HTS MODELLING WORKGROUP

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The role of ferromagnet to prevent the flux-jump occurrence: a numerical study

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Roadmap and Outline

1. **Motivations and Background**
2. **Experimental procedure and characterization**
3. **Modelling:**
   - ✓ A-V formulation
   - ✓ Coupling of the electromagnetic and thermal equations
4. **Modelling validation**
   - ✓ Comparison with experimental data
5. **Strategies to mitigate the thermo-magnetic instability occurrence**
6. **Summary and conclusions**

Low-frequency magnetic fields shielding

WHY ?

- electromagnetic noise - stray field reduction → Pieces of equipment integration and electromagnetic compatibility
- protection of space surrounding intense magnetic field source → Pieces of equipment integration and electromagnetic compatibility
- low magnetic field background → protection of magnetic field sensitive detectors *(e.g. SQUIDs)*

HOW ?

- Active solutions → Magnets
- Passive solutions
  - Ferromagnetic (FM) materials
  - Superconducting (SC) materials
  - Hybrid configurations (SC+FM)

low performance

↓

high performance

HOW

- Active solutions → Magnets
- **Passive solutions**
  - Ferromagnetic (FM) materials
  - Superconducting (SC) materials
  - Hybrid configurations (SC+FM)

low performance ↓ *high performance*

REQUIRES

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

MgB_2 fabrication process

MgB_2 bulk was 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**

Ability to shape and size bulks — **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.
$AR=h/R_o=2.25$
$AR'=d/R_o=1.83$

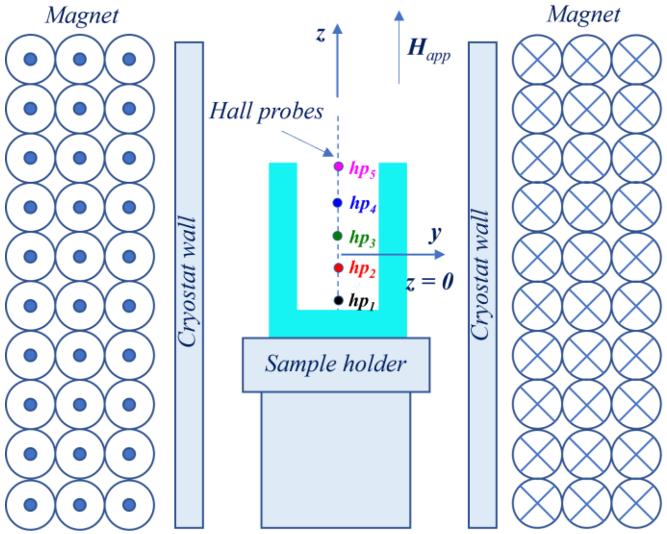
BN addition [wt.%]: 10
Final sample density: ∽2.50 g/cm^3

AR= height/average diameter ~ 1

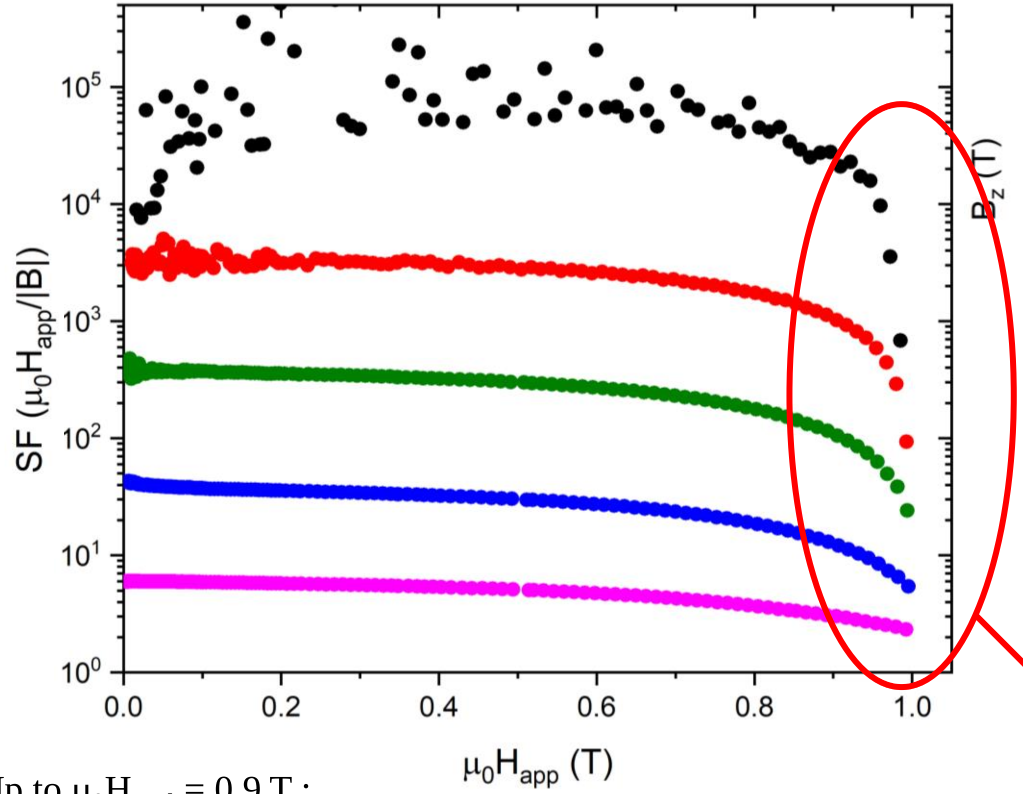
L. Gozzelino et al., Supercond. Sci. Technol., 33, 044018 (2020)
G. Aldica, et al., Patent No RO130252-A2, DPAN 2015-383635

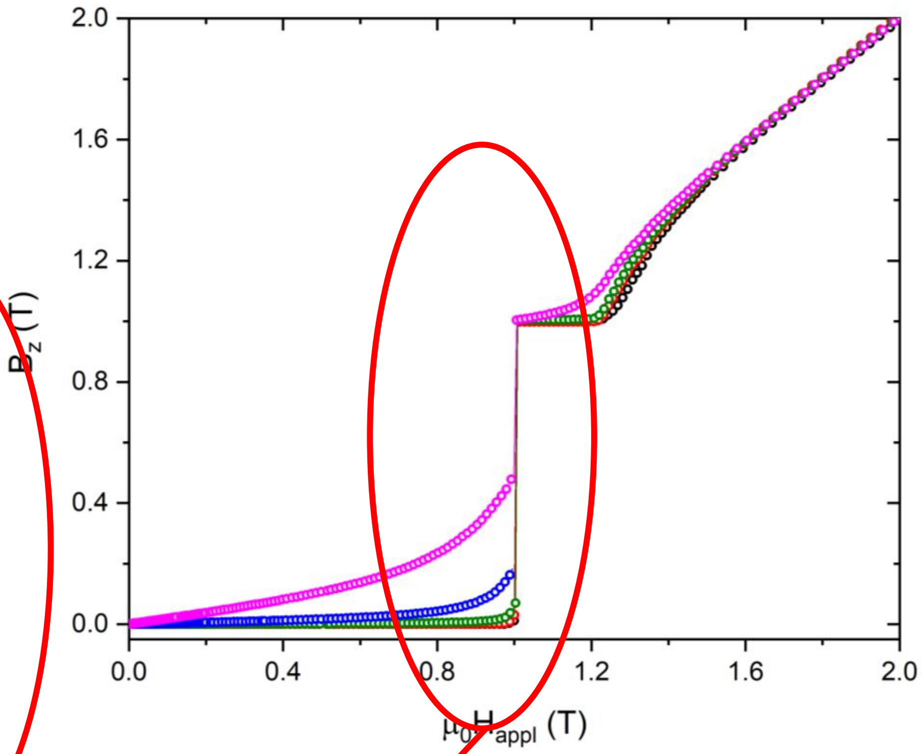
MgB_2 cup: shielding in axial-field orientation

T_{OP}=30 K



(a) AF





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

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

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

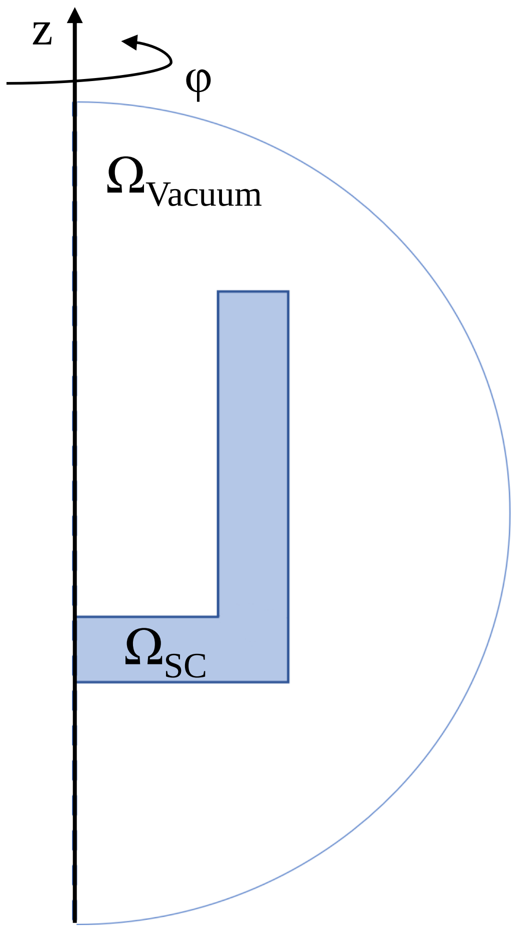
position z_1: SF > 10^4
position z_2: SF > 10^3
position z_3: SF > 10^2

Flux-jumps occurence!

The thermo-magnetic instabilities have to be taken into account!

Modelling: A-V formulation

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



Dimensions not to scale

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

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

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

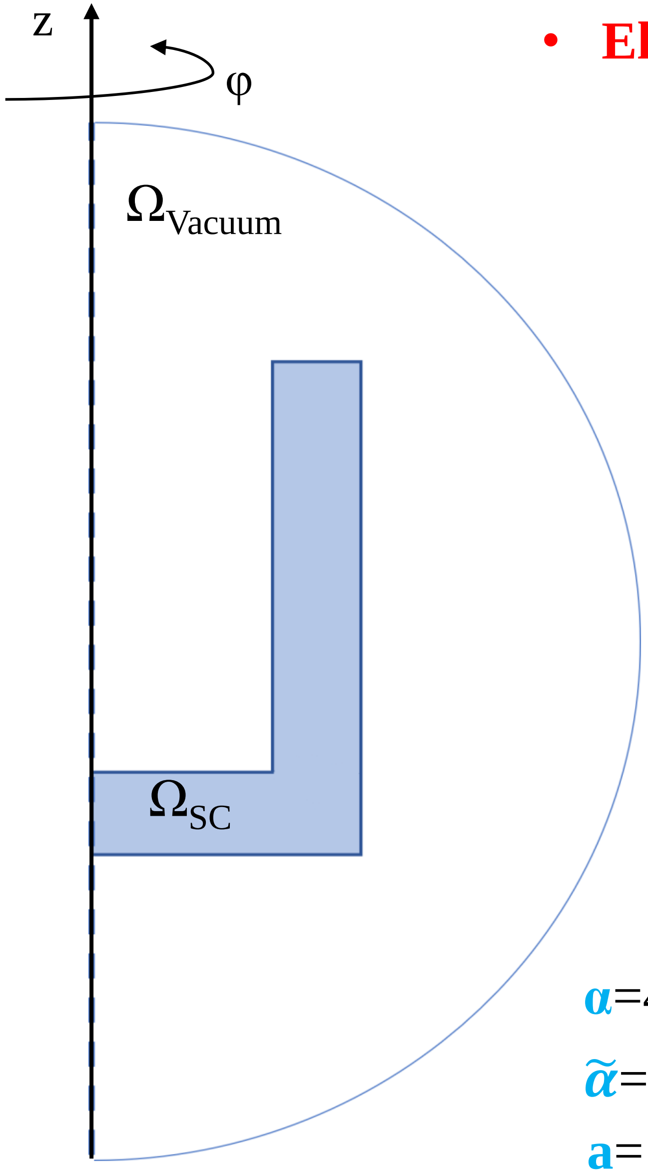
E-J relation smoothly approximating the critical state model

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)

• 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

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

$$\gamma(T) = \boldsymbol{l} \cdot T + \boldsymbol{g} \cdot T^2$$

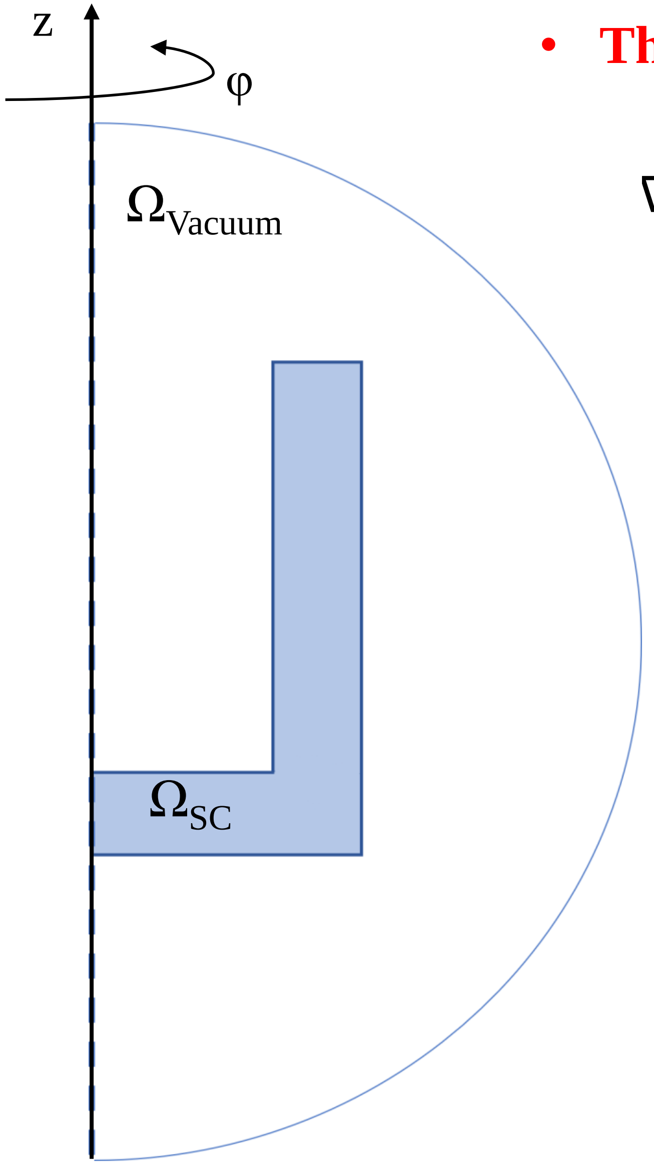
$$J_{c,0}(T) = \boldsymbol{\alpha}\left[1-\left(\frac{T}{T_C}\right)^{\tilde{\alpha}}\right]^{\boldsymbol{a}}$$

$$\mathrm{B}_0(T) = \boldsymbol{\beta}\left[1-\left(\frac{T}{T_C}\right)^{\tilde{\beta}}\right]^{\boldsymbol{b}}$$

α=4.841 x 10^{-9} A/m^2	β=1.658 T	
$\tilde{\alpha}$=1	$\tilde{\beta}$=5	l=0.024 K^{-1}
a=1.507	b=1.694	g=0.003 K^{-2}

Fit coefficients obtained by experimental J_c-B curves

M. Fracasso et al., Supercond. Sci. Technol. 36 (2023) 044001



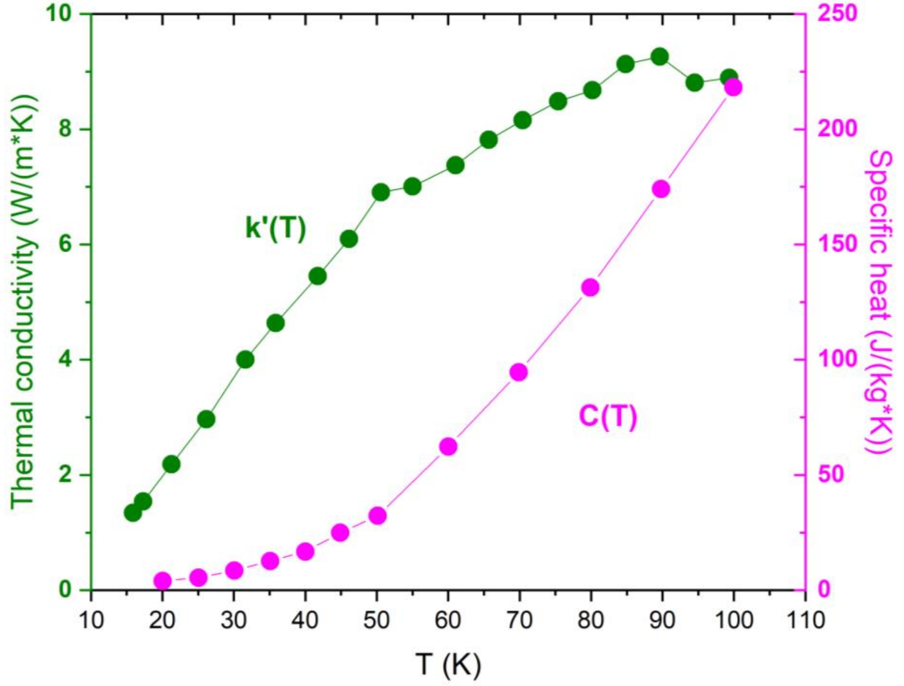
- **Thermal behaviour of SC region Ω_{SC}**

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

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

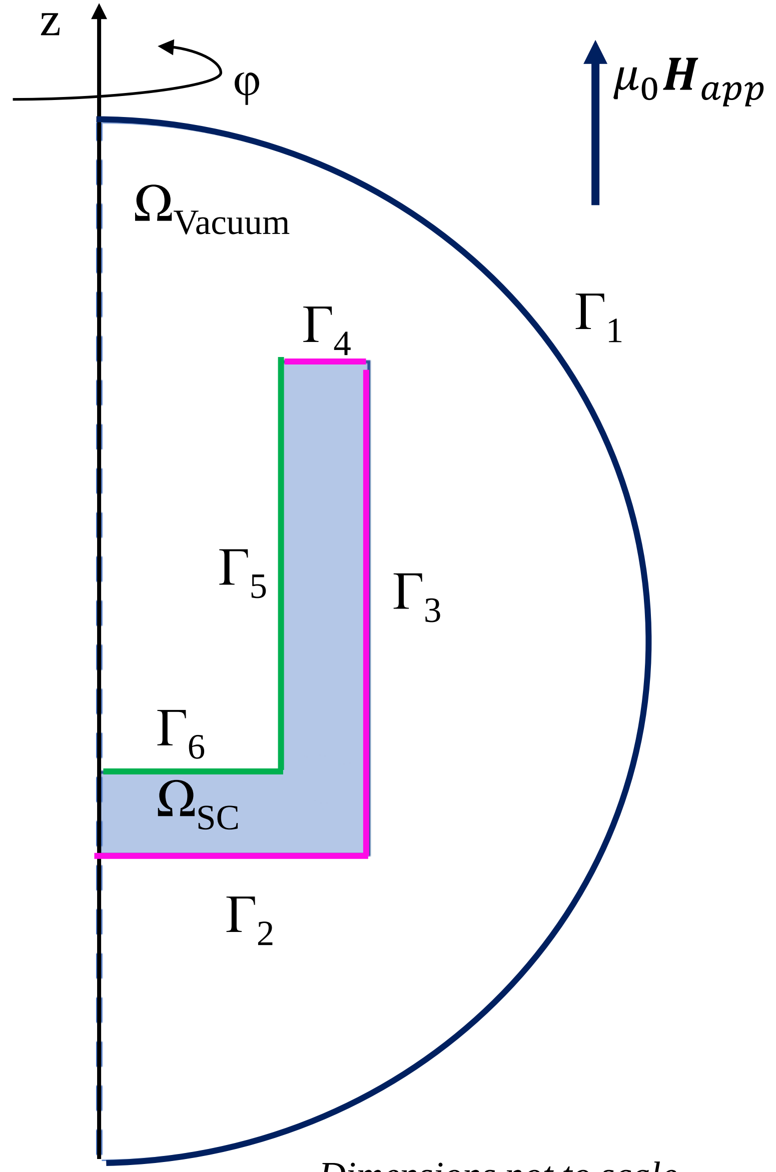
ρ_m=2.50 g/cm^3

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 worsens the thermal properties of the materials so *k'(T)= k(T)/5* is assumed

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



Dimensions not to scale

- **Electromagnetic boundary conditions**

Γ_1 : at large distance from the shield, the field was assumed equal to $\mu_0 \boldsymbol{H}_{app}$ and increasing with a ramp rate of 0.035 T/s

- **Thermal boundary conditions**

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

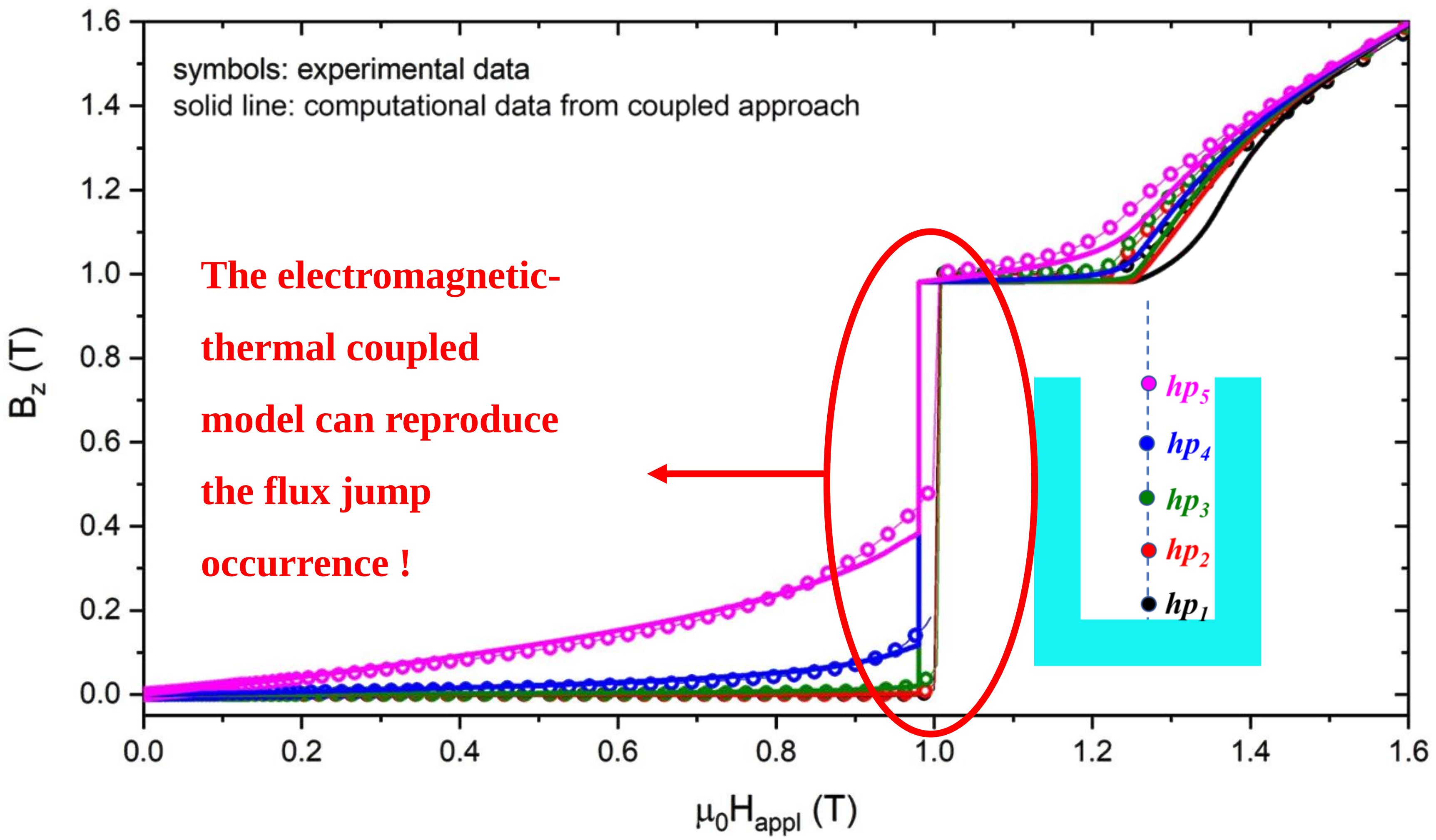
$$\boldsymbol{n} \cdot (k(T)\nabla T) = \Upsilon \cdot (T_{OP} - T)$$

where Υ = 3000 W/(m^{2}K) was determined through iterative adjustments

Γ_5, Γ_6 : $\boldsymbol{n} \cdot (k(T)\nabla T) = 0$

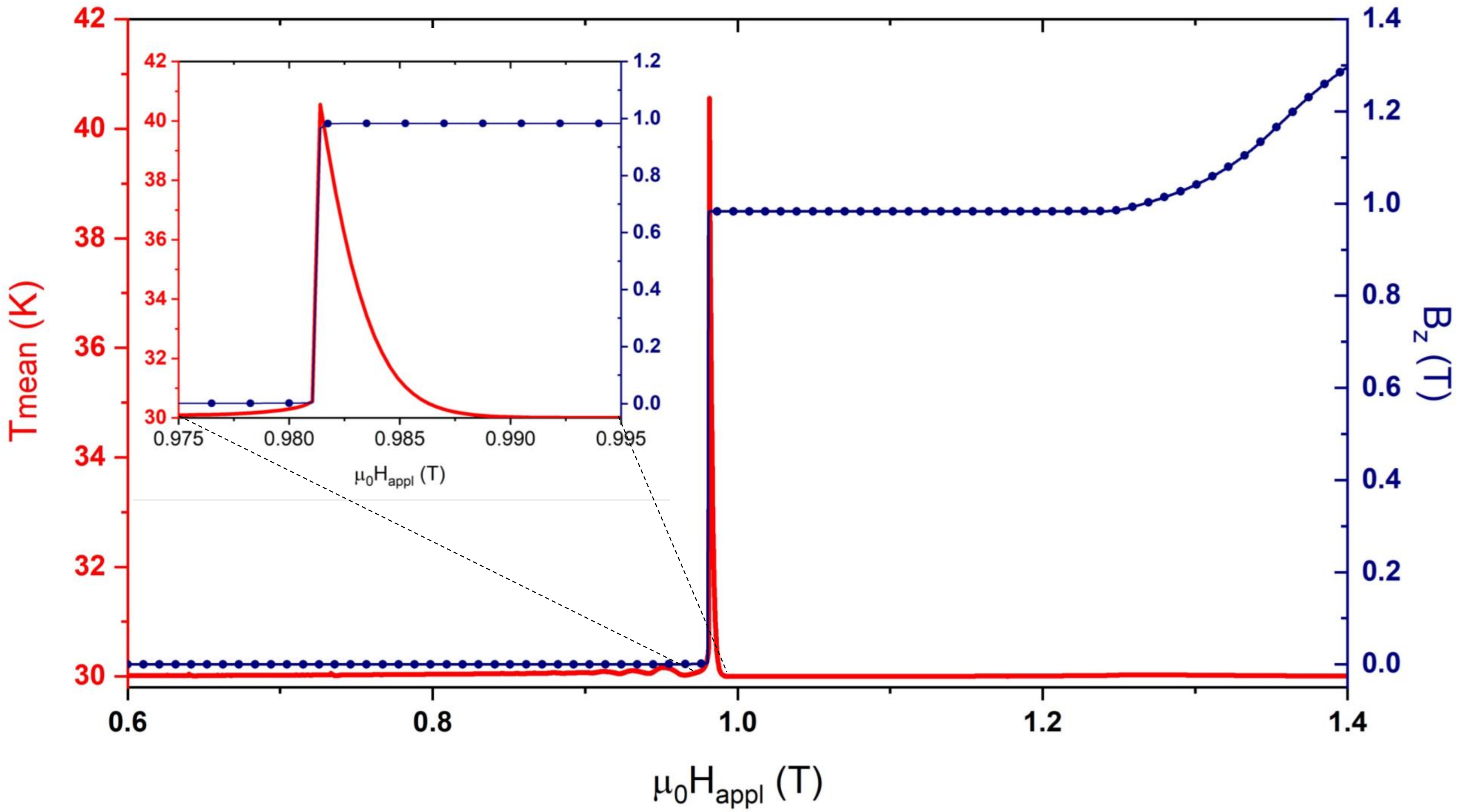
M. Fracasso et al., Supercond. Sci. Technol. 36 (2023) 044001

T_{OP}=30 K

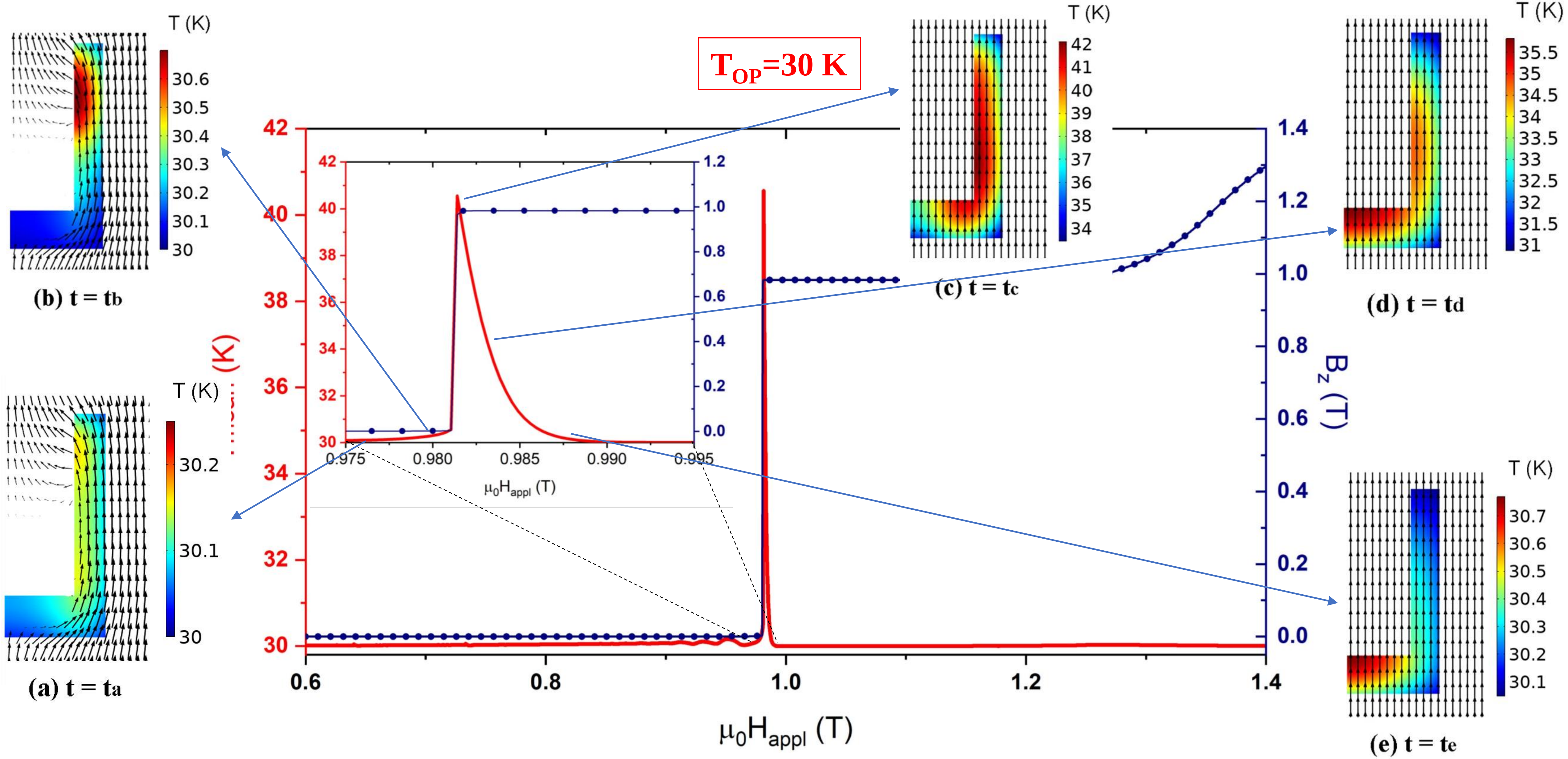


symbols: experimental data
solid line: computational data from coupled approach
The electromagnetic-thermal coupled model can reproduce the flux jump occurrence !
hp5
hp4
hp3
hp2
hp1
Bz (T)
μ0Happl (T)

T_{OP}=30 K



42
40
38
36
34
32
30
Tmean (K)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
B_z (T)
0.6
0.8
1.0
1.2
1.4
μ0Happl (T)
0.975
0.980
0.985
0.990
0.995



T_OP=30 K
(a) t = ta
(b) t = tb
(c) t = tc
(d) t = td
(e) t = te
T (K)
μ0Happl (T)
Bz (T)

Strategies to mitigate the thermo-magnetic instability occurrence

1 Improving the thermal conductivity k(T) of the MgB_2 sample

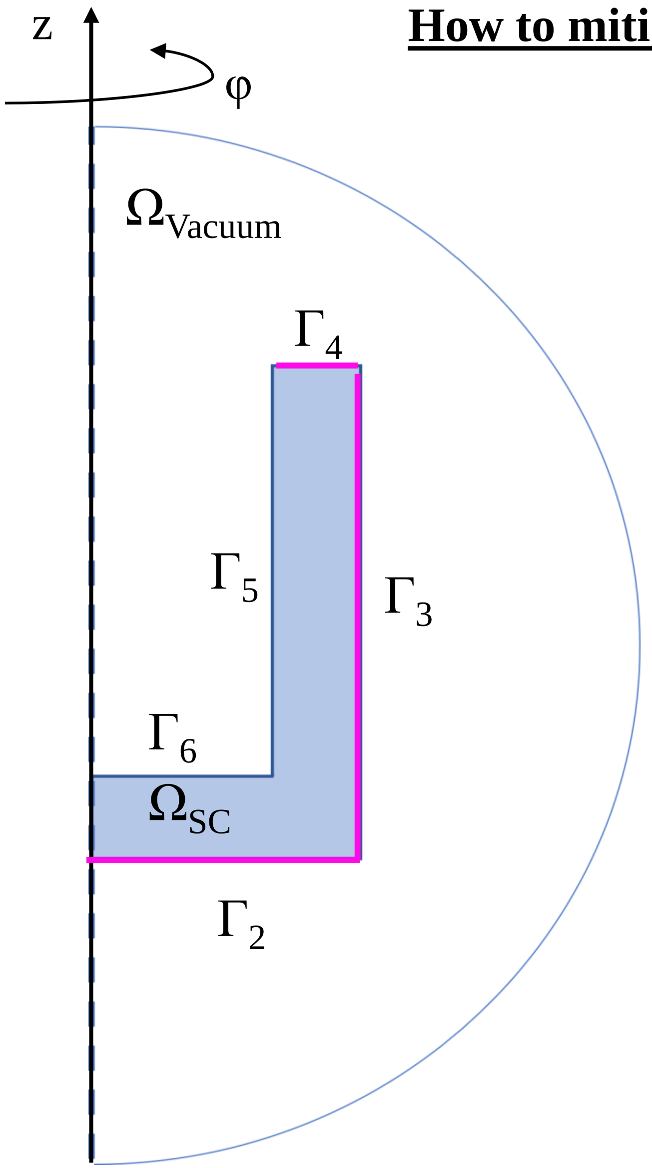
2 Improving the thermal exchange between the SC sample and the cooling system

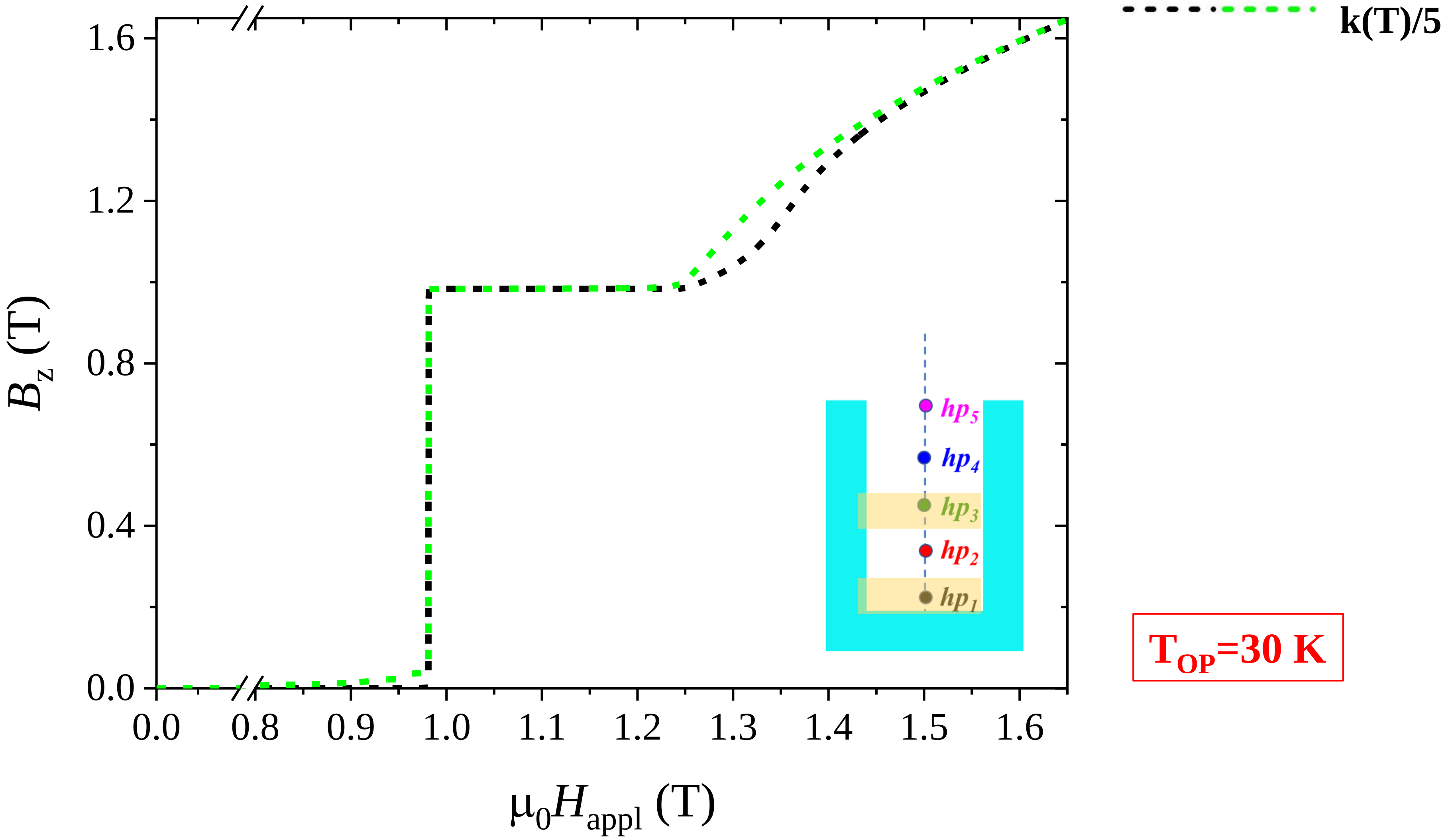
3 Superimposing of a ferromagnetic cup

- changes of the distribution of the magnetic flux line
- acts as an additional thermal shield

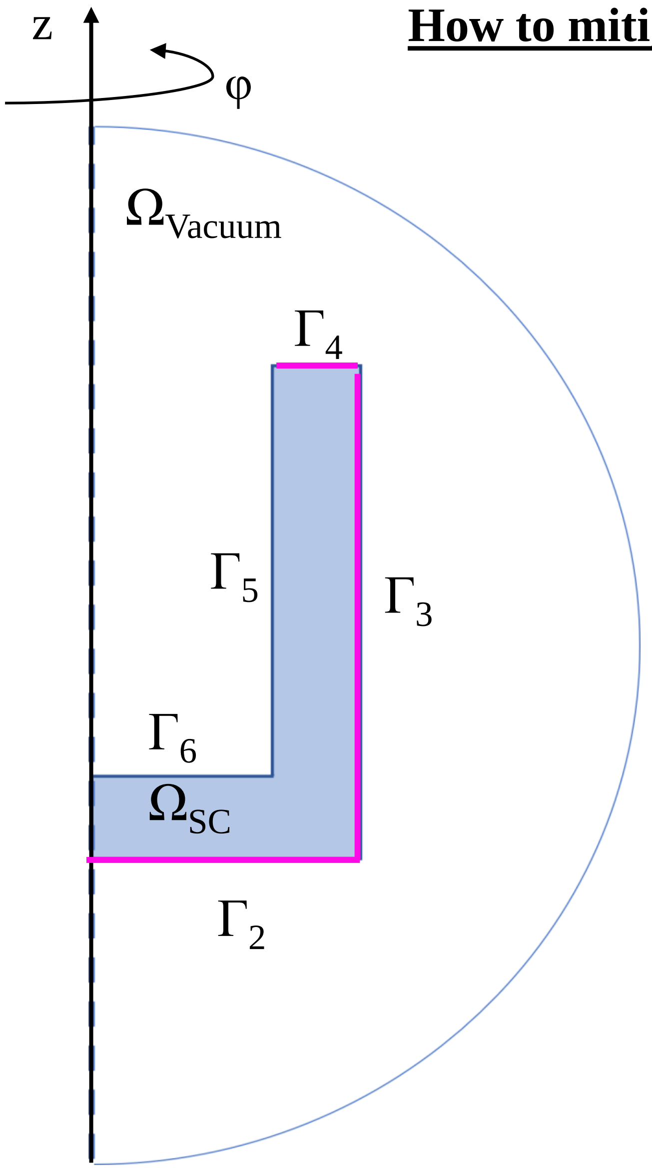
4 Superimposing of a ferromagnetic cup and improving the thermal exchange between the SC sample and the cooling system

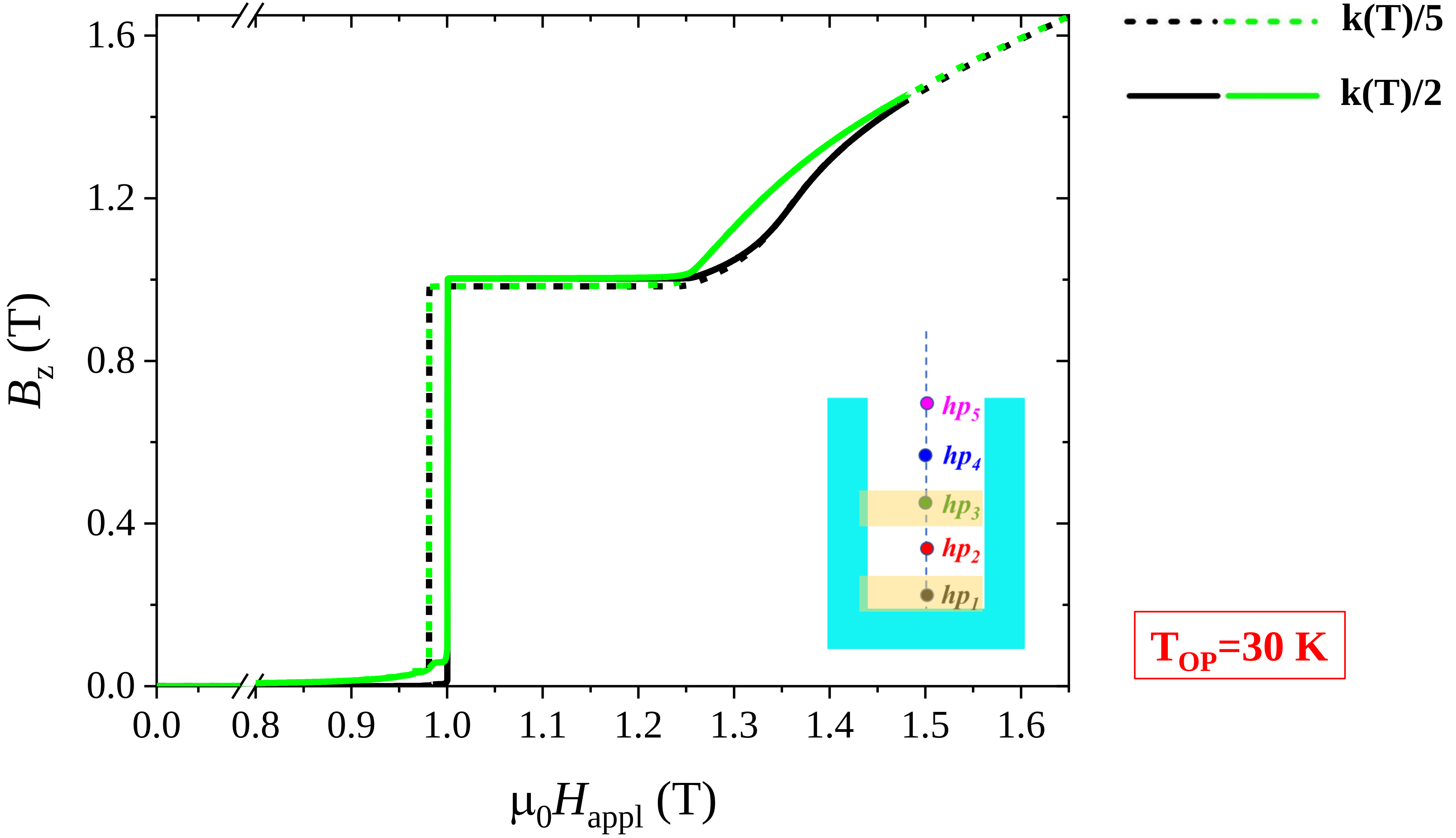
How to mitigate the flux jump occurrence? ① Improving the thermal conductivity k(T)





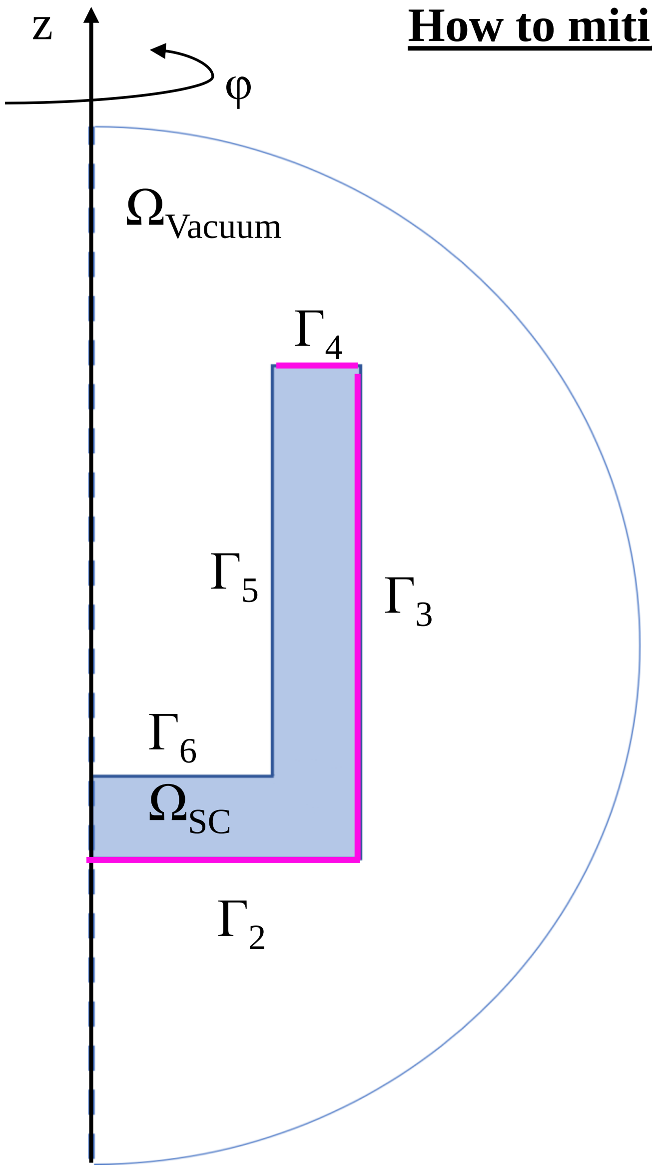
How to mitigate the flux jump occurrence? ① Improving the thermal conductivity k(T)

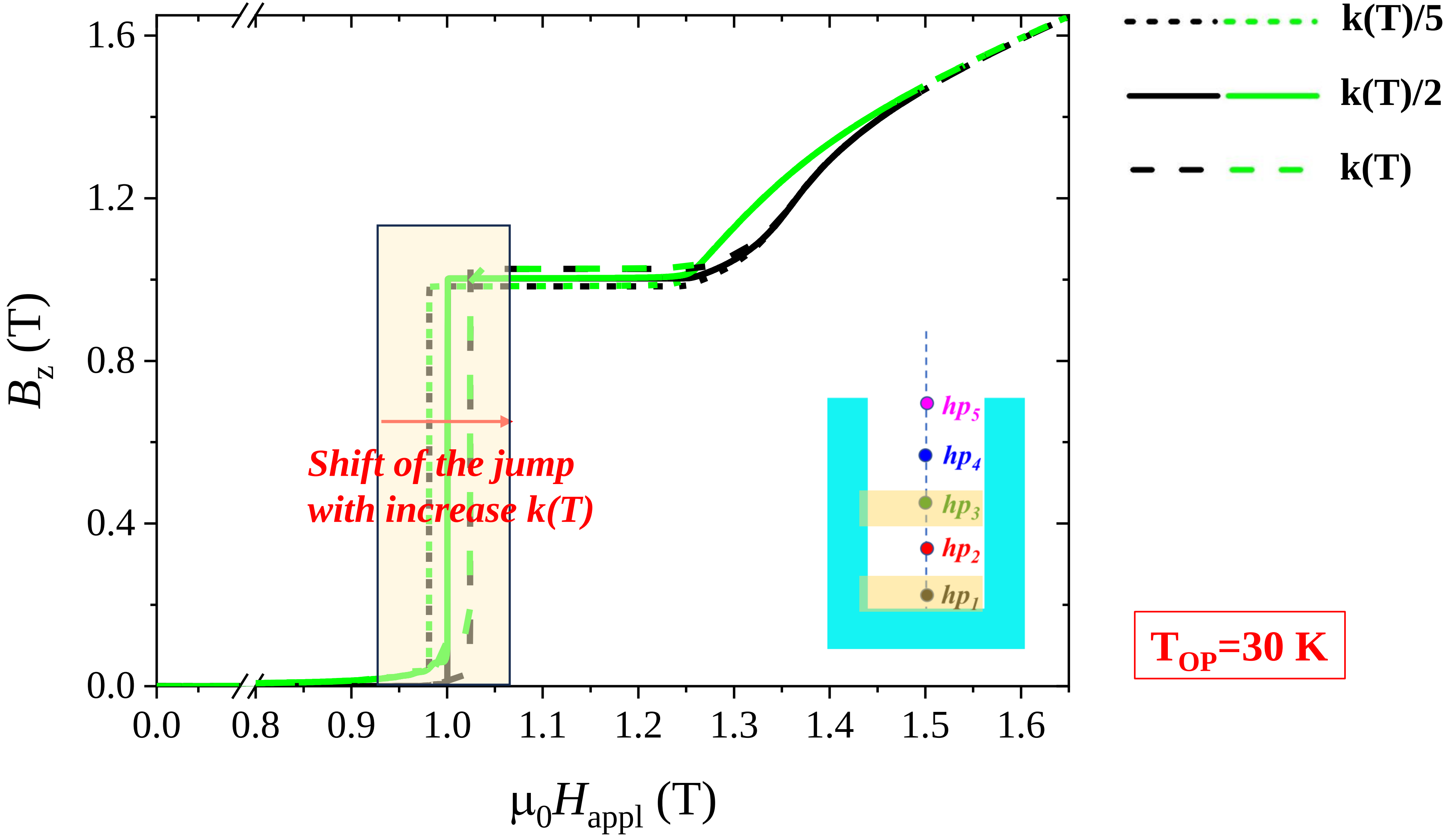




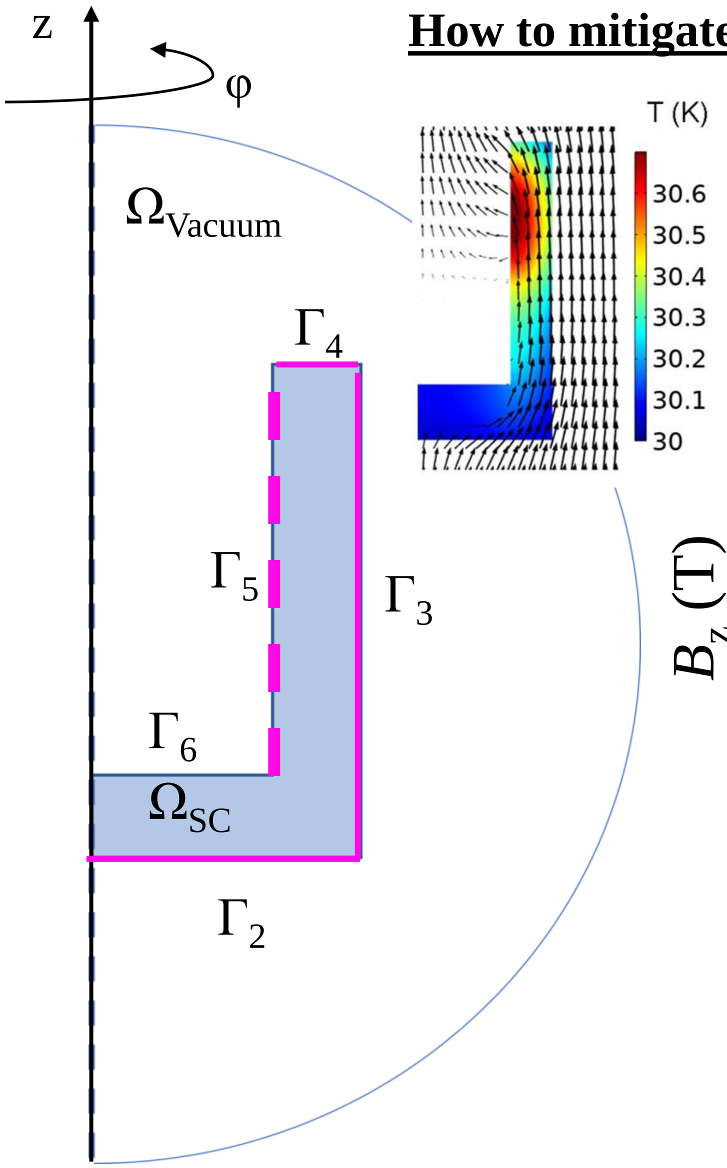
T_{OP}=30 K

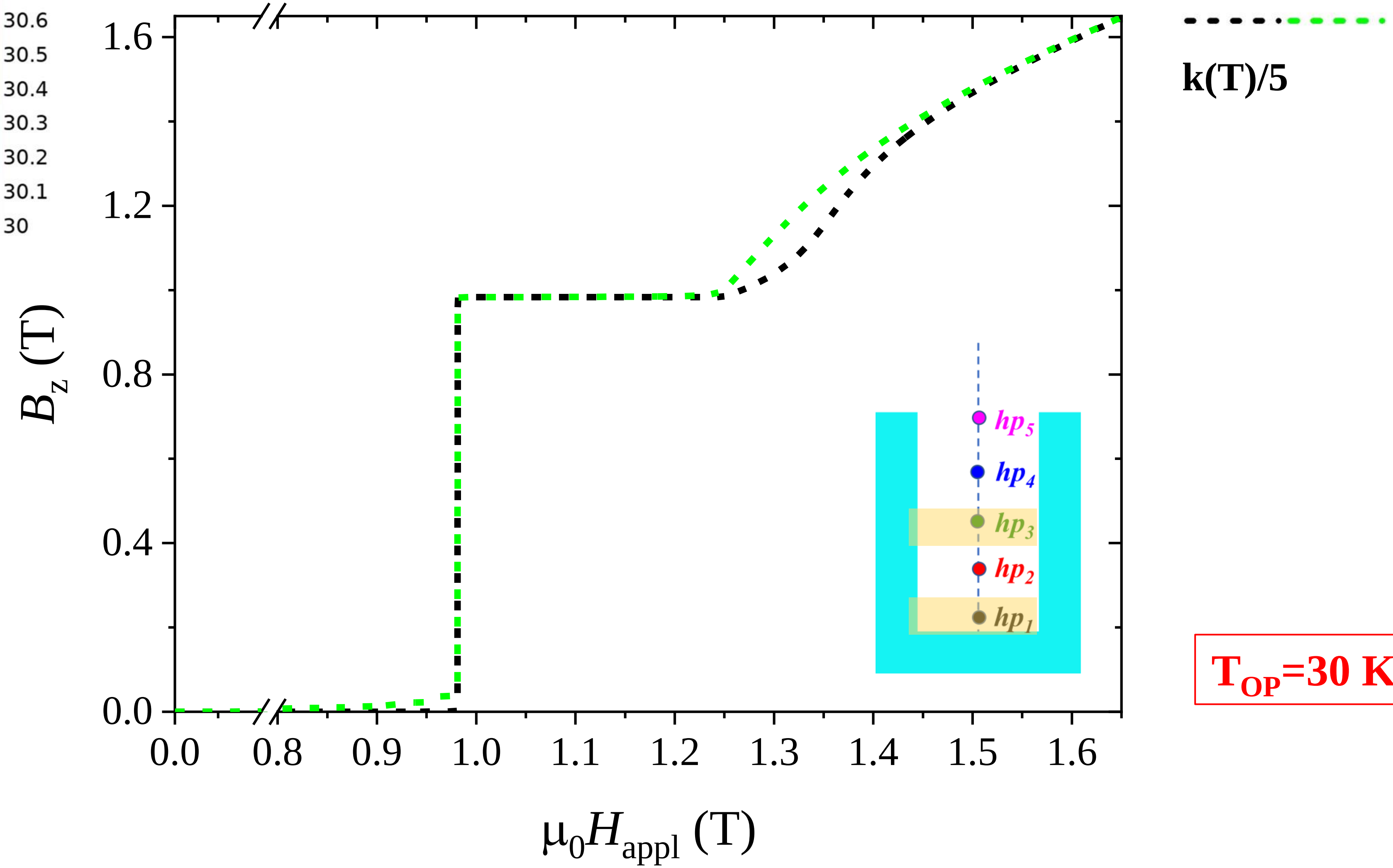
How to mitigate the flux jump occurrence? ① Improving the thermal conductivity k(T)





How to mitigate the flux jump occurrence? ② Improving the thermal exchange





T_{OP}=30 K

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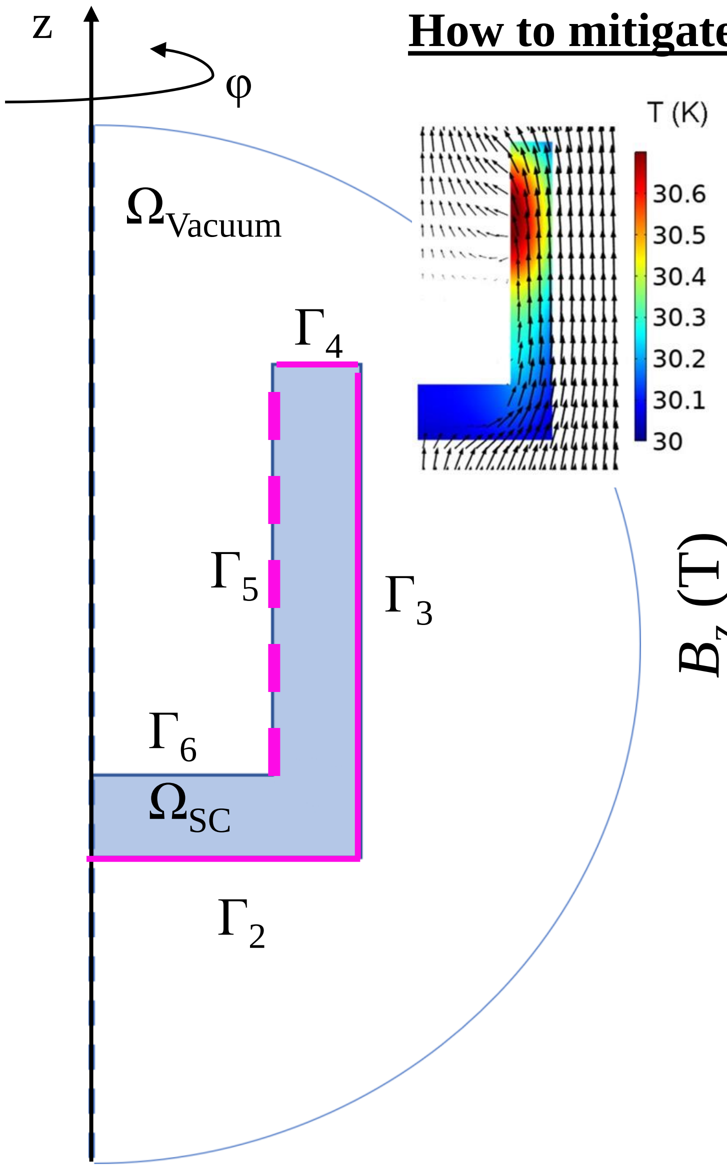
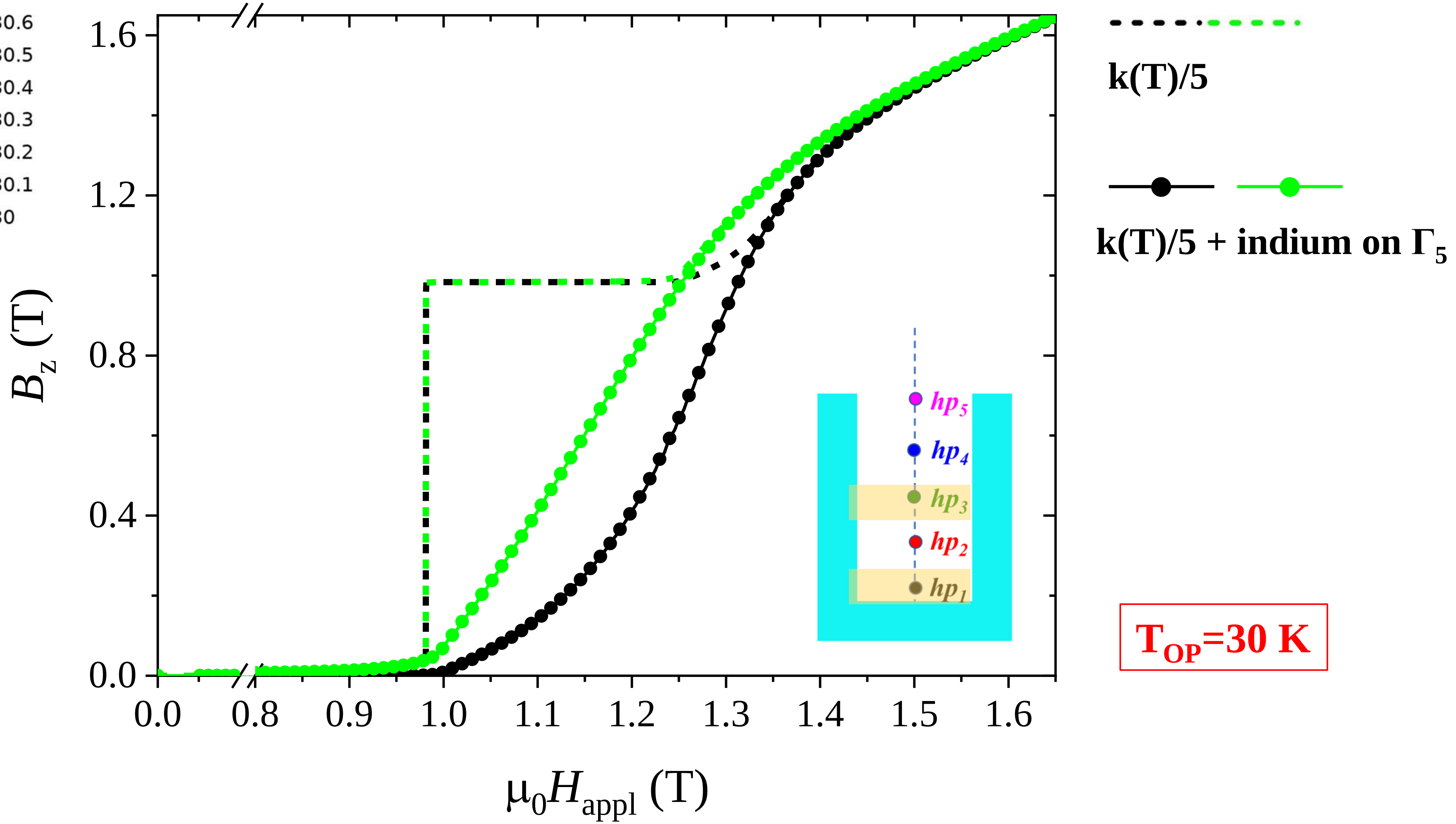
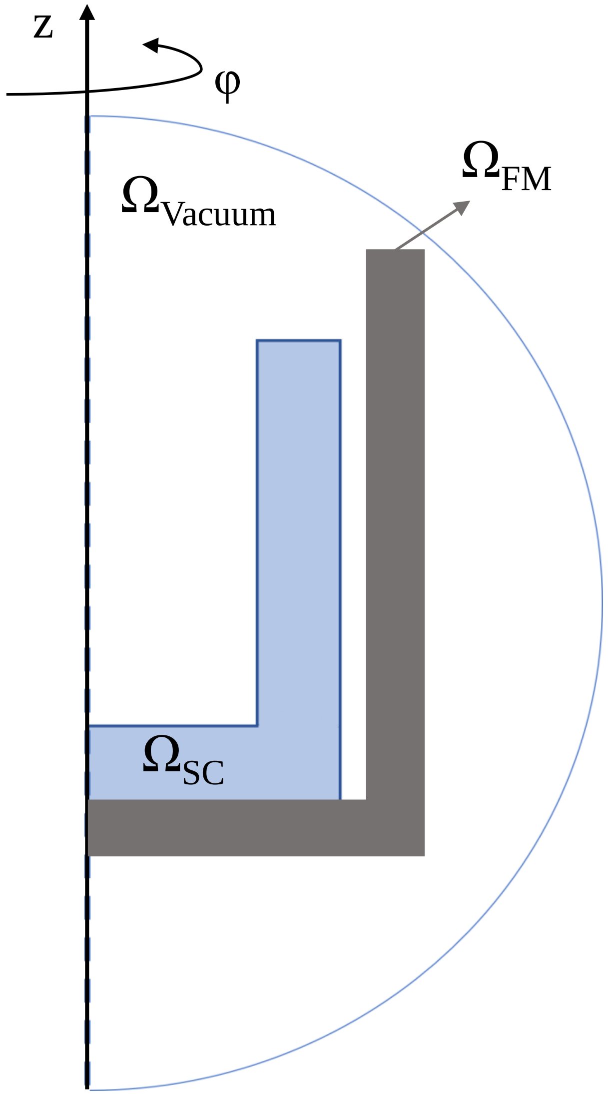
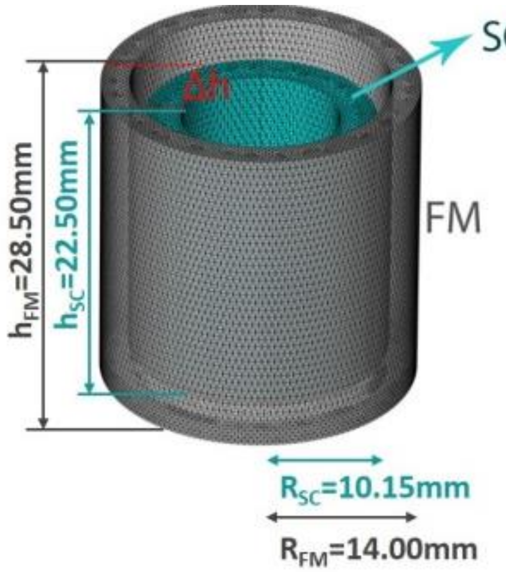
How to mitigate the flux jump occurrence? ② Improving the thermal exchange





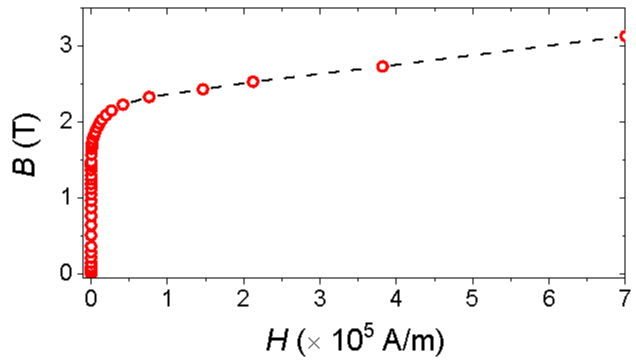
How to mitigate the flux jump occurrence? 3 Superimposing of a ferromagnetic cup





To model the **ferromagnetic material (soft iron)** :

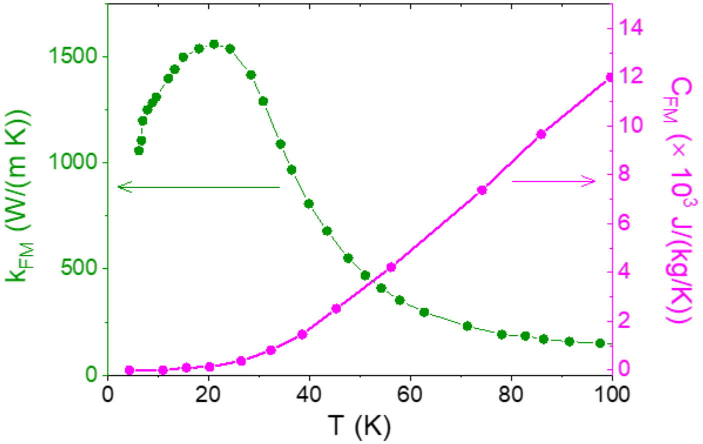
- $\vec{A}$-formulation
- *B-H* curve measured experimentally
  - ➢ negligible hysteresis losses



$k_{FM}(T)$ and $C_{FM}(T)$ take the piecewise cubic interpolations of literature data

S. Arajs et al.
JAP, 36 (1965) 2210

K.K. Kelley
J. Chem. Phys., 11 (1943) 16



L. Gozzelino et al., SuST 35.4 (2022) 044002

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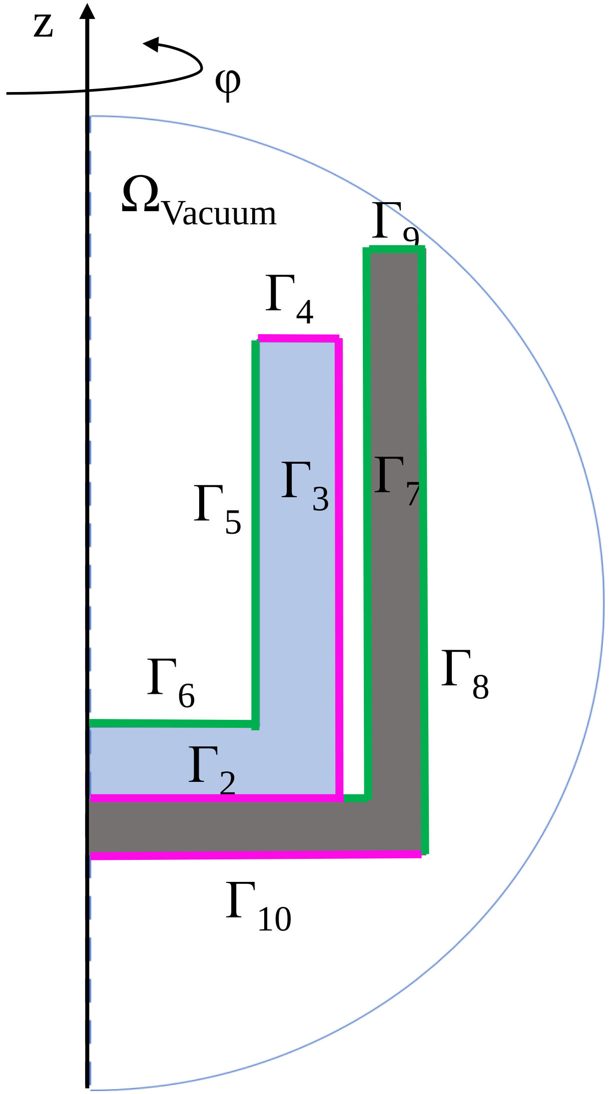
How to mitigate the flux jump occurrence? ③ Superimposing of a ferromagnetic cup



Coupling between Ω_{SC} , Ω_{FM} and Ω_V:

$\Gamma_2, \Gamma_3, \Gamma_4$: SC cooled through the thermal contact with FM shield (via indium layer)

$$\vec{n} \cdot (k'(T) \nabla T) = \Upsilon' \cdot (T_{FM} - T_{SC})$$

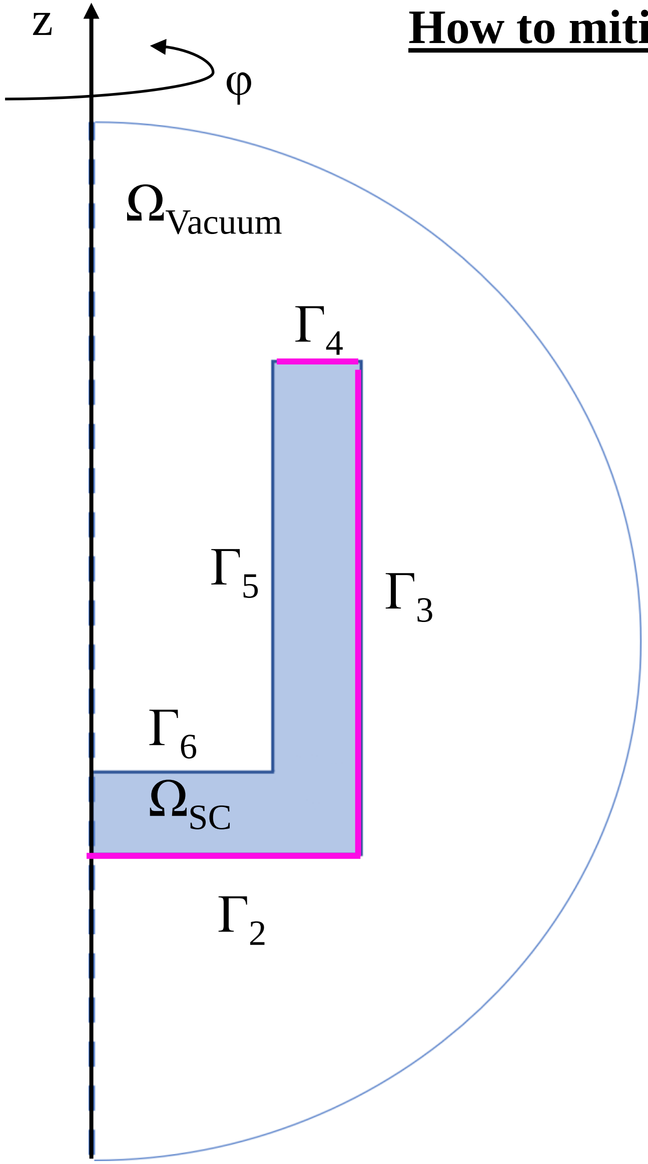
Γ_{10} : FM cooled through the thermal contact with the cryocooler refrigeration stage (via indium layer)

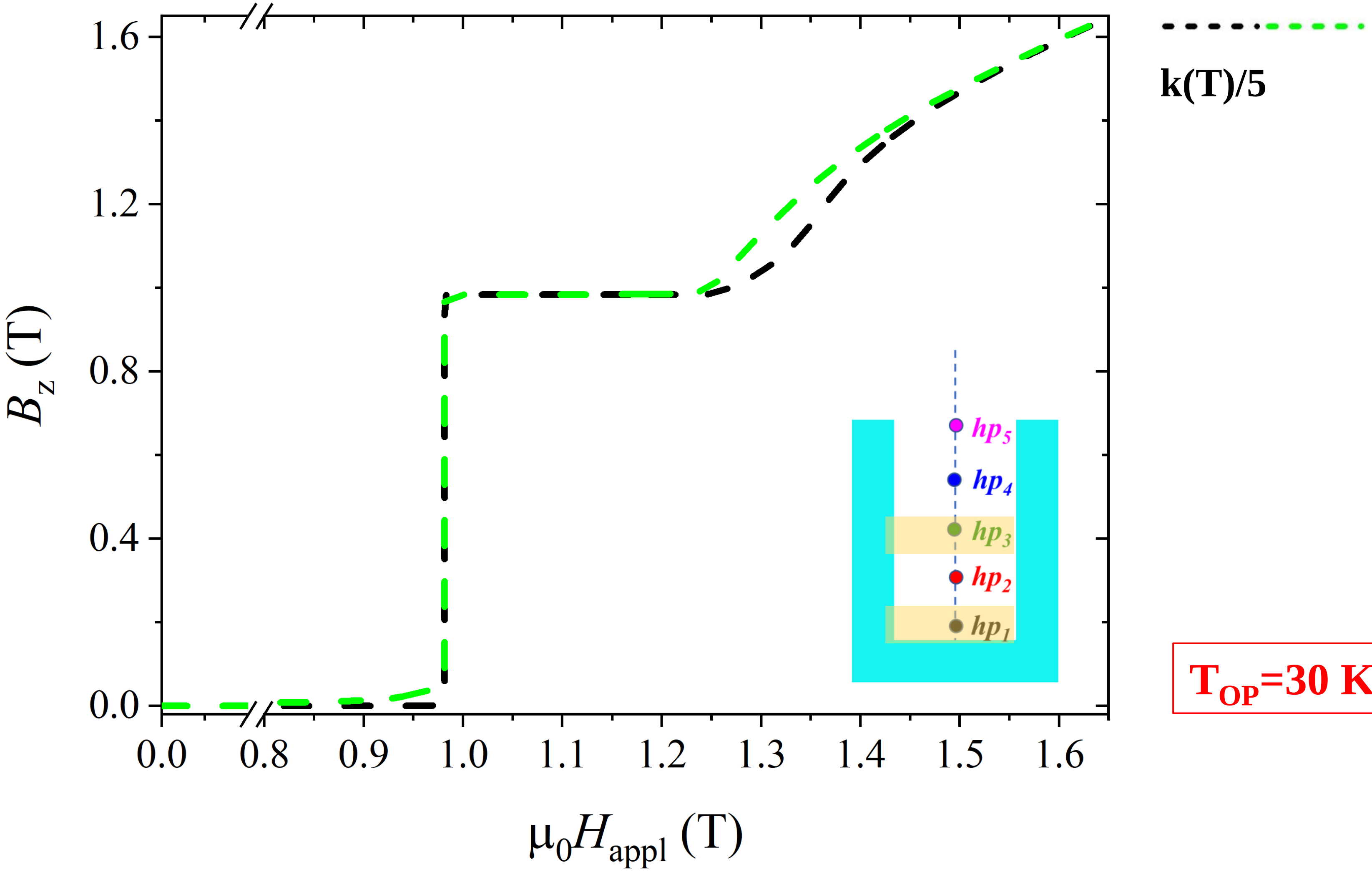
$$\vec{n} \cdot (k_{FM}(T) \nabla T) = \Upsilon \cdot (T_{OP} - T_{FM})$$

$\Gamma_5, \Gamma_6, \Gamma_7, \Gamma_8, \Gamma_9$: $\vec{n} \cdot (k'(T) \nabla T) = 0$

$$\vec{n} \cdot (k_{FM}(T) \nabla T) = 0$$

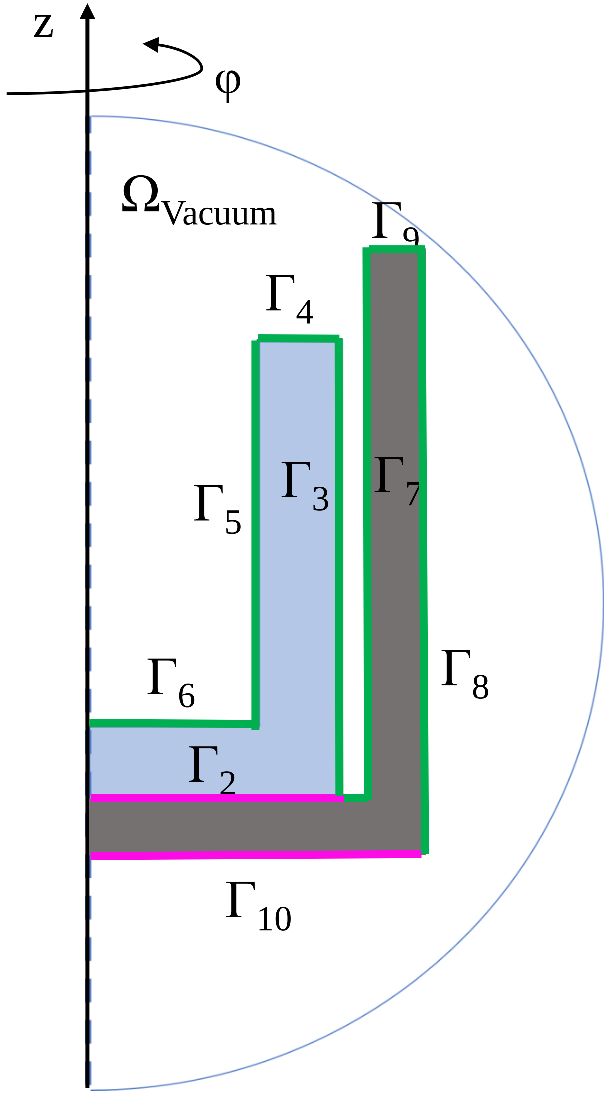
How to mitigate the flux jump occurrence? (3) Superimposing of a ferromagnetic cup

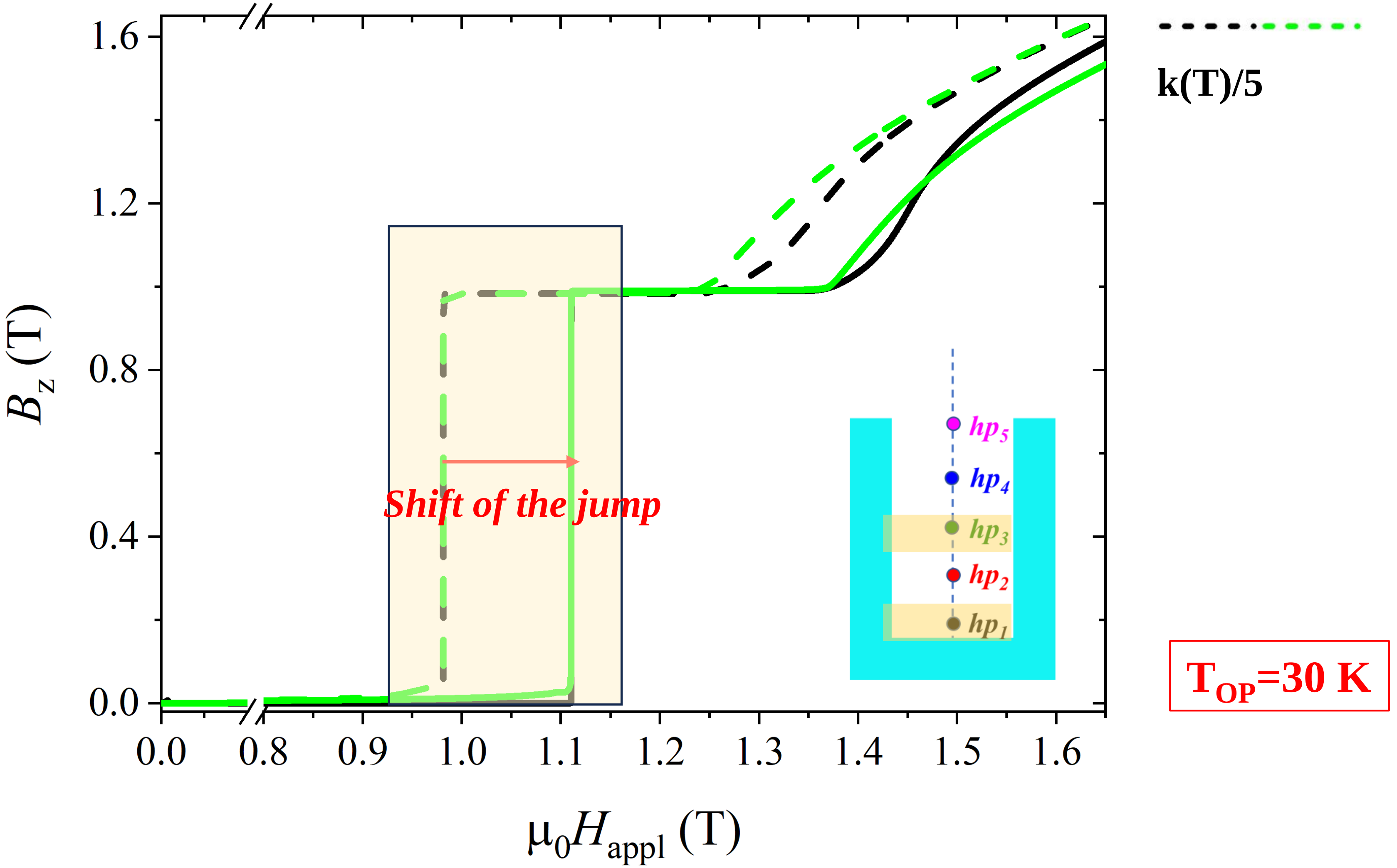




T_{OP}=30 K

How to mitigate the flux jump occurrence? 3 Superimposing of a ferromagnetic cup





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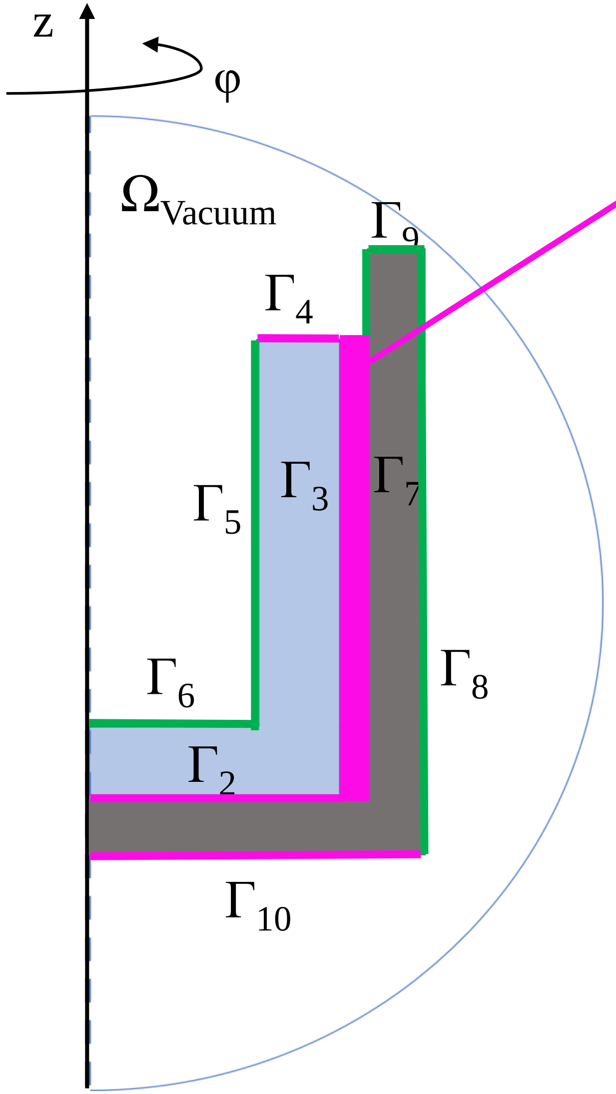
How to mitigate the flux jump occurrence?

4 Superimposing of a ferromagnetic cup cup and improving the thermal exchange



Filling the gap between the SC and FM cups with an indium layer

Coupling between Ω_{SC}, Ω_{FM} and Ω_V:

$\Gamma_2, \Gamma_3, \Gamma_4, \Gamma_7$: SC cooled through the thermal contact with FM shield

$$\vec{\boldsymbol{n}} \cdot (k'(T)\nabla T) = \Upsilon' \cdot (T_{FM} - T_{SC})$$

Γ_{10} : FM cooled through the thermal contact with the cryocooler refrigeration stage (via indium layer)

$$\vec{\boldsymbol{n}} \cdot (k_{FM}(T)\nabla T) = \Upsilon \cdot (T_{OP} - T_{FM})$$

$\Gamma_5, \Gamma_6, \Gamma_8, \Gamma_9$:

$$\vec{\boldsymbol{n}} \cdot (k'(T)\nabla T) = 0$$

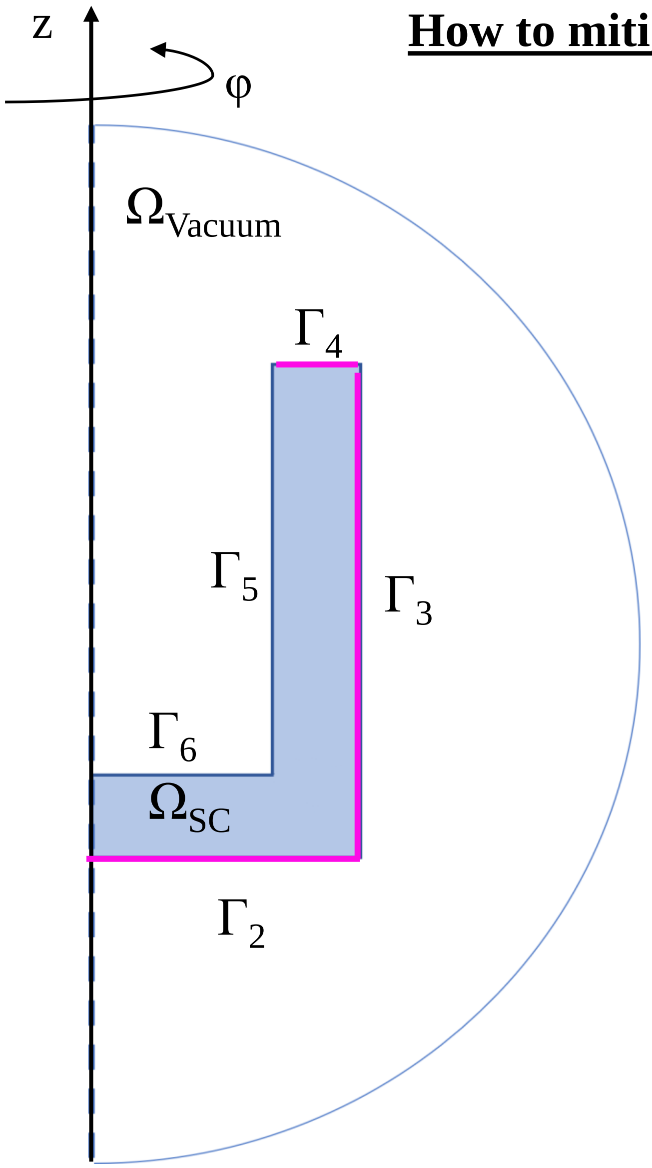
$$\vec{\boldsymbol{n}} \cdot (k_{FM}(T)\nabla T) = 0$$

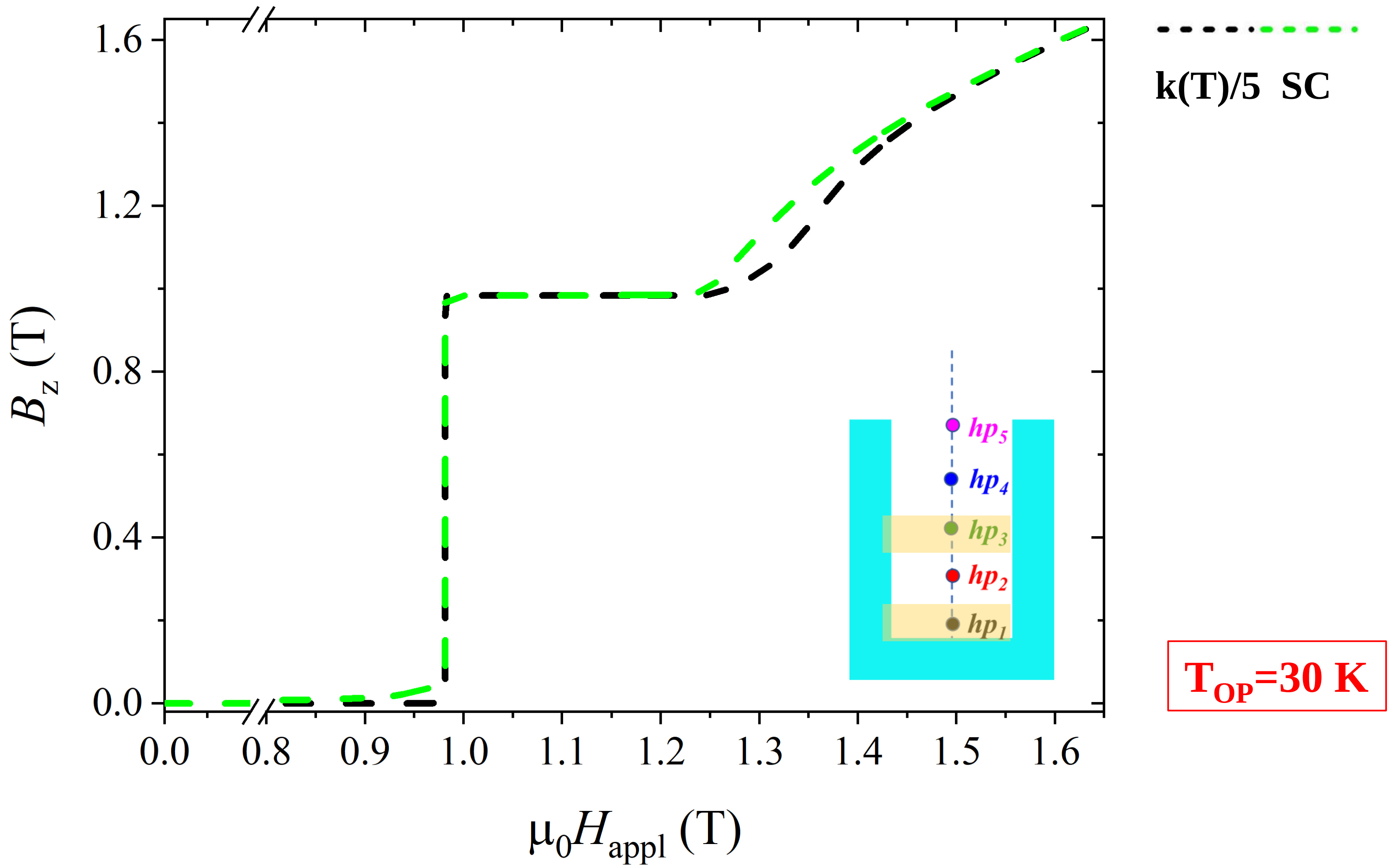
$T_{OP} = 30$ K

$k'(T) = k_{Zou}(T)/5$

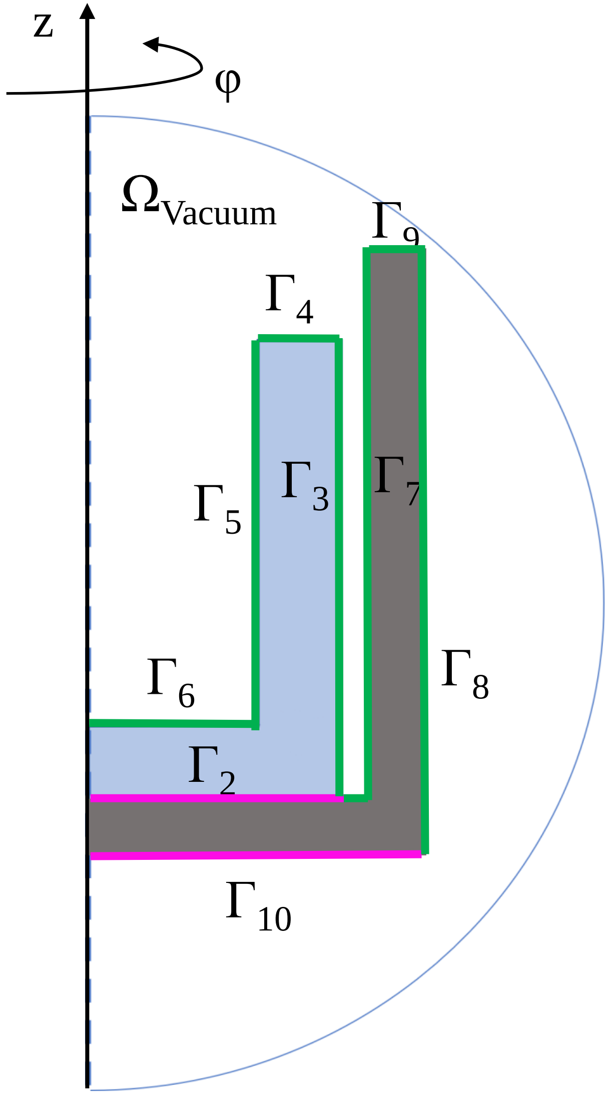
How to mitigate the flux jump occurrence?

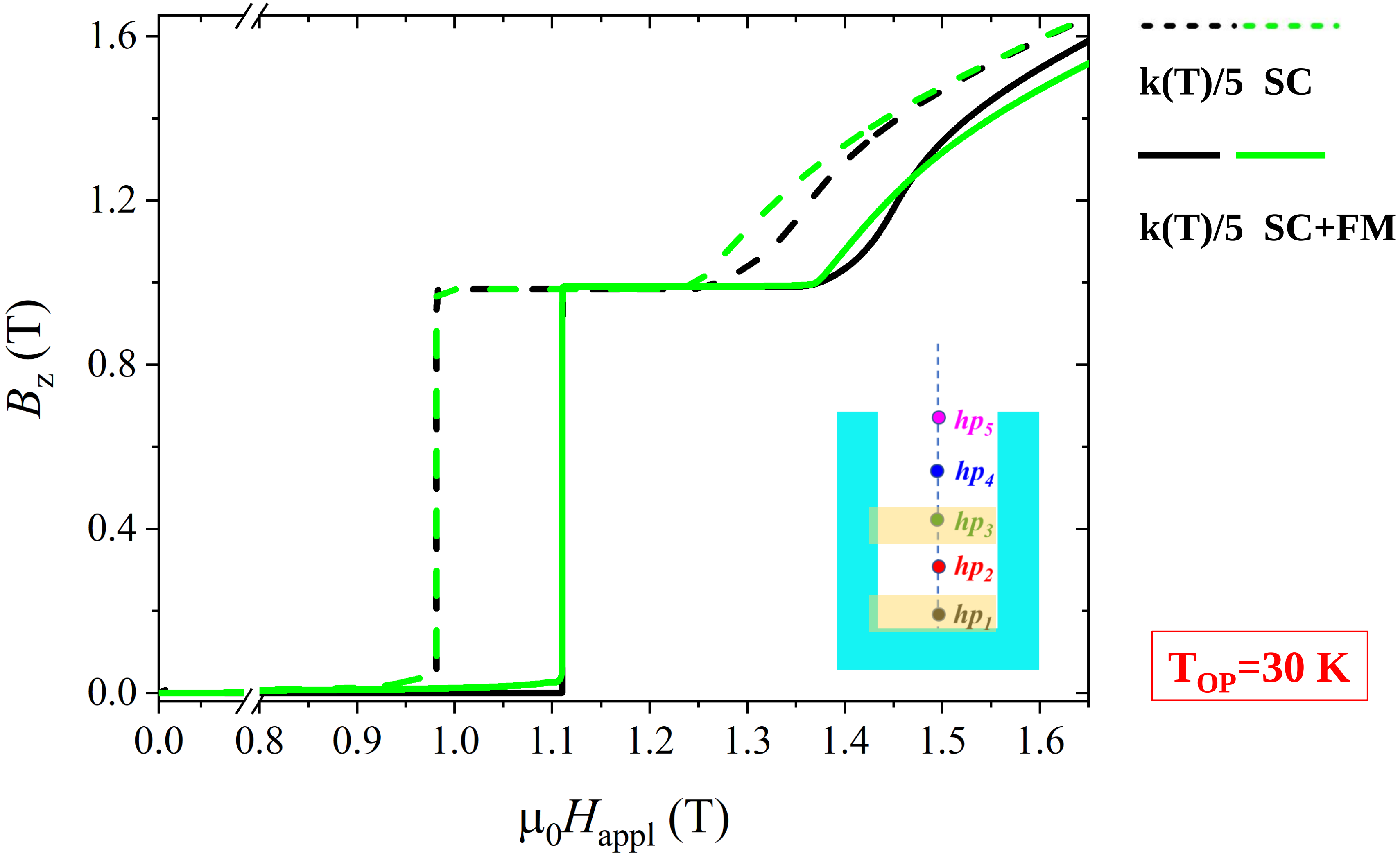
4 Superimposing of a ferromagnetic cup cup and improving the thermal exchange



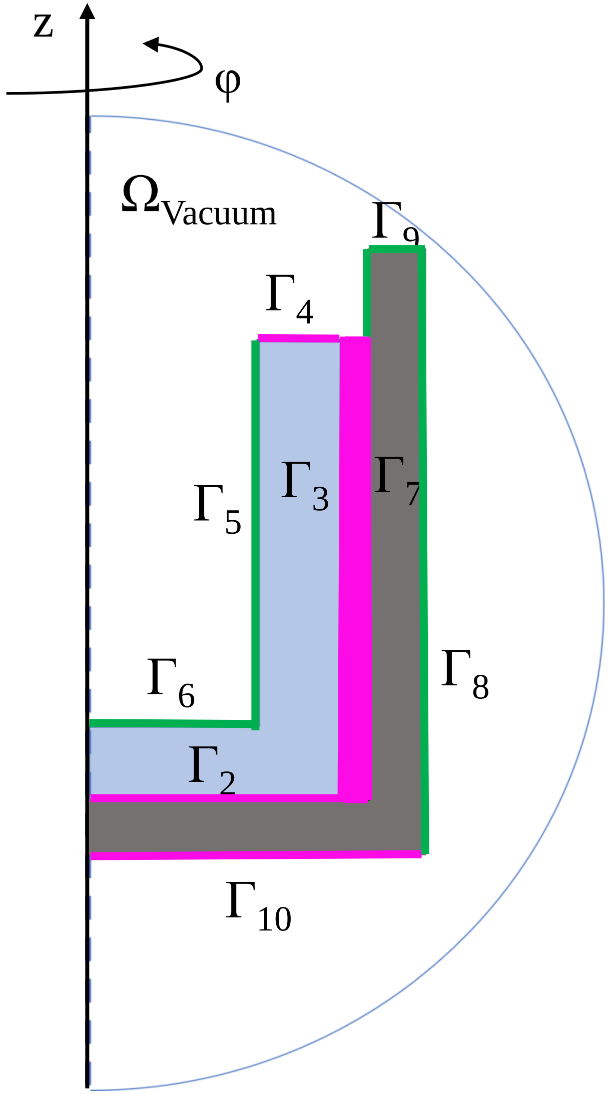


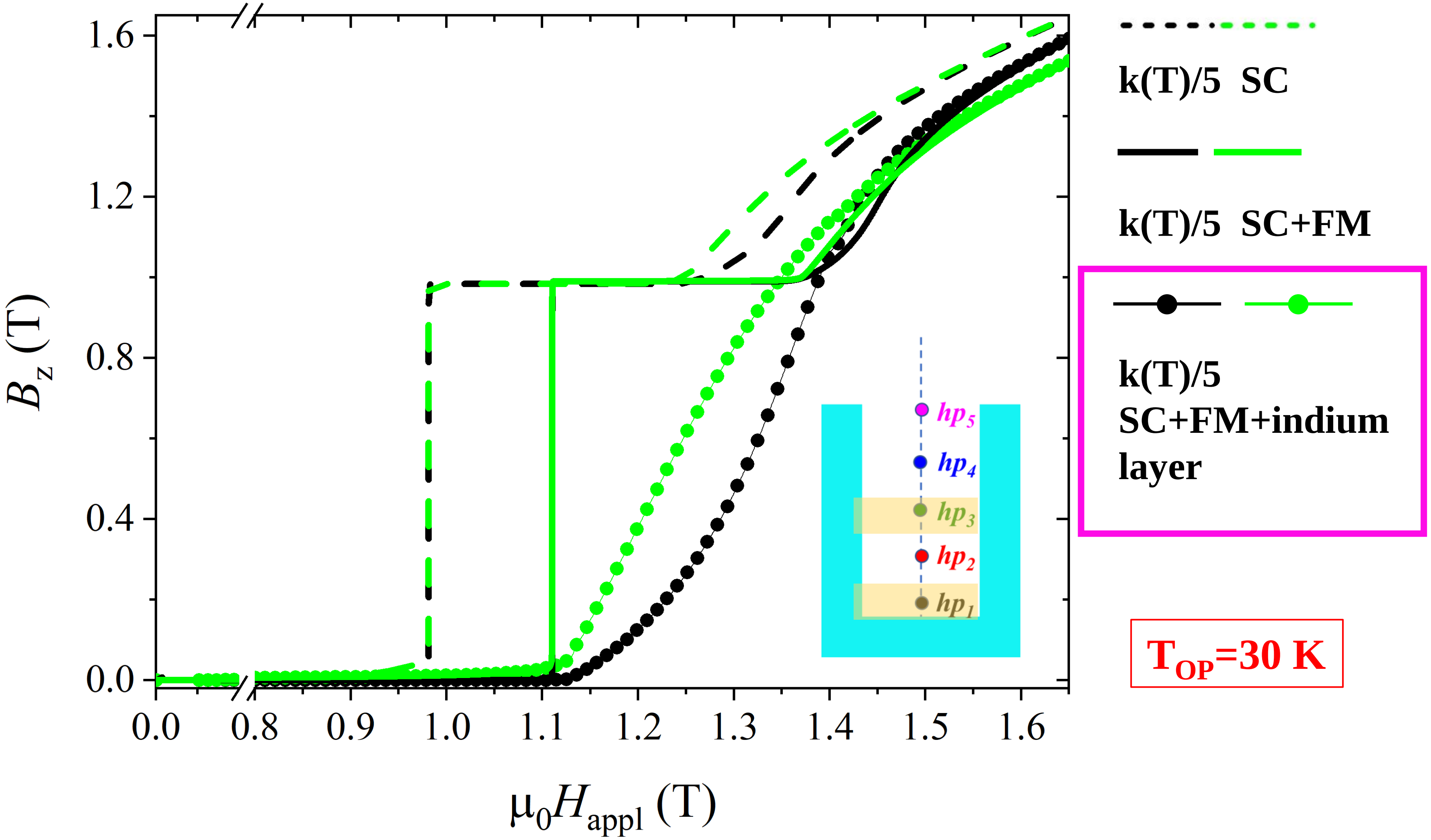
How to mitigate the flux jump occurrence? 4 Superimposing of a ferromagnetic cup cup and improving the thermal exchange





How to mitigate the flux jump occurrence? ④ Superimposing of a ferromagnetic cup cup and improving the thermal exchange

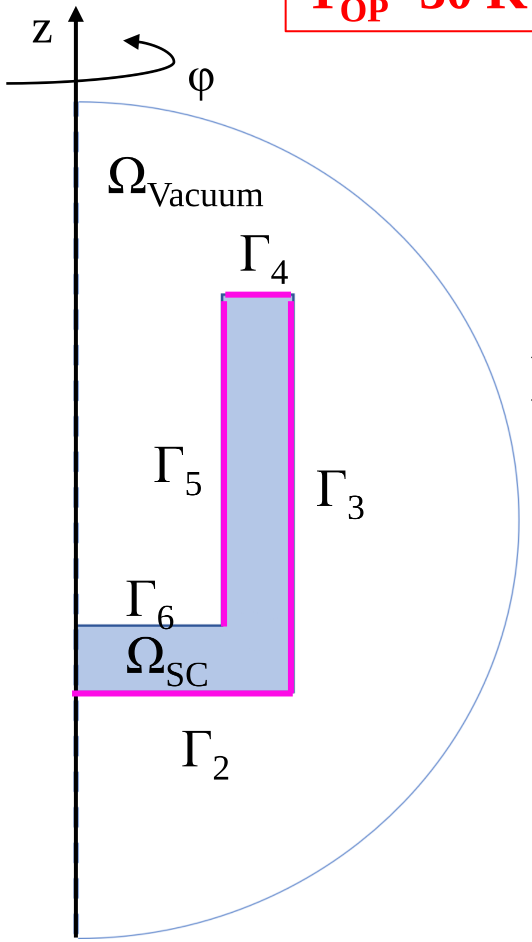


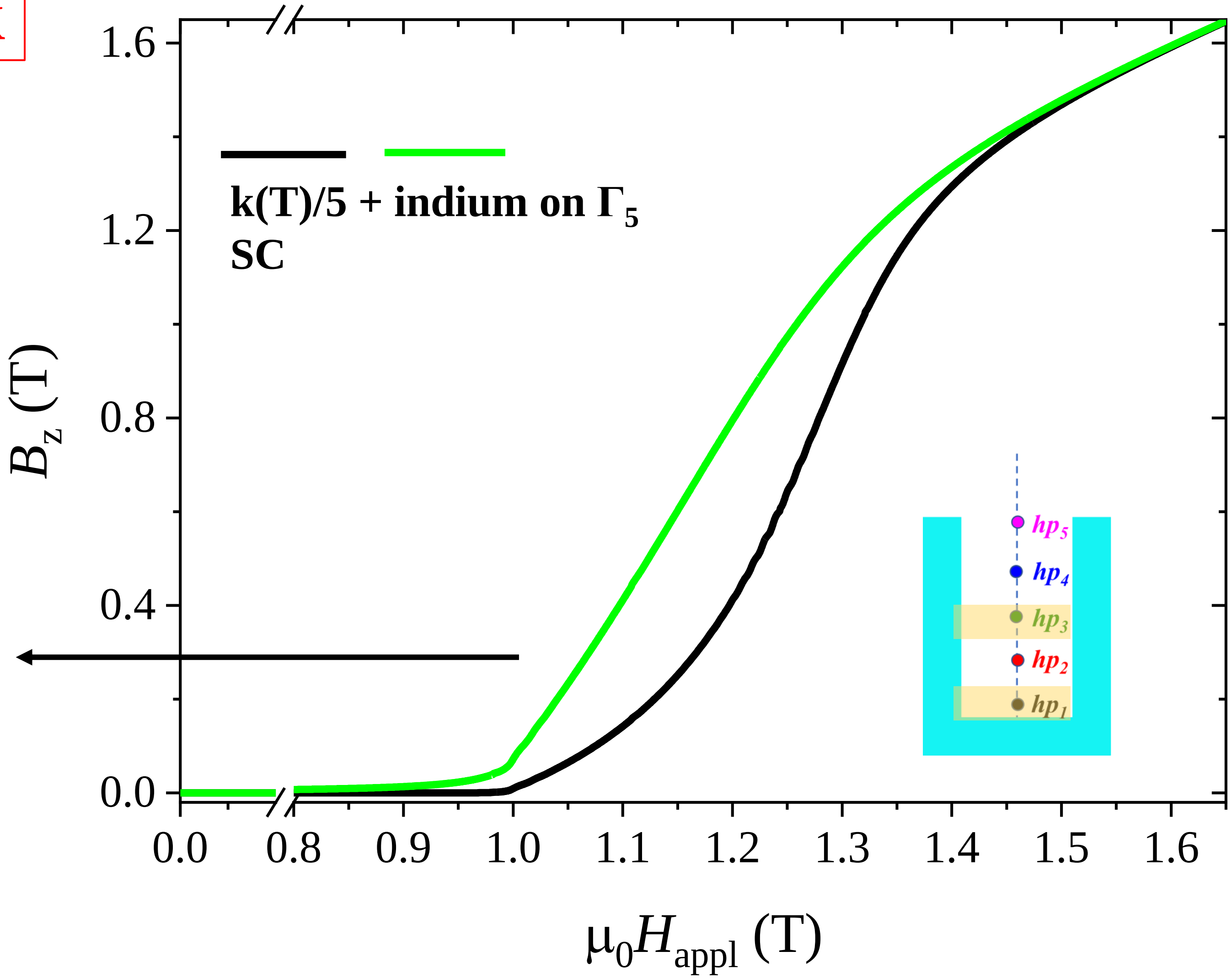


T_{OP}=30 K

How to mitigate the flux jump occurrence? Comparisono of the most efficient strategies

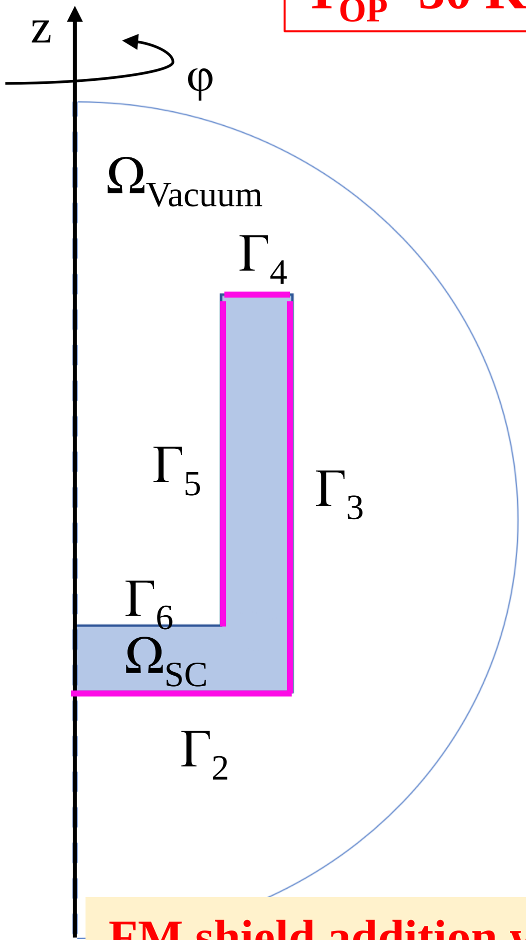
T_{OP}=30 K

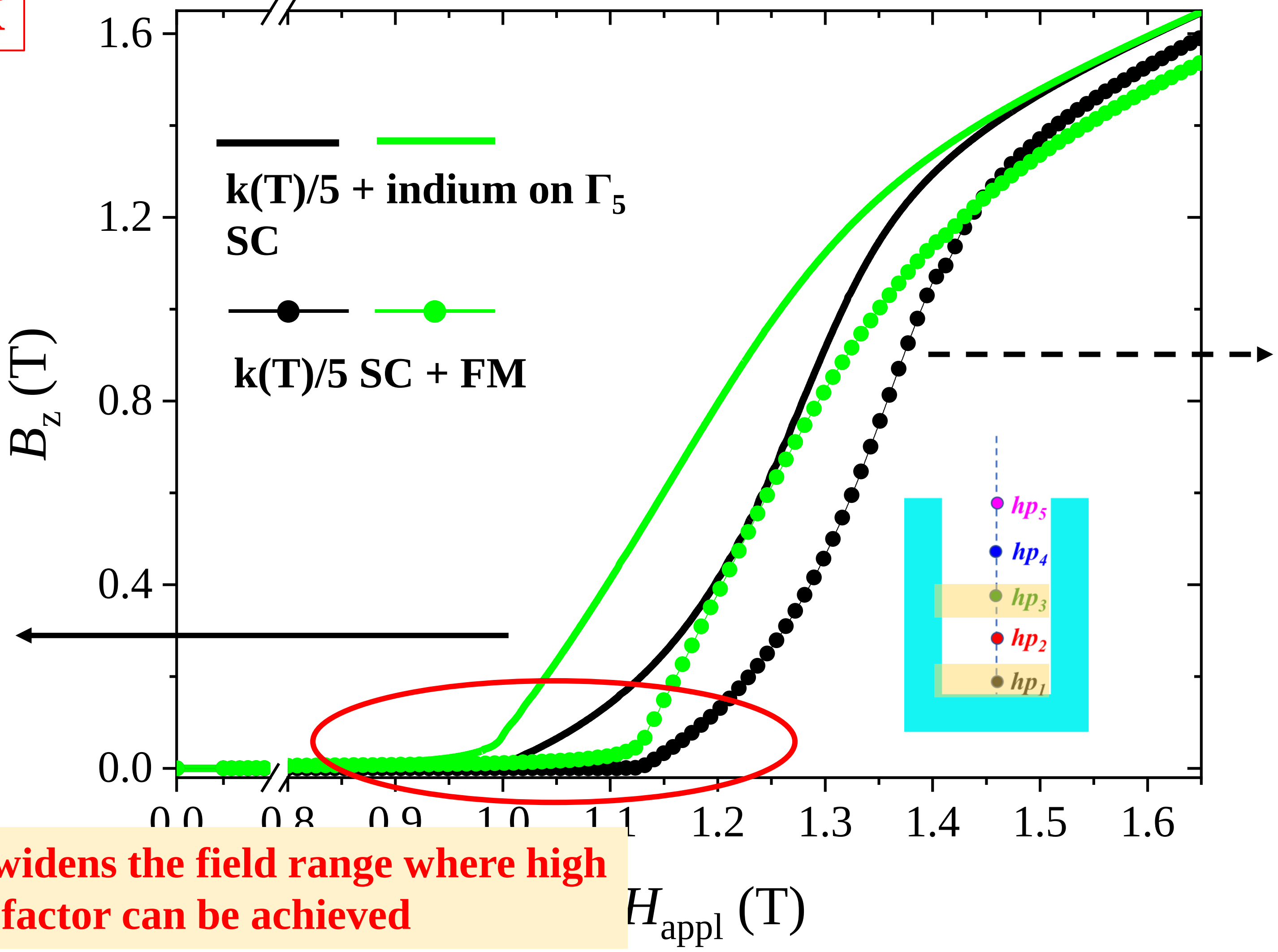


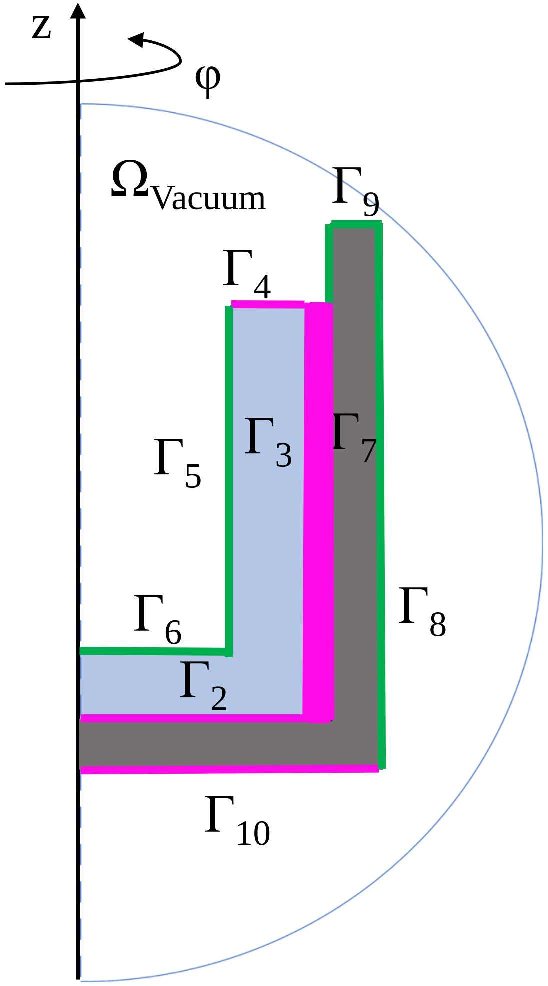


Comparisono of the most efficient strategies

T_{OP}=30 K







FM shield addition widens the field range where high shielding factor can be achieved

Summary and conclusions

- Fully machinable MgB_2 bulks were fabricated via SPS (MgB_2 powders + h-BN powders)
  $T_{c,onset}$ = 38.9 K, $J_c > 4.0 \times 10^8$ A/m^2 (T = 20 K, $\mu_0 H_{appl}$ = 2.0 T), *uniform on cm scale*

→ **! A weakness was found** → ! occurrence of thermomagnetic instabilities

→ **Numerical analysis to** → predict the flux jump occurrence and test solutions to mitigate the phenomenon

→ **No flux jump occurrence is expected:**

→ Improving the thermal exchange across the inner lateral wall of the SC shield

→ Superimposing a ferromagnetic shield

(also widening the applied field range where elevated SFs can also be achieved)

Acknowledgements

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ELÚ

Mykola Solovyov , Fedor Gömöry

Hi-SCALE

Hi-SCALE COST Action

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Thank you for your kind attention!

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