Magnetisation ac-loss measurements on YBa$_2$Cu$_3$O$_7$ tapes with weakly-ferromagnetic NiW substrates.

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Abstract. The commonly-used NiW substrate for RaBiTS-process 2G conductors is weakly-ferromagnetic, so that the interaction between the superconductor and the magnetic material is important, particularly for AC applications. We have studied the AC losses in a model system of a high-current 2G YBCO tape that has been fabricated on a non-ferromagnetic substrate (Hastelloy), with and without adjacent weakly-ferromagnetic Ni-5at%W tape(s). This approach allows us to explore fully the interactions between substrate and superconductor. The sample architectures examined were YBCO, NiW-YBCO, NiW-YBCO-NiW, YBCO-NiW and NiW in magnetic fields applied perpendicular, parallel and at 45° to the tape normal. The power losses were measured in applied ac-magnetic fields of up to 100 mT rms at close to power line frequencies and at liquid nitrogen temperature. In addition, complementary magnetisation measurements were made on some architectures. Below the penetration field of the superconducting tape, the overall AC losses in the perpendicular field orientation are reduced significantly by a single adjacent NiW layer, with a further slight decrease with the addition of a second NiW layer. Above the penetration field the losses are not altered greatly. At very low fields the dominant loss mechanism appears to be the ferromagnetic hysteresis loss.

1. Introduction

High-Temperature Superconductors (HTS) have yet to have a significant impact on large scale ac-applications such as electrical generators, motors and transformers, where they have the potential to increase efficiency and contribute to energy savings. A significant barrier is that HTS conductors suffer from relatively large power dissipation in ac-transport current or ac–external magnetic field conditions. The multifilamentary approach to mitigation of ac-loss in 1st generation (1G) Bi-2223 tapes is ill-suited to the architecture of 2nd generation (2G) YBCO conductors. Indeed, because the aspect ratio of the superconductor cross-section in the 2G conductors is even more extreme than in 1G conductors, the ac loss problem is further accentuated.

There have been suggestions [1] that incorporation of appropriately-shaped ferromagnetic elements in the conductor architecture can reduce the ac loss, essentially through the constraint that magnetic flux has to enter and exit a high-permeability region perpendicular to the interface. Inevitably, there will be an accompanying magnetic hysteresis loss in the ferromagnet.

Duckworth et al. [2] have shown that ac-transport current losses in RaBiTS-produced YBCO coated conductors on Ni-W substrates exhibit an additional ferromagnetic loss component. Suenaga et al. [3] examined the magnetisation losses of stacks of octagonal discs of YBCO on Ni5%W substrates. A reduction in loss at applied fields below the penetration field was observed, qualitatively consistent
with the flux constraint mentioned above. A numerical study of a superconducting strip in close proximity to ferromagnetic material has been undertaken by Farinon et al. [4], where a reduction of loss is predicted, but one that is rather strongly-dependent on spacing between ferromagnet and superconductor.

The aim of our experimental study is to investigate the ac loss behaviour of a YBCO tape fabricated on a non-magnetic substrate interacting with a weakly-ferromagnetic tape, so that the superconductor and the ferromagnetic tape can be individually well-characterised, and thereby their interaction can be quantified properly.

2. Experimental

The loss measurements were performed by an electrical method using a set-up similar to the system described by Šouc et al. [5] and referred here to as the ‘calibration-free system’ or CFS. Two large racetrack coils (sample coil and cancellation coil) were wound utilising a specially-produced cable, which consists of 6 copper strands wound around a central strand insulated from the outer 6 strands. The outer strands carry the ac current producing the applied external magnetic field, while the central strand forms a voltage pick-up coil. The current passes through the coils in series, while the voltage loops of the coils are connected together in such a way as to cancel the inductive voltage when the coils are excited. The advantage of this arrangement is that because the voltage pick-up coil has a geometry identical to the current-carrying coil, no calibration-factor is needed. Two lock-in amplifiers were used to record a) the difference voltage from the inner windings of the sample and cancellation coils, and b) the voltage from an additional rectangular pick-up coil placed in the bore of the cancellation coil. The latter signal provides the phase reference for the loss component as well as a measure of the amplitude of the ac magnetic flux density B. In addition, magnetisation measurements were performed with a commercial Vibrating Sample Magnetometer (VSM). The magnetic field frequency of our CFS measurements was f=59 Hz, while the VSM measurements were close to dc (sweep rate: 270 A m⁻¹ s⁻¹). All measurements in this study were performed in liquid nitrogen at 77 K.

In order to avoid complicating history effects, for each configuration successive measurements were made with increasing field amplitude. When changing configurations, the sample was warmed to room temperature.

Table 1. Geometrical details of the architectures used in this study.  

| t = thickness, w = width. YBCO thickness includes that of the buffer and silver layers. |
|---|---|---|---|---|---|---|
| M | M | S | M | S | M | S |
| t = 80 µm | Ni5at%W | Ni5at%W | Ni5at%W |
| w = 3.8 mm | Vacuum | Vacuum | |
| t ~ 10 µm | Grease | Grease | |
| t = 15 µm | Copper | Copper | Copper | Copper |
| w = 4.08 mm | YBCO | YBCO | YBCO | YBCO |
| t = 50 µm | Hastelloy | Hastelloy | Hastelloy | Hastelloy |
| w = 4.0 mm | Copper | Copper | Copper | Copper |
| t = 15 µm | Copper | Copper | Copper | Copper |
| w = 4.08 mm | Vacuum | Vacuum | |
| t ~ 10 µm | Grease | Grease | |
| t = 80 µm | Ni5at%W | Ni5at%W | |
| w = 3.8 mm | | | |
The five architectures examined were: 1) YBCO-Hastelloy only (S – superconductor) 2) NiW substrate only (M – magnetic substrate), 3) NiW-YBCO-Hastelloy (MS), 4) NiW-YBCO-Hastelloy-NiW (MSM) and 5) YBCO-Hastelloy-NiW (SM). The sample dimensions and different configurations are listed in Table 1. The NiW tapes were attached to the 2G conductor with a thin layer, of order 10 µm, of vacuum grease. Note that the spacing between superconductor and ferromagnet is smaller in the MS configuration (~25 µm) than in the SM configuration (~75 µm), because of the intervening Hastelloy substrate in the latter. Also, the textured Ni-5at%W tape is very slightly narrower than the 2G conductor. The content of tungsten was confirmed by determining the Curie temperature using thermogravimetry performed with the sample in a magnetic field gradient. The critical current (self-field, T=77 K) of the YBCO on Hastelloy 2G conductor was measured to be $I_c = 79.2$ A (sheet critical current density $K_c = 19.8$ kA m$^{-1}$). The entire tape was coated with a copper layer approximately 15 µm thick.

The loss measurements were performed with the applied field always perpendicular to the tape rolling direction, and (i) perpendicular to the wide face of the tape ($B_{appl} \parallel c$-axis), (ii) at 45 degrees and (iii) with the field oriented parallel to the wide face. Piece lengths of 100 mm were used in the calibration-free system, and of 10 mm in the VSM.

3. Results

3.1 The NiW tape

The NiW tape is indeed magnetically soft, with a Curie temperature of 338 K, consistent with a composition of 5at%W [6]. The initial permeability $\mu_{init}$ is sufficiently high for demagnetising effects still to be large, even with the field in the plane of the tape. A rough estimate of $\mu_{init}$ from the latter measurements, utilising the effective demagnetising factors for rectangular prisms tabulated by Chen et al. [7] and assuming magnetic isotropy, gives a value of $\mu_{init} \sim 100$.

For the AC loss in the NiW tape, the two measurement techniques are complementary (figure 1): the CFS technique is better suited to low applied fields, but at high fields its residual background signal tends to obscure the tape loss. Reassuringly, where the data sets overlap, there is excellent agreement. For a field applied at 45°, to a good approximation the loss corresponds simply to the field component perpendicular to the tape face.

![Figure 1. Hysteresis loss per cycle per unit length of the NiW tape as a function of applied field amplitude at 77 K, for the applied field parallel, at 45°, and perpendicular to the tape surface. Low field data obtained with the CFS system, high field data with VSM.](image-url)
3.2 The 2G tape

Figure 2 shows the loss per cycle for the stand-alone 2G tape. The CFS data accord well with theory [8], both qualitatively and quantitatively; the fit uses solely the measured sheet critical current density $K_c$. At low fields, the dependence is between $B^4$ and $B^3$, which confirms that any eddy current losses (which would go as $B^2$, and so become dominant) in the copper coating are negligible. At high fields, the losses approach a linear dependence somewhat sooner than theory suggests, but the latter ignores any potential field-dependence of the critical current, which certainly is becoming significant at fields of order 100 mT.

An apparent discrepancy is that the magnetically-measured (VSM) loss is significantly smaller than that obtained electrically (CFS). However, it must be remembered that in real superconductors, the electric field $E$ is not simply a step function at the critical current density $J_c$, but is rather a steep function of the current density $J$, typically $E \sim J^n$ [9]. Thus, the apparent $J_c$ is dependent upon the magnitude of $E$ in the relevant assessment. The VSM field sweep-rate induced $E$ fields are typically $10^{-6}$ V m$^{-1}$; in the CFS rig, an AC amplitude of 100 mT at 59 Hz yields an $E$ field that is 4 or 5 orders of magnitude larger. A typical value of $n$ for 2G tapes under these conditions might be ~20, so that the effective $J_c$, and so also the losses, in the two experiments might differ by a factor of order 2. We emphasise that these are rough estimates only, but they suffice to show that the apparent discrepancy is likely to be no more than an artefact arising from the very different rates of change of $B$ in the two measurements. We have checked also that the apparent discrepancy is the same for all the
architectures we have looked at, and so does not in any way affect our discussion of the impact of the different architectures on AC losses.

The data for a field applied at 45° can be brought into near-coincidence with the field-perpendicular data by a simple shift along the abscissa by $\sqrt{2}$, i.e., the loss is determined by the normal component of the applied field. Our measured losses with the field set nominally-parallel to the 2G tape are indeed small, and lie within the uncertainty of the angular alignment.

3.3 Compound Architectures

The impact of introducing magnetic layers is shown for the field-perpendicular configuration in figure 3; here the loss per cycle is divided by $B^2$, yielding a function that for the superconductor alone has a maximum at an applied field amplitude close to $\mu_0 K_C$, corresponding here to 25 mT. In this regime, the introduction of a single magnetic layer reduces the loss by 20 to 30%, with a somewhat smaller reduction when the magnetic layer is spaced 50 µm further away (the SM configuration) than in the MS configuration. The addition of a second magnetic layer (MSM configuration) brings about a further substantial reduction. For comparison, the stand-alone NiW magnetic losses are shown too.

**Figure 3.** Normalised hysteretic loss per cycle per unit length for the different architectures as a function of applied field amplitude (field perpendicular to tape surface). The arrow indicates the field amplitude $\mu_0 K_C$, at which the normalised loss should peak. Note that at low field amplitudes, the addition of magnetic layers increases the loss. The normalised loss in the NiW tape is shown too for both field orientations.

At field amplitudes considerably higher than $\mu_0 K_C$, the impact of the magnetic layers becomes negligible. This is not because the magnetic tapes are saturated – in this perpendicular field orientation much higher fields are needed – but rather reflects the saturation of the current distribution within the superconductor. It is noteworthy that at fields small compared with $\mu_0 K_C$, the relative loss order is inverted, with the MSM configuration having the highest loss. Moreover, this loss is very much larger than the stand-alone magnetic tape loss for this, perpendicular, field orientation, and has magnitude approaching that of the field-parallel stand-alone magnetic tape loss. Thus in this situation, it is the...
distortion of the applied field by the screening currents induced in the superconducting tape that generates significant lossy parallel field component at the magnetic tape.

We have looked at other field orientations, but in rather less detail. For a 45° orientation, to a first approximation the losses in the compound structures scale with the normal component of the field, as they do for the bare superconducting tape. When the field is parallel, magnetic losses become large (figure 1), and totally dominate any small losses contributed by the superconducting tape.

4 Initial susceptibility

As we have already indicated, the calculation of the critical state in the presence of magnetic layers is a complex task, because even with simplifying assumptions, it is essentially a non-linear problem. However, the initial flux entry (i.e., the initial susceptibility) into a superconductor is linear, so that calculation of the impact of ferromagnetic material (of constant high permeability, so as to retain linearity in the problem) is more straightforward; Farinon et al. have followed this approach [4].

It is well-known that for a field applied perpendicular to a superconducting film or plate, demagnetising effects dominate. For a thin rectangular film of width $2a$ and length $2b$, the sample magnetic moment $m = -4a^3 \beta H$, where $\beta$ has been tabulated by Brandt [10]; note that this result is independent of film thickness. For our sample dimensions, the Brandt expression yields $m/H = 1.45 \times 10^{-7}$ m$^3$; the initial slope of the superconducting sample magnetisation loop (figure 4) is $-1.05 \times 10^{-7}$ m$^3$. This level of agreement is typical for thin films – it has to be noted that the Brandt calculations makes a number of simplifying assumptions. More relevant to the present study is that in the MSM configuration this slope is reduced by a factor of 2, and by factors of about 1.3 and 1.4 in the SM and MS configurations respectively.

Interestingly, the impact of adjacent magnetic layers on the initial susceptibility is quantitatively similar to that on the ac loss.

![Figure 4](image-url)
5 Conclusions
This presence of a weakly-ferromagnetic substrate adjacent to a YBCO film can make a substantial
difference to the ac loss when exposed to an external applied magnetic field. A loss reduction of up to
50% can be obtained in the technologically-relevant regime where the currents in the superconductor
have a magnitude approaching the critical current.

The behaviour of these composite structures is complicated, and cannot be simply treated as a
superposition of one element on another: the magnetic layer modifies the critical state within the
superconductor, and – although less important in applications – the superconductor distorts the fields
at the magnetic layers, so as to increase the magnetic loss at low AC field amplitudes.

It might have been anticipated that for the magnetic layers to have significant impact, there needs
to be minimal spacing $t$ between them and the superconductor, perhaps that the “magnetic spacing” $\mu t$
should be small compared with the tape half-width $a$. In fact, these results have been obtained with
structures in which the spacing is of order 50 $\mu$m, and $\mu t$ is about 5 mm, somewhat larger than $a$.

These results should give encouragement to investigation of more elaborate architectures, but,
given the difficulty of numerical modeling, they should be ones where the individual components can
be well-characterised, as we have done here.

Acknowledgements
We are grateful to SuperPower Inc. (YBCO tapes) and American Superconductor Corporation (NiW
substrates) for supplying us with excellent samples. This work was supported by the New Zealand
Foundation for Research, Science and Technology. ADC thanks Industrial Research Ltd for their
generous hospitality.

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