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Abstract
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Based on a study of the thermophysical properties, we derived a practical formula for the normal zone propagation velocity appropriate for REBa$_2$Cu$_3$O$_{7-x}$ coated conductors in high magnetic fields. An analytical expression to evaluate the current sharing temperature as a function of the operating conditions is also proposed. The presented study has allowed us to account for experimental results not fully understood in the framework of the models widely used in the literature. In particular, we provided a fundamental understanding of the experimental evidence that the normal zone propagation velocity in REBa$_2$Cu$_3$O$_{7-x}$ coated conductors can be mainly determined by the operating current, regardless of the applied field and temperature. Published by AIP Publishing.
shifting occurs is much larger than in LTS.\textsuperscript{13} The deduced expression is
\[
\text{NZPV} \approx J \left[ \frac{1}{\rho_n(T)} \left( C_n(T) - \frac{d\kappa_n}{dT} \right) \right]^{1/2}
\]
\[
\times \left[ \int_{T_\text{op}}^{T_t} C_\text{S}(T) dT \right]^{1/2} \int_{T_\text{op}}^{T_t} C_\text{S}(T) dT \right]^{1/2} \right).
\]

The subscripts \(n\) and \(s\) refer to the normal and superconducting state, respectively. However, in REBCO CCs, one can consider that \(C_n \approx C_T\) and \(\kappa_n \approx \kappa_T\), because variations in the overall specific heat and thermal conductivity due to the transition from the superconducting to the normal state are negligible.\textsuperscript{15,16} The transition temperature, \(T_t\), has been introduced in place of \(T_C\) in Eq. (2) in order to define an effective superconducting/normal boundary during a quench when current sharing effects are important. In LTS, \(T_t\) is normally considered to be the average value between the temperature at which the current sharing starts \((T_{CS})\) and the critical temperature \((T_C)\), i.e., \(T_t \equiv (T_{CS} + T_C)/2\). In HTS, \(T_t\) is more properly evaluated as the temperature at which the heat generation term in Eq. (1) assumes its average value in the current sharing temperature range, i.e., when

\[ g(T_i) = \int_{T_{CS}}^{T_{CS}} g(T) dT \] \(\text{NZPV} \approx J \left[ \frac{\rho}{C} \left( T_i - T_{op} \right) \right]^{1/2} \).

Different approaches have been proposed to evaluate the NZPV by Eq. (4). Iwasa has shown that for \((T_i - T_{op})/T_{op} \ll 1\), \(C\), \(\rho\), and \(\kappa\) can be conveniently evaluated at \(T = T_i\), using for \(C\) the average value in the range \(T_{op} - T_C\).\textsuperscript{9} The two procedures lead to similar values for the NZPV in LTS and are, in general, not applicable to HTS. Nevertheless, their use has been extended in the practice also to HTS,\textsuperscript{5,10,16} because of the complications encountered when solving the more general Eq. (2). In particular, the calculation of the NZPV from Eq. (2) is hindered by the need of details about the \(\kappa(T)\) curve of the conductor at the conditions realized in a magnet. It is worth mentioning that, in order to bypass these difficulties, an approximation of Eq. (2) alternative to Eq. (4) has been derived under the less stringent assumption that only the \(T\) dependence of the electrical resistivity is negligible.\textsuperscript{17-19} However, this hypothesis is correct only for LTS because their transition temperature typically falls in the low-temperature region where \(\rho \approx \rho_{Res}\), the residual electrical resistivity.

Recently, we reported on the thermal conduction properties of REBCO CCs from different manufacturers in magnetic fields up to 19 T.\textsuperscript{15} In Figure 1, the experimental \(\kappa(T)\) curves of the CC from SuperPower are shown as measured at \(B = 0\), 7, and 19 T. The solid line is the best-fit curve obtained by fitting the experimental data at \(B = 0\) considering that \(\kappa \approx \kappa_{Cu} + \kappa_{Cu}\).\textsuperscript{15} \(\kappa_{Cu}\) is the thermal conductivity of the copper, whose dependence on the residual resistivity ratio is described in Ref. 20, and \(\kappa_{Cu}\) is the conductor’s cross-section fraction occupied by the stabilizer. Dashed lines, associated with in-field data, have been calculated in the framework of the Wiedemann–Franz law supposing that \(\kappa(T,B) \approx [\rho(T,0)/\rho(T,B)]\kappa(T,0)\) and using magnetoresistance data measured on Cu specimens extracted from the CC, as described in Ref. 15. At low \(T\), electron-defect scattering processes dominate the heat propagation. Thus, the effect of the magnetic field is in some way analogous to that of disorder in the system: both reduce the electron mean free path and, consequently, \(\kappa\). On increasing \(T\), the field-induced effects on \(\kappa\) become less important and the \(\kappa(T)\) curves associated with different \(B\) values approach each other. This is a consequence of the fact that electron-phonon scattering events start to be more relevant than electron-defect ones in determining the heat conduction for \(T \approx 50\, \text{K}\).

Data reported in Figure 1 exhibit typical features of \(\kappa(T,B)\) curves of REBCO CCs produced by different manufacturers\textsuperscript{15} and provide us the necessary understanding to formulate a practical expression for the NZPV suitable for 2G HTS. \(T_t\) assumes values higher than \(\approx 45\, \text{K}\) in HTS. In this range of temperatures, the derivative of \(\kappa(T)\) is strongly reduced on increasing the field, as implied in Figure 1. It follows that in Eq. (2) the term \(\int_{T_\text{op}}^{T_t} C_\text{S}(T) dT\) becomes negligible with respect to \(C_\text{S}(T_i)\) in case of operation at intense fields, and Eq. (2) can be approximated by

\[ \text{NZPV} \approx J \left[ \frac{\rho(T_i)\kappa(T_i)}{C(T_i)\int_{T_\text{op}}^{T_t} C(T) dT} \right]^{1/2}. \]
than 7% at 19 T. Results very similar to those reported in Figure 2 have been obtained for the CCs from other manufacturers investigated in Ref. 15. Indeed, the validity of the approximation that leads to Eq. (5) relies on the \( \kappa(T, B) \) properties of copper, which gives the predominant contribution to the overall thermal conductivity of the tape. Thus, Eq. (5) can be generally used to study quench processes in Cu-stabilized 2G HTS in the presence of intense fields. For the sake of completeness, we want to mention that Dresner published in 1994 a study in which closed formulas for the NZPV are derived considering specific dependencies of the specific heat on the temperature. In a general case of arbitrary dependence of \( C \) on \( T \), he proposed to solve Eq. (1) disregarding the entire term \( \nabla \cdot \kappa(T) \nabla T \) when \( T > T_C \). This corresponds to neglect not only the term \( \kappa \nabla^2 T \) as done (and justified) by Whetstone and Roos but also the term \( \nabla \kappa \nabla T \). These assumptions lead to an expression for the NZPV formally analogous to Eq. (5), with \( T_c \) in the place of \( T \), since the author did not consider the current sharing effect.\(^{21}\) However, Dresner did not justify the hypothesis of neglecting the \( T \) dependence of \( \kappa \). The validity of this assumption, which leads to Eq. (5), has been fully demonstrated in this letter in the case of Cu-stabilized REBCO CCs submitted to intense fields.

Eq. (5) can be further simplified considering that in the framework of the Wiedemann–Franz law \( \rho(T) \kappa(T) \approx L T \). This reduces the parameters needed to perform the calculation to: \( L, C \), and \( T_c \) (apart from \( J_c \)), \( L \) values of REBCO CCs are available in the literature.\(^{15}\) It has been shown that \( L \) does not noticeably depend on \( B \).\(^{15}\) The specific heat of CCs can be calculated from data of the component materials, considering that \( C(T) = \sum v_i C_i(T) \), \( v_i \) being the volume fraction occupied by the \( i \)-th component. It is expected that the predominant contributions come from the substrate and the stabilizer, because of the large \( v_i \) values. However, we have experimentally investigated the \( C(T) \) curve using a Quantum Design PPMS, in order to get more precise results. Data relative to the tape from SuperPower are shown in the inset of Figure 1. Details on the critical current surface of the CC are needed to determine \( T_c \). Recently, it has been shown that the \( T \) dependence of \( J_c \) of CCs from different manufacturers can be described over a broad range of temperatures and fields by an exponential law, \( J_c(T, B) = J_c(T = 0, B) e^{-T/T^*} \). Deviations from this behavior are observed at temperatures \( \approx 50 \) K.\(^{22}\) The exponential dependence of \( J_c \) is connected with the presence of defects generating weak isotropic pinning, and \( T^* \) is the characteristic pinning energy at these defects.\(^{23,24}\) Other dominant pinning mechanisms can lead to different \( J_c(T, B) \) characteristics.\(^{25}\) The \( T^* \) values associated with tapes from different manufacturers, for different orientations between the field and the tape surface, are reported in Ref. 22. From the expression for \( J_c(T, B) \), one can easily deduce the following formula that relates \( T_{CS} \) to parameters directly chosen by the magnet designer, namely, the operating conditions and the current margin

\[
T_{CS} \approx T_{Op} - T^* \ln \frac{I_{Op}}{I_c(B_{Op}, T_{Op})}. \tag{6}
\]

\( T_c \) can be evaluated from Eq. (3), using \( T_{CS} \) values from Eq. (6) and the expression for \( J_c(T, B) \) reported in Ref. 22. We have also verified that the approximated formula \( T_c \equiv (T_{CS} + T_C)/2 \) leads to a good estimation for \( T_c \), with differences within \( \approx 5\% \), when \( T \approx 20 \) K. At 4.5 K, the discrepancies increase up to \( \approx 10\% \).

In Figure 3, we report the NZPV as determined from Eq. (5) considering that \( \rho(T_c) \kappa(T_c) \approx L T_c \), using \( L \) values reported in Ref. 15, \( T_c \) calculated using the definition given in Eq. (3), and experimental \( C(T) \) data shown in the inset of Figure 1. \( I_{Op} \) has been varied in the range 0.2–0.9 \( I_c \), using for \( I_c(T, B) \) the values reported in Table I. These have been measured on CCs extracted from the same batch of the sample used for the thermal conduction studies, with the field applied parallel to the wide surface of the tape. Figure 3 shows that the NZPV is mainly determined by the operating current. The points associated with different temperatures and fields approximately reconstruct a single line in a log–log plot, defining a power-law dependence of the NZPV on \( I_{Op} \). This behavior is unexpected if compared with what is observed in LTS. Indeed, both in NbTi and Nb3Sn, a clear dependence of the NZPV on \( B \) is found.\(^{17}\) The contrast

![Figure 2](https://example.com/figure2.png)

**FIG. 2.** Relative error when using Eq. (5) in the place of the more general Eq. (2) for different operating conditions \( (T_{Op}, B) \), as determined for the CC from SuperPower.

![Figure 3](https://example.com/figure3.png)

**FIG. 3.** Dependence of the NZPV on the operating current at different \( T_{Op} \) and \( B \), deduced from Eq. (5) (lines and symbols) and from Eq. (4) following the procedure described by Iwasa\(^3\) (lines without symbols).
between the result shown in Figure 3 and what is observed in LTS is certainly related with the different $I_C(T, B)$ characteristics of the materials. NZPV values calculated from Eq. (4) following the procedure described by Iwasa\textsuperscript{5} are shown in Figure 3 as lines without symbols. Data associated with different operating conditions do not lie all on a same straight line in a log–log plot. Discrepancies between results from Eqs. (4) and (5) become more evident, both qualitatively and quantitatively, on decreasing the operating temperature. This is worth to underline in view of applications of CCs in very high field magnets. Our results about the dependence of the NZPV on $I_{op}$ at different operating conditions are confirmed by the experimental NZPV studies performed on a SuperPower tape extracted from another batch with respect to ours.\textsuperscript{10} The experimental confirmation strengthens the validity of the analytical procedure proposed in this letter to determine the NZPV. When comparing experimental data quantitatively with theoretical expectations, one has to take into account the so-called minimum propagation current ($I_{mp}$), i.e., the operating current below which there is no quench triggering even for pulses with an energy exceeding the stability margin.\textsuperscript{10,16} $I_{mp}$ values reported in the literature for CCs are in the range of $10 - 30$ A.\textsuperscript{16} The effect of $I_{mp}$ on the measured NZPV can be neglected when $I_{op} \gg I_{mp}$. Samples investigated by us and in Ref. 10 present slightly different $I_C$ characteristics. Nevertheless, we verified that for $I_{op} \cong 100$ A, which is much larger than the expected $I_{mp}$, discrepancies between values shown in Figure 3 and data from Ref. 10 are below 25%.

Results from Eq. (5), combined with longitudinal and transverse $\kappa$ data, allow calculating the transverse NZPV.\textsuperscript{5,9} In Ref. 26, we have reported experimental values for the square root of the ratio between the transverse and longitudinal components of $\kappa$ for various CCs. Typical values are of the order of 0.1. These data provide lower limits for the anisotropy of the NZPV in a winding, since the contact thermal resistance or the presence of other materials, which could reduce the overall transverse $\kappa$, have not been considered.

In summary, an approximated equation has been derived for the longitudinal NZPV, Eq. (5), particularly suitable for 2G HTS in intense magnetic fields. An analytical expression to evaluate the current sharing temperature as a function of the operating conditions, Eq. (6), has also been proposed. The presented study has allowed us to take into account experimental results not fully understood in the framework of models widely used in the literature.

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\begin{table}[h]
\centering
\caption{Critical current densities of the investigated CC.}
\begin{tabular}{ll}
\hline
$\text{I}_C$ & $\text{I}_C$  \\
$\text{(4.5 K, 7 T)} \approx 1600$ A & $\text{(4.5 K, 19 T)} \approx 1160$ A \\
$\text{(20 K, 7 T)} \approx 830$ A & $\text{(20 K, 19 T)} \approx 640$ A \\
$\text{(30 K, 7 T)} \approx 530$ A & $\text{(30 K, 19 T)} \approx 360$ A \\
$\text{(40 K, 7 T)} \approx 300$ A & $\text{(40 K, 19 T)} \approx 190$ A \\
\hline
\end{tabular}
\end{table}

21L. Dresner, Cryogenics 43(2), 111 (1994).