Current distribution and critical state in superconducting silver-sheathed (Bi,Pb)-2223 tapes

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Abstract

A novel method for the unambiguous determination of the self-field critical current of superconducting silver-sheathed (Bi,Pb)2Sr2Ca2Cu3O10−δ/(Bi,Pb)-2223/Ag tape conductors is presented which is based on the measurement of the distribution of the perpendicular magnetic field component above current-carrying tapes by scanning Hall probe magnetometry. From the evolution of the sheet current density distribution across the tape width with increasing transport current, a characteristic current I∗ can be identified, above which additional current is distributed homogeneously over the entire (Bi,Pb)-2223 and Ag volumes, respectively, and which represents a realistic estimate of the intrinsic critical current associated with the critical state scenario: It corresponds to full penetration of the transport current into the volume of the superconductor and does not depend, as is the case for the determination of the transport critical current from current–voltage characteristics, on experimental parameters such as the choice of an electric field criterion. © 1998 Elsevier Science B.V. All rights reserved.

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1. Introduction

In the development of high-Tc tape conductors for electrical power applications, an understanding of the mechanisms determining the current distribution in the tapes, its correlation with microstructure and tape geometry as well as its dependence on processing and operational parameters is of crucial importance both for the design and characterization of the conductors. Current imaging methods which non-invasively determine the local current flow patterns in conductors from measurements of the associated magnetic field, are well suited to address this problem experimentally. They can complement transport experiments, such as measurements of the...
current–voltage ($I-V$) characteristics and the transport AC loss, which provide information about dissipation processes typically integrated over the entire conductor cross-section and on a length scale of a few mm along the conductor. Various experimental techniques including magneto-optical imaging, scanning Hall probes, and arrays of micro-Hall sensors have been used to map the magnetic field distribution above and determine the current distribution within both ceramic, thin-film, and single crystal superconducting samples [1–7] and silver-sheathed (Bi,Pb)$_2$Sr$_2$Ca$_2$Cu$_2$O$_{8+\delta}$ ((Bi,Pb)-2223/Ag) composite conductors [8–11].

The magnetic inversion problem of determining a current distribution from its magnetic field has no unique solution in the general, three-dimensional case. If, on the other hand, the current flow is restricted to a two-dimensional (2D) sheet, then a unique solution exists, and various methods have been developed to implement the inversion. One example is an algorithm using Fourier transforms (FTs) and spatial filtering to deconvolve the current density and the Green’s function in Biot–Savart’s law. An inversion based on this method was implemented by Roth et al. [12] for the case of an infinitely thin sample or, equivalently, a sample-sensor separation much larger than the sample thickness. In another approach, the current flow is described as a distribution of current dipoles and the matrix equation obtained after discretization of Biot–Savart’s law is solved [2]. This procedure was extended to samples of arbitrary thickness by Wijngaarden et al. [4]. Other inversions are based on the finite-element method [13], or on direct integration of Biot–Savart’s law in the special case of superconductors in the mixed state [14].

In the present work, we apply the FT/spatial filtering technique of Roth et al. [12], modified for the case of samples of arbitrary thickness in the one-dimensional (1D) limit. We demonstrate that the evolution of the sheet current density distribution $J_x(x)$ across the width of both mono- and multifilamentary (Bi,Pb)-2223/Ag tapes for increasing transport current $I$ unambiguously defines a characteristic current $I^*$ which marks the full penetration of the superconducting volume by the transport current and thus corresponds to the intrinsic critical current of the tape. We show that the scanning Hall probe technique allows a non-invasive determination of the distribution of superconducting material across the tape width, and that the combination of this information with the $J_x$ data can be used to estimate the distribution of critical current densities.

2. Experimental

The (Bi,Pb)-2223/Ag monofilamentary and multifilamentary tapes are produced by a standard powder-in-tube method. The tapes are typically 3 mm wide and 0.3 mm thick.

In the scanning Hall probe experiment, a micro-Hall probe with an active area of $30 \times 30 \, \mu\text{m}^2$ is moved across the broad surface of a tape and measures the magnetic field component perpendicular to the tape surface with a resolution of $\sim 0.8 \, \text{A/m}$ (corresponding to a magnetic induction $B \sim 1 \, \mu\text{T}$). The scanning range of 30 mm allows to map the magnetic field far outside the tape, thus facilitating the magnetic inversion procedure described in the following section. As illustrated below, the spatial resolution of the experiment is determined by the separation between the sensor and the current-carrying volume elements in the sample, or by the sensor size, whichever is greater. In the present case, the separation between the sensor plane and the sample surface is about 50 $\mu\text{m}$, so that even for the thinnest samples, the spatial resolution is limited by that distance rather than the spatial extension of the sensor. Thus, the step size can be increased from its minimum value of 1.5 $\mu\text{m}$ to $\sim 30 \, \mu\text{m}$ to avoid unnecessary oversampling. All the low-temperature measurements presented were taken at $T = 77$ K with the tape and the scanning assembly immersed in liquid nitrogen, under self-field conditions created by transport currents $I$ of up to 60 A flowing through the tapes.

The separation $h$ between the sensor and the sample is determined from fits of the magnetic field distribution $H_x(x)$, measured above current-carrying silver tapes with dimensions similar to those of the (Bi,Pb)-2223/Ag tapes, to the analytical expression for the magnetic field of a conductor with rectangular cross-section [15], with $h$ being the only free parameter. Typically, $h$ is found to be of the order of 50 $\mu\text{m}$. 


For comparison, local DC $I$–$V$ characteristics were measured simultaneously at the Hall probe scan position, using a voltage tap spacing of 5 mm.

3. Magnetic inversion procedure

The magnetic inversion represents a crucial element of the investigation of current flows using magnetic field mapping techniques. Previous studies on tape conductors either contain very little information about the details of the inversion process [10,16] or determine the current density $j$ by applying Ampère’s law $j = \nabla \times \mathbf{H}$, which is strictly valid only inside the conductor, to $H_y(x)$ data measured 0.5 mm above the sample [11]. Therefore, a brief description of the inversion method used is given here.

The sample considered is an infinitely long strip of half width $2a$ and thickness $d$, with the sample cross-section given by $x \leq a$, $|z| \leq d/2$ and an applied transport current $I_y$ flowing along the $y$ coordinate. The current density $j_\parallel(r)$ is assumed to have no component in $z$ direction and to be distributed homogeneously over the sample thickness, i.e., $j_\parallel(r) \equiv (0, j_y(x), 0)$ does not depend on $z$. Therefore, the results of the magnetic inversion will be given in the form of the sheet current density distribution $J_y(x) = j_y(x)dz = j_y$. The perpendicular component of the magnetic field associated with the current flow in the sample, measured at a height $h$ above the midplane of the conductor, is given by Biot–Savart’s law:

$$H_y(x) = -\frac{1}{4\pi} \int_{-a}^{+a} \int_{-\infty}^{+\infty} \int_{-d/2}^{+d/2} \frac{j_y(x') \delta(x-x')}{[(x-x') + (y-y') + (h-z')]^{3/2}} dz'dy'dx'. \quad (1)$$

Integration over $y'$ and $z'$, respectively, yields

$$H_y(x) = \int_{-a}^{+a} j_y(x')G(x-x')dx'. \quad (2)$$

with

$$G(x) = -\frac{1}{2\pi} \arctan \left( \frac{x d}{x^2 + h^2 - d^2/4} \right). \quad (3)$$

Eq. (2) represents a convolution of the current density $j_y$ with the Green’s function $G$. Using the convolution theorem, $j_y$ can be expressed as

$$j_y(x) = FT^{-1}\left\{FT\{H_y(x)\}\right\}, \quad (4)$$

where $FT$ and $FT^{-1}$ represent the forward and inverse Fourier transforms, respectively, and

$$FT\{G(x)\} \equiv \mathcal{G}(k) = \frac{i}{k} \sinh \left( \frac{|k|d}{2} \right) e^{-|k|h}. \quad (5)$$

In the limit $d \to 0$ (‘thin sample’ case), the expressions for the Green’s function $G$ and its Fourier transform $\mathcal{G}$ in Eqs. (3) and (5) reduce to those used previously, for example, by Johansen et al. [5]:

$$G(x) = -\frac{d}{2\pi} \frac{x}{x^2 + h^2},$$

$$FT\{G(x)\} \equiv \mathcal{G}'(k) = \frac{d}{2} \frac{sgn(k)}{e^{-|k|h}}. \quad (6)$$

In the case $d \sim h$ and for larger aspect ratios $d/2a \leq 1$, i.e., for field measurements taken close to the surface of ‘thick samples’, the inversion based on Eq. (6) is numerically less stable than the procedure using the
modified expression for \( \mathcal{G} \) in Eq. (5). This is a consequence of the fact that in this parameter range, \( \mathcal{G} \) may become many orders of magnitude smaller than \( \mathcal{G} \). As discussed by Roth et al. [12] and illustrated by Wijngaarden et al. [17], due to the exponential term in Eqs. (5) and (6), the division in Eq. (4) strongly amplifies Fourier components at high spatial frequencies, particularly for large observation distances \( h \). The ‘thick sample’ case is an experimentally relevant scenario, which is realized, for example, in field mapping experiments on silver-sheathed (Bi,Pb)-2223 tape conductors with a typical tape thickness of 0.3 mm, aspect ratio of 0.1 and separation between the sensor and the tape surface of 0.05 mm.

We note that Eq. (5) corresponds to the 1D limit of the generalization of the FT inversion to 2D samples of arbitrary thickness which was recently proposed by Johansen et al. [18].

The problem of enhanced high-wavenumber noise due to division by small Fourier components in Eq. (4) requires the introduction of a low-pass cutoff filter. The result of the inversion turns out not to be very sensitive to the particular choice of the window function with which FT \( G \) is multiplied to implement the filter. Generally, window functions with discontinuous derivatives, such as the box or triangular windows, tend to result in stronger oscillatory behaviour of the solution compared to smoother window functions such as the Hanning window,

\[
W_{uf}(k) = \begin{cases} 
\frac{1}{2}[1 + \cos(\pi k/K)], & |k| \leq K, \\
0, & |k| > K, 
\end{cases}
\]

which is used here. The choice of the wavenumber cutoff \( K \) depends on the noise spectrum (which is extremely sensitive to the separation \( h \) between the current-carrying volume and the sensor due to the \( e^{-|k|h} \) term in Eq. (6)), and on the discretization step width \( \Delta \). We define the cutoff via \( K = \alpha \pi / \Delta \) with \( 0 < \alpha \leq 1 \), and typically choose \( \alpha = 0.6 \).

In an experiment, the magnetic field \( H(x) \) is measured only in a finite region \([x_{\text{min}}, x_{\text{max}}]\), whereas the spatial integral in \( \text{FT}\{H(x)\} \) extends over an infinite interval. The magnetic field due to a current distribution in a conductor measured at a point far away from the conductor is not very sensitive to small variations of the current distribution over length scales small compared to the relevant conductor dimensions. As noted by Pashitski et al. [19], one can exploit this fact to subtract an auxiliary magnetic field term \( H_{\text{aux}}(x) \) from the experimental data \( H_{\exp}(x) \) which matches the field values measured outside the sample and corresponds to a fictitious current density distribution \( j_{\text{f}}(x) \) inside the sample:

\[
j_{\text{f}}(x) = \text{FT}^{-1}\left\{ \frac{\text{FT}\{H_{\exp}(x) - H_{\text{aux}}(x)\}}{\text{FT}\{G(x)\}} \right\} + j_{\text{n}}(x).
\]

Eq. (8) becomes exact in the limits \( x_{\text{min}} \to -\infty, x_{\text{max}} \to +\infty \). Depending on the characteristics of the particular dataset to be inverted, \( j_{\text{n}}(x) \) is chosen as a homogeneously distributed current flowing through a long conductor with either a rectangular or elliptical cross-section, with the width and aspect ratio of the conductor corresponding to that of the sample. The associated magnetic field component \( H_{\text{c}}(x) \) can be calculated using, for example, the complex analytical function method of Beth [15,20].

4. Results and discussion

We first illustrate the non-invasive determination of the distribution of superconducting material across the tape width. The method is based on the observation that far above the critical temperature \( T_c \) of the superconducting material the conductivity of silver is about three orders of magnitude larger than that of the superconductor, so that a transport current will flow almost exclusively within the sample volume occupied by the silver. Therefore, assuming that the current distributes homogeneously throughout the silver, the sheet
current density distribution $J(x)$ determined far above $T_c$ should reflect the distribution of the silver (or, correspondingly, of the superconducting material), averaged over the tape thickness.

Shown in Fig. 1 are the magnetic field and corresponding sheet current density distributions, $H(x)$ and $J(x)$, determined at $T = 293$ K for a monofilamentary tape with a cross-section illustrated by the micrographs at the bottom of the panels. From Fig. 1(b), it is evident that $J(x)$ traces the distribution of silver material across the tape width, averaged over the tape thickness, which is represented by the quantity $1 - f(x)$, where $f(x)$ denotes the fraction of a unit cross-sectional area centered at $x$ (i.e., a slice along $(x, |y| \leq d/2$) occupied by the superconducting material. The distribution $f(x)$ is determined from the optical micrograph of the tape cross-section shown at the bottom of the panels.

In Fig. 2, similar data are shown for an untwisted 19-filament tape with a filament configuration illustrated by the cross-sectional micrograph at the bottom of the panels. Again, there is good agreement between the
$J_x(x)$ data and the distribution of superconducting material determined from the micrograph, with nearly all the local extrema in $1-f(x)$ being reflected in $J_x(x)$. The difference in the modulation amplitude of the oscillations in the two quantities is likely to be related to the broadening of the $J_x(x)$ distribution resulting from the magnetic inversion compared to the original current flow pattern. This broadening is due to the finite resolution of the $H_x$ measurement, the limited scanning range, and the finite sensor size.

The results presented in Figs. 1 and 2 illustrate that the determination of $J_x(x)$ at room temperature from scanning Hall probe experiments provides a valuable tool for the non-invasive imaging of the distribution of superconducting material across the tape width.

The evolution of $H_x(x)$ and $J_x(x)$ for a monofilamentary tape when the transport current $I$ is increased from 0 to 50 A in steps of $\Delta I = 5$ A is illustrated in Fig. 3(a) and (b). The transport critical current $I_c$, corresponding to a 1 $\mu$V/cm electric field criterion in the $I-V$ characteristic measured simultaneously across the scanned region is $I_c = 38$ A. As has been noted previously [11,16], the behaviour of monofilamentary tapes is qualitatively described by the critical state model for the case of a superconducting wire with an elliptical cross-section. This is confirmed quantitatively for the present data in Fig. 3(a) and (b) by comparison with the predictions of the critical state model for a long superconducting wire with an elliptical cross-section [21], which are shown in Fig. 3(c) and (d). Here, the conductor dimensions and the separation between the conductor and

![Diagram](image)

Fig. 3. (a) Distribution of the perpendicular magnetic field component $H_x(x)$ across a monofilamentary (Bi,Pb)-2223/Ag tape conductor carrying different transport currents $I$, measured at a distance $h = 0.05$ mm from the tape surface at $T = 77$ K. (b) Corresponding sheet current density distribution $J_x(x)$. (c),(d) $H_x(x)$ and $J_x(x)$ for a superconducting wire with elliptical cross section and dimensions identical to those of the tape in (a) and (b), calculated using the critical state model [21] for the same separation between the conductor and the field plane as in (a) and (b).
the plane of the field point were chosen identical to the experimental values for the monofilamentary tape. The differences in the maximum value of the calculated $J_y(x)$ compared to the $J_y(x)$ from the inverted field data are due to the fact that the cross-section of the filament is only approximately described by an ellipse, with the ends of the filaments being tapered and the middle section showing a slight waist, which is also clearly visible in the density distribution determined geometrically and electrically shown in Fig. 1(b). We note that the integral of the experimentally determined $J_y(x)$ over the tape width corresponds to the total transport current through the tape to within 0.3%.

The results in Fig. 3(b) exhibit another characteristic feature not discussed previously: While initially the current gradually penetrates more and more into the interior of the superconducting filament as $I$ increases, there is a qualitative change in the sequence of current distributions $J_y(x)$ above a characteristic current $I^* = 30$ A: The shape of the $J_y(x)$ curves for $I > I^*$ remains virtually unaffected by the increasing current, in stark contrast to the systematic changes observed for $I < I^*$. To clarify this point further, we plot the difference between consecutive $J_y(x)$ traces, i.e., $\Delta J_y(x, I) = J_y(x, I) - J_y(x, I - \Delta I)$ with $I$ as a parameter in Fig. 4. $\Delta J_y(x, I)$ illustrates where the additional current flows as $I$ is increased. Initially, the extra current is added at the outer edges of the superconducting filament. As $I$ increases, the outer regions carry the maximum current possible (corresponding to the critical current density), so that the additional current has to be added further inside the superconductor. Eventually, just below the characteristic current $I^*$, all the extra current goes into the central part of the filament (note that the changes in the current density for the outer regions are very small). At $I^*$, the current is distributed homogeneously throughout the entire cross-section of the superconductor; thus, $I^*$ can be identified with the critical current of the critical state model [21,22]. For $I > I^*$, we observe a dramatic change in the way extra current distributes itself in the tape: Instead of being added to the central section of the superconducting filament, $\Delta J_y(x)$ exhibits a broad distribution across the entire sample which remains nearly unchanged as $I$ is increased further, except for a characteristic increase at the very outer edges of the sample for the highest current. Since even for the highest current values $\Delta J_y(x)$ has a maximum in the central region, the majority of the additional current is still being transferred into the superconductor, whose (flux flow) resistivity therefore must still be comparable to that of the silver sheath. The slight increase in $\Delta J_y(x)$ close to the outer edges at maximum current may be an indication for the onset of current transfer from the superconducting filament into the Ag sheath.

To further illustrate the significance of the characteristic current $I^*$ and to compare it with the transport critical current $I_{T_C}$ determined from the $I$–$V$ characteristics, we plot in Fig. 5 the $I$ dependence of $J_y$ taken at three fixed positions, two of which (labelled ‘A’ and ‘C’, respectively, in the inset of Fig. 5) are close to the

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Fig. 4. Differential sheet current density distribution $\Delta J_y(x)$ for the monofilamentary (Bi,Pb)-2223/Ag tape derived from the data in Fig. 3(b), plotted for different transport currents $I$. See text for the definition of $\Delta J_y(x)$. 

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outer edges of the filament, whereas the other (labelled ‘B’) is in the center of the sample. Note that the $J_y(I, y)$ values are normalized with respect to the values $J_y(I, y_m)$ measured at the maximum current $I_m = 50$ A. At the edge positions, the $J_y(I)$ curves exhibit a steep initial increase, followed by a plateau region where the current remains essentially unchanged. In contrast, the current density at the center increases only gradually at low currents, with a sharp increase close to the characteristic current $I^*$, where all three curves meet. Finally, for $I > I^*$, we observe a linear increase of $J_y$ with $I$ everywhere in the sample, corresponding to additional current being distributed homogeneously over the cross-section of the conductor.

The value of $I_c = 38$ A is indicated in the figure by a vertical dashed line, illustrating that $I_c$ is considerably higher than $I^*$ and can merely be considered an upper limit for the critical current. We want to emphasize that, while $I^*$ is a well-defined quantity corresponding to dramatic qualitative changes in the way current is flowing through the conductor, the value of $I_c$ depends on extrinsic parameters such as the electric field criterion employed in its definition, making it necessarily more arbitrary in character.

In Fig. 6, we show $H_y(x)$ and the associated $J_y(x)$ data for the untwisted 19-filament tape for increasing transport current $I$. The contributions from five individual stacks of filaments which are decoupled even for the
lowest currents are clearly visible. As in the case of the monofilamentary tape, a plot of the differential sheet current density \( \Delta J_x(x) \), which is shown in Fig. 7, illustrates the redistribution of the current. With increasing current, we observe a sequence of pronounced, localized maxima of \( \Delta J_x(x) \) corresponding to the majority of the excess current being transferred into individual stacks of filaments. As the position of these maxima shifts, one can watch these groups of filaments ‘switch off’: For currents beyond the one where a particular local maximum in \( \Delta J_x(x) \) is observed, there is almost no change in the current density at that position, i.e., the filaments are saturated, and additional current has to flow elsewhere. This is clearly demonstrated in Fig. 7 for the group of filaments located close to the outer edge of the sample at \( x \approx 7 \) mm.

We can easily identify the characteristic current \( I^* = 14 \) A above which additional current is distributed homogeneously across the entire conductor. As in the case of the monofilamentary tape, the value of \( I^* \) is lower than that of the transport critical current \( I_s = 15 \) A. The \( \Delta J_x(x, I) \) traces obtained at the highest currents \((I = 30 \text{ A}, 40 \text{ A})\), are not shown in Fig. 7; they remain virtually unchanged compared to those for \( I \approx 20 \) A.

According to the critical state model, at the critical current the local current density \( j_x \) corresponds to the critical current density \( j_s \) throughout the entire superconducting volume. Therefore, one can estimate the distribution of the local critical current density \( j_x(x) \), averaged over the filament thickness, using the information about the local distribution of superconducting material across the tape width. This is accomplished by dividing the data for the sheet current density distribution \( J_x(x) \) at \( I = I^* \) by the distribution of the superconducting cross-sectional area per unit length, represented by the quantity \( f(x) \). We recall that \( 1 - f(x) \) can be determined non-invasively from the sheet current density distribution measured at temperatures well above the critical temperature (cf. Fig. 1b and Fig. 2b, respectively). The result of this procedure applied to the data for the monofilamentary tape is shown in Fig. 8, where the solid line represents the distribution of the critical current density \( j_x(x) \) and the points illustrate the sheet current density distribution \( J_x(x) \) at \( I = I^* \).

It should be noted that the division by \( f(x) \) may lead to an overestimate for \( j_x(x) \) in the vicinity of the positions \( x \) where the quantity \( f(x) \) approaches zero, i.e., where the room-temperature sheet current distribution \( J_x(x) \) representing \( 1 - f(x) \) is close to its maximum value. For an ideal filament, this is the case everywhere outside the superconductor where, on the other hand, \( J_x(x) \) at \( I = I^* \) vanishes, so that one has \( j_x = 0 \). In the experimental data, however, the distinction between the superconducting material and the silver sheath is not perfectly sharp due to the broadening of the magnetic features used to determine \( J_x(x) \), as discussed above. In addition, there may be some finite fraction of the total current flowing in the silver sheath and a slight offset in the absolute positions measured at room temperature and at 77 K due to thermal contraction. Consequently, the sharp decrease in \( j_x(x) \) in Fig. 8 close to the filament edges at \( x \approx 3.2 \) mm and \( x \approx 5.6 \) mm, respectively, is

![Fig. 7. Differential sheet current density distribution \( \Delta J_x(x) \) for the 19-filament (Bi,Pb)-2223/Ag tape derived from the data in Fig. 6(b), plotted for increasing transport current \( I \). See text for the definition of \( \Delta J_x(x) \).](image-url)
Fig. 8. Distribution of the critical current density $j_c(x)$ (solid line, right axis) for the monofilamentary (Bi,Pb)-2223/Ag tape determined from the $J_x(x)$ data at $I = I^*$ (points, left axis) and from the distribution of superconductivity material $f(x)$ in Fig. 1(b).

likely to be an artefact of the division used to scale the sheet current density $J_x(x)$ by the effective cross-section per unit length $f(x)d$.

5. Summary

We have investigated the sheet current density distributions $J_x(x)$ across (Bi,Pb)-2223/Ag composite tape conductors using scanning Hall probe magnetometry. From the $J_x(x)$ data at temperatures well above $T_c$, the distribution of superconducting material across the width of the conductor, averaged over its thickness, can be obtained, thus enabling non-invasive characterization and monitoring of the conductor geometry.

We observe dramatic changes in the evolution of $J_x(x)$ with increasing transport current $I$, defining a characteristic current $I^*$ which heralds the onset of homogeneous distribution of current throughout the superconducting filament and thus corresponds to the critical current associated with the critical state. The value of $I^*$ is found to be smaller than that of the transport critical current $I_{d}$ determined from simultaneous measurements of the $I-V$ characteristics across the scanned section of the conductor. The clear correlation of $I^*$ with characteristic changes in the current flow makes it a natural choice for the definition of the intrinsic critical current, unlike $I_{d}$, which depends on the particular choice of the electric field criterion.

When combined with information about the distribution of superconducting material inside the conductor, the $J_x(x)$ data allows the determination of the distribution of critical current densities across the width of the tape, averaged over its thickness.

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