

# Annuli of coated conductors with a ferromagnetic substrate: magnetic shielding properties at 77 K and at room temperature

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SEOUL NATIONAL UNIVERSITY  
서울대학교공과대학



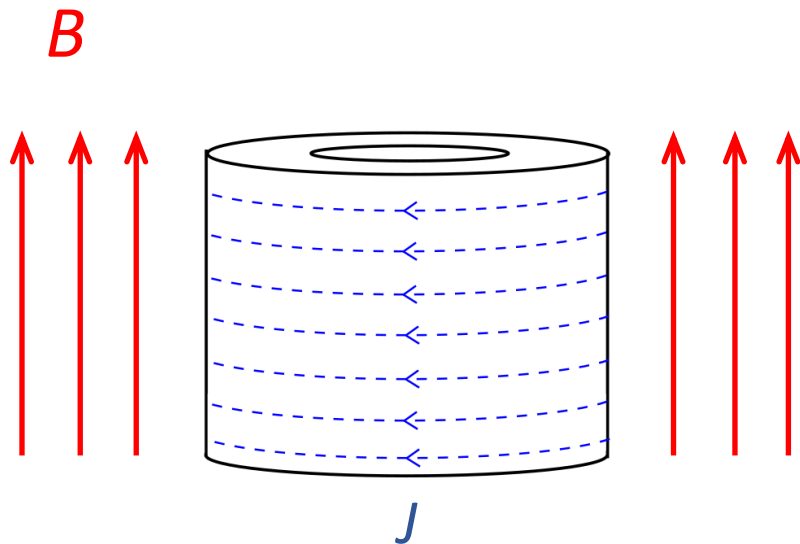
**UNIVERSITY OF  
CAMBRIDGE**

# Introduction

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In the context of magnetic shielding:

- High-permeability ferromagnetic materials saturate at  $B \approx 1 \text{ T}$
- Bulk superconductors can act as very efficient shields
- Persistent **current loops** generated by the **applied field**

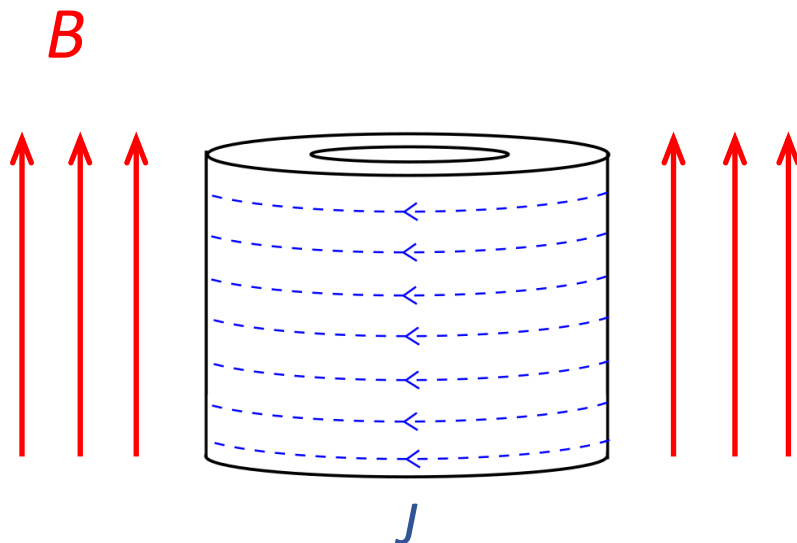


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In principle, possibility to shield a quasi-DC flux density  $B \gg 1 \text{ T}$  with superconducting materials

Record at 77 K: shielding up to  $B \approx 0.3 - 0.4 \text{ T}$  with melt-textured  $(\text{RE})\text{Ba}_2\text{Cu}_3\text{O}_7$

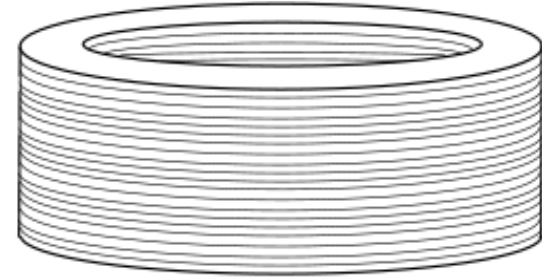
Yang P.T. *et al.*, *Supercond. Sci. Technol.* (2017) **30** 085003

Yang P.T. *et al.*, *Supercond. Sci. Technol.* (2019) **32** 115015

# Introduction

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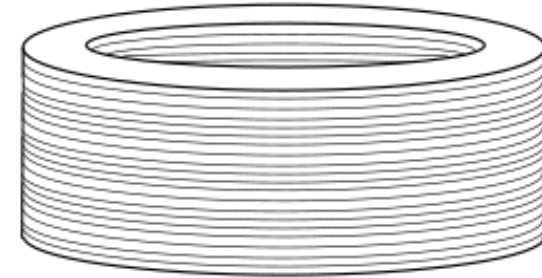
- Possibility to use a stack of coated conductors (CC) annuli of large width as a cylindrical shield
- The shielding performances can be improved by using a ferromagnetic substrate



# Introduction

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- Possibility to use a stack of coated conductors (CC) annuli of large width as a cylindrical shield
- The shielding performances can be improved by using a ferromagnetic substrate



## **Purpose of this work :**

**Investigate the magnetic shielding properties of such a stack**  
**Investigate the role played by the ferromagnetic substrate**

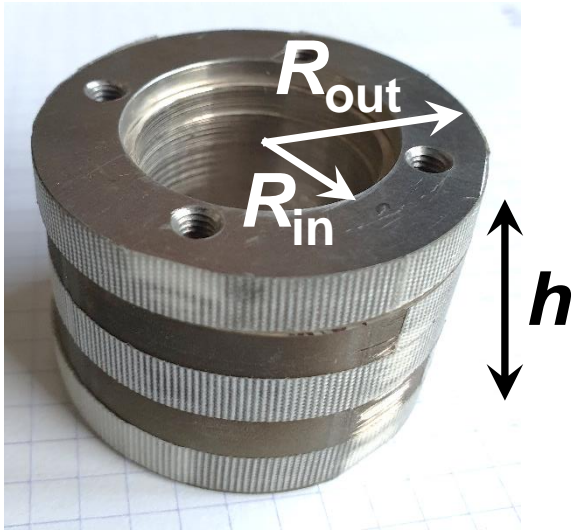
- Measurements of
  1. The magnetic properties of the CC ferromagnetic substrate
  2. The shielding performances of a stack of large CC annuli
- Comparison of experimental results with numerical simulations

1.

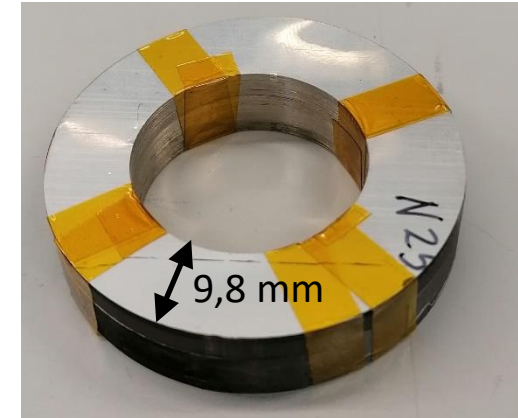
Magnetic properties of the Coated Conductors  
(CC) ferromagnetic substrate

# Experimental set-up and measurement method

Stack of 294 CC annuli dug in 46 mm wide tapes



$$\begin{aligned} R_{\text{out}} &= 22.5 \text{ mm} \\ R_{\text{in}} &= 13 \text{ mm} \\ h &= 24 \text{ mm} \end{aligned}$$



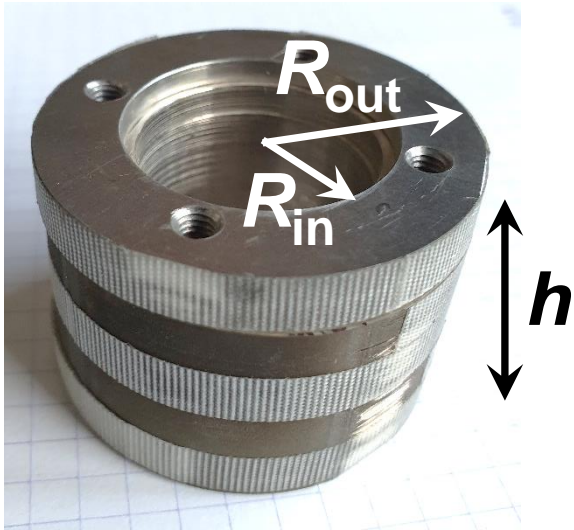
- Stack of 294 coated conductors
- American Superconductor (RE)BCO tape
- 75  $\mu\text{m}$  thick Ni5W substrate

S. Hahn *et al.*, *IEEE Trans. Appl. Supercond.*, **22**, 4302204 (2012)

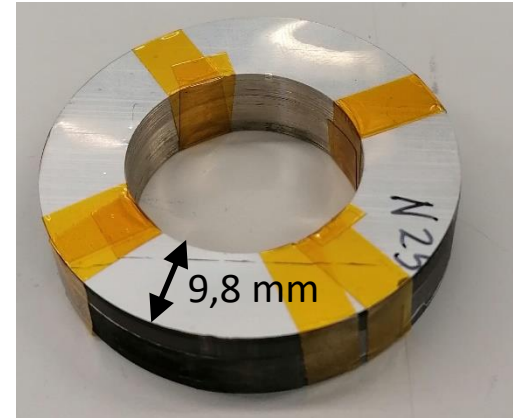
A. Patel *et al.*, *Supercond. Sci. Technol.*, **30**, 024007 (2017)

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## Advantages of this sample:

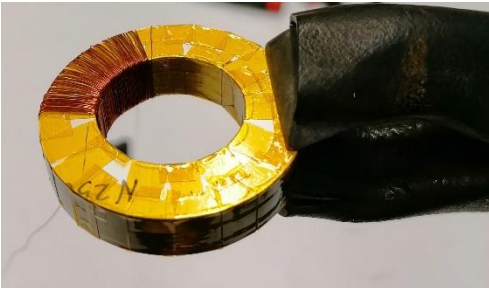
- Closed magnetic circuit
- No demagnetizing effect
- Best configuration to measure magnetic properties



# *Experimental set-up and measurement method*

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**Measurement coils :**



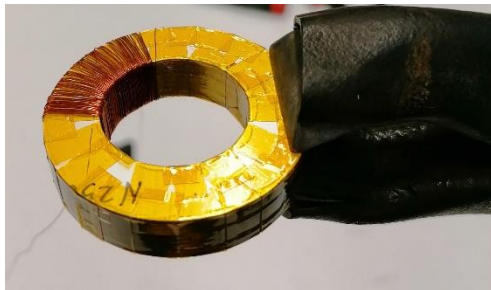
# Experimental set-up and measurement method

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## Measurement coils :

### Secondary winding

- $B$  measurement
- Small section wire
- $N_s = 433$  turns
- Wound as close as possible from the tapes



# Experimental set-up and measurement method

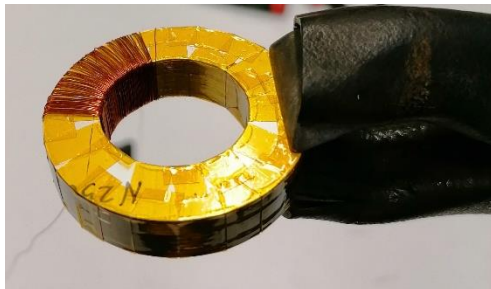
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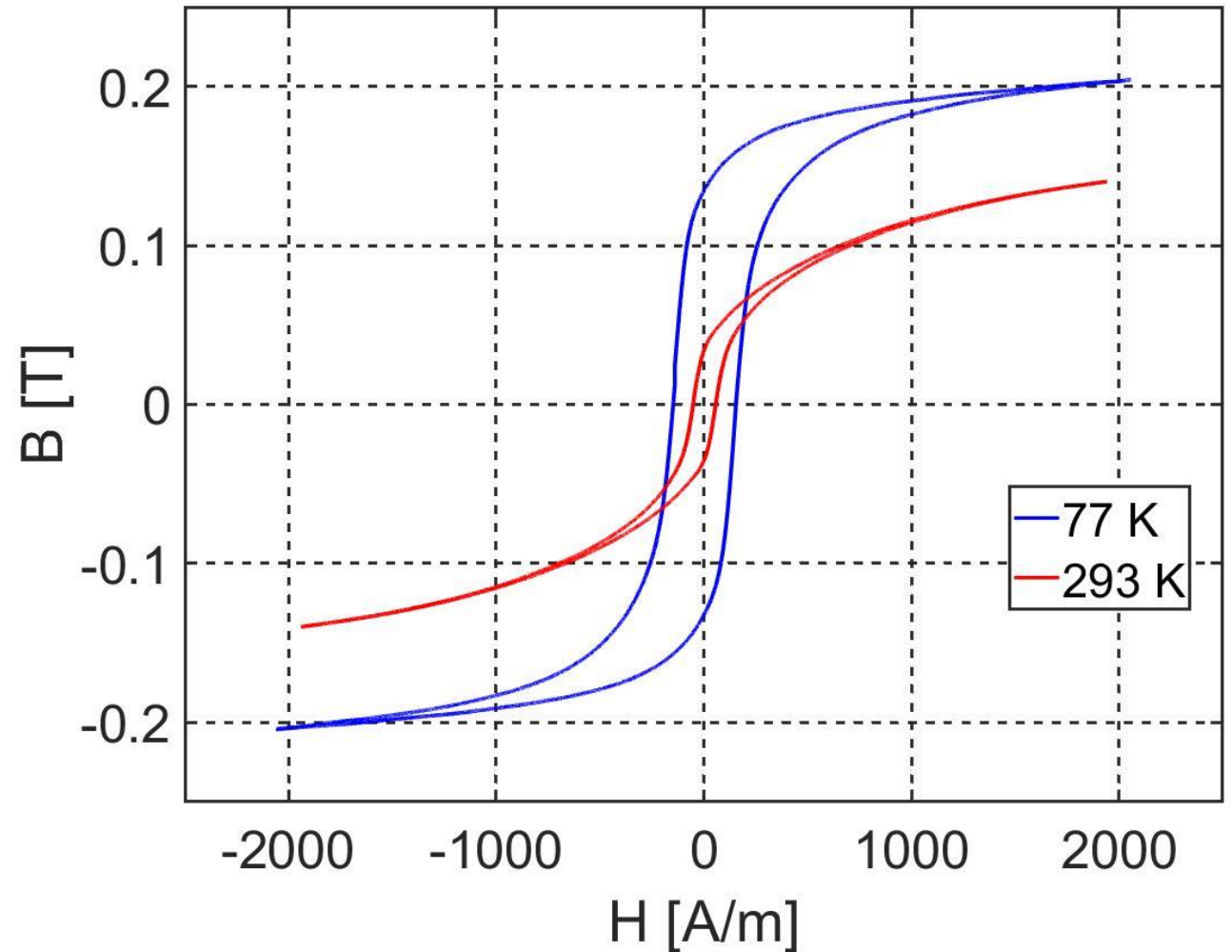
### Primary winding

- Sample Magnetization ( $H$  field)
- Large section wire
- $N_p = 368$  turns



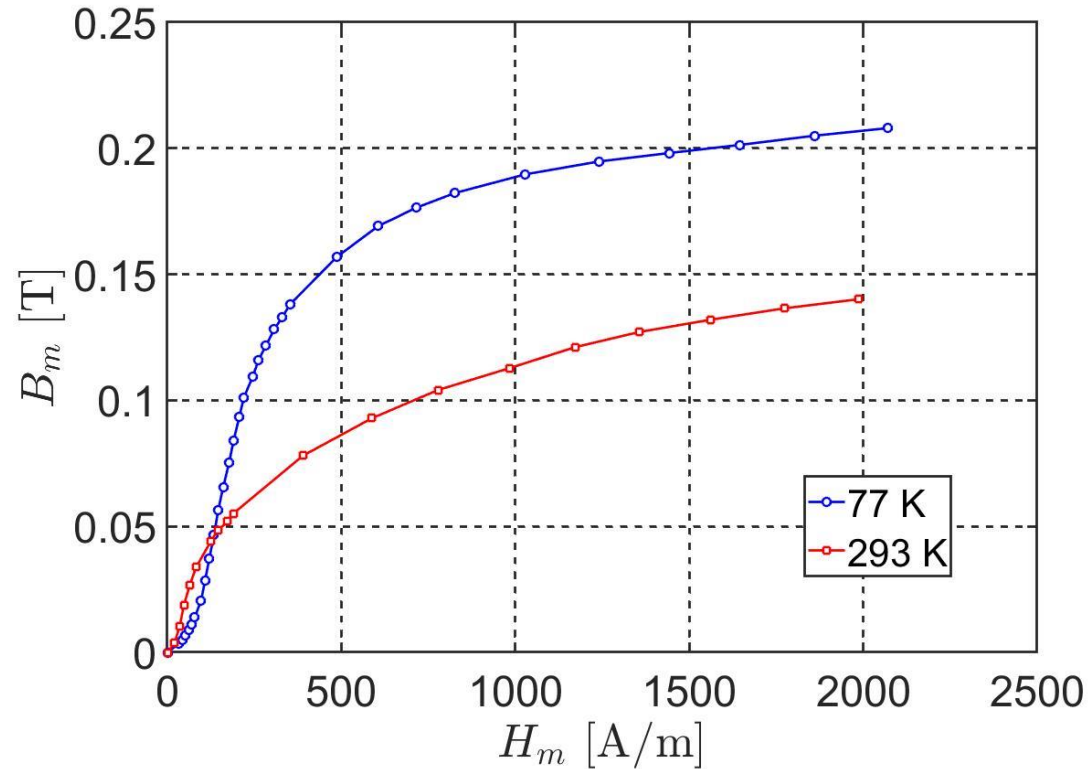
# Measurement results

- Hysteretic cycles measured in low frequency AC (30 Hz)
- Temperatures investigated : room temperature (293 K) and 77 K
- Measurements at different frequencies show that eddy current losses are negligible

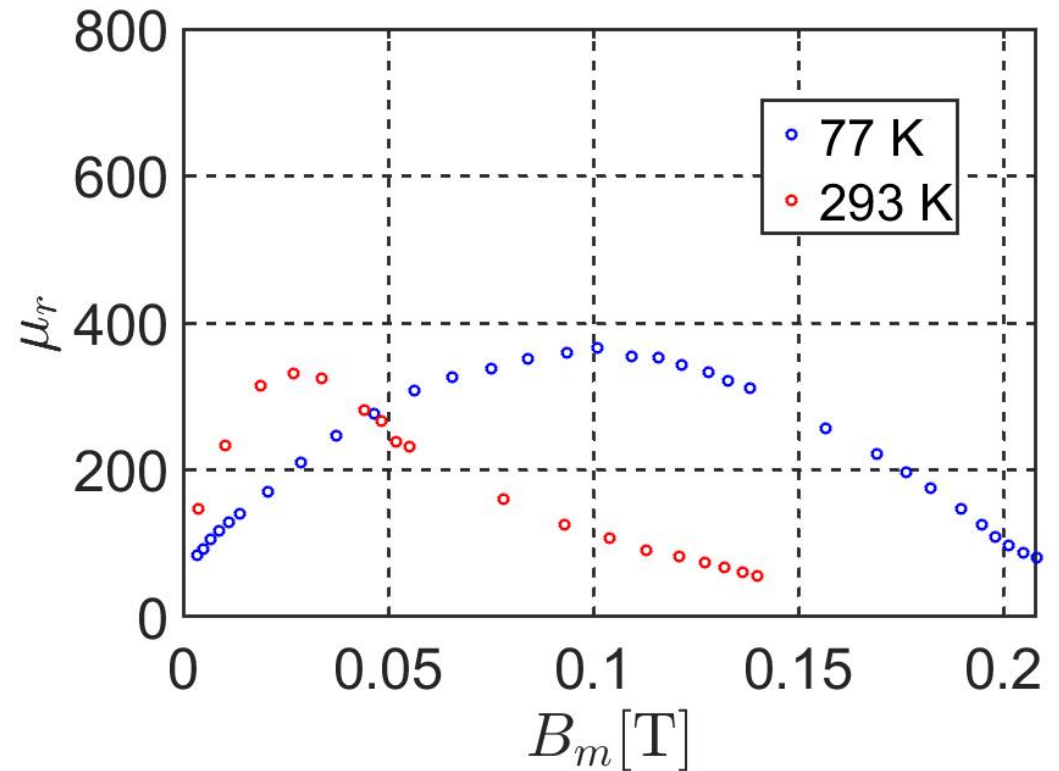


# Measurement results

## First magnetization curve

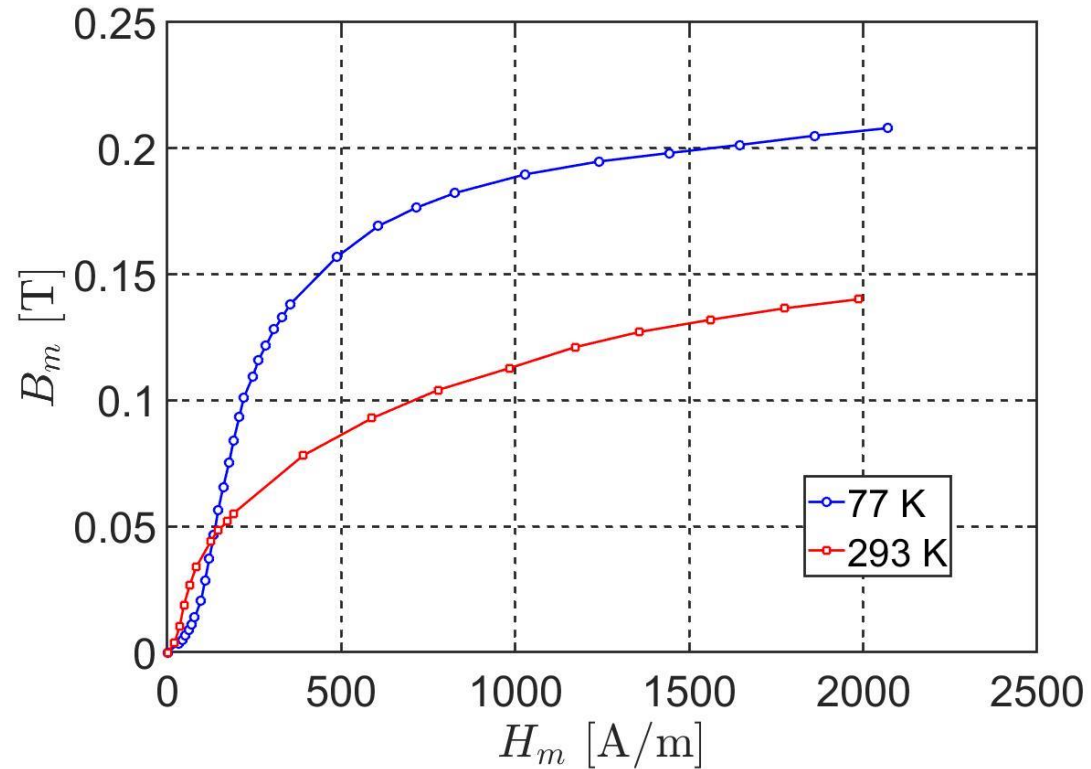


## Magnetic permeability

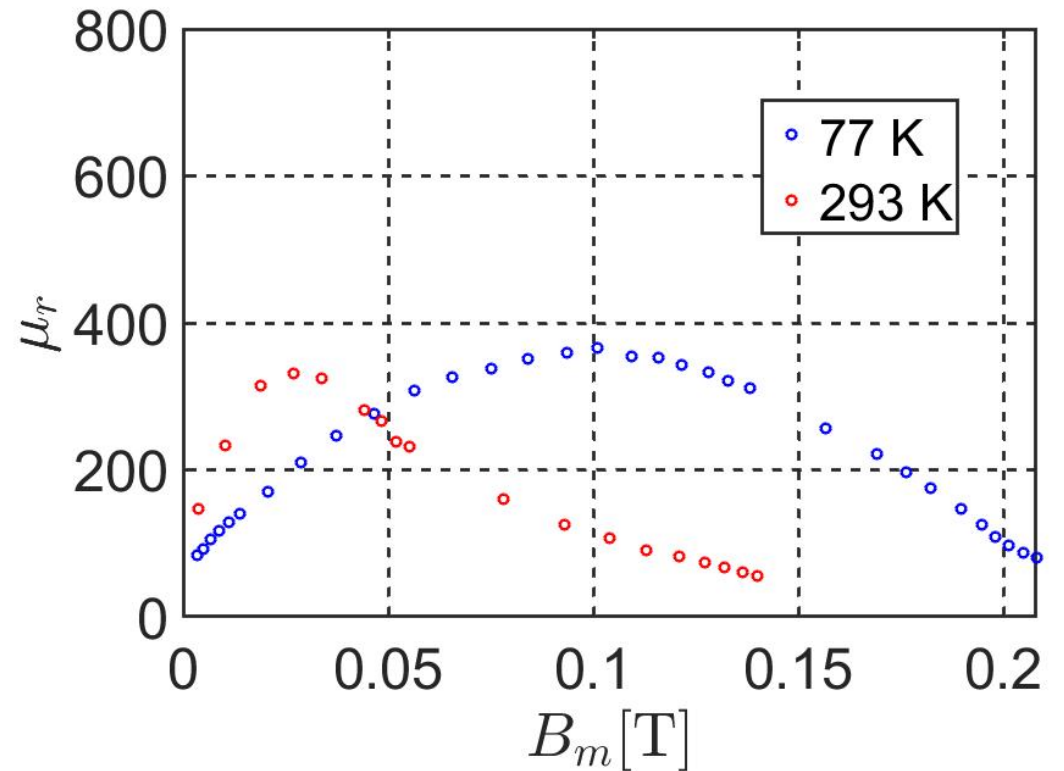


# Measurement results

First magnetization curve



Magnetic permeability



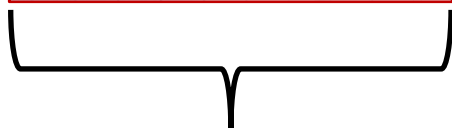
Results can be inserted in numerical models simulating the HTS/Ferromagnetic material coupling

2.

Magnetic shielding performance of the stack  
of CC annuli

# Experimental set-up and measurement method

Shielding performance measured on two different aspect ratios : **A** and **B**



## Sample A

- Initial sample
- $h = 24$  mm

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- Sample used for magnetic property measurement
- $h = 9$  mm

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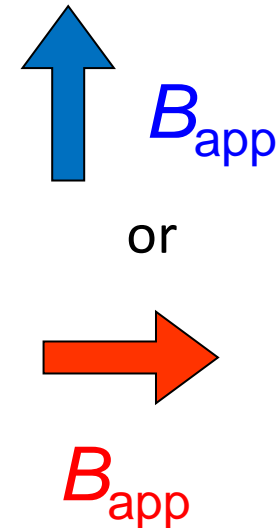
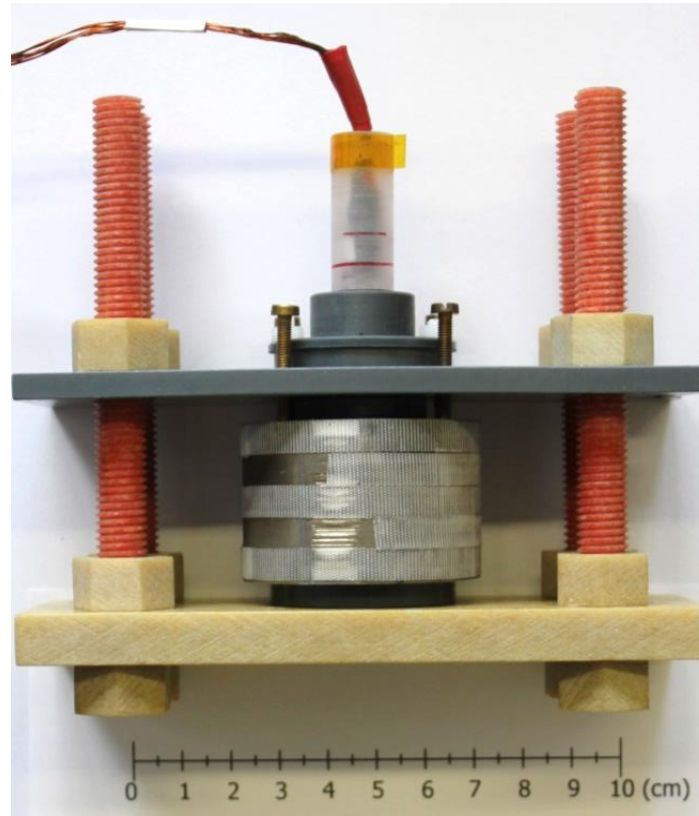
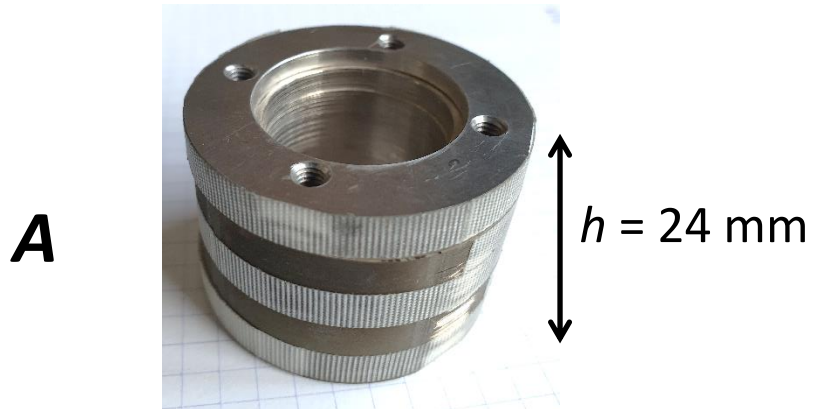
## Sample B

- Second sample
- $h = 15$  mm



# Experimental set-up and measurement method

- Measurement of the flux density inside the samples at the centre of the stack  $B_{in}$
- Measurement under **axial** and **transverse** configurations
- Measurement at room temperature and at 77 K

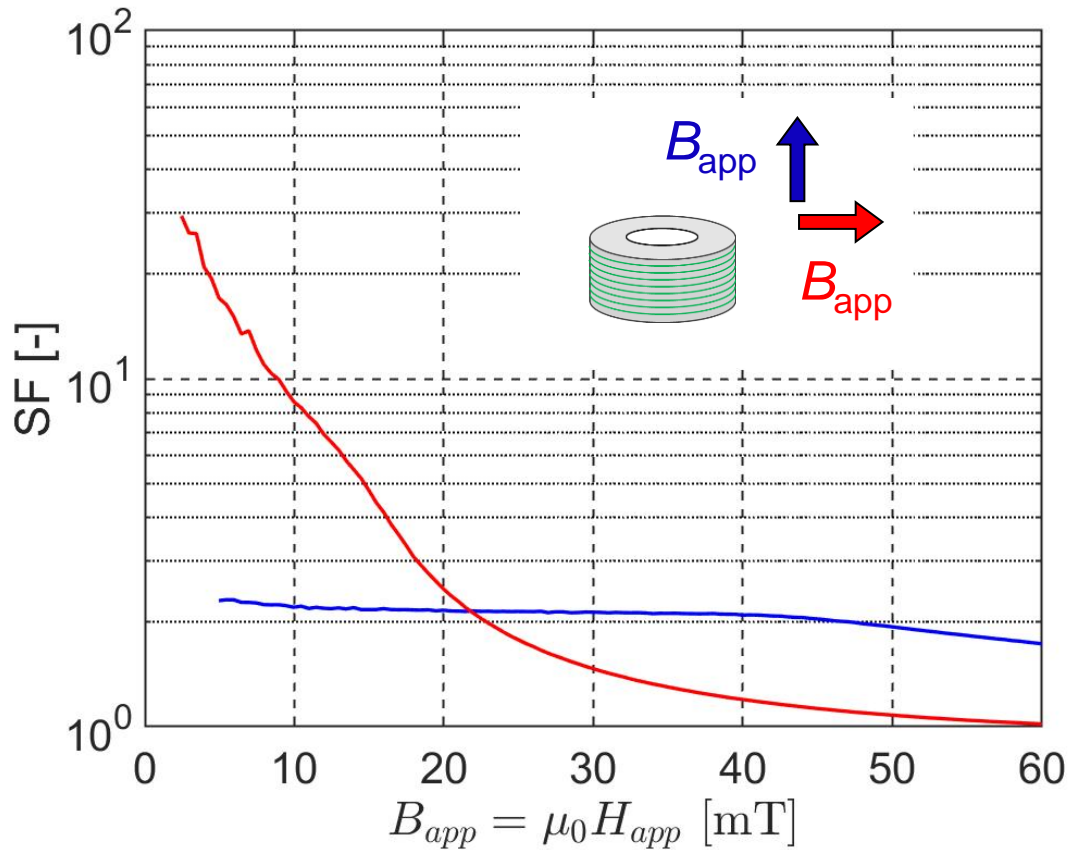


Shielding factor:

$$SF = \frac{B_{app}}{B_{in}}$$

# Experimental results at room temperature

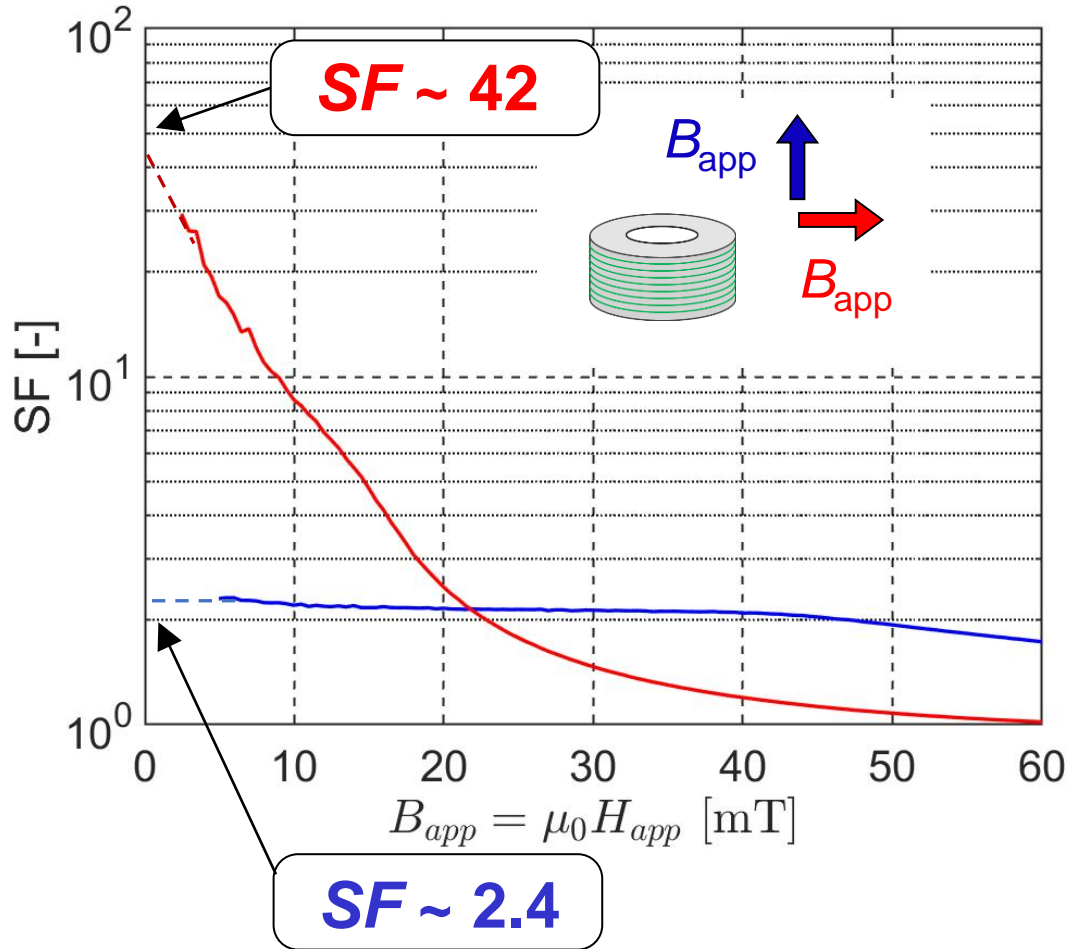
Sample A ( $h = 24$  mm)



- Existence of  $SF > 1$  for both orientations
- **Transverse SF** strongly field dependent
- **Axial SF** almost field independent ( $\approx 2$ )

# Experimental results at room temperature

Sample A ( $h = 24$  mm)



- Taking into account a filling factor of the ferromagnetic material  $f = 0.92$

$$\mu_{xy} = f \mu_r \quad \mu_z = \frac{1}{(f/\mu_r) + (1-f)}$$

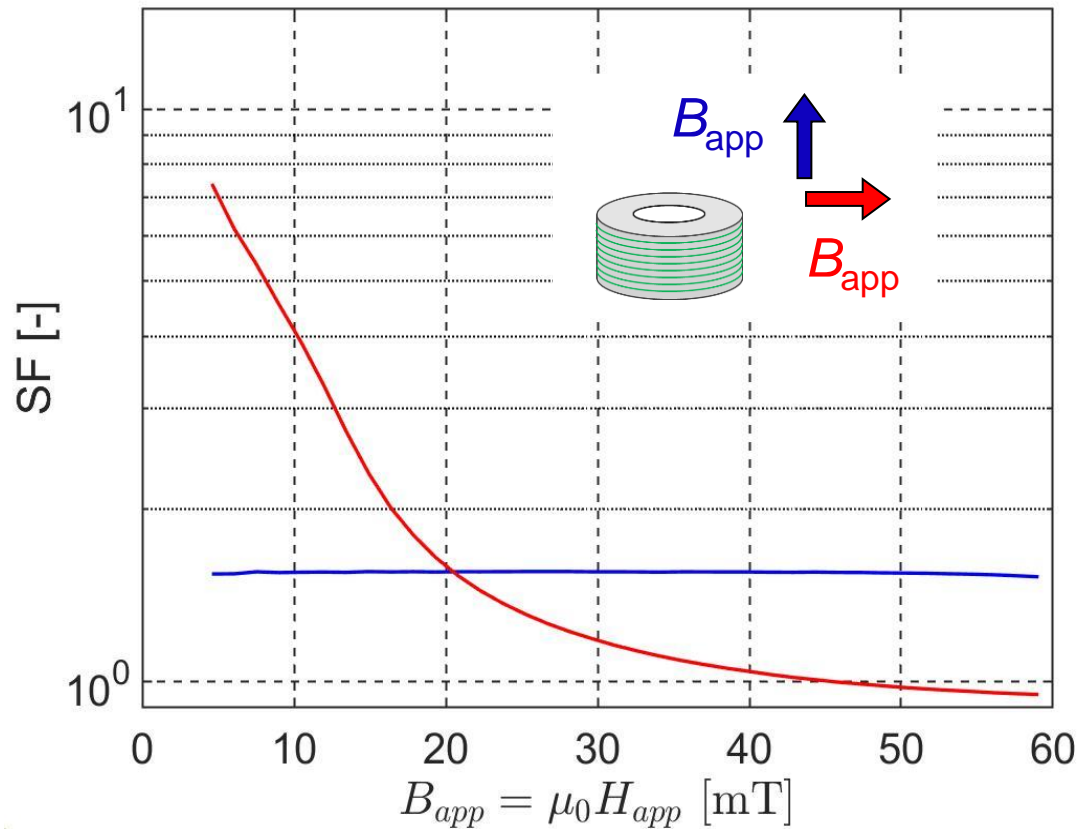
- Using formulas for ferromagnetic shields, and an 'average'  $\mu_r = 300$ , analytical formulas (Mager 1970) for ferromagnetic shields give

$$SF_{trans} = 24.6$$

$$SF_{axial} = 2.7$$

# Experimental results at room temperature

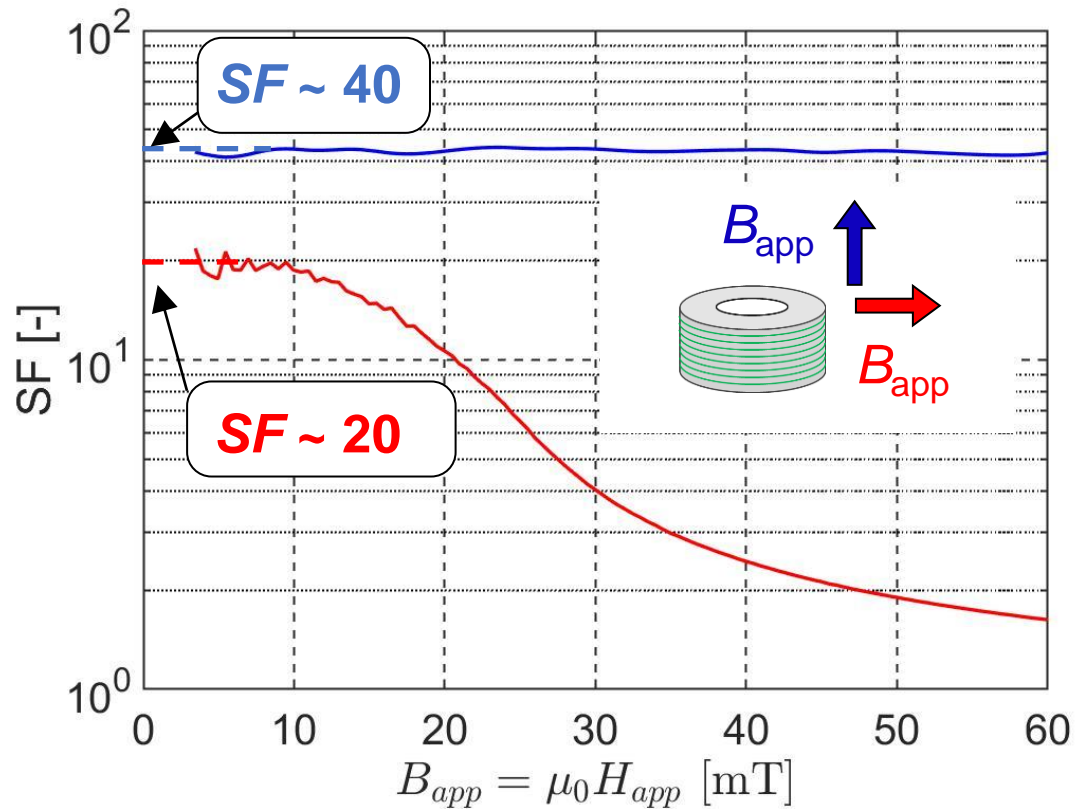
Sample B ( $h = 15$  mm)



- Similar properties but smaller shielding factor for both orientations

# Experimental results at 77 K

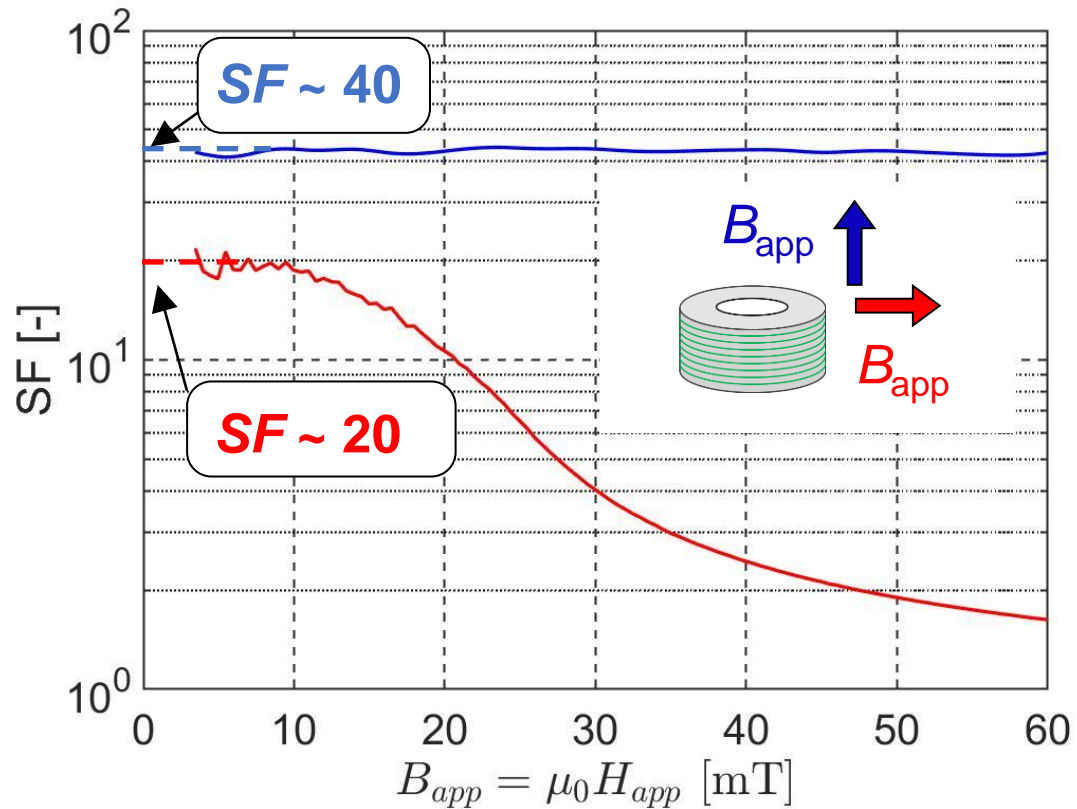
Sample A ( $h = 24$  mm)



- Transverse *SF* strongly field dependent
- Axial *SF* almost field independent ( $\approx 40$ ) and much higher than at 300 K
- The ferromagnetic layer gives rise to a significant transverse shielding ( $\approx 20$ ), in spite of the layered structure

# Experimental results at 77 K

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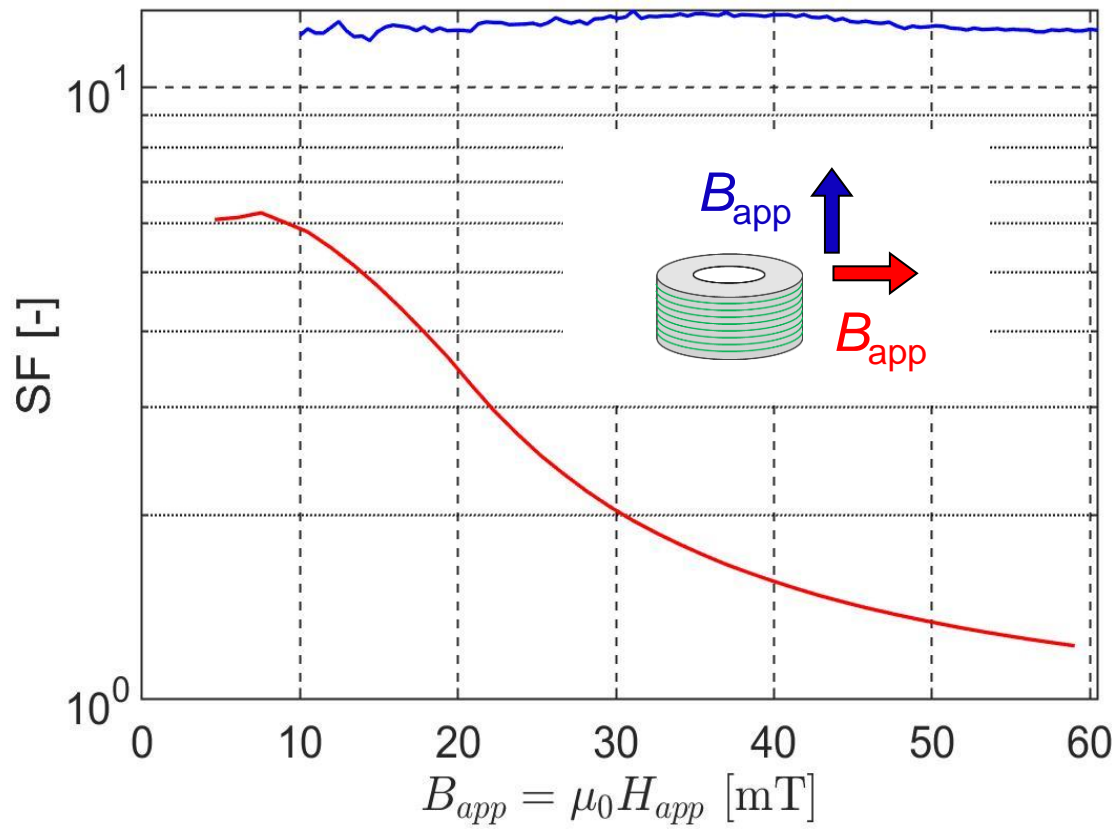


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Sample B ( $h = 15$  mm)



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# Numerical modelling

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- Homogeneous model with both superconducting and ferromagnetic properties solved with an  $h$ - $\varphi$  formulation

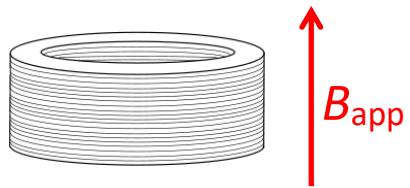


# Numerical modelling

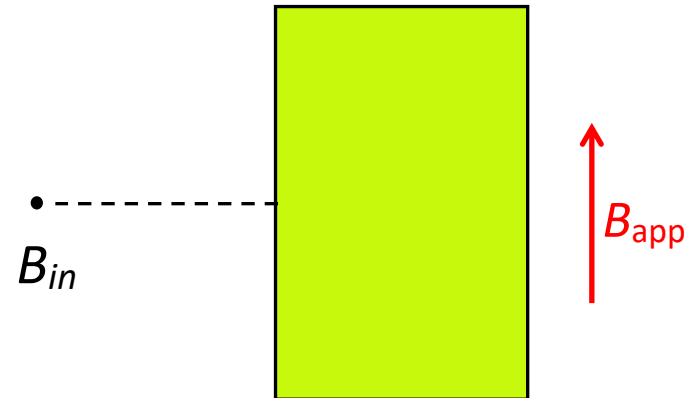
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## Axial shielding



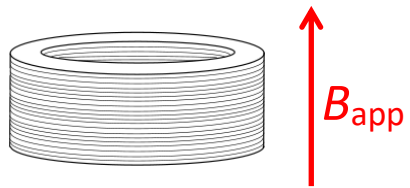
2D-axisymmetric



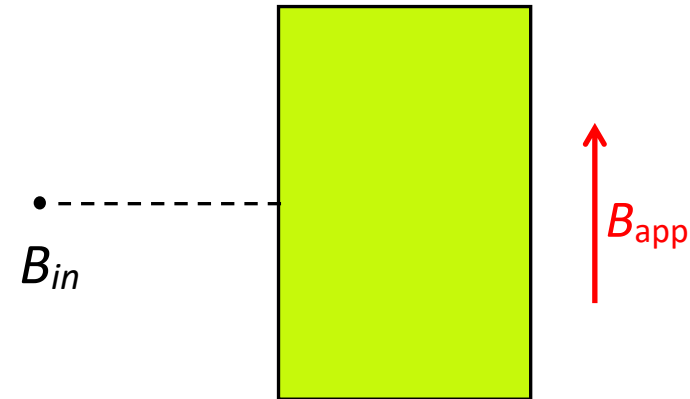
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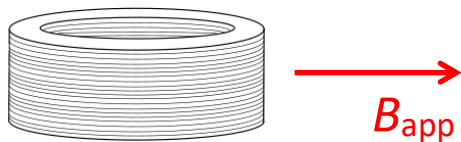
## Axial shielding



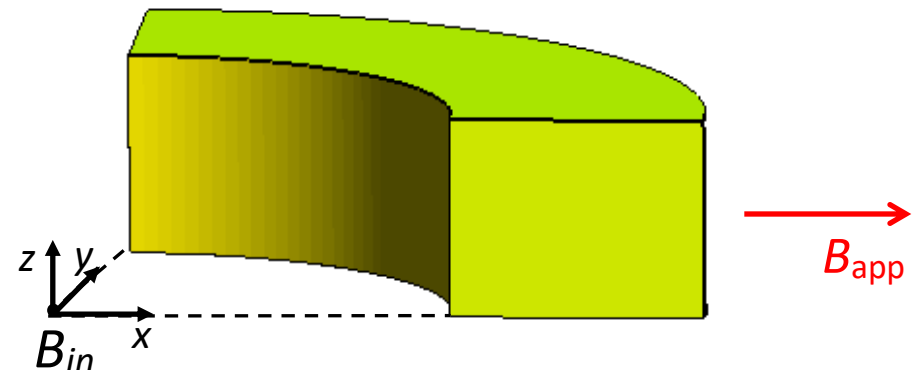
2D-axisymmetric



## Transverse shielding



3D



# Numerical modelling

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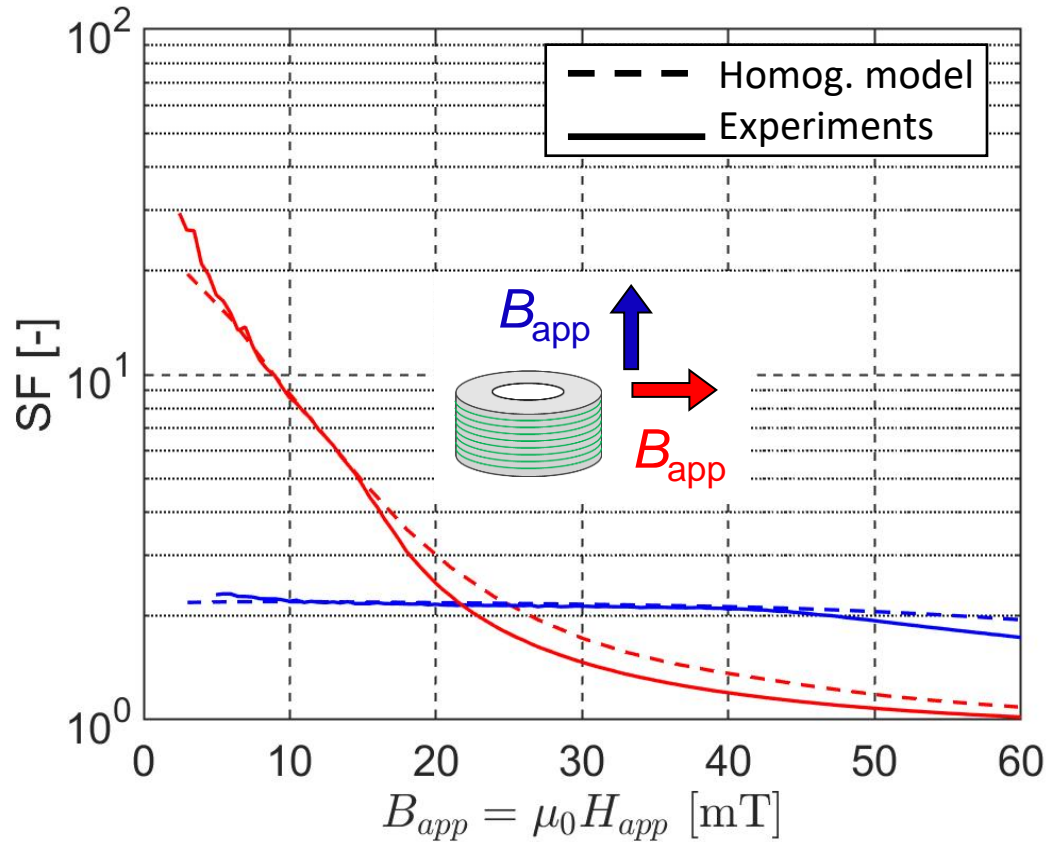
## Model parameters

- Filling factor  $f = 0.92$  : ratio  $\frac{Vol_{Ferro}}{Vol_{HTS}}$  leading to  $\mathbf{j}_s = \mathbf{j}/(1 - f)$
- Anisotropic resistivity  $\boldsymbol{\rho}(\mathbf{j}_s)$ : highest possible value for the z-component ( $\rho_z = 0.01 \Omega\text{m}$ )
- Anisotropic permeability  $\boldsymbol{\mu}(\mathbf{B})$  taking into account the experimental measurements
- Field dependence of the critical current:  $j_c(B) = 1.6 \times 10^8 \left(1 + \frac{B}{0.1}\right)^{-1}$
- Finite element solver GetDP

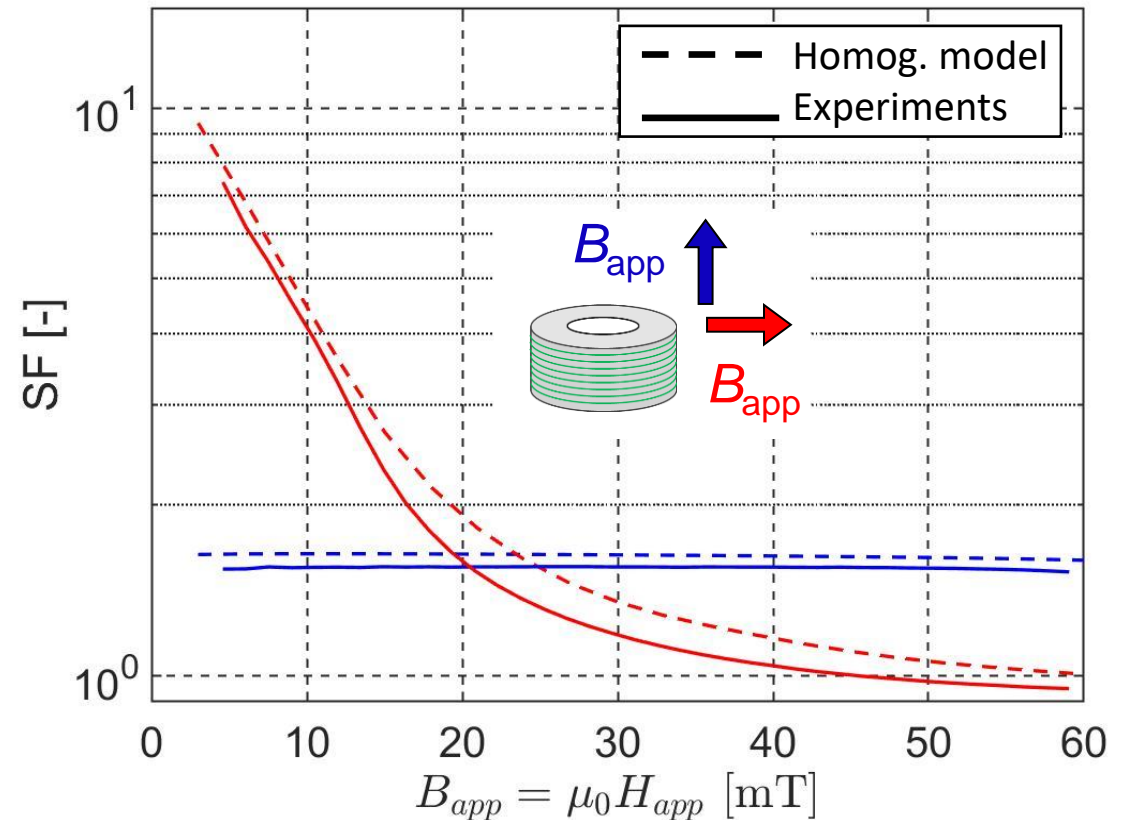
*“Life-hts: Liege university finite element models for high-temperature superconductors,” [www.life-hts.uliege](http://www.life-hts.uliege).*

# Experimental vs. numerical results at room $T$

Sample A ( $h = 24$  mm)



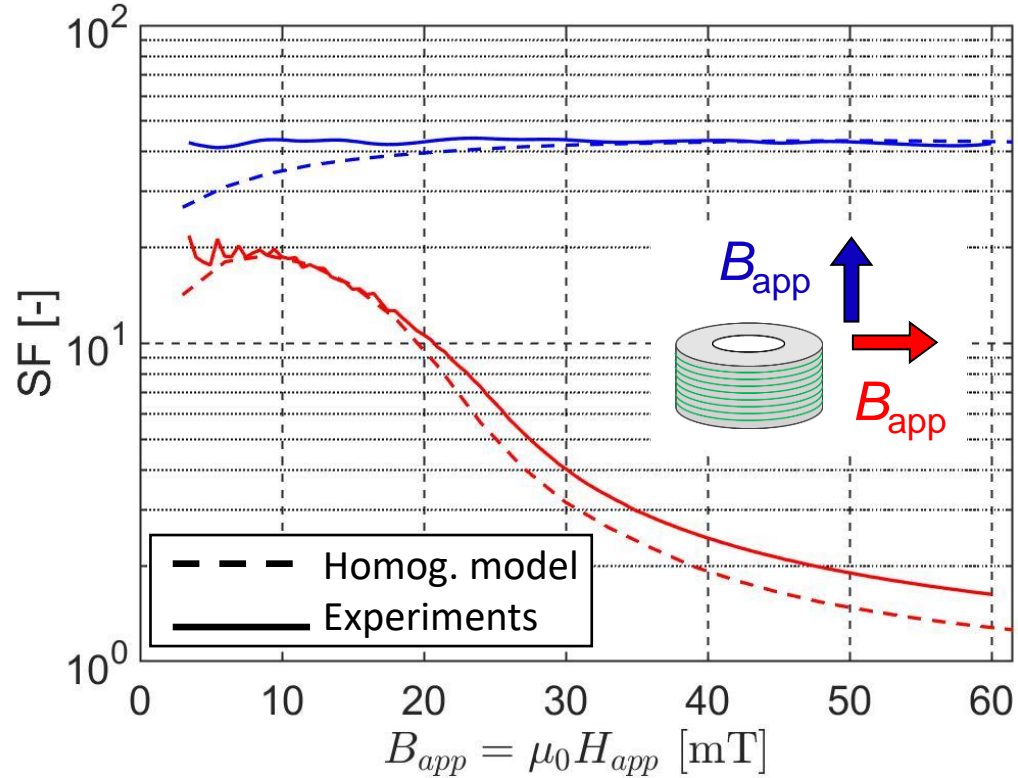
Sample B ( $h = 15$  mm)



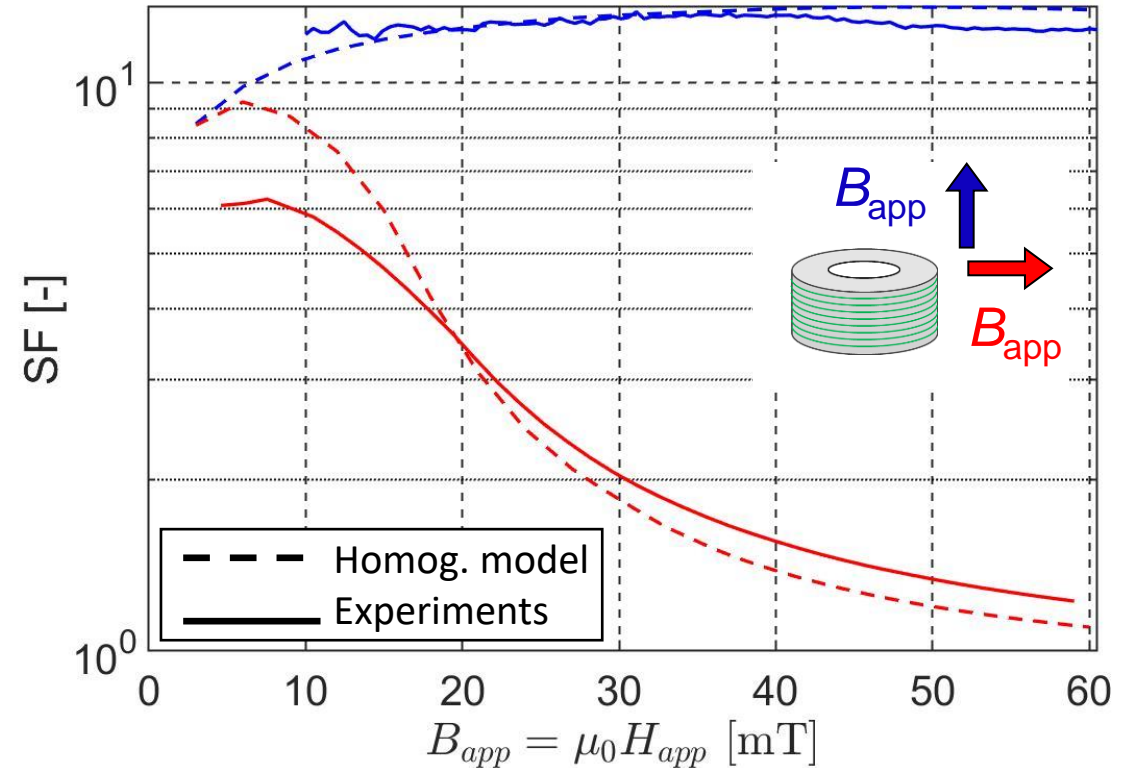
Nice agreement for both aspect ratios

# Experimental vs. numerical results at 77 K

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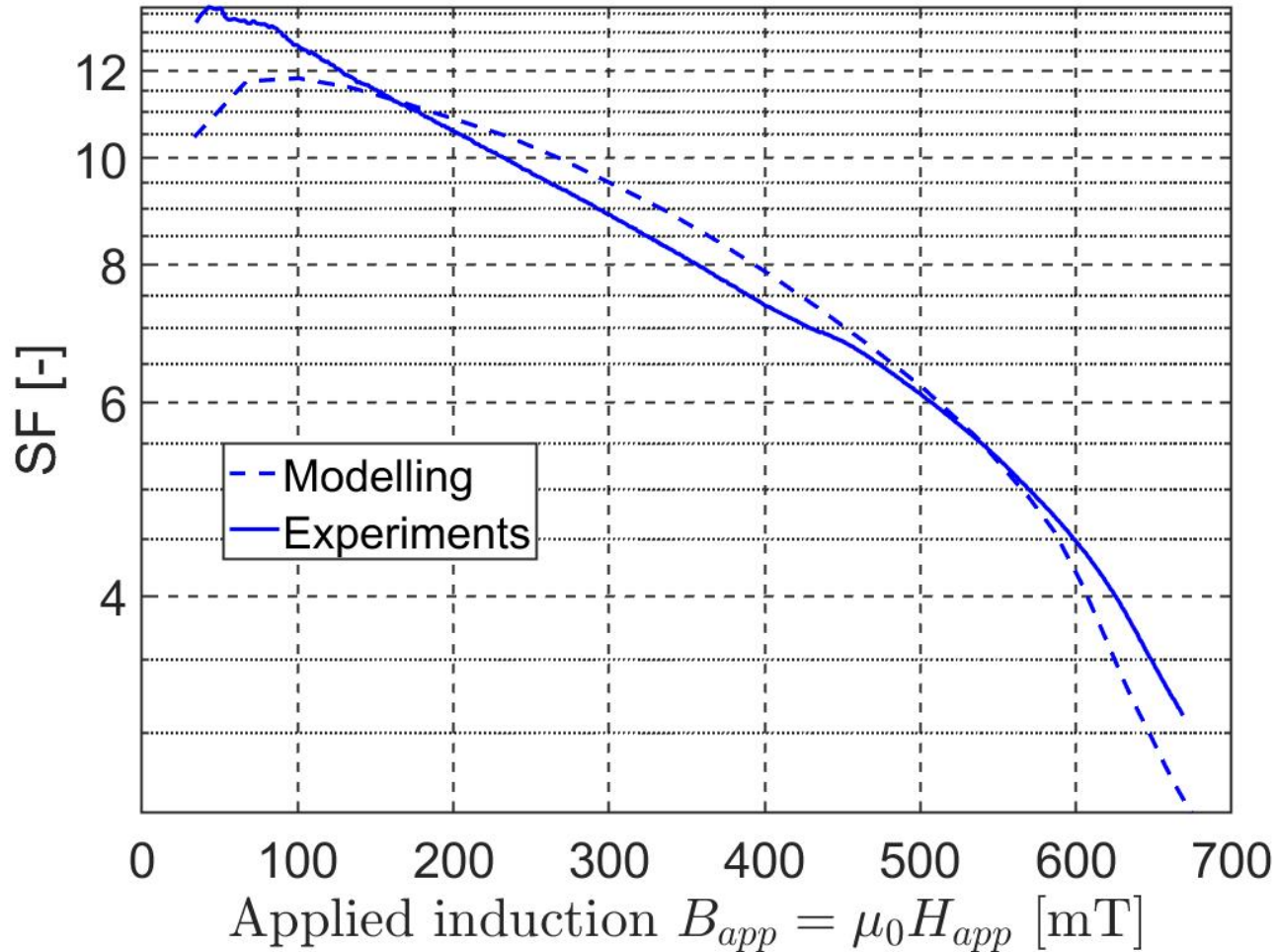


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Nice agreement for both aspect ratios

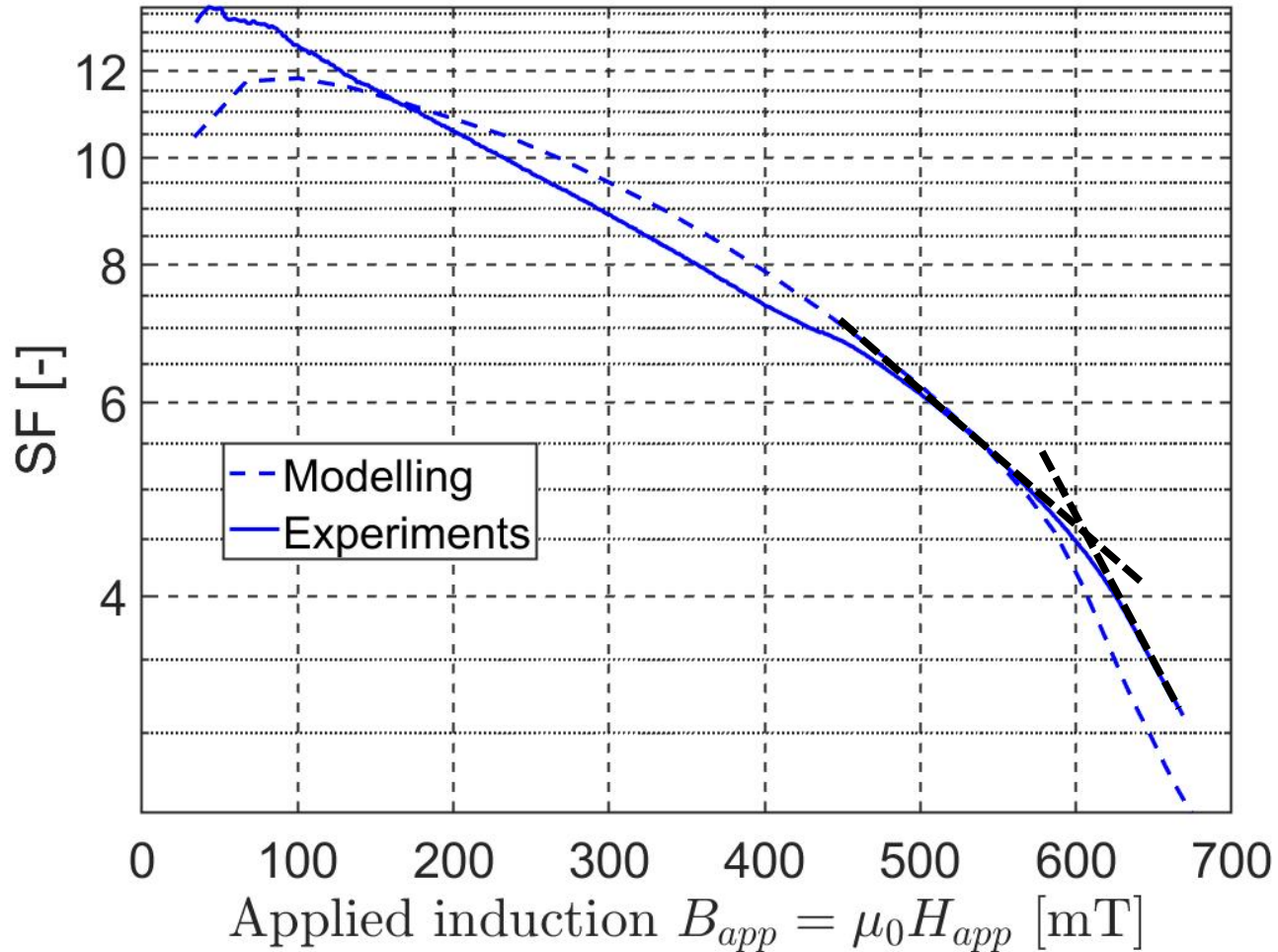
# Experimental vs. numerical results at 77 K



- Measurements up to 670 mT
- Axial shielding for sample **B**

• Still good agreement with modelling

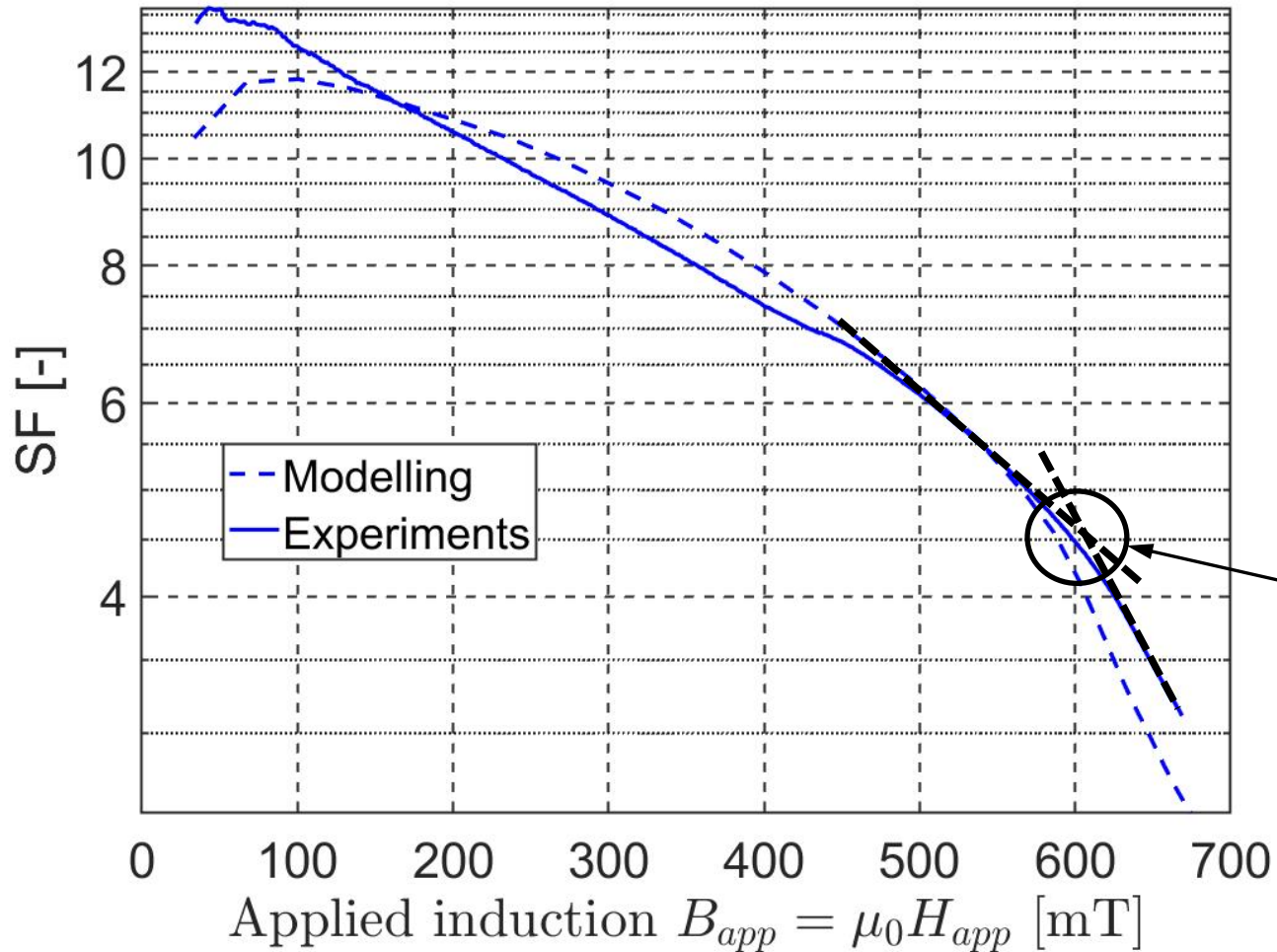
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Sample fully penetrated



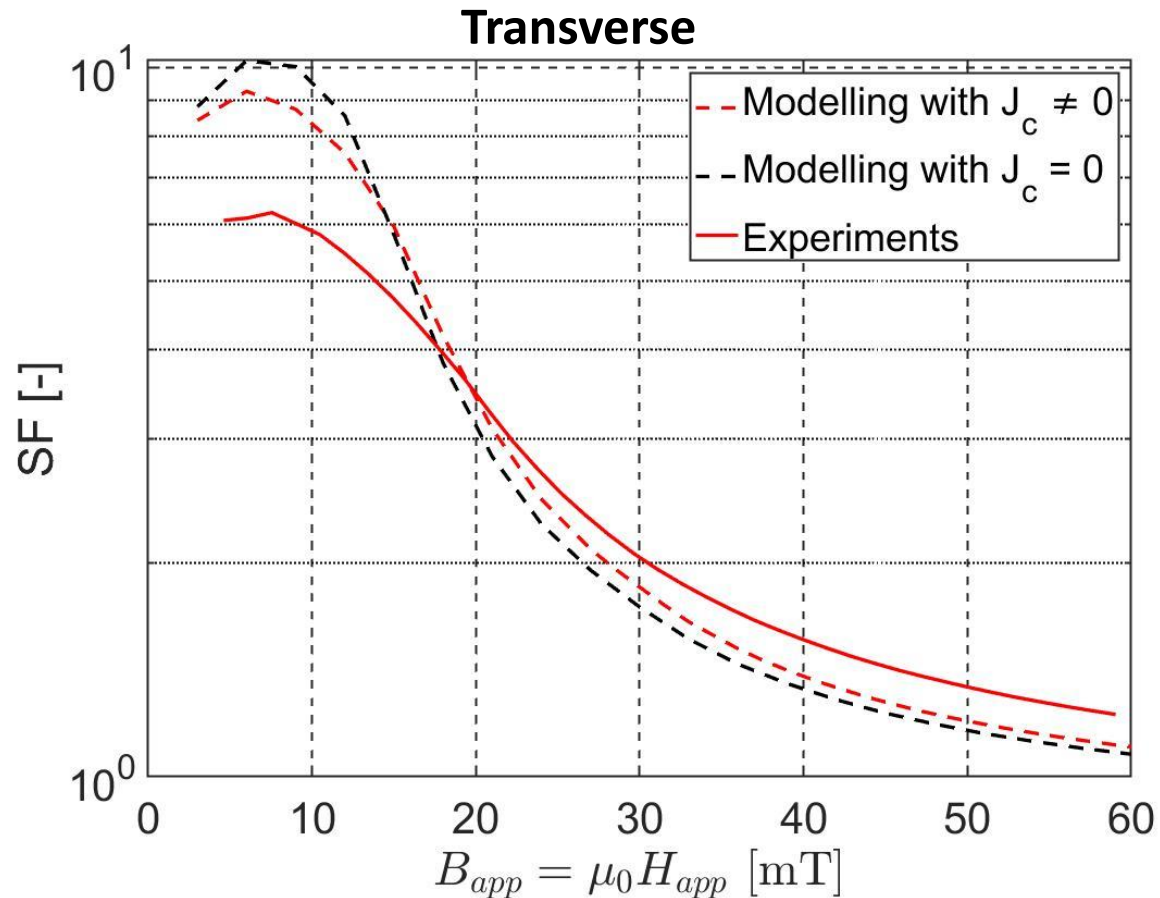
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- Influence of HTS in transverse shielding (what if  $J_c = 0$  ?)

# Experimental vs. numerical results at 77 K

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- Low influence of HTS on the transverse  $SF$
- Due to the aspect ratio of the HTS layer in tapes

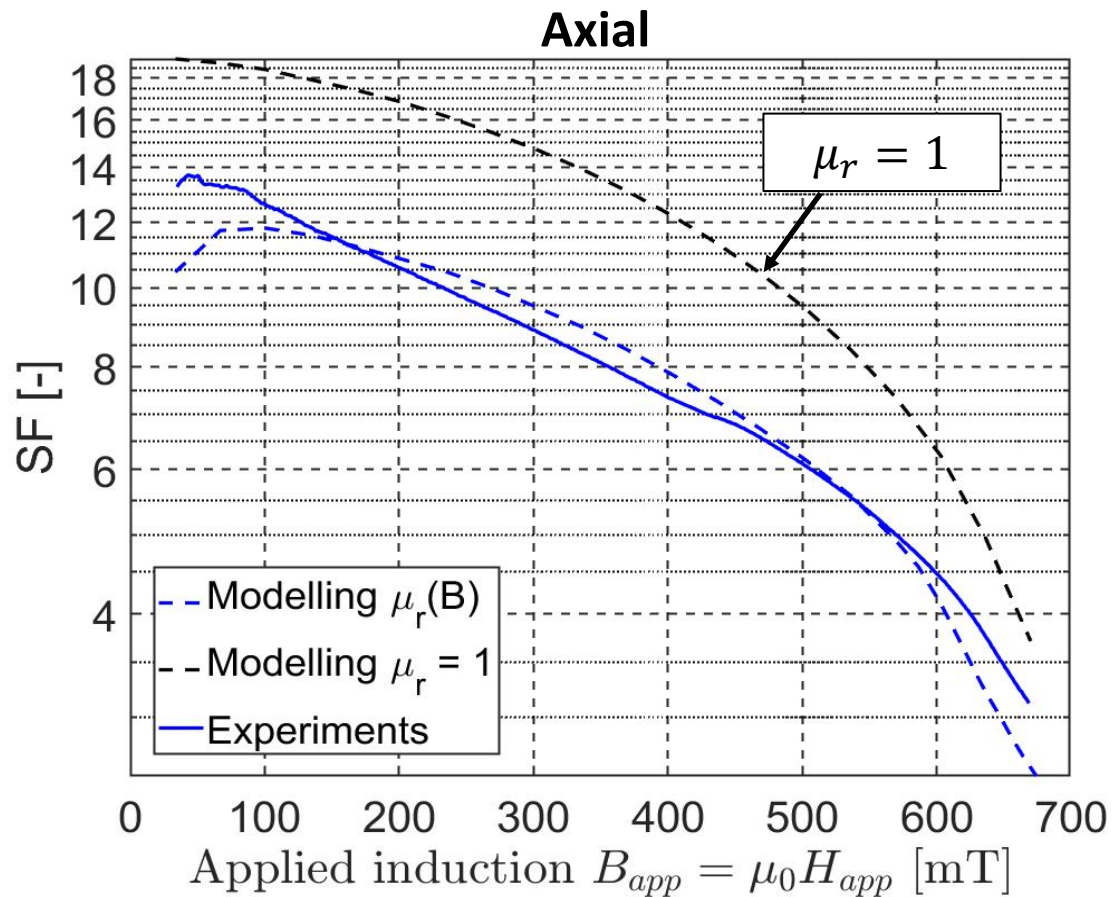
# *Experimental vs. numerical results at 77 K*

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- Influence of ferromagnetic material (FM) in axial shielding (what if  $\mu_r = 1$  ?)

# Experimental vs. numerical results at 77 K

- Influence of ferromagnetic material (FM) in axial shielding (what if  $\mu_r = 1$  ?)



- Presence of FM results in a decreased  $SF$
- Attraction of field lines by FM  
→ **increased field penetration**

# Conclusions

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- Measured magnetic properties on Ni5W substrate can be inserted in numerical models
- A finite  $SF$  is found at room  $T$  in both axial and transverse configurations
- Magnetic shielding survives up to quasi-static field  $\sim 600 \text{ mT}$
- Numerical simulations are found to be in good agreement for samples with different aspect ratios at both 77 K and room  $T$

➡ Models could simulate various geometries

- Ferromagnetic layer in the scope of magnetic shielding with annuli ?
  - ✗ Decreases the  $SF$  in axial shielding
  - ✓ Possibility to shield at  $T > T_c$
  - ✓ Possibility to shield transverse fields (e.g. non-uniform stray field)