Describing and understanding the influence of the inhomogeneity of the applied field on the behaviour of an HTS magnetic screen

Nicolas Rotheudt
Montefiore Research Unit
University of Liège
Liège, Belgium
Nicolas.rotheudt@uliege.be

Jean-François Fagnard
Montefiore Research Unit
University of Liège
Liège, Belgium
JF.Fagnard@uliege.be

Tomas Hlasek
CAN SUPERCONDUCTORS, s.r.o.
Kamenice, Czech Republic
University of Chemistry and Technology
Prague, Czech Republic
tomas.hlasek@can-superconductors.com

Jan Plechacek
CAN SUPERCONDUCTORS, s.r.o.
Kamenice, Czech Republic
jan.plechacek@can-superconductors.com

Philippe Vanderbemden
Montefiore Research Unit
University of Liège
Liège, Belgium
Philippe.Vanderbemden@uliege.be

***Abstract*—In this communication, we explore experimentally and numerically how the behaviour of a high-temperature superconducting (HTS) magnetic screen is influenced by the inhomogeneity of the applied field to which it is subjected. This HTS screen is either a 30 mm-diameter disc-shaped bulk or a combination of this bulk with closed-loop coated conductors. Two methods are followed to vary the inhomogeneity of the DC applied field. First, a unique source coil is employed, with a variable distance between the screen and the coil. Such a study is performed (i) experimentally using a bespoke 3-axis cryogenic Hall probe at 77 K and (ii) numerically with a 2D axisymmetric finite element model solved with the H-ϕ formulation. Second, the magnetic screening properties obtained for different geometries of the source coil are compared numerically. Both methods lead to similar conclusions: HTS magnetic screens are more effective for strongly inhomogeneous fields, as they take advantage of the natural curvature of the flux lines.**

***Keywords*—magnetic screening, magnetic shielding, inhomogeneous field, coated conductors, bulk superconductors, 2D finite element modelling, magnetic measurements.**

I. Introduction

High-amplitude, quasi-static, inhomogeneous stray magnetic fields are produced by a number of engineering applications. These stray fields must be attenuated to protect human operators and sensitive equipment. While this attenuation is conventionally achieved using a ferromagnetic shield or screen, weight-sensitive and high-field applications require other solutions to be found. HTS materials have the ability to shield static magnetic fields very efficiently [1]. In our previous works [2,3], we demonstrated that passive HTS screens combining a bulk superconductor and jointless closed loops made of 2G HTS tapes offer promising prospects to achieve a scalable magnetic screening effect against inhomogeneous applied fields. The goal of the present work is to investigate the impact of this inhomogeneity on the magnetic screening effect.

In the first part of this work, we perform magnetic measurements using a unique coil and by varying the distance between the HTS screen and the coil. In the second part, we use a 2D axisymmetric finite element model [3] to confirm the conclusions of the analysis performed experimentally and compare the screening effects obtained with various coils. In order to quantify the inhomogeneity of the applied field, we rely on (i) l_c the characteristic length over which the field decreases by a certain percentage and (ii) R_c the local radius of curvature of the flux lines. Mathematical definitions are in

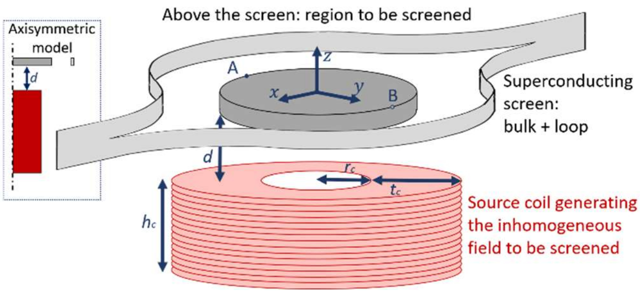

Fig. 1: Schematic illustration of the investigated geometry.

[4]. Strongly inhomogeneous fields are characterised by a small l_c and a small R_c. At a larger distance of a source coil, both l_c and R_c increase, resulting in an applied field that increasingly resembles a homogeneous field.

II. Preliminary Experiments

The typical investigated geometry is shown in Fig. 1. The bulk used is a 30 mm-diameter, 5 mm-thick, single-domain melt-textured (SDMG) GdBCO/Ag disc produced at CAN Superconductors, s.r.o. The closed-loop coated conductors are obtained from 10 mm-wide 2G GdBCO tape from Shanghai Superconductor Technology. Experiments are carried out at 77 K for two screens and three different distances between the screen and the coil: the bulk alone and a hybrid screen combining the bulk with a 60 mm-diameter loop. For each considered distance the current in the source coil is adjusted such that, the DC magnetic field $\mu_0 H_{app}$ in the absence of screen is the same (~35 mT) at the centre of the bottom face of the bulk. A bespoke, 3-axis cryogenic Hall probe [5] is used to map the three components of the flux density B above the superconducting screen.

The main observation is that the screening factor $SF = |\mu_0 H_{app}|/|B|$ increases when the distance between the screen and the coil decreases. For the bulk alone, the maximum SF increases from 7.5 to 14 at 4.7 mm above the bulk when d roughly decreases from 13 mm to 5 mm. Similar observations hold for the hybrid screen.

III. Numerical Study

The 2D axisymmetric FE model [3] is implemented with Gmsh and GetDP, based on the Life-HTS toolkit [6]. The inset in Fig. 1 schematically shows the simplified 2D geometry consisting of the exciting coil, the bulk and an HTS loop (1 mm thick, 5 mm high). The solver uses the H-ϕ formulation. The coil representing at best the experimental source coil is referred to as ‘coil 1’ in the following.

Figure 2 shows the SF predicted at 4.7 mm above the bulk as a function of d, for coil 1. Results are given for two screens similar to the measured screens: the 30 mm-diameter bulk alone and the hybrid screen combining this bulk with a 60 mm-diameter closed loop, as indicated by the schematic drawings. Again, the current is adjusted in the coil such that, for each d, the applied field at the centre of the bottom of the bulk is the same (120 mT). The arrows on the bottom right corner give the corresponding SF values obtained for a homogeneous applied field of 120 mT.

It can be seen that SF decreases with increasing d, being bounded below and tending towards the SF obtained under a homogeneous field. A larger distance d between the coil and the screen implies that the inhomogeneity of the applied field at the location of the screen is weaker (larger l_c and R_c) and tends towards a homogeneous field. This is fully consistent with the previous observation related to the limit of SF for $d \to \infty$. The results from Fig. 2 highlight thus that strongly inhomogeneous fields are more effectively attenuated by HTS magnetic screens.

The influence of the inhomogeneity of the applied field on SF can be explained intuitively based on the physical working principle of hybrid HTS screens. Screening effectively an inhomogeneous applied field consists in confining all the field lines to one side of the screen by forcing them to return to the source coil and opposing all the possible paths reaching the region to be protected. In the case of a hybrid screen, the flux lines are deflected by the bulk exactly where the loops are used optimally to oppose the applied field, i.e. at their vicinity. If the loops are able to generate an opposite field locally comparable to the field to be screened and if the spacing between the bulk and the loops is such that most flux lines are deflected either all around the loops, or back to the source coil, then remarkable scalable screening properties are obtained. Therefore, inhomogeneous fields, where the field lines naturally tend to be strongly curved (small R_c) and tend to return to the source coil over short distances (small l_c), are more effectively screened since the superconductors can take advantage of the natural curvature of the flux lines.

In addition to coil 1, a coil (coil 2) with different dimensions is considered. Figure 3 shows two sets of field lines: in red, the applied field lines and in blue, the lines with the screen made of a bulk and two loops (40 mm and 50 mm diameter, i.e. they are spaced by 5 mm in the simulation). The results are shown for very small applied fields < 2 mT at the location of the screen, hence the superconductors are weakly penetrated. Changing the geometry of the coil affects the shape of the applied field lines: the inhomogeneity is stronger for coil 1 than for coil 2; at the centre of the bottom of the bulk, l_c = 5.2 and 26 mm respectively. The screening properties are observed to vary with the geometry of the coil: more blue flux lines reach the region above the bulk with coil 2 than with coil 1. This observation is consistent with that from Fig. 2, i.e. the natural curvature of the flux lines improves the screening effect. Other simulations show that the SF at 4.7 mm above the centre of the bulk is maximised for loops separated by 7.5 mm for coil 1 (SF = 48.5) and by 12.5 mm for coil 2 (SF = 15.7). This highlights the importance of considering the inhomogeneity of the field to optimise the design of HTS screens, e.g., choosing the best loop diameter.

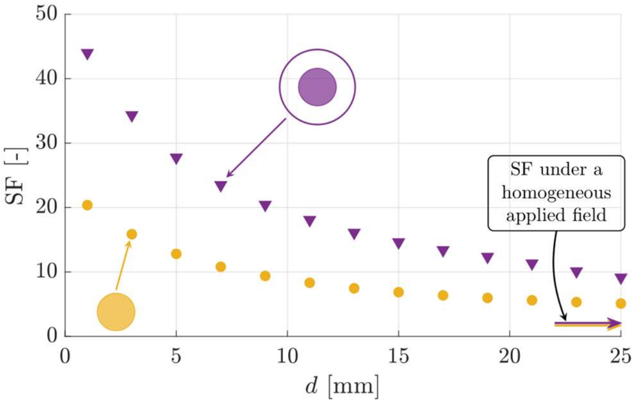

Fig. 2: SF(d) computed at 4.7 mm above the centre of two types of screen, with coil 1. Yellow circles: 30 mm-diameter disc-shaped bulk used alone. Violet triangles: hybrid screen combining this bulk with a 60 mm-diameter closed loop. Applied field ~120 mT at the bottom of the screen for all d. The arrows give the corresponding SF values for a homogeneous field ~120 mT.

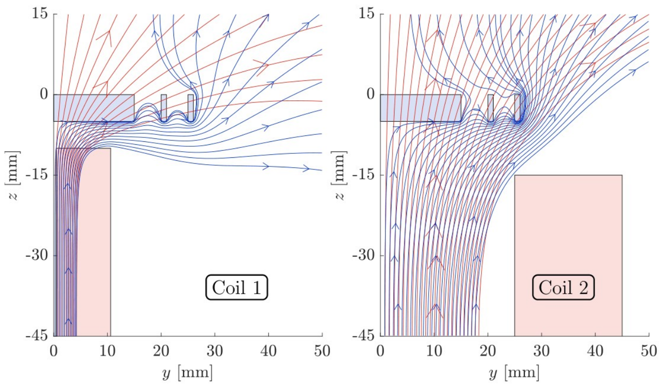

Fig. 3: Numerically computed flux lines for < 2 mT applied on the screen. Red: applied field. Blue: flux density with the screen.

In conclusion, the numerical and experimental results presented in this work describe the notable influence of the inhomogeneity of the applied field on the magnetic screening properties of HTS structures. Strongly inhomogeneous fields are more effectively attenuated, as the natural curvature of the flux lines is beneficial for the screening effect. This result demonstrates that the inhomogeneity of the applied field is an important parameter be considered when designing an HTS screen for practical applications.

Acknowledgment

N. Rotheudt is recipient of a research grant from F.R.S-FNRS. This work is supported by F.R.S.- FNRS grant CDR J.0184.23.

References

[1] L. Gozzelino *et al.* “Screening of magnetic fields by superconducting and hybrid shields with a circular cross-section,” *Supercond. Sci. Technol.*, vol. 35, Art no. 044002, 2022.

[2] N. Rotheudt *et al.* “Improving the screening ability of high-temperature superconductors by combining disk-shaped bulks and closed-loop coated conductors,” *Supercond. Sci. Technol.*, vol. 37, Art no. 065008, 2024.

[3] N. Rotheudt *et al.* “Design rules to scale-up magnetic screens made of bulk superconductors and closed-loop coated conductors: modelling and experiments”, *Supercond. Sci. Technol.*, vol. 38, Art no. 025012, 2025.

[4] N. Rotheudt, M. Fracasso *et al.* “Superconductor-based passive shielding and screening systems,” *Supercond. Sci. Technol.*, vol. 38, Art no. 043002, 2025.

[5] N. Rotheudt *et al.* “Adapting a commercial integrated circuit 3-axis Hall sensor for measurements at low temperatures: Mapping the three components of B in superconducting applications”, *Cryogenics*, vol. 133, Art no. 103693, 2023.

[6] Life-HTS: Liege University Finite Element Models for High Temperature Superconductors. https://www.life-hts.uliege.be