Experimental and Numerical Investigation of Shielding Performance of Superconducting Magnetic Shields Using Coated Conductor Tapes

著者	Y Nagasaki, M Solovyov, F Gomory
journal or publication title	IEEE Transactions on Applied Superconductivity
volume	28
number	4
page range	6601905
year	2018-02-21
URL	http://hdl.handle.net/10097/00127188

doi: 10.1109/TASC.2018.2808374

Experimental and Numerical Investigation of Shielding Performance of Superconducting Magnetic Shields Using Coated Conductor Tapes

Y. Nagasaki, M. Solovyov, and F. Gömöry

***Abstract*— This study investigated the magnetic shielding performance of various configurations of superconducting cylinders based on high temperature superconducting Coated Conductor (CC) tapes. We applied AC magnetic fields with various frequencies and amplitudes to superconducting cylinders with CC tapes. The magnetic shielding performances of the cylinders with a variety of layer number and length of the cylinder were compared. We also performed the numerical simulations, and got the same tendency as the experimental results. We clarified that the shielding factor lineally increases with the layer number of the CC tape. More than five layers of the CC tape wound with the same orientation and angle to cover the gaps of an inner layer achieves 98% attenuation of the magnetic field. However, the simulation and experimental results show that shielding factor is not greatly improved by increasing the length of the cylinder due to the magnetic field penetration from the gaps between each winding of the CC tape. This study demonstrates a good possibility and also the limitation to use CC tapes for the magnetic shielding.**

***Index Terms*— Coated Conductors, High-temperature superconductors, Magnetic shield, ReBCO**

I. Introduction

Superconducting magnetic shields can be used for a wide range of applications to attenuate magnetic fields, e.g. Magnetic Resonance Imaging (MRI), Superconducting QUantum Interference Devices (SQUID), and biological experiments which are susceptible to ambient magnetic fields. The cost and size for the shielding system can be greatly reduced by using a High-Temperature Superconducting (HTS) shield since the shield can be operated at liquid nitrogen temperature (77 K). The size and weight can be further reduced by using commercial Coated-Conductor (CC) tapes instead of superconducting bulk materials, and also a larger shield can be easily fabricated by using a longer length of tapes. However, the shielding property of superconducting cylinders using CC tapes is not the same as that of cylinders using a bulk superconducting material due to the magnetic field penetration from the gaps of each winding of the tape.

A theoretical model for the magnetic shielding performance of semi-infinite type-I superconducting cylinders was proposed by Cabrera B [1]. The shielding efficiency inside of the superconducting tube along the axis was expressed by simple formulas [1]. There has been a lot of studies about the shielding property of bulk HTS tubes [2-11]. Kvitkovic et al investigated the shielding properties of HTS cylinders and sheets made of CC tapes. They measured the dependence of the shielding efficiency on the amplitude, frequency of the magnetic field, and temperature [12-14]. However, the dependence of the shielding performance on the geometry of the cylinder using CC tapes, e.g., length of the cylinder and layer number of the winding of CC tapes, has not been well investigated and modeled. The optimal configuration of the shielding cylinder needs to be clarified to utilize HTS magnetic shields based on CC tapes for shielding applications.

Our research group has tested several configurations of the CC tape arrangement and measured AC losses for the magnetic cloak application [15, 16]. This study investigated the magnetic shielding performances of various configurations of superconducting cylinders using CC tapes on the basis of experiments and numerical simulation. The relationship between the geometry of the HTS shield and the shielding property was clarified to achieve a higher shielding factor for a practical use of the magnetic shield based on CC tapes.

II. Experiments and Numerical Model

A. HTS cylinders

A Rare Earth Barium-Copper-Oxide (ReBCO) Coated-Conductor tape with the width of 12 mm described in Table I was used to fabricate magnetic shielding cylinders for the measurement of the shielding property. The tape was helically wound around a fiberglass tube as shown in Fig. 1. Each layer of the tape was not insulated, wound with the same orientation and angle, and shifted by the half tape width to cover the gaps of an inner layer to remove the anisotropy of the magnetic shielding property [16]. We made three kinds of the HTS cylinders with the various lengths (95 mm, 145 mm, 185 mm) and the same diameter (45 mm) as shown in Table I to investigate the dependence of the magnetic shielding performance of the HTS shield on the aspect ratio of the cylinder.

This work was supported by grant APVV-15-0257 and in part by Japan Society for the Promotion of Science.

Y. Nagasaki, is with GeoCosmo Science and Research Center, NASA Ames Research Park, Moffett Field, CA 94035-0001 USA (e-mail: nagasaki.yoh@gmail.com).

M. Solovyov, F. Gömöry is with Institute of Electrical Engineering, Slovak Academy of Sciences, 84104 Bratislava, Slovakia

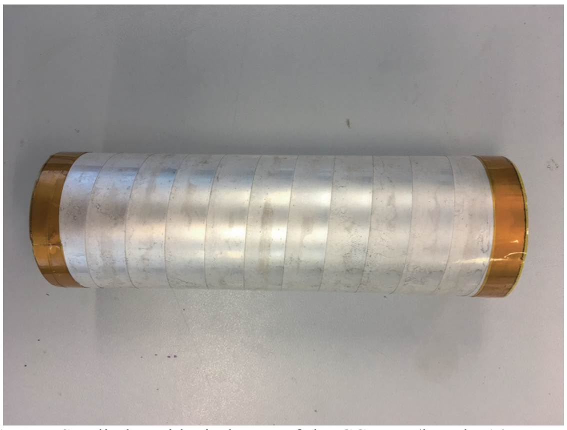

Fig. 1. HTS cylinder with six layers of the CC tape (length: 145 mm, inner diameter: 45 mm).

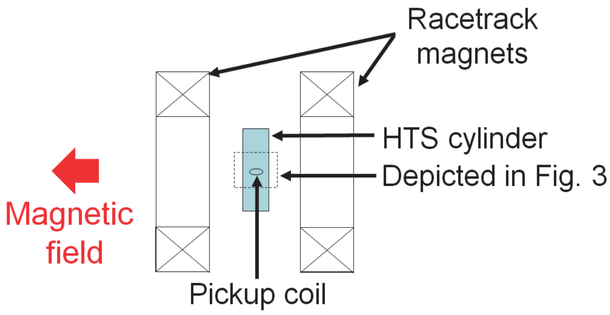

Fig. 2. Experimental setup for the measurement of the magnetic shielding performance of the HTS cylinders.

TABLE I
DESCRIPTION OF THE HTS TAPE AND CYLINDERS USED FOR THE MEASUREMENTS

	Cylinder
CC tape	ReBCO (12 mm width, 0.1 mm thickness, produced by SuperPower)
Critical current of the tape (for electric field criteria E_c = 1.0×10^{-4} V m^{-1})	500 A
n-value	21
Full penetration field of the tape	~40 mT
Number of layers	1- 6 layers
Inner diameter	45 mm
Length	95 mm, 145 mm, 185 mm

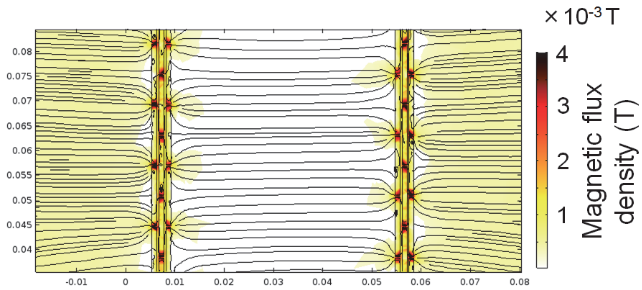

Fig. 3. Distribution of the magnetic flux density around three layers of the HTS cylinder with the length of 145 mm calculated by the developed numerical model (t = 1/4f). A part of the cross section of the HTS cylinder described in Fig. 2 is enlarged. The streamline shows the magnetic flux line. The transverse AC magnetic field (1 mT, 144 Hz) was applied to the HTS cylinder.

B. Measurement Detail

To investigate the magnetic shielding performances of the HTS shields with the CC tape, a transverse AC magnetic field B was applied to the HTS cylinders as

$$B = B_{ap}\sin(2\pi f t) \quad (1)$$

where the frequencies, f, were in the range of 18 - 144 Hz, amplitudes, B_{ap}, were from 1 to 16 mT, and t was time. The magnetic field at the center of the cylinders was measured by three orthogonal pick-up coils. Fig. 2 describes the setup for the experiments. We used a double racetrack magnet to produce the uniform magnetic field along the axis of the cylinder. The magnets and the HTS cylinders were immersed in the liquid nitrogen, and all measurements were performed at 77 K. The shielding factor in this paper is defined by the ratio between the applied field and center field inside of the HTS cylinder as follow,

$$SF \text{ (Shielding Factor)} = B_{ap}/B_{in} \quad (2)$$

where B_{in} denotes the magnetic field amplitude at the center of the HTS cylinder and B_{ap} from (1) denotes the amplitude of the applied field, generated by the racetrack magnets at the same point but without the magnetic shield.

C. Numerical model

We have developed a 3D model of the HTS cylinders based on the CC tape with the AC/DC module in the COMSOL Multiphysics® to compare the simulation results with the experimental ones. Each layer of the tape does not have any contact with adjacent layers, which means we assumed that the layers were insulated in the simulation. The power law was used for the electric field, $\boldsymbol{E}$, and current density, $\boldsymbol{J}$, characteristics of the HTS,

$$\boldsymbol{E}(J) = E_c(\boldsymbol{J}/J_c)^n \quad (3)$$

where E_c is the electric field criteria for the critical current density J_c (same as in Table I). The n-value used for the simulation was 21. J_c was defined by dividing the critical current of the tape (500 A) by the cross sectional area of the SC layer. We assumed the thickness of the CC tape (or SC layer) as 1 mm in the simulation to reduce the calculation cost. For the assumed 1 mm thickness of the SC layer, the value of J_c was 4.2×10^7 A m^{-2}. About 1000 times thicker layer allows us to generate a mesh with a reasonable number of elements for the FEM simulation, and reduce the calculation complexity.

The magnetic field dependence of the critical current density was not used since the variation of the magnetic field in the area where the HTS cylinder placed was less than 10% of the applied

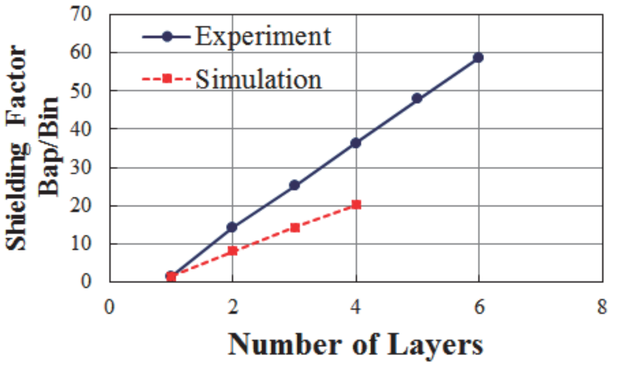

Fig. 4. Relationship between the shielding factor and the layer number of the CC tape of the HTS cylinder with the length of 145 mm. The frequency and amplitude of the applied field were 144 Hz and 1 mT, respectively.

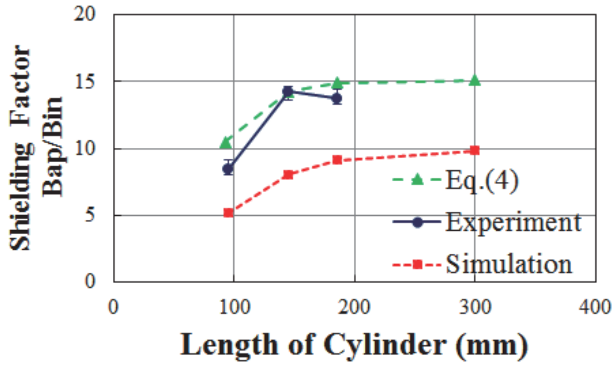

Fig. 5. Relationship between the shielding factor and the length of the HTS cylinder with two layers of the CC tape. The frequency and amplitude of the applied field were 144 Hz and 1 mT, respectively.

magnetic field B_{ap}.

Fig. 3 shows an example of the magnetic flux density distribution around three layers of the HTS cylinder calculated by the developed model. A part of the cross section of the HTS cylinder shown in Fig. 2 is described. As can be seen in Fig. 3, the magnetic flux density is concentrated at the gaps between each layer of the CC tape, and the magnetic flux line is penetrated to inside of the cylinder from the gaps. The developed model show the way of magnetic field penetration to inside of the HTS cylinder from the gaps between the CC tapes. This can be the dominant mechanism of the field penetration for a small number of layers and the magnetic fields much lower than the full penetration field.

III. Results and Discussion

A. Layer number dependence of the shielding factor

We measured and simulated the shielding factor of the various layer numbers of the HTS cylinders with the length of 145 mm to investigate the relationship between the layer number of the cylinder and shielding factor.

Fig. 4 shows the dependence of the shielding factor on the layer number of the CC tape of the HTS cylinder. The frequency and amplitude of the applied magnetic field in this experiment were 144 Hz and 1 mT, respectively. As can be seen in Fig. 4, both of the experimental and simulation results indicate that the shielding factor lineally increases with the layer number. Both results do not show any saturation when the layer number is increased up to six layers. With more than five layers of the CC tape, 98% of the magnetic field is attenuated by the HTS cylinder.

A modeling approach that considers completely insulated CC tape layers predicts the improvement of shielding in proportion to the number of layers as illustrated in Fig. 4. A similar relation was found in the experiments, however the shielding factors measured at 1 mT and 144 Hz were higher. It can be explained by the different geometry of the cylinders in the experiments and the simulation. As mentioned in Section II.C, the thickness of the superconducting layer was assumed as 1 mm in the simulation to reduce the calculation cost. The critical current density was adjusted in the simulation to 1000 times smaller than the real value of the critical current density of the tape to achieve the same value of the tape's critical current. Moreover, the insulated layers were assumed in the simulation, although the layers were not insulted in the experiments. These differences may cause the discrepancy between the experimental and simulation results. To clarify the cause of this discrepancy will be a focus of our study.

B. Cylinder length dependence of the shielding factor

We also measured and simulated the shielding factor of the various lengths of the HTS cylinders to investigate whether the shielding factor is improved by increasing the length of the HTS cylinder based on the CC tape.

Fig. 5 shows the experimental and simulation results of the dependence of the shielding factor on the length of the HTS cylinder. Due to the limitation of the bore size of the racetrack magnets, the maximum length of the cylinder was 185 mm in the experiment. As can be seen in Fig. 5, the shielding factor does not largely increase with the length of the two layer cylinder. The shielding factor does not increase as we expected with the length of the cylinder in the both case of the experiment and simulation.

The magnetic field inside of the HTS cylinder, B_{in}, can be expressed mainly by adding two kinds of the penetration fields as follows,

$$B_{in} = B_{end} + B_{gap} \tag{4}$$

where B_{end} denotes the center field penetrated from the end of the cylinder, and B_{gap} denotes the center field penetrated from the gaps between each winding of the tape. For semi-infinite type-I superconducting cylinders, the penetration field from the end of the cylinder, B_{end}, for the transverse field can be obtained by the following equation [1].

$$B_{end} = B_{ap} e^{-1.84\frac{z}{r}} \tag{5}$$

where z is the distance from an end of the cylinder, r is the inner radius, and the coefficient of the exponential, 1.84, is the first zero of the Bessel function of the first kind. This equation

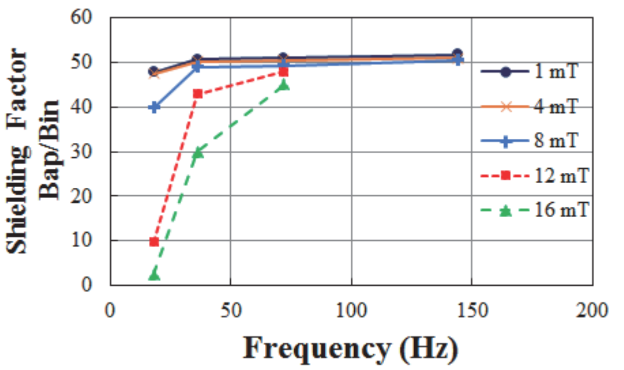

Fig. 6. Experimental result of the dependence of the shielding factor of the HTS cylinder on the frequency and amplitude of the applied magnetic field (cylinder with the length of 145 mm and six layers of the CC tape).

indicates that the shielding factor exponentially increases with the length of the cylinder. The previous studies show that this equation can be also applied to HTS cylinders using bulk materials [2, 3].

We estimated the difference of B_{end} among the different lengths of the cylinder using (5), and the shielding factor for each length of the cylinder from (4). We assumed the constant B_{gap} over the different lengths of the cylinders based on the result of the 145 mm length cylinder. The estimation results of the shielding factor are also shown in Fig. 5 as a dashed line. The estimation of the shielding factor from (4) agrees well with the experimental results, and the shielding factor does not greatly increase by increasing the length of the cylinder. These results imply that the variations of the shielding factor against the length of the cylinder in Fig. 5 can be explained by the difference of B_{end}. B_{end} does not largely affect the shielding factor since B_{end} is much smaller than B_{gap} and $B_{in} \approx B_{gap}$ when the length of the HTS cylinder is longer than around 100 mm.

This study indicates that increasing the layer number of HTS cylinders is effective than increasing the length of the cylinders to improve the magnetic shielding performance of the HTS cylinders using CC tapes. The magnetic field penetration from the gaps between each winding of the tape is dominant than the penetration from the end of the cylinders for the shielding factor.

As shown in Fig. 5, the shielding factors from the simulation results are also smaller than those from the experimental results with a various lengths of the cylinder. In order to check if the discrepancy of the shielding factor between the experiments and simulation could be due to coupling currents through the tapes, we performed measurements for other frequencies and amplitudes.

C. Frequency and amplitude dependence of the shielding factor

AC magnetic fields with various frequencies and amplitudes were applied to the HTS cylinders with the length of 145 mm and six layers of the CC tapes, and the frequency and amplitude dependence of the shielding factor was measured.

The results are described in Fig. 6. As can be seen in Fig 6, the shielding factor decreases as the frequency of the magnetic field decreases or the amplitude of the magnetic field increases. The frequency dependence of the shielding factor shows that the possibility of the screening currents forming larger loops, coupling the non-insulated tapes and layers through galvanic connections on touching surfaces. These coupling currents highly depend on the frequency of the magnetic field due to the normal resistances in the tapes and contact resistance. This may also explain the discrepancy between the simulation (that disregarded the coupling currents) and experiment.

On the other hand, in case of bulk HTS cylinders, the AC frequency dependence of the shielding factor follows the power law of HTS [7]. The effect of the power law can also explain the frequency dependence of the shielding factor from Fig. 6. For the HTS cylinder with the CC tape, the effect of the power law becomes less dominant at a higher frequency since the effect of the magnetic field penetration from the gaps of each winding of the tape is dominant for the shielding factor, although the shielding factor decreases at a lower frequency by following the power law.

The amplitude dependence can be explained by the fact that more magnetic field penetrates through the tapes as the amplitude of the magnetic field increases. The field penetration or the decrement of the shielding factor started from the magnetic field below the full penetration field of the tape shown in Table I. This is because, in the case of the HTS shield based on the CC tapes, the magnetic field is concentrated at the gaps of the tapes as shown in Fig. 3, and the tape's edges experience a larger magnetic field than the applied magnetic field.

IV. Conclusion

We investigated the magnetic shielding performance of several configurations of HTS cylinders based on CC tapes. AC magnetic fields with various frequencies and amplitudes were applied to the HTS cylinders with the CC tapes, and the shielding factors were obtained with changing the layer number and length of the cylinder. We also performed numerical simulations, and compared the simulation results with the experimental ones. We clarified that more than five layers of the CC tape wound with the same orientation and angle to overlap the gaps of an inner layer reduces the magnetic field penetration and achieves 98% attenuation of the magnetic field. Both of the experimental and simulation results show that the shielding factor proportionally increases with the layer number of the CC tape. However, the shielding factor is not greatly improved by increasing the length of the cylinder with two layers due to the magnetic field penetration from the gaps of each winding of the CC tape. We found a discrepancy between the experimental and simulation results in this study. To clarify the cause of the discrepancy is our future study.

References

[1] B. Cabrera, "The use of superconducting shields for generating ultra-low magnetic field regions and several related experiments," Ph.D., Stanford University, Ann Arbor, 1975.

[2] O. G. Symko, W. J. Yeh, D. J. Zheng, and S. Kulkarni, "Magnetic shielding and relaxation characteristics of superconducting YBa2Cu3O7 tubes," *J. Appl. Phys.*, vol. 65, pp. 2142-2144, 1989.

[3] H. Matsuba, A. Yahara, and D. Irisawa, “Magnetic shielding properties of HTc superconductor,” *Supercon. Sci. Technol.,* vol. 5, no. 1S, p. S432, 1992.

[4] F. Pavese, M. Bianco, D. Andreone, R. Cresta, and P. Rellecati, “Magnetic shielding properties of YBa2Cu3O7−x thick films deposited on silver cylinders with the continuous detonation spray technique,” *Physica C: Superconductivity,* vol. 204, no. 1, pp. 1-7, Dec. 1992.

[5] J. Karthikeyan, A. S. Paithankar, R. Prasad, and N. C. Soni, “Magnetic shielding and harmonic generation in high-Tc superconducting tubes,” *Supercon. Sci. Technol.,* vol. 7, no. 12, p. 949, 1994.

[6] S. Denis, M. Dirickx, V. Ph, M. Ausloos, and B. Vanderheyden, “Field penetration into hard type-II superconducting tubes: effects of a cap, a non-superconducting joint, and non-uniform superconducting properties,” *Supercon. Sci. Technol.,* vol. 20, no. 5, p. 418, 2007.

[7] S. Denis, L. Dusoulier, M. Dirickx, V. Ph, R. Cloots, M. Ausloos, and B. Vanderheyden, “Magnetic shielding properties of high-temperature superconducting tubes subjected to axial fields,” *Supercon. Sci. Technol.,* vol. 20, no. 3, p. 192, 2007.

[8] J.-F. Fagnard, S. Denis, G. Lousberg, M. Dirickx, M. Ausloos, B. Vanderheyden, and P. Vanderbemden, “DC and AC Shielding Properties of Bulk High-Tc Superconducting Tubes,” *IEEE Trans. Appl. Supercond.,* vol. 19, no. 3, pp. 2905-2908, Jun, 2009.

[9] J. F. Fagnard, M. Dirickx, M. Ausloos, G. Lousberg, B. Vanderheyden, and V. Ph, “Magnetic shielding properties of high-Tc superconducting hollow cylinders: model combining experimental data for axial and transverse magnetic field configurations,” *Supercon. Sci. Technol.,* vol. 22, no. 10, p. 105002, 2009.

[10] J. F. Fagnard, S. Elschner, J. Bock, M. Dirickx, B. Vanderheyden, and P. Vanderbemden, “Shielding efficiency and E(J) characteristics measured on large melt cast Bi-2212 hollow cylinders in axial magnetic fields,” *Supercon. Sci. Technol.,* vol. 23, no. 9, p. 095012, 2010.

[11] J. F. Fagnard, S. Elschner, A. Hobl, J. Bock, B. Vanderheyden, and P. Vanderbemden, “Magnetic shielding properties of a superconducting hollow cylinder containing slits: modelling and experiment,” *Supercon. Sci. Technol.,* vol. 25, no. 10, p. 104006, 2012.

[12] J. Kvitkovic, S. Pamidi, and J. Voccio, “Shielding AC magnetic fields using commercial YBa2Cu3O7-coated conductor tapes,” *Supercon. Sci. Technol.,* vol. 22, no. 12, p. 125009, 2009.

[13] J. Kvitkovic, P. Patil, S. V. Pamidi, and J. Voccio, “Characterization of 2G Superconductor Magnetic Shields at 40-77 K,” *IEEE Trans. Appl. Supercond.,* vol. 21, no. 3, pp. 1477-1480, 2011.

[14] J. Kvitkovic, S. Patel, and S. Pamidi, “Magnetic Shielding Characteristics of Hybrid High-Temperature Superconductor/Ferromagnetic Material Multilayer Shields,” *IEEE Trans. Appl. Supercond.,* vol. 27, no. 4, 2017, Art. no. 7801113.

[15] M. Solovyov, J. Souc, J. Kovac, F. Gomory, E. Mikulasova, M. Usakova, and E. Usak, “Design of Magnetic Cloak for Experiments in AC Regime,” *IEEE Trans. Appl. Supercond.,* vol. 26, no. 3, 2016, Art. no. 0500206.

[16] M. Solovyov, J. Šouc, F. Gömöry, M. O. Rikel, E. Mikulášová, M. Ušáková, and E. Ušák, “Bulk and CC-Tape Based Superconducting Shields for Magnetic Cloaks,” *IEEE Trans. Appl. Supercond.,* vol. 27, no. 4, 2017, Art. no. 7740032.