Normal Zone Propagation Velocity and Minimum Quench Energy of Stainless Steel Double-Layered Superconducting Wires Under External Magnetic Fields

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Received: 31 January 2019 / Accepted: 6 August 2019 / Published online: 12 August 2019
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Abstract
A comprehensive study of the quench properties of single laminated wires having a double-layered superconducting structure is presented. In particular, we have focused on the influence of the angle and intensity of an external magnetic field perpendicular to direction of the applied current on the minimum quench energy (MQE) and normal zone propagation velocity (NZPV) values. We conclude that strong changes on the NZPV are mainly determined by the intensity of the applied current, while the orientation and magnitude of the applied field have a less but not negligible impact on the resulting NZPV. The quench parameters are also reported for the case when the applied current is considered as a constant parameter in which case the MQE has been found to reach a maximum value when the in-field critical current is the largest.

Keywords Normal zone propagation velocity · Minimum quench energy · Double-layered superconducting tape

1 Introduction
Systematic studies on the quench properties of commercially available superconducting tapes are important for the deployment and optimization of novel superconducting technologies. Various quench detection methods have been proposed to protect devices from any destructive hot spots although more rapid and sensitive methods are still desired [1–3]. Understanding the quench phenomenon is also important for the development of resistive-type superconducting fault current limiters [4]. These devices use the resistance of the superconducting composite which is developed during a quench event to reduce a fault current to safety thresholds. The superconducting state is then restored when the operating current returns below the critical current of the superconductor. In order to determine the actual recovery time and it is necessary to analyze the velocity of propagation of the quenched zone, also called the normal zone propagation velocity (NZPV). This is a challenging task in most practical applications where the superconductor is subjected to the influence of $B_0$.

To the best of our search in literatures, a comprehensive study is missing: on the field angular dependence of the quench dynamic for second generation of high temperature superconducting (2G-HTS) tapes under various experimental conditions. In order to understand the influence of external magnetic fields on the quench behavior of 2G-HTS tapes, specifically designed for current-limiting and current-lead applications, we present a systematic study on the field angular dependence of the quench dynamic for double-layered American Superconductor (AMSC) tapes under various conditions. The most important parameters on the characterization of quench dynamics, i.e., NZVP and the minimum quench energy (MQE), are addressed.

2 Experimental Conditions
For the conducted experiments, we chose the Amperium® 8612 stainless steel laminated wire manufactured by American Superconductor (AMSC), with its unique
characteristic of having two HTS/substrate layers placed back-t0-back for composing the core of the tape, and more details of this wire can be found in [5]. The test sample (160 mm in length, 12 mm in width, and 0.3 mm in thickness) was placed on a sample holder made from a tufnol support board coaxially connected by a stainless steel rod to a high precision manual rotation stage with a gradation of 1° and vernier of 5′. Technical information concerning the experimental setup, including the locations of the voltage taps, thermocouples, and power chip resistor (heater), as well as other important considerations for the adequate measurement of the NZPV can be found in [6]. For the magnetic measurements, a Hall probe was soldered onto a printed circuit board aligned parallel to the surface of the SC tape, and within less than 1 mm of separation between them.

The main purpose of the study presented in this paper is to determine the influence of external magnetic fields on the NZPV and MQE values of the AMSC 8612 double-layered HTS tape. Thus, firstly, critical current measurements were performed by slowly ramping up the current while measuring the resulting electric field $E$ between the set of voltage taps and in self-field conditions. The experimental procedure was repeated multiple times in the presence of $B_0$ with intensities ranging from 50 up to 400 mT, and for different field orientations. Finally, with the data collected, the average critical current across the entire sample is determined for each one of the experimental conditions. All the measurements were performed at the temperature 77 K.

The angle of the applied magnetic field is defined as 0° when the direction of the field is perpendicular to the broad surface of the SC sample. Once thermal equilibrium is established, the transport current is slowly ramped up from 0 A with a fixed rate of 10 A/s, and stopped when a voltage drop of 10 μV is observed in some section of the tape. This

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Fig. 1 Critical current measurements, $I_c$, as a function of the applied magnetic field at different angles (top) and intensities (bottom). Normalized values regarding the critical current at self-field conditions ($I_c^* = 532$ A) are also displayed (left axis)
procedure has been repeated three times for a more accurate estimation of $I_c$. An average $I_c$ at self-field of 532 A has been obtained, using the standard electric field criteria of 1 $\mu$V/cm.

Then, five different magnitudes of $B_0$ were applied, namely, 50 mT, 100 mT, 200 mT, 300 mT, and 400 mT, and the field angles considered are within the range of $-20^\circ$ to $120^\circ$, in intervals of $2^\circ$. Only for the angular regions around the $0^\circ$ [$-4^\circ$, $+4^\circ$] and $90^\circ$ [$86^\circ$, $94^\circ$], the data were collected in intervals of $1^\circ$. In this way, the two expected peaks over these two angular regions are better described.

The derived $I_c$ values as a function of the intensity and direction of $B_0$ are presented in Fig. 1, with some of these values presented in Table 1. It can be observed that the average $I_c$ of the double-layered HTS tape is strongly dependent on the intensity of $B_0$, dropping from 0.95 $I_c^*$ at 50 mT to less than 0.4 $I_c^*$ at 400 mT. This tape does not show a strong dependence with the direction of $B_0$ at low and moderate fields as is the case reported for most of the single layer HTS tapes commercially available [7].

Once the $I_c$ value has been determined under the different experimental conditions, it is necessary to determine the minimum quench energy (MQE) under certain operating conditions (field, temperature, current). This value is ascertained by measuring the minimum voltage pulse (is this value or duration or both) which has to be applied to the soldered heater in order to initiate an irreversible quench.

Thus, after setting up the external magnetic field to a specific value, and locking the rotation stage at a given angle, the transport current was slowly ramped up to a certain fraction of the corresponding $I_c$ value (Fig. 1), ranging between 0.3 and 0.9 $I_c^*$, and held steady during the subsequent measurements.

The MQE needs to be determined at multiple current values (different fractions of $I_c^*$), and it is advisable to start at the highest current as the quench energy slightly increases each time the current is lowered. This makes the next measurement of the MQE more predictable and therefore reduces the number of tests required. On the other hand, in order to

**Table 1** Critical current $I_c$ (A) of Amperium® type 8612 wire under various field orientations and magnitudes

| $B_0$/mT | $-15^\circ$ | $0^\circ$ | $15^\circ$ | $30^\circ$ | $45^\circ$ | $60^\circ$ | $75^\circ$ | $90^\circ$ | $105^\circ$ |
|---------|-------------|---------|---------|---------|---------|---------|---------|---------|---------|
| 50 mT   | 500         | 497     | 500     | 504     | 507     | 509     | 508     | 511     | 507     |
| 100 mT  | 426         | 422     | 429     | 434     | 439     | 442     | 445     | 448     | 442     |
| 200 mT  | 301         | 300     | 306     | 311     | 321     | 330     | 340     | 344     | 336     |
| 300 mT  | 238         | 239     | 242     | 245     | 251     | 261     | 274     | 283     | 268     |
| 400 mT  | 192         | 194     | 196     | 200     | 205     | 210     | 219     | 235     | 212     |

**Fig. 2** Voltage and temperature profiles vs time for samples in: a the absence of an external magnetic field, and b, c with $B_0 = 300$ mT. In a, b, the transport current was set at 119.5 A, and the magnitude of the heater pulse was 19.5 V and 19.8 V, respectively. In c, the applied current was 215.1 A, and the magnitude of the heater pulse was 15.9 V. The position of the pulse chip resistor, voltage taps, and thermocouples is also illustrated. The duration of the heater pulse was 200 ms for all cases. The vertical arrow indicates the starting time for the heater pulse.
calculate the NZPV along the longitudinal direction, the sample is quenched under the MQE conditions, such that the NZPV is calculated using the time (∆t) taken for a normal zone front to propagate from a voltage tap or a thermocouple to its immediate neighbor. The relative distance between the voltage tap and analogously the thermocouples is of 10 mm. For defining the time lag (∆t) for each one of the cases, a reference voltage (V_{ref}) or reference temperature (T_{ref}) is selected in regions where two adjacent voltage or temperature traces are almost parallel to each other. In this way, an average propagation speed for one specific section can be achieved by direct comparison of the distance between adjacent voltage (or temperature) taps and the time lag (∆t).

3 Results and Discussion

During the experiments, some unique features of the temperature profiles vs. time have been observed (Fig. 2). For smaller transport currents, there was a distinctive crossing between temperature traces TC1 and TC2, and traces of TC1 even crossed over TC3 in some cases, which indicates a more gentle temperature rise in the area closer to the heater. Further experiments have been performed with identical setups but with different samples, and with the heater and all thermocouples replaced, but in all cases similar, we have obtained similar results for all field orientations. This distinctive crossing has also been observed by others in Ag-sheathed Bi-2223

![Fig. 3 NZPV (left) and MQE (right) as a function of the field orientations and under different transport current conditions, \( I_c \), for samples subjected to an external field of magnitude: (a) 50 mT, (b) 100 mT, (c) 200 mT, (d) 300 mT, and (e) 400 mT, respectively.](image)
superconducting tapes [8], and AMSC Cu-stabilized YBCO-coated conductors [9, 10]. Magnetization currents were thought to be responsible for this crossing, and to assess this additional experiment has been performed in the absence of external magnetic fields, the results of which are reported in Fig. 2a.

For the self-field case (Fig. 2a), the temperature profiles correspond with the voltage profiles for each measured region, i.e., the temperature rise is observed after a rise in the voltage is seen at the corresponding region (reaching 0.026 V for TC1, 0.024 V for TC2, and 0.020 V for TC3). On the other hand, when the sample is subjected to 300-mT field at 0 (Fig. 2b, c), a discernible temperature rise is observed even before the rise of the voltage in the section V7–V6 is detected (Fig. 2c). In fact, a higher voltage level needs to be reached before the temperature begins to change, namely, 0.038 V for TC1, 0.028 for TC2, and 0.008 for TC3, with an applied current of 215.1 A. In this case, a much longer time lag (Δt = 2.7 s) is observed for the voltage rise between V6–V5 and V5–V4; it compared with the Δt = 1.5 s obtained for the self-field condition. Finally, it is to be noticed that the temperature at which TC1 and TC2 cross at self-field conditions is ~130 K, which

![Fig. 4](https://example.com/fig4.png)

*Fig. 4* Same as Fig. 3, but with the NZPV and MQE as function of the transport current, $I_t/I_c$. 

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is substantially greater than the one observed at 85 K for the sample under a 300-mT field and \( I = 119.5 \) A (Fig. 2b). Then, we have observed that this crossing disappears when a higher current is applied (see e.g., Fig. 2c). One possible reason for this unusual behavior might be the heat leak at the heater location. In fact, when a small transport current is applied, a longer time is required to initiate a quench which can be propagated across the superconductor, i.e., when the initial normal zone starts to expand under the effects of Joule heating and the boiling of the liquid nitrogen. The Joule heating at the quenched zone heats up not only the superconducting tape but also the heater when the heat pulse ends. Thus, as the applied current is small, the Joule heating is also moderate, what leads to a slower normal zone expansion rate, and a larger heat leak at the heater. Therefore, it explains why the temperature trace of TC1 has a gentler slope than that observed in the other thermocouples, and why the crossing effect is not seen for larger applied transport currents. Likewise, it suggests that the areas close to the weak point where the heat disturbance is originated may be more vulnerable when the operating current is much smaller than the critical current.

Concerning the results obtained for the NZPV and MQE, our results are presented as a function of the direction of \( B_0 \) (Fig. 3), its intensity (Fig. 4), and the intensity of the transport current (Fig. 5), for the sake of clarity, and under a wide set of experimental conditions. In Fig. 3, it can be observed that the NZPV of the double HTS-layered AMS8612 tape shows a clear angular dependence with the intensity of the magnetic field, with the occurrence of a peak at 90° \( (B_0 \parallel ab) \) as the field increases, contrary to what is observed with the MQE. A less notorious

![Fig. 5](same as Fig. 3, but with the NZPV and MQE as function of the external magnetic field)
angular dependence with the intensity of the transport current is observed for magnetic fields lower than 300 mT, although it is clear that the NZPV increases as $I_t$ increase for all the cases. It must to be noticed that the occurrence of the peak on the NZPV as a function of $B_0$ coincides as well with the magneto angular dependence of $I_c$ as it is shown in Fig. 1.

In Fig. 4, it can be observed that the NZPV and MQE show opposite tendency with increasing applied current for all the measured field orientations. The slopes of the two tendencies are reduced with increasing external fields. This fact is due to drop on the critical current with the increasing of the external magnetic. In general, we have observed that the NZPV reaches its maximum at 90° whereas the MQE reaches its minimum at this angle, opposite to what is observed at 0°, regardless of the intensity of the applied current or field. This illustrates an intrinsic trade-off between stability (high MQE) and the requirements for fast quench detection (high NZPV). On the other hand, in Fig. 5, the behavior of the NZPV and MQE as function of $B_0$ is shown, where an opposite tendency is observed in comparison with analysis performed for their dependence with the transport current (Fig. 4).

We have obtained that the NZPV decreases as a function of $B_0$ with an average decay ratio of maximum 10 mm/s for each 50-mT increment within 0 to 400 mT, although for $B_0 \leq 100$ mT, the observed trend for the MQE does not seem to follow a well-defined pattern with $I_t \leq 0.6I_c$. However, a relatively steady rise (in average) of the MQE is observed for greater magnetic fields, and the calculated values for the MQE are found in the range of 1 to 2 J.

4 Conclusion

In summary, the in-field quench behavior of the double-layered 2G-HTS AMSC8612 stainless steel laminated wire has been studied. As far as is known to the authors, no other comprehensive study like that reported in this manuscript has been presented so far. The most important parameters related to the quench dynamics, i.e., the critical current density, the NZPV, and the MQE values for different applied transport currents, and by varying the intensity and angle of an external applied magnetic field, are all reported for a wide set of experimental combinations. We found that the NZPV does not show much variation with respect to field orientation, but it increases substantially with increasing applied current. The MQE reaches a distinctive peak at 90°, which corresponds to the peak in the critical current (Fig. 1), and the minimum value is observed at around 45°.

Acknowledgments The experiment was executed with the help from the Electrical Engineering Division, Department of Engineering, University of Cambridge. Authors would like to thank the members of staff for their important help.

Funding Information This work was supported by the EPSRC under Grant NMZF/064.

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