3D modeling of stack-type superconducting magnetic bearings

Asef Ghabeli, Francesco Grilli, Jens Hänisch

Günter Fuchs, Oliver de Haas, Pengbo Zhou

Maximum speed of 603 km/h!

Yamanashi: Japanese low-T_c superconducting maglev train

In 2 hours instead of 12 hours!

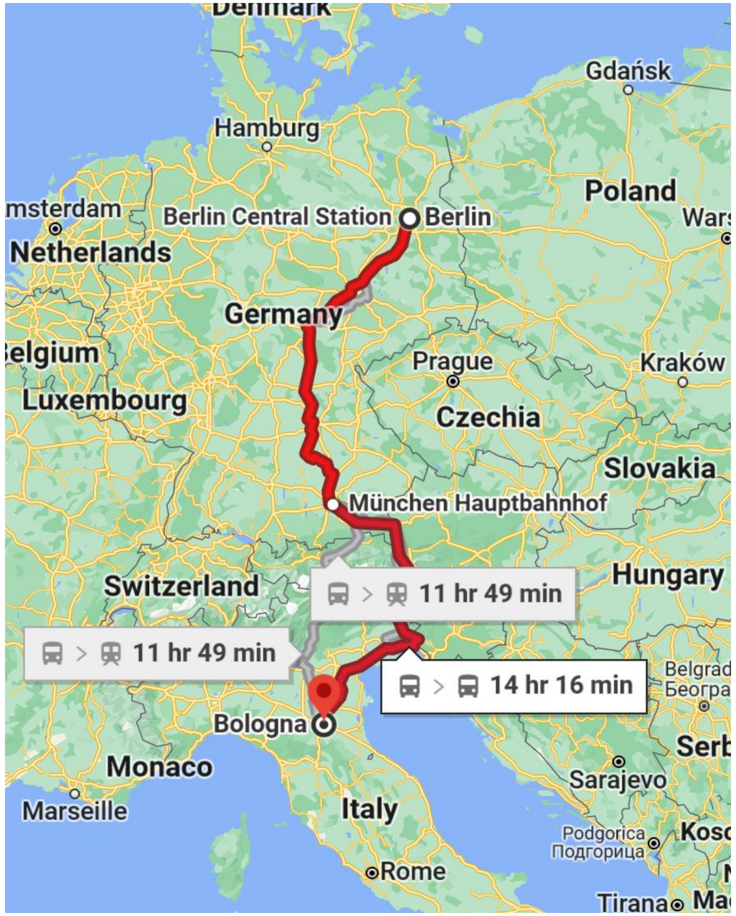
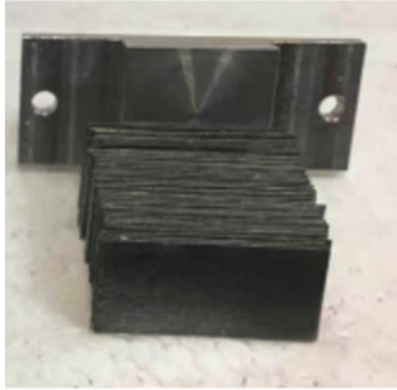


Figure: scmaglev.jr-central-global.com

Superconducting tape stack

Superconducting bulk



Left Figure : Nariki et al, Jpurnal of Physics. (2008)

Right Figure: Patel et al, Supercond. Sci. Technol. (2017)

Advantages of tape stacks over bulks

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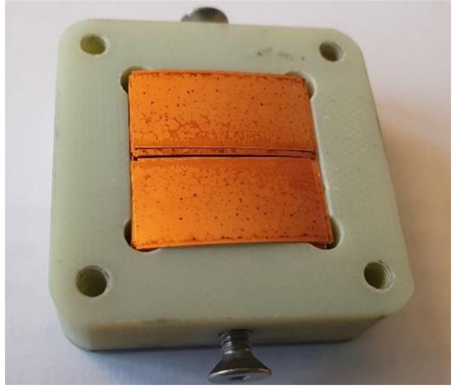
- Better mechanical properties
- Better thermal conductivity
- Possibility of having more flexible configurations
- Higher engineering J_c and levitation force
- Possibility of increasing engineering J_c by reducing thickness of tape



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  - Field cooling (FC)
- Summary

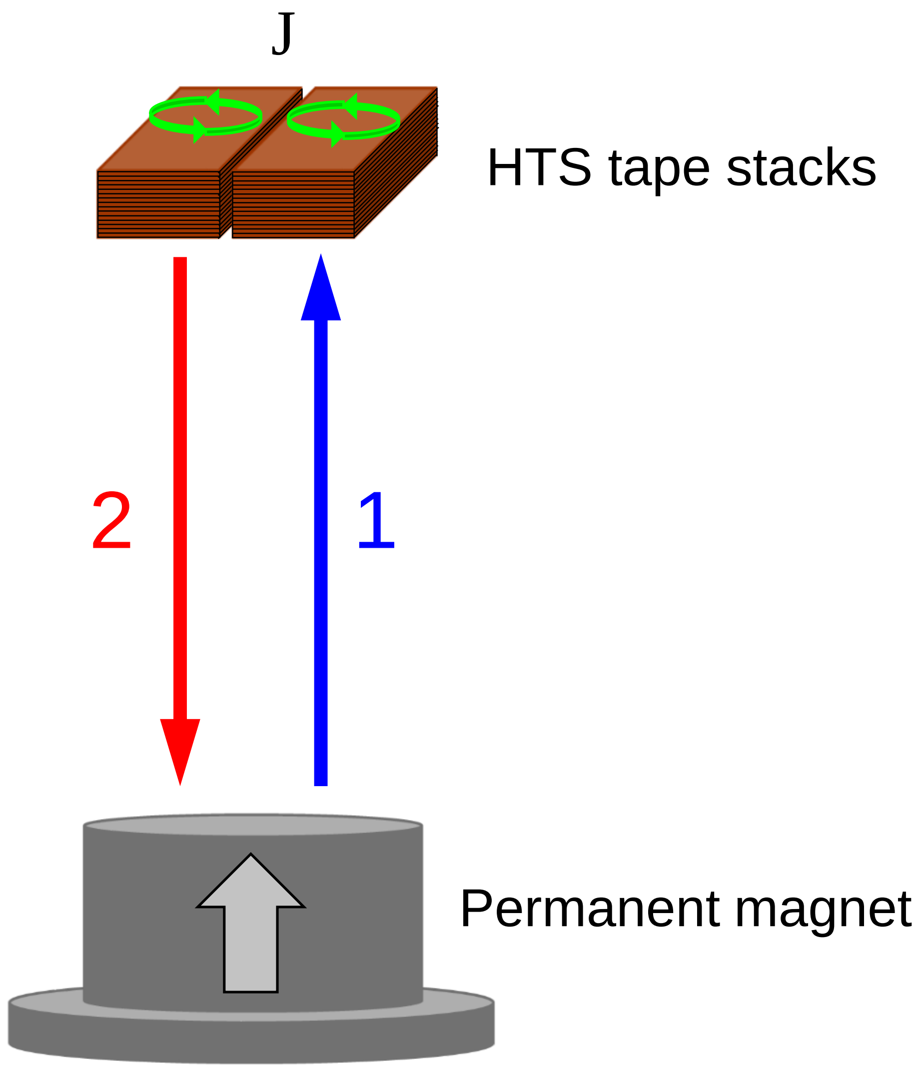
Calculation of levitation force

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

Lorentz force

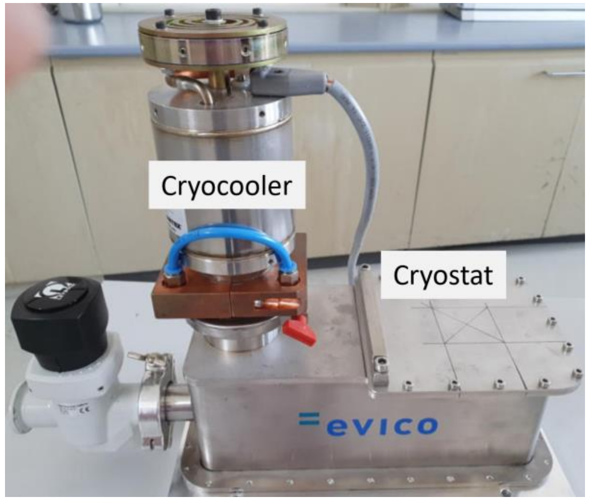
between field of permanent magnet

& magnetization current in tape stacks



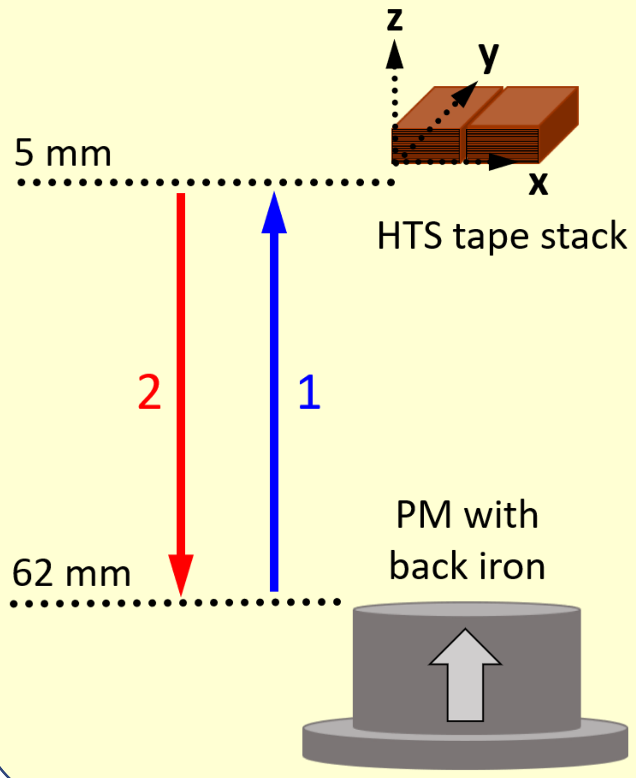
Studying different cases at different temperatures

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

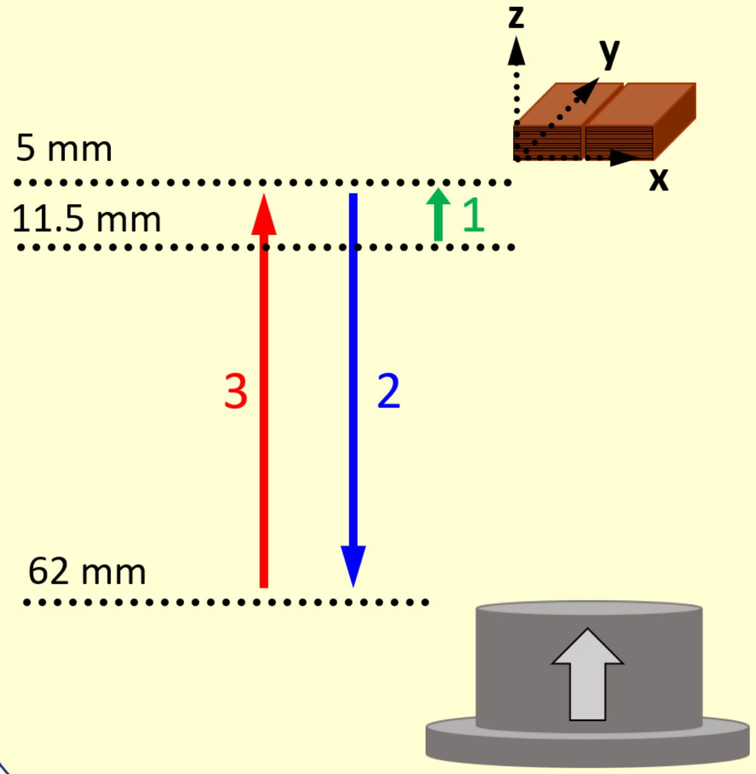


57 K < Temperatures < 77 K

Zero Field cooling

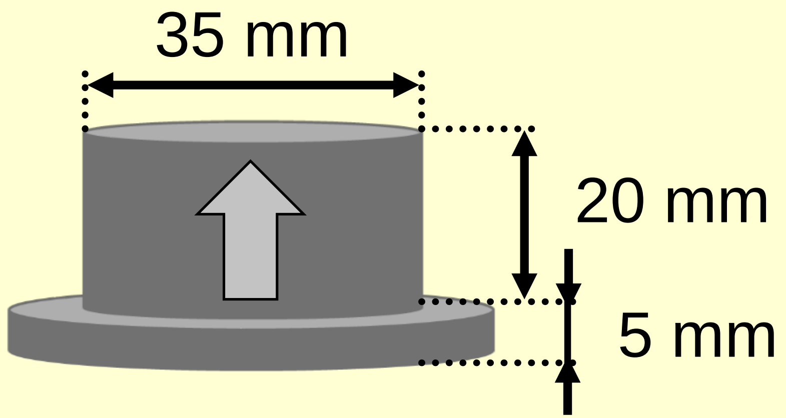


Field cooling



Input parameters

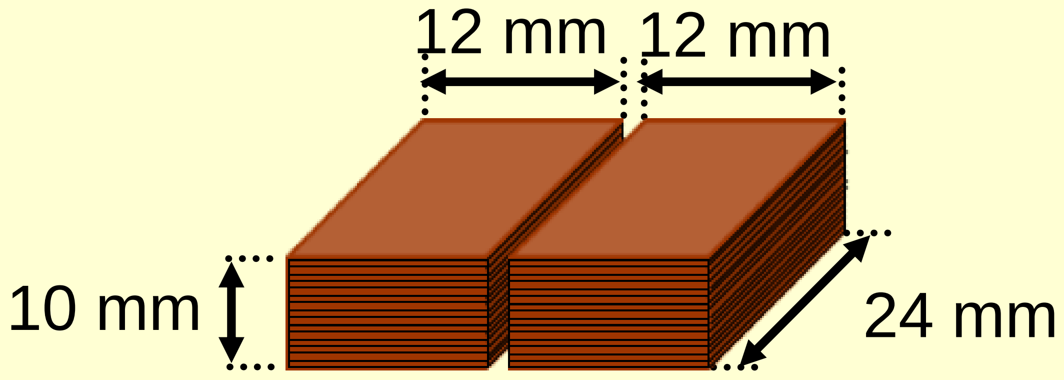
Cylindrical magnet with back iron



Remanent flux density (B_r) = 1.35 T

Magnet movement speed = 10 mm/s

HTS tape stacks



No. of tapes in each stack: 132

Self-field critical current = 400 A

n-value = 29

Minimum Electromagnetic Entropy Production method (MEMEP 3D)

Initially developed by **Milan Kapolka** and **Enric Pardo**

Institute of Electrical Engineering, Slovak Academy of Sciences

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

$$\nabla \times \mathbf{T} = \mathbf{J}$$

$\mathbf{T}$ → effective magnetization

$\mathbf{A}$ vector potential ⟶ calculated analytically

known variables — unknown variable

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

Three-dimensional electromagnetic modeling of practical superconductors for power applications, Milan Kapolka, PhD thesis
arXiv preprint arXiv:1605.09610 (2016)

Minimum Electromagnetic Entropy Production method (MEMEP 3D)

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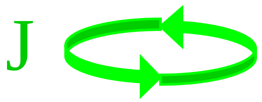
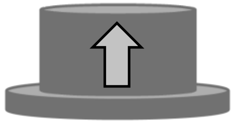




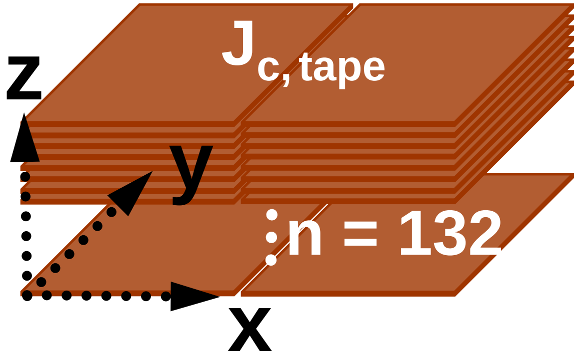
Dissipation factor
(E-J power law)

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

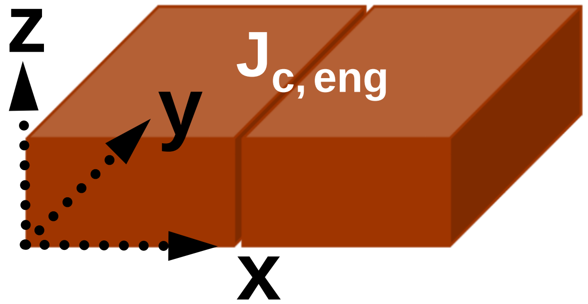
Minimum of this equation in each time step is
the unique solution of Maxwell differential equation

Homogenization process

HTS tape stacks



Homogenized Bulks



Current flows only in **x** and **y** directions

Thickness of SC layer

$$J_{c,\,eng} = n \times \frac{\delta}{\Delta_{bulk}} J_{c,\,tape}$$

Height of bulk

SuperOx tape I_c (B,θ) measurement

T = 77 K

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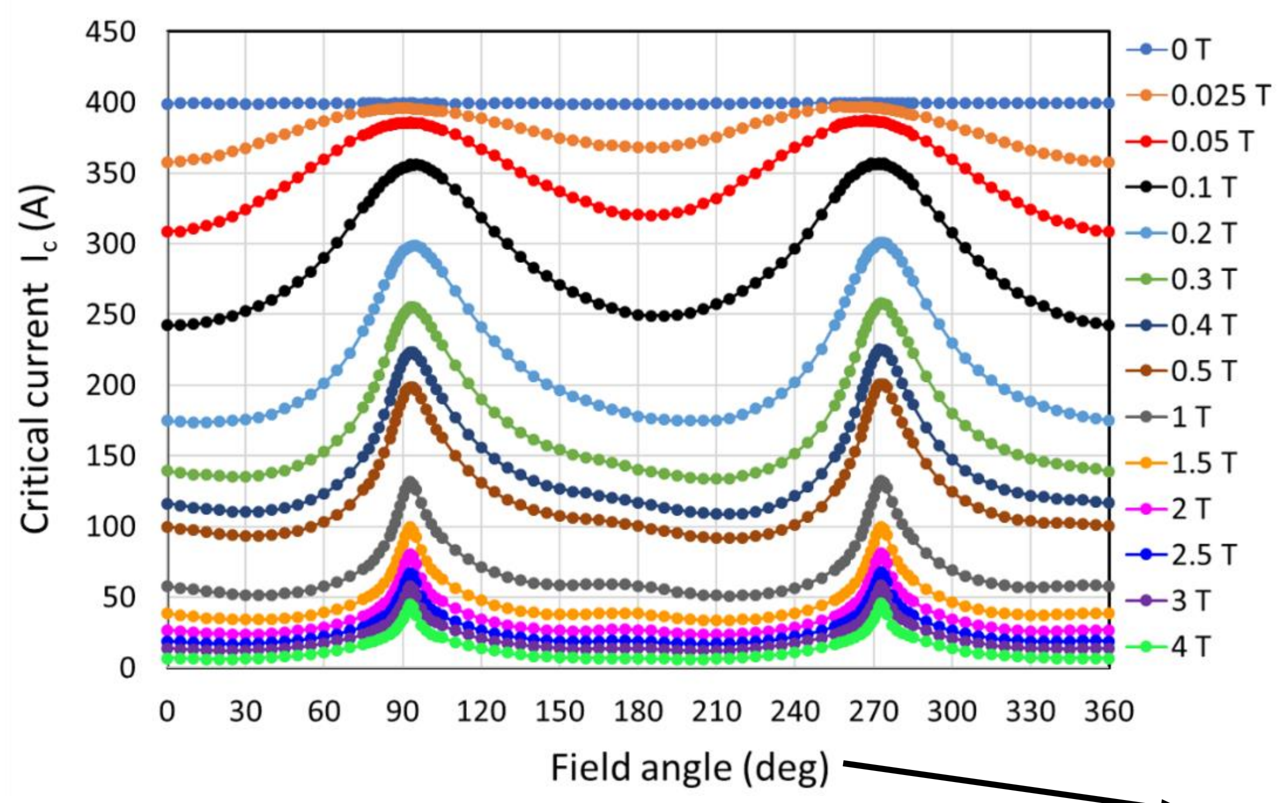
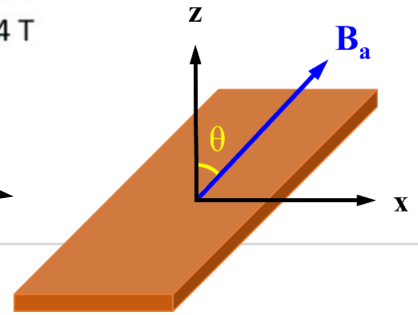




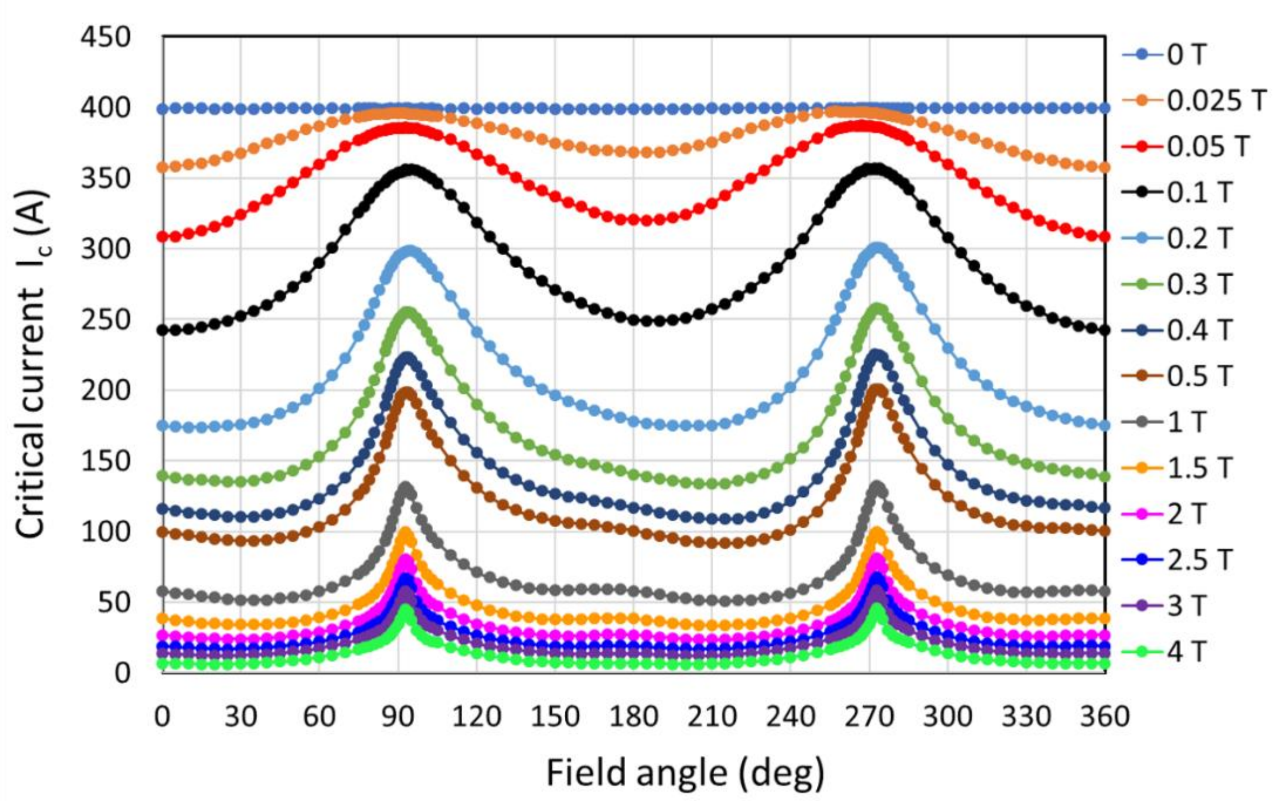
Data was measured by SuperCurrent facility in

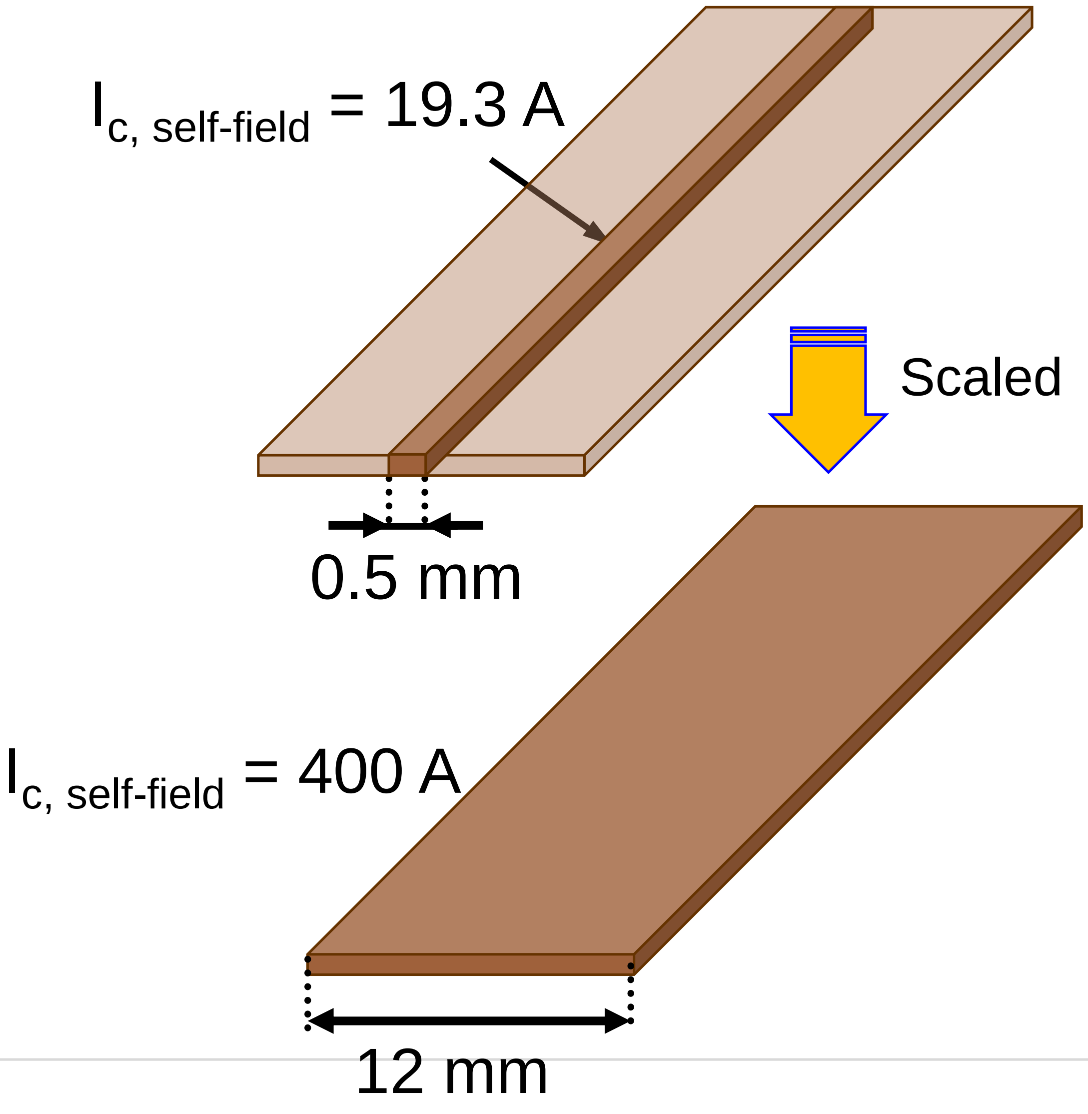
ROBINSON RESEARCH INSTITUTE
Kitenga me te tono rangahau
VICTORIA UNIVERSITY OF WELLINGTON
TE HERENGA WAKA

Scaling the data is necessary

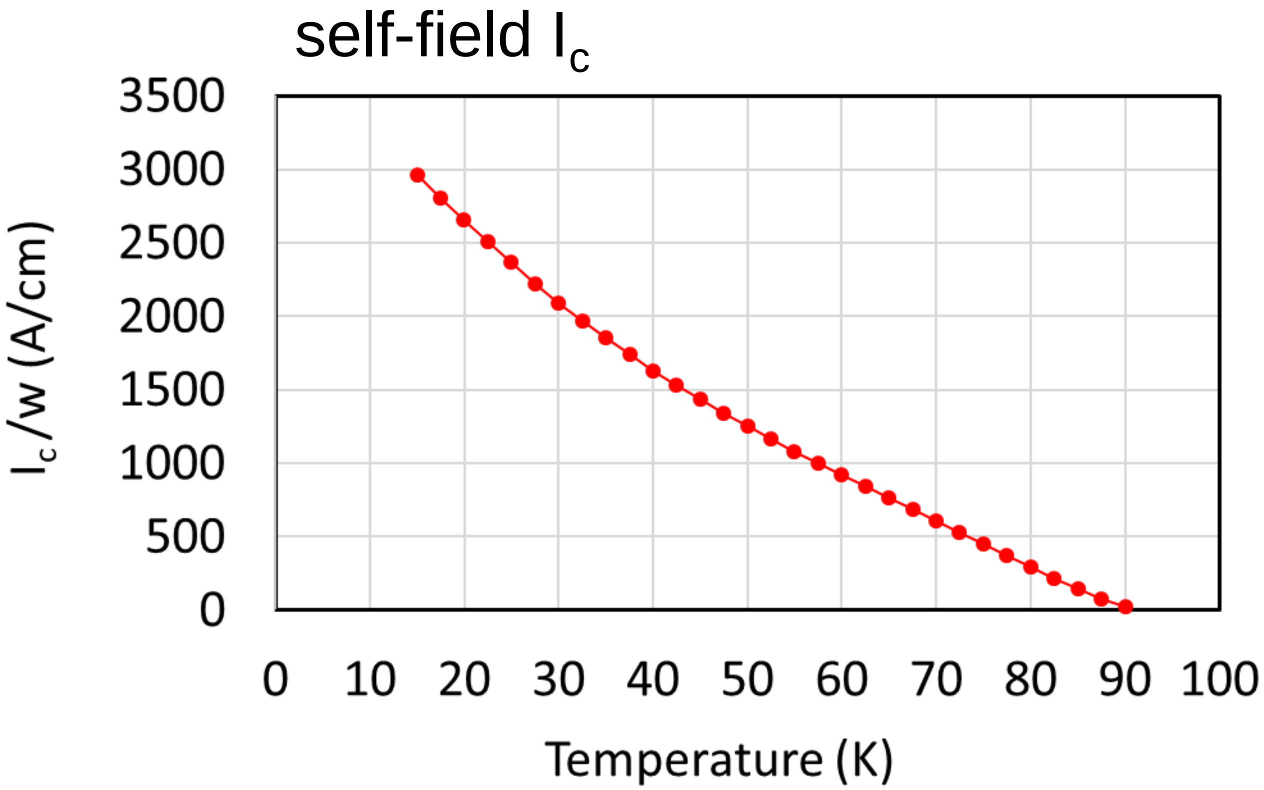
T = 77 K

Scaled data to a second measurement on whole 12 mm width of tape



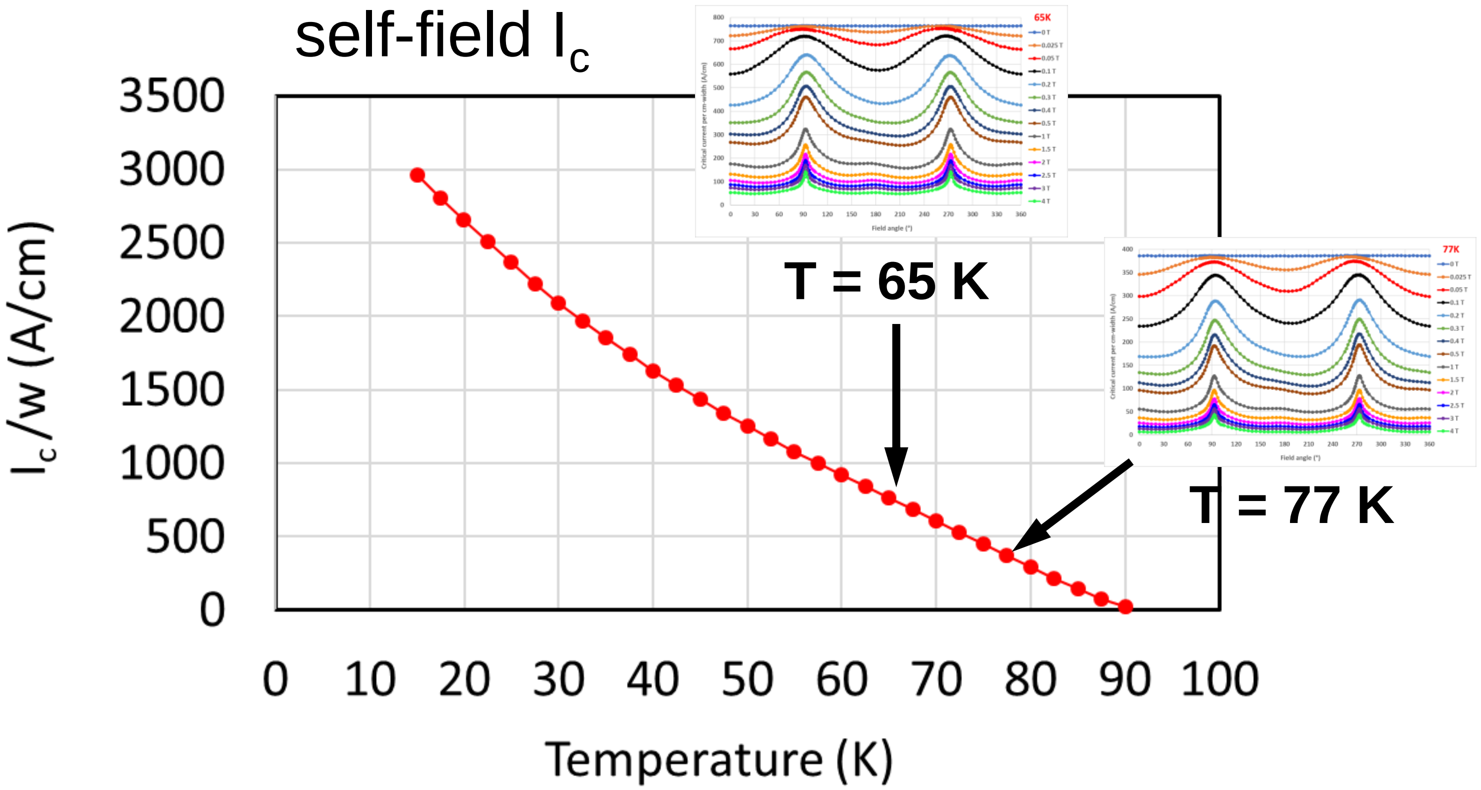


Calculating $I_c(B, \theta)$ at different temperatures



I_c changes almost linearly with temperature

Calculating $I_c(B, \theta)$ at different temperatures



I_c changes almost linearly with temperature

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

Calculation time is around 17 hours

Element numbers $49 \times 49 \times 15 \approx 36000$

Time steps ≈ 110

Computer specification

AMD Ryzen Threadripper 3970x 32-core processor

128 GB RAM

Ubuntu 20.04.4 LTS operating system

Calculation time

≈ 17 hours

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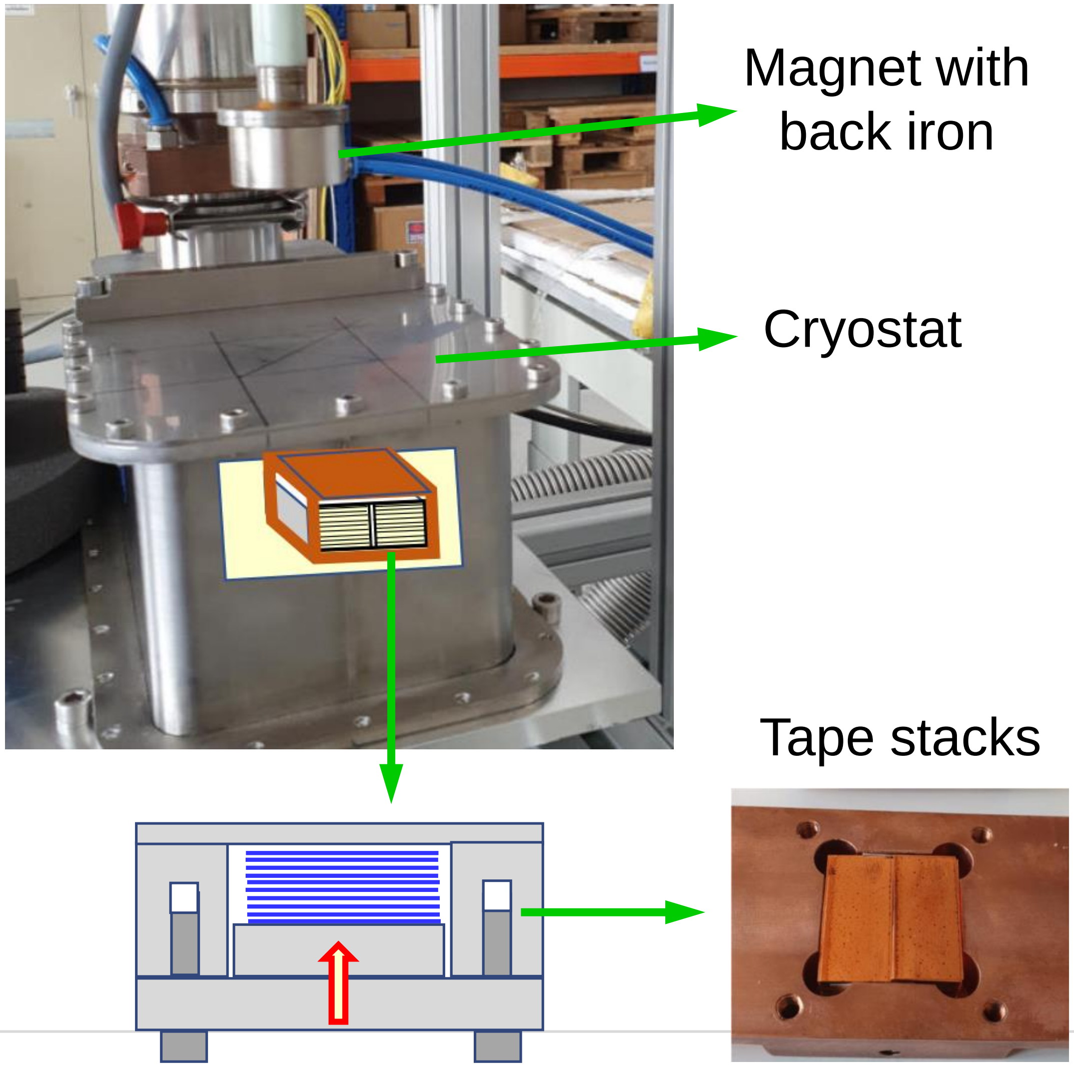
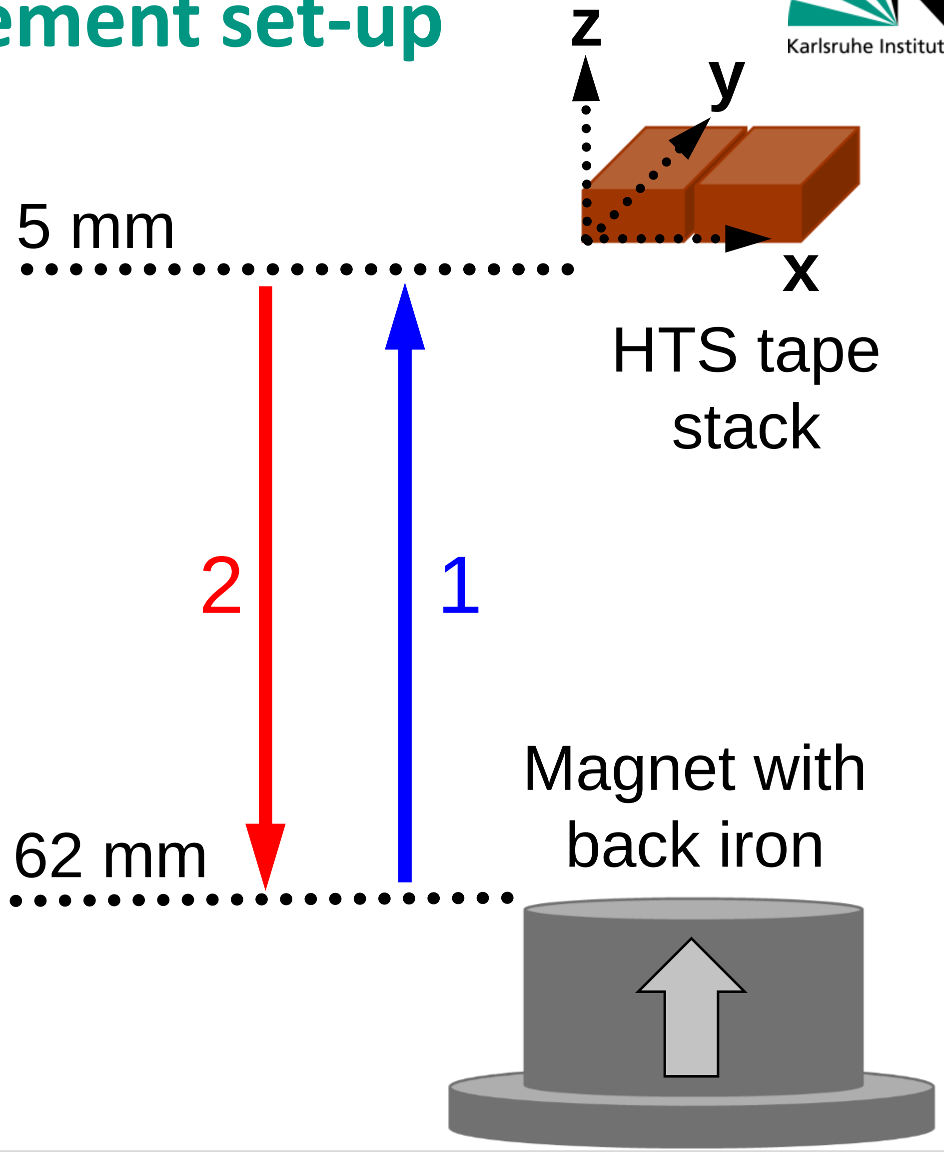
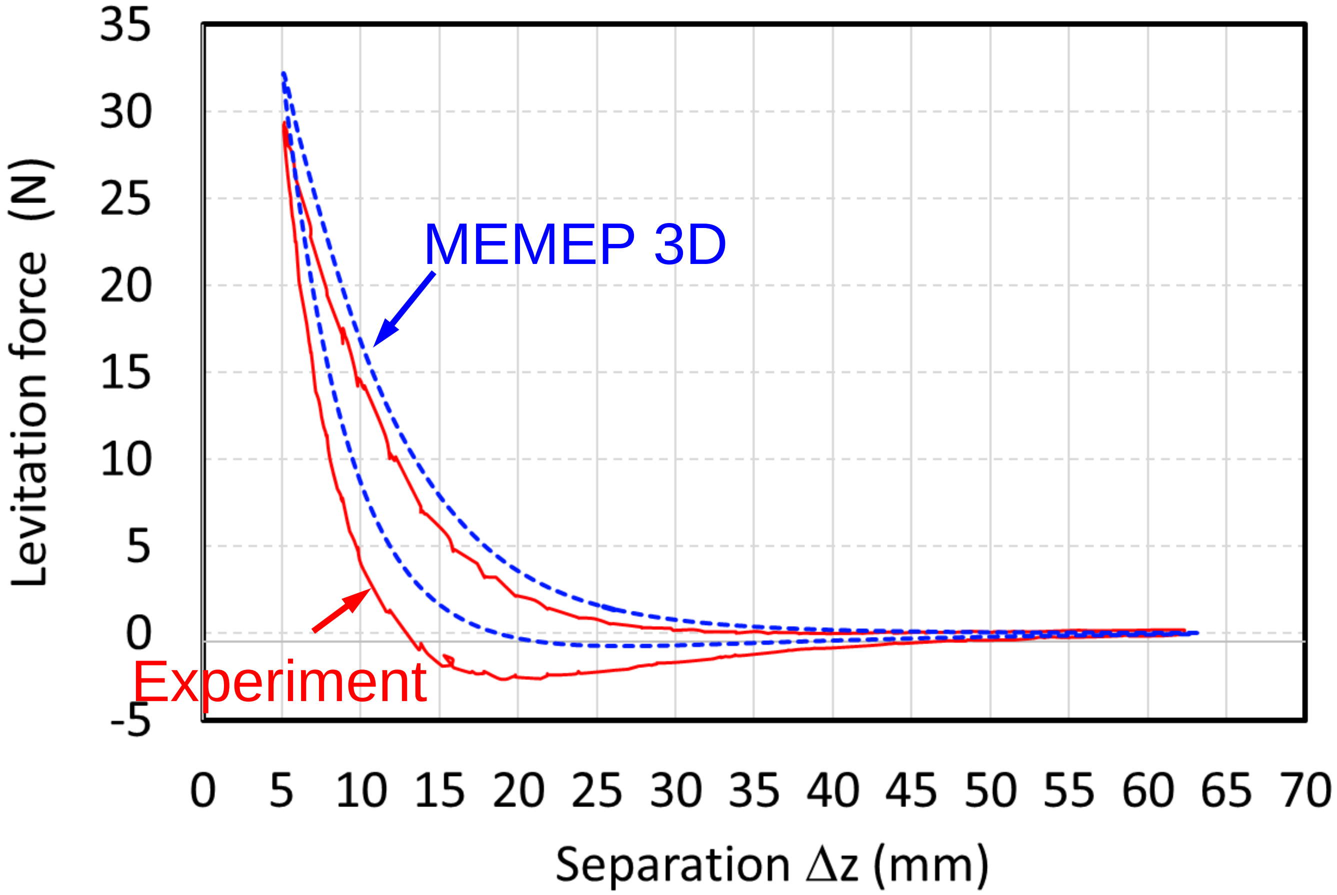
Zero field cooling case and measurement set-up





Zero field cooling at 77 K



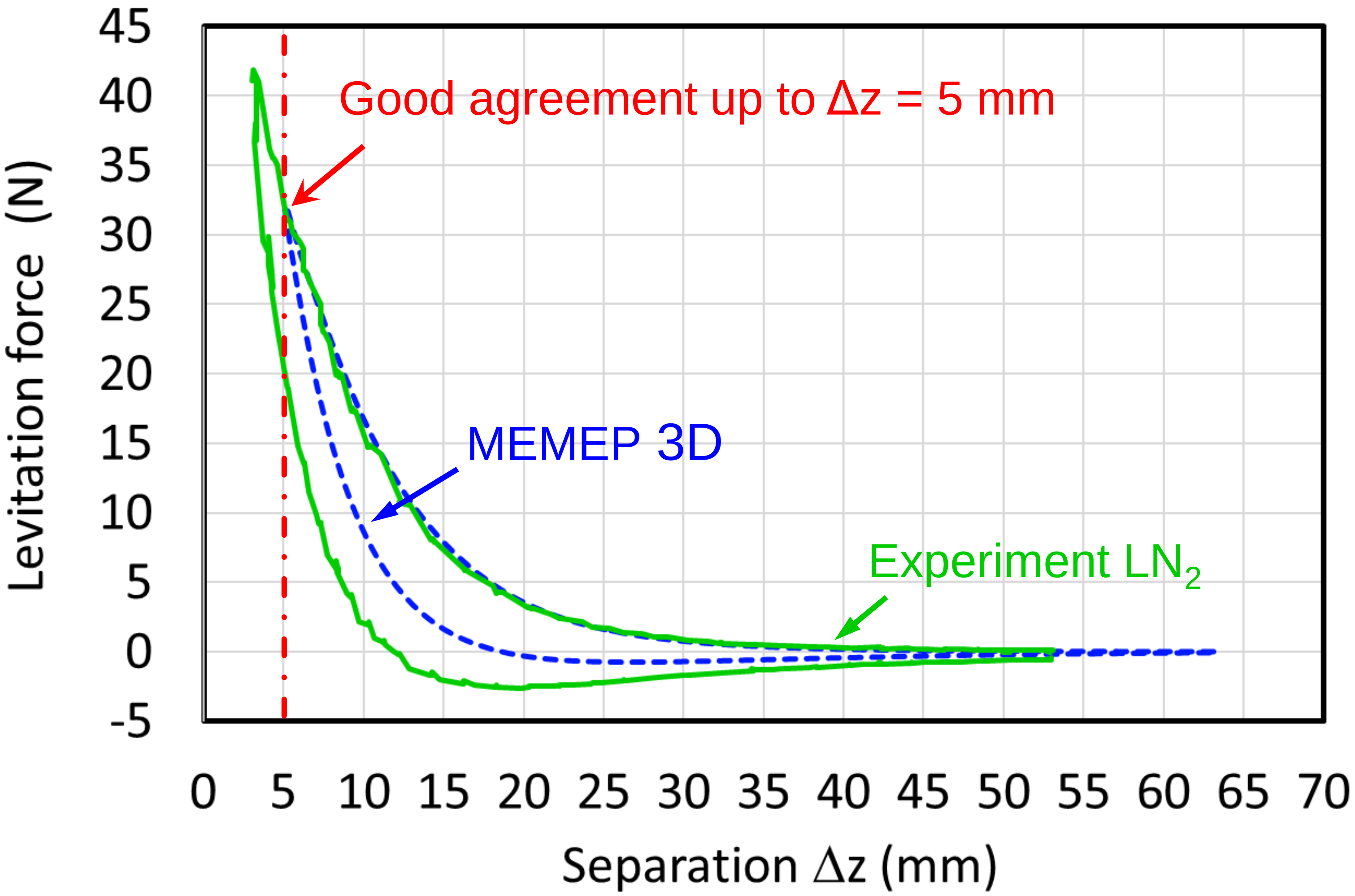
Maximum levitation force

Experiment : 29.4 N

Model : 32.1 N

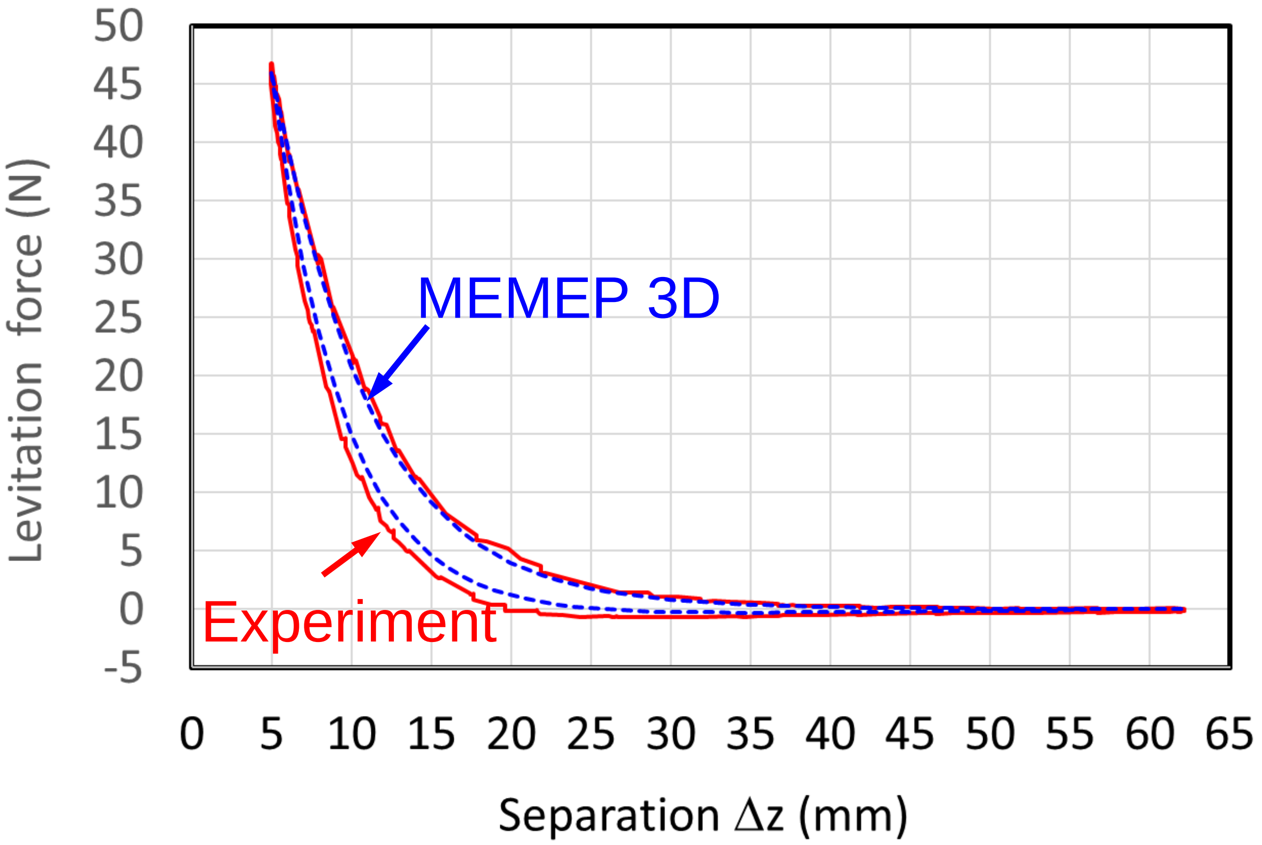
Error: 9%

Zero field cooling at 77 K comparison with LN_2 measurement



Measurement error in cryostat at 77 K ?!

Zero field cooling at 69 K



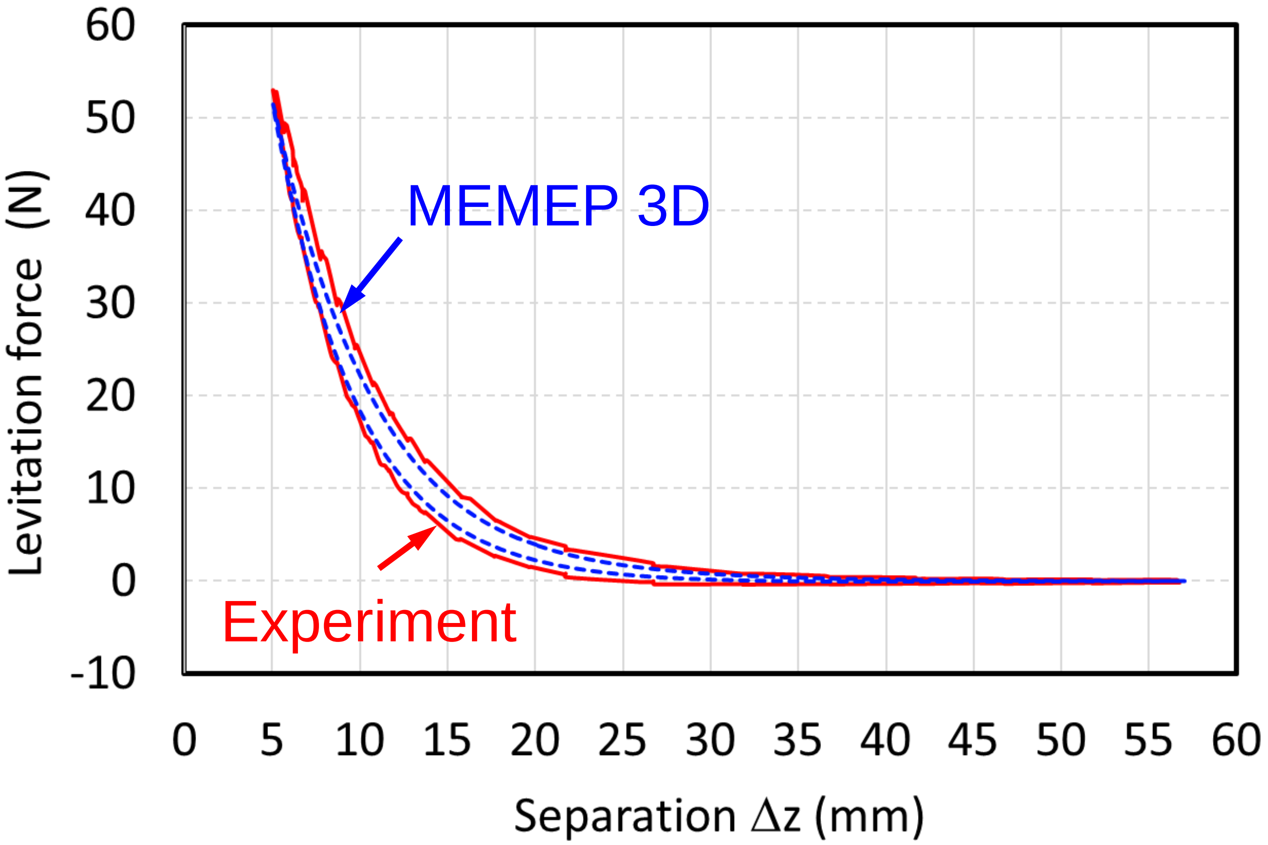
Maximum levitation force

Experiment : 46.8 N

Model : 46.2 N

Error: 1.3%

Zero field cooling at 57 K



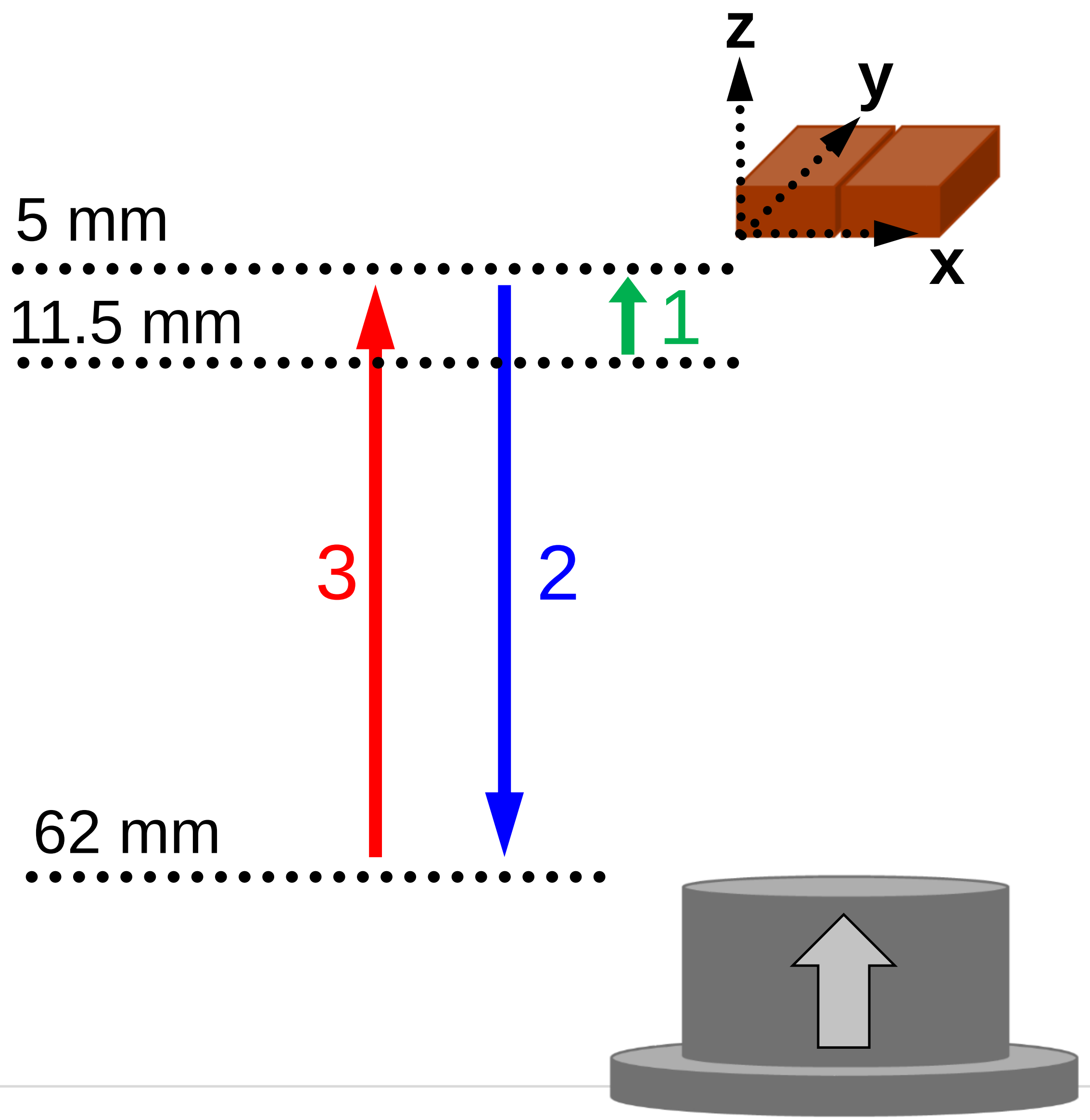
Maximum levitation force

Experiment : 53 N

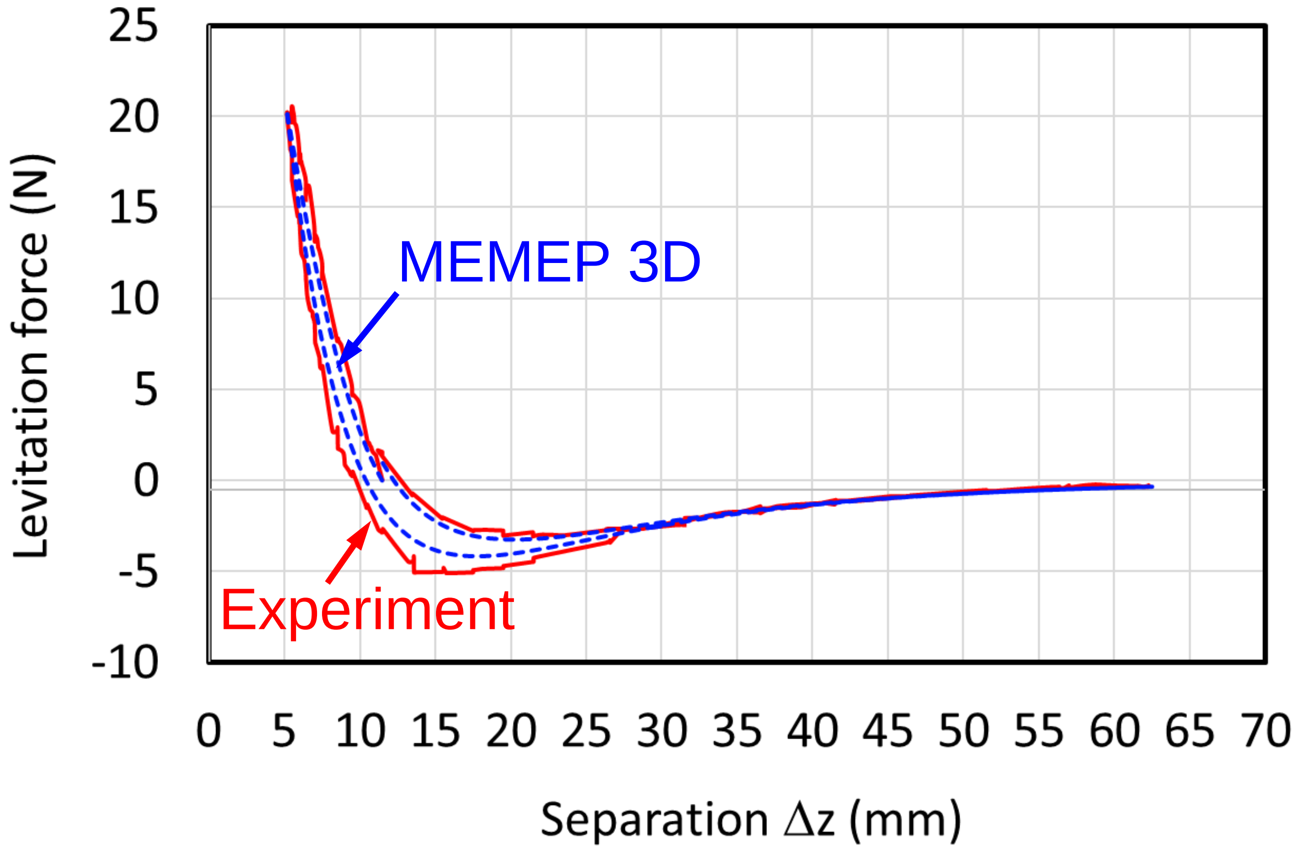
Model : 51.5 N

Error: 3%

Field cooling cases



Field cooling at 75 K



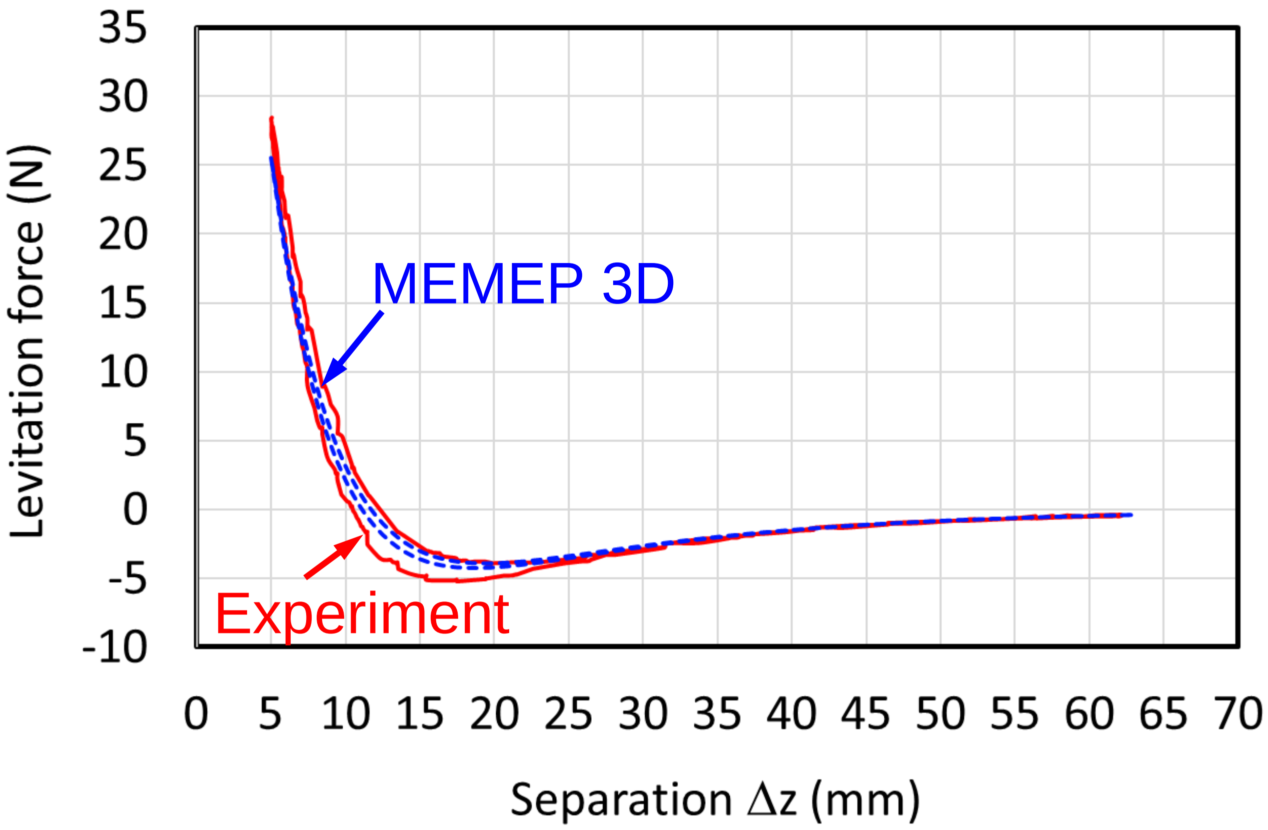
Maximum levitation force

Experiment : 20.5 N

Model : 20.2 N

Error: 1.5%

Field cooling at 57 K



Maximum levitation force

Experiment : 28.5 N

Model : 25.9 N

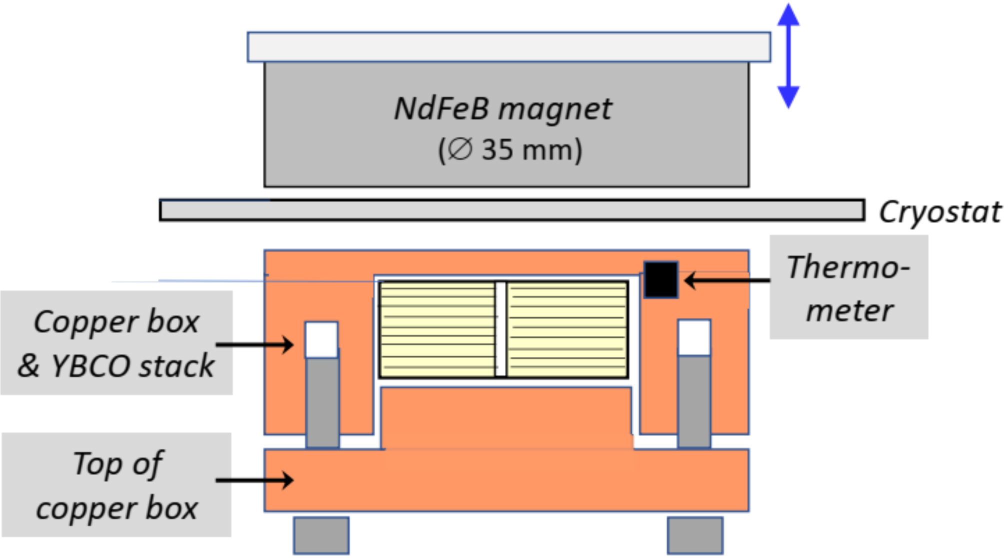
Error: 9%

Measurement error should not be neglected

Error is below 10% in all cases

Case	Temperature (K)	Error (%)
ZFC	77	9
	69	1.3
	57	3
FC	75	1.5
	57	9

- Separation (Δz) measuring error
- Temperature measuring error
- Force measuring error



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Summary and future work

- Developing full 3D simulation to model levitation force under various temperatures
- The first model to predict levitation force without manipulation of I_c with error < 10%
- Other than modeling errors, measurement error is the cause of disagreement
- Implementing proper I_c (B, θ) is important to obtain a good agreement

Future work

- Impact of tape thickness reduction on levitation force with Halbach magnet as guideway

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Thanks for your attention!