Trapped Fields >1 T in a Bulk Superconducting Ring by Pulsed Field Magnetization


Abstract—One potential application of magnetized RE-Ba-Cu-O (where RE = rare earth or Y) bulk superconductors is as a high-field alternative to conventional permanent magnets in desktop NMR and MRI systems. Pulsed field magnetization (PFM) is one of the most promising practical methods of magnetizing such bulks. However, the trapped fields obtained by PFM are much lower than those obtained using quasi-static methods like field-cooling magnetization (FCM) due to heating during PFM. Furthermore, bulk superconducting rings have proved more difficult to magnetize via PFM than discs. The reported trapped fields in single bulk superconducting rings magnetized by PFM are less than 0.35 T at the centre of the bore due to thermomagnetic instabilities. In this work, systematic PFM measurements on a bulk Gd-Ba-Cu-O ring were carried out and a trapped field of 1.3 T at 55 K was achieved using a multi-pulse, stepwise cooling (MPSC) method. In the MPSC method, a sequence of pulsed fields is used to magnetize the ring bulk. The pulsed field is increased in small increments and the sample temperature is decreased sequentially. Consequently, as some field is already trapped after the first pulse, the motion of the flux for subsequent pulses will be reduced, leading to less heat generated in the bulk sample. This greatly improves the thermomagnetic stability of the PFM process, enabling larger trapped fields.

Index Terms—High-temperature superconductivity, bulk superconductors, bulk superconducting rings, trapped field magnets, pulsed field magnetization, multi-pulse stepwise cooling, waveform control

I. INTRODUCTION

The ability to trap high fields in RE-Ba-Cu-O (where RE = rare earth or Y) bulk superconducting materials makes them very attractive for a wide range of applications [1]. Bulk superconducting rings can provide reasonably uniform, high magnetic fields. These can potentially improve the performance of compact desktop NMR and MRI systems which currently employ permanent magnets. Using the field-cooling magnetization (FCM) method, a stack of magnetized REBa-Cu-O bulk superconducting rings has been used successfully to demonstrate NMR and MRI [2]–[4]. However, FCM requires expensive superconducting magnets and long magnetization times.

In contrast, the pulsed field magnetization (PFM) method is fast, compact and cost-effective method of magnetizing RE-Ba-Cu-O bulk superconducting discs [5], [6]. The trapped fields obtained by PFM are generally lower than those obtained using FCM due to the movement of magnetic flux causing heating [7], [8]. The heating problem is worse in the case of bulk superconducting rings during PFM because the magnetic flux penetrates from both the inner and outer edges of the sample [9], [10]. This can result in significant heating [11], causing the magnetization current to be disrupted and the trapped field to reduce significantly [12], [13]. As a result, it has been very challenging to magnetize bulk superconducting rings with high trapped fields. In the literature to date, reported trapped fields in bulk superconducting rings magnetized by PFM have been less than 0.35 T at the centre of a single bulk superconducting ring [13]–[16].

The heating issue during the PFM process has been mitigated for disc bulk superconductors by employing various multi-pulse PFM methods and trapped fields up to 5 T or more have been achieved [5, 17]. As an alternative method of increasing the trapped field, Hirano et al. [16] magnetized a composite stack of two MgB2 ring bulks to 1.61 T by elongating the magnetizing pulses and inserting iron yokes in the bore of the sample as well as the magnetizing split coil. However, the maximum trapped field in the single ring bulk superconductor in that work was still only 0.34 T.

Recently, we have applied the the waveform control pulse magnetization (WCPM) method [18] to modify the waveform of the magnetizing pulses to increase trapped fields in a Gd-Ba-Cu-O bulk superconducting ring using single-pulse PFM [19]. We found that the trapped field was enhanced significantly when an optimum magnetizing pulse was used and a maximum trapped field of 0.76 T at 73 K was achieved.

In this work, we combine this WCPM method with multipulse stepwise cooling (MPSC) to magnetize a single-grain, Ag-containing Gd-Ba-Cu-O ring bulk, at temperatures down to 55 K, demonstrating for the first time that trapped fields >1 T are readily achievable in ring bulks magnetized by PFM.
II. EXPERIMENTAL DETAILS

The sample under investigation is a single-grain, Ag-containing Gd-Ba-Cu-O ring bulk. The sample was fabricated by the top-seeded melt-growth technique using the buffer-seed technique [20]. The ring was grown as such, rather than post growth-machining a disc bulk. The outer diameter, inner diameter and the height of the ring bulk in its final form are 30.8 mm, 12.5 mm and 11.9 mm, respectively.

All the PFM measurements were performed using a portable PFM system developed in the University of Cambridge’s Bulk Superconductivity Group, based on a previously reported system for magnetizing disc bulks [6]. The PFM system can generate a pulsed magnetic field of different waveforms with a peak value up to ~5 T. The pulsed field is generated by discharging a capacitor bank through a copper-wound solenoid or split coil. The pulse waveform is controlled by an insulated gate bipolar transistor (IGBT). The IGBT acts as a switch with controllable switch frequency. By changing the duty cycle and frequency of the gate voltage to the IGBT pulses of different waveforms can be generated. The rise time of the magnetizing pulses can be modified from 25 to 116 ms. Hereafter, we refer to the peak value of the magnetizing pulse as the ‘applied field’ for simplicity.

To measure the trapped field in the sample bore, a linear array of three Hall sensors (Lakeshore HGT-2101) were mounted in a copper housing inside the sample bore such that one Hall sensor is located at the centre of the bore and the other two are 3 mm above and below the centre. The Hall sensors were calibrated in-house with the sensitivity of about 0.21 V/T when a current of 1 mA is applied. A thermometer (Lakeshore Cernox® 1070 CU HT) was mounted inside the sample holder to measure its temperature and set the operating temperature appropriately.

The sample was first cooled down from the normal state to the superconducting state, then either a single pulsed field (single-pulse) or a sequence of multiply-pulsed fields (MPSC) were applied to magnetize it. For the MPSC sequence, the wait time between two successive pulses was from ~5 min (at 77 K) to ~15 min (at 55 K) to allow sufficient time for the sample to return to its operating temperature before applying the next pulse. Hereafter, we refer to the trapped field at the centre of the ring bore as the ‘trapped field’ (unless stated otherwise). The trapped fields given in this paper were measured 15 sec after applying the magnetizing pulse. More details on the experimental setup can be found in reference [19].

III. RESULTS AND DISCUSSION

A. Single-Pulse PFM Measurements

The sample was characterized by FCM at 77 K and the maximum trapped field was found to be 0.65 T inside the sample bore [20]. The trapped field above the bore region was quite uniform and largely the same on the top and bottom surfaces, indicating a high-quality sample [19].

B. MPSC PFM Measurements

Multi-pulse techniques, such as iterative pulsed-field magnetization with reducing field amplitude (IMRA) [22] and

![Fig. 1. Trapped field versus applied field at different temperatures for single-pulse PFM of the Ag-containing Gd-Ba-Cu-O ring bulk superconductor under investigation. The rise time of the magnetizing pulses is 25 ms. The data for 73 and 70 K were reported previously in [19].](image-url)
multi-pulse stepwise cooling (MPSC) [23], [24], can increase the trapped field in single-grain bulk discs, with fields of up to 5 T or more having been achieved [5, 17]. Here, we explore the application of the MPSC method to ring bulks, to reduce heating [8], improve thermomagnetic stability and avoid flux jumps.

In our approach to the MPSC method, a sequence of incrementally-increasing pulses coupled with decreasing temperature steps were applied to magnetize the ring bulk. Post-pulse flux motion for pulses subsequent to the first pulse, is significantly reduced as a result of this process [9], generating less heat and producing a higher final trapped field. In the following sub-sections, we investigate some of the key MPSC parameters, including the step size of the applied field and the rise time in order to optimize the process for higher trapped fields.

1) Adjusting the Multi-Pulse Field Step Size

In Fig. 2, the trapped field as a function of applied field is shown for three MPSC sequences with different field step sizes and stepwise cooling from 73 to 65 K. The rise time of all of the magnetizing pulses is 25 ms.

In Sequence 1A, the field steps are on average 0.1 T. This sequence increases the trapped field to 1.1 T at 65 K, without causing any flux jumps, for an applied field up to 3.75 T. This final trapped field is almost four times of that obtained by single pulses at 65 K (see Fig. 1).

Since ring bulks are very sensitive to the applied field, as shown in Fig. 1, the step size in the MPSC sequence is very important. For Sequence 1B, which has the largest field steps, a flux jump occurred at the end of the sequence (3.75 T at 65 K) and the final trapped field was reduced significantly to 0.2 T, even though the same applied field was used in the other two sequences. The pulses in Sequence 1C have an intermediate field step size and the final trapped field at 65 K was slightly lower than that of Sequence 1A.

2) Adjusting the Rise Time of the Magnetizing Pulses

Heating in single-pulse PFM can be reduced by using magnetizing pulses with a longer rise time, as demonstrated for ring bulks using WPCM in [19]. The maximum trapped field in our sample increased to 0.76 T from 0.60 T at 73 K using single-pulse PFM with a magnetizing pulse of longer rise time. We repeated the MPSC measurements using magnetizing pulses of different rise times and the results are summarized in Fig. 3. The magnetizing pulses in the three sequences shown in Fig. 3 have different rise times but the field step size was kept constant: the pulses in sequences 2A, 2B and 2C have rise times of 25, 44 and 69 ms, respectively. These field steps were approximately 0.1 T from 2.5 to 4 T for all three sequences.

It has been suggested that a magnetizing pulse with a longer rise time reduces the flux propagation velocity in a RE-Ba-Cu-O bulk superconductor during the PFM process, and hence, lowers heating in the bulk due to the viscous loss [25]. The results show that a magnetizing pulse of longer rise time is particularly effective for the first pulse, where a relatively large movement of flux is involved and as demonstrated for single pulses in [19]. However, for subsequent pulses, the sequences with longer pulse rise times did not result in higher final trapped fields. In fact, the results suggest a shorter rise time for subsequent pulses may be slightly beneficial for increasing the trapped field, which is exploited in the next sub-section.

3) Optimizing the Multi-Pulse Sequences

In order to increase the trapped field in the ring bulk further, the MPSC method was applied down to a temperature of 55 K. Sequences with different combinations of rise time and field step size were used, based on the conclusions of the previous two sub-sections.

Fig. 4 shows the data for two such MPSC sequences. Sequence 3A is a simple MPSC sequence with roughly uniform field step increments of 0.1 T and stepwise cooling temperatures of 73, 65, 60 and 55 K. A maximum trapped field of 1.2 T at 55 K (final applied field 4.6 T) was achieved. The rise time of the pulses used in this sequence were kept constant at 25 ms.
In Sequence 3B, a pulse of a longer rise time of 69 ms was applied initially at 73 K to obtain a higher initial first-pulse trapped field, then applied pulses of rise time 25 ms were used for the rest of the sequence. In addition, several pulses of the same magnitude were applied during this sequence – the most obvious in Fig. 4 being several pulses of 3.75 T at 65 K – and the highest trapped field of 1.3 T was recorded at 55 K (final applied field 4.6 T).

It is not easy to predict the exact pulse sequence that will lead to the highest trapped field. For example, for Sequence 3B in Fig. 4, the trapped field was increased by 20% by simply applying the same applied field of 3.75 T repeatedly at 65 K. However, even though it is not trivial to predict the optimum MPSC sequence to achieve the highest trapped field, these results suggest that even a simple MPSC sequence with small and uniform field increments, such as Sequence 3A in Fig. 4, can achieve a higher trapped field. The achievement of 1.3 T at 55 K is about four times that of the highest trapped field reported for any single ring bulk using PFM to date.

C. Trapped Field Uniformity within the Ring Bore

In general, high and stable magnetic field homogeneity is essential for NMR and MRI magnets. We therefore assessed the homogeneity of the field within the bore of the bulk ring along its central axis. In Fig. 5, the maximum trapped field at each temperature for MPSC Sequence 3B (see Fig. 4) is shown as a function of position within the bore. The trapped fields at the centre and near the bottom of the sample were similar for all temperatures and became more homogeneous as the temperature was lowered. At 55 K, the variation of trapped field from the centre to 3 mm below the centre at 55 K was within the limit of measurement error (about 5 mT).

However, the trapped field near the top of the sample was always lower. It is likely that this is due to the fact that there was no direct contact between the top surface of the sample and the copper sample holder. Heat was thus less effectively removed nearer the top of the sample during the magnetizing process. This could be mitigated in the future by redesigning the copper sample holder: it was shown recently in [26], for example, that an ‘encapsulated head’ cooling architecture can significantly improve the PFM of bulk MgB2, which are highly susceptible to thermomagnetic instabilities [27].

The trapped field distribution became more homogenous as the temperature was lowered and was more homogenous towards the bottom surface. The variation of trapped field from the centre to 3 mm below the centre at 55 K was within the limit of measurement error (about 5 mT). Although the field homogeneity does not yet meet the standards required for NMR/MRI applications, it has been demonstrated that a bulk superconducting ring can be magnetized with trapped fields >1 T with reasonably good homogeneity using the MPSC PFM technique. This is a promising step forward in magnetizing bulk, single-grain superconducting rings for use in practical engineering applications.

IV. CONCLUSION

In this paper, systematic single-pulse and MPSC PFM measurements were performed on a single-grain, Ag-containing Gd-Ba-Cu-O bulk superconducting ring. The measurements were conducted at temperatures down to 55 K using a portable magnetizing system.

The ring was firstly characterised using single-pulse PFM and a maximum trapped field of 0.6 T at 73 K was recorded. The trapped field was limited due to thermomagnetic instabilities, especially below 70 K. Next, various MPSC sequences were investigated to increase the trapped field in the ring. For a fixed pulse rise time (25 ms), it was found that the trapped field increased when a smaller step size between subsequent pulses was used. For a sequence of fixed step sizes, a longer
pulsed magnetic field would only increase the trapped field significantly for the first pulse of the sequence and there was no significant enhancement of the trapped field at the end of the sequence. Finally, an MPSC sequence that included a longer first-pulse rise time and multiple pulses of the same magnitude for some steps achieved a trapped field of 1.3 T at 55 K. This is about four times that of the highest trapped field reported for any single ring bulk using PFM to date and is a promising step forward in magnetizing bulk, single-grain superconducting rings for use in practical engineering applications.

**DATA STATEMENT**

Data related to this publication are available at the University of Cambridge data repository (https://doi.org/10.17863/CAM.81777).

**REFERENCES**


