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Magnetisation loss in stacks of high-T_c superconducting tapes in a perpendicular magnetic field

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Abstract

Magnetisation loss is an important factor in the design of superconducting transformers and motors. In these devices the tapes are usually placed face-to-face. Then the magnetisation loss is influenced by the mutual magnetic shielding between adjacent tapes. The shielding is investigated by measuring the magnetisation loss in stacks with various numbers of Bi-2223 tapes, exposed to a 48-Hz perpendicular magnetic field at 77 K. In a stack the penetration field is increased and the magnetisation loss below penetration is greatly decreased, compared to the behaviour of a single tape. The loss at high magnetic-field amplitudes is unaffected. The measured loss is compared to the loss calculated with two different models. The effect of shielding is qualitatively well described with an analytical model. However, predictions made with a numerical model display a better quantitative agreement with the measurement results. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Bi-2223 tapes are used for the construction of prototype high-T_c superconducting transformers [1,2] and motors [3]. A critical issue in the design of these devices is the AC loss, which consists of magnetisation and transport-current losses. Both loss components are typically measured in single tapes placed in free space. In transformer and motor windings the tapes are usually stacked face-to-face. This type of stacking increases the transport-current loss and decreases the magnetisation loss in a magnetic field oriented perpendicular to the tape plane [4]. The decrease in magnetisation loss is due to the mutual shielding between the tapes in the stack. Each tape in the stack is shielded from the external magnetic field by the screening currents in adjacent tapes. The shielding effect increases with the number of tapes in the stack and decreases with increasing distance between the tapes. The magnetisation and transport-current losses are calculated for stacks with an infinite number of tapes separated by an arbitrary

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distance [4]. When many tapes are stacked close together, the stack can be described as an infinite slab with the Bean critical-state model [5]. These descriptions are invalid if the stack comprises less than 20 tapes [6]. This paper presents the magnetisation loss measured in stacks comprising relatively few tapes that are close together. The stacks are exposed to a perpendicular magnetic field and the tapes carry no transport current. The results are compared to predictions of the magnetisation loss, made with analytical and numerical models of the stack.

2. Measured magnetisation loss

The measurements are made on a Bi-2223 tape with a critical current of 35 A and a cross-section of 3.6×0.25 mm^2. The filamentary region has a cross-section of 3.2×0.18 mm^2 and contains 55 non-twisted filaments embedded in a AgPd matrix [7]. Samples 95 mm long are cut from the tape and are stacked directly on top of each other. The stacks are cooled to 77 K and exposed to a 48 Hz perpendicular magnetic field. The magnetisation loss is calculated from the changes in magnetic moment, which are detected by a pickup coil around the stack [8]. The pickup coil extends above and below the stack, in order to detect its entire magnetic moment. The loss Q is expressed in Joule per magnetic-field cycle, per m^3 of sample volume. The loss is normalised with the square of the magnetic-field amplitude B_a. The result is the commonly used dimensionless loss function Γ defined as $\mu_0 Q/2B_a^2$. This loss function is displayed by symbols in Fig. 1 as a function of the magnetic-field amplitude. Different types of symbols correspond to stacks with different numbers of tapes.

In this double-logarithmic plot, the loss functions have a slope of about 0.5 at low magnetic-field amplitudes B_a. They have a slope of -1 at high B_a. Then the loss per cycle Q is proportional to B_a in agreement with the Bean critical-state model. The loss functions have a maximum at approximately the penetration field B_p of the stack. The penetration field increases with the number of tapes in the stack. The maximum value of the loss function decreases with increasing number of tapes. At high B_a the stacking has no significant influence on the magnetisation loss. The mutual shielding between the tapes is insignificant at high B_a because the magnetic field of the screening currents is much weaker than the external magnetic field. At low B_a the shielding effect is significant and causes a decrease in the magnetisation loss. At a fixed magnetic-field amplitude, the loss is approximately proportional to $1/n_t$ where n_t is the number of tapes in the stack. It would be useful to predict this loss with a theoretical model.

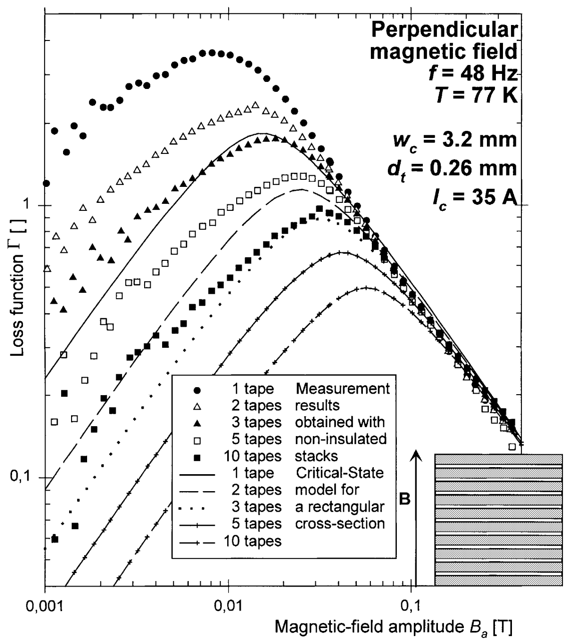

Fig. 1. Magnetisation-loss function measured in stacks of tapes exposed to a perpendicular magnetic field. Each series of symbols represent a stack with a different number of tapes. For increasing number of tapes, the penetration field of the stack increases and the loss at low magnetic-field amplitudes decreases. The loss at full penetration is independent of the number of tapes. The lines are loss functions calculated with the analytical model for a rectangular superconductor, given by Eqs. (1)–(5). The parameters used are indicated in the figure. The shift of the penetration field is described and the model results are correct above penetration. However, the calculated loss is clearly too small at low field amplitudes.

3. Analytical model based on rectangular cross-section

Imagine a stack of tapes with non-twisted filaments, oriented perpendicularly to the magnetic field. Under certain conditions of symmetry the screening and coupling currents flow in a plane perpendicular to the field [9]. Then any normal-conducting or insulating layers between the tapes have no influence on the current pattern. The only effect of these layers is a decrease in the critical-current density $J_{c,stack}$ averaged over the stack. The current pattern in the stack is then similar to the current pattern in a single superconductor with a rectangular cross-section and a critical-current density $J_{c,stack}$. The same is true for the magnetic moment and for the magnetisation loss.

A superconductor with a general rectangular cross-section is treated by Hartmann [10]. According to his Eq. (2.72) the magnetisation loss in Joule per m^3 per cycle is

$$Q = B_p M_p q(b), \tag{1}$$

where B_p is the penetration field and M_p is the magnetisation of the conductor at an external magnetic field equal to B_p. The normalised field $b = B_a/B_p$, where B_a is the external-field amplitude. The dimensionless normalised loss $q(b)$ is the same for any cross-section shape. For a circular cross-section, $q(b)$ is given by Hartmann in Eqs. (2.63) and (2.64). These equations are approximated in this paper by

$$\begin{aligned} q(b) &= \tfrac{4}{3}b^3(2-b) \quad \text{for } b<1, \\ q(b) &= \tfrac{4}{3}(2b-1) \quad \text{for } b>1. \end{aligned} \tag{2}$$

A superconductor is assumed to have a rectangular cross-section with dimensions $d\xi$ parallel to the magnetic field and d/ξ perpendicular to the field. Then the cross-section area is d^2 and the aspect ratio is ξ^2. The penetration field is given by Eq. (2.75) in Ref. [10]:

$$B_p = \frac{\mu_0 J_c d}{2\pi}\left[\xi \ln\left(\frac{\xi^4+1}{\xi^4}\right) + \frac{2}{\xi}\arctan \xi^2\right]. \tag{3}$$

The magnetisation at the penetration field is given by Eq. (2.76):

$$M_p = \frac{J_c d}{4\xi}. \tag{4}$$

The loss in an arbitrary cross-section shape can be calculated from the loss in a circular cross-section, using shape factors calculated from the B_p and M_p of both cross-sections [9].

Two points are not clear in Ref. [10]:

(1) According to Eq. (2.56) the loss Q in a circular cross-section is given by $q(b)B_p^2/\mu_0$ which does not agree with Eq. (2.72) in the same publication. In this paper the problem is avoided by directly using Eq. (1) for the loss in a rectangular cross-section.

(2) It is not made clear whether b is defined with the penetration field of a rectangular cross-section, or with that of an equivalent circular cross-section. In the calculations below, the difference between both penetration fields is always smaller than 10%. Slightly better results are obtained by using the penetration field of the rectangular cross-section. This definition is also more logical and agrees with Eq. (2.73) in Ref. [10] although it does not strictly agree with Eq. (2.56).

Model results calculated with Eqs. (1)–(4) are compared with the measured loss displayed in Fig. 1. The effective critical-current density $J_c = J_{c,stack}$ is given by $I_c/d_t w_c$. Here w_c is the width of the filamentary region and d_t is the tape thickness plus a stack spacing. In this case the spacing is small because there is no insulating material between the tapes. The values of d and ξ are obtained from $d/\xi = w_c$ and $d\xi = n_t d_t$. Here n_t is the known number of tapes in the stack. Then the model has three parameters: I_c, w_c and d_t. Eq. (4) becomes $M_p = I_c/4d_t$ and Eq. (3) becomes

$$B_p = \frac{\mu_0 I_c}{2\pi}\left[\frac{n_t}{w_c}\ln\left(\frac{n_t^2 d_t^2 + w_c^2}{n_t^2 d_t^2}\right) + \frac{2}{d_t}\arctan\frac{n_t d_t}{w_c}\right]. \tag{5}$$

For $n_t \to \infty$ the penetration field B_p converges to $\mu_0 J_c w_c/2$, which is equal to the penetration field in the critical-state model for an infinite slab with thickness w_c.

The lines in Fig. 1 represent model results calculated with the known values for I_c, w_c and d_t. The parameter values are indicated in the figure.

The constant loss at high field amplitudes is predicted well by the model. The model also describes qualitatively the observed increase in B_p and the decrease in the maximum value of the loss function. However, quantitatively the model predictions are wrong by at least a factor 2 at low magnetic-field amplitudes. Better agreement is obtained by using w_c as a fit parameter. With the value $w_c = 10.5$ mm, the penetration field and the loss-function maximum are rather well described. However, at low field amplitudes the predicted slope remains 1 while the measured slope is about 0.5. Furthermore a tape width of 10.5 mm is clearly too high. A fit procedure with all three parameters does not lead to better agreement or more realistic values for the tape width.

It is concluded that the analytical model given in Eqs. (1)–(4) is a good qualitative description of the magnetisation loss in a stack of tapes. However, it cannot be used to make reliable quantitative predictions. Possibly the expressions in Ref. [10] have been checked only for aspect ratios close to 1. The deviations may be due also to the assumption of a fixed screening-current density (independent of B or dB/dt) which forms the basis of the critical-state model. The critical-current density is decreased especially by perpendicular magnetic fields. Significant flux creep is expected to make the screening currents dependent on dB/dt.

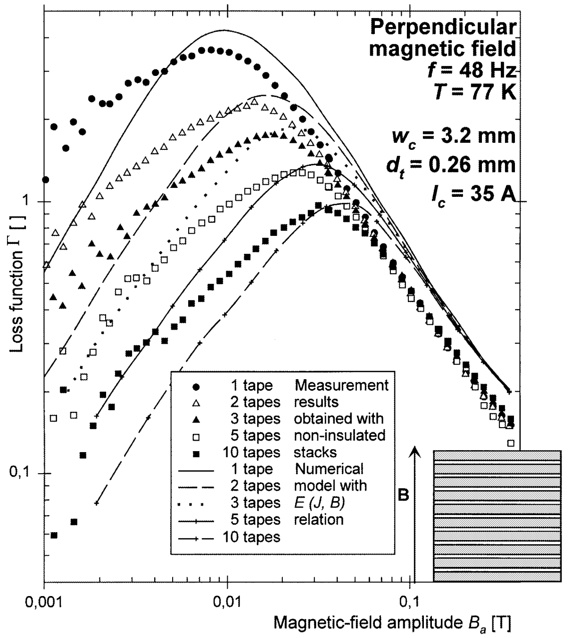

Fig. 2. Magnetisation-loss function measured in stacks of tapes exposed to a perpendicular magnetic field. The measured data are the same as in Fig. 1. The lines are calculated using a numerical model based on a general $E(J,B)$ relation. At high magnetic-field amplitudes the predicted loss functions are to the right of the measured ones. The current density assumed in the model is too high. At low amplitudes the predicted slope of the loss function is again too high. However, the shift of the penetration field with increasing number of tapes is well described. Furthermore the quantitative agreement is better than in Fig. 1, where the analytical model is evaluated with the same parameters.

4. Numerical model with $E(J,B)$ dependence

The magnetisation loss is calculated with a numerical model [11]. The current density J is related to the electric field E via the power law relation: $E = E_0(J/J_c)^n$. Here E_0 is the electric-field value used to define the critical current: usually $E_0 = 10^{-4}$ V/m. The critical-current density J_c and the exponent n both depend on the local magnetic field. The model is a two-dimensional description of the superconductor cross-section. The stack of tapes is modelled as an homogeneous superconductor with a total thickness $n_t d_t$ and width w_c, similarly to the analytical model discussed in the previous section. The model is evaluated using the actual tape parameters. In Fig. 2 the results are compared to the magnetisation loss measured in the stacks. This figure should be compared to Fig. 1 where the same set of parameters was used as input for the analytical model. The predictions of the numerical model are clearly better.

At high magnetic-field amplitudes the loss predictions of the numerical model are about 35% too high. The predicted penetration fields are too high by the same factor. The calculated loss functions are all shifted to the right compared to the measured ones, indicating that the model uses a 35% too high current density at high field amplitudes. Probably in this tape the dependence of J_c on the magnetic field is stronger than assumed in the model. The increase of the penetration field with the number of tapes is predicted better than with the analytical model. At low magnetic-field amplitudes, both models predict a slope of 1 for the loss function. For unknown reasons the measured loss has a smaller slope. Therefore the loss predicted with the numerical model is generally too small at low field amplitudes. However, the error is much smaller than with the analytical model.

5. Conclusions

The magnetisation loss in stacks of Bi-2223 tapes is measured at 77 K in a 48-Hz perpendicular magnetic field. The penetration field increases with the number of tapes in the stack. At low magnetic-field amplitudes the magnetisation loss decreases greatly with increasing number of tapes. The loss decrease is due to mutual shielding of adjacent tapes in the stack. The loss at full penetration is not affected. The effect of shielding is qualitatively described with an analytical description based on the critical-state model. However, this description does not lead to reliable quantitative predictions. Better agreement is obtained using a numerical model, based on a general $E(J,B)$ relation. This model makes errors smaller than 50% at high and moderate magnetic-field amplitudes. At low amplitudes, both models predict a slope of 1 for the loss function. The observed slope of 0.5 is therefore still unexplained.

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