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Transport current measurement of $I_c(T, B, \theta)$ and $n(T, B, \theta)$ for a bulk REBCO superconductor

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Abstract—Bulk rare-earth barium cuprate (REBCO) high-temperature superconductors are attractive for many electromagnetic applications due to their ability to support large current densities and trap large magnetic fields. At present, magnetisation techniques are the predominant method of measuring the critical current density, J_c, for bulk superconductors, due to the abundance of measurement devices and ease of sample preparation and measurement. However, this approach does not provide direct access to measurements of magneto-angular anisotropy of J_c nor n-value. By contrast, transport current techniques allow direct measurement of the full thermo-magneto-angular dependence of both I_c and n, but limited data is available for REBCO bulks, due to the difficulties of sample preparation and measurement. This work introduces a reproducible method to prepare a single-grain bulk GdBCO-Ag superconductor for transport current characterisation, and presents measured data for both I_c and n that has been obtained over a broad parameter-space. The measured n-values are lower than is commonly assumed, with typical n-values at 77 K being in the range of 10 to 14. An accurate value of n is required when computationally modelling transient effects.

Index Terms—Critical current density, current transport measurements, HTS, REBCO, bulk superconductors.

I. INTRODUCTION

RARE-earth barium cuprate (REBCO, where RE is either Y or a rare-earth element) ceramics are a class of high-temperature superconductor (HTS) that are commonly used in electromagnetic applications due to their ability to support large current densities and trap large magnetic fields [1]–[3]. Applications of REBCO bulks include quasi-permanent magnets, undulators, magnetic levitation, bearings, NMR and MRI imaging [1]–[9]. Numerical simulations provide a fast and cost-effective means of advancing these technologies, but require data of the critical current density, J_c, and flux-flow exponent, n, of the superconductor to be accurately input for a wide range of conditions. This includes values measured under strong external magnetic fields, which are common operating conditions for bulk HTS devices.

The most common way to obtain J_c data from a superconducting bulk is via magnetisation measurement techniques, which have been used extensively to characterise YBCO, GdBCO and other bulks [10]–[15]. The standard technique is to cut samples into cuboids of $\sim$2 mm side length, and then use a magnetic properties measurement system to measure M-H loops and then calculate J_c from the hysteresis loop width using the extended Bean model [16]. Alternative magnetic techniques to determine J_c include using magneto-optics [17], [18] and Hall probe arrays [19], [20].

Magnetisation techniques are used because the measurement instruments are widely available, little sample preparation is needed, and measurements are relatively straightforward to perform. However, the resultant values of J_c are calculated indirectly, with J_c assumed to be uniform throughout the sample. This means that this approach cannot distinguish inhomogeneity within a sample due to magneto-angular anisotropy or microstructure. Although the microstructure within a particular sample cannot be distinguished, Shi et al. have performed systematic examinations into the J_c distribution within a single-grain GdBCO bulk, examining how it changes with the distribution of Gd-211 particle density and sample porosity [11], [12]. It is also difficult to determine the n-value of a bulk sample in this way, as this requires a transient relaxation measurement [21]–[23], which is typically dominated by the inductance of the measurement coils themselves. Most published n-values correspond to YBCO at 77 K, and typically vary between 10 and 50 [21], [24]. A further issue is that constituent elements within the measured sample may also be paramagnetic, which can also complicate determination of loop widths.

An alternative method, which is widely used to determine I_c of superconducting tapes and wires, is through a 4-point transport current measurement. In this case the voltage across a sample is measured whilst a transport current is applied. The resulting direct measurement enables n to be obtained by simply fitting the measured voltage response to the E-J power law [25], [26]. The temperature, and the magnitude and direction of an applied magnetic field can all be varied to investigate the thermo-magneto-angular anisotropy of the measured sample, $I_c(T, B, \theta)$. However, obtaining a dataset that covers multiple temperatures, fields and angles with this technique requires specialist equipment. Additionally, sample I_c values of $\leq$ 1kA, are typically required, as these can be accessed using standard laboratory current supplies. In the case of high performance REBCO bulks, this means that very thin sample cross-sections are needed, which are difficult to prepare without causing damage to the sample due to the brittle nature of REBCO bulks [27]. This problem is exacerbated as bulk

manufacturing technology continues to improve and deliver ever increasing values of bulk J_c (which require even thinner cross-section samples for a transport measurement).

Due to these difficulties, a comprehensive dataset of transport J_c and n-values for REBCO bulks is yet to be published, with previous works being predominantly focused on the LN2 temperature, self-field case for YBCO [28]–[32]. Other bulks such as DyBCO, (NdEuGd)BCO and GdBCO-Ag have also been investigated, but to a lesser degree [14], [33], [34]. Some critical current angle-dependence has been measured, such as in [28], [29], however the I_c data is mostly sparse, unpublished for n-values and over 20 years old, when bulk manufacturing technology was less refined.

In this work, a new sample preparation technique is introduced, which enables transport current measurements of thin sample bars cut from a bulk REBCO superconductor. Measurements of $I_c(T, B, \theta)$ and $n(T, B, \theta)$ are then presented for a sample cut from a top-seeded melt growth (TSMG) GdBCO-Ag bulk. These measurements demonstrate the efficacy of this approach, and provide initial data on the strong anisotropic dependence on magnetic field magnitude and direction that is observed in these materials.

II. METHODOLOGY

A. Measuring $I_c(B, \theta)$

The SuperCurrent transport current measurement system has been developed to characterise HTS coated-conductor tapes using a 4-point method [35]. This specific system employs an HTS magnet and rotating sample probe to measure I_c and n for transport currents up to 1.6 kA, at $B \leq 8$ T, $\theta = -360°$ to $+360°$ and $T \geq 15$ K [35], [36]. Automated measurements enable the scanning of a large parameter space, and it has been used extensively to characterise coated-conductor HTS tapes [37]–[43] and BSCCO wires [44]. However, measurements of bulk HTS samples have not previously been attempted in this system.

The SuperCurrent system determines the critical current of a superconductor at each temperature and field through scanning the input current to measure a V-I curve. Values of I_c and n are calculated by fitting the $V(I)$ dependence to

$$V = V_c \left(\frac{I}{I_c} \right)^n + V_0 + V_1 I, \tag{1}$$

where V_c is the voltage criterion (here 1 µV/cm), n the flux-flow exponent, V_0 the instrumental zero offset and V_1 accounts for dynamic and contact resistances.

The system applies a logarithmically incremented current [35] so as to limit Joule heating by reducing the time that the sample is held at higher currents. Each increment takes 20 ms to ramp and stabilise the current, and the voltage is measured and averaged over 20 ms. A typical V-I curve is shown in Fig. 1. The SuperCurrent system also incorporates a rotation stage that enables $I_c(B, \theta)$ measurement. Two embedded Hall sensors mounted on the sample probe measure the magnitude and direction of the applied field, and can be used to detect and correct for angular misalignment [35].

It should be noted that the maximum transport current utilised in the results reported here was limited to around
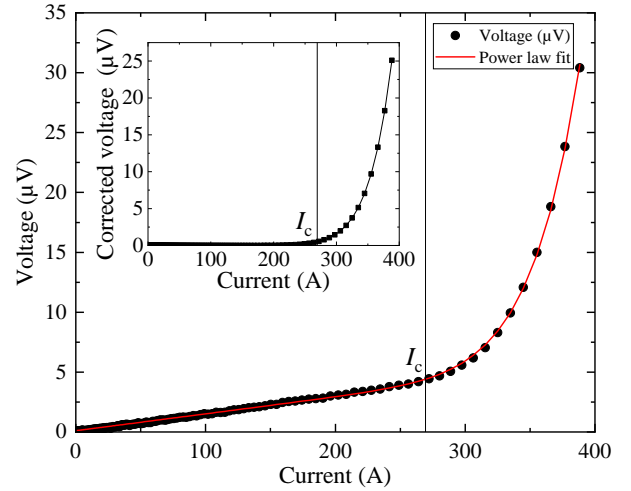

Fig. 1. Example of a measured V-I curve for a GdBCO-Ag bulk (taken at 77 K and 0.5 T) and fit to the power law presented in Eq. 1. The inset shows the V-I response after the offset and dynamic and contact resistances are corrected for.

450 A due to the soldering method used to connect samples to the measurement probe. Standard sample probes are designed for flat, wide and flexible coated conductor tapes, rather than solid crystals with thin square cross-sections. The gap between the high-current copper contacts on the probe was slightly larger than the length of the cut crystal bars. This gap was bridged with extra tabs of silver, however this increased the joint resistance to the sample and caused excessive joule heating above 500 A. In the future, a specialised sample probe better suited to these solid crystals will be constructed, which will enable ∼1 kA of transport current to be injected without incurring this heating.

B. Sample preparation

Commercially available 35 mm diameter single-grain GdBCO-Ag bulk (CAN SUPERCONDUCTORS) was prepared by standard top-seeded melt growth technique from precursor powder with nominal composition $Gd_{1.8}Ba_{2.45}Cu_{3.4}O_x$ + 10 w.t.% Ag_2O [45]. An NdBCO thin film on MgO substrate was used as a seed, with a small (8mm diameter) buffer pellet (from the same precursor powder). The grown bulk was then annealed in flowing O_2 (360-400°C, 2 weeks).

The GdBCO bulk was cut parallel to the a-b plane into ∼0.8 mm thick wafers using a diamond wire band saw (Fig. 2a-b), and the wafer surfaces were polished using P2500 SiC paper to reduce edge damage. Rectangular bars of width ∼2 mm were then cut from the wafers (Fig. 2b-c). The bars were then coated by evaporating a ∼15µm thick layer of Ag and then Cu onto both sides of the sample under vacuum (Fig. 2d). This coating was added to protect the samples from damage caused by flux and indium diffusion during soldering in the sample mounting process, which was observed to severely degrade I_c in initial measurements.

The bars were then soldered onto a 0.8 mm thick brass sheet in order to add thermal mass and protect the sample from the large Lorentz forces that occur during transport
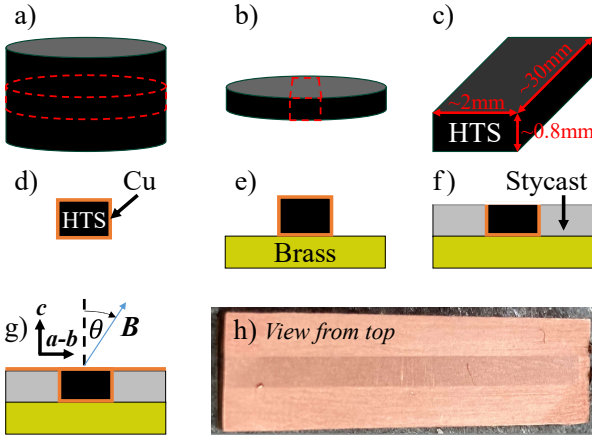
Fig. 2.   a)-g) Simplified sketches showing the sample preparation technique described in Sec. II-B, not to scale. a)-c) The GdBCO-Ag bulk (black) is cut into a bar. d) Ag (omitted for simplicity) and Cu (orange) are evaporated onto the surface of the bar to reduce sample degradation during soldering. For mechanical and thermal reinforcement, the sample is soldered to a brass sheet (yellow, e), potted in Stycast (grey, f), and Ag and Cu are again evaporated onto the top surface (g). The field angle, θ, is defined in (g) for a given field $\boldsymbol{B}$. h) Top view photograph of $1.59 \times 0.58 \times 30$ mm^3 GdBCO-Ag sample prepared for transport current measurement in the SuperCurrent system with the method described in Sec. II-B.
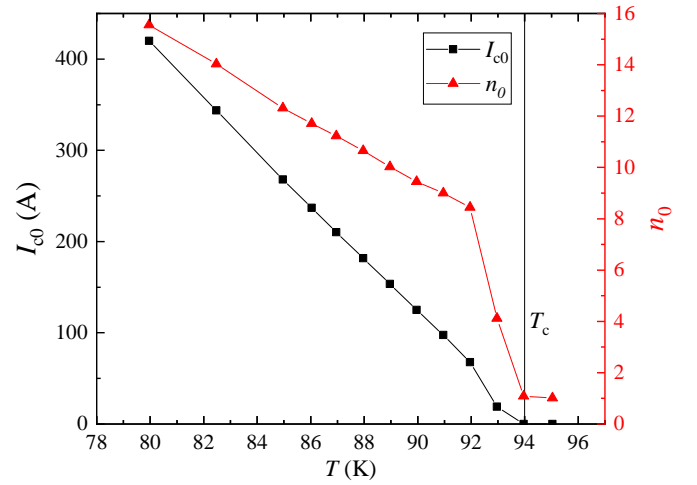

Fig. 3.   Measured temperature dependence of self-field ($B = 0$ T) critical current (black) and flux-flow exponent (red) for a $1.59 \times 0.58 \times 30$ mm^3 GdBCO-Ag sample. The black vertical line shows the measured T_c value.

current measurements at fields of up to 8 T (Fig. 2e). Further mechanical reinforcement was added by potting the sample in 2850FT Stycast with 23LV catalyst (Fig. 2f). After potting, the top surface of the epoxied sample was polished using P2500 SiC paper to further thin the sample and expose the superconductor. Finally, a $\sim$15µm thick layer of Ag and then Cu was evaporated onto the exposed surface under vacuum (Fig. 2g). A fully prepared sample is shown prior to mounting in the SuperCurrent system in Fig. 2h.

The results presented in Sec. III were measured for a $1.59 \times 0.58 \times 30$ mm^3 GdBCO-Ag bar. The wafer used to make this bar was cut at approximately half the thickness of the initial bulk, and was fully in the c-growth sector.

III. Results and Discussion

A. Temperature dependence

An initial measurement was performed to determine the critical temperature, T_c, of the GdBCO-Ag sample, by using a slow ramp rate of +1 K/min and a fixed transport current of 10 mA. This was found to be (94.0 ± 0.2) K.

The measured self-field temperature dependence of I_c and n are shown in Fig. 3. Above T_c, $I_{c0} = 0$ A and $n_0 = 1$ as expected. Below T_c, after an initial sharp increase, both I_{c0} and n_0 increase, approximately linearly, as the temperature decreases. This trend has been previously observed for many HTS wire samples [37]–[44]. To ensure reliability and check for sample degradation, measurements were repeated and found to be consistent.

B. Field dependence

The field dependence of $I_c(T, B, 0°)$ and $n(T, B, 0°)$ are presented for temperatures between 70 K and 90 K in Fig. 4. Here, $\theta = 0°$ refers to an applied magnetic field parallel to

the c-axis of the sample (see Fig. 2g). To the best of our knowledge, this is the first transport current measurement data for I_c and n of a REBCO bulk taken whilst cryocooling to temperatures below liquid nitrogen.

We observe a 'fishtail' effect [46] in the field dependence of I_c for $T < 77$ K, which is characterised by the emergence of a second peak at higher B. This is seen in both $I_c(T, B, 0°)$ and $n(T, B, 0°)$. For $T \geq 77$ K, I_c monotonically decreases as B increases. This fishtail effect has previously been observed in the $J_c(T, B, 0°)$ data of many bulk samples calculated using magnetisation techniques [47]–[50], including for GdBCO-Ag [13], and is attributed to a change of pinning mechanism as the applied field increases [46].

An important feature to observe in Fig. 4, is that the measured n-value varies markedly with applied field and temperature, and never exceeds an absolute value of $\sim$16. This differs significantly from values often used for bulk GdBCO-Ag in numerical simulations, which typically assume a constant value of $n \approx 20$ regardless of field magnitude [13], [51]–[53].

The absolute magnitude of the n-value is important when modelling transient effects in REBCO bulks, as it accounts for flux-creep relaxation. This is particularly the case for situations where the external conditions change rapidly, such as in pulsed field magnetisation [54]. As n is a power-law exponent and bulk applications typically require high-field conditions, an unrealistically high and constant n-value could lead to significant differences between simulation and experiment.

C. Magneto-angular dependence

Fig. 5 shows the $I_c(B, \theta)$ and $n(B, \theta)$ dependence for a range of applied fields at 77 K. There is a strong angular dependence in both I_c and n, particularly in the region of the 90° peak. Local maxima are observed when B is parallel to both the crystallographic c-axis and a-b plane.

Measurements were initially made for $-40° \leq \theta \leq 360°$, but due to high translational symmetry the parameter space
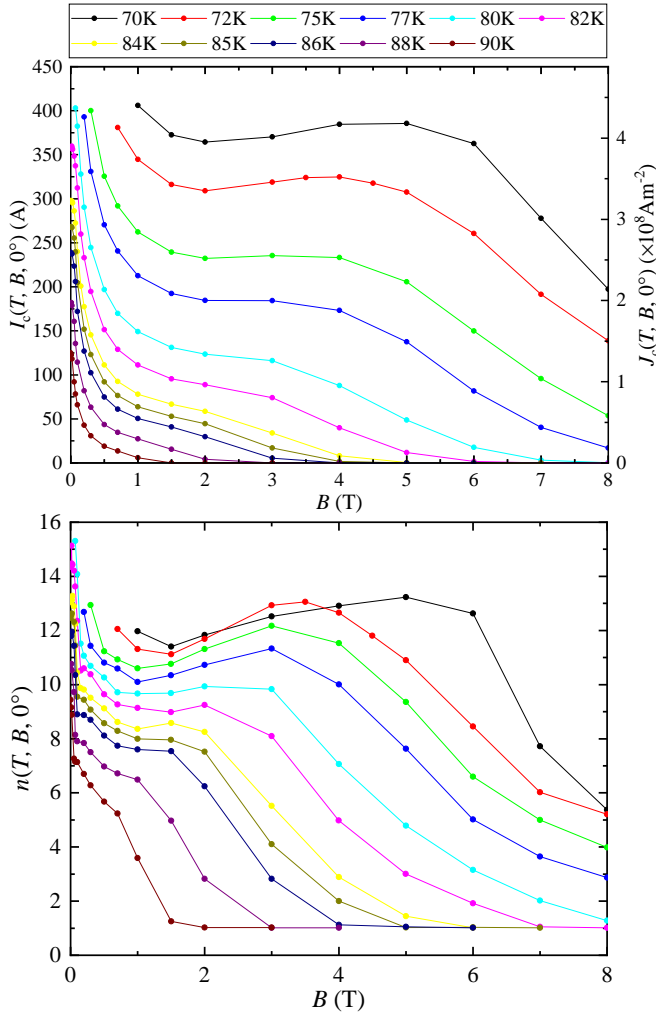
Fig. 4. Measured field dependence of critical current (top) and flux-flow exponent (bottom) for $\theta = 0°$ ($B\|c$) at a range of temperatures from 70 K to 90 K for a $1.59 \times 0.58 \times 30$ mm^3 GdBCO-Ag sample. A second y-axis on the top graph shows the critical current density.
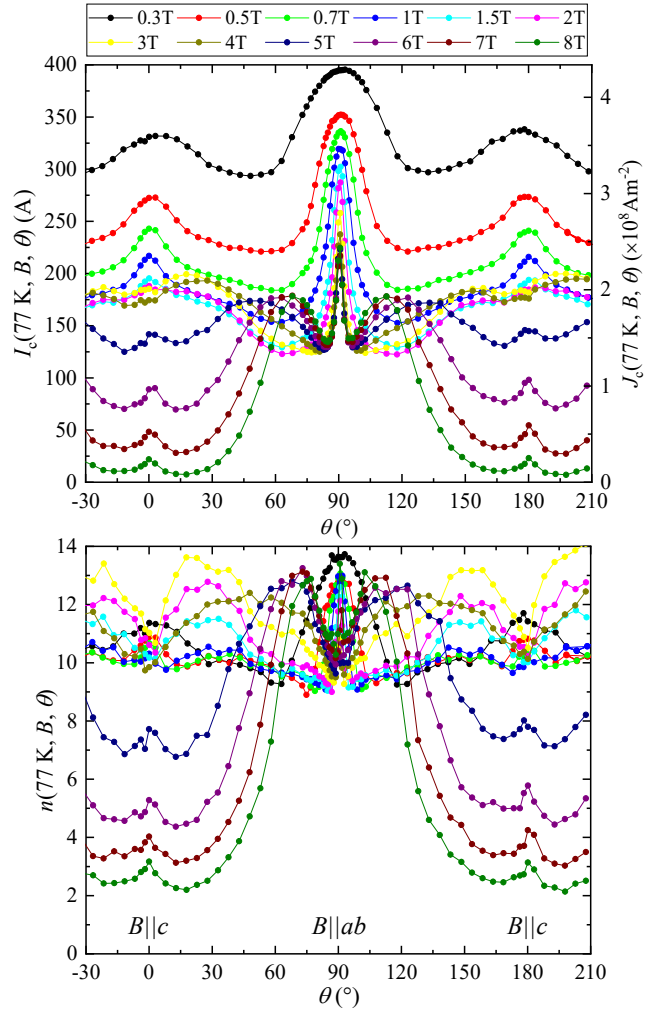

Fig. 5. Measured field-angle dependence of critical current (top) and flux-flow exponent (bottom) at 77 K and a range of field magnitudes from 0.3 T to 8 T for a $1.59 \times 0.58 \times 30$ mm^3 GdBCO-Ag sample. The critical current density is also shown.

was reduced to between $-30°$ and $210°$ to shorten measurement time. Translational symmetry was quantified by comparing two I_c values $180°$ apart, and for each such comparison a difference of $< 2\%$ was observed. To ensure reliability and check for sample degradation, measurements at $B = 0.5$ T and 1 T were repeated for multiple θ values and found consistent.

A fishtail effect is also present in the $I_c(77\,\text{K}, B, \theta)$ data of Fig. 5, and can be observed by considering how I_c changes with B along lines of constant θ. For example, I_c values within the range $\theta = 60$ to $80°$, and $\theta = 100$ to $120°$ exhibit a minima at $B = 2$ T and then increase again as the field is further increased to 8 T. The second peak in the fishtail shape in the field dependence of I_c was observed to occur at higher B as θ is rotated from $0°$ to $90°$, before disappearing once $B\|ab$. This angular behaviour has been observed before in YBCO bulks [55], [56].

There is extensive depression of I_c at $B = 8$ T for $\theta < 45°$ and $\theta > 135°$. However, the measured voltage response still exhibits non-linear E-J behaviour that is characteristic of the superconducting flux-flow regime.

IV. CONCLUSION

A reproducible method to prepare a single-grain bulk GdBCO-Ag superconductor for transport current characterisation has been established. The described method is transferable to other bulk superconductors, and incorporates thermal and stress reinforcement to minimise the effect of large Lorentz forces during characterisation.

Measurements of both $I_c(T, B, \theta)$ and $n(T, B, \theta)$ have been obtained from these samples using a SuperCurrent system. These measurements were shown to be reliable and did not incur sample degradation during the measurement process. This enables automated transport current characterisation across a wide range of field magnitudes (0 to 8 T), orientation (-360 to $+360°$) and temperature (70 to 95 K), thus generating a comprehensive set of useful data to use as input for computational numerical models. Measured n-values were lower than is commonly assumed for bulk REBCO superconductors, with n-values at 77 K not exceeding 14. Lower temperature/higher I_c measurements will be achievable with further improvements to the sample mounting geometry on the sample probe.

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