CORE
Metadata, citation and similar papers at core.ac.uk
Provided by Apollo

Demagnetization study of pulse-field magnetised bulk superconductors

J. Srpčič, *Student Member, IEEE*, D. Zhou, K. Y. Huang, Y. Shi, A. Dennis, M. D. Ainslie, *Senior Member, IEEE*,
A. M. Campbell, R. Bause, M. Boll, M. Filipenko, D. A. Cardwell, and J. H. Durrell

Abstract— **$GdBa_2Cu_3O_{7-\delta}$ bulk superconductors are a route to higher magnetic fields in rotating machines. Here we examine the resistance of pulse-field magnetized bulks to the demagnetization fields they may experience in such a system. The bulks were magnetized at 77 K, after which several thousand cycles of AC field were applied. Subsequently, the decay of the trapped field was characterized. We found the decay per cycle decreases with frequency and is, normalized to the initial trapped field, largest at the edge of the bulk. At 77 K the reduction in trapped field proved significant (25% in the center for 150 mT (peak) AC field at 6 Hz), however reducing below 1% when lowering the temperature to 60 K. We explain this observation as being due to increased flux pinning strength at low temperatures. When applying an AC field we found a temperature rise that increased with applied field amplitude and frequency. However, when applying an AC field of amplitude 45 mT with a frequency of 48 Hz we found an increase of the bulk temperature of only 100 mK. Therefore, we conclude the temperature rise within the analyzed AC field frequency and amplitude range does not contribute significantly to the decay of trapped field.**

***Index Terms*—Flux pinning, high-temperature superconductors, superconducting magnets, trapped field attenuation, trapped field magnets.**

I. INTRODUCTION

BULK superconducting materials have the ability to act as quasi-permanent trapped field magnets. Effective flux pinning permits high current densities which in turn can generate large persistent magnetic fields. The largest achieved trapped field to date is 17.6 T at 26 K in a 25 mm diameter Ag-doped $GdBa_2Cu_3O_{7-\delta}$ (GdBCO) bulk using field-cooled magnetization (FC) [1]. In contrast, the magnetic fields that can be achieved with the use of conventional magnets are an order of magnitude lower. Nonetheless, for any practical application the use of superconducting magnets requires cooling and magnetization systems, which makes portability an issue to be resolved. If the superconductor is to be incorporated into a lightweight rotating machine the magnetization system must be portable (or integrated in the machine design, such as using the armature coils [2]), fast and quickly repeatable.

Pulsed-field magnetization (PFM) has shown significant potential as an activation technique, with the highest trapped field so far being 5.2 T at 30 K in a 45 mm GdBCO bulk [3]. With PFM the magnetic field is applied to the superconductor in the form of one or more short pulse(s), on the order of hundreds of milliseconds in duration, by discharging a capacitor bank through a solenoid coil. Thus, PFM is both much faster and energy-efficient than FC, which makes PFM more suitable for portable applications. Recently, a portable magnetic field exceeding 3 T at 50 K has been achieved using a portable cryocooler [4].

High-temperature superconductors exhibit flux creep, an outflow of flux vortices, which manifests itself as an approximately logarithmic decay of trapped field over time [5]. The rate of decay is determined by the balance between the Lorentz force, which is the main driving force that would move the flux vortices, the pinning force, which would act to anchor the flux vortices to pinning centers in the bulk [6] [7] and the thermal activation of the vortices. The Lorentz force emerges from the interaction of the current density with the magnetic field. Conversely, the pinning force has to do with disorder in the bulk and is, itself, temperature-dependent. Thus, the magnetic and thermal conditions both play an important role in determining the rate of decay. A higher temperature leads to a higher rate of decay [8], which can additionally be greatly accelerated by external field perturbations [9] [10].

In general, there are two main mechanisms which can lead to a reduction in the trapped field of the superconductor: a change of the distribution of current density, and a reduction of its amplitude [11]. Any change in the external field causes a flow of screening currents to oppose the change, which leads to current redistribution in the bulk, whereas any movement of flux vortices due to the changing magnetic field leads to heating and a reduction of the critical current density [12]. As such, the governing mechanism of trapped-field decay will depend on the specific parameters of the examined system, such as the cooling power relative to the heat generation, the frequency of applied AC field and its amplitude relative to the peak trapped field in the bulk.

All AC rotating machines present a complex and time varying magnetic field environment [13] [14]. The aim of this study is to simulate potential magnetic conditions in a superconducting rotating machine and apply them to bulk

---

This work was supported by Siemens AG. The work of M. D. Ainslie was supported in part by a Royal Academy of Engineering Research Fellowship and in part by an Engineering and Physical Sciences Research Council (EPSRC) Early Career Fellowship EP/P020313/1. All data are provided in full in the results section of this paper.

J. Srpčič, D. Zhou, K. Y. Huang, Y. Shi, A. Dennis, M. D. Ainslie, A. M. Campbell, D. A. Cardwell and J. H. Durrell are with the Bulk Superconductivity Group, Department of Engineering, University of Cambridge, Cambridge UK (author e-mail: js2308@cam.ac.uk).

R. Bause, M. Boll and M. Filipenko are with Siemens AG, Coperate Technology, eAircraft, Willy-Messerschmidt Straße 1, 82024 Taufkirchen.

superconducting materials. This entails first using PFM to activate the superconductor, followed by external AC field application during which the decay of the trapped magnetic field is measured.

II. EXPERIMENTAL

The sample characterized was a single-grain Ag-doped GdBCO bulk of 16 mm diameter and 8 mm thickness, manufactured by the top-seeded melt growth technique [15]. The peak trapped field achieved in the sample using PFM at 77 K was 0.6 T, which indicates that the critical current density of the bulk is on the order of $10^8\ A/m^2$. Larger bulks up to 30 mm in diameter are now routinely grown with similarly high critical current densities [16] and we therefore believe the data gathered here can be scaled to represent larger bulks in the tesla range, useful for applications. For PFM a copper coil was submerged in liquid nitrogen (with the bulk in the center of the bore) and connected to a capacitor bank (the schematic of the experimental apparatus is shown in Fig. 1. For the measurements in LN_2 the same coil as in Fig. 1 was used; however, the bulk was inserted into the bore of the coil simply with a fiberglass holder and cooled with LN_2). The pulsed field, produced by the coil, was characterized with calibrated Hall sensors (for a detailed description of the PFM setup see [4]). After PFM the same coil was connected to an AC current source to provide the external alternating magnetic field. The AC field was applied parallel to the direction of magnetization, which was along the *c*-axis of the bulk. The trapped magnetic flux density was measured locally with three Hall probes, which were mounted on the top surface at distances of 0 mm, 2 mm and 4 mm from the center. Each experiment started with PFM at 77 K, followed by a 10-minute waiting period to allow for flux creep. Afterwards, 5000 cycles of AC field of various amplitude and frequency were applied. In the absence of AC field and in the time it would take to apply 5000 cycles at any frequency, the trapped field was found to decay less than our measurement error (1%).

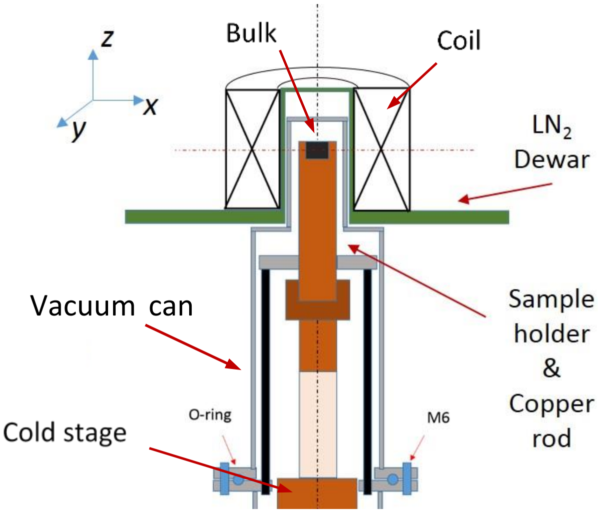

Fig. 1. A schematic of the experimental apparatus.

To measure the temperature of the bulk during AC field application, a Cernox temperature sensor (Lake Shore Cryotronics) was mounted on the center of the top surface of the bulk and insulated from the liquid nitrogen with polystyrene.

In a second set of measurements the bulk was magnetized with PFM at 77 K and afterwards cooled down to temperatures of 20 K, 40 K and 60 K. At these temperatures, 5000 cycles of AC field were applied and the rate of decay was measured. To provide sufficient cooling the bulk was attached to the cold stage of a GM cryocooler with the lowest achievable temperature around 15 K.

III. RESULTS AND DISCUSSION

The sample was magnetized using PFM with peak magnetic fields of 3.2 T, 2 T and 1 T, which resulted in central trapped fields of 0.6 T, 0.2 T and 0.05 T, respectively. Each case also resulted in a different radial field profile (Fig. 2). The conical shape of the field profile following the 3.2 T pulse indicates a fully magnetized bulk. In the remaining two cases the bulk is under-magnetized to different degrees, and the trapped field profile may no longer be axially symmetric. However, these three initial conditions were used to illustrate the effect of the local field gradient on the local decay rate of the trapped field in the bulk.

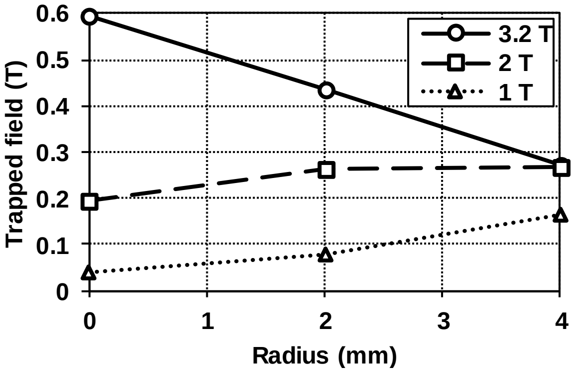

Fig. 2. Trapped field profile 10 min. after magnetization for pulse strengths 3.2 T (circles), 2 T (squares) and 1 T (triangles).

In the case of an infinitely long axially symmetric bulk, where the current density *J(r)* (*r* is the radial coordinate from the center of the bulk) inside the bulk is perpendicular to the induced magnetic field *B(r)* everywhere, the local Lorentz force *F(r)* on a flux vortex can be written in the scalar form [17]

$$F(r) = J(r)B(r) = -\frac{1}{\mu_0}\frac{dB(r)}{dr}B(r). \quad (1)$$

The Lorentz force is a function of both the magnetic field *B(r)* and its derivative *dB(r)/dr* (which is proportional to the current density as per Ampere's law). Thus, the shape of the trapped field must play an important role in determining the local rate of decay. This was supported by the measurements of field decay for all three initial magnetizations after applying 5000 cycles of 45 mT peak AC field at different frequencies (Fig. 3 (a)-(c)). The decay ΔB was obtained by subtracting the measured flux density after application of the AC field from its value after PFM. At a given frequency, the decay rate increases with the distance from the center of the bulk, as the external field penetrates the sample from the sides.

The decay rate decreases with frequency at all radii which we assign to the frequency dependence of the penetration depth [18]. In normal metals the penetration depth of an AC magnetic field is inversely proportional to the square root of the frequency ω. Interestingly, the field decay, shown in Fig. 3 (a) (green dashed line), follows the same dependence $\sim \omega^{-1/2}$.

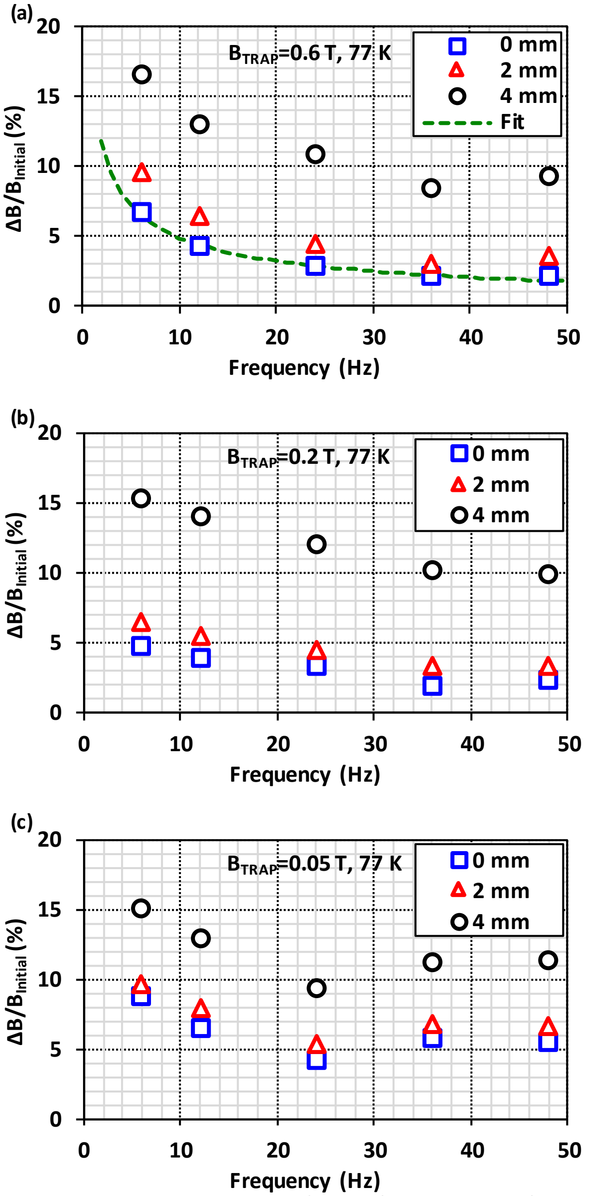

Fig. 3. Frequency dependence of decay following each of the initial magnetizations: (a), (b) and (c) respectively after 3.2 T, 2 T and 1 T pulse. Dashed green line in (a) is a least-square fit to the 0 mm data of an $\omega^{-1/2}$ frequency dependence, similar to the frequency dependence of penetration depth in metals. In (c), the apparent rise of decay at 36 Hz may be attributable to measurement error due to the small values of decay.

Measurements of temperature of the bulk during AC field application at 77 K show that the temperature rise is higher at higher applied fields and higher frequencies (Fig. 4). Here, the AC fields were applied to a non-magnetized bulk.

In the first set of measurements, the field frequency was kept constant at 48 Hz (Fig. 4 (a)) and the bulk temperature was measured as a function of applied field amplitude. The measurements were made 60 s after the start of AC field application. In the initial heating stage after the start of the AC field application, the temperature started rising with a rate proportional to the field amplitude, and stabilized after about 30 s. Qualitatively, if the applied magnetic field is larger, it can penetrate further into the bulk and so the volume in which vortices move and generate heat is increased, causing a larger temperature rise.

For the second set of measurements the polystyrene insulation had to be remade due to leakage. The two sets of data are thus not directly comparable, however they are internally consistent. In the second set of measurements, the field amplitude was kept constant at 25 mT and the bulk temperature was measured at various frequencies of applied field (Fig. 4 (b)). The temperature rise per cycle in the initial heating stage was independent of frequency; while at higher frequencies it took more cycles to reach the (higher) equilibrium temperature. The data points in Fig. 4 (b) were measured 180 s after the start of the AC field application, when the bulk temperature stabilized for all frequencies of the applied field.

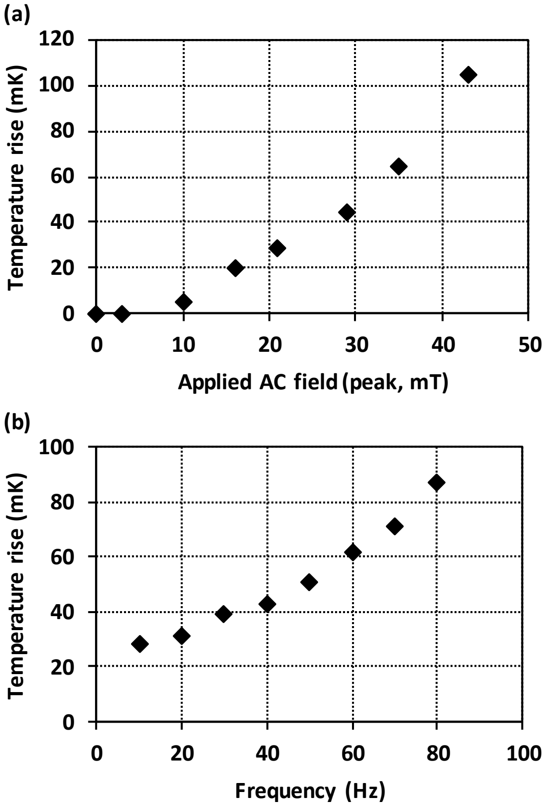

Fig. 4. (a) Temperature rise on the bulk surface during 48 Hz AC field application for different field values (in liquid nitrogen). (b) Temperature rise during 25 mT (peak) AC field applications for frequencies up to 80 Hz (in liquid nitrogen).

Varying the frequency of applied AC field leads to two opposing effects in terms of heat generation. Firstly, at a higher frequency there is a larger induced electric field $\boldsymbol{E}$ in the bulk (as per Faraday's law of induction $\nabla \times \boldsymbol{E} = -\partial \boldsymbol{B}/\partial t$), consequently leading to a higher heat generation per unit volume [19]. Secondly, increasing the AC field frequency causes the penetration depth to decrease, thus decreasing the volume where heat is generated. Our measurements show that the former is the dominating effect within our measured field and frequency range, as the temperature rise in the bulk increases with frequency.

Within the measured field amplitude and frequency range the temperature rise was lower than about 100 mK. The temperature rise increases with frequency, whereas the trapped field decay rate decreases with frequency. Therefore, we conclude that the temperature rise does not contribute significantly to the rate of decay of trapped field. We assign this as being due to a relatively small volume of the bulk, leading to a low generation of heat, which can be sufficiently removed from the bulk by the liquid nitrogen.

Lowering the temperature after magnetization and thus increasing the pinning force is expected to improve bulk performance and decrease decay due to the AC field [20]. To confirm this, the bulk was magnetized using PFM at 77 K, and afterwards cooled down to 20 K, 40 K, or 60 K. Then, 5000 cycles of 150 mT (peak) AC field were applied at 6 Hz. A higher amplitude and lower frequency of the AC field were chosen in order to cause a higher decay of trapped field per cycle. The decay was measured with five Hall sensors on the top surface: -5 mm, -2.5 mm, 0 mm, 2.5 mm and 5 mm from the center. The decay at 77 K is significant, even more than 50% of the trapped field on the edges (Fig. 5 (a), black circles). However, upon cooling to 60 K, the decay already drops effectively to zero. This is because the pinning force increases, causing vortices to be more firmly held in place, and because the bulk is no longer fully magnetized (J_C increases with the pinning force). Thus, any current redistribution does not necessarily cause the reduction of trapped field as it would in a fully magnetized sample.

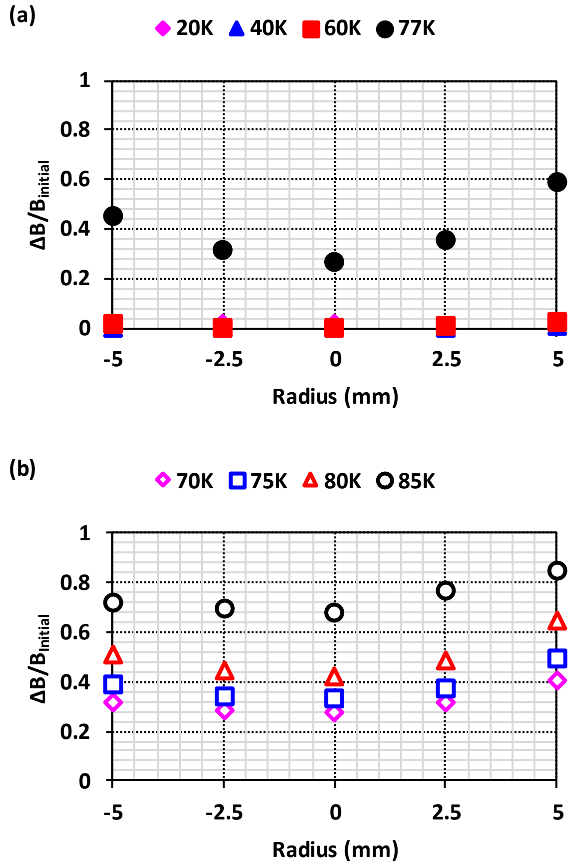

Fig. 5. (a) Decay of trapped field ΔB after 5000 cycles at each respective temperature (20 K, 40 K, 60 K or 77 K), divided by the initial trapped field $B_{Initial}$ 10 min. after PFM at 77 K. Data points for temperatures 20 K, 40 K and 60 K are all lower than 0.03.(b) Decay of trapped field ΔB after 5000 cycles, divided by initial trapped field $B_{Initial}$, of a fully magnetized bulk at each respective temperature (70 K, 75 K, 80 K or 85 K).

This significant reduction in demagnetization due to external AC magnetic fields is very promising for applications as temperatures as low as 20 K are now easily achievable with commercial cryocoolers and few practical applications are expected to employ liquid nitrogen.

In potential applications the bulk could be magnetized at a higher temperature and cooled down to effectively eliminate decay. Furthermore, at low temperatures PFM does not magnetize the bulk to its full capability, leading to a lower rate of decay, than a fully FC-magnetized bulk. The tradeoff for this is a lower achievable trapped field using PFM.

To investigate the temperature dependence of decay in a fully magnetized sample, the sample was pulsed at a low temperature of 40 K and warmed up to a temperature of 65 K, at which the trapped field started to decrease. At that temperature, the bulk was fully magnetized. The decay for temperatures between 70 K and 85 K is shown in Fig. 5 (b). At 85 K the decay is severe, up to 80% at 4 mm, but a decrease in temperature of only 15 K leads to a reduction of decay by more than one half. Thus, even in a fully magnetized sample the decay dramatically decreases at lower temperatures.

IV. CONCLUSION

In this study, we have investigated the effect of external AC magnetic fields on the rate of trapped-field decay in GdBCO bulks, magnetized with PFM. We studied the effect of the subsequent application of AC magnetic field at a range of frequencies up to 48 Hz and amplitudes up to 45 mT applied parallel to the direction of magnetization. Other configurations, such as the crossed-field configuration (where the field is applied perpendicular to magnetization), have been shown to potentially have a greater effect on the decay of trapped field [21] [22]. However, it is difficult to predict the exact magnetic fields in AC rotating machines, and an understanding of this geometry is important.

We have shown that controlling the temperature after magnetization provides a reliable way of reducing the decay of trapped field practically to zero for the AC fields we applied. Cooling a fully magnetized bulk after magnetization increases the pinning strength which intrinsically reduces the rate of decay, but also increases the critical current density, rendering the bulk no longer fully magnetized and thus intrinsically more stable [23]. Any subsequent external field perturbations that cause current redistribution thus do not lead to a reduction of trapped field. Bulks in applications using PFM at low temperatures (~20 K) are unlikely to ever be fully magnetized and are therefore inherently robust against external AC fields.

REFERENCES

[1] J. H. Durrell, A. R. Dennis, J. Jaroszynski, M. D. Ainslie, K. G. B. Palmer, Y. Shi, A. M. Campbell, J. Hull, M. Strasik and E. E. Hellstrom, “A Trapped Field of 17.6 T in Melt-Processed, Bulk Gd-Ba-Cu-O Reinforced with Shrink-Fit Steel,” *Superconductor Science and Technology,* vol. 27, no. 8, 2014.

[2] H. Matsuzaki, Y. Kimura, I. Ohtani, M. Izumi, T. Ida, Y. Akita, H. Sugimoto, M. Miki and M. Kitano, “An axial gap-type HTS bulk synchronous motor excited by pulsed-field magnetization with vortex-type armature copper windings,” *IEEE Transactions on Applied Superconductivity,* vol. 15, no. 2, 2005.

[3] H. Fujishiro, T. Tateiwa, A. Fujiwara, T. Oka and H. Hayashi, “Higher trapped field over 5T on HTSC bulk by modified pulse field magnetizing,” *Physica C,* pp. 334-338, 2006.

[4] D. Zhou, M. D. Ainslie, Y. Shi, A. R. Dennis, K. Huang, J. R. Hull, D. A. Cardwell and J. H. Durrell, “A portable magnetic field of >3 T generated by the flux jump assisted, pulsed field magnetization of bulk superconductors,” *Applied Physics Letters,* vol. 110, 2017.

[5] P. W. Anderson, “Theory of Flux Creep in Hard Superconductors,” *Phys. Rev. Lett.,* vol. 9, no. 7, pp. 309-311, 1962.

[6] G. Blatter, M. V. Feigel'man, V. B. Geshkenbein, A. I. Larkin and V. M. Vinokur, “Vortices in high-temperature superconductors,” *Reviews of Modern Physics,* vol. 66, no. 4, 1994.

[7] M. E. McHenry and R. A. Sutton, “Flux pinning and dissipation in high tmeperature oxide superconductors,” *Progress in Materials Science,* vol. 38, pp. 159-310, 1994.

[8] Y. Yeshurun, A. P. Malozemoff and A. Shaulov, “Magnetic relaxation in high-temperature superconductors,” *Reviews of Modern Physics,* vol. 68, no. 3, pp. 911-949, 1996.

[9] K. Yamagishi, J. Ogawa, O. Tsukamoto, M. Murakami and M. Tomita, “Decay of trapped magnetic field in HTS bulk caused by application of ac magnetic field,” *Physica C,* Vols. 392-396, pp. 659-663, 2003.

[10] J. F. Fagnard, M. Morita, S. Nariki, H. Teshima, H. Caps, B. Vanderheyden and P. Vanderbemden, “Magnetic moment and local magnetic induction of superconducting/ferromagnetic structures subjected to crossed fields: experiments on GdBCO and modelling,” *Superconductor Science and Technology,* vol. 29, 2016.

[11] P. Vanderbemden, Z. Hong, T. A. Coombs, S. Denis, J. Schwartz, I. B. Rutel, N. Hari Babu, D. A. Cardwell and A. M. Campbell, “Behavior of bulk high-temperature superconductors of finite thickness subjected to crossed magnetic fields: Experiment and model,” *Physical Review B,* vol. 75, no. 17, p. 174515, 2007.

[12] J. Zou, M. D. Ainslie, D. Hu and D. A. Cardwell, “Influence of Time-Varying External Magnetic Fields on Trapped Fields in Bulk Superconductors,” *IEEE Transactions on Applied Superconductivity,* vol. 25, no. 3, pp. 1-5, 2015.

[13] M. Qiu, H. K. Huo, Z. Xu, D. Xia and L. Z. Lin, “Electromagnetic phenomena in HTS bulk subjected to a rotating field,” *IEEE Transactions on Applied Superconductivity,* vol. 14, no. 2, pp. 1898-1901, 2004.

[14] K. Yamagishi, J. Ogawa and O. Tsukamoto, “Rotation Test of a Superconducting Bulk Rotor Shielded With Superconducting Rings,” *IEEE Transactions on Applied Superconductivity,* vol. 25, no. 3, 2014.

[15] K. Konstantopoulou, Y. Shi, A. R. Dennis, J. H. Durrell, J. Y. Pastor and D. A. Cardwell, “Mechanical characterization of GdBCO/Ag and YBCO single grains fabricated by top-seeded melt growth at 77 and 300 K,” *Superconductor Science and Technology,* vol. 27, no. 11, 2014.

[16] M. D. Ainslie, H. Fujishiro, H. Mochizuki, K. Takahashi, Y.-H. Shi, D. K. Namburi, J. Zou, D. Zhou, A. R. Dennis and D. A. Cardwell, “Enhanced trapped field performance of bulk high-temperature superconductors using split coil, pulsed field magnetisation with an iron yoke,” *Superconductor science and technology,* vol. 29, 2016.

[17] R.-P. Sawh, R. Weinstein, R. Carpenter, D. Parks and K. Davey, “Observation of flux-creep in direction opposite to the Lorentz force,” *Superconductor Science and Technology,* vol. 30, no. 4, 2017.

[18] H. Ueda, M. Itoh and A. Ishiyama, “Trapped field characteristic of HTS bulk in AC external magnetic field,” *IEEE Transactions on Applied Superconductivity,* vol. 13, no. 2, p. 2283, 2003.

[19] M. D. Ainslie and H. Fujishiro, “Modelling of bulk superconductor magnetization,” *Superconductor Science and Technology,* vol. 28, no. 5, 2015.

[20] K. Yamagishi, I. Asaba, S. Sekizawa, O. Tsukamoto, J. Ogawa, K. Kukikawa and M. Hirakawa, “AC losses in HTS bulk at various temperatures,” *IEEE Transactions on Applied Superconductivity,* vol. 15, no. 2, 2005.

[21] J. Ogawa, M. Iwamoto, K. Yamagishi, O. Tsukamoto, M. Murakami and M. Tomita, “Influence of AC external magnetic field perturbation on trapped magnetic field in HTS bulk,” *Physica C,* vol. 385, pp. 26-30, 2003.

[22] A. M. Campbell, “Flux cutting in superconductors,” *Superconductor Science and Technology,* vol. 24, no. 9, 2011.

[23] A. Yamamoto, A. Ishihara, M. Tomita and K. Kishio, “Permanent magnet with MgB2 bulk superconductor,” *Applied Physics Letters,* vol. 105, 2014.