

The MgB₂ bulk cylinders as magnetic shields for physical instrumentation

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Abstract – The need of a superconducting magnetic shield erases in several physical apparatus, going from the small SQUID sensors to the large superconducting magnets for physical experimentation and clinical MRI. It is presented the possibility to realize cylindrical magnetic shields by HTS bulk MgB₂ (T_c=39 K), obtained by the innovative process of Reactive Liquid Infiltration of the Mg melt in Boron powders. A complete shielding up to at least 2 T can be obtained also at the lower temperatures, 4.2 K, where thermal instabilities of the other LTS shields prevent their use.

I. INTRODUCTION

Among the various magnetic shielding applications the most demanding are for the high field superconducting magnets. The large fringing magnetic fields resulting from these magnets can badly effects either nearby sensible instrumentation either people. A common way to approach the problem is to add in series to the superconducting magnets an external second layer of superconducting windings (active shielding). This external windings is able to shape the fringing field in the limited space between magnet and the winding itself and today it is used for the high field NMR magnets and it is considered for future high field MRI [1]. A potential alternative superconductive shielding method (passive shielding) may be considered applying the well-known characteristic of absolute diamagnetism of the superconductors. By clamping, outside the main magnet, some superconducting rings, during the magnet charge they expel its fringing field, developing persistent currents. The net effect is a substantial reduction of the fringing field of the magnet.

II. PASSIVE MAGNETIC SHIELDING

The typical behavior of the internal field, inside a superconducting cylinder of thickness s , at its center, when an axial magnetic field is applied, is schematized in Fig. 1. The penetration field, H_p , is defined as the maximum applied field at which a complete shielding is detected and, according to the Bean simple model, this

field is related to the critical current density of the material J_c , by the relation:

$$H_p = J_c s \quad (1)$$

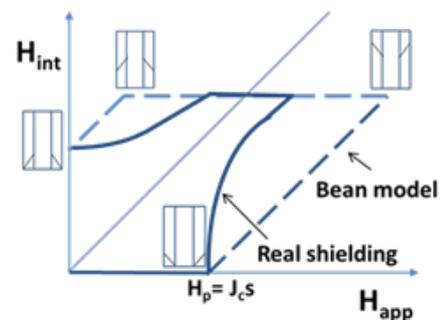


Fig1. Schematic behavior of internal field, H_{int} , when an axial field, H_{app} , is applied to a superconducting cylinder. At each corner is represented the model field distribution inside the cylinder.

The simplicity of the Bean model is related to the assumption that inside the superconductor the current density is constant along the cylinder thickness and its value J_c is independent from the local magnetic field. Even if it is only partly verified, the Bean model gives an estimation of the passive shielding capability of a superconducting cylinder.

The characteristics of the superconductors to develop currents which contrast an applied DC magnetic field is unique and opposed to the passive shielding mechanism of a soft magnetic alloys, which works by concentration in its interior the magnetic flux lines. The need of a superconducting shielding, vs the classical solution, is evident in the protection of an high field superconducting magnet, like those in use for analytical high field NMR or for clinical low field MRI, due to the saturation of the classical alloys. Among the superconducting shielding solutions, the advantages of a passive shield are: a) less need of superconducting wires to build-up the system; b) self-adjusting field level at different internal fields, without any feedback active mechanism; c) by using an HTS bulk materials it is possible to limit the volume of

the cryostat for the main magnet and therefore the volume of the liquid Helium. Critical issues of the use of the HTS bulks are: a) to stay away from the thermal instabilities conditions (quenches); b) to use HTS with well-connected grains in order to minimize the flux creep and guarantee a current persistence above an acceptable limit; c) the superconducting rings must have high mechanical strength to resist to the magnetic forces, developed during the shielding. Of course the introduction of a passive shielding will represent not a straightforward addition of a shield at one already existing superconducting magnet, but it will require a precise recalculation of the inner field of the magnet, as a function of the currents, and also the shaping of the field at the border of the winding will need a fine tuning, with the use of shimming, as it is ordinary practice for every magnet.

III. THE BULK MgB_2 SOLUTION

Among the HTS bulk materials, there is a challenge between cuprates ($T_c=90-110$ K) and MgB_2 ($T_c=39$ K) and the last material, even with a lower T_c , has chance to find its way. One of its distinctive characteristics is a very low barrier for the supercurrents at the grains boundaries, which imply the possibility to use the polycrystalline form, easy to produce, instead of the textured form needed for the cuprates. Consequently the MgB_2 critical current densities has interesting values also at 20 K, in a field of 1-2 T (of the order of 10^3 A/mm²), and the typical flux creep of the HTS materials is very limited in MgB_2 , showing values similar to the LTS NbTi material.

The research on MgB_2 , either in bulk or in wire form, is focusing on the enhancement of the pinning properties to increase the critical current in magnetic field and, for the low temperatures applications, to limit the thermal instability, generate by its very low heat capacity in this range of temperatures, similarly to LTS.

For a passive shielding the main material feature is to assure good connectivity to the entire shield, therefore a bulk MgB_2 pieces today can guarantee this properties, more than a winding of MgB_2 wires, which cannot yet be joined with resistivity below 10 n Ω .

The manufacturing processes that realize optimal connectivity among the MgB_2 grains are mainly two: the High Pressure techniques [2] and the Mg Infiltration technique [3]. The last process is preferred for its easiness, being pressure-less and applicable to large superconducting pieces[4].

A) The Mg-RLI process

The innovative densification of MgB_2 through the Reactive Liquid Infiltration by Mg melt (Mg-RLI) was discovered in the Research Labs of Edison SpA, Milano, Italy, at the early time (2001) of the announcement of the MgB_2 superconductivity [5]. Without to enter in the details of the technique, elsewhere reported [6], it is worth to mention that the Mg-RLI process is based on the

natural reaction of the reactants Mg and B, by self-infiltration of the Mg melt in preforms of B powders, with the reactants not mixed together, but separated in vicinal zones and both sealed in a steel container to prevent any their contact with the air. By this process it is possible the densification of superconducting MgB_2 pieces as cylinders, rings, tubes and various other shapes of large dimensions, several tens of cm wide, as illustrated in Fig. 2.

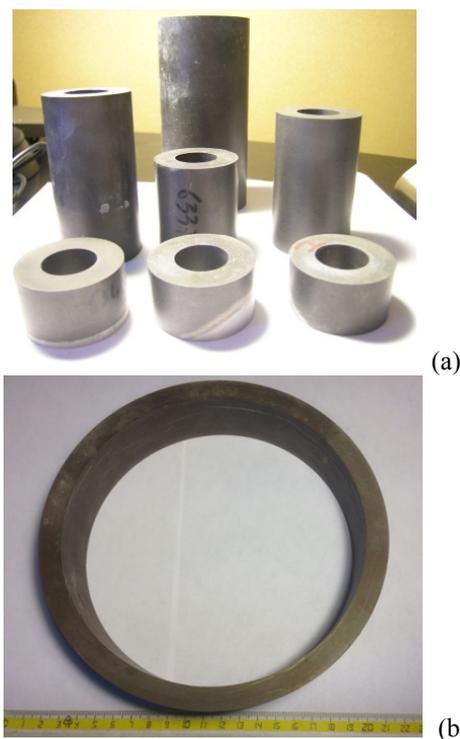


Fig. 2. MgB_2 Cylinders (a) and ring (b) produced by the Mg-RLI process

For the production of the larger pieces, peculiar attention must be devoted to the design of the boron preform and of the steel container, because the differential thermal expansion of the steel and of the MgB_2 , can create cracks during the cool down.

The superconducting quality of the resulting products are very dependent from the purity of the boron powders and, as mentioned before, from the addition of doping agents to the reactants, mainly carbonaceous products in an amount of few %.

B) The MgB_2 superconducting characteristics

The main superconducting characteristics of the MgB_2 derived by the Mg-RLI material have been described, as a function of temperature and magnetic field, in several papers and the perspective uses are at intermediate temperatures up to 25 K, where enough critical current density can be maintained up to 2 T: a field at the limits of the classical electromagnets. As reported in Fig.3, the

polycrystalline MgB₂ bulks have good critical current density: up to 10³ A/mm² @ 2.5 T and 4.2K.

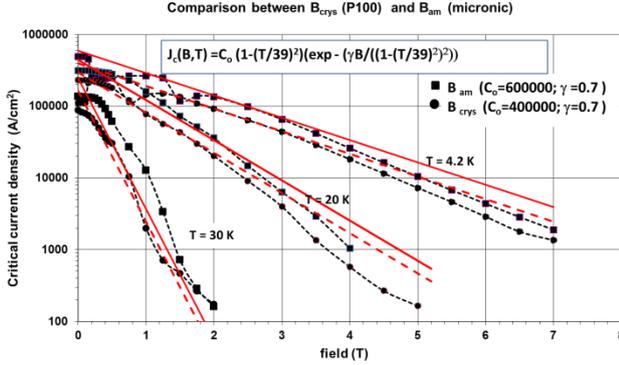


Fig.3 $J_c(B, T)$ measured for MgB₂ bulks obtained by Mg-RLI, with Boron of different grain size. The calculated values, with the formula (2) are reported in red: for B_{am} (full line) and for B_{crys} (dashed line)

To have an analytical model, more appropriate than the simple Bean model, to describe the behavior of the superconducting cylinder as a function of the temperature and magnetic field we have fitted the J_c experimental values resulting from magnetization cycles of MgB₂ materials obtained by two Boron powders of different grain size (B_{crys} powders had a grain size less than 100 micron, B_{am} powders had a grain size less than 5 micron). The actual analytical model, given by an exponential formula, has only two parameters (C_o , γ) and the two MgB₂ samples obtained by the two different boron powders differ only for the C_o value. The model is:

$$J_c(B, T) = C_o (1 - (T/T_c)^2) \exp - (\gamma B / (1 - (T/T_c)^2)) \quad (2)$$

where $T_c=39$ K, $\gamma =0.7$ 1/T and $C_o= 600000$ A/cm² for B_{am} and $C_o= 400000$ A/cm² for B_{crys} . Higher critical current densities (up to 5÷7 time the original one) have been obtained at fields larger than 3T by doping MgB₂ with carbon black (2.5wt%), but with a concomitant reduction of the critical current density at the lower fields (about half). Therefore for not too large fields it is preferred don't use doped MgB₂.

IV. MAGNETIC RELAXATION

The very low grain boundary barrier to the superconducting currents of MgB₂ is beneficial either in reaching high current densities, either in minimizing the unwanted characteristics of the magnetic relaxation or flux creep, that affect the permanent superconductivity of all the HTS materials. The magnetic relaxation is critical in all the long term superconducting applications, as it is the passive shielding. The parameter which describes the magnetic relaxation rate is S:

$$S = - 1/M \Delta M / \Delta \text{Log}(t) \quad (3)$$

and it is a constant typical of the superconducting material. For the MgB₂ by Mg-RLI using B_{crys} , it was measured $S=0,00189$ @4.2K, 5.7 T [7], and it is previewed a lower value by using B_{am} . This value is smaller than the value of the textured REBCO cuprates by about a factor of 4. To give an order of magnitude of this magnetic relaxation phenomena it can be considered that @4,2K, 4 T the measured value $S= 0,00137$ corresponds to a decreasing of the trapped magnetic field or of the persistent currents of 1% in about two years.

V. SHIELDING APPLICATIONS

Even if for high-frequency varying fields (> 500 Hz) a classical shield can be made by a high conductive metal (like Al, Cu) which develops eddy currents, the low-frequency regime and the DC regime requires or a classical high permeability soft magnetic alloy (like mu-metal alloy: 77%Ni, 16%Fe, 5%Cu, 2%Cr) or a superconducting shield, when the magnetic fields are high enough or the weight of the magnetic alloy is a critical issue. Here we discuss briefly various applications where the passive superconducting shielding solution is of interest.

A) Low fields electronic devices and disturbances

Accurate magnetic field detectors (like SQUID) have sensitivity of the order 1÷100 nT, therefore any external magnetic field noises, DC or AC (typically at 50 Hz) must be shielded during the measurements. For example few years ago it was tested an MgB₂ cup like shield on a particularly wide SQUID detector operating at 3 K, with a gradiometric magnetic field pickup-loop of about 1mm² size, having a sensitivity of about 8 $\mu\Phi_0$ /rtHz, which corresponds to the field gradient baseline noise of about 5 pT/(cm rtHz). This device was shielded by an MgB₂ cup of about 30 mm inner diameter, obtained by Mg-RLI, and it was verified a shielding efficiency two times more than an equivalent Pb superconducting shield [8]. Indeed the higher critical temperature of MgB₂, respect to the LTS materials, guarantees that the superconducting shielding will not do a transition to normal state, in presence of even moderately high magnetic disturbances. (H_{c2} of Nb is about 700 mT at 4.2K). Furthermore the SQUID detectors can suffer from the flux penetration and trapping, that starts at the lower field H_{c1} , therefore it is critical also this critical field in the practical devices. MgB₂ shows different H_{c1} values in its various forms (single crystal, polycrystalline, thin film), but all are substantially higher than the Nb ($H_{c1} = 150$ mT at 4.2 K, versus 200-500 mT for MgB₂)

In the shielding of the biomedical advanced detectors for magnetoencephalography, for magnetocardiography, etc., superconducting shields have been already tested [9,10] but the majority of the commercial systems are

based on the classical magnetic shielding alloys, that would be necessary thick and less effective at low temperatures respect to a superconducting shield. If a properly cryogenic shield is introduced at the right position, it will be avoidable also the construction of Magnetic Shielding Rooms (MSR) which realize a complete field-free space but with demanding technologies, as it is realized for the world largest shielded room, in Berlin[11]. Therefore, the innovative cryogenic detector devices should profit of superconducting shields made by cups, cylinders, plates and various shapes of MgB₂.

B) High fields instrumentation

Many physics instrumentations or apparatus need to work in a fairly magnetic free environment, in the nearby presence of very high magnetic fields. An example are the large superconducting high field magnets for analytical NMR, made by several pancakes joined by superconducting alloys of very limited critical field. Today, the practical solution to realize these joints is to move far away the junctions from the fringing high field zone, even if this solution has the penalty of occupy a larger volume at cryogenic temperatures. A way to solve this problem should be to shield the joints with small MgB₂ hollow cylinders. To respond to this need it was measured the axial shielding capability of an MgB₂ cylinder, 70 mm height, 18 mm of hole diameter and 8.75 mm thickness, obtaining a complete shielding at the cylinder center, at 4.2K during ZFC (Zero Field Cooling) up to 2 T, with no presence of flux jumps[12]. More recently a hollow MgB₂ cylinder, made by RLI, was subjected to a transversal field up to 5 T at 4.2K, without the detection of any flux jumps. The vortex penetration was initiated at 0.6 T (lower critical field) and at 1.5 T the shielding was more than 70% of the applied field, including the stray field due to the transversal field disposition [13]. This level of shielding has been considered acceptable by CERN to protect a volume of about one dm³ containing the current measuring part of a new Superconducting DC Current Transformer, subjected to a stray field of about 0.5 T, mainly transversal [14]. As far as AC magnetic fields of frequency of the order of 50 Hz are considered, it was demonstrated that small MgB₂ cylinders can shield field up to 1 T [15]. If the shape of the MgB₂ magnetic shield need to be designed in a complex form and it requires the joining of several pieces, it will be possible to joint these superconducting pieces with the same Mg-RLI process [16].

C) Space applications

In the space applications, the magnetic shields must have the correct functionality and must be made of a light material. In this respect the MgB₂, with a density of about 2.4 g/cm³, is the lightest superconducting material of practical interest. One space application consists to

protect an infrared sensor and the nearby other instrumentation of the payload from the fringing field of a magnet (1.5÷2 T) used to cool, by an Adiabatic Demagnetization Refrigeration (ADR), the sensor at less than 100mK [17]. Furthermore due to volume limitations of the payload, the shield should be positioned very near to the magnet. A possible solution, in this case, to avoid a large reduction of the inner field of the magnet by the presence of the passive superconducting shield, it will be to design an hybrid shield, with an internal soft magnetic alloy to correctly shape the inner field, and with an external MgB₂ layer to drastically reduce the residual external fringing field.

Among the large scale space applications, there is a sort of scientific dream, exposed long time ago from the father of the astronautics, Wernher Von Braun [18], of the use of “mighty(superconducting)” magnets to deviate the giant solar flares of charged particles far from the spaceship. Can the light MgB₂ transform this dream in a prophecy? In this field, today there is also an European space research program to realize an active shielding by MgB₂ wires to protect a spaceship [19], but the technological achievements at our disposal can design also a shield made by bulk MgB₂ rings charged by repetitively compressed fields in a flux pump [20], therefore avoiding an on board current supply. Finally, the massive MgB₂ rings by the Mg-RLI process are mechanically strong enough, to require a minimum mechanical support. On the contrary the superconducting wires, either LTS or MgB₂, needed to construct the active shield, have a substantial proportion of metal sheaths that increase the overall weight of the superconductive winding.

VI. DISCUSSION AND PERSPECTIVES

The development of the HTS materials received a wider improvement by the advent in 2001 of the MgB₂: a HTS material of lower superconducting quality but much more easiness in production. Nevertheless the large effort that the superconductivity's research community is still dedicating to the cuprates and recently (from 2008) also to the iron based superconductors, has limited a rapid industrial development of this material. MgB₂ is today squeezed between the still well set industrial LTS materials, with NbTi and Nb₃Sn wires and Nb bulk and, on the other side, the HTS cuprates tapes and bulks. But the HTS cuprates, from 25 year, represent a continuous promise without market for their high cost. The use of MgB₂ is facilitated from the Mg-RLI manufacturing process and it is easy to predict that the first applications will be dedicated to the shielding of LTS magnets and apparatus. The main reasons for that are: a) the cool down of MgB₂ shields can profit of an already set cooling system; b) the passive shielding don't need any technical design of supplementary current leads. With respect to the passive shielding made by LTS materials, like Nb or

NbTi sheaths, MgB₂ is much more light and it has a higher value of the lower critical field, so that the penetration and trapping of vortices is delayed. To mention the weaknesses of MgB₂, which must be taken into account in the bulk applications, the main issue is due to the brittleness of the material. As for the other ceramic materials, MgB₂ has a very low strain to rupture (about 0.3%), even if its stress intensity factor, K_{1C}, can reach values in the range of several MPa m^{1/2} [21], similar to ceramic composites. Other weaknesses are related to the MgB₂ small heat capacity, at low temperature, that can generate at temperature ≤ 10 K, flux jumps, similar to the other LTS materials. To avoid the flux jumps one can apply two alternatives: to introduce inside the material non superconducting impurities that reduce the wideness of the current paths; or to divide the shield in thin rings glued by a metal, like Mg, thinner than the thermodynamical thickness, above which there isn't cooling power to stop the catastrophic growing of a normal zone of the flux jump. The interesting features of the initial experimentation on the shielding properties on MgB₂, by Mg-RLI, are that the flux jumps are very limited, probably due the intrinsic composite nature of these products.

REFERENCES

- [1] H. Wada, M. Sekino, H. Ohsaki, T. Hisatsune, H. Ikehira, and T. Kiyoshi, "Prospect of High Field MRI" *IEEE Trans. on Appl. Supercon.* **20**(3), 115-122 (2010)
- [2] A Serquis, L Civalè, JY Coulter, DL Hammon, XZ Liao, YT Zhu, DE Peterson, FM. Mueller, VF Nesterenko, and SS Indrakanti, *Supercond. Sci. Technol.* **17**, L35-L37 (2004)
- [3] G. Giunchi "High density MgB₂ obtained by reactive liquid Mg infiltration" *Int. Jour. of Mod. Phys. B* **17**, Nos 4,5 & 6 453-460 (2003)
- [4] G. Giunchi, G. Ripamonti, T. Cavallin, E. Bassani "The reactive liquid Mg infiltration process to produce large superconducting bulk MgB₂ manufactures" *Cryogenics* **46**, 237-242 (2006)
- [5] J. Nagamatsu, N. Nakagawa, T. Muranaka, Y. Zenitani, J. Akimitsu, *Nature* **410**, 63 (2001).
- [6] G. Giunchi, S. Ceresara, G. Ripamonti, S. Chiarelli, and M. Spadoni "MgB₂ Reactive Sintering From the Elements" *IEEE Trans. on Appl. Supercond.*, vol. 13, no. 2, June 2003 [1]
- [7] Z. Y. Zhang, S Choi, S Matsumoto, R Teranishi, G Giunchi, A Figini Albisetti, and T Kiyoshi "Magnetic Amplifiers Using Different MgB₂ Bulk Superconductor" *Supercond. Sci. Technol.* **25**, p 025009, (2012)
- [8] G. Giunchi, E. Bassani, J. Hassel, P. Helistö, J. Penttilä "MgB₂ cylindrical cup for magnetic shielding in pulse tube cryostat" *Adv. in Cryo. Eng.: Trans. of CEC*, vol 55, 1636-1640, (2010)
- [9] J Luomahaara, P T Vesanen, J Penttila, J O Nieminen, J Dabek, J Simola, M Kiviranta, L Gronberg, C J Zevenhoven, R J Ilmoniemi and J Hassel "All-planar SQUIDS and pickup coils for combined MEG and MRI" *Supercond. Sci. Technol.* **24** (2011) 075020
- [10] Panu T. Vesanen, et al. "Hybrid Ultra-Low Field MRI and Magnetoencephalography System Based on a Commercial Whole-Head Neuromagnetometer" *Mag. Res. in Medicine* **69**:1795–1804 (2013)
- [11] Silvia Knappe-Grueneberg, Allard Schnabel, Gerd Wuebbeler, and Martin Burghoff "Influence of demagnetization coil configuration on residual field in an extremely magnetically shielded room: Model and measurements" *Journal of Applied Physics* **103**, 07E925 (2008)
- [12] J.J.Rabbers, M.P.Oomen, E. Bassani, G. Ripamonti, G. Giunchi "Magnetic shielding capability of MgB₂ cylinders" *Super. Sci. Technol.*, **23**, p 125003, (2010)
- [13] G. Giunchi, G. Montenero, A. Figini Albisetti, A. Ballarino "Magnetic shielding and field trapping of a superconducting MgB₂ cylinder in a transversal field" Paper 4MPo2B-07, ASC 2014, Charlotte (NC), 14/8/2014, and submitted to IEEE TAS.
- [14] P. Arpaia, A. Ballarino, G. Giunchi and G. Montenero "MgB₂ cylindrical superconducting shielding for cryogenic measurement applications: a case study on DC current transformers" *J. of Instrumentation* **9**, P04020 (2014)
- [15] T. Cavallin, R. Quarantiello, A. Matrone, G. Giunchi "Magnetic shielding of MgB₂ tubes in applied DC and AC field" *Journal of Physics: Conference Series* **43** (2006) 1015–1018
- [16] G. Giunchi, L. Saglietti, G. Ripamonti, A. Figini Albisetti, E. Bassani, and E. Perini "Superconducting Joints Between MgB₂ Wires and Bulks" *IEEE Trans. on Appl. Supercond.*, vol. 20, No. 3, June 2010
- [17] T. Prouvé, J.M. Duval, N. Luchier, S. D'Escrivan "Experimental results on MgB₂ used as ADR magnetic shields, and comparison to NbTi" *Cryogenics* (in press) Available online 3/4/2014
- [18] Wernher Von Braun "Will mighty magnets protect voyagers to the planets" *Popular Science*, pp98-100&198 (January 1969)
- [19] SR2S (Space Radiation Superconducting Shield) EU Seventh Research Programme, G.A.#313224. Three years program, started January 2013.
- [20] A. F. Hildebrandt, D. D. Elleman, F.C. Whitmore, and R. Simpkins "Some Experimental Consequences of Flux Conservation within Multiply-Connected Superconductors" *J.App.Phys.* **33**(7)(1962)2375-2377
- [21] G. Giunchi, G. Ripamonti, E. Perini, S. Ginocchio, E. Bassani and T. Cavallin, "Highly densified MgB₂ bulks by reactive Mg liquid infiltration" *Advances in Science and Technology* Vol. 47 (2006) pp. 7-16