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Modeling and Measurement of the Levitation Force in Superconducting Magnetic Bearings with Thinned HTS Tape Stacks

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2025 EUCAS

21 to 25 September

Motivation

Dimensions	2.5 x 1.2 m
Passengers	2
Drive power	3.4 kW
Levitation force	6000 N
Max. speed	20 km/h

SupraTrans: Example of superconducting maglev technology at KIT

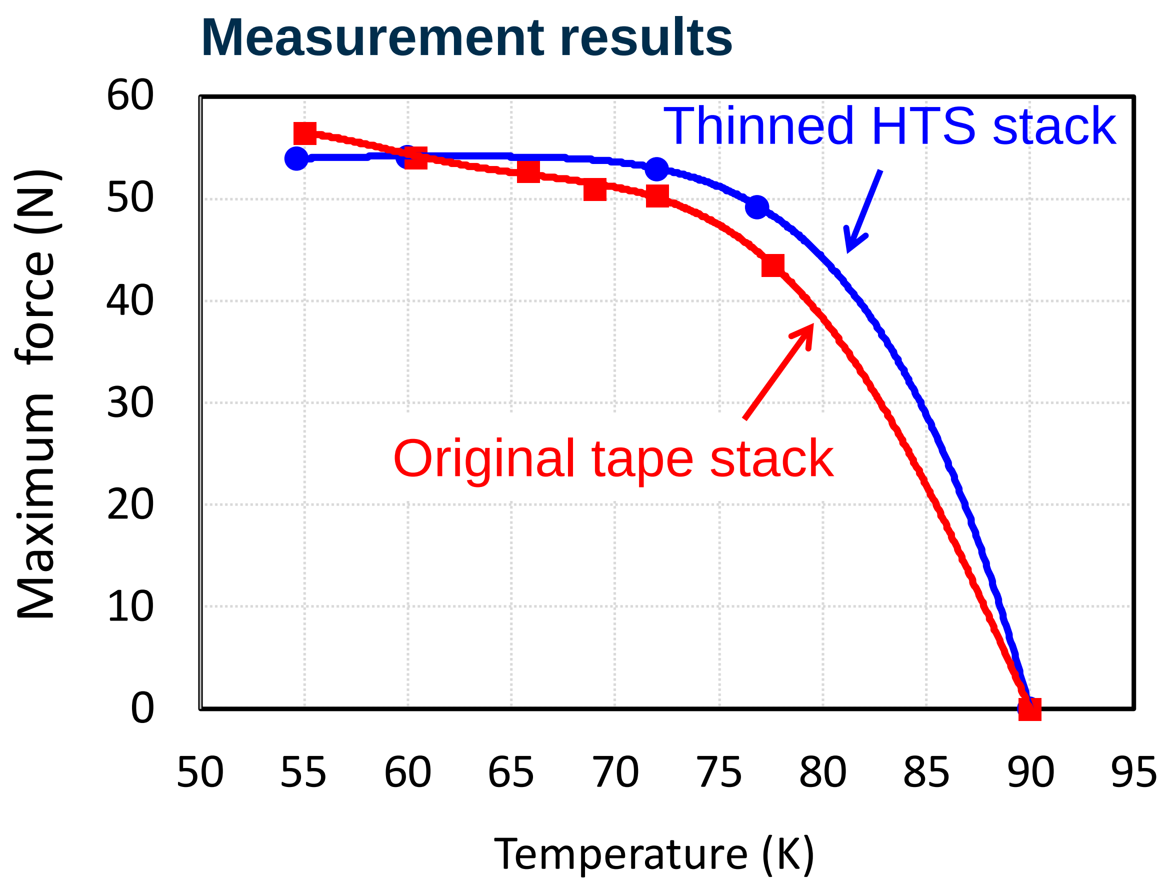
Karlsruhe Institute of Technology (KIT)

Leibniz Institute for Solid State and Materials Research (IFW)

Advantage of high levitation force in Maglev trains

- Can carry **heavier loads / more passengers**
- Allows a **larger gap** between train and track → safer & smoother
- Provides **more stability** at high speeds → less vibration
- Reduces **cooling demand** per unit of lift

Thinning HTS tape leads to higher levitation force



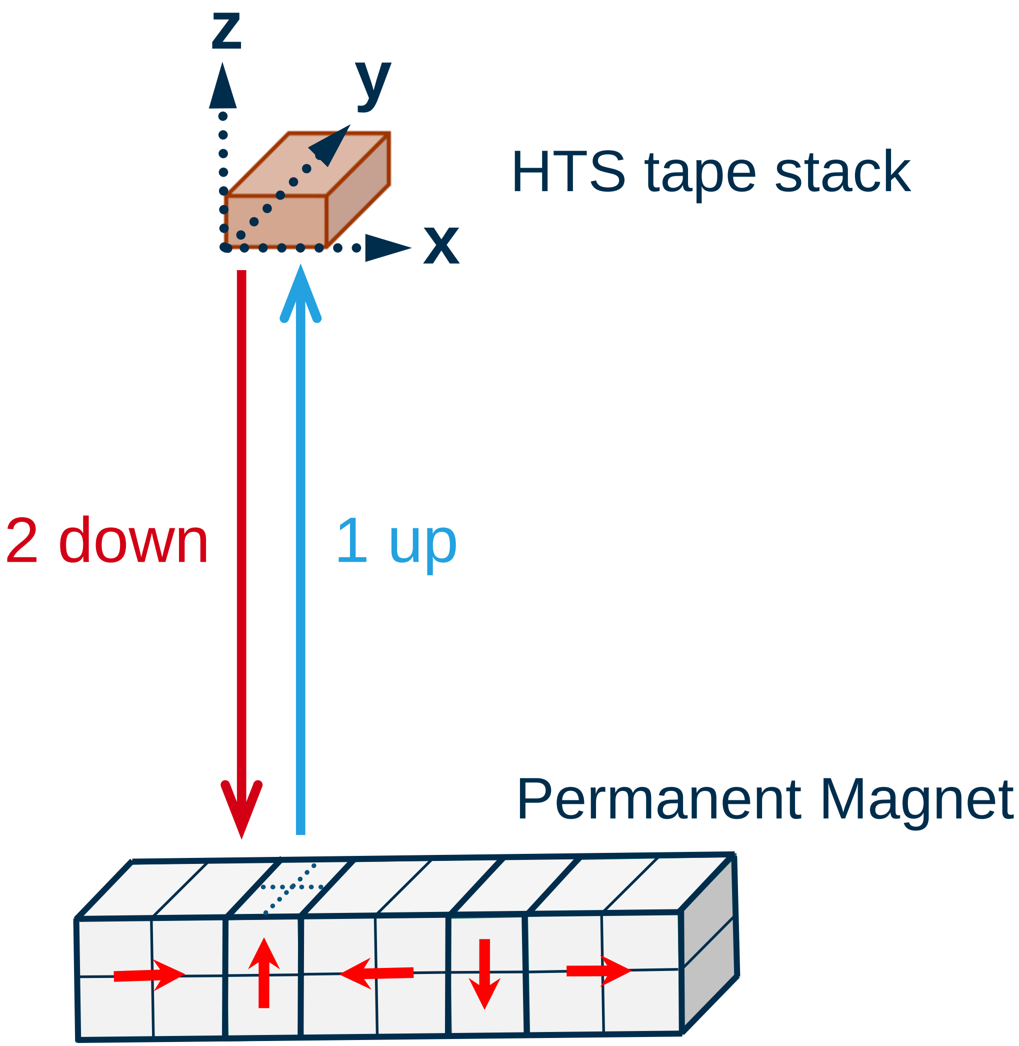
Content

1. Measurement
   - I_c (B, θ) of tape
   - Electropolishing
   - Setup
   - Levitation force
2. Modeling
   - Models introduction
   - 3D model vs experiment
   - 2D model vs experiment
   - 3D model vs 2D model
3. Summary

Lorentz force generation during zero-field cooling

$$\mathbf{F} = \int_{\Omega} \mathbf{J} \times \mathbf{B} \, d\Omega$$

Lorentz force between field of PM and magnetization current in tape stack



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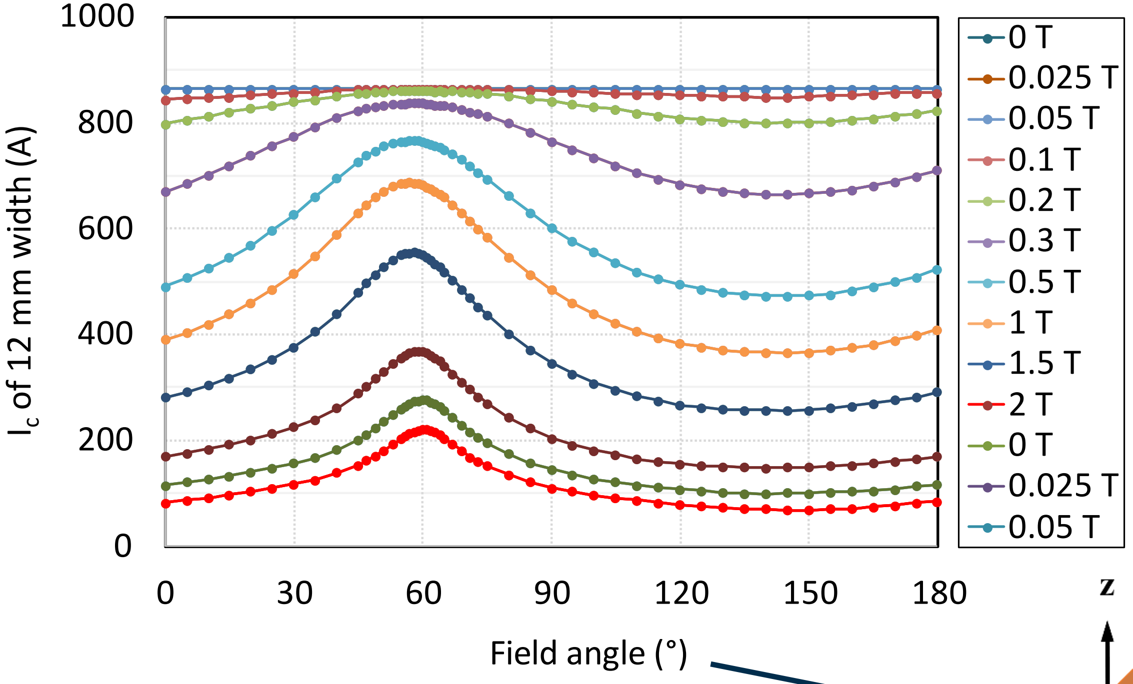
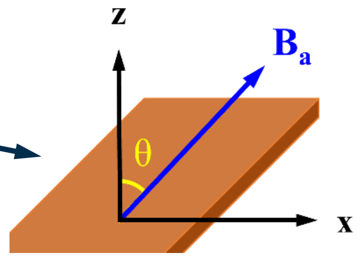
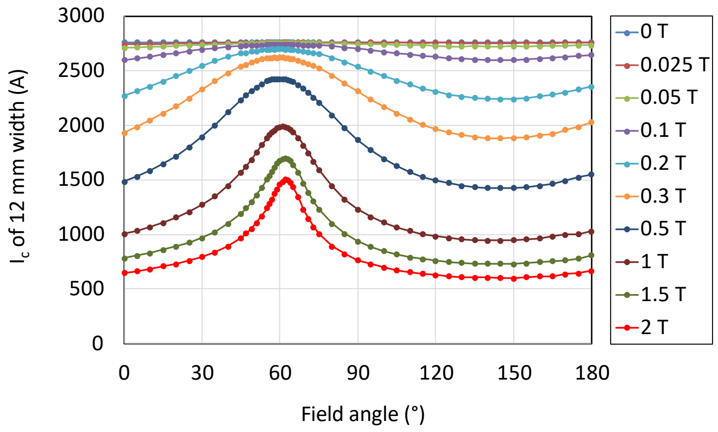
I_c (B,θ) measurement of THEVA tape

77 K $I_{c,self\text{-}field}$ = 864 A

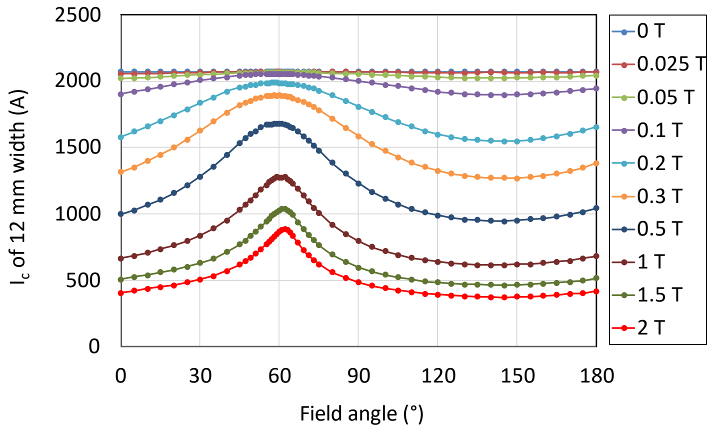




50 K $I_{c,self\text{-}field}$ = 2760 A



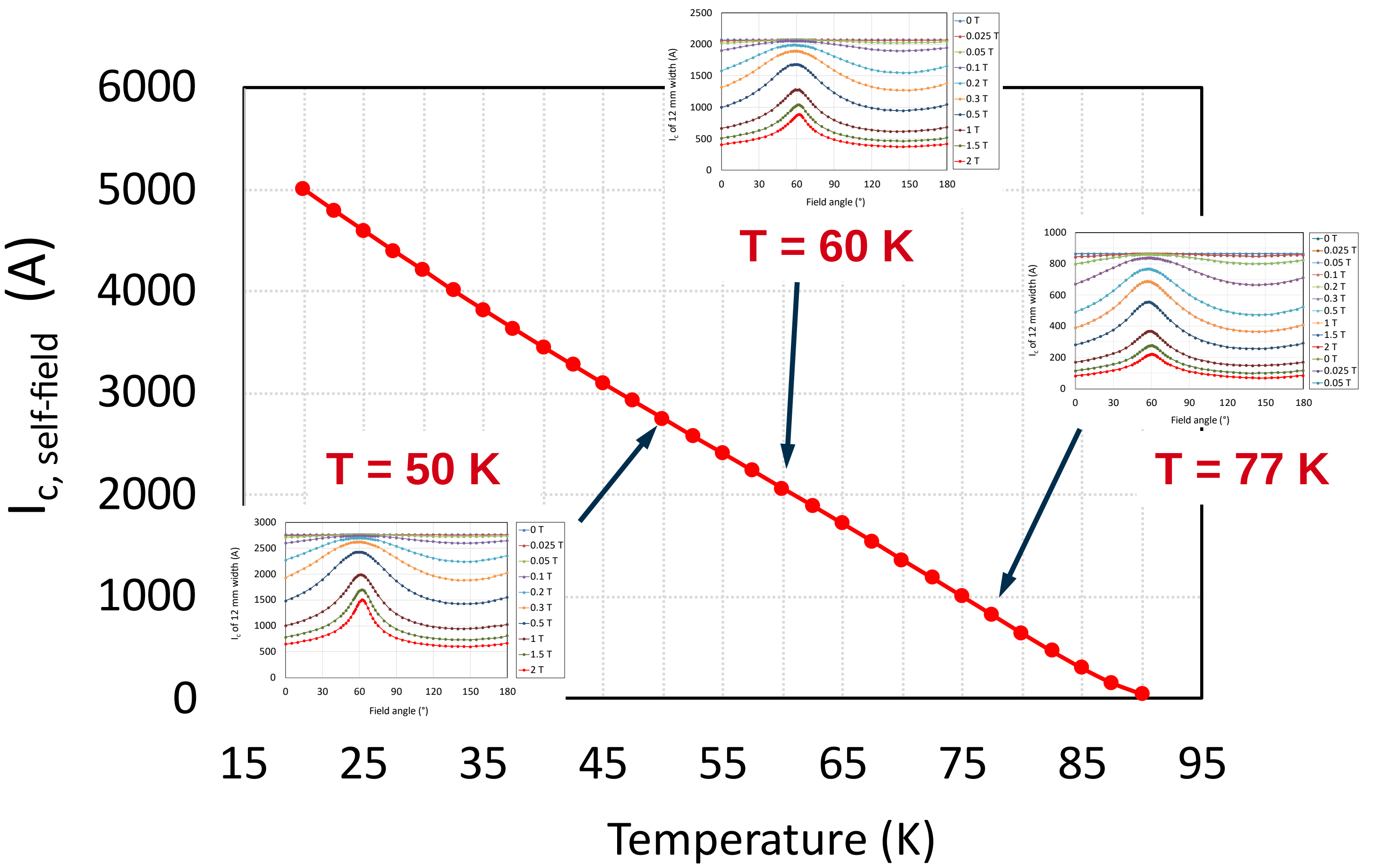
60 K $I_{c,self\text{-}field}$ = 2072 A



Paihau—Robinson Research Institute
VICTORIA UNIVERSITY OF WELLINGTON TE HERENGA WAKA

Data was measured by SuperCurrent facility at Robinson Research Institute in New Zealand

Obtaining I_c (B,θ) at any temperature using linear interpolation



I_c changes linearly with temperature

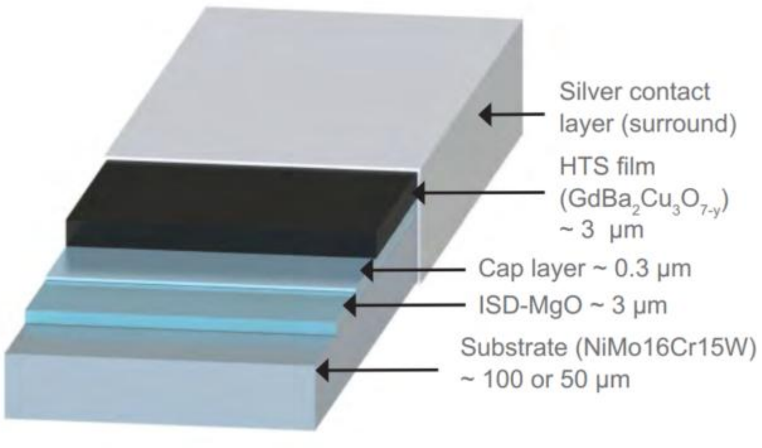
$$J_c = \left[\frac{J_{c2} - J_{c1}}{T_2 - T_1} (T - T_1) \right] + J_{c1}$$

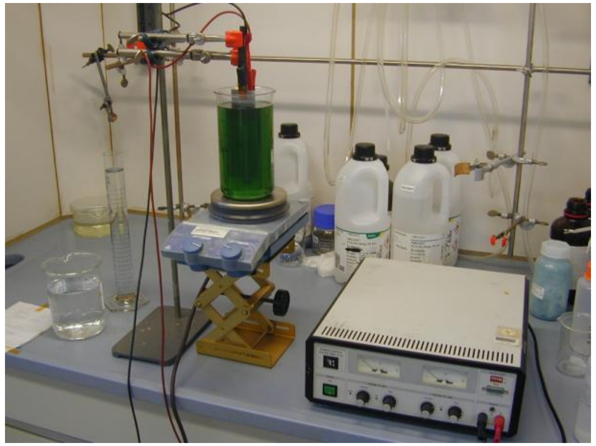
Electropolishing process of THEVA tapes

1. Frontside was covered with Kapton foil
2. Silver was etched away and dissolved
3. Hastelloy layer was electropolished

20% thickness reduction: 61 µm ⇨ 49 µm

Original tape

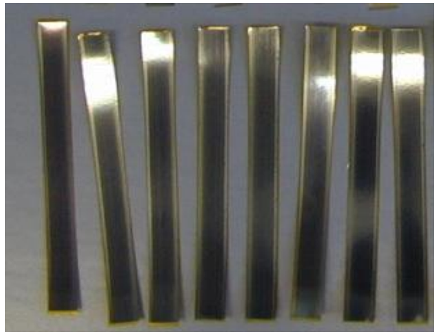




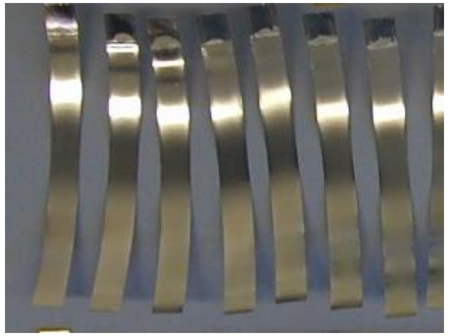
Electropolishing
in a bath of
55% Phosphoric acid
35% Sulfuric acid
10% Citric acid

1

2

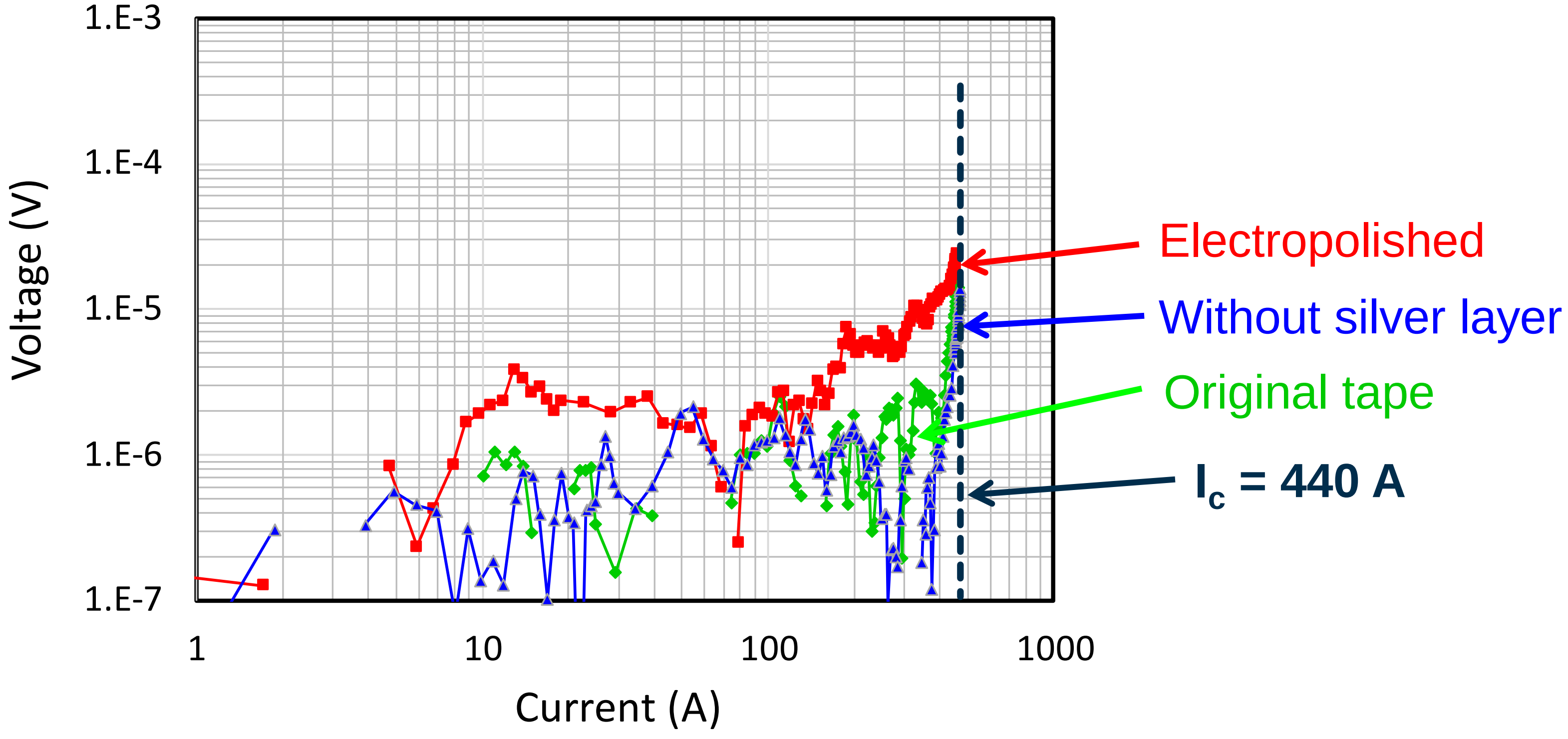


3



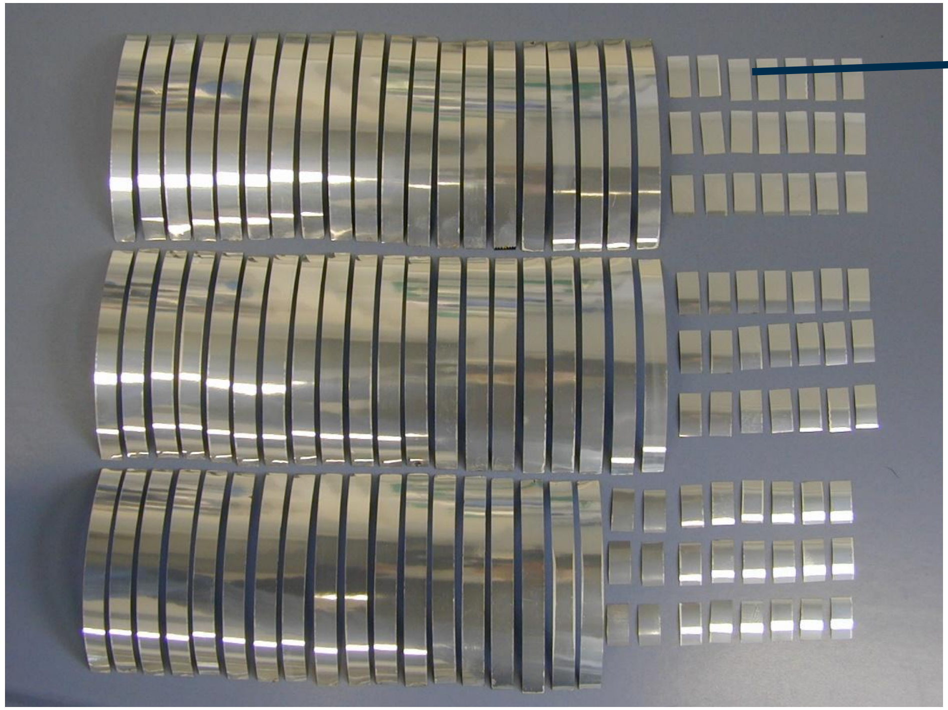
Electropolishing has no influence on I_c of SuperPower tapes

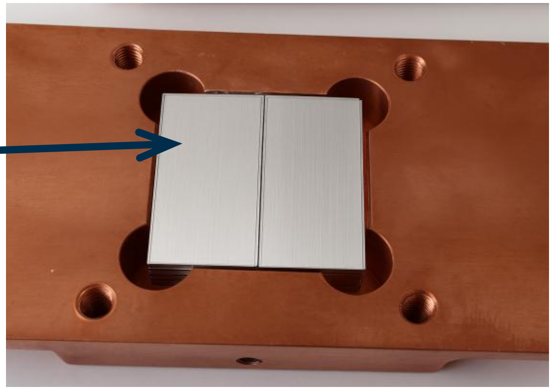
- Negligible influence on superconducting properties and critical current
- All samples have critical current of 440 A

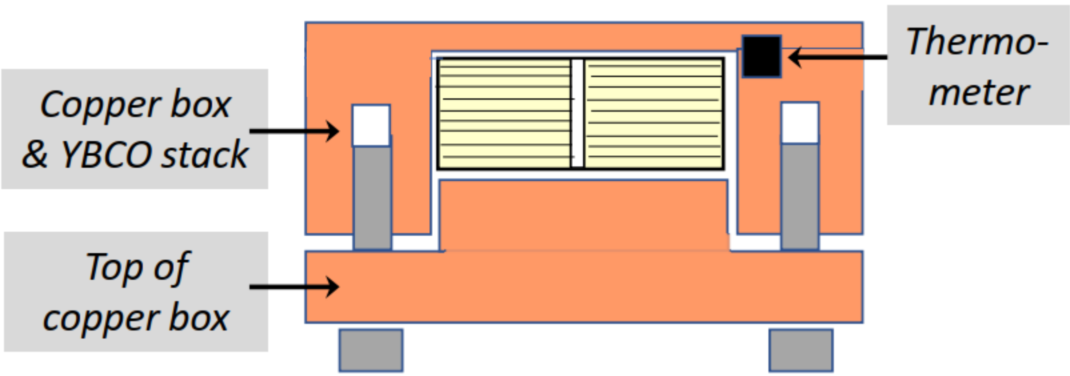


HTS tape stack made of 205 electropolished THEVA tapes

THEVA TPL 1120

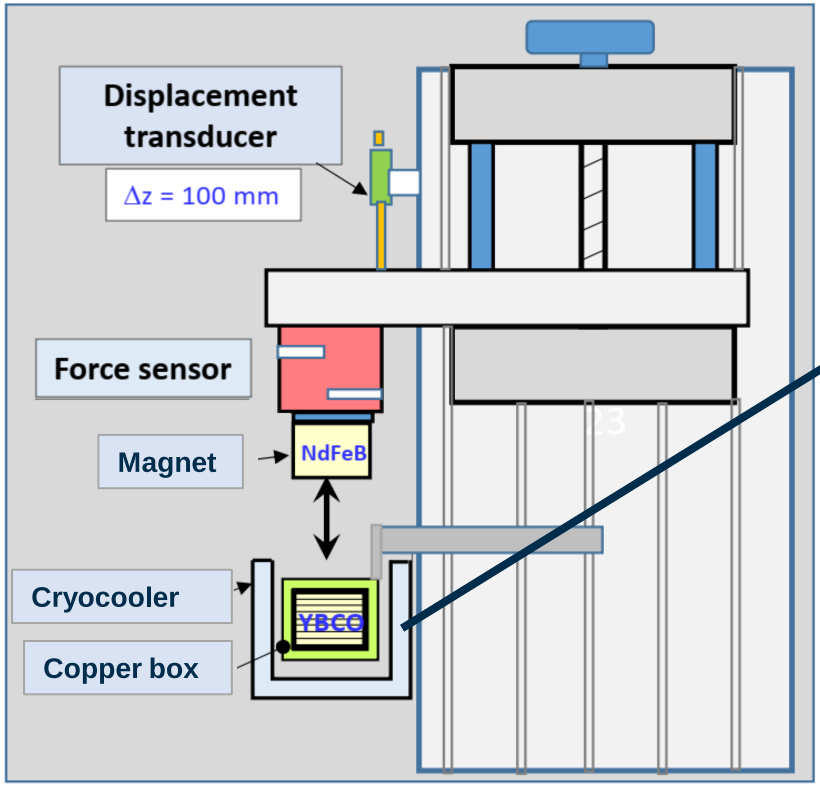


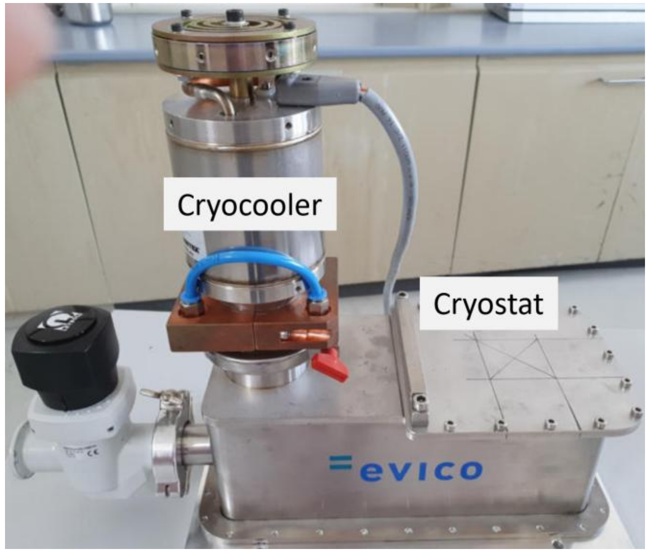


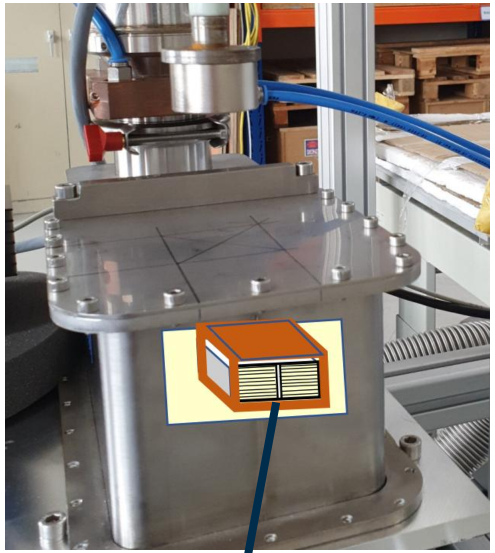


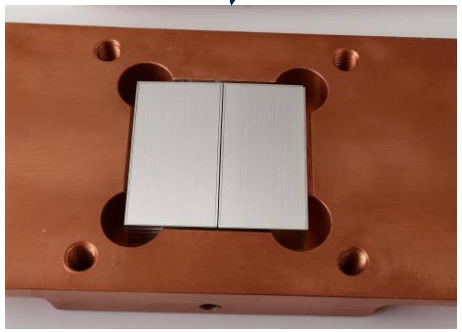
Measurement setup

Cryocooler



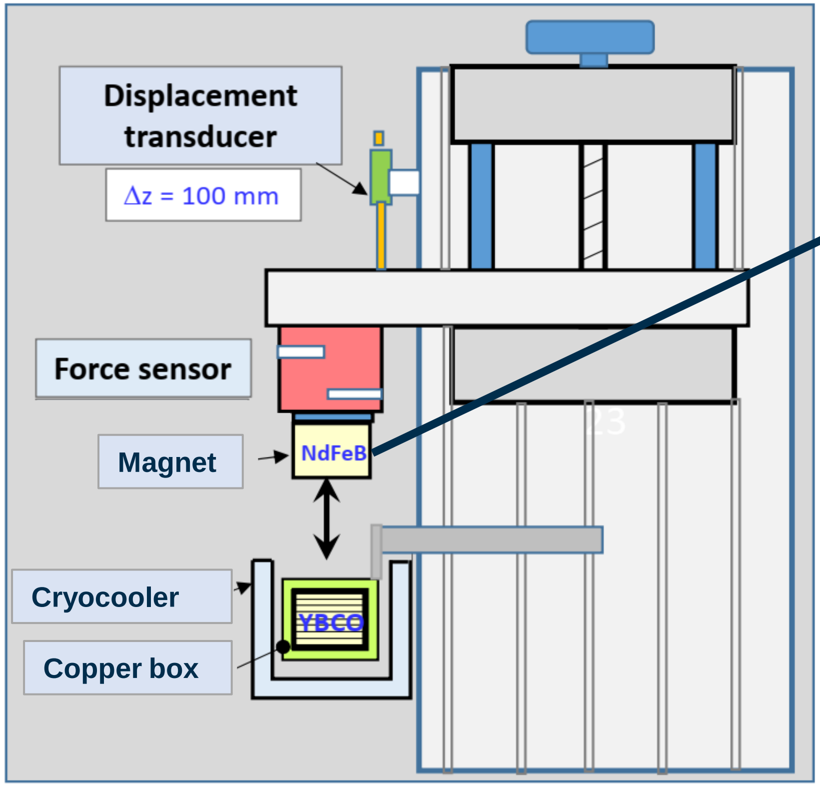




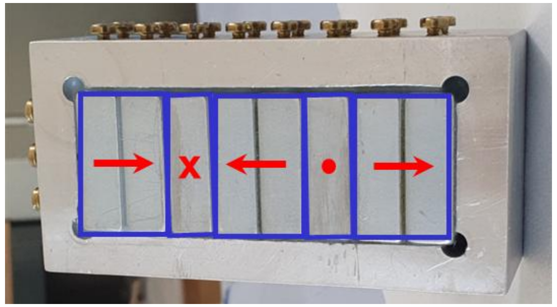


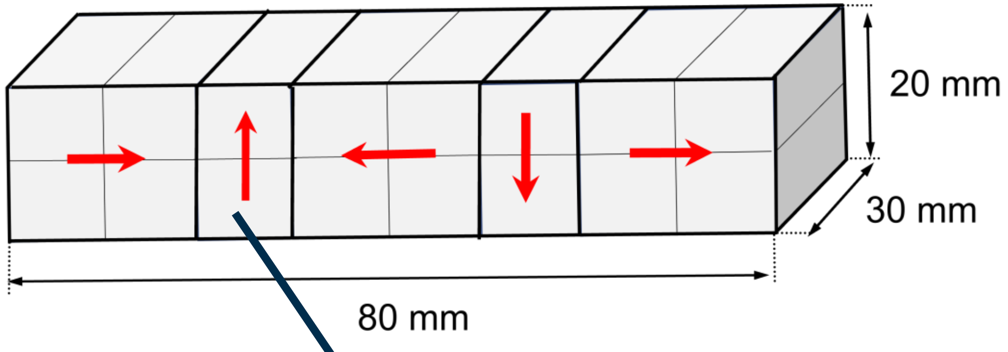
Copper box with HTS tape stack

Measurement setup



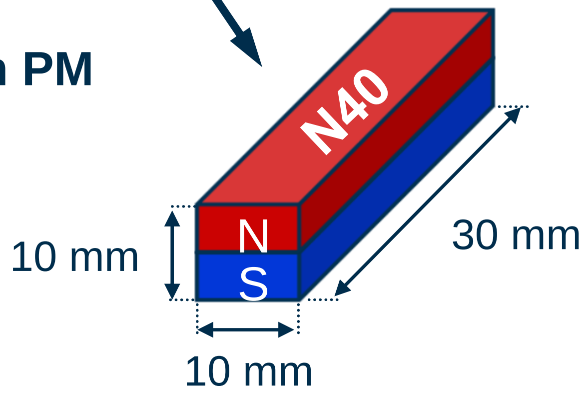
Halbach PM





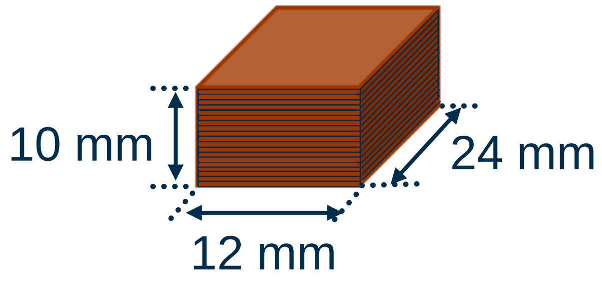
Neodymium PM

$B_r = 1.26$ T



Zero-field cooling measurement schematic and parameters

HTS tape stack

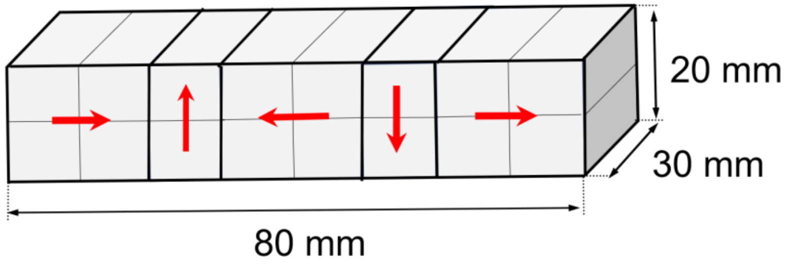


No. of electropolished tapes = 205

$I_{c,\ self\text{-}field}$ (54.7 K) = 2440 A

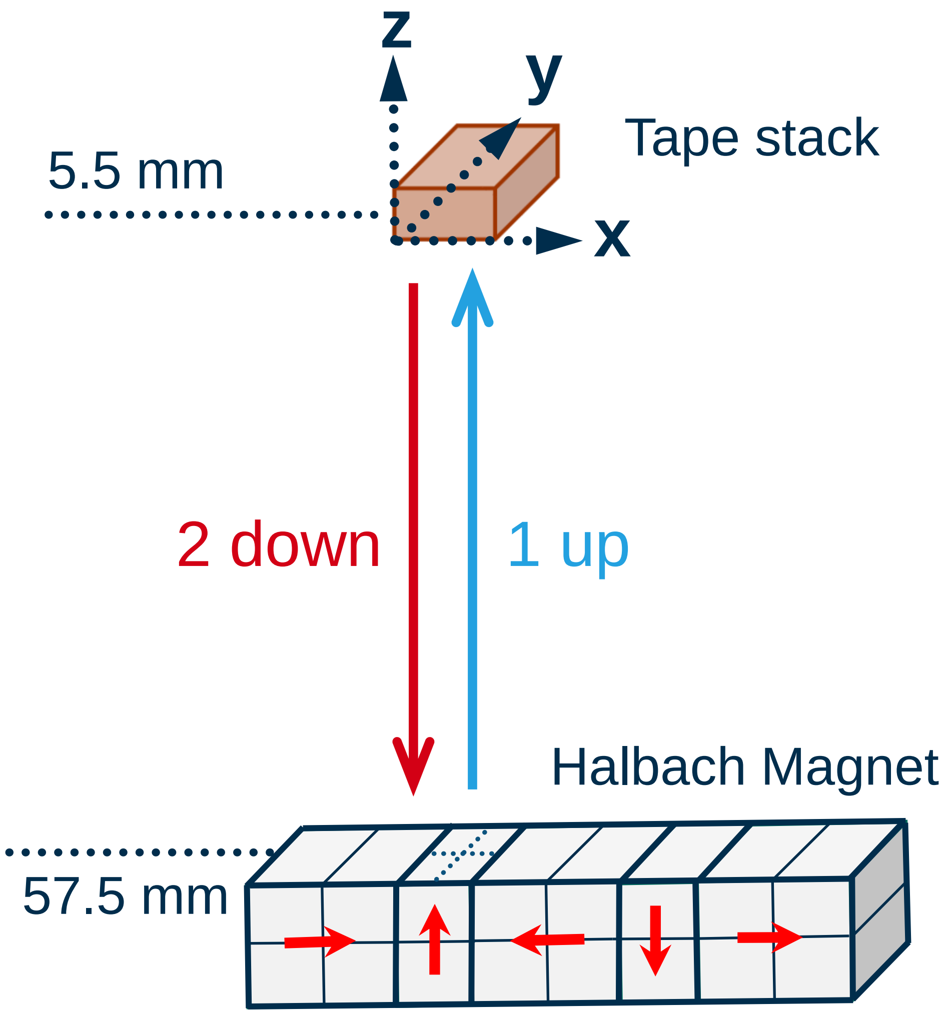
n-value = 35

Halbach magnet

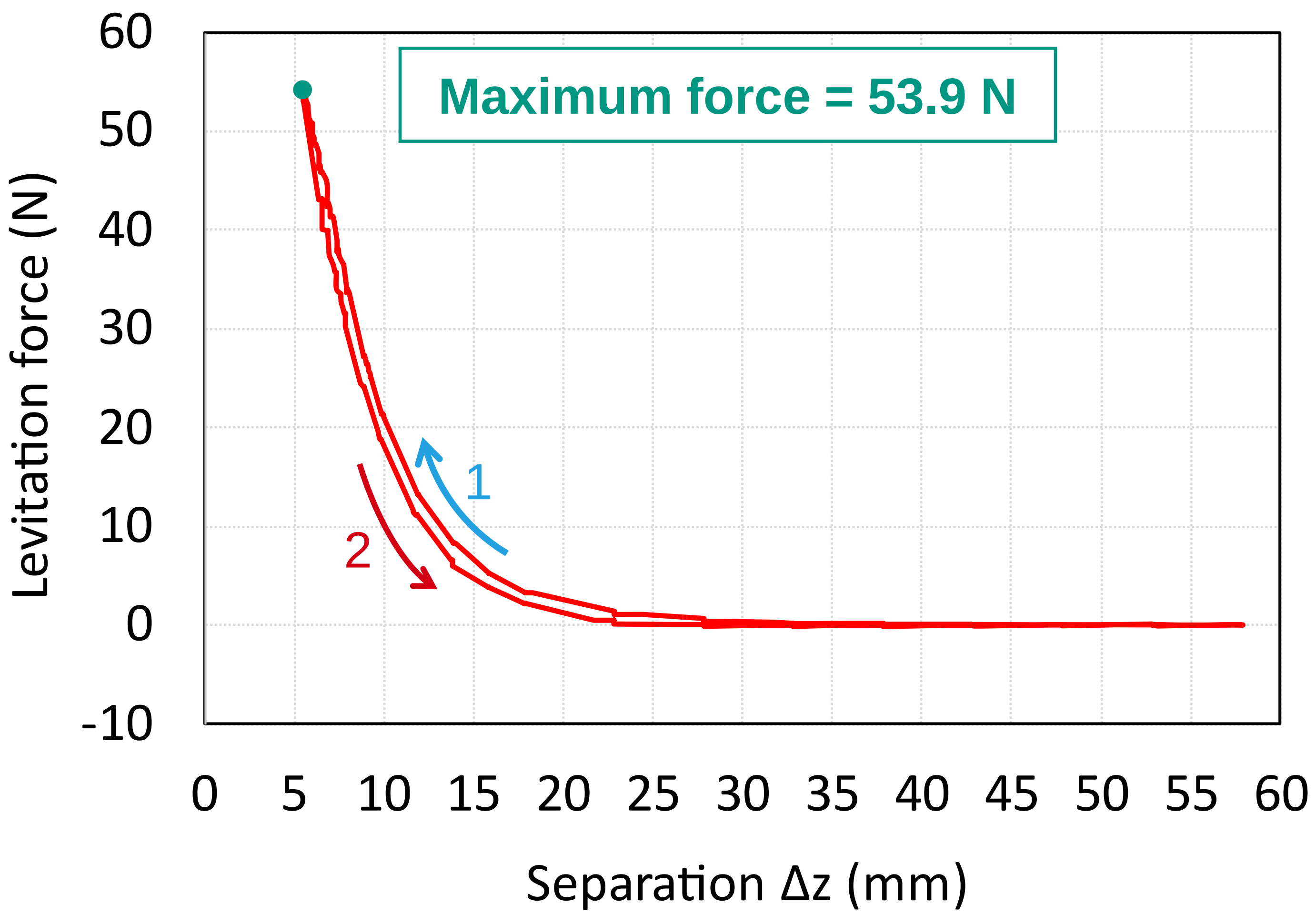


Remanence B_r = 1.26 T

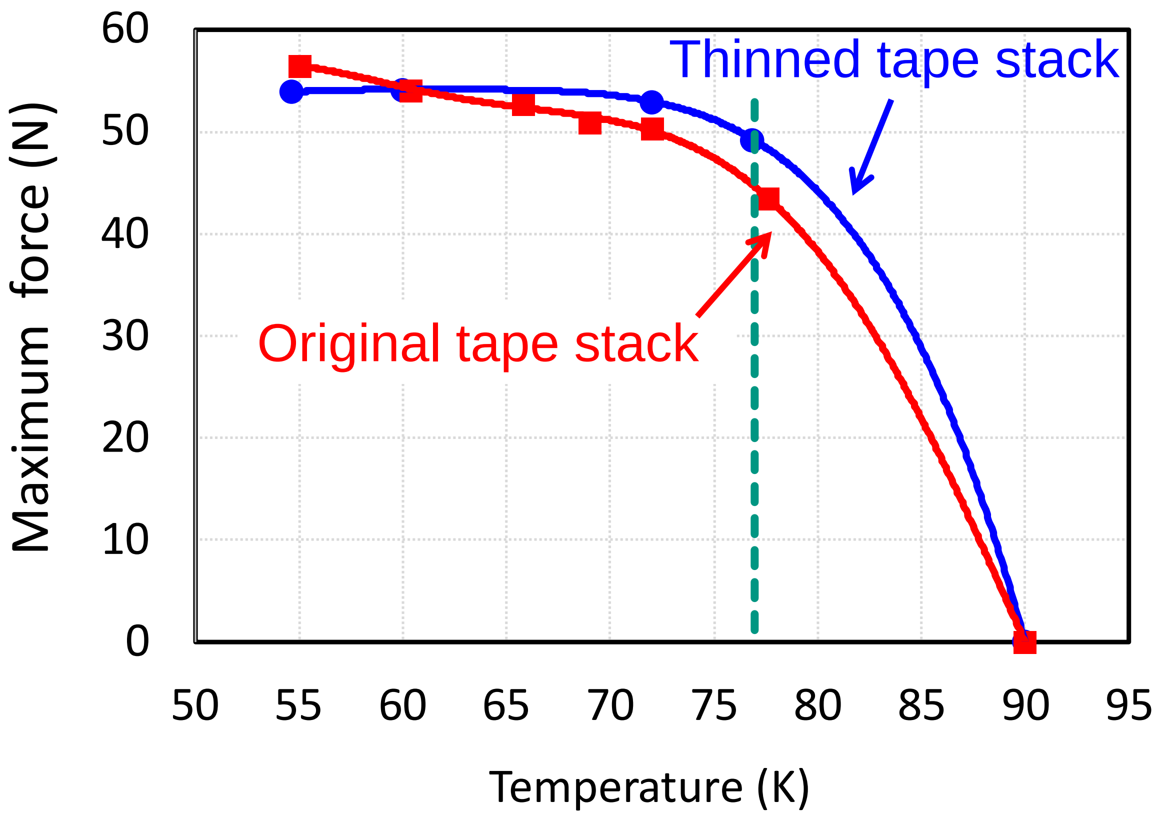
Movement speed ≈ 10 mm/s



Measurement result of levitation force at 54.7 K



Maximum levitation force vs temperature: Original vs electropolished THEVA tape stack



At 77 K

Maximum levitation force

$$\frac{\text{Thinned}}{\text{Original}} = 1.14$$

Engineering J_c

$$\frac{\text{Thinned}}{\text{Original}} = 1.24$$

Levitation force increases with critical current density

$J_{c,\,tape}$

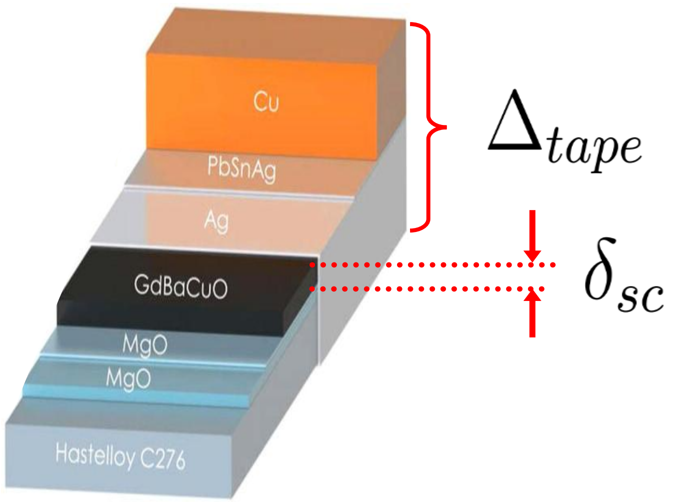
More advanced tape with higher critical current density

We can achieve this by electropolishing the HTS tape

$$J_{c,\,eng} = \frac{\delta_{sc}}{\Delta_{tape}} J_{c,\,tape}$$

δ_{sc} → Superconductor layer thickness

Δ_{tape} → Total tape thickness



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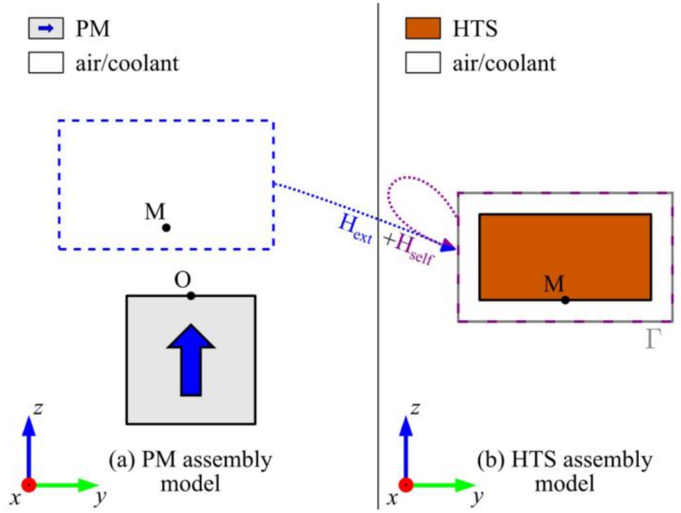
Introduction to Two-Dimensional models

Segregated H-formulation method



Proxima Fusion

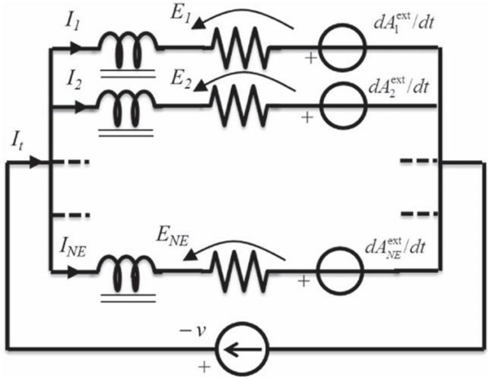
KIT Karlsruher Institut für Technologie

Magnetostatic PM model +
Time-dependent H-formulation HTS tape model

Unidirectional coupling between PM and HTS model

Quéval et al, Supercond. Sci. Technol. 31, 2018

A - φ formulation method



$$\boldsymbol{E} = -\frac{\partial \boldsymbol{A}^J}{\partial t} - \frac{\partial \boldsymbol{A}^{ext}}{\partial t} - \nabla\varphi$$

The problem is formulated using the A−ϕ potential decomposition.
The current density is discretized using nodal shape functions.

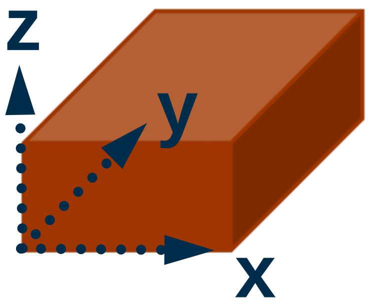
Introduction to Three-Dimensional models

MEMEP 3D

Variational method based on $\mathbf{T}$-formulation

$$L = \int_V dv[\frac{1}{2}\frac{\Delta \mathbf{A}_J}{\Delta t} \cdot (\nabla \times \Delta \mathbf{T}) + \frac{\Delta \mathbf{A}_M}{\Delta t} \cdot (\nabla \times \Delta \mathbf{T}) + U(\nabla \times \mathbf{T})]$$

Minimum of this equation in each time step is the unique solution of Maxwell differential equation



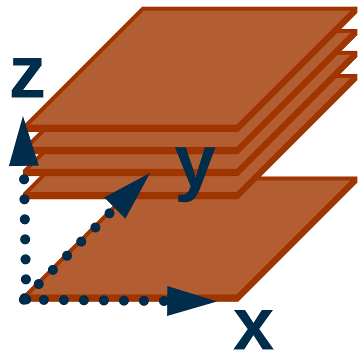
E. Pardo et al, J. Comput. Phys., 2017

M. Kapolka et al, Supercond. Sci. Technol., 2019

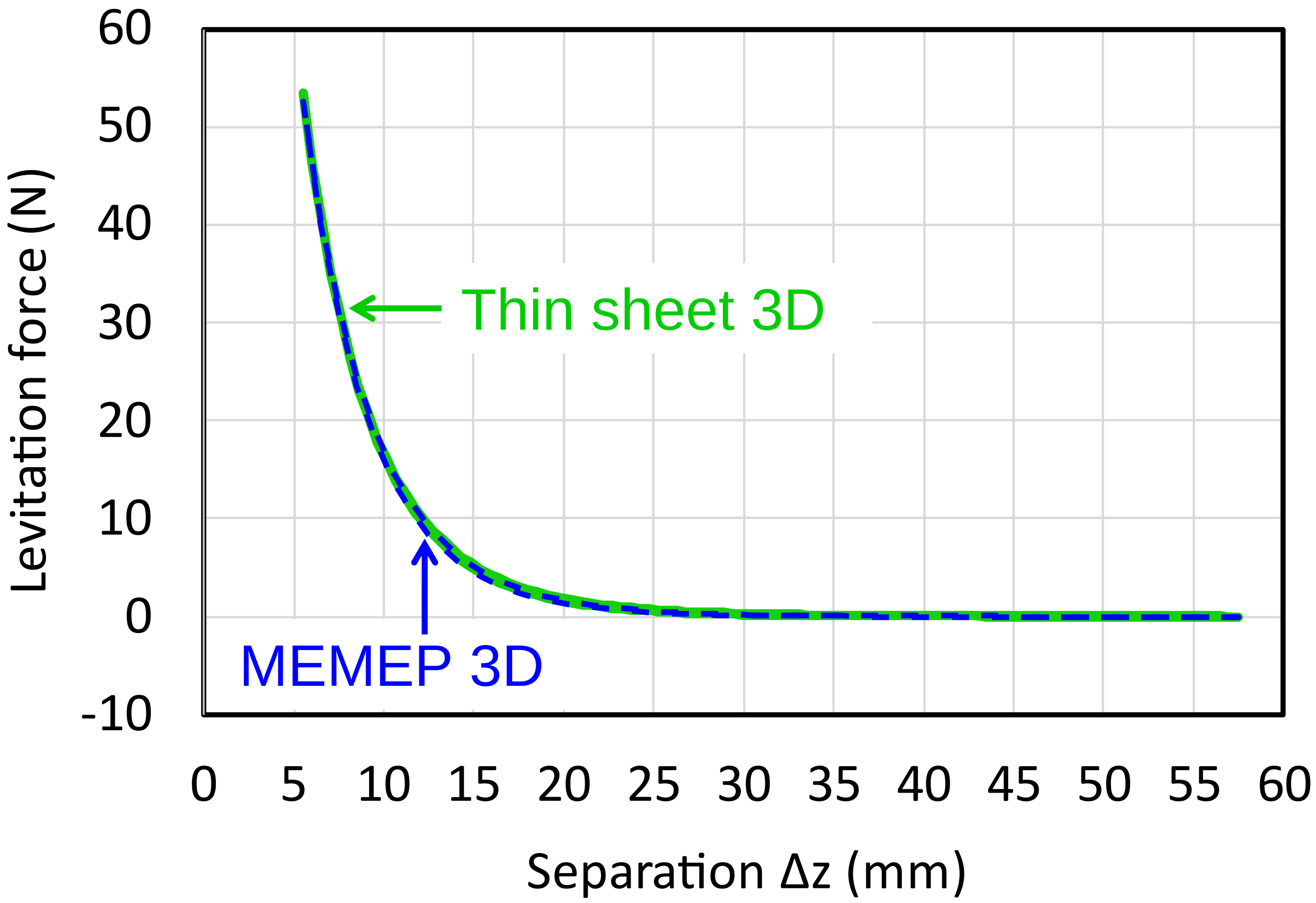
THIN SHEET 3D

Volume Integral Equation method based on current vector potential $\mathbf{T}$

$$\int_{\tau_c} W \cdot \left(\rho \boldsymbol{J} + \frac{\mu_0}{4\pi}\frac{\partial}{\partial t}\int_{\tau_c}\frac{\boldsymbol{J}(\boldsymbol{r}')}{\boldsymbol{r}-\boldsymbol{r}'}d^3\boldsymbol{r}' + \frac{\partial \boldsymbol{A}^{ext}}{\partial t} + \nabla\varphi \right) dV = 0$$



Comparison of levitation force at 54.7 K : 3D models



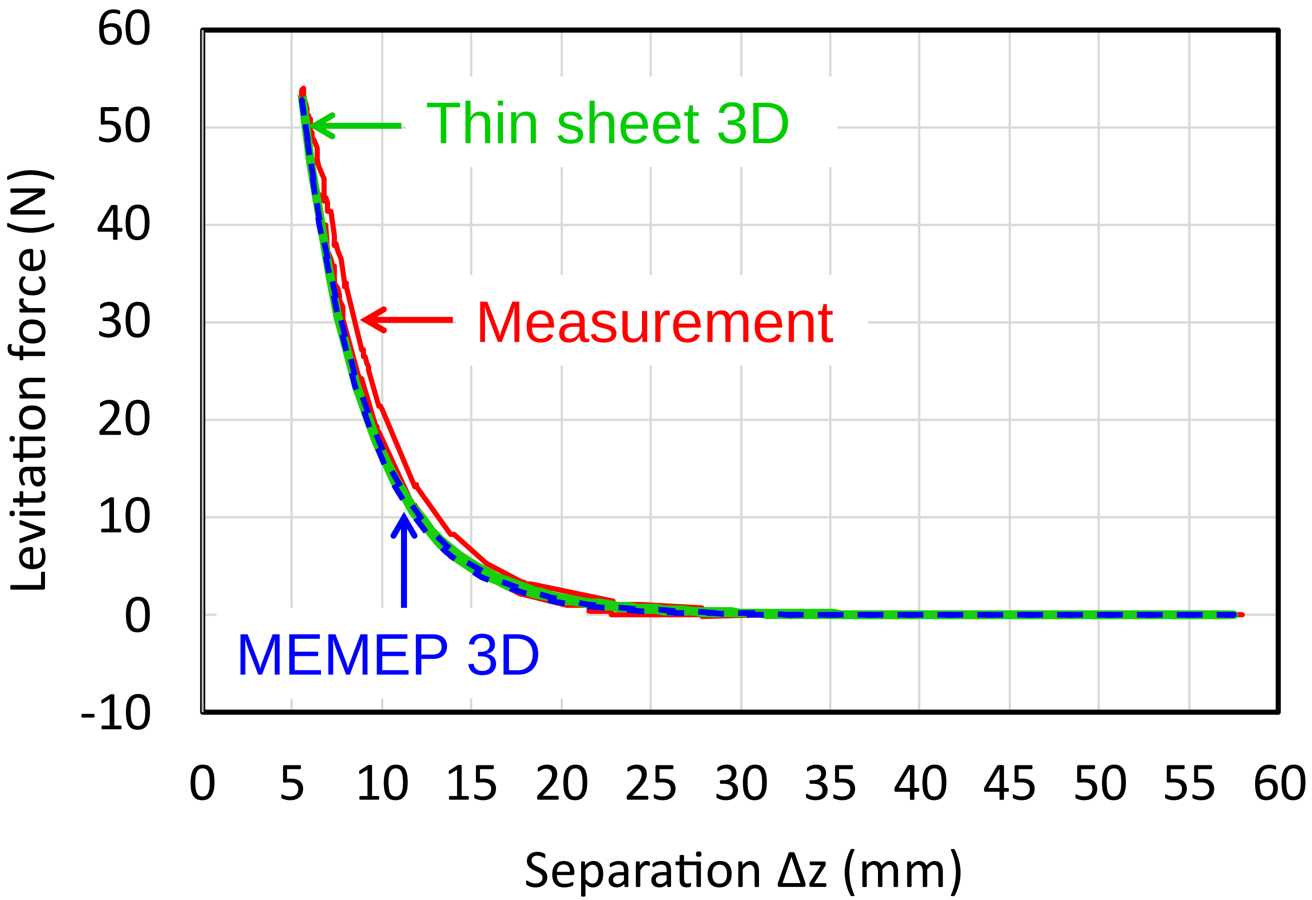
Maximum levitation force

MEMEP 3D : 52.7 N

Thin sheet 3D : 53.5 N

1.1% difference

Comparison of levitation force at 54.7 K : 3D models vs measurement



Maximum levitation force

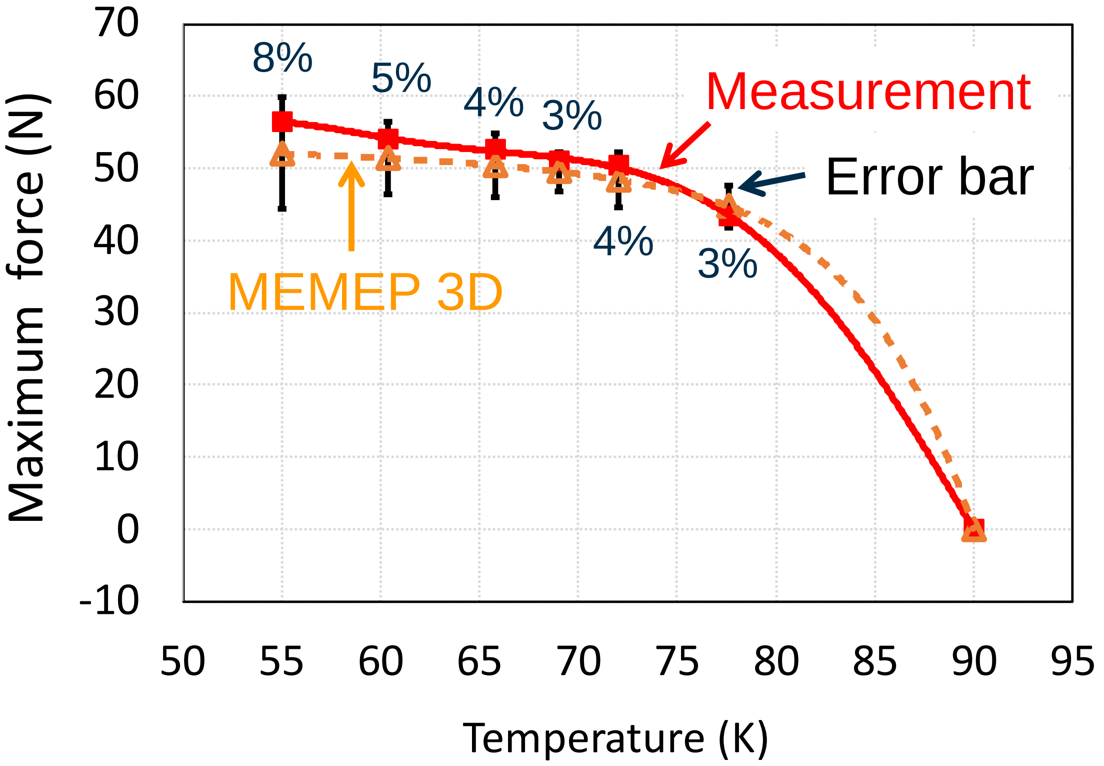
Measurement : 53.9 N

MEMEP 3D : 52.7 N — **2.2% error**

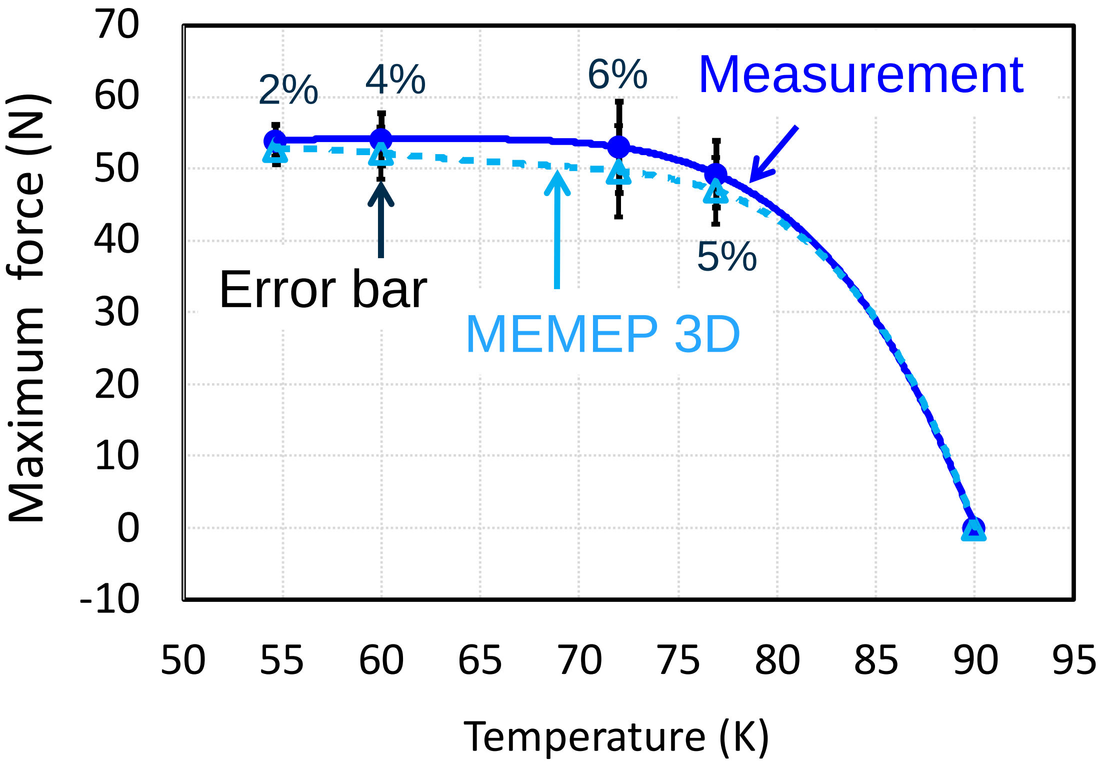
Thin sheet 3D : 53.5 N — **0.7% error**

Comparison of maximum levitation force vs temperature: 3D model vs measurement

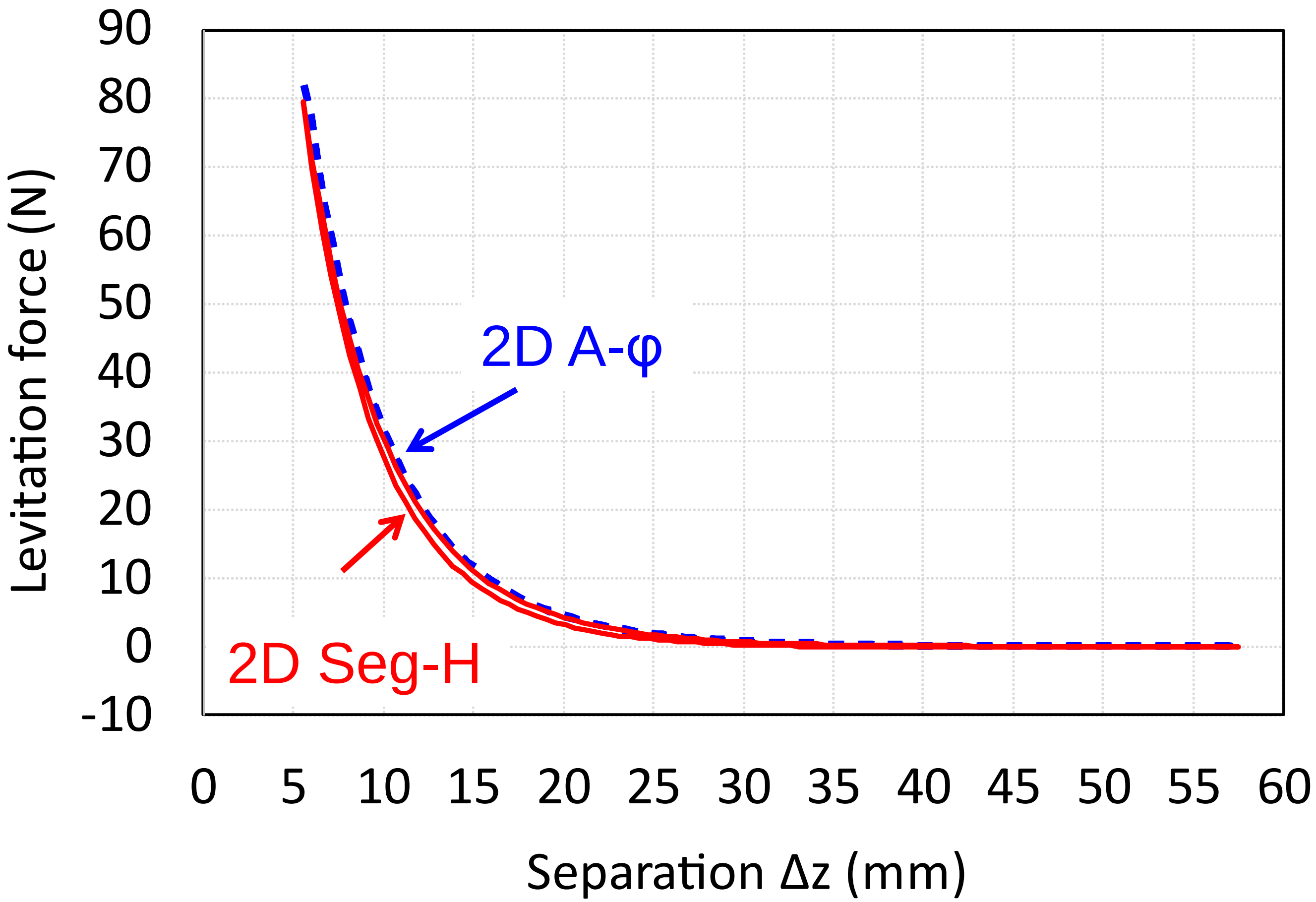
Original tape stack



Thinned tape stack



Comparison of levitation force at 54.7 K : 2D models



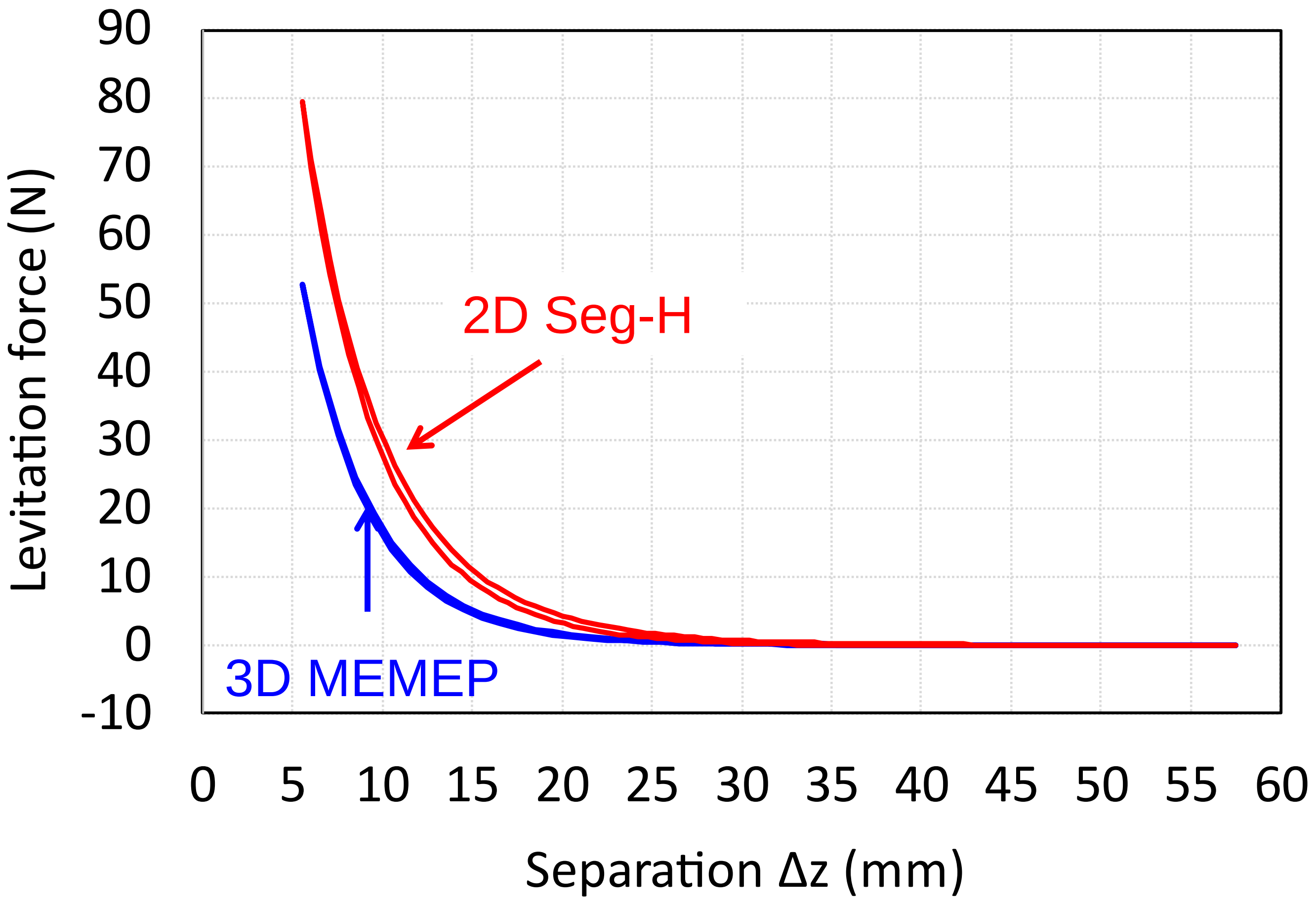
Maximum levitation force

2D A - φ : 83 N

2D Seg-H : 79.5 N

4% difference

Comparison of levitation force at 54.7 K : 2D and 3D models



Maximum levitation force

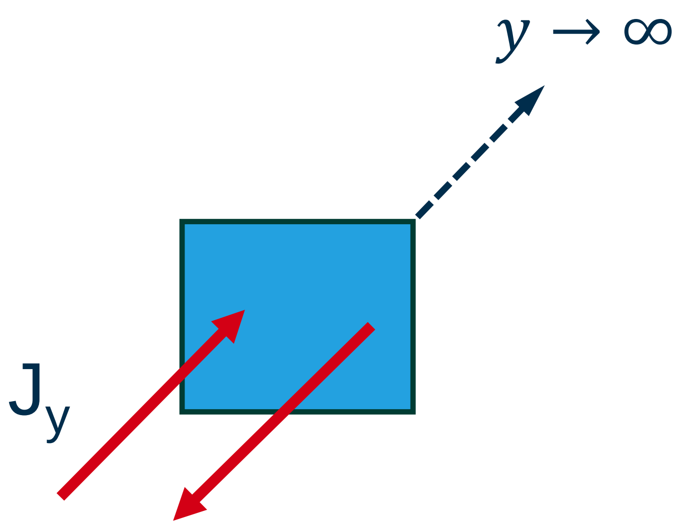
3D Model : 52.7 N

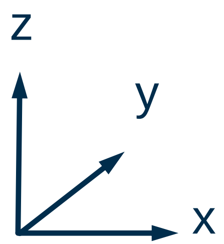
2D Model : 79.5 N

51% difference

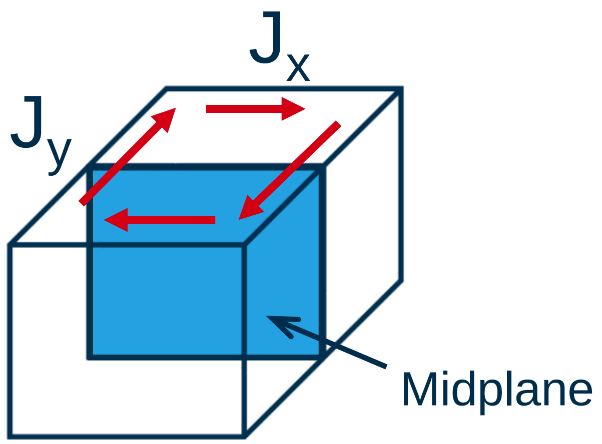
Current flow direction in 2D vs 3D model

2D model





3D model

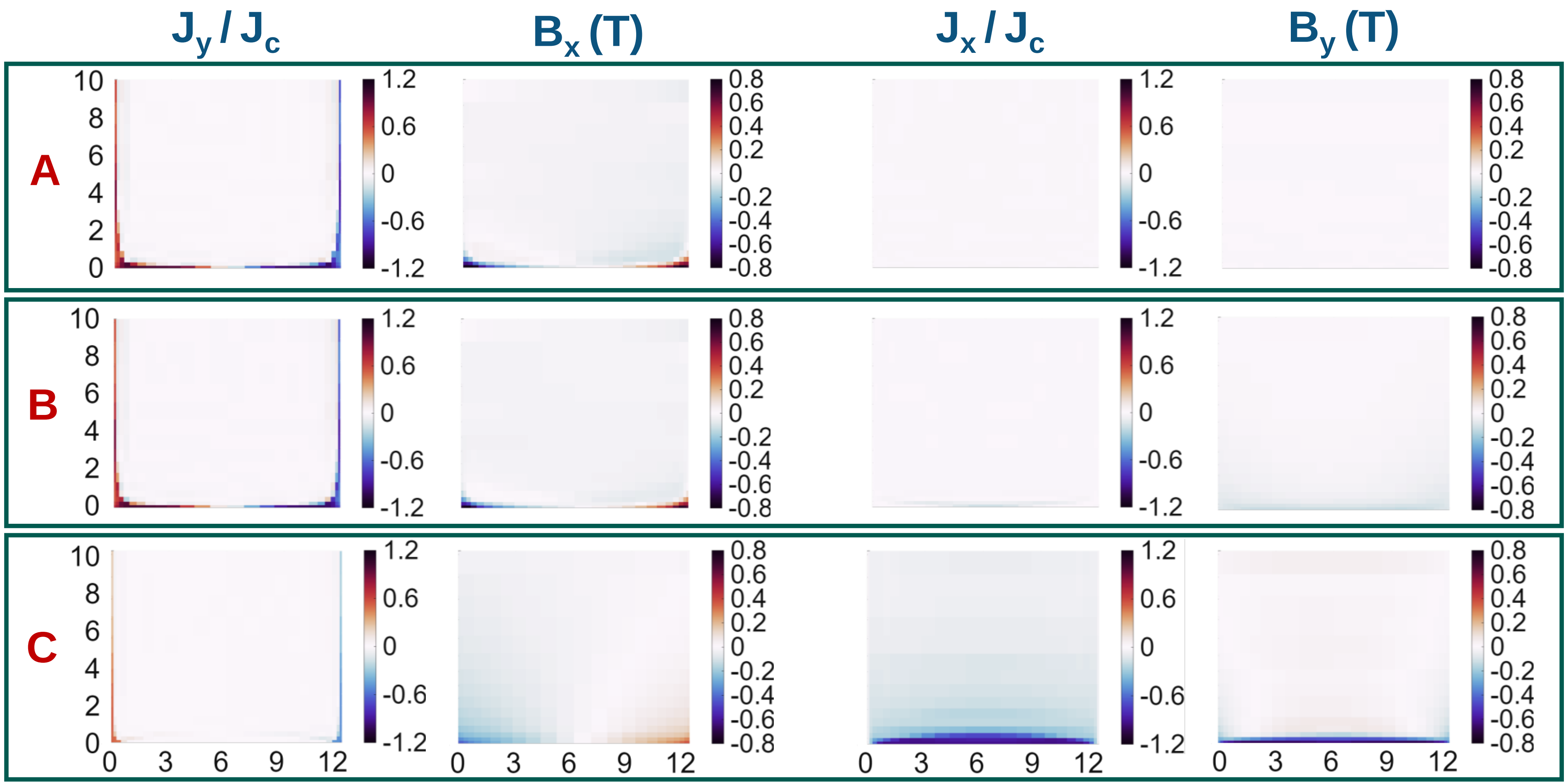


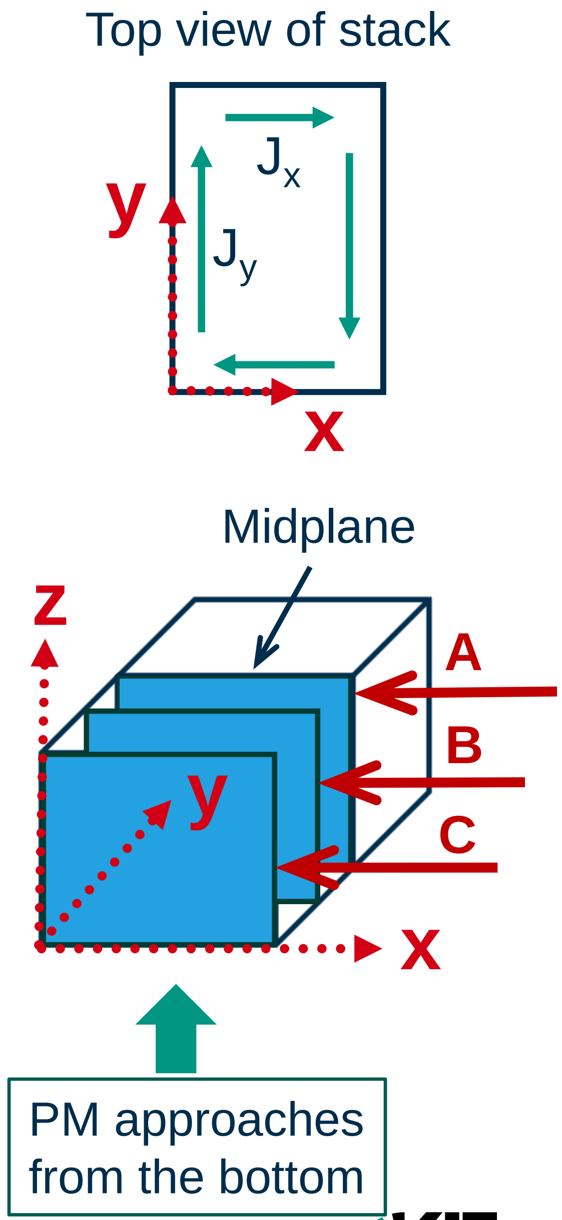
Force calculation in different xz-planes along depth

$F_z = -\underbrace{J_y \times B_x}_{1} + \underbrace{J_x \times B_y}_{2}$

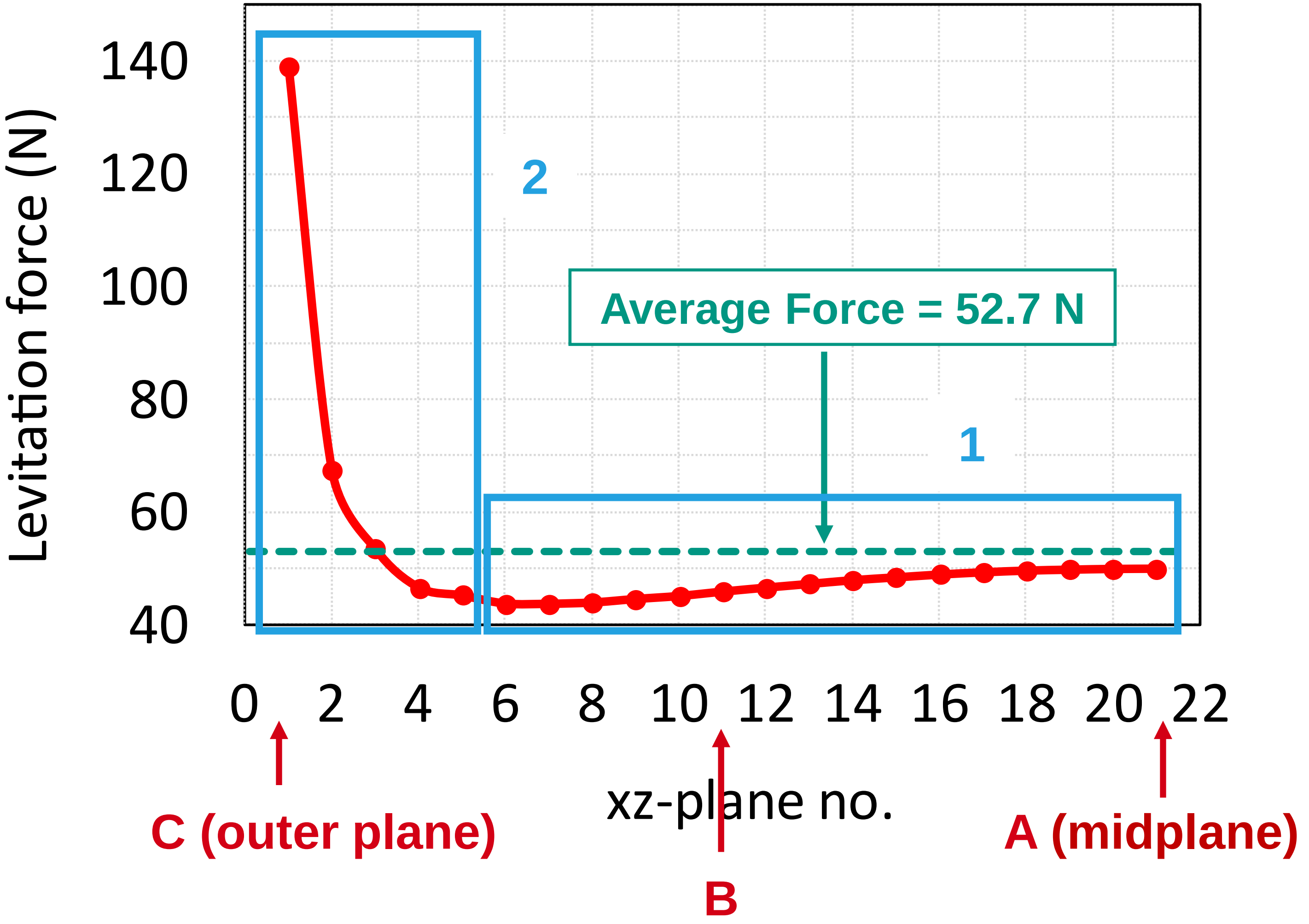
1 → 2D & 3D

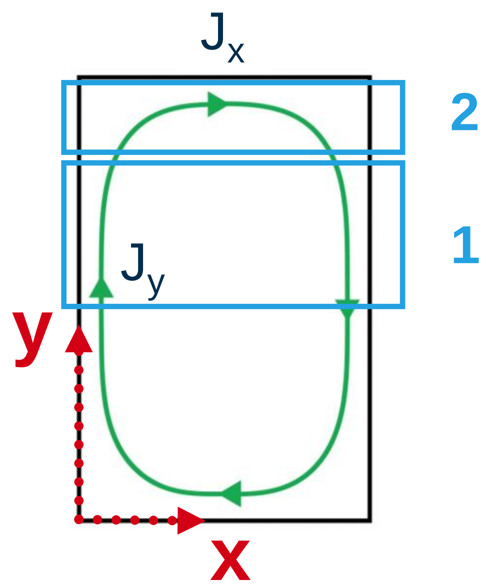
2 → only 3D

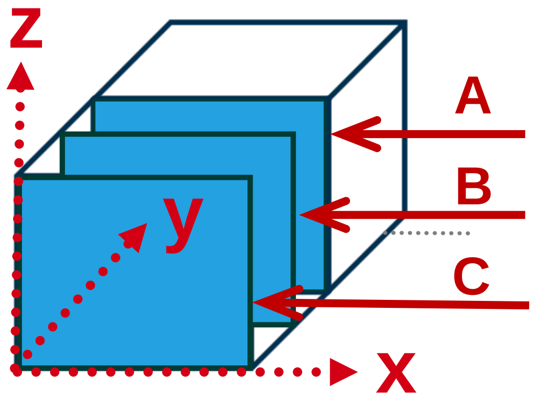




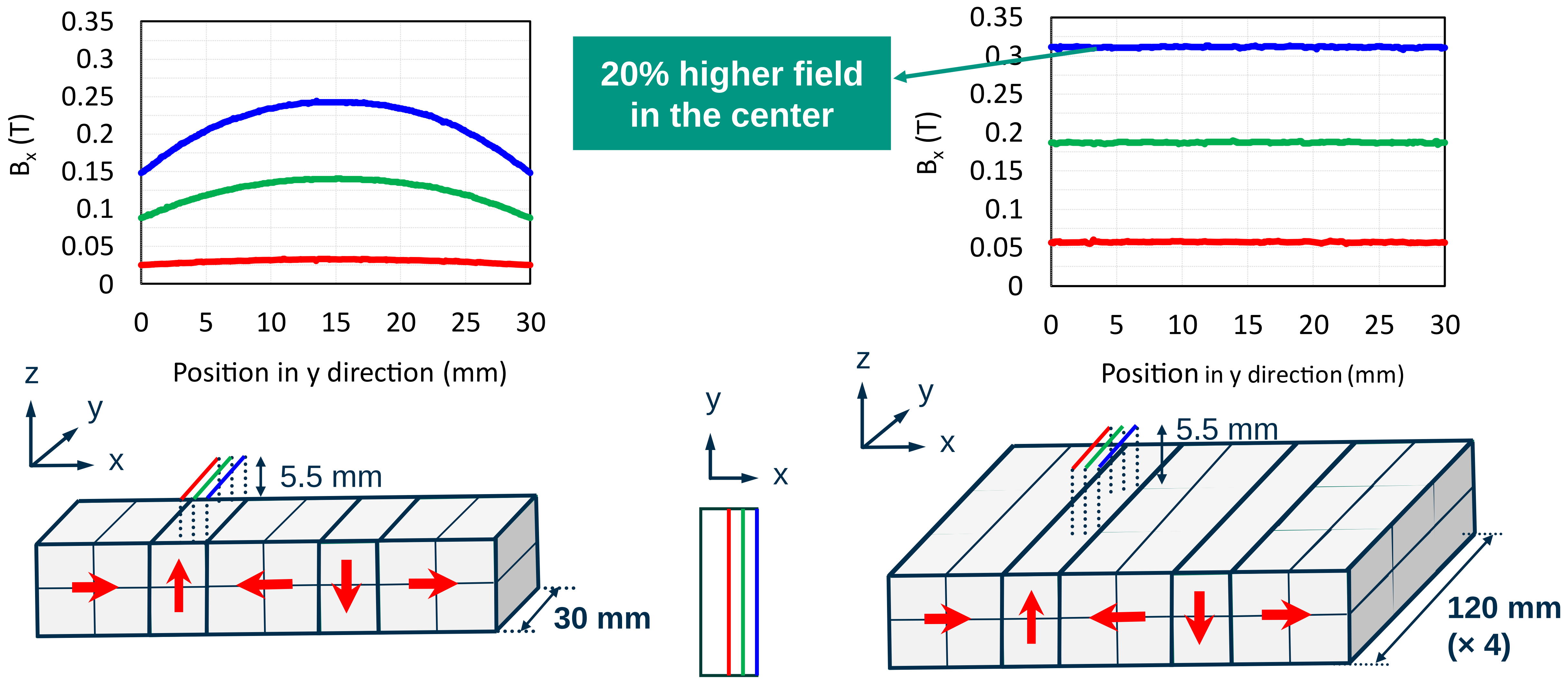
Levitation force distribution in xz-planes along depth



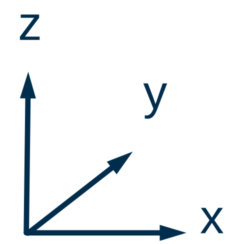




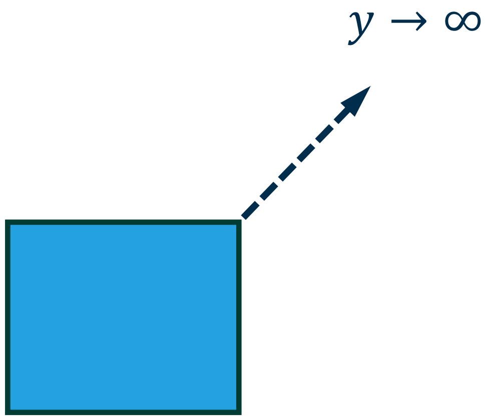
Influence of 3D model depth on magnetic field value



Comparison of 2D and long-depth 3D model

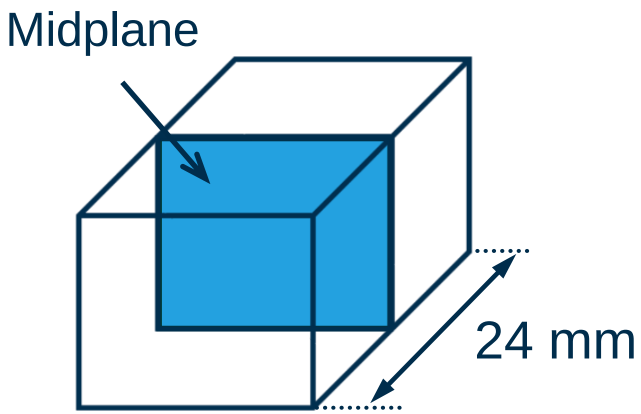


2D model



$F_{xz\text{-plane, max}}$ = 3312 N/m

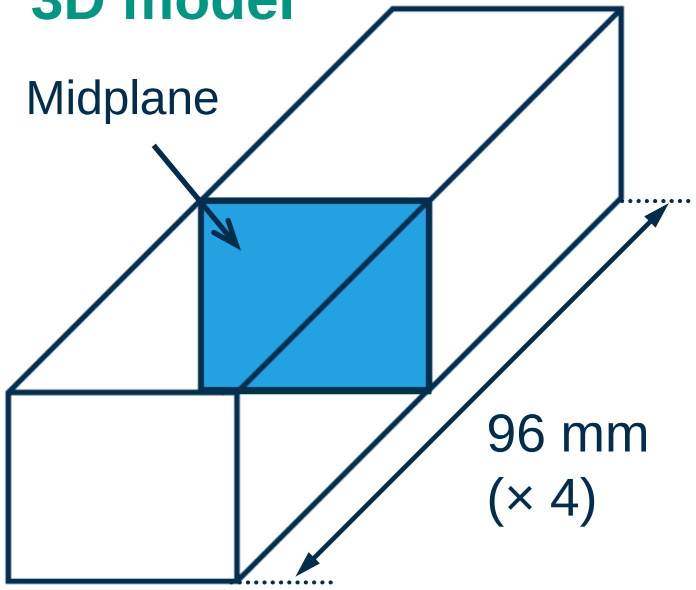
3D model



$F_{xz\text{-plane, max}}$ = 2080 N/m

59% less force

3D model



$F_{xz\text{-plane, max}}$ = 3281 N/m

1% less force

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Summary

- Electropolishing was applied to thin HTS tapes in a tape stack without affecting the I_c of the tapes
- The thinned tape stack exhibited a 14% increase in levitation force at 77 K
- Two 3D models showed very good agreement with experimental results for the levitation force
- Two 2D models were consistent with each other, but not with the 3D models
- Low depth of the 3D models is the reason for discrepancy between the 2D and 3D models

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