Critical current in nonhomogeneous YBCO coated conductors

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Abstract. The critical current of an YBCO tape is determined by the magnetic field inside
the YBCO layer and the quality of YBCO material. In thick YBCO layers the average critical
current density is reduced by the self-field and decreased material quality. In this paper the
combined influence of the material nonhomogeneities and self-field on the critical current of
YBCO tapes is scrutinised. First, the zero field critical current density was assumed to decrease
along the YBCO thickness. Secondly, the possible defects created in the cutting of YBCO tapes
were modelled as a function of lowered critical current density near the tape edges. In both
cases the critical current was computed numerically with integral element method. The results
suggest that the variation of zero field critical current density, \( J_{c0} \), along the tape thickness does
not effect on the critical current if the mean value of \( J_{c0} \) is kept constant. However, if \( J_{c0} \) is
varied along the tape width the critical current can change due to the variated self-field. The
computations can be used to determine when it is possible to evaluate the average zero field
critical current density from a voltage-current measurement with an appropriate accuracy.

1. Introduction
Superconducting YBCO tapes are expected to have a large impact on electrical engineering.
Especially power grid components like power cables, fault current limiters, synchronous
condensers, transformers, generators and motors have been widely studied [1]. During the
past ten years the tape development has also been fast leading to high critical current values.
However, numerical electromagnetic modelling can provide a way to further understand tape
behaviour and thereby lead tape manufacturers towards even higher critical currents in the
future.

In this paper the current density and the magnetic fields inside the nonhomogeneous YBCO
layer were simulated numerically with integral element based method [2]. This custom made
algorithm is exploited here because the critical current density of YBCO depends strongly on the
magnetic field and its orientation. The special attention is paid into a nonhomogeneities created
during the manufacturing of YBCO tapes. The quality of YBCO is better next to the substrate
than on the surface because the quality of the texture weakens as the YBCO layer grows and
the quality reduces along tape thickness direction for example due to the microcracking [3]. On
the other hand, the cutting of the tapes to their final width causes defects to the tape edges [4].
Here these nonhomogeneities were modelled as a varying intrinsic critical current density on the
YBCO cross-section. The algorithm presented here can also be used to model other possible defects such as scratches on YBCO[5, 6].

2. Numerical model
In the numerical model the self-field critical current, \( I_c \), was computed from the intrinsic material properties of YBCO. The cross-section of YBCO was divided into rectangular elements as shown in figure 1 a) and then \( J_c(x, y) \) was solved with integral element method described in detail in the reference [2]. The magnetic field dependence of the YBCO was described with Kim model [7] which was extended to take into account the material anisotropy as

\[
J_c(x, y) = J_{c0}(x, y) \cdot \left( 1 + \frac{\epsilon B}{B_0} \right)^{-\alpha},
\]

where

\[
\epsilon = \sqrt{\cos^2(\theta) + \gamma^{-2} \sin^2(\theta)}.
\]

\( B \) is the norm of the magnetic flux density, \( \theta \) is the angle between the field and the y-axis, \( \alpha = 0.65 \) the Kim model exponent, \( B_0 = 0.20 \) the reference field and \( \gamma = 5 \) the anisotropic scaling factor [2]. The intrinsic critical current density, \( J_{c0}(x, y) \), was varied spatially in order to study the effect of the nonhomogeneity of YBCO on \( I_c \).

Finally, \( I_c \) was obtained as

\[
I_c = \int_S J_c(x, y) \, ds
\]

where \( S \) is the cross-section of the tape.

3. Results and discussion
The computations were performed for a standard 4 mm \( \times \) 1.5 \( \mu \)m tape. Although the tape with fixed cross-section dimensions is studied the critical current per unit width \( I_{c/w} \) is presented here. \( I_c \) depends linearly on the tape width \( w \) if the aspect ratio is over 1:100 and therefore the presented results can be generalised to describe YBCO tapes independent of \( w \) [2]. As a default the mean value of intrinsic critical current density, \( J_{c0\text{mean}} \), was equal to 2 MAcm\(^{-2} \) and thus the theoretical critical current without the self-field \( I_{c0/w} \) was equal to 300 Acm\(^{-1} \). In a homogeneous tape this corresponded to \( I_{c/w} = 244 \text{ Acm}^{-1} \) which is a normal value for a modern YBCO tape [8].

First, the effect of the \( J_{c0}(y) \)-dependence was studied. Figure 1 presents a simple special case in which \( J_{c0}(y) \) was a polynomial of first degree such that \( J_{c0}(x, y) \) equals 3 MAcm\(^{-2} \) in the proximity of the substrate and degrades linearly with the increasing \( y \) to 1 MAcm\(^{-2} \) at the surface. Also the consequent \( J_c(x, y) \) and the self-field are shown in figure 1. This type of nonhomogeneity did not effect on the computed \( I_{c/w} \).

In fact, the results suggested that if \( J_{c0\text{mean}} \), was equal to 2 MAcm\(^{-2} \) any \( J_{c0}(y) \geq 0 \) lead to the approximately same result, \( I_{c/w} \approx 244 \text{ A} \). Naturally, it was not possible to study every possible \( J_{c0}(y) \)-distribution here and therefore the result was checked statistically. \( I_{c/w} \) was computed 1000 times with different \( J_{c0}(y) \)-dependencies which were determined such that \( J_{c0} \) at the nodes were arbitrarily chosen between 0 and 4 MAcm\(^{-2} \). After that the \( J_{c0} \)-values were multiplied by a constant which resulted in the mean value 2 MAcm\(^{-2} \). The difference between the maximum and minimum value of \( I_{c/w} \) was only 18 mAcm\(^{-1} \). This can be partially explained by the high aspect ratio which implies that the magnetic flux density components in perpendicular with the tape broad face are almost independent of the \( J_{c}(y) \)-profiles. Also high \( \gamma \)-value reduces the importance of the tape parallel component of magnetic field. In fact \( I_{c/w} \)
converges only to 245 Acm$^{-1}$ when $\gamma \to \infty$ which means that $B_x$ is negligible. However, the $J_c(x, y)$-distributions can be substantially different and depend only on $x$.

The previous result suggests that $I_{c/w}$ is independent of the $y$-directed nonhomogeneity and can be computed directly from $I_{c0/w}$ as summarised in figure 2. In fact, there is no difference if the high $I_{c/w}$ value is caused by a thick layer or a high quality YBCO as long as the aspect is high enough. In figure 2 $I_{c/w}$ was also computed with several $\gamma$-values.

The nonhomogeneity along the $x$-direction had a considerable influence on $I_{c/w}$ which was studied with

$$J_{c0}(x, y) = J_{c0\text{mean}} \cdot \left[1 - a + 4aw^{-1}|x|\right],$$

(4)

where constant $a \in [-1, 1]$ defines the nonohomogeneity. $a < 0$ corresponded to a tape where the good quality conductor is concentrated in the middle. $a = 0$ corresponded to the homogeneous YBCO and $a > 0$ to a tape where the best material is located on the edges. The $J_c(x, y)$-distributions shown in figure 3 were computed with $a = -0.5$ and $a = 0.5$ leading to the critical current values 234 Acm$^{-1}$ and 249 Acm$^{-1}$ respectively. The latter is even better than in the homogeneous YBCO layer.

Finally, $I_{c/w}$ was computed as a function of $a$ with various $J_{c0\text{mean}}$ between 1 and 5 MAm$^{-2}$. The resulting normalised critical currents $I_{c/w}/I_{c0/w}$ are shown in figure 4. The maximum critical currents were obtained when $a$ was between 0.39 and 0.47. With the studied values of $J_{c0\text{mean}}$ the benefit compared to the homogeneous YBCO was 1.3 to 4.2 %. This situation is however hard to achieve in tape manufacturing but for example when several tapes are placed next to each other the weakest tapes should be placed in the middle in order to achieve the optimal critical current. On the other hand at $a = -1$ the critical current reaches its minimum which was 5.7 to 11.3 % lower value that could be reached with the homogeneous tape.

4. Conclusions

A numerical algorithm was applied in order to compute self-field critical currents of nonhomogeneous YBCO tapes. The nonhomogeneity was taken into account as a varying intrinsic critical current density along the tape cross-section. The nonhomogeneity along the tape thickness did not effect on the critical current due to the high aspect ratio of the YBCO layer. In that case the self-field critical current was determined only by the zero field critical current.

However, the nonhomogeneity along the tape width had a substantial effect on the self-field critical current. Generally, the self-field critical current weakens if most of the YBCO is distributed in the tape centre but the tape performance can be even improved by concentrating most of the YBCO near to the tape edges. Although, too high concentration on the edges will cancel the improvement. For example, the computations showed that the homogeneous tape with 450 Acm$^{-1}$ zero field critical current density had self-field critical current of 340 Acm$^{-1}$ but depending on the studied nonhomogeneity the tape self-field critical current varied between 307 and 351 Acm$^{-1}$. In addition, these self-field effects have an increasingly important role when the tape performances rises.

These results presented in this paper can be used in the tape design and can also be applied to a case where several tapes placed by each other. Then the weakest tapes should be placed in the middle of the tape array.

References

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Figure 1. a) YBCO cross-section is discretised into 512 rectangular elements in which critical current density is computed. b) Zero field critical current density distribution of nonhomogeneous YBCO. c) Computed critical current distribution when self-field is taken into account according to Kim model [7]. d) Self-field. Color scales in b) and c) are the same.

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Figure 2. Critical current per tape width as a function of theoretical value computed from intrinsic current density. Computations were repeated for various anisotropic scaling factors.

Figure 3. Self-field critical current distributions with a) $a = -0.5$ and b) $a = 0.5$. The latter case leads to even better critical current than with homogeneous YBCO ($a = 0$). Thick lines represent $J_c(x)$. 
Figure 4. Normalised critical currents $I_{c/w}/I_{c0/w}$ computed with nonhomogeneous YBCO layer. $a = -1$ corresponds to tape where YBCO is concentrated in middle and there is no superconductivity on tape edges. $a = 1$ means opposite situation and $a = 0$ corresponds to homogeneous YBCO layer. Curves from top to bottom correspond to $J_{c0\text{mean}} = 1$, 2, 3, 4 and 5 MAcm$^{-2}$. Maximum values of each curve are shown with (o).