Magnetic shielding using high-temperature superconductors

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Abstract. Magnetic shields of various high-temperature superconductors, $YBa_2Cu_3O_{7-x}$ (YBCO), $YBa_2Cu_3O_{7-x}$–Ag composites (random inclusions as well as non-random coatings) and $Bi_2Sr_2Ca_2Cu_3O_x$ (BSCCO) were prepared by uniaxial as well as isostatic compression with various dimensions. The shielding properties were measured at 77 K for dc and ac magnetic fields in the range of frequencies from 100 Hz to 10 kHz. The critical penetration field (CPF), defined as the value of the applied magnetic field at which a detectable field was observed inside the cylinder, varied from cylinder to cylinder and also with the ageing of the cylinders in the case of YBCO shields. The highest value of CPF was 16 G at 77 K for YBCO shield prepared by isostatic compression. Even though the stability of BSCCO shields with respect to ageing is good, the CPF values are very low compared to those for YBCO. Detailed studies were performed in the case of YBCO shields. The CPF decreased as a function of time over a period of 90 days. The CPF decreased as the frequency of the applied field was increased. The wave form of the field inside the pot for a sinusoidal applied field was highly distorted and showed the presence of higher harmonics with appreciable amplitude. The wave form was Fourier-analysed to yield the field inside the shield along with the harmonics. The shields with Ag addition seem to give better performance at high fields.

Keywords. High-temperature superconductors; magnetic shielding; $YBa_2Cu_3O_{7-x}$; $Bi_2Sr_2Ca_2Cu_3O_x$; YBCO–Ag composites.

1. Introduction

Electromagnetic shielding is one of the subjects of interest in which the high-T_c superconductors can be put into application. Many researchers all over the world started working in this area of high-T_c materials because this is likely to be commercialized soon. Magnetic shielding is crucial to many advanced technological applications. This plays a vital role in medical industry, physics research and the electronic industry. For example, with the discovery of SQUIDs it is now possible to detect very small changes in magnetic fields as in biomagnetic applications. These fields are of the order of few picogauss and are of low frequency of a few hertz. When compared to even the earth's field these are smaller by several orders and demand a very effective shielding of the order of 120–200 dB for any useful application.

It also finds applications in high-energy physics for providing a field-free region for the charged particles as well as for shielding human beings and other sensitive instruments against steady as well as pulsed fields. There is no need to say that sophisticated electronic instrument calibrations require electromagnetic shielding of

very high order. The earth is not the only source of magnetic field. Power lines and EM waves from different transmitters etc. are also sources of disturbances. A good review on the importance of shielding can be had from Newman (1990). Conventional high-sensitivity magnetometers and SQUIDs for physics as well as for biomagnetic applications use Nb shields normally.

Metals with high conductivity, like Cu, are good shields as they can shield high-frequency fields to the required levels and also they are cheaper and economical compared to superconductors, which require a cryogen for cooling. But metals are ineffective in providing shielding against low-frequency fields and dc fields. Only superconductors are the solution for this. Advent of high-T_c materials brought down the cost because they can use a comparatively cheaper cryogen like liquid nitrogen. Also, these materials, even though they have low J_c values, have fairly good shielding properties.

Magnetic shielding using high-T_c materials was extensively studied by various groups (Hattori *et al* 1988; Aswathi *et al* 1989; Cui *et al* 1989; Purpura and Clem 1989; Shigematsu *et al* 1989; Symko *et al* 1989; Willis *et al* 1989; Vlakhov *et al* 1991, etc for YBCO cylinders; Karthikeyan *et al* 1989, etc for plasma spray coated films; and Russell and Taylor 1989, etc for discs). For useful applications studies on closed enclosures are essential. In this paper we report the fabrication of shields with high-T_c materials and an outline of the results.

2. Experimental

Details of the experimental arrangement can be had from Ganesan and Srinivasan (1989). It consists of a long solenoid producing an axial magnetic field, at the centre of which is placed the shield of the superconductor. The solenoids were calibrated using a flux meter (Siemens). The shield was closed with a lid of the same material to provide a totally enclosed region for study. A search coil with an effective area of $2121 \times 10^{-4} \, \text{m}^2$ was placed coaxially at the centre of the cylindrical pot. For dc measurements the search coil was connected to the flux meter. The smallest detectable field in this arrangement was 50 mG. For ac measurements the search coil was connected to a Tektronix dual trace oscilloscope. The smallest detectable field for ac measurements is determined by noise in the circuit and was 100 mG at 1 kHz.

The critical penetration field (CPF) is defined as the minimum value of the applied field at which a detectable signal is seen from the search coil. In dc measurements, the current through the solenoid was slowly increased till the flux meter showed a non-zero reading. In ac measurements the amplitude of the ac current through the solenoid was varied till the signal from the search coil showed a detectable emf. AC measurements were carried out in the range of frequencies from 100 Hz to 10 kHz. Most of the measurements were done at 77 K with the cylinder in a bath of liquid nitrogen. A few measurements were performed at 4·2 K with the cylinder immersed in liquid helium.

2.1 *Shields of YBCO prepared by axial compression*

Seven cylinders of YBCO were examined. All of them had the same dimensions of 4 cm outer diameter, 5 cm height and 1 cm wall thickness. These cylinders were

prepared from YBCO powder prepared by solid state reaction technique. The powder was single-phase $YBa_2Cu_3O_{7-y}$ as ascertained by X-ray powder diffraction. The powder was dry-compressed axially in a die to 10 ton pressure to form a cylindrical pot. The cylinder was then kept in a furnace and its temperature was raised at the rate of 60°C/h to 950°C. The pot was annealed in air at this temperature for 24 h and slow-cooled to room temperature. A subsequent oxygen treatment was given as follows: 900°C for 24 h, slow cooling to 600°C and maintaining at that temperature for 24 h, and then slow cooling to room temperature in 24 h, all the above processes being carried out in flowing oxygen. The warming and cooling rates were chosen so as to avoid cracks in the cylinder due to the differential expansion during the warming and cooling cycles. A YBCO disc of the same thickness was also prepared in the same fashion to cover the disc. The total weight of the cylinder and the disc is about 220 g. The X-ray powder diffractogram shows that the samples were in single phase with orthorhombic structure having unit cell dimensions $a = 3\cdot830(3)\text{Å}$, $b = 3\cdot901(3)\text{Å}$, $c = 11\cdot704(7)\text{Å}$. A pellet of the material prepared under the same conditions showed zero resistance at 90 K.

2.2 *Shields of YBCO prepared by isostatic compression*

YBCO shields were also prepared by isostatic compression using the facilities available at DMRL, Hyderabad. The necessary dies and rubber bags were made for this purpose. Superconducting YBCO powder was used for making the shields. Five such shields were prepared with varying wall thickness and also with flat as well as hemispherical bottom. Typical dimensions of the shields are 50 mm in length and 40 mm in outer diameter. After compression the shields were sintered in air for 24 h at 930°C, with heating and cooling rates maintained at 60°C/h to avoid cracking due to thermal contraction. These shields were then oxygen-annealed at 900°C for 24 h and at 600°C for another 24 h with the same heating and cooling rates of 60°C/h.

2.3 *Shields of YBCO with Ag*

One such shield was prepared with 10% silver powder added before making the compression. Silver powder was added to the superconducting powder and was mixed thoroughly for 24 h in a ball mill before it was isostatically compressed. Sintering as well as oxygen annealing procedures are essentially same as above except that the maximum temperature was restricted to 850°C.

One of the shields of YBCO was prepared by the non-random ceramic coating of the grains of YBCO by Ag. In this method each superconducting YBCO grain is coated with Ag by chemical process and then the bulk material was fabricated and oxygen-annealed. The details of preparation of such composites can be had from Srinivas and Subba Rao (1992).

2.4 *Shields of BSCCO prepared by isostatic compression*

Shields of BSCCO materials were prepared from the superconducting BSCCO powder prepared by nitrate precursor technique and the shields were formed by isostatic
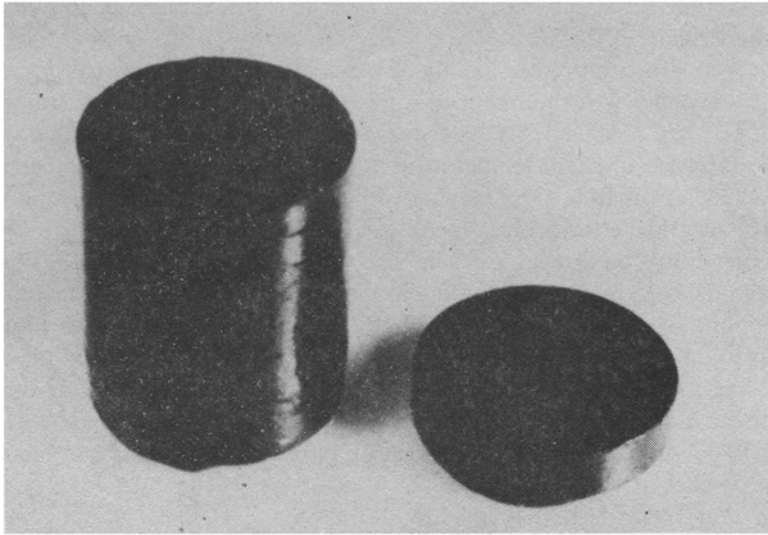
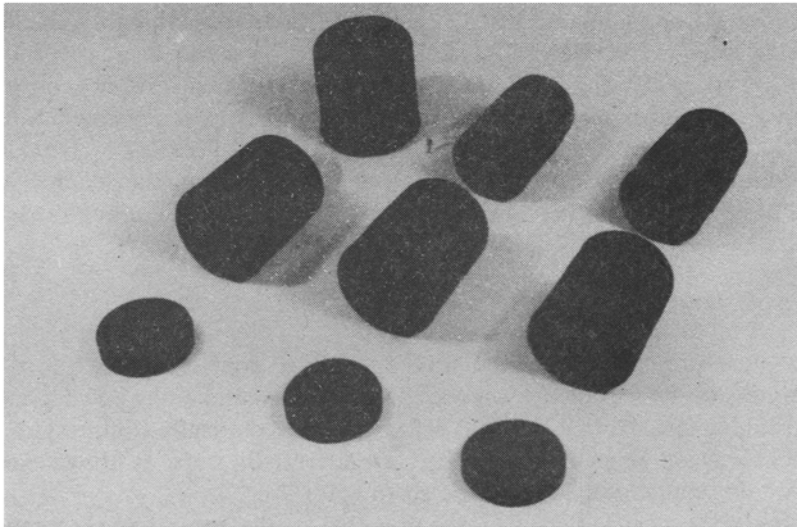**Figure 1.** Photograph of the YBCO shield prepared by axial compression.

Figure 2. Photograph of the YBCO shields prepared by isostatic compression.

compression into the required shapes. Different shapes of the shields were tried to see whether it is possible to fabricate such shapes which may be useful while implementing the applications.

Figure 1 shows the photograph of one of the shields of YBCO prepared by axial compression. Figure 2 shows the YBCO shields prepared by isostatic compression. The detailed analysis of the results on these shields will be published elsewhere. This

figure is repeated here for the sake of completeness. Figure 3 shows the BSCCO shields prepared by isostatic compression.

3. Results and discussion

Table 1 gives the CPF values for different shields. YBCO shields prepared by isostatic compression (iso) show improved shielding compared to the shields prepared by axial compression. The CPF of the YBCO shield (axial) was 12 G at 77 K for dc field and decreases as the frequency of the applied field is increased in the case of ac fields. The CPF of the YBCO shields (iso) are·16–17 G at 77 K. The frequency response is of the same nature as that of axially prepared shields. The addition of Ag to YBCO does not improve CPF but it improves the shielding effectiveness to three times compared to the shields without Ag. However, the effect of frequency on CPF is to
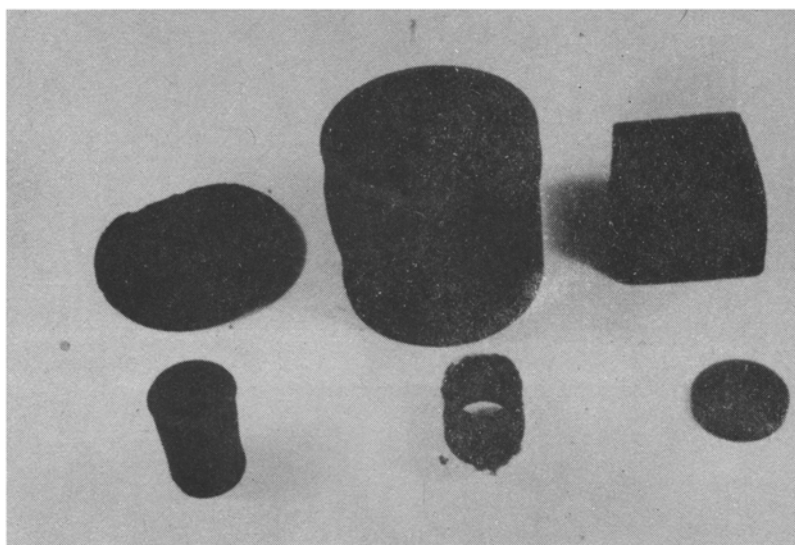

Figure 3. Photograph of the BSCCO shields prepared by isostatic compression.

Table 1. Description, wall thickness and CPF values for six high-T_c shields.

Description	Wall thickness d (mm)	CPF (G)
YBCO (axially compressed)	10	12
YBCO (isostatically compressed)	10	12
YBCO (isostatically compressed)	4	15
YBCO (isostatically compressed) + 10% Ag	8	16
YBCO + Ag (non-random composite)	6	5
BSCCO (isostatically compressed)	4	1

decrease CPF more rapidly than in the case of YBCO without Ag. The results are in good agreement with those reported in the literature.

The field inside the shield was highly distorted showing the presence of higher harmonics with appreciable amplitude. Figure 4 shows the oscilloscope trace of the signal inside the shield along with the applied field of amplitude 44 G at 426 Hz. The waveform of the field inside was Fourier-analysed to yield the fundamental as well as harmonics. Figure 5 shows a sample plot of B(inside) as a function of B(applied) for a shield of YBCO prepared by axial compression as well as the harmonics. Such an estimate of the magnitude of the field inside the shield is very useful to understand the performance of the shield. The field inside the shield is the combination of fundamental and harmonics of the applied frequency. The estimation of the harmonics is useful to study the nonlinearity of the system and the associated hysteretic behaviour. Also the ratio of the field penetrated to the field applied gives the effectiveness of the
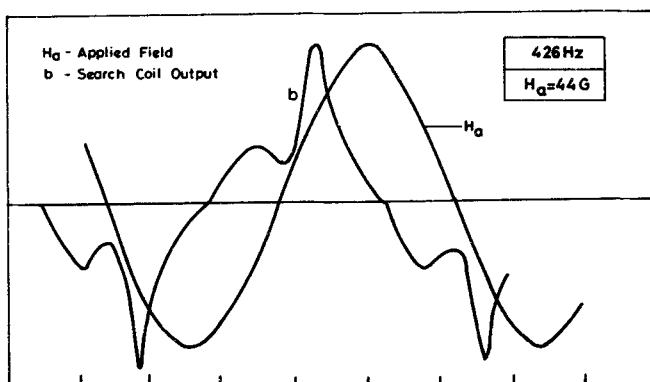

Figure 4. Oscilloscope trace of the field inside and that of the applied field for the shield of YBCO prepared by axial compression.
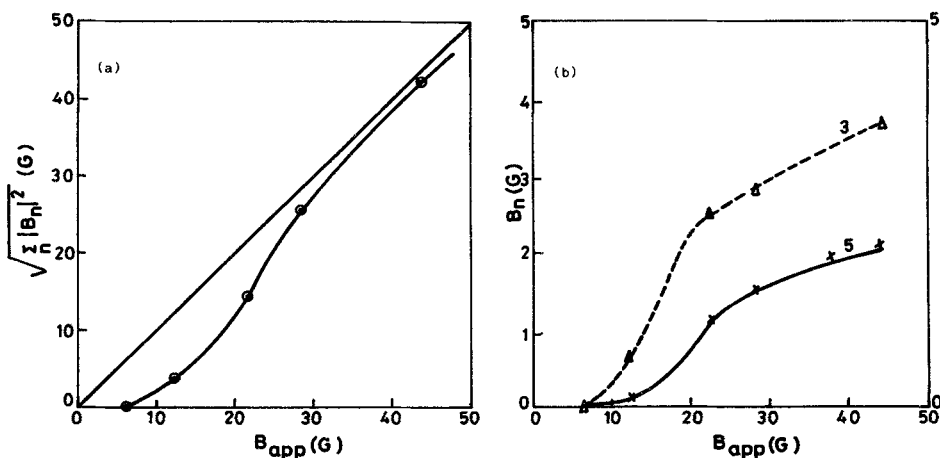

Figure 5. (a) The magnitude of the maximum magnetic induction field inside the shield as a function of the applied field. (b) Variation of the third and fifth harmonics inside the shield as a function of the applied field for the shield prepared by axial compression.

shield. This idea of the penetrated field is very important in designing multilayer shields.

Shields of YBCO with Ag prepared by non-random ceramic coating method show a CPF of about 5 G only. The different shields of BSCCO materials show CPF values in the range 1–2 G only. Even though the absolute value of CPF is very low compared to that for YBCO, these shields are attractive because of less degradation of shielding properties with ageing. In the case of YBCO CPF decreased from 12 G to 2 G in a period of 90 days. Detailed ageing studies on BSCCO shields are being carried out. It is worth mentioning here that Koike *et al* (1991) have developed a large magnetic shielding vessel of BSCCO (dimensions are 320 mm diameter, 640 mm depth and 25 mm thickness) which can provide a shielding effectiveness of 100 dB for weak fields.

With YBCO shields fields up to 15–20 G can be shielded effectively. The addition of Ag does not bring about an increase in CPF. However, for the same value of CPF, the YBCO–Ag composite has a larger shielding effectiveness than the YBCO shields for fields as large as three times CPF. The low value of CPF in these materials is due to the low value of J_c. We are trying to prepare a shield of YBCO prepared by melt-grown process so that the J_c values can be made high. Regarding long-term stability the BSCCO shields seem to be promising provided their J_c values can be increased. In conclusion, magnetic shields can be fabricated out of high-T_c materials which can provide a shielding effectiveness of 60–100 dB at low frequencies over a volume of about 30–40 cm^3. Fabrication of large shields or even shielded rooms for neuromagnetic measurements may be the immediate future outcome of the application of high-T_c materials.

References

Aswathy S, Ganesan V, Chandrasekaran K D, Subba Rao G V and Srinivasan R 1989 *DAE Symposium on Solid State Physics, Madras, India*
Cui C J, Wang S G, Jiang H M, Li J Z, Lin C D, Liu H Z, Zheng Q L, Fu Y S, Luo Z L and Qiao W C 1989 *IEEE Trans. Mag.* **25** 2273
Ganesan V and Srinivasan R 1989 *High Temperature Superconductors*, IIT Madras Newsletter **2** 1
Hattori T, Higemoto N, Kanazawa S and Kobayashi M 1988 *Jpn. J. Appl. Phys.* **27** L1120
Karthikeyan J, Paithankar A S, Sreekumar K P, Venkataramani N and Rohatgi V K 1989 *Cryogenics* **29** 915
Koike A, Hoshino K, Ohta H, Kotaka H, Sudoh E, Katoh K and Takahara H 1991 *Physica* **C185–189** 2613
Newinan D 1990 *Superconductor Ind.* **Fall** 16
Purpura J W and Clem T R 1989 *IEEE Trans. Mag.* **25** 2506
Russel G J and Tayler K N R 1989 *J. Appl. Phys.* **66** 5498
Shigematsu K, Ohta H, Hoshino K, Takayama H, Yagishita O, Yamazaki S, Takahara H and Aono M 1989 *Jpn. J. Appl. Phys.* **28** L813
Srinivas B and Subba Rao G V 1992 *Bull. Mater. Sci.* **15** 403
Symko O G, Yeh W J, Zheng D J and Kulkarni S 1989 *J. Appl. Phys.* **D65** 2142
Vlakhov E S, Kovachev V T, Polak M, Majoros M, Dimitriev Y B, Jambazov S, Kashchieva E and Staneva A 1991 *Physica* **C175** 335
Willis J O, McHenry M E, Maley M P and Sheinberg H 1989 *IEEE Trans. Mag.* **25** 2502