Influence of crossed fields in structures combining large grain, bulk (RE)BCO superconductors and soft ferromagnetic discs

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Abstract. Bulk (RE)BCO superconductors are able to trap record magnetic fields and can be used as powerful permanent magnets in various engineering applications such as rotating machines and magnetic bearings. When such superconducting (SC) "trapped field magnets" are combined to a ferromagnetic (FM) disc, the total magnetic moment is increased with respect to that of the superconductor alone. In the present work, we study experimentally the magnetic behaviour of such hybrid FM/SC structures when they are subjected to cycles of applied field that are orthogonal to their permanent magnetization, i.e. a "crossed-field" configuration. Experimental results show that the usual "crossed-field demagnetization" caused by the cycles of transverse field is strongly reduced in the presence of the ferromagnet.

1. Introduction

Due to their strong flux pinning ability, bulk (RE)$Ba_2Cu_3O_{7-\delta}$ (REBCO) superconductors (where "RE" denotes a rare-earth ion) form the basis of "trapped field superconducting magnets" with unprecedented characteristics [1-5]. They can be used in a range of power applications including levitation guideways or rotating machines [6-8]. Several physical phenomena, however, cause the trapped flux density generated by such superconducting permanent magnets to decrease after they have been magnetized. The first is flux creep, which usually leads to a logarithmic time-dependence decay of the magnetization [9,10]. The second is related to the interaction of the bulk superconductor with the magnetic fields required for the operation of the device. As an example, the superconductor placed in the rotor of a synchronous motor is subjected to the rotating field generated by the stator [11]. Due to transients that can arise e.g. during a sudden change of mechanical load in the device, the superconductor is likely to be subjected to parasitic time-varying fields [12,13]. In addition to causing losses and self-heating due to vortex motion [14,15], these parasitic fields may substantially reduce the trapped flux density in the superconductor when their direction is orthogonal to that of the main magnetization [16,17]. This phenomenon, called "crossed-field demagnetization" or "collapse of the magnetic moment" has been studied for a long time in superconducting materials of various types [17-22] and is still an intense subject of research [23-25] due to the complexity of physical phenomena involved [26,27].

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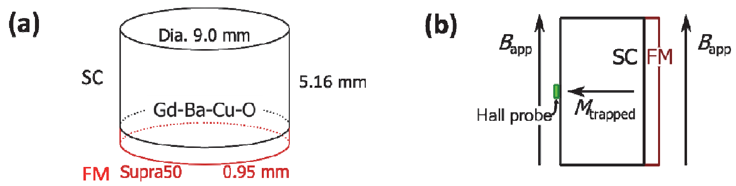

Figure 1. (a) Schematic representation of a superconductor/ferromagnet (SC/FM) hybrid structure made of a 5.16 mm thick $GdBa_2Cu_3O_7$ superconductor attached to a 0.95 mm thick ferromagnetic disc made of "*Supra50*" material (b) Schematic representation of the hybrid SC/FM structure subjected to a crossed-field experiment. $M_{trapped}$ is the permanent magnetization trapped by the superconductor. B_{app} represents the transverse magnetic flux density, applied perpendicularly to $M_{trapped}$. The Hall probe is used to measure the axial component of the flux density, i.e. along the direction of $M_{trapped}$.

Recently, it was shown both experimentally and numerically that the magnetic performances of trapped field superconducting (SC) magnets can be enhanced by combining them to a short section of soft ferromagnetic (FM) material, thereby realizing a hybrid superconductor / ferromagnet (SC/FM) structure [28,29]. Up to now, the magnetic properties of these structures were investigated for a range of applied fields applied *parallel* to the trapped magnetization. The aim of the present work is to study experimentally the properties of such SC/FM structures in the crossed configuration, i.e. when the applied field is *perpendicular* to the trapped magnetization. The corresponding decay of flux density at the surface of the hybrid SC/FM structure will be compared to that occurring at the surface of a superconductor alone. This will allow us to draw conclusions about the practical use of such hybrid SC/FM structures used as trapped field magnets in engineering applications.

2. Experiment

Crossed-field measurements are carried out on bulk, large grain $GdBa_2Cu_3O_7$ (Gd-Ba-Cu-O) superconductor from Nippon Steel & Sumitomo Metal Corporation. The studied superconducting sample is a disk of 9 mm in diameter and 5.16 mm in thickness. The hybrid SC/FM structure is made by attaching a 0.95 mm thick ferromagnetic disk of the same diameter as the superconductor, as shown in figure 1(a). The soft ferromagnetic material is "*Supra50*" from Aperam. Its magnetic properties were characterized independently in an earlier work [28].

The magnetic properties of the $GdBa_2Cu_3O_7$ superconductor (SC) and the hybrid (SC/FM) structure are first characterized at 77 K in a bespoke magnetometer designed to accommodate large bulk samples up to 17 mm in diameter. The design, physical operation, and calibration of the experimental system are described extensively in a previous work [30]. The magnetometer is able to measure magnetic moments in excess of 1 Am^2 (1000 emu), which is two orders of magnitude above the maximum magnetic moment of commercial cryogenic measurement systems. The samples are first magnetized by a field-cooled (FC) process down to $T = 77$ K under 0.625 T in a separate electromagnet. Then the magnetic moment is recorded over time using the magnetometer.

The crossed-field behaviour is then studied at 77 K using a custom probe with a rotating sample holder that can be inserted in the experimental chamber of a Quantum Design Physical Property Measurement System (PPMS). The system includes a AREPOC HPP-VU Hall probe placed against the superconductor. The Hall probe is used to record the axial flux density at the centre of the circular face, as shown in figure 1(b). A field-cooled (FC) procedure under a constant 1 T background axial field is used to magnetize permanently the superconductor or the hybrid structure. After the magnetizing field is switched off, the sample is rotated by 90°; the axial trapped flux density at the surface of the sample is measured by the Hall probe for 1500 s to record the natural relaxation of the sample magnetization caused by flux creep effects. Then 10 cycles of magnetic field perpendicular to the trapped flux density are applied following a triangular waveform at a sweep rate of 3.3 mT/s. Two sets of experiments with different amplitudes (50 mT and 100 mT) are carried out. It should be noted that the mechanical components of the rotating sample holder are designed carefully to withstand the possibly high magnetic torque resulting from the interaction between the magnetized sample and the externally applied transverse magnetic field [31].

3. Results and discussion

Figure 2 compares time-dependence of the trapped magnetic moment of the bulk superconducting sample (SC) and that of the hybrid (SC/FM) structure at $T = 77$ K. The elapsed time t corresponds to that after the magnetization process. The red dashed lines in figure 2 are a linear regression of the data in a log-log scale. As can be seen, the magnetic moment of both samples exhibits a power law behaviour. Fitting the experimental magnetic moment to the theoretical law [9]

$$m(t) = m_0\left(1+\frac{t}{t_0}\right)^{\frac{1}{(1-n)}}$$

allows one to obtain the initial magnetic moment m_0 and the n value of the $E \sim J^n$ power law. For the $GdBa_2Cu_3O_7$ superconductor (SC), this procedure leads to $m_0 = 0.12$ Am² and $n = 32.9$. If a field-independent critical current density is assumed and, at first approximation, finite size effects are neglected, J_c can be estimated from the magnetic moment m_0 using $J_c \approx 3m_0/(aV)$, where a is the sample radius and V its volume. This gives $J_c \approx 2.44 \times 10^8$ A/m², which is amongst the highest reported values for large grain, bulk (RE)BCO superconductors [4]. The same procedure applied on the (SC/FM) hybrid structure gives $m_0 = 0.13$ Am² and $n = 32.1$. The 8 % increase of magnetic moment is in excellent agreement with previous observations and calculations made on other hybrid structures involving $YBa_2Cu_3O_7$ superconductors with ferromagnetic discs of different thicknesses [28,29]. In addition, the relaxation behaviour of the trapped magnetic moment of the hybrid structure is almost unaffected by the presence of the soft ferromagnet.

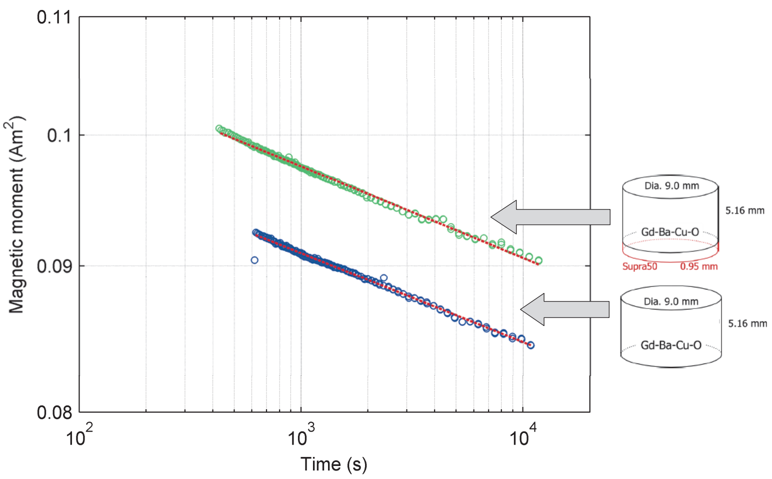

Figure 2. Magnetic moment vs. time for the bulk superconductor alone (blue) or for the hybrid superconducting/ferromagnet structure (green). The red dashed lines are obtained by linear regression on the data in a double logarithmic scale.

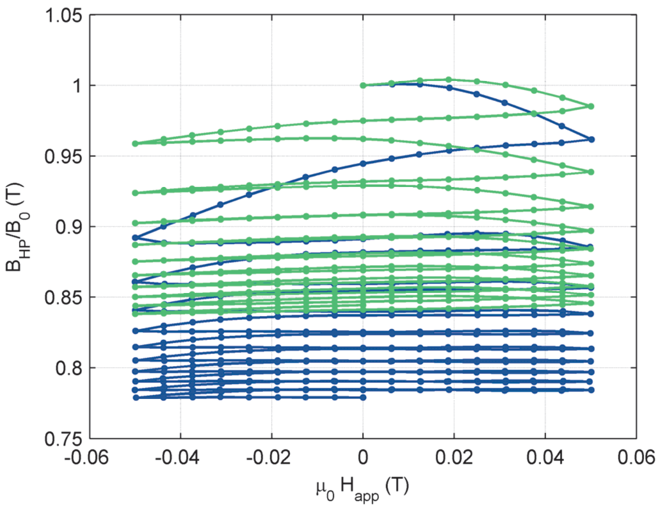

Figure 3. Decrease of the axial component of the flux density (normalized to the flux density before applying the transverse field) measured by the Hall probe B_{HP} during application of 10 cycles of transverse fields, as shown in figure 1(b). The measurement is carried out on the superconductor alone (blue) and on the SC/FM hybrid structure (green). The measurement temperature is 77 K.

Now we examine the results obtained in the crossed-field configuration. Figure 3 shows the flux density measured by the Hall probe against the sample surface during 10 cycles of the crossed field (amplitude = 50 mT) for the superconductor alone (blue) and for the hybrid structure (green). For clarity, data are normalized with respect to the flux density before applying the transverse field (B_0). For both samples, the largest decrease occurs during the first cycle. Remarkably, the hybrid structure is much less affected by the transverse field than the superconductor alone. The decrease after the first cycle of transverse field is ~ 4% for the hybrid structure, against ~ 11% for the superconductor alone. This behaviour is confirmed for the next cycles: after 10 cycles, the total decrease is ~ 22% for the superconductor only, while it is only ~ 16% for the hybrid structure. Figure 4 compares the normalized flux density as a function of crossed-field cycles for two transverse field amplitudes of 50 mT and 100 mT. In both cases, the demagnetization is seen to be appreciably smaller for the case of the hybrid structure. Note also that the relatively large decays observed in figures 3 and 4 are measured at 77 K. In engineering applications where the operating temperature is in the range of 30 - 50 K, the critical current and the creep exponent are higher than at 77 K and the overall decay of the magnetization for a given crossed field amplitude is much smaller than those observed in the present work.

The above results point out the beneficial effect of a ferromagnetic piece on one side of the superconductor to reduce the crossed-field attenuation of the available flux density. These results can be understood by the shielding effect provided by the ferromagnet. Due to the low reluctance path, a part of the transverse flux density lines are expected to be diverted from the bulk superconductor, thereby minimizing the redistribution of persistent currents that usually takes place in the presence of crossed fields [20-22]. In the present case, it should also be emphasized that the self-heating of the superconductor caused by the time-varying transverse field can be neglected because of the low-value of the sweep rate used [14,25].

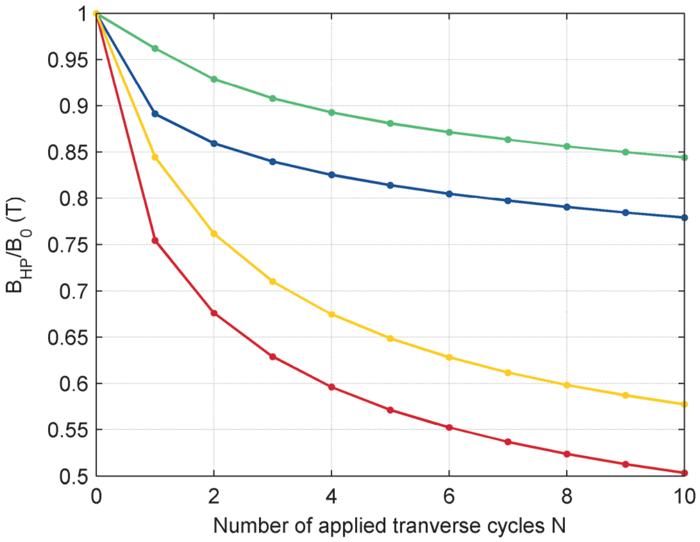

Figure 4. Magnetic flux density B_{HP} measured by the Hall probe as a function of the number of full transverse applied field cycles. For a cycle amplitude of 50 mT, the measurements are in blue and green for the SC alone and SC/FM structure, respectively. The corresponding data recorded at 100 mT for the SC alone and SC/FM structure are in red and yellow, respectively.

5. Conclusion

In this work we investigated the effect of a ferromagnetic disc placed against a bulk $GdBa_2Cu_3O_7$ superconductor when it is first fully magnetized and then subjected to various cycles of transverse field perpendicular to the trapped magnetic moment. The results give evidence that the addition of a ferromagnetic disc on one side of the superconductor reduces the collapse of the trapped flux density against the other face of the superconductor. Therefore one can conclude that the presence of the ferromagnet is not only helpful in increasing the trapped magnetic moment but also to reduce the detrimental effect of crossed fields. Such a result is important for use of bulk melt-textured superconductors in engineering applications.

Acknowledgements

The research was funded through the University of Liège (ULg) and an ARC grant for Concerted Research Actions, financed by the French Community of Belgium (Wallonia-Brussels Federation), under reference ARC 11/16-03.

References

[1] Durrell J H *et al.* 2014 *Supercond. Sci. Technol.* **27** 082001
[2] Tomita M and Murakami M 2003 *Nature* **421** 517
[3] Teshima H, Morita M and Hirano H 2006 *J. Phys.: Confer. Series* **43** 1031
[4] Devendra Kumar N, Rajasekharan T, Muraleedharan K, Banerjee A and Seshubai V 2010 *Supercond. Sci. Technol.* **23** 105020
[5] Doyle R A, Bradley A D, Lo W, Cardwell D A, Campbell A M, Vanderbemden P and Cloots R 1998 *Appl. Phys. Lett.* **73** 117
[6] Werfel F N, Floegel-Delor U, Rothfeld R, Riedel T, Goebel B, Wippich D and Schirrmeister P 2012 *Supercond. Sci. Technol.* **25** 014007

[7] Zhen Huang, Wei Xian, Min Zhang, Chudy M, Chen Y, Zhaoyang Zhong, Baghdadi M, Wei Wang, Spaven F, Matsuda K and Coombs T A 2013 *IEEE Trans. Appl. Supercond.* **23** 5200204
[8] Zhou D, Izumi M, Miki M, Felder B, Ida T and Kitano M 2014 *Supercond. Sci. Technol.* **25** 103001
[9] Gurevich A and Küpfer H 1993 *Phys. Rev. B* **48** 6477
[10] Cardwell D A *et al.* 2005 *Supercond. Sci. Technol.* **18** S173
[11] Campbell A M 2014 *Supercond. Sci. Technol*. **27** 124012
[12] Qiu M, Huo H K, Xu Z, Xia D, Lin L Z and Zhang G M 2005 *IEEE Trans. Appl. Supercond.* **15** 3172
[13] Yamagishi K, Ogawa J and Tsukamoto O 2015 *IEEE Trans. Appl. Supercond.* **25** 5201905
[14] Vanderbemden P, Laurent P, Fagnard J F, Ausloos M, Hari Babu N and Cardwell D A 2010 *Supercond. Sci. Technol.* **23** 075006
[15] Zushi Y, Asaba I, Ogawa J, Yamagishi K, Tsukamoto O, Murakami M and Tomita M 2004 *Physica C* **412-414** 708
[16] Ogawa J, Iwamoto M, Yamagishi K, Tsukamoto O, Murakami M and Tomita M 2003 *Physica C* 386 26
[17] Vanderbemden P, Hong Z, Coombs T A, Ausloos M, Hari Babu N, Cardwell D A and Campbell A M 2007 *Supercond. Sci. Technol.* **20** S174
[18] Funaki K and Yamafuji K 1982 *Jpn. J. Appl. Phys*. **21** 299
[19] Fisher L M, Kalinov A V, Savel'ev S E, Voloshin I F, Yampol'skii V A, LeBlanc M A R and Hirscher S 1997 *Physica C* **278** 169
[20] Badía A, and López C 2007 *Phys. Rev. B* **76** 054504
[21] Vanderbemden P, Hong Z, Coombs T A, Denis S, Ausloos M, Schwartz J, Rutel I B, Hari Babu N, Cardwell D A and Campbell A M 2007 *Phys. Rev. B* **75** 174515
[22] Luzuriaga J, Badia-Majos A, Nieva G, Giordano J L, Lopez C, Serquis A and Serrano G 2009 *Supercond. Sci. Technol.* **22** 015021
[23] Baghdadi M, Ruiz H S and Coombs T A 2014 *Appl. Phys. Lett.* **104** 232602
[24] Celebi S, Sirois F and Lacroix C 2015 *Supercond. Sci. Technol*. **28** 025012
[25] Fagnard J F, Kirsch S, Morita M, Teshima H, Vanderheyden B and Vanderbemden P 2015 *Physica C* **512** 42
[26] Campbell A M 2011 *Supercond. Sci. Technol.* **24** 091001
[27] Mikitik G P and Brandt E H 2004 *Phys. Rev. B*. **69** 134521
[28] Philippe M P, Fagnard J F, Kirsch S, Xu Z, Dennis A R, Shi Y H, Cardwell D A, Vanderheyden B and Vanderbemden P 2014 *Physica C* **502** 20
[29] Philippe M P, Ainslie M D, Wéra L, Fagnard J F, Dennis A R, Shi Y H, Cardwell D A, Vanderheyden B and Vanderbemden P 2015 *Supercond. Sci. Technol.* **28** 095008
[30] Egan R, Philippe M, Wera L, Fagnard J F, Vanderheyden B, Dennis A, Shi Y, Cardwell D A and Vanderbemden P 2015 *Rev. Sci. Instrum.* **86** 025107
[31] Koblischka M R, van Dalen A J J and Ravi Kumar G 1996 *J. Supercond.* **9** 143