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Current–voltage characteristics of double disordered REBCO coated conductors exposed to magnetic fields with edge gradients

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Abstract

A study of HTS-coated tapes which are exposed to a low and medium field with a gradient in the flux density is performed in order to enable relevant and accurate tape characterization as well as to determine the relevant information for applications, where a magnetic field gradient occurs. In particular, the study is focused on ultra-high-magnet-field YBCO-coated tapes. Such tapes based on double disordered YBCO layer with intrinsic and extrinsic precipitations exhibit a ‘champion’ performance in ultra-high (31 T) magnetic fields. Alternative measurement techniques, based on miniature permanent magnets or a pulsed electro-magnet was developed to characterize the critical current, \(I_c\), in 0.5 and 3 T fields at 77 K, \(B//c\), respectively. For the field dependence of the critical current, an ‘extended alpha approximation’ is suggested, which enables a sufficiently accurate description of the tape behavior in the low and medium field range, i.e. from 0 to 6 T. Local and integral voltage response in the tapes are analyzed and compared with experimental results. Observations of the effect that gains the influence of local \(I_c\)-inhomogeneities exposed to a spatially confined magnetic field are described and discussed. The effects of local heating and cooling are shown to be limited via lowering the transport currents and finally a reduced power dissipation in the tape exposed to a localized magnetic field with two gradient zones was demonstrated. Correction factors needed to determine the critical current from the field dependence of the integral voltage response are derived and discussed.

Keywords: high-temperature superconductors, superconducting tapes, yttrium compounds, laser ablation, epitaxial growth, superconducting materials

(Some figures may appear in colour only in the online journal)

1. Introduction

REBCO coated tapes are gaining importance due to their outstanding performance in high and ultra-high magnetic fields [1–3] and their favorable mechanical stability [4]. Magnet applications dominate here [5, 6], but also applications in accelerators/colliders [7] as well as in fusion technologies [8, 9] are becoming essential.

Despite the fact that the performance of the REBCO tapes is sufficient for magnets only at temperatures below 40 K (rather seldom at 77 K [10]), the characterization, especially of long-length tapes, is generally performed at 77 K, the temperature of liquid nitrogen. In this case, routine characterization becomes really feasible because it neither consumes expensive gases nor need significant amounts of energy. In addition, the ability to simulate or predict the behavior of high-field REBCO tape at helium temperatures...
based on data obtained at 77 K was demonstrated [11]. In this work, a relatively good correlation between critical currents at high fields, helium temperatures and the temperature of liquid nitrogen was found, when the characterization at 77 K is performed in a magnetic field of several Tesla. These studies were conducted with HTS coated tapes from various manufacturers, but not with tapes having a double-disordered (DD) structure [3], where ‘intrinsic’ and ‘extrinsic’ nano-precipitations [12] are introduced.

The DD-HTS tapes demonstrate champion values for the critical current at highest magnetic fields (at 31 T, and helium temperatures) [12]. Nevertheless, they show a poor current performance at 77 K, where the most feasible characterization is possible. In addition, there is essentially no correlation between critical currents at these two temperatures [12, 13]. This is obviously a result of vortex pinning by defects having a low activation energy, especially for intrinsic pinning, that becomes very efficient at liquid helium temperature while thermal ‘depinning’ is dominating at 77 K [14].

Another aspect is the tape performance under conditions with a magnetic field gradient. In applications, field gradients prevail in the windings of electrical machines and power devices. Another typical example is a Roebel cable in which each strand periodically changes position and is therefore, in external field, always affected by field gradient zones. Moreover, field gradients are a typical ‘attribute’ in all methods for magnetic characterization of long-length HTS coated tapes, especially in case of moving tapes.

The subject of the present study is the current transport in HTS-coated tapes which are exposed to low and medium field with a flux density gradient. In particular, the study focuses on DD YBCO-coated tapes, which have not yet been adequately parameterized at 77 K. The modeling of field dependences of critical currents as well as \( n \) - and \( \alpha \)-values (defined by conventional relationships \( I_c \sim (H)\theta \) and \( I_c \sim B^{-\alpha} \)) is therefore another goal of our study.

| Tape ID | Short ID | \( I_c(77 \text{ K, SF}) \) (A) | \( I_c(4.2 \text{ K, } 5 \text{ T}) \) (A) | HTS thickness (\( \mu \text{m} \)) | \( I_c(4.2 \text{ K, } 5 \text{ T}) \) |
|---------|----------|-----------------|-----------------|----------------|----------------|
| PL10    | #1       | 42.5            | 870             | 1.40           | 20             |
| PL21    | #2       | 33.5            | 1020            | 1.38           | 30             |
| PL30    | #3       | 34.5            | 804             | 1.50           | 23             |
| PL41    | #4       | 60.0            | 854             | 1.50           | 14             |
| PL5–123 | #5       | 39.5            | 630             | 1.90           | 16             |

The tape samples had a width of 4 mm and a length up to 20 cm. Depending on characterization technique, the sample length was adjusted to 3 and 7 cm (samples \#1–\#4) and 12–20 cm for the group of samples \#5.

The critical current of all used samples was routinely quantified on site at 77 K in self-field and 4.2 K at 5 T (\( B_{//c} \)), where the \( I_c \) varies from 33.5 to 60 A and from 630 to 1020 A, respectively. The samples \#1–\#4 were additionally investigated at the Atom Institut in Vienna at 77 K in 0–6 T fields (\( B_{//c} \)). The results of these measurements are shown and discussed in chapter 3. Pieces of samples \#5 were investigated in the pulsed 3 T electromagnet and miniature permanent magnet assembly as it will be described in the next sections of chapter 2. The quality of all selected samples is supposed to be similar as the parameterization obtained from measurements of samples \#1–\#4 shall be applied to samples \#5 in order to determine \( I_c \) in the pulsed field. The YBCO layer thickness was between 1.38 and 1.90 \( \mu \text{m} \), while the highest critical currents at 4.2 K were found in the thinnest HTS layer.

### 2.2. Experimental setup with small permanent magnets

We used stacks of two permanent magnets in our experiments: either (a) with a 0.67 mm gap between the rectangular SmCo magnets (12 mm \( \times \) 10 mm \( \times \) 5 mm) or (b) with a 0.3 mm gap between the cylindrical Nd magnets with 4–5 mm radius and different thicknesses of 2 and 6 mm which simplify operation of the magnet assembly. For all experiments with miniature magnets, 12 cm long samples from tape \#5 were fixed on the sample holder, 4-point connected and fully dipped into liquid nitrogen. The voltage contacts were separated by 3 cm and the critical current was measured with and without magnets. The assembly with rectangular magnets is shown in figure 1. In the course of tests a reproducibility of critical current was always checked by comparison of \( I_c \) measured before and after assembling of magnets.

The field distribution of both used magnet stacks shown in figure 2 was measured with a standard GaAs Hall sensor (model CYSJ362A) at room temperature. For both magnet assemblies the maximum flux density in the center of the magnet stack was between 0.5 and 0.6 T. The gradient regions are distributed symmetrically. For both magnet configurations (i) a very sharp gradient at the edge of the magnets and (ii) zero-crossings of the magnetic field can be observed. Obviously, the normal component of the field change sign...
outside the magnet at a very short distance (of ∼1 mm) to its edge.

Within these studies a scratch was introduced on the tape surface with a hard metal knife and $I_c$ was measured again with and without field. The scratch was about 2 cm long in the direction of the tape. The results support our ideas of tape behavior in field gradients and are presented in section 5.

2.3. Pulsed electromagnet

Several samples have been investigated in an on-site developed electromagnet device, shown in figure 3, which is capable to reach 3 T magnetic fields in pulsed operation mode. Figure 5 shows the circuit diagram of the experimental assembly. It consists of two copper coils connected in series and is fully covered by liquid nitrogen when operated. Since there is no iron or other soft magnetic core, the induced flux density is proportional to the supply current and independent of temperature. The diameter of the windings is 10 cm and the height of each coil is 2.3 cm. The coils are separated by a gap of 2 mm height and 6 mm width where samples can be pulled through. Cooled down to 77 K, a maximum supply current of 700 A induces a magnetic field with a flux density of 3 T. The radial distribution of the magnetic field inside the gap is shown in figure 4. The highest flux density can be observed in the center of the device from where it monotonously decreases. At the entrance slit of the magnet the direction of the normal component of the magnetic field reverses which is observed by a zero-crossing in the field distribution.

The duration of a pulse can be varied between 0.3 and 3 s during which the magnetic field is first increasing to ∼3.1 T
and then slowly decreasing due to increasing resistance in the copper windings resulting from heating and the limited voltage output of the power supply. By waiting at least 60 s after each pulse, full cooldown of the magnet system ensured no temperature differences between two subsequent field pulses. Current through the coil was measured by a current clamp (model Chauvin Arnoux PAC22) and registered in a digital oscilloscope.

In the 6 mm wide and 2 mm high slit in the split electromagnet, a 4 mm wide tape kept under tension was introduced. In the period between subsequent current pulses, the tape remained fully immersed in liquid nitrogen. Flat one-sided insulated, 50 μm thick copper tapes were used for the voltage signal wires. They were soldered to the tape, both coming out at the same entrance of the slit in order to reduce the influence of the voltage induced by the pulsed flux density. The voltage (potential) contacts were positioned symmetrically with respect to the center of the magnet at distance of 10 cm. The output signal is then amplified with a low noise, in-house designed 60 dB amplifier and stored in a digital oscilloscope. The mounted sample was connected to a current power supply PS3 as shown in figure 5 and loaded with a specific constant DC transport current before each operation of the magnet. The voltage signal was then measured during the magnet pulse. The experiment was repeated with different values of the transport current. The magnitude of these currents varied from 0 to 10 A with a 1 A increment. Both current directions were investigated. It was estimated that the deviation of the selected DC transport current in the experiment is within 0.1% and the deviations of the magnet power supply and voltage signal are within 1% of the nominal values.

2.4. Voltage response in pulsed field

The typical behavior of the voltage signal in our experiments is described in the following section. All data are synchronized by setting the time $\tau = 0$ s at the onset of the flux density ramp-up. Figure 6(a) shows the oscillogram of both, the voltage drop $U(\tau)$ in the tape (2) and the inverted current in the windings (1), which is proportional to the field, for a sample tape #5 with an 8 A current load. The field quickly builds up after switching of the magnet ($\tau = 0$ s) at a maximum rate of $16 \text{T s}^{-1}$ which is reached after 50–60 ms at 0.9 T. Thereby induced voltage is visible in the signal (3).

‘Natural’ (as a consequence of inductively induced currents) and ‘artificial’ (as non-linear performance of the power supply of the magnet) changes of the time derivative of $B$ seem to be unavoidable. Flux vortices, penetrating the tape, are pushed inside the tape while the external flux density is increasing. These moving vortices render sub-critical currents dissipative. The gradient in the vortex density caused by the transport current, which is symmetric outside the magnet is pushed to one side due to the interaction with the superimposed magnetic field. This shift and the resulting voltage signal in the tape is proportional to the sub-critical transport currents. This is in agreement with the observation of an increasing amplitude of peak (3) in figure 6 with increasing transport current. The following peak, after the increasing voltage at (2), in figure 6(a), also named ‘second peak’, is resulting from dissipative current ($J > J_c$) in the region of highest magnetic field. We also assume that deviations of the symmetry in the electric configuration of the voltage contacts can influence the first peak (3). In this case, some lateral component of the field of the electromagnet may be the source of influence. It is not purpose of this study to investigate the possible influence of these systematic effects at the fast field ramping and therefore we decided not to evaluate the measurements during the first 200–250 ms of the current pulse and distinguish the ‘induced peak’ from the main one. Fortunately, the relative level of this peak quickly reduces when the transport current increases to 8 or 10 A (as it is shown in the oscillogram in figure 6(a)). In this case, measurements of $V(\tau)$ are more reliable, reproducible and easy.

\[ \text{Figure 5. Experimental setup of the pulsed 3 T electromagnet.} \]

\[ \text{Figure 6. Current (1) and voltage drop (2) across a 10 cm long tape placed in the inhomogeneous field of the 3 T electromagnet with an 8 A current load in the tape. The blue curve shows the (inverted) current pulse, $I_{\text{in}}$, for energizing the magnet. The output voltage signal is amplified by a factor of 1000. (b) Details on distinguishing of first voltage response peak in expanded scale.} \]
The ‘induced peak’ (3’) can be distinguished by subtracting the exponential extrapolation (2') from the measured voltage signal.

After reaching the maximum flux density, the field starts decreasing at a rate not faster than 1 T s\(^{-1}\) due to the increasing resistance of the copper windings. During this phase of slowly lowered field, the voltage across the tape is declining.

The difference in time position of the maximal field and maximal voltage response is observed in figure 6. This delay of about 20–30 ms originates obviously from minor heat diffusion that may cause a slight expansion of the dissipative zone formed in the tape in the inhomogeneous magnetic field. This effect is not large because of the suppressed heat generation described in section 5.1. It has been taken into account only when high voltage responses (at > 20–30 \(\mu\)V cm\(^{-1}\)) are considered.

In additional experiments with samples #1 and #2 we found \(I_c = 4\) A at 77 K in 3 T external field (\(B//c\)) which is shown in figure 7. In our experiments, the applied transport current is variable from 0 to 10 A and is therefore in a range to exceed \(I_c\) in the pulsed magnetic setup, if field and current are sufficiently high. This fits the observation that the maximum value of the voltage signal increases with increasing tape current. For current loads below the critical current at maximum field (e.g. \(I = 2\) A) no ‘second peak’ is visible. At \(I = 0\) A no voltage drop after the fast magnetic ramping period can be detected within the resolution limit of the setup. Averaging the noise in the voltage signal from maximum field to the end of the pulse in cases \(I = (1–3)\) A gives a voltage level of 2–3 \(\mu\)V which originates from energy dissipation of moving vortices out of the tape due to the decreasing field and directed current. For \(I = 4\) A, the voltage drop is decaying after the ‘induced peak’ from 20 \(\mu\)V at maximum field to 1 \(\mu\)V at the end of the pulse. At \(I = 5\) A the ‘second peak’ is evolving whose maximum is increasing with higher current load.

The field is not distributed homogeneously (see figure 4) which causes a spatial dependence of the voltage drop. The total voltage response is determined as the integral value of all contributing voltages along the tape. The field gradient points towards the center for which reason the central parts of the tape are contributing the most to the voltage signal.

3. Critical current, \(n\) and \(\alpha\)-values

In order to understand the tape behavior in magnetic field gradients, a drastic variation of \(n\)-values and \(I_c\) has to be taken into account in the low field range [15–17]. Deriving an analytical description for the empirical field dependence of the critical current and the associated parameters is the first step in the complicated task of describing the performance of HTS tapes in field gradients. The purpose of this section is to provide reliable approximations that can be further employed in evaluating the integral behavior of the tape in an inhomogeneous field with variable amplitude.

The critical currents \(I_c\) versus the flux density were evaluated from 3 cm long pieces of 4 mm wide UHF tapes with the IDs #1–#4 as listed in table 1. The values for \(I_c(B)\) were obtained from the \(V–I\) curves with a standard criterion (i.e. 1 \(\mu\)V cm\(^{-1}\)) at 77 K and 0–6 T flux density (\(B//c\)). These characterization measurements were performed at the Ato- minstitut in Vienna in an experimental setup that can provide homogeneous fields up to 17 T within a bore of 30 mm. The critical currents are shown in figure 7.

In contrast to \(I_c(B)\) dependences which nearly follow the ‘alpha law’ at high fields (e.g. at >5 T) and 4.2 K, a \(B^n\) dependence seems to be insufficient for a description of the experimental data (see dashed curve in figure 7) at 77 K and a broader field range: it fits only below 1 T [17, 18]. Some earlier attempts [19–21] to propose ‘universal’ approximations at low and medium fields, did not result in a sufficient, wide-field ‘tool’ for \(I_c(B)\) modeling. The most successful
physical models (e.g. [22]) based on vortex theory that considers twin boundaries, dislocations and nanorods need determination of 12 physical parameters of the HTS film [23]. Technical HTS layers, especially if having a DD structure (i.e. with additional nano-inhomogeneities of other art), will need even more parameters. Thus, alternative ways for a simplified mathematical description of these systems are required in parallel to the physical modeling.

The approximation of $I_c(B)$ behavior is more complicated and requires either a field-dependent exponent instead of a constant $\alpha$, or more ‘exotic’ approximation functions such as a logarithmic dependence also shown in figures 7(a) and (b) (dotted line). One of the best solutions found for the present case is given by

$$I_c(B) = I_0 \cdot (B + \delta_0)^{-(\alpha_0 + \beta \cdot B)}.$$  \hspace{1cm} (1)

This formula (1), which we denote as ’extended alpha approximation’ (EAA), fits well with the experimental points (see figure 7) with $I_0 = I_c(1 \text{T})$, $\alpha_0$, $\beta$, and $\delta_0$ are assumed to be dimensionless with $\alpha_0 = 0.3$, $\beta = 0.2$ and $B$ being the applied magnetic field divided by 1 T. The ’shift’ parameter $\delta_0 = 0.01$ is needed to avoid divergence at $B = 0$. For DD tapes of different quality, $I_0$ must be varied in order to achieve a satisfactory agreement with experiment. For example, $I_0 = 10 \text{A}$ has to be assumed for one tape (represented by squares) in figure 7, while a tape with lower currents (triangles) requires $I_0 = 8.5 \text{A}$.

For samples with increased critical current (from 25–30 to 70–100 A) at self-field (SF), $\alpha_0$ decreases from 0.3 to 0.2 and $\beta$ increases from 0.2 to 0.26. It is interesting to note that a very similar $I_c(B)$ behavior demonstrate ‘High Field’ tapes from SuperPower [24] shown in figure 8 by circles and the dashed line. For comparison, curves following from alternative models [14, 22, 23] based on vortex line lattice are shown in figure 8; referring to [23], a ‘%+n’ BZO case was considered in respective curve which however is far from agreement with $I_c(B)$ for BHTS-DD tape.

On a semi-log scale, the discrepancy of the experimental data with the logarithmic approximation (see figure 7(b)) becomes more apparent in the 3–6 T range. So with a ‘lower degree’ of double disorder, the logarithmic approximation deviates from experiment, especially at high fields. The EAA on the other hand provides a good fit in a relatively wide field range and for different structural features of REBCO coated tapes. Note that in the range 0–6 T, the ‘effective’ $\alpha$-value

$$\alpha_{eff}(B) = \alpha_0 + \beta \cdot B,$$  \hspace{1cm} (2)

which is the exponent in equation (1), varies from +0.3 at low field to +1.5 at 6 T. This implies that the ‘classic’ alpha-law in this range is considerably detuned, while the EAA approximation can be used with better success. At higher fields and 77 K, $I_c(B)$ is of less interest because the critical currents are too small for applications (<< 2 A cm$^{-1}$-width).

For the analytical parameterization of the tape behavior, the $n$-values defined as the exponent in the power-law

$$U = U_{cr} \cdot \left(\frac{I}{I_c}\right)^n$$  \hspace{1cm} (3)

play an important role [15, 18]. The voltage criterion $U_{cr}$ here corresponds to the voltage drop $U$ at $I = I_c$.

Experimental field dependences of the $n$-values for different samples are shown in figure 9. The samples represent short sections of long length tapes. Despite different origins and internal structures of the REBCO layers, the $n(B)$ behavior of DD-tapes is more or less similar to $n(B)$ observed upon irradiation of HTS layers with heavy ions [18]. This may indicate certain similarity of their nano-morphologies.
Approximation of this $n(B)$ dependence with a simple exponential function as
\[ n(B) = P \exp(-\alpha_1 B) \] (4)
is also not sufficient at low fields. With $P = 15$ and $\alpha_1 = 0.245$, equation (4) gives a good match only in fields above 1 T (see figure 9). Below this threshold, another approximation is needed. We propose a function with a similar structure as equation (1):
\[ n(B) = [a + b/(B + \delta_1)] \exp(-\alpha_1 B). \] (5)

As can be seen in figure 9, the approximation provides a good fit over a wide field range (from 0 to 6 T) with the following parameters: $a = 15$, $b = 0.2$, $\delta_1 = 0.02$ and $\alpha_1 = 0.245$. It has been mentioned above, that these values are dimensionless and $B$ has thus to be normalized by 1 T. For DD-HTS tapes of different quality, $a$ and $b$ values may need to be ‘fine-tuned’: e.g. for the tape with higher $I_c$ at self-field (see figure 8), these parameters are $a = 17.5$ and $b = 0.15$ (see dotted line in figure 9).

It is important to note that some formulas, partly similar to our approaches have been suggested earlier in [21, 28]. They are a pure parameterization that does not clarify the physical nature of the effects. Under this viewpoint, the original power law (equation (3)) can be considered as approximation as well. Assigning the meaning of the $n$-values to the pinning potential [29] is in practice shadowed by the inhomogeneity of $I_c$ over the tape length which strongly impacts on the $n$-value [30]. The latter dependence plays the dominating role in long-length coated conductors [13, 30].

A typical example for the parameterization of $I_c(B)$, $n(B)$ and $\alpha_{\text{eff}}(B)$ calculated from equations (1), (5) and (2), respectively, is depicted in figure 10. As mentioned above, $\alpha_0 = 0.3$ and $\beta = 0.2$. It is obvious that $n$ and $\alpha_{\text{eff}}$ depend strongly on the field: $\alpha_{\text{eff}}$ triples within the 0–3 T range, while $n(B)$ and $I_c(B)$ are reduced by factors of 3.5 and 9, respectively.

4. Voltage response

4.1. Local response

In a more general form, equation (3) can be expressed as
\[ U(B) = (dU/dx)_{cr} \Delta x (I/I_c(B))^{n(B)}, \] (6)
where $I$ denotes the transport current, $(dU/dx)_{cr}$ represents the voltage drop per unit length (i.e. an electric field) used as the criterion for $I_c$, and $\Delta x$ is the distance between the potential contacts in the 4-probe method. Substituting $I_c(1 \text{T})$ from equation (1) and $n(B)$ from equation (5) to equation (6) we derive the following expression for the voltage response of the tape:
\[ U(B) = (dU/dx)_{cr} \Delta x \left[ \frac{I}{I_0} (B + \delta_0)^{(\alpha_0 + \beta B^{1/2})} \right]^{n(B)}, \] (7)
where $I_0 = I_c(1 \text{T})$ is the critical current at $B = 1 \text{T}$, $B[/c$, 77 K. Equation (6) represents the voltage response of tape which is homogenous at least within the length $\Delta x$. It is assumed also that the field does not change within this length.

Equation (7) is a form of combined $n$-$\alpha$-relationship within the EAA approximation where the voltage response at $B > 0.1 \text{T}$ becomes proportional to $U \sim 1/B^{-n_{\alpha_{\text{eff}}}}$ which can be considered as new, field dependent correction coefficient
\[ U = U_{\text{cr}} \cdot \left( \frac{I}{I_0} \right)^n (1/B^{-n_{\alpha_{\text{eff}}}}) \] (8)
that allows to keep a ‘traditional’ power layout of the relationship.

4.2. Integral response in gradient magnetic field

If the field is inhomogeneous in longitudinal direction, i.e. along the $x$-coordinate, the following integral expression following from equation (7) may be used to determine the integral voltage response $U_{\text{int}}$:
\[ U_{\text{int}} = (dU/dx)_{cr} \int_0^{\Delta x} \left[ \frac{I}{I_0} (B(x) + \delta_0)^{(\alpha_0 + \beta B(x)^{1/2})} \right]^{n(B(x))} dx. \] (9)

It is assumed here that the $\Delta x$-interval is centered at $x = 0$. This expression is particularly suitable for a field formed by a symmetrical magnet system. $(dU/dx)_{cr}$ is conventionally assumed to be 1 $\mu$V cm$^{-1}$. However, we will show in further sections that this assumption is not strictly met in many cases of an inhomogeneous magnetic field.

4.3. Permanent magnet: local and integral response

In the following section the previously derived EAA approach is used to model the electric fields appearing in UHF-YBCO tapes which are exposed to magnetic fields originating from experimental setups with neodymium magnets. The mini-assembly of two permanent magnets described in section 2.2 yields a magnetic field $B(x)$ similar to a ‘blunt knife’ [31] with a flat top in the center and very large edge gradients (see figure 2 and figure 11). The dependences of the electric field
Figure 11. Distributions of the measured magnetic field $B(x)$ (filled circles) and calculated local electric field $E(x) = U/dx$ (open squares) along a 4 mm wide DD-YBCO tape at 77 K in the assembly of permanent magnets (see section 2.2 and figure 1). Different loads of constant DC currents on the tape from 10 to 12 A were assumed. The distributions of the electric field with DC currents are calculated with the EAA evaluation using equations (5) and (7) with the following parameters: $I_0 = 8.5$ A, $\alpha_2 = 0.3$ and $\beta = 0.2$. $\alpha_0 = 0.01$, $a = 15$, $b = 0.2$, $\delta_1 = 0.02$ and $\alpha_1 = 0.245$.

on the coordinate $x$ are calculated for various transport currents, $I$, using the EAA approximation from equations (5) and (7) using the parameters listed above and also in the caption.

The electric fields occurring in the tape are relatively high. They exceed 0.1 $\mu$V mm$^{-1}$ which represents a conventional criterion (1 $\mu$V cm$^{-1}$). However, this does not lead to significant thermal effects. A simple estimation of the heat generated in the tape gives a maximal value of 1.35 mW cm$^{-2}$ (see table 2). This is a much lower power than the power loss at self-field measurements, in which the transport current is at least three times higher. Due to the direct contact with liquid nitrogen, which allows for a cooling power up to 8 W cm$^{-2}$ [25], the heating corresponds to only 0.017% of this value (see table 2) and cannot contribute to a considerable change in temperature and lateral temperature gradients in the tape. We also found that the modified EAA relationship (7) is valid in this ‘overcurrent’ regime.

In general, the width of the distributions of the electric field is nearly the same, with FWHM = 7 mm, for different transport currents. The width of the $B(x)$ distribution is slightly larger with FWHM = 8 mm. The inverted magnetic field (return field), which is observed at $|x| > 5$ mm, has practically no influence on the integral voltage response, since the ‘negative’ field (see curve $B(x)$ in figure 11) is below 0.06 T which is insufficient for a considerable voltage signal.

The measured $V$–$I$ curves for a short piece of DD-YBCO tape (with parameters similar to tape #4) recorded in the miniature assembly of permanent magnets are shown in figure 12. A 4 mm wide tape was characterized by the 4-probe technique in LN2 with a distance of 8 cm between current contacts and a gap of 3 cm between the potential contacts. The integral voltage drops calculated using equation (9) as a function of the transport current are depicted in figure 12 at self-field (curve 1') and 0.5 T (curve 2'). The $V$–$I$ dependences derived from the EAA are within $\sim$2% accuracy with the experiment.

The critical currents determined from the data shown in figure 12 depend on the assumed characterization length. This length is ‘formally’ 3 cm (see ‘crl’). Regarding the calculated electric field distributions which are shown in figure 11 it can be concluded, that the actual voltage drop occurs within 0.8 cm, corresponding to the width of the distribution of the calculated electric field. The difference between respecting ‘formal’ or ‘actual’ characterization length on $I_0$ is not too high: 12 A and 11 A, respectively. Anyway this topic will be discussed in following section.

4.4. 3 T electromagnet: tape response in pulsed field

The field distribution in the 3 T electromagnet yields nearly linear radial slopes and a ‘blunt knife’-like maximum, which are shown in figures 4 and 13. The local electric field appearing in a UHF-YBCO tape exposed to such a magnetic field is shown in figures 13 and 14 for different transport currents as indicated in the plots. A detailed view of the electric field in the UHF-tape is shown in figure 14. Minima of the tape response are defined by the zero crossings of the $B$ ($x$) curve.

The integral voltage response over 100 mm calculated from (9) with $d$ critical currents in permanent magnetic fields (figures 8 and 9) and experimental $B(x)$ dependences for the tape placed in the electromagnet is depicted in figure 15 as solid curves. The curves are labeled by the transport currents flowing through the tape. As expected, the voltage response decreases dramatically, by two orders of magnitude, by increasing the flux density from 1 to 3 T.

The experimental field dependences of the integral voltage response over a distance of 100 mm are shown in figure 15 for three different transport currents: 4, 6 and 8 A. These dependences were measured using the pulsed field technique and method described in sections 2.3 and 2.4.

The voltage response observed in figure 15 for transport currents of 6 and 8 A exceeds the conventional criterion of 10 $\mu$V (along 10 cm) significantly. Despite entering a highly dissipative regime, the experimental points closely follow the EAA prediction (solid curves), confirming that there are no other effects influencing the superconducting behavior.

Apparently, the critical currents can be determined from the $U$($B$) dependences shown in figure 15 using a ‘standard’ voltage criterion. However, this is not entirely sufficient because the transition zone is confined to the central part of the magnet. Corrections will be discussed in chapter 5.

5. Discussion

The description of the integral voltage response following from the experiment as well as the EAA approach, when a tape is exposed to a magnetic field with edge gradients, allows the analysis of some intrinsic features of tape behavior under gradient conditions. These features are described and discussed below.
5.1. Heat dissipation

In both cases, permanent and pulsed magnetic field, relatively high voltages are induced. Such voltages would cause a quench event at self-field, that occurs when the heat power exceeds the cooling power. Under field conditions, this power is much lower, even at a low field of 0.5 T, due to the drastically reduced critical current, as shown in section 4.3. The estimated heat balance is shown in table 2. In this table, $S$ denotes tape surface per cm-tape length, $P$ denotes Joule’s heat generated in 1 cm$^2$ of the tape, and $P/P_{cooling}$ is assumed to exceed 1.

| Magnet type      | $B_{max}$ | $I_{max}$ | $U_{max}$ | $S$  | $P$ | $P/P_{cooling}$ |
|------------------|-----------|-----------|-----------|------|-----|-----------------|
| Permanent        | 0.53      | 12        | 45        | 0.4  | 1.4 | 0.017%          |
| Electromagnet    | 3         | 8         | 900       | 0.4  | 18.0| 0.225%          |

Table 2. Heat dissipation and LN2 cooling assuming a cooling power of 8 W cm$^{-2}$ [29].

Figure 12. $V–I$ curves measured by the 4-probe technique (curves 1 and 2) and calculated (curves $1'$ and $2'$) from the EAA approach using the integral equation (9). 1, 1' corresponds to self-field; 2, 2' corresponds to 0.5 T generated by the miniature permanent magnet assembly. The in-field data employed for the integration are depicted in figure 7(a). The voltage criterion ($cr_1$) of 3 $\mu$V cm$^{-1}$ shown in the plot corresponds to the overall distance between the potential contacts. Experimental curves are provided with respective $n$-values.

Figure 13. Electric field, appearing in a 4 mm wide DD-YBCO tape at 77 K due to $B(x)$ of the pulsed 3 T electromagnet (see sections 2.3, 2.4 and figure 2). DC currents from 5 to 8 A applied to the tape are indicated. Distributions are calculated with the EAA model using equations (5) and (7) with the following set of parameters: $I_0$ = 8.5 A, $\alpha_0$ = 0.3 and $\beta$ = 0.2, $\delta_0$ = 0.007, $a$ = 15, $b$ = 0.2, $\delta_1$ = 0.02 and $\alpha_1$ = 0.245.

5.1. Heat dissipation

In both cases, permanent and pulsed magnetic field, relatively high voltages are induced. Such voltages would cause a quench event at self-field, that occurs when the heat power exceeds the cooling power. Under field conditions, this power is much lower, even at a low field of 0.5 T, due to the drastically reduced critical current, as shown in section 4.3. The estimated heat balance is shown in table 2. In this table, $S$ denotes tape surface per cm-tape length, $P$ denotes Joule’s heat generated in 1 cm$^2$ of the tape, and $P/P_{cooling}$ is assumed to exceed 1.

Figure 14. Detailed view of the electric field in DD-tape exposed to the magnetic field of the 3 T electro-magnet (see figure 13). Minima of tape response are defined by the zero crossings of $B(x)$. The respective low level of tape response has less interest from practical viewpoint because of the extremely low electrical field ($<10^{-12}$ V cm$^{-1}$).

Figure 15. Calculated (lines) and measured (markers) integral voltage response over 100 mm in DD-YBCO coated tape at 77 K located in the electromagnet. $I_c$ of the 4 mm wide tape employed in measurements and modeling was 8.5 A at 1 T. $B//c$. Calculations are based on independent measurements made in permanent field and dc current.
be 8 W cm\(^{-2}\) \cite{25} (as the worst case of single side cooling of the tape with average density of 7.9 g cm\(^{-2}\)).

Additionally, the heat capacity of the 0.1 mm thick tape (that equals to \(\sim 0.5 \text{ J g}^{-1} \text{ K}^{-1}\)) limits the increase of tape temperature to 0.034 K s\(^{-1}\) in the case of the permanent magnet and 0.44 K s\(^{-1}\) in the case of the electromagnet in the adiabatic limit.

The influence of thermal effects even at high ‘over-voltages’ therefore seems negligible. Nevertheless, in situations with strong field gradients lateral thermal diffusion is to be expected.

5.2. ‘Zooming’ effect

Spatially changing magnetic field, in particular a double gradient case as a ‘blunt knife’-like field, leads to an inhomogeneous electric field within the tape. For tapes with homogeneous \(I_c\), the main response is formed in the area where the field is at highest level (see figures 11 and 13). In tapes with inhomogeneous \(I_c\), defects that are in the part of the tape that is exposed to the field will be most important. Those parts of the tape which are exposed to a lower magnetic field retain a higher \(I_c\) while we apply transport currents corresponding to the much lower \(I_c\) at the highest field. In other words, the applied current, \(I_c\) is typically low enough to cause no voltage response in low field areas. However, this does not apply to ‘severe’ local defects (as e.g. scratches, cracks, macro inclusions that may introduce even a discontinuity in current flow), which reduce \(I_c\) in the ‘low’ field zone more than the magnetic field in the ‘high’ field zone. Anyway, ‘out-of-field’ inhomogeneities that reduce the local \(I_c\) by a factor of up to 3 and 8 will not be detected in measurements of the integral response (at 0.53 and 3 T, respectively). This so-called ‘zooming’ effect results in the selection of the ‘influential’ area given by the shape of the magnetic field. Using the integral response, this allows to detect tape inhomogeneities that are located at the maximum of the blunt-knife field.

Thus, only a small part of the integration distance contributes to the response. Figure 16 illustrates this effect in case of a longitudinal scratch. The integral voltage responses 1 and 3 correspond to \(V-I\) curves measured in self-field without and with scratch, respectively. Curves 2 and 4 refer to the same tapes 5 exposed to the field of the permanent magnet assembly 6 (0.53 T). The scratch 7 was made with a hard steel knife along 24 mm in longitudinal direction of the tape. The voltage contacts 8 were positioned at a distance \(\Delta x_0 \approx 30 \text{ mm}\), while the part of the tape exposed to the magnetic field corresponds to \(\Delta x_0 \approx 9 \text{ mm}\). It was confirmed in preliminary tests that a transversal artificial scratch with a width of 12 \(\mu\text{m}\) completely interrupts the superconducting current. For parallel current, the scratch narrows the tape cross-section not only due to the scratch width, but also via a zone with a high concentration of cracks. This defect zone surrounds the scratch by a damaged HTS layer. Such defect zones together with an imperfect alignment of the scratch with respect to the longitudinal direction should result in inhomogeneous critical current densities in the two channels at both sides of the scratch. These \(I_c\) inhomogeneities lead to a reduced \(n\)-value \cite{30} e.g. from 12 to 9.4 as indicated in figure 16. The evaluation and comparison of the critical currents for curves 1 and 3 in figure 16 show a degradation of the critical current by 10 %, as additionally specified in table 3. Consequently, a first interpretation suggests that the width of the damaged area is \(\sim 0.40 \text{ mm}\), which corresponds to 10% of the width of the investigated tapes. Nevertheless, the decrease of the critical current is considerably lower when an \(\sim 8 \text{ mm-long tape section is exposed to a blunt knife-like field with a FWHM} \sim 8 \text{ mm of 0.53 T}.\) The \(I_c\) reduction is only \(\sim 4.5\%\) instead of 10% at self-field, as shown in table 3.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure16.png}
\caption{(a) \(V-I\) curves measured via the 4-probe technique in DD-YBCO coated tape without scratch (curves 1 and 2) and with scratch (curves 3, 4). Dependences 1 and 3 refer to self-field measurements; curves 3 and 4 correspond to measurements at 0.53 T (\(B//c\), 77 K) in the miniature permanent magnet assembly. (b) The EAA2 curve given by \(I_c(B) = 10 (B + 0.01)^{-0.3} (0.3 + 0.2 B)\) is compared with curve PL2 calculated from the ‘simple power law’ \(I_c(B) = I_c(B_0) (B/B_0)^{\alpha} (B/B_0 + 1)^{\beta}\) with \(\alpha = -0.3\) used in figure 7(b) at \(B_0 = 0.005 \text{ T}\) and \(I_c(B_0) = 39 \text{ A}\) (following from curve 1). Dependences 2’ and 4’ are calculated from the EAA approximation using integral equations (10)–(11). The voltage criterion ‘cr1’ corresponds to an electric field of 1 \(\mu\text{V cm}^{-1}\) averaged over the distance between the voltage contacts. Experimental curves are provided with respective \(n\)-values. (c) Layout of tape-magnet-scratch arrangement.}
\end{figure}
integral voltage response in inhomogeneous magnetic fields. However, this is not completely correct.

In analyzing the ‘zooming’ effect, the integral voltage response expressed by equation (9) can be approximated by splitting the equation into two parts. Referring to the experimental results of the blunt-knife-like flux density distribution in figure 2, the flux density distribution is considered to be composed of two parts with homogeneous flux density distributions. One with \( B(x) = 0 \) and the other one with \( B(x) = B_{\text{m}} \):

\[
U_{\text{int}} \approx \left( \frac{dU}{dx} \right)_{\text{cr}} \left( \frac{I}{I_0} \right)^{n(0)} \cdot \delta_0 \cdot \delta_{\text{m}}(0) \left( \Delta x_0 - \Delta x_m \right) + \left[ \frac{I}{I_0} B_{\text{m}}^{\alpha_0 + \beta_0} \right] \delta_{\text{m}}(n(m)) \Delta x_m, \tag{10}
\]

where \( n(0) \) denotes the \( n \)-value at self-field. The first, out-of-field term, which contains \( \Delta x_0 - \Delta x_m \), is negligible compared to the second, in-field term containing \( \Delta x_m \), if the coefficient \( \delta_0 = 0.01 \) is much smaller than the applied field.

Equation (10) reduces then to

\[
U_{\text{int}} \approx \left( \frac{dU}{dx} \right)_{\text{cr}} \left( \frac{I}{I_0} \right)^{n(0)} \cdot B_{\text{m}}^{\alpha_0 + \beta_0} \delta_{\text{m}}(n(m)) \Delta x_m. \tag{11}
\]

\( I - V \) dependences derived from the EAA equation (11) are plotted in figure 16(b) using the same set of EAA parameters as in figure 16 and the \( n \)-values shown in figure 16.

The agreement with experiment is not perfect because of the difference of the in-field \( I_c \) measured with and without scratch: This difference is \( \sim 0.55 \) A in experiments, while the EAA approach yields \( \sim 0.85 \) A. The values and respective ratios of these currents are summarized in table 3. A ‘simple power law’ approach (see PL2 curve in figure 16(b)) shows considerably higher misfit with experiment (curve 2).

The observed discrepancy originates probably from macro effects that define a distribution of the shielding currents in this ‘double channel’. Thus, the zooming effect resulting from the EAA is not sufficient to fully describe the behavior of the scratched tape in the local magnetic field.

### 5.3. Measurements at stationary conditions and scanning modulus

To determine the critical current from measurements of the integral voltage response in inhomogeneous magnetic fields, it is necessary to find the intersection of the \( U_{\text{int}}(B) \) curve with the ‘integral’ criterion that equals to the product of local criterion \( (dU/dx)_{\text{cr}} \) (typically 1 \( \mu \)V cm\(^{-1} \)) and \( \Delta x_m \), the length of the tape within the magnet. Because of the field gradients, the voltage response originates from a part of \( \Delta x_m \) only, where the field is strong enough to cause dissipation. As follows from figure 13, the FWHM of the \( U(x) \) distribution corresponds to \( \sim 30 \) mm independently of the transport current. This means that the ‘influential’ magnetic field is concentrated within an ‘effective’ distance \( \Delta x_m = 30 \) mm. The critical voltage response

\[
U_\text{cr} = (dU/dx)_{\text{cr}} \cdot \Delta x_m \tag{12}
\]

will be reached when

\[
U_\text{cr} = (dU/dx)_{\text{cr}} \cdot \Delta x_m' = \left( \frac{I(B)}{I_0} \frac{\delta_0^{(\alpha_0 + \beta_0 B)}}{\delta_0^{(\alpha_0 + \beta_0)}} \right)^{n(B)}. \tag{13}
\]

This follows from equation (7) at \( I = I_c \), where \( I_c \) is the transport current at which the criterion (12) is reached. From equations (12) and (13) follows that

\[
\frac{I(B)}{I_0} \frac{\delta_0^{(\alpha_0 + \beta_0)}}{\delta_0^{(\alpha_0 + \beta_0)}} = \frac{\Delta x_m}{\Delta x_m'}. \tag{14}
\]

Introducing \( C = \Delta x_m/\Delta x_m' \) we derive \( I_0 = I_0(1T) \) as an ‘invariant’ that should remain constant at different \( B \):

\[
I_0 = \frac{I(B)}{I_0} \frac{\delta_0^{(\alpha_0 + \beta_0 C^{-1} \cdot n(B)}}{\delta_0^{(\alpha_0 + \beta_0)}} \tag{15}
\]

\( I_0 \)-values derived from the experimental data (achieved at pulsed field) shown in figure 15 are summarized in table 4.

The extrapolation procedure for \( U_{\text{int}}(B) \) using the EAA equations provides satisfactorily \( I_0 \) values even when the \( \alpha \)- and \( n \)-parameters were chosen with some deviation.

\( I_0 \) obtained from data from different transport currents and fields seems to be sufficiently accurate, exhibiting a minor deviation of \(<2.5\% \) from the de facto \( I_0 = 8.5 \) A.

These relationships suggest an opportunity to interpret the variation \( U_{\text{int}}(B) \) in terms of variations of the effective critical current in the case when the tape is moving through a stationary field zone. An example of such a procedure is given in figure 17 where the dependence of \( I_0 = I_0(1T) \) on the variation of the internal voltage drop \( U_{\text{int}} \) is plotted assuming \( B_{\text{max}} = 2.6 \) T and a constant transport current \( I = 6 \) A. The solid line and calibration point \( (U_{\text{int}} = 75 \ \mu \text{V} \text{ at } I = 6 \) A) are derived from figure 15 at \( B = 2.6 \) T. It was considered that \( I \) and \( I_0 \) are always occur in the equations e.g. (7) and (9) as the ratio \( U/I_0 \). This leads to the inversely proportional influence of \( I_0 \) when it becomes a variable at constant \( I \).

Following equations (7) and (9), any variation of \( U_{\text{int}} \) at a constant transport current \( I \) results from a change of \( I_0 \) because \( I_0 \sim (U_{\text{int}})^{-1/n} \). A 50% deviation of voltage \( U_{\text{int}} = 75 \ \mu \text{V} \) leads to only 6% deviation of the evaluated critical current \( I_0 \) (see dotted lines in figure 17). This

---

**Table 3. Influence of a longitudinal scratch.**

| Data source | \( B \) | \( I_c \) | \( I_{c,\text{cr}} \) | \( I_c - I_{c,\text{cr}} \) | \((I_c - I_{c,\text{cr}})/I_c\) |
|-------------|--------|--------|-----------------|-----------------|-----------------|
| Experiment  | SF     | 39.00  | 35.99           | 4.00            | 10.0%           |
| Experiment  | 0.53   | 12.10  | 11.55           | 0.55            | 4.5%            |
| EAA calculation | 0.53 | 12.30  | 11.45           | 0.85            | 6.9%            |
Table 4. Derivation of $I_c$ and $I_0$ from the pulsed measurements using the EAA equations (5) and (15). Experimental dependences shown in figure 15 for $I$ of 6 and 8 A were extrapolated to the integral criterion of 10 $\mu$V. At $I = 4$ A, the simple intersection of the experimental dependence with 10 $\mu$V defines $I_c$.

| $B$ T | $I_c$ A | $n(B)$ | $C = 3.33$ | $I_0(1$ T $)A$ | $\Delta I_0/I_0$ % |
|------|--------|--------|-------------|----------------|------------------|
| 2.8  | 4.0    | 7.5    | 0.831       | 8.28           | -2.5%            |
| 2.0  | 6.0    | 9.2    | 0.860       | 8.58           | +1.0%            |
| 1.4  | 8.0    | 10.5   | 0.876       | 8.71           | +2.4%            |

Table 5. Field deviation of dependence of critical current defined from EAA at 10 times higher voltage criterion, i.e. at 10 $\mu$V cm$^{-1}$ instead of 1 $\mu$V cm$^{-1}$. Calculations are based on approximate equation (8) assuming that $I_c/I_0 \approx B^{-\alpha eff} (U_{c2}/U_{c1})^{n(B)}$ where $U_{c2}/U_{c1} = 10$.

| $B$, T | 0.5  | 1    | 1.5 | 2    | 3    |
|--------|------|------|-----|------|------|
| $n(B)$ | 13   | 11   | 10  | 9    | 7    |
| $\alpha eff$ | 0.40 | 0.50 | 0.65 | 0.70 | 0.90 |
| $I_c/I_0$ | 1.58 | 1.23 | 0.97 | 0.80 | 0.52 |

Figure 17. Example of dependence of $I_c$ on variation of the internal voltage drop $U_{int}$ measured in the course of tape translation or sample exchange at $B = 2.6$ T and transport current $I = 6$ A. Solid line is derived as ‘cut’ of plot of figure 15 at $B = 2.6$ T.

Figure 18. Field dependence of alternatively defined lift factors from our analyses and from modeling based on vortex line lattice, V Pan [25].

that in this case $I_c$ reduces with field growth for $B > 1.5$ T, while at lower fields $I_c$ increases. In more general cases, when the integral equation (9) is required, a more precise deviation of $I_c$ may be derived for any kind of field distribution.

5.4. Comparison of tape performance at 77 and 4.2 K

Extremely high lift factors defined as $LF(B) = I_c(B, 4.2K)/I_c(B, 77K)$ of 300–1500 are observed. They increase with increasing flux density. This significantly (almost by one order of magnitude) differs from the dependence given by modeling according to [22] as shown in figure 18. On the other hand, the commonly used lift factor defined as $LF(B) = I_c(B, 4.2K)/I_c(SF, 77K)$ decreases with flux density (see figure 18).

This shows that the $I_c$ suppression with field is much more efficient at 77 K than at 4.2 K. On the other hand, the influence of local macro defects reduces $I_c$ in both cases within $B = 3–6$ T range.

This creates the basis for a prediction of the tape behavior at 4.2 K using $I_c$ measurements at 1–3 T, $B//c$ and 77 K [11, 27, 26].

6. Summary

Two field-gradient techniques were developed to evaluate the integral voltage response of DD-YBCO coated tapes under an applied transport current. They are based either on a permanent magnet assembly or a pulsed electromagnet.

As a tool for this evaluation, an ‘EAA’ is proposed that allows us to match the field dependence of critical current, $n$- and alpha values to experimental data. Such analytical approaches have proven to be very useful for achieving either a gradient model or a ‘dynamic’ (i.e. time-dependent) model, or both together.

In a local magnetic field of 0.5 and 3 T with gradients from both sides, the validity of the extended $n$- and alpha-laws was confirmed, even when the transport current in the
tape is twice as high as the critical current at the respective field. It is shown that an extremely high voltage response (>80 μV cm⁻¹) is generated in this case while the heat power is rather low due to the relatively low transport currents required in the applied magnetic field.

The same approach for tapes in inhomogeneous fields can be used at 4.2 K and a wide field range.

The suggested tools and results of the present study can be employed directly for the analysis of tapes moved through the characterization zone, which includes a local field with edge gradients and a current source. This task, along with a correlation analysis of the ‘in-field’ I, measured at 77 and 4.2 K in DD-YBCO coated tapes, is the goal of our next study aiming at a quality control tool for tapes to be used at high fields and low temperatures.

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