Superconductive and hybrid shielding design: a 3D-modeling study

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Bulk superconductors have recently found a mighty application in magnetic shielding [1] and MgB_2 has been proved to be a very promising option, allowing the fabrication of large and suitable-shaped samples [2]. For this purpose, a combination of modelling procedure and growth technique able to manufacture properly shaped products with high and homogeneous critical current density, can be a successful approach guiding the whole optimization process.

In this work, we exploit a 3D modeling procedure based on a vector potential formulation by finite element calculations with COMSOL Multiphysics® [3] to calculate the shielding properties of cup-shaped superconductors (SC) with and without the superimposition of a ferromagnetic (FM) shield. Relying on the past validation of the model [4], this numerical procedure was applied to explore new shield design with similar aspect ratio but optimized performance. The shielding efficiency of three different cup-shaped arrangements were compared both in axial-field (AF) and transverse-field (TF) configurations, studying the effect of superimposing ferromagnetic vessels of different sizes around the superconductor.

In particular, focusing on the most efficient hybrid arrangement, we investigated the effects of ferromagnetic shield addition for different angles of the applied magnetic field and compared the results with that obtained with the only SC arrangement.

Modelling

Superconducting shield modelling

- Finite element method (FEM) solving A-V Formulation by COMSOL Multiphysics® [5]
- Ensuring the collinearity between the current density and the local electric field [6] and considering an isotropic J_c the current density is related to the electric field, and, therefore to the time derivative of **A** by

$$\vec{J} = \frac{J_c}{|E|}\left(|E_x|\tanh\left(\frac{E_x}{E_0}\right)\hat{\imath} + |E_y|\tanh\left(\frac{E_y}{E_0}\right)\hat{\jmath} + |E_z|\tanh\left(\frac{E_z}{E_0}\right)\hat{k}\right)$$

- The J_c behaviour was modelled by

$$J_c(B) = J_{c,0}\,exp\left[-\left(\frac{B}{B_0}\right)^{\gamma}\right]$$

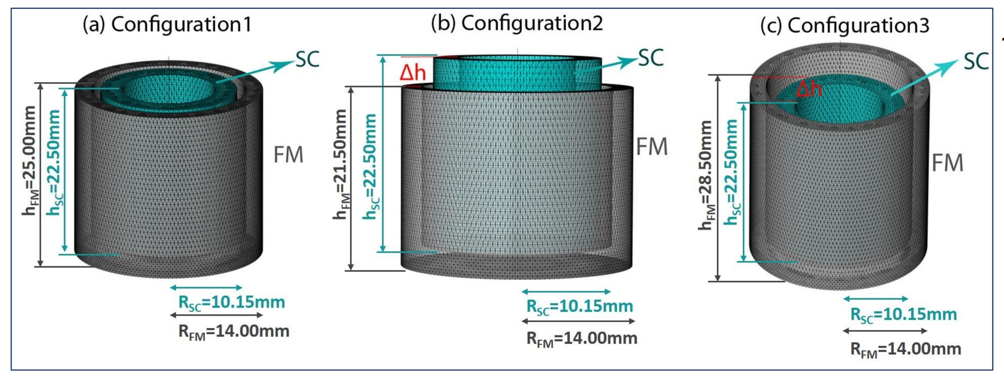
where $J_{c,0}$ = 5,02*10⁸ A/m², B_0 = 0,98 T and γ = 3,78 are the constant parameters obtained fitting the experimental curves at T = 30 K [7].

Ferromagnetic shield modelling

Ferromagnetic shield made out of Fe ARMCO and modelled starting from its experimental BH curve.

Effect of different arrangements

The model validation is presented in [4] and it allows to implement the computational procedure in order to explore new hybrid (SC+FM) configurations. Based on previous study outcomes [8], [9], the performances of three different cup-shaped arrangements were investigated in both AF and TF configurations.

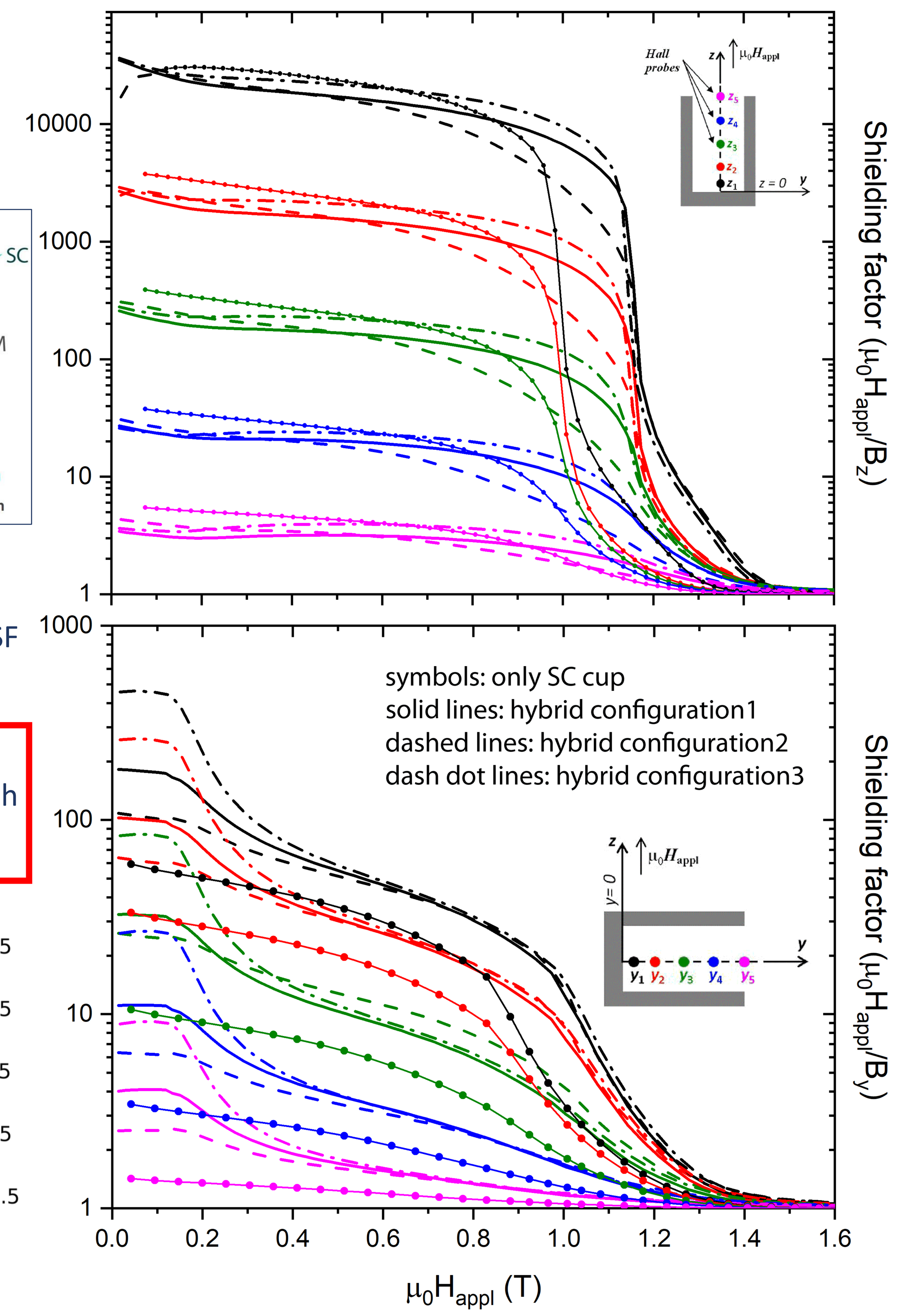


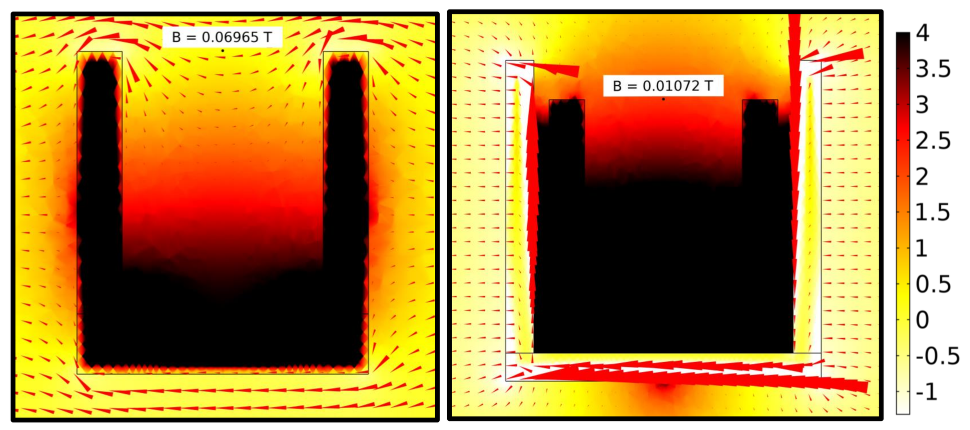
AF configuration

Adding FM sheet enlarges the high-shielding region up to a field of ≈ 1.2 T, even though at lower fields higher values of SF can not be gained.

TF configuration

Low transverse field: best performance → from **SF ≈ 50** with only SC to **SF=450 using Configuration3**

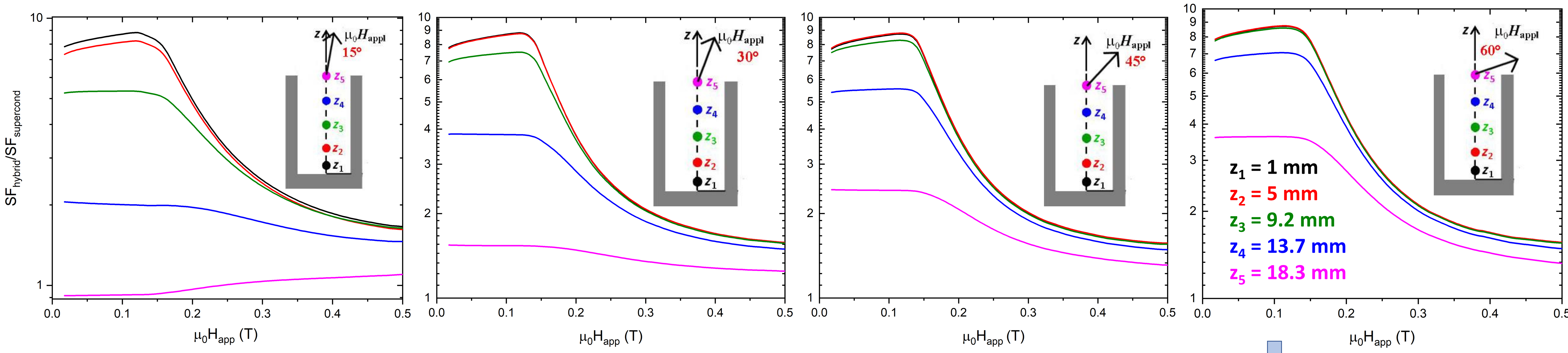




log(SF)=log($\mu_0 H_{appl}$/|B|) (surfaces) and the magnetic flux flow (arrows) plotted at 0.1 T for TF configuration

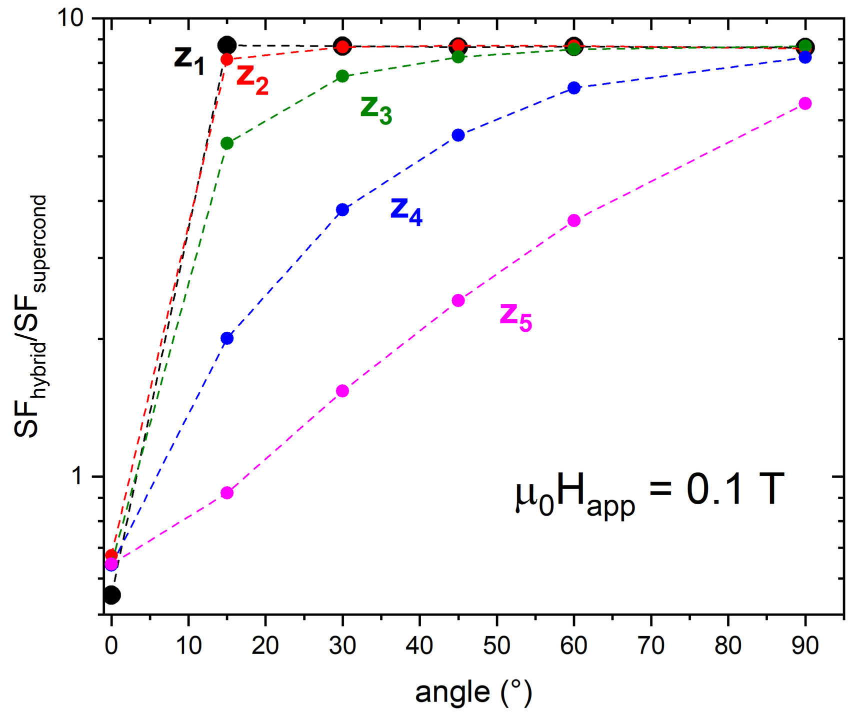
Study of different angles of H_{appl}

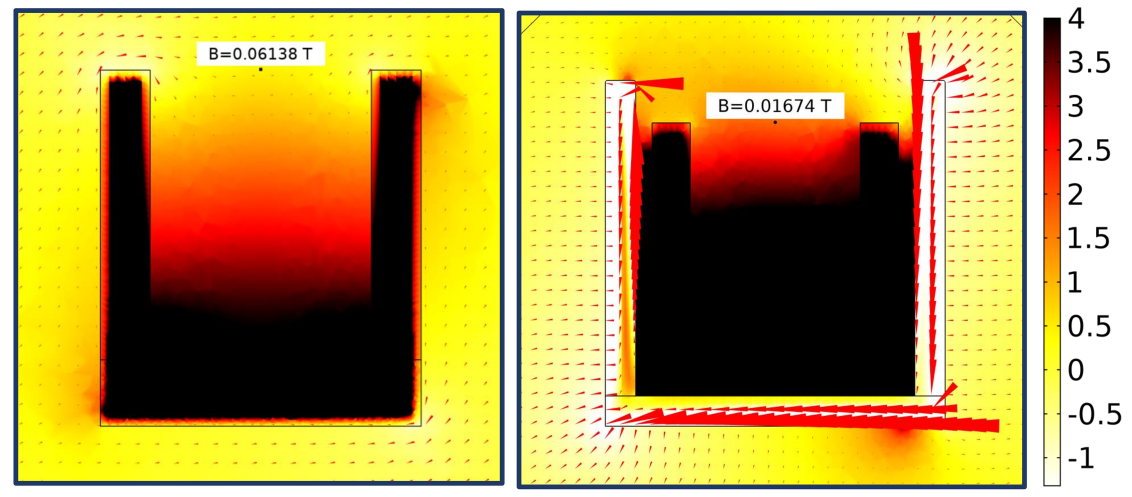
The shielding performances of only SC cup and hybrid configuration3 (i.e. the hybrid configuration were the best performance are expected) are investigated for different angles of the applied magnetic field, namely 15°, 30°, 45° and 60° with respect to the cup axis. We focused on low applied field, where the use of a hybrid configuration could be dubious.



The addition of FM cup can improve the shield efficiency of the only SC arrangement, reaching SF_{hybrid} values up to 8 times greater than $SF_{supercond}$, for each H_{app} angles. In particular:

- for the inner probes z_1 and z_2 a constant gain is reached by using the FM addition
- for the outer probes z_3, z_4, and z_5 improvements are obtained with increasing angles of magnetic applied field





log(SF)=log($\mu_0 H_{appl}$/|B|) (surfaces) and the magnetic flux flow (arrows) plotted at 0.1 T for H_{app} at 60°

Conclusion

1. New and efficient geometries can be investigated by 3D modelling
2. **AF configuration for only MgB_2 cup**
   - In the inner half of the shield: T = 30K **SF > 10²** up to $\mu_0 H_{appl}$ ≈ 1.0 T
   - Near the closed extremity: T = 30K **SF > 10⁴** up to $\mu_0 H_{appl}$ ≈ 1.0 T
   - **Ferromagnetic shield addition**

     ⇨ allows the persistence of a great-SF region up to a field of ≈ 1.2 T but decreases the SF at low field
3. **TF configuration for only MgB_2 cup**
   - In the inner half of the shield: T = 30K **SF > 7** up to $\mu_0 H_{appl}$ ≈ 0.4 T
   - Near the closed extremity: T = 30K **SF > 40** up to $\mu_0 H_{appl}$ ≈ 0.4 T
   - **Ferromagnetic shield addition**

     ⇨ allows the persistence of a great-SF region up to a field of ≈ 1T

     ⇨ low field: improved performance → from SF=40 to SF=120 (configuration2) and to **SF=450 (configuration3)**
4. **H_{app} angles between 0° and 90°**
   - The addition of the FM shield always improves the performance of the structure
   - Near the closed extremity of the shield the enhancement is almost independent from the angle, whereas it increases with the angle near the open extremity

References

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