Effect of Discontinuities and Penetrations on the Shielding Efficacy of High Temperature Superconducting Magnetic Shields

R Hatwar\textsuperscript{1,2}, J Kvitkovic\textsuperscript{1}, C Herman\textsuperscript{2}, S Pamidi\textsuperscript{1}

\textsuperscript{1} Center for Advanced Power Systems, Florida State University, Tallahassee, Florida 32310 USA
\textsuperscript{2} Heat Transfer Lab, Mechanical Engineering Department, Johns Hopkins University, Baltimore, Maryland 21218 USA

E-mail: rajeev.hatwar@jhu.edu

Abstract. High Temperature Superconducting (HTS) materials have been demonstrated to be suitable for applications in shielding of both DC and AC magnetic fields. Magnetic shielding is required for protecting sensitive instrumentation from external magnetic fields and for preventing the stray magnetic fields produced by high power density equipment from affecting neighbouring devices. HTS shields have high current densities at relatively high operating temperatures (40-77 K) and can be easily fabricated using commercial HTS conductor. High current densities in HTS materials allow design and fabrication of magnetic shields that are lighter and can be incorporated into the body and skin of high power density devices. HTS shields are particularly attractive for HTS devices because a single cryogenic system can be used for cooling the device and the associated shield. Typical power devices need penetrations for power and signal cabling and the penetrations create discontinuities in HTS shields. Hence it is important to assess the effect of the necessary discontinuities on the efficacy of the shields and the design modifications necessary to accommodate the penetrations.

1. Introduction
Sensitive electronic equipment such as SQUIDS in magneto-encephalography [1, 2] and other medical applications require a high level of magnetic shielding to protect them from spurious magnetic fields. Further, devices that generate strong magnetic fields also need to be shielded in order to contain their magnetic fields and ensure proper functioning of other instruments in their vicinity. Conducting materials can be used for AC magnetic shielding applications, but for frequencies lower than 1 kHz ferromagnetic materials, such as mu-metal, are normally used. High temperature superconducting (HTS) materials are usually more efficient in shielding than ferromagnetic materials [3]. HTS materials such as YBa\textsubscript{2}Cu\textsubscript{3}O\textsubscript{7} (YBCO) have been demonstrated to be suitable for shielding both for DC and AC magnetic fields [4, 5]. Second generation (2G) HTS have been successfully developed on a commercial level with excellent superconducting and mechanical properties. Long lengths of 2G HTS are being produced at various widths up to 45 mm [6].

Various studies have been done in the past on magnetic shields made of superconducting bulk material and tapes. Kvitkovic et. al. have studied the effect of the geometry, operating temperature, and interlayer separation on magnetic shielding efficacy of shields made of 2G HTS [7-11]. Fabrication of large practical shields requires many sections of HTS and magnetic shields needed for
large high power density machines will need to allow access to power feedthroughs and sensor wiring. Aging and mechanical stresses will also lead to spots of degraded superconducting properties [12, 13]. The effect of different forms of discontinuities have been studied in the past. Denis et. al. studied the shielding properties of a polycrystalline Bi-2223 HTS hollow tubes under axial field [14]. The effect of a cap on the end of the tube and the effect of a hole in the cap was studied in another paper [15]. They further analysed the effect of non-superconducting joints on shielding efficacy[15]. Fagnard et. al. analysed the effect of slits in the superconducting bulk materials under DC magnetic field [16].

So far the effects of discontinuities and penetrations, in two parallel rectangular superconducting HTS sheets with hole, on their shielding performance in AC magnetic field have not been studied. Therefore it is important to quantify the effect of discontinuities on shielding efficacy of HTS magnetic shields and examine potential solutions to mitigate the negative effects of the penetrations and discontinuities.

The present work focuses on understanding the effect of a circular hole on the magnetic shielding efficacy of a 2G HTS shield. This paper presents the results of experimental studies of the shielding factor at variable amplitudes and frequencies of an external magnetic field on the shield with and without an opening, and a simple method to mitigate the negative effects of an opening.

2. Experimental

A helical copper magnet [17] was used to generate a transverse external AC magnetic field. Magnetic shields were kept in a uniform AC magnetic field, which was perpendicular to the surface of the shields. The external magnetic field, \( B_{\text{ext}} \), was calculated based on the current supplied to the magnet and the previously measured magnet constant. The internal magnetic field, \( B_{\text{int}} \), was measured using a calibrated Hall Probe placed inside the magnetic shield, at mid distance between two parallel rectangular plates and at the centre of the rectangular plates as shown in Figure 1.

The dimensions of the rectangular plates are 60 mm × 100 mm and the distance between the two parallel sheets is 38 mm. The support structure for the magnetic shield is made of G-10 plates. Three layers of YBCO tapes are attached onto the G-10 plates using cryogenic Kapton adhesive tape. Each layer consists of three pieces of 45 mm wide 2G HTS superconducting tape, manufactured by
American Superconductor Corporation [6]. Holes were drilled at the centre of the shield, at the same height as the Hall probe Figure 1. The size of the hole was varied with diameters of 1 mm, 3 mm, 6 mm, and 12 mm to study the effect of the size of discontinuities and penetrations on the shielding effect. A 45 mm × 45 mm section of the HTS tape is placed on top of the 12 mm hole to mask the opening, with a G-10 fiberglass piece in between them. The distance between the mask and the shield was varied between 2 mm and 4 mm, for the two configurations shown in Figure 2.

The shielding factor, \( SF \), is a measure of the effectiveness of the magnetic shield and it is expressed as:

\[
SF (%) = 100 \times \frac{B_{\text{ext}} - B_{\text{int}}}{B_{\text{ext}}}
\]

The frequency of the AC magnetic field was varied from 20 Hz to 400 Hz. The experimental setup was maintained at 77 K by immersing in a liquid nitrogen bath. All magnetic field magnitudes are expressed in rms values. Details of the experimental setup are described elsewhere [11].

3. Results and discussion

The variation of shielding factor of the shield without any opening with \( B_{\text{ext}} \) for different frequencies is shown in Figure 3. It can be seen that for lower \( B_{\text{ext}} \), the shielding factor increases with increasing frequency. The shielding factor decreases as the \( B_{\text{ext}} \) increases. The shielding factor at 20 Hz goes down from 44 % to 1.5 % as the \( B_{\text{ext}} \) increases from 2.5 mT to 63 mT. A similar trend is observed for other frequencies. This can be explained by the fact that the critical current, \( I_c \), decreases with increasing \( B_{\text{ext}} \) which leads to a lower shielding factor for higher \( B_{\text{ext}} \). So for high \( B_{\text{ext}} \), the shielding factor for higher frequency is lower. The shielding factor at 31.5 mT for various frequencies is in the range of 4 to 7%.

![Figure 3. Variation of shielding factor with external magnetic field for 3 layer shield with no holes.](image)

Figure 4 shows the variation in the shielding factor with \( B_{\text{ext}} \) at 20 Hz for different sizes of holes. Similar to the case of a shield with no opening, the shielding factor for the shield with a hole decreases with increasing \( B_{\text{ext}} \). Further, it can be seen that the shielding factor decreases with increasing hole size. For \( B_{\text{ext}} \) of 2.5 mT, the shielding factor is 44 % with no hole and 37.5 %, 25.5 % and 22 % for 1 mm, 6 mm and 12 mm hole size, respectively. The effect of hole size gradually diminishes as \( B_{\text{ext}} \) increases. There is a decrease of shielding factor from 10.7 % to 4.8 % as the hole size increases from no hole to 12 mm hole at 21 mT. At 63 mT this reduction in shielding factor is from 1.5 % to 0.03 %. A similar trend is observed for 400 Hz as shown in Figure 5. The frequency dependence of the shielding factor at different applied magnetic field amplitudes for different hole sizes is depicted in

![Figure 5. Frequency dependence of shielding factor at different applied magnetic field amplitudes for different hole sizes.](image)
Figures 6 and 7. It can be seen that at lower $B_{ext}$, the dependence of shielding factor on frequency is high and as $B_{ext}$ increases the effect of frequency diminishes to a small value.

**Figure 4.** Variation of shielding factor with external magnetic field at 20 Hz for different sizes of holes.

**Figure 5.** Variation of shielding factor with external magnetic field at 400 Hz for different sizes of holes.
In order to assess ways to mitigate the effect of the hole, a piece of superconducting tape of smaller dimension (45 x 45 mm²) was used as a mask for the opening. The mask was placed at a distance of 2 mm or 4 mm in front of the 12 mm hole. The effect of the mask layer on the shielding factor at 20 Hz is shown in Figure 8. Both configurations were able to successfully compensate for the 12 mm hole. The shielding factor at 10.5 mT increased from 8.14 % to 27.48 % with the addition of the mask at a distance of 4 mm. This was higher than 22 %, the shielding factor obtained with a sheet without any hole. When the mask was placed at 2 mm the shielding factor further increased to 35%. So the mask
not only compensated for the effect of the hole, but also enhanced the shielding. Similar behaviour is observed at 400 Hz as shown in Figure 9. Figures 10 and 11 show the effect of the mask layer, covering the 12 mm hole, on the shielding factor at different $B_{\text{ext}}$ for frequencies ranging from 20 to 400 Hz. It can be seen that at lower $B_{\text{ext}}$ (3.2 mT), although the shielding factor improves with the mask, it is unable to compensate fully. Whereas for $B_{\text{ext}} > 7$ mT the shielding factors recover completely with the use of the mask and are above the curve representing a sheet without any hole.

Figure 8. Effect of the mask placed at a distance of 2 mm and 4 mm from the 12 mm hole at 20 Hz.

Figure 9. Effect of the mask placed at a distance of 2 mm and 4 mm from the 12 mm hole at 400 Hz.

4. Conclusion
The effect of discontinuities, such as penetrations necessary for pipes and cables, in superconducting magnetic shields fabricated from 2G HTS tapes on the shielding efficacy is studied with the goal finding ways to mitigate the negative effects. It is shown that the decrease in the shielding factor caused by a penetration can be mitigated using a superconducting mask to cover the hole applied at certain distance.
The shielding factor showed a strong dependence on the magnitude and frequency of the external magnetic field. The shielding factor decreases with increasing external magnetic field and increases with increasing frequency. The discontinuity in the superconducting shield caused by a hole leads to a drop in shielding factor and the extent of the drop increases with increasing hole size. A superconducting mask is shown to mitigate the negative effect and provides a simple method to manage the need for access to the magnetically shielded space for electrical and signal cables and other piping. Further work is needed to optimize the dimension and location of the mask layer to enable fabrication of practical superconducting shields for large volumes that require penetrations.
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