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High force magnetic levitation using magnetized superconducting bulks as a field source for bearing applications

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Abstract

The ability of high temperature superconducting bulks to trap magnetic fields of several tesla allows them to generate very high levitation force. This paper reports the development of a bulk-bulk superconducting rotary bearing design which uses superconducting bulks on both the rotor and the stator. An evaluation is made of the effectiveness of pulsed fields for magnetizing bulks. Modeling of the bulks using the perfectly trapped flux model is also reported to assess the limits of the bearing design. The results demonstrate the feasibility of a (RE)BCO-MgB\textsubscript{2} bulk bearing capable of force densities of the order of 100N/cm\textsuperscript{2}. The design and construction of a unique system capable of magnetizing a 25 mm (RE)BCO bulk and measuring levitation force between this bulk and a coaxial MgB\textsubscript{2} hollow cylinder is outlined.

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1. Introduction

The ability of bulk superconductors to trap significant fields and maintain them for long periods of time make them potentially useful for a variety of applications. One of those applications is superconducting magnetic bearings which rely on the unique property of stable levitation when a bulk superconductor is field cooled (FC). Such bearings have allowed frictionless rotation in flywheel energy storage systems [1, 2] where they have been used to support over a tonne in mass. Although successful, a limitation to existing designs is the field strength of rare earth permanent magnets. Far more compact bearings can be realised by using a more powerful field source. This paper explores the effectiveness of pulse field magnetization for the magnetized bearing concept first reported in [3] and the experimental system developed to prove the concept.

2. The effectiveness of pulsed field magnetization

The most practical method currently available to magnetize a bulk is using a pulsed field from a copper coil connected to a capacitor bank. It is now practical to trap 2 to 5 T in bulk samples using pulsed field magnetization and the techniques of IMRA (Iteratively Magnetizing pulsed field operation with Reducing Amplitudes) and MPSC (Multi-Pulse technique with Step-wise Cooling) have been introduced to maximize trapped flux [4, 5]. They achieve this by replacing flux lost from the periphery of the sample during initial pulses due to excessive heating, and by broadening the conical trapped field profile resulting from pulses at fixed temperature only.

| Pulsed field type       | $B_{\text{trap}}/B_{\text{applied}}$ | $B_{\text{trap}}/B_{\text{ideal}}$ | $\Phi_{\text{trap}}/\Phi_{\text{ideal}}$ |
|-------------------------|-------------------------------------|-----------------------------------|-------------------------------------|
| Quasi static ZFC        | 1/2                                 | 1                                 | 1                                   |
| Single pulse            | $\approx 1/4$                       | 1/2 - 2/3                         | $< 1$                               |
| IMRA (fixed temperature)| 1/4 - 1/3                           | $\approx 2/3$                     | $\approx 1$                         |
| MPSC + IMRA             | 1/3 – 3/4                           | –                                 | –                                   |

Table 1: Peak trapped field and total flux for various pulsed field methods compared to the ideal maximum trapped field possible if using field cooling. For a given optimum applied field and temperature, IMRA is needed to maximise trapped field and flux. Only MPSC combined with IMRA is able to trap a field more than twice the applied field.

Figure 1: Trapped field profiles for a 26mm diameter GdBCO bulk magnetized at 77K. a) Field cooled. b) Pulse magnetized with an optimum applied field. Field cooling traps a higher peak field (0.90 T) than pulsed magnetization (0.63 T), but using IMRA allows pulsed magnetization to give approximately 95% of the field cooled trapped flux.
Due to the problem of heat generation, pulse field magnetization is sometimes regarded as incapable of trapping significant fields. However as Table 1 illustrates, while a single pulse gives a poor result compared to quasi static zero field cooling (ZFC), IMRA and MPSC can succeed in giving a high trapped field for a given applied field whereas the trapped flux (often just as important for applications) can be made to be almost as high as for the ideal field cooled case. Experimental results for a GdBCO bulk are shown in Figure 1 to demonstrate the effectiveness of IMRA for trapping a significant flux even though the peak of the trapped field may be flattened. The real effectiveness of pulsed magnetization comes when using both the IMRA and MPSC techniques together. H. Fujishiro et al. have demonstrated a trapped field of 5.2 T in a 45 mm diameter bulk using a 6.7 T applied field [6].

3. Bearing design

3.1. Geometry and initialization procedure

The geometry of the design presented uses cylindrical bulks stacked along their common axis and magnetized with alternating polarity. This creates high field gradients like the permanent magnet stacks used in existing cylindrical superconducting bearings. (RE)BCO would be ideal for these bulks and could be magnetized by a coil on the stator. To allow practical field cooling of the passive stator part of the bearing after magnetization of bulk (RE)BCO on the rotor, a superconductor with a lower $T_c$ or irreversibility field line is needed. MgB$_2$ fits this criterion as well as being economical to produce in bulk form in a variety of different geometries such as a hollow cylinders [7].

The $T_c$ of MgB$_2$ make it possible to magnetize the (RE)BCO rotor bulks above 40 K with a high trapped field using MPSC and then cool the whole system down below 40 K in the operating
configuration so that field cooling of an MgB$_2$ hollow cylinder is achieved. Following magnetization between 40 K and 77 K the bearing can be cooled to an operating temperature of 20 – 25 K.

3.2. An ideal bulk pair

An indication of how high the load for a bearing made of magnetized bulks could be, a magnetized pair of 50mm (RE)BCO bulks is considered. Details of the method and advantage, of magnetizing a pair of bulks rather than a single bulk for a field source has previously been described in detail [3]. Figure 3a shows a pair of bulks with an average current density that could be achieved by MPSC, being displaced relative to another field cooled superconductor. Unlike a permanent magnet, the shielding of the (RE)BCO field source enhances force by a factor of 2. The perfectly trapped flux model (PTF) [8] assumes a very high $J_c$ for both superconductors. While this is an excellent approximation for the magnetized (RE)BCO, it is less accurate for MgB$_2$ at 20 K but close enough to give a reliable indication of the maximum force possible. Figure 3b shows the force is enough to stably levitate over 1 tonne at $\Delta z = 6\text{mm}$, giving a force density of over 160 N cm$^{-2}$ compared to 14 N cm$^{-2}$ for permanent magnet designs.

Figure 3: a) Distortion of field lines resulting from the displacement of a pair of (RE)BCO bulks magnetized with opposite polarity before field cooling inside a hollow superconducting bulk. b) The ideal force vs displacement prediction.

4. Pulse magnetization and levitation force measurement system

4.1. Design and construction

A unique levitation force measurement system has been constructed to allow investigation into pulsed field magnetization of superconducting bulks and forces between a magnetized bulk and another superconductor. Measurements will follow after the completion of signal processing electronics, however all mechanical parts of the system including the pulse field coil have been completed and tested. An overview of the system can be seen in Figure 4a with the bulk samples and their precision engineered stainless steel casings shown in Figure 4b. The 10 T, 12 ms rise time, magnetizing coil shown in Figure 4c required copper windings with significant mechanical reinforcement in the form of glass fibre/stycast composite (blue) and an external tight fitting stainless steel cylinder. After magnetization of the YBCO bulk, it can be aligned inside an MgB2 cylinder before the system is cooled further to around 20 K. It is then possible to measure levitation force between the MgB2 and YBCO bulks up to 1 kN. A levitation force equivalent to 100 kg should easily be achieved given the high trapped fields possible as supported by modeling predictions.
4.2. Predictions using perfectly trapped flux model

In order to predict and support the experimental results for force displacement curves that will follow, the PTF model has been applied to a number of cases all involving a 25.5 mm diameter magnetized YBCO sample. As force ideally scales with the square of trapped field, 1 T trapped field (1mm above bulk surface) has been modeled. Figure 5a shows that even when using a single magnetized bulk rather than a pair, forces as high as a 1 kN can be achieved for a trapped field just over 3 T. A more fundamental experiment that will be tried is ZFC of an MgB2 disk. In this case the predicted forces are extremely high. In reality the high fields applied to the MgB2 would cause significant flux penetration so this case is valuable for probing the breakdown of the PTF model and verifying critical state models. Due to the lack of radial stability the ZFC case is of less importance for applications than the field cooled cases.

Figure 4: a) Photo and engineering drawing for system based around an 50mm bore Oxford Instruments Variox cryostat. Cooling of the sample is through helium gas convection with a minimum temperature of 13 K. The force rating for the system is 1 kN. b) YBCO and MgB2 bulk samples and sample holders. c) Construction of glass fibre/steel reinforced 10 T, 65 mm bore pulse field coil.
5. Conclusions

Progress in the study of a new bearing design using magnetized (RE)BCO bulks instead of permanent magnets has been reported. The effectiveness of pulse magnetization has been carefully reviewed and supported with experimental results to demonstrate the power of techniques involving pulse sequences. By considering a geometry which uses a pair of magnetized bulk and a combination of two superconductors, (RE)BCO and MgB$_2$, a practical design for the bearing may be possible. The reported development of a system capable of magnetizing bulks with applied fields up to 10 T and then measuring force interactions will prove a valuable tool for investigating general interactions between bulk superconductors and well as being able to prove the concept of the bearing design presented.

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