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An MgB₂ superconducting shield for a cryogenic current comparator working up to 34 K

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Abstract

Preliminary results of measurements performed on two bulk MgB₂ cylinders intended for use as toroidal magnetic shields with a novel cryogenic current comparator are reported up to 37 K, showing an attenuation factor greater than 10⁶ at 27 K, lowering by a factor of 10 at 34 K.

1. Introduction

A cryogenic current comparator (CCC) able to operate at temperatures higher than the traditional design working with liquid helium will represent a substantial improvement in metrological laboratories. Previous studies for producing magnetic shields, intended for static fields or low frequencies, were performed at INRIM⁴, by depositing thick layers (50–100 µm) of YBCO on silver substrate via hypersonic thermal spray (HVOF) [1, 2] or electrophoretic [3] techniques. At 77 K, the attenuation factors, measured on elongated cylinders covered by the YBCO thick films, were ranging from 10³ to 10⁵, at best, depending on the deposition technique (compared with the 10⁴–10⁵ literature values for bulk YBCO). The maximum shielded magnetic fields were in the range of a few tenths of a millitesla. Specific studies were later performed at INRIM [4] for developing a shield for CCC suitable for HTS fabrication, by adapting the needs of the CCC to the constraints placed by the brittle nature of the HTS. These studies brought us to a geometry consisting of an open torus with elongated U-shaped coil recess (two such tori are used, one capping the other and with opposite (180°) openings). Figure 1 reports a cross section of one open torus, which requires some special fabrication procedures whose description is beyond the scope of this communication, and the attenuation factor computed with a mathematical model. These data dictate a substantial improvement in the material characteristics, for a high-temperature system becoming competitive with the traditional low-temperature CCC. Recent new studies have been started in order to obtain better characteristics while using the specific geometry shown in figure 1(a). We now present a new approach using bulk MgB₂ as superconducting material, working at temperatures up to 34 K and we illustrate its first measured relevant magnetic shielding capabilities, which are very promising for future CCC developments.

2. CCC shield implementation with MgB₂

The fabrication of the shield geometry of figure 1(a) is much simplified when bulk MgB₂ is used.

Indeed this new superconducting material can be densified at about 90% of the theoretical value by applying the reactive liquid Mg infiltration (RLI) technology, invented in the EDISON Laboratories [5]. This is based on a pressureless process of in situ type, in which the liquid Mg infiltrates a preform of boron powders: both Mg and B located inside a sealed metallic container. Designing the shape of the boron preform similar to the target open torus magnetic shield of figure 1(a), we are able to manufacture a semi-finished object that requires minimal machining operations to reach the final shape. The reaction takes place at 850 °C and is held...
for 2 h. The resulting MgB$_2$ shield can be extracted from the metallic container by the usual lathe turning operations and electroerosion process if accurate dimensions must be obtained. In the present case we have prepared two prototype open torus MgB$_2$ shields of slightly different dimensions (#1: L50 x D,49 mm; #2: L110 x D,32 mm), leaving in influent metallic external sheaths.

The polycrystalline MgB$_2$ material resulting from the RLI process has very good crystalline grain connectivity and can sustain very high currents in a persistent way [6, 7]. This characteristic is peculiar to the MgB$_2$ and renders the material more interesting, even in the presence of the penalty of a lower critical temperature with respect to superconducting oxides, which require a costly grain texturing process to reach high current densities.

A further peculiarity of the RLI process in the CCC application is the relatively easy to produce slots in the shield with low width-to-height ratio, so that it is likely to obtain a high attenuation rate.

3. Experimental set-up and preliminary results

Since the transition temperature is close to 38 K, a liquid or solid cryogen as the cooling means is not convenient. It is much simpler to take advantage, nowadays, of a closed-cycle refrigerator. In principle a single-stage refrigerator could nowadays reach these low temperatures. However, also for the purpose of studying the change of the shielding capabilities with temperature, a two-stage refrigerator with base temperature close to 10 K was used at INRIM to characterize two shields.

For the purpose of the shielding measurements, the toroidal shields were used before cutting the longitudinal opening needed for use in a CCC, so that the measurements are performed on closed circular cylinders with inner slot of height-to-width ratio of about 16 for #1 and 25 for #2.

A fluxgate triaxial sensor was used for the measurements: the present noise limit of the sensor was about 0.1 mOe due to an imperfect shielding of the wiring connecting it to the measuring instrument, having a maximum full scale of 1.2 Oe.

The sensor is placed axially to the cylinder and can be moved up and down to explore more than the full length of the cylinder, the usual technique used to test hollow cylinders [2].

One coil, 10 mm high, was placed at the bottom of the recess and particular care was taken to ensure that the wires bringing the current to it do not produce, within the sensitivity, any cylinder-axis component.

Measurements were performed first by mapping the field produced by the coil with the material in the non-superconducting state: the maximum generated external field was limited to 100 Oe due to the maximum steady current allowed in the field-generating coil, correspondingly limiting the maximum measured attenuation factor to 10$^6$, due to the noise of the fluxgate. Then the shield was brought below its transition temperature, which was observed to occur at about 37 K for #1 and >37 K for #2, less than a kelvin narrow. The inner field with the shield superconducting was measured at 27 K for #1 and at several temperatures from 27 to 37 K for #2.

At 27 K no inner field increase with the coil current up to its maximum was observed over the full length of the cylinder (the local earth’s magnetic field being trapped in) of the cylinder axis. These results correspond to an attenuation factor higher than 10$^6$.

On the other hand, by repeating the measurements for higher temperatures on #2, the maximum attenuation factor was observed to decrease as shown in figure 2. Above this temperature, the attenuation factor abruptly started accelerating its rate of decrease, indicating that the superconducting transition is effectively starting to occur above about 34.5 K.

4. Conclusions

The present results indicate that the adopted geometry is suitable for the fabrication of a CCC with HTS superconducting shield, using bulk MgB$_2$ produced by RLI technology. Further work is merely necessary to find the actual attenuation factor limit beyond the present limit of...
10°, improving the noise level of the fluxgate probe, also in order to compare these results with previous studies [7] on the temperature dependence of $J_c$.

As the final step in the CCC shield development, the cylinder will be cut and capped with a second slotted cylinder and the residual field produced by two opposite identical currents will be measured by coupling the fluxgate probe to the internal bore, and eventually using a high-$T_c$ SQUID for the same purpose.

References


