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***Abstract*—(RE)BCO bulks prepared by seeded melt growth process have a non-uniform local critical current density distribution along the c-axis. To clarify its impact, we measured the levitation force of such bulk above a permanent magnet in two configurations: bottom seed and top seed. This is only by considering a non-uniform J_c distribution, that we were able to reproduce both measurements with an H-formulation finite element model.**

***Keywords*—HTS bulk, critical current density, levitation force**

I. Introduction

High temperature superconductors (HTS) have the potential to trap or shield large magnetic fields at 77 K. This is particularly attractive for a variety of high field permanent magnet applications, including electrical machines and magnetic bearings. In an attempt to fabricate practical materials, (RE)-Ba-Cu-0 bulks ((RE)BCO where RE = rare earth element) have been developed by melt process techniques. The seeding requirement for the controlled fabrication of these material [1] is the root of several distinct features of seeded melt growth (RE)BCO bulks.

One of them is the formation of growth sector boundaries (GSB) and growth sector regions (GSR). It has been reported that J_c is higher along the GSBs than in the GSRs. For example, Fujishiro *et al.* characterized the inhomogeneity of a GdBCO bulk by measuring the magnetization of small samples cut from various positions in the bulk [2]. They showed that J_c is 20 % higher below the seed crystal, compared with that on the growth sector regions (GSR). It is also slightly enhanced on the growth sector boundaries (GSB). This non-uniformity of J_c in the ab-plane can be modeled by a cosine function [3]. In addition, J_c also varies as a function of the position relative to the seed. It has been reported that J_c is lower "at the edge with respect to the center and at the bottom with respect to the top" [3]. This might be linked to the mechanism of the crystal growth of bulk superconductors [1], [4]. This non-uniformity of the local critical current density J_c can play a significant role. For example it affects the maximum temperature rise, and the magnitude and shape of the trapped field profile during pulse field magnetization [2], [3]. We show here that it can affect the levitation performance as well.

To do so, we report and discuss the measurement and modeling of the levitation force of a (RE)BCO bulk above a PM for the two configurations shown in Fig. 1. In the bottom seed (BS) configuration, the seed is on the bottom surface of the bulk, near the PM. In the top seed (TS) configuration, the seed is on the top surface of the bulk, opposite to the PM.

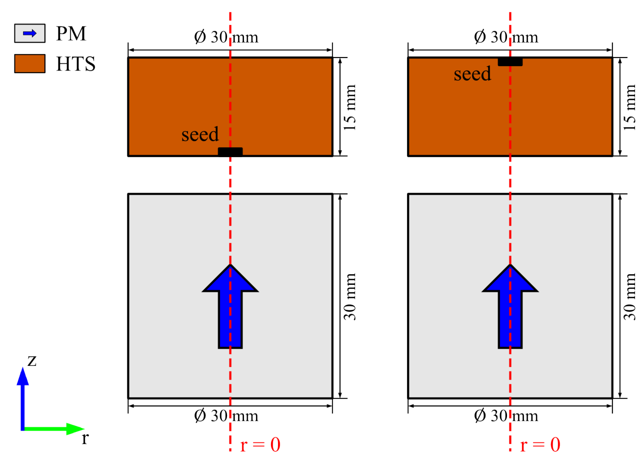


Figure 1. (left) BS configuration, (right) TS configuration. The arrow indicates the PM magnetization direction.

II. Measurement

The experimental setup used to measure the levitation force has been described in [5]. The permanent magnet (PM) is a cylindrical Nd-Fe-B PM having a remanent magnetic flux density of 1.27 T. The bulk is a cylindrical single domain seeded melt growth YBCO bulk.

The levitation force is measured for a zero field cooling (ZFC) sequence: the bulk is cooled down at a distance of 100 mm above the center of the PM (the field is negligible); then the bulk is moved at a speed of 1 mm/s, first vertically downward until the gap between the bulk and the PM is 5 mm, then vertically upward to its initial position.

The measured levitation forces are plot in Fig. 2. The maximal levitation force measured in BS configuration is 30 %

higher than the one measure in TS configuration. This result can only be explained by the non-uniformity of J_c between the top and the bottom side of the bulk, ie. along the c-axis.

III. Modeling

The 2D axisymmetric finite element (FE) model used here to reproduce the levitation force experiment has been described in [5]. The idea behind it is to decouple the problems. First we calculate the magnetic field generated by the PM magnet using an A-formulation (magnetostatic) FE model. Second we calculated the induced current in the HTS domain with an H-formulation FE model. The relative movement between the PM and the HTS is modeled by time-dependent Dirichlet boundary conditions mimicking the motion. We underline that this model has been extensively validated.

For the HTS domain, the resistivity is modeled using an E-J power law model ($E_c = 10^{-4}$ V/m, n = 21 [3]). The dependence of the critical current density J_c on the magnetic field $\mathbf{B}$ is described using an isotropic Kim-like model,

$$J_c(\mathbf{B}) = \frac{J_{c0}}{1 + \frac{|\mathbf{B}|}{B_0}} \quad (1)$$

where J_{c0} is the local self-field critical current density to be determined, and B_0 is a material parameter set to 0.37 T [5].

A. Uniform J_c model

First we assume that J_{c0} is uniform in the bulk. To obtain its value, it is common practice to consider the ZFC sequence in BS configuration, and to identify it so that the simulated maximum levitation force is equal to the measured value. Accordingly, J_{c0} is set here at $2.4 \cdot 10^8 \mathrm{A/m^2}$. The simulated levitation force for both configuration have been added to Fig. 2. The model with uniform J_c overestimates the force in the TS configuration.

B. Non-uniform J_c model

Second we assume that J_{c0} is non-uniform in the bulk. For example, one can assume that it is a linear function of the distance to the seed along the c-axis,

$$J_{c0}(z) = J_{c0,S}\left(1 - c_0|z - z_S|\right) \quad (2)$$

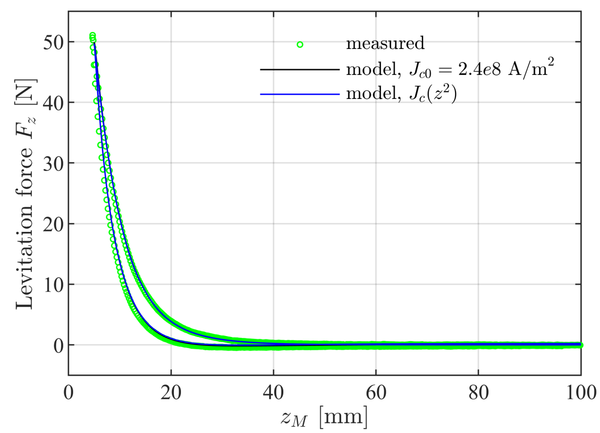
where $J_{c0,S}$ is the local critical current density at the seed location (0,z_S) and c_0 describes the degradation of J_c with the distance from the seed in the c-axis direction. Alternatively, one can assume that J_{c0} is a cubic function of the distance to the seed along the c-axis,

$$J_{c0}(z) = J_{c0,S}\left(1 - c_0|z - z_S|^2\right) \quad (3)$$

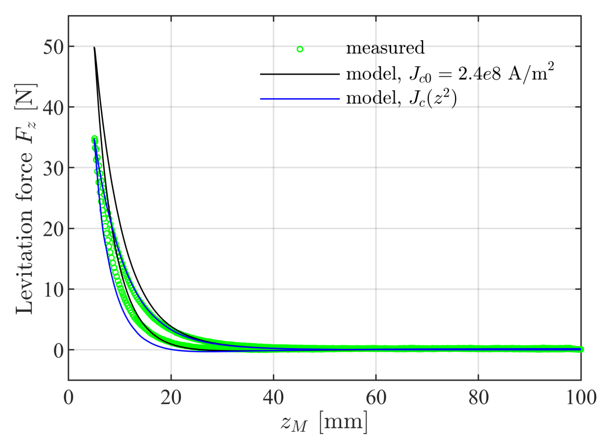
The corresponding simulated levitation forces have been added to Fig. 2. Now the agreement between the measurements and the model is good both for the BS and TS configurations. Note that the simulated hysteretic loop is slightly too large for the TS configuration. This suggests that other local properties of the bulk influence the levitation force.

IV. Conclusion

The non-uniform local critical current density should be taken into account when designing systems using seeded melt growth (RE)BCO bulks. Indeed, in an optimal design, the bulk would tend to be fully penetrated by supercurrents. In that situation, the performance of the real bulk would probably by lower than the one estimated using an uniform J_c.



(a) BS configuration



(b) TS configuration

Figure 2. Levitation force for the ZFC sequence

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