Quench nucleation obtained by local reduction of $I_c$ in coated conductors

F Roy$^1$, B Dutoit$^1$ and F Sirois$^2$

$^1$ EPFL, École polytechnique fédérale de Lausanne, Lausanne 1015, Switzerland
$^2$ École polytechnique de Montréal, Montréal, QC H3C 3A7, Canada

E-mail: francois.roy@epfl.ch

Abstract. The normal zone propagation velocity in coated conductors is very small compared to YBCO on sapphire. For fault current limiter, it is more difficult to use them and obtain predictable behaviors under electrical faults. In the present work, we have measured the normal zone propagation on short coated conductors samples submitted to current pulses of variable length and amplitude (from 10-500 ms and $\approx$0.9-2.0 $I_c$ respectively). The normal zone nucleation is obtained using a magnetic tip to reduce locally the critical current density of the tape. This reproducible technique allows to choose and modify the initial nucleation site position as well as to perform multiple experiments on the same sample without making any physical defect on the conductor. The normal zone propagation measurements as well as the characteristic shape of the resulting I-V curves obtained from various current pulse waveforms are presented here. From the experiments, it is shown that field-induced defects allow to increase the normal zone propagation velocity as well as to reduce the initial delay before quenches in coated conductors. In addition, sub-cooled measurements have shown that an increase of the heat diffusivity obtained by lowering the coolant temperature improve the quench propagation.

1. Introduction

The overall growing needs of electrical energy as well as the increased interconnections of the actual/future grids lead to higher fault currents. This has the consequence that, in the near future, networks may reach or even exceed their limits with respect to the short-circuit current withstand capability of actual protection devices [1]. Accordingly, there are many efforts deployed to incorporate new technologies from those that have been traditionally installed to modernize aging-electrical grids and make them more secure and efficient. Superconducting power equipment as fault current limiters (FCLs) could be an important element in those efforts [2; 3].

Up to now, some of the promising FCLs projects are plan to use coated conductors as current limiting component [4]. Besides the actual producing cost of such conductors, one of the important issue related to their prospective use is the difficulty to anticipate and prevent destructive quenches as well as to ensure a uniform transition of the superconductor over its entire length. The ability of conductors to quench uniformly is characterized by the normal zone propagation velocity (NZPV). There are several ways to act on the NZPV, e.g. acting on substrate thermal properties [5; 6], stabilizer architecture [7], interfacial resistance [8] or trough shunts configurations [9; 10]. In the present work, we investigate the influence of field-induced-defects and of the coolant temperature on the normal zone propagation.
2. Experimental setup

Measurements of the NZPV are made on 4 mm-wide, 50 mm-long coated conductors provided by SuperPower.inc having, basically, the structure Hastelloy®/MgO/YBCO/Ag – see product datasheet SF4050 [11]. The experimental setup is based on a typical voltage taps arrangement – see figure 1, in which quenches are monitored through 16 thin aluminum wires (diameter \( \approx 100 \, \mu m \)) soldered at the tape center. Each wire is disposed approximately \( 2.5 \pm 0.2 \, \text{mm} \) apart along the tapes length, allowing voltage measurements at the terminals of 15 equally spaced sections of the conductor.

Samples are submitted to current-driven pulses of different amplitude and duration i.e. 80-175 A and 10-500 ms respectively. Quench nucleation is obtained using a small permenorm® electromagnet used to create non-destructive, variable-size field-induced defects in one of the 15 wire-delimited sections of the tape. In order to reach a reasonable magnetic field, the magnet coil is made of 610 turns of 0.2 mm diameter-size copper wires. Using coil current \( (I_m) \) in the range 0.5-2 A, we measured the localized DC magnetic flux with a small, movable cryogenic Hall probe \((0.127 \times 0.127 \, \text{mm}^2 \text{ active area})\) controlled by a steeper motor placed at the exterior of the cryostat. The magnetic flux obtained from the coil has shown to be as large as 225 mT – see figure 2. Considering the inset in figure 2, which is the field dependance of the critical current [11], we estimate the reduction of \( I_c \) to be as large as 70% for the section being in the magnet air-gap. All our data acquisition and controls are realized with a standard National Instruments M-series DAQ card [12], allowing a 16-bits quasi-simultaneous voltage monitoring of the sections with a sampling rate up to 125 kS/channel.

The measurements methodology is as follows: defects in tapes are produced using a localized DC magnetic field. During the imposition of transport-current pulses, quenches are initiated in the magnet air-gap, where the external magnetic flux is maximum. Due to current redistribution and heat generation, the normal zone start to propagates in the sections adjacent to the coil air-gap, building up an electric potential difference between the end-taps of the corresponding sections. This voltage, directly associated to the normal state arising in the material, gives an estimate of the transition dynamics occurring during the current pulses.

Figure 3 illustrates typical time-resolved voltage traces obtained during the experiments.

![Figure 1](image1.png)

**Figure 1.** Voltage taps (16 overall) are \( \approx 2.5 \pm 0.2 \, \text{mm} \) apart and made of 100 \( \mu m \) aluminum wire to reduce probe artifacts on the measurements. The permenorm® coil is made of 610 turns of 0.2 mm diameter-size copper wire. On the left picture, S11 and S10 represent wire-delimited sections (respectively sections 11 and 10) for which the voltage is monitored – see for example figure 3.
Figure 2. Hall probe mapping of the magnetic flux generated by the magnet carrying 0.25-2.00 A in liquid nitrogen along the length of the samples for an air-gap of d = 1.5 mm. Note that the field saturates with the coil-current ($I_m$). This seems to be due to the pole-tips of the magnet which locally reach the saturation field of permenorm® ($\approx 1.5$ T). The dashed-lines drawn on the figure delimits the sections which are numbered in blue at the top of the figure. The inset depicts the field dependance of $I_c$ used in this work [11]. The red curve in the inset represents the Kim’s law, which is expressed here as $I_c(B) = I_c(T=77)(1 + B/B_0)^{-1}$.

A estimate of the temperature (obtained from the tape $R(T)$ curve above $T_c$) is also placed on the right abscissa. Still on figure 3, the black-dashed line represents the quench criterion used into this entire work to defined relevant times. Those are $\Delta t_{ini}$, $t_1$ and $t_2$ which are obtained for values of the voltage at which the corresponding tape resistance ratio $R/R(300)$ reach 0.1. $\Delta t_{ini}$ represents the initial delay before the quench apparition, $t_1$ is the first reference time to determine the NZPV, corresponding to the resistance apparition in section 10, and $t_2$ is the second reference time corresponding to the resistance apparition in section 9. The NZPV is thus obtained with the following formula:

$$NZPV = \frac{0.25 \text{ cm}}{t_2 - t_1}$$

We used section 9 and 10 to determine the NZPV in order to reduced the error due to field overflowing from section 11 – see figure 2. This field overflow induce a larger flux-flow resistance nearby the defect that increases significantly the NZPV. Note that the small lag observed between the transition of sections 10/12 and 9/13 might caused by uncertainty on the taps spacing as well as to the tape orientation in the coolant (the tape is placed vertically). Due to buoyancy forces and bubbles forming at the tape interface, we expect different heat transfer for sections placed above section 11. For instance, sections 12, 13, 14, etc. Since NZPVs are low, current pulses have to be terminated before the whole spreading of the normal zone through the entire length of the tape. This, in order to avoid thermal runaway ($I_c$ degradation is observed over 500 K) and destructive hot-spots. Accordingly, in the present setup, 5 sections (12.5 mm) were sufficient to estimate the NZPVs.
Figure 3. Typical time-resolved voltage measurements for a current pulse of 140 A and 20 ms of duration (see the waveform in the inset). Each curve represents the resistance increase coming from the build-up electrical field generated in the sections. Section 11 (labeled with a “M”) is the section in which the magnet is located. The NZPV is obtained using equation 1. The DC current in the coil ($I_m$) is 2 A and the air-gap 1 mm. The black-dashed line represents the quench criterion corresponding to $R = 0.1R(300)$.

3. Results

The first thing to note from figure 3 is that, as expected, the first section presenting a growing voltage is the section in which the magnet is located (section 11, orange curve), followed by the adjacent sections, i.e. 10/12, 9/13 etc. One may also notice that all the curves presented in the figure show a kink. The kink appearing on all curves is observed once the section under study becomes fully normal (confirmed by numerical simulations). Since the magnetic field generated by the coil ($I_c$ reduction) is more intense in section 11 – see figure 2, the kink is observed at a smaller temperature in this section than in the others. Considering the relatively long tap spacing (2.5 mm), we expect the temperature to be not uniform across the whole sections. Once the farthest end (from the defect) of a section transit to the normal state, the closest end already at a temperature above $T_c$. Nevertheless, the voltages monitored during experiments represent an average of the sections temperatures. This averaging artifact may explain the discrepancy observe in the transition temperature (around 160 K instead of 90 K). This phenomenon is emphasized by the low NZPV values observed in coated conductors. This is further supported by the fact that adjacent sections begin to show potential difference once the former sections are fully normal i.e. just after the kink appears, without overlap, meaning that the normal zone front is very steep.

Figure 4 shows NZPV obtained by varying current pulses amplitude and duration for different DC coil-currents. According to this figure, one can notice that the velocities have about twice the magnitude than that usually found in literature for similar tape – see for example [13]. This is explained by the absence of the copper clad, usually present on commercial tape, as well as to the magnetic field overflowing from section 11 that, we supposed, respectively helps to reduce heat generation during the current pulse and increases the flux-flow resistance along the tape length. Besides this fact, figure 4 shows that over 120 A ($\approx 1.4 I_c$) the effect of the coil current (localized magnetic field) is more important than at lower current pulses, where
Figure 4. NZPV as a function of current pulse amplitude (the top axis displays the normalized current, i.e. $I/I_c$). $I_m$ is the DC current passing through the magnet. The magnet air-gap is 1 mm. Note that the critical current without any defect is $I_c=86$ A [11]. At $I = I_c$, the NZPV is approximately $11 \pm 1$ cm/s for any field-induced defect.

the NZPVs seems independent of the defect strength ($I_m$). This feature may come from ohmic losses occurring in the silver shunt once the superconductor has transited. As a matter of fact, an increase of the defects strength allows more current to be diverted into the shunt, which contributes additional heat and thus increases the velocities. Since losses are proportional to $RI^2$, the effect of the magnetic flux becomes less apparent at lower pulse amplitude; we believe that the NZPV is roughly proportional to Joule losses occurring in the tape.

Another important feature observed from voltage traces is the time needed for the normal zone to appears in the samples. Following figure 5, it can be shown that, at currents below 140 A, smaller defects take more time to make section 11 transiting (large $\Delta t_{ini}$). In fact, most of the samples that were burned during experiments was at low transport-current pulses (below the sample $I_c$, not below the defect $I_c$). The energy injected in the tape being proportional to pulses duration, the flux-flow resistance developing along the length of the conductor was large enough to burn those samples. This initial time is of primary concerns for making FCLs since during faults, meters of conductors must quench quickly in order to rapidly detect and interrupt the electrical fault. This is particularly true if the prospected FCL must deal with transient currents in the range of the critical current.

Finally, thermal effects on the NZPV were observed in sub-cooled liquid nitrogen (at ambient pressure). Figure 6 shows velocities obtained for transport current pulses of 150 A with coil-current of 2 A. For this particular current value, a considerable reduction of the NZPVs with the bath temperature is observed. However, if we consider the temperature dependance of $I_c$ (see top axis), the NZPVs are larger in comparison with experiments made at 77 K for the same normalized current $I/I_c$ (figure 4). The improvement is approximately equals to 30% and 11.5% at $I =1.42I_c$ and $I =1.62I_c$ respectively. In fact, the reduction of the temperature improves the thermal diffusivity (reduces the heat capacity) of the substrate [14] and also diminish the heat
Figure 5. Initial time before quenching ($\Delta t_{ini}$) for a magnet air-gap of 1 mm. Long initial times make the propagation hard to achieve and lead to hot-spots.

Figure 6. NZPVs for a sub-cooled tape. This measurement was done by reducing the pressure into the cryostat which, in turn, induces the temperature reduction. Once the minimum temperature was reached, the ambient pressure was reestablished inside the cryostat. Then the response to current pulses of 150 A, with $I_m=2$, was monitored at every 10 seconds during the bath warming-up ($\approx 10$ minutes). The top axis shows the normalized current ($I/I_c(T)$) obtained from a linear extrapolation, i.e. $I_c(T) = I_{c0}(T_c - T)(T_C - T_0)^{-1}$, $T_0=77$ K and $T_c=90$ K.
transfer [15] expected at such time-scale (tens of ms). This improve the propagation velocities and confirms our belief that the NZP is mostly a thermal effect.

4. Conclusion

The present work shows that field-induced defects can improve the normal zone propagation velocity. Considering the NZP to be mostly a thermal effect, we believe that the improvement is related to the local reduction of $I_c$, and consequently to the additional heat generated in the stabilizer. Results also showed that induced-defects can reduced the initial delay before quench propagation in coated conductors begins, and make them more prompt to respond to an electrical fault. This is particularly true for currents in the range of $I_c$. From the experiments presented here, sub-cooled experiments have shown that lowering the bath temperature causes an improvement in the NZPVs, considering normalized currents. This confirms that the NZP is mostly a thermal effect since this improvement seems to originate from the increase of the heat diffusion arising with the reduction of the coolant temperature.

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