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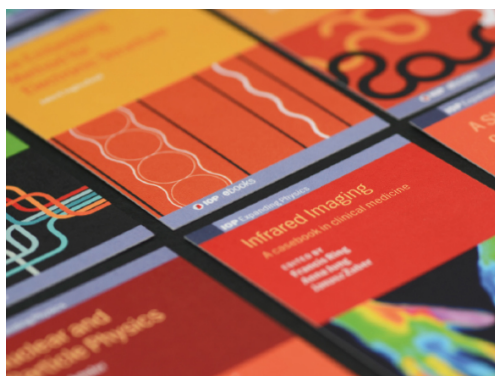
## The effect of facet lines on critical current density and trapped field in bulk RE–Ba–Cu–O single grains

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# The effect of facet lines on critical current density and trapped field in bulk RE–Ba–Cu–O single grains

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## Abstract

Bulk, single grain RE–Ba–Cu–O (where RE = rare earth or yttrium) [(RE)BCO] high temperature superconductors could potentially be used to generate stable magnetic fields for magnetic resonance imaging (MRI) and nuclear magnetic resonance (NMR). In these applications, however, the homogeneity of the magnetic field is of critical importance. As a result, the spatial distribution of critical current density,  $J_c$ , within the bulk single grain and the effects of the magnetisation process, which are primary drivers of the uniformity of the achievable trapped magnetic field, are fundamental to assessing the performance of these technologically important materials. This paper reports the systematic measurement of the distribution of  $J_c$ – $B$  at 77 K over a vertical cross-section of a single grain along a facet line and through the seed crystal [(110)- $F$ ] at 20 positions within a 20 mm diameter Gd–Ba–Cu–O sample in an attempt to understand and assess the distribution of  $J_c$  along this microstructural feature. A comparison of the data within the whole vertical plane across the seed measured along the  $a$  or  $b$  direction within the [(100)- $a$ ] plane shows that  $J_c$ – $B$  at 77 K at the facet line is more than 10% higher for applied fields between 0.2 T and 2.5 T. The effect of the  $J_c$ – $B$  relationship of the facet line on the overall trapped field measured in an individual bulk sample was investigated by measuring the magnitudes of trapped fields and their contour maps for sections cut from four single grain samples of GdBCO–Ag at different sizes and shapes parallel to the  $ab$ -plane from the top to the bottom of the bulk sample. Based on the results reported here, we demonstrate a method to achieve more uniform trapped fields through an optimal arrangement of an assembly of sections of individual GdBCO single grains.

**Keywords:** (RE)BCO, facet lines, bulk superconductors,  $J_c$  distribution, trapped field, uniformity, homogeneity

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

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## 1. Introduction

RE–Ba–Cu–O (where RE = rare earth or yttrium) [(RE)BCO] bulk, single grain superconductors can trap magnetic fields of over 17 T [1, 2]. Their application as pseudo-permanent magnets, therefore, is expected to have a transformative effect on numerous engineering applications that rely on, or benefit from, high magnetic fields relative to those available using traditional iron-based ferromagnets. Considerable research has been carried out since (RE)BCO high temperature superconductors (HTSs) were first discovered over three decades ago [3]. Understandably, much research effort to date on bulk superconductors has focussed on the improvement of growth processes, although, as more practical applications emerge [4], tailored fabrication processes that meet the specific requirements of particular applications are increasingly crucial for their commercialisation.

In certain practical applications, and most notably MRI and NMR, a uniform distribution of the trapped field, or at least a well characterised field distribution, is required. The trapped field at any position in a static trapped field state is, according to the Biot–Savart law, given by a volume integral across the bulk superconductor taking into account the effect at that position of the field generated by current density within each infinitesimal volume of the entire sample. The presence of a uniform trapped field above the surface of a cylindrical single grain, therefore, implies directly that the magnitude of trapped field at all positions within a concentric circle is the same.

The current density at a point in a fully magnetised sample is affected by the local  $J_c$  as well as other larger-scale properties of the single grain. As a result, an understanding of the local  $J_c$  distribution within a single grain is expected to elucidate the achievable homogeneity of the static trapped field, which is a key measure of the quality of a single grain. More importantly, the distribution of  $J_c$  within a single grain impacts strongly on the dynamics of magnetic flux penetration during magnetisation, and particularly during pulsed field magnetisation (a practical magnetisation method) where local  $J_c$  fluctuations result in changes in the amount of heat generated, which, in turn, limit the current required to generate the trapped field [5]. Local fluctuations in  $J_c$  also account for avalanche flux jumps and huge variations in the observed values and topographies of trapped field at the different steps in the pulsed field magnetisation processes [5]. An accurate knowledge of the distribution of  $J_c$  is therefore required for basic theoretical modelling research and to develop applications of these technologically important materials.

One of the approaches taken to elucidate the effect of the spatial variation of  $J_c$  on trapped field is to examine the single grain microstructure. Below the depairing current,  $J_c$  in a superconductor depends on the density and effectiveness of flux pinning centres [6]. The most effective pinning centres are ideally of the size of a vortex core, which, in HTS materials, is typically several tens of nanometres (for example, the size of vortex core of YBCO is about 15 nm at 4.2 K [7]). Therefore,  $J_c$  is linked closely to the microstructure of the single

grain on the nanoscale. It was reported as early as 1992 that  $J_c$  is proportional to the volume fraction of RE<sub>2</sub>BaCuO<sub>5</sub> (RE-211) [8] within the continuous bulk REBa<sub>2</sub>Cu<sub>3</sub>O<sub>7- $\delta$</sub>  (RE-123) superconducting matrix. Consequently, the size and distribution of RE-211 particles have been reported by many researchers [9–15], with a higher  $J_c$  being achieved generally in samples containing fine RE-211 inclusions [16]. The distribution of RE-211 particles is sometimes reported based on analysis of a half of a cross-section of a single grain, and assuming the single grain is axisymmetric [17–19]. It has been found that the distributions of RE-211 reported to date generally exhibit the same trends (with some variation) and can be explained broadly by particle push/trap theory [20]. For example, there are typically fewer and larger RE-211 particles at positions close to the seed, and more and smaller RE-211 particles at positions further away from the seed. The presence of nano-sized inclusions in the single grain microstructure has been reported by many researchers [21–25], although it is difficult to analyse these inclusions quantitatively and chemically on a large scale with the current level of measurement technology. To date, therefore, there has been no definitive correlation between  $J_c$  and microstructure in (RE)BCO bulk single grain superconductors.

In addition to inferring the spatial variation of  $J_c$  from the observed distribution of likely pinning centres, it is also possible to extract the distribution of  $J_c$  from magnetisation measurements on small specimens sectioned from the bulk using the extended Bean model [26]. Unfortunately, only a limited number of studies report a detailed distribution of  $J_c$  in (RE)BCO single grains, perhaps due to the requirement for repetitive and cumbersome measurements of many small sub-specimens cut from a parent single grain. The Cambridge Bulk Superconductivity Group has published two studies [27, 28] 23 years apart that report the distribution of  $J_c$  of (RE)BCO at 77 K with contradictory results: the first paper [27] shows an increasing  $J_c$  in the vertical plane along the  $a$  or  $b$  ( $a/b$ ) direction [(100)- $a$ ] in a YBCO single grain from a position immediately beneath the seed to a position towards the edge of the sample (i.e. from the centre of the single grain towards its periphery when the seed is located at its centre). The second study [28], on the other hand, shows a decreasing  $J_c$  in the [(100)- $a$ ] plane in a GdBCO single grain from a position immediately beneath the seed to a position towards the edge of the sample. It was determined, shortly after publication of the first paper, that the specimen used in the earlier study exhibited a lower critical transition temperature ( $T_c$ ) at the position immediately beneath the seed due to contamination from the seed crystal elements [29], which reduces  $J_c$ . The later paper [28] addressed this issue by using a buffer technique to grow the single grain [30], which eliminated the harmful element of the diffusion of Nd into the sample immediately beneath the seed so that  $T_c$  measured at this position is the same as that at other positions within the single grain.

Even so, these two studies only reported the distribution in the (100)- $a$  plane. The ability to predict the overall trapped field, e.g. by numerical modelling, using these data needs to assume that the single grains are axisymmetric. A cursory

visual inspection of any bulk superconductor sample, however, suggests this assumption is questionable, given that the presence of features such as facet lines and  $a/b$  and  $c$ -growth sectors is observed within the single grain microstructure. Microstructural analysis [14] suggests there is less misorientation between low angle sub-grains at the position of facet lines compared to the  $a/b$  direction at the top surface of a single grain, which could be a decisive factor in determining the local values of  $J_c$ . Therefore, this has motivated the present study to measure  $J_c$  within the (110)- $F$  plane and compare this with that within the (100)- $a$  plane, in order to understand whether  $J_c$  values within concentric circles around the  $ab$ -plane are the same.

After observing the differences in  $J_c$  between the (110)- $F$  and (100)- $a$  planes with a single grain, three sets of GdBCO–Ag single grains of different sizes and shapes were investigated by measuring the trapped fields of sections cut parallel to the  $ab$ -plane from the top to the bottom of the sample in order to understand the effects of the differences in  $J_c$  within the (110)- $F$  and (100)- $a$  planes on the measured trapped fields. GdBCO–Ag, rather than GdBCO, was used for the second part of the study given its enhanced mechanical strength and that the difference in properties at facet lines and the general  $a/b$  direction is an issue common to all (RE)BCO single grains. Finally, the facet lines of a stack of two top slices cut from a single grain but rotated by  $45^\circ$  relative to the position of their facet lines were measured and a more uniform trapped field distribution was achieved for the two-slice stack.

## 2. Experimental approaches

### 2.1. Measurement of $J_c$ – $B$ curves at 77 K and the microstructures of Gd-211 particles

A sample grown in the same batch as one reported in a previous study [28], where  $J_c$ – $B$  curves within the (100)- $a$  plane were measured, was used in this research to ensure comparability of the physical properties. The GdBCO single grain, which was grown from a composition of mixed precursor powder of (75 wt% Gd-123 + 25 wt% Gd-211) + 0.5 wt% CeO<sub>2</sub>, is shown in figure 1(a). The maximum  $\rightarrow$  trapped field of this sample measured at 77 K was 0.65 T, which correlates well with that of the sample measured in the previous study [28]. The single grain sample was cut parallel to a facet line along the dashed lines indicated in figure 1(c). A thin slab about 2 mm in thickness was extracted from the sample after cutting, which was then cut further parallel to the  $c$ -axis and cleaved along the  $ab$ -planes into smaller sub-specimens. These correspond to the locations 1ta, 1tb, 1tc, and so on, as illustrated schematically in figure 1(f), and are each of approximate dimensions  $a \times b \times c$  of  $1.8 \times 2.8 \times 1.5$  mm<sup>3</sup>. The critical superconducting transition temperature ( $T_c$ ) and  $M$ – $H$  loop of each sub-specimen (20 in total from locations 1ta to 4ta of the first row to 1te to 4te of the fifth row in the figure) were measured using a magnetic property measurement system (MPMS-3). This involved applying a test field of 2 mT (zero-field cooled) perpendicular to the  $ab$ -plane of each sub-specimen

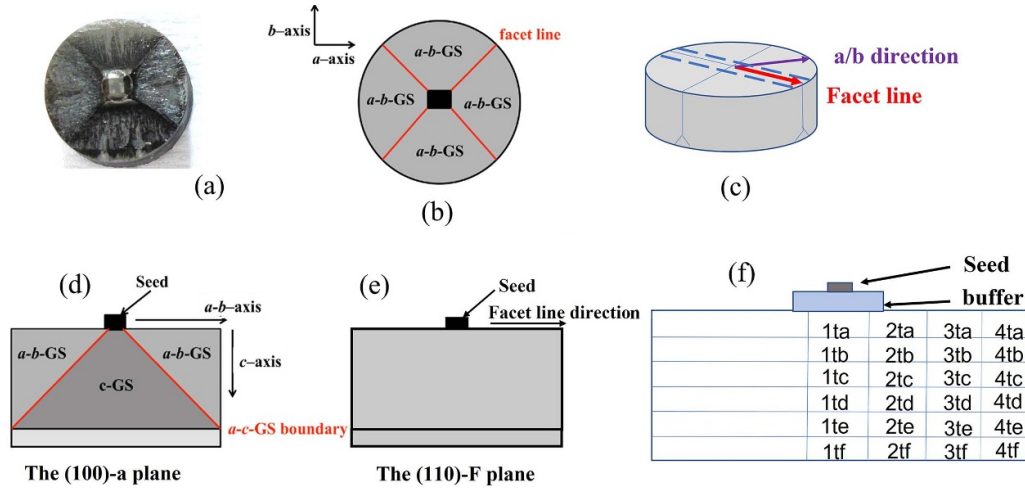
for the measurement of  $T_c$ . The critical current  $J_c$  was then calculated from the extended Bean model [26] using the  $M$ – $H$  loop data measured for each cuboid at 77 K for an applied field cycle of  $0 \rightarrow 7$  T  $\rightarrow 0$ , where  $a < b$  and  $c$  is the dimension in the  $c$  direction aligned parallel to the applied field. The sub-specimens from the previous study [28] were remeasured for comparison with the results of the measurements along the facet line and to eliminate the effects of changes in superconducting properties associated with the degradation of the sample over time in the measured  $M$ – $H$  loops and  $T_c$ . The microstructures of the sub-specimens were also examined via high-resolution scanning electron microscopy (SEM) to assess their porosity and Gd-211 particle content along the facet line and in the  $a/b$  direction.

### 2.2. Trapped field measurement

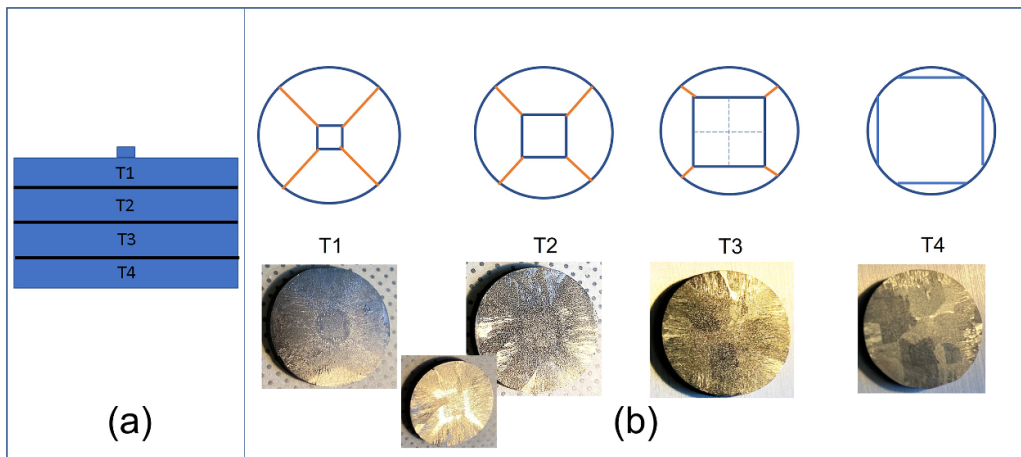
It is well known that single grains exhibit facet lines with four-fold symmetry on their top, seeded surface when grown via the top-seeded melt-growth (TSMG) technique [31]. These facet lines, which are extremely prominent in the as-grown sample microstructure, as shown in figure 1(a), usually divide the single grain into five regions: four  $a$ – $b$  growth ( $a$ – $b$ -GS) sections and one  $c$  growth section ( $c$ -GS), as shown in figures 1(b) and (d). We have observed from magnetisation measurements in this study that the facet lines generally increase the magnitude of the local  $J_c$  by at least 10% at all values of applied field.

The geometry of the facet line is different if a single grain sample is cut parallel to its  $ab$ -plane from top to bottom, as illustrated in figure 2, from the top sections of the sample (T1, T2), through to the bottom sections (T3 and T4). The photographs (also shown in figure 2) of the cut sections of a GdBCO–Ag single grain reveal these features. The boundaries of the growth sectors and facet lines of sections T1, T2, T3 and T4 can be seen to match the schematic illustrations in the same figure, although T3 and T4 also contain more (low angle) sub-domains that make the facet lines less distinct. The presence of longer facet lines is evident in section T1 than in T2 and T3, and there are almost no facet lines present in section T4. As a result, the fractional content of  $c$ -GS within the sections increases from T1 to T4. Supercurrent in (RE)BCO single grains flows mainly in the  $ab$ -planes due to the relatively large anisotropy in critical current density in these materials [32] when the applied field is perpendicular to the  $ab$ -plane. It is therefore reasonable to assume that the properties of  $ab$ -plane sections of a single grain are representative of the entire bulk sample in the magnetisation processes in this study. Each section was field cooled at 77 K in an applied magnetic field of 1.0 T prior to 2D trapped field mapping using a rotating Hall sensor array. Four single grain samples of GdBCO–Ag of different sizes and shapes were examined in this manner.

The GdBCO–Ag single grains used in this study were grown from a composition of mixed precursor powder of (75 wt% Gd-123 + 25 wt% Gd-211) + 0.5 wt% CeO<sub>2</sub> + 0.1 wt% BaO<sub>2</sub> + 10 wt% AgO<sub>2</sub> using standard silver containing TSMG techniques [33, 34].



**Figure 1.** The general features of a single grain. (a) A photograph of the top surface of the 20 mm diameter GdBCO single grain used to measure  $J_c$ . Schematic illustrations of (b) the top surface of a single grain and its four  $a$ - $b$  growth sectors ( $a$ - $b$ -GS) and facet lines, (c) the position of the thin slab (blue dashed lines) within the (110)- $F$  plane extracted from the single grain for the measurement of  $J_c$ , (d) the (100)- $a$  plane crossing the seed and its 2  $a$ - $b$ -GSs and a  $c$ -GS (e) the (110)- $F$  plane and (f) the (110)- $F$  plane of the thin slab extracted from the centre of the sample and the notations of each specimen used for the  $J_c$ - $B$  measurements.



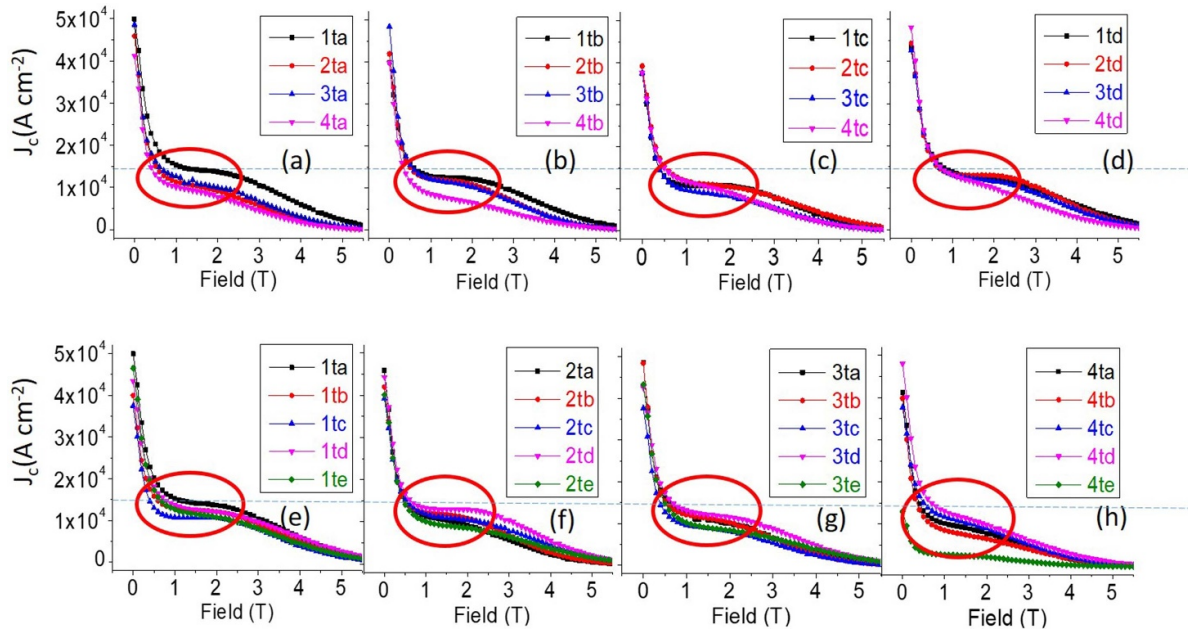
**Figure 2.** (a) A schematic side view of the sections cut from a single grain. (b) Photographs of cut sections T1, T2, T3 and T4 of the GdBCO-Ag single grain and schematic illustrations of the facet lines demonstrating how the growth sectors evolve through the thickness of the sample. The inset smaller photograph shows section T2 from another angle, within which the facet lines can be seen more clearly.

### 3. Results and discussion

#### 3.1. Comparison of $J_c$ - $B$ curves and microstructure analysis of embedded Gd-211 particles

Figure 3 shows  $J_c$ - $B$  curves measured for sub-specimens within the (110)- $F$  plane at the 20 positions indicated in figure 1(f). Most of the  $J_c$ - $B$  curves exhibit a plateau in their  $J_c(B)$  characteristic in the field region from 0.2 T to 2.5 T (circled in red), which is the specific region of interest given that the present samples generally exhibit trapped fields of up to 2.5 T at 77 K, where the plateau ends (the maximum trapped field at the top surface is 0.65 T at 77 K for the sample in figure 1(a)). The top four sub-figures, (a)-(d), are the  $J_c$ - $B$  curves for the a, b, c and d layers, where we observe that, broadly speaking,  $J_c$ - $B$  decreases from the top to the bottom of

the single grain (apart from layer d which sometimes exhibits a higher  $J_c$ ). Similarly, the sub-figures (e)-(h) reveal a trend in  $J_c$ - $B$  decreasing from the centre to the edge of the sample, suggesting that the trends of the variation in  $J_c$ - $B$  at (110)- $F$  plane are the same as those observed at the (100)- $a$  plane [28]. Note that the  $T_c$  of both of the specimens at the top layer of the (110)- $F$  plane and the remeasured (100)- $a$  plane are 0.1–0.3 K lower than those of the (100)- $a$  plane measured in the earlier study of 20 months ago [28]. This may suggest some degradation of the single grain samples. Most of the specimens (apart from those specimens at positions 4) measured in this study, however, have onset  $T_c$  of  $93.2 \pm 0.2$  K and transition width  $< 1.2$  K. This makes the comparison of  $J_c$  at 77 K at different positions within single grain between the (110)- $F$  and (100)- $a$  planes both fair and valid.



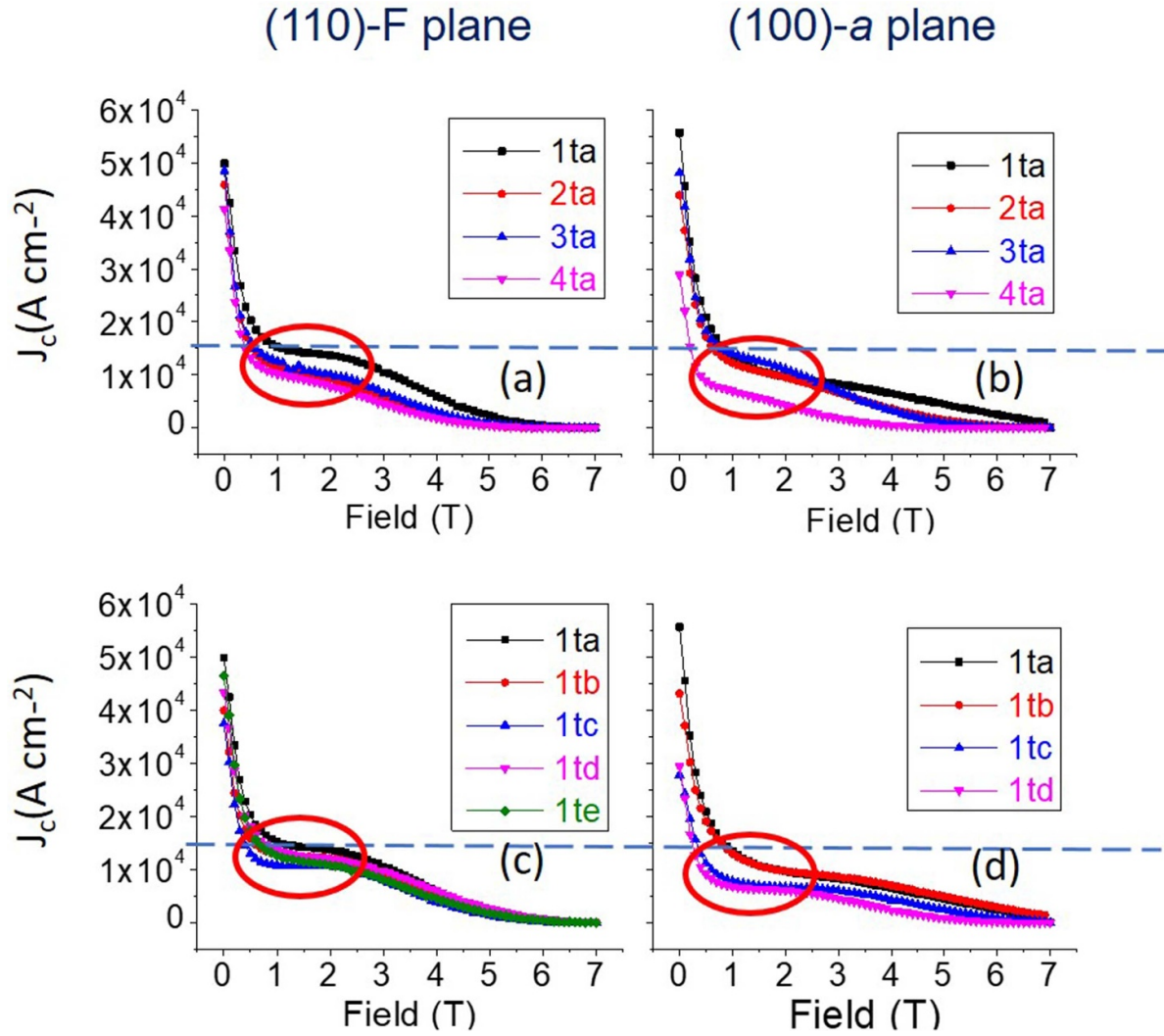
**Figure 3.**  $J_c$ - $B$  curves of 20 sub-specimens cut from the (110)- $F$  plane, as indicated in figure 1(f). (a)–(d)  $J_c$ - $B$  curves for layers a, b, c and d at positions 1–4 in figure 1(f); (e)–(h)  $J_c$ - $B$  curves at positions 1, 2, 3 and 4 positions for layers a, b, c, d and e in figure 1(f). The red circles indicate the regions where the applied fields are of particular interest in this study and their positions help to see the trend of the plateaus of  $J_c$ - $B$ .

Figure 4 shows a comparison of  $J_c$ - $B$  within the (110)- $F$  and (100)- $a$  planes. It can be seen that the  $J_c$ - $B$  curves are higher within the red circles in figures 4(a) and (c) than along the  $a/b$  direction in figures 4(b) and (d). In addition, the peak effect [35, 36] (or plateau) along the facet lines is more pronounced in the facet line data. This comparison indicates that, not only are the radial values of  $J_c$  non-uniform in a single grain (as observed for the  $a/b$  growth direction) as the locations of the sub-specimens move further away from the seed, but also there is an observable difference in  $J_c$  between the facet line and the  $a/b$  growth direction at the same radius of around +10% in the regions highlighted.

The microstructure of the top surface of the single grain sample was examined by high resolution SEM looking, primarily, at the distributions of secondary phases, such as embedded Gd-211 particles, which act as effective flux pinning centres. Photographs were taken at 1 mm intervals along the  $a/b$  direction and a facet line at the top surface, as shown in figure 5, which illustrate the typical microstructures at the top surface of the GdBCO single grain used to measure  $J_c$ - $B$ . It can be seen that the Gd-211 particles become smaller with increasing the distance from the seed,  $r$ , and that the number of Gd-211 particles increases along both the facet line and the  $a/b$  direction by comparing the SEM images (horizontally) at  $r_1$  and  $r_2$  in figures 5(b(I)) and (b(II)) or figures 5(b(III)) and (b(IV)). Furthermore, there are generally fewer Gd-211 particles present in the facet line compared to the individual growth sectors at the same distance from the seed by comparing the SEM images (vertically) at  $r_1$  in figures 5(b(I)) and (b(III)) and at  $r_2$  figures 5(b(II)) and (b(IV)), respectively, which has not been observed previous studies. The observed distribution of Gd-211 inclusions is described well by the

particle push/trap model [20], developed initially by Endo *et al* which explains the observed macro-segregation of Gd-211 particles in (RE)BCO single grains grown by an undercooling method. Numerous authors have confirmed these observations experimentally [12, 18, 20]. This is expected because conventional TSMG of (RE)BCO single grains fulfils the requirements in the push/trap model that the growth is controlled by undercooling and that the RE-211 particles are rather inert to the liquid phase (given that the growth rates are very low because the solubility of RE in the liquid phase is low).

Two specific trends in the observed Gd-211 particle density are particularly notable. Firstly, the volume fraction of Gd-211 increases as the area under investigation moves further away from the seed in both the (110)- $F$  plane and the (100)- $a$  plane [28]. Secondly, and contrary to the observed normal trend of increased Gd-211 density leading to increased critical current, a lower density of Gd-211 is observed in the facet line plane, despite its enhanced  $J_c$ - $B$  properties. For example, the SEM images in figures 5(b(I)) and in (b(II)) are equivalent to the positions of specimens 1a in figures 4(a) and (b) of the  $J_c$  measurements; the SEM images in figures 5(b(III)) and in (b(IV)) are equivalent to positions of the specimens 2a or 3a in figures 4(a) and (b) of the  $J_c$  measurements. If  $J_c$  was proportional to the volume fraction of  $\text{RE}_2\text{BaCuO}_5$  (RE-211) within the continuous bulk  $\text{REBa}_2\text{Cu}_3\text{O}_{7-\delta}$  (RE-123) superconducting matrix [8],  $J_c$  at position 1a would be lower than that at 2a or at 3a;  $J_c$  at (110)- $F$  plane (figure 4(a)) would be lower than the  $J_c$  at (100)- $a$  plane. These observations based on comparison of the  $J_c$  measurements of 20 specimens within the (110)- $F$  and (100)- $a$  planes contradict those of a previous study [8]. This second observation suggests that Gd-211 particles are unambiguously not the only factor that



**Figure 4.** Comparison of  $J_c$ - $B$  curves at 77 K at (a) the (110)- $F$  plane and (b) at the (100)- $a$  plane of the sub-specimens, at positions 'a' layer (i.e. beneath the seed along the  $a$  direction) in figure 1(f).  $J_c$ - $B$  curves at 77 K at (c) the (110)- $F$  plane and (d) at the (100)- $a$  plane of the specimens for the '1' positions in figure 1(f).

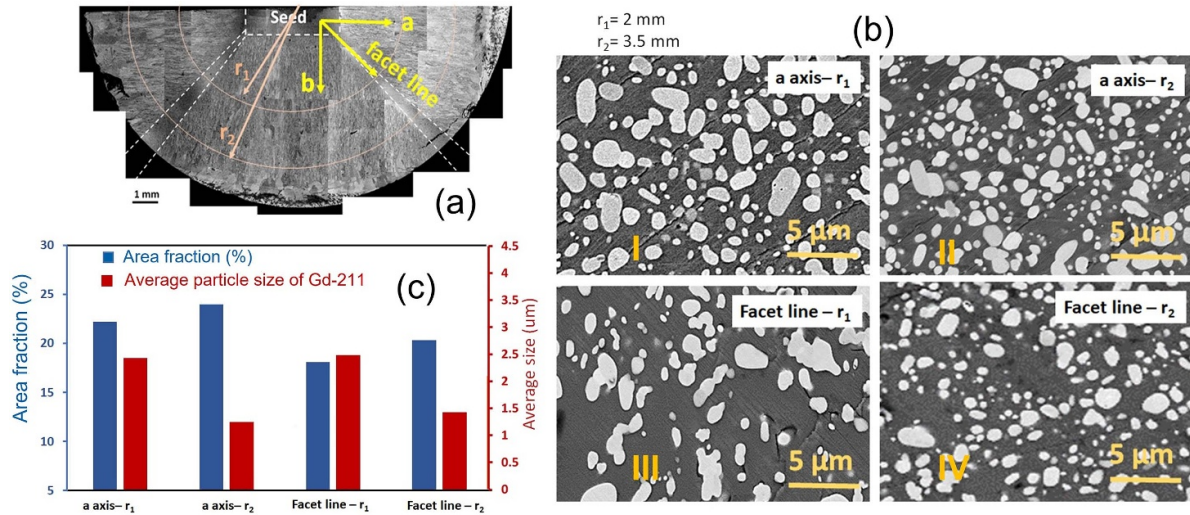
determines  $J_c$  in bulk, single grain superconductors. This is to be expected since any nano-sized, non-superconducting phase inclusion could theoretically form an effective flux pinning centre and the presence of any large, non-superconducting phase could cause a larger scale inhomogeneity in the critical current. Of particular significance is the reduced presence of low-angle-misorientated sub-grains in the facet line compared to the individual growth sectors [17], which may be a contributing factor to the observed higher  $J_c$  along the facet lines. Further research is needed to correlate  $J_c$ - $B$  clearly with sample microstructure, and this is on-going.

### 3.2. The effect of the difference of $J_c$ - $B$ between the (110)- $F$ and (100)- $a$ planes on trapped field

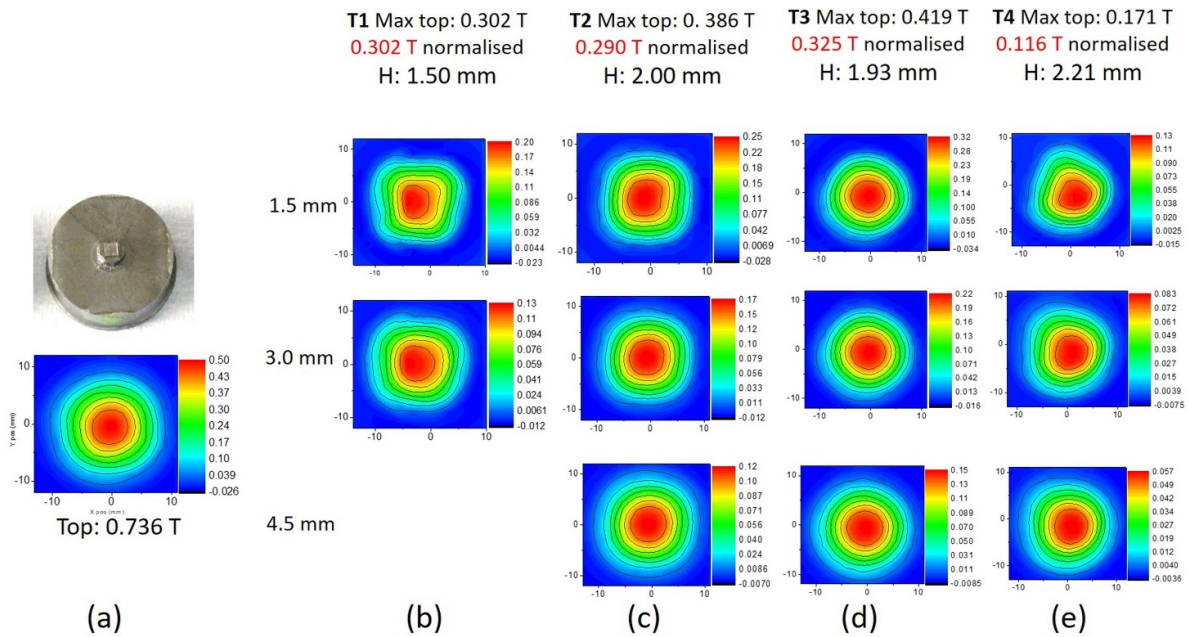
In general, it is necessary to integrate  $J_c$  across the radius,  $r$ , of the single grain in order to calculate the trapped field of the sample, which requires knowledge of the  $J_c$  distribution in the  $ac$ -planes within the whole  $a/b$ -growth-sector ( $a$ -GS) and is

not practical to measure. However, if the change in  $J_c$ - $B$  across the entire  $a/b$  growth region is less than that between the (110)- $F$  plane and the (100)- $a$  plane, for example, then the gradual change in  $J_c$  may be modelled using a cosine function [37, 38] from the  $a/b$  direction to the facet line around the  $ab$ -plane. In this case, the effect of any difference in  $J_c$  on the measured trapped field, such as a deviation from circular symmetry in the field distribution contour maps within a given section can be seen. Furthermore, if the geometry of the facet lines is not the same in each section, as shown in figure 2, then the contour maps of the trapped field of each section should be different, as can also be seen in the measurements of the contour maps of the trapped fields from the cut sections from the top to the bottom of the sample (T1 to T4 shown in figure 2).

Any given trapped field could theoretically be generated from an infinite number of  $J_c$ - $B$  curves given that it is an integral of  $J_c$  across  $r$ . Here we present examples from four GdBCO-Ag single grains of different sizes and shapes and cut into thin sections to demonstrate statistically the effect



**Figure 5.** Microstructure of embedded Gd-211 particles observed at different distances from the seed along a facet line and along an  $a/b$  direction of the top surface of a GdBCO single grain of diameter 20 mm. (a) Locations where the SEM images were taken. (b) SEM images taken at the top surface of the sample along the  $a$ -axis at distance  $r_1$  (I) and  $r_2$  (II) and along the facet line at  $r_1$  (III) and  $r_2$  (IV) (c) the area fractions and average particle size of Gd-211 at distance  $r_1$  and  $r_2$  along the  $a$ -axis and the facet line, respectively.

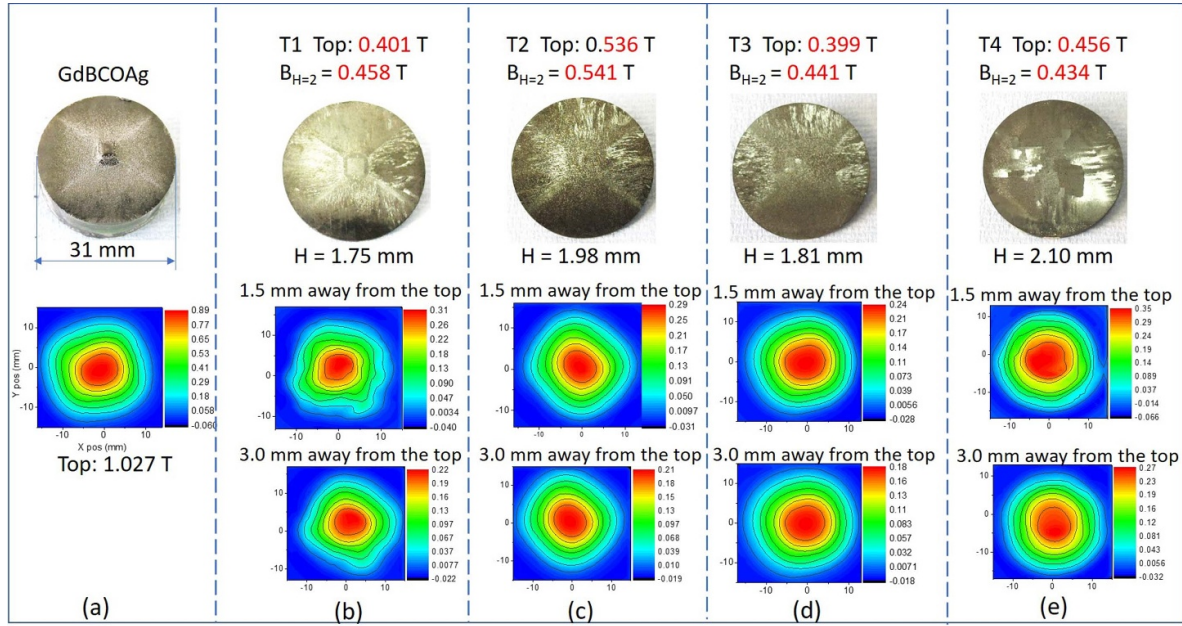


**Figure 6.** Trapped fields (maximum value and contour maps) of the 20 mm diameter GdBCO–Ag single grain and its four sections T1, T2, T3 and T4 cut parallel to the  $ab$ -plane. (a) A photograph of the GdBCO–Ag single grain and its contour map measured 1.5 mm above its polished top surface. (b) Contour maps of section T1 measured at 1.5 mm and 3.0 mm above its surface. (c) Contour maps of section T2 measured at 1.5 mm, 3.0 mm and 4.5 mm above its surface. (d) Contour maps of the section T3 measured at 1.5 mm, 3.0 mm and 4.5 mm above its surface. (e) Contour maps of the section T4 measured at 1.5 mm, 3.0 mm and 4.5 mm above its surface.

of the difference in  $J_c$ – $B$  between the facet line and the  $a/b$  direction.

Figure 6 shows contour maps of four sections of a fully grown 20 mm diameter GdBCO–Ag single grain cut parallel to the  $ab$ -plane. The maximum trapped field values measured above the top surfaces of each section, including the trapped field values normalised by section thickness at a measurement height of 1.5 mm, are also shown for each section for ease of comparison. It can be seen that the GdBCO–Ag single grain

is of high-quality with a trapped field of 0.736 T at the centre of its top surface. In addition, the shape of the contour map measured at 1.5 mm above the top surface of each section exhibits a geometry somewhere between that of a square and a circle with concentric and uniform contour lines, as shown in figures 6(b)–(e). This evolves, broadly, from a square-like shape for section T1 to a more circular geometry for T3. Significantly, the facet lines are longer at the top surface (T1) due to the formation of the different growth sectors, resulting in



**Figure 7.** Trapped fields (maximum values and contour maps) of a 31 mm diameter GdBCO-Ag single grain. (a)–(e) Photographs of the sample, its maximum trapped field and contour maps measured at 1.5 mm of the whole sample and at 1.5 mm and 3 mm above the surface of each section T1, T2, T3 and T4 cut parallel to the  $ab$ -plane, respectively.

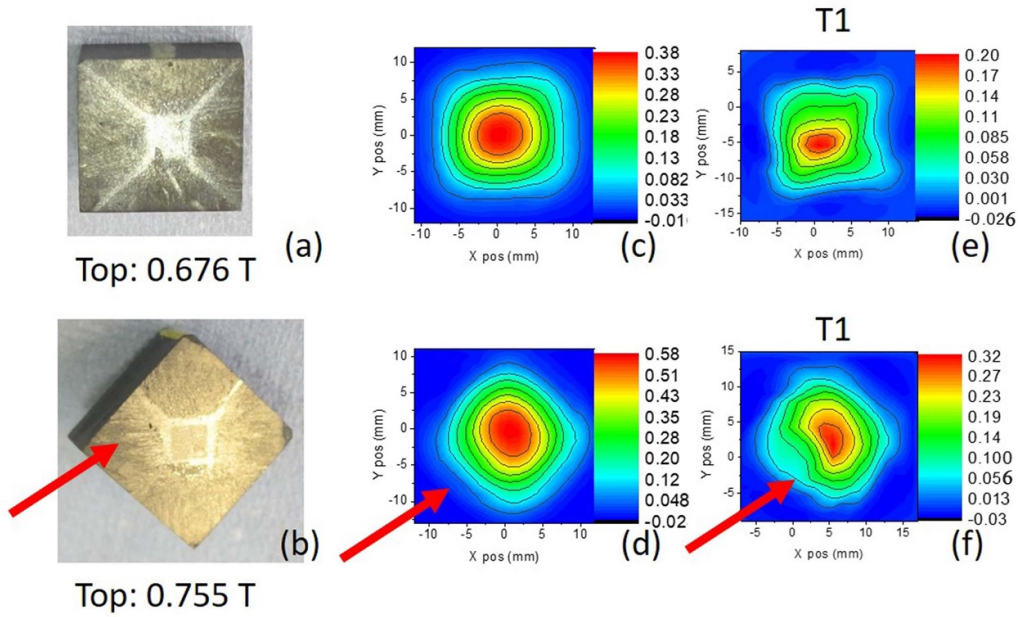
the more square-like, trapped field geometry. The facet lines become shorter for sections T2 and T3 and the contour maps are, correspondingly, more circular. Section T4 corresponds to the bottom of the single grain, where the microstructure is usually more non-uniform compared to the top sections, due generally to a variation in both growth conditions and local sample composition, which are difficult to control. As a result, the distribution of  $J_c$  for section T4 is rather complicated, and the shape of trapped field is difficult to predict. The effect of a full-length facet line on the shape of the contour map has been predicted by various numerical models [5, 37, 39–41] assuming an inhomogeneous sample with the same constant  $J_c$ , but with  $J_c$  varying as a cosine function over the  $ab$ -plane. A  $J_c$  of  $1 \times 10^8 \text{ A m}^{-2}$  is assumed typically in these models with a  $x$ - $y$  spatial variation  $\pm 0.1 \times 10^8 \text{ A m}^{-2}$  within the  $ab$ -plane and the highest value defined at the facet line [5, 37, 38] at the same radius. A similar distortion of the shape of the trapped field profile can be seen in the present study as predicted from the models, which did not include a field-dependent  $J_c$ . This effect is particularly apparent for section T1 in figure 6(b), which contains the longest facet lines and corresponds more accurately to the assumptions made in the models, suggesting that they are reasonable and reflect the variation of  $J_c$  in the real samples, although it is not known whether  $J_c$  varies as a cosine function precisely within the  $ab$ -plane.

It is clear that the trapped field (or magnetic flux density) decreases relatively quickly when measured further away from the surface of the section (i.e. from 1.5 mm to 4.5 mm) and the shape of the contour maps becomes more circular (see figure 6). The trapped field at any position in a given section is the result of the interaction of the magnetic flux lines

within each superconducting layer across many layers of adjacent  $ab$ -planes at different distances from the measured surface in a single grain, which tends to reduce the value of the trapped field and increase its uniformity with increasing distance from the surface of the section. Apparently, the shape of the trapped field measured for the parent single grain used to cut the sample into four sections should reflect a superposition of the trapped fields measured for sections T1, T2, T3 and T4, as shown in figure 6(a). As anticipated, the top layers of a single grain dominate the shape and value of trapped field of the as-processed parent single grain. This explains why fully grown single grains generally exhibit squarer trapped field geometries.

A GdBCO-Ag single grain 31 mm in diameter was also cut into four sections and the trapped field measurements repeated. A similar trend in the changes in shape of the trapped fields were observed, as shown in figure 7. These data confirm that the contour maps close to the top surface are generally of a square geometry indicating clearly that there are no defects present in the single grain microstructure that have a more significant effect on  $J_c$  than that between the facet lines and  $a/b$  directions. We can conclude, therefore, that is a common feature of good (RE)BCO single grains of GdBCO-Ag.

The contour maps measured 3.0 mm above the surface of each specimen are consistent with those in figure 6 and exhibit a more uniform magnetic field. This suggests that applications that do not use trapped field at the immediate surface of the single grain but at a position more distant from the surface will benefit from a more uniform trapped field distribution, which may be beneficial to the further development of single GdBCO-Ag grains for practical applications.



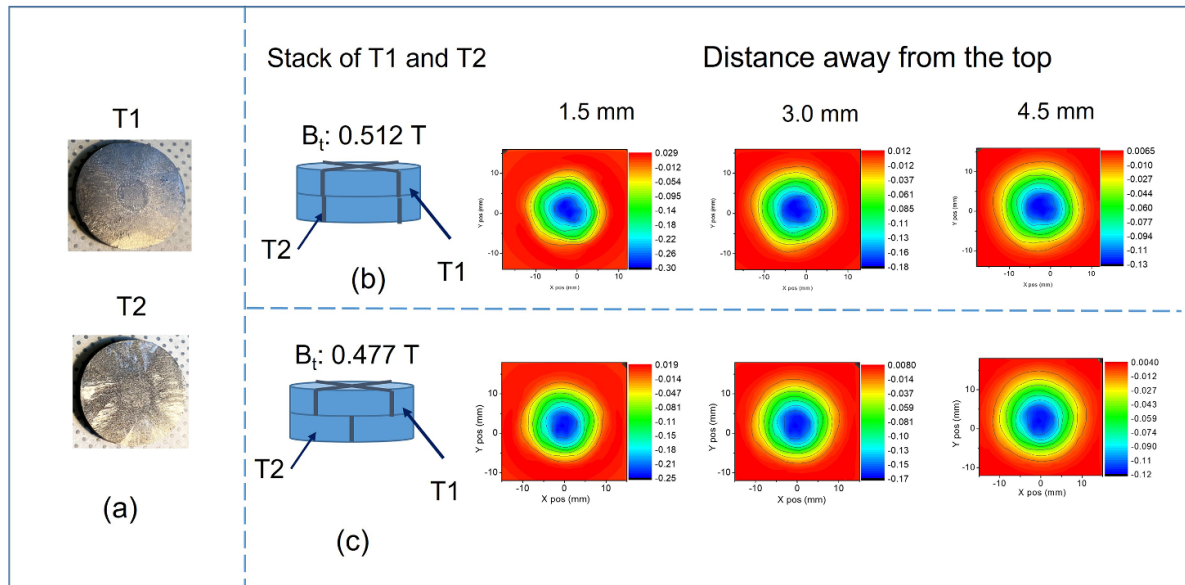
**Figure 8.** Photographs and contour maps of two cut, square GdBCO–Ag single grains grown from different orientations of the seed crystal. (a) A cut, square GdBCO–Ag single grain with maximum trapped field 0.676 T at 77 K. (b) A cut, square GdBCO–Ag single grain with the seed crystal orientated at  $45^\circ$  compared to the sample in (a) with maximum trapped field 0.755 T at 77 K. (c) and (d) Contour maps of the whole, as-processed samples (a) and (b) measured at 1.5 mm above the top single grain surface at 77 K. (e) and (f) Contour maps of the top section T1 of samples (a) and (b) measured at 1.5 mm above the surface at 77 K.

The morphology of the top surface of a (RE)BCO single grain sample melt processed from a cylindrical precursor green body is generally between that of square-planar or circular (sometimes termed a ‘squirrel’), and particularly so when the single grain does not extend to the circumference of the pellet, due primarily to the square planar nature of the growth fronts. As a result, the trapped field contour map usually takes the approximate geometrical shape of the single grain. The formation of a trapped field contour map in a shape between that of a square and a circle may be attributed generally to the non-superconducting nature of the thin edges of the sample (i.e. the arc sectors defined by the planar growth front and the circumference of the disc). This observation, therefore, may detract from the above discussion. To demonstrate the effect of facet lines on trapped field more clearly, two square samples of area  $17 \times 17 \text{ mm}^2$  were cut from two individual single grains of diameter 25 mm, as shown in figure 8. The edge of the sample in figure 8(a) is parallel to an  $a/b$  direction, whereas the edge of the sample in figure 8(b) is parallel to a facet line. It can be seen from figures 8(c) and (d) that the shape of the four sides of the trapped field contour map of sample (a) is straighter and less protruding than the centres of the four sides in figure 8(b), although it is not very apparent because the effects of facet line from top to bottom of the sample integrate together (there is no facet line at the bottom of the single grain). This effect is more pronounced for the thin sections cut from the top surfaces of the samples in figures 8(a) and (b), as shown in figures 8(e) and (f). It can be seen that the contour map of figure 8(e) is straighter or even concave, whereas the contour map in figure 8(f) is protruding. This is because

the top sections of samples T1 and T2 (figures (a) and (b)), exhibit more apparent differences in lengths and orientation of the facet lines that change significantly the shapes of the contour maps. Unfortunately, one corner (indicated by the red arrow) of the contour map in figure 8(f) does not follow the trend due to an unidentified feature in the single grain microstructure, such as the disappearance of a facet line, which can be seen in the top surface of the sample. This suggests both that defects may exist within the sample, and that they have a greater influence on the geometry of the trapped field (such an effect is often observed when a GdBCO single grain is cut into sections). It indicates further that the effect of  $J_c$  of a facet line on trapped field is only apparent in good samples with relatively uniform  $a/b$  growth sectors so that any differences in  $J_c$  over the entire region of the section are larger than those between the facet line and the  $a/b$  direction.

### 3.3. Generation of a uniform trapped field through the arrangement of samples

The measurements reported in this study indicate consistently that  $J_c$  in GdBCO–Ag single grains is enhanced at the facet lines, which impacts clearly on the measured trapped fields. However, this effect can only be observed generally at the top surface of good samples, in which the difference in  $J_c$  between the (110)- $F$  and (100)- $a$  planes is higher than other differences in  $J_c$  caused by non-superconducting defects within the entire growth sector. Single grains can contain an inherent non-uniform  $J_c$  distribution, although their physical appearance and ability to generate a single-peak trapped field indicates



**Figure 9.** Trapped fields and contour maps of a stack of sections T1 and T2 shown in figure 5 with the facet lines oriented at  $45^\circ$  to each other. (a) Photographs of sections T1 and T2. Schematic illustration of the T1 and T2 stack assembly and the measured contour maps at 1.5, 3.0 and 4.5 mm above the top surface of the stack (b) without and (c) with a  $45^\circ$  offset.

them still to be single grains. The trapped field of a whole single grain is generally more uniform than cut, thin sections as a result of the stacking many thin *ab*-planes. The trapped fields measured further away from the surface of the single grains (i.e. at 3.0 mm and 4.5 mm from the top surfaces of the sample) are considerably more uniform than those at intermediate surfaces, as seen from the contour maps in figures 7 and 8, due primarily to the interaction of the individual flux lines generating a more uniform trapped field. These observations suggest that arranging an assembly from separate sections is another way of achieving increased uniformity of trapped field over the entire surface of the assembled sections.

The trapped fields of two stacked sections T1 and T2, where the T2 facet lines are aligned and offset by  $45^\circ$  to one another, are shown in figure 9. It can be seen that the contour map of the trapped field of the stacked arrangement with the  $45^\circ$  offset exhibits a more uniform trapped field distribution, which is particularly apparent when measured close to the stack surface. This arrangement also exhibits greater circular symmetry in the shape of the contour map. This is consistent with the results of a recent model by the Cambridge Bulk Superconductivity Group in which a similar arrangement of single grain (RE)BCO rings improved significantly the uniformity of the magnetic field within the bore of a two-ring stack [42]. The resulting levitation force can also be optimised by arranging bulk, single grain samples based on the internal distribution of  $J_c$  [43]. These results and observations suggest clearly that a more uniform net trapped field can be achieved by arranging selectively single grain sections or rings that contribute optimally to the trapped field even when each component within the assembly does not itself exhibit a uniform trapped field distribution due to a non-uniform distribution of  $J_c$ .

#### 4. Conclusions

Detailed analysis of 20 sub-sections of a half cross-section of a GdBCO single grain shows that  $J_c$ - $B$  characteristics at 77 K measured within the (110)- $F$  plane along facet lines are typically more than 10% higher than those measured in the (100)- $a$  plane, and particularly when the applied field is between 0.2 and 2.5 T. Three sets of four sections cut parallel to the *ab*-plane of a high quality GdBCO-Ag single grain indicate that the trapped fields of the top layers of the sample exhibit a squarer trapped field contour map geometry, whereas the bottom layers in a fully grown single grain tend to exhibit a more circular shape. Microstructural analysis of the Gd-211 particle distribution in these single grains shows that there are fewer Gd-211 particles present within the facet lines, suggesting that Gd-211 inclusions are not the only intrinsic factor determining  $J_c$  in this study. The difference in  $J_c$  behaviour at the facet lines and the *a/b* direction of a single grain outside the facet line vicinity is attributed to variations in the sample microstructure and to the presence of other defects. An arrangement based on a stack of sections is proposed specifically to reduce the effect of the observed variation in  $J_c$  to provide a more uniform trapped field of the assembled stack. This has been achieved by stacking two sections with square shaped contour maps cut parallel to the *ab*-plane but rotated by  $45^\circ$  to each other to generate a uniform, circular trapped field, demonstrating that it is possible to achieve a uniform trapped field from non-uniform single grains that exhibit non-uniform  $J_c$ .

#### Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: <https://doi.org/10.17863/CAM.84356>.

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## References

- [1] Tomita M and Murakami M 2003 High-temperature superconductor bulk magnets that can trap magnetic fields of over 17 tesla at 29 K *Nature* **421** 517–20
- [2] Durrell J H *et al* 2014 A trapped field of 17.6 T in melt-processed, bulk Gd–Ba–Cu–O reinforced with shrink-fit steel *Supercond. Sci. Technol.* **27** 082001
- [3] Bednorz J G M and Muller K A 1986 Possible high  $T_c$  superconductivity in the Ba–La–Cu–O system *Z. Phys. B* **64** 189–93
- [4] Durrell J H, Ainslie M D, Zhou D, Vanderbemden P, Bradshaw T, Speller S, Filipenko M and Cardwell D A 2018 Bulk superconductors: a roadmap to applications *Supercond. Sci. Technol.* **31** 103501
- [5] Ainslie M D, Fujishiro H, Ujiie T, Zou J, Dennis A R, Shi Y-H and Cardwell D A 2014 Modelling and comparison of trapped fields in (RE)BCO bulk superconductors for activation using pulsed field magnetization *Supercond. Sci. Technol.* **27** 065008
- [6] Campbell A M and Evetts J E 1972 Flux vortices and transport currents in type II superconductors *Adv. Phys.* **21** 199–428
- [7] Maggio-Aprile I, Renner C, Erb A, Walker E and Fischer Ø 1995 Direct vortex lattice imaging and tunneling spectroscopy of flux lines on  $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$  *Phys. Rev. Lett.* **75** 2754–7
- [8] Murakami M 1992 Processing of bulk  $\text{YBaCuO}$  *Supercond. Sci. Technol.* **5** 185
- [9] Nariki S, Sakai N, Murakami M and Hirabayashi I 2004 Effects of  $\text{Dy}_2\text{BaCuO}_5$  contents on microstructure and mechanical strength of Ag-added Dy–Ba–Cu–O bulk superconductors *Physica C* **412–414** 651–6
- [10] Nariki S, Sakai N, Murakami M and Hirabayashi I 2006 Effect of  $\text{RE}_2\text{BaCuO}_5$  refinement on the critical current density and trapped field of melt-textured (Gd, Y)–Ba–Cu–O bulk superconductors *Physica C* **439** 62–66
- [11] Zhang Z W, Shi Y, Zhai W, Dennis A R and Cardwell D A 2017 Effect of Pt and  $\text{CeO}_2$  on growth of Y-123/nano- $\text{Y}_2\text{O}_3$  single grain superconductors *IEEE Trans. Appl. Supercond.* **27** 6800804
- [12] Diko P, Gawalek W, Habisreuther T, Klupsch T and Görnert P 1995 Influence of  $\text{Y}_2\text{BaCuO}_5$  particles on the microstructure of  $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$  (123)- $\text{Y}_2\text{BaCuO}_5$  (211) melt-textured superconductors *Phys. Rev. B* **52** 13658–64
- [13] Cloots R, Koutzarova T, Mathieu J P and Ausloos M 2005 From RE-211 to RE-123. How to control the final microstructure of superconducting single-domains *Supercond. Sci. Technol.* **18** R9
- [14] Morita M, Tanaka M, Takebayashi S, Kimura K, Miyamoto K and Sawano K 1991 Effect of Pt addition on melt-processed  $\text{YBaCuO}$  superconductors *Jpn. J. Appl. Phys.* **30** L813–5
- [15] Jirsa M, Muralidhar M, Murakami M, Noto K, Nishizaki T and Kobayashi N 2000  $J_c$ -B performance study of an OCMG (Nd–Eu–Gd)-123 material doped by sub-micrometre Gd-211 particles *Supercond. Sci. Technol.* **14** 50–57
- [16] Nariki S, Sakai N, Murakami M and Hirabayashi I 2004 High critical current density in RE–Ba–Cu–O bulk superconductors with very fine  $\text{RE}_2\text{BaCuO}_5$  particles *Physica C* **412–414** 557–65
- [17] Goodfellow A, Shi Y-H, Durrell J H, Dennis A R, Cardwell D A, Grovenor C R M and Speller S C 2016 Microstructural evolution in multiseeded YBCO bulk samples grown by the TSMG process *Supercond. Sci. Technol.* **29** 115005
- [18] Zhai W, Shi Y, Durrell J H, Dennis A R and Cardwell D A 2014 The influence of Y-211 content on the growth rate and Y-211 distribution in Y–Ba–Cu–O single grains fabricated by top seeded melt growth *Cryst. Growth Des.* **14** 6367–75
- [19] Congreve J V J, Shi Y H, Dennis A R, Durrell J H and Cardwell D A 2016 Microstructure and composition of primary and recycled single grains of YBCO, GdBCO–Ag, and SmBCO–Ag bulk superconductors *J. Am. Ceram. Soc.* **99** 3111–9
- [20] Endo A, Chauhan H S, Egi T and Shiohara Y 1996 Macrosegregation of  $\text{Y}_2\text{Ba}_1\text{Cu}_1\text{O}_5$  particles in  $\text{Y}_1\text{Ba}_2\text{Cu}_3\text{O}_{7-\delta}$  crystals grown by an undercooling method *J. Mater. Res.* **11** 795–803
- [21] Babu N H, Cheng L, Iida K and Cardwell D A 2006 Nano-composite single grain  $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}/\text{Y}_2\text{Ba}_4\text{CuBiO}_y$  bulk superconductors *J. Phys.: Conf. Ser.* **43** 377
- [22] Iida K, Babu N H, Reddy E S, Shi Y H and Cardwell D A 2005 The effect of nano-size  $\text{ZrO}_2$  powder addition on the microstructure and superconducting properties of single-domain Y–Ba–Cu–O bulk superconductors *Supercond. Sci. Technol.* **18** 249
- [23] Koblishka M R and Murakami M 2000 Pinning mechanisms in bulk high- $T_c$  superconductors *Supercond. Sci. Technol.* **13** 738
- [24] Koblishka-Veneva A, Mücklich F, Koblishka M R, Hari Babu N and Cardwell D A 2007 Crystallographic orientation of  $\text{Y}_2\text{Ba}_4\text{CuMO}_x$  (M=Nb, Zr, Ag) nanoparticles embedded in bulk, melt-textured YBCO studied by EBSD *J. Am. Ceram. Soc.* **90** 2582–8
- [25] Shi Y, Hasan T, Babu N H, Torrisi F, Milana S, Ferrari A C and Cardwell D A 2012 Synthesis of  $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$  and  $\text{Y}_2\text{BaCuO}_5$  nanocrystalline powders for YBCO superconductors using carbon nanotube templates *ACS Nano* **6** 5395–403
- [26] Chen D X and Goldfarb R B 1989 Kim model for magnetization of type-II superconductors *J. Appl. Phys.* **66** 2489–500
- [27] Dewhurst C D, Wai L and Cardwell D A 1997 Distribution of critical current density in large  $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$  grains fabricated using seeded peritectic solidification *IEEE Trans. Appl. Supercond.* **7** 1925–8
- [28] Shi Y, Gough M, Dennis A, Durrell J H and Cardwell D A 2020 Distribution of the superconducting critical current density within a Gd–Ba–Cu–O single grain *Supercond. Sci. Technol.* **33** 044009
- [29] Lo W, Cardwell D A, Dewhurst C D, Leung H T, Chow J C L and Shi Y H 1997 Controlled processing and properties of large Pt-doped Y–Ba–Cu–O pseudocrystals for electromagnetic applications *J. Mater. Res.* **12** 2889–900

- [30] Shi Y H, Dennis A R and Cardwell D A 2015 A new seeding technique for the reliable fabrication of large, SmBCO single grains containing silver using top seeded melt growth *Supercond. Sci. Technol.* **28** 035014
- [31] Cardwell D A 1998 Processing and properties of large grain (RE)BCO *Mater. Sci. Eng. B* **53** 1–10
- [32] Blatter G, Feigel'man M V, Geshkenbein V B, Larkin A I and Vinokur V M 1994 Vortices in high-temperature superconductors *Rev. Mod. Phys.* **66** 1125–388
- [33] Shi Y, Kumar Namburi D, Zhao W, Durrell J H, Dennis A R and Cardwell D A 2015 The use of buffer pellets to pseudo hot seed (RE)–Ba–Cu–O–(Ag) single grain bulk superconductors *Supercond. Sci. Technol.* **29** 015010
- [34] Shi Y, Hari Babu N, Iida K, Yeoh W K, Dennis A R, Pathak S K and Cardwell D A 2010 Batch-processed GdBCO–Ag bulk superconductors fabricated using generic seeds with high trapped fields *Physica C* **470** 685–8
- [35] Murakami M, Yoo S-I, Higuchi T, Sakai N, Weltz J, Koshizuka N and Tanaka S 1994 Flux pinning in melt-grown  $\text{NdBa}_2\text{Cu}_3\text{O}_y$  and  $\text{SmBa}_2\text{Cu}_3\text{O}_y$  superconductors *Jpn. J. Appl. Phys.* **33** L715–7
- [36] Murakami M, Sakai N, Higuchi T and Yoo S I 1996 Melt-processed light rare earth element–Ba–Cu–O *Supercond. Sci. Technol.* **9** 1015–32
- [37] Zhang M, Matsuda K and Coombs T A 2012 New application of temperature-dependent modelling of high temperature superconductors: quench propagation and pulse magnetization *J. Appl. Phys.* **112** 043912
- [38] Ainslie M D, Zou J, Mochizuki H, Fujishiro H, Shi Y-H, Dennis A R and Cardwell D A 2015 Pulsed field magnetization of  $0^\circ$ – $0^\circ$  and  $45^\circ$ – $45^\circ$  bridge-seeded Y–Ba–Cu–O bulk superconductors *Supercond. Sci. Technol.* **28** 125002
- [39] Ainslie M D and Fujishiro H 2015 Modelling of bulk superconductor magnetization *Supercond. Sci. Technol.* **28** 053002
- [40] Shiraishi R and Ohsaki H 2006 Flux dynamics in inhomogeneous bulk superconductor during pulsed field magnetization *IEEE Trans. Appl. Supercond.* **16** 1794–7
- [41] Yokoyama K, Oka T, Fujishiro H and Noto K 2008 Numerical analysis of bulk superconducting magnet magnetized by pulsed-field considering a partial difference of superconducting characteristics *IEEE Trans. Appl. Supercond.* **18** 1545–8
- [42] Beck M and Ainslie M D 2022 Mitigating ab-plane critical current density inhomogeneity in bulk HTS rings for the generation of NMR-grade magnetic fields *IEEE Trans. Appl. Supercond.* **32** 6800705
- [43] Cheng Y, Zheng J, Huang H and Deng Z 2021 A reconstructed three-dimensional HTS bulk electromagnetic model considering  $J_c$  spatial inhomogeneity and its implementation in a bulks combination system *Supercond. Sci. Technol.* **34** 125017