alpha$ value from the fit of the experimental data. Fig. 4 reports the slope coefficients $K_V I_0^\alpha$ obtained from the experimental data reported in Fig. 3 as a function of $I_0$ and the numerical fit from which the value $\alpha = 3.90$ has been obtained.

Figure 3. Measured voltages $V(t, I_0)$ for different $I_0$ values in the time interval where a linear behavior is observed. All curves have been translated to a common origin with the same voltage starting point.

Figure 4. Plot of the slope coefficients $K_V I_0^\alpha$ for different $I_0$ values and their best fit line with $\alpha = 3.90$. 
The good agreement between the experimental values and the fitting line justify the assumptions made on Eq. 2 and the results that are consequence of this model. The value of $\alpha$ indicates how the maximum available length $\Delta S$ changes upon different bias current $I_0$.

From Eq. 5 we can note that for value of $\alpha < 1$ the length $\Delta S$ increases while the current $I_0$ increases. If $\alpha > 1$, like with our experimental data, the increase of the bias current $I_0$ leads to a reduction for the maximum length $\Delta S$ available for voltage taps placement.

The value $\alpha = 1$ is a particular case where the length $\Delta S$ is independent from the current $I_0$ and, the placement of voltage taps do not depend on the bias current $I_0$ and taps may be always optimized.

5. Final remarks and conclusions

The developed model, despite being simple and able to describe only partially the quench behavior, can forecast the maximum $\Delta S$. With our experimental data with $I_0 = 50A$ and assuming $T_{\text{MAX}} = 400 K$ the model gives a maximum time $\Delta S = 7.75 s$. This time value together with a NZPV velocity of 2.1 cm/s determine a maximum length $\Delta S = 16 cm$. This value represents the space that the normal zone front wave can travel before reaching temperatures able to destroy the tape.

The behavior of the temperature increase obtained with this model is in good agreement with the data obtained with a more complex FEM simulation on a tape with the same properties. The proposed bias current dependence of the voltages detected by the taps after the quench seems to agree with our experimental measures. This model may be useful after, the first preliminary measures, with a brand new experimental apparatus. Once the range of currents has been chosen, the model can be used to optimize the length and the subsequent voltage taps placement. Within this model it is possible to estimate the maximum tape length that can be used for NZPV measurements within the chosen bias current range. The placement of voltage taps at distances longer than the length $\Delta S$ is useless. These taps cannot be reached by the normal zone propagation front wave without a severe damage of the tape. For very high bias current the length $\Delta S$ may become very short and smaller than the distance required to obtain the NZPV asymptotic value 0. The consequently measured values of NZPV taken in these conditions may be incorrect.

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