Magnetization of rectangular 2G HTS stacks and dragging forces developed inside a multipolar magnetic channel: trapped field, current distribution and forces

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Abstract. It is well established that stacks of 2G HTS tapes suppose an interesting alternative to the use of YBCO bulks in many applications involving superconducting trapped fields, such as: electrical thrusters, motors or levitation devices. The analysis of the inhomogeneous magnetization processes is a fundamental topic to determine the performance of stacks in such devices.
In this work, the behaviour of rectangular stacks with lengths of 30 mm and 60 mm, built from different commercial 2G HTS tapes of 12 mm width, is experimentally studied focusing on the magnetic field trapping performance and the dragging forces over the stack when interacting with an external inhomogeneous magnetic field.
Trapped magnetic field distribution was measured with a scanning Hall probe magnetometer after a magnetization process of the samples done by applying an inhomogeneous magnetizing field produced by a sequence of pairs of opposite permanent magnets (PM). The current density distributions were obtained by solving the quasi-3D inverse problem. The trapping capability was also compared to that obtained when homogeneous magnetizing fields were applied with an electromagnet.
The forces developed when the sample was displaced inside the gap between two opposite PM arrays, the magnetic channel, were measured. The experiments were performed by cooling the stack inside the channel (FC) or dragging it to the magnetic channel after cooling it outside, in zero field conditions (ZFC). A load cell was used in two ways in order to measure the magnetic forces in the stack when it was displaced through the magnetic channel. In the experimental rig the velocity of the displacement can be controlled thus allowing the exploration of the influence of the scan speed. The forces associated to the electromagnetic interaction and the induced current distributions in the stack were evaluated.
Experimental data are phenomenologically discussed in order to assess the relevant parameters when applying the stacks on devices and compared with existing simulations.

SAMPLES

Stacks made of SuperPower 2G superconducting tapes
Table I. Parameters:

Sample (Stack Name)	Tape used	I_c (A) 77K Self-field	Layers	Width (mm)	Length (mm)	Total Thickness (mm)	Mass (g)
L30-AP	SF12050-AP (advanced pinning)	281	9	12	30	0.510	1.48
L60-AP	SCS12050-AP (Advanced pinning)	364	9	12	60	0.866	4.95
L60-CF	SF12100-CF 2.5Ag (Cable Formulation)	392	9	12	60	0.997	5.99

Hall probe measurements

- We show in this work measurements of the vertical magnetic induction field B_z in the remnant state after a sample magnetization in a FC process at 77K, when the applied magnetic field was eliminated.
- Distance between the sample surface and the Hall probe: 0.45 mm
- Grid steps in a rectangular grid of the measured $B_z(x,y)$ map: $\Delta x = 5\ \mu m$ (transversal axis), $\Delta y = 200\ \mu m$ (longitudinal axis)
- Hall probe active area = 300 x 300 μm^2

Computation of current density distribution

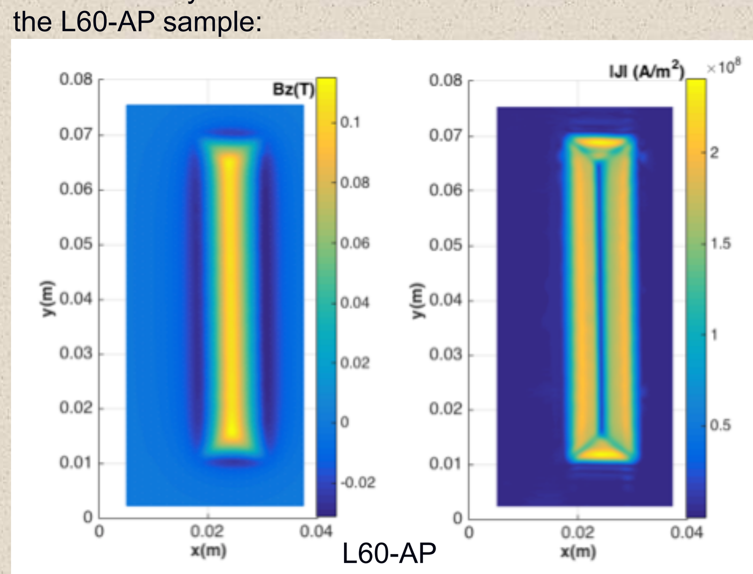
- The current on the stack sample has been computed using the discretization and inversion procedure for thin films and bulk domains developed by the authors, which can be applied both to closed circuits and to domains with transport of current.
- The inversion of the resulting linearized system yields 2-dimensional maps for the magnetization M and planar circulating current density $\mathbf{J}=(J_x J_y)$.
- In the case of a stack, the computed magnetization M, resp. current **J**, are the average along thickness, i.e. over stacked tapes, of their M, resp. **J**.
- The magnetic field induced by the stack with the calculated current **J** in all its layers matches the measured field with an error below 1%.
- The current maps have been obtained with a resolution of 0.175 x 0.2 mm², which has been achieved through SSA filtering of the Hall probe measurements and Fourier inversion of the linear system (to be discussed elsewhere).

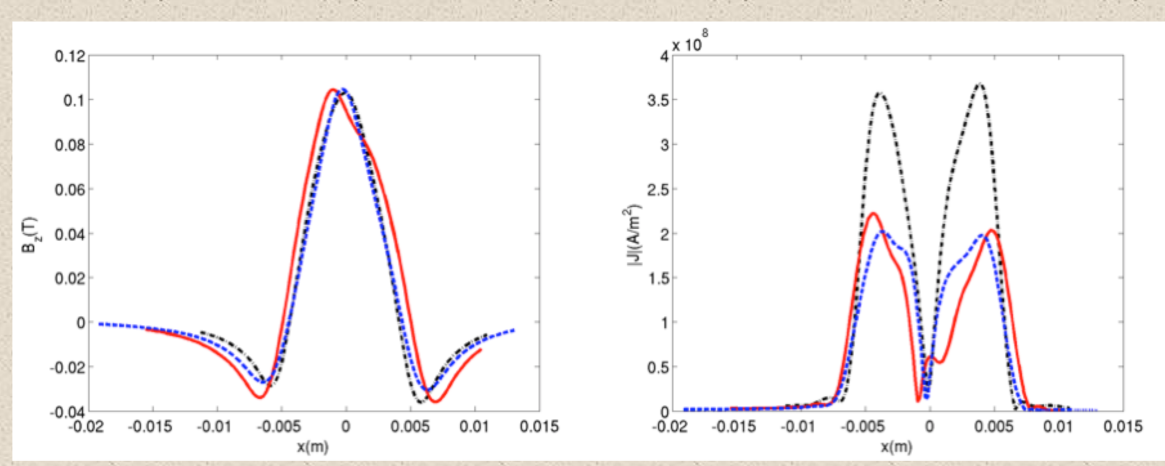
Trapped fields and current distributions from Hall probe measurements

I. Homogeneous FC magnetization process

Homogeneous applied field B_{ap}= 1T using an electromagnet

Trapped magnetic field $B_z(x,y)$ in the remnant state was measured for the 3 sample, and a map of computed current density was obtained. Below we show the result for the L60-AP sample:





Cross section profiles of: (A) measured magnetic field $B_z(x)$ taking the central position of each sample as a origin for this comparison; (B) computed current density at the same positions. Samples: L30-AP black, L60-AP blue, L60-CF red.

Table II. Summary of results for 3 samples

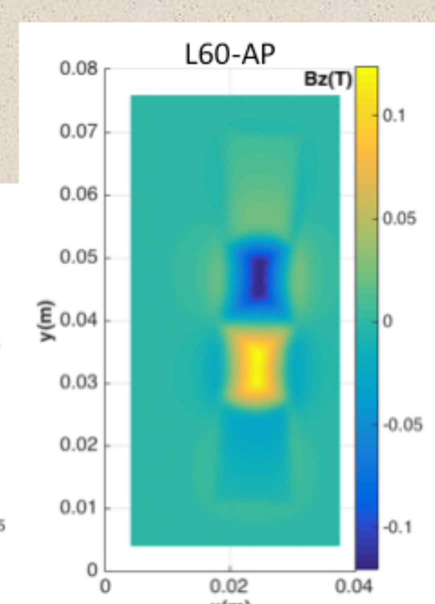
sample	Trapped field max B_z(mT)	Calculated density J_c(A/m²)	Expected engineering density (see Table I) J_c(A/m²)
L30-AP	105	3.8 x 10⁸	4.13 x 10⁸
L60-AP	112	2.4 x 10⁸	3.15 x 10⁸
L60-CF	110	2.3 x 10⁸	2.95 x 10⁸

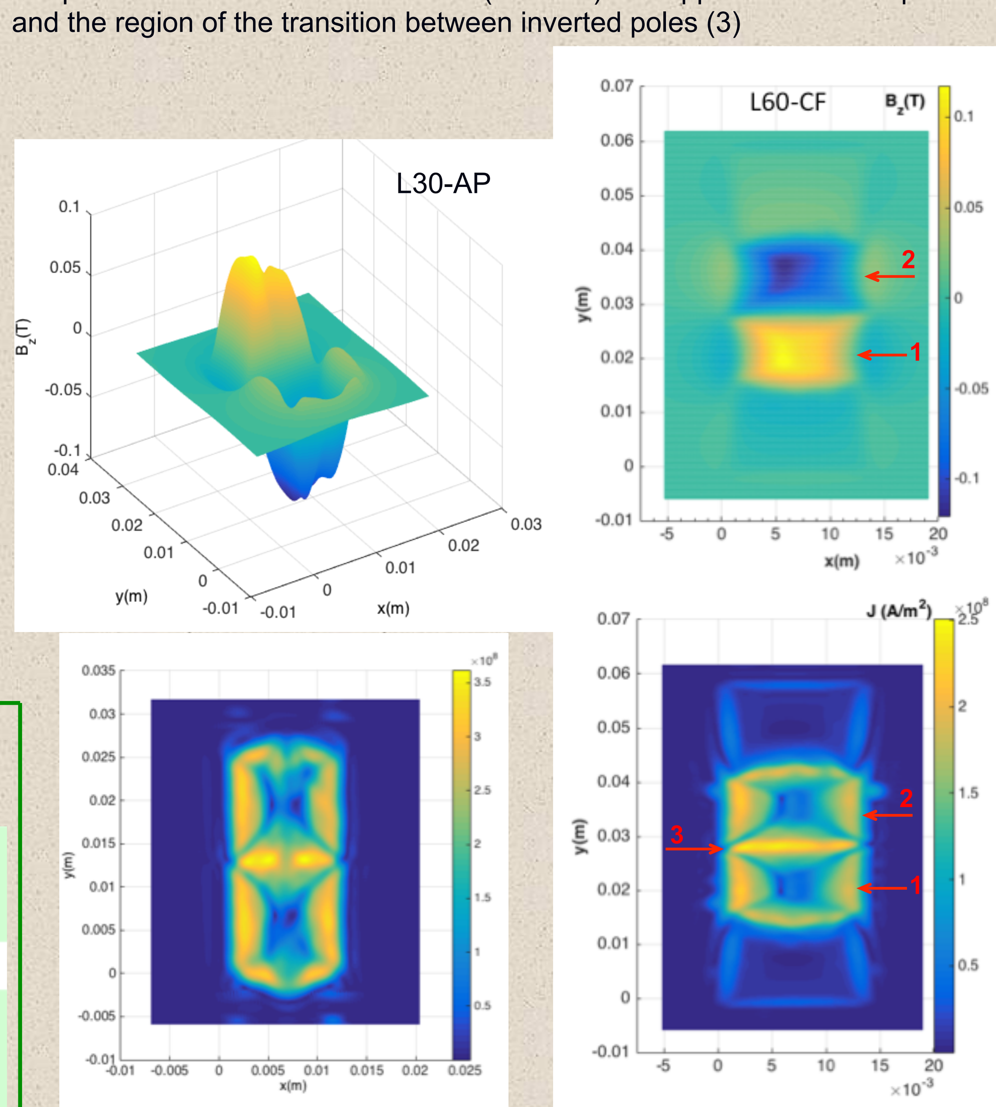
The measured field distributions are those expected for rectangular thin samples with high uniformity in their superconducting properties. The maximum values of trapped field are around 10-12% of applied field. The computed current distributions on the stack samples shows that current forms a ring around the stack with a maximum values indicated in Table II. It is worth to remark that those values correspond to the so called engineering current density, which considers the section of the full sample, not only superconducting layers. Comparing the values with the expected engineering densities according I_c given by the manufacturer, the differences are within the reasonable margin of dispersion.

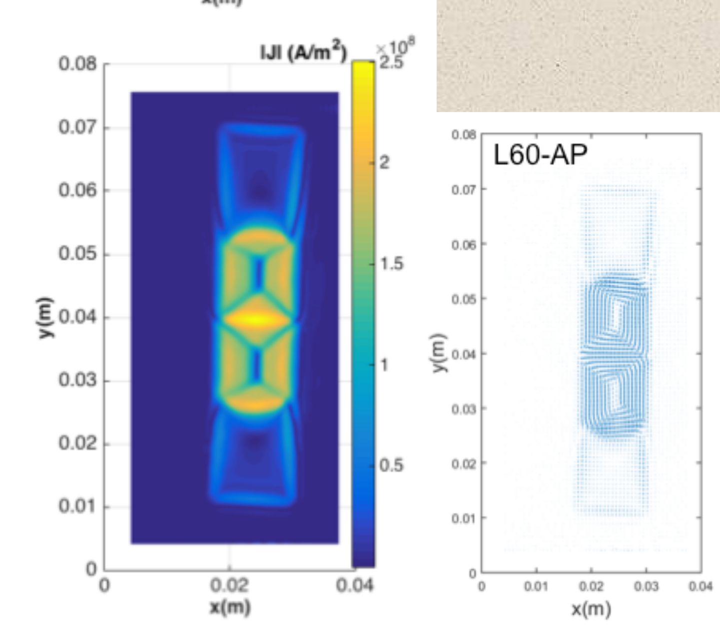
II. Inhomogeneous FC magnetization process

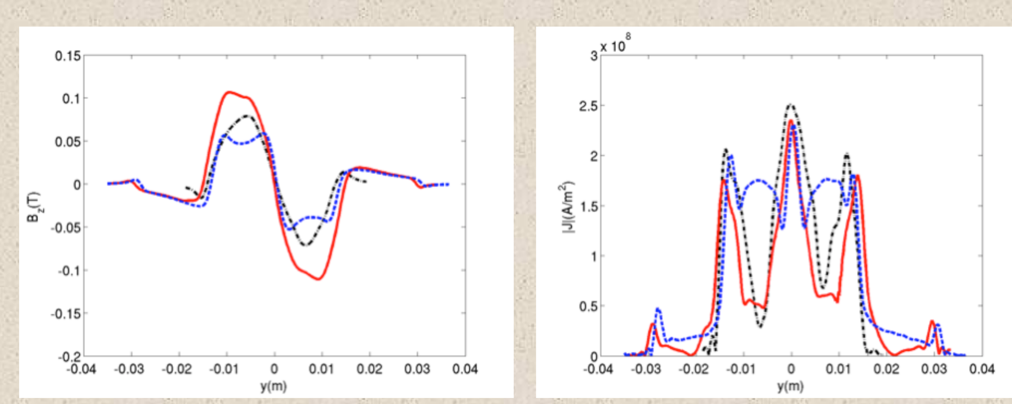
Field was applied using 2 permanent magnets Nd-Fe-B of 10 mm width each one in a sequence of inverted poles

Hall probe measured trapped field distributions in the remnant state, and their corresponding maps of the computed current density. Arrows indicate the positions of the maximum value (1 and 2) of trapped field in the poles and the region of the transition between inverted poles (3)









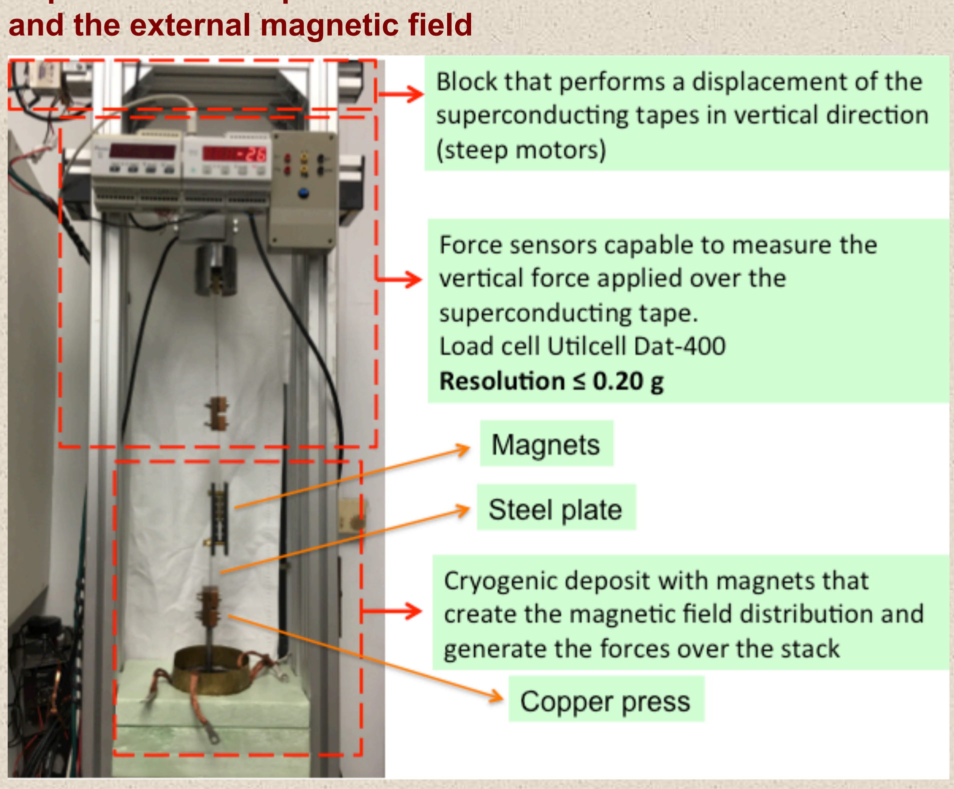
(A) Magnetic induction longitudinal sections (taking the central position of each sample as a origin for this comparison); (B) Longitudinal sections of computed current density at the same sections.
Samples: L30-AP black, L60-AP blue, L60-CF red

Table III. Summary of results for 3 samples

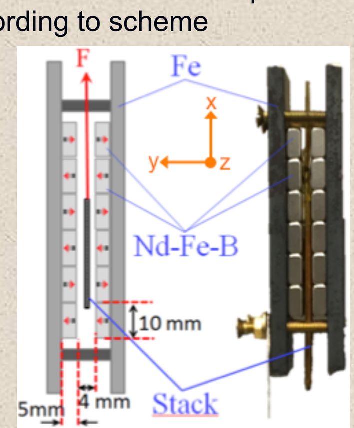
sample	Trapped field Pole 1 B_z(+) B_z(mT)	Trapped field Pole 2 B_z(-) B_z(mT)	Calculated J_c (A/m²) (region 3)	Calculated J_c(A/m²) current ring around pole1(+)	Calculated J_c(A/m²) current ring around pole2(-)
L30-AP	86	87.8	3.6x10⁸	1.9x10⁸	1.7x10⁸
L60-AP	119	117	2.5x10⁸	2x10⁸	2x10⁸
L60-CF	107	111	2.5x10⁸	2.1x10⁸	2.1x10⁸

The structure of the trapped field reproduces the configuration of two reversed poles in which there are no significant asymmetries, with values of the trapped field higher than 15% of applied field.
The current forms two running rings with opposite senses of movement. Both rings have individual peak values summarized in Table III, and a central region (here named region 3) of superposition of current loops where the current density reach the maximum value. We can observe that those values are closer to their respective values determined in the homogeneous magnetization process.

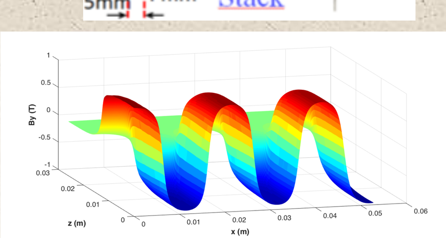
Experimental setup to measure the force between stack and the external magnetic field



Multipolar magnetic channel
The magnets system is composed by six pairs of Nd-Fe-B magnets that configure an alternate horizontal magnetic field in each pair of magnets according to scheme



Initial position of the stack when it is cooled:



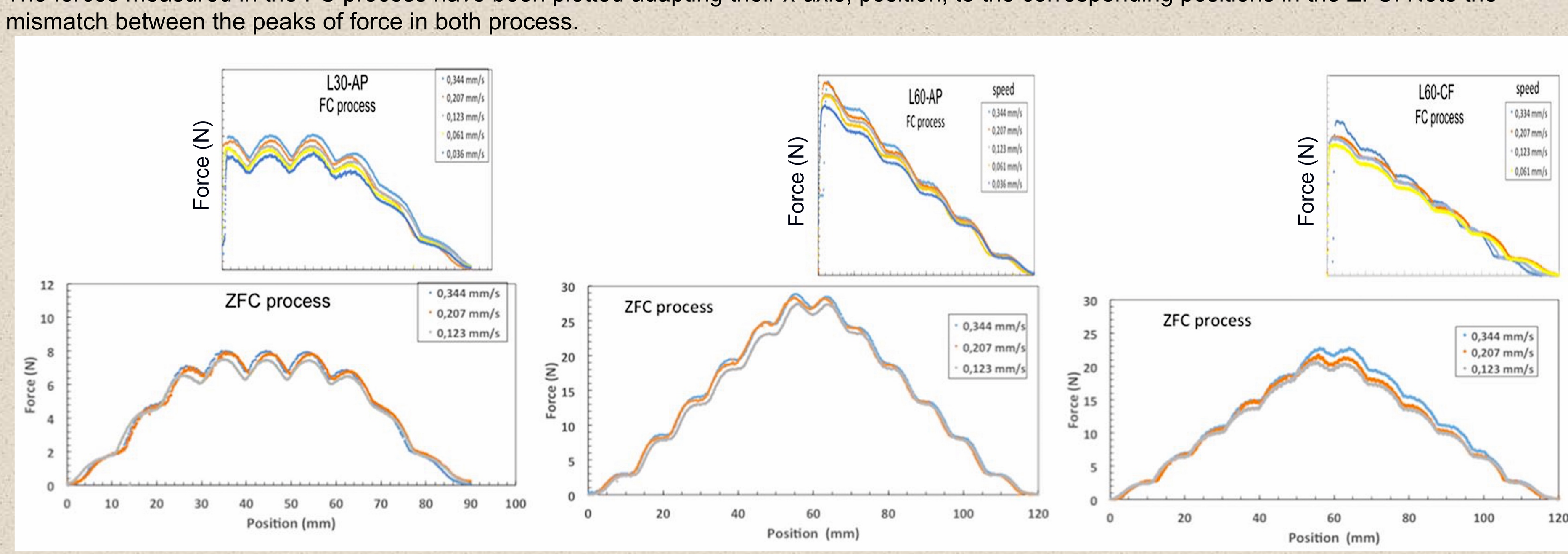
Transversal component B_y of the magnetic flux density in the gap region of the multipolar magnetic channel measured with the Hall probe system

In terms of superconducting devices the experiment allows to study of the behaviour of tape stack as a rotor while multipolar channel acts as an stator

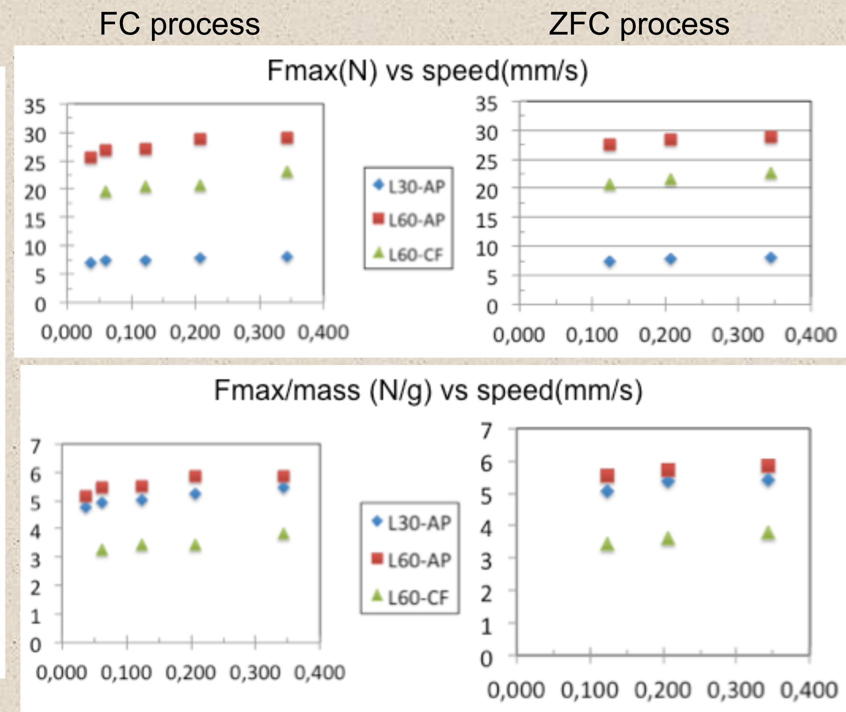
Dragging forces over the stack interacting with an external inhomogeneous magnetic field

Measured force results for each sample. The experiment was made for different velocities of the stack displacement inside the magnetic channel and was performed for both FC and ZFC cooling processes

The forces measured in the FC process have been plotted adapting their x-axis, position, to the corresponding positions in the ZFC. Note the mismatch between the peaks of force in both process.



Summary of the results obtained for the maximum forces measured over the satcks



Several speeds of stack movement have been tested in order to evaluate different rates of the induced critical currents.
The relationship between sample length and magnetic channel length (60 mm) determines the effect of the edges in the interaction with the magnetic field, and consequently the oscillation in the value of the force.
Logarithmic dependence between the force and the traveling speed is observed from the measured values.
The force per unit of active mass (considering all mass of the stack) is in the order of 5-7 N/g, higher than the ones achieved in conventional linear motors. So, the results confirm the potential of 2G tapes to be used in this type of devices.
Experimental results showed in this work provide an important set of parameters that will be necessary for the development of simulation models (i.e. 2D simulation using H-formulation implemented by FEM) for the forces in order to scale up the tape stack properties towards device applications.

In the context of this work, we recommend other recent works of our group:
- EUCAS 2017: 1LP3-17 "Dragging hysteresis forces in a linear displacer with Coated Conductor Stacks" J. López et al.
- "Proposal of a novel design for linear superconducting motor using 2G tape stacks" G.G. Sotelo et al. (to be published)

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