Modeling of ferromagnetic/high-Tc superconductor structures for shielding applications

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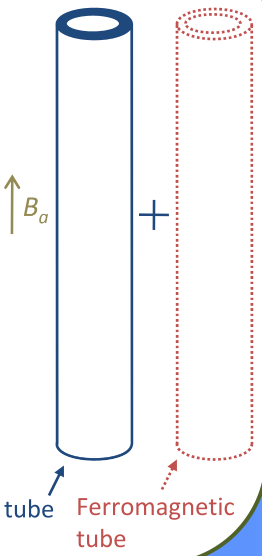
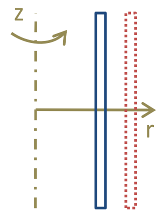
Introduction

When subjected to a uniform magnetic flux density, ferromagnetic materials can be regarded as magnetic flux concentrators. In the same magnetic environment, high-temperature superconductors (HTS) rather expel the surrounding magnetic flux. Putting these materials together in macroscopic hybrid ferromagnetic / superconductor structures enables for significant improvements of the magnetic properties of each materials considered separately.

In particular, we study in this work how ferromagnetic tubes could enhance the shielding properties of HTS tubes subjected to a uniform magnetic field parallel to its axis.



1. Numerical method



- ***Axisymmetric*** *geometry*
- *Uniform magnetic field parallel to z-axis that* ***varies linearly with time*** *(1mT/s)*
- ***Finite-element*** *(FEM) simulations based on a formulation in vector potential* $\mathbf{A} = A\mathbf{e}_\theta$

$$\nabla \times \left(\frac{1}{\mu(r,z,A)}\nabla \times A\right) = -\sigma(A)\frac{\partial A}{\partial t}$$

2.Materials parameters

Superconductor (Bi-2223)

Height : 80 mm
Internal radius : 6 mm
Wall thickness : 1.6mm

Power law conductivity + Kim model

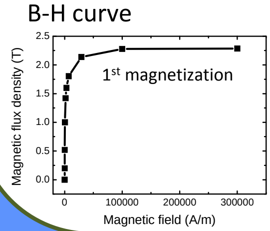
$$\sigma(A) = \frac{J_c}{E_c^{1/n}}\left(-\frac{\partial A}{\partial t}\right)^{\frac{1-n}{n}}$$

$$Jc = \frac{J_{c0}}{1+|\mathbf{B}|/B_1}$$

n= 25
$B_1 = 5$ *mT*
$J_{c0} = 1.782\ 10^7$ *A/m²*

Soft ferromagnetic tube (1020 steel)

B-H curve

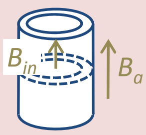


Thickness of the tube : 1 mm

μ is obtained from a fit on experimental B-H relationship

3. Shielding properties of single tubes

Shielding factor of a tube (*SF*)



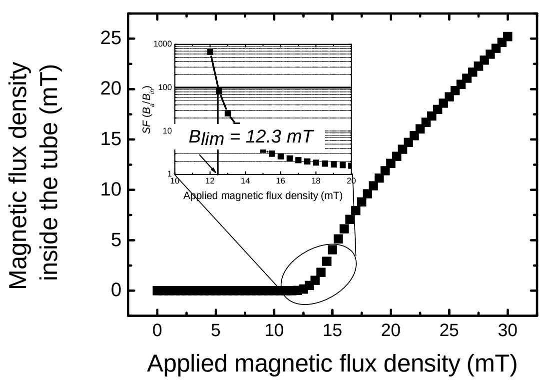
SF = B$_a$/B$_{in}$

B_a : uniform applied magnetic flux density
B_{in} : magnetic flux density measured at the center of the tube

Definition of the shielding limit (B_{lim})

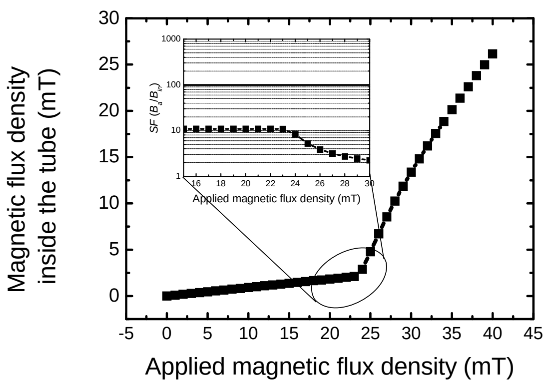
B_{lim} is the applied magnetic flux density such that ***SF = 100*** [1]

Superconductor (Bi-2223)



- *B_{lim} = 12.3 mT*
- *SF_{HTS} > 10^2* if *B* < *B_{lim}*
- **Very good shielding properties**

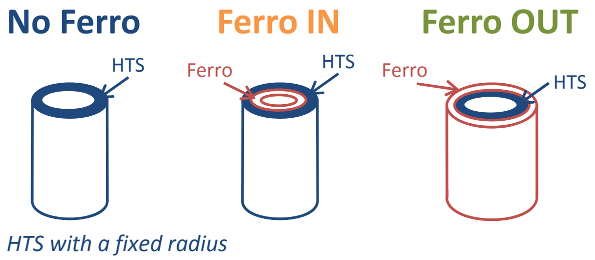
Soft ferromagnetic tube



- *B_{lim}* cannot be defined in this case
- *SF_{Ferro}* constant when the tube is not saturated
- **A ferromagnetic tube is a less efficient shield**

[1] Denis S *et al. 2007 Supercond. Sci. Technol.* **20** 192

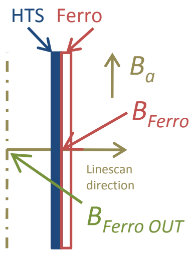
4. Ferromagnetic tube inside or outside the HTS tube ?



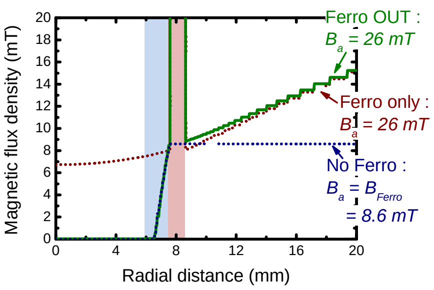
Ferro OUT

In this configuraton, B_{lim} is increased by a factor of ~2 as compared to the HTS tube alone

Ferro OUT = direct combination of shielding properties of the HTS tube and of the ferromagnetic tube considered separately

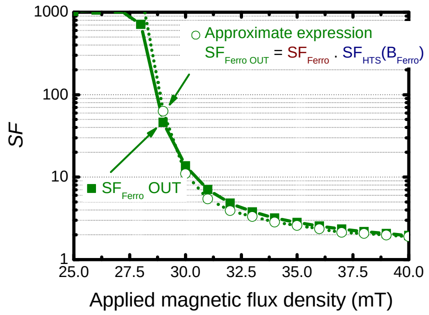


Magnetic flux profile (@center)



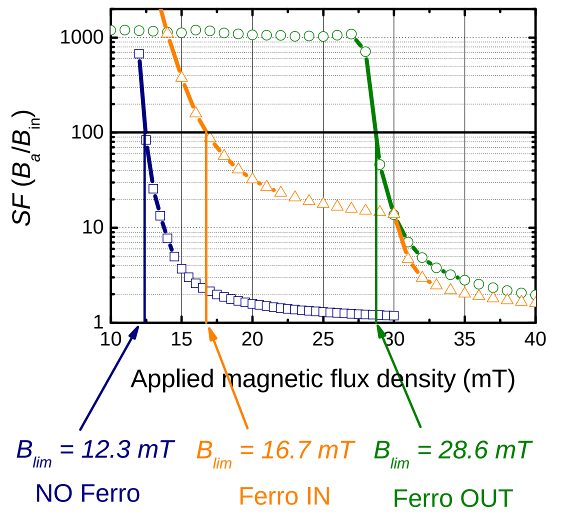
$$B_{Ferro\ OUT} \approx B_{Ferro} \cdot SF_{HTS}\,(B_{Ferro})$$
$$\approx B_a \cdot SF_{Ferro} \cdot SF_{HTS}\,(B_{Ferro})$$

Approximate expression for the shielding factor



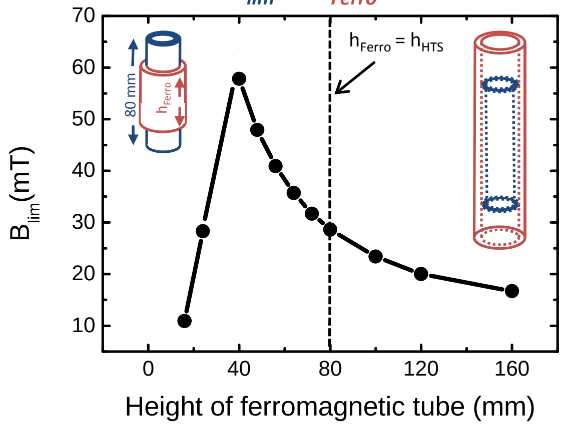
In the Ferro OUT configuration, the SF of the hybrid tube is approximately given by the product of the SF of the single tubes

Comparison of the shielding limit (B_{lim})



5. Influence of the height of the ferromagnetic tube (Ferro OUT)

B_{lim} vs h_{Ferro}

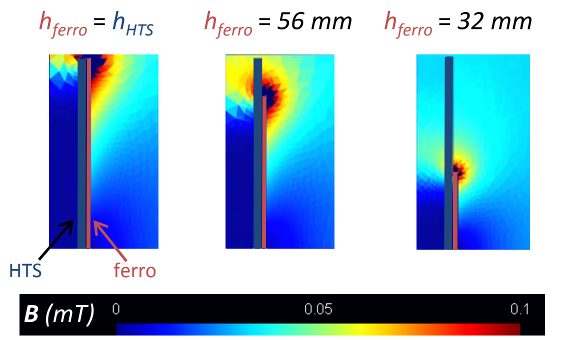


HTS with a fixed height (80 mm)

B_{lim} is increased by a factor ~ 2 when h_{Ferro} = 40 mm

Distribution of the magnetic flux density

*(Norm of **B**)* B_a = 22 mT



Reduction of the shielded domain if h_{Ferro} is reduced

Acknowledgments

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