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Physics Procedia 67 (2015) 945 – 951

Physics Procedia

25th International Cryogenic Engineering Conference and the International Cryogenic Materials Conference in 2014, ICEC 25–ICMC 2014

# Measurement and analysis of normal zone propagation in a ReBCO coated conductor at temperatures below 50 K

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**Abstract**

Measurements of the quasi-adiabatic normal zone propagation velocity and quench energies of a Superpower SCS4050 copper stabilised ReBCO superconducting tape are presented over a temperature range of 23 − 47 K; in parallel applied magnetic fields of 6, 10 and 14 T; and over a current range from 50% to 100% of $I_c$. The data are compared to results of analytic predictions and to one-dimensional numerical simulations. The availability of long lengths of ReBCO coated conductor makes the material interesting for many HTS applications operating well below the boiling point of liquid nitrogen, such as magnets and motors. One of the main issues in the design of such devices is quench detection and protection. At higher temperatures, the quench velocities in these materials are known to be about two orders of magnitude lower compared to low temperature superconductors, resulting in significantly smaller normal zones and the risk of higher peak temperatures. To investigate whether the same also holds for lower temperatures more extended data sets are needed, both as input and as validation for numerical design tools.


Peer-review under responsibility of the organizing committee of ICEC 25-ICMC 2014

*Keywords:* Normal Zone Propagation, Quench Energy, High Temperature Superconductor, ReBCO, Coated Conductor

## 1. Introduction

In the present context, for the construction of HTS devices it is important to know the quench propagation characteristics of ReBCO tape conductor throughout the envisaged operational temperature-, magnetic field- and current ranges. However, even if applications are foreseen at temperatures ranging all the way from 4.2 K to 77 K and all of them typically involve current levels of several hundreds of amperes, almost all data available on the normal zone propagation velocity and minimal quench energies of ReBCO coated conductor lie in the temperature range of 40 − 77 K and currents below 100 A. Measurements on non-stabilized coated conductor samples in self field were performed by Trillaud [1] and Young [2]. Measurements on stabilized conductor are available from Wang [3],

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Peer-review under responsibility of the organizing committee of ICEC 25-ICMC 2014
doi:10.1016/j.phpro.2015.06.159

Angrisani [4] and Park [5]. The Normal Zone Propagation (NZP) experimental setup at the University of Twente, allows for measurements at lower temperatures and much higher currents. This paper presents the measured normal zone propagation velocities and minimal quench energies of a copper stabilized SuperPower SCS4050 ReBCO coated conductor; over a temperature range of 23 − 47 K; in parallel applied magnetic fields of 6, 10 and 14 T; and over a current range from 50% to 100% of $I_c$. The measurements presented are performed under quasi-adiabatic conditions. This means that the normal zones that are created can only expel their Ohmic heat through the sample itself, towards the colder and still superconducting sample parts at either side of the zone. Nearly no heat is transferred to the sample holder itself (on a time scale relevant for the propagation of the zone).

The measurement is performed using a time-of-flight type of experiment. This type of experiment has been used at the University of Twente since the late eighties of last century and was originally designed by Ten Kate [6] and Boschman [7] to characterize Low Temperature Superconducting wires at a constant temperature of 4.2 K. In 2007 it was redesigned by Van Weeren [8] to operate at variable baseline temperature for the study of quench propagation in Magnesium di-Boride ($MgB_2$). In a time-of-flight type of experiment, temperature, magnetic field and current through the sample are allowed to stabilize at chosen values before a localized heat pulse is injected. If the pulse does not trigger a quench, the temperature is allowed to stabilize again, after which a pulse with increased energy is injected. When a quench does occur, the speed of the superconducting-to-normal transition front is derived from voltage-versus-time recordings at various distances from the initial heat pulse location. The quench energy equals the energy deposited in the last heat pulse.

## 2. Sample Holder

Figure 1 gives a schematic overview of the sample holder. A helical ReBCO sample (I) is mounted between two copper flanges (II) that are kept at a temperature of 4.2 K by a liquid helium reservoir inside of the hollow sample holder (III). This allows the soldered contacts to be cooled efficiently and prevents them from warming up the sample. Low temperature solder is used for the joints. This simplifies the mounting of the samples and prevented the current leads (IV) from being de-soldered from the inside of the sample holder. The current through the sample is supplied via the copper flanges by two $Nb_3Sn$ current leads which are both connected through the helium bath. The main advantage is that the leads are kept at 4.2 K at all times, without influencing the adiabatic conditions of the sample. Underneath the sample a newly constructed embedded heater (V) allows to raise its global temperature. However, as discussed in the introduction, this needs to be performed as adiabatic as possible. Small nylon ridges (VI) on the surface of the embedded heater elevate the sample slightly from the holder, reducing thermal contact. A number of voltage leads are lead out through the vacuum tube (VII). To prevent convective heat transfer the sample chamber is pumped vacuum (VIII). The holder is inserted in a 15 T solenoidal magnet.

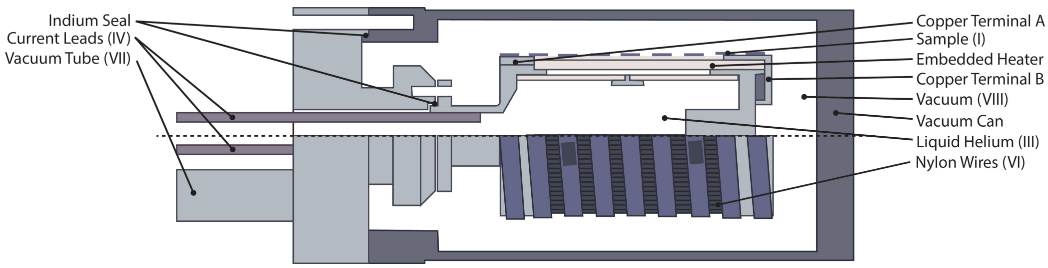



Fig. 1. Geometry of the sample holder rotated on its side. The top half of the picture shows a cross sectional view. The roman numerals are referred to in the text.

## 3. Sample Layout

Figure 2 presents a schematic overview of all the electrical and thermal connections of the sample. The sample is a superpower SCS4050 tape, which has a 50 $\mu$m thick hastelloy C-276 substrate and is stabilized using 20 $\mu$m thick copper plating on both sides. One of the concerns is to prevent the quench from getting 'caught' between two components acting as heat drains. If the length of the normal zone caught between two components is not sufficient to set off the quench detector, the tape will heat up locally causing it to burn out. To avoid this problem the quench heater ($HQ$), in the form of a ceramic surface mounted resistor, is glued at the center of the tape using an alumina loaded epoxy (see Figure 3). The quench heater is surrounded by three voltage taps soldered to the sample on each side ($V1$, $V2$ and $V3$). Because the quench propagation velocity in ReBCO is relatively low, especially at lower current levels (see Section 4), it is necessary to place the voltage taps with 5 mm spacing. In order to reach the sensitivity required to measure the critical current, the voltage taps need to span at least 50 mm in length. Both requirements can be met by using overlapping voltage taps. The first voltage tap is placed at a distance of 10 mm from the quench heater, which has a length of 6 mm, making the length of the normal zone 26 mm when it enters the first voltage tap. Unfortunately this configuration does not allow positioning a temperature sensor at the origin of the quench. To keep the temperature sensors as close to the quench heater as possible two CERNOX thermometers ($T1$, $T2$) are placed in between the voltage taps. Next to the thermometers, also inside the voltage taps, two small heaters ($H1$ and $H2$) are placed that allow fine tuning of the temperature. Outside the vacuum jar on the current leads an additional voltage tap ($Qd$) measures the voltage over the entire sample, including its joints, for the triggering the quench protection. The quench protection is complemented with a timed shutdown of the sample current. It should be noted that all electrical connections near and on the sample, are made using a 0.1 mm diameter manganin wire, in order to keep the experiment as adiabatic as possible. Also only a minimal amount of solder is used for making the electrical connections.

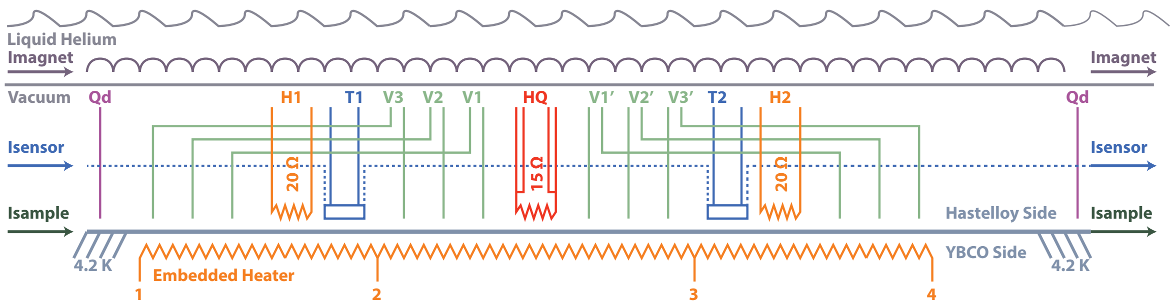



Fig. 2. Scheme of the electric and thermal connections in the sample holder of the NZP experiment. Tags are referred to in the text.

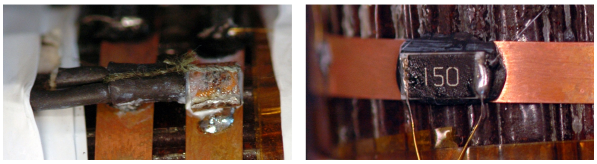


Fig. 3. Photograph of the thermal anchoring method used for the thermometer in a soldered casing and thermal paste (left) and the quench heater with alumina loaded epoxy (right).

## 4. Results and Analysis

Because it is chosen to measure at a certain set percentage of the critical current, it is first necessary to measure the $I_c(B,T)$ values. Due to the design of the sample holder there is an upper limit on the temperature of 47 K due to helium bubbles forming on the inside of the former, causing the temperature to fluctuate, and a lower limit around 23 K due to the critical current of the $Nb_3Sn$ leads exceeding the current required to perform an $I_c$ measurement. The measured critical current of the sample as function of temperature and magnetic field is presented in Figure 4. Note that the critical current for all measurements is defined using the customary threshold field $E_0$ of 10 $\mu$V/m and that the magnetic field is applied parallel to the tape. The N-values for all measurements are found to be in the range of

8 to 14, with a vague minimum around 37 K, which shifted slightly under the influence of magnetic field. However, this should be confirmed by more accurate measurements under more stable temperature conditions.

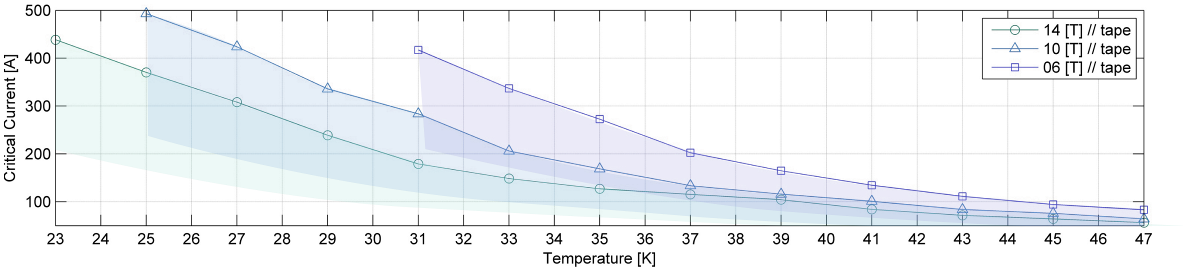



Fig. 4. Measured critical current of tape sample SCS4050 as function of temperature and magnetic field at $B$ = 6, 10 and 14 T, applied parallel to the tape. The critical current is defined at an electric field criterion of $E_0 = 10\ \mu\mathrm{V/m}$. The shaded areas represent the range from 50 − 100% of $I_c$ in which the NZP measurements where conducted.

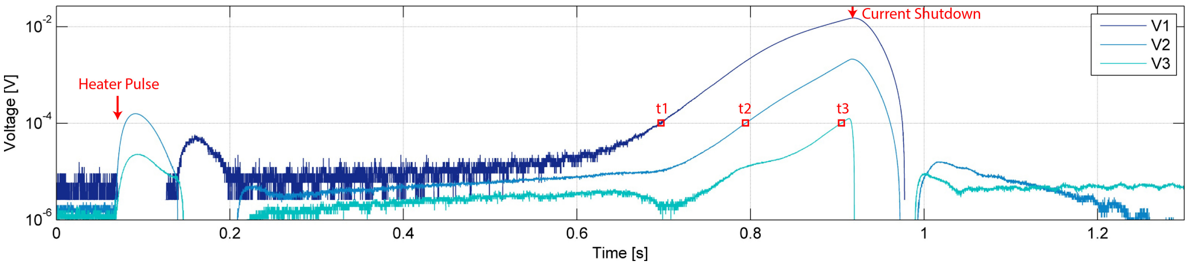



Fig. 5. Measured voltages over the voltage taps as function of time for a quench in a ReBCO coated conductor at a start temperature $T_{op}$ of 35 K, a magnetic field of 14 T and a current $I$ of 117.2 A, which corresponds to 90% of $I_c$.

The normal zone propagation velocity is derived from the voltage against time recordings. As an example, Figure 5 shows the voltage recordings of a quench at 35 K, 14 T and 90%$I_c$ (note that the vertical axis is on a logarithmic scale). After the initial quench heater pulse, which shows up as an induced voltage in the recordings, there is a slow rise in voltages, until the front of the normal zone fully enters the voltage taps at which point the voltages suddenly start to rise quickly. For the data to be of use, it is of great importance that the determined velocities are the actual steady-state velocities of the normal zone front and not the transients related to the initial build-up of a minimum propagation length. There are two indications that this is indeed the case:

1. The voltage profiles from the successive voltage taps that are used for the determination of the velocity are nearly identical in shape but shifted in time. If they are related to initial transients, the profiles would differ in shape.
2. The time-dependent numerical model presented in Section 5, clearly confirms that the quench propagates at or near the steady state velocity once it reaches the position of the voltage taps.

To find the normal zone propagation velocity, first the time delay between the voltage profiles is determined by taking a certain threshold voltage, at which the slope of the profiles is approximately equal for all three curves. For most measurements this voltage lies around 100 $\mu$V. From the time delays between the three voltage profiles and the distance with which the voltage taps are shifted with respect to each other, the normal zone propagation velocity is calculated. In Figure 6 all measured data of the normal zone velocity and the quench energy are presented. The error on the measured normal zone velocities is estimated to be ±10%. This estimate is based on the difference in velocities attained when using different threshold voltages and the uncertainty in the distance with which the voltage pairs are shifted. The plotted quench energies have been compensated for the heater efficiency, the fraction of the total dissipated heat that is transferred from the heater to the tape before the quench occurs. This fraction is estimated to be approximately 20% based on numerical simulations. This way of presenting $V_{nzp}$ and $MQE$ data is common throughout literature, but since $I_c(B, T)$ is itself a function of different variables, it 'mixes' the influence of the three parameters $I$, $B$ and $T$. A different but very interesting way to represent all normal zone velocities is on a log-log scale against sample current (see Figure 7). It can be seen that all data collapse on a single line. This means that within the measured parameter domain $V_{nzp}$ depends mainly and unexpectedly on the sample current only. The line fitted to the data can be described by the following power law

$$V_{nzp} = 10^{P_2} I^{P_1}, \quad (1)$$

where $P_1$ and $P_2$ are the fitting parameters, which are determined using a root-mean-square fit. The values found for these coefficients are −4.382 and 1.49 respectively, for which the maximum deviation between the measured data and the fit is only 6%. Note that the power-law coefficient $P_1$ is surprisingly close to 1.5.

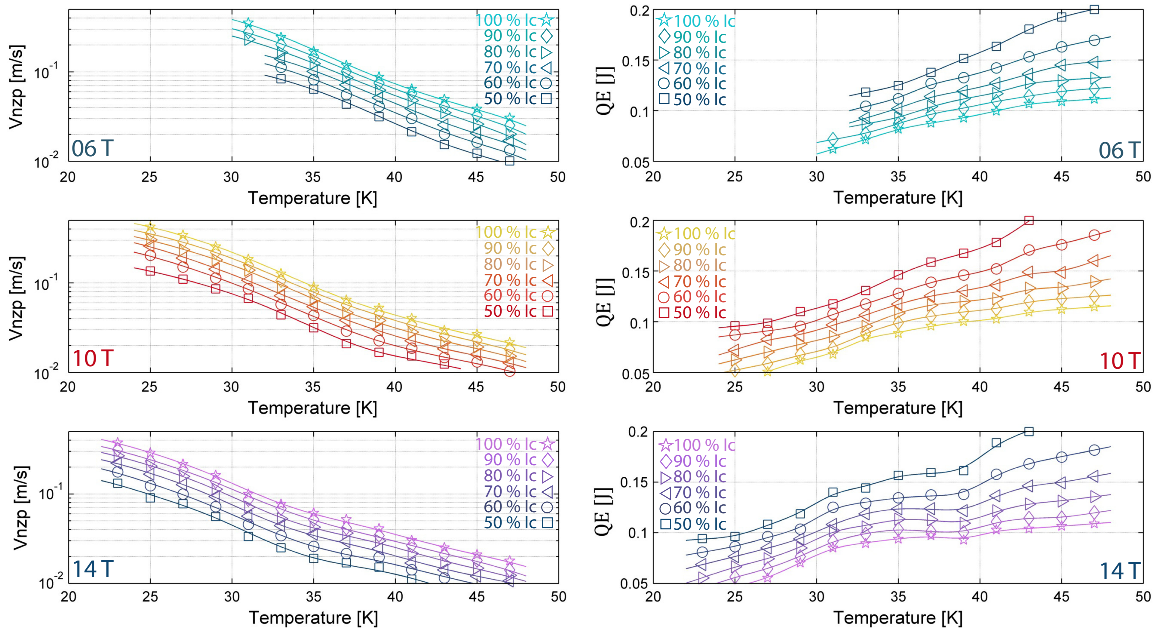
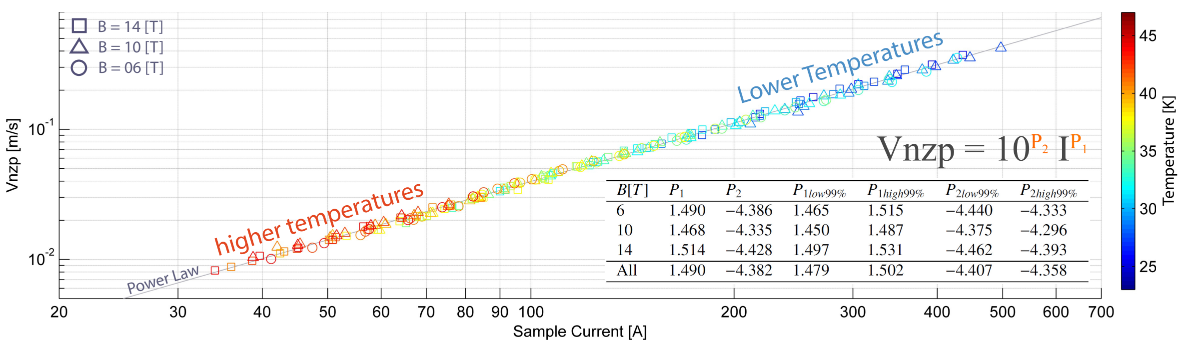



Fig. 6. Measured normal zone propagation velocity (left) and quench energy (right) as function of field, temperature and percentage of the critical current. The data for the quench energy is compensated for an estimated heater efficiency of 20%. Note that the normal zone velocities are plotted on a semi-log scale while the quench energies are plotted on a linear scale.




| $B[T]$ | $P_1$ | $P_2$ | $P_{1low99\%}$ | $P_{1high99\%}$ | $P_{2low99\%}$ | $P_{2high99\%}$ |
|---|---|---|---|---|---|---|
| 6 | 1.490 | −4.386 | 1.465 | 1.515 | −4.440 | −4.333 |
| 10 | 1.468 | −4.335 | 1.450 | 1.487 | −4.375 | −4.296 |
| 14 | 1.514 | −4.428 | 1.497 | 1.531 | −4.462 | −4.393 |
| All | 1.490 | −4.382 | 1.479 | 1.502 | −4.407 | −4.358 |

Fig. 7. Normal zone propagation velocity plotted on a log-log scale against the sample current at all measured magnetic fields and temperatures. The color of the data points denotes the temperature and the shape of the data points denotes the magnetic field magnitude. The solid gray line represents a power-law relation. The table shows the fitting coefficients for the power law describing the normal zone propagation velocity and their 99% confidence bounds.

## 5. Comparison with Analytic and Numerical Models

Because the superconducting to normal transition in HTS occurs over a much larger temperature range than LTS, it is important for both analytic and numerical models, to model the superconductor as a normal conducting element in parallel with a superconducting element. However an analytic solution of the heat equation at the normal zone front, taking the current sharing between these elements into account, results in an implicit solution as shown by Dresner [9]. For this reason Dresner showed that this full solution could be best approximated using a more simple step function model, with a discontinuous transition between the fully superconducting to the fully normal conducting regime at a certain transition temperature $T_t$, which is the average between the current sharing temperature and the critical temperature: $T_t = (T_{cs} + T_c)/2$. The normal zone velocity is then given by Wilson [10] and Iwasa[11]. The numerical model on the other hand employs a one dimensional finite difference method of the heat equation, allowing implicit solution of the current sharing. At the center of the tape the quench is initiated by increasing the energy in the heat-pulse until the normal zone develops, similar to how the measurement is carried out (see Figure 8). The length of the normal zone is determined using the electric field criterion. From the time derivative over the length the velocity of its front(s) is determined. The velocity stabilizes after an initialization transient. For both analytic and numerical models, especially at the lower currents, better agreement with the measured data can be achieved by including a small cooling term, which is estimated at about 0.1 W/mK. This agrees with the estimated heat flux through the nylon ridges. Both models show an agreement with all measured $Vnzp$ within a maximum deviation of 25%. These deviations can be expected due to the simplifications made and because the material properties are taken from literature. Agreement between models and MQE data are qualitatively reasonable but quantitatively less satisfactory, due to uncertainties in the quench heater efficiency.

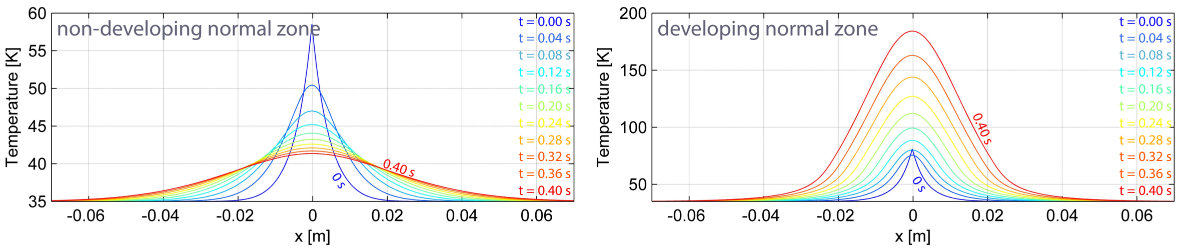



Fig. 8. Demonstration of the transient solution of the normal zone development inside SCS4050 ReBCO coated conductor at 35 K, 90%$Ic$. Plotted are the temperature profiles of the conductor as function of time. On the left the pulse energy is lower than the minimal quench energy and the normal zone disappears again. On the right side the pulse energy exceeds the minimum quench energy and a propagating normal zone results.

## 6. Conclusion

The measurement of the normal zone propagation velocity and the minimal quench energy of a ReBCO coated conductor is presented as function of temperature, percentage of the critical current and applied magnetic field. The measurements show that the normal zone propagation velocity (in the range investigated) seems to depend only on the current through a simple power law relation. The minimal quench energy, on the other hand, depends on all parameters $B$, $T$ and $I$. The data are compared to results of analytic and numerical descriptions for the normal zone propagation and the minimal quench energy. For the normal zone velocity a reasonably good agreement is found between the measurements and both the analytic and numerical models. For the minimum quench energy the quantitative behavior of the measured data is similar to the model predictions. Differences between model and measurements are caused by the inability to compensate correctly for the efficiency of the heater, which is unknown because the thermal resistance of the boundary between the heater and the tape is difficult to determine.

## Acknowledgments

SuperPower Inc. is greatly acknowledged for supplying the coated conductor tape.

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