Improvement of the Magnetic Shielding Effects by the Superposition of a Multi-Layered Ferromagnetic Cylinder over an HTS Cylinder: Relationship Between the Shielding Effects and the Layer Number of the Ferromagnetic Cylinder

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Abstract. The idealized magnetic shielded vessel can be realized by making use of a high-critical temperature superconductor (HTS). It is difficult for practical applications, however, to fabricate a shielding vessel that has a high value of the maximum shielded magnetic flux density $B_{s0}$. The present authors have improved the value of $B_{s0}$ for the Bi-Pb-Sr-Ca-Cu-O (BPSCCO) cylinder used as the shielding vessel, by the superposition of a four-layered soft-iron cylinder over the BPSCCO cylinder, termed the four-layered superimposed cylinder. The $B_{s0}$ value of $610\times10^{-4}$ T for the four-layered superimposed cylinder, is found to be about 4 times larger than that of a single-BPSCCO cylinder, and is theoretically analyzed by use of a new analysis method. The experimental values of the maximum shielded magnetic flux density $B_{sn}$ of $n$-layered superimposed cylinders are found to agree well with those of the theoretical analysis. Experimental results revealed several characteristics of the magnetic shielding within the $n$-layered superimposed cylinders. Also discussed is the new analysis method for the relationship between the $n$ and $B_{sn}$.

1. Introduction

Magnetic shields are required to reduce any external magnetic noise in very low magnetic measurements, such as biomagnetic measurements using a SQUID magnetometer. The magnetic shielding is customarily done with Mu-metal, an alloy that impedes penetration of a magnetic field to a high degree. However, it is not ideal for shielding magnetic fields with low values and very low frequencies [1]. The high-critical temperature superconductor (HTS) cooled by liquid nitrogen is an ideal material for use as magnetic shielding, due to its property of perfect diamagnetism. It is difficult for practical application, however, to fabricate a shielding vessel that has a high value of the maximum shielded magnetic flux density $B_{s0}$. Accordingly, it is necessary to improve the value of the maximum shielded magnetic flux density for HTS vessels [1]-[3].

In the present research, in order to simplify the theoretical analysis, the evaluation of the magnetic shielding effect is limited to a bulk Bi-Pb-Sr-Ca-Cu-O (BPSCCO) cylinder. It is intended to demonstrate an improved value of $B_{s0}$ by the superposition of a $n$-layered soft-iron cylinder over a BPSCCO cylinder, termed the $n$-layered superimposed cylinder. A new theoretical analysis is discussed and used to interpret the experimental results. The experimental values of the maximum shielded magnetic flux density $B_{sn}$ for the $n$-layered superimposed cylinders were found to agree well
Table 1. Properties of the BPSCCO and soft-iron cylinders.

| Cylinder       | Inner radius \( r_{in} \) (mm) | Wall thickness \( t \) (mm) | Length \( l \) (mm) | Magnetic shielding factor \( G_n \) | Maximum shielded magnetic flux density \( B_n \) (\( \times 10^{-4} \) T) |
|----------------|---------------------------------|-----------------------------|-------------------|-------------------------------|----------------------------------|
| BPSCCO         | 13.1                            | 2.2                         | 142               | -                             | -                                |
| 1st soft-iron  | 17.5                            | 1.6                         | 180               | \( G_1=1.65 \)                | \( B_{s1}=244 \)                  |
| 2nd soft-iron  | 19.8                            | 1.6                         | 180               | \( G_2=1.41 \)                | \( B_{s2}=344 \)                  |
| 3rd soft-iron  | 22.7                            | 1.6                         | 180               | \( G_3=1.34 \)                | \( B_{s3}=461 \)                  |
| 4th soft-iron  | 28.7                            | 1.6                         | 180               | \( G_4=1.45 \)                | \( B_{s4}=668 \)                  |

with those of the theoretical analysis.

The present paper demonstrates the effects of \( B_{sn} \) on, of \( B_{in} \) on, of \( B_{ex} \), of the magnetic noise power (NP) of the \( B_{in} \) with and without a \( B_{ex} \) on, of \( B_{sn} \) on the axial direction \( z \) within the \( n \)-layered superimposed cylinder, and of \( B_{in} \) on the axial direction \( z \). Here, the \( B_{sn} \) is the magnetic flux density within the superimposed cylinder under a constant application of \( B_{ex} \) having values less than that of \( B_{sn} \), and is measured by use of an HTS dc-SQUID magnetometer. In addition, a discussion is conducted on the new analysis method for the relationship between the \( n \) and \( B_{sn} \).

2. Experimental procedure

The four-layered superimposed cylinder is constructed by the superposition of a four-layered commercial soft-iron cylinder over a commercial BPSCCO cylinder, in a coaxial configuration. Table 1 lists the dimensions of the inner radius \( r_{in} \), wall thickness \( t \), and length \( l \), of the BPSCCO and soft-iron cylinders. The soft-iron cylinders are degaussed by ac and dc magnetic fields under a temperature of 77.4 K, prior to carrying out the measurements. The outer surface of the BPSCCO cylinder is wrapped with several turns of fluoroplastic tape, using the troidal winding method, for the purpose of avoiding any sudden temperature change. No significant changes in the characteristics of the degree of magnetic shielding were observed when the BPSCCO cylinder was exposed to about 600 cycles of temperatures between room temperature (300 K) and the boiling point of liquid nitrogen (77.4 K).

The magnetic shielding effects are evaluated with the BPSCCO and \( n \)-layered superimposed cylinders placed in a homogeneous dc magnetic flux density \( B_{ex} \), applied parallel to the axial direction of the cylinders. The magnetic shielding effects of all cylinders are measured with the use of a gaussmeter (Lakeshore, 450) for values of \( B_{ex} \) greater than that of \( B_{sn} \). The dependences of \( B_{in} \) on applied \( B_{ex} \) values less than that of \( B_{sn} \), and of the magnetic NP are measured by use of an HTS dc-SQUID magnetometer (Conductus, iMC-303), and a spectrum analyzer (Agilent, 35670A), respectively, such as reported in Ref. [2].

3. Results and discussion

3.1. Result of \( B_{sn} \) as function of \( n \)

The maximum shielded magnetic flux density \( B_{s1} \) in the center of the one-layered superimposed cylinder, that is, the superposition of a one-layered soft-iron cylinder over a BPSCCO cylinder, can be written following Ref. [4] for the case in which the end effects of the ferromagnetic cylinder are neglected, as

\[
B_{s1} = B_{s0} \left[ 1 + 4N \left( 1 + \frac{\mu_s}{4} \left( 1 - \frac{r_{in}^2}{r_{out}^2} \right) \right) \right] = B_{s0} G_1.
\]

Here, \( B_{s0} \) is the maximum shielded magnetic flux density for the single-superconducting BPSCCO cylinder, \( N \) the demagnetizing factor represented by the axis ratio \( (\rho=l/2r_{out}) \) of the ellipsoid, \( \mu_s \) relative permeability such as shown in Ref. [4], \( l \) the length, \( r_{in} \) and \( r_{out} \) are the inner and outer radii of the ferromagnetic cylinder, and \( G_1 \) the combination of the bracketed terms in Eq. (1). In addition, it is
assumed that the persistent current flow in the surface of the superconducting cylinder in the magnetic flux density also exists in the air gap between the BPSCCO and soft-iron cylinders. When the $G_2$, $G_3$, and $G_4$ are denoted as the magnetic shielding factors of the second-, third-, and fourth-ferromagnetic cylinders, the maximum shielded magnetic flux density $B_{s4}$ of the four-layered superimposed cylinder can be expressed as

$$B_{s4} = B_{s0} G_1 G_2 G_3 G_4.$$  \hspace{1cm} (2)

Theoretical values of the $G_n$ and $B_{sn}$ are also listed in Table 1.

Fig. 1 shows the experimental measured values (solid circles) and theoretical values (open circles) as a function of the layer number $n$ for the superimposed cylinder at 77.4 K. The theoretical values are obtained by use of Eq. (2). As shown in this figure, the experimental values agree well with theoretical values. The $B_{s4}$ value of $610 \times 10^{-4}$ T for the four-layered superimposed cylinder, is found to be about 4 times larger than that of the single-BPSCCO cylinder. The results lead to an important criterion for use in the design of a highly effective magnetic shielding vessel having high reliability.

### 3.2. Results of various magnetic effects

The results shown in Fig. 2 denote the values of the magnetic flux density $B_{in}$ within the $n$-layered superimposed cylinders as a function of the layer number $n$ at 77.4 K. Solid and open squares denote the results of measurements with and without a $B_{ex}$ of $120 \times 10^{-4}$ T, respectively. The value of $B_{in}$ into BPSCCO cylinder, in general, is dominated by the vortex state with the increase of magnetic field on the cylinder surface. Therefore, it can be seen that the values of $B_{in}$ for the two-, three-, and four-layered superimposed cylinders are almost the same as the value of $B_{in}$ for the single-BPSCCO cylinder in the absence of a $B_{ex}$. Magnetic noise power $NP$ as a function of $n$ are also conducted with and without a $B_{ex}$ of $120 \times 10^{-4}$ T. These results exhibited similar tendencies such as in Fig. 2 (not shown). That is, the values of magnetic noise power $NP$ with and without the $B_{ex}$ of $120 \times 10^{-4}$ T for the single-BPSCCO cylinder are found as approximately $6 \times 10^{-4}$ $(\Phi_0/\text{Hz})^{1/2}$ and $2 \times 10^{-6} \Phi_0/\text{Hz}^{1/2}$ under a frequency of 5 kHz, respectively. The values of magnetic NP in the absence of a magnetic field ($B_{ex}=0$) is, furthermore, maintained at an approximately constant state versus the $n$, and are almost the same as the values for the two-, three-, and four-layered superimposed cylinders. These results exhibit important criteria for evaluating a vessel used in the application of reliable magnetic shielding.

The typical distribution characteristics of $B_{in}$ along the axial direction $z$ of the BPSCCO cylinder are displayed in Fig. 3. The curves (a), (b), and (c) represent the single-BPSCCO (open circles), one-layered superimposed cylinder (solid circles), and four-layered superimposed cylinder (open squares), respectively, at a temperature of 77.4 K. The regions of constant $B_{sn}$ for the cylinders are within approximately ±50 mm of the center of the cylinders (location of the Hall sensor).

![Figure 1](image1.png)  
**Figure 1.** Values of the $B_{sn}$ as a function of the number of layers $n$ of the superimposed cylinder at 77.4 K. The solid and open circles are the experimental and theoretical values, respectively.

![Figure 2](image2.png)  
**Figure 2.** Characteristics of $B_{in}$, with and without a $B_{ex}$ of $120 \times 10^{-4}$ T, as a function of the $n$ of the superimposed cylinder. Solid and open squares are the values of $B_{in}$ for with and without the $B_{ex}$, respectively.
Figure 3. Distribution of the values of $B_{in}$ along the axial direction $z$ of the superimposed cylinder at 77.4 K. Curves (a), (b), and (c) represent the single-BPSCCO (open circles), one-layered superimposed cylinder (solid circles), and four-layered superimposed cylinder (open squares), respectively. The value of $z=0$ denotes the center of the cylinder.

The plotted points in Fig. 4 denote the values of $B_{in}$ along the axial direction $z$ of the $n$-layered superimposed cylinders under a constant condition of a $B_{ex}$ of 120x10^{-4} T, at 77.4 K. The curves (a), (b), and (c) represent the single-BPSCCO (open circles), one-layered superimposed cylinder (solid circles), and four-layered superimposed cylinder (open squares), respectively. The results for the two-, three-, and four-layered superimposed cylinders are almost the same as the characteristics of the four-layered superimposed cylinder (not shown). Furthermore, it is found that the values of $B_{in}$ at the centers of the two-, three-, and four-layered superimposed cylinders are almost the same as the value of $B_{in}$ (approximately 2x10^{-12} T) at center of the single-BPSCCO cylinder in the absence of $B_{ex}$, such as was shown in Refs. [3] and [5].

4. Conclusion
The present research has examined a new analysis method for the maximum shielded magnetic flux density for a multi-layered superimposed cylinder. The measured results were shown to agree well with those of the theoretical analysis for the $n$-layered superimposed cylinder, such as shown in Fig. 1. The value of the maximum shielded magnetic flux density $B_{sn}$ (610x10^{-4} T) for the four-layered superimposed cylinder, was found to be about 4 times greater than that of single-BPSCCO cylinder.

By measuring the values of magnetic flux density $B_{in}$ within the multi-layered superimposed cylinders along the axial direction $z$ of the cylinder, under a constant condition of an applied excitation magnetic flux density $B_{ex}$, it was found that the values of $B_{in}$ at the centers for the two-, three-, and four-layered superimposed cylinders were almost the same as the value of $B_{in}$ at the center of the single-BPSCCO cylinder without a $B_{ex}$. These results lead to an important criterion for use in the design of a highly effective magnetic shielding vessel having high reliability.

References
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