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Magnetic levitation using a stack of high temperature superconducting tape annuli

A Patel¹, S Hahn², J Voccio³, A Baskys¹, S C Hopkins¹ and B A Glowacki^{1,4}

¹ Applied Superconductivity and Cryoscience Group, Department of Materials Science and Metallurgy, University of Cambridge, 27 Charles Babbage Road, Cambridge, CB3 0FS, UK

² Applied Superconductivity Center, National High Magnetic Field Laboratory, Florida State University, 2031 East Paul Dirac Drive, Tallahassee, FL 32310, USA

³ Francis Bitter Magnet Laboratory, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

⁴ Institute of Power Engineering, ul. Mory 8, 01-330 Warsaw, Poland

E-mail: ap604@cam.ac.uk

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Abstract

Stacks of large width superconducting tape can carry persistent currents over similar length scales to bulk superconductors, therefore giving them potential for trapped field magnets and magnetic levitation. 46 mm wide high temperature superconducting tape has previously been cut into square annuli to create a 3.5 T persistent mode magnet. The same tape pieces were used here to form a composite bulk hollow cylinder with an inner bore of 26 mm. Magnetic levitation was achieved by field cooling with a pair of rare-earth magnets. This paper reports the axial levitation force properties of the stack of annuli, showing that the same axial forces expected for a uniform bulk cylinder of infinite J_c can be generated at 20 K. Levitation forces up to 550 N were measured between the rare-earth magnets and stack. Finite element modelling in COMSOL Multiphysics using the H-formulation was also performed including a full critical state model for induced currents, with temperature and field dependent properties as well as the influence of the ferromagnetic substrate which enhances the force. Spark erosion was used for the first time to machine the stack of tapes proving that large stacks can be easily machined to high geometric tolerance. The stack geometry tested is a possible candidate for a rotary superconducting bearing.

Keywords: high temperature superconductor, critical state modelling, HTS tape, superconducting levitation, magnetic bearings, coated conductor

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

1. Introduction

Stacks of high temperature superconducting (HTS) tapes have proven potential to act as composite superconducting bulks, for either trapped field magnets or as passive components of a magnetic levitation system. An increasing selection of stack size and geometry can now be fabricated from commercial tape as illustrated in figure 1. Experiments on stacks made from standard 12 mm wide commercial tape have shown that

high fields can be trapped using both the pulsed field method of magnetization [1], and field cooling [2]. Large width tape is produced by some manufacturers prior to slitting to smaller standard 12 or 4 mm widths. American Superconductor produce 46 mm wide tape which was used to create square annuli with a 26 mm hole. These annuli were then stacked to form a stack with a 26 mm bore capable of generating a uniform persistent field when magnetized using field cooling [3, 4]. The trapped fields achieved inside the bore were 3.5 T at 4.2 K and 0.65 T at 77 K giving such a stack of annuli potential to be used in a small scale NMR/MRI device. The work presented here used annuli taken from exactly the same stack, although the outer surface of the stack was machined to achieve a hollow cylinder geometry.



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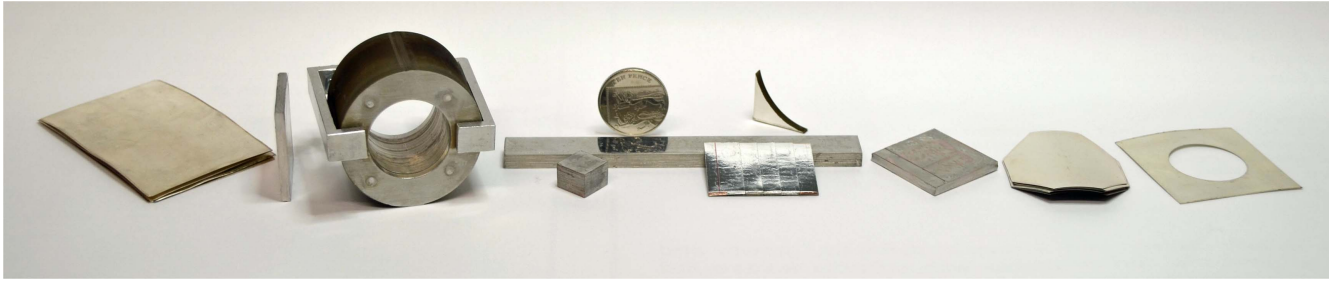


Figure 1. Selection of various stacks of HTS tape and tape pieces illustrating the range of shapes and sizes of composite bulk that can now be produced for magnetic levitation and trapped field magnets.

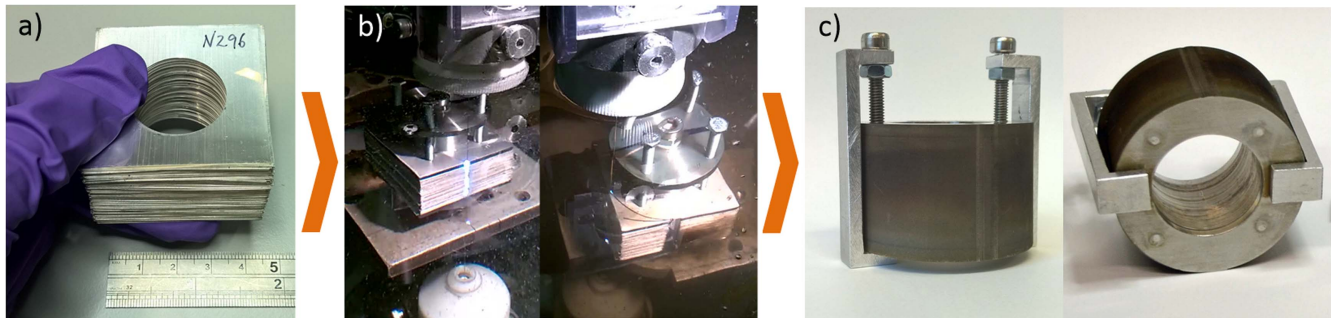


Figure 2. Stages of fabrication of hollow cylinder stack of HTS tapes. (a) Loose stack of 46 mm square tape annuli. (b) Spark erosion machining under water to cut square stack into cylindrical outer geometry. (c) Resulting stack showing high geometric tolerance on machined outer surface.

Superconducting levitation offers stable contactless bearings, enabling very low loss [5]. It is standard to use HTS (RE)Ba₂Cu₃O_{7-d}, ((RE)BCO) bulk superconductors, where ‘RE’ stands for rare earth, for magnetic levitation, but stacks or blocks made from HTS tape have previously been investigated in the context of maglev applications showing that stable levitation of RE permanent magnets (PMs) is possible [6, 7]. There are two types of bearing geometry; cylindrical and planar as illustrated in [8]. They require the superconducting bulk stator to be in the form of a hollow cylinder or flat disk respectively, the research reported here is targeting the cylindrical bearing geometry. Cylindrical bearings have previously been used for large scale flywheel energy storage systems such as the one produced by ATZ GmbH [9]. The superconducting stator part is made of many tessellated (RE)BCO bulk pieces to form an approximate cylinder.

The cylindrical geometry has previously been investigated by using HTS tape in the form of a coil to create a hollow cylinder with a bore of 35 mm [10]. Over 300 N of axial force was measured in this case for a pair of rare-earth magnets. This approach has the advantage of creating composite bulk cylinders of potentially unlimited diameter, but the currents induced in such a cylinder can be complex due to no directly circulating current paths around the bore. Although more limited in size, the annuli however, do allow directly circulating current paths around their bore and so should have very similar levitation force behaviour compared to a hollow bulk cylinder. The main advantage of using the stack of commercial HTS tape annuli for superconducting levitation is the predictability and uniformity of the superconducting properties related to available commercial tape.

2. Annuli stack geometry and fabrication

2.1. Annuli pieces and spark erosion machining of stack

The tape used was produced by American Superconductor and had a nominal I_c range of 200–350 A cm⁻¹ w at self-field and 77 K. The tape is based on a rolling assisted biaxially textured substrate (RABiTS) process for the 75 μm thick Ni-5W substrate, with the buffer layers deposited by reactive sputtering and the (RE)BCO layer by metal organic deposition of TFA based precursors. The stabilizer consisted of a 3 μm silver layer, with the (RE)BCO layer being approximately 1 μm thick, giving a total tape thickness of approximately 80 μm.

The total stack consisted of 294 layers. The original annuli layers shown in figure 2(a) had their 26 mm hole machined using mechanical boring for previous trapped field tests. For the present experiment, the annuli stack had to fit inside the 50 mm cylindrical bore of the measurement system cryostat, therefore the square geometry had to be machined. The loose square annuli were clamped in a custom stainless steel rig visible in figure 2(b). A spark erosion machine, or electric discharge machine, was then used to cut the stack outer surface into a circle of 45.5 mm diameter. The method works by applying a high voltage between the sample and a 0.3 mm diameter wire whilst under water which has controlled ion concentration. The sample must be electrically conducting and so cannot be a bulk (RE)BCO superconductor. The sample is moved via a 2-axis stage following a pre-programmed path which defines the cut. The voltage creates highly localised sparks between the wire and sample

which melt and erode the sample as the wire moves through it. The cut width is 0.3 mm and the resulting sample dimensions have a tolerance of less than 0.1 mm making the method highly precise. The great advantage of the method is that no stress is applied to the sample itself unlike most other machining methods such as lathe turning and abrasive grinding. The parts cut away are not necessarily damaged and could be used for other applications. Laser cutting cannot be used for very thick samples and water jets leads to high distortion and poor tolerance. It is clear from figure 2(c) that spark erosion results in a surface with high geometric tolerance.

It is perhaps surprising that sparking HTS layers underwater can be a reliable and accurate method of machining. Critical current tests were performed on a control stack made from 12 mm wide SuperOx tape. The central layer of a 5 layer stack had a measured I_c of 458.2 A. This stack was subsequently cut in half along the transport axis. A critical current test was then performed again on one half of the central layer of tape (width 5.80 mm) giving an I_c of 207 A. Assuming constant surface current density, it can be deduced from the sample widths and measured I_c that the cut damage region is approximately 0.37 mm from the cut surface. This is likely an over estimate as the J_c of a tape is usually worse at the tape edges compared to the central region, however this test allows us to say with some confidence that damage to the HTS layer is limited to no more than 0.4 mm from the cut. Scanning Hall probe magnetometry of the trapped field of single tape layers that have been cut, also back up this result as the trapped fields indicate current flowing very close to the cut edges. A curious result of this machining method is that most of the resulting layers in the stack are weakly fused together on the cut surface which can aid stack integrity and handling after cutting.

2.2. Final hollow cylinder stack geometry

The overall geometry of the system is shown in figure 3. Due to stacking volume fraction of the annuli, the effective tape thickness used in the modelling was $83 \mu\text{m}$. Two Nd-Fe-B PMs 23 mm in diameter were stacked together and coaxially aligned with the annuli, as shown in figure 3, via a central rod. This typical arrangement produces high magnetic field gradients for the superconductor to maximise stiffness. The centrally aligned position shown in figure 3 was always used for field cooling of the annuli stack before any movement, and so is associated with the $z = 0$ position in later graphs. Movement only occurred for positive z displacement but force behaviour is expected to be the same if moving in negative z due to the symmetry of the assembly. The gap between the PMs and annuli was 1.5 mm, which is smaller than the 2.5 mm used for the tape coil experiment in [10] and so was expected to lead to the larger levitation forces. The height of the PMs is not ideal given the height of the annuli stack, but shorter Nd-Fe-B magnets were not available in the desired diameter and machining such ceramic magnets is not possible. However, the dimensions of the PMs do not prevent high

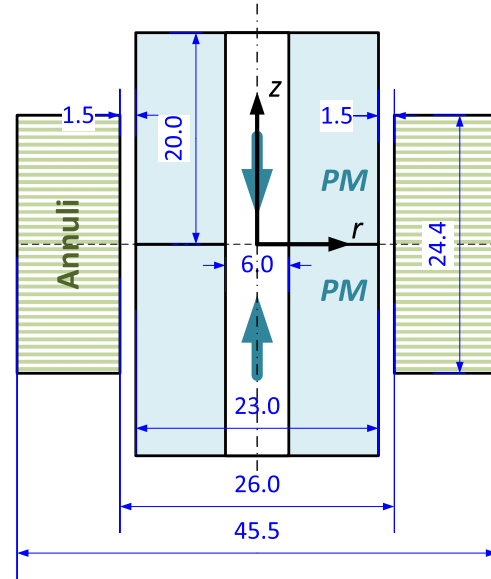


Figure 3. Schematic showing the experimental geometry with a pair of permanent magnets coaxially aligned inside a stack of cylindrical tape annuli (294 layers) in the field cooling position. Units: mm.

gradients and magnitudes of magnetic flux density being generated.

The levitation force system was built around an Oxford Instruments Variox cryostat with indirect cooling of the coil samples via helium gas between a cold head and the samples. The cold head takes the form of a ring embedded in the wall of the cryostat bore which is 50 mm in diameter. The helium gas is at 1 bar pressure. As no significant heat is generated during the levitation tests, the cooling power available is more than enough to maintain the sample at stable cryogenic temperatures down to 10 K. The annuli stack sample holder is rigidly mounted to the cryostat but the PM stack is attached to a G10 epoxy glass rod. The rod is moved up and down using a linear stage driven by a stepper motor. A step size of 0.2 mm was chosen to achieve sufficient resolution. The load cell was rated for up to 1000 N and had an error of $\pm 0.7\%$. Force is measured when the rod is momentarily stationary between movement steps of the linear stage. This ensures that no friction forces resulting from guides and seals influence the force measurement. Further details of the levitation force system can be found elsewhere [11].

3. Experimental levitation force measurements

3.1. Force hysteresis

After cooling of the tape annuli to the desired operating temperature in the position shown in figure 3, the PM stack was displaced upward in the positive z direction by 40 mm (extraction) and then back down 40 mm (insertion) to the starting position, all at a speed of 1 mm s^{-1} , but with momentary pauses every 0.2 mm for load cell measurement. This resulted in the hysteresis curves shown in figure 4 for the three temperatures tested. The levitation force is defined in

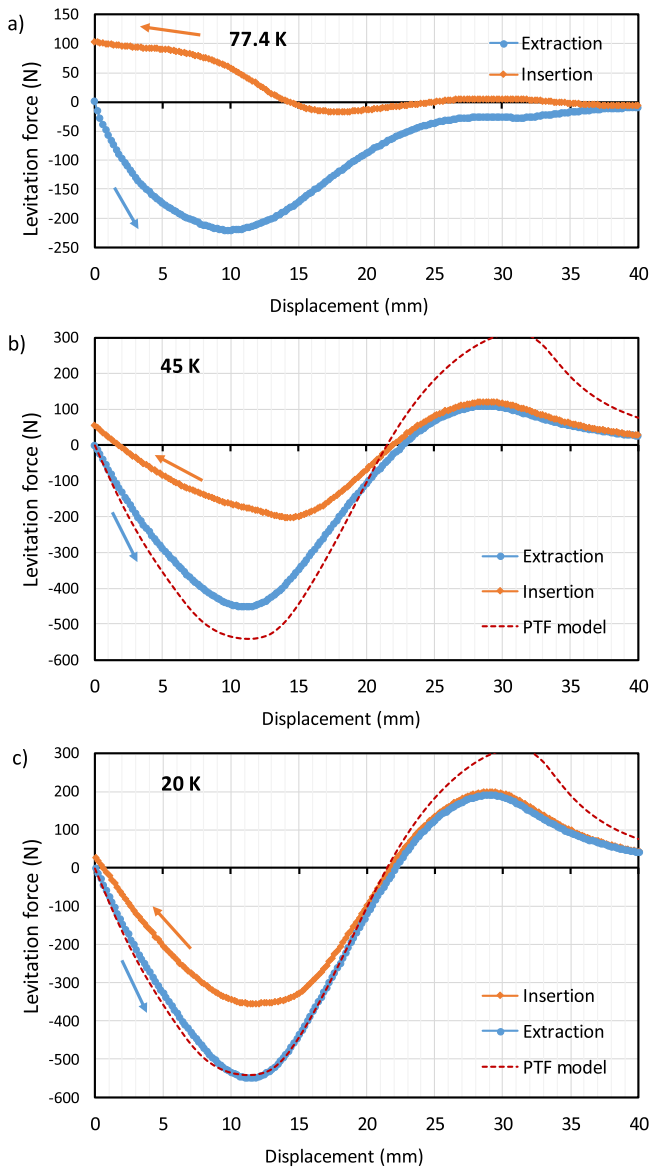


Figure 4. Experimental hysteresis levitation force curves following field cooling at various temperatures. Displacement is in the positive z direction (see figure 3) and levitation force is also defined by the direction of positive z . Dotted line for PTF simulation assumes infinite J_c . Arrows represent movement direction.

terms of the positive z direction in figure 3, which means that a negative levitation force is attractive. It is clear that the temperature has a strong influence on the hysteresis, as expected, with the lowest temperatures exhibiting the smallest hysteresis due to high J_c . Conversely 77.4 K shows significant irreversible behaviour, suggesting large-scale penetration of the flux originating from the PM inside the annuli stack. The peak force for the 20 K curve is 549 N and is the same (within measurement error) to the theoretical maximum predicted by the perfectly trapped flux (PTF) model (red dotted line) which considers infinite J_c . It is surprising that the experimental curve can be so coincident with the PTF curve as the PTF curve usually represents an upper asymptote. However more representative modelling detailed in section 4 taking into account the ferromagnetic properties of the tape substrate,

predict higher levitation forces which explains why the experimental results can match or even exceed a PTF model without ferromagnetic properties. An ‘ideal bulk’ superconductor is not considered as being ferromagnetic so the comparison here is still valid for evaluating the annuli stack performance.

For stable levitation, a negative gradient on the hysteresis curve is required. This means that the present system would be operated at below 10 mm displacement, if supporting a static axial load such as a flywheel. This gives enough margin for stability if displaced further. Force behaviour for displacements greater than, say, 10 mm for this system are not of much practical significance.

It is worth commenting on how the force curves compare to similar experiments in which a composite bulk hollow cylinder was made of HTS pancake coils [10]. For all temperatures, the force for the coil sample was lower but this is largely due to the weaker magnetic fields being used in that case. The highest force measured for the coil experiment was 317 N at 20 K. The gap between PMs and coils was 2.5 mm in the previous study compared to 1.5 mm for the present study which largely explains the difference. The key difference between the two experiments is more to do with shape of the levitation force curves. The previous coil tests produced curves with lower stiffness than expected from modelling and compared to the annuli stack. This is due to the more complex currents set up inside the coils compared to the simple circulating currents induced in the annuli stack. A more quantitative evaluation of the levitation force in both cases should be made by comparison to modelling results which offer a prediction for the maximum performance expected for the exact field generated by the PMs used and exact component dimensions.

4. Modelling of superconducting levitation force

Two different FEM techniques were used to simulate and understand the levitation force experiments. The PTF model as described in [12, 13] estimates levitation forces involving superconducting domains by perfectly preserving the magnetic flux density inside the domain when there is movement. This is physically equivalent to an infinite J_c and therefore induced surface currents. It was achieved here by preserving the magnetic vector potential in the superconducting domain as in [14, 15] and is a simple and fast computation tool using a time independent solver. Due to the limited fields produced by rare earth PMs, it is often a good approximation, but breaks down if the J_c is not high enough.

The critical state model [16], on the other hand, simulates real induced currents within the superconducting domain and so is a more accurate tool and is necessary to determine current flow paths, however computation times are considerably longer than the PTF model.

Table 1. Descriptions and values of parameters used in modelling.

Parameter	Description	Value
E_0	Electric field constant in equation (1)	$1 \times 10^{-4} \text{ V m}^{-1}$
$I_{c0} = I_c(77 \text{ K, SF})$	Tape critical current at 77.4 K and self-field	$220 \text{ A cm}^{-1} \text{ w}$
$L_0(T)$	Lift factor for tape I_c defined by equation (3)	$-0.135 T + 11.725$
$B_0(T)$	Flux density constant in equation (2)	$-0.0103 T + 0.9888$
n	n -value in equation (1)	9
v	Speed of PM movement in model and experiment	1 mm s^{-1}

4.1. Modelling parameters for the critical state model

The H-formulation for magnetic fields was used in COMSOL Multiphysics 5.0 as in the two previous works [17] and [10]. The framework used an E - J power law to simulate the critical state, where E_ϕ and J_ϕ are the azimuthal electric field and current density respectively.

$$E_\phi = E_0 \left(\frac{J_\phi}{J_c(B, T)} \right)^n. \quad (1)$$

The Kim model [18] with temperature dependent parameters was used to describe the dependence of the critical current density (equivalent to the engineering critical current density J_e for the experiment) on field:

$$J_c(B, T) = J_e = \frac{I_{c0} L_0(T)}{wd [1 + B/B_0(T)]}. \quad (2)$$

A full description of the parameters used is given in table 1. This equation and the parameters listed in table 1 were the same as that used for the previous modelling of levitation force for HTS pancake coils [10]. The motivation behind equation (2) is to use a simple mathematical framework that can easily fit typical measured J_e values for commercial superconducting tape over 10–77 K and fields of 0–4 T, as these are the ranges of interest for superconducting bearings. The temperature dependent lift factor is defined below, where SF is the self field, and I_c refers to tape critical current.

$$L_0(T) = \frac{I_c(T, B = 0)}{I_c(77.4 \text{ K, SF})}. \quad (3)$$

The L_0 factor and the B_0 Kim law parameter are fitted to typical HTS tape data such as [19] and then approximated with a linear temperature dependence given in table 1 to give $B_0(T)$ and $L_0(T)$. $J_c(\theta)$ anisotropy is ignored in our model, as it is not assumed to significantly affect the force based on preliminary test models. An n -value of 9 was used. Although this may seem low, using a high n -value showed no change in the force values or induced current pattern and only increased computational time and instability therefore 9 was sufficient for the current study.

The movement of the PMs was implemented by modelling the PMs as a thin layer of current density on the circumferential surface based on the theoretical equivalence of remanent magnetization and surface current density for a PM: $J_s = B_{\text{rem}}/\mu_0 \text{ A m}^{-1}$. The thin layer currents approximating the ideal surface current density J_s , were then moved along

the z direction by defining them with a time and space dependent current density $J(z, r) = J_0(vt, r) \text{ A m}^{-2}$, where v is the speed at which the domain moves and was 1 mm s^{-1} for both experiment and model.

4.2. Ferromagnetic substrate consideration

The RABiTS substrate of the HTS tape is ferromagnetic which is an effect which must be considered in the modelling. Ferromagnetic permeability data for typical RABiTS substrates at 77 K as reported in [20], was used to create an interpolated BH or permeability $\mu_r(B)$ curve. The same data was used for modelling AC losses in HTS tape [21]. In order to determine the effect of the ferromagnetic substrate alone without superconductivity, the PM stack was moved in and out of the annuli stack at 100 K. The results in figure 5 show that forces over 40 N are generated which means the ferromagnetic effects cannot be ignored if trying to model the levitation force curves. There was no hysteresis which shows that the HTS layer was normal and the substrate is acting as a soft ferromagnetic material. Simple FEM modelling was done in the AC/DC module to determine the force between the PMs and the magnetic annuli using the interpolated data mentioned previously. The permeability of the substrate was multiplied by 0.90 to account for the fact that 10% of the stack volume is not substrate. A very close match was obtained between the modelling and experimental force data suggesting the validity of using the data to model the combined superconducting-ferromagnetic case.

4.3. PTF model results

The 2D axially symmetric PTF model was applied to the same geometry as the experimental system shown in figure 3, resulting in the force–displacement curves shown in figure 6. Two models were solved, with and without ferromagnetic substrate. The effect of the ferromagnetic substrate was approximated by using an isotropic and uniform $\mu_r(B)$ relation as detailed in the previous section. Because the PTF model is equivalent to having infinite J_c , there is no hysteresis in either of the curves. It is clear that the effect of the ferromagnetic substrate on levitation force is significant. This can be explained qualitatively by considering the enhanced field that is trapped inside the superconducting stack when it is field cooled. Similar enhancement can be achieved by fixing PMs in various positions onto the superconducting bulk itself to increase the trapped field [14], but it is clearly more elegant

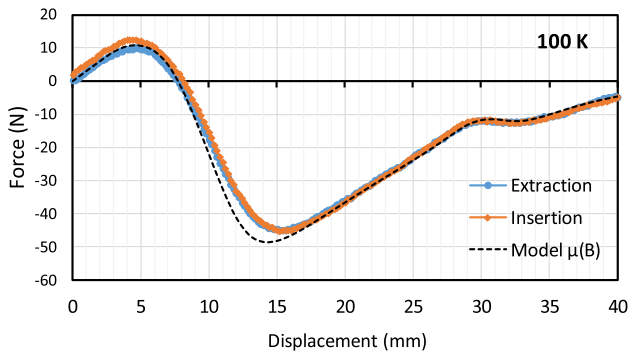


Figure 5. Force due to the effect of the ferromagnetic tape substrate at 100 K. The HTS layer is normal as confirmed by a lack of hysteresis. FEM modelling using $\mu(B)$ data agrees well with experiment.

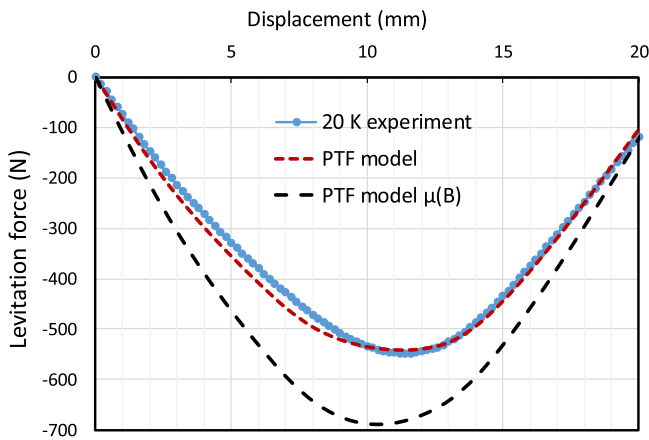


Figure 6. Perfectly trapped flux (PTF) model results with and without ferromagnetic substrate effect compared to the 20 K force curve.

and effective for the superconducting bulk itself to be ferromagnetic, an effect that can only be achieved by using stacks of HTS tape. This allows for the experimental axial levitation force to match that which is expected for an ideal bulk having infinite J_c but no ferromagnetism. As in the case for previous experiments with bulk superconducting cylinders [14], the PTF model curve approximately gives the maximum stiffness for initial displacement and also the maximum force. This implies that forces over 600 N may be possible using higher J_c tape. The critical state modelling in the next section shows that the measured force is lower than the PTF ferromagnetic model due to the depth over which currents are induced in the composite bulk cylinder.

4.4. Critical state modelling results

The critical state model is excellent for showing the magnitudes and depths over which currents should be induced in a superconducting cylinder at different temperatures when moving a PM stack. A superconducting cylinder was modelled in a 2D axisymmetric geometry with the same dimensions as the annuli stack shown in figure 3. Figure 7 shows the circulating current density induced in the cross-section of the cylinder wall for the three different

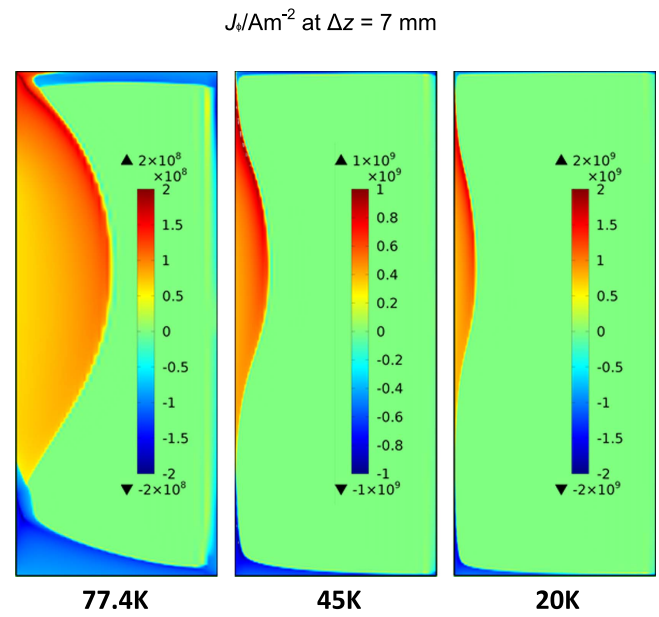


Figure 7. Current densities induced inside the HTS annuli stack as rectangular green cross-sections for different temperatures and for a 7 mm PM stack displacement.

temperatures modelled for an example displacement of 7 mm. One central region of current dominates (red/yellow) but there are also two smaller oppositely flowing regions of current (blue) at the top and bottom of the stack. These regions are related to the field poles of the PM stack. The central expelled flux from the PM stack is axially symmetric and so can be considered as a single pole, in addition to the poles on the top and bottom of the PM stack. The number of current regions induced in the cylinder should be equal to the number of poles for the PM stack (three in this case). As the two ends of the PM stack are outside the annuli, the current regions associated with these end poles are relatively small. This is unlike the case of the HTS coils previously tested [10]. The higher the temperature, the lower the J_c and so the greater the depth over which current is induced which relates to large hysteresis. The 77.4 K case therefore explains why significant hysteresis can be seen at this temperature in the experimental force curves. At 45 K and below, it is clear that the high J_c leads to more effective shielding of the stack interior, confining the induced current to a thinner layer near the inner surface. In these cases, most of the stack volume is not active in the magnetic levitation and therefore, for this application, the wall thickness of the annuli stack could be halved without any real change in the levitation force. In figure 4, there is significant departure from the PTF curve at very large displacements such as 30 mm for all temperatures. This is because larger displacements continue to induce currents deeper into the cylinder than shown in figure 7, and particularly from the top of the cylinder which only has a thin layer of current visible for 7 mm displacement. The greater the depth the currents are induced over, the greater the departure from the PTF model. For 30 mm displacement at 77 K, the critical state shows almost all the cross-sectional area in the top half of the cylinder is saturated with current

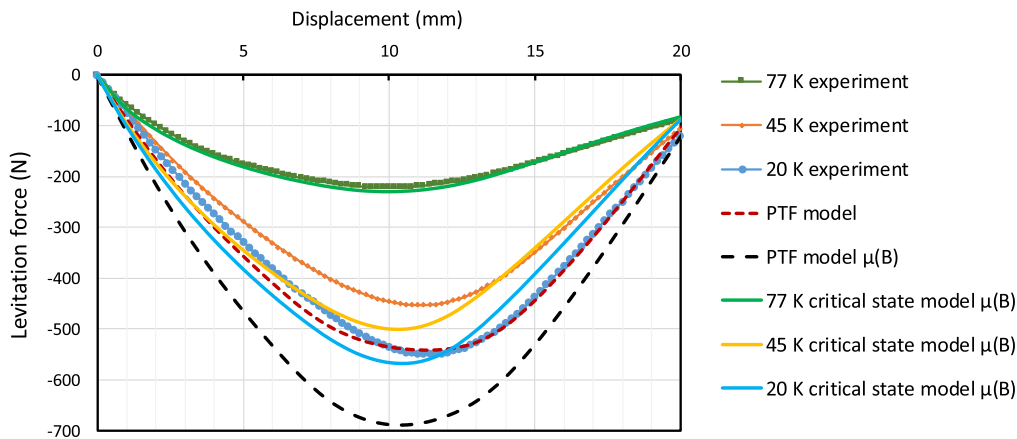


Figure 8. Summary of critical state model, PTF model and experimental levitation force curves.

which explains the unusual flat force behaviour at these displacements seen in figure 4.

Figure 8 summarises the critical state levitation force results. The larger flux penetration and deeper induced currents for 77 K, correspond to significantly lower levitation force. The most important unknown parameter for the critical state modelling was I_{c0} . As this is not exactly specified for the wide tape used, the method used was to choose the value that gave the closest match to the 77 K experimental force curve. This was found to be 220 A cm^{-1} w to the nearest 10 A, and so it was this value that was used in the modelling. The lift factor in table 1 then resulted in higher scaled critical current values for the 45 and 20 K models. Due to the unknown I_{c0} , the purpose of the critical state modelling is to qualitatively reproduce the general features of the force curves and reveal the nature of the current flow as in figure 7. There are however important comparisons to be made between the modelling and experiment. Although I_{c0} was chosen so the 77 K model curve matched the magnitude of the experimental curve, it is noteworthy that the shape of the two curves match very well which suggests that the model is accounting well for the superconducting and magnetic behaviour at 77 K. The force magnitude of the 20 K modelling curve matches reasonably well to experiment but the 45 K curve has a noticeable difference. There are three potential causes for these differences. Firstly, the lift factor and Kim law parameters used for the model are estimates based on typical HTS tape rather than the exact HTS tape product used. Secondly, the field dependant permeability of the substrate is temperature dependent. Data was used for 77 K [20], but this may give errors for lower temperatures. Thirdly the effect of anisotropic permeability due to gaps between the substrates has not been considered as the H-formulation implementation in the AC/DC module of COMSOL, does not allow field dependant anisotropic permeability. Despite these factors, the modelling is sufficiently accurate to explain the general force behaviour of the system. In particular, it is the critical state model for 20 K which confirms that a composite bulk with finite J_c and ferromagnetic properties, can give rise to forces between those predicted by the ideal PTF model, with and without ferromagnetism.

5. Summary

Wide width HTS tape can be machined into annuli and used for magnetic levitation suited to a cylindrical rotary bearing geometry. Stable superconducting levitation for an HTS annuli stack made from 46 mm wide tape was proven with over 500 N of force measured. Higher forces can be expected in future for tape with a higher J_c . Interestingly, the effect of the ferromagnetic substrate was to significantly enhance the stable axial levitation force to values higher than possible with a uniform bulk of infinite J_c . Spark erosion has been shown to be a practical and accurate method of machining stacks of HTS tape which is only possible due to the largely metallic and therefore normally conductive composition of the stacks.

Both PTF models and full critical state models explained the force behaviour, induced currents and the effect of the ferromagnetic substrate. The 2D axisymmetric critical state model is well suited to modelling the annuli stack due to its symmetry and because all the induced currents are purely azimuthal. Most of the annuli stack cross-section had no currents induced in it and so a much smaller cylinder wall thickness can be used in an optimised system which would save material. Previous experiments have shown high trapped field in a stack of the same HTS tape annuli using field cooling magnetization. The current authors are conducting pulsed field magnetization tests for the same stack reported in this paper to prove its suitability as a practical trapped field magnet.

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