A numerical study on flux-jump occurrence in MgB_2 bulks

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***Abstract*—Among the superconducting materials, MgB_2 has been proved to be one of the most promising options for the fabrication of magnetic shields. However, thermo-magnetic instabilities can arise in the material because of its low heat capacity and high critical current density. To be able to predict these phenomena, giving insight into the behaviour of a superconducting device, can guide and optimize suitable solutions for shielding applications. In this work, the flux-jump occurrence in MgB_2 disk- and cup-shaped bulks is investigated in axial-field orientation.**

Keywords—magnetic shielding, thermal instabilities, numerical modelling, bulk superconductor

I. Introduction

Due to the low-cost and non-toxic precursors (e.g., not containing rare earth elements), the low weight density, and the long coherence length, MgB_2 is one of the most promising superconducting (SC) materials for bulk applications such as permanent magnets and magnetic shields [1], [2].

However, thermomagnetic instabilities, such as flux jumps, were observed in MgB_2 bulks [3], [4]. It is well known that the occurrence of these instabilities, caused by small temperature fluctuations or by variations of the external magnetic field, can drastically deteriorate the intrinsic capacity of the SC to shield magnetic fields [4]. Relying on suitable simulation tools can be a successful approach to deeply understand this behaviour and optimize the shielding devices [5].

In this work, we applied the numerical procedure based on the magnetic vector-potential (A) formulation described in [6] coupled with a thermal model to predict the flux-jump phenomena inside disk- and cup-shaped MgB_2 bulks when an external field is applied parallel to the sample axis.

II. Modelling

The electro-thermal formulation combines the magnetic vector potential formulation [6] and the heat balance equation. The model was implemented by a finite element calculation using COMSOL Multiphysics® [7] through the AC/DC module coupled with the Heat Transfer module. Moreover, taking advantage of the symmetry of the samples here investigated, we used a 2D axisymmetric approach.

A. Electromagnetic modelling

The electromagnetic behaviour of the MgB_2 bulks was modelled introducing the hyperbolic tangent function proposed in [6] as a smooth approximation of the $E - J$ stepwise behaviour predicted in the critical state model. Hence, the electrical conductivity σ takes the general form:

$$\sigma = \frac{1}{|\mathbf{E}|} J_c(B,T) \cdot tanh\left(\frac{|\mathbf{E}|}{E_0}\right) \tag{1}$$

where E_0 is the threshold electric field taken as 10^{-4} V m^{-1}. The critical current density, J_c, depends on the local magnetic field and temperature through the following general form [8], [9]:

$$J_c = f(T) \cdot exp\left[-\left(\frac{B}{B_0(T)}\right)^{\beta}\right] \tag{2}$$

where

$$\begin{aligned} f(T) &= \alpha[1-(T/T_c)^2]^{3/2} \\ B_0(T) &= b[1-(T/T_c)^2]^{3/2} \end{aligned} \tag{3}$$

In the following calculations, the critical temperature and the fit parameters were assumed equal to $T_c = 39$ K and $\beta = 1.37$, $\alpha = 3.1 \times 10^9$ A m^{-2}, $b = 2$ T as in [9].

B. Thermal modelling

To model the behaviour of temperature field in the superconductor, the following diffusion equation was used:

$$\nabla \cdot (\kappa(T)\nabla T) - C(T) \cdot \rho_m \cdot \frac{\partial T}{\partial t} + Q = 0 \tag{4}$$

where $Q = \mathbf{E} \cdot \mathbf{J}$ is the heat source and $\kappa(T)$, $C(T)$ and $\rho_m = 2590$ kg m^{-3} are the thermal conductivity, specific heat and mass density, respectively. The temperature dependent behaviour of $\kappa(T)$ and $C(T)$ wew included in the model via piecewise cubic interpolations of the experimental data of the sample HIP#38 reported in [10].

The bulks were considered bathed in a generic cryogenic medium and the heat flux density between the superconductor and surrounding medium was described by the formula proposed in [9] as

$$\mathbf{n} \cdot (-\kappa \nabla T) = A(T^{\sigma_A} - T_0^{\sigma_A}) \tag{5}$$

where $\mathbf{n}$ is the unit vector normal to the sample surface, $T_0 = 10$ K is the cryogenic bath temperature and $A = 0.05$ W m^{-2} K$^{-\sigma_A}$ is a fixed empirical constant. σ_A is a dimensionless parameter here set to 4 [9].

III. Numerical Results

First, we investigated the magnetization process of a MgB_2 disk. Starting from a zero-field-cooling condition, an external magnetic field ($\mu_0 H_{app}$) ramping from 0 to 4 T with a rate of 0.05 T/s was applied. In the magnetization curve of the disk, the flux-jumps occur at time frames $t_1 - t_2$ and $t_3 - t_4$ (Fig.1). The insets (a) and (b) show how the external magnetic field abruptly penetrates in the SC after the first flux-jump.

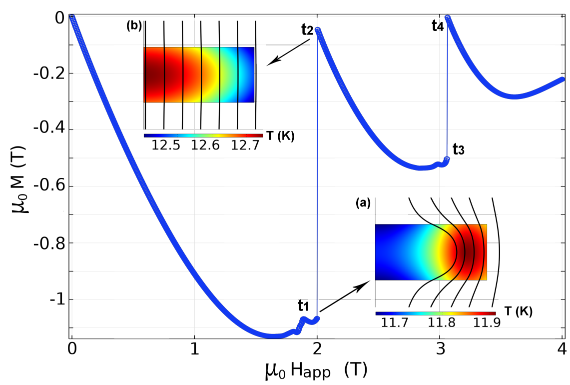

Fig. 1. *Magnetization curve of a MgB_2 disk (radius R=10 mm and height h=5 mm). Insets (a) and (b) show the magnetic flux lines and temperature distributions at time t_1 and t_2, respectively.*

Relying on these results, the same approach was then applied to a cup-shaped MgB_2 bulk. In Fig.2 the magnetization curve of the SC cup is plotted and the occurrence of two flux-jumps at time frames $t_A - t_B$ and $t_C - t_D$ clearly emerges.

Considering the specific application of the MgB_2 cup as a magnetic shield [4], [11] we also calculated the magnetic flux density and the shielding factor along the cup axis. The main panel of Fig.3 shows the z-component of the magnetic flux density (B_z) calculated at five positions z_1-z_5 along the axis of the cup. The shielding factor, defined as $SF = \mu_0 H_{app}/B_z$, was plotted in the inset at the same positions. As can be seen, the shielding performances abruptly worsen when the first flux-jump occurs causing the field penetration. In the innermost position z_1, the SF drops from 200 to 1.

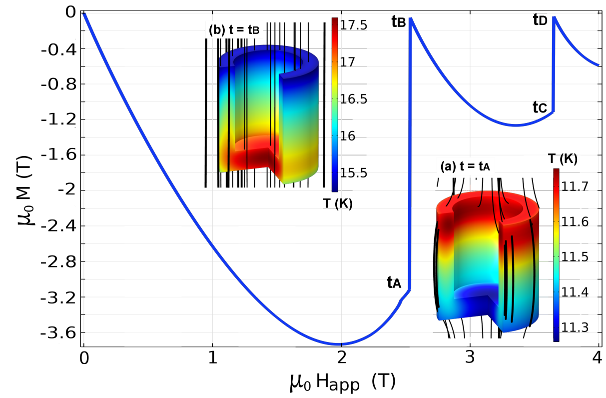

Fig. 2. *Magnetization curve of a MgB_2 cup-shaped bulk. Insets (a) and (b) show magnetic flux line and temperature distributions at times t_A and t_B, respectively. The sizes of the cup are the same as those reported in [4].*

Since the parameters used to model the SC cup behaviour were taken from literature, the computed curves and the experimental one obtained in [4] do not show a quantitative agreement. However, the qualitative behaviour of the curves well reproduces the experimental data.

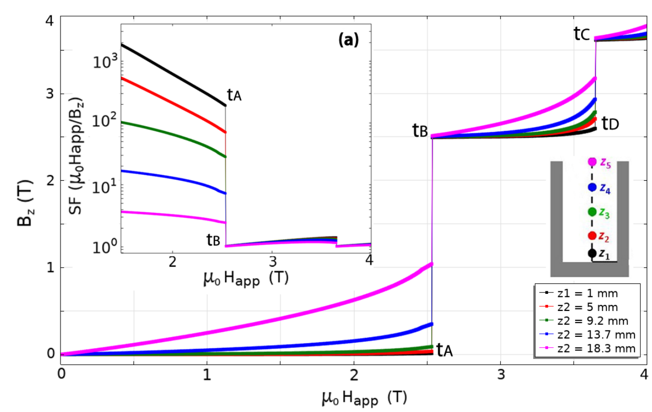

Fig. 3. *Main figure: z-component of the magnetic flux density (B_z) calculated at z_1-z_5 positions (see legend), along the axis of the cup (we assumed (x,y,z) = (0,0,0) as the coordinate of the shield closed extremity). Inset (a): SFs behaviours calculated in the same five positions z_1-z_5.*

This work is a preliminary study on the thermal instabilities in MgB_2 bulks. In a more wide perspective, being able to reproduce this type of phenomena could be a key feature to predict the performances of a SC shield in a more realistic way and optimize its shape and thermalization.

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