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Abstract

Stacks of high temperature superconducting tape, magnetized using pulsed fields, provide a new type of permanent magnet using superconductors. To optimize the trapped field in such stacks, the role of stabilization layers was investigated by pulse magnetizing a 12 mm square stack of 15 tape layers over a temperature range of 15–77 K. The stacks consisted of commercial tape with a silver stabilizer of 1–3 μm or tape with an additional 20 μm layer of copper on top of 1 μm of silver. It was found that the trapped field and flux are relatively insensitive to the stabilizer thickness, and 1 μm of silver only, led to the highest trapped field. An FEM model was also developed for a stack that considered for the first time both the actual thickness of metallic and superconducting layers, to investigate the effect of heating and heat transfer when a stack of tapes is magnetized.

Keywords: superconducting permanent magnet, coated conductor, superconducting bulk, pulsed field magnetization, GdBCO, H formulation, trapped field

(Some figures may appear in colour only in the online journal)

1. Introduction

Stacks of second generation, high temperature superconductor (2G HTS) tapes or coated conductors are increasingly being explored for their ability to act as trapped field magnets, which show potential for a variety of applications such as motors and generators. It has previously been shown that a stack created from standard 12 mm wide commercial tape can trap 2 T using the pulsed field method of magnetization [1], and 7 T between two stacks using field cooling [2]. Field cooling has also been used to show that stacks of tape can produce very well defined fields with a high level of uniformity. Arrays of tape stacks have been used to produce patterned fields [3], and tape with a width greater than 12 mm has been used to create stacks which have been field cooled for desktop NMR applications [4] and also pulse magnetized [5]. Recently, self-supporting stacks of tape with layers soldered together, have been produced [6], resulting in a type of composite superconducting bulk practical for applications. This includes pulse magnetization of 12×120 mm rectangular stacks with potential to act as field poles in a motor [7]. It has also been shown that stacks of tapes suffer significantly less cross-field demagnetization than bulks which gives them advantages in rotating machines [8].

Data comparing similar sized stacks of tape with bulk superconductors, show that stacks which trap a lower field than a bulk at 77 K, can significantly outperform a bulk at temperatures lower than 50 K [1]. It is believed to be the increased thermal stability of the stacks subject to a pulsed field which causes this enhancement, but a more detailed understanding of the thermal stability of a stack and in particular, the role of the substrate and stabilizer, is needed to explain their performance. It is the purpose of the work reported to understand the difference in the magnetic and thermal dynamics of a stack of tapes compared to a plain bulk conductor, when pulse magnetized, which can guide work in optimizing stacks of tapes to maximize trapped field and flux.

The scale of the coated conductor industry allows for an ever-increasing choice of options for both substrate and stabilizer parameters. This provides motivation for understanding which parameters, particularly for the stabilizer, will give the highest trapped field or flux.

2. Pulsed field magnetization experiments with varying stabilizer thickness

2.1. Superconducting tape specifications

The 12 mm tape used for the pulse magnetization experiments reported was produced by SuperOx [9]. The tape had a nominal I_c rating of 400 A at self-field and 77 K. The basic architecture of the tape is similar to that produced by several other manufacturers. The tape is based on a 60 μm thick Hastelloy substrate, with the functional layers deposited by the IBAD-MgO/PLD-GdBCO route and top stabilizing layer of silver. The thickness of silver on the different tape samples ranged from 1–3 μm, with one sample having an additional 20 μm of copper on top of the silver layer. The parameters for modelling the stacks of tape were based on the real SuperOx tape architecture used in the experiments. Thermal properties can vary considerably between different materials in 2G HTS tape. For example, around 40 K, the thermal conductivity of silver is 50 times greater than YBCO (*ab*-plane) and 130 times greater than Hastelloy [10]. A full graphical illustration of differences in the thermal conductivity and heat capacity of tape materials can be found in [10].

2.2. Pulse magnetization system and applied fields

The pulse magnetization system used is based on an Oxford Instruments Variox cryocooler and allows pulsed fields of up to 10 T to be used, with an in-house made pulse field coil, at temperatures down to 10 K. The applied field has a duration of 28 ms and a pulse rise time of 12 ms. The trapped field was measured 0.8 mm above the sample surface using an array of 9 hall probes including a central Arepoc LHP-MP cryogenic hall probe. This array allows the trapped field profile to be measured at any desired time. The software is a key innovation in the system as it allows for full automation of set of pre-programmed pulsed field sequences such as those shown in table 1. The measurement of the trapped field profiles is

Table 1. Summary of the sequence of pulses applied. The magnitude of the first pulse is the start field, then the pulses are incrementally smaller (by the Interval given).

Temperature/K	Start field/T	End field/T	Interval/T	Number of pulses
77.4	1.3	0.9	0.04	11
55	2.5	1.7	0.08	11
35	2.9	1.5	0.1	15
15	3.1	1.2	0.1	20

also automated making the system a powerful tool for systematic study of pulse magnetization as well a demonstration of the automation needed for applications.

15 square pieces were cut from the different tapes and stacked to give 12 mm square stacks with an approximate thickness of 0.9 mm. The IMRA method (Iterative magnetization with reducing amplitudes) was used by applying a series of pulses with reducing amplitude [11]. All field profiles were measured 30 s after a pulse to allow time for the most rapid flux creep, which occurs before 30 s. The IMRA pulse sequence was applied at 4 different temperatures starting with 77.4 K as detailed in table 1. After magnetization at each temperature stage was complete, the sample was cooled to study the performance at the next temperature stage. In most cases, the fact that there is already a trapped field left over from a previous IMRA temperature stage did not matter as the starting applied fields were enough to fully penetrate the sample (effectively wiping out all of the previous persistent currents). However, even in the case that this is not true, the pre-existing trapped field would only increase the field attainable at the lowest temperature stages. For more details on this see the MPSC method of pulse magnetization (multi-pulse with stepwise cooling) [11].

For any new sample it is impossible to know the optimum IMRA sequence to apply at each temperature before testing but the fields chosen were based on many previous studies such as [1], conducted in the same system with similar 12 mm square tape stacks. However it is normal practice, as for the experiments here, to choose a slightly higher start field than necessary as the drop in trapped field for an underestimate in the optimum applied field, is more significant than for an overestimate [12].

Although the total number of pulses applied was large, there was only a significant increase in field and flux for the last 15 K temperature stage. The routine procedure may therefore be simplified in future and for applications to only include a few pulses for all but the lowest temperature stages.

2.3. Trapped field and flux results

The trapped field profiles achieved for the 1 μm silver stabilizer sample are given in figure 1 as an example of typical profiles achieved. They all have an expected conical shape with clear increase in trapped field and total flux when decreasing the temperature, which provides justification for operating below 77 K. A close comparison of the final
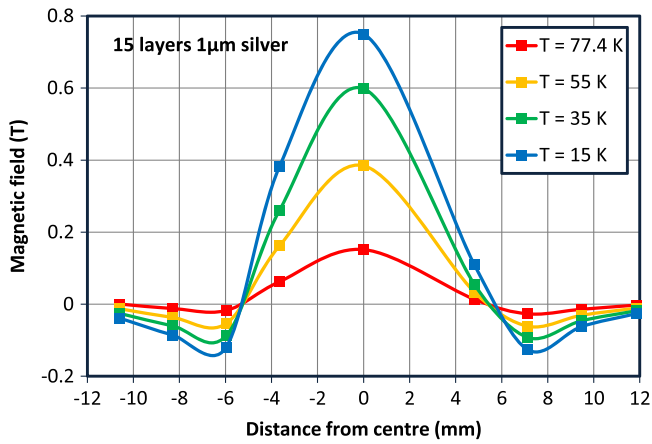
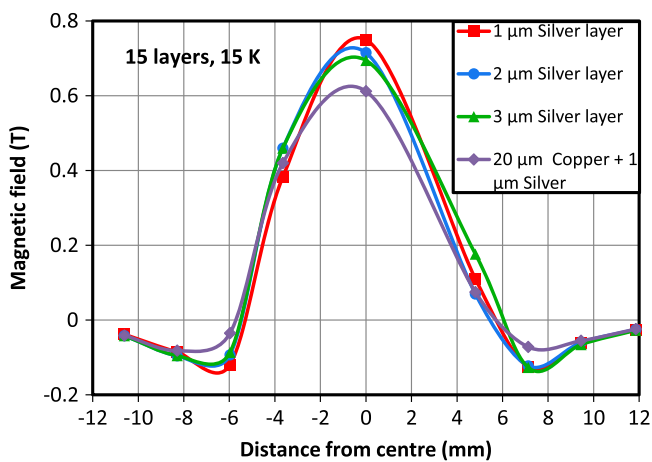**Figure 1.** The trapped field profiles for a tape stack with 1 μm silver stabilizer.

Figure 2. The effect of stabilizer thickness and type on trapped field profiles for the final 15 K magnetization stage. Sample edges are at ±6 mm which defines the 'trapped flux' region.

maximum trapped field profiles achieved after the 15 K magnetization stage is shown in figure 2 for all the different stabilizer samples tested. Firstly it is clear that the changes in the profiles are not so large for varying the silver layer between 1 and 3 μm, which shows that the performance is not so sensitive to the stabilizer thickness. A clearer difference is seen when looking at the results for 20 μm copper stabilized tape which shows a reduced central field. The two most natural parameters to summarize these types of trapped field profiles are the maximum central field and total trapped flux, which have been calculated for all the profiles and summarized in figure 3. The total trapped flux shown in figure 3(b) was calculated by giving the negative distance points a positive radius, interpolating the field between all the positive radius points and then integrating this field profile as a function of radius over a circular area of 12 mm diameter, assuming axial symmetry of the field. The assumptions in this calculation (including assuming a circular rather than square sample), result only in an estimate of the absolute trapped flux, but still allows relative comparisons of trapped flux between different samples thanks to the high degree of symmetry all the trapped fields appear to have.

Figure 3 shows that the central trapped field increases quite linearly as you decrease temperature but the effect saturates slightly when approaching 15 K. The trapped flux however shows a highly linear increase for reducing temperature all the way down to 15 K. For stabilizer thicknesses that are much smaller than the tape thickness, e.g. silver 1–3 μm, the results suggest that increasing thickness increases total trapped flux but decreases the central trapped field. This result agrees with previous modelling [13] which showed that increasing mean radial thermal conductivity for a uniform bulk (equivalent to a stack with a thick stabilizer) increases the flow of heat from the sample outer regions to the sample centre. This has the effect of enhancing J_c in the outer edges (which contribute most to total flux) at the expense of decreasing J_c at the sample centre, hence why increasing stabilizer thickness would enhance total flux but reduce central trapped field. Caution should however be taken when trying to reach definitive conclusions from the results of the silver stabilized samples because of the relatively small differences in field and flux values.

Now considering the more extreme case of the 20 μm copper +1 μm silver sample, this has a 33% higher thickness than the 1 μm silver sample. This height increase starts to affect the results as the lower tape layers are now much further away from where the field is being measured. By assuming uniform persistent currents in the samples and the same I_c for all the tape, a simple simulation can be made to predict the drop in central field and flux expected simply from spacing the current carrying YBCO layers further apart (increasing sample height but decreasing J_e). This simulation shows that geometric factors alone would result in a field and flux for the copper stabilized sample of 89% compared to the 1 μm silver sample. Based on this value, it is not surprising that the copper stabilized sample performed worst for central field and flux, with possible eddy current heating also cancelling any effects of enhanced radial thermal conductivity.

3. Modelling a stack of tapes

Finite element modelling of stacks of tape with actual layer thicknesses was carried out to help understand the dynamic inside the samples during magnetization. The modelling of pulsed field magnetization was carried out using the H-formulation for magnetic fields, coupled with heat transfer in the finite element modelling package COMSOL Multiphysics 4.4. The framework used the *E*–*J* power law and is the same as that used in [13]. Cylindrical symmetry was assumed for the stacks which is an acceptable approximation and necessary for solving the models in a reasonable time. Pulse magnetization was simulated at 40 K using a single pulse per model only, for simplicity. Also, insulating buffer layers were not considered and thermal contact between layers was assumed to be perfect. This approximation was taken because the buffer layers are only 200–250 nm thick, but they are poorly conducting oxides, so this should be taken into account in future models.
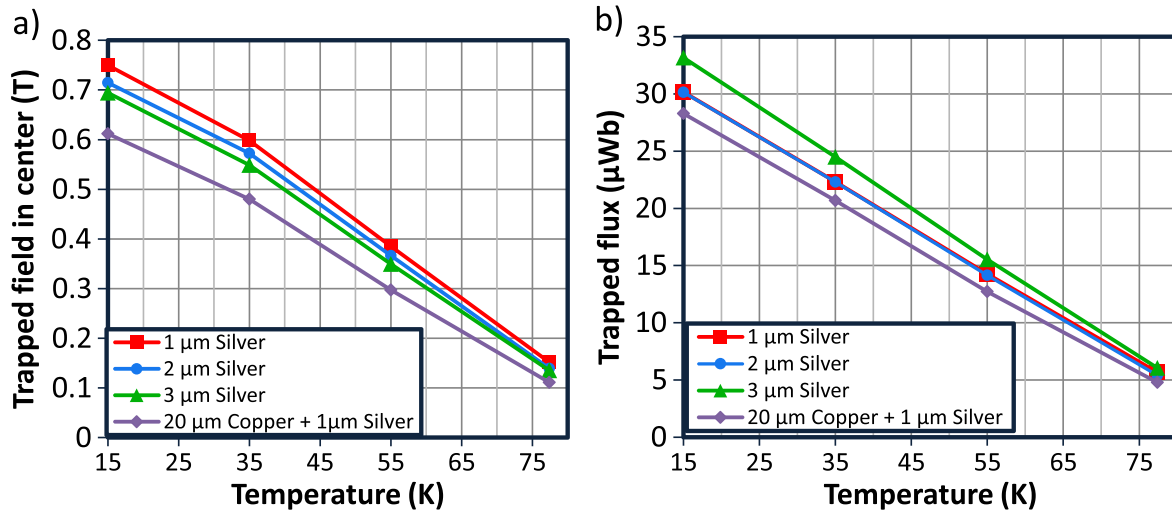
Figure 3. (a) The maximum trapped field ($r=0$) and (b) trapped flux for 15 layer stacks after IMRA magnetization at each temperature stage.

Table 2. Descriptions and values of parameters used in modelling.

Parameter	Description	Value
n	n-value in E–J power law	9 for $0 \leqslant t < 0.1$ s, 21 for $t \geqslant 0.1$ s
E_0	Electric field constant E–J power law	1×10^{-4} V m^{-1}
B_0	Flux density constant in equation (1)	1.3 T
a	Constant in equation (2)	5 MA cm^{-2}
T_c	Critical temperature of bulk	92 K
T_0	Equilibrium temperature of bulk	40 K
Q_c	Cooling power density per degree temperature rise	0.005 W m^{-3} K^{-1}
t_0	Pulsed field rise time	14 ms
B_a	Applied pulsed field amplitude	1 T
J_c	Critical current density at 77.4 K for the (RE)BCO layers	0.79 MA cm^{-2}
J_e	Engineering critical current density at 77.4 K for modelled bulk and tape stack with only 1 μm silver stabilizer	15 kA cm^{-2}
I_c	Critical current for a single tape layer at 77.4 K	100 A

3.1. Modelling equations and parameters

The applied pulsed field was half a sinusoid with a peak of 1 T. The Kim model was used to describe the dependence of the critical current density on field:

$$J_c = \frac{J_{c0}(T)}{1 + B/B_0} \tag{1}$$

with the temperature dependence of J_c given by:

$$J_{c0}(T) = a\left[1 - \left(\frac{T}{T_c}\right)^2\right]^{3/2}. \tag{2}$$

The total cooling power applied to the models when a cold head was used is described by the same function used in [13], which gives the cooling of a coldhead that responds linearly to temperature increases above the equilibrium temperature. The power saturates at a maximum of 75 mW for a temperature rise greater than 15 K which, although small, was chosen to give a time for the temperature to decay back to

equilibrium of about 10 s which is what is typically observed in the experimental system. The full list of parameters used in the model are given in table 2. As in previous modelling using the same framework [13], two different n values were used; $n=9$ for $0 < t < 0.1$ s (which includes the 28 ms pulsed field) and $n=21$ for $0.1 \leqslant t < 10$ s. Typical n values for bulk (RE) BCO and tapes are over 20, however for rapid pulsed fields applied to bulks as in [13], the trapped field immediately after a pulse is relatively insensitive to n value. It was therefore assumed that this is also the case for the stacks of tape modelled with thin layers, which helped these models to be solved by avoiding instability associated with higher n values. However this assumption may be a source of error. After 0.1 s, $n=9$ gives far too high flux creep so $n=21$ was chosen as a compromise.

The equilibrium temperature, T_0, was 40 K for all the models as this is roughly in the middle of the temperature range used to magnetize the samples in the experimental system. All the trapped field and flux values were evaluated at 0.8 mm above sample to match the experiments.
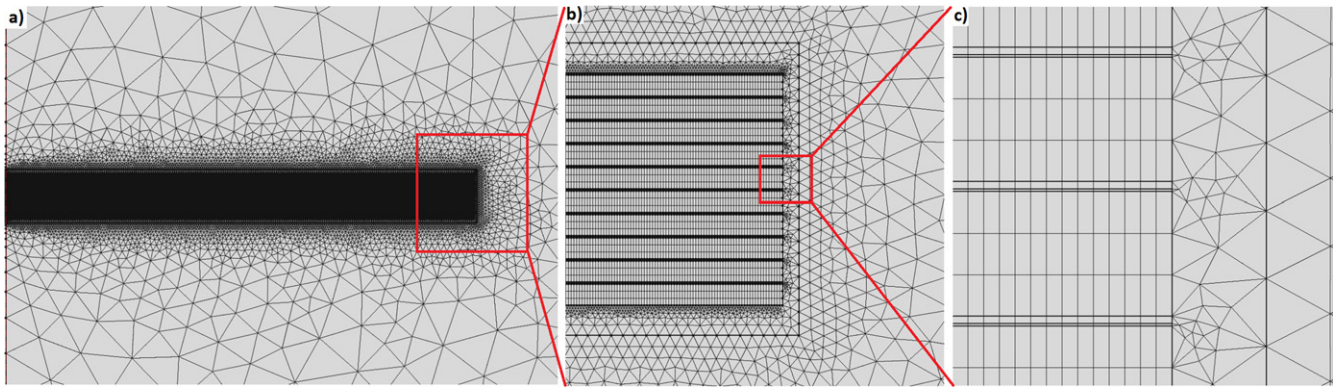
Figure 4. (a) and (b) Typical finite element mesh used for a stack of 10 tapes, 12 mm in diameter with the zoomed in mesh (c) showing individual Hastelloy, (RE)BCO and silver layers. The mesh contains ~80 000 domain elements.

The remaining thermal and electrical cryogenic properties, which vary with temperature, were taken from [14] for silver [15], for Hastelloy and [16] for (RE)BCO.

Figure 4 shows a typical mesh used for the finite element models which all contained 10 tape layers. Although this is less than would be used in a normal stack acting as a trapped field magnet, this was the most that could be solved for in a reasonable time. A mapped mesh was used inside the stack to carefully control the number and distribution of elements. A mesh sensitivity analysis determined that using a single quadratic element for the height of the (RE)BCO layer was sufficient to give reliable results whilst giving a reasonable computing time.

3.2. Comparing stacks of tape to bulks of the same J_e

The most basic understanding of how a stack of tapes behaves during pulsed magnetization, can be gained by comparing it to a plain uniform bulk superconductor with the same engineering current density J_e. In the simplest field cooling mode, a stack of tapes and a bulk with the same overall geometry and J_e should trap exactly the same trapped field profile above the sample surface, however this is not necessarily true for pulsed magnetization due to heating in the superconducting layer and differences in the thermal properties of the substrate and stabilizer in a stack compared to bulk (RE)BCO.

As the silver layer is a flat electrically conducting pane, it is plausible to expect some unwanted eddy current heating to occur during a pulse. However analysis of the stack of tapes model with 1 μm of silver shows that the silver layer contributes less than 0.5% of the total heat generated and so it can be assumed for this section that all heat is generated in the YBCO layer for a stack of tapes. A schematic can therefore be drawn as in figure 5 showing the heat flow resulting from a pulse. The silver layer acts to transfer heat more quickly to the centre of the stack which means that it is effectively increasing the ab-plane conductivity if considering the sample as a uniform bulk as for the modelling conducted in [13]. The thick Hastelloy layer primarily acts as a heat sink. Considering adiabatic pulse magnetization, where there is no external heat transfer from the sample, an interesting question arises. Is it better to generate all the heat in a thin high current
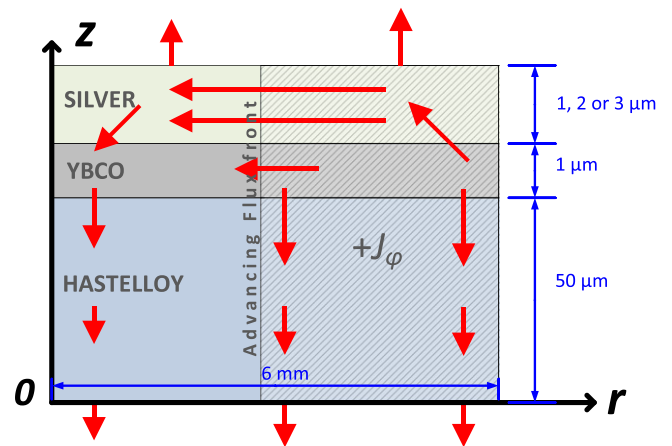

Figure 5. Schematic showing heat flow in a single tape layer of a pulse magnetized stack. A third of the way into a pulse is shown as an example with heat generated at the advancing flux front. Almost all the heat is generated in the (RE)BCO layer but there is significant transfer to the substrate and stabilizer. Heat transfer outside stack ignored.

Table 3. Values of the surface trapped magnetic field and flux for the modelled bulk YBCO and the stack of tapes (with no external cooling), and percentage increase for a stack of tapes compared to the bulk.

	Trapped centre field/T		Trapped flux/μWb	
Time after pulse	0 s	10 s	0 s	10 s
Bulk YBCO— uniform J_c	0.3024	0.1748	14.71	6.568
Stack of tapes	0.3084	0.1797	15.21	6.833
Increase	1.97%	2.76%	3.40%	4.05%

density superconducting layer and dump it all in a heat sink of another material or is it better to generate it uniformly in a large low current density superconducting region, which also sinks the heat? Table 3 shows the results for the stack and bulk with the same J_e magnetized at 40 K. 10 tapes were modelled with a 1 μm silver stabilizer giving a stack height of 520 μm, the same as the bulk analogue. It is clear that

although there are differences, they are relatively small which suggests that in this case, spatially separating out the heat generation and heat sinking does not in theory lead to a significant difference in trapped field and flux performance. At the temperature simulated, the effective mean volumetric heat capacity of the stack is very similar to that of bulk YBCO [10], so it can be concluded that for the same overall J_e and volumetric heat capacity, concentrating the superconducting region in a thin layer does not make much difference to trapped fields for adiabatic pulse magnetization. Both models assumed a J_c lower than typically found in the samples (the tape I_c was modelled as 100 A rather than the 400 A for the experiment tape), the applied field of 1 T was not quite enough to fully penetrate the samples and the temperature rises were ≈ 3 K, less than experimentally observed. These compromises were needed to allow the stacks of tape model to solve as it was prone to instability. It may be that for high J_c and B_a, the differences in table 3 would increase, but they are unlikely to be large.

There are therefore a number of possible explanations why experimentally the trapped field for stacks of tape tends to increase more significantly compared to bulks when lowering magnetization temperature as in [1] (with no heat sinks attached to the samples). Bulks have non-uniformities leading to hotspots [17, 18] and instabilities during pulse magnetization, but this was not considered in the model. The J_c in tape layers is relatively uniform, reducing the chance of flux instabilities and if instabilities do occur, the silver layer is likely to supress hotspots. Understanding these dynamical effects for non-uniformities in a stack requires creating a full 3D model with layered structures, a task beyond the scope of the present study. So for now, the proposed reasons for the observed high trapped fields for pulse magnetized stacks of tape at low temperatures remain a hypothesis.

3.3. Stacks of tape with different stabilizer thickness

The thickness of the silver layer was also varied in the model to see what the effect was on trapped field and flux. 10 layers were again considered with stabilizer thicknesses of 1 and 3 μm of silver and also 20 μm copper $+1$ μm silver. After applying the single 1 T pulsed field, the central field and flux were calculated. In addition to providing no external cooling to the samples as for the models in the previous section, a coldhead was also modelled for each stabilizer case. The coldhead acted as an external heat sink in direct contact with the sample and provided cooling power as described in section 3.1, via a copper ring and baseplate on the sample. Surprisingly most of the differences in trapped field and flux for all the models were less than 1% and at most only 2%. These small differences make it difficult to draw any conclusions about the effect of stabilizer thickness. The differences are probably small because of the low J_c and B_a considered compared to the experiments as described in section 3.2, resulting in trapped fields of ~0.2 T compared to ~0.5 T in the experiment. Assumptions made for the n value could also contribute an error. The corresponding temperature rises of ≈ 3 K in the models are probably too small for the

stabilizer thickness to make any real difference and also indicate heat generation that is too low to see the real benefits of the coldhead. The small changes compared to the experimental results suggest that the greater the I_c of the tape and the larger the fields that are applied to fully penetrate the sample, the more sensitive the trapped field and flux will be to the stabilizer thickness. The presence of a coldhead or heat sink directly mounted on a stack, has never been tested experimentally before, so it is not clear what enhancement to trapped fields it could allow.

4. Summary

Pulse magnetization using multiple pulses at various temperatures was performed for stacks of superconducting tape showing a strong increase in trapped field and flux when decreasing temperature, the latter of which has a highly linear trend. The effect of various stabilizers was investigated as there now exists a wide choice of tape specifications for commercial tape. For 12 mm square stacks it was found that 1 or 2 μm of silver stabilization only, is ideal for optimum trapped field and flux, although the performance is relatively insensitive to the stabilizer thickness. Additional copper stabilizer which is typically 10 s of microns thick is not ideal for stacks of tape, although may have potential benefit if attaching the stack to a coldhead or heat sink. Modelling considering the actual thickness of layers in stack was performed showing that eddy current heating in the silver layers is negligible. It also suggests that concentration of the current carrying regions into thin planes alone should not lead to significant differences in performance compared to a uniform current carrying region, as in the case of an ideal bulk. The computational challenges involved in solving a stack of tapes with real layer thicknesses forced a number of assumptions to be made which may have suppressed temperature rises, limiting the accuracy of the results. Due to the difficultly in solving these models for current densities and applied fields as high as those used experimentally, future modelling will focus on improving previous models which use a single domain with homogeneous but anisotropic properties to approximate real multi-layer stacks. This will allow fast means of predicting performance in new experiments. The effect of thermal contact resistance due to buffer layers will be considered as well as the angular dependence of J_c on field to give more reliable models. Finally, experiments are currently under way to determine whether the mounting of external heat sinks onto stacks or tape can enhance performance by utilizing efficient conduction of heat via the stabilizing layers.

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