IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2015.
EUCAS 2015 poster paper 3A-LS-P-04.08. EUCAS Young Investigator Prize 2015 in Large Scale.
Submitted to *IEEE Trans. Appl. Supercond.* for possible publication.

Magnetic levitation between HTS tape stacks and permanent magnets for rotary bearing applications

3A-LS-P-04.08

UNIVERSITY OF CAMBRIDGE | SKF | ASCG APPLIED SUPERCONDUCTIVITY AND CRYOSCIENCE GROUP

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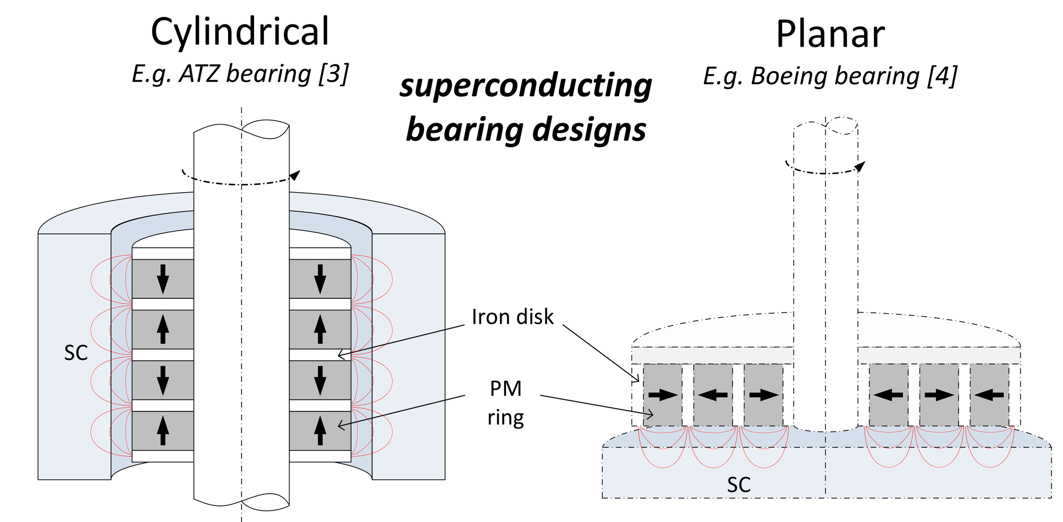
1. Introduction – stacks of tape as composite bulks



Stacks of superconducting tape can be used as composite superconducting bulks for both trapped field magnets and for magnetic levitation. Previous experiments performed by the current authors showing that 12mm square stacks can trap over 7 T [1] but there exists little previous quantitative work on the magnetic levitation performance of stacks of tape especially below 77 K. Some previous work has investigated performance in the context of maglev applications [2], however our present research effort 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 on the left, and the axial levitation force results presented, prove that stacks of tape can generate stable levitation force giving them potential for bearing applications. By creating slabs (such as the one shown on the right) or pancake coils, HTS tapes can be applied to both cylindrical and planar geometries of potentially any size. They also have the advantage of having very consistent superconducting properties thanks to large scale coated conductor production.

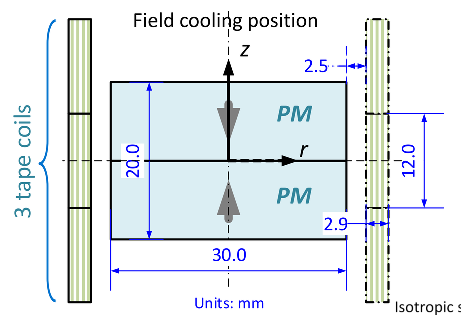
By overlapping standard 12mm wide HTS commercial tape, composite bulk slabs can be fabricated with potentially unlimited size.

2. HTS pancake coils and slab samples

Two sample geometries were created, pancake coils acting as bulk cylinders for cylindrical bearings and a stack of tapes in the form of a slab for planar bearings. The pancake coils were wound by ASCG using uninsulated SuperOx tape (12 mm wide, 65 µm thick, $I_{c,min}$ 430 A) having only silver stabilization. The slab was created with solder plated copper stabilized tape by SuperOx, compressing the tape layers 'face to back' with 735 N at 215°C. Cylindrical NdFeB PMs were used for coaxial field cooling of the coils and slabs.

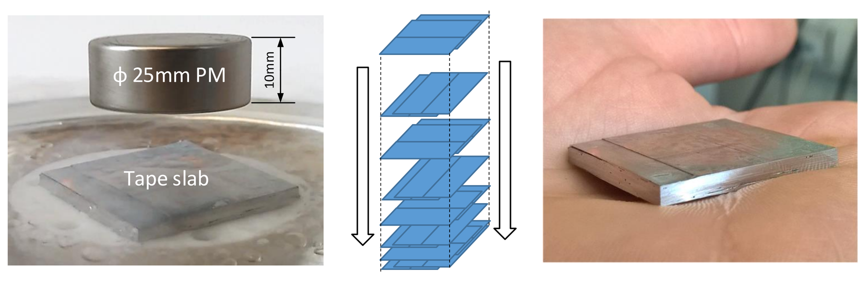
Cylindrical geometry

Coil parameters	
Coil inner diameter/mm	35
Coil thickness/mm	2.9
Number of turns per coil	39
Total Length of tape used/m	14.1

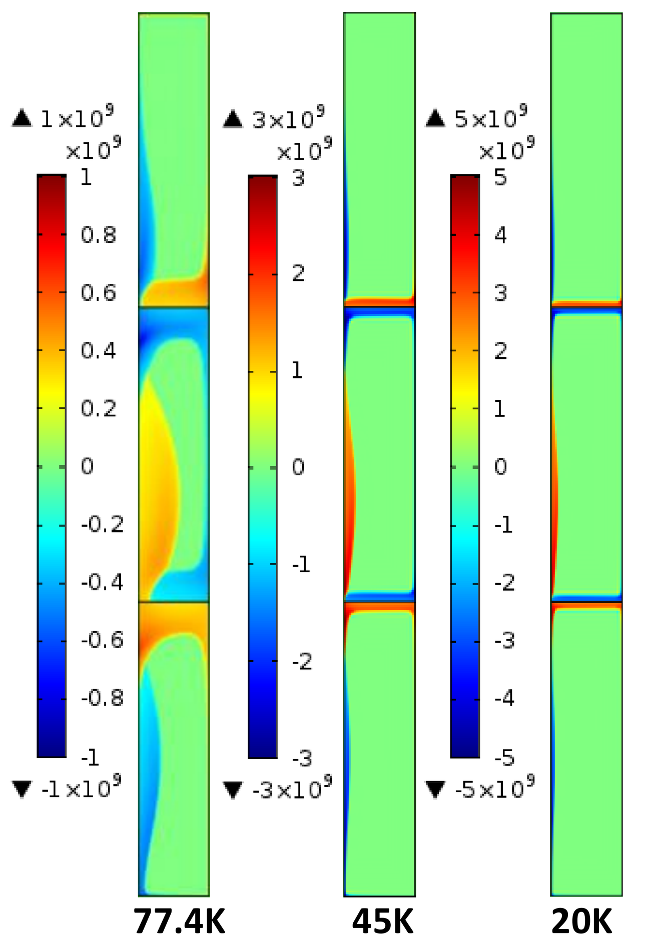


Planar geometry

Slab parameters	
Slab size/mm	30x30
Slab thickness/mm	3.2
Number of layers	40
Total Length of tape used/m	2.4



4. Critical state modelling



Induced currents in the cross-section of the tape coils modelled as axi-symmetric bulk cylinders with total current constrained to be zero in each domain

A critical state model was developed in Comsol Multiphysics 5.1 using an *E-J* power law and the *H*-formulation to simulate induced currents dependent on both temperature and field [5]. Readily available data for SuperOx tape was used to create an effective engineering current density for the coils with a Kim law field dependence and temperature dependent lift factor fitted to the data. A temperature and field dependent *n*-value was also used for reliable force creep simulation

E-J power law

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

n-value

$$n(B,T) = \frac{n_0}{1+B/B_{0n}}\left(\frac{T_{0n}}{T}\right)$$

Critical current density

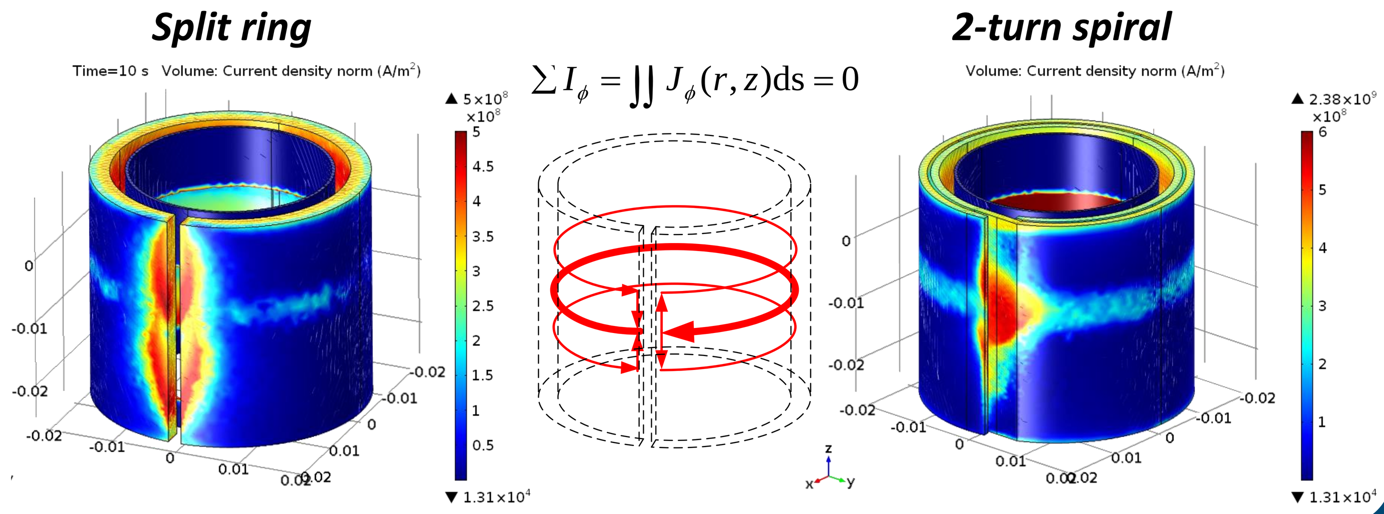
$$J_c(B,T) = J_e = \frac{I_{c0}L_0(T)}{wd\left[1+B/B_0(T)\right]}$$

Lift factor in $J_c(B,T)$

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

Parameter	Value
n value	Movement: 9 Force creep: $n(B,T)$
$I_{c0} = I_c(77K,SF)$	500 A
Lift factor $L_0(T)$	$-0.135T + 11.725$
Kim law const $B_0(T)$	$-0.0103T + 0.9888$
Tape thickness d	65 µm

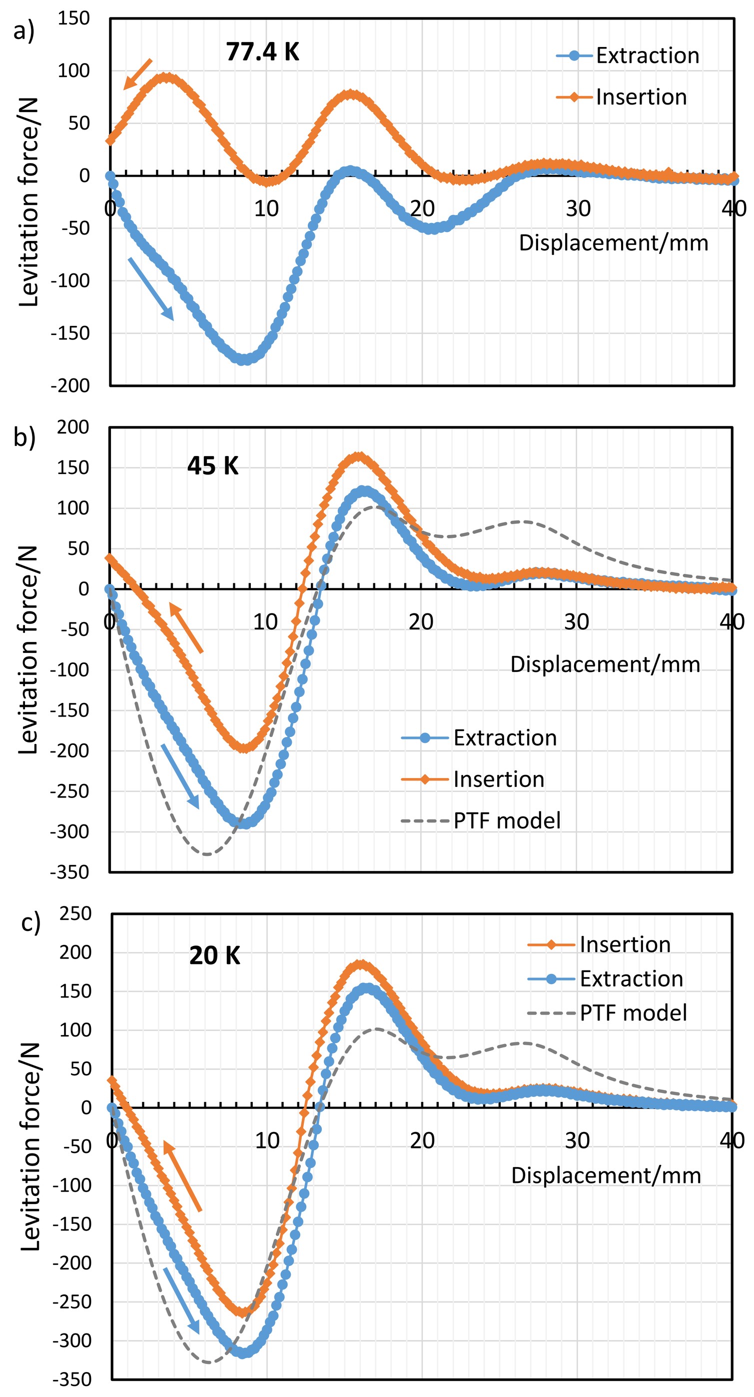
The figure above shows the induced currents responsible for the critical state (CS) levitation force curves plotted in Section 3. A constraint forces the total current circulating in each cylinder to be zero as the coils cannot sustain a net transport current which gives rise to extra current regions on the boundaries between the domains. The CS curves clearly show the decrease in force for increased temperatures which corresponds to currents being induced deeper into the cylinder walls. Consistency with the PTF model is achieved for 20 K where J_c is very high. 3D models shown below help explain where the current actually goes for domains that cannot carry a net circulating current such as a split ring or simple spiral. The graphs below show that current is diverted at the boundary and turns around to form the counter circulating currents. These diversions do not prevent the currents from sustaining levitation forces close to that for solid uniform superconducting cylinders explaining why pancake coils work.

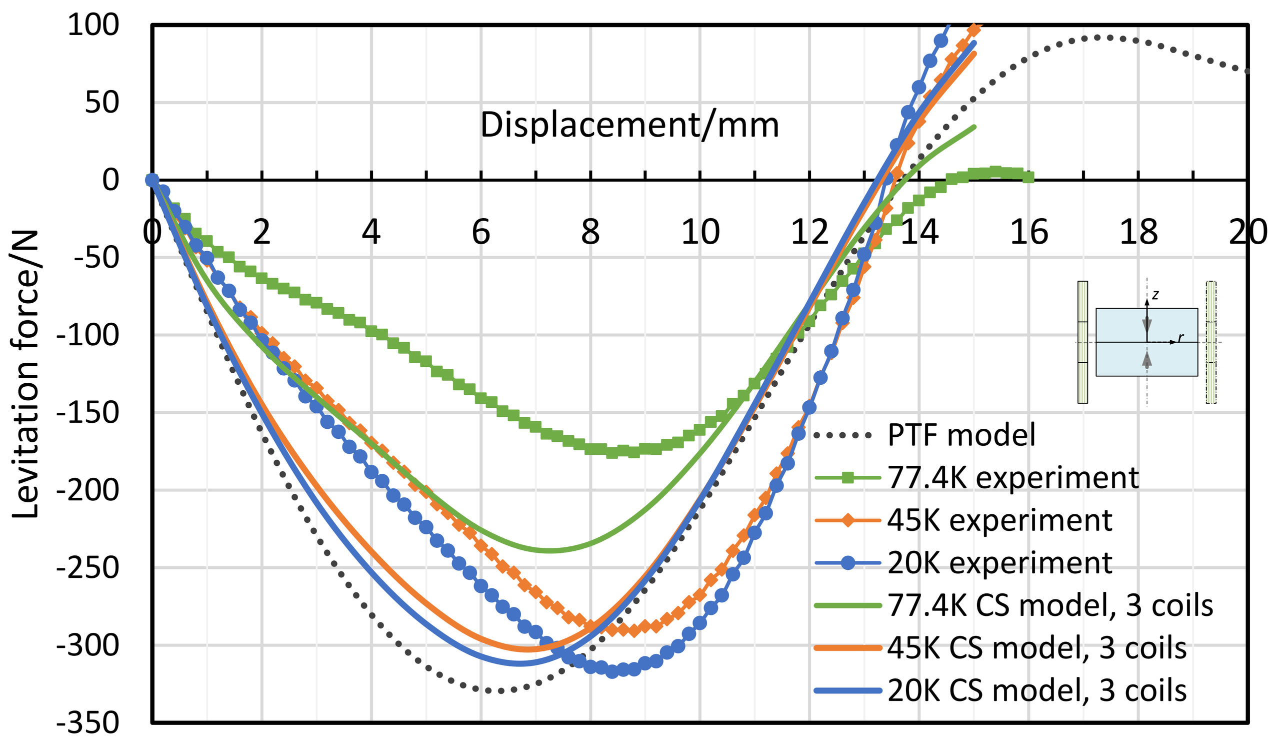


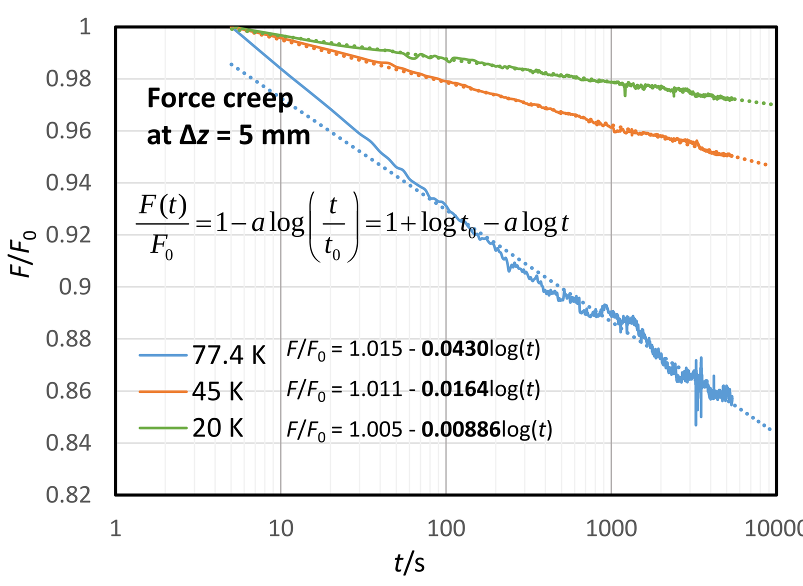
3. Levitation force measurements between PMs and coils/slab

Cylindrical geometry (coils)

The graphs on the right show the hysteresis force curves obtained for the PM pair inside the 3 coils, The PMs were moved from their field cooled position at 1 mm/s, stopping every 0.2 mm for force measurement. Hysteresis is large at 77.4 K but mostly disappears at lower temperatures due to increased J_c. **Over 300 N of force** can be generated at 20 K which is close to the theoretical maximum predicted for a uniform bulk cylinder with infinite J_c of the same dimensions as the coils. The theoretical curve comes from the Perfectly Trapped Flux (PTF) model [5] which effectively 'freezes' the flux inside the superconducting domain at field cooling. A summary of the force curves is shown below along with a comparison to critical state (CS) modelling which accounts for real induced currents as elaborated in Section 4. There is reasonably good agreement in terms of force magnitude although the peak in force occurs at a larger displacement than predicted.

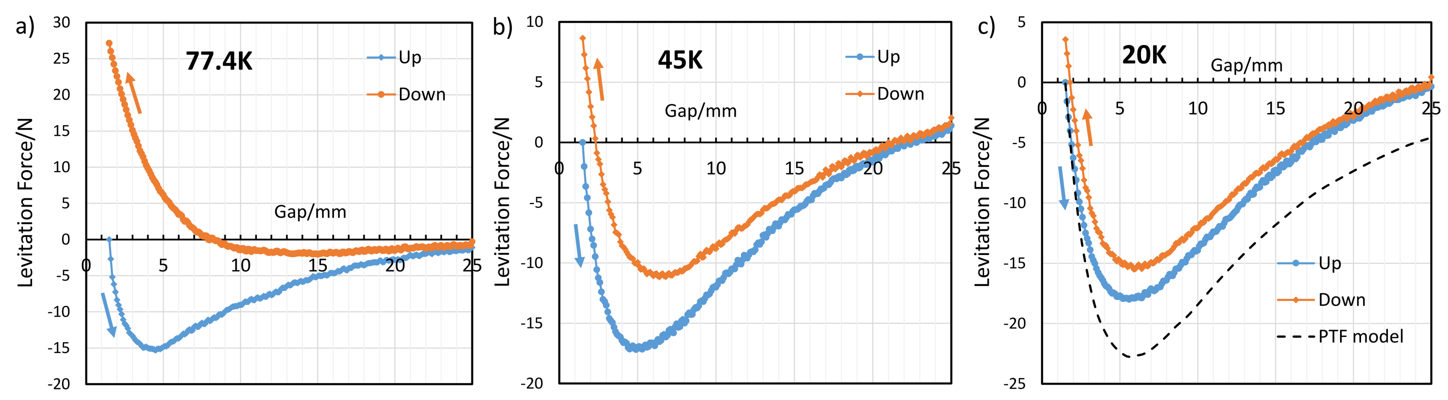






- **It is remarkable that any persistent force can be sustained by the coils** given that they do not allow any directly circulating current paths! This can be explained by the critical state modelling.
- Force creep measurements prove levitation force is stable and not purely dynamic. Δz = 5 mm chosen as this displacement gives a stable force with large margin for overload (force gradient must be negative for stability).
- Logarithmic decay measured which matched expected behaviour for a bulk cylinder with reduced creep rate for lower temperature
- Force creep rates *a* are similar to bulks and as low as **0.9% per time decade** for 20 K

Planar geometry (slab)



Hysteresis curves on the left show the force obtained between the 25mm PM and the slab when field cooling at a 1.5 mm gap. The smaller forces are expected due to the lower field produced by the single PM, and significantly lower field gradients.
The PM-superconductor active area is also ≈ 4 times smaller than for the cylindrical case. As for the coils, the hysteresis is reduced and force magnitude increased when lowering temperature. There exists a larger difference between the PTF model for an ideal superconductor and the 20 K force curve motivating further optimisation of the slabs for this levitation geometry.

5. Conclusions

- Stable axial magnetic levitation has been proven for HTS tape coils and slabs acting as composite superconducting bulks with cylindrically symmetric field sources. This is despite the samples having < 2% (RE)BCO by volume.
- Forces over 300 N were measured which, for the lower temperatures, is close to that expected for an ideal bulk with infinite J_c
- The pancake coils have potential to be used as passive components in cylindrical type bearings and the slabs in planar type bearings for applications such as flywheel energy storage
- The main practical advantages of stacks of tape such as the coils and slab tested are: **consistent superconducting properties, flexible geometry, high thermal stability and mechanical strength** giving them potential for engineering applications

FUTURE WORK

- Future tests include using wider tape for coils and slabs and also using 40 mm tape annuli which allow net circulating current
- A variety of stacking arrangements for slabs can be evaluated and experiments scaled to test larger slab sizes
- Dynamic stiffness tests will be performed for amplitudes < 1 mm and frequencies > 10 Hz which is relevant for applications

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EUCAS 2015