

# Characterization of 2G Superconductor Magnetic Shields at 40–77 K

Jozef Kvitkovic, Parikshit Patil, Sastry V. Pamidi and John Voccio

**Abstract**—Magnetic shielding properties of second generation (2G)  $\text{YBa}_2\text{Cu}_3\text{O}_7$  superconducting tape were characterized in the temperature range of 40-77 K. Description of the apparatus that enabled variable temperature shielding property measurements is presented. Temperature stability of  $\pm 1$  K was achieved using a combination of conductive thermal anchor of the shields to the cryocooler cold head and helium gas environment. Lower temperatures resulted in significant enhancement in shielding properties. Shielding factors of up to 95% were achieved for both DC and AC magnetic fields by using shields consisting of multiple layers of 2G tape in sheet and coil configurations. Effect of frequency, temperature and number of layers on the shielding efficacy is presented.

**Index Terms**—AC magnetic field, Hall probe, magnetic shielding, shielding factor, variable temperature measurements, 2G coil, 2G sheet,  $\text{YBa}_2\text{Cu}_3\text{O}_7$  superconducting tape.

## I. INTRODUCTION

MAGNETIC field sensitive experiments require shielding of the instrumentation from external magnetic fields to minimize noise from background magnetic fields. Likewise electrical machines generating strong magnetic fields need to be shielded to protect surroundings from disruptive magnetic fields. Magnetic shields prepared from high temperature superconducting materials can be smaller in size and lower in weight than shields made of ferromagnetic metals because of their higher saturation induction in constant magnetic fields. Second Generation superconducting tapes based on  $\text{YBa}_2\text{Cu}_3\text{O}_7$  (YBCO) are a promising candidate for shielding applications because of their high critical current densities at liquid nitrogen temperature and significant enhancement of their superconducting properties when operated at temperatures less than 77 K.

Studies of shielding properties of high temperature superconducting materials are rare compared to their electric power and magnet applications. There are, however, a few studies on the preparation and investigation of the magnetic shielding properties of the high temperature bulk superconductors based on  $\text{Bi}_2\text{Ca}_2\text{Sr}_2\text{Cu}_3\text{O}_{10}$  [1],  $\text{YBa}_2\text{Cu}_3\text{O}_7$

[2] and  $\text{MgB}_2$  [3]. Recent commercial production of second generation YBCO, coated conductors with improved critical current densities, long lengths and large surface areas [4] has enhanced opportunities to fabricate low cost and high efficiency magnetic shields from 2G superconducting tapes [5,6]. In magnetic shielding applications, the source of magnetic field could be either external when the space inside the shield is shielded or internal with the magnetic field source is shielded from outside the shield. Superconductors shield magnetic fields by generating screening currents. In an applied magnetic field, screening currents flow in the superconductor producing a magnetic field which is opposite in direction with respect to the original magnetic field. At low frequencies, (<1 kHz) normal conductive materials are not effective in shielding magnetic fields due to weak skin effect, as skin depth is inversely proportional to the square root of frequency. However, London penetration depth for superconductive material (analogous to skin depth at low frequencies) is generally independent of frequency and therefore superconducting materials offer relatively frequency independent shielding properties. Some degree of frequency dependence is, however, to be expected in commercial 2G YBCO coated conductors due to the presence of normal metal as the substrate and the stabilizer material.

With the advent of tapes with widths of 40 mm or more and excellent critical current characteristics over a wide temperature range, 2G materials offer many advantages to fabricate practical magnetic shields for a variety of applications. To enable practical applications of superconducting magnetic shields it is necessary to study their shielding characteristics under a wide range of operating conditions and in a variety of practical possible configurations.

This paper describes the fabrication and characterization of magnetic shields fabricated from 40 mm wide YBCO 2G coated conductor tape. Magnetic shielding properties of shields with multiple layers were measured in both DC and AC magnetic fields in the temperature range of 40-77 K.

## II. EXPERIMENTAL

The Second Generation High Temperature Superconductor tape is based on YBCO Coated Conductor Technology (CCT). One of the technologies used for commercial fabrication for of 2G superconducting tape uses Roll Assisted Bi-axially Textured NiW Substrate (RABiTS) onto which a thin epitaxial oxide buffer layer was deposited by metal oxide deposition (MOD) technology. The NiW substrate which is used in the process is weakly ferro-magnetic ( $T_{\text{Curie}} \sim 55$  °C), and its

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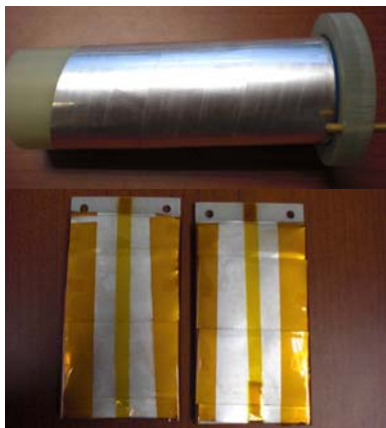


Fig. 1. Photographs of shield coil and two sheets fabricated using YBCO superconductor tape.

influence on shielding properties of the superconductor is insignificant. The superconducting YBCO layer is grown using solution-based Metal Organic Deposition (MOD) process. The tape surface was passivated by deposition of several microns of silver. The technological process allows wider widths of tapes (40 mm or wider). The experimental samples used in magnetic shielding measurements have nominal width of 40 mm and had critical current of  $\sim 800$  A at 77 K in self-field measured using the  $1\mu\text{V}/\text{cm}$  criterion.

Superconducting shields used in the study were fabricated in two configurations, viz coils and sheets. Shields in both configurations were fabricated with 1-4 layers of superconducting tape. The details of fabrication procedure are described below:

Single-layer coils were fabricated using approximately 0.5 m of the conductor. The solenoid coil was wound on a 50 mm fiberglass epoxy former with 3 turns. The turn-to-turn gap was minimized by packing the turns next to one another as closely as possible. The practical coil length was 10 cm. After characterizing the shielding properties of the single layer coil, a second layer was wound by offsetting the layers by half-width of the conductor such that the second layer covers the turn-to-turn gaps of the first layer. The process of winding and characterizing was repeated with each successive layer. The top and bottom ends of each layer were not connected in any way.

Superconducting shields with sheet geometry were fabricated by gluing sections of superconductor tapes 40 mm wide on fiberglass plates with dimensions 6 cm x 10 cm. A pair of identical sheets arranged parallel to each other with a gap of 18 mm constituted the shields with sheet geometry. Successive layers of superconducting tape were added after characterization of the shields. As with the coils, the successive layers were offset by a half-width of the tape to cover inter-turn gaps of the previous layer. Fig. 1 depicts photographs of some typical shields fabricated and characterized in the present study. There is no electrical insulation between successive layers in all investigated geometries. External AC magnetic fields with variable amplitude and frequency were produced using a special double helix dipole magnet which is 114 cm long with inner diameter of 17 cm.

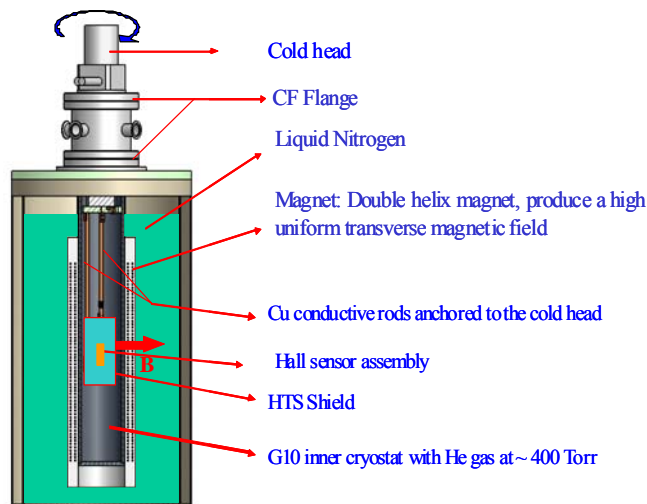


Fig.2. A schematic of the variable temperature shielding property measurement apparatus.

The magnet windings are made of two sets of tilted copper coils, each consisting of three layers. The tilted coils are connected in series in such way as to cancel the axial field component and produce a pure transverse field which is perpendicular to the magnet axis. During the operation, the magnet coils are cooled with liquid nitrogen. The magnet constant of the assembled coils is 1.487 mT/A. The magnet produces a uniform transverse magnetic field, with less than 1% variation in a cylindrical region with 10 cm in diameter and 20 cm in length. Details of the magnet design are described elsewhere [7].

The sample chamber is made up of a thick walled glass fiber reinforced plastic (GFRP) tube which is 109 cm in length and 14.5 cm in inner diameter. The tube is sealed at the bottom. The top of the tube is attached to a stainless steel CF flange and the flange-tube joint was sealed with Stycast. A feed through collar with four KF40 ports sits on the top of the tube flange. The bottom of the collar seals the steel flange that supports the GFRP tube. The cold head of a Cryomech AL330 sits on the top of the collar and seals the collar via a CF flange. The cold head, the collar, and the GFRP tube together form the vacuum tight measurement chamber. The collar provides access to the current leads, instrumentation wiring, and vacuum ports. The sample holder is suitable for measurements in helium gas atmosphere at pressure 400 Torr to provide better thermal equilibrium.

In the shielding property measurements, AC magnetic field inside center of the shields was measured by the AC Hall probe magnetometer which consists of a Hall probe (HHP-MP) prepared at the Institute of Electrical Engineering, Slovak Academy of Sciences, Bratislava, Slovakia. A DC current source (Lake Shore, C120) is used for the excitation current of the Hall probes. A lock-in amplifier (Stanford Research Systems, SR 830) is used to measure the voltage output of the Hall-probes. The Hall probes used are suitable for measurement of AC magnetic fields at cryogenic temperatures and they have low offset voltage and high degree of linearity. The Hall probe has an active measurement area of  $100\mu\text{m} \times 100\mu\text{m}$  and a sensitivity of 75-85 mV/T at a nominal control current of 10 mA. The value of Hall probe sensitivity depends

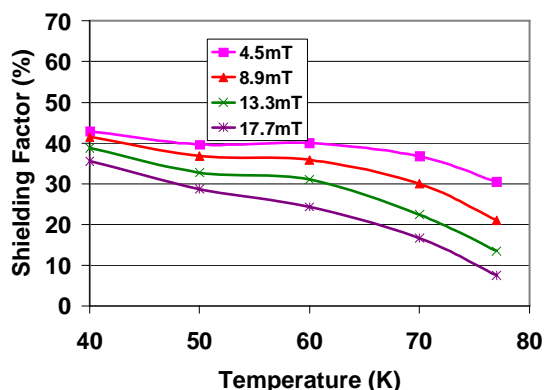


Fig. 3. Temperature dependence of shielding factor for 1-layer sheet at 160Hz, parameter is AC magnetic field.

on temperature and frequency. The details of the Hall probes used are described elsewhere [5].

The characteristics of the shields were measured in the temperature range of 40-77 K. In a measurement, the shield was arranged in such a way that it sits in the uniform magnetic field region of the magnet with the magnetic field perpendicular to the axis of the shields (that is, perpendicular to the wide face of the YBCO tape). Thick copper rods function as thermal anchors between the cryocooler cold head and the experimental shield. Fig.2 depicts the sample chamber assembly inside the bore of the double-helix magnet. The transverse component of the magnetic field inside the coils and sheets was measured as a function of magnetic field and frequency. The schematic of the measurement instrumentation in the perpendicular magnetic field configuration is described in detail in [6]. Desired temperature of the shields was achieved by using control heaters wound on the copper rod anchors. The heater current is controlled using a Lake Shore 340 Temperature Controller. After each measurement the shields were slowly warmed to the next higher temperature (< 1 K/min) in order to prevent damage to the superconducting tape due to the thermal shock. After the measurements on a one-layer shield, the shield was removed from the sample chamber, successive layers were added, and characterization was repeated as described above.

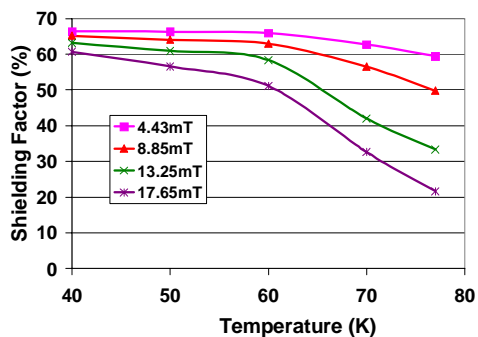


Fig. 4. Temperature dependence of shielding factor for 1-layer coil at 160Hz, parameter is magnetic AC field.

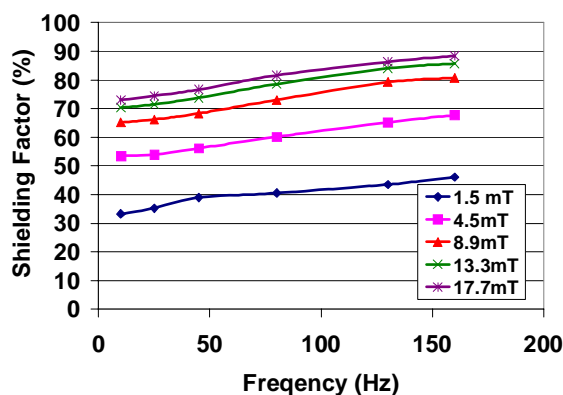


Fig. 5. Frequency dependence of shielding factor for 3-layer sheet at 40 K, parameter is AC magnetic field.

### III. RESULTS AND DISCUSSION

The shielding efficiency as denoted by the shielding factor is defined as the percentage of external field that is shielded:

$$\text{Shielding factor (\%)} = (B_{\text{ext}} - B_{\text{int}}) * 100 / B_{\text{ext}}$$

where  $B_{\text{ext}}$  is the external applied magnetic field and  $B_{\text{int}}$  is the magnetic field in the center of the shield. Measurements were performed with magnetic field orientation perpendicular to the axis of the coils and sheets. The discussion below pertains to shielding of variable frequency AC magnetic field using 2G superconductor sheets and coils. Shielding properties were measured as a function of magnetic field (all magnetic field values are RMS values), frequency, temperature, and number of layers.

Fig. 3 shows the variation of AC shielding factor of a 1-layer sheet for a frequency of 160 Hz as a function of temperature for four different magnetic fields ranging from 4.5 mT to 17.7 mT. As seen in the figure, the shielding factor decreases with increase in temperature and the magnetic field. The maximum shielding value of 42% was obtained at a magnetic field of 4.5 mT and drops to <10% at 17.7 mT and 77 K.

Fig. 4 depicts the variation of AC shielding factor of a 1-layer coil for a frequency of 160 Hz as a function of temperature for four different magnetic fields ranging from

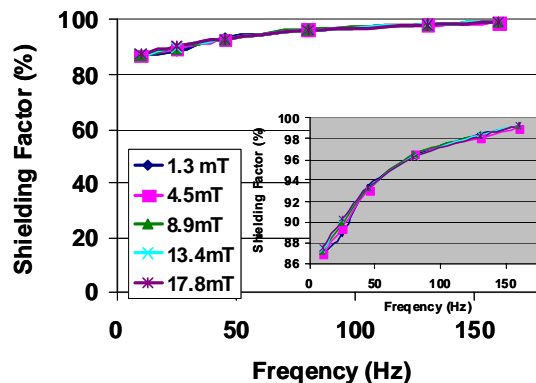


Fig. 6. Frequency dependence of shielding factor for 3-layer coil at 40 K, parameter is AC magnetic field. The detail of the same plot is in the insert.

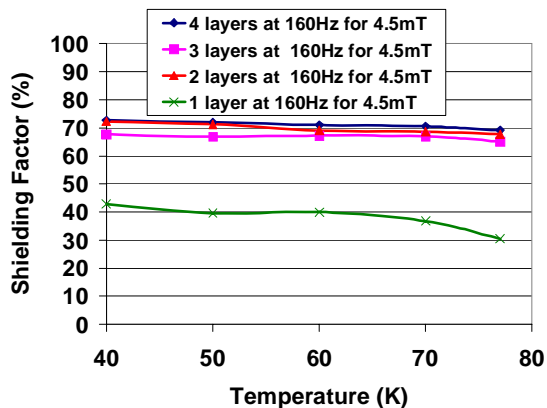


Fig. 7. Temperature dependence of shielding factor for sheets at 160Hz and 4.5mT, parameter is number of sheet layers.

4.5 mT to 17.7 mT. Compared to the corresponding shielding values of the sheet geometry presented in Fig. 3, coil geometry exhibits significantly higher shielding factors. The trends of shielding factor variation for increasing magnetic field or temperature, however, are similar.

The frequency dependence of the AC shielding factor for three layer sheets at 40 K is presented in Fig. 5. Two additional sheet layers increased the SF from ~40% to >80% at 160 Hz. The SF also increases with increase in frequency from 10 Hz to 160 Hz. The effect of frequency is similar for all magnetic field values studied.

Fig. 6 presents frequency dependence of the AC shielding factor for 3-layer coil at 40 K in 1.3–17.8 mT magnetic field range. The SF increases with frequency as was observed in 1-layer reaching 99% and a plateau at frequencies > 150 Hz. The detail in the insert shows that the curves for several frequencies overlap exhibiting only weak magnetic field dependence in the measured frequency range. The addition of the two additional layers enhances shielding properties from 65% for one layer to 87%-99% for 3 layers. It should be noted that additional layers not only add superconducting layers but also cover the inter-turn gaps. The observed increase to ~99% can be attributed to the larger amount of superconductor and the absence of through gaps in 3 layers coils.

Fig. 7 shows the temperature dependence of the AC shielding factor for sheets with increasing number of layers for a magnetic field of 4.5 mT and a frequency of 160 Hz. The highest shielding factor measured was ~70% for sheets with two or more layers. These data suggest that the addition of more layers to a 2-layer sheet is not beneficial because it did not enhance the shielding properties.

Fig. 8 depicts temperature dependence of the AC shielding factor of coils with up to 4 layers. The behavior of the coils is significantly different compared to that of sheets. The shielding factor of 3 and 4-layer coils is ~99% and is constant across the whole temperature interval. Only the 1-layer coil exhibits some temperature dependence.

As seen from the data presented in figures 6 and 8, shields fabricated from commercial 2G superconducting tape in coil configuration exhibit significant shielding factors of up to 99% at 160 Hz and 17.8 mT. Shielding factors observed for

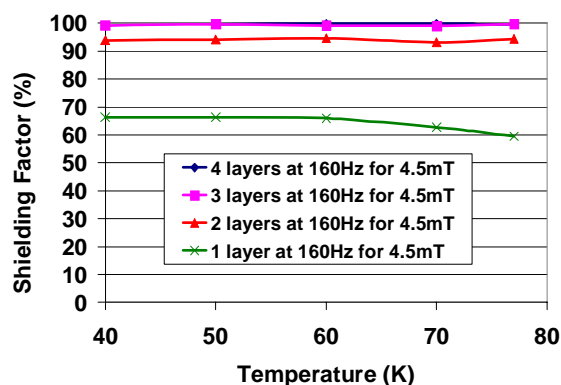


Fig. 8. Temperature dependence of shielding factor for coils at 160Hz and 4.5mT, parameter is number of coil layers.

sheet configuration are lower and drop with increasing temperature. The temperature dependence is stronger for sheets than for corresponding coils. Further, significant differences are also observed in the frequency dependence between coils and sheets, which are perhaps due to the existence of multiple turns in coils as coils have closed shape, which at higher frequencies gets better electromagnetically coupled for the screening currents which enhance the shielding factors. It can also be seen that the shielding factor increases about 20% for sheets, where as it is < 15% for coils when the frequency is increased from 10 Hz to 160 Hz.

#### IV. CONCLUSIONS

A versatile apparatus for characterizing magnetic shielding properties at variable temperature is presented. Magnetic shields were fabricated in coil and sheet geometries using 40 mm wide 2G superconducting tape. Shielding factors up to 99% are demonstrated at magnetic field of 18 mT and frequency of 160 Hz. Some interesting differences in frequency dependence of shielding factors on the geometry of the shields were observed. For both sheet and coil configurations, the shielding factor can be increased by lowering the temperature. The shielding factor increases with increasing frequency at constant external magnetic field. Further experiments are necessary to study the role of open and closed shield shapes, substrate structure and conductive normal metal in superconducting tapes. High values of shielding factor underline the potential for fabricating practical magnetic shields using commercial 2G superconducting tapes. Expected improvements in cryogenic technology and availability of long lengths and wider tapes will enhance the potential for superconducting magnetic shields for a variety of technical applications.

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