HTS 2020 Modelling

7th International Workshop on Numerical Modelling of High Temperature Superconductors
22nd – 23rd June 2021, Virtual (Nancy, France)

Superconducting and hybrid magnetic shields: from comparison between 3D modelling and experiment to the numerical analysis of new shielding configurations

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Politecnico di Torino 1859

INFN Istituto Nazionale di Fisica Nucleare SEZIONE DI TORINO

Outline

- Motivation and starting point
- 3D modelling
- Comparison between experiment and computation results
  - ✓ Axial and transverse field configuration
  - ✓ Different shapes
  - ✓ Superconducting and hybrid (superconducting/ferromagnetic) shields
- Numerical analysis of new hybrid shield configurations
- Conclusions

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Low-frequency magnetic fields shielding …

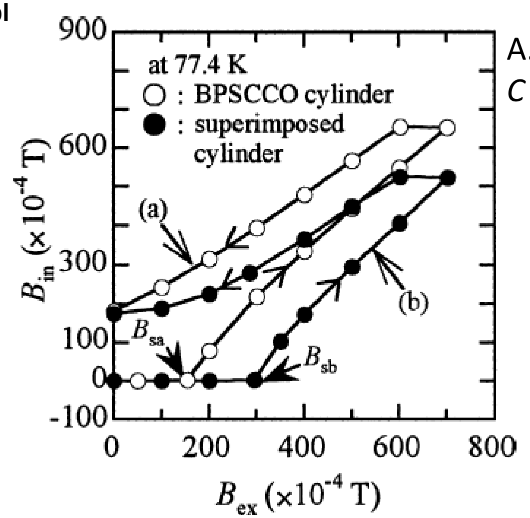
- is crucial for:
  - **electromagnetic noise - stray field reduction** → equipment integration/compatibility
  - **low magnetic field background** → protection of magnetic field sensitive detectors

- **can be achieved (passive solutions) using:**
  - **ferromagnetic (FM) materials**
  - **superconducting (SC) materials**
    - **SC cuprates (YBCO, BSCCO)**
    - **MgB_2**

J-F. Fagnard et al., *SUST* 23 (2010) 095012
L. Wéra et al., *IEEE TAS* 27 (2017) 6800305
CAN SUPERCONDUCTORS - https://www.can-superconductors.com

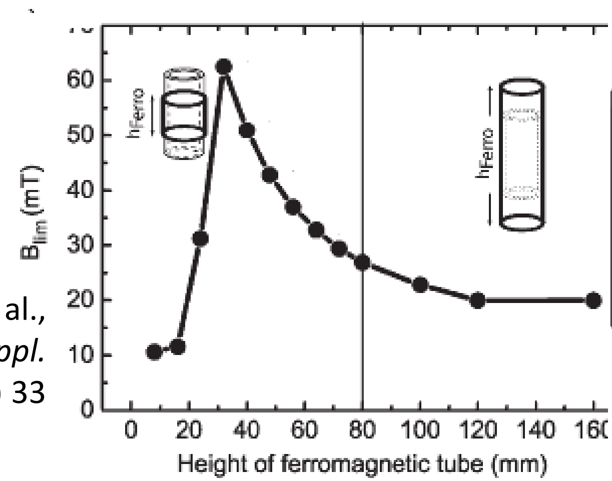
J. J. Rabbers et al., *SUST* 23 (2010) 125003
G. Giunchi et al., *IEEE TAS* 28 (2018) 6801705
L. Gozzelino et al., *SUST* 33 (2020) 044018

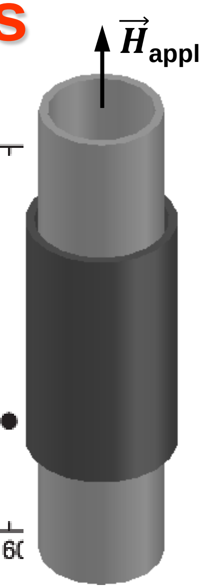
Hybrid solution: SC-FM superimposed shields



A. Omura et al., *Physica C* 386 (2003) 506

G.P. Lousberg et al., *IEEE Trans. Appl. Supercond.* 20 (2010) 33





samples with small aspect ratio

(1.5 < AR < 2.5) of height/outer radius

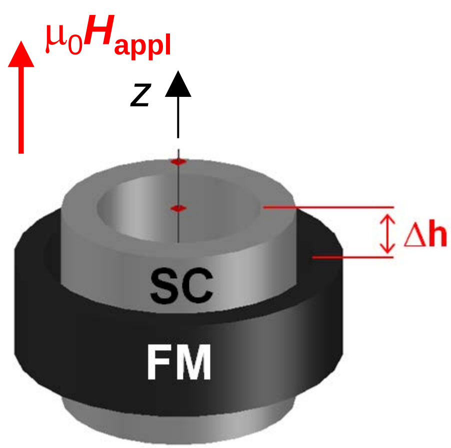
SC inner radius: 7.0 mm

SC outer radius: 10.0 mm

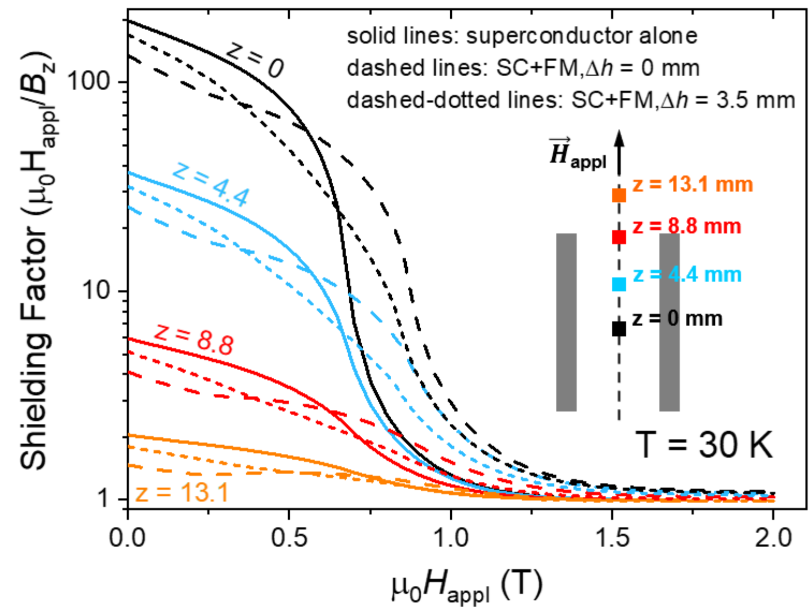
SC Height: 17.5 mm

FM inner radius: 11.5 mm

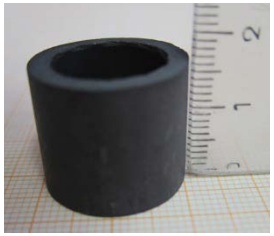
FM outer radius: 7.0 mm



MgB_2 /Fe ARMCO



Effect of magnetic field orientation



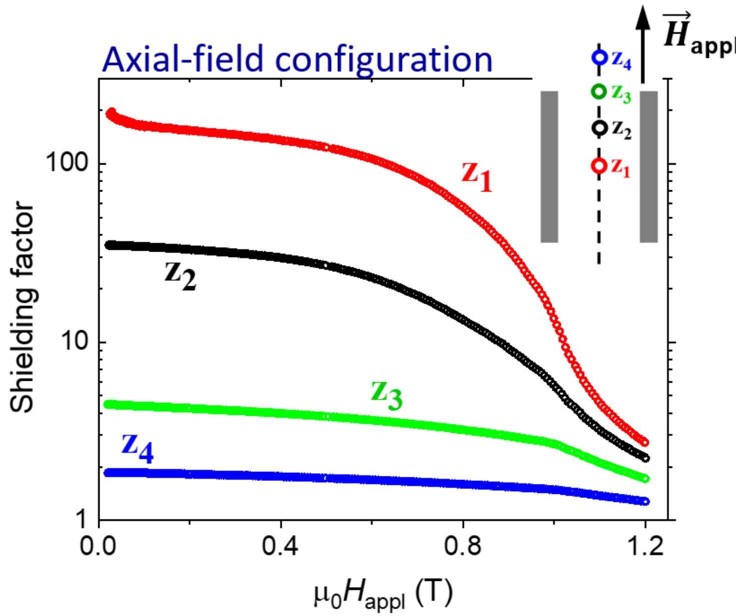
MgB_2 tube

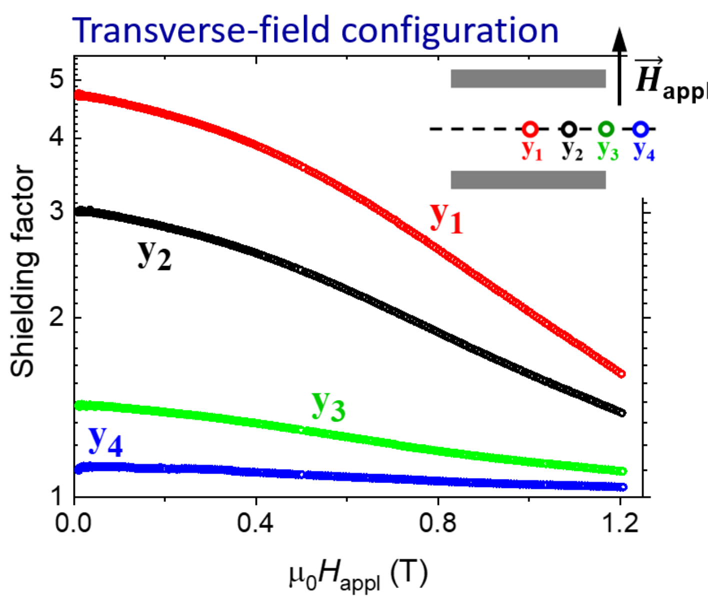
Inner radius: 7.0 mm

Outer radius: 10.0 mm

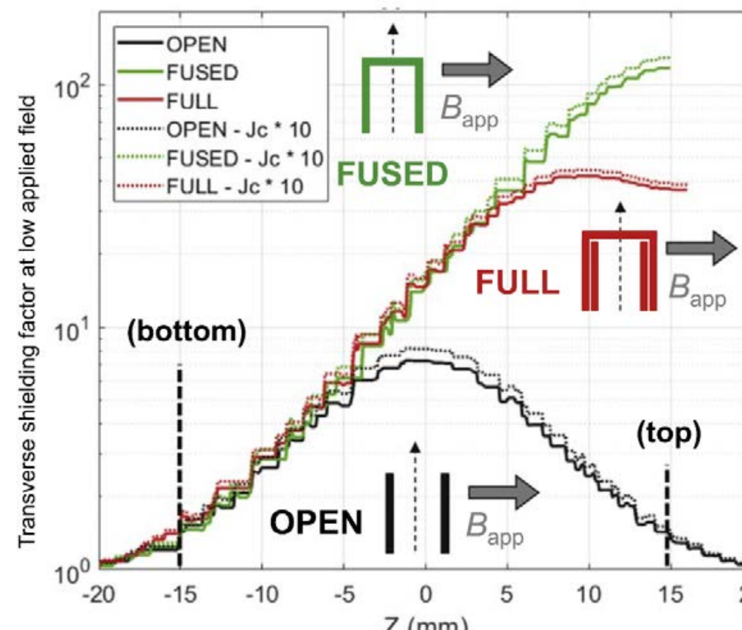
Height: 17.5 mm

L. Gozzelino et al., *SUST* 32 (2019) 034004





Choice of sample geometry is crucial to optimize the shielding performance in relation to the field orientation



J. F. Fagnard et al., *SUST* 32 (2019) 074007

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- **Superconductor 3D modelling**
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3D modelling

To model the **superconductor** :

- $\vec{A}$-formulation based procedure

A.M. Campbell, *Supercond. Sci. Technol.* 20 (2006) 292.
F. Gömöry et al., *Supercond. Sci. Technol.* 22 (2009) 034017.

- Starting from the virgin state, the magnetic field penetrates monotonically from the surface when H_{appl} increases monotonically

⇨ relation between the electric field and the current density

$$\boldsymbol{J} = \boldsymbol{J}_c \tanh\left(-\frac{1}{E_c} \cdot \frac{\partial A}{\partial t}\right)$$

$E_c = 1\times10^{-4}$ V/m

For 3D extension:

- Collinearity between the current density and the local electric field $\partial A_x : \partial A_y : \partial A_z = J_x : J_y : J_z$
- Isotropic J_c

M. Solovyov and F. Gomory, *Supercond. Sci. Technol.* 32 (2019) 115001

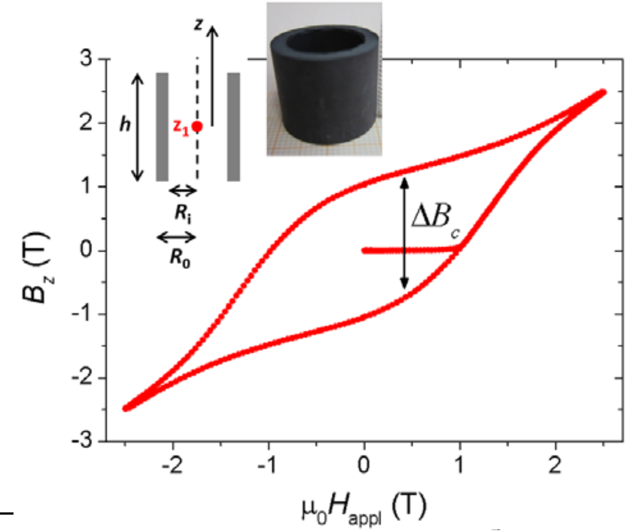
$$\vec{J} = \frac{J_c}{|\vec{E}|}\left(|E_x|\tanh\left(\frac{E_x}{E_c}\right)\hat{u}_x + |E_y|\tanh\left(\frac{E_y}{E_c}\right)\hat{u}_y + |E_z|\tanh\left(\frac{E_z}{E_c}\right)\hat{u}_z\right)$$

3D modelling

$$\vec{\mathbf{J}} = \frac{\boldsymbol{J}_{\mathbf{c}}}{|\vec{\boldsymbol{E}}|}\left(|\boldsymbol{E}_{\mathbf{x}}|\tanh\left(\frac{\boldsymbol{E}_{\mathbf{x}}}{\boldsymbol{E}_{\mathbf{c}}}\right)\hat{\boldsymbol{u}}_x + |\boldsymbol{E}_{\mathbf{y}}|\tanh\left(\frac{\boldsymbol{E}_{\mathbf{y}}}{\boldsymbol{E}_{\mathbf{c}}}\right)\hat{\boldsymbol{u}}_y + |\boldsymbol{E}_{\mathbf{z}}|\tanh\left(\frac{\boldsymbol{E}_{\mathbf{z}}}{\boldsymbol{E}_{\mathbf{c}}}\right)\hat{\boldsymbol{u}}_z\right)$$

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

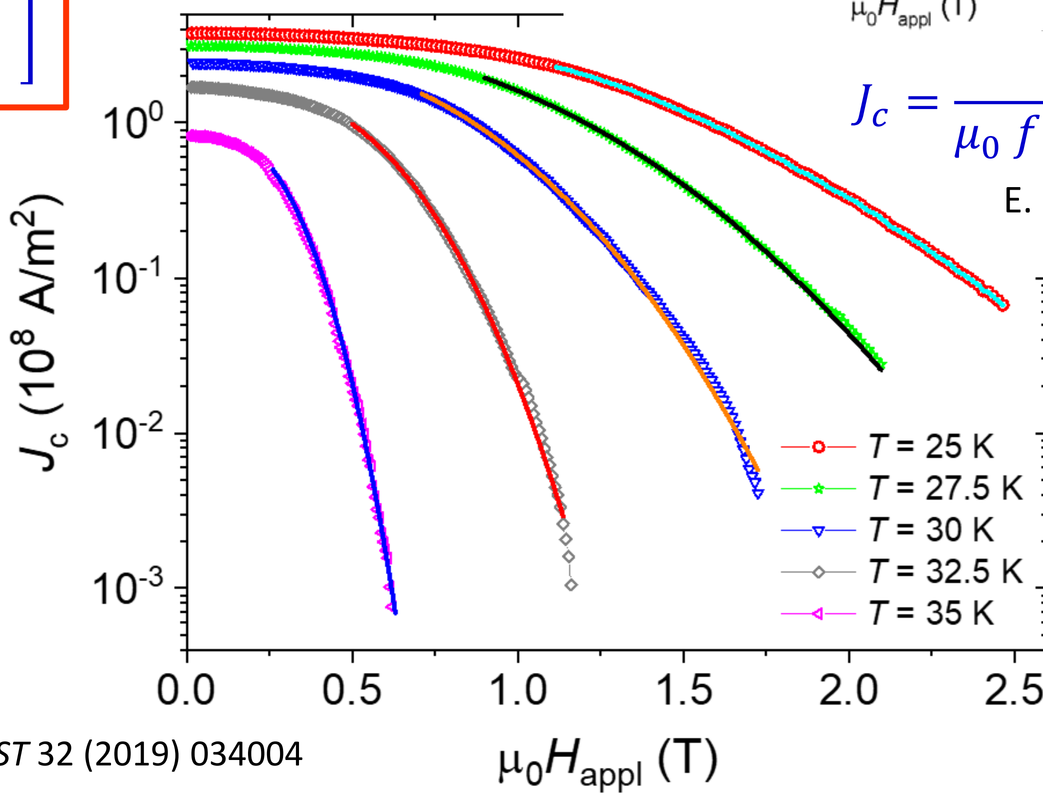
3D modelling



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

$$J_c = \frac{\Delta B_c}{\mu_0\, f(R_0, R_i, h, z)}$$

E. Bartolomé et al., *PRB* 72 (2005) 024523



L. Gozzelino et al., *SUST* 32 (2019) 034004

3D modelling

To model the **ferromagnetic material** :

- $\vec{A}$-formulation
- interpolation of the B-H_{appl} curve measured experimentally

Boundary condition: at a large distance from the shield, the field was assumed constant, equal to $\mu_0 \vec{H}_{app}$

Numerical modelling was implemented by means of the commercial **finite-element software COMSOL Multiphysics®**

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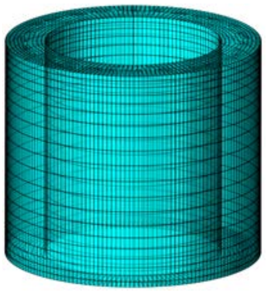
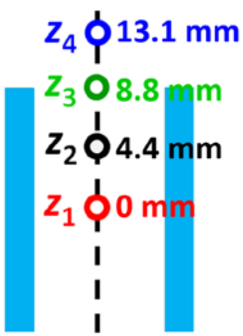
Comparison between experiment-computation results:

superconducting tube

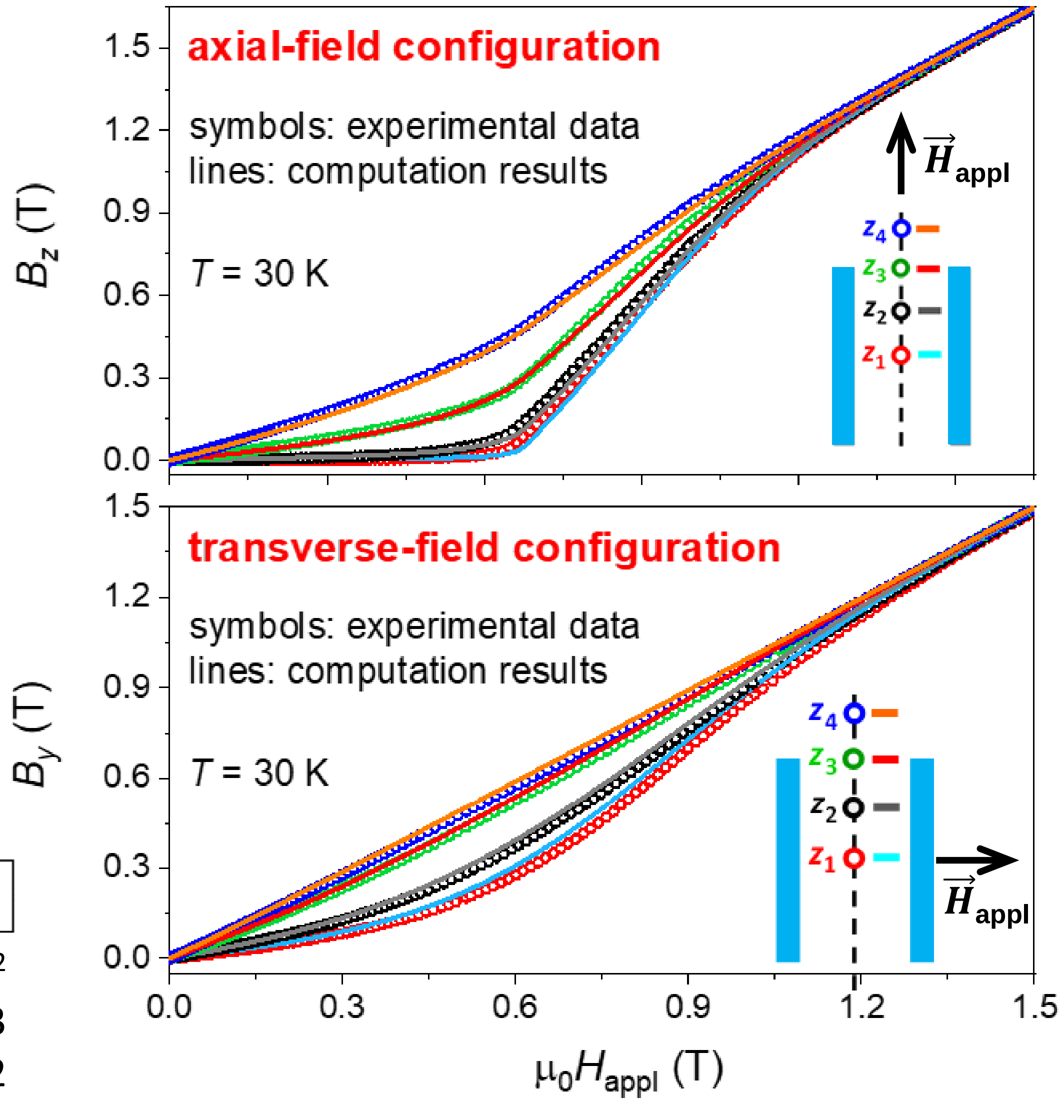


MgB_2 tube
Inner radius: 7.0 mm
Outer radius: 10.0 mm
Height: 17.5 mm



$$j_c(B) = j_{c0} \exp\left[-(B/B_0)^{\gamma}\right]$$

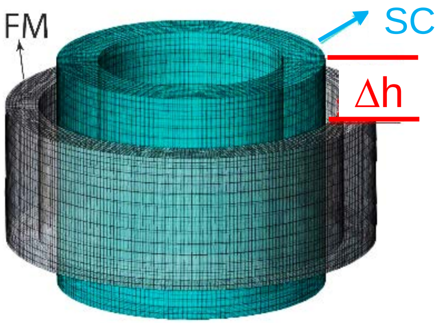
$j_{c0} = 3.01\times10^8$ A/m^2
$B_0 = 0.83$
$\gamma = 2.52$



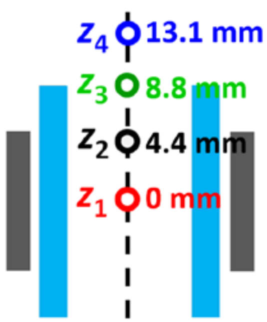
REMARKABLE AGREEMENT!

Comparison between experiment-computation results:

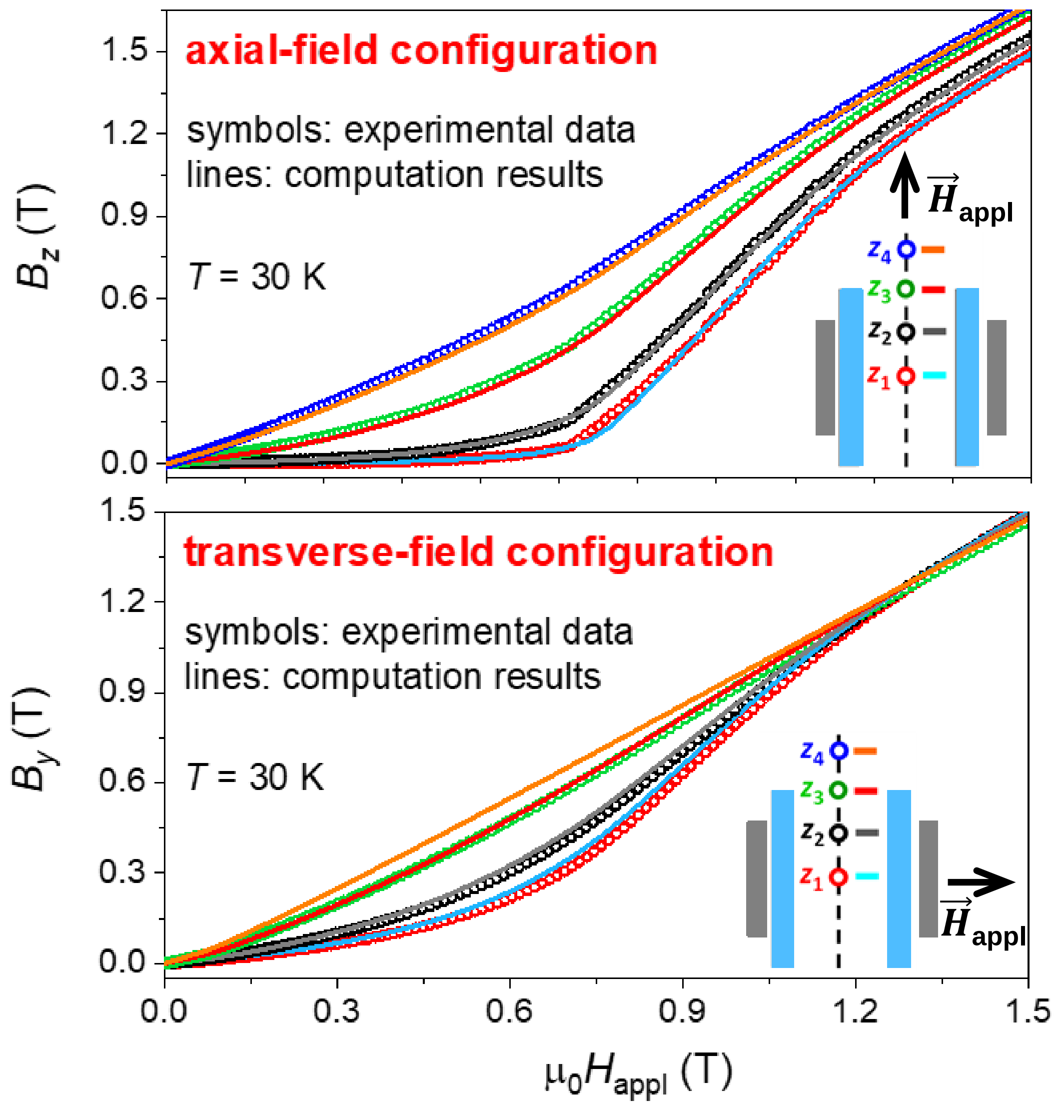
superconducting + ferromagnetic tubes



MgB_2 tube + Fe tube
Fe inner radius: 11.5 mm
Fe outer radius: 14.0 mm
Fe height: 10.5 mm
Δh = 3.5 mm

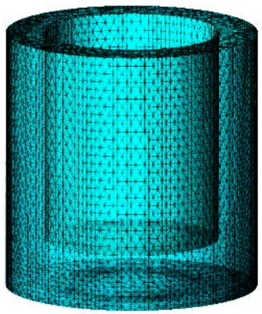


$j_{c0} = 3.01\times10^8$ A/m^2
$B_0 = 0.83$
$\gamma = 2.52$

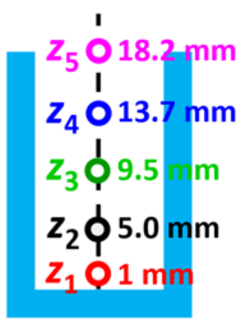


REMARKABLE AGREEMENT!

Comparison between experiment-computation results: superconducting cup

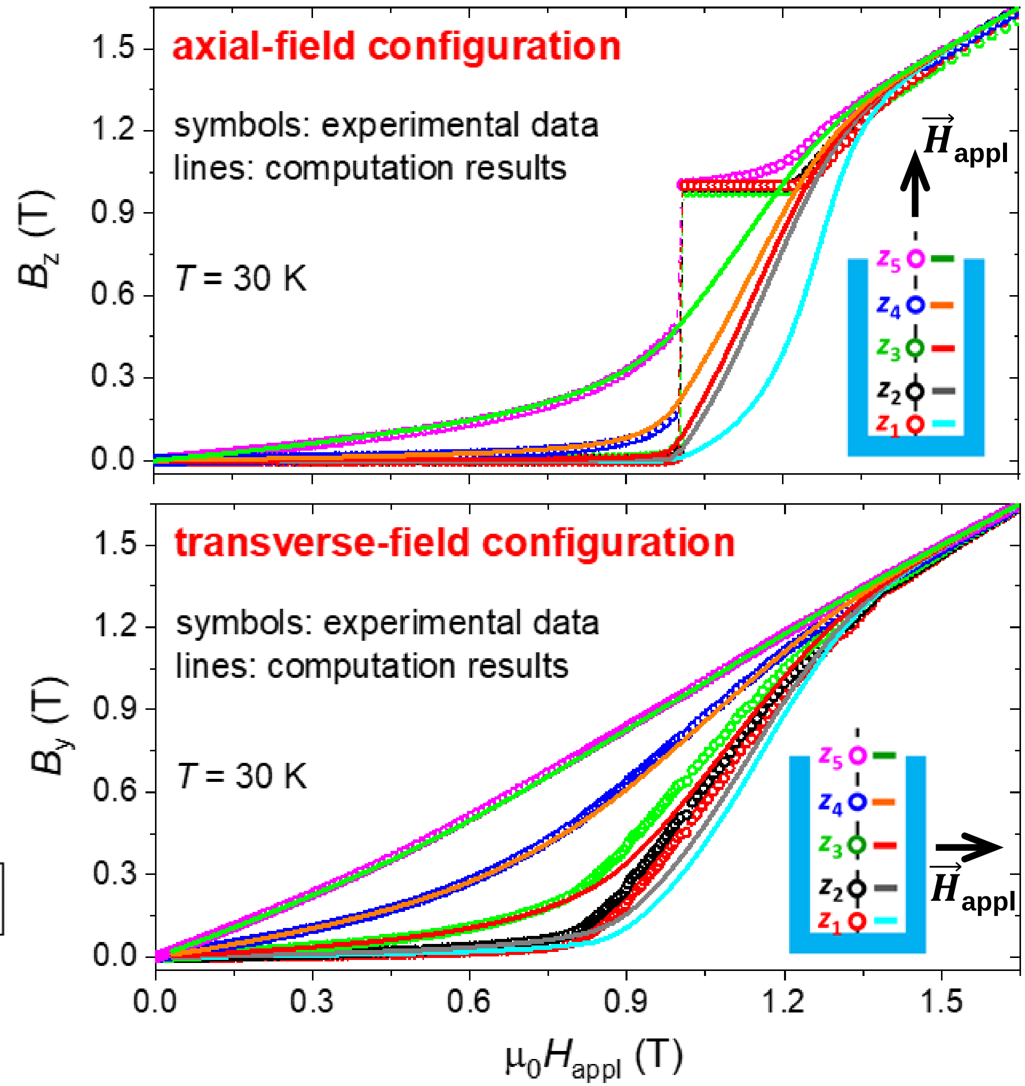


MgB_2 cup
Inner radius: 7.0 mm
Outer radius: 10.0 mm
Ext. height: 22.5 mm
Int. Depth: 18.3 mm



$$j_c(B) = j_{c0} \exp\left[-(B/B_0)^{\gamma}\right]$$

$j_{c0} = 5.02\times10^{8}$ A/m^2
$B_0 = 0.98$
$\gamma = 3.78$



GOOD AGREEMENT but…

- calculation can not reproduce the flux jump occurrence
  - ➔ model upgrading is ongoing
- some discrepancy in TF configuration at high fields
  - ➔ cup base roughness

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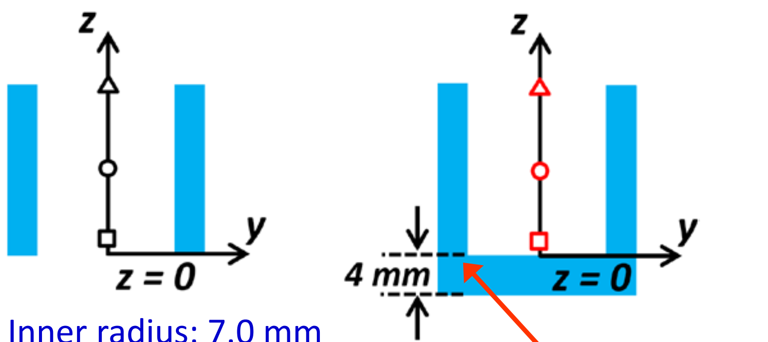
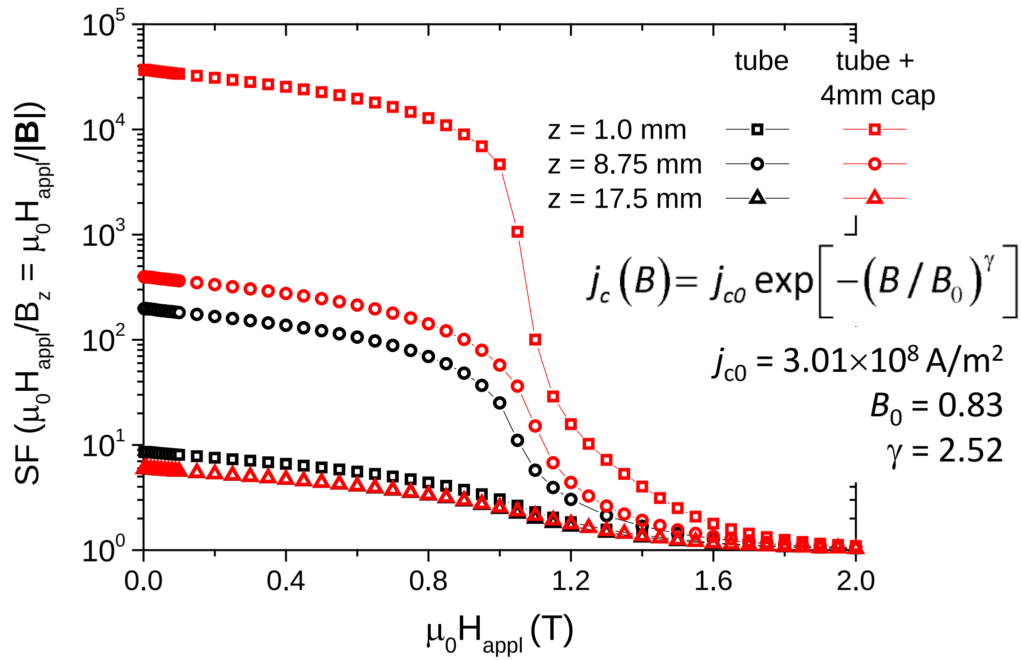
New shielding arrangements

- Magnetic mitigation solutions in situations (e.g. space) where the space occupied by the shield must be minimized
  - ✓ samples with small aspect ratio (1.5 < AR < 2.5) of height/outer radius

- **Cup-shape shields**

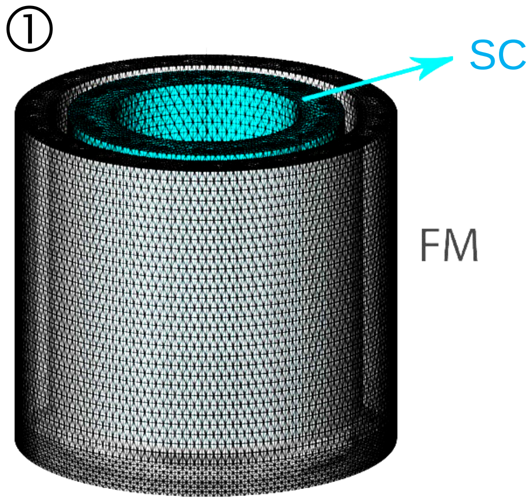


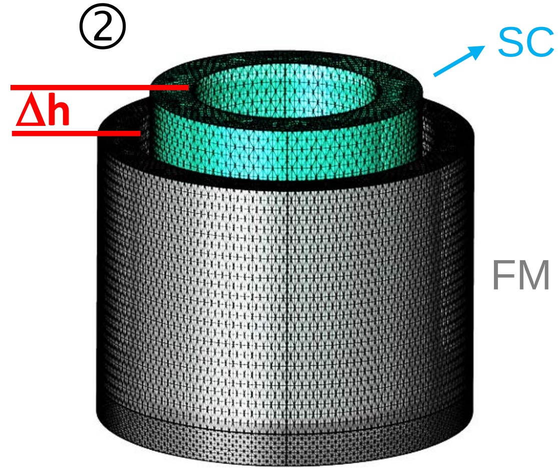
Inner radius: 7.0 mm
Outer radius: 10.0 mm
Height: 17.5 mm

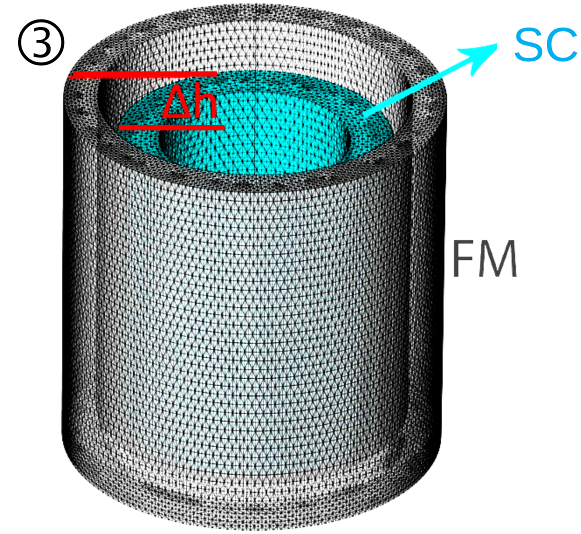


- Effect of Fe shield superimposition for different applied field orientation

New shielding arrangements







MgB_2 cup

SC inner radius: 7.0 mm
SC outer radius: 10.0 mm
SC int. Depth: 18.3 mm
SC ext. height: 22.5 mm

Fe cup

FM inner radius: 11.5 mm
FM outer radius: 14.0 mm
Int. depth: 22.5 mm
Ext. height: 25.0 mm

Δh = 0

MgB_2 cup

SC inner radius: 7.0 mm
SC outer radius: 10.0 mm
SC int. Depth: 18.3 mm
SC ext. height: 22.5 mm

Fe cup

FM inner radius: 11.5 mm
FM outer radius: 14.0 mm
Int. depth: 19.0 mm
Ext. height: 21.5 mm

Δh = - 3.5 mm

MgB_2 cup

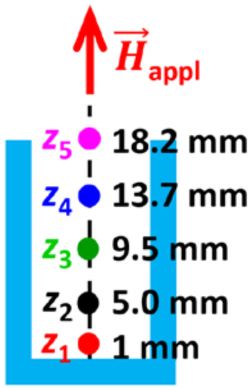
SC inner radius: 7.0 mm
SC outer radius: 10.0 mm
SC int. Depth: 18.3 mm
SC ext. height: 22.5 mm

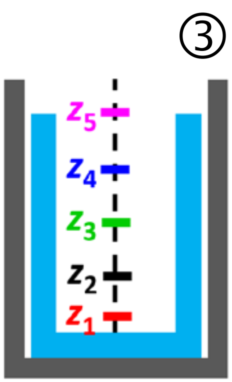
Fe cup

FM inner radius: 11.5 mm
FM outer radius: 14.0 mm
Int. depth: 26.0 mm
Ext. height: 28.5 mm

Δh = + 3.5 mm

Shielding in axial-field configuration





$$j_c(B) = j_{c0}\exp\left[-(B/B_0)^{\gamma}\right]$$

$j_{c0} = 5.02\times10^8$ A/m^2

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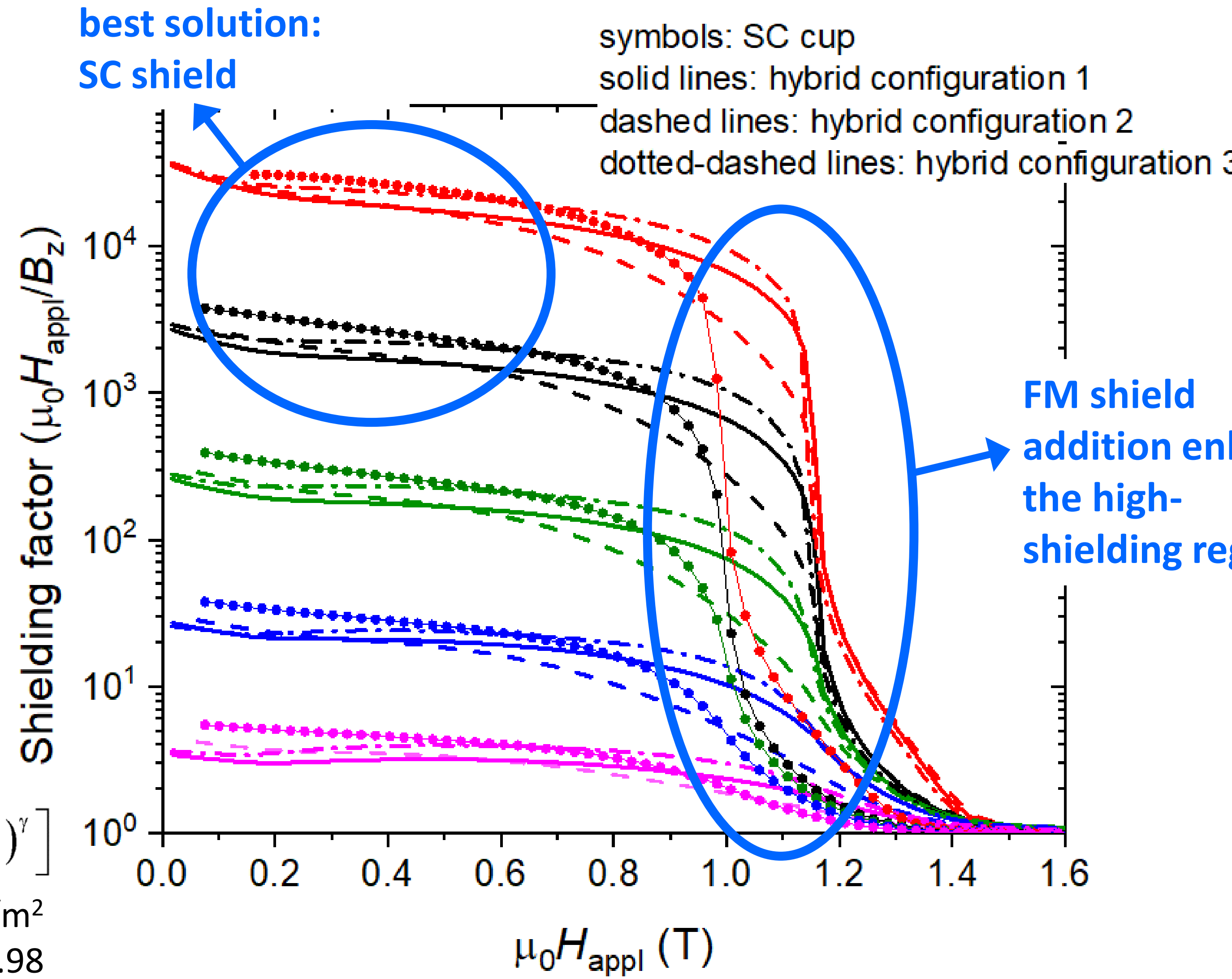
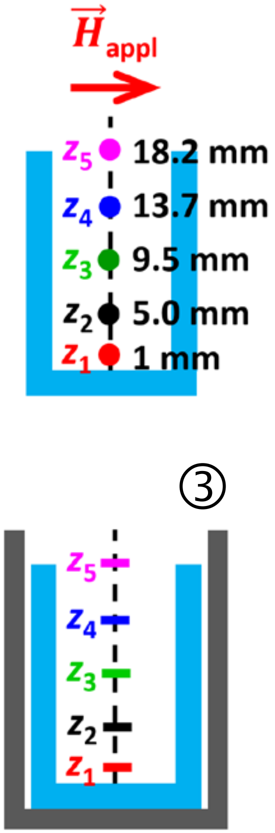


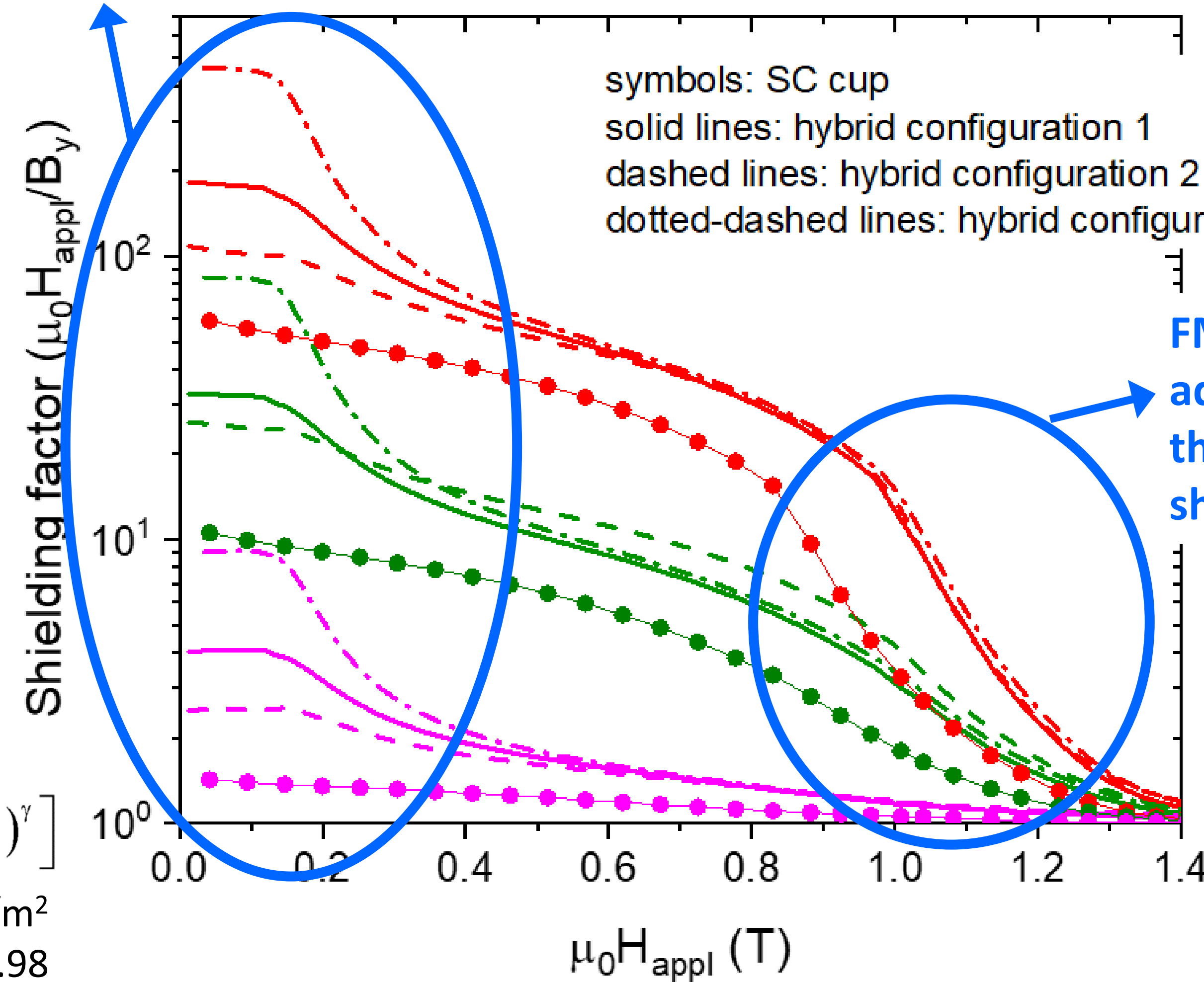
FM shield addition enlarge the high-shielding region

Shielding in transverse-field configuration

Fe addition ➔ SF enhancement:

Position z_1, $\mu_0 H_{appl}$ = 0.10 T, SF_{sc} = 55 ➔ $SF_{hybrid\ 3}$ = 460





FM shield addition enlarge the high-shielding region

$$j_c(B) = j_{c0} \exp\left[-(B/B_0)^\gamma\right]$$

$j_{c0} = 5.02\times10^8$ A/m^2

B_0 = 0.98

γ = 3.78

Shielding in transverse-field configuration:
shielding factor distribution

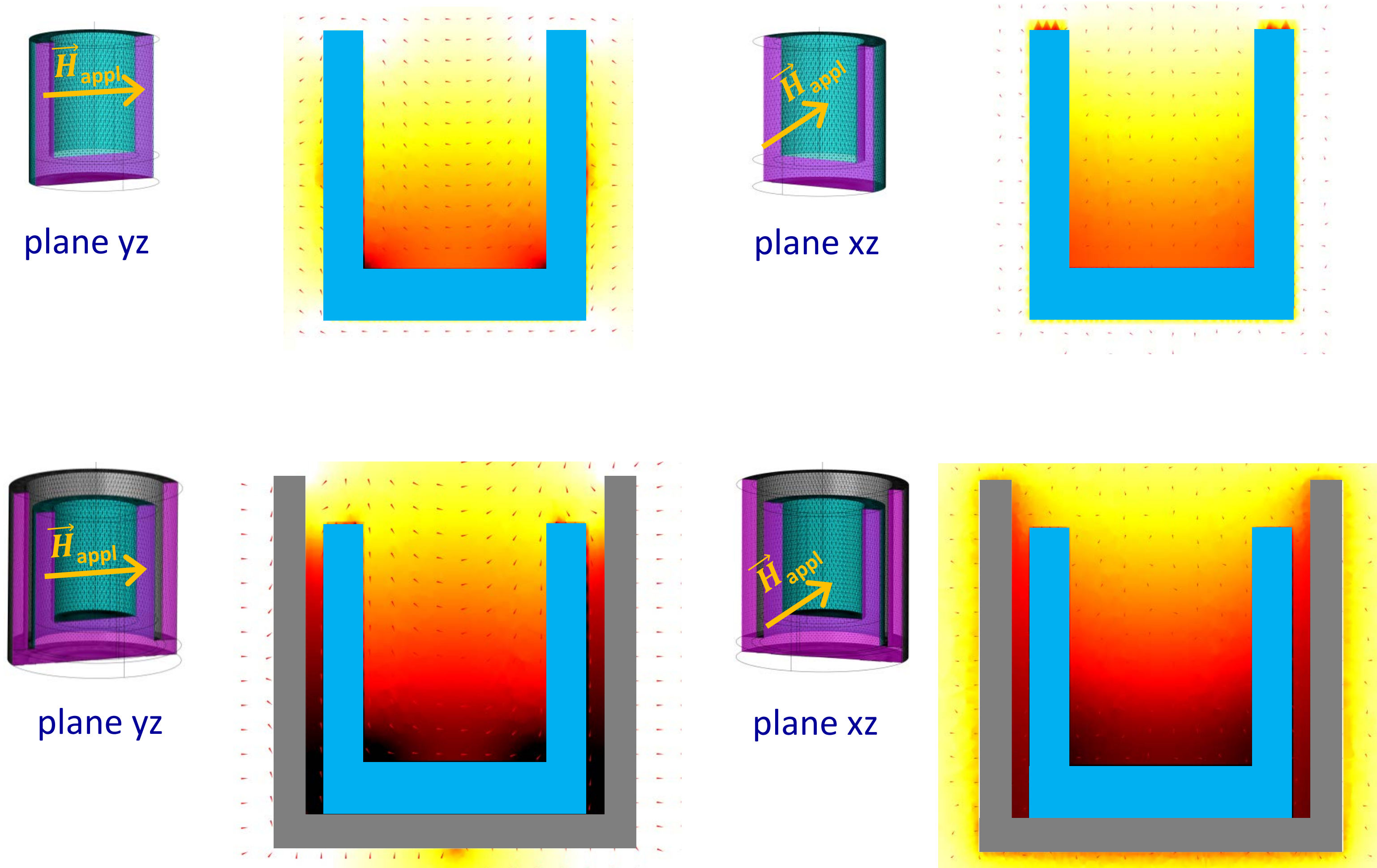
$\mu_0\vec{H}_{appl}$ = 0.1 T $\hat{u}_y$

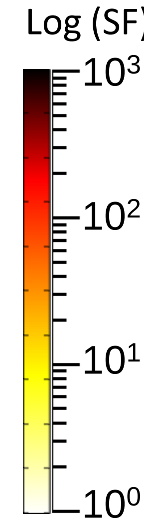
$$j_c(B) = j_{c0}\exp\left[-(B/B_0)^{\gamma}\right]$$

j_{c0} = 5.02×10^8 A/m^2
B_0 = 0.98
γ = 3.78

Superconducting cup

Hybrid configuration 3





Conclusions

- 3D modelling is crucial to investigate new and more efficient shield configurations

- Numerical procedure based on $\vec{A}$-formulation
  - Collinearity between local $\vec{J}$ and $\vec{E}$
  - Isotropic J_c (B)
  - Computation running on a commercial finite element code

Computation outputs well reproduce shielding experimental results obtained with superconducting and hybrid shields

- Numerical simulations guide new shield designs
  - Ferromagnetic cup addition of a superconducting cup-shield

Axial field-configuration

➔ low field: ☺ superconducting shield

➔ high field: ☺ hybrid shield

Transverse-field configuration

➔ ☺ hybrid shield in the whole investigate range of field

Other field orientations ? ➔ see poster M. Fracasso (Session PS2-PM – Tuesday, 17.30-18.30)

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