AC Loss and Voltage Signal in a Pancake Coil Made of Coated Conductor with Ferromagnetic Substrate

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Abstract - **The voltage signal and the ac loss in a pancake coil made of a coated conductor tape with magnetic substrate is measured. The experimental data have been analysed with the help of numerical calculations. It is found that while for a single tape the ac loss is dominated by the substrate, for the coil it is dominated by the superconducting layer. Moreover, the substrate increases the ac loss generated in the superconducting material, making it similar to a slab. A compensation method for the voltage signal is also described, thanks to which the contribution from the substrate and the superconducting layer can be distinguished.**

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Superconductor-ferromagnetic composite conductor. Ac loss. Pancake coil. YBCO coated conductor.

I. INTRODUCTION

ReBCO coated conductors are the most promising high-temperature superconducting tapes [1], [2]. This technology requires a highly textured metallic substrate. It has been shown that a good texture can be achieved by a moderately magnetic Ni-W alloy, from which some commercial tapes are produced [3]. Although this substrate is not highly magnetic, its hysteresis loss is already important in comparison to the low ac loss in the superconducting layer [4], [5]. Moreover, its permeability changes the ac loss properties of the superconductor [6]. Actually, the effect on a superconducting film from a magnetic material has been a theoretical subject of study by several authors [7], [8], [9], [10].

Due to practical reasons, a very common way of winding a magnet is in the shape of pancake coils piled together. The behaviour of already one pancake coil made of this superconducting-ferromagnetic composite is expected to be more complicated than a single tape. A remarkable experimental work has been published by Polak. *et al* [11]. However, in that article there are several questions left open, like the contribution of the ac loss from the ferromagnetic material and the anomalous shape of the voltage signal.

In this article, we measure the ac loss and the voltage signal in one superconducting pancake coil. The ac loss is measured by electrical methods, which have more accuracy than the calorimetric techniques. All the results are thoroughly analysed with the aim of understanding the dominant loss mechanisms in the coil at several current amplitudes. The discussion have been done with the help of numerical calculations, based on the critical state model.

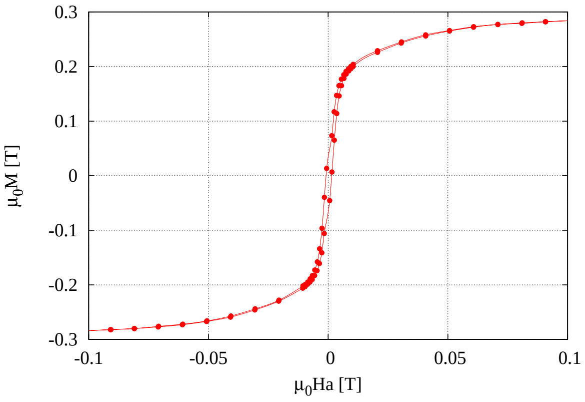

Fig. 1. Magnetization loop of the Ni-W magnetic substrate as a function of the applied parallel field H_a.

II. EXPERIMENTAL METHOD

A 13-turn coil has been prepared in the same way as in [12], using a YBCO coated conductor tape [3], with a cross section of 4 × 0.19 mm^2 and a critical current I_c of 88 A in self field. The superconducting layer and the substrate cross-sections are around 2 μm × 3.8 mm and 80μm × 3.8 mm, respectively. The inner coil diameter is 17.1 cm. One side of the tape have been covered by 0.08 mm Kapton insulating tape, which also fixed the distance between the turns. The critical current of the coil has been determined at slowly increasing DC current, obtaining[1] 66.5 A.

The magnetization loop of the substrate have been measured under parallel applied field by means of a SQUID magnetometer, Fig. 1. The measurements have been performed at 100 K, well above the superconductor critical temperature. Due to the high width-to-thickness ratio of the samples, the demagnetizing effects are small [13], [14] and do not appreciably modify the magnetization loops, except close to the remanence. Thus, the applied magnetic field H_a is approximately the local internal field. Athough the measured loop is representative for part of our discussion, for estimating the AC loss due to the substrate we use the data from ac measurements published Grilli *et al.* in [4] because ac measurements provide a higher accuracy at low applied field amplitudes.

The voltage signal in the coil loss have been inductively measured by means of a transformer, as detailed in [12]. In this way, the response of all the coil, including the magnetic substrate, can be measured. The ac loss is obtained by measuring the first harmonic of the voltage in phase with the current, which is sinusoidal, and multiplying both rms values.

III. AC LOSS AND MAGNETIC FIELD MODELLING

In our previous works, we showed that the ac loss in a pancake coil can be simulated by minimization of the magnetic energy variation [15], which assumes the critical state model (CSM) [16], [12]. In this article, we use the same method as in Refs. [16], [12], assuming a constant critical current density J_c. Although actual tapes usually present a nonuniform field dependent J_c, calculations with a constant J_c are already useful in order to identify the loss mechanisms.

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[1] Actually, in order to protect the coil, this current has never been reached; the critical current was obtained by extrapolation of the DC current-voltage curve.

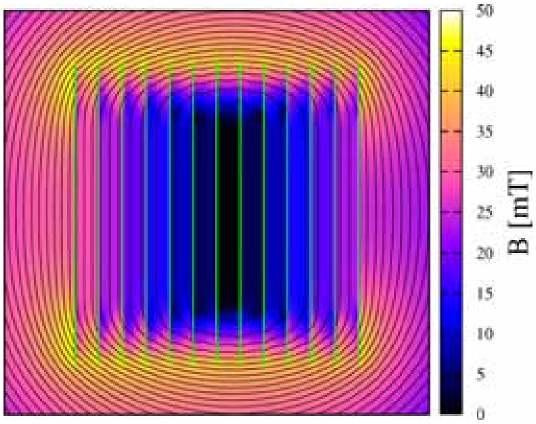

Fig. 2. Calculated magnetic field lines and magnetic field intensity (colormap/grayscale) created by the supercurrent $\mathbf{H}_s$ (ignoring the magnetic parts) at the current peak for $I_m = 33.25$A ($I_m \approx 0.5 I_c$). In the plot, it is shown the coil cross-section, where the internal coil radius is in on the left. The green (gray) straight lines represent the superconducting region. The field lines show the correct magnetic field direction but not its magnitude.

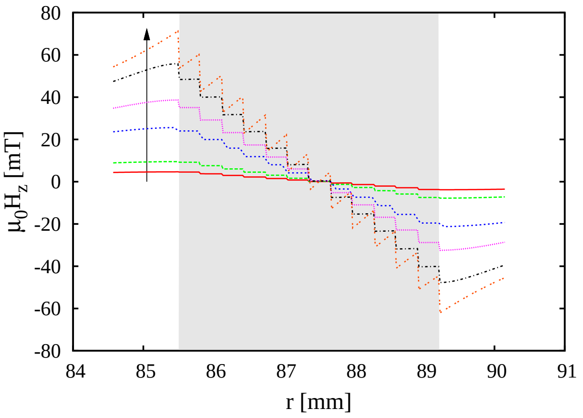

Fig. 3. Calculated axial component of the magnetic field created by the superconducting layer, $H_{s,z}$, at the current peak and $z = 0$ as a function of the radial coordinate r. The origin of the axial coordinate z has been taken at the coil mid plane. The different curves are, following the arrow direction, for $I_m = 6.65, 13.3, 33.25, 46.55, 59.85, 66.6 (\approx I_c)$ in A. The shaded zone represents the coil region.

The magnetic field calculated ignoring the magnetic parts, $\mathbf{H}_s$, is presented in Fig. 2, for the current amplitude $I_m = 33.25$A ($I_m \approx 0.5 I_c$) at the current peak. It can be seen that in most of the substrate region, the magnetic field is parallel to the tape surface. In our system, the magnetic parts are very thin. Then, due to demagnetizing effects, the perpendicular component of the field practically does not magnetize the material [13], [14]; only the parallel one produces a significant magnetization. In order to estimate the AC loss due to the magnetic substrate, we evaluate the axial field, $H_{s,z}$, at the horizontal mid plane shown in Fig. 3.

IV. RESULTS AND DISCUSSION

A. Voltage signal

In our case, the coil radius is relatively large, resulting in a large self inductance. As a consequence, the measured signals were practically sinusoidal, different from the triangular signals reported by Polak *et al.* for a coil with a small radius [11]. Actually, for an accurate

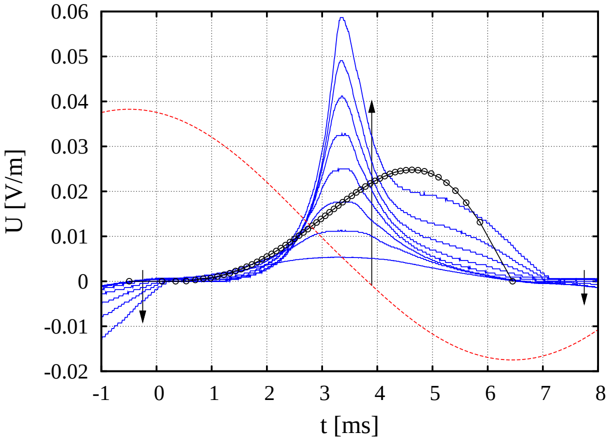

Fig. 4. Measured voltage signal per unit tape length U (solid lines) for the current amplitudes $I_m = 7.1, 14.1, 21.2, 28.3, 35.4, 42.4, 49.5, 56.6, 63.6$ A (constant I_m increment) in the arrow directions. The line with symbols is the numerically calculated U from the superconducting layer at $I_m = 63.6$ A (Sec. III) and the dash line is the sinusoidal current in arbitrary units.

analysis of the voltage signal it is necessary to appropriately remove the inductive signal. If no magnetic material is present, we can use the compensation that we described in [17], [12] in order to see the effect of the flux penetration in the superconductor. Otherwise, it is possible to make the following compensation. A magnetic material saturates for enough large applied field. Beyond this field, the voltage produced by the material as a consequence of an increasing (or decreasing) applied field vanishes. Therefore, for large enough field amplitudes, the voltage from the flux due to the magnetic material becomes null with null derivative close to the field peak. Concerning the superconducting layer, the voltage due to current penetration (practically) vanishes and gets null derivative after the current peaks, as can be seen in the calculated coil signal for $I_m = I_c$ in Fig. 4. Consequently, the voltage can be compensated by removing a sinusoidal signal quater period shifted with respect to the current with an amplitude that creates a null derivative after the current peaks for large current amplitudes.

The measured voltage signals after compensation are shown in Fig. 4. The main features of the voltage from the magnetic material and the superconducting layer can be distinguished, as explained below.

For low current amplitudes, the voltage signal is roughly sinusoidal (Fig. 4). This is caused by two effects. First, the magnetic fields generated at low amplitudes are so small that the magnetic material is practically linear and the induced voltage is sinusoidal. Second, since the slope in the $M(H_a)$ curve is large, we expect that the resulting signal will be much larger than that from the superconducting layer. Actually, our compensation should vanish the superconductor voltage at low amplitudes [17], [12].

For large current (and high local field) amplitudes the behavior is more complicated. At low applied fields, the magnetic material has a very large susceptibility $\chi \equiv M/H_a$. Therefore, for a small variation of H_a, M varies a lot and also the flux that it creates, producing a relatively large voltage. When H_a increases, the slope of the $M(H_a)$ curve decreases and so does the associated voltage, approaching to zero at large values. Then, the voltage from the magnetic material produces a sharp peak around $H_a = 0$, corresponding to $I = 0$. This peak is clearly seen in the measurements for large current amplitudes, Fig. 4. In our case, the average field applied to the substrate at the critical current is around 25 mT (Fig. 3), for which the slope in the $M(H_a)$ curve is still not zero. However, it is much smaller than close to $H_a = 0$ and the approximation that the voltage is zero there with null derivative can be done. Indeed, according to the measured $M(H_a)$ loop, a constant ramp increase in H_a would produce at least a 30 times smaller voltage at 25 mT than at 0 field. Besides, the voltage from the magnetic material must be null at the current peaks because the instantaneous time derivative of H_a is zero and so it is for $M[H_a(t)]$.

The typical voltage signal from the superconducting layer is represented by the simulated curve for the coil in the CSM (Fig. 4), corresponding to the largest measured amplitude ($I_m = 63.6$A). The characteristic peak from the superconductor appears for the measurements at the largest I_m. However, its height is lower than expected. There are several factors that could explain this, like a smooth $E(J)$ relation (where E is the electrical field), and a nonuniform J_c with larger values at the tape ends [17], [18][2]. Since the magnetic material does not produce any signal at the current peak, the voltage there must be caused by the superconductor. The signal from a superconductor with a smooth $E(J)$ relation is delayed in time compared to that if the CSM is assumed. This explains the shape of the measured voltage signal close to the current peak. Furthermore, the peak from the substrate at large I_m should practically coincide with $I = 0$. In reality, the contribution from the superconductor shifts the peak of the resulting signal.

The voltage signal at high currents also evidences that the ac loss is dominated by the superconducting layer. This can be seen as follows. The signal from the magnetic material is practically symmetric with respect to the the centre of the current half cycle. Since the loss is the integration of the product between the voltage and the current, the contribution from this voltage is very small. Besides, the superconducting layer produces a significant voltage at the current peaks, contributing significantly to the loss.

B. *AC loss*

The ac loss per unit length and cycle, Q, for the pancake coil and a short tape sample is shown in Fig. 5. The presented measured curves are for a frequency of 72Hz but data for other frequencies, ranging from 36Hz to 144H, showed no difference within the measurement accuracy. This evidences that the involved ac loss is of hysteresis nature and that the effect of the eddy currents in all the tape metallic parts are negligible.

In Fig. 5 we also included the CSM calculations for the coil and the Norris' formula for a strip [19], using the respective measured I_c. It can be seen that the loss close to I_c for the coil is roughly 5 times higher than for the short sample, a proportion similar to the predicted one by the theoretical curves. Although the loss close to I_c for the tape is similar to the Norris' result, the CSM calculation for the coil departures significantly from the measured data. Some improvement could be done by using a field and position dependence of J_c. However, in this article we discuss only the effect of the magnetic substrate.

In order to better identify the loss mechanisms, the normalized ac loss per unit length and cycle (essentially divided by I_m^2) is presented in Fig. 6.

After doing this, there appears a peak in the resulting curve for one single tape. This peak comes from the contribution from the substrate, explained as follows. The relevant applied magnetic field felt by the substrate is roughly proportional to the current in the tape. At very low current amplitudes, the area of the minor magnetization loops in the substrate increases with increasing the amplitude, typically by a power around 3 [20], so that the normalized loss increases. For higher amplitudes, the substrate saturates, its

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[2] Actually, in [18] it is shown that a lower J_c at the ends creates a larger voltage but the opposite also applies.

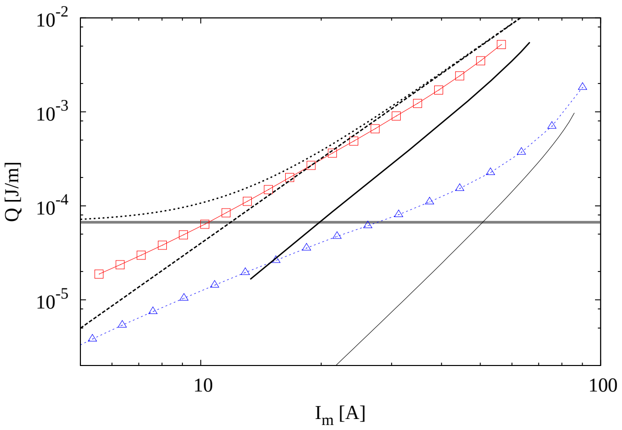

Fig. 5. AC loss per cycle and unit tape length, Q, as a function of the current amplitude I_m. Lines with symbols are for the coil (squares) and the the short sample (triangles). The thick solid black line is is for the calculated coil loss for the CSM (Sec. III); the dash line and the thin black one are for a slab with the same average critical current density and the Norris strip formula, respectively [19]. The horizontal thick gray line represents the maximum possible Q from the substrate hysteresis. The dot line is for a slab plus the maximum Q from the substrate.

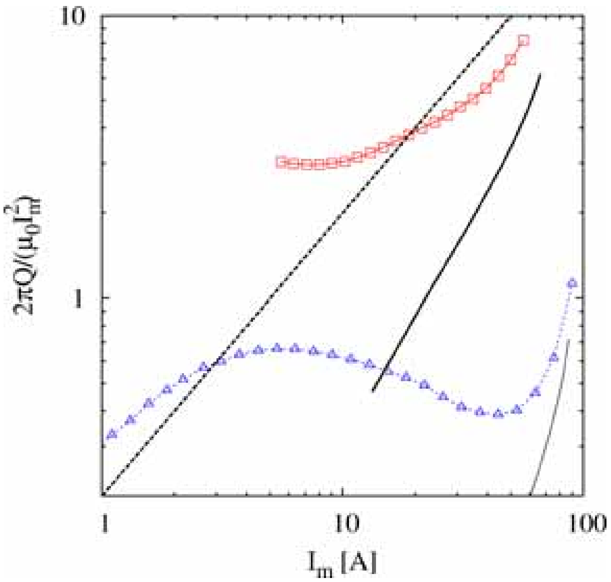

Fig. 6. Normalized ac loss per unit length $2\pi Q/(\mu_0 I_m^2)$, where I_m is the ac current amplitude, for the same cases as in Fig. 5.

loss becomes constant, and the normalized loss decreases, explaining the peak. Actually, the peak appears before the loss is completely saturated because the loop area saturates smoothly with the applied field amplitude. However, the presence of the peak evidences that the loss is dominated by the substrate. In the part of the curve where the loss increases again, it is dominated by the superconducting layer. The current amplitude at which the substrate loss saturates can be estimated by taking into account the magnetization loss in the substrate published in [4]. With our substrate cross-section, the maximum loss per unit length from the magnetic material is around $6.7 \cdot 10^{-5}$ J/m. In Fig. 5, this quantity is indicated by a horizontal gray line, well below the total loss for high I_m.

For the coil, the saturation of the substrate happens at a much lower I_m because the generated field is larger. As seen in Fig. 6, the normalized loss presents a minimum, symilarly to the tape. This indicates that beyond the minimum, around $I_m = 8$A, the loss is dominated by the superconducting layer, in agreement with the maximum possible loss from the substrate.

Above, we discussed the contribution to the loss from the magnetic substrate. However, such substrate modifies the ac loss in the superconducting layer [7], [8], [9], [6], [10]. As experimentally shown by M. Suenaga and Q. Li for uniform applied magnetic fields [6], the effect of the magnetic substrate in the superconductor can be qualitatively explained by the magnetic mirror effect [7]. In our case, the superconductor in each coil turn is surrounded by two magnetic foils, which create a infinite set of virtual images of the superconducting layer. Moreover, the magnetic field created by the other real coil turns is shielded by the magnetic layers [9]. Consequently, the magnetic field in the superconducting parts is the same as in a coil with a large number of turns, generating the same ac loss as a slab [16]. The ac loss curve for the equivalent slab is included in Figs. 5 and 6, crossing the measured ac loss for the coil. The larger loss from the coil at low current amplitudes could be explained by a contribution from the substrate, represented also in 6. For larger current amplitudes, the magnetic material starts to saturate, presenting a lower susceptibility and the magnetic mirror effect is substantially reduced. Indeed, at the critical current, $H_{\mathrm{s},z}$ at the most external turns is around 50mT (Fig. 3) for which the susceptibility is only around 5.

V. **CONCLUSION**

In this article we have measured the voltage signal and the ac loss in a small 13 turn pancake coil made of a coated conductor tape with magnetic substrate. The measurements have been analysed with the help of numerical calculations based on the critical state model.

The ac loss for one tape is dominated by the magnetic substrate, except close to the critical current. Besides, the ac loss in the coil is mainly produced by the superconducting layer. This means that the substrate does not limit the possibility to reduce the ac loss in a coil, for example by striation plus transposition of the superconducting layer [21]. However, in a cable or a fault-current limiter, where the field amplitudes are symilar to a single tape, the loss from the substrate is very important. Moreover, the substrate increases the ac loss per unit length in the coil, resulting in a similar loss per unit length to a slab (or a coil with a very large number of turns). Therefore, we expect that the relative increase in the loss must be lower for coils already with a larger number of turns. However, the effect of the magnetic material on the superconductor should be analysed in more detail by means of simulations taking into account the magnetic substrate.

We have also discussed the coil voltage signal at a sinusoidal current. It has been seen that an appropriate compensation of the inductive signal is required for a detailed analysis. For this purpose, a compensation for a superconductor-ferromagnetic composite have been introduced, that can be applied if there is at least one current amplitude for which the magnetic material is substantially saturated. The resulting signals were dominated by the magnetic substrate for low current amplitudes but at higher currents, the contribution from the superconducting layer is significant, specially close to the current peaks, where the signal from the magnetic material vanishes.

In conclusion, we have reported a procedure for the analysis of the voltage signal and the ac loss in superconducting coils containing magnetic parts, thanks to which the dominating loss mechanisms have been identified.

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