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

- **Magnetic system:** The magnetic system is composed by six pairs of Nd-Fe-B magnets that configure an alternate horizontal and magnetic field in each pair of magnets according to scheme.
- **Initial position of the stack when in contact:** PC
- **Transversal component B_{t} of the magnetic field flux density:** The transversal component of the magnetic field flux density in the gap between the sample and the 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.

Acknowledgments

Spanish Government for Severo Ochoa Programme (Centres of Excellence in R&D: SEV-2015-0539); Consolider Excellence Network (CSD2009-00067:RSD) and project MAT2014-56683-C2-1-R; European Union for EUTOPA/TES project (FP7-NMP- Large-2011-986); Catalan Government for 2014-SGR-753; Spanish Government for Severo Ochoa Programme Centres of Excellence in R&D.

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**Abstract.** It is well established that stacks of 2G HTS tapes suppose an interesting alternative to the use of YBCO bulk 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 behavior 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 in 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.

### Hall probe measurements

- **In this work:** Hall probe active area = 300 x 300 µm²
- **Grid steps in a rectangular grid of the measured B\(\times\)(x,y) map:** \(\Delta x=5\) µm (transversal axis), \(\Delta y=200\) µm (longitudinal axis)
- **Hall probe active area:** 300 x 300 µm²

### Computation of current density distribution

- **The current on the stack samples 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.**
- **In the case of a stack, the computed magnetization M, resp. current J, are the average along thickness, i.e. over ap: current density j(x,y).**
- **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 117 x 0.2 mm², which have also been obtained 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

- **Trapped magnetic field B_{t}(x) in the remanent state was measured for the 3 samples, and a map of computed current density was obtained. Below we show the result for the L60-AP sample.**

#### II. Inhomogeneous FC magnetization process

- **Hall probe measured trapped field distributions in the remanent state, and their corresponding maps of the computed current density.**

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

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

### Experimental results

- **The structure of the trapped magnetic field reproduces the configuration of the reversed poles in which there are no significant asymmetries, with values for the in-phase and quadrature components.**
- **The currents form two running rings with opposite sense of movement. Both rings have individual peak values summarized in Table II, and in central region (here named region 3) of superposition of current loops 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.**

### Summary of the results obtained for the maximum force measured over the stack

- **The measured field distributions are those expected for rectangular stack samples with magnetic field 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 show that current density reach the maximum value where the current density reach the maximum value.**
- **The relationship between sample length and magnetic channel length (60 mm) determines the effect of the edges in the interaction with the magnetic channel.**
- **The interaction between inverted poles (3) forms a ring around the stack with a maximum values indicated in Table II.**

### Table II. Summary of results for 3 samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>Trapped Field B_{t}(x)</th>
<th>Current Density j(x,y)</th>
<th>Expected engineering density (see Table I)</th>
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</thead>
<tbody>
<tr>
<td>L60-AP</td>
<td>105</td>
<td>3.0 x 10^6</td>
<td>4.1 x 10^6</td>
</tr>
<tr>
<td>L30-AP</td>
<td>112</td>
<td>2.4 x 10^6</td>
<td>3.1 x 10^6</td>
</tr>
<tr>
<td>L60-CF</td>
<td>120</td>
<td>2.3 x 10^6</td>
<td>3.9 x 10^6</td>
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- **The measured forces have been plotted adapting their x-axis, position, to the corresponding positions in the ZFC.**
- **Note the logarithmic dependence between the force and the traveling speed is observed from the measured values.**
- **The relationship between sample length and magnetic channel length (60 mm) determines the effect of the edges in the interaction with the magnetic channel.**
- **The interaction between inverted poles (3) 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 densities which only considers the section of the full samples, not only superconducting layers.**
- **Comparing the values with the expected engineering densities according to given by the manufacturer, the differences are within the reasonable margin of dispersion.**

### Table III. Summary of results for 3 samples

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

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