HTS 2022 Modelling

8th International Workshop on Numerical Modelling of High Temperature Superconductors
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A numerical study on flux-jump occurrence in MgB_2 bulks

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Outline

Motivations and Background

*Modelling: **A**-V formulation*

Coupling of the electromagnetic and thermal equations

Results

Conclusions

Motivations and Background

Low-frequency magnetic fields shielding

WHY
- electromagnetic noise - stray field reduction → equipment integration/compatibility
- low magnetic field background → protection of magnetic field sensitive detectors

HOW → Passive solutions
- Ferromagnetic (FM) materials
- Superconducting (SC) materials → MgB_2

REQUIRES
- manufacturing techniques able to provide suitably shaped objects
- modelling procedures able to guide the shielding devices optimization depending on the required working conditions

Motivations and Background

MgB_2 fabrication process

MgB_2 bulks were obtained from commercial MgB_2 powders (Alfa Aesar) mixed with hexagonal BN. The powders were loaded into a graphite die system of ∽20 mm inner diameter and processed by spark plasma sintering (SPS) at 1150 °C for a dwell time of 8 min. The maximum pressure applied on the sample during sintering was 95 MPa.

☺ Improve machinability of the bulks

☹ Thermal properties get worse

The as-prepared bulks are machinable:

- **an axial hole can be drilled using bits with different radii**
- **the final product is refined using a lathe machine**

<u>Ability to shape and size bulks</u>

key aspect for magnetic shielding applications in order to reach high performances of magnetic mitigation in relation to working conditions.

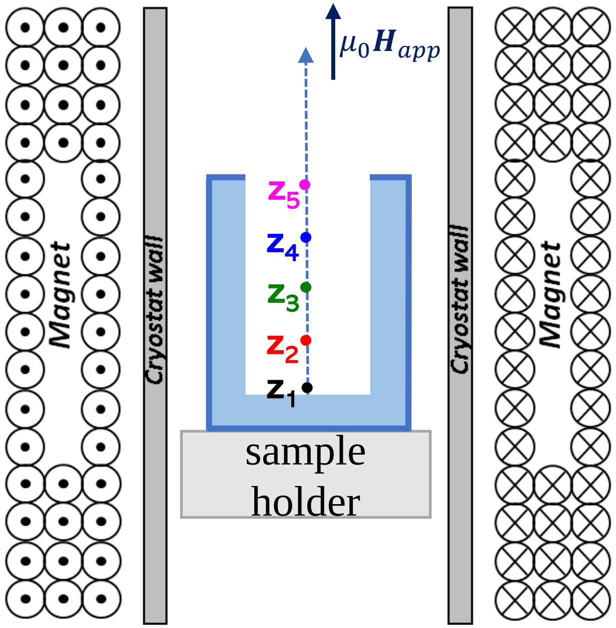

Geometrical parameters:
inner radius R_i=7.0 mm,
external radius R_o=10.15 mm,
external height h_e=22.5 mm,
internal depth d_i=18.3 mm.
$AR=h/R_o=2.25$
$AR'=d/R_o=1.83$
Powders (LTS):
BN addition [wt.%]: 10
Final sample density: ∽2.50 g/cm^3

AR= height/average diameter ~ 1

L. Gozzelino et al., Supercond. Sci. Technol., 33, 044018 (2020)
G. Aldica, et al., Patent No RO130252-A2, DPAN 2015-383635

Motivations and Background

MgB_2 cup: shielding in axial-field orientation



From the closed extremity (mm):

z_5 = 18.3 - edge

z_4 = 13.5

z_3 = 9.0 - centre

z_2 = 5.0

z_1 = 1.0

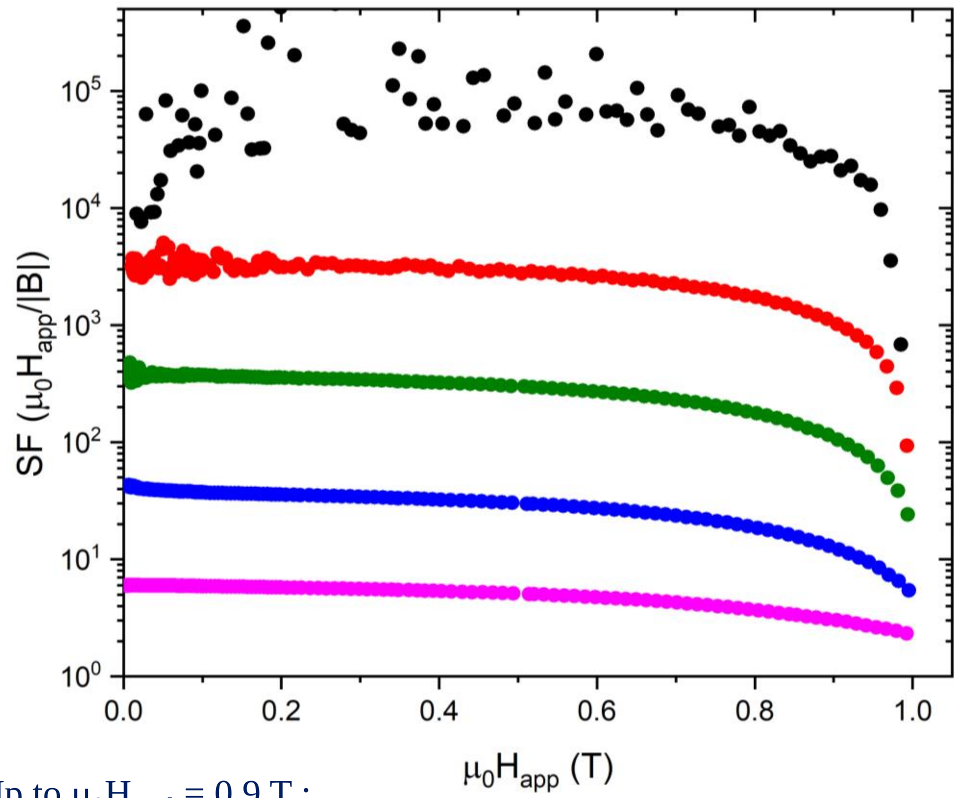
$$\mathbf{SF} = \frac{\mu_0 H_{appl}}{|B|}$$

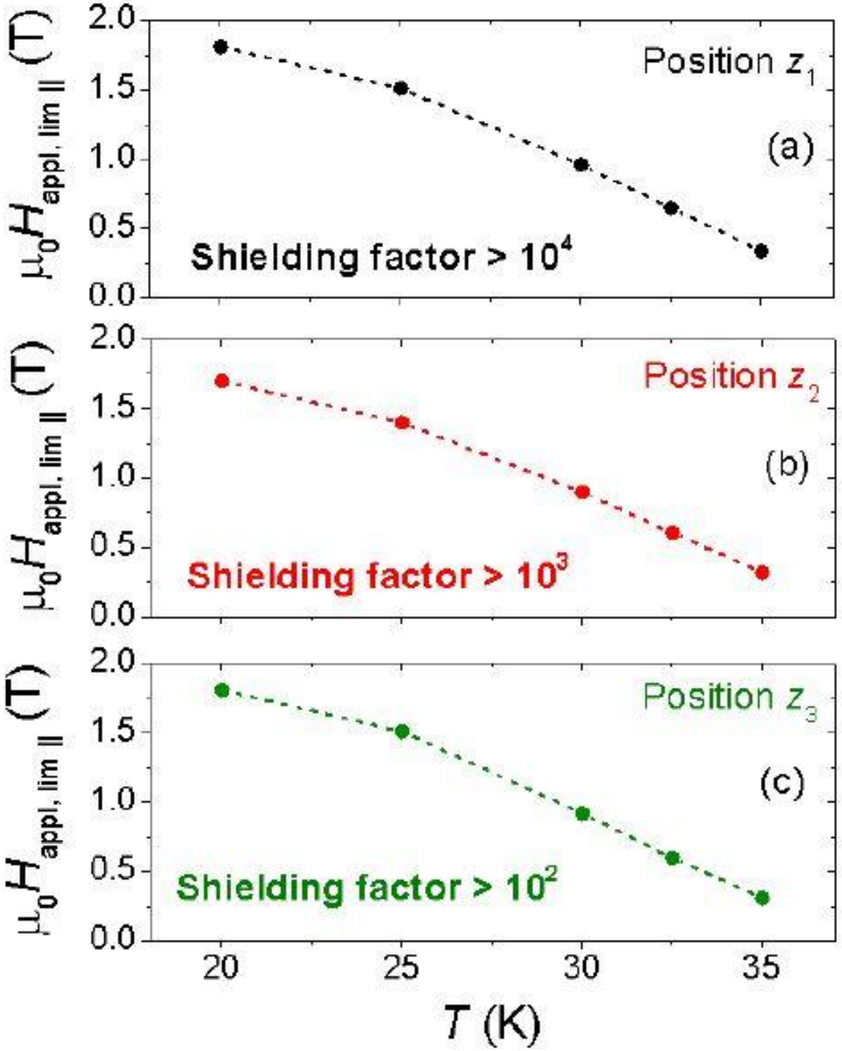
Up to $\mu_0 H_{appl}$ = 0.9 T :

position z_1: SF > 10^4

position z_2: SF > 10^3

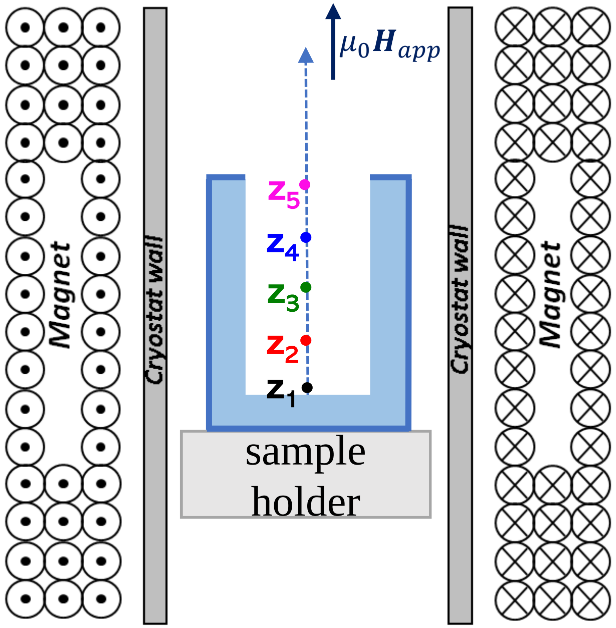
position z_3: SF > 10^2





Motivations and Background

MgB_2 cup: shielding in axial-field orientation



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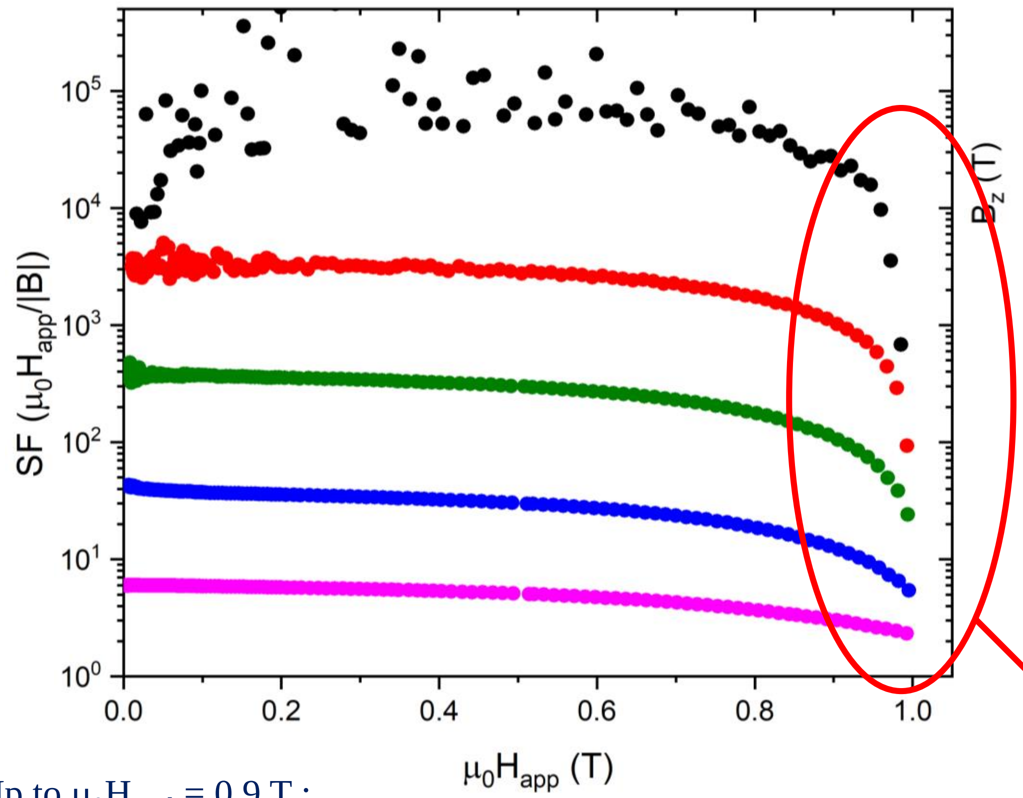
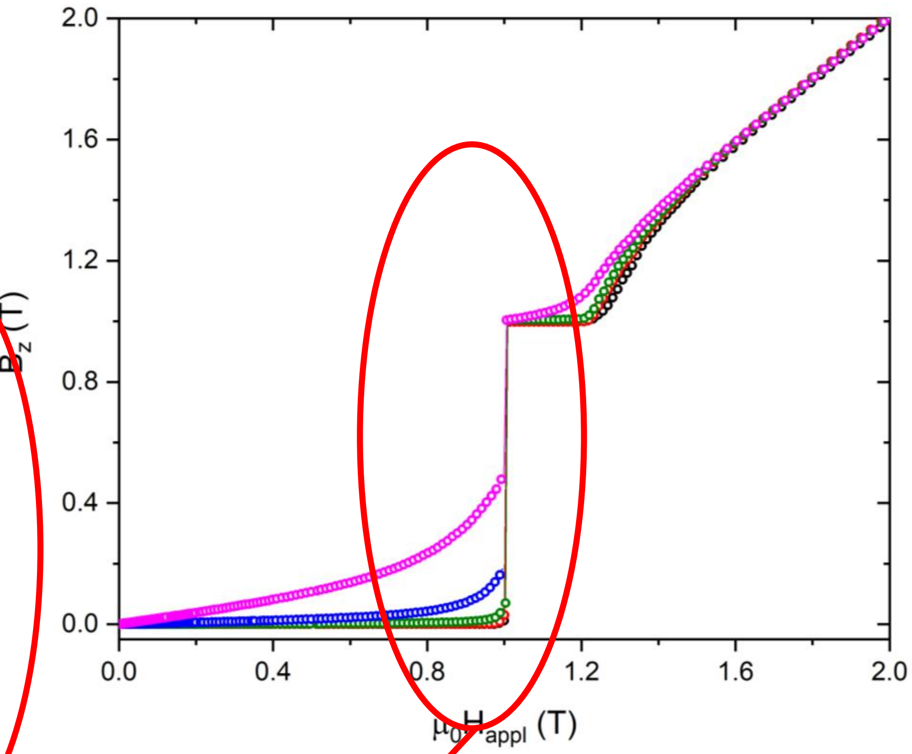


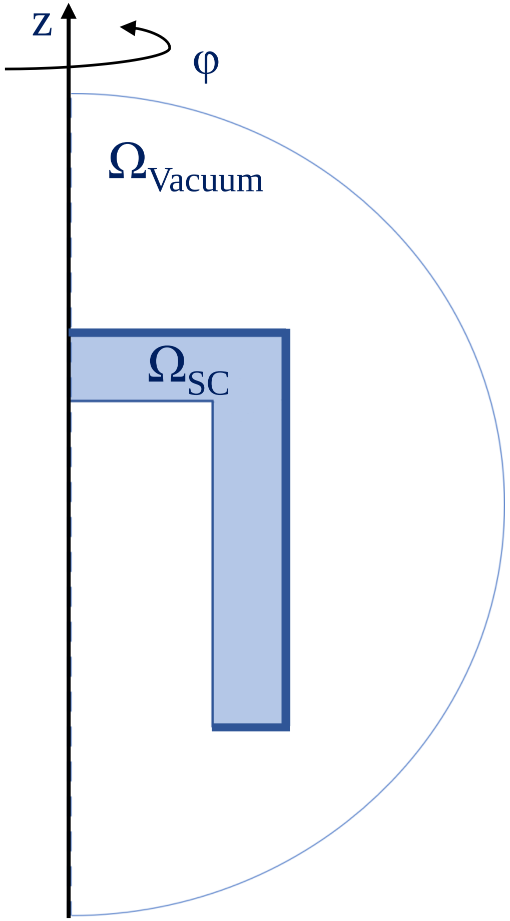


Flux-jumps occurence!

Shielding performances have to be improved

Modelling: A-V formulation

Finite element method (FEM) solving A-V Formulation by COMSOL Multiphysics® 6.0 (2D axisymmetric geometry)



$$E_\varphi = -\frac{\partial A_\varphi}{\partial t}$$

a relation between the electric field and the current density is needed

$$E_\varphi = \mathrm{E}_0 \left(\frac{J_\varphi}{\mathrm{J_c}}\right)^{\mathrm{n}}$$

if n >>1

E-J relation smoothly approximating the critical state model

$$\boxed{J_\varphi = J_c(B) \cdot \tanh\left(\frac{E_\varphi}{E_c}\right)}$$

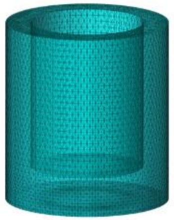
The J_c curves (obtained from magnetic induction cycles measured at different temperatures) were fitted by

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

Campbell A M, Supercond. Sci. Technol. 20, 292–5, (2007)
Gomory et al. Supercond. Sci. Technol., 22, 034017, (2009)
Solovyov M. and Gomory F., Supercond. Sci. Technol. 32, 115001, (2019)

Modelling: A-V formulation

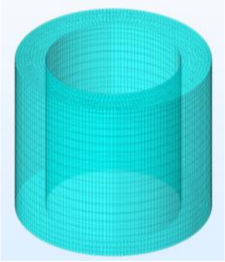
Cup shaped geometry



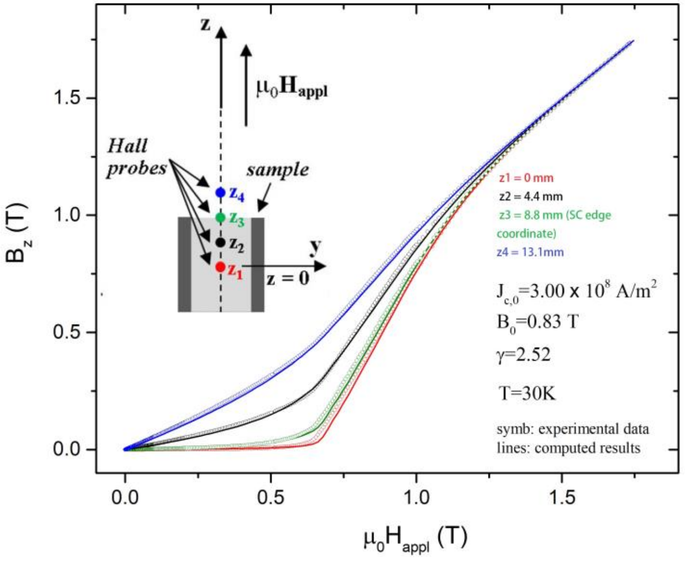
Inner radius: 7.0 mm
Outer radius: 10.0 mm
Ext. height: 22.5 mm
Int. Depth: 18.3 mm

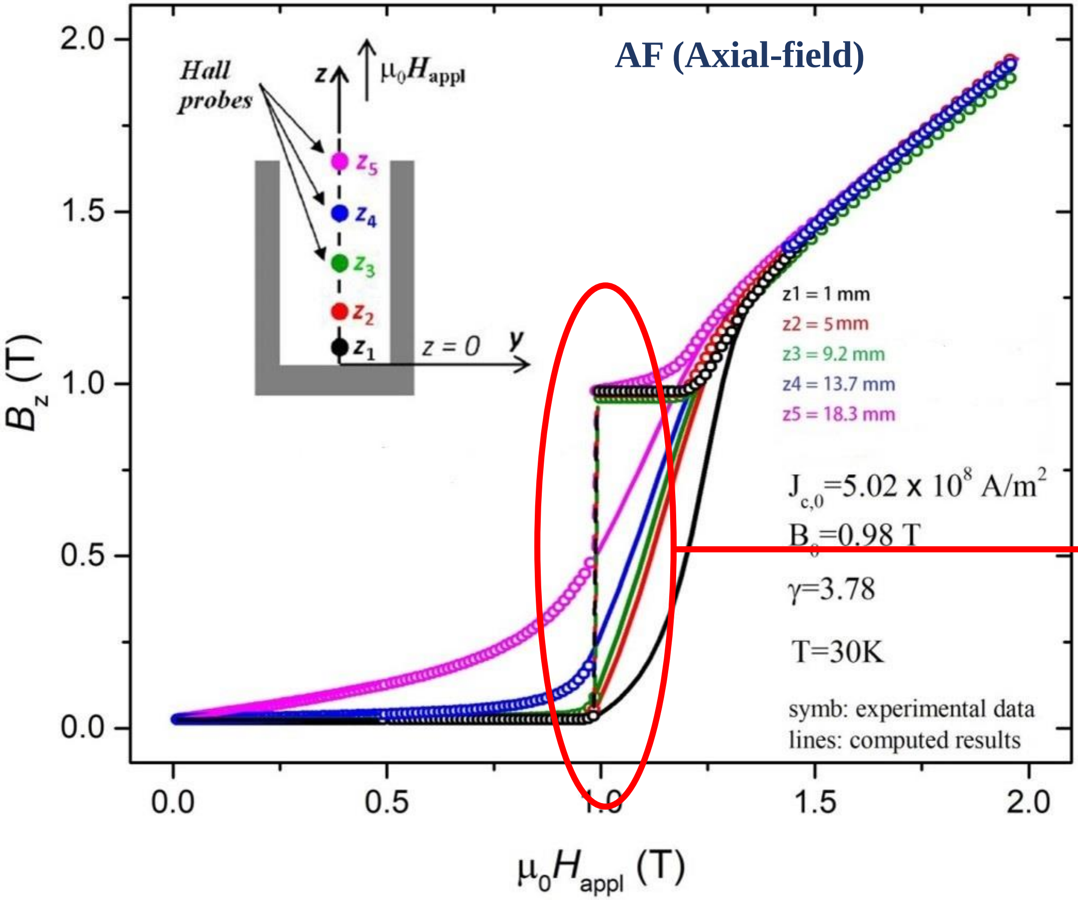
Comparison between experimental data and computational results for cup shaped MgB_2

GOOD AGREEMENT provided that no flux jump occurs



The model was validated also for tube-shaped geometry

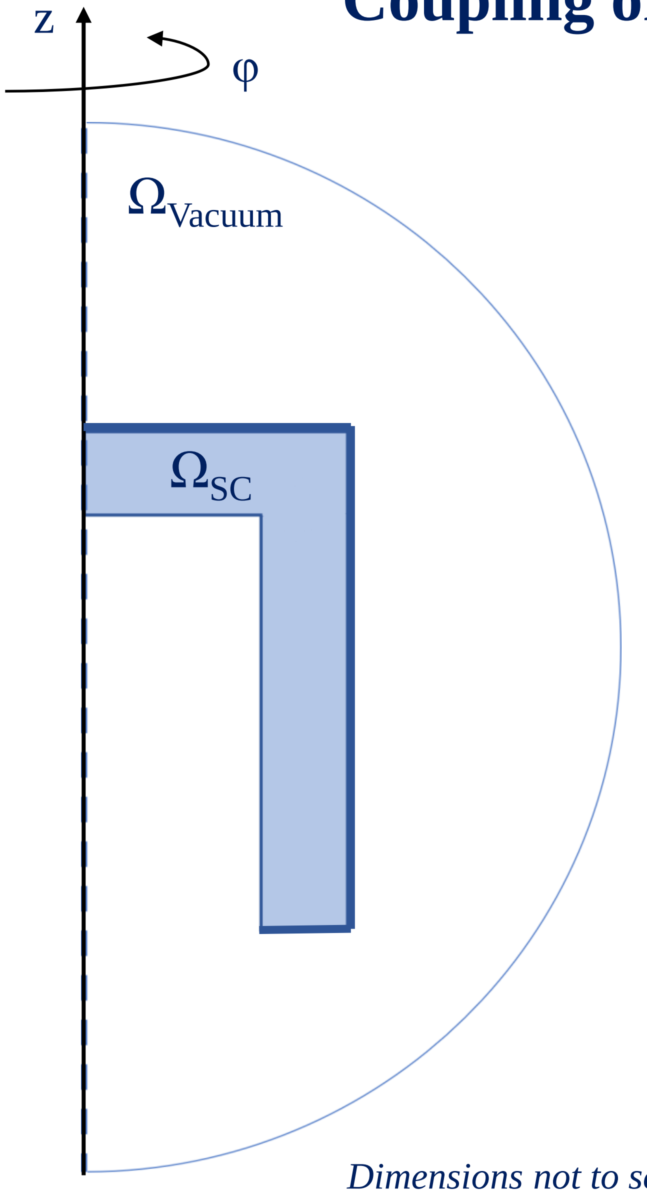




The model can not reproduce the flux jump occurence!
The electro-thermal instabilities have to be taken into account

L. Gozzelino et al., Supercond. Sci. Technol., 35, 044002, (2022)

Coupling of the electromagnetic and thermal equations



Dimensions not to scale

- **Electromagnetic behaviour of SC region Ω_{SC}**

$$J_{\varphi} = J_C(B,T) \cdot tanh\left(\frac{|E_{\varphi}|}{E_0}\right)$$

$E_0 = 10^{-5}$ V/m

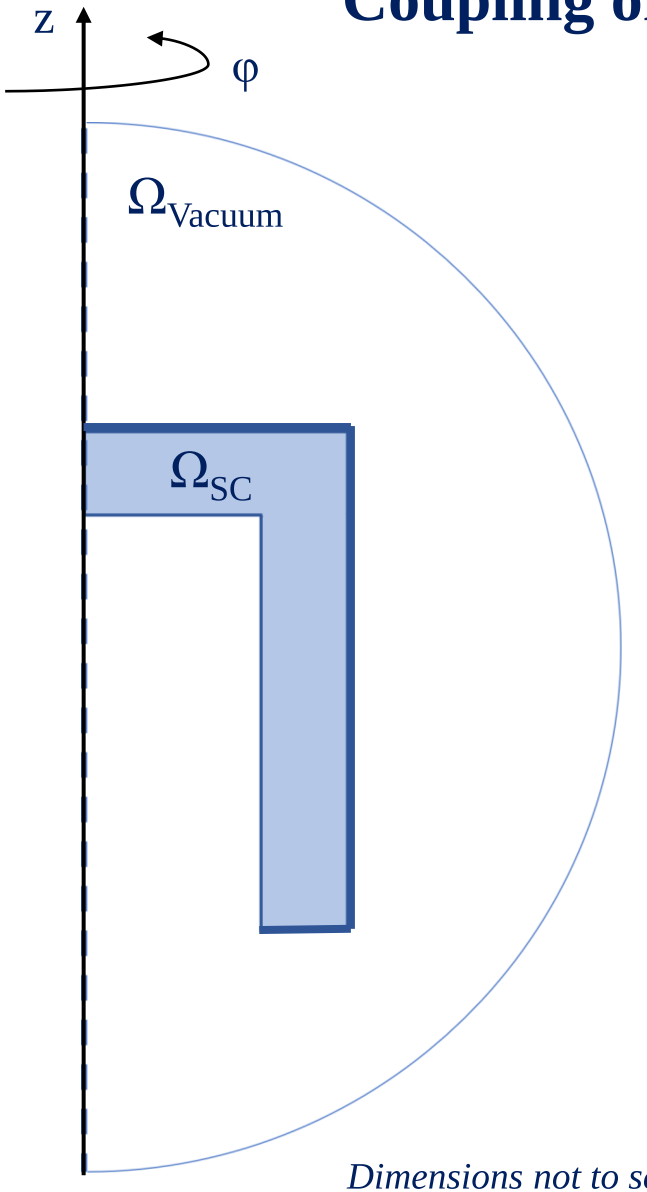
$$J_C(B,T) = f(T) \cdot \exp\left[\left(-\frac{B}{B_0(T)}\right)^{\gamma}\right]$$

$$B_0(T) = \beta\left[1-\left(\frac{T}{T_C}\right)^2\right]^{1.39}$$

$$f(T) = \alpha\left[1-\left(\frac{T}{T_C}\right)^2\right]^{1.45}$$

J. Xia et al., Supercond. Sci. Technol. 30, 075004, (2017)

Coupling of the electromagnetic and thermal equations



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$$J_\varphi = J_C(B,T) \cdot tanh\left(\frac{|E_\varphi|}{E_0}\right) \qquad E_0 = 10^{-5}\ \text{V/m}$$

$$J_C(B,T) = f(T) \cdot \exp\left[\left(-\frac{B}{B_0(T)}\right)^{\gamma}\right]$$

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$$f(T) = \alpha\left[1-\left(\frac{T}{T_C}\right)^2\right]^{1.45}$$

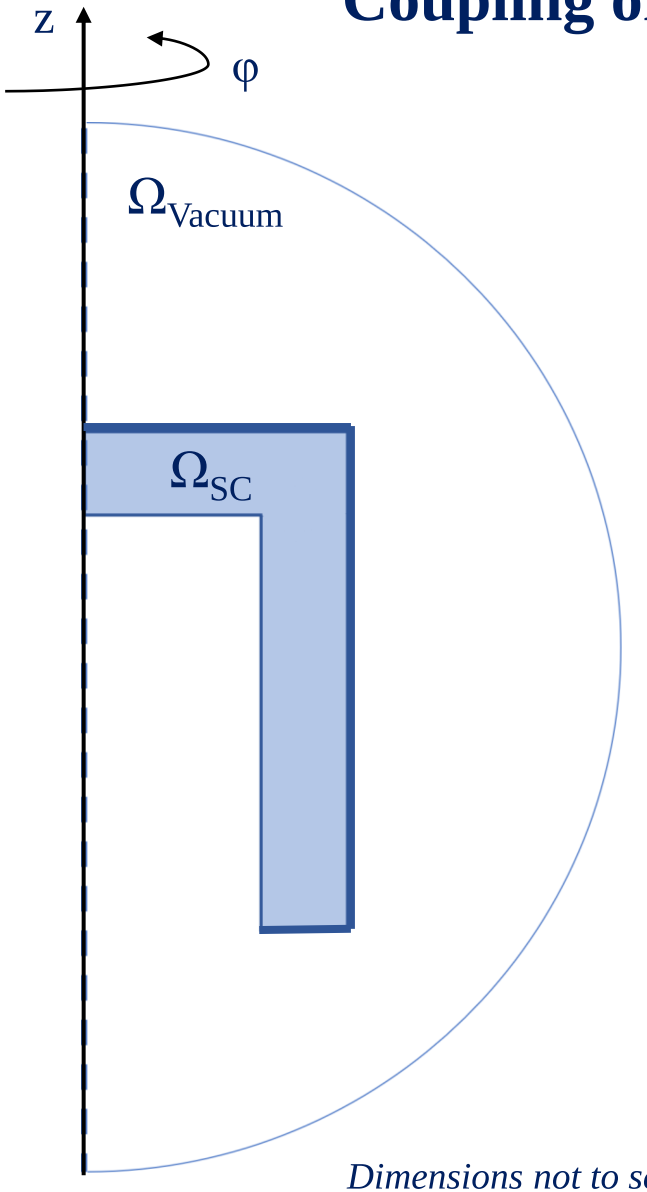
α=1.95397 x 10^{-9} A/m^2

β=3.46849 T

γ=3.88

Fit coefficients obtained by experimental Jc-B curves

Coupling of the electromagnetic and thermal equations



Dimensions not to scale

- **Thermal behaviour of SC region Ω_{SC}**

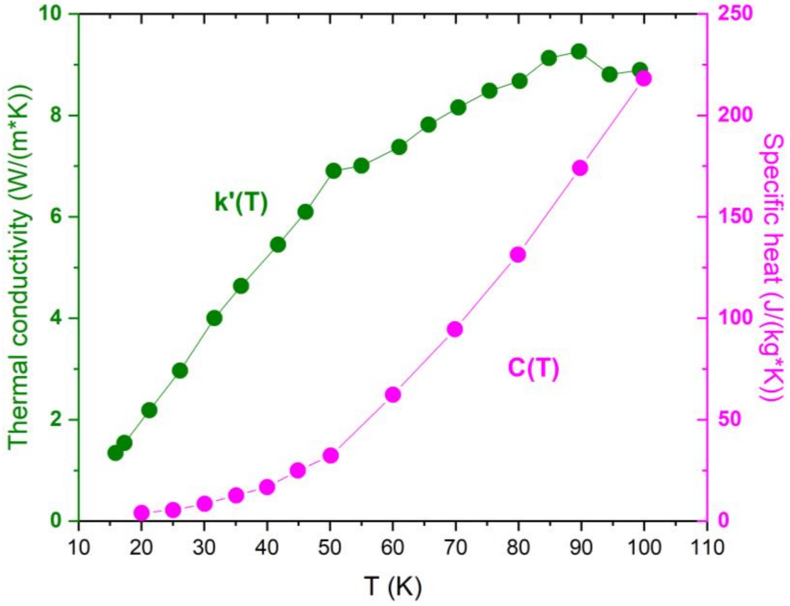
$$\nabla \cdot (k(T)\nabla T) - C(T) \cdot \rho_m \cdot \frac{\partial T}{\partial t} + Q = 0$$

Heat source $Q = E_\varphi \cdot J_\varphi$

$\rho_m = 2.50\ g/cm^3$

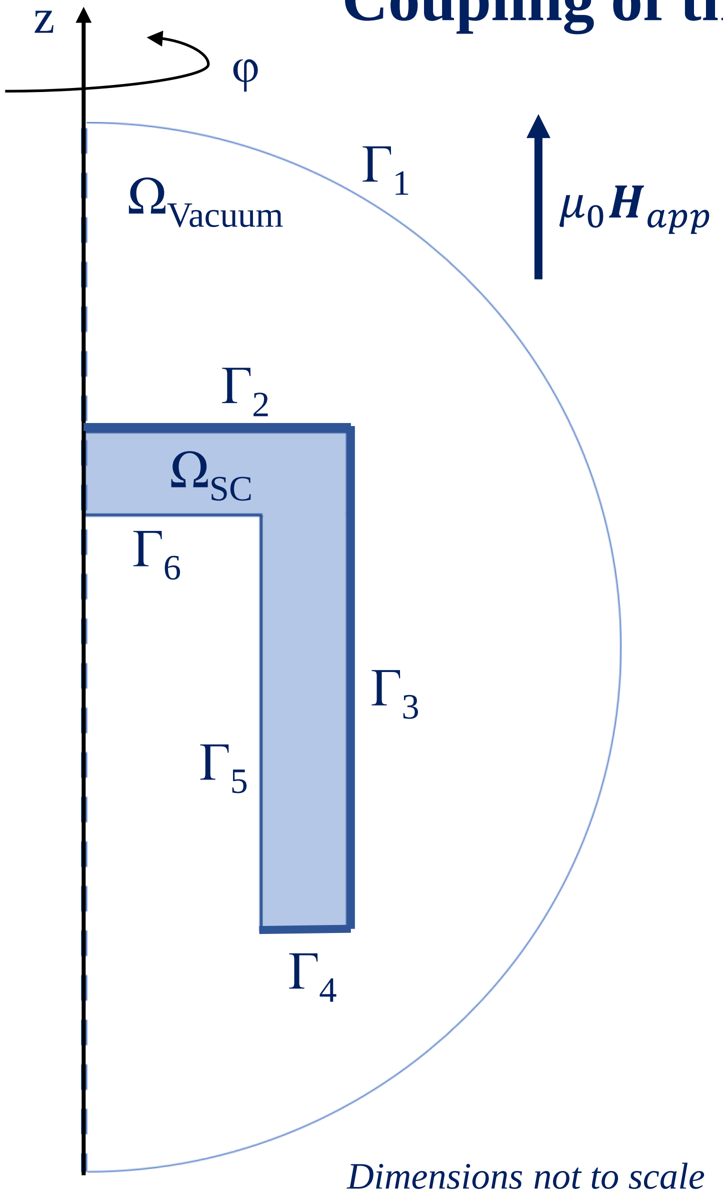
k(T) and $C(T)$ take the piecewise cubic interpolations of the experimental data of the sample HIP#38 reported in J. Zou et al.

(!) the addition of BN worsen the thermal properties of the materials so *k'(T)= k(T)/10* is assumed



J. Zou et al., Supercond. Sci. Technol., 28, 075009, (2015)

Coupling of the electromagnetic and thermal equations



Dimensions not to scale

- **Boundary conditions**

$\boldsymbol{\Gamma_1}$: at large distance from the shield, the field was assumed constant, equal to $\mu_0 \boldsymbol{H}_{app}$ with a ramp rate of 0.035 T/s

$\boldsymbol{\Gamma_2, \Gamma_3, \Gamma_4}$: the sample was cooled throught the thermal contact with the cold head and indium layer described by

$$\boldsymbol{n} \cdot (k(T)\nabla T) = A \cdot (T_{OP} - T)$$

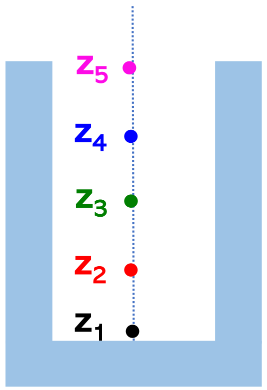
where A= 6000 W/(m^{2}K) was determined through iterative adjustments

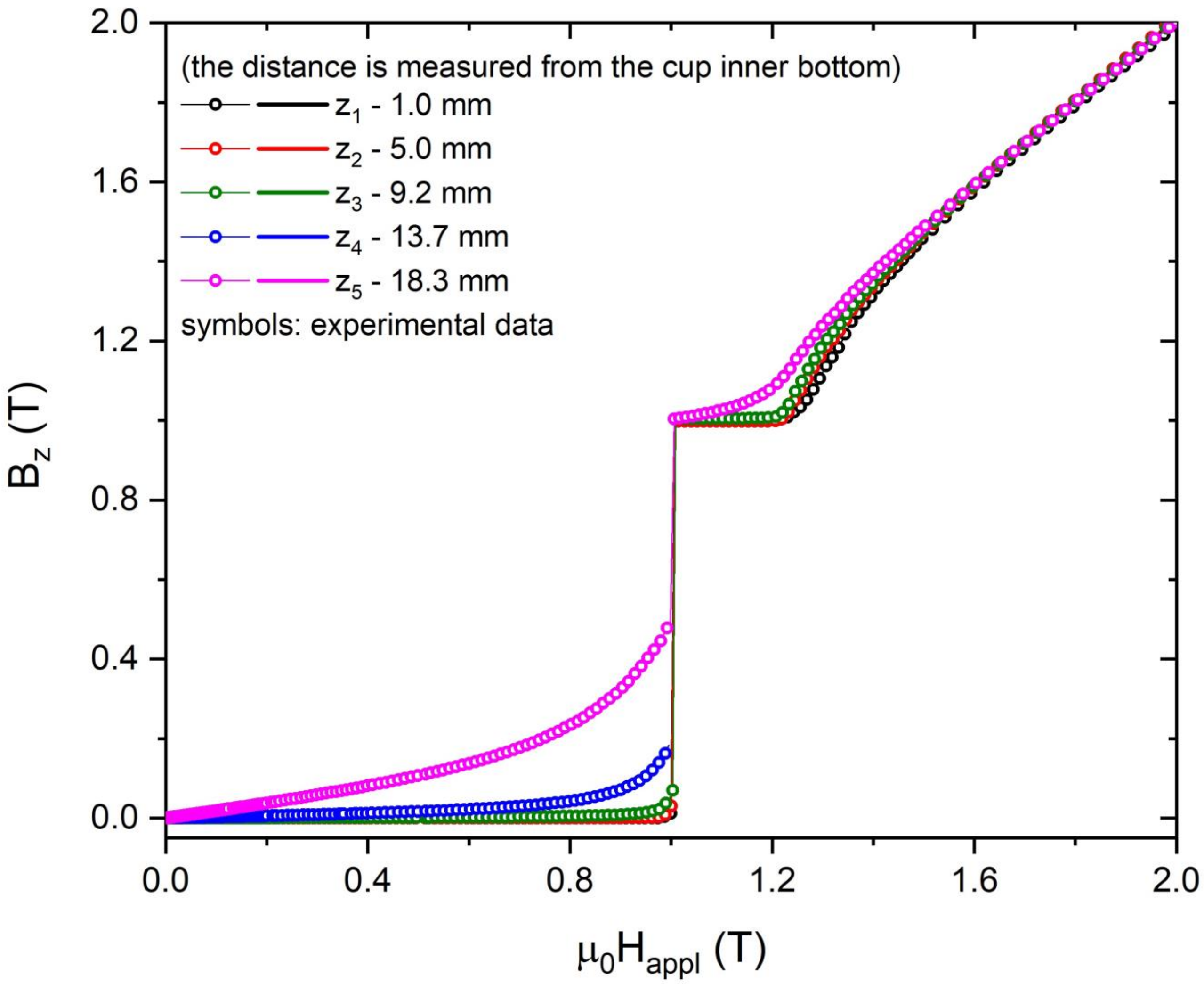
$\boldsymbol{\Gamma_5, \Gamma_6}$: $\boldsymbol{n} \cdot (k(T)\nabla T) = 0$

Z. Jing, Supercond. Sci. Technol., 35, 054006, (2022)

Results

T_{OP}=30 K





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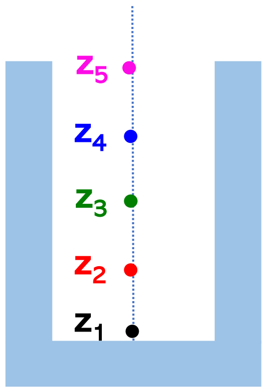
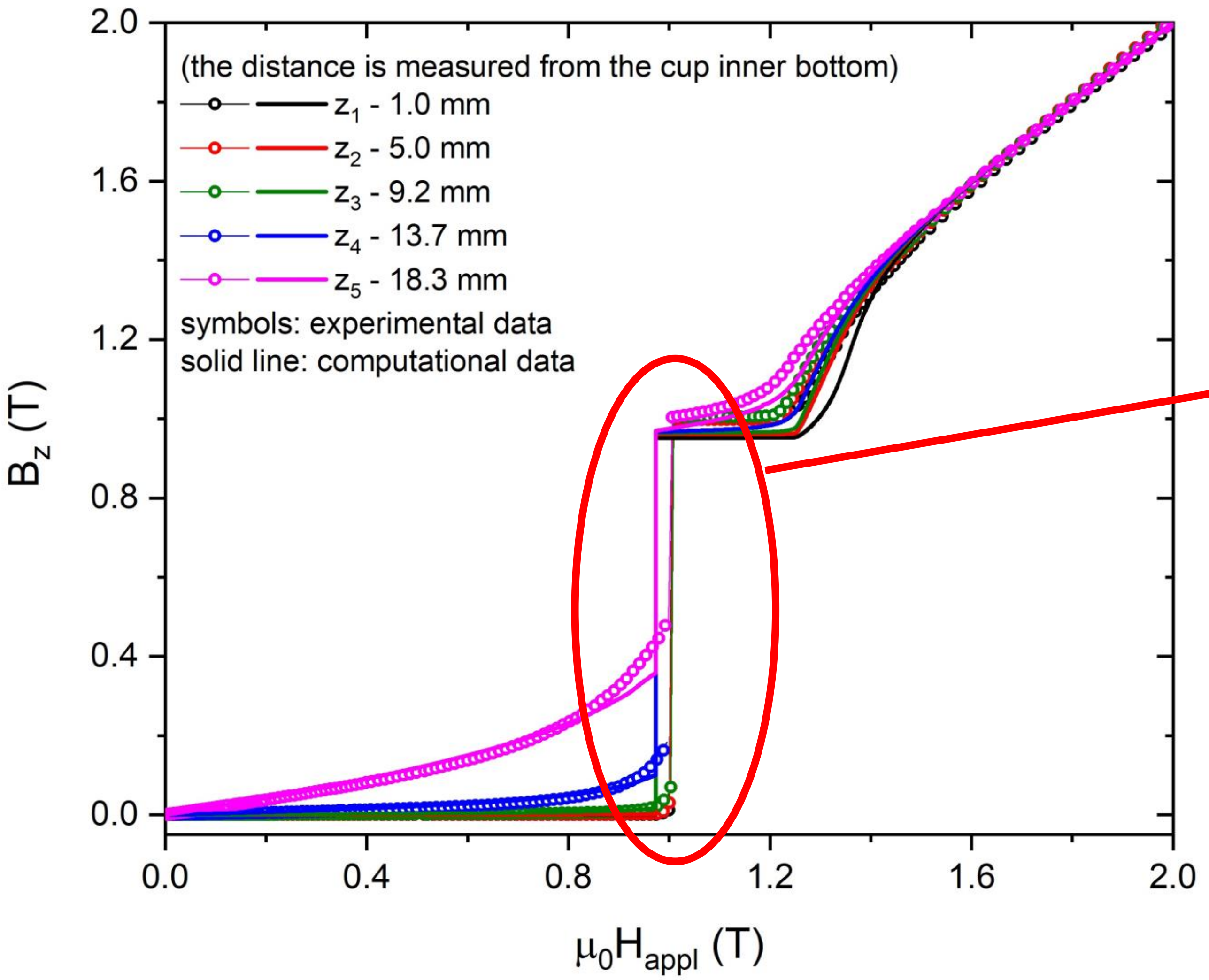
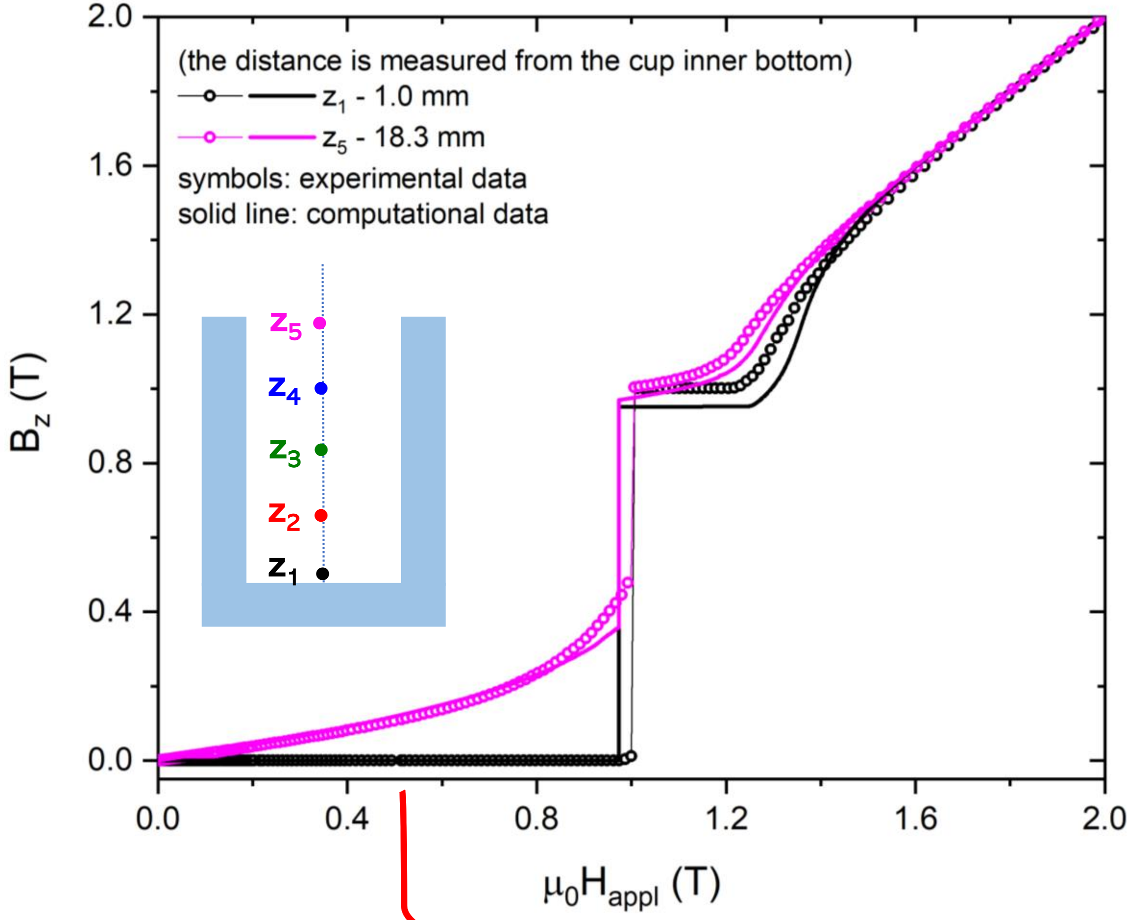


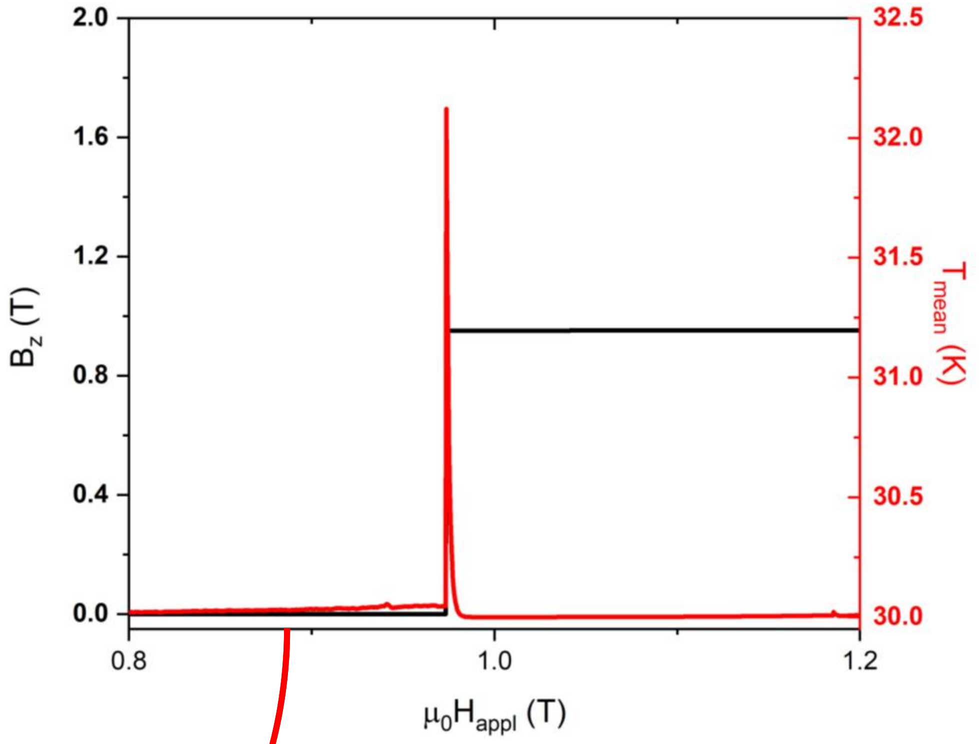


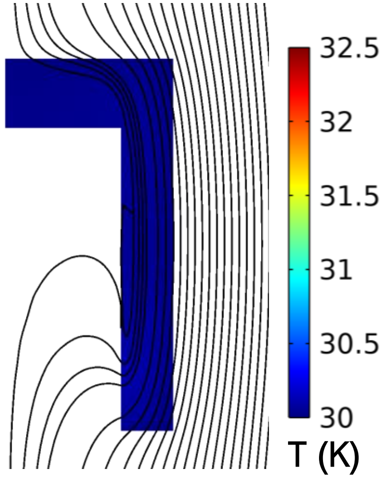
The electromagnetic-thermal coupling can reproduce the flux jump occurrence !

T_{OP}=30 K

Results







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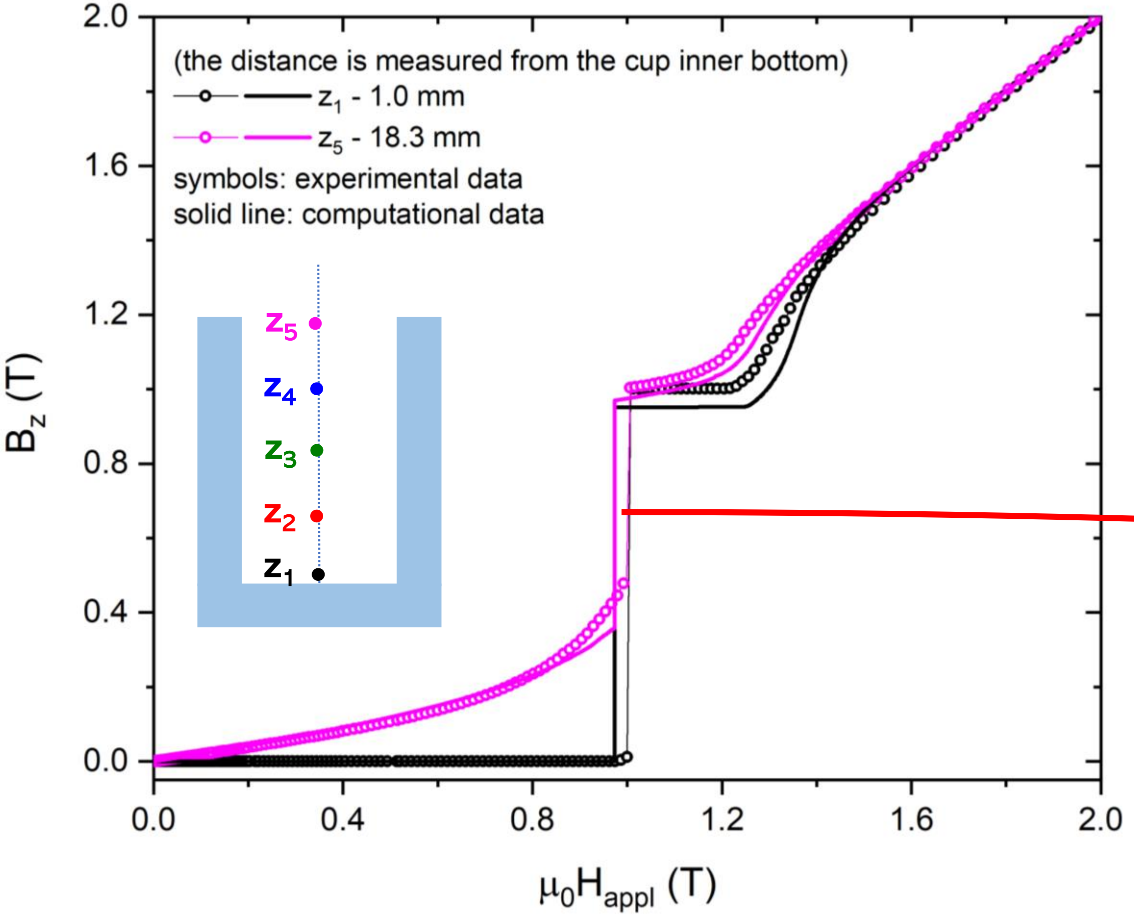

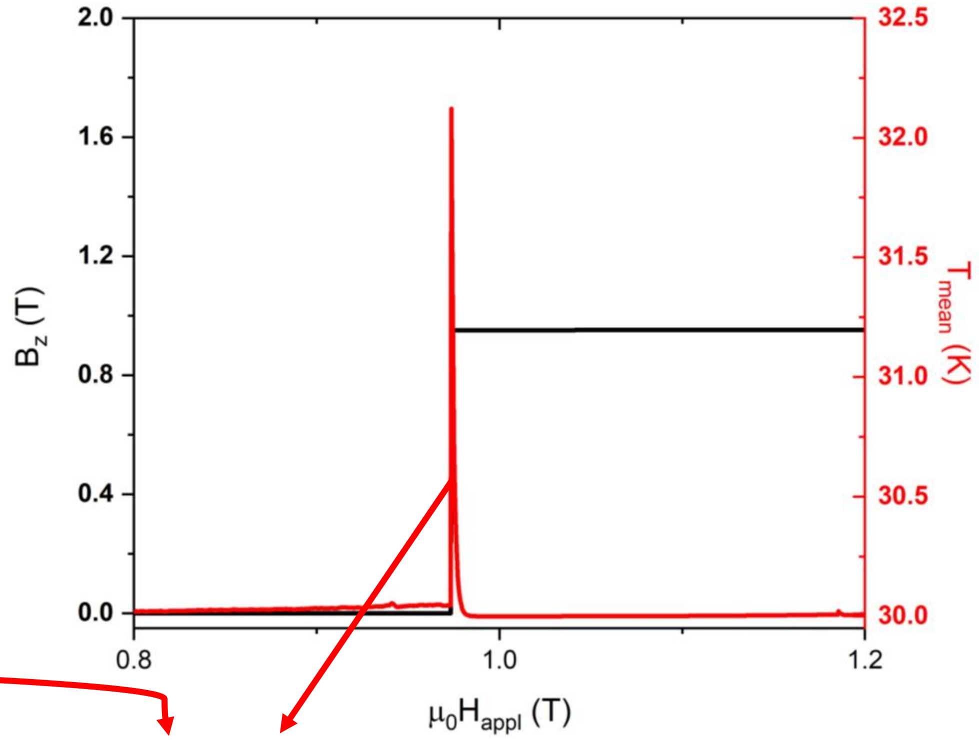

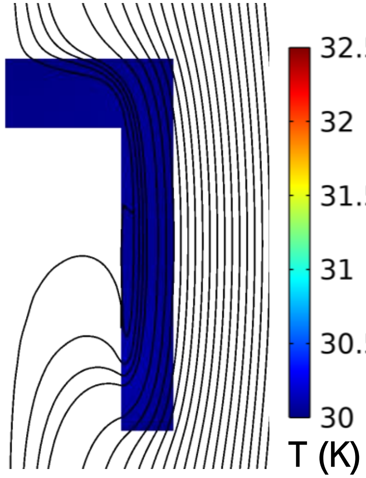

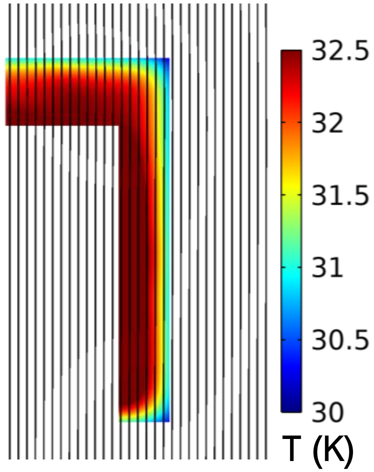

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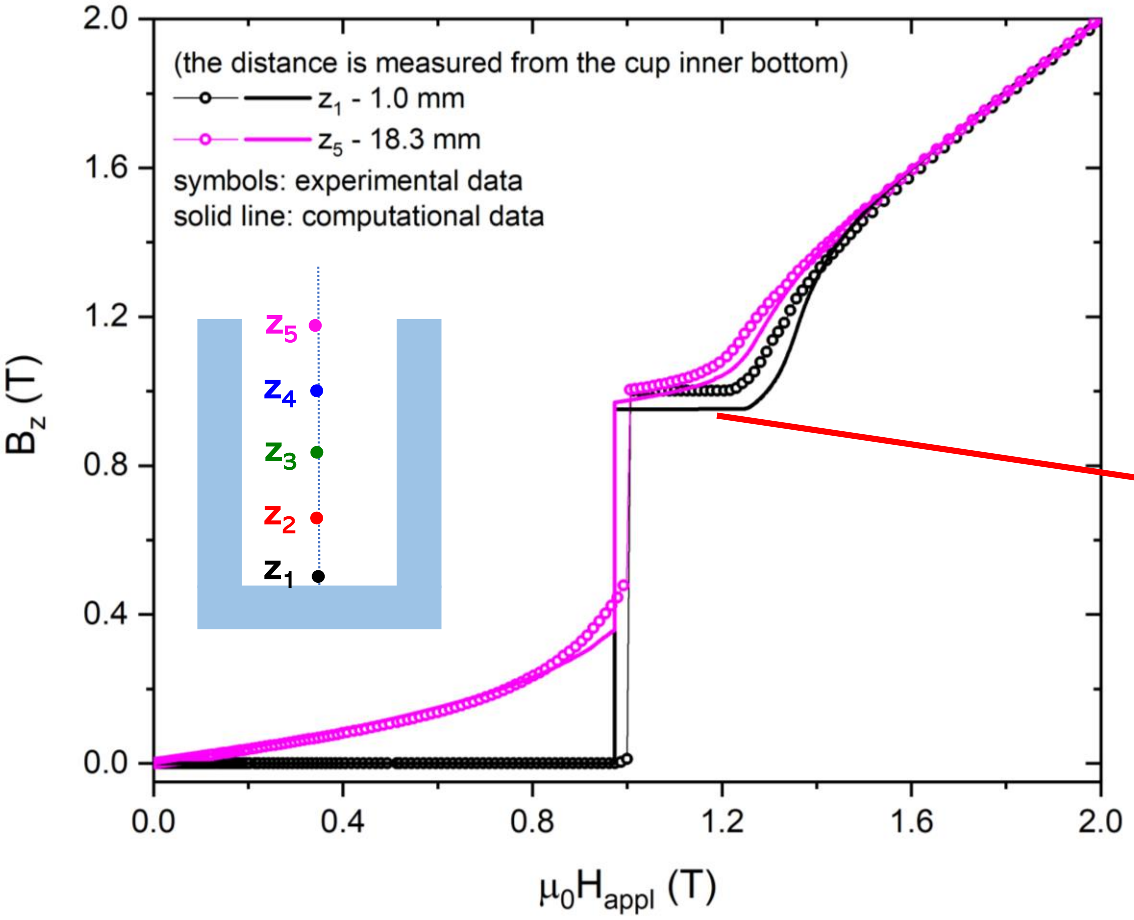
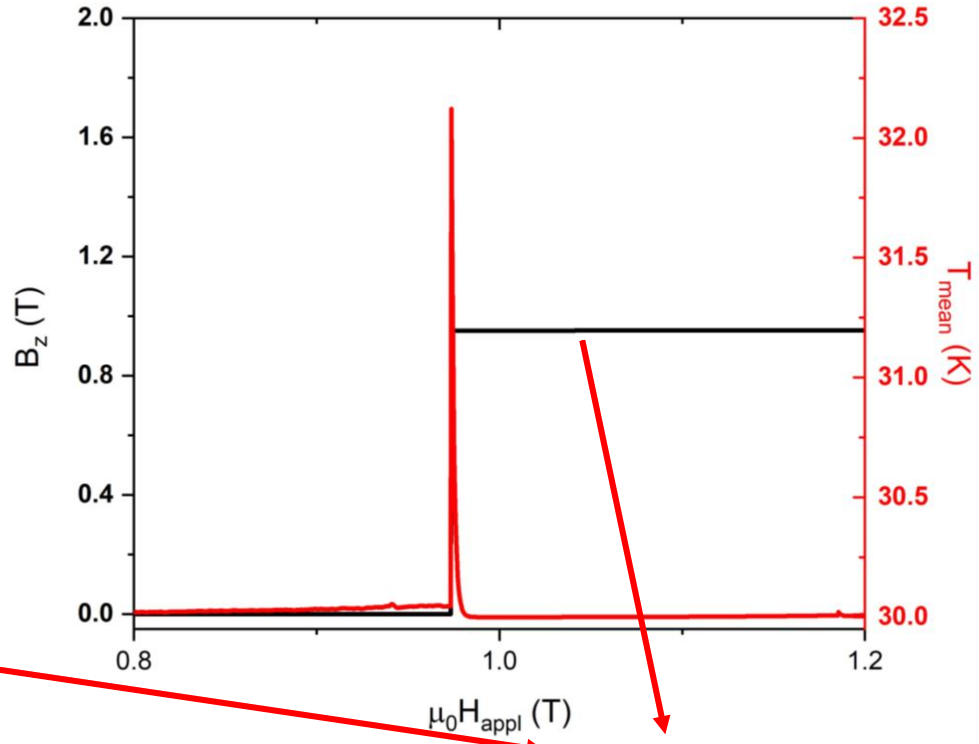
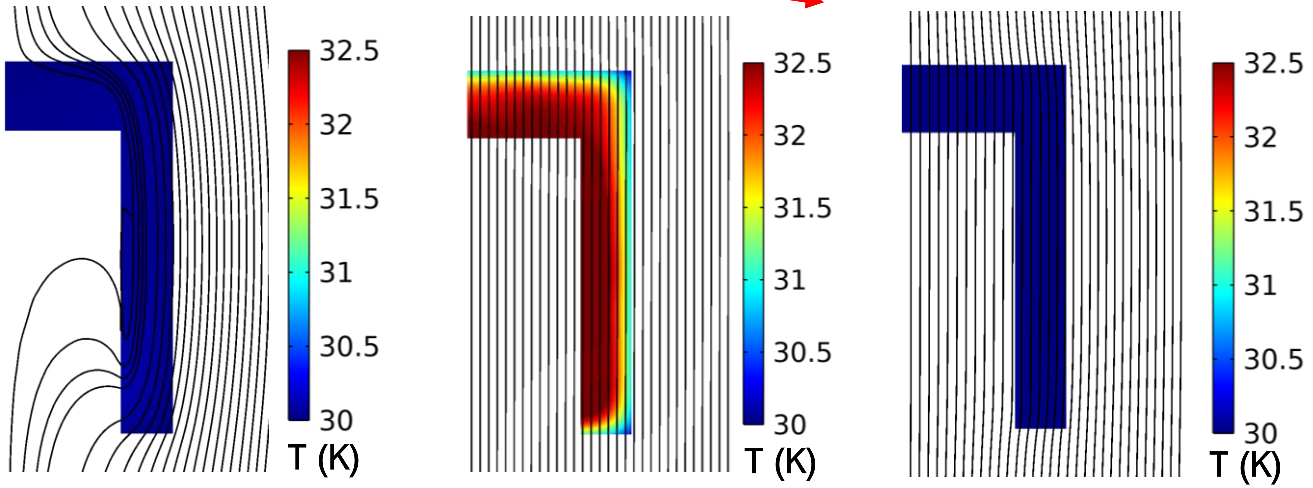
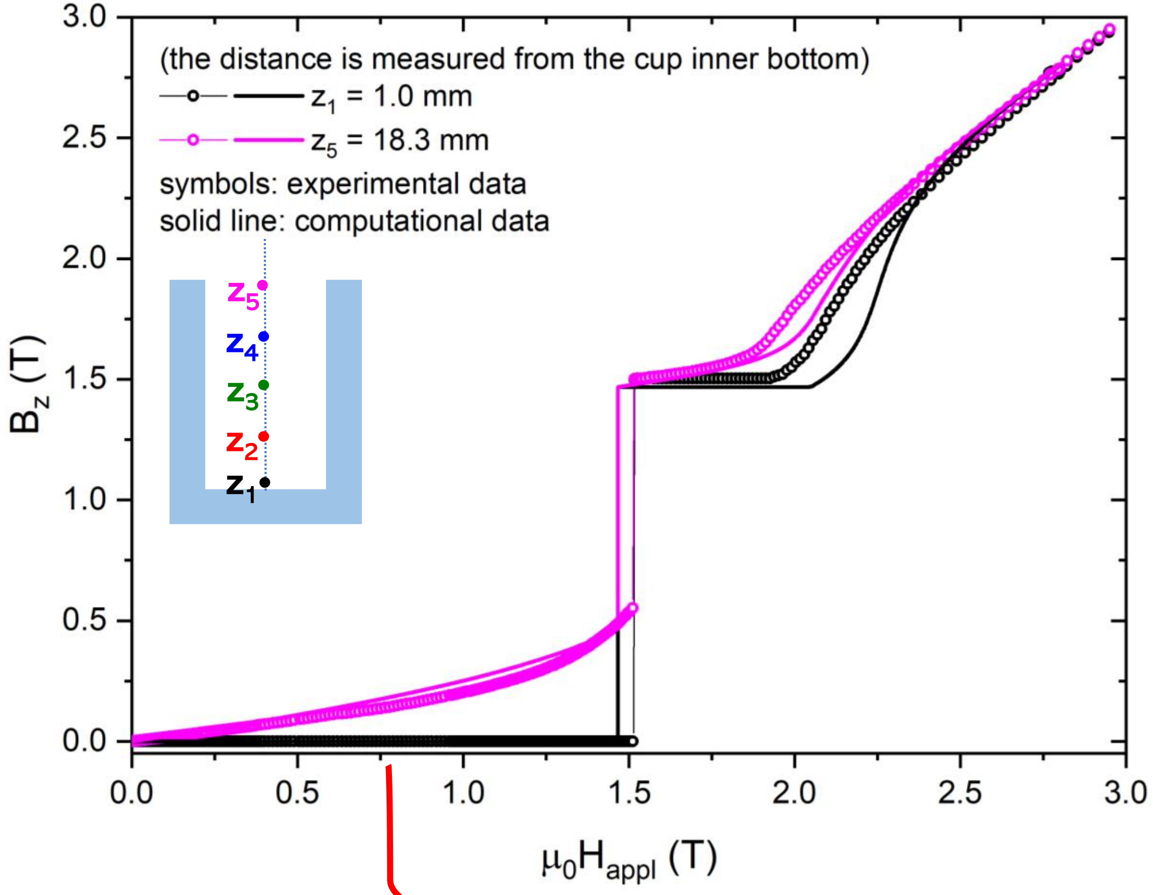


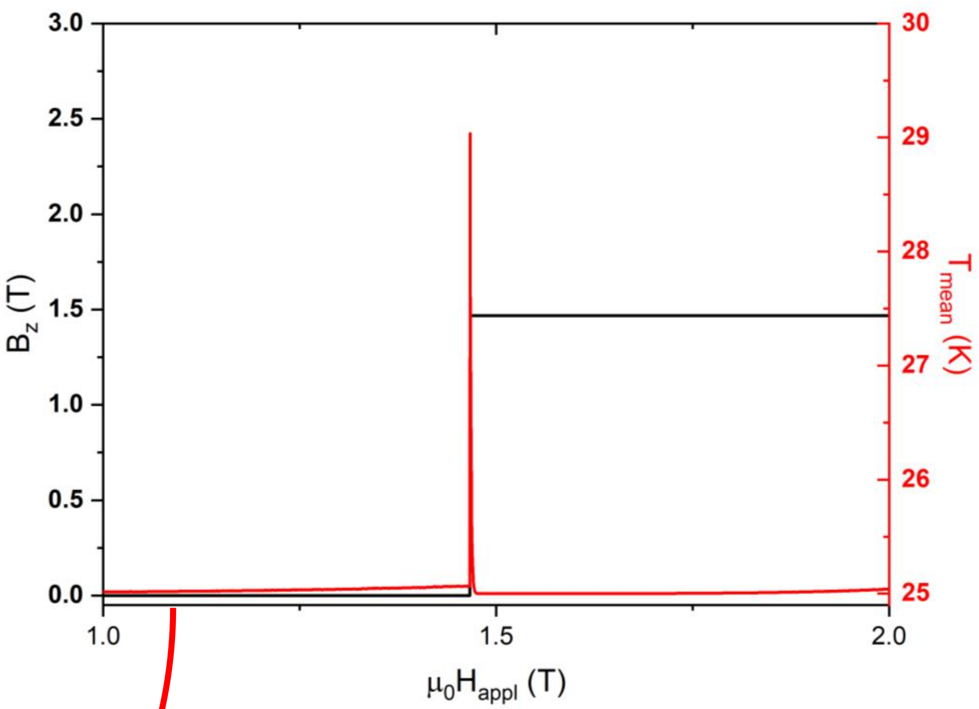


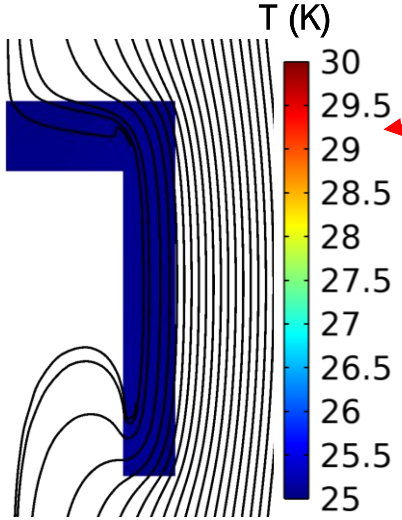


Results

T_{OP}=25 K







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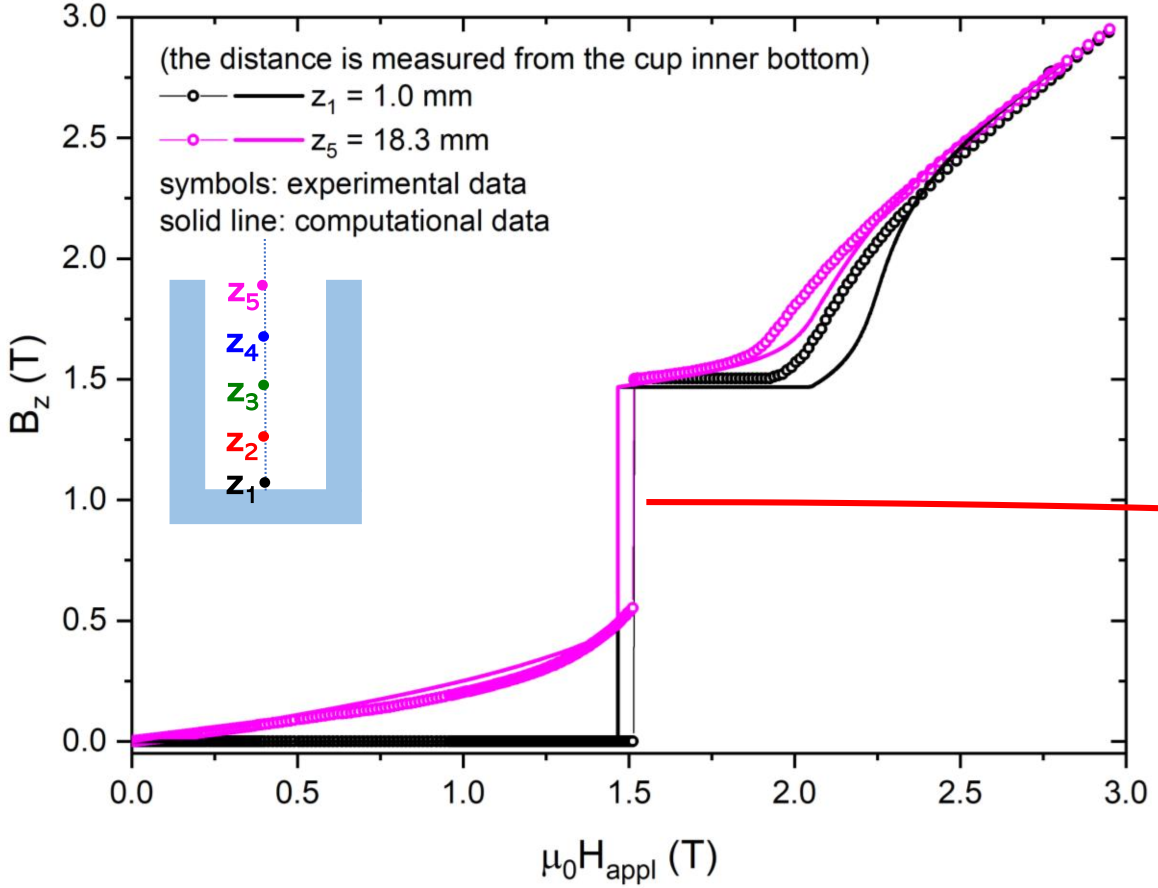

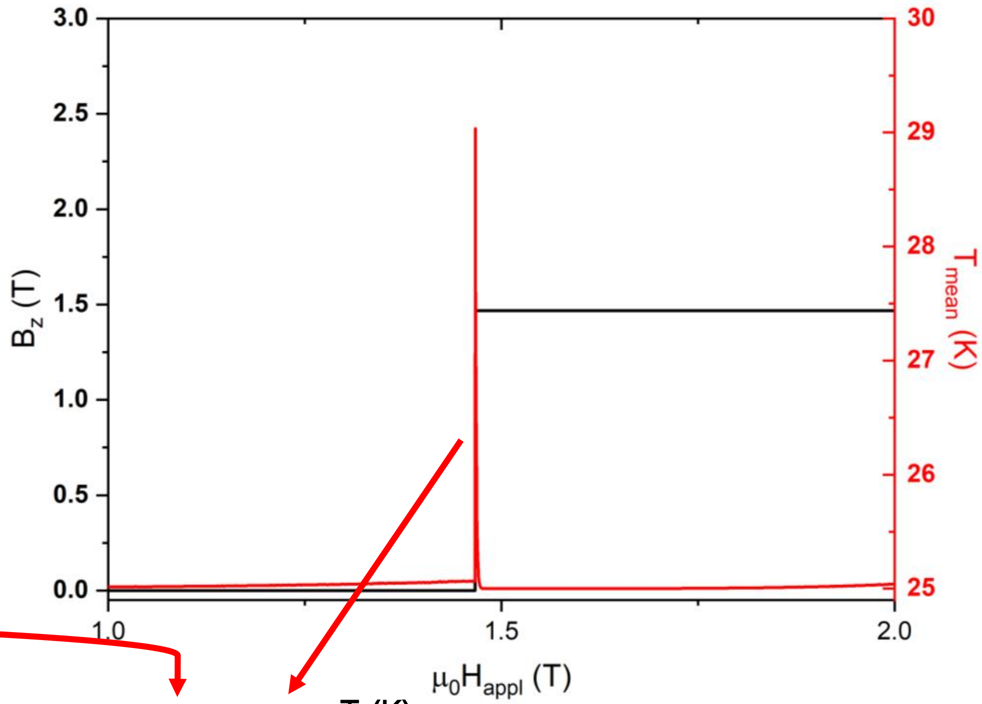

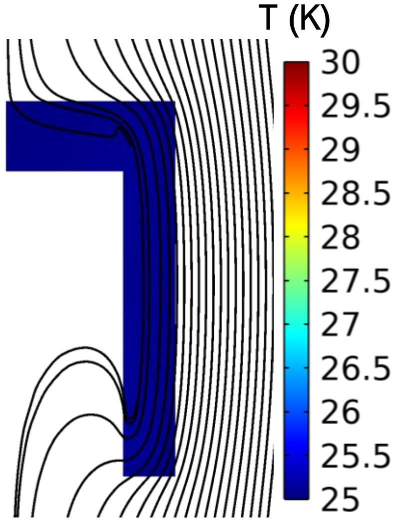

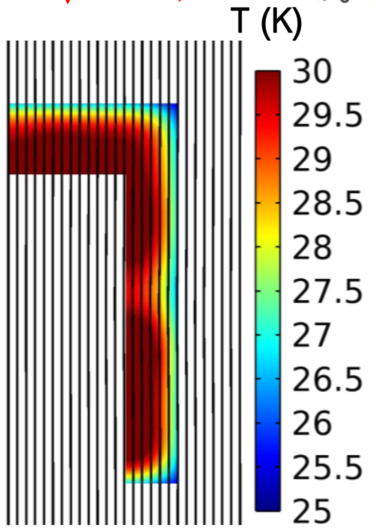

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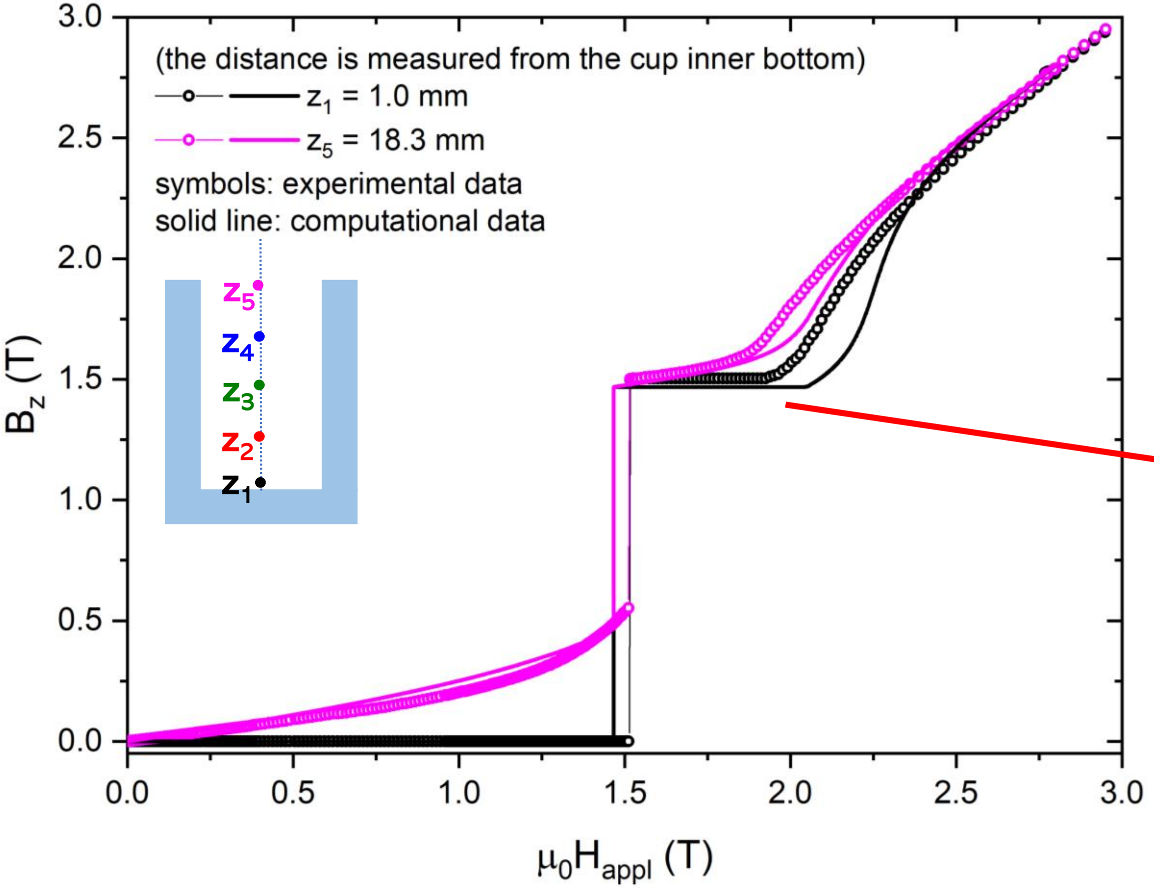
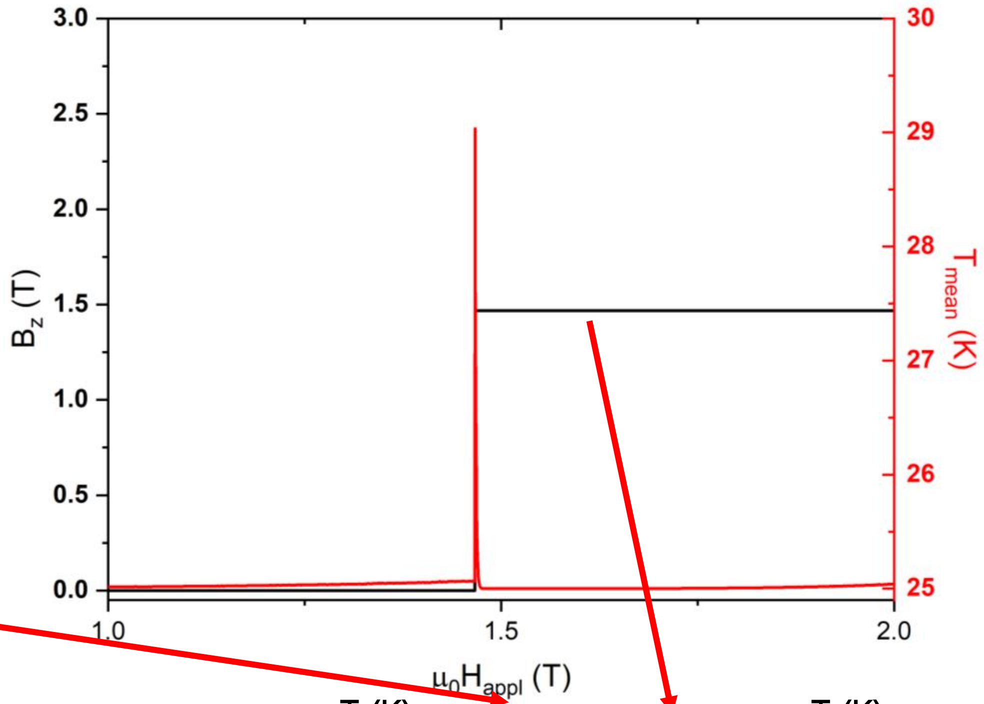
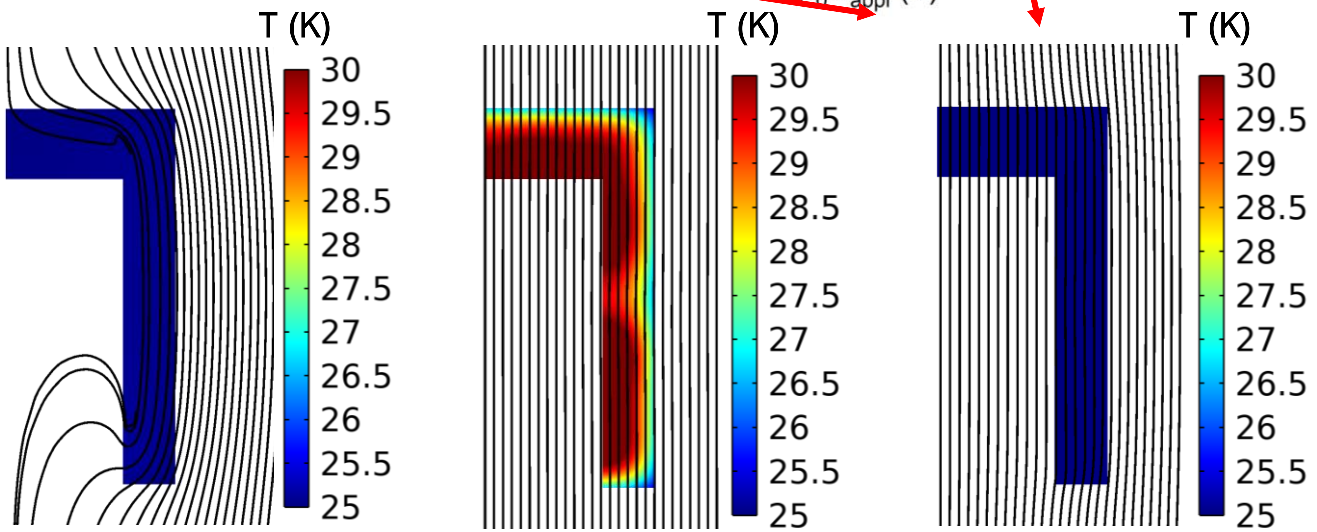






Conclusions

- MgB_2 cup-shaped shield

→ <u>Axial-field orientation :</u> near the close extremity: T = 25 K: Shielding factor > 10^4 up to $\mu_0 H_{appl}$ = 1.5 T
T = 30 K: Shielding factor > 10^4 up to $\mu_0 H_{appl}$ = 0.9 T

(!) Flux jump occurrence sharply worsens the shielding properties of the cup-shaped shield

- Modelling is crucial to improve shielding abilities

- Electro-thermal coupling well reproduce the flux jump occurrence in the experimental data

  → possibility to predict and prevent electro-thermal instability

- Future works: → implement the model with a further refinement of the MgB_2 thermal properties and thermal boundary conditions

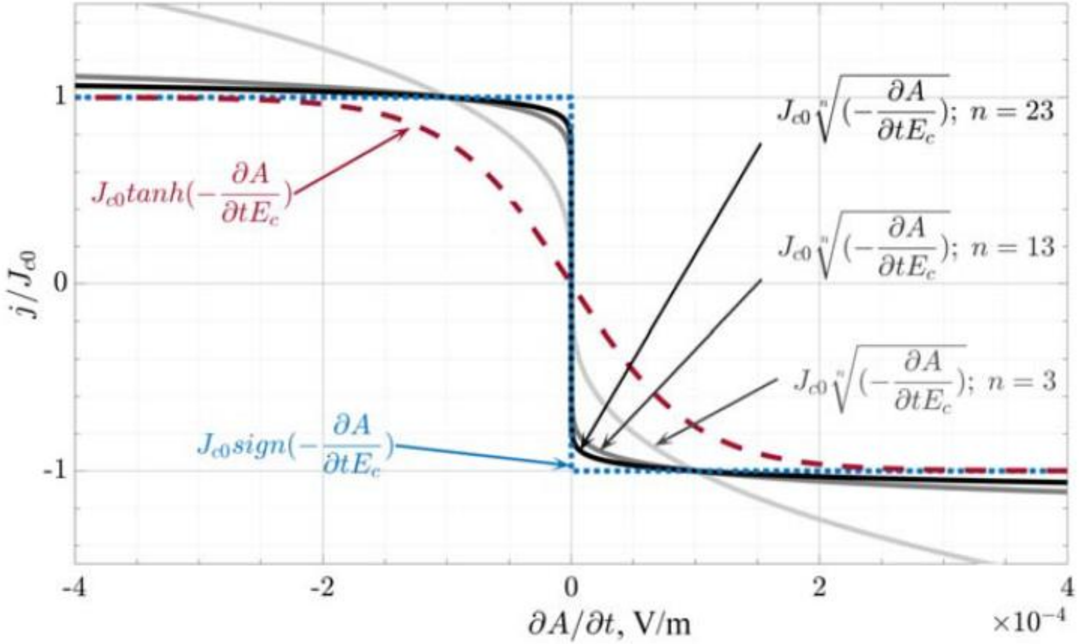
  → investigate the coupling of the electro-thermal equations in MgB_2/ferromagnetic shielding configurations

Thank you for your kind attention!

Acknowledgements:

- P. Badica and his group for providing us with the MgB2 bulk samples.
- European Cooperation in Science and Technology – Cost Action CA19108
- Slovak Research and Development Agency - contract no. APVV-16-0418

Backup slide



Taking advantage of the tubular geometry of the sample we calculated *Jc* from the magnetic induction cycles as proposed by Bartolomé *et al*. for finite superconducting rings [11]:

$$J_c = \frac{\Delta B_c}{\mu_0\ \mathrm{f}(r_{\mathrm{out}}, r_{\mathrm{in}}, h, z)}$$

$$\mathrm{f} = \left(\frac{h}{2} - z\right)\ln\left(\frac{r_{\mathrm{out}} + \sqrt{r_{\mathrm{out}}^2 + (z - h/2)^2}}{r_{\mathrm{in}} + \sqrt{r_{\mathrm{in}}^2 + (z - h/2)^2}}\right) + \left(\frac{h}{2} + z\right)\ln\left(\frac{r_{\mathrm{out}} + \sqrt{r_{\mathrm{out}}^2 + (z + h/2)^2}}{r_{\mathrm{in}} + \sqrt{r_{\mathrm{in}}^2 + (z + h/2)^2}}\right)$$