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Experimental and 2D/3D modeling investigation of DC magnetic shielding by machinable MgB_2 bulks

By

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Abstract

The main purpose of this thesis is to investigate and to exploit the superconducting properties of magnesium diboride (MgB_2) bulk samples with the aim to develop magnetic shields meeting the practical requirements of both high shielding factors and space-saving solutions. The project involves both an experimental and computational point of view. Experiment outputs give a first hint on the shielding ability of specific compositions/shapes as well as the parameters needed to model the material (e.g. the magnetic field dependence of the critical current density, $J_c(B)$). The numerical analysis aims to guide the design of more efficient magnetic shields and to predict their performance as a function of the magnetic field and temperature.

In more detail, the shielding properties of an open and a single-capped MgB_2 tube (the former henceforth denominated just tube and latter cup) with an aspect ratio of height to diameter close to one were experimentally characterized by means of cryogenic Hall probes. The samples were obtained by Spark Plasma Sintering (SPS) [**?**] of commercial MgB_2 powder of different purity mixed with hexagonal boron nitride (BN). Moreover, the characterization of a hybrid tube-shaped shield, obtained by superimposing a soft Fe shell on the MgB_2 tube, was performed as well. The magnetic flux density was measured at fixed positions along the axis of the shields in both axial (AF) and transverse (TF) field orientations. These measurements allowed the evaluation of the shielding efficiency providing the shielding factor, i.e. the ratio of the applied magnetic field to the measured magnetic flux density. From the same measurements, the dependence of the superconductor critical current on temperature and magnetic flux density was calculated as well (needed also for modeling the material). These measurements highlight two weaknesses of these shields: a huge decrease of their shielding ability when the applied field is tilted away from the screen axis and the occurrence of thermo-magnetic instabilities (namely, flux jumps) that cause abrupt magnetic field penetration inside the samples.

To investigate how overcoming these bottlenecks without useless experimental trials, a computational approach was adopted. To model the electromagnetic behaviour of the superconductor, a computational approach able to predict the shielding behaviour of the bulks placed either in the axial or transverse applied field orientation was chosen. While the former orientation can be modelled by a 2D axisymmetric simulation, the latter needs a 3D approach. For this purpose, a 3D simulation study was implemented by means of the commercial finite-element software COMSOL Multiphysics® [**?**]. Therefore, a numerical procedure based on the 3D vector-potential (**A**) formulation described in [**?**] was applied, assuming an electric field-current density (E-J) relation approximating the critical state in the superconductor.

To validate this modeling approach, two strategies were adopted. At first, I numerically analysed the shielding capability of superconducting tube- and cup-shaped shields, with dimensions replicating that of the samples experimentally characterized. Their shielding properties were calculated both in AF and TF orientations. In the case of the superconducting tube, the effect of the superimposition of a shorter ferromagnetic (FM) tube was also investigated. Simulation data were then compared with those previously measured experimentally on the same shielding arrangements, evidencing a good agreement. Then, I compared the results achieved on the tubular geometry with the above-mentioned A-formulation approach with those attained with the most used and already validated, 3D magnetic field (**H**) formulation (still implemented by means of COMSOL Multiphysics®). A good agreement was again obtained in AF, TF and intermediate field orientations, also evidencing how the adopted **A**-formulation is more advantageous in terms of time consumption.

Afterwards, I applied this as-validated model for investigating the shielding ability of new screening configurations. In particular, exploiting the peculiarity of FM tubular samples to provide high SFs in transverse field geometry [**? ?**], I focused on hybrid arrangements, consisting of two coaxial cylindrical shields assumed made of MgB_2 (SC shield) and soft Fe (FM shield) having either equal or different heights. This analysis evidenced that the positive/negative effect of the addition of the FM shell strongly depends on the field orientation and on the relative height of the two components. In particular, the comparison between the shielding performances of these new hybrid configurations and the SC-only shields highlighted how the superimposition of a ferromagnetic shell is very efficient in mitigating the strong decrease of the superconductor shielding ability even for small tilt angle of the applied field.

The last numerical study focuses on the prediction of thermo-magnetic instabilities via a numerical multiphysics analysis, coupling the magnetic study based on the **A**-formulation with a thermal one. This approach allowed me to predict and study the flux jumps phenomena, already observed during the experimental measurements. In particular, taking advantage of the cylindrical symmetry of the investigated layouts and since the flux jumps were experimentally observed only in the AF orientation, a 2D axisymmetric model was implemented in the software package. The model was validated by comparing the computational outputs with the experimental results measured at different operational temperatures, namely 20 K, 25 K, and 30 K. The analysis shows an excellent agreement between the measured and calculated data, proving its reliability in reproducing the experimental shielding factor curves and their abrupt decrease caused by the flux jump events. The as-validated model was then used to investigate possible solutions to mitigate or even avoid the flux jump occurrence, such as enhancing the material thermal conductivity and the heat exchange with the cooling stage.