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AC magnetization loss in striated YBCO conductors

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Abstract. Magnetization AC losses in striated YBCO conductors in a perpendicular applied AC magnetic field were investigated with special regard to the coupling current AC loss (CCAC). The AC loss of YBCO samples of different length L was measured by using rectangular-shaped pick-up coils being slightly shorter than the samples. The AC loss distribution along the length of the tapes was investigated by using short pick-up coils. It was found that CCAC loss per unit length does not depend on the position of the pick-up coil (with respect to the sample centre) and its length. The CCAC loss per unit length scales with the square of the sample length L^2 up to the maximal value of longitudinal coupling current of about $0.1 \cdot I_c$ (I_c - critical current).

1. Introduction

The progress in development of YBCO coated conductors opens wide perspectives for practical DC and AC applications of superconductivity. Unfortunately, the high aspect ratio of YBCO tapes leads to high hysteresis AC loss in perpendicular magnetic fields. The striation of YBCO tapes is one of the possibilities to decrease the AC losses [1]. Hysteresis AC loss in striated conductors decreases with the number of filaments but additional coupling current AC loss (CCAC) appears [2] due to finite resistivity between the filaments.

The CCAC loss is well known for multifilament low-T_c superconductors (SC) and BSCCO tapes [3, 4] and can be reduced by twisting of the superconducting filaments. In untwisted flat superconducting cables the CCAC loss (Q_c) for a sinusoidal external field was calculated using Campbell's model [4]:

$$\frac{Q_c}{V} = \gamma \frac{B_a^2}{\mu_0} \frac{\chi_0 \pi \omega \tau}{1+\omega^2 \tau^2}\,;\; \tau = \frac{\mu_0}{\chi_0 \rho_{tr}} \left(\frac{L}{\pi}\right)^2; \quad \chi_0 \approx \frac{\pi \cdot W_s}{4 d_s} \tag{1}$$

where B_a is the magnetic field amplitude, χ_0 depends on the geometry of the SC, Ws and d_s are width and thickness of the superconducting region, respectively, $\omega = 2\pi f$ with f as the AC field frequency; τ the time constant of magnetic flux diffusion, L the length of tape, ρ_{tr} the effective transverse matrix resistivity and γ = 3.3 as an empirical factor. The precise computation of the coupling loss from this expression is a complicated task because τ depends on ρ_{tr} which is difficult to measure correctly.

For striated YBCO conductors another model has been developed [2]:

$$\frac{Q}{L} = (n+1)t^2 d \cdot J_c B_a + \frac{\pi^2}{6}\frac{Wd(LB_a)^2 f}{\rho_{tr}} \tag{2a}$$

where the first term represents hysteresis AC loss (Q_h) and the second one CCAC loss. The resistivity ρ_{tr} was calculated using the anisotropic continuum model [2]:

$$\rho_{tr} = nR_g \frac{Ld}{W} \tag{2b}$$

Here, W and t are the width of tape and filament, respectively, d is the thickness of the SC, n the number of striations, R_g and ρ_{tr} are the effective transverse resistance and resistivity, respectively and j_c the critical current density. It should be noticed that expression (1) reduces to expression (2a second term) for $(\omega\tau)^2 << 1$. The remaining difference is only numerical coefficients 2γ in (1) and $\pi^2/6$ in (2). Estimating τ for our 85 mm long sample, we obtained $\tau \sim 10^{-4}$ (for calculating resistivity ρ_{tr} we used expression (2b) and for a minimal value of $R_gL \approx 4\mu\Omega\cdot$m [2]). Indeed, the condition $(\omega\tau)^2 << 1$ is always fulfilled for our experiments. Model (1) was developed for low fields below full penetration field $B_a < B_p$. In contrast, model (2) is valid for higher fields $B_a > B_p$.

$$B_p \approx \mu_0 j_c(0)\frac{d}{\pi}\left(\ln\left(\frac{t}{d}\right)+1\right) \tag{3}$$

Both models yield for $(\omega\tau)^2 << 1$ a quadratic dependence of the coupling loss per unit length on the sample length, i.e. $Q_c/L \sim L^2$. Both models also predict that the transverse electric field and the transverse coupling current density should increase linearly from zero at the sample center to their maximum values at the edges. Therefore, the CCAC loss should be increase from zero at the sample center to its maximum value on the edges of the striated sample. It should be noted that in twisted wires theory predicts [3] that electrical field and coupling currents do not change along the sample length and the CCAC loss remains constant along the sample length. In the present paper, the distribution of the CCAC loss along the length of striated (untwisted) YBCO conductors and the dependence of the CCAC loss on the sample length were investigated.

2. Experimental equipment

Magnetization AC losses in two striated YBCO tapes were investigated at 77K for AC fields up to 0.2 T and for frequencies from 50 up to 200 Hz. A sinusoidal AC magnetic field which is generated by a copper magnet was applied perpendicular to the sample plane. The radial homogeneity of the magnetic field in the centre of the magnet is about 2%. The loss components of the voltage signal induced in the pick-up coil was measured by means of a lock-in amplifier [5]. We used rectangular flat pick-up coils with 10 turns of length L_{coil} being in the range between 2 and 5 cm. The coils were three times wider than the sample. The out-of-phase signal is compensated by a rotatable compensation coil. The in-phase signal from the pick-up coil was used for the calculation of the AC loss in J per cycle:

$$\frac{Q}{L} = \frac{C\cdot\pi}{2}\cdot\frac{W_c \cdot V_{rms}\cdot B_{rms}}{\mu_0 \cdot k \cdot L_c f} \tag{4}$$

Here, V_{rms} is the loss voltage (in-phase with the AC field) in V; B_{rms} is the effective value of the applied AC field in T; W_{c} and L_{c} are the width and length of the pick-up coil (both in m), respectively; f is the frequency of the AC field in Hz; k is the number of turns of the pick-up coil; $\mu_o = 4\pi\cdot 10^{-7}$ H/m is the free-space permeability and $C \sim 1$ is a calibration constant.

Each pick-up coil has been calibrated using a standard copper tape. In this way, the relative measurement error was less than 10% for coils longer than 3cm. For the shortest coils we used 20 turns (instead of 10 turns) in order to increase the sensitivity of the measurement. Nevertheless, the relative error of the measurement of about 15% was achieved.

The superconducting YBCO tapes provided by SuperPower are 4mm wide. The striated tapes consist of 5 filaments and have critical currents of I_c = 50A (sample A) and 58A (sample B) in self-field at T = 77K. As reference sample we used an unstriated tape (I_c = 65A). The measurements were performed for several sample lengths in the range between 3 and 8 cm. Additionally, the transverse resistivity (TR) between the filaments was measured using the standard four-contact method.

3. Results and discussion

We mainly focused on AC fields amplitudes B_a above the full penetration field B_p, because from the practical point of view these fields are more interesting for applications. The expression for the hysteresis loss (Q_h) in (2a) is valid for $B_a > B_p$. It is convenient to normalize the total AC loss (Q) in (2a) by B_a [1]. Then, Q/B_a consists of two terms, the first one Q_h is practically constant [6] and the second one is the coupling AC loss which depends linearly on field and frequency [7].

In figure 1, the field dependence of the total AC loss of sample B is shown for different frequencies. In contrast to the unstriated reference sample (inset figure 1), the AC loss of the striated sample strongly increase with the frequency. The linear frequency dependence and the absence of eddy current losses allows us to conclude that the discrepancy between striated and unstriated sample is due to CCAC loss. Notable is that the total AC loss of sample B at $B_a > B_p$ and at low frequencies is about five times less compared with the reference sample which well agrees with model (2a).

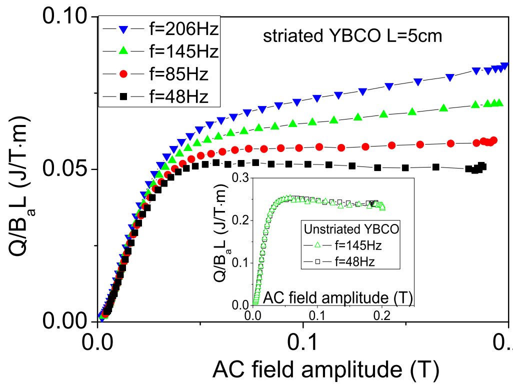

Figure 1. AC loss in striated and unstriated (inset) YBCO tapes in dependence of applied AC magnetic field.

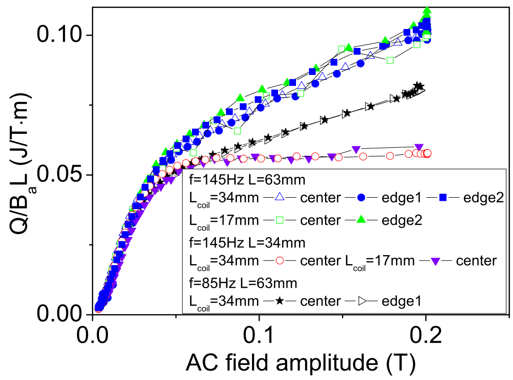

Figure 2. AC loss in striated YBCO tape measured in the sample's centre and edges. Lower curves – data after cutting the sample.

The advantage of using our technique is that we can measure AC loss along the sample length by pick-up coils shorter than the sample length. In figure 2, field dependence of the total AC loss of sample B for its initial length of 63 mm is shown for different frequencies. At first, the AC loss was measured using a pick-up coil with a length of L_p = 34 mm located at the center of the sample and at both edges of the sample. The losses measured for the sample center and for one sample edge coincided, whereas the loss obtained for the other sample edge was slightly higher. However, this small discrepancy is most probable due to some non-uniformity of the sample. Then, the AC loss of this sample was measured using a short pick-up coil (L_p = 17mm). Again, the AC losses in the center and at the edges were found to coincide within the error of the measurement. Finally, the edges of the sample were cut and the AC loss of a 34 mm long central part of the sample was measured using pick-up coils of different length (L_p=17mm and L_p=34mm). In this case, the CCAC loss decreased about four times which is expected from the relation $Q_c/L \sim L^2$. Again, the same AC loss data were obtained by using the two different long coils. Similar measurements were repeated on several samples which allow us to conclude that in such kind of striated samples, the CCAC loss is nearly constant along the sample length. This means that the transverse electrical field (E_{tr}) and transverse coupling current density (J_{tr}) most probably are constant along the sample length. In order to fulfill the requirements of a zero net-current, an electrical field E_{tr} can be assumed as step function, negative from the one side and positive from the other side of the sample figure 3. Using that we obtained expressions for electrical field E_{tr} and coupling currents J_{tr}:

$$E_{tr} = -\frac{1}{2} L \dot{B}_a \operatorname{sgn}(x) \text{ and } J_{tr} = -\frac{L \dot{B}_a}{2\rho_{tr}} \operatorname{sgn}(x) \tag{5}$$

Now we can compute the transverse coupling current loss integrating over the volume where J_{tr} flows and time averaging gives:

$$Q_c = \frac{\pi^2}{2} \frac{LWd(LB_a)^2 f}{\rho_{tr}} \tag{6a}$$

In the same way like in [2] we suppose that effective thickness where the CCAC loss occurs is about thickness of the superconducting layer d. It is important to admit that choice of d not influence on the final result if we approximate ρ_{tr} by anisotropic continuum model (see expression (2b)) and finally within this model we get:

$$\frac{Q_c}{L} = \frac{\pi^2}{2} \frac{(WLB_a)^2 f}{nR_g L} \tag{6b}$$

The expression (6b) differ from (1) (at $(\omega\tau)^2$<<1) and (2a) only in a numerical factor, but the dependence from field, frequency and length is the same. It is interesting to admit that the prefactor in (6b) is $0.5\pi^2 \approx 4.9$ which is close to $2\gamma=6.6$ in model (1), whereas in model (2a second term) the prefactor is $\pi^2/6 \approx 1.6$.

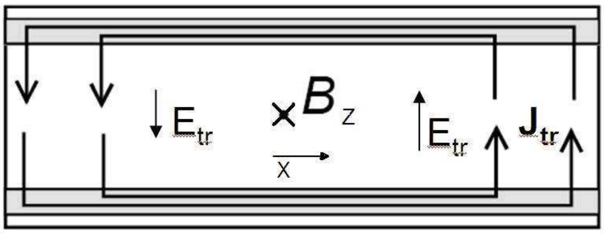

Figure 3 Schematic picture of the coupling current in striated BYCO (for simplicity only edges filaments are shown). Coordinate origin in the middle of the conductor.

Thus, there is evidence to suggest that the measured value of loss does not depend on the pick-up coil length and the position of the coil along the sample length. We also investigated the dependence of the CCAC loss on the sample length using our technique. In order to exclude the contribution of the hysteresis loss, it is convenient to normalize the total loss difference (measured at different frequencies, but the same AC field) by the square of the AC field and the difference of the frequencies. According to (6b) we obtain:

$$\Delta Q_c^{norm} = \frac{1}{LB_a^2}\left[\frac{Q(f_1, B_0) - Q(f_2, B_0)}{f_1 - f_2}\right] = \frac{\pi^2}{2} \frac{W^2}{nR_g L} L^2 \tag{7}$$

This quantity depends only on the sample length and the transverse resistivity between the filaments. So if (nR_gL) remains constant along the length of the sample, this quantity is expected to depend quadratically on the sample length L.

In figure 4, experimental ΔQ_c^{norm} data for sample B are plotted in dependence on the sample length for different values of Δf and fields. It is seen that at low field amplitudes, the experimental data well agree with expression (7) for all values of Δf. However, at higher fields the experimental data deviate from the theoretical curve for sample lengths larger than 50 mm. This deviation increases with increasing value of frequencies. We suppose that this is related to the CCAC loss saturation at high fields and frequencies. In order to define the empirical criteria for the applicability of expression (7), ΔQ_c^{norm} was plotted in dependence from the sample length at a certain value of Δf and for different AC field amplitudes (figure 5). It is seen that the CCAC loss is well described by the expression (7) below and above the full penetration field of $B_p \approx$ 50mT but deviates from theoretical curve at high fields. Using expression (5) we can calculate the maximal value of longitudinal coupling current ($I_{long.c.c}$) passing along the superconducting filaments in the center part of the sample. In the same way like in

[2] we multiplied J_{tr} in (5) by superconductor thickness d and half of length $L/2$. Let us assume that $I_{long.c.c}$ should be less than some portion of the critical current $m{\cdot}I_c$:

$$\frac{\pi \cdot f \cdot B_a W L^2}{2nR_g L} \le m \cdot I_c \tag{8a}$$

Using equations (7) and (8a) we get for the minimal value of m_{min}:

$$m_{\min} = \frac{f \cdot B_a \cdot \Delta Q_c^{norm}}{\pi \cdot W \cdot I_c} \tag{8b}$$

Taking ΔQ_c^{norm} and the values of f and B_a at which the experimental data deviate from the theoretical curve figure 5 we found that m_{min} is about 0.1. Thus, according to our data up to a maximal longitudinal coupling current of $I_{long.c.c}$~ $0.1I_c$ the CCAC loss scales with L^2.

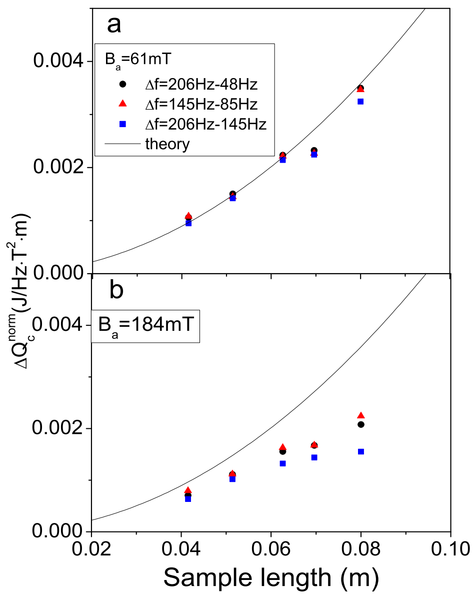

Figure 4. Normalised AC coupling loss (see text) in striated YBCO tape (sample B) vs. sample length for different frequency differences.

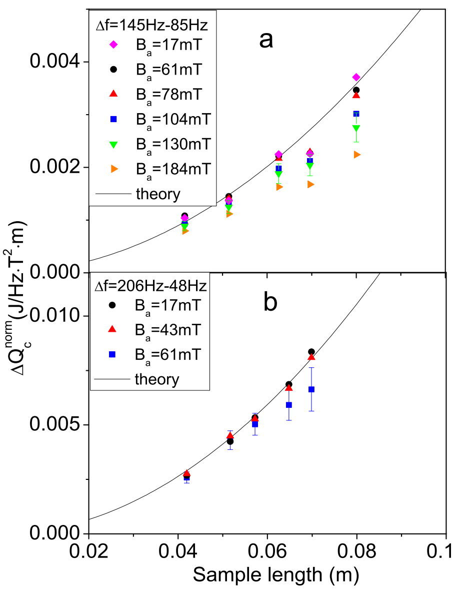

Figure 5. Normalised AC coupling loss (see text) in striated YBCO tape (sample B – a) (sample A – b) vs. sample length for different AC fields.

It is important to admit that the effective transverse resistivity R_gL obtained by fitting experimental data with expression (7), agrees with standard four–contact measurements within 50% of magnitude. These measurements were done on short pieces < 5 mm and it was found that the value of R_gL varies from piece to piece. It seems that such short samples are not sufficiently uniform in order to make more precise comparison between theory and experiment.

4. Conclusion

The coupling current AC loss (CCAC) in striated YBCO conductors was investigated. Experimentally it was found that the CCAC loss remains constant along the length of the SC. This result contradicts to existing analytical models for CCAC loss calculation. Therefore, a simple model was developed which is based on experimental results. This model yields the same total CCAC loss dependence on magnetic field, frequency and length of the sample as existing models, but assumes, in contrast to these models, a constant CCAC loss along the length of the striated conductor. Furthermore, the dependence of the CCAC loss from the total sample length was investigated. It was found that a quadratic dependence of the coupling loss per unit length on the sample length is valid both for AC fields below and above the full penetration field. This quadratic law remains valid up to a maximal longitudinal coupling current of about $0.1 \cdot I_c$. To check the numerical constants in the expression for the CCAC loss precise measurements of the transverse resistivity are required.

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[6] It is not exactly constant because J_c depends on B_a
[7] In our case the eddy current AC loss is at least two orders of magnitude lower than the other terms. It has been checked experimentally by removing the superconductor from the tape.