This is the author's version of an article that has been published in this journal. Changes were made to this version by the publisher prior to publication.
The final version of record is available at http://dx.doi.org/10.1109/TASC.2016.2539261

FERMILAB-CONF-16-357-T
ACCEPTED

Feasibility study of a MgB_2 superconducting magnetic cloak

Giovanni Giunchi, Daniele Turrioni, Vladimir Kashikhin, Hogan Nguyen and Emanuela Barzi

***Abstract*— The magnetic shielding capability of bulk MgB_2 hollow cylinders can be fruitfully combined with an external paramagnetic sheath, to tailor the shape of the external magnetic flux lines. By appropriate selection of the external sheath permeability and thickness it is possible to leave the magnetic flux lines unaltered by the shield (cloaking effect). Preliminary measurements have been performed at 4.2 K on shielding capability of bulk cylinders, subjected to axial and transversal magnetic field up to 5 T. The cloaking conditions have been modelled to find the optimized thickness to realize the cloaking effect. The MgB_2 material of the superconducting shield is also optimized to avoid low temperature flux jumps, without losing its shielding capability.**

***Index Terms*— Magnetic shielding, mixture permeability, MgB_2, infiltration process, magnetic cloaking.**

I. Introduction

The magnetic field is commonly shielded by superconducting materials, which are perfect diamagnets (μ=0). In doing that, the superconductor modifies the magnetic flux distribution in the nearby space external to it, where the repelled flux lines must be accommodated. Starting from the theoretical description of Pendry et al. [1] of composite structures made by a bilayer superconductor/ paramagnet, it has been evidenced that it is possible to avoid flux deformation in the space outside the bilayer, at least for simple geometries and DC magnetic field. The external paramagnetic material (μ>1) concentrates the flux lines in itself, therefore acts in an opposite way with respect to the superconductor. By optimizing the magnetic permeability μ of the paramagnet and its thickness it is possible, in principle, to avoid any flux line deformation (perfect cloaking). A few years ago a first experiment by Sanchez et al. [2] was published on the feasibility of magnetic cloaking by using wound YBCO coated conductors surrounded by an appropriate paramagnetic alloy. Even if the cloaking was not perfect, it was demonstrated that the flux deformation was less than few percent. This result opened the way for applications of magnetic cloaking to some physics experiments that need such peculiar condition, mainly in the particle accelerator field [3,4]

Manuscript received September 8, 2015.
G. Giunchi, Materials Science Consultant, Milano, Italy (e-mail: giovanni.giunchi@gmail.com).
D. Turrioni, V. Kashikhin, H. Nguyen and E. Barzi are with Fermilab, Batavia(IL).

Our present effort is to optimize the superconducting material in order to realize bilayer systems that can be fruitfully applied in a real accelerator. We chose bulk MgB_2 as superconductor, instead of the HTS materials, due to its almost complete magnetic shielding capabilities in fields < 2T, its high mechanical strength and modulus and its workability in form of long tubes by the infiltration process [5].

II. The Magnetic Field Cloaking Problem

The computed analytical functions of the permeability vs. the thickness of the paramagnetic alloy [2], are valid, as complete cloaking, in two limiting cases: a) an infinite long tube, b) a sphere. More complex evaluations by finite elements solution of the Maxwell equations are needed for more complicated geometries.

A. Infinite cylinder:

$$\mu_2 = \frac{{R_2}^2 + {R_1}^2}{{R_2}^2 - {R_1}^2} \quad (1a)$$

B. Sphere:

$$\mu_2 = \frac{2{R_2}^3 + {R_1}^3}{2({R_2}^3 - {R_1}^3)} \quad (1b)$$

where R_1= external superconductor radius, R_2= external paramagnet radius and μ_2=paramagnet permeability

As shown in Fig.1 the spherical case requires a paramagnetic material with about half permeability with respect to the infinite cylinder, to produce a complete cloaking at given R_1/R_2 ratio. By using the same paramagnetic material in both cases, the layer thickness of the spherical case is about half.

It is therefore useful to realize a closed tube with semi-spherical ends. Practical issues about the paramagnetic layer include the material choice and the precision in the realization of a given thickness. The paramagnetic material may be designed according to a number of strategies: by preparing an alloy by mixing two appropriate metals of different permeability (i.e. a diamagnetic low melting metal and a low permeability stainless steel powder) or by using a commercial alloy of low permeability, like the $Fe_{18}Cr_9Ni$ used in [2]. In both cases the ratio of thickness of the superconductor and paramagnet is fixed by the exact value of the permeability, which depends by the magnetic field at the low temperature of the experiment.

Operated by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the United States Department of Energy.

FIG. 1

Figure 1 – Analytical behaviour of the permeability of the paramagnetic material vs. the geometrical parameters of a double layer tube (Superconductor/Paramagnet), under condition of perfect cloaking

Because the permeability value is difficult to determine exactly, one expects that also the thickness cannot be precisely defined in advance.

Further uncertainty for the thickness, by using a single metallic material, is originated by the wide variation of metals permeability and in particular of stainless steel with cold deformation. For example the R.T. permeability of INOX C302 can vary from 1 to 6, depending on cold deformation. In the case of an infinite tube, the relation (1a) can be rewritten as function of the paramagnetic thickness x= R_2-R_1, as:

$$\mu_2 = \frac{x + 2\,R_1\,(1 + \frac{R_1}{x})}{(\,x + 2\,R_1)} \qquad (2)$$

In Figure 2 the permeability as function of the paramagnetic layer thickness x is plotted for typical R_1 values (mm).

At small thicknesses (i.e. less than 2 mm), there is a steep variation of the permeability, therefore the thickness becomes a critical parameters, to match precisely the cloaking condition. If one assumes an acceptable limit for the cloaking condition (i.e. a relative permeability uncertainty, $\Delta\mu_2/\mu_2$, of less than 0.25 %), the corresponding uncertainty in the paramagnetic thickness, Δx, may be computed by the equation:

$$\Delta x = \left(\frac{\partial\, ln \mu_2}{\partial x}\right)^{-1}_{R_1} \Delta\mu_2/\mu_2 \qquad (3)$$

For example, assuming R_1= 50 mm and a relative permeability uncertainty of 0.25 %, an acceptable variation of the paramagnetic thickness Δx of < 10 μm corresponds to a paramagnetic layer thickness > 3.8 mm. The values of permeability useful in this example are of the order of 10.

To obtain such a permeability we can anticipate that an appropriate mixture of a diamagnetic metal, as Mg, with nickel powders (μ about 500) may be added to the surface of the superconducting part and polished at the right thickness.

III. Large MgB_2 Tubes by the Infiltration Technique

The MgB_2 material can be formed in large tubular objects by the Reactive Liquid Infiltration (RLI) technique [6].

FIG. 2

Figure 2 – Analytical behavior of the permeability of the paramagnetic material vs. its thickness, for different radii of the superconducting material.

This technique uses preferably crystalline boron powders of large size (> 50 μm). They are attacked by the Mg melt and give rise to a composite material made by residual borides, of composition Mg_2B_{25} [7], embedded in the MgB_2 superconducting matrix. A typical morphology of the material is shown in Figure 3. The presence of the non-superconducting borides does not reduce excessively the overall critical current density. This is due to thin superconducting MgB_2 channels, crossing the borides. With the RLI process a MgB_2 hollows cylinder of 140 mm in external diameter and thickness of about 5 mm has been obtained, to be used as magnetic shield at CERN, in a prototype Superconducting DC Current Transformer (SDCCT) [8]. To realize long superconducting cylinders by the RLI process, there is no technological hurdles and it is possible to perform superconducting joints between short cylinders [9].

IV. The MgB_2 Magnetic Shielding Characteristics

The magnetic shielding of MgB_2 obtained by the RLI process has been tested in several conditions, at liquid He temperature [10], and at higher temperatures up to the critical one [11] and both in DC and AC magnetic field conditions [12].

At 4.2 K, where the first applications are foreseen to shield LTS magnets, the shielding of axial fields up to 2 T have been verified in the center of an hollow MgB_2 cylinder 70 mm high.

FIG. 3

Figure 3 – Typical optical microscope images of the MgB_2 bulk superconductor produced by the infiltration process. L and XL distinguish MgB_2 made by different boron grain size pellets. The larger magnification image (to the right) represents XL-type material.

FIG. 4

Figure 4 – Typical magnetization cycle, taken by a vibrating sample magnetometer (VSM) instrument at 4.2 K, for a well-connected bulk MgB_2 produced by RLI process with micronic boron powders.

This happened without the typical instability of LTS bulk superconductors to flux jumps. Indeed the HTS superconductors have higher heat capacity at low temperature, thus their instability is drastically reduced. For MgB_2, an intermediate superconductor, the flux jump instabilities are reduced but are still present, as demonstrated by the magnetization cycles of well-connected bulk MgB_2 obtained by RLI process on micron size boron powders, (see Figure 4).

Better results on magnetic stability are obtained for MgB_2 samples produced by the RLI process, using larger boron powders (> 100 μm), as is reported in the following section.

V. Preliminary Field Shielding Evaluations

One hollow cylinder and two MgB_2 tubes with the following dimensions were prepared by the RLI process:

- Hollow cylinder #A: OD/ID= 40.3 mm/25.5 mm, H= 42.5 mm , made by L-type boron powders
- Tube #B1: OD/ID= 24.7 mm/16.7 mm, L= 123 mm , made by L-type boron powders
- Tube #B2: OD/ID= 25 mm/17 mm, L= 127 mm, made by XL-type boron powders.

(L-type means about 50 μm and XL-type more than 100 μm)

The samples were measured at 4.2 K and submitted to a varying magnetic field up to 5 T (ramp rates of 0.25-0.5 T/min), produced in a NbTi superconducting magnet, of useful cold bore of 147 mm and height of 270 mm.
The magnetic field was measured by a gaussmeter moved in the field direction (z axis), or by fixed Hall sensors placed in three positions inside the MgB_2 tubes, along the central axis (H1 (central), H2 (22 mm apart), H3(44 mm apart)).

A Axial field
Sample #A was positioned with its axis collinear with the field (z axis) and its magnetization cycle at the center of the cylinder is reported in Figure 5. The first flux jump occurred just after the penetration field, at about 3 T. Next, the

FIG. 5

Figure 5 – Magnetization loop at 4.2 K for the MgB_2 hollow cylinder(#A, see text), in variable axial field at ramp rate of 0.25 T/min. Magnetization was measured at the center of the cylinder.

The penetration field of this hollow cylinder, H_P =2.93 T, is quite large and it is related to the critical current density, J_c, by the relation [13]:

$$H_P = J_c d \frac{\ell}{4\bar{a}} \ln\left[\frac{4\bar{a}}{\ell} + \left(1 + \left(\frac{4\bar{a}}{\ell}\right)^2\right)^{1/2}\right] \quad (4)$$

occurrence of the jumps is quite erratic, varying from cycle to cycle where d is the thickness of the hollow cylinder = 7.4 mm, ℓ is the cylinder height = 42.5 mm and ā is the mean radius of the hollow cylinder = 16.45 mm. The resulting J_c = 400 A/mm^2 .
Figure 6 reports two z-axis scanning with a Gaussmeter: one along the external wall of the hollow cylinder, to check the modification of the outer stray field, due to the superconducting currents in the cylinder; the second inside the cylinder, to measure its shielding capability.

B. Transversal field
The tubes were positioned symmetrically around the central point of the bore. The magnetization cycles for the two tubes #B1 and #B2 are compared in Figure 7a and 7b, where three

FIG. 6

Figure 6 – Behavior of the measured axial shielded field, along the z axis (field direction), for the MgB_2 hollow cylinder #A, positioned in the center of a superconducting solenoid set at 2 T. The light upper curve shows the field outside the cylinder. In the inset we enlarge the field scale inside the cylinder.

Hall sensors were positioned along the central axis inside the tube, as indicated before.
Sample #B2, made by XL boron powders, shows very few flux jumps. A rough estimation of the J_c for XL-type material can be done by a simple model which relates the penetration field (H_p=1.8 T) to two infinite opposite linear currents on the equator. Using a cross section of the tube of 4 x 20 = 80 mm^2 the result is about 300 A/mm^2. This estimate can be confirmed by comparing the ΔM behavior of the two samples, at fields >2.5 T where flux jumps are not present: the critical current density of #B2 is only slightly reduced with respect to sample #B1, which is made by L boron powders, as estimated in the above paragraph. A reduction of the critical current density in #B2 is expected by the presence of XL-type borides impurities, which reduce the superconductive cross section. Nevertheless the experimental J_c reduction is limited when compared with the reduction of the superconductive cross section appearing in the micrographs: this suggests that MgB_2 superconducting channels, thin and not visible at micron resolution, must be still present inside the borides grains. These thin MgB_2 channels inside the XL boride grains could presumably have a positive effect in flux jumps reduction. At this stage, this is only a preliminary hypothesis that requires more detailed and quantitative description of the phenomenon.

VI. Magnetic Cloaking Applications

Magnetic cloaking will find useful applications in the particle accelerator field, where several experiments need to shield locally the particle beam from unwanted magnetic fields, avoiding the modifications that the shield induces on the surrounding magnetic field distribution. One of these experiments is the Muon g-2 measurement, under commissioning at Fermilab [14]. To improve substantially the luminosity of a muon beam running in the transverse field of about 1.5 T of the accelerator ring, a new cloaking superconducting channel for the insertion of the beam in the accelerator may be designed. The choice of an MgB_2 superconducting tube, instead of a NbTi based tube, is favoured by the larger thermal stability of MgB_2 at 4.2 K. Accordingly, as the presented results demonstrate, one can use thick bulk superconducting material if space constrains allow, rather than cumbersome multilayer assemblies of LTS superconductors. A further future accelerator which may benefit of a magnetic cloaking device is the Electron Ion Collider (EIC), where the magnetic field of the detectors, should not alter the quality of the colliding beams (polarization and dispersion). On these ideas is actively working a research group at the Stoney Brook University[3].

VII. Conclusion

The concept of DC magnetic cloaking has been approached by controlling the magnetic shielding behaviour of long and thick MgB_2 tubes, made by the RLI process. Thermal instability at 4.2K, common to all LTS bulk materials, affects the present experiments at fields larger than 1 T, but by

Fig. 7

Figure 7 – Magnetization cycles for MgB_2 tubes subjected to a transversal field (ramp rate of 0.5 T/min) : a) tube #B1 made by L-type boron powders, b) tube #B2 made by XL-type boron powders.

properly varying the superconductor microscopic morphologies of MgB_2, it was possible to extend this limit to more than 2 T. This field is of interest and acceptable for several cloaking applications in the accelerator field.

Acknowledgements

GG acknowledges the FNAL Contract N. 621102 to manufacture MgB_2 shielding tubes and Paolo Arosio and Rinaldo Gabardi of E.P.C. srl (Italy) for their support in the MgB_2 samples preparation

References

[1] Pendry J B, Schurig D and Smith D R 2006 "Controlling electromagnetic fields" *Science 312 1780–2*

[2] F. Gomory et al. "Experimental Realization of a Magnetic Cloak" *Science 335, 1466 (2012)*

[3] EIC R&D Project eRD2, Progress Report RD2013-2: A Compact Magnetic Field Cloaking Device. Reporting Period: July 2014 to December 2014.11

[4] E. Barzi, D. Turrioni, V. Kashikhin, H. Nguyen, G. Giunchi "Feasibility study of Hybrid Magnetic cloak for accelerator Magnets" Poster presentation at Frontier Detectors for Frontier Physics 13th Isola d'Elba, May 2015

[5] G. Giunchi "High density MgB_2 obtained by reactive liquid Mg infiltration" *International Journal of Modern Physics B17, Nos 4,5 &6 (Mar 2003) 453-460*

[6] G. Giunchi et al. "The reactive liquid Mg infiltration process to produce large superconducting bulk MgB2 manufacts" *Cryogenics 46, 237-242 (2006)*

[7] G.Giunchi, L. Malpezzi, N.Masciocchi "A new crystalline phase of the boron-rich metal-boride family: the Mg2B25 species" *Solid State Sciences vol 10, 1202-1208 (2006)*

[8] P. Arpaia et al. "MgB_2 cylindrical superconducting shielding for cryogenic measurement applications: a case study on DC current transformers" *J. of Instrumentation 9 (2014) P04020*

[9] G. Giunchi, L.Saglietti, G. Ripamonti, A. Figini Albisetti, E.Bassani, E.Perini "Superconducting Joints between MgB2 wires and bulks" *IEEE Trans.on Appl. Supercond Vol 20(3), 2010, 1524-1527*

[10] J.J.Rabbers et al. " Magnetic shielding capability of MgB2 cylinders" *Supercond. Sci. Technol., 23, (2010), p 125003*

[11] T. Ujiie, T. Naito, H. Fujishiro, A. Figini Albisetti and G. Giunchi "Shielding and trapped field properties of large MgB2 bulk" *Physics Procedia 58 (2014) 306 – 309*

[12] T. Cavallin, R. Quarantiello, A. Matrone, G. Giunchi "Magnetic shielding of MgB_2 tubes in applied DC and AC field" *J of Phys : Conf. Series 43 (2006) 1015-1018*

[13] S. Denis et al. „Magnetic shielding proprierties of high temperature superconducting tubes subjected to axial fields" *Supercond. Sci. Technol.,20, (2007), 192-201*

[14] "Muon g-2 Experiment at Fermilab, http://muon-g-2.fnal.gov/