




Advantages of multi-seeded (RE)–Ba–Cu–O superconductors for magnetic levitation applications

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Abstract

Large, single grain (RE)Ba₂Cu₃O₇ (where RE is a rare-earth element or yttrium) high temperature superconductors are technologically important materials due to their ability to trap large magnetic fields and to provide stable magnetic levitation for a number of potential high field applications. The fabrication of samples in the large single grain form is a challenge, however, due to the characteristic slow growth rate of these materials and the need to produce samples that are electrically well-connected in order to generate trapped magnetic fields that are significantly greater than those produced by conventional permanent magnets (PM). In this work, we investigate whether large, single grain samples are optimum for the generation of high levitation forces for engineering applications. Three large bar-shaped Y–Ba–Cu–O samples of dimensions 60 × 20 × 12 mm³ were prepared for this investigation, including one single-seeded, one multi-seeded and one consisting of three square samples packed together closely in an array. The processing of these samples is described and their trapped field and levitation performance at 77 K measured using different PM arrays. We find that the multi-seeded samples and those assembled from smaller, individual bulk superconductors are able to achieve a higher levitation force than an equivalent single seed sample arrangement, at least in some geometries. This result is significant in that it suggests clearly that it is not always necessary to fabricate bulk (RE)BCO superconductors in the form of very large single grains for levitation applications, although the specific configuration of the system does need to be considered on an application-by-application basis.

Keywords: levitation, multi-seeding, single grain, magnetisation, close packed

(Some figures may appear in colour only in the online journal)

Introduction

Bulk single grains of cuprate high temperature superconductors (HTS), such as (RE)Ba₂Cu₃O₇ [(RE)BCO] where RE is a rare-earth element or yttrium, are able to trap magnetic fields that are almost ten times greater than those generated by permanent

magnets [1, 2]. Potential applications of these potentially important technological materials include MRI, energy storage flywheels, motors and levitation systems [3–8], where a high magnetic field strength is required and energy efficiency is a critical consideration. The ability to fabricate large, single grains of (RE)BCO, either in length or cross-sectional area, has generally been considered essential for developing such practical applications of these materials for the past three decades.

However, there is a practical limitation to the size of (RE) BCO single grains and to their associated superconducting properties. To obtain the required crystallographic quality and



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texture, it is necessary to initiate growth from a single crystal seed, followed by a subsequent slow growth process of typically $5\text{--}10\text{ mm d}^{-1}$ [9, 10]. It is possible to initiate growth using multiple seeds [11–15] and reduce growth times, although the connectivity between the resulting independent grains is not always as good as that within a single grain. This leads typically to the production of multi-seeded samples that exhibit multiple peaks in their trapped field profile. As a compromise to the use of large single grains, an assembly of 344 $\text{YBa}_2\text{Cu}_3\text{O}_7$ (YBCO) small single grains, each of 30 mm in diameter and 15 mm in height [16], have been used in a Maglev test vehicle incorporating HTS capable of short-range, small-scale human transportation. Multi-seeded samples have also been used in other levitation systems reported recently. For example, Deng *et al* [17] observed that the levitation force of a multi-seeded sample was higher than that of a single-seeded single grain. Similar phenomena have been observed by Shi *et al* in a comparative study of the levitation forces obtained from single seed-seeded and a four-seeded $\text{GdBa}_2\text{Cu}_3\text{O}_7\text{--Ag}$ multi-seeded sample of diameter 31 mm [18]. This suggests that large single grains with high trapped field may not always be required for levitation applications of bulk (RE)BCO at 77 K using permanent magnets as the source of external field.

It is well-known that the shape of both the superconductor and the magnet system has a significant effect on levitation force, and that the static levitation force is strongly dependent on the properties of the product of the magnetic moment of the bulk sample and the gradient of the external magnetic field [19–21]. As a result, there are some unanswered issues surrounding the use of multi-seeded samples for practical applications. For example, the comparative levitation study by Deng *et al* [17] was actually performed on bar-shaped, multi-seeded and cylindrical samples, which makes interpreting the results of this work more complex.

The comparison of the levitation force between single-seeded and multi-seeded samples of the same size has not, to our knowledge, been carried out, due, we suspect, to a lack of availability of very large, bar-shaped samples. In order to compare systematically the levitation force of large, bar-shaped geometries, three YBCO superconducting bulk samples of 60 mm in length, 20 mm in width and 12 mm in depth were fabricated by three different routes: single seed, multi-seeded using three seeds and a simple assembly of individual, single grain samples. Here we report the trapped field and levitation force of these three samples when used to levitate three different permanent magnet arrays. In addition, the remanent trapped field remaining in the bulk samples after the initial levitation measurements was characterised in order to assess the extent to which current had penetrated into the different samples during the magnetisation process.

Experimental

Five individual $\text{YBa}_2\text{Cu}_3\text{O}_7$ single grain samples were fabricated via the top seeded melt growth (TSMG) technique. The composition of the precursor powder was 75 wt%

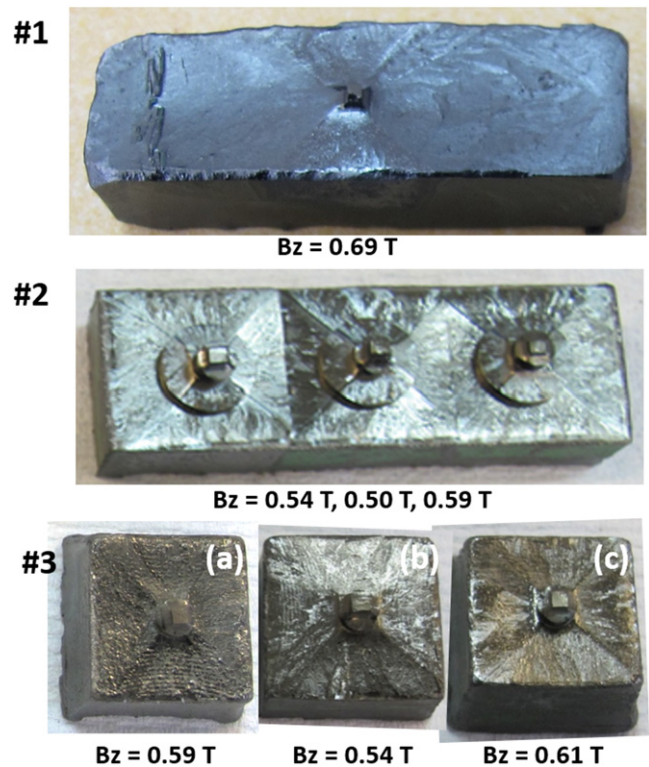


Figure 1. YBCO bulk samples investigated as part of this study. (a) Sample #1 a YBCO single grain sample $60 \times 20\text{ mm}^2$ with max. $B_z = 0.69\text{ T}$ at 77 K. (b) Sample #2 a multi-seeded YBCO sample with maximum $B_z = 0.54\text{ T}$, 0.50 T and 0.59 T for each separately seeded grain, respectively. (c) Sample #3 a close packed YBCO bulk sample array containing three square single grains with $B_z = 0.59\text{ T}$, 0.54 T and 0.61 T , respectively, when measured separately. (Note: the maximum values of B_z are achieved at the centres of each single grain.)

$\text{YBa}_2\text{Cu}_3\text{O}_7 + 25\text{ wt\% Y}_2\text{BaCuO}_5 + 0.5\text{ wt\% CeO}_2$, with the main Y-123 and Y-211 precursors (99.9% purity) supplied by Toshiba Ltd, Japan and the CeO_2 (99.9% purity) by Alfa Aesar. The mixed precursor powders were pressed uniaxially into the required dimensions of $75 \times 25 \times 14\text{ mm}^3$ for Samples #1 and #2, and $25 \times 25 \times 14\text{ mm}^3$ for Samples 3(a), (b) and (c) that constituted Sample #3. $\text{NdBa}_2\text{Cu}_3\text{O}_7$ seeds with buffers [22–24] were placed on the top surfaces of each pressed sample before being loaded into a box furnace for melt-processing in air using a conventional TSMG heating profile [23], as indicated in figure 2. The samples were annealed subsequently in pure oxygen (99.9%) at a temperature in the range of 450°C – 400°C for 10 days to allow the Y-123 lattice structure to transform from the non-superconducting tetragonal phase to the superconducting orthorhombic phase and for the optimum T_c to be achieved. The oxygenated samples were then polished and assembled into aluminium mounts using Stycast® 2850 FT epoxy with a 23 LV catalyst.

Figure 1 shows photographs of the top surfaces of the samples fabricated for this study, with the maximum trapped field measured perpendicular to the top surface, B_z , indicated for each sample. Sample #1 is a YBCO single grain seeded using a single $\text{NdBa}_2\text{Cu}_3\text{O}_7$ seed, Sample #2 is a YBCO bulk

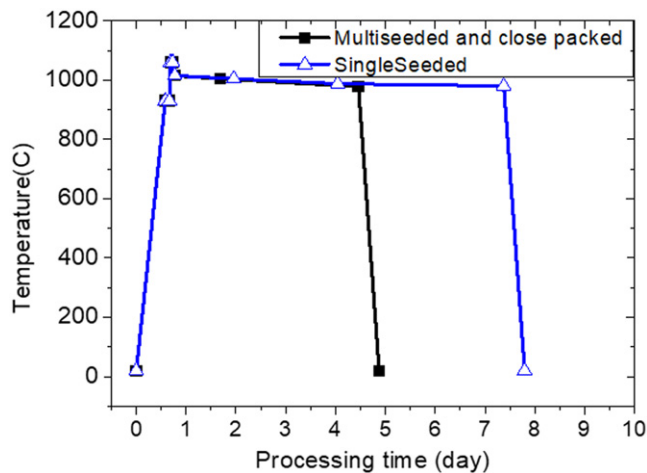


Figure 2. Heating profiles used to fabricate the three samples. The blue lines represent the heating profile of the single-seeded samples and the black lines represent the heating profile of the multi-seeded samples and the samples used in the close packed array.

sample seeded using three, well-aligned $\text{NdBa}_2\text{Cu}_3\text{O}_7$ seeds in 0-0-0 [14] arrangement and Sample #3 consists of three individual YBCO single grains (seeded by $\text{NdBa}_2\text{Cu}_3\text{O}_7$ seeds) 3(a), (b) and (c), each of dimensions $20 \times 20 \text{ mm}^2$. Significantly, the surface area of each of the three samples was $60 \text{ mm} \times 20 \text{ mm}$ when polished and, in the case of Sample #3, assembled.

The trapped field of each individual bar-shaped sample was measured at 77 K after field-cooling (FC) in an applied magnetic field of 1.4 T using a rotating array of Hall probes, with the active element of each probe positioned approximately 2.0 mm above the top surface of the sample during scanning. The maximum trapped field value of each sample was also measured using a hand-held Hall probe, where the active element was located 0.5 mm above the contact position with the sample surface.

The levitation force was measured at 77 K using stacks of two, three and five NdFeB permanent magnets of dimensions $20 \times 50 \times 3 \text{ mm}^3$ with surface centre fields of 0.20 T (maximum 0.28 T at the edges), 0.26 T (maximum 0.35 T at the edges) and 0.34 T (maximum 0.42 T at the edges) for each stack. Permanent magnets with a surface area of $20 \times 50 \text{ mm}^2$ were selected to have a similar area to that of the three samples, since the use of a magnet array of similar geometry to the superconducting bulk samples leads generally to the largest levitation force [25]. The samples were zero field cooled (ZFC) in liquid nitrogen for the levitation experiments. The magnets were then moved towards the samples at a speed of 0.4 mm s^{-1} from a distance of 80 mm, with a calibrated load cell used to determine the levitation force between each superconducting sample and the permanent magnet.

The remanent trapped field in the bulk superconductors was measured using the rotating Hall probe array after the levitation force had been recorded and the permanent magnet array withdrawn vertically from the sample (i.e. in the reverse of the direction in which it had been applied).

Results and discussion

Growth of bar-shaped single grains

The growth of smaller samples, such as the individual constitutive elements of Sample #3, is relatively straightforward, as is the fabrication of the multi-seeded Sample #2 after the seeds are aligned. The growth of a large bar from a single seed (Sample #1) proved to be most challenging, and required numerous fabrication attempts. The growth of such a large bar type sample could fail for a number of reasons, including the formation of multiple, poorly connected sub-grains and mechanical failure during post-fabrication polishing. Furthermore, the processing time, as shown in figure 2, for fabricating a single grain of length 60 mm and 20 mm width is typically 2 to 3 days longer than that of the multi-seeded samples. The processing time for Sample #2, on the other hand, is the same as that for the individual single grains that constitute Sample #3. It is not clear, therefore, that the processing of bulk samples in the form of a single-seeded bar is a practical proposition, even though the peak trapped field of these samples is notionally superior.

Surface trapped fields

The Bean model [26] predicts that the maximum trapped field at the surface of a fully magnetised slab of type II superconductor in the direction parallel to the applied field is proportional to $J_c \times a$, where J_c is the critical current density and a is the half width of the sample. Consequently, the trapped field does not depend on the magnetisation process once the sample is fully magnetised. Trapped field is, therefore, often taken as a convenient figure of merit for bulk superconductors given the repeatability of its measurement, independently of the magnetisation technique employed, once the sample is fully magnetised. From figures 1 and 3, we can see that the single grain Sample #1 exhibits the highest trapped field and the broadest single peak. This means that Sample #1 is, by this measure, of the highest quality and therefore the best sample of the three measured. Although Samples #2 and #3 appear to exhibit similar trapped fields, the maximum trapped fields at the centres of each single grain in Sample #3 are higher than those of Sample #2. Therefore, the rank-order of performance in terms of maximum trapped fields for the three samples investigated in this study (from high to low) is: 1. Sample #1 (single-seeded); 2. Sample #3 (close packed); 3. Sample #2 (multi-seeded). These three samples have the same half width of 10 mm, which is the value a in the Bean model, suggesting that Sample #1 has the best superconducting properties overall (i.e. average critical current density, J_c).

Figure 3 shows the trapped field distribution of the three samples, measured at 77 K, 2.0 mm above the top surface after FC magnetisation. In each case, the applied field of 1.4 T was clearly sufficient to fully magnetise these samples. The trapped field results are generally as would be expected from the morphology of the three samples investigated. The single-seeded Sample #1 has a single peak with the highest

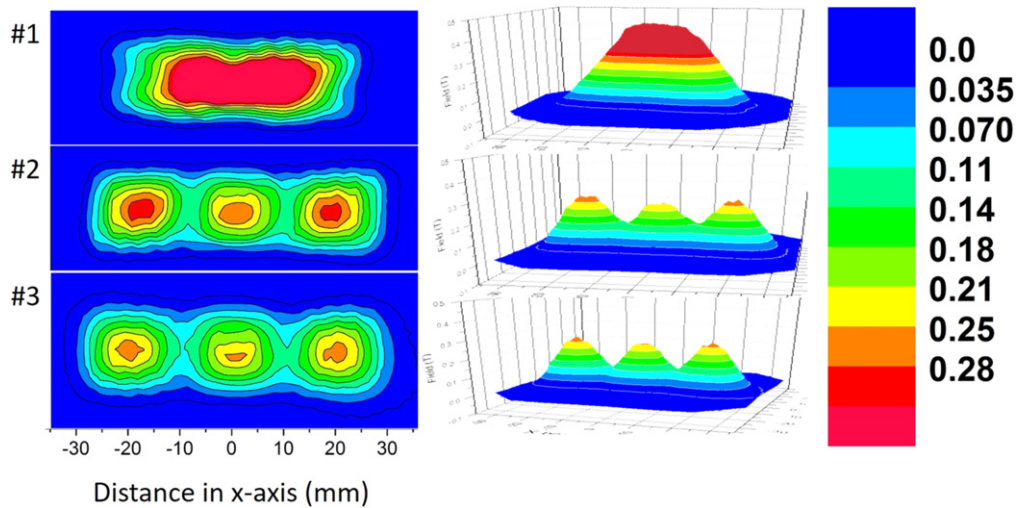


Figure 3. Trapped field distributions of the three samples at 77 K magnetised by a FC process at 2.0 mm above the top surface of each sample. Sample #1 is single-seeded, Sample #2 is multi-seeded and Sample #3 is the loose packed sample array.

maximum trapped field at the centre of the sample, whereas the multi-seeded Sample #2 and the close packed Sample #3 all exhibit three peaks, with the maximum trapped field occurring at the centre of each single grain. It is interesting to note in figure 3, that, at a distance of 2.0 mm away from the top surface, the multi-seeded Sample #2 exhibits higher trapped fields B_z along the vertical axis at the centres of each single grain compared the close packed single grains, although Sample #3 shows higher maximum peaks between the positions of the seeds. This is due to the ‘coupling’ effect between the better connected grains in the multi-seeded samples, as suggested in previous research [17]. In consequence, the magnetic flux vector at 2.0 mm above the top surface of this sample is oriented more vertically. As a result, the merit order of the peak trapped field at the surfaces of some samples could differ from that measured several millimetres away due to the difference in the distribution of flux, which, in turn, is due to the differences in the geometries of the bulk samples.

It can be concluded from this observation that the rank-order of the maximum trapped field and the distribution of field at positions above the top surface of the samples are influenced not only by the quality of each individual single grains, but also by how the grains are arranged, which, in turn, may affect the properties required for practical applications.

Levitation forces

Figure 4 shows the measured levitation forces between the magnet and each of the three samples for a permanent magnet comprising of a stack of individual $20 \times 50 \times 3 \text{ mm}^3$ NdFeB permanent magnets of length 6 mm (figure 4(a)), 9 mm (figure 4(b)) and 15 mm (figure 4(c)). It can be seen that the resultant forces observed for all the samples are higher when the number of permanent magnets is increased in the levitation measurement. For example, the maximum levitation force of Sample #1 increases from 60 to 75 N and then to

90 N when the permanent magnet increases from 6 to 9 and then to 15 mm in length. This is simply because the magnetic field of the magnet stack with this simple rectangular geometry increases from 0.20 T, 0.26 T and 0.34 T, respectively, as the height of the stack increases. This increase is well below any flux or current saturation point for the superconducting samples at 77 K. We can also see from figure 4 that Sample #2, the multi-seeded sample, exhibits consistently the highest levitation force of the three samples studied, whereas its peak trapped field is the lowest. This phenomenon is clearly apparent from the insets in figure 4. The order of the levitation forces of the samples, in descending order, is: Sample #2 (multi-seeded); Sample #3 (close packed array); Sample #1 (single-seeded), which is the reverse of the order observed for the peak trapped field measurements at the immediate top surfaces of the samples.

Another observation from figure 4 is that, while the rank-order of performance does not change, the relative performance of the three samples does vary. When the external field is lower, such as in the case of figure 4(a), the close packed Sample #3 exhibits a similar levitation force to the multi-seeded Sample #2. When the external field is higher, however, as is the case in figure 4(c), the close packed Sample #3 exhibits a similar levitation force to the single-seeded Sample #1. This suggests that the relative rank-order performance of the samples could change and that it is, perhaps, overly simplistic to say that one particular type of sample exhibits superior levitation performance for applications than another without specifying the measurement geometry. The rank-order of the levitation force of these three samples only maintains the ranking over the range of the external fields investigated in this study, and may change with changing external field outside this range.

In other words, the observation that the levitation force of the multi-seeded sample is the highest might not be universally correct and may change when external field or the geometry of the sample changes. We would emphasise that the results of this study were obtained within the range of the

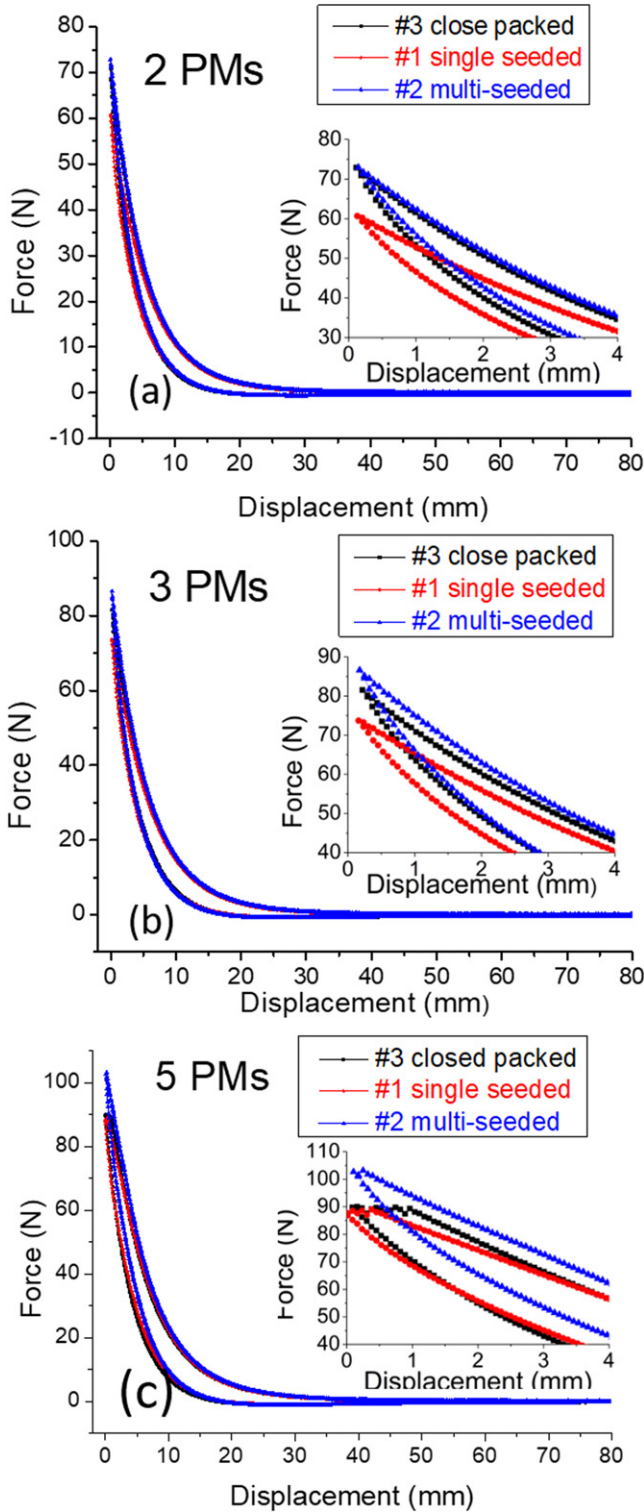


Figure 4. Levitation force measured at 77 K using a stack of permanent magnets of different heights $D \times L \times H$; (a) $20 \times 50 \times 6 \text{ mm}^3$ (b) $20 \times 50 \times 9 \text{ mm}^3$ and (c) $20 \times 50 \times 15 \text{ mm}^3$. The solid red symbols represent the forces between the permanent magnet stack and Sample #1 during the process when they are moved towards and away from the samples; the solid black dots and blue triangle represent the same forces for Samples #3 and #2, respectively. The insets show the same measurement at lower displacements from 0 to 4 mm.

applied fields and geometries of the samples studied. The interactions between the sample and the external field combine to yield the resulting levitation force.

It can be concluded that the observations made in previous research [17, 18], that multi-seeded bulk superconductors can exhibit higher levitation forces than single-seeded samples, are consistent with the observations of the present study under the experimental conditions described. It is emphasised, however, that these results are sensitive to the levitation geometry into which the samples are incorporated.

Trapped fields after the samples are partially magnetised through levitation

Sanchez *et al* [27] pointed out the magnetic Lorentz force, F_z , per unit length, L , in the superconductor, arising from the interaction of the currents in the superconductor with the field created by a permanent magnet (PM), can be calculated directly as follows:

$$\frac{F_z}{L} = \mu_0 \int_s J_c H_e dS \cong \mu_0 \sum_{j=1}^n H_{e,j} I_j, \quad (1)$$

where dS is the infinitesimal area in the cross-sectional surface of the superconductor, J_c is the critical current density in the ab -plane, $I_c = J_c \Delta S$, and H_e is the horizontal component of the permanent magnet field at the desired position. Equation (1) is valid at any position along the z -axis for the currents induced during the displacement of the superconductor relative to the permanent magnet for all positions of the sample.

Equation (1) suggests that the levitation force is associated with both the applied field and the currents induced in the superconductor when the magnets push against it. While it is natural to assume that samples with a larger critical current would exhibit a larger levitation force [3], this will only apply to situations when the samples are fully magnetised, which is not the case in the present study.

The levitation force measured in the present study under a static ZFC process is consistent with other studies using similar experimental arrangements [3, 25, 28, 29]. It can be understood from the Bean model [26], shown in figure 5(a), that the critical external field B^* , which leads to the full penetration of the slab, is given by the equation, $B^* = \mu_0 J_c a$, where a is $20/2 \text{ mm} = 10 \text{ mm}$ in the present study. The external field in a ZFC process needs to be $2B^*$ to fully magnetise the superconducting slab, or, in other words, to achieve the maximum trapped field $B_{\max} = B^*$ (the external field in FC processes needs to be B^* to fully magnetise the slab to $B_{\max} = B^*$). When the applied field is less than B^* in a ZFC process, the penetration of the field will be described by the blue line shown in figure 5(b), and the resulting distribution of the trapped field when the applied field is reduced to zero will be as shown by the dashed red line. The ZFC process applied prior to the levitation measurement in the present study is represented by the situation shown in

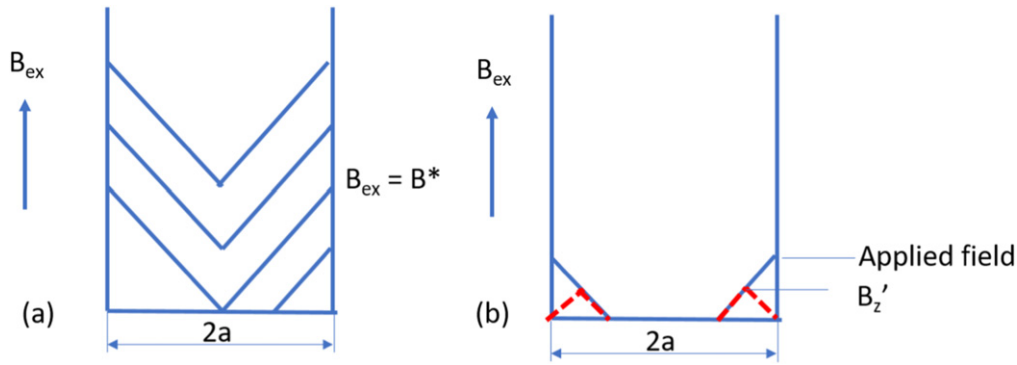


Figure 5. Schematic illustration of a thin HTS slab of infinite length width and $2a$ with its plane parallel to a uniform external field, B_{ex} . (a) Field distributions of a fully magnetised slab using Bean model for increasing applied field. (b) Distribution of magnetic fields with low applied field in a ZFC process.

figure 5(b), and is limited by the surface field of the permanent magnet stack. Therefore, following the levitation force measurements, which can be considered effectively to be a ZFC process, the trapped field profiles are expected to take the form of the red dashed line in figure 5(b). The resulting maximum trapped field B_z' values should, therefore, be half of the maximum applied field at the position where the maximum levitation force has been achieved, with the distribution of B_z' indicating the distribution of the induced current within the sample.

The trapped fields B_z' of the bulk samples were measured following measurement of the levitation force, based on the critical state analysis described above, in order to investigate further the distribution of the induced current at which the maximum levitation force is achieved.

The distribution of B_z' measured at 77 K and 2.0 mm above the top surface of the samples using a hand Hall probe is shown in figure 6. The multi-seeded Sample #2 exhibits a peak trapped field of 0.064 T, 0.069 T and 0.111 T, respectively, after being magnetised by the 6, 9 and 15 mm permanent magnet stacks. The close packed Sample #3 exhibits a peak trapped field of 0.055, 0.067 and 0.088 T, while the peak trapped fields for the single-seeded Sample #1 are 0.082, 0.092 and 0.111 T. It should be noted that the peak values of trapped field B_z' are not obtained at the centres of the top surfaces of the samples, but at positions close to the edge of their top surfaces. It is clear by comparing the maximum trapped fields of the samples with the values when they were fully magnetised (0.69, 0.59 and 0.61 T at 77 K in figure 1), that these samples were far from fully magnetised during the levitation force measurements shown in figures 4(a)–(c), since this is essentially a ZFC process with an applied field from a permanent magnet stack of relatively low inherent field.

It can be seen from figures 6(a)–(c) that, when the external field increases (6, 9 and 15 mm of PM height), the area of Sample #3 (close packed array) also increases, which, in turn, indicates that the length-scale of the induced current is longer. This pattern can be seen for Sample #2 (multi-seeded) and Sample #1 (single-seeded). This explains the levitation

force results in figure 4, where the external field applied to each sample changes.

It can be seen from the measured levitation forces shown in figures 6(a), (d) and (g) that, when the applied field is generated by a PM stack of length 6 mm, the total trapped magnetic flux decreases in the following order: single-seeded; close packed array; multi-seeded. The single-seeded sample (figure 6(d)) exhibited the highest trapped field at its edges, although the field at the centre of this sample is the lowest of the three samples investigated. This explains why the total trapped magnetic flux in the single-seeded sample is the lowest. Equation (1) indicates the magnetic moment is an integral of J_c over the sample area penetrated by the induced current. The single-seeded Sample #1 has the least penetrated current loop, which means that this sample exhibits good screening of magnetic field from the PM compared to both the multi-seeded Sample #2 and the close packed Sample #3, which explains why Sample #1 exhibits the lowest levitation force. The diameter of the induced current loop is not the real length of the samples in that some of the boundaries between the grains are easier for the flux to penetrate during the magnetisation process, depending on both the microstructure and/or texture of the individual single grain boundaries.

The multi-seeded sample combines grain boundaries and connectivity between the three individual grains, with the ‘coupling effect’ [12, 13, 17, 30–32] making the induced current loop larger. The flux enters this sample more easily and therefore the induced trapped magnetic flux is higher. This coupling effect was observed in this study when the trapped field 2 mm away from the top surface of the samples was measured, as presented in the Results and Discussion section of this paper.

A similar pattern can be seen when PM stacks of height 9 and 15 mm are used as external field sources, as shown in figures 6(b), (e) and (h) and (c), (f) and (i). It can be seen that the magnetic moment of the multi-seeded and the close packed samples yields a similar trapped magnetic flux under conditions of both low and high field from the PM stack. This observation is consistent with the results of the levitation force measurements in figure 4, taking into the account that the

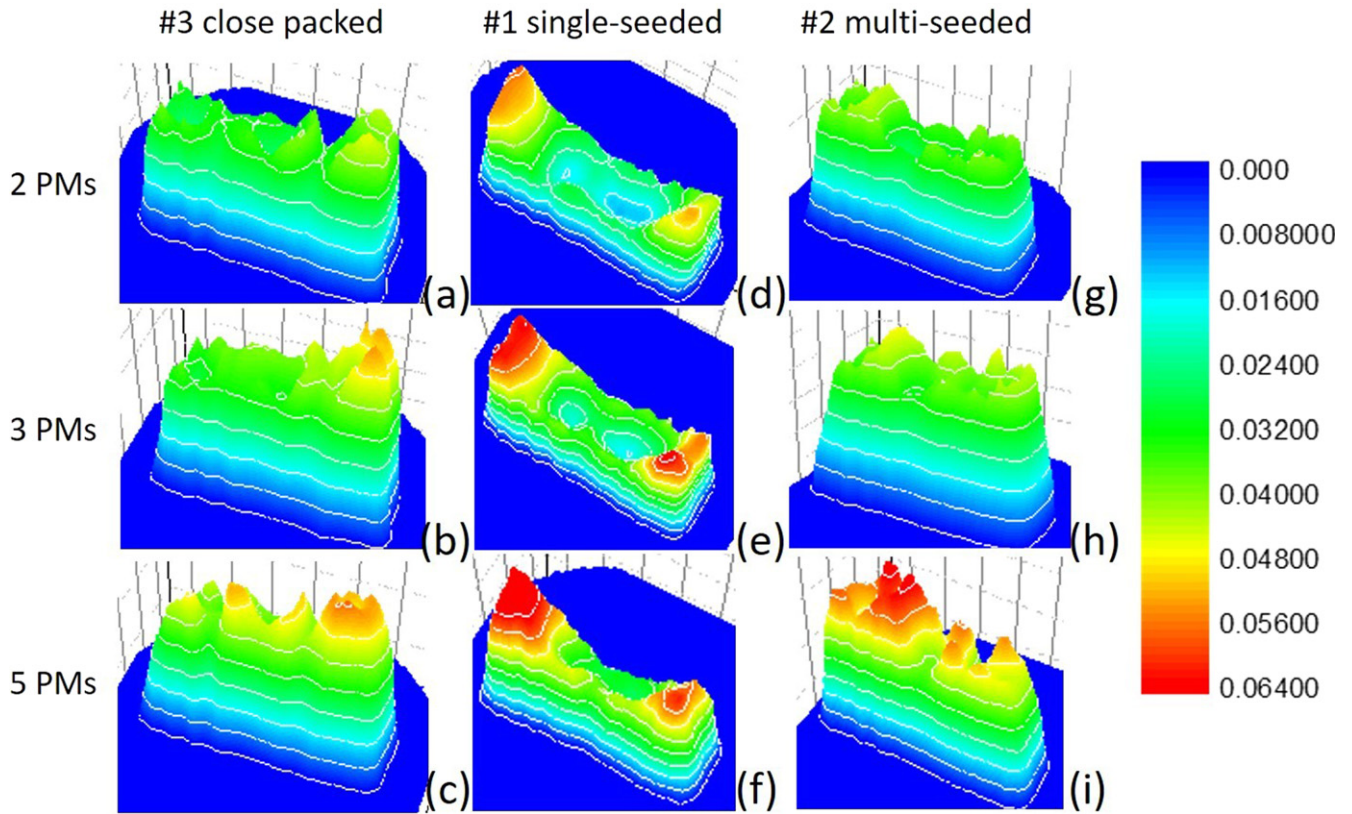


Figure 6. The 3D trapped field B_z -xy profiles of the samples after levitation force measurement using a stack of permanent magnets at 77 K (a) Sample #3 (close packed array) magnetised by two PMs, (b) Sample #3 (close packed array) magnetised by three PMs, (c) Sample #3 (close packed array) magnetised by five PMs, (d) Sample #1 (single-seeded) magnetised by two PMs, (e) Sample #1 (single-seeded) magnetised by three PMs, (f) Sample #1 (single-seeded) magnetised by five PMs, (g) Sample #2 (multi-seeded) magnetised by two PMs, (h) Sample #2 (multi-seeded) magnetised by three PMs and (i) Sample #2 (multi-seeded) magnetised by five PMs.

observation that the maximum magnetic moments are twice high as the corresponding values of B'_z when the levitation forces reach a maximum. Of course, the measurement of the magnetic moment using the rotating Hall array is of only limited precision. However, the overall trend of the total magnet moment presented in figure 6 agrees well with the results of the levitation force measurements in the present study.

Although the value of trapped field is a measure of sample quality, we observe that in some situations (such as levitation at 77 K using permanent magnets) that this is not always the best figure of merit to use when considering the potential of the bulk superconductor to generate levitation force. The present experimental investigation suggests that there is an optimal superconducting element to match any given permanent magnet array, which is not simply a bulk superconductor with the highest possible critical current, which is consistent with the assertions made in previous studies [21]. The multi-seeded sample studied here, for example, achieved an optimum magnetic moment and levitation force at 77 K for a particular intermediate value of critical current density via the coupling of geometry and superconducting properties, compared to the single-seeded and close packed samples, which is potentially very important for achieving practical applications of bulk (RE)BCO superconductors.

Conclusions

The fabrication of a large, YBCO single grain of dimensions $60 \times 20 \times 12 \text{ mm}^3$ enabled the comparison of levitation forces at 77 K generated by three samples of the same overall geometry; single-seeded, multi-seeded and a close packed array of bulk single grains. The measured levitation forces of these samples show that the maximum levitation force, in descending order, is: multi-seeded; close packed; and single-seeded. This merit order is consistent with that observed as the height of the permanent magnet stack is increased from 6 to 15 mm. The merit order of the observed peak trapped field, however, follows the opposite trend.

Measurements of the induced trapped magnetic flux of the bulk samples has revealed that increased penetration of the current loop in the multi-seeded sample leads to the highest levitation force. The combination of grain boundaries and the connectivity between the three individual grains of the multi-seeded sample allows flux to penetrate more easily in this sample, which results, therefore, in the largest induced current loop. Indeed, even the close packed array of samples can produce a higher flux and higher levitation force than that observed for the single-seeded, bulk sample.




This study suggests that a single grain with a high peak trapped field may not be required, or even optimal, for obtaining the highest levitation force in a practical levitation

system, and, in particular, when the superconducting bulk samples are not fully magnetised, as is the case when using permanent magnets. This is a common situation in applications of the levitation force of bulk HTS. More broadly, the use of peak trapped field as a figure of merit for bulk superconductors is clearly not appropriate in levitation applications where the source, and therefore the limitation of, magnetic flux is provided by a permanent magnet array. As a result, changing the external field, optimising the shape of the single grains, manipulating the inter-grain connectivity and assembling an array of smaller single grains are all possible approaches to shaping the magnetic field and optimising the levitation force for practical applications.

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