

Study of thermal effects in bulk RE-BCO superconductors submitted to a variable magnetic field

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Abstract. When bulk RE-BCO superconductors are used as permanent magnets in engineering applications, they are likely to experience transient variations of the applied magnetic field. The resulting vortex motion may cause a significant temperature increase. As a consequence the initial trapped flux is reduced. In the present work, we first focus on the cause of a temperature increase. The temperature distribution within a superconducting finite cylinder subjected to an alternating magnetic field is theoretically predicted. Results are compared to experimental data obtained by two temperature sensors attached to a bulk YBCO pellet. Second, we consider curative methods for reducing the effect of heat flux on the temperature increase. Hall-probe mappings on YBCO samples maintained out of the thermal equilibrium are performed for two different morphologies : a plain single domain and a single domain with a regularly spaced hole array. The drilled single-domain displays a trapped induction which is weakly affected by the local heating while displaying a high trapped field.

1. Introduction

The potential of bulk melt-processed RE-BCO materials to trap large magnetic inductions at 77 K makes them attractive for various engineering applications, including rotating machines or magnetic bearings [1-4]. In such applications, the superconductor – used as a strong permanent magnet – may experience periodic or transient variations of the magnetic field, leading to some vortex motion near the sample edge [4, 5]. The resulting heat dissipation may give rise to a significant temperature increase which, in turn, reduces the initial trapped flux.

In the present work we first consider the temperature distribution within a bulk type-II superconductor subjected to an alternating magnetic field. The temperature distribution predicted with a numerical modeling is compared to the experiment. Next, we investigate means of limiting the temperature rise within the superconductor by increasing its surface/volume ratio. Results obtained on a plain single domain are compared to a single domain containing a regularly spaced hole array.

2. Experiment

2.1. Synthesis process

Bulk melt-processed YBCO single domains were synthesised by a top seeding technique described in ref. [5 ,6]. Single domains containing a regularly spaced hole array were also prepared [7]. The holes (1 mm diameter) are parallel to the c-axis and are arranged in a regular squared pattern (1.5 mm spacing). All samples have a cylindrical geometry (typically 20 mm diameter and 8 mm thickness).

2.2. Thermal measurements

A YBCO bulk sample ($T_c \sim 92$ K) was instrumented with type E thermocouples attached to the top surface. The sample **and the thermocouples are** embedded in epoxy resin (thickness = 5 mm) and immersed in liquid nitrogen ($T = 77$ K). The sample is then submitted to a variable magnetic field parallel to the c-axis. The temperature at the top surface of the sample is recorded using a NI multi-channel acquisition card.

2.3. Magnetic measurements in the presence of a temperature gradient

The principle of the experiment is to carry out a miniature Hall probe mapping of the sample top surface twice. First, the sample is permanently magnetized along the c-axis by field cooling down to $T = 77$ K under 0.4 T; the field is then switched off. After the first mapping, a heat flux is injected inside the sample with a heater attached on the sample lateral surface. When the thermal steady state is reached, a second mapping of the residual induction is carried out while the heat flux is kept constant.

3. Results and discussion

3.1. Study of temperature rise caused by an AC magnetic field

Figure 1 shows the time-dependence of the temperature $T(t)$ measured at two locations of the top surface of a bulk YBCO single domain when an AC magnetic field ($\mu_0 H = 94$ mT, $f = 50$ Hz) is applied parallel to the c-axis. Both temperatures are found to increase quasi-linearly and then exhibit a steady-state regime after approximately 150 s. The temperature reached in the steady state (not shown on fig. 2) is ~ 2 K higher for the central position ($T \sim 90.2$ K) than near the edge ($T \sim 88.2$ K).

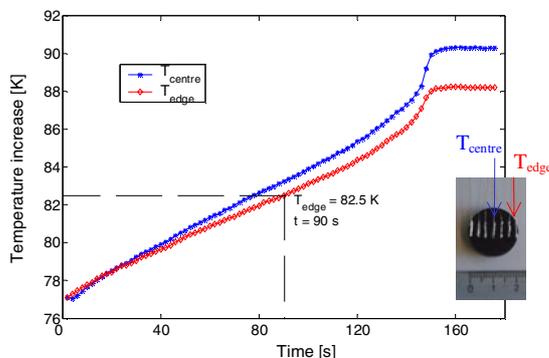


Figure 1 : Temperature measured at the top surface of a cylindrical YBCO single domain subjected to an AC field (94 mT - 50 Hz) ; Inset : location of sensors

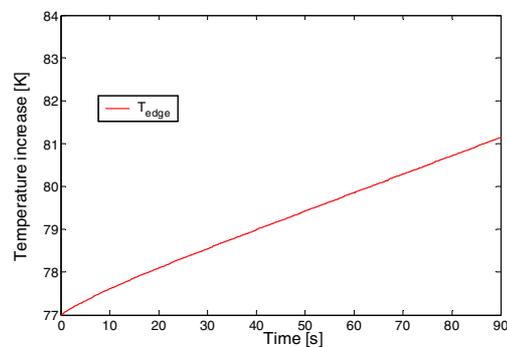


Figure 2 : Temperature on the top surface calculated in a finite type-II superconductor subjected to an AC field (94 mT - 50 Hz)

Such a result is expected since the cooling in the periphery is more efficient than in the centre. The results are in agreement with those obtained recently by Tsukamoto et al. [8] who measured the temperature distribution *after* the application of the external AC magnetic field. The data displayed in figure 1, however, refer to the temperature rise measured *during* the application of the magnetic field.

The results shown in figure 1 can be compared to a modeling based on the a 2D Bean model in a type-II superconducting finite cylinder. The computation of the local electric field gives the distribution of dissipated power and a finite element method is used to obtain the temperature distribution. The results of such a study are shown in figure 2 : the time-dependence of the temperature at the top surface near the sample edge ($r = 9.75$ mm) is plotted for a 94 mT / 50 Hz magnetic field applied parallel to the c -axis. The following parameters were used : temperature independent critical current density $J_c = 8000$ A/cm², thermal conductivity $\kappa = 4$ W/mK. As can be seen from figure 2, a satisfactory agreement is obtained. The agreement fails at higher temperatures because our theoretical model does not take the temperature and field-dependence of J_c into account.

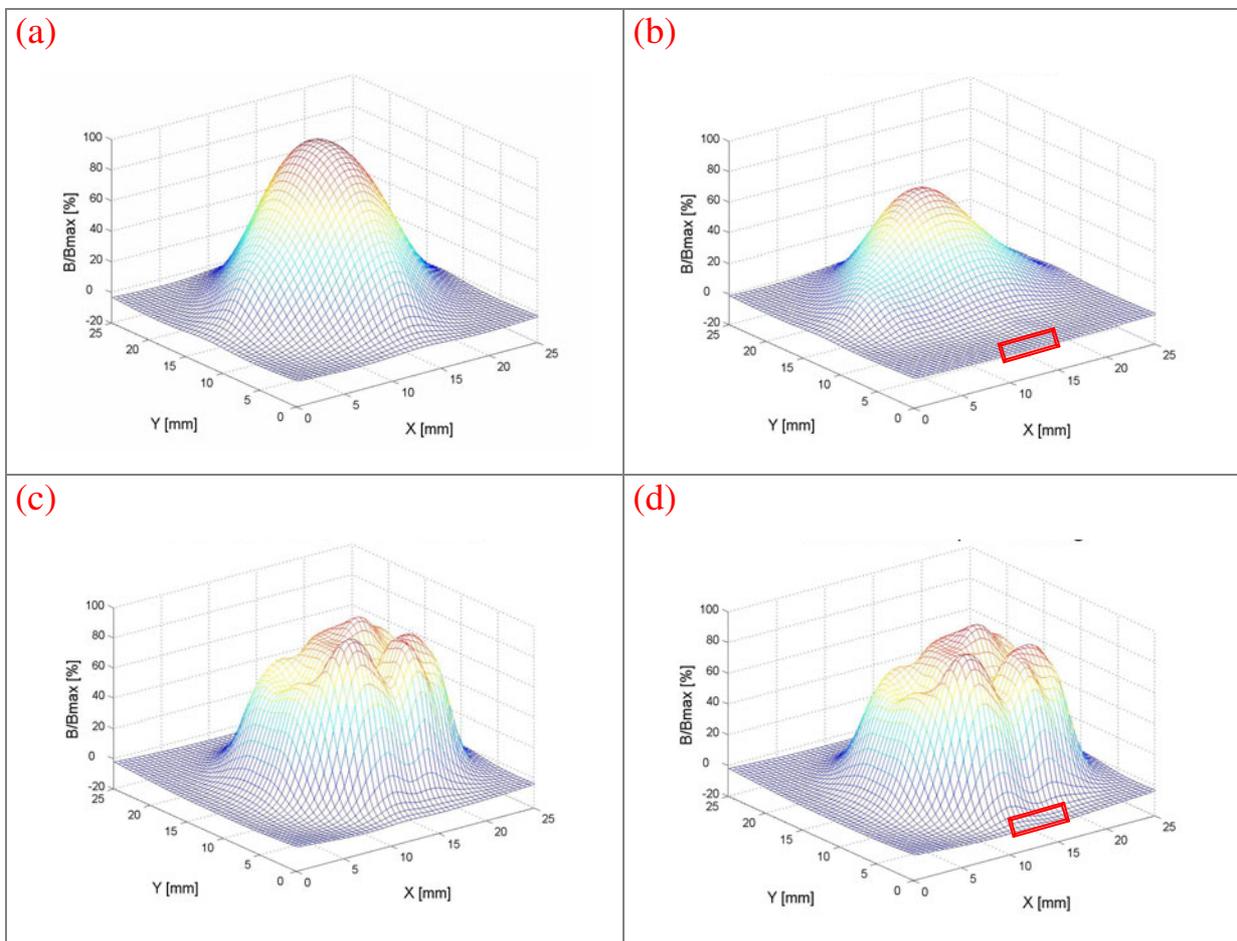


Figure 3 : Left : initial trapped flux recorded 15 min after the magnetization process in order to avoid flux creep effects. Data are normalized with respect to the maximum field B_{max} (a) plain sample ($B_{max} = 141.6$ mT), (c) drilled sample ($B_{max} = 79.2$ mT). Right : residual trapped flux when the heater is activated : (b) plain sample, (d) drilled sample. The heater location is represented by a rectangle.

3.2. Magnetic measurements in the presence of a temperature gradient

Figure 3 shows the trapped flux in the presence (right) or in the absence (left) of a 10 W heat flux injected to the sample from the side. In the case of the plain sample (top), the heater causes a reduction of about 50 % of the average induction. On the contrary, the drilled single domain is found to be much less affected by a local heating while displaying a satisfying trapped flux. In a previous work [5], we have developed a numerical modeling of the temperature distribution in the steady state into a drilled sample in order to obtain design rules. First, the holes should be placed as near as possible from the edge. Second, a hole density of about 10 % is sufficient to provide a sufficient temperature stability [5].

4. Conclusions

Theoretical approach and experimental measurements on bulk YBCO single domains show that a variable magnetic field can induce a significant temperature increase. Therefore it is of importance to facilitate heat draining by increasing the surface exchange with the cryogenic coolant. Hall probe mappings in the presence of a temperature gradient show that samples containing a regularly spaced hole array are an efficient solution as far as temperature stability problems are concerned.

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References

- [1] Campbell A M and Cardwell D A, 1997 *Cryogenics* **37**.
- [2] Yamachi N, Nishikawa T, Tomita M and Murakami M, 2002 *Physica C* **378-381** 377.
- [3] Krabbes G, Fuchs G, Verges P, Diko P, Stöver G and Gruss S, 2002 *Physica C* **378-381** 636.
- [4] Zeisberger M and Gawalek W, 1998 *Mat. Sci. Engineering B* **53** 193.
- [5] Laurent P, Mathieu J P, Mattivi B, Fagnard J F, Meslin S, Noudem J G, Ausloos M, Cloots R and Vanderbemden P, 2005 *Supercond. Sci. Technol.* **18** 1047.
- [6] Mathieu JP, Koutzarova T, Rulmont A, Fagnard J F, Laurent P, Mattivi B, Vanderbemden Ph, Ausloos M and Cloots R, 2005 *Supercond. Sci. Technol.* **18** 136.
- [7] Noudem J G, Meslin S, Harnois C, Chateigner D and Chaud X, 2004 *Supercond. Sci. Technol.* **17** 169.
- [8] Tsukamoto O, Yamagishi K, Ogawa J, Murakami M and Tomita M, 2005 *Journal of Materials Processing Technology* **161** 52.