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Magnetic Levitation between a slab of soldered HTS Tape and a Cylindrical Permanent Magnet

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***Abstract*—Stacks of commercial high temperature superconducting tape can be cut and soldered together to form slabs of a large range of shapes and sizes. They are most interesting for magnetic levitation applications due to the flexibility of geometry allowing them to be created in large thin slabs suitable for planar rotary magnetic bearings and linear maglev bearings. In the present study, the axial levitation force was measured between a field cooled slab of 30 mm square and a 25 mm diameter rare-earth permanent magnet which produced a cylindrically symmetric field necessary in the context of rotary bearings. The force results were compared to that achieved between the same permanent magnet and a larger 43 mm diameter bulk MgB_2 disk as well as to FEM modelling using the Perfectly Trapped Flux approximation.**

***Index Terms*— magnetic levitation, superconducting bearing, stack of HTS tapes, superconducting tapes.**

I. Introduction

STACKS OF high temperature superconducting (HTS) tape can be used as composite superconducting bulks for both trapped field magnets and for magnetic levitation. Previous experiments have shown that 12 mm square stacks made from commercial tape can trap over 7 T [1] when field cooled (double stack) and 2 T [2] when pulse magnetized (single stack) but there exists little previous quantitative work on the magnetic levitation performance of stacks of tape especially below 77 K. Work has also been done on stacking annuli made from larger width tape to form a uniform field persistent magnets [3,4]. Some previous work has investigated performance of stacks of tape in the context of maglev applications [5], however the work reported is directed towards using tape to create composite bulks suitable for rotary magnetic bearings which offer stable and passive levitation. There are two main geometries for superconducting bearings shown in Fig. 1. Cylindrical and planar. Both geometries have stacked rare-earth permanent magnets (PMs) with opposing field poles in order to generate high magnetic field gradients as well as field magnitude. Both cases use field cooling of the superconducting stator part in the field of the PMs before releasing the load allowing it to displace axially until its weight is in equilibrium with a levitation force. The force occurs due to the induced currents in the superconducting stator which takes the shape of a hollow cylinder or planar disk. So far, only (RE)BCO bulks have been used in large scale superconducting bearings, with some axial force experiments done using MgB_2 bulks [6]. Due to size and geometry limitations for (RE)BCO bulks, these bearings create the hollow cylinder and disk for cylindrical and planar geometries respectively, by tessellating trapezoidal or hexagonal bulk pieces. The best examples of operational superconducting bearings are those in the ATZ GmbH flywheel energy storage system (cylindrical type) [7] and the Boeing flywheel system (planar type) [8]. MgB_2 bulks are less limited by size constraints [9] but must operate below 40 K.

Recently, the first axial levitation force tests for the cylindrical type geometry were performed using HTS tape as a composite bulk [10]. The hollow cylinder was formed of 3 pancake coils with a 35 mm inner diameter wound using 12 mm wide commercial tape. A force of over 300 N could be generated using a pair of PMs stacked with their poles opposing each other. This force was close to the theoretical maximum expected for a bulk cylinder of infinite J_c. There has so far been no study applying stacks of tape to the planar rotary bearing geometry. The ideal use of HTS tape in this case is in the form of soldered slabs produced by SuperOx. Solder plated tape [11] can be stacked, compressed and heated resulting in self-supporting composite bulk slabs of potentially unlimited size. Preliminary results using PM Halbach arrays as a field source show very promising levitation properties of these slabs for linear bearing maglev applications and are being commercialized with those applications in mind [12].

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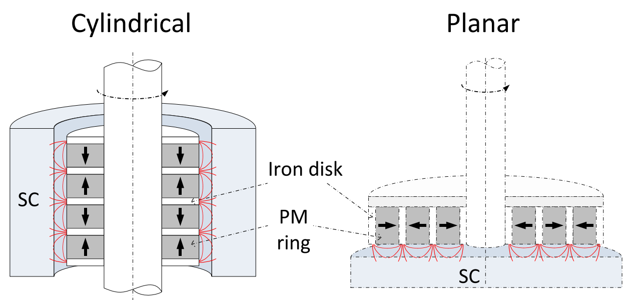

Fig. 1. Cylindrical and planar geometries for superconducting bearings rely on creating a superconducting (SC) hollow cylinder or disk as a stator.

II. Sample Details and Measurement System

A. Slab Specifications and Fabrication

TABLE I
HTS TAPE PROPERTIES AND SLAB SPECIFICATIONS

Property	Value
Tape minimum I_c/A	480
Tape average I_c/A	500
Substrate thickness/μm	65
HTS layer thickness/μm	1.5
Silver stabilizer thickness/μm	1.5
Copper stabilizer thickness/μm	2.5 per side
Average total tape thickness in slab/μm	80
Average solder layer thickness per tape in slab/μm	7
Slab dimensions/mm	30 x 30 x 3.2
Slab number of tape layers	40
Total length of tape used in slab/m	2.4

12 mm wide solder plated HTS tape produced by SuperOx was used to create the slab shown in Fig. 2.(a)., with the full tape properties given in Table I. The slab was created by cutting and stacking 30 mm long pieces of tape with two tape pieces per layer. A single stacking unit consisted of the two layers half offset (shifted by 6 mm) in order to create a 30 mm square unit as shown in Fig. 2.(c). which is the maximum square size that could be accommodated in our test system. An isotropic arrangement was chosen such that the stacking unit was rotated by 90˚ through the stack. Other arrangements such as anisotropic arrangements where each stacking unit is rotated 180˚ through the stack also exist, as well as well as stacking two layers in a unit 'face to face' such that the HTS layers are separated only by the stabilizer and solder. A full investigation of the effect of these different arrangements is left for future study.

Once the layers were arranged, the stack was compressed with 735 N of force and heated to 215˚C, melting the solder and bonding the layers together. Most of the initial solder plating layer of 10 μm per side (20 μm in total), was expelled leaving only an average total of 7 μm per tape. Subsequent polishing on a grinding wheel easily achieved high tolerances for the slab widths and thickness, a process more challenging for brittle bulk (RE)BCO material.

The ideal choice of a PM field source for our tests would be like the PM arrangements shown in Fig. 1. for the planar bearing. However it is harder to obtain such ring magnets of the desired size and strength unlike simply stacking cylindrical PMs together with opposite poles [10] which is an excellent small-scale imitation of the cylindrical type rotor used in bearings. Flat pot magnets are available which produce high field gradients but typically have very low field magnitude more than 1 mm away from their surfaces. Therefore a single 25 mm diameter Nd-Fe-B magnet was used as shown in Fig. 2.(b). which produced a center field of 0.42 T, 0.5 mm from its surface at 77 K and below, corresponding to a remnant magnetization of 1.4 T which was used in FEM modelling.

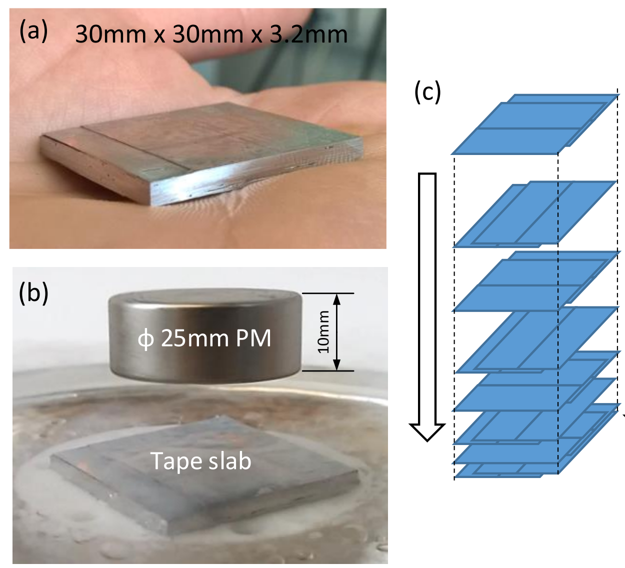

Fig. 2. (a) Slab made from solder plated HTS tape can be machined and polished to give high geometric tolerance. (b) A 25 mm diameter Nd-Fe-B magnet was used for levitation force tests. (c) Stacking arrangement for the slab with a half offset pair of tapes in each layer.

B. Levitation Force Measurement System

The levitation force measurement 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. This allows cooling of samples down to 10 K. As a result, 3 temperatures were chosen for the tests, 77.4 K, 45 K and 20 K to investigate temperature dependence. The slab was heated up to 100 K between temperature stages using a local heater in order to ensure a current free sample when field cooling for the next test. The slab was secured with a 1 mm thick stainless steel plate and the field cooling gap (between PM and slab surface) was 1.5 mm which is the smallest that could practically be achieved. As a results, hysteresis loops were conducted only increasing the gap from this position and then returning rather than approaching closer than 1.5 mm which would undoubtabley give the largest forces. A step size of 0.1 mm was chosen to achieve sufficient resolution with measurements being taken stepwise, pausing before reading force from a load cell. The measurements can therefore be considered quasi-static rather than dynamic. Further details and schematics of the levitation force system can be found elsewhere [13].

III. Levitation Force Results

A. Field Cooled Slab

Fig. 3. shows the force hysteresis results for the slabs when increasing the gap to 25 mm and then returning to the 1.5 mm field cooling gap. Significant hysteresis is observed for large displacements at 77.4 K which corresponds to irreversible behavior. This hysteresis is reduced when decreasing the temperature and is lowest for 20 K as expected due to an increase in J_c. The largest force magnitude was 18.0 N for 20 K.

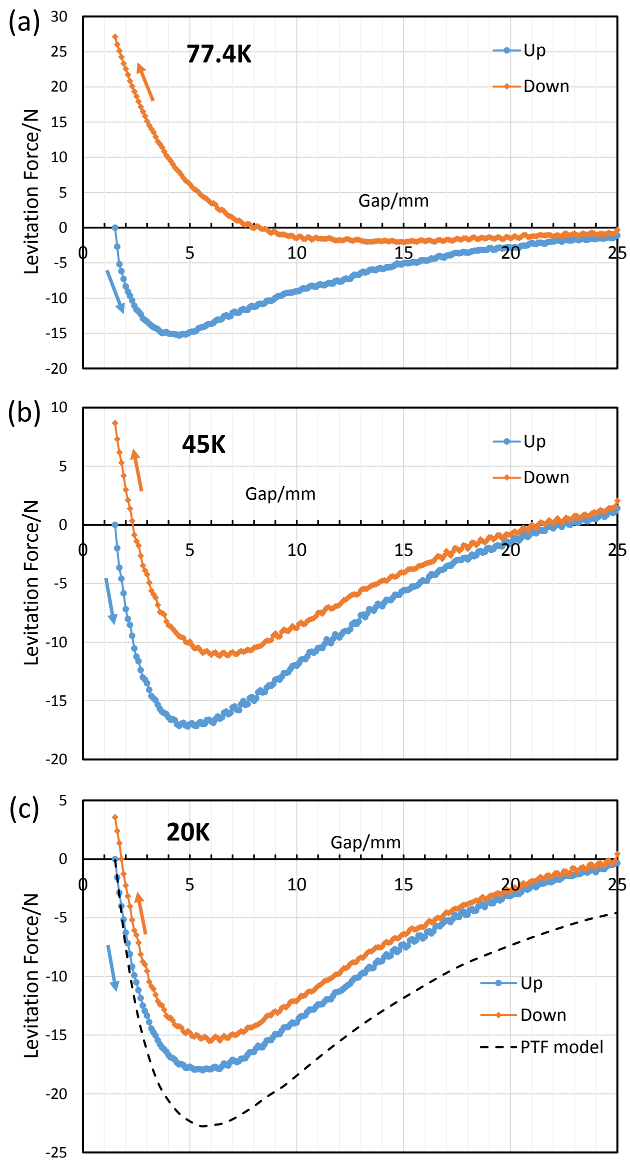

Fig. 3. Hysteresis force curves for the 30 mm square slab and PM, field cooled with a 1.5 mm gap at various temperatures. (a) The 77.4 K curve shows significant hysteresis but still has stability for displacements below 4 mm. (b) 45 K has decreased hysteresis and increased magnitudes. (c) 20 K has the highest force magnitudes and lowest hysteresis.

For comparison, an axisymmetric Perfectly Trapped Flux (PTF) model was implemented in COMSOL Multiphysics 5.1 to predict the maximum force a superconducting object of specified dimensions can give rise to by assuming infinite J_c. The model works by perfectly preserving the flux inside the superconductor at field cooling regardless of movement of the field source. This can be seen in Fig. 4. for the flux lines at a 4 mm gap and corresponds to induced surface currents. It is the distortion of the field lines, as can be seen in the figure, which give rise to restoring forces that are calculated using a Maxwell surface stress tensor. More details of how this model is implemented can be found elsewhere [14,15]. The slab was approximated as a 30 mm diameter disk with the same thickness as the real slab. The largest force magnitude for the 'up' curve of 20 K is 21% lower than the PTF model, however this difference is less for smaller displacements which are more relevant to applications. The results suggest that the stacking arrangements and slab size may be further optimized to reduce the difference between PTF model and experiment for the PM used, when displacing by more than a few mm. It is important to note the reasons why the forces measured are smaller than those measured for a PM stack inside HTS pancake coils acting as bulk hollow cylinders [10]. As mentioned before, both the field magnitude and field gradients are lower for the PM used here which can be seen in Fig. 4. Also, the active surface area between the PM and slab is about 4 times smaller than for the previously published cylindrical test. One puzzling feature of the hysteresis that cannot easily be explained, is why the force becomes positive for large displacements in the 45 K case. Basic modelling predicts the $F = 0$ line as an asymptote for large displacements. The current flow inside composite bulks such as this slab can be difficult to understand without detailed 3D FEM modelling which could be performed in future to gain a more detailed understanding of the relation of levitation force to currents within the slab.

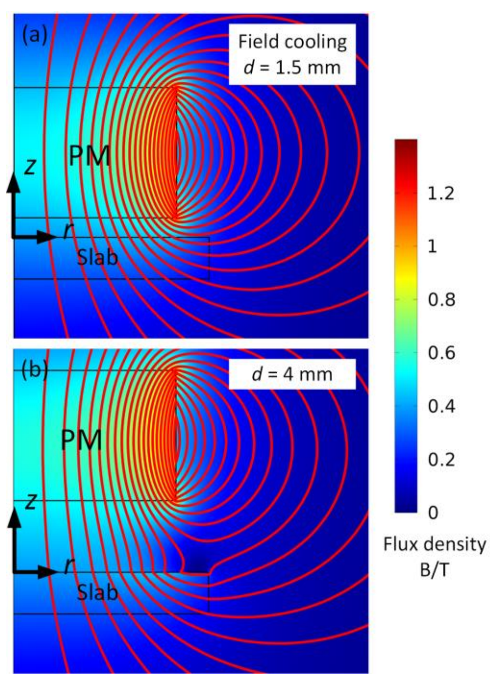

Fig. 4. Perfectly Trapped Flux model results. (a) Flux lines and flux density for the PM and slab in the field cooling position. (b) Flux lines and flux density for an example displacement showing the preserved flux line pattern inside the field cooled slab and resulting flux distortion outside.

B. *Field Cooled MgB_2 Bulk Disk*

In order to compare the performance of the slabs to the simplest case of a bulk superconductor, tests were performed on a 46 mm diameter, 11 mm thick MgB_2 bulk disk using the same PM as for the slab and also the same 1.5 mm field cooling gap. The best MgB_2 bulks are known for their uniform and isotropic J_c properties and polycrystalline form allowing for easily modelled and understood current flow when field cooling. The bulk used was produced by Edison SpA using the reactive liquid Mg infiltration process [9] capable of producing bulks of different shapes including hollow cylinders for magnetic levitation [16,6]. Due to its larger size, the bulk produced larger levitation forces than the slab as expected which is shown in Fig. 5. The hysteresis was small in this case which indicates a high J_c and is also partly due to the larger bulk size. The force curve closely matches the PTF model predictions for less than 10 mm gap showing that the model is a good approximation for the bulk. The growing difference between the PTF model curve and experiment is not fully understood but could be a result of the changing domain alignments in the Nd-Fe-B magnet at cryogenic temperatures. Only the surface field can be measured in our system and is used to give a value to the uniform axial magnetization of the PM in the model.

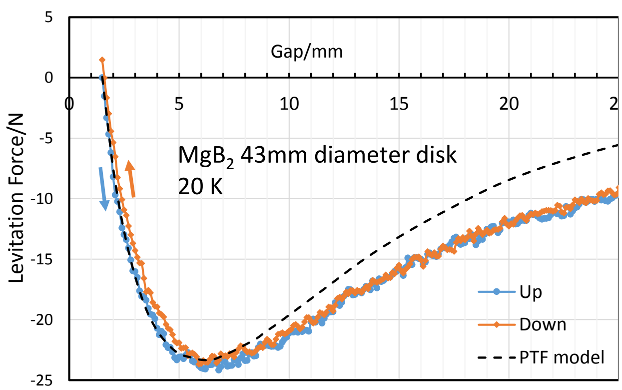

Fig. 5. Hysteresis force curves for a 46 mm diameter, 11 mm thick MgB_2 bulk and PM, field cooled with a 1.5 mm gap at 20 K.

A comparison of the force results between the slab and MgB_2 bulk show that although the MgB_2 bulk produced a larger force due to its larger size, the peak force for the slab was only around 20% smaller than the bulk despite the slab being about 5.5 time smaller in volume.

Although these initial results are positive, further improvement can be expected when tailoring the slab for the type of PM tested by, for example, increasing its thickness which may allow it to behave more like an ideal superconducting bulk as described by the PTF model curves. However the slab may be close to optimum for small sub-mm displacements (currently difficult to test in our system) and high magnetic field gradients such as those produced by Halbach arrays in linear bearings.

IV. Summary

Axial force tests between a cylindrical PM and a 30 mm square slab of HTS tape have confirmed that stable levitation can be achieved by the slabs with up to 18 N measured. Force hysteresis is significantly reduced by lowering temperature. A comparison to experimental force curves for an MgB_2 bulk shows that the slab performed well considering its size although further optimization may be needed for the specific type of PM used considering the PTF model. It may be that a thicker slab would appear to behave closer to an ideal superconducting bulk of infinite J_c described by the PTF model, considering the low field gradients produced by our PM. Future tests will include testing other stacking arrangements including anisotropic slabs, ones with 'face to face' stacking and larger slab sizes. Halbach PM arrays will also be used to compare the forces for slabs to those produced by (RE)BCO bulks. Dynamic stiffness tests will be performed for amplitudes < 1 mm and frequencies > 10 Hz which is relevant for real bearing applications.

There are a number of practical advantages for stacks of tape over conventional (RE)BCO bulks for magnetic levitation applications, which drive continued research. Their superconducting properties are consistent and reproducible due to the growing scale of the commercial coated conductor industry. The geometry is highly flexible and can be precisely tailored. They also have high thermal stability and mechanical strength which aids their cooling and mounting respectively.

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