HTS MODELLING 2016

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# Passive magnetic field shielding by superconducting and superconducting/ferromagnetic superimposed systems

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# Outline

- Background
- Superconducting vs. hybrid superconducting/ferromagnetic shields
  - ✓ experimental results
  - ✓ experimental vs. modelling
  - ✓ towards new hybrid shield configurations:
    - *- height difference between the edges of the SC/FM shields*
    - *- modulation of the lateral gap between SC/FM shields*
    - *- multilayer arrangements*
- Conclusions

# Magnetic shielding

**Why ?**

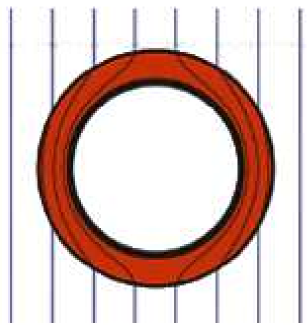
- **electromagnetic noise - stray field reduction** → 
  - Equipment integration
  - Worker protection
- **low magnetic field background** → Protection of magnetic field sensitive detectors

**How ?**

- **Active solutions** → Magnets
- **Passive solutions** → **Ferromagnets + superconductors**
  - **ferromagnets**
  - **superconductors**

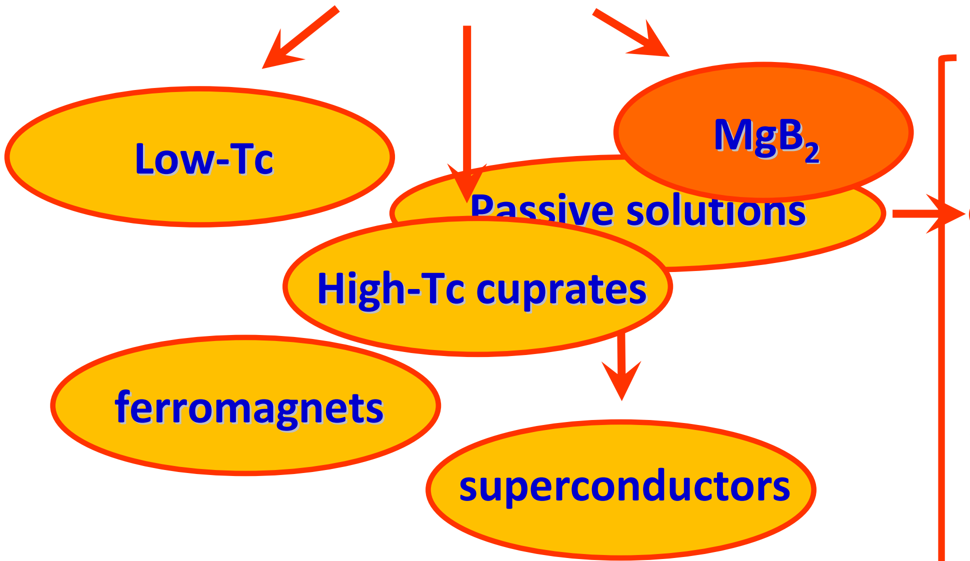
**Ferromagnets + superconductors** → improvement of the shielding efficiency

**Ferromagnets + superconductors** → cloak effect



F. Gomory et al., *Science* 335 (2012) 1466

# Magnetic shielding

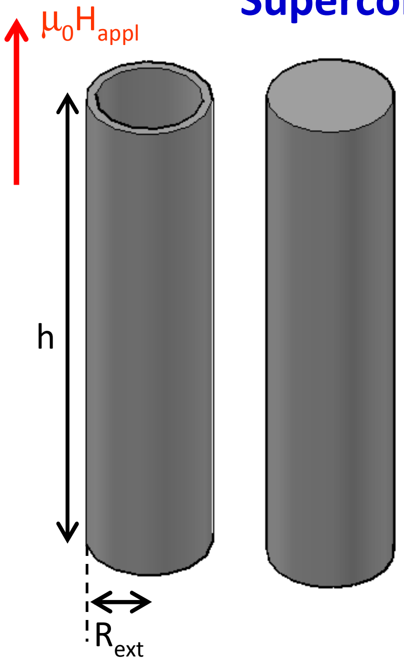



**Ferromagnets + superconductors**

- low cost of raw materials
- low density
- working temperature easily achievable using cryogen free cryocoolers
- randomly oriented grain boundaries in MgB$_2$ are not obstacles to current flow
- easy to be jointed

# Magnetic shielding

## Superconducting shields



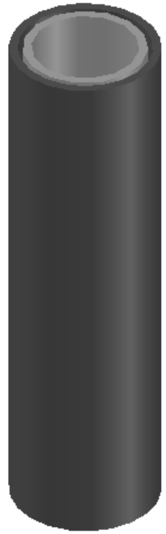

Pb-doped BSCCO-2223 – 77 K

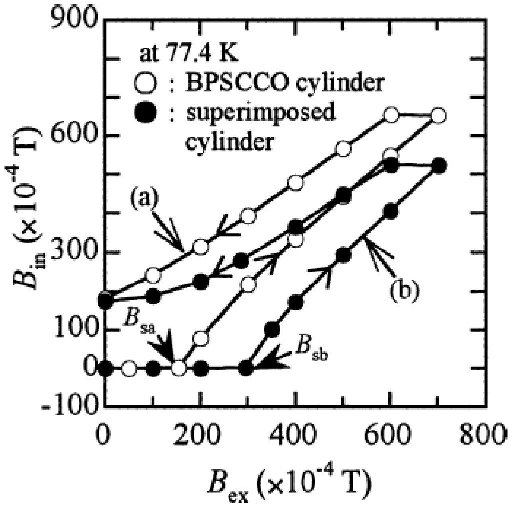
| h/Rext | System 1 Blim (T) | System 2 Blim (T) |
|---|---|---|
| 1 | --- | 10.69 |
| 2 | --- | 11.66 |
| 3 | 6.41 | 12.63 |
| 4 | 12.83 | 13.41 |
| 5 | 13.61 | 13.80 |
| 6 | 14 | 14 |
| 7 | 14 | 14 |
| 8 | 14 | 14 |

$R_{ext}$ = 8.0 mm
$R_{int}$ = 6.5 mm

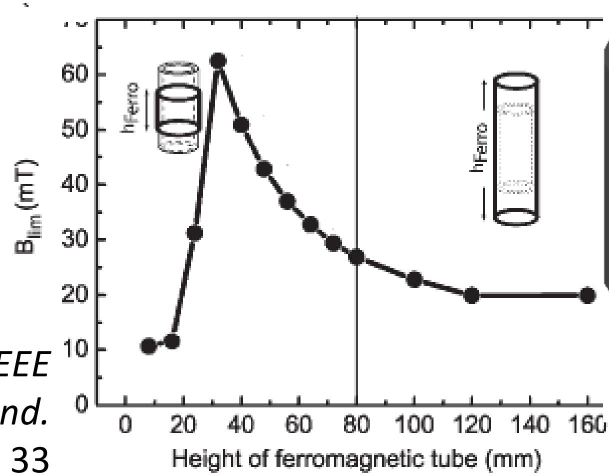
D. Denis et al., *Supercond. Sci. Technol.* 20 (2007) 418

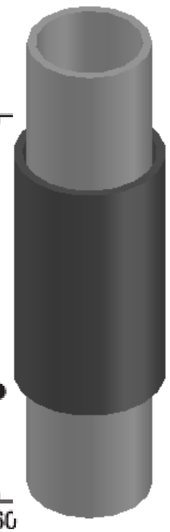
## Ferromagnetic layer addition






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



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

## Open question:

**Field mitigation requirement in situations where the space occupied by the shield must be minimized:**

- **reduction of the shield height**
- **analysis of the edge effect**

# $MgB_2$ cup

❖ Produced by a **microwave-assisted Mg-RLI technique** in boron powder preforms:

➢ heating processes in Ar flow with liquid Mg infiltration in B cup-shaped preform (650°C for 3 hours; 900° C for 20 hours)

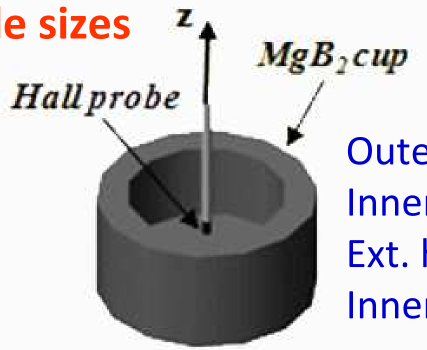
➢ microwave heating (1600 W, 2.45 GHz for 30 min in Ar atmosphere) to minimize the unreacted Mg amount

L. Gozzelino et al., *Supercond. Sci. Technol.* 25, 115013 (2012) and refs. therein

➔ **production of manufacts of different shapes and easily scalable sizes**

$T_c = 37.3$ K

$\Delta T_c = 0.5$ K

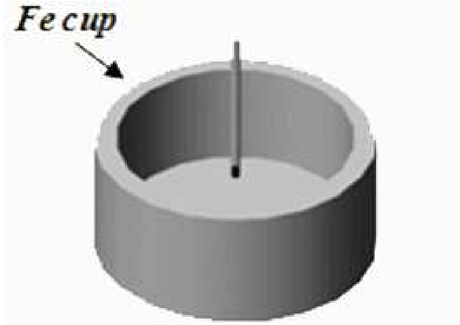



Outer radius: 10.5 mm
Inner radius: 7.5 mm
Ext. height: 10.5 mm
Inner depth: 7.5 mm

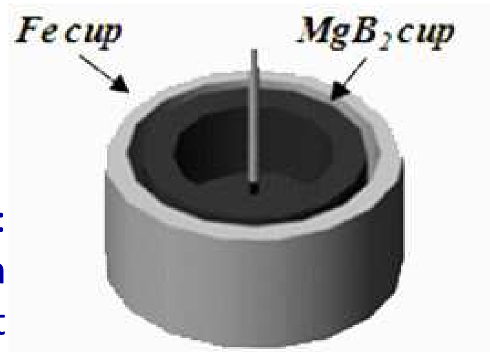
**Aspect ratio of height/radius ~ 1**

# Fe cup

❖ Made of a commercial **ARMCO-iron.**

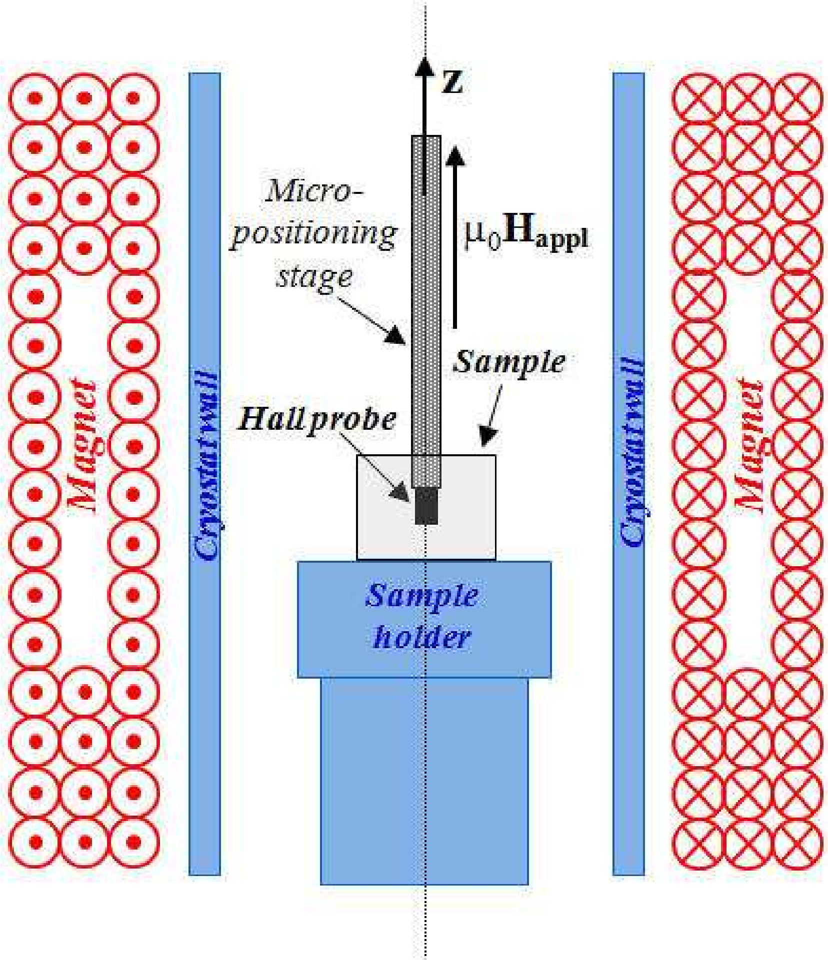



Outer radius: 14.0 mm
Inner radius: 11.5 mm
Ext. height: 12.5 mm
Inner depth: 10.5 mm

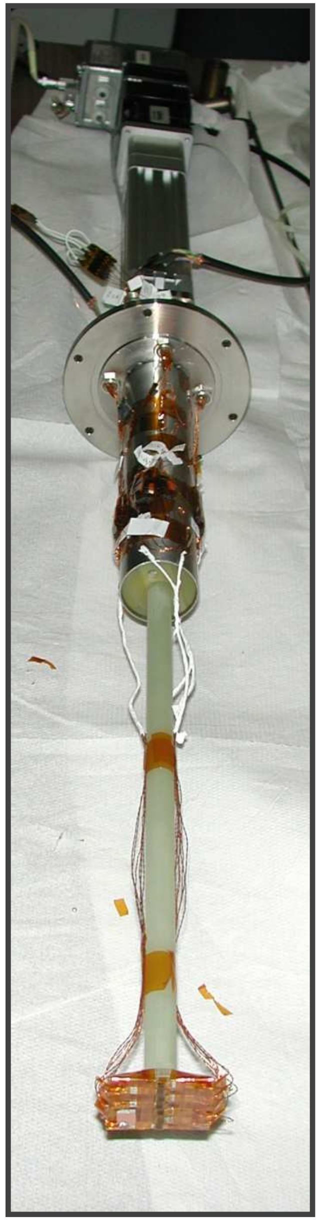



Hybrid configuration:
Lateral air gap: 1.0 mm
Edge of both the cups at the same height

# Experimental set-up

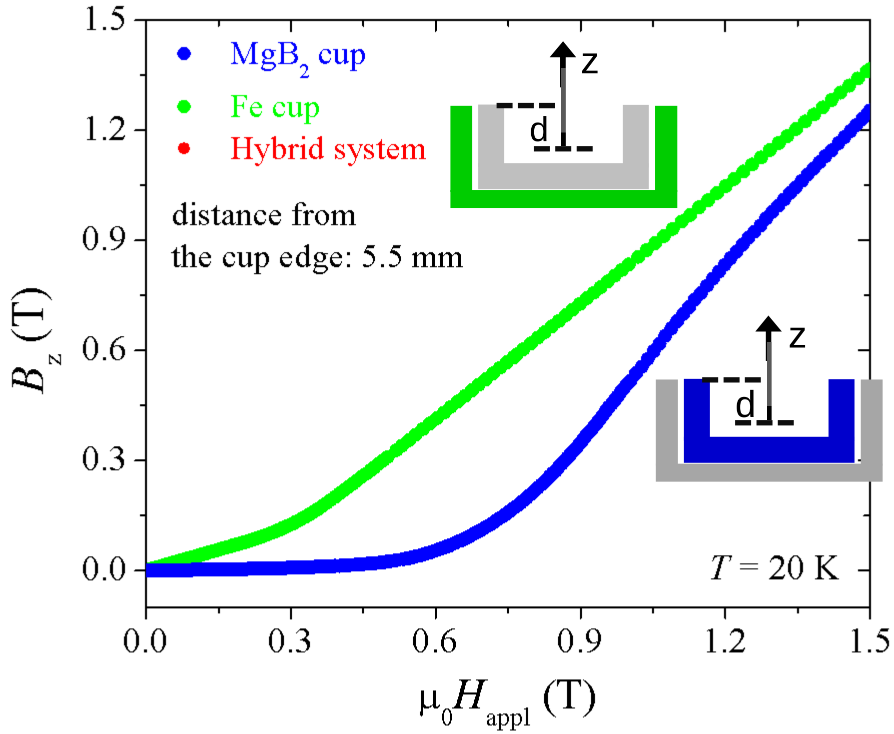



- cryogenic Hall probe(s) mounted on a custom-designed stage moveable along its axis with a spatial resolution of 1 µm (movement range: 10 cm)
- Cryomagnetics cryogen-free magnet (0-6T)
  ➔ axial magnetic field
- samples cooled by means of a cryogen-free Leybold RNK 10-300 cryocooler
  ➔ zero field cooling



L. Gozzelino et al., *IEEE Trans. Appl. Supercond.* 21 (2011) 3146

# $MgB_2$ /Fe hybrid shield: shielding vs. applied field




superconducting cup:
more efficient shield than
ferromagnetic cup

L. Gozzelino *et al., Supercond. Sci. Technol.* 25 (2012) 115013

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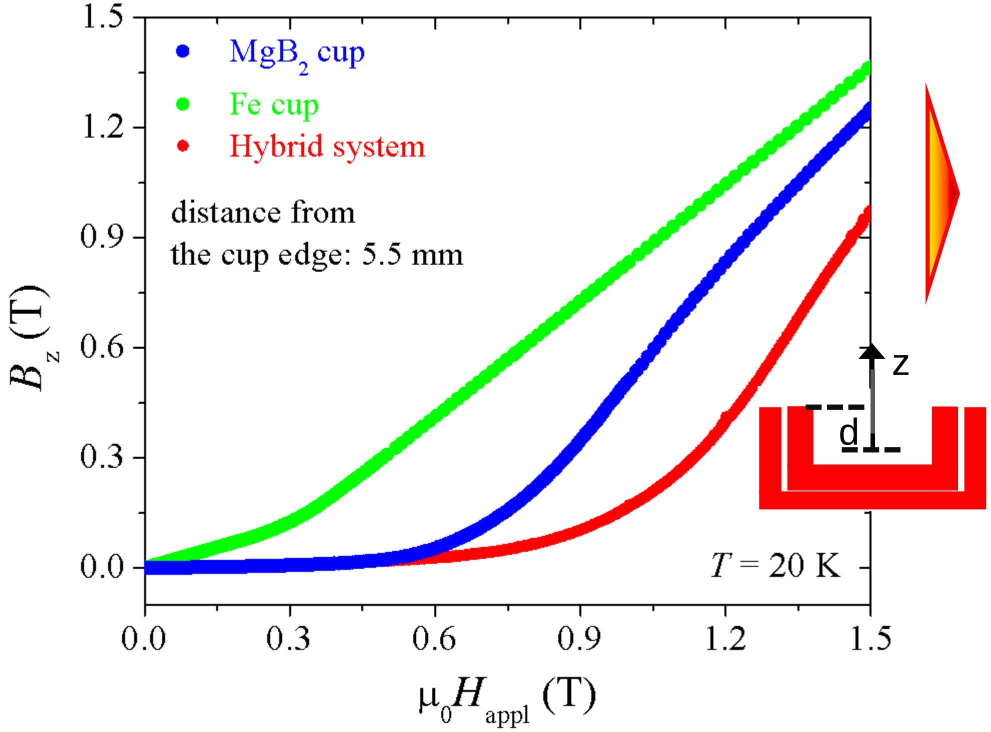
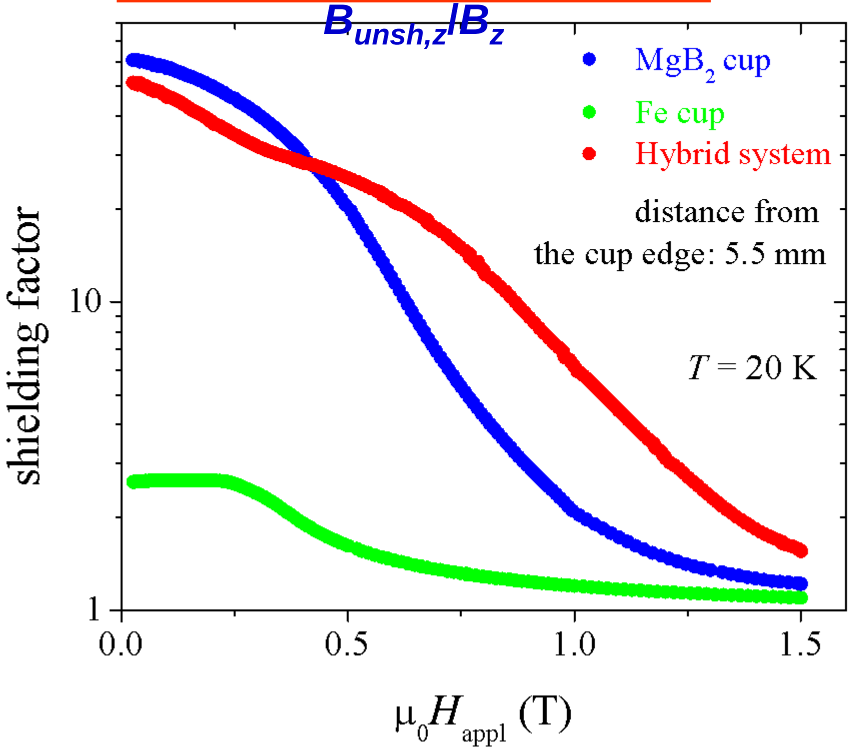



Shielding factor = $B_{unsh,z}/B_z$



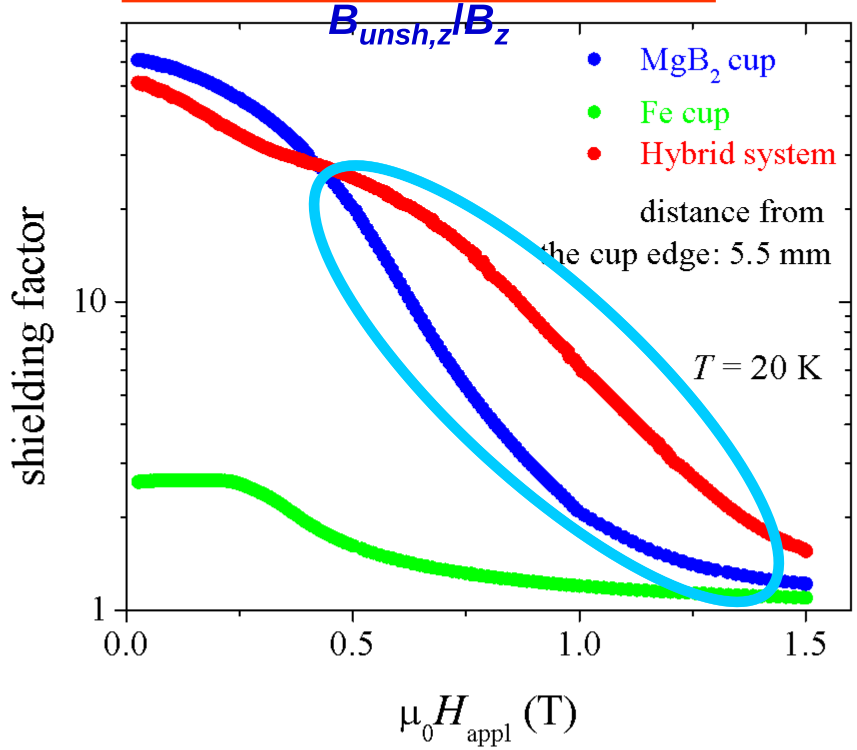

L. Gozzelino *et al., Supercond. Sci. Technol.* 25 (2012) 115013

# $MgB_2$ /Fe hybrid shield: shielding vs. applied field

**hybrid shield:**
**best shielding efficiency at higher fields**

**enhancement of the shielding factor in the hybrid configuration higher than a factor of 3 at $\mu_0 H_{appl}$ = 0.9 T and T = 20 K**

**Shielding factor = $B_{unsh,z}/B_z$**

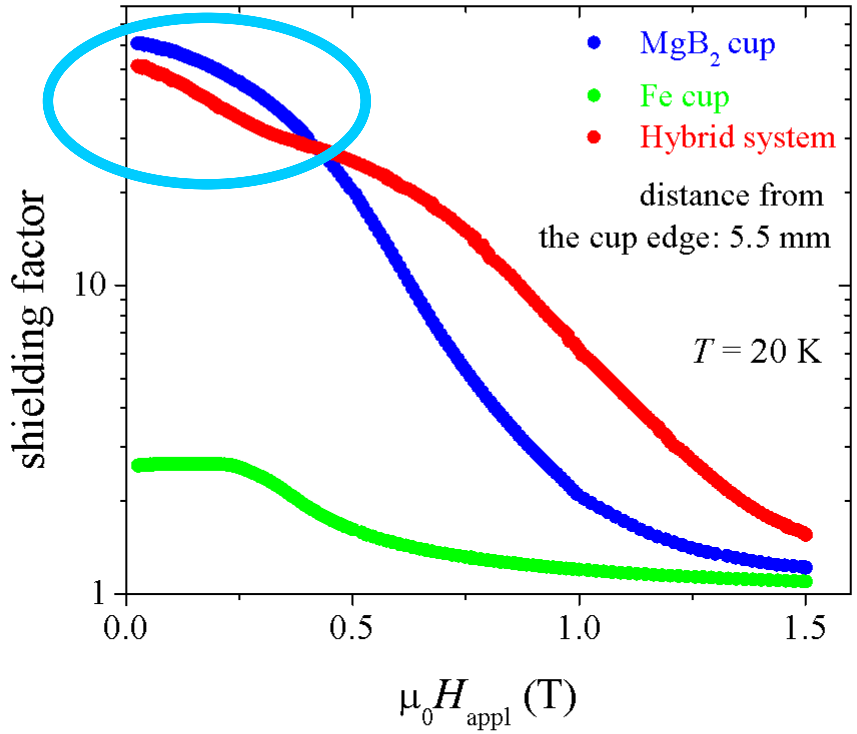



L. Gozzelino *et al., Supercond. Sci. Technol.* 25 (2012) 115013

# $MgB_2$ /Fe hybrid shield: shielding vs. applied field

**superconductor shield: best shielding efficiency at lower fields**

Fe cup induces a stronger curvature and a greater accumulation of the magnetic flux lines at the $MgB_2$ cup edge

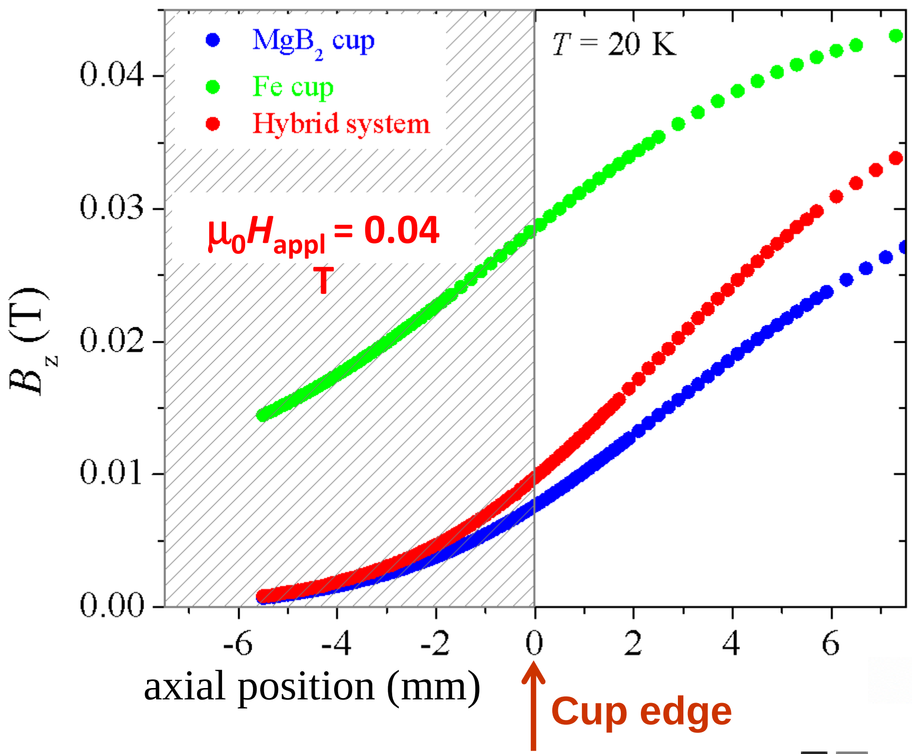


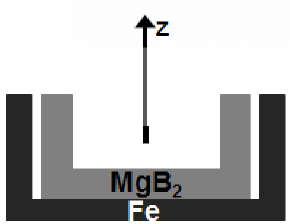

Shielding factor of the hybrid system: **no straightforward composition of the independent contributions** of the two shields:

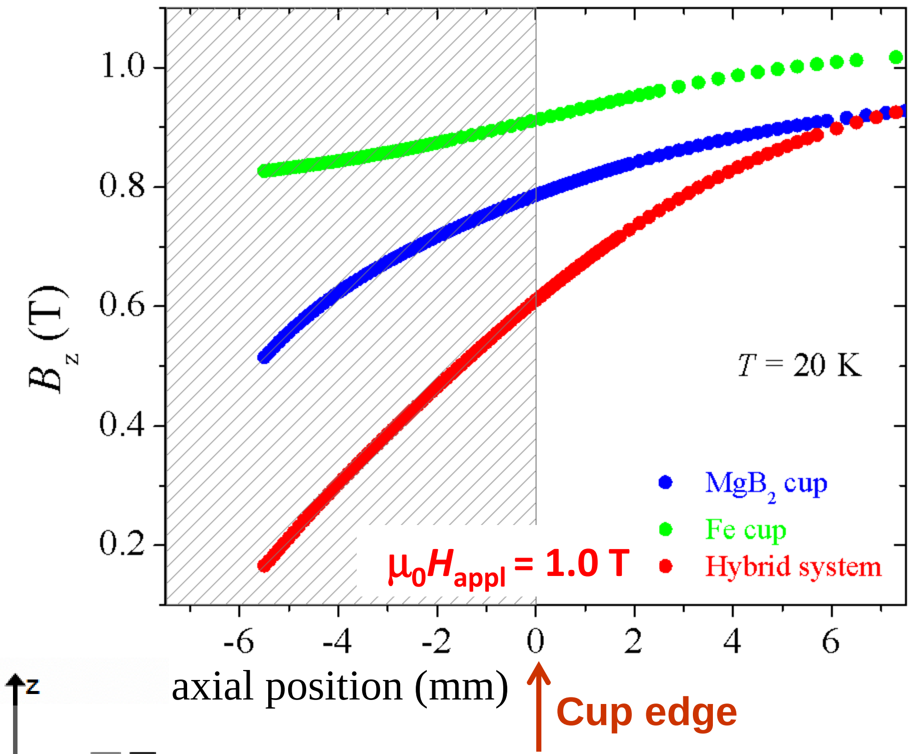
$$SF_{hybrid\,system}(\mu_0 H_{appl}) = SF_{Fe}(\mu_0 H_{appl}) \times SF_{MgB2}(B_{interface,z})$$

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

# $MgB_2$ /Fe hybrid shield: shielding vs. position




**shielding effects are present all along the cup axis, also close and outside the cup opening**

L. Gozzelino *et al, IEEE Trans. Appl. Supercond.* 23 (2013) 8201305

# Model

- To model the **superconductor :**

- **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, magnetic field penetrating monotonically from the surface when $H_{appl}$ increases monotonically

$$\nabla \times \nabla \times \mathbf{A} = \mu_0 \mathbf{J_c}\, tanh\left(-\left|\mathbf{A}\right|/A_n\right)$$

where $\mathbf{J_c} = k\left(B/B_{irr}\right)^{\gamma}\left(1 - B/B_{irr}\right)^{\delta}\, \mathbf{u_\phi}$
and $A_n = 5\times10^{-8}$ T/m.

K.Kitahara et al., *Physica C* 445-448 (2006) 471.
D. Dew-Hughes, *Philos. Mag.* 30 (1974) 293.

At T = 20 K, $k = 1.16\cdot10^{8}$ A/m², $\gamma = -0.4$, $\delta = 2.0$, $B_{irr} = 4.25$ T.

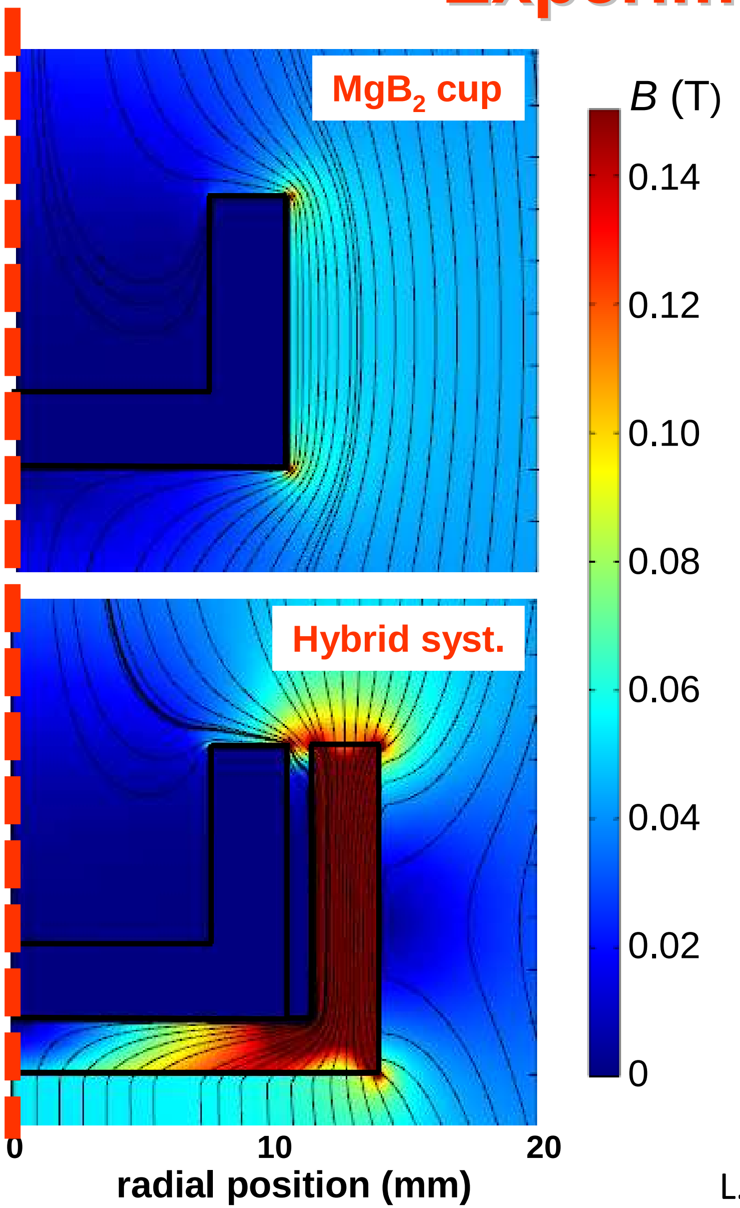
- 2D axisymmetric configuration

- The **ferromagnetic cup** was modelled starting from the experimental BH curve.

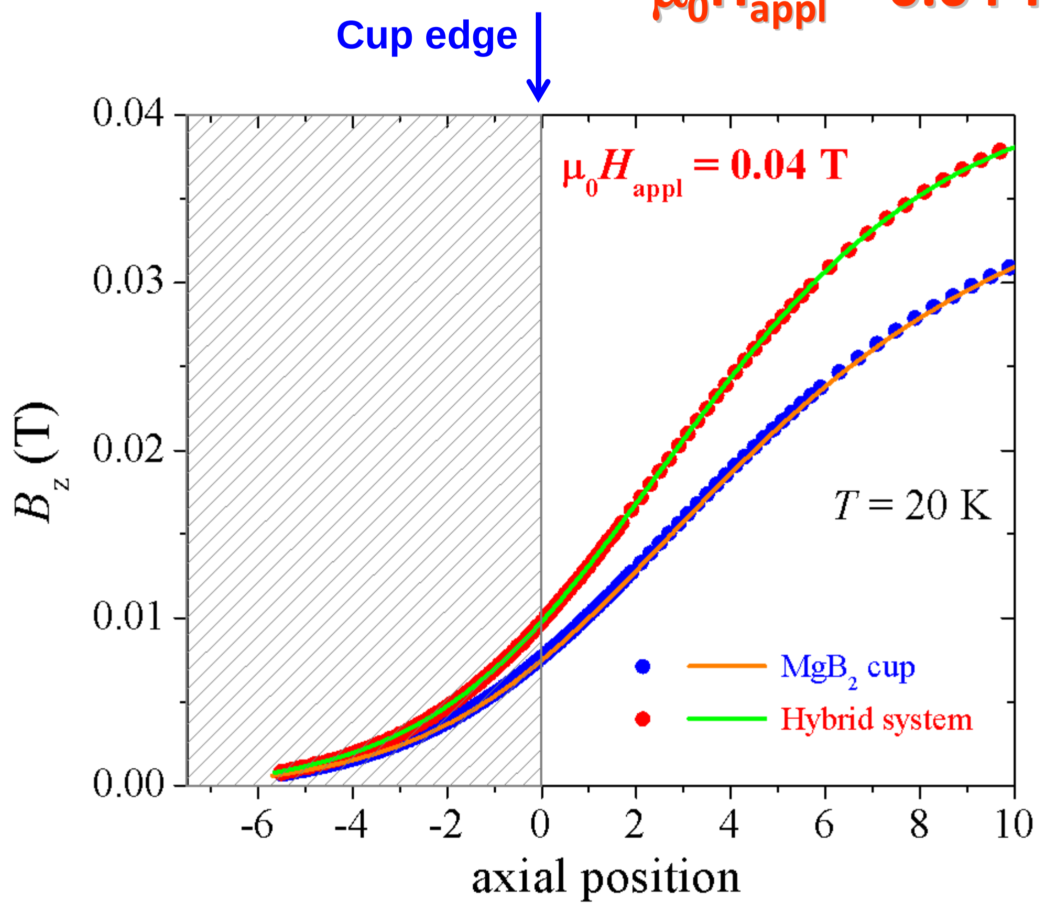
- **Boundary condition**: at a large distance from the sample, the field was assumed constant, equal to $\mu_0 H_{appl}$ and parallel to the cup axis.

- Commercial finite-element software (COMSOL 4.3b)

# Experimental vs. modelling



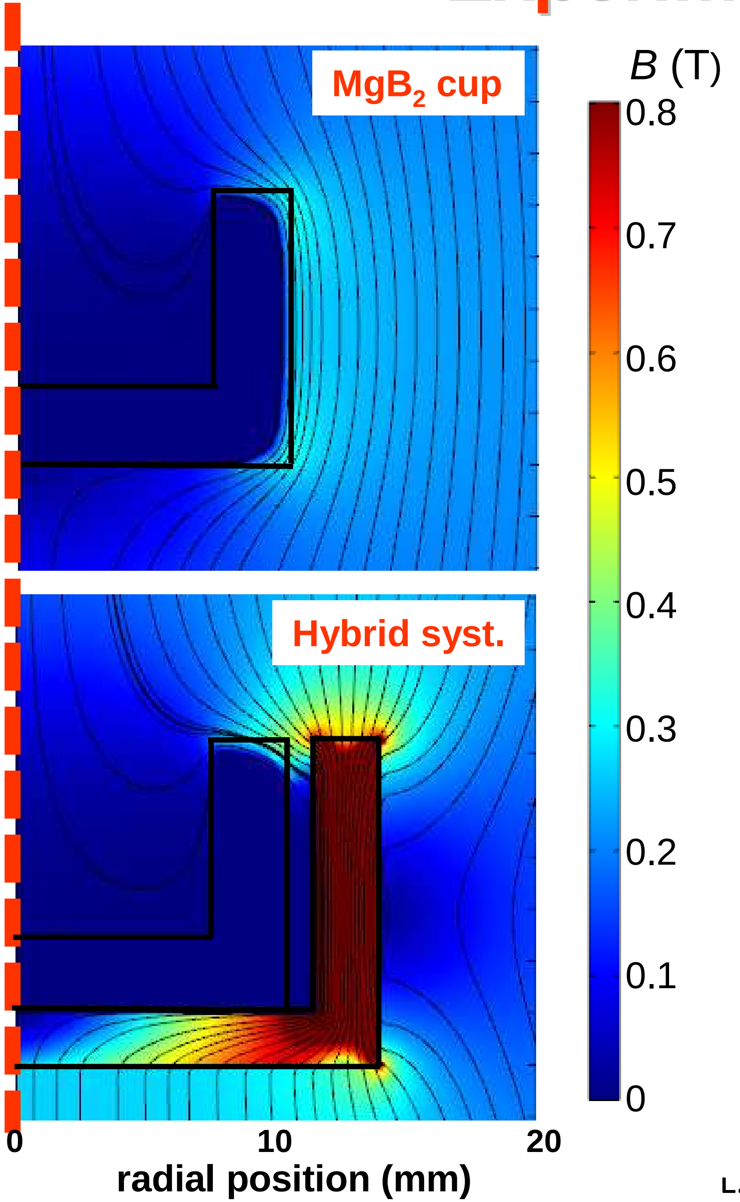

$\mu_0 H_{appl}$ = 0.04 T



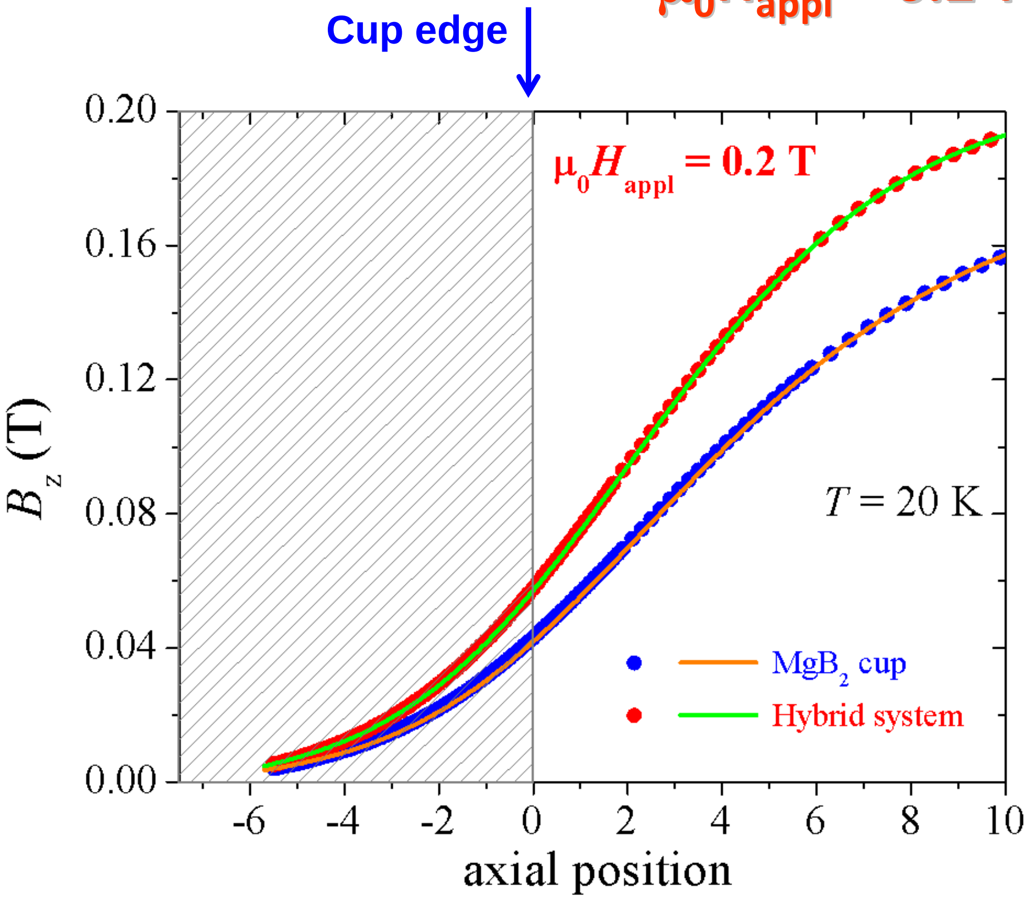

**Very good agreement !**

L. Gozzelino *et al., Supercond. Sci. Technol.* 29 (2016) 034004

# Experimental vs. modelling




$\mu_0 H_{appl} = 0.2$ T

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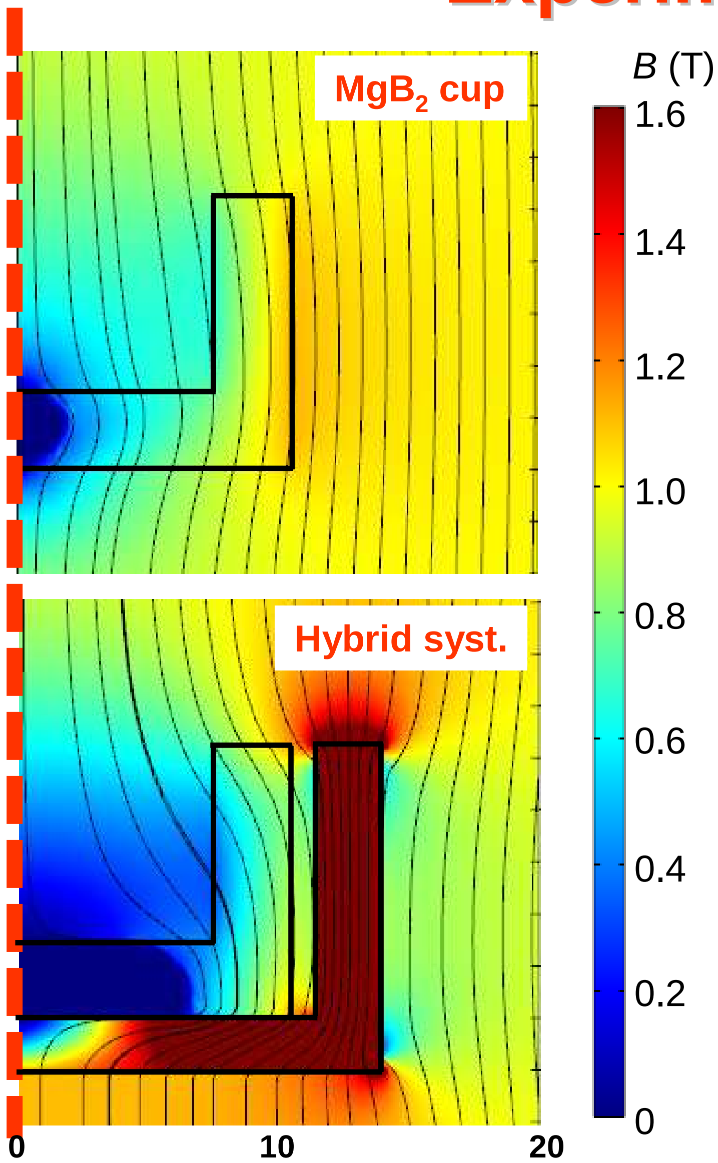
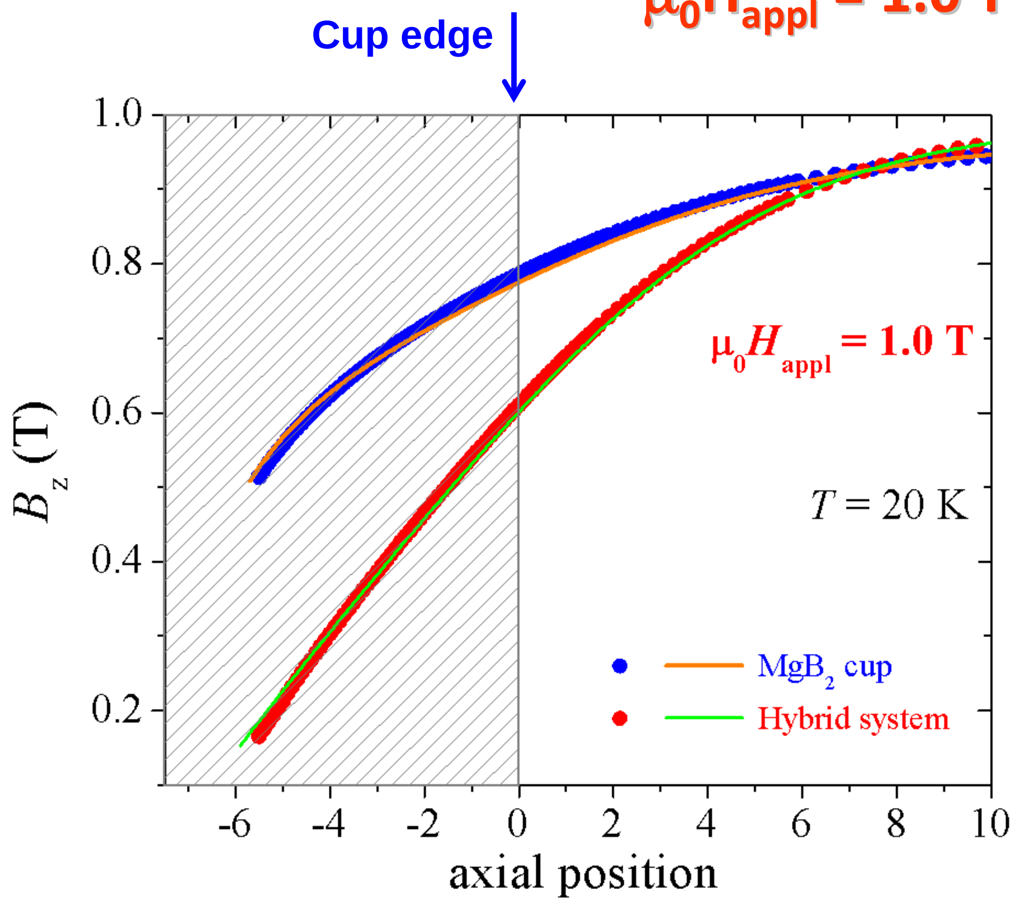
L. Gozzelino *et al., Supercond. Sci. Technol.* 29 (2016) 034004

# Experimental vs. modelling



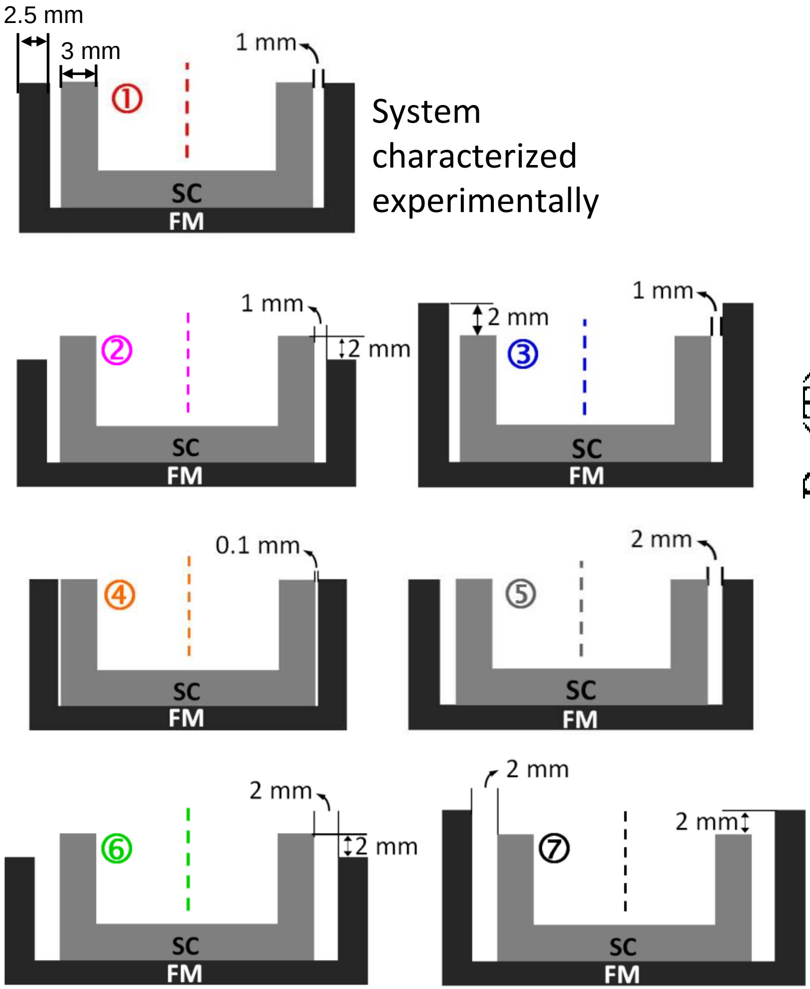

$\mu_0 H_{appl}$ = 1.0 T

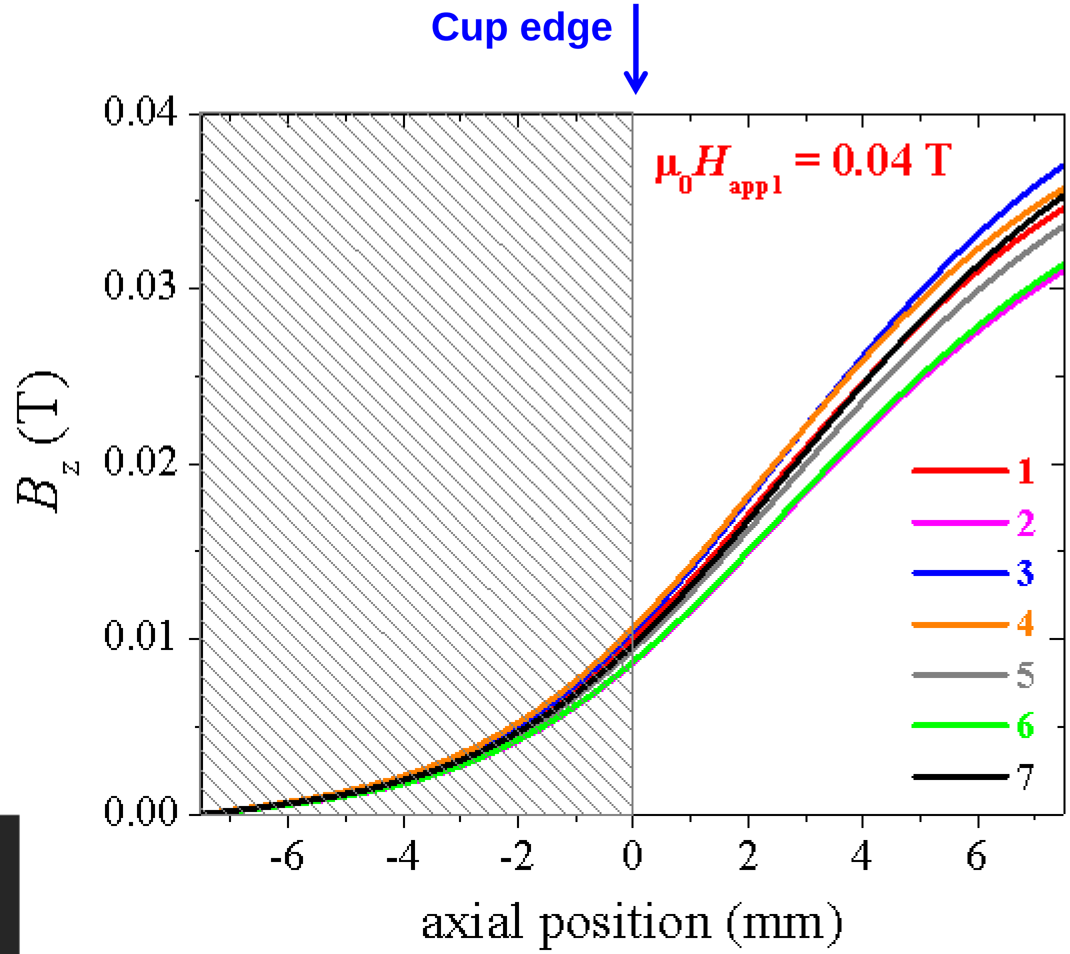



**Very good agreement !**

Gozzelino *et al.*, *Supercond. Sci. Technol.* 29 (2016) 034004

# Towards new shield configurations:
## height difference between edge – air gap modulation



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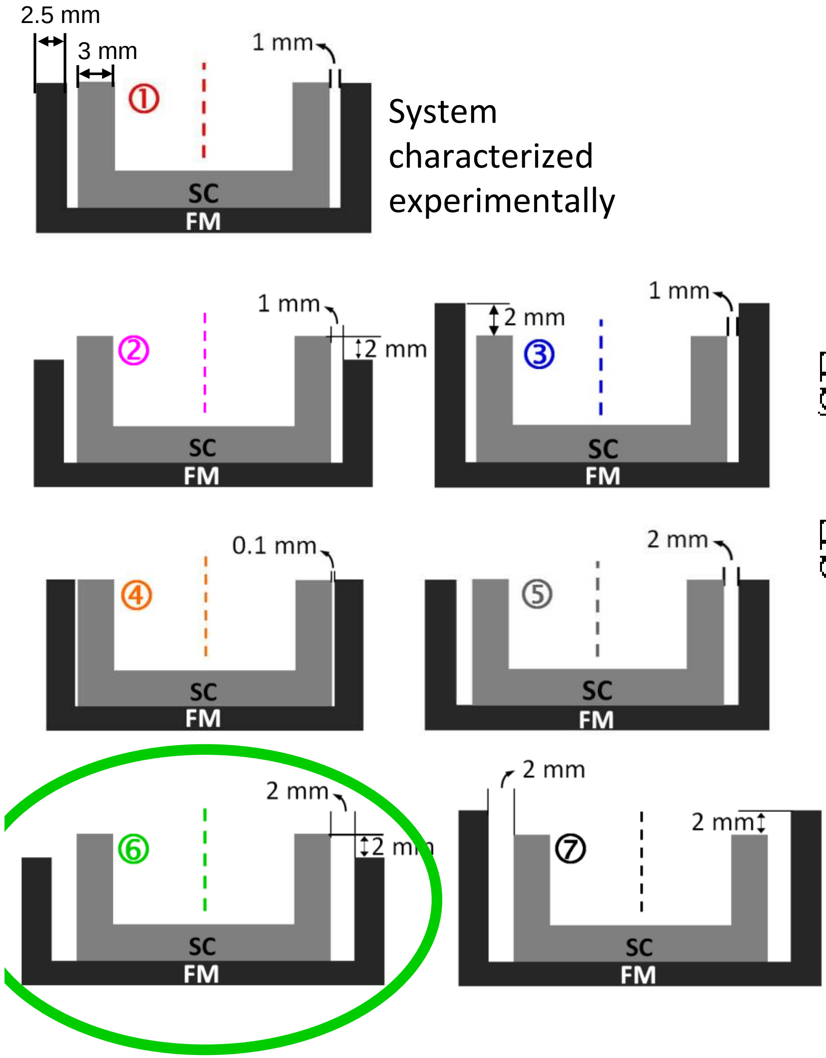


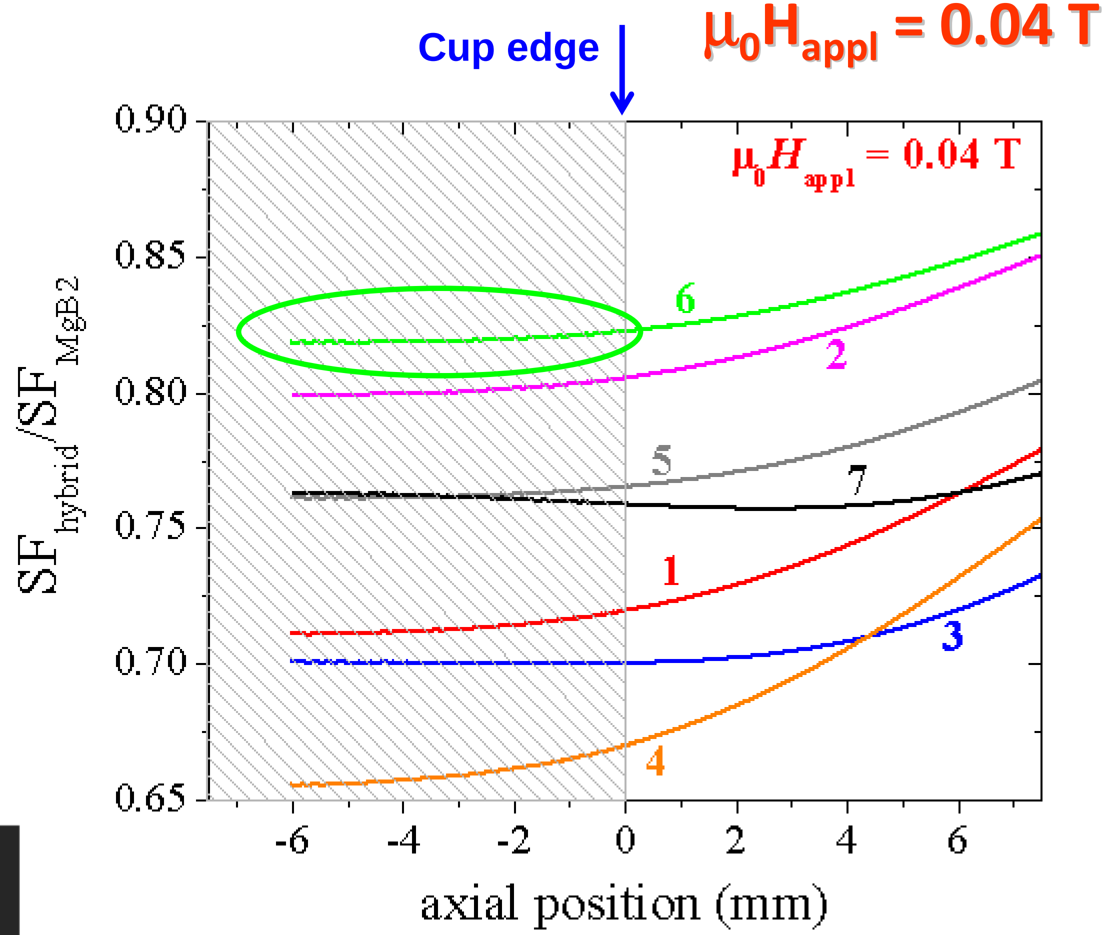


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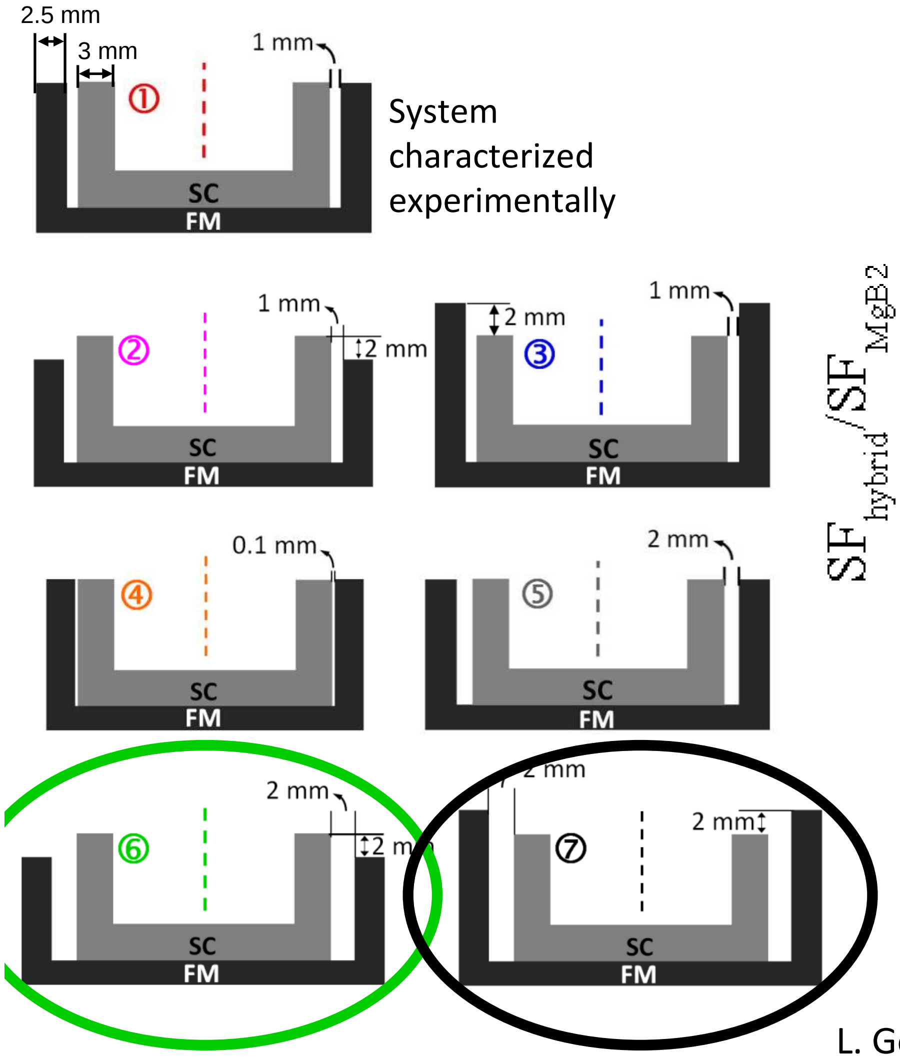
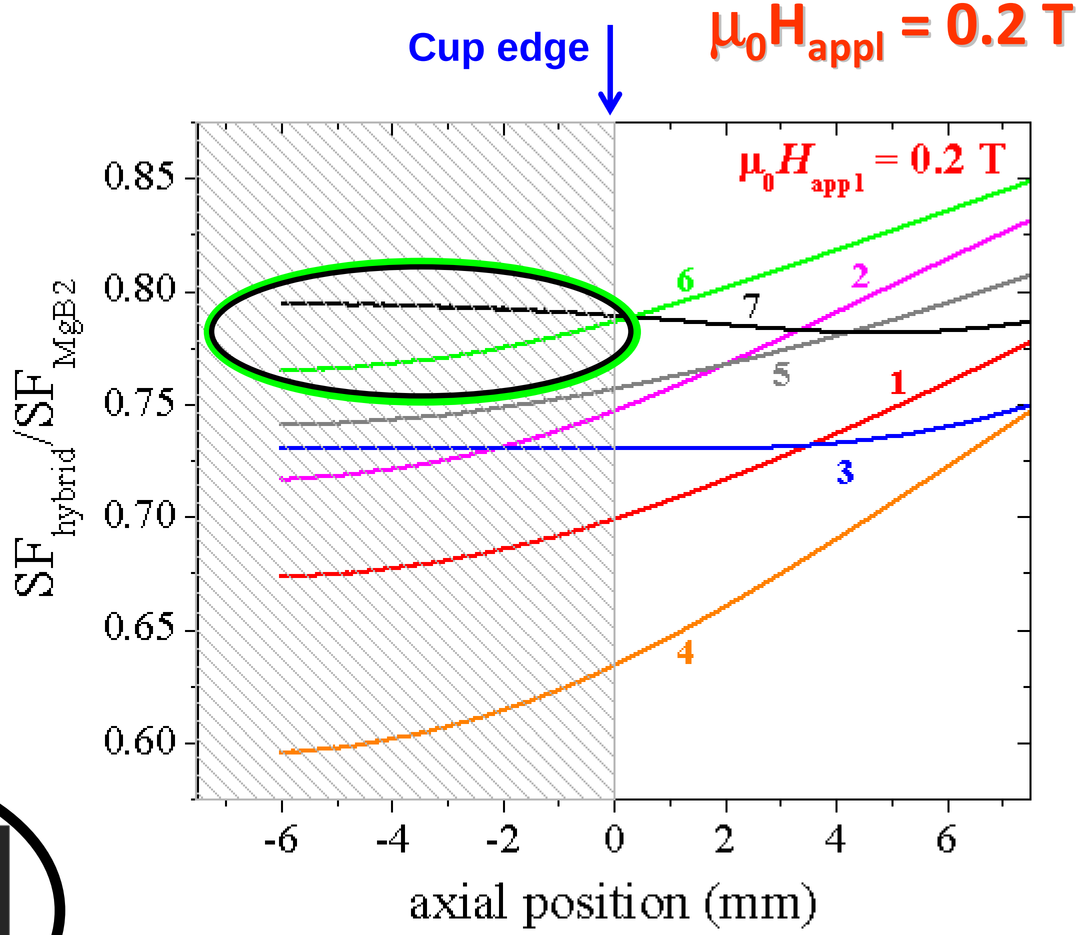
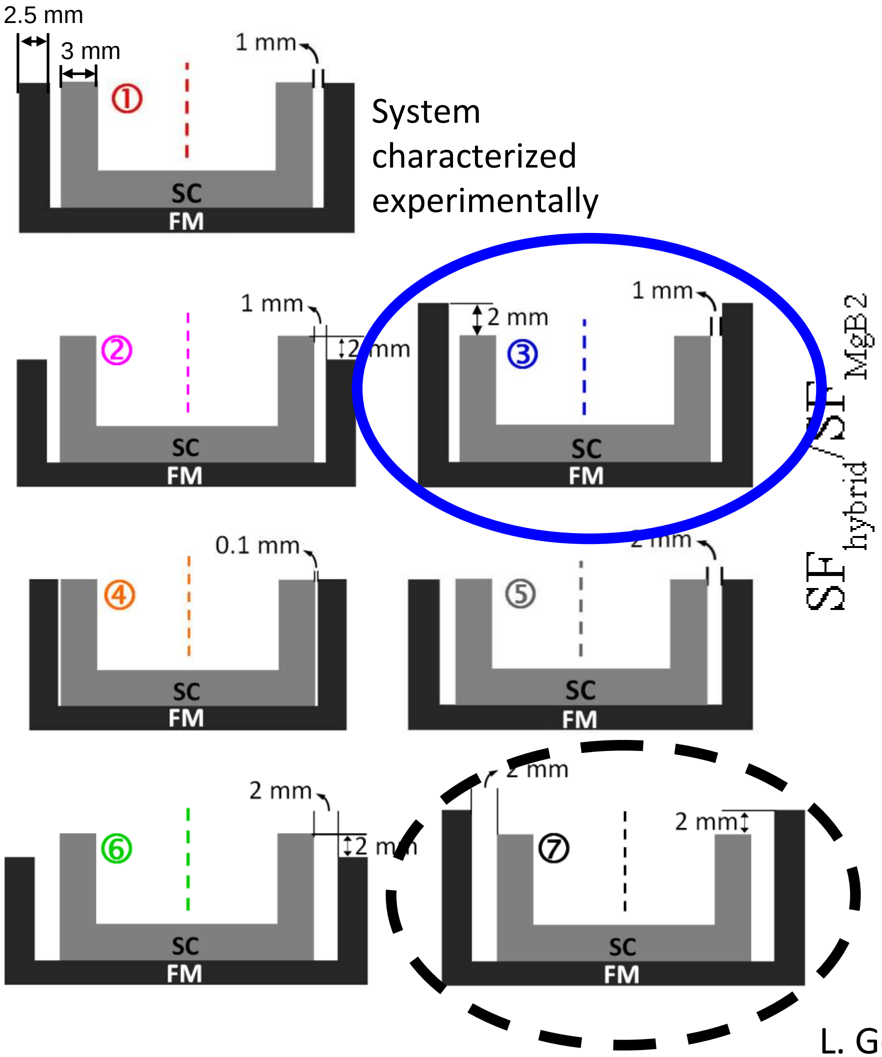


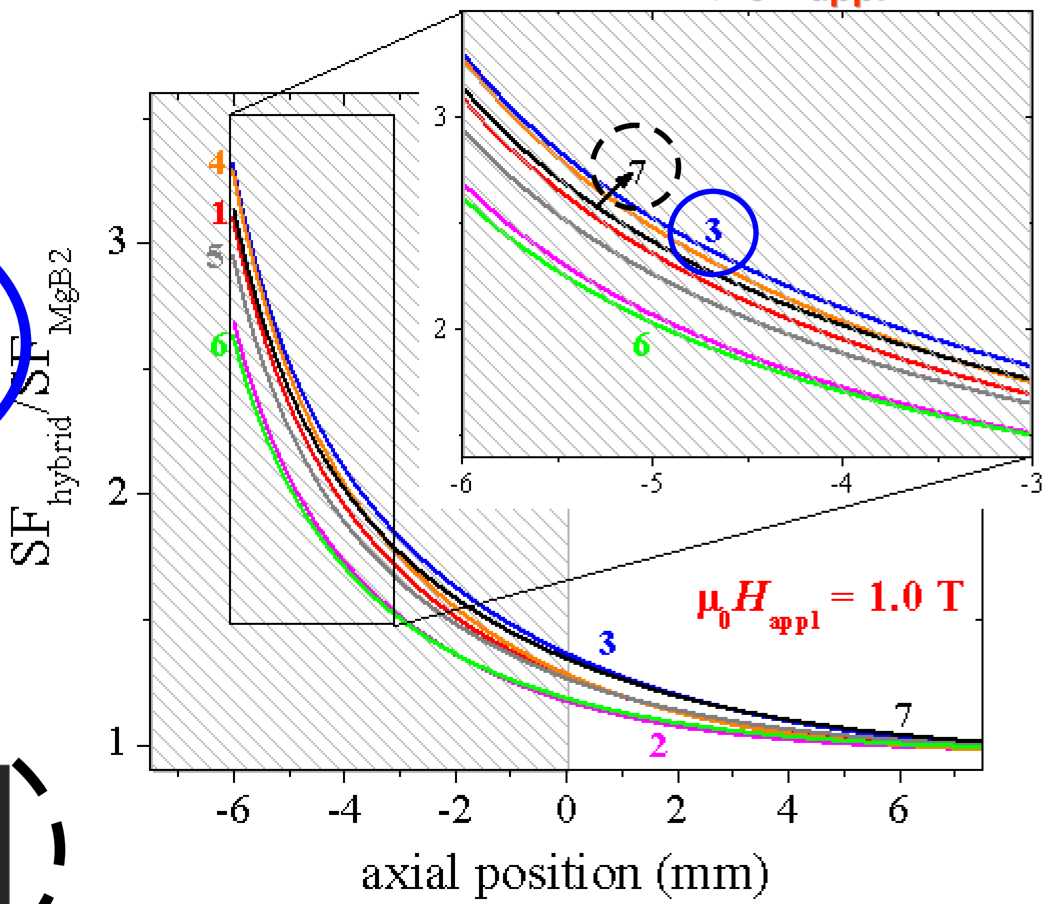

L. Gozzelino *et al.*, *Supercond. Sci. Technol.* 29 (2016) 034004

# Towards new shield configurations:
## height difference between edge – air gap modulation

$\mu_0 H_{appl}$ = 1.0 T

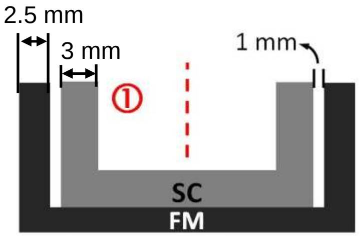



System characterized experimentally

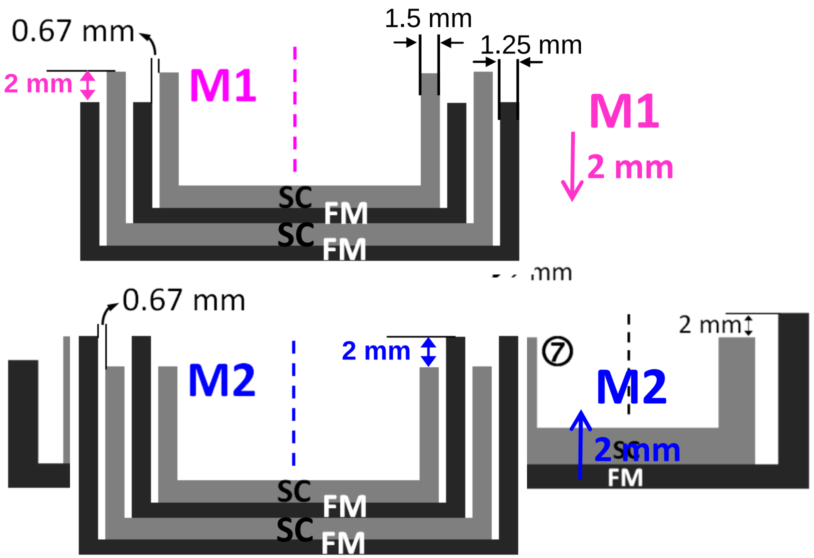



L. Gozzelino *et al.*, *Supercond. Sci. Technol.* 29 (2016) 034004

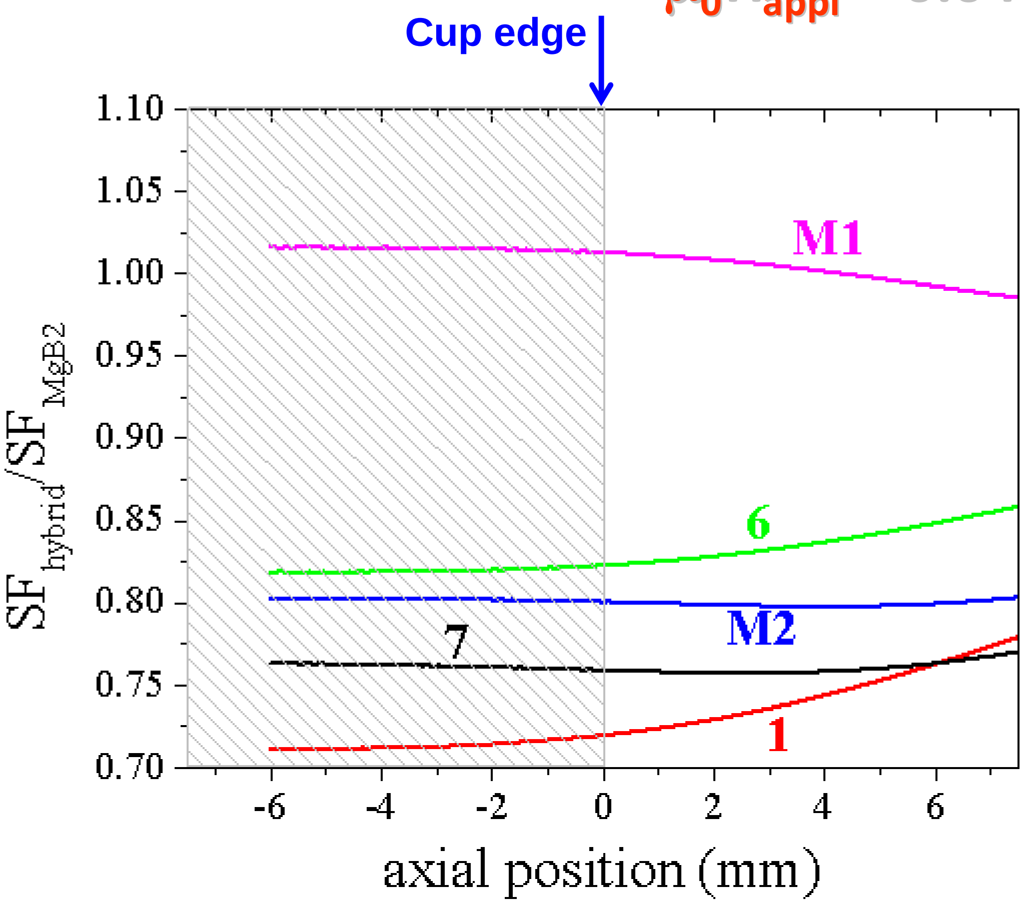
# Towards new shield configurations:
## multilayer configurations



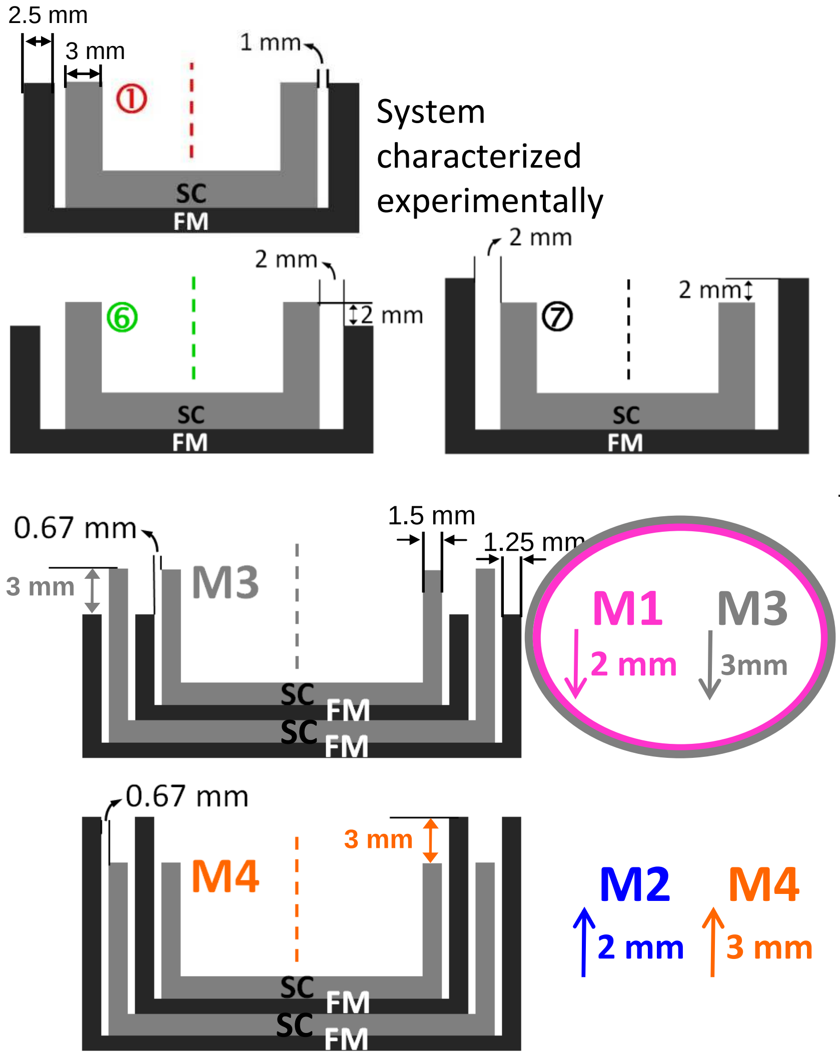

System characterized experimentally

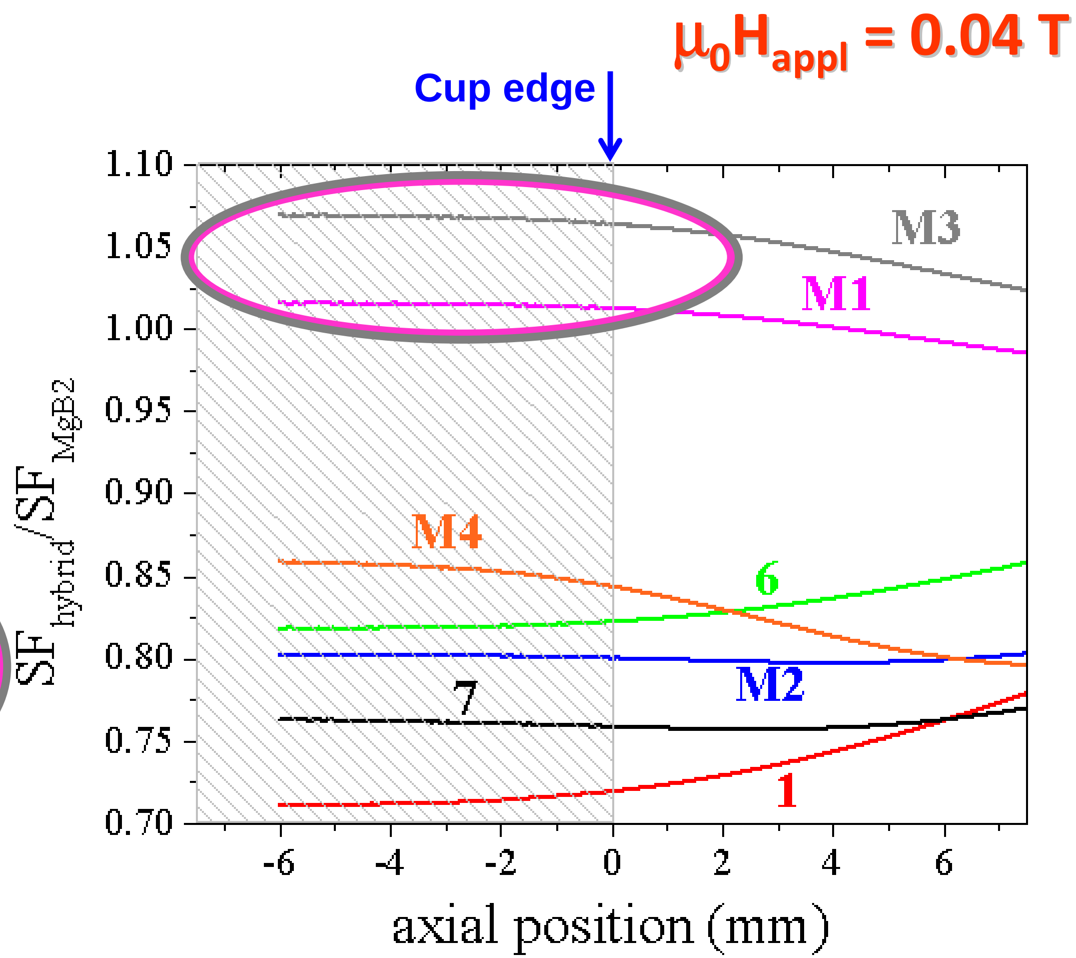



$\mu_0 H_{appl}$ = 0.04 T



# Towards new shield configurations:
## multilayer configurations



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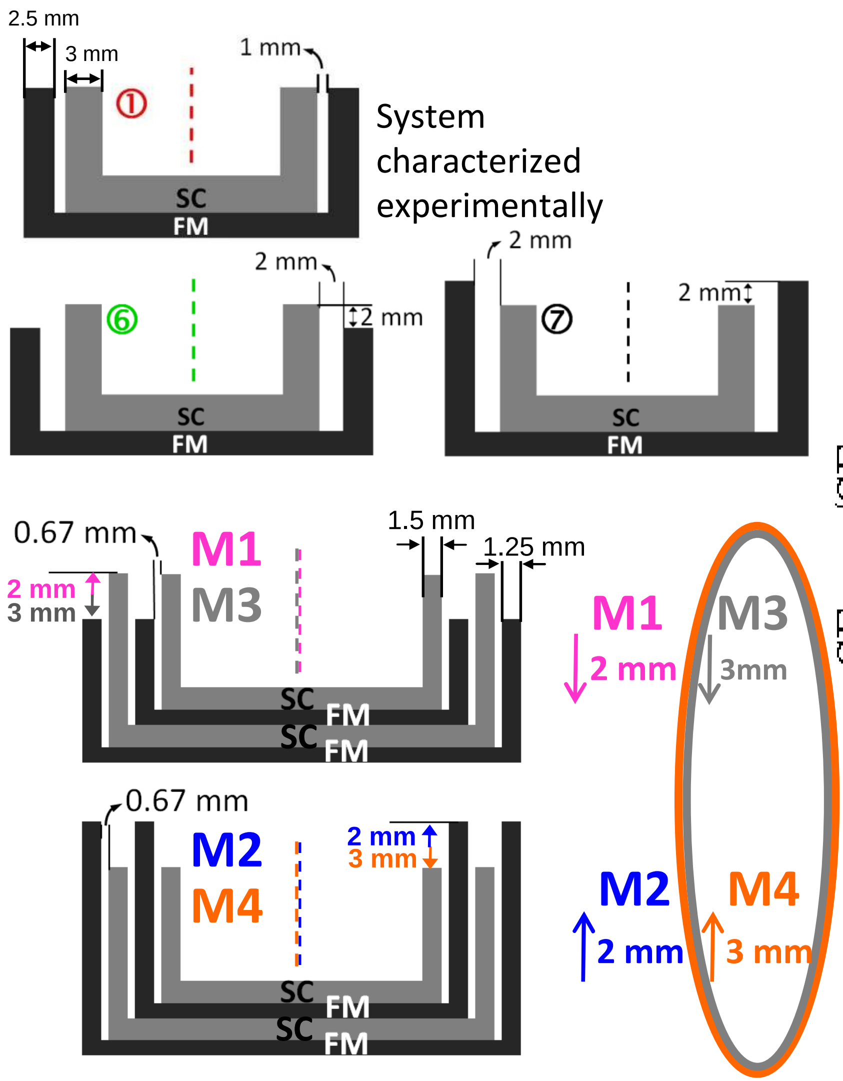
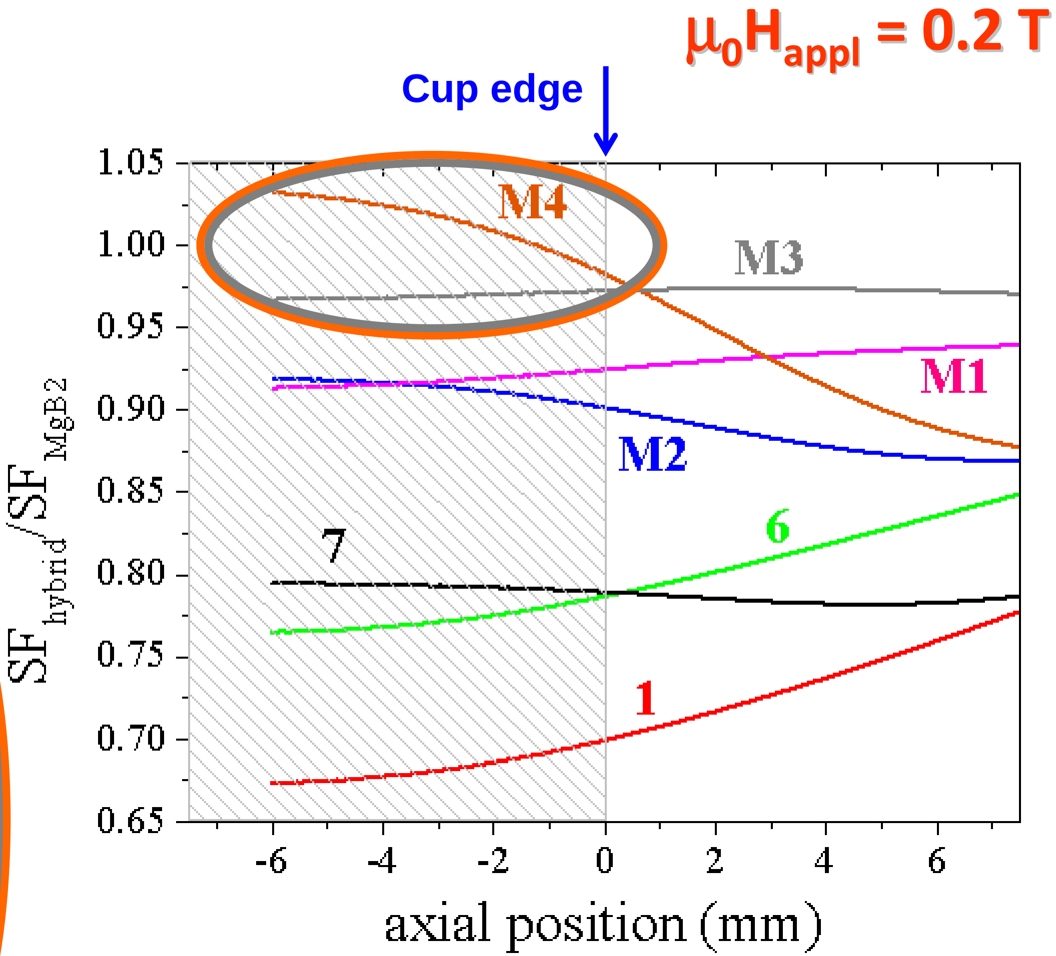
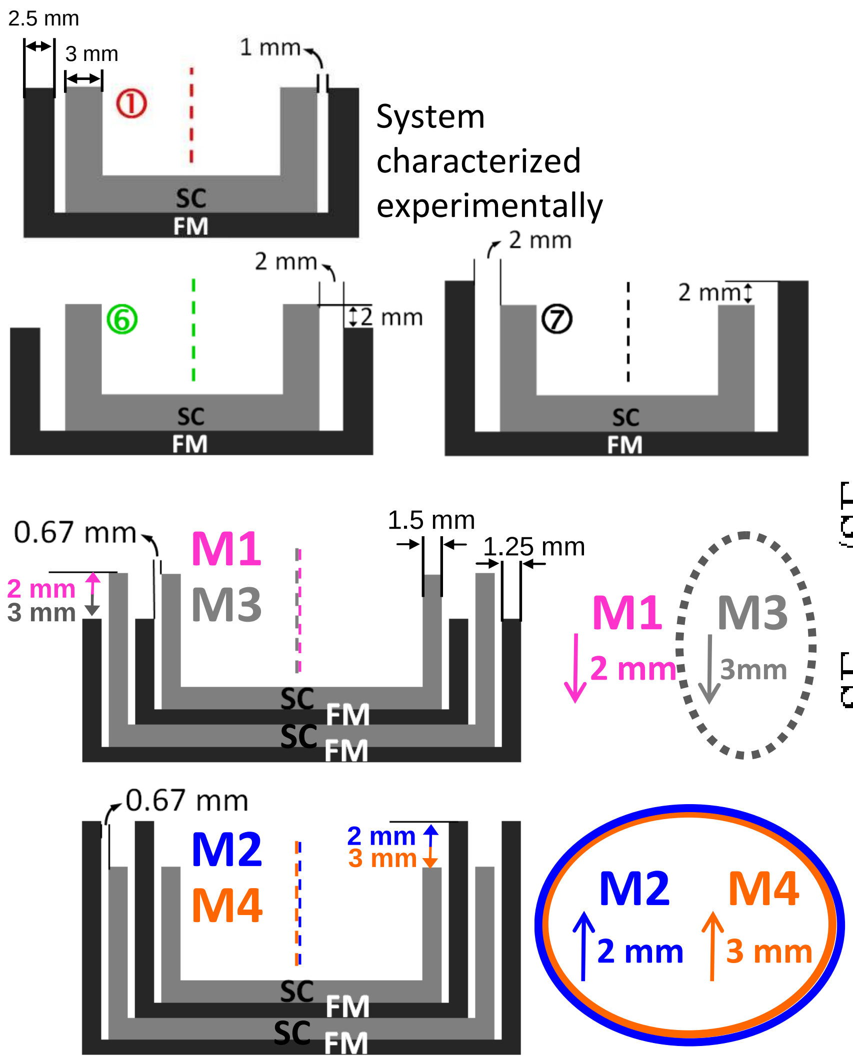
## multilayer configurations

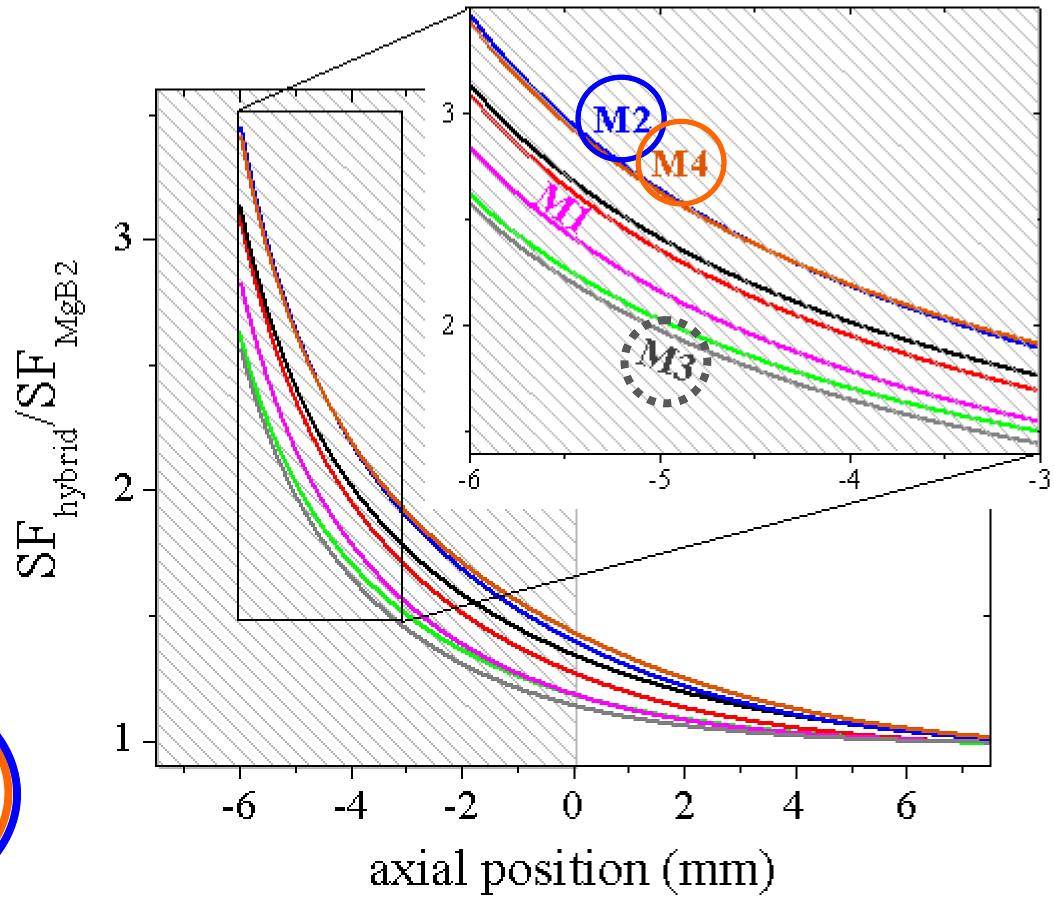


# Towards new shield configurations:
## multilayer configurations

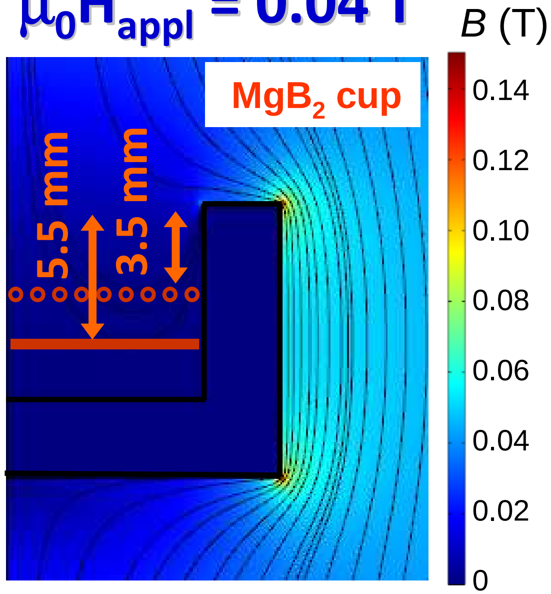
$\mu_0 H_{appl}$ = 1.0 T

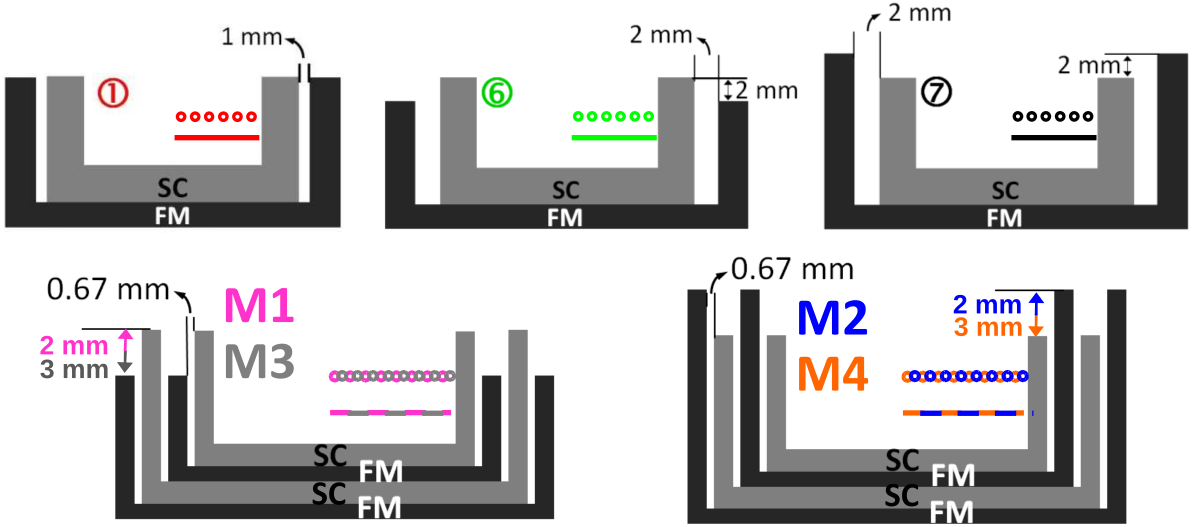


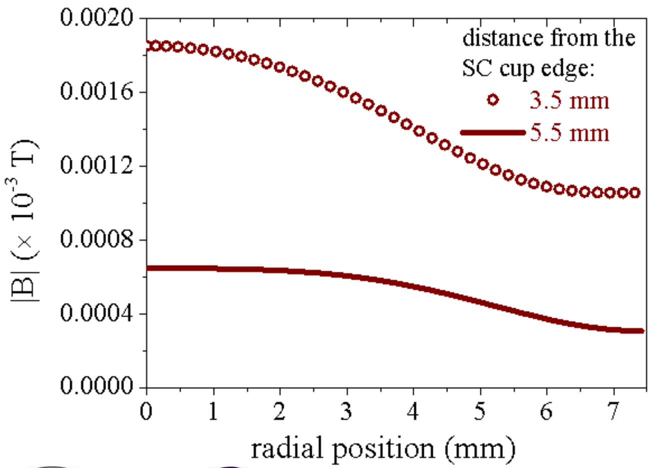



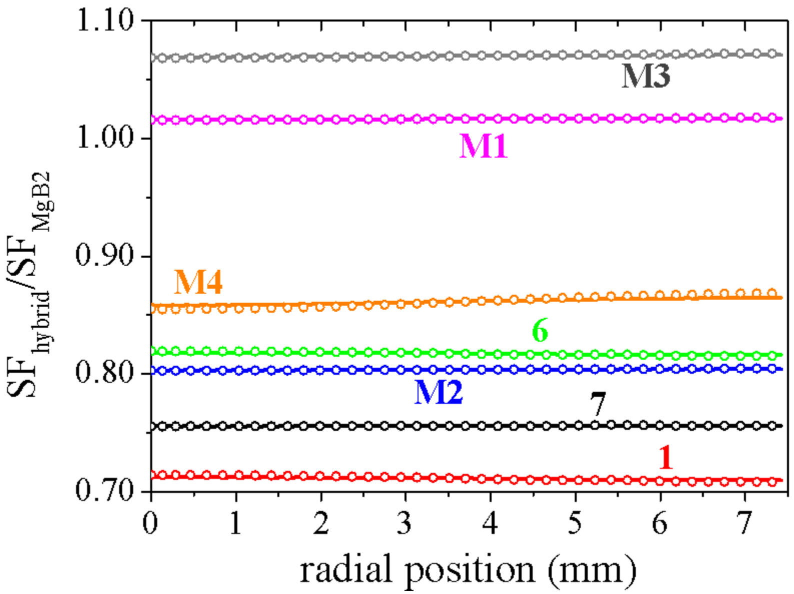
# Towards new shield configurations:
## out of axis shielding behaviour

$\mu_0 H_{appl}$ = 0.04 T




Shielding factor:
$|B_{unsh}|/|B|$

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# Conclusions

**Comparison of the shielding properties of $MgB_2$ and $MgB_2$/Fe cups :**

- **The presence of the ferromagnetic layer can strongly affect the shielding efficiency of the superconductor**
  - ➔ **low field: ☺ superconducting cup**
  - ➔ **high field: ☺ hybrid system**

- **Enhancements of the shielding capability of the hybrid system can be achieved by a suitable shaping of the Fe cup with respect to the $MgB_2$ one**
  - **☺ height difference between the edge of the SC/FM shields**
  - **☺ multilayer systems**


# Thanks to:

- F. Gömöry
- M. Chiampi, A. Manzin, L. Zilberti
- INFN SR2S-RD experiment

# Conclusions

**Comparison of the shielding properties of $MgB_2$ and $MgB_2$/Fe cups :**

- **The presence of the ferromagnetic layer can strongly affect the shielding efficiency of the superconductor**
  - ➔
  - ➔

**THANK YOU !**

- **Enl**
  **ach** **e**
  - ☺
  - ☺


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