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Portable, desktop high-field magnet systems using bulk, single-grain RE–Ba–Cu–O high-temperature superconductors

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Abstract

Bulk high-temperature superconducting materials can trap magnetic fields up to an order of magnitude larger than conventional permanent magnets. Recent advances in pulsed field magnetization (PFM) techniques now provide a fast and cost-effective method to magnetize bulk superconductors to fields of up to 5 T. We have developed a portable, desktop bulk high-temperature superconducting magnet system by combining advanced PFM techniques with state-of-the-art cryocooler technology and single-grain, RE–Ba–Cu–O [(RE)BCO, where RE is a rare-earth element or yttrium] bulk superconducting materials. The base temperature of the system is 41 K and it takes about 1 h for the system to cool down to 50 K from room temperature. A capacitor bank, combined with easily-interchangeable, solenoid- or split-type copper magnetizing coils and an insulated bipolar gate transistor acting as a high-speed switch, allows magnetic pulses to be generated with different pulse profiles. The system is capable of trapping magnetic fields of up to ∼3 T. In this work, we report the results of the magnetization of a range of single-grain Y–Ba–Cu–O, Eu–Ba–Cu–O and Gd–Ba–Cu–O (GdBCO), bulk superconducting discs using this system. A higher trapped field was recorded using a split coil incorporating iron yokes at temperatures of 65 K and above, whereas at lower temperatures, a higher trapped field was obtained using the solenoid coil. The GdBCO sample achieved the highest trapped field for both single-pulse (SP) and two-stage-multi-pulse (TSMP) methods using the solenoid coil. Maximum trapped fields of 2.26 T at 55 K and 2.85 T at 49 K were recorded at the centre of the top surface of the GdBCO sample for the SP and TSMP methods, respectively. The PFM process is substantially an adiabatic process so, therefore, the thermal contact between the sample and sample holder is of critical importance for cooling the bulk sample during application of the pulse. The design of the sample holder can be modified easily to enhance the thermal stability of the sample in order to achieve a higher trapped field.

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

1. Introduction

Bulk, single-grain RE–Ba–Cu–O [(RE)BCO, where RE is a rare-earth element or yttrium] high-temperature superconductors (HTS) can trap magnetic fields almost ten times larger than those achieved in conventional permanent magnets [1]. This remarkable property has considerable potential for a wide range of engineering applications that rely on large magnetic fields, such as magnetic separation [2], magnetic drug delivery systems [3] and desktop magnetic resonance imaging or nuclear magnetic resonance systems [4–6]. However, one of the major obstacles to exploiting bulk superconductors in commercial applications is the availability of a fast and cost-effective magnetizing process. Traditional field-cooling magnetization (FCM) or zero-field-cooling (ZFC) magnetization methods require large and expensive magnets (usually superconducting) and long magnetization times (e.g. hours). The pulsed field magnetization (PFM) technique provides a relatively fast and cost-effective way of magnetizing bulk (RE)BCO HTS single grains to high trapped fields [7–9]. Nevertheless, there are still a number of technical issues that need to be resolved before conventional permanent magnets can be replaced by bulk HTS. The PFM method, in general, magnetizes bulk HTS at fields lower than quasi-static FCM/ZFC techniques due to the rapid flux motion during the PFM process [10, 11]. The heating issue during the PFM process has been mitigated for single-grain, bulk superconductors of disc geometry by employing various multi-pulse PFM methods and trapped fields up to 5 T or greater have been achieved in individual samples [7, 9]. The trapped field can also be enhanced by increasing the rise time of the magnetizing field [12–14]. The waveform of the magnetizing field, in turn, can be controlled by inserting a copper plate between bulk superconducting rings in a stack arrangement [12] or by using waveform control pulse magnetization (WCPM) [13, 14]. In the WCPM method, an insulated gate bipolar transistor (IGBT) is used as a high-speed switch and the waveform of the magnetizing pulse is modified by changing the switching frequency of the IGBT. It has also been demonstrated that the use of a split coil with iron yokes can enhance further the resulting trapped field in the single-grain sample [15].

The Bulk Superconductivity Group at the University of Cambridge has developed a new PFM system based on a system reported previously for magnetizing bulk (RE)BCO single grains of disc-shaped geometry [8, 16]. The cryocooler of the original system has been upgraded in the present study to a Sunpower CryoTel GT cryocooler. The more powerful cryocooler, together with a shorter thermal path between the cryocooler and the sample, leads to a reduced cooling time. Moreover, the new system enables the application of different PFM techniques to enhance the final trapped field in the bulk superconductor. Significantly, this enables the PFM system to generate a pulsed magnetic field of different waveforms with a peak value up to ~5 T. The pulse waveform can be controlled by an IGBT. In addition, either a solenoid coil or a split coil (with or without iron yokes inserted into its bore) can be used for the magnetizing coil fixture. We have used this portable system to magnetize a bulk Gd–Ba–Cu–O (GdBCO) ring to 1.3 T at its centre, which is a new record trapped field for a bulk superconducting ring geometry [14]. In this work, we present the details of the system and the results of magnetizing three single-grain Y–Ba–Cu–O (YBCO), Eu–Ba–Cu–O (EuBCO) and GdBCO disc-shaped, single-grain bulk superconductors. The effect of the choice of the magnetizing coil, sample size and other factors on the final trapped field of these samples is reported and discussed.

2. Experimental details

2.1. The portable system

2.1.1. The capacitor bank. The pulsed field is generated by discharging a capacitor bank through a copper-wound solenoid or split coil to generate a pulsed magnetic field of peak value up to ~5 T. The electronic circuit for the capacitor bank includes an IGBT, which serves as a fast-switching device to control the current flow through the excitation coil when the capacitor is discharging, and hence the magnitude and frequency of the applied pulse. The shape of the pulses can be varied by controlling the duty cycle and frequency of the gate voltage of the IGBT. Figure 1 shows examples of the magnetic pulses generated by the system when different duty cycles and frequencies of gate voltage were used. The rise time and the full-width half-maximum of the pulses can be changed from ~25 ms and ~70 ms to ~70 ms and ~180 ms, respectively. More details on the capacitor bank and associated electronics can be found in [14]. Hereafter, we refer to the peak value of the magnetizing pulse as the 'applied field' for simplicity.

2.1.2. The magnetizing coils. The system is designed so that either a solenoid or split coil can be used for magnetization interchangeably. Figure 2 shows a schematic diagram of the experimental arrangement when the solenoid and split coils are used in separate processes. Different sample holders (also shown in figure 2) are employed for the different coils but the overall dimensions of the magnet system are about the same: ~800 mm × 450 mm × 400 mm. The performance of the solenoid coil and split coil during PFM has been studied extensively [10, 15]. It has been observed that a split coil with integral iron yokes can enhance the trapped field significantly compared to that achieved with the solenoid coil arrangement [15]. In the present system, cylindrical iron yokes of diameter 20 mm can be inserted into the bores of the split coils with a distance of ~10 mm between the surfaces of the iron yoke and

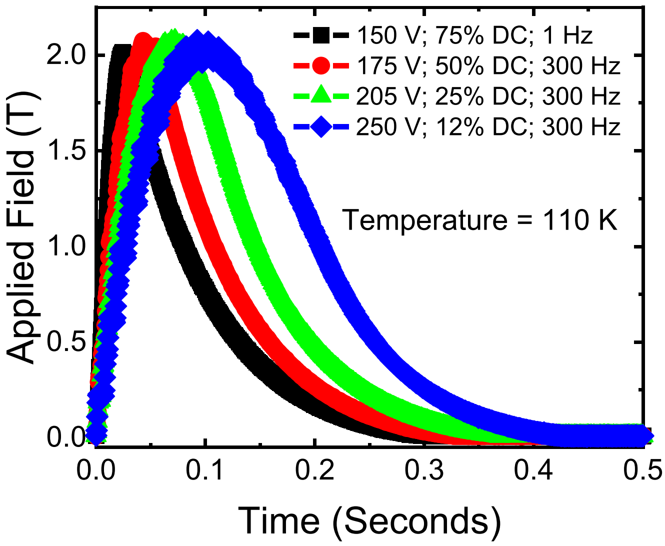

Figure 1. Applied pulsed magnetic field versus time when different duty cycles and frequencies of the gate voltage of the IGBT were used. The rise time and the full-width half-maximum of the pulses can be changed from ∼25 ms and ∼70 ms to ∼70 ms and ∼180 ms, respectively.

the sample. The top surface of the sample is about 5 mm from the outside of the top surface of the vacuum can in the solenoid coil system, and about 3 mm from the outside of the side surface in the split coil system.

2.1.3. The cryocooler. The cryocooler has been upgraded from a Sunpower CryoTel® CT Stirling-cycle cryocooler in the previous system [8] to a CryoTel® GT Stirling-cycle cryocooler in the new system. This enables a compact and highly portable system since neither a compressor nor a water-cooling system are required in the design. The cooling power of the GT cryocooler is ∼2 W and 16 W at 40 K and 77 K, respectively, with a maximum power consumption of 240 W. The base temperature of the cryocooler is 36 K in the absence of a heat load connected to the cold tip. It takes approximately 1 h to cool the sample holder from room temperature to ∼50 K for both the solenoid and split coil systems. The base temperatures of the loaded solenoid and split coil systems are 41 K and 44 K, respectively. The vacuum pumps can be stored in the space below the cryocooler, and the capacitor bank and magnetizing coils can be removed after magnetizing the sample to maintain system compactness and portability. The magnetic field, parallel to the crystallographic *c*-axis of the sample, can then be accessed on the outer surface of the vacuum can for both options (see figure 2 and section 2.1.2).

2.1.4. Bulk superconductor sample holders and samples

2.1.4.1. Sample holders. The copper sample holders, which were designed to accommodate samples up to 41 mm in diameter, are mounted as close as possible to the cold tip of the cryocooler to provide maximum cooling power to the (RE)BCO single grain. The distance between the centre of the sample and the cold tip of the cryocooler is ∼120 mm. The sample holder is connected mechanically to the cryocooler by just a few thin copper plates for the split coil system since the cryocooler is more susceptible to damage by the large electromagnetic forces applied to the sample holder during PFM for the split coil system. These thin copper plates provide a sufficient thermal link, but a weak mechanical connection between the cryocooler and the sample. As a result, the sample can be cooled sufficiently while avoiding damage to the cryocooler by movement of the sample holder during the PFM process. Both sample holders are slotted heavily to reduce eddy-current heating and Lorentz forces during the application of each pulse.

2.1.4.2. Bulk superconductor samples. The bulk samples studied here were YBCO, EuBCO and GdBCO single grains of disc geometry. The samples were fabricated by top seeded melt-growth (TSMG) using the buffer-seed technique [17] with the dimensions given in table 1. The YBCO and EuBCO samples were fabricated by CAN Superconductors and the GdBCO sample was fabricated in-house by the Cambridge Bulk Superconductivity Group.

2.2. Magnetic field measurement for FCM and PFM

2.2.1. FCM. Samples magnetized using the FCM process was cooled from room temperature to 77 K using a liquid nitrogen bath in an applied field of 1.5 T generated by a copper electromagnet. The applied field was then removed and the trapped field profiles at 1.5 mm above the top and bottom surfaces of the sample were measured using a rotating array of 18 Hall sensors (Lakeshore HGT-2101). A hand-held gaussmeter was also used to probe the maximum trapped field on the surface of the samples (table 1).

2.2.2. PFM. An SF field was used to magnetize the sample via the single-pulse (SP) PFM method after it had been cooled down to the target operating temperature below the transition temperature, T_c, of the superconductor. A thermometer (Lakeshore Cernox® 1070 CU HT) was mounted inside the sample holder to measure its temperature and set the measurement temperature appropriately. A pulsed field was applied to the sample in the two-step multi-pulse (TSMP) method at a temperature below T_c, T_1, followed by a second, larger pulsed field applied at a lower temperature, T_2 (i.e. $T_2 < T_1 < T_c$) [8]. A linear array of six Hall probes (Lakeshore HGT-2101) was mounted on the top surface of each disc-shaped single-grain sample spanning from the centre to the edge of the disc, given the circular symmetry of the single grain, in order to measure the magnetic field distribution across the sample surface. The separation between adjacent probes was ∼3.4 mm. The Hall sensors were calibrated in-house with a sensitivity of approximately 0.21 V T^{-1} for a drive current of 1 mA. Data were taken at every 0.5 ms for the first 10 s, with the sampling rate decreasing to one measurement every 100 ms for the remainder of the data collection for each measurement.

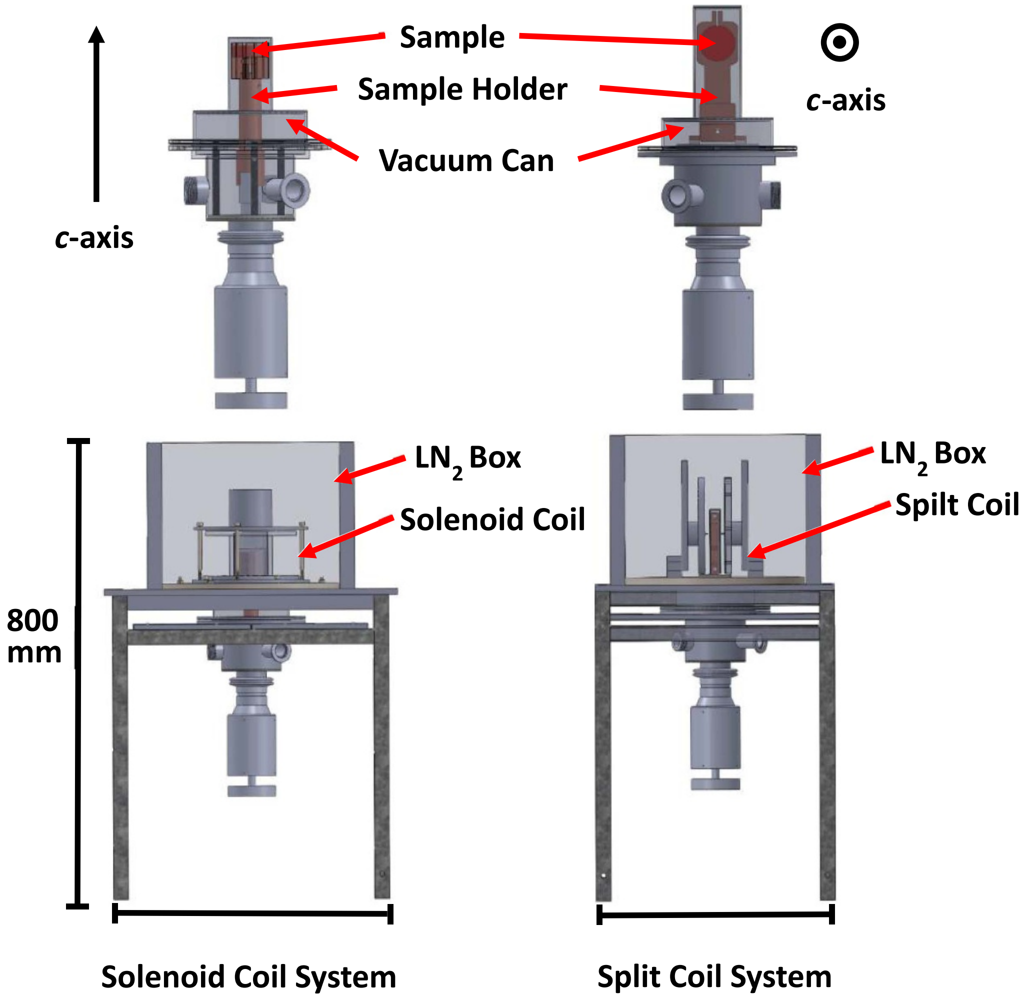

Figure 2. Schematic diagrams of the portable bulk superconducting magnet for the solenoid (lower left) and split coil (lower right) pulsed field magnetization systems. The support frame has dimensions of 550 × 450 × 400 mm. Schematic diagrams showing how the sample, sample holder and cryostat are connected are shown in the upper left and upper right, for the solenoid and split coil systems, respectively.

Table 1. Sample dimensions and FCM results at 77 K. The YBCO and EuBCO samples were fabricated by CAN Superconductors using the top seeded melt-growth (TSMG) technique. The GdBCO sample was fabricated in-house by TSMG using the buffer-seed technique.

Composition	Diameter, D (mm)	Thickness, H (mm)	FCM trapped field at 77 K (T) (see section 2.2.1)
YBCO	41.1	14	1.07
GdBCO	36.3	12.1	1.17
EuBCO	41.1	13	1.26

The trapped fields presented here were measured 15 s after application of the magnetizing pulse to allow both for flux creep and for the sample to cool back to its stable operating temperature. Hereafter, we refer to the trapped field at the centre of the top surface of the sample generally as the 'trapped field' (unless stated otherwise).

3. Results and discussion

3.1. FCM results

Figure 3 shows the FCM measurements at 77 K using a 1.5 T copper electromagnet for the YBCO, EuBCO and GdBCO bulk, single-grain discs, using a rotating array of 18 Hall sensors 1.5 mm above the top surface of each sample. As shown in the figure, each sample exhibits the usual cone-shaped trapped field profile across its surface, indicating well-grown single-grains. A handheld gaussmeter was also used to probe the maximum trapped field on the top surface of each sample. The EuBCO sample exhibits the highest trapped field of 1.26 T (handheld gaussmeter) and also the most symmetric field distribution (see figure 3(a)). The GdBCO and YBCO samples exhibit trapped fields of 1.17 and 1.07 T, respectively (handheld gaussmeter). The FCM data suggest that the EuBCO sample would potentially have the highest trapped field if all three samples are fully magnetized at the same temperature.

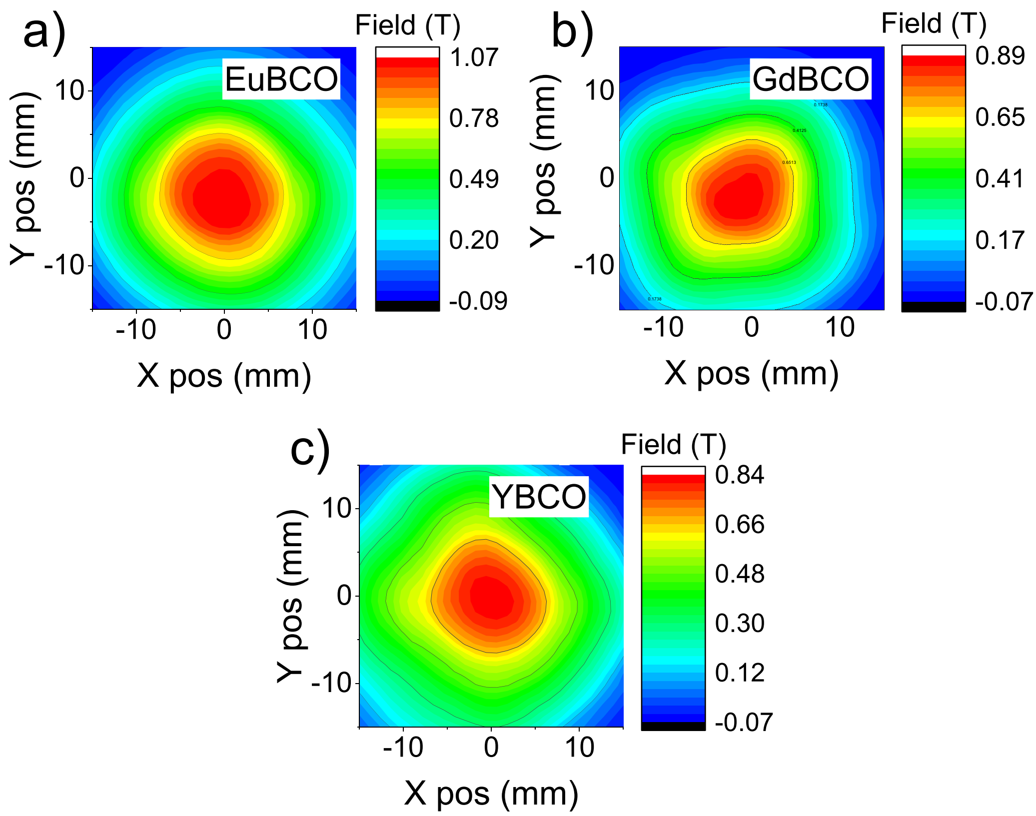

Figure 3. Trapped magnetic flux density measured using a rotating array of 18 Hall sensors 1.5 mm above top surface of (a) EuBCO, (b) GdBCO and (c) YBCO single-grains using FCM at 77 K. The EuBCO sample exhibits the highest trapped field of 1.26 T, as measured by a handheld gaussmeter on its top surface, and also the most symmetric field distribution.

3.2. Trapped field performance

3.2.1. Solenoid coil system

3.2.1.1. SP PFM. The results of the SP measurements for all samples using the solenoid system are summarized in figure 4. It can be seen that flux starts to penetrate into the centre of the sample for each sample at a fixed temperature when the applied field is above a threshold value. The trapped field increases with increasing applied field as more flux penetrates into the centre of the sample. The trapped field reaches a maximum before decreasing as the applied field increases further due to the heat generated by the rapid motion of flux in the presence of a relatively large, applied field. The maximum trapped field (B_{max}) increases as temperature decreases from 77 K, with a higher applied field required to achieve B_{max}. The samples exhibit a similar value of B_{max} at 77 K. EuBCO has the highest B_{max} and YBCO has the lowest at 65 K. These results are consistent with those obtained from the FCM measurements at 77 K. Both EuBCO and GdBCO exhibit a similar B_{max} and YBCO the lowest B_{max} when the temperature is lowered further to 55 K and below. The GdBCO sample achieved almost the same trapped field as EuBCO at a higher temperature (55 K vs 50 K) and lower applied field (3.50 T vs 3.68 T), which is an important consideration for practical applications. The results of FCM and the consistently lower maximum trapped field compared to the PFM magnetization process suggest that YBCO has the lowest J_c of the three samples studied. The EuBCO sample has a higher B_{max} than GdBCO at 65 K, which could be due to a higher J_c or because of its larger size. The highest B_{max} for the EuBCO, GdBCO and YBCO samples recorded using the SP method are 2.22 T at 50 K, 2.26 T at 55 K and 1.96 T at 47 K, respectively.

3.2.1.2. TSMP PFM. The deleterious effect of heating during the PFM process has been mitigated for the bulk single-grain disc samples by employing various multi-pulse methods, allowing trapped fields up to 5 T or more to be achieved [7, 9]. Here, we explore the application of the TSMP method to reduce heating and enhance the final trapped field. Figure 5 shows the trapped field profile on the top surface of each sample when the optimum TSMP pulse sequences were applied. The first pulse for all samples was applied at 77 K and the second pulse at 45 K, 49 K, and 45 K for the EuBCO, GdBCO and YBCO samples, respectively. The YBCO sample was not fully magnetized after the second pulse and the final trapped field was similar to the SP results, as shown in figure 5. A larger second pulse at 45 K led to an even lower trapped field for the YBCO sample (data not shown). Both the EuBCO and GdBCO samples exhibit higher final trapped fields of 2.60 and 2.85 T, respectively, under these magnetizing conditions.

3.2.1.3. Sample sizes. In the simplest form of the Bean critical state model [18, 19], the maximum trapped field at the centre of the top surface of a bulk superconductor of disc

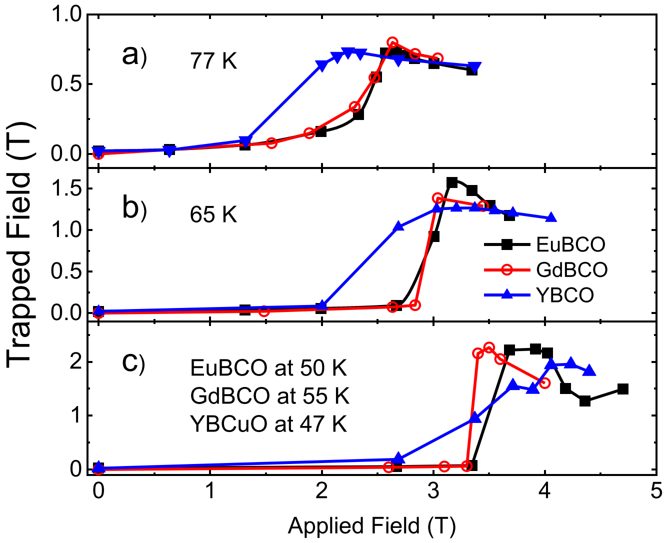

Figure 4. Trapped field as a function of applied field for the three single-grain samples at different temperatures using the single-pulse method. Maximum trapped fields were recorded for the EuBCO, GdBCO and YBCO samples of 2.22 T at 50 K, 2.26 T at 55 K and 1.96 T at 47 K, respectively.

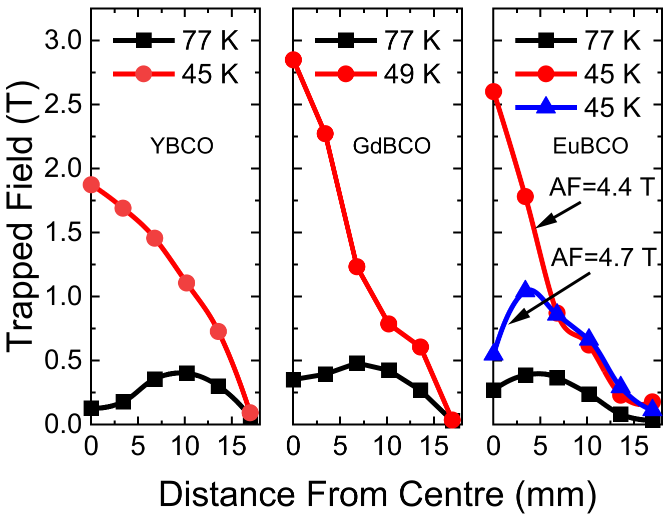

Figure 5. Trapped field measured across the top surface versus distance from the centre of the top surfaces of the three single-grain samples using the two-step multi-pulse method. The GdBCO sample achieved the highest trapped field of 2.85 T at 49 K. The trapped fields for the EuBCO and YBCO samples are 2.60 T at 45 K and 1.87 T at 45 K. For the EuBCO sample, the trapped field dropped significantly when the applied field (AF) of the second pulse was increased by a mere 0.3 T from 4.4 to 4.7 T.

geometry is directly proportional to the diameter of the sample. A larger sample, therefore, will generate a higher trapped field when it is fully magnetized. In this case, however, a higher applied field is required to force magnetic flux to penetrate further into the centre of the sample, which may cause thermal instability due to an increase in the heat generated during the pulse, triggering flux jumps. As a result, only a relatively low trapped field can be achieved ultimately by an SP process. A trapped field for the EuBCO sample of about 3.2 T was

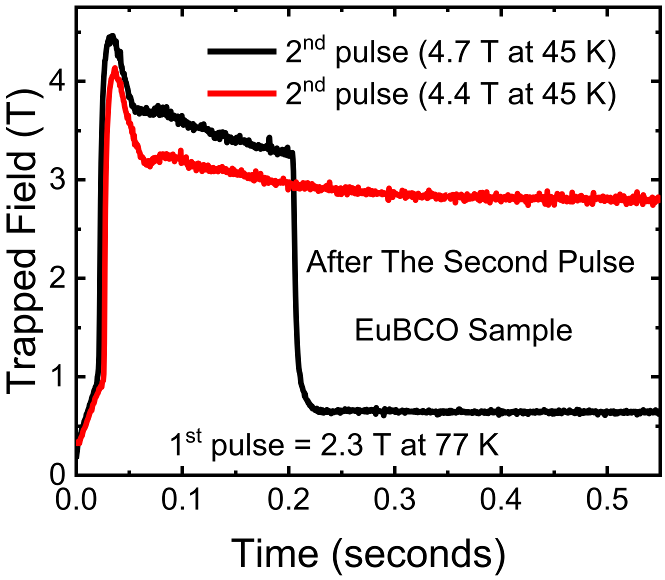

Figure 6. Trapped field versus time after the second pulse using the TSMP method for the EuBCO sample. Increasing the applied field slightly from 4.4 to 4.7 T for the second pulse triggered a flux jump at 0.2 s, which reduced the final trapped field significantly.

observed after 0.1 s following the application of a second pulse of increased field intensity from 4.4 to 4.7 T, as shown in figure 6. It can be seen that the trapped field decreased subsequently and significantly to ∼0.5 T as a result of a second flux jump (indicated by an abrupt decrease in trapped field) that occurred after 0.2 s. It is likely a trapped field >3 T could be achieved if the thermal stability of the sample can be improved further to avoid the second flux jump.

The PFM process is a substantially adiabatic due to the ceramic-like nature of bulk HTS materials and their relatively low thermal conductivity, together with the short duration of the applied field. Therefore, cooling of the sample is achieved generally by the flow of heat through the adjacent sample holder during the quasi-adiabatic PFM process, rather than via the cryocooler itself. Therefore, the thermal contact between the sample and the sample holder is of critical importance in keeping the sample thermally stable and to achieve a high trapped field.

3.2.2. Split coil system. The SP and TSMP methods were used to magnetize the GdBCO sample using the split coil, which generated the highest final trapped field when used with the solenoid coil.

3.2.2.1. SP results. The SP results using a split coil with and without iron yokes are shown in figure 7, together with the results for the solenoid coil. B_{max} is about 15% higher at 65 K and above when the iron yoke is inserted into the bore of the split coil. Furthermore, B_{max} is less than 1.6 T and the effect of the iron yoke is pronounced. B_{max} was 2.12 T at 55 K when the iron yoke was used, which is slightly lower than the value (2.26 T) obtained using a solenoid coil at the same temperature.

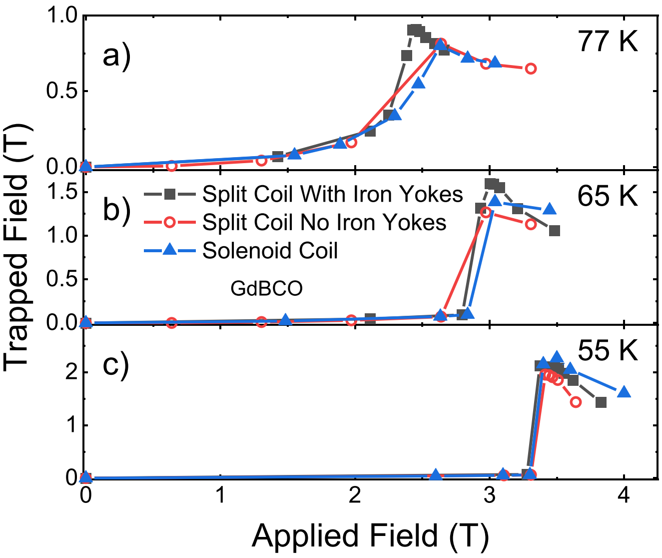

Figure 7. Trapped field versus applied field for the GdBCO sample using the SP method at different temperatures. The measurements were conducted using a solenoid and a split coil with and without iron yokes. Highest trapped fields of 0.91 and 1.59 T were achieved for the split coil system with iron yokes at 77 K and 65 K, respectively. At 55 K, the solenoid coil system achieved the highest trapped field of 2.26 T.

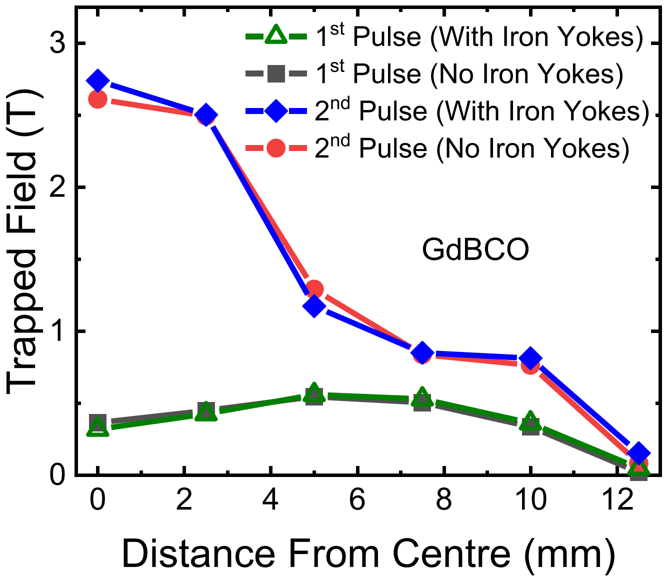

Figure 8. Trapped field versus distance from the centre of the top surface of the GdBCO sample using the TSMP method for the split coil system with and without inserting iron yokes into the bore of the coil. The first pulse of 2.4 T (2.3 T) was applied at 77 K (77 K) and the second pulse of 4.2 T (4.2 T) was applied at 45 K (48 K) for the split coil system (with iron yokes). A maximum trapped field of 2.74 T was achieved for the split coil with iron yokes after the second pulse at 48 K.

3.2.2.2. TSMP results. The trapped fields for the GdBCO sample using the TSMP method with the optimum pulse sequence are shown in figure 8. Again, the trapped field was higher when the iron yoke was used and a final trapped field of 2.74 T was obtained after the second pulse at 48 K, which is only ∼5% higher than that obtained without the iron yoke at 45 K. The effect of the iron yokes is more significant when the final trapped field is lower than 2 T. A higher trapped field was achieved when a solenoid coil was used, which is consistent with the SP results.

Both the edges and the bottom of the bulk single-grain samples measured in the current experimental arrangement are in direct contact with the solenoid sample holder, resulting in direct cooling of the sample through these surfaces. The bottom of the sample is not in direct contact with the sample holder in the split coil system, however, leading directly to less effective cooling after application of the magnetizing pulse compared to the solenoid system. This almost certainly explains why the solenoid coil system is able to generate a slightly higher trapped field than the split coil system without iron yokes at all temperatures for both SP and TSMP methods, in contrast to the results of [15], in which the sample was cooled only from its bottom surface in the case of the solenoid coil.

It has been shown that significantly less flux exits the bulk sample when the iron yokes are present in a split coil [15], resulting in a higher trapped field after the magnetization process is complete. However, the iron yoke studied in [15] had a cross-sectional area much larger than that of the sample. In the present study, the diameter of the cross-section of the iron yoke is only 55% of that of the smallest sample measured. Therefore, it is expected that higher trapped fields could be achieved by using a larger bore split coil with a larger diameter iron yoke, as shown for the solenoid coil arrangement in [20].

4. Conclusions

The ability to provide magnetic fields of several tesla in bulk, single-grain HTS materials makes them very attractive for potential application in portable high-field magnet systems. We have developed a portable, desktop magnet system that pulse-magnetizes such bulk samples with trapped fields of up to ∼3 T. The design of the system is based on flexibility, portability and the capability of applying advanced PFM techniques, including both solenoid and split coil magnetization. Significantly, the cryogenic system does not require a compressor or dedicated water-cooling system, making it highly portable, and the cooling time for the system from room temperature to 50 K is about an hour.

We have used the system to successfully pulse-magnetize YBCO, EuBCO and GdBCO single-grain bulk superconductors at temperatures down to 45 K using SP and TSMP methods, using both solenoid and split coils. The highest trapped field of 2.85 T was achieved in a 36.3 mm diameter GdBCO disc at 49 K using the TSMP method and the solenoid coil.

The GdBCO single grain trapped the highest field of 2.26 T at 55 K for the solenoid coil system using the SP method. The maximum trapped fields for the EuBCO and YBCO samples using the SP method were 2.23 T at 50 K and 1.96 T at 47 K, respectively. The trapped fields in the GdBCO and EuBCO samples increased to 2.85 T at 49 K and 2.60 T at 47 K, respectively, for the TSMP method. However, the trapped field in the YBCO sample dropped slightly to 1.87 T for this magnetization technique.

The GdBCO sample was magnetized using the split coil with and without iron yokes in the split coil bore. A higher trapped field was recorded consistently for both the SP and TSMP methods when the iron yokes were inserted at all temperatures. Maximum trapped fields using the SP and TSMP methods with (and without) the iron yoke were 2.12 T (1.95 T) at 55 K (55 K) and 2.74 T (2.61 T) at 48 K (45 K), respectively. Higher trapped fields could potentially be achieved by redesigning the split coil with a wider bore to accommodate a larger diameter iron yoke.

We have demonstrated that the portable and low-cost PFM system designed and developed by the Cambridge Bulk Superconductivity Group is able to magnetize successfully HTS samples of diameter up to 41 mm to almost 3 T using advanced PFM techniques. The design of the system can be modified easily to magnetize larger samples or a stack of samples for a wide range of potential high-field applications.

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.82795.

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