Simplified method to determine absolute ac-loss values of superconducting tapes for varying sample geometries

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Abstract. The measurement of energy dissipation in superconducting high T$_c$ tapes in an external ac-field is of major concern for their technical application at 50 Hz. The widely used technique is based on the measurement of the magnetization loop which is proportional to the dissipated energy. Since the proportionality constant depends on the geometry of the sample and of the pick-up coils used, calibration of the system is necessary. A convenient way is the calibration with a calorimetric measurement which however leads, at 77 K, to the problem of long thermal time constants. It requires furthermore a special preparation of the sample which must be thermally insulated from the cooling bath. This paper gives a simple relationship between the sample geometry and the calorimetric calibration factor, empirically deduced from measurements on tapes and stacks of tapes with rectangular cross sections. The accuracy of the method is within about $\pm 10\%$, which is sufficient for most technical applications.

1. Introduction
The measurement of ac-losses by the magnetization method requires calibration for obtaining absolute values. Calibration can be done in principle with a sample of known losses. The geometry and magnetization pattern of the test sample must however be the same as those of the sample to be measured. This condition cannot always easily be fulfilled. A convenient way of calibration is the calorimetric measurement. It has, compared to other calibration techniques, the advantage of a direct measurement of the power loss and calibration errors connected with the calculation of energy dissipation from a measured pick-up voltage are excluded.

While the boil-off technique is not useful for measuring small losses, an improved type of calorimetric measurement with increased sensitivity and reduced thermal time constants uses the slight temperature increase of a thermally insulated sample as a measure of losses [1]. The combination of a magnetization with a calorimetric calibration combines the advantage of both techniques.

The calorimetric calibration at 77 K is however, due to long thermal time constants, time consuming and less sensitive compared with the magnetization measurement. We therefore propose a simplified method to determine absolute ac-loss values of superconducting tapes for varying sample geometries without a calibration. Its accuracy is still sufficient for most technical applications.

2. Experimental methods of ac-loss measurements
Here we give a short overview about the most frequently used measuring techniques, the measurement of the sample magnetization during a field cycle, which needs, for a non slab geometry, a calibration and the calorimetric measurement, which gives directly the power loss.
The total sample magnetization is due to filament hysteresis, coupling currents between filaments and eddy currents in the normal conducting matrix. The energy losses per cycle are proportional to the enclosed area of the magnetization loop. The magnetisation measurement is standard and will not be discussed here.

Figure 1. Principle of the magnetization method and sample magnetization vs. external magnetic field.

2.2. Calorimetric method

Figure 2 shows the principle of the calorimetric method and demonstrates a complete measuring run including the calibration. The sample is connected via a thermal resistance to the liquid nitrogen bath. The ohmic heater which is in close contact with the sample is used for calibration. When the ac-field is switched on, the sample temperature rises above the nitrogen bath temperature following an exponential law in time and saturates at $\Delta T$. After switching off the ac-field, the temperature drops back to the bath temperature with a thermal time constant $\tau$. The same temperature increase is obtained by switching on an appropriately adjusted ohmic heater power. The ac-losses of the sample are therefore given by its power.

The time span and the temperature range shown in grey in the figure should be understood as typical examples. While the temperature increase is proportional to the ac-losses, the thermal time constant $\tau$ is a property of the measuring device. Here $\tau$ is about 50 s. A shorter thermal time constant would be advantageous, but is difficult to realize for a device at 77 K. This long time constant represents the greatest disadvantage of the calorimetric method. Waiting four time constants to reach thermal equilibrium, it takes at least a few minutes for one measuring point, if a calibration is not performed for each point. A complete measuring run with calibration as shown in figure 2 takes however about half an hour.

Figure 2. Principle of the calorimetric method, temperature trace and calibration heater power in a measurement run, $\tau$ is here the thermal time constant of the device.

2.3. Combination of magnetization and calorimetric method
Figure 3 shows a cross section of the measuring device and of the sample with a pick-up coil directly wound around it, with ideally no space in-between. The thermal insulation is achieved by a body of epoxy resin with a rectangular space for the sample which is, after sample mounting, filled with oil. For more details see [1].

3. The calibration factor

If the sample is an infinite slab with the magnetic field parallel to the infinite dimension, the energy loss per unit volume and per cycle in a harmonic ac-field \( B(t) = B_0 \sin \omega t \) is obtained by multiplying the measured compensated pick-up voltage signal \( \Delta U(t) \) with \( B(t) \), integrating over one cycle and dividing by the sample cross section \( d \tilde{L} \) and by the number of pick-up coil turns \( N \)

\[
Q_{slab} = \frac{1}{\mu_0 d \tilde{L} N} \int_0^{2\pi/\omega} B(t) \Delta U(t) \, dt .
\]  

(1)

The losses of a sample with a finite height \( h \) are, at the same measured \( \Delta U(t) \), by a factor of \( c \) higher, i.e. \( Q = c \cdot Q_{slab} \). This calibration factor depends on the geometry of the pick-up coil and on the sample dimension \( h \) in field direction. If the sample geometry deviates largely from the slab geometry like that shown in figure 3, the factor \( c \) can become rather large. As long as the condition \( d \ll L \) is fulfilled, the losses per unit volume are not expected to depend on the sample length \( L \).

4. Dependence of calibration factor on sample geometry

The measured signal \( \Delta U(t) \) is highest, if the pick-up coil is close to the sample and the dimensions of its cross section are small compared to the smallest sample dimension. We here consider only this case: the pick-up coil is directly wound around the sample, see figure 3. In this case the calibration factor \( c \) is expected to depend only on the sample aspect ratio \( r = d/h \). In the practical case there is however always a small space between sample and pick-up coil which leads to an inevitable error.

Figure 4 shows measured calibration factors (i.e. calorimetric losses divided by losses according to Eq. 1) for a large number of twisted and untwisted BSCO tapes and stacks of tapes, as well as for stacks of YBCO tapes in perpendicular field. The BSCO stacks were also measured in parallel field (the samples with \( r < 1 \)). The aspect ratio \( r \) is determined from the envelope of the superconductor areas, not from the sample dimensions including the matrix. For single BSCO tapes the largest dimensions of the filamentary area from the cross section micrographs are taken for calculation of \( r \).

For comparison we also measured copper strips of 10 mm width \( d \) and various thicknesses \( h \) at 77 K. They have the smallest \( c \)-values. For these samples the condition of no space between sample and pick-up coil is nearly ideally fulfilled.

Taking into account that \( c(0) = 1 \) (the value for an infinite slab), we can fit the results for the super-
conductor samples with $c(r) = 1 + 1.16 \, r$. The reason for higher $c$-values, compared to the Cu-samples, has to be found in the non-perfect geometry of the pick-up coil with respect to the sample width. For the BSCO samples and stacks the minimum distance between superconductor area and pick-up coil is given by the dimension of the silver matrix. For the YBCO stacks the mean width of the pick-up coil was about 1.5 mm larger than the tape width of 6 mm. This leads to a smaller ac-signal and hence to a larger $c$-value of the superconductor samples, compared to the ideal case.

For a single YBCO tape we measured $c = 57$ for the pick-up coil wound closely around the tape. It is clear that for a thin superconducting layer of 1.8 μm thickness the relation given above cannot be valid, because the dimension of the pick-up coil isn’t small compared to the sample dimension.

Finally it should be mentioned that several error sources play a role in the scattering of measured data: We have an absolute error in the calorimetric calibration measurement of about 5%. Determining the aspect ratio of a sample stack of thin tapes which are not exactly stacked leads to an additional error in $r$. For a single BSCO-tape the calculation of the aspect ratio from the cross section micrograph of its superconducting area is also connected with a considerable uncertainty.

5. Discussion

The proposed method allows a simple measurement of absolute ac-losses for samples of rectangular cross section in an external ac-field without calibration. Measuring condition is a pick-up coil of small cross section wound directly around the sample. The losses were calculated for an infinite slab, see, Eq. 1, and multiplied with a calibration factor $c$, empirically deduced to be $c = 1 + 1.16 \, r$, were $r$ is the aspect ratio of the sample, more precisely of the cross section envelope of superconducting areas of the sample. The accuracy of about ±10% is sufficient for most practical applications.

For a comparison of the results with theoretical models we use the shape factor $n = (1-D_{el})^{-1}$ introduced by Campbell [2] in order to account for a non-slab geometry. The demagnetization factor $D_{el}$ which is zero for an infinite slab, may be approximated by replacing the rectangular cross-section by an elliptical one with the principal axes $d$ and $h$. For such a case Osborn [3] gives $D_{el} = d/(d+h)$. Combining these equations and putting $r = d/h$ yields $n = 1 + r$. This function is also shown in figure 4. It is in between the data for copper samples and superconducting samples.

References

[1] C. Schmidt, Cryogenics 41 (2001) 393
[2] A.M. Campbell, Cryogenics 22 (1982) 3
[3] J.A. Osborn, Phys. Rev., 67 (1945) 351