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Quench propagation in coated conductors for fault current limiters

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Abstract

A fundamental understanding of the quench phenomenon is crucial in the future design and operation of high temperature superconductors based fault current limiters. The key parameter that quantifies the quenching process in superconductors is the normal zone propagation (NZP) velocity, which is defined as the speed at which the normal zone expands into the superconducting volume. In the present paper, we used numerical models developed in our group recently to investigate the quench propagation in coated conductors. With our models, we have shown that the NZP in these tapes depends strongly on the substrate properties.

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Introduction

Superconducting resistive Fault Current Limiters (FCLs) are based on the fast superconducting to resistive state transition occurring in superconductors at $I > I_c$. They are promising devices to become one of the first large scale commercial application of high-temperature superconductors (HTS) in the industry to achieve higher stability and reliability of electrical power grids [1-3]. As coated conductors (CC) are now produced with high critical current, long length and as their prices should drop in the future, CC appear to be well suited for FCL manufacturing [4, 5]. The ideal conductor for FCLs needs to transit rapidly and homogeneously to the normal state. In addition, heat diffusion trough these tapes should be as fast as possible in order to avoid apparition of burned spots with local destruction of the superconductor. However experimental measurements in YBCO tapes have shown that the NZP velocity in CC is not as fast as expected (in the range of 0.1 to 4 cm/s) and have poor thermal properties from a diffusion point of view [6-8]; other recent experiments demonstrate that the normal zone propagation (NZP) in CC are strongly dependent on substrate thermal properties [8, 9]. In this work, we present numerical simulations regarding substrate effect on the NZP. Our model's parameters are chosen according to experimental values – see, for instance, [10, 8]. These simulations were done using a strictly-thermal model , i.e. we compute the temperature rise resulting from Joule heating in a nonlinear resistivity material ($DyBa_2Cu_3O_7$, termed DyBCO in the text), without considering Faraday's law and eddy current effects, which is easily justified here since the DyBCO layer is in a very resistive flux flow state even at time $t = 0$.

Numerical model

Physical description

Our geometrical model is based on 1-mm width by 5-mm long CC having a structure Hastelloy®/MgO/DyBCO/Ag, in which the superconducting DyBCO layer is electrically isolated from the hastelloy substrate trough a tick MgO buffer layer of 4 μm [8, 10]. The thickness of the hastelloy layer is 90 μm. For the DYBCO and Ag layer, 300 nm (t_{Sc}) and 40 nm respectively. For our base case simulation, we intentionally omitted the buffer layer (assimilated to the substrate), we multiplied the thickness of the Ag and DyBCO layers by a factor 100 and adapted the related physical parameters with an aspect ratio approximation described in previous works [11].

The FCL macroscopic behavior is implemented with a power law resistivity derived from experimental data obtained by Therasse et al. [8]. The coupling between electrical and thermal physics is done in the critical current density expression $\big(J_c(T)\big)$, that we consider independent of the magnetic field, i.e.

$$\rho_{Sc} = \begin{cases} 0 & \text{if } J < J_c(T), \\ \rho_{ff} & \text{if } J \geq J_c(T) \mid \rho_{ff} < \rho_{norm} \\ \rho_{norm} & \text{if } \rho_{ff} \geq \rho_{norm}. \end{cases} \tag{1}$$

$$\rho_{ff}(\mathbf{J}, T) = \rho_{min}\left(\frac{|\mathbf{J}|}{J_c(T)} - 1\right)^{n-1} \tag{2}$$

$$J_c(T) = J_{c_0}\,\frac{T_c - T}{T_c - T_0} \tag{3}$$

where ρ_{min}=8.8×10^{-10} Ωm, n=3.9, T_c=90 K, T_0=77 K and J_{c_0}=1×10^{10} Am^{-2}, which gives an I_c of 3 A.

The strictly-thermal model

Based on a previous magneto-thermal model [11, 12], some assumptions have been used in order to save computation time and look at the physical parameters that actually determine the NZP.

a) The total current flowing in the tape is constant.

b) We are in the flux-flow regime: $J/J_c(T) \geq 1$.

c) The current density is uniform in each layer of tape [12].

d) We neglect losses in the interlayers i.e. Ag/DyBCO and DyBCO/Hastelloy®.

For this model, a typical transient conduction equation is used to simulate heat generation and diffusion:

$$Q = \rho_m C_p \frac{\partial T}{\partial t} - \nabla \cdot (-k \nabla T) = \rho J^2 \tag{4}$$

where Q is the power dissipated in the tape, ρ_m is the layer mass density, C_p the heat capacity and k the thermal conductivity tensor, that we considered, for simplicity, independent of the temperature.

Depending of the simulation, we may had to consider heat transfer with the liquid nitrogen bath. In this particular case, we used the following equation at the tape-liquid interface:

$$\hat{\mathbf{n}} \cdot (k \nabla T) = h(T_s - T_0) \tag{5}$$

Where h is termed the convection heat transfer coefficient –see Fig. 4, T_s is the surface temperature of the tape, and $\hat{\mathbf{n}}$ the unit vector normal to the tape surface.

Current sharing within the conductive layers (DyBCO and Ag) is implemented by considering slices along the conductor length composed of parallel resistors – see Fig. 1. The current density is assigned to each resistor by the following equations:

$$J_{Sc_i} = \frac{\mathcal{R}_{Ag_i}}{\mathcal{R}_{Ag_i} + \mathcal{R}_{Sc_i}} \frac{I}{S_{Sc}} \tag{6}$$

$$J_{Ag_i} = \frac{\mathcal{R}_{Sc_i}}{\mathcal{R}_{Ag_i} + \mathcal{R}_{Sc_i}} \frac{I}{S_{Ag}} \tag{7}$$

Where, I is the transport current, S_{Sc} and S_{Ag} are the cross-section (plane x0y) area of the DyBCO and Ag films, i is the slice number,

$$\mathcal{R}_{Sc_i} = \frac{1}{V_i} \int_{V_i} \rho_{Sc} \tag{8}$$

$$\mathcal{R}_{Ag_i} = \frac{1}{V_i} \int_{V_i} \rho_{Ag} \tag{9}$$

and, V_i is the volume of the integrated element. Considering assumption b) and the fact that the flux-flow resistivity is strongly related to the temperature [8], Eq. 2 becomes:

$$\rho_{ff}(\mathbf{J}, T) \approx \rho_{ff}(T) = \rho_{min} \left(\frac{f J_{c_0}}{J_c(T)} - 1 \right)^{n-1} \tag{10}$$

Where f is the source amplitude factor. The remaining values used for our model, are those presented in one of our previous papers [11].

Results

Effect of the substrate thermal parameters

The thermal diffusivity is defined as:

$$\alpha = \frac{k}{\rho_m C_p} \qquad [\mathrm{m/s^2}] \tag{11}$$

To observe the effect of thermal substrate parameters on the NZP velocity (NZPV), we simulated substrates having the same mass density ρ_m=10 000 kgm^{-3} but with different values of C_p and k, hence, having different thermal diffusivity (α). Table 1 summarize these thermal substrate parameters effects.

At this point, note that the initial normal zone (INZ) size have an influence on the NZPV since it is the average resistivity of each sub-element ($\mathcal{R}_{Sc_i}$ in Eq. 8) that gives the amount of current passing trough the INZ (smaller INZ gives smaller velocity).

By studying the 3D temperature profile evolution for these different substrates, we have shown that low C_p values are responsible for a fast transition of the tape (facility to raise the temperature over the critical temperature) and high k values result in a faster spreading of heat (ability to conduct heat).

Table 1 proposed NZPV value that seems in disagreement with the last statement concerning k. As a matter of fact, for C_p=10 J/kgK, we see that the NZPV is less important for k=100 W/mK than for k=1 W/mK. With k=1 W/mK, the thermal conductivity of the substrate is seven times smaller than the thermal conductivity of the superconductor. In this case, heat travels mostly in the DyBCO layer until a sufficient temperature gradient is reached in the substrate, allowing heat transfer from the conducting layers (heat source) to the substrate.

In an attempt to understand by simulation the results obtained by Antognazza et al. [9], we compared the effect of two different substrate, i.e. sapphire and hastelloy on their switching behavior. Sapphire, has a thermal diffusivity that is more than 1000 times larger than hastelloy. With sapphire, both $\rho_m C_p$ and k increase the diffusion coefficient, i.e. $\rho_m C_p$ is smaller and k is larger than for hastelloy. By comparing the NZP of these two tapes, we observed a NZPV approximately 20 times larger for the tape made of sapphire substrate.

Figure 2 allows to observe the temperature and resistivity profiles in the z0y plane for these two cases at the instant where complete transition of the tape made of sapphire occurred. The initial temperature in each case was that of liquid nitrogen, i.e. 77 K. As shown in 1-a, (sapphire), heat spread much more easily along the wire (heating up DyBCO) than for the tape made of hastelloy (2-a), where heat is generated more locally. Figures 2 (1-b) and (2-b) show the resistivity map for both substrates. In the case of hastelloy, only a partial transition is achieved in comparison to the sapphire case.

As expected from experiments realized at the University of Geneva [9], heat generated in the sapphire case remains low until a fast transition occurs. Once the heat generated reaches a threshold value, the low heat capacity of sapphire increase the temperature of the tape almost instantaneously to the critical value and to the maximum power generation ($t_{Sc}\rho_{Sc}J^2$=3.9 kW/cm^2). Then it seems that the fast spreading of heat in sapphire helps to uniformly switch the tape to the normal state. For the hastelloy case, heat is generated almost directly after the beginning of the simulation but the full transition takes more time to reach. In fact, as we have shown in Fig. 2, the low diffusivity of hastelloy result in a very localized heat generation. In this case, even if the tape has not completely transited (lower power generation), the local temperature could be high enough to induce damage in the superconductor.

Effect of the substrate thickness

Since substrate have a significant influence on the thermal behavior of CCs, we investigated the substrate thickness dependence on the NZP. Figure 3 shows different simulations performed for each substrates i.e. sapphire and hastelloy for adiabatic [adia] (no heat transfer with the liquid nitrogen bath) and pool boiling [fct] conditions. Furthermore, for the adiabatic case, we consider the effect of the addition of a non-conductive MgO buffer film (ρ_m=3580 kg/m^3, C_p=877 J/kgK, k=60 W/mK and thickness=4 μm) at the interface between the DyBCO and substrate layers [adia-buf] on the NZPV.

Figure 3 allows to observe an interesting behavior of CCs. As expected, thicker substrates, due to their higher mass, absorb more heat and accordingly, reduce the NZPV. Nevertheless, it can be shown that the NZPV tends to become constant as thickness increases. In the case of hastelloy, this thickness is less important than for sapphire since thermal diffusivity in hastelloy is a small fraction of the sapphire diffusivity. This confirms assumptions made by Antognazza et al. [9] concerning the parameters choice (reduced thickness) for an analytic 1D approximation of the NZPV [13].

Furthermore, the effect of the buffer layer, seems to be more important in the sapphire case than in the hastelloy case. For the sapphire case, MgO, which have a thermal diffusivity about 200 times smaller than the substrate, reduces considerably the NZPV. For the hastelloy case, the effect of the buffer layer is the opposite i.e. we observe an increase of velocities since the ratio of diffusivity is about 10 times larger for hastelloy. In fact, Fig. 3 allows to observe that when the substrate have a size in the range of the buffer layer, both substrate have more or less the same NZPV (around 110 cm/s).

To conclude this section, it is worthwhile to note that pool boiling, implemented by the function shown in Fig. 4, seems to have larger effects for thinner substrate than for thicker ones since less heat is absorbed by the substrate. Hastelloy substrate is less dependent on this parameter than sapphire since velocities involved are at least one order of magnitude smaller for hastelloy than for sapphire.

Effect of transport current on the NZPV

NZPV measures are quite hard to obtain for a large range of current values since localized heat generation in hastelloy leads to a notable deterioration of the superconductor, even for short current pulses [8]. Nevertheless, some simulations have been done to observe the transport-current dependence of the NZPV. Figure 5 allows to observe this dependence for the same geometries and thermal conditions as in the previous section, i.e. [adia], [adia-buf] and [fct]. In this figure, we also include simulations for the base case (without buffer layer and heat exchange), in the hypothetical scenario where no current sharing between the silver and DyBCO layers is possible i.e. the silver layer acting only as a thermal resistance [adia-ns]. For these particular simulations we observed that the current-sharing effect becomes important only around 1.5 I_c and above, being more pronounced in the hastelloy case than in the sapphire case. In fact, it seems that the exchange of current leads to a reduction of the NZPV due to a reduction of the cross-sectional resistivity of the silver/normal-DyBCO parallel resistance that is obviously less important than the normal-DyBCO resistance alone. This 1.5 I_c value correspond to a change in the propagation scheme for the tapes and leads to an exponential growth of the

NZPV. As a matter of fact, over this threshold value, the power generated in the silver layer becomes more important and heat start to travel more from the silver layer than from the DyBCO film by itself – see Fig. 6. This scheme seems to be responsible of the exponential growth observed on the NZPV curves – see Fig. 5. Since MgO acts as an heat barrier along the thickness for the sapphire case, the buffer layer have a significant effect on the NZPV for this case.

It is also interesting to note that, for both substrate, heat transfer with the nitrogen bath do not seems to have an influence on the NZP. This seems to be due to the fact that, for a significant substrate thickness (90 μm in this case), heat is more absorbed by the substrate than exchanged with the surrounding coolant. In that sense, the adiabatic theory seems to be confirmed for the base case geometry.

Conclusion

The strictly-thermal model developed in this paper is very light in terms of computation time. It allows to observe important parameters influencing the NZP by considering the problem from a pure thermal point of view. With this model, we have shown that the NZP depends strongly on substrate thermal parameters.

By comparing two substrates of very different properties, i.e. sapphire and hastelloy, we have demonstrated how sapphire shows better performance than hastelloy for FCL purposes. Indeed, sapphire, which is a more diffusive substrate helps to heat and switch regions of the line adjacent to the normal zone, which avoid hot-spots formation.

Moreover, the substrate thickness have important effect on the behavior of CCs. For the sapphire case, the presence of a relatively thick buffer layer changes considerably the performance of the device, whereas they are not much altered in the hastelloy case.

Finally, the NZPV dependence on the transport current has been illustrated. Over a threshold value of around $1.5 I_c$, the NZPV curves show an exponential growth due, at a glance, to a different heat transfer scheme.

Further work should consider that sapphire have thermal parameters that are strongly dependent on the temperature [14]. In addition, we did not consider recovery mechanisms as well as the interfacial losses that seems to play an important role on the NZP [15, 16]. These issues must be taken into account to improve our model and explore other features related to the NZP.

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Tables

Table 1: Effect of substrate thermal parameters on the NZP.

α (m^2/s)	C_p (J/kgK)	k (W/mK)	NZPV (cm/s)
1×10^{-5}	100	10	26
1×10^{-5}	**10**	**1**	**548**
1×10^{-5}	1000	100	4
1×10^{-3}	**10**	**100**	**381**
1×10^{-3}	1	10	1224
1×10^{-3}	100	1000	38

Figure captions

Fig. 1 Our base case geometrical model consists in three layers Hastelloy/DyBCO/Ag. To simulate current sharing, we subdivide each conductive layers, i.e. Ag and DyBCO, in sub-elements. The uniform current density in these sub-elements is obtained by Eqs. 6 and 7.

Fig. 2 Temperature (a) and resistivity (b) comparisons in the z0y plane for tapes made of sapphire (1) and hastelloy (2) once the full-transition is reached in the tape made of sapphire (t =2.6 ms). For sapphire, heat spreads easily along the tape, avoiding local heating (1-a). The low heat capacity value of sapphire ensures a rapid transition of the whole tape (1-b). The INZ is the white circle in each figure.

Fig. 3 Effect of the substrate thickness on the NZPV for the hastelloy and sapphire cases under different simulations conditions. [adia]: the base case without thermal exchange with the liquid nitrogen bath. [adia-buf]: the same base case as with [adia] but with the substitution of 4 μm of hastelloy substrate for 4 μm of MgO. [fct]: the base case but with pool boiling. The dashed line represents the thickness at which the substrate and buffer layer are of the same size.

Fig. 4 Convective heat transfer coefficient for the model [11]. (a) free convection; (b) nucleate boiling; (c) transition boiling; and (d) film boiling. T_0 is the liquid nitrogen boiling temperature.

Fig. 5 Effect of the transport current on the NZPV for the hastelloy and sapphire cases over different simulations. [adia], [adia-buf] and [fct] correspond to the same conditions as previously described in Fig. 3. The additional curve [adia-ns] represents simulations in which no current-sharing between the silver and DyBCO layers have been set.

Fig. 6 Two possible mechanisms/schemes for the heat propagation that can explain the exponential growth of the NZPV curves for current values larger than $1.5I_c$. (a) for values below $1.5I_c$ (red arrows), heat travels mostly along the width of the tape. (b) for values over $1.5I_c$, the contribution of heat generated in the silver film cannot be neglected, and heat travels mostly along the thickness of the tape leading to faster velocities.

Figures

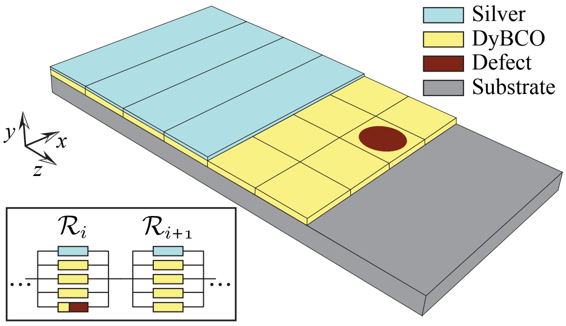


Figure 1:

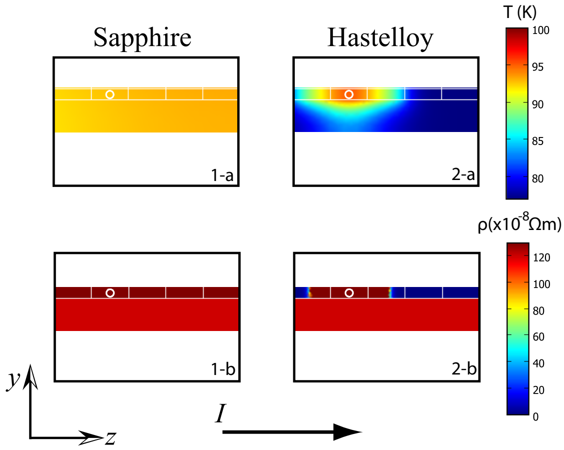


Figure 2:

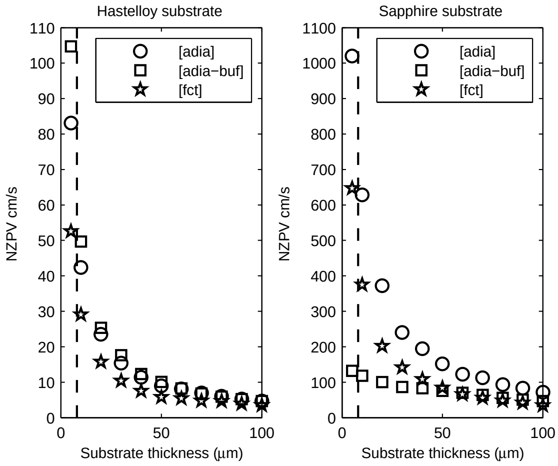
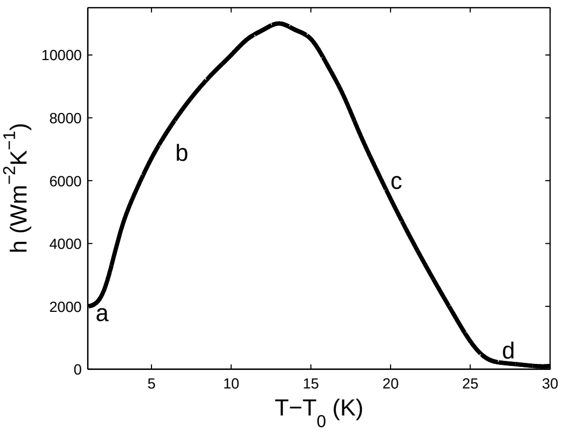


Figure 3:



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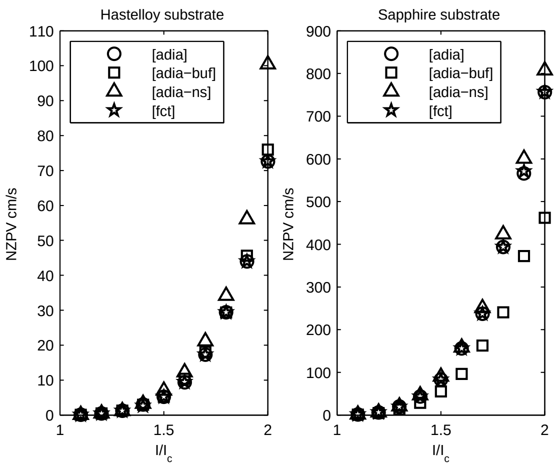

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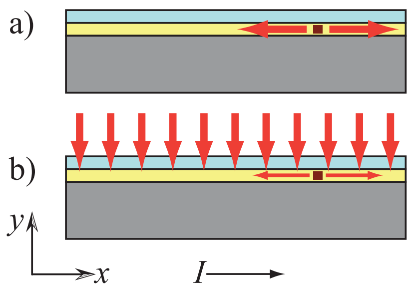

Figure 6: