Published in *IEEE Trans. Appl. Supercond.* **23** (2013) 8200504, doi: 10.1109/TASC.2012.2235514.

Magnetic shielding with YBCO coated conductors: influence of the geometry on its performances

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Abstract

A superconducting magnetic shield can be built as a stack of several sections of milled 2G coated conductors. Each section consists of a closed loop where persistent currents can flow and provide a strong attenuation of external dc magnetic fields. The purpose of the present work is to study experimentally several geometries of such magnetic shields made out of $YBa_2Cu_3O_7$ (YBCO) coated conductors from SuperPower. Our aim is to investigate in details the influence of the aspect ratio and the number of layers of the assembly on the magnetic shielding properties. In order to do so, the magnetic shield is subjected to an axial quasi-static ("dc") magnetic field ramped slowly at a fixed sweep rate. A Hall probe is used to measure the local magnetic induction inside the assembly as a function of the applied magnetic induction. Results show that the shielding factor, *SF*, (defined as to ratio between the applied magnetic induction and the magnetic induction measured inside the shield) is improved for increasing aspect ratios of the global coated conductor assembly and that the threshold magnetic induction (defined for *SF* = 10) increases with the number of layers. Using a double layer of 18 sections at T = 77 K, dc magnetic fields up to 56 mT can be shielded by a factor larger than 10. Finally, the effect of an air gap of constant width between coated conductor sections is also characterized.

Index terms

YBCO coated conductors, magnetic shielding.

1. Introduction

Magnetic shielding at low frequency is of technological importance in various devices requiring an ultra-low magnetic background, e.g. superconducting quantum interference devices or cryogenic current comparators. The attenuation of low frequency magnetic field in a given region of space is traditionally realized with ferromagnets such as permalloy or mu-metal, due to their high magnetic permeability. If low temperatures are allowed by the application, however, much more superior performances can potentially be achieved with superconducting materials [1]. Unlike classical ferromagnets, the shielding effect in superconductors is due to macroscopic shielding currents flowing at the outer perimeter of the sample and cancelling out the applied external magnetic field. Today, most shields made of high-temperature superconductors are made out of hollow bulk materials, e.g. $YBa_2Cu_3O_7$ (YBCO) [2], $Bi_2Sr_2CaCu_2O_8$ (Bi-2212) [3]-[4], $Bi_2Sr_2Ca_2Cu_3O_{10}$ (Bi-2223) [3]-[4] or MgB_2 [5]. It is also possible to use shield arrangements made of second generation (2G) YBCO coated conductors, in order to take advantage of their attractive properties: a high critical current density J_C that is weakly field-dependent, a good mechanical resistance and thermal stability thanks to the metallic substrate, and the availability of long samples with a good critical current uniformity.

In order to make a magnetic shield with coated conductor tapes, one has to build a coil where lossless shielding current loops can be generated. An elegant solution, coming from an original idea from Levin *et al.* [6] and Lee *et al.* [7] is to mill a slit in the middle of a coated conductor section in order to form a closed superconducting loop in which persistent currents can flow. These current loops can be stacked along a cylinder to form a magnetic shield (see Figure 1) which is able to shield axial dc magnetic fields [8].

Compared to bulk high temperature superconductors (HTS), a coated conductor shield has an advantage of scalability- –height can be easily changed by changing the number of coated conductor sections and different diameters can be obtained by using different length for the initial coated conductor section. Other advantages are possibly lower cost and availability of large scale manufacturing capacities. Compared to a solenoid type shield [8], the persistent currents can flow in each individual loops without encountering any resistive joints.

Two factors are used to evaluate the magnetic shielding performances: the axial shielding factor at the centre and the threshold induction above which the shielding ceases. The axial shielding factor SF is defined as $SF = B_{app}/B_{in} = \mu_0 H_{app}/B_{in}$ where B_{app} is the applied magnetic induction and H_{app} is the applied magnetic field, and B_{in} is the axial component of the magnetic flux density measured at the centre of the shield. The threshold induction B_{lim} is defined as the applied magnetic field such that the shielding factor equals 10.

Our recent study [8] has demonstrated the ability of a magnetic shield made out with coated conductor loops to shield a dc magnetic field up to 5 mT at 77 K. However, due to the small aspect ratio of the shield, a low shielding factor ($SF < 50$) has been observed. The aim of the present work is to improve significantly the performances of a magnetic shield made out of 2G coated conductors subjected to an axial dc magnetic field modifying their geometrical parameters.

For a HTS tube, the shielding performances can be improved by increasing the tube height and its thickness. In this work, we characterize the shielding performances of structures having increasing number of coated conductor loops along the axis of the shield or having increasing number of layers. Finally, the influence of a constant gap between tapes is also examined in order to evaluate the shielding efficiency reduction.

2. Experiment

2.1. Shield geometry

Similar to the works described in [6]-[8], a slit - 1 mm wide and 126 mm long - is first milled along the centerline of a 12 mm x 154 mm section of coated conductor tape from Superpower. Then, both sides of the cut are extended around a 60 mm cylinder (as shown on Figure 1 (a)) and sections are stacked on top of one another. As shown on Figure 1 (b), the shield dimensions are characterized by the diameter of the tube along which tapes are stacked D = 6 cm and by h, the height which corresponds to the distance between the borders of the extreme loops.

As mentioned above, the effects of three geometrical parameters were studied independently: n, the number of coated conductor loops along the axis of the shield, g, the gap size between each tape, and l, the number of layers. The aspect ratio AR of the shield is defined as $AR(n,g) = h(n,g)/D$ and increases with n and g but is virtually unaffected by l. Finally, the effect of how loops with different superconducting performances are arranged together is also taken into account. In practice indeed, all tape sections do not have the same critical current density J_C. In order to have a smooth and symmetrical distribution of the coated conductors along the axis, we have chosen to place them from highest-J_C to lowest-J_C from the center to extremities of the stack. This procedure requires the critical current flowing in each individual loop to be known before building the shield.

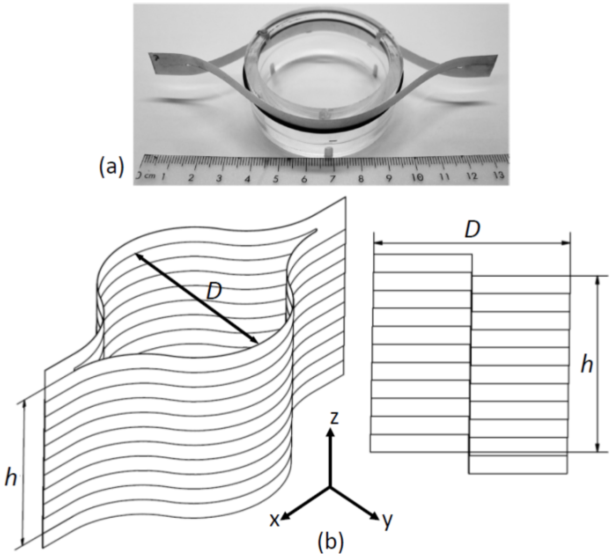

Figure 1. Picture of a single loop. (b) Shield dimensions: diameter D = 60 mm and height h.

Table 1 summarizes the characteristics of the six studied shields. Shields # 1-3 do not contain any air gap (g = 0 mm) and are made of only one layer (l = 1); they differ only by the number of loops n. It should be noted, however, that a small vertical and/or lateral gap can still be present between some sections. Shield # 4 has the same number of loops per layer (n = 18) as the shield # 2 but contains a second layer, consisting of a superposition of two coated conductor sections before placing them on the cylinder. Strictly speaking, shields # 2 and # 4 have not the same *AR* because tapes are not superimposed perfectly. Finally, shields # 5 and # 6 are made with the same coated conductor loops as shield # 2 but the individual loops are separated by air-gap widths equal to 1 mm and 2 mm, respectively.

Table 1. Shield characteristics.

Shield number	1	2	3	4	5	6
Tape number n along the shield axis	11	18	36	18	18	18
Number of layers l	1	1	1	2	1	1
Total tape number within the shield $n_{tot} = n.l$	11	18	36	36	18	18

2.2. Experimental setup

The experimental conditions are the same for all the studied shields. Each shield is zero-field-cooled down to T = 77 K and is axially subjected to a uniform axial quasi-static magnetic field generated with a source coil of 450 mm height and 200 mm diameter. Two coils were used, depending on the required amplitude of the magnetic field. The maximum magnetic inductions they can generate are respectively 45 mT and 200 mT, the later performance being achieved by cooling down the whole coil in a liquid nitrogen bath.

All magnetic shielding measurements were carried out with a magnetic field slowly ramped up at a sweep rate of 0.5 mT/s. The increase of B_{lim} with the sweep rate has already been reported in [3] and [8] so this effect is not discussed in the present paper.

A Hall probe is used to measure the axial component of the local magnetic induction Bin on the axis of the shield and at an elevation that corresponds to half height of the shield.

2.3. Critical current of each conductor section

The axial induction B_Z is measured at the center of the loop by using a Hall probe 2 min after switching off the applied field. The persistent current in each loop can be determined from the expression of the magnetic induction inside a circular loop. Taking into account the eyed shape of the loop, this expression becomes [6]:

$$B_z \approx K \frac{\mu_0 I_C}{D} \tag{1}$$

where $K \approx 0.96$ is a coefficient which depends on the loop geometry ($K = 1$ for a thin circular loop) and $D = 6$ cm is the diameter of the cylindrical holder around which loops are mounted.

The best tape has a maximum critical current of about 156 A. The critical current density J_C can be approximated by $J_C = I_C/(w.d) = 27\ 10^5$ A/cm² where $w = 5.5$ mm is the width of a side of the loop and $d \approx 1$ µm is the thickness of the superconducting layer. This value is close to the average nominal critical current density of 33 10^5 A/cm² measured by SuperPower at 77 K [9].

Among the 48 milled coated conductor sections, 28 % have a critical current below 100 A. In the worst case, a critical current of 8.5 A was measured. The corresponding tape sections were rejected for assembling the shielding structure. This reduction is probably due to the machining process, micro cracks due to bending, defects or stress concentration at the ends of the slit.

3. Results and Discussion

3.1. Influence of number of coated conductors

First we examine the effect of the aspect ratio and the number of layers on the shielding performances. The geometrical properties of the first four shields are reported in Table 1.

Figure 2 shows the axial shielding factor *SF* measured at the center of different shields as a function of the applied magnetic induction B_{app}. The inset shows the measured magnetic induction B_{in} as a function of B_{app}.

For $n = 11$ (#1), we can see that the *SF* is lower than 20 for low B_{app} and the threshold induction B_{lim}, defined for *SF* = 10, is equal to 26.7 mT. For $n = 18$ (#2), the *SF* is between 70 and 80 for low B_{app} and B_{lim} = 36.3 mT. For n = 36 (#3), the *SF* attains 100 for low B_{app} and B_{lim} = 39.7 mT. Finally, for the double layered shield, the *SF* is similar to that of the single layered shield but B_{lim} = 56.8 mT.

The results plotted in Figure 2 give us direct experimental evidence that both the *SF* and the threshold induction B_{lim} globally increase with n and with the aspect ratio of the shield. A major difference, however, can be noticed by comparing how magnetic shielding performances are improved when the total number of sections is doubled from 18 to 36. If the sections are still placed on a single layer (thereby doubling the total height of the shield), the shielding factor at low fields is multiplied roughly by 1.2 and the threshold field is increased by 9%. If the sections are superimposed on two layers, the shielding factor at low fields is virtually unaffected whereas the threshold field increases significantly (multiplication by 1.5). The behaviour at low applied fields can be explained by the fact that, as the height increases, the contribution due to penetration through both open ends is reduced at the centre of the shield. This effect can also be seen in the slope of B_{in} before penetration (inset of Figure 2): the slope decreases with increasing n. It should be also emphasized that the major *SF* improvement occurs when n increases from 11 to 18, whereas between $n = 18$ and $n = 36$, the *SF* improvement is smaller. If n is increased beyond 36 we cannot expect a significant improvement because the *SF* at the centre remains limited by the penetration via the small gaps that can exist between loops or because of a lateral misalignment of loops.

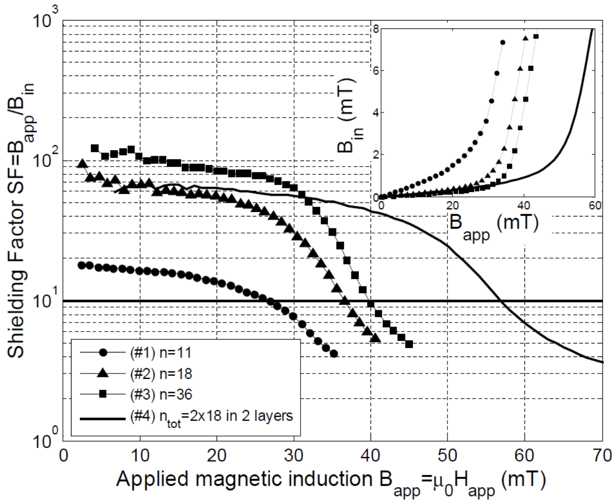

Figure 2. *SF* measured at the centre of different shields as a function of the applied magnetic induction B_{app} with $n = 11$ (circles), $n = 18$ (triangles), $n = 36$ (squares) and two layers of 18 sections (plain). Inset: magnetic induction B_{in} at the centre as a function of B_{app}.

The superposition of the sections in two layers leads to an increase of the threshold induction B_{lim} but does not improve the *SF* at low fields. This can be explained because their *AR* is similar (see Table 1). Note that the coated conductor loops used in the second layer have lower critical currents than the coated conductors used for the first layer. Therefore, we can assume that the B_{lim} could be improved by using better coated conductor loops for the second layer. Finally, it should be mentioned that the tapes of the second layer do not overlap the tape of the first layer, so there are still gaps through which the magnetic field is able to enter in the shield.

This effect of increasing the aspect ratio and/or the thickness of magnetic shield is very similar to that observed on HTS tubes [3], [4] and [10]: the *SF* and B_{lim} both increase with tube height and B_{lim} increases with the thickness since the penetration field is $J_C \cdot d$ for a tube of infinite length (assuming that J_C is field independent), where d is the thickness of the tube.

3.2. Gap size effect

Let us now consider three shields with the same number of coated conductor ($n = 18$) but with three different gap sizes g (0 mm, 1 mm and 2 mm). The geometrical properties of these three shields are reported in Table I.

Figure 3 shows axial *SF* measured at the center of the shield as a function of the applied magnetic induction B_{app}. The inset shows the measured B_{in} as a function of B_{app}. The curve that corresponds to $g = 0$ mm (#2) was already described in the previous section. For $g = 1$ mm (#5), we can see that the *SF* is about 50 for low B_{app} and $B_{lim} = 33.9$ mT. For $g = 2$ mm (#6), the *SF* is about 40 for small B_{app} and $B_{lim} = 30.2$ mT. The *SF* and the threshold induction both decrease with g because the gap between each loop allows the field to penetrate easily inside the shield. The effect of this penetration mode can be observed in the evolution of B_{in} as a function of B_{app}: the slope before penetration increases with the gap size.

From the data displayed in Figure 3, it is somewhat surprising that magnetic inductions up to 30 mT can still be attenuated by a factor larger than 10 even when individual loops are separated by 2 mm air-gaps.

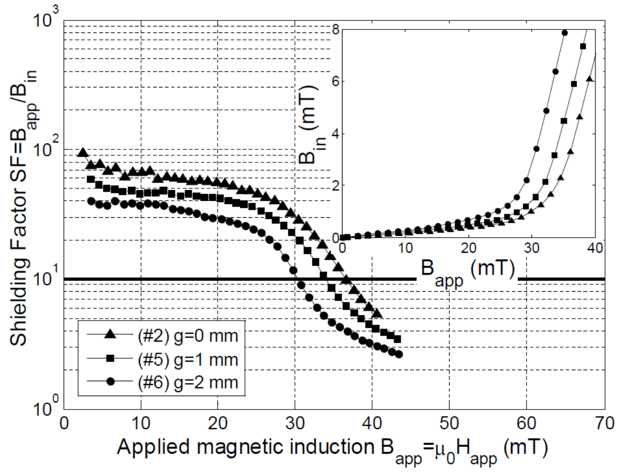

Figure 3. *SF* measured at the centre of the shield as a function of B_{app} for different shields with g = 0 mm (triangles), g = 1 mm (squares), g = 2 mm (circles). Inset: dependence of B_{in} vs. B_{app}.

It should be noticed, however, that the gap is still much smaller than the average diameter of the stack (60 mm), therefore flux leakage is expected to occur mainly near the tapes but has less effect at the centre of the stack. The study about the influence of intentionally inserted air gaps can also be helpful in understanding how 'accidental' gaps between loops may degrade the shielding properties. The results of Figure 3 show the worst case for which a gap exists between each loop. However, if a single gap appears within the shield, we can expect that the reduction of the shielding performances will be smaller. Moreover, we can assume that the performance reduction will be higher if the gap is located at the centre of the shield than at the extremity because the penetration through the gap will compete with the penetration through the open end. This effect has been experimentally and numerically shown in [3] and [11] for a superconducting tube with a horizontal cut in the median plane.

4. Conclusion

We studied how dc magnetic shielding made with 2G coated conductors can be improved by modifying geometrical parameters of the shield. The shielding performances were described by the shielding factor and the threshold induction. First, we have shown experimentally that the shielding factor and the threshold induction can be improved by increasing the number of coated conductor loops along the axis of the shield thereby increasing the aspect ratio. Moreover, the threshold induction can also be improved by adding a second layer as the threshold induction was of 56 mT which is one order of magnitude higher than the threshold magnetic field of 5 mT obtained previously for this kind of structure in [8]. It has also been shown how the *SF* amplitude and the threshold induction are reduced by the presence of a constant gap between coated conductor sections.

In summary, good shielding performances require the highest aspect ratio, one or more layers and as small gap as possible between coated conductor sections. However, beyond the geometry considerations, particular attention must be paid when assembling the shield in order to achieve good performances. The critical current of each tape has to be known and tapes must be carefully selected and placed along the structure to overcome non-uniformities and to insure an overall symmetry. In order to evaluate the volume that can be shielded, the *SF* has to be measured at different locations inside the eyed shape cross section and along the axis.

Acknowledgment

The authors thank the Royal Military Academy for the YBCO tapes and, FNRS and University of Liège for cryofluid, equipment and travel grants.

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