3D modeling of HTS tape stacks in superconducting magnetic bearings with real thickness

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Since 1969

Karlsruhe Institute of Technology

German Transrapid TR-07
Electromagnetic Levitation (EML)

Japanese Yamanashi
Electrodynamics Levitation (EDL)

Speed up to 500 km/h!

Full-sized HTS Maglev trains

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SupraTrans II
IFW-Dresden, Germany (2011)

Century
Southwest Jiaotong Univ., China (2012)

MagLev-Cobra
COPPE/UFRJ, Brazil (2015)

Can carry up to 15 passengers!

Full-sized HTS Maglev trains

Made with YBCO bulk!

The production of YBCO bulks is very material, energy and time consuming

YBCO bulk have poor mechanical properties

Much lower critical current density compared to YBCO tapes

Maglev trains with HTS tape stacks

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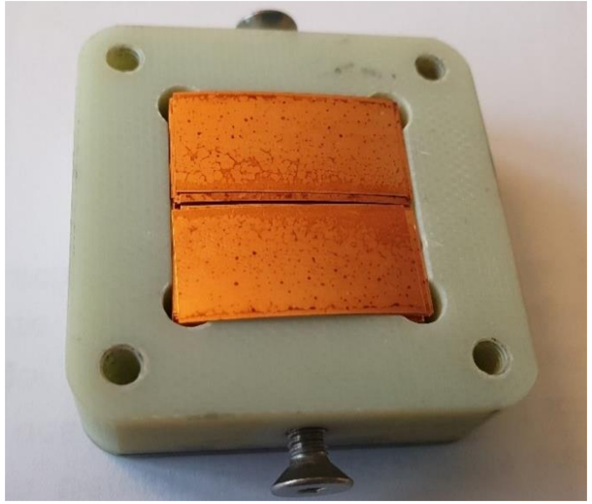
Levitation force can be increased by reducing the tape substrate thickness

YBCO tape stacks have better mechanical properties

YBCO tape stacks have better thermal conductivity

Possibility of having flexible configurations of tape stacks



Minimum **E**lectro**m**agnetic **E**ntropy **P**roduction method in **3D** (**MEMEP 3D**)

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MEMEP 3D is a variational method based on T-formulation

Variational methods are based on a certain functional

Differential equations in the problem are solved by minimizing the functional

MEMEP 3D method was implemented in an in-house open-source software

coded in C++ by **Milan Kapolka** and **Enric pardo** from IEE SAS

https://github.com/epardov/MEMEP3Dtool

How MEMEP 3D solves the problem?

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Current density

External field

$$L = \int_\Omega \mathrm{d}^3\mathbf{r}\left[\frac{1}{2}\frac{\Delta \mathbf{A}_J}{\Delta t}\cdot\Delta\mathbf{J} + \frac{\Delta \mathbf{A}_a}{\Delta t}\cdot\Delta\mathbf{J} + U(\mathbf{J}_0+\Delta\mathbf{J}) + \nabla\varphi\cdot(\mathbf{J}_0+\Delta\mathbf{J})\right]$$

Superconducting or normal conducting region

Dissipation factor

Potential due to transport current

$$U(\mathbf{J}) = \int_0^{\mathbf{J}} \mathbf{E}(\mathbf{J}')\cdot d\mathbf{J}'$$

A is vector potential

Δ is change between two time steps

Can include any E-J relation such as E-J power law

How MEMEP 3D solves the problem?

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$$L = \int_\Omega \mathrm{d}^3\mathbf{r}\left[\frac{1}{2}\frac{\Delta\mathbf{A}_J}{\Delta t}\cdot\Delta\mathbf{J} + \frac{\Delta\mathbf{A}_a}{\Delta t}\cdot\Delta\mathbf{J} + U(\mathbf{J}_0 + \Delta\mathbf{J}) + \nabla\varphi\cdot(\mathbf{J}_0 + \Delta\mathbf{J})\right]$$

Minimum of this functional is the unique solution of the Maxwell differential equation

How MEMEP 3D solves the problem?

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$\nabla \times \mathbf{T} = \mathbf{J}$ T is called effective magnetization

Is calculated analytically or imported for various sources of external field

During Minimization (Open-circuit case)

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

Known variables

Only unknown variable

$$\mathbf{A}[\mathbf{J}](\mathbf{r}) = \frac{\mu_0}{4\pi}\int_V \mathrm{d}V' \frac{\mathbf{J}(\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|}$$

How MEMEP 3D solves the problem?

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After Minimization (Open-circuit case)

Become known variable

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

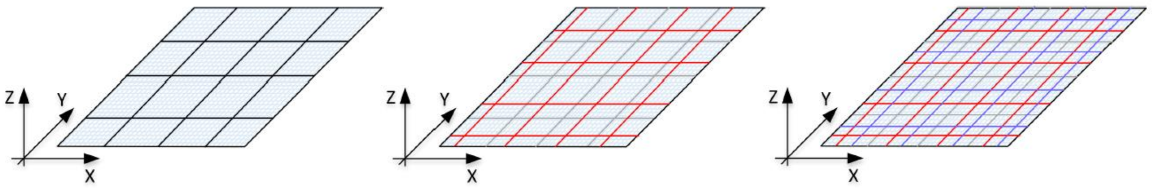
Effective magnetization (T) → Current density (J) → Vector potential (A) → Scalar potential (φ)

We do not need to solve scalar potential in the functional

Faster calculation speed with MEMEP

MEMEP has some features to speed up the calculation:

Sectors



Parallel programming

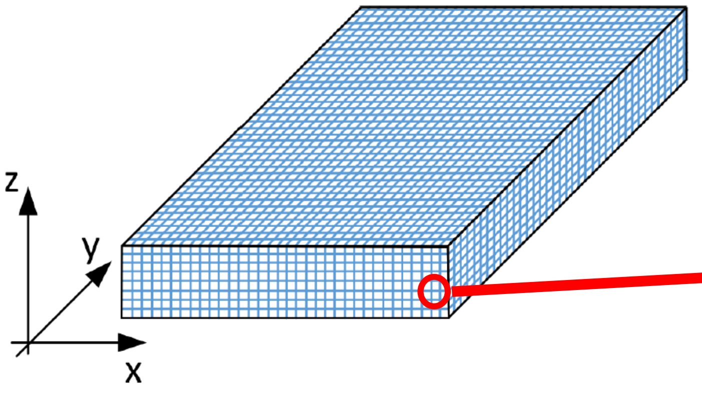
In one computer or in a cluster

Meshing only inside the sample

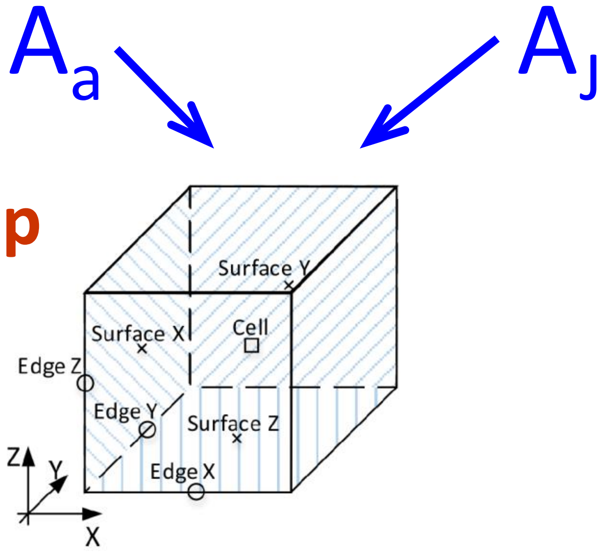
Less number of degrees of freedom and higher computational speed

How to model the movement?

There is no mesh in the air ⟶ no moving mesh is needed



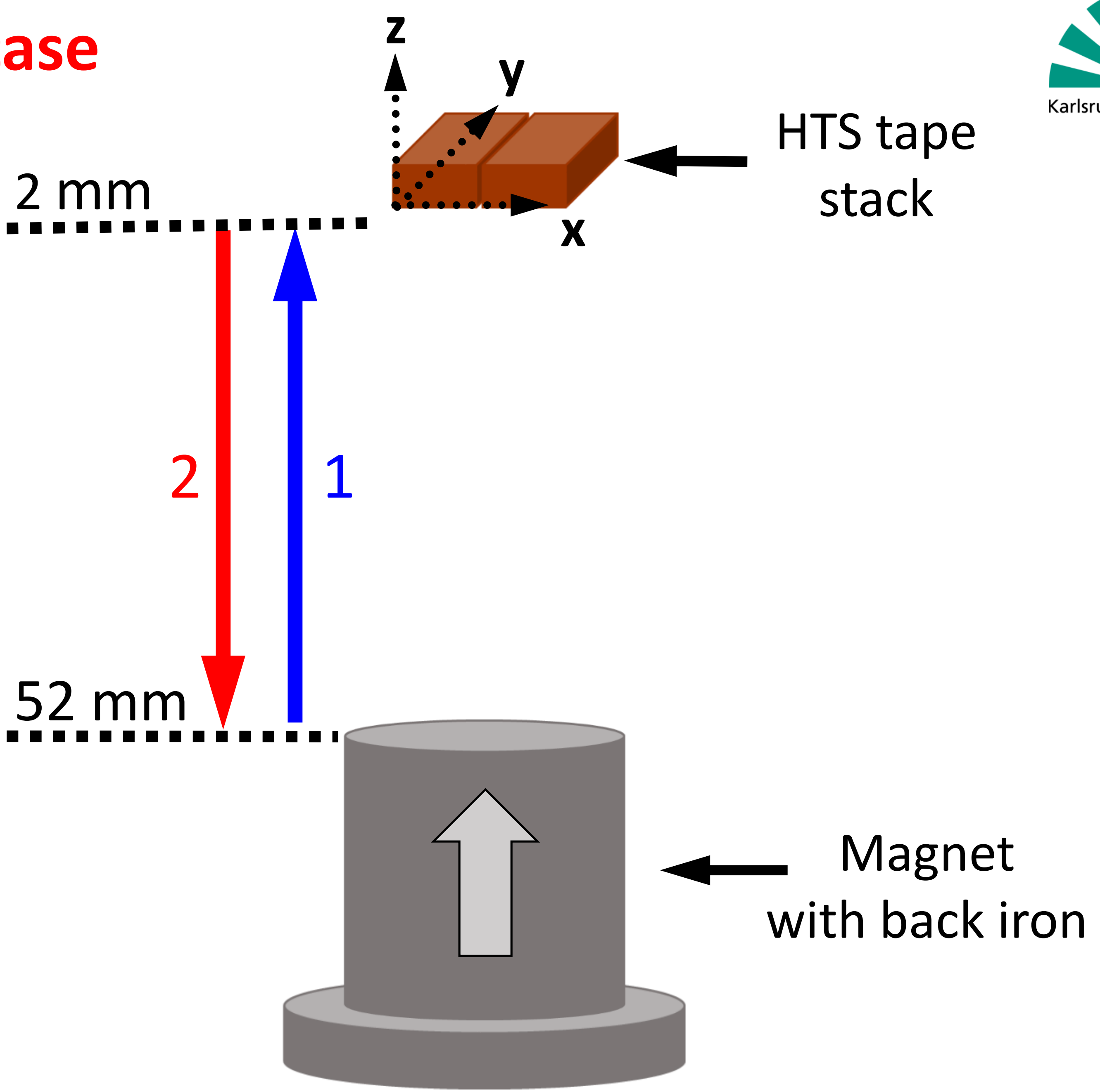
At each time step



A_J is already calculated by volume integral of J

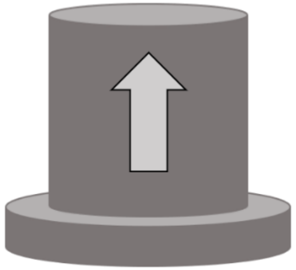
We only need to calculate **A_a** at each element position

Zero Field cooling case



Input parameters of problem

Cylindrical Permanent Magnet with back iron



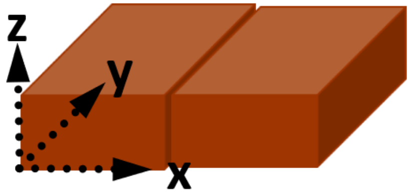
Diameter = 35 mm

Height = 20 mm

Remanent flux density (B_r) = 1.65 T

Magnet movement speed = 10 mm/s

HTS tape stack



width = 2×12 mm

Depth = 24 mm

Height = 10 mm

Measured tape critical current I_c = 400 A

Engineering critical current I_c = 4.4 × 10^8

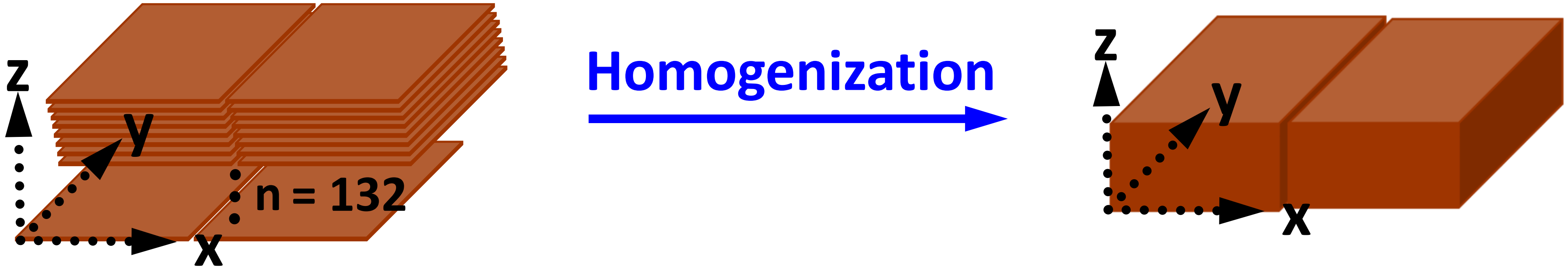
$$I_{c,\,Bulk} = I_{c,\,Tape} \times \frac{Thickness_{bulk}}{132 \times Thickness_{tape}}$$

Measured n-value = 32

Homogenization process

HTS tape stack

Bulk



$I_{c,\ tape}$

$I_{c,\ homo}$

Current is limited to flow in z direction

Modeling details

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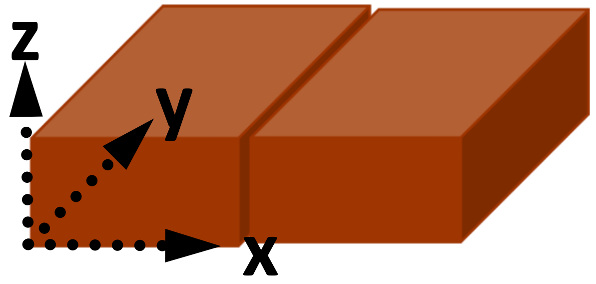
An anisotropic Kim like model is used to describe the dependence of I_c on the magnetic field

$$J_c(\mathbf{B}) = \frac{J_{c0}}{\left(1 + \frac{\sqrt{k^2 B_{//}{}^2 + B_{\perp}{}^2}}{B_0}\right)^{\alpha}}$$

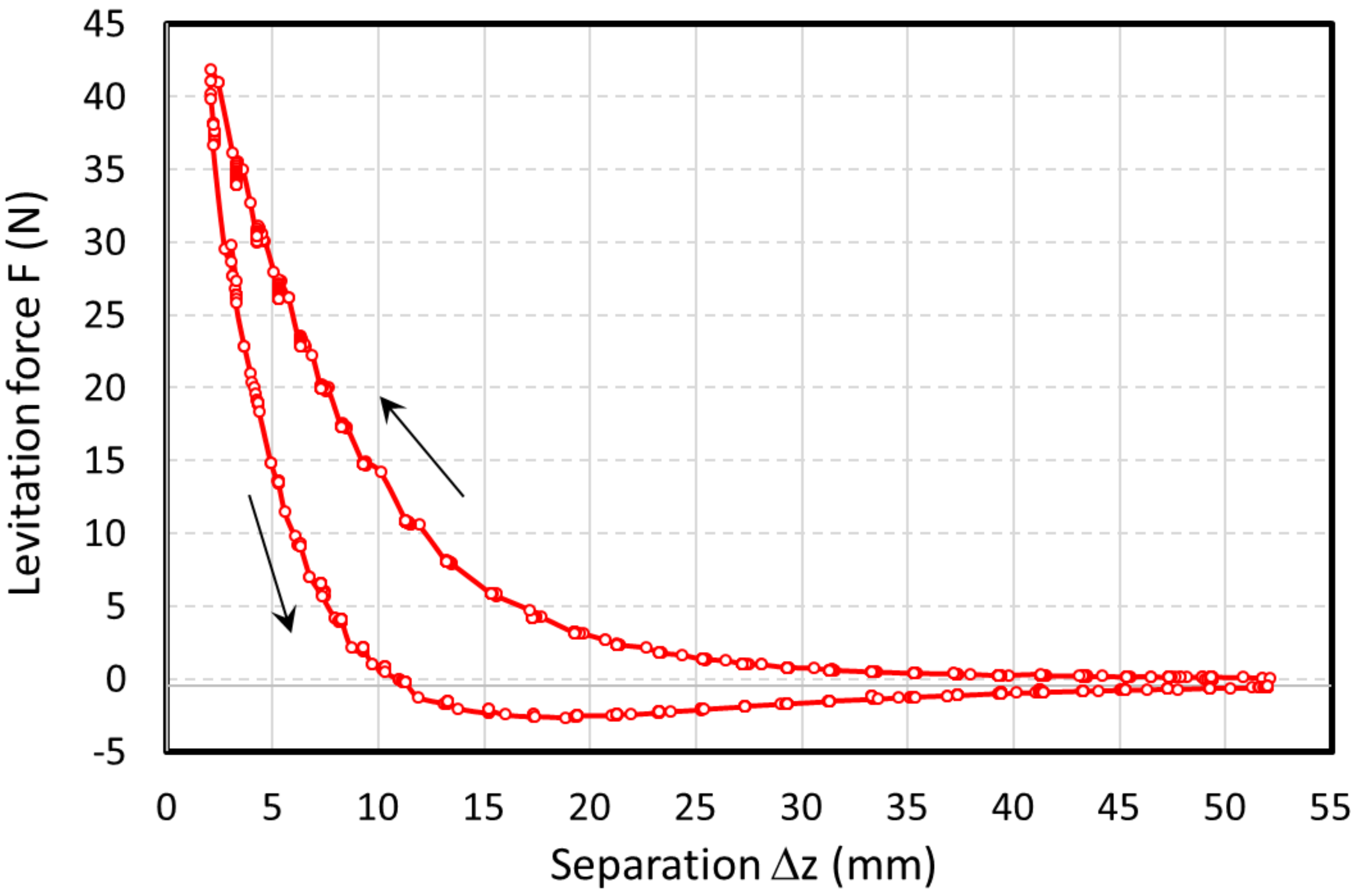


Force in z direction is calculated by

$$F_z(t) = \iiint_{\Omega sc} (J_x \, . \, B_y - J_y \, . B_x) \ dx \, dy \, dy$$

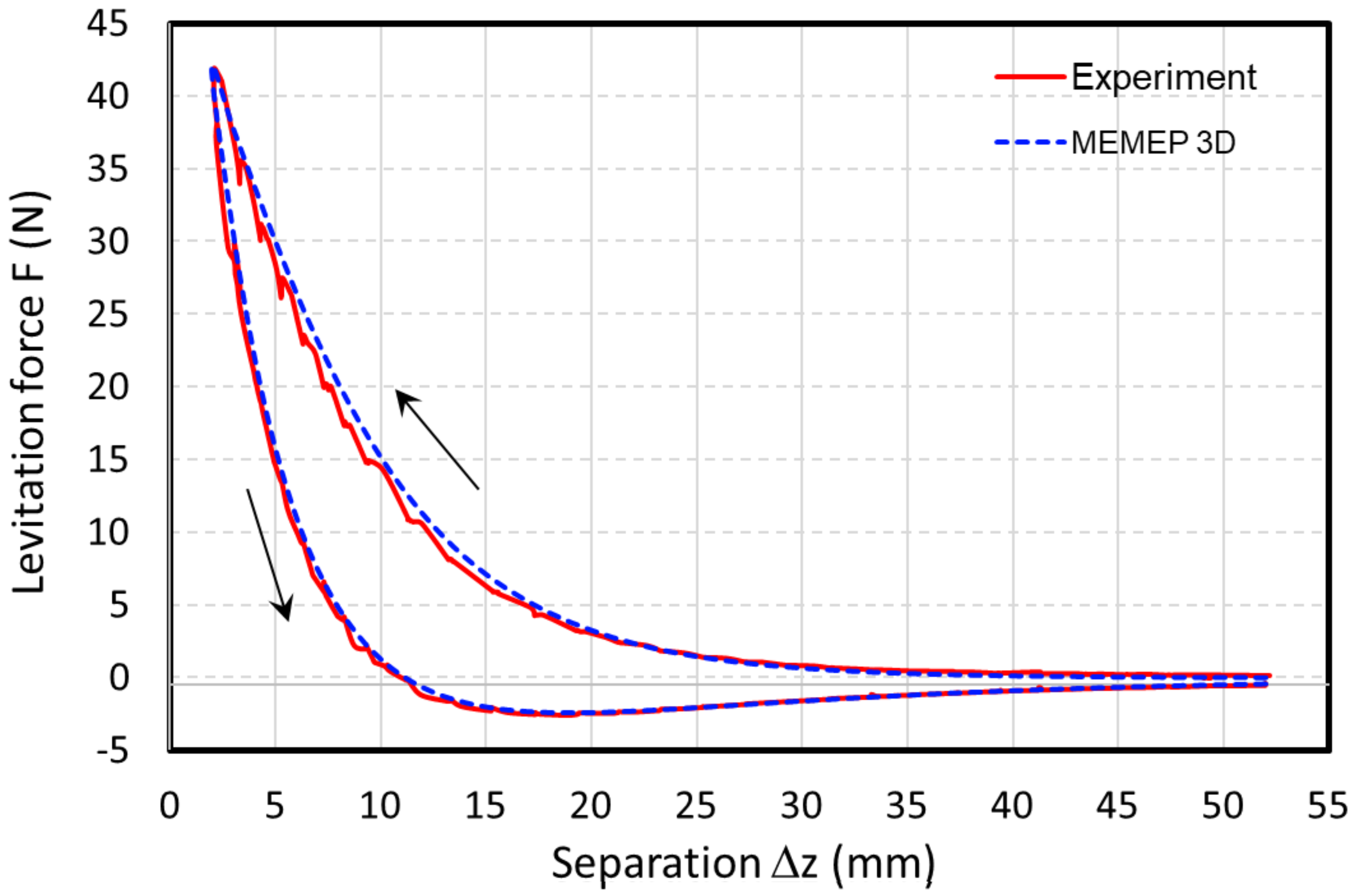
Modeling vs experimental results

Zero field cooling



Modeling vs experimental results

Zero field cooling



Good agreement between the model and experimental results!

Obtaining good agreement is possible using Kim like model instead of using experimental $J_c(B,\theta)$

Calculation time

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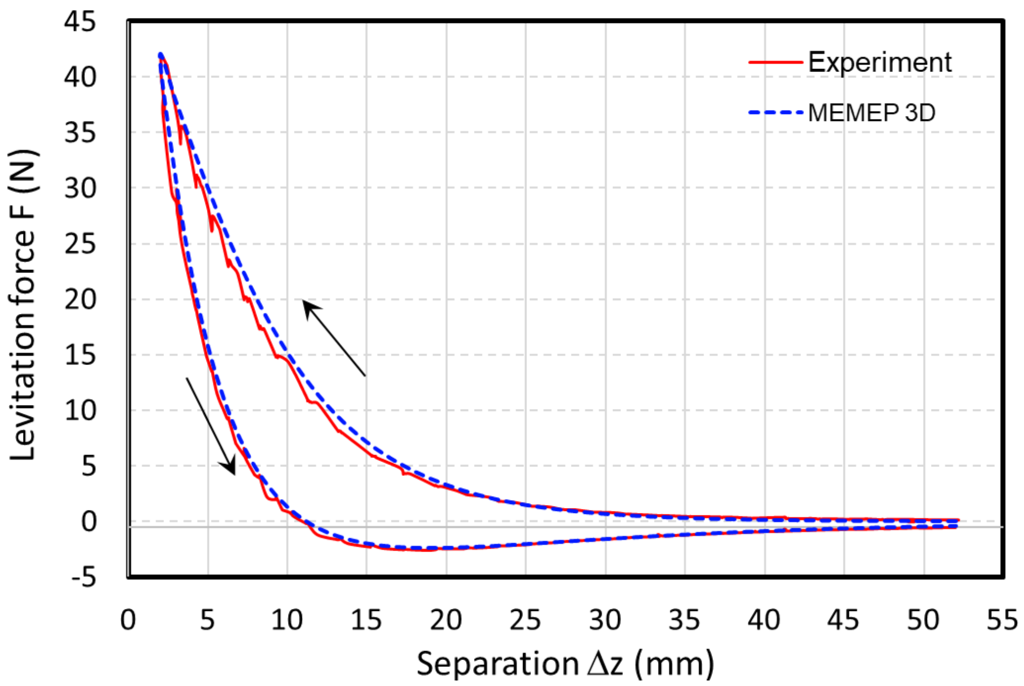
Zero field cooling



31 × 31 × 13 = 12,493 elements

Computer specification

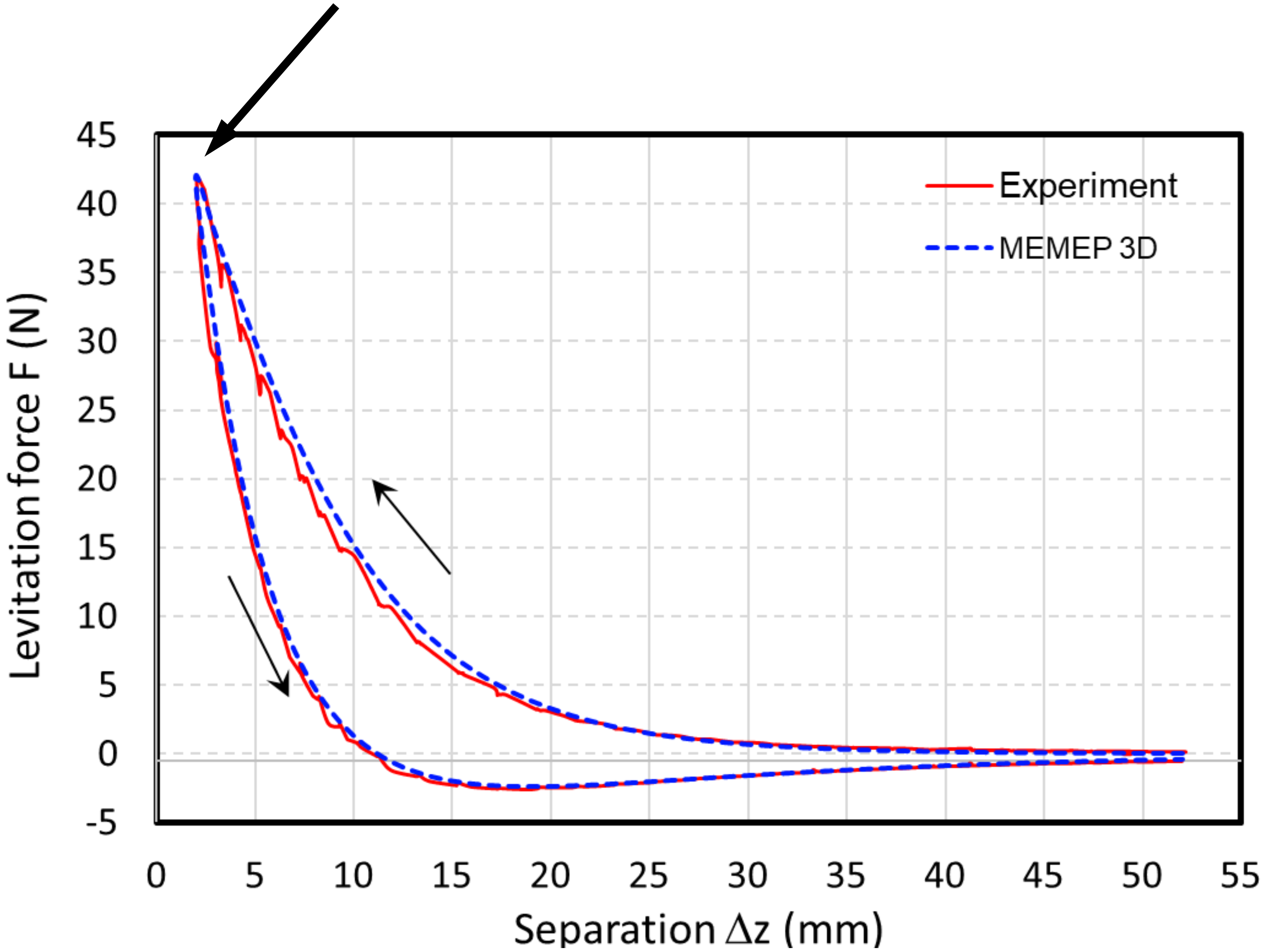
AMD Ryzen threadripper 3970x 32-core processor
128 GB RAM
Ubuntu 20.04.4 LTS operating system

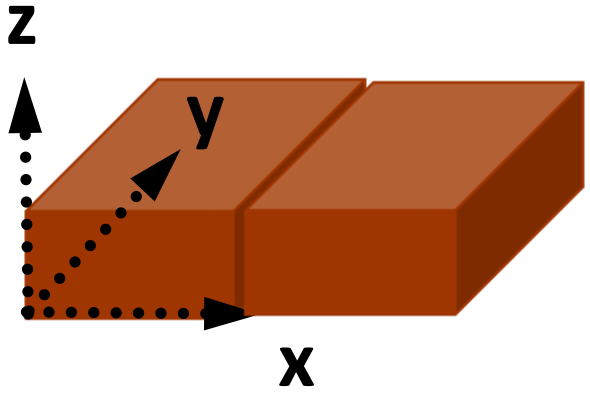
Simulation time

1 hours and 36 minutes

Screening current distribution

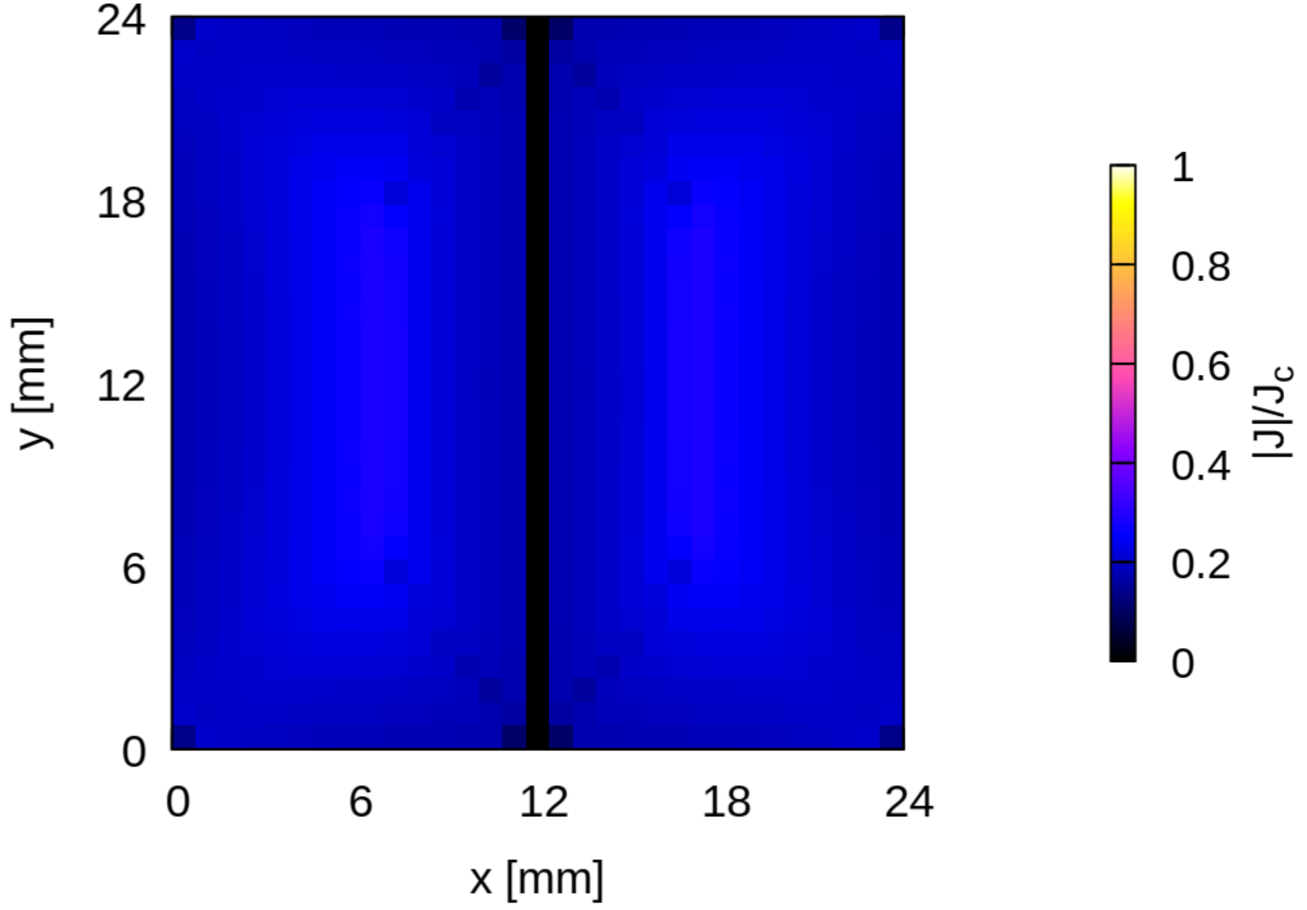
At minimum distance of Δz = 2 mm

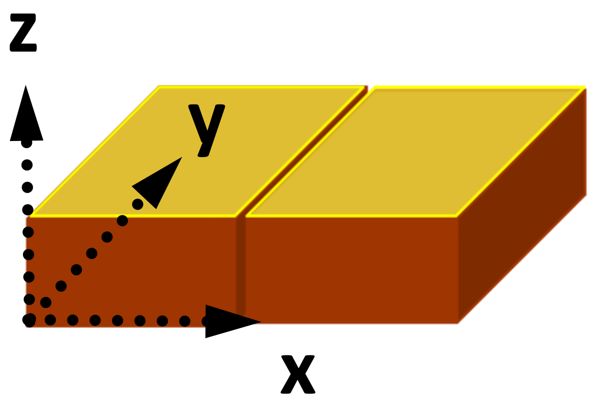




Screening current distribution in z-plane

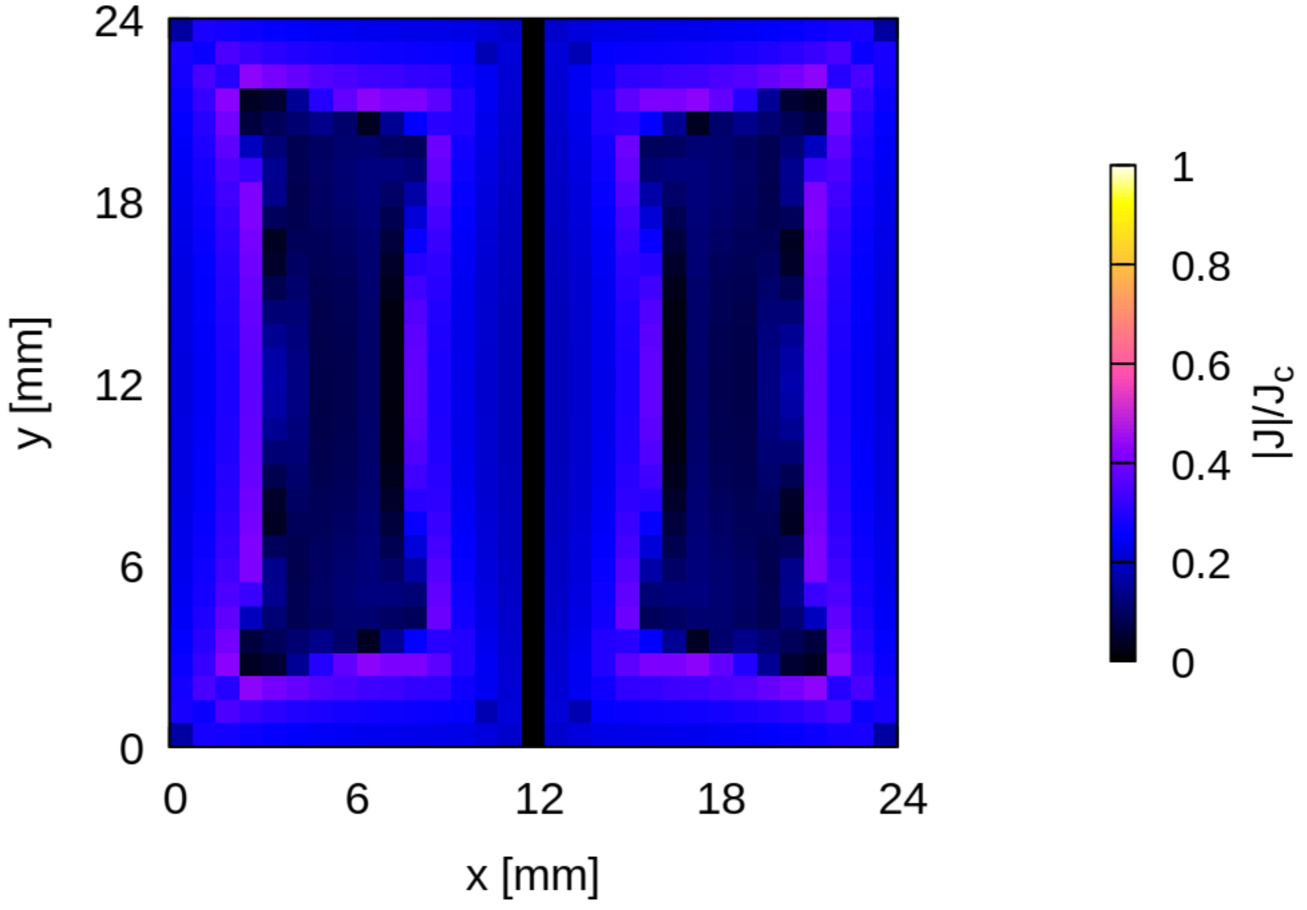
z = 0.3 mm

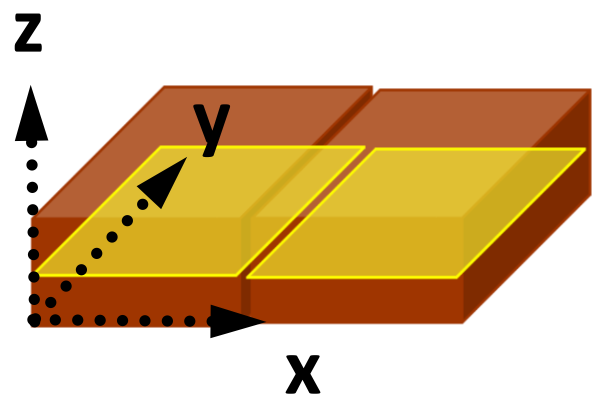




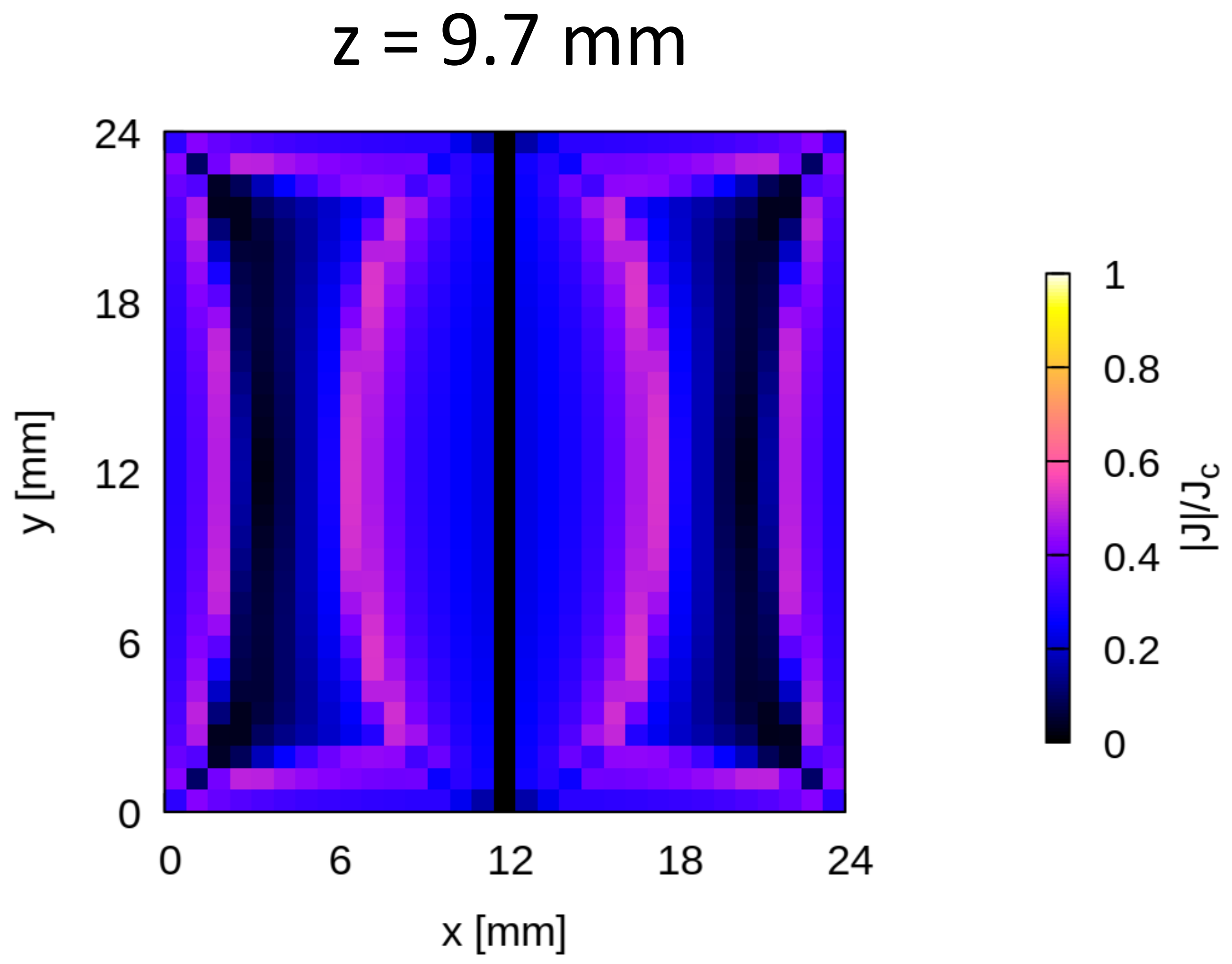
Screening current distribution in z-plane

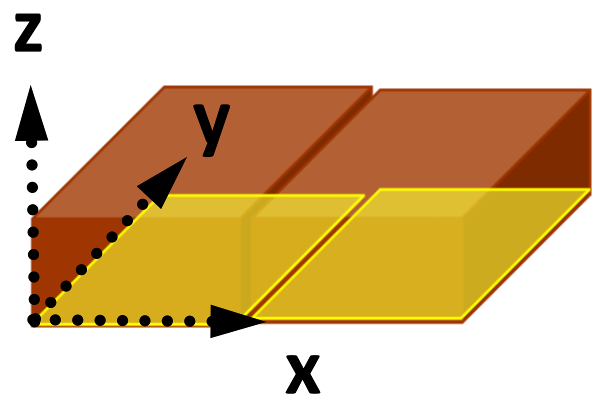
z = 5 mm





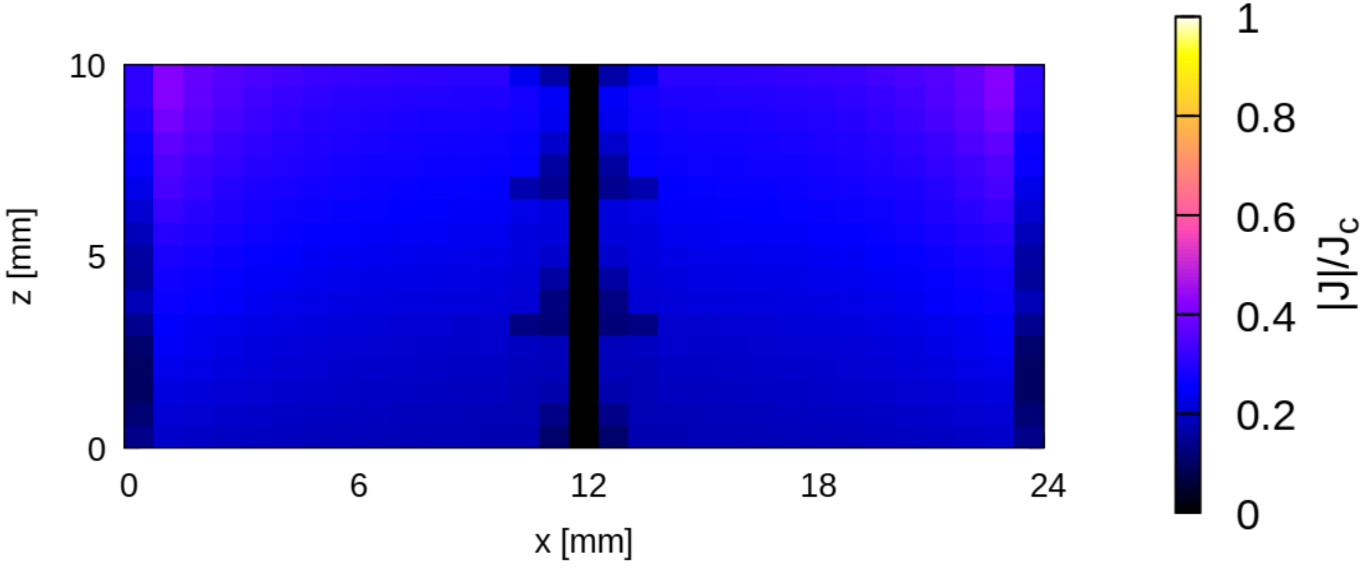
Screening current distribution in z-plane

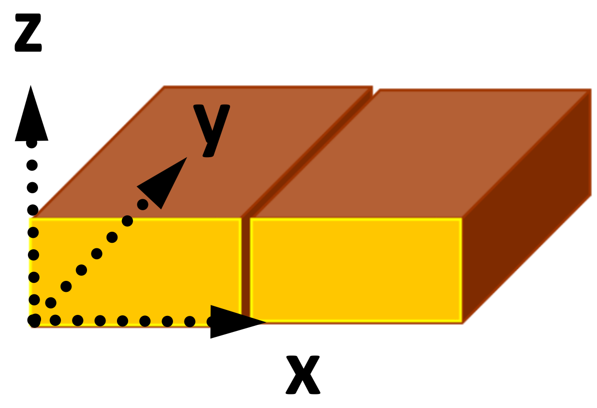




Screening current distribution in y-plane

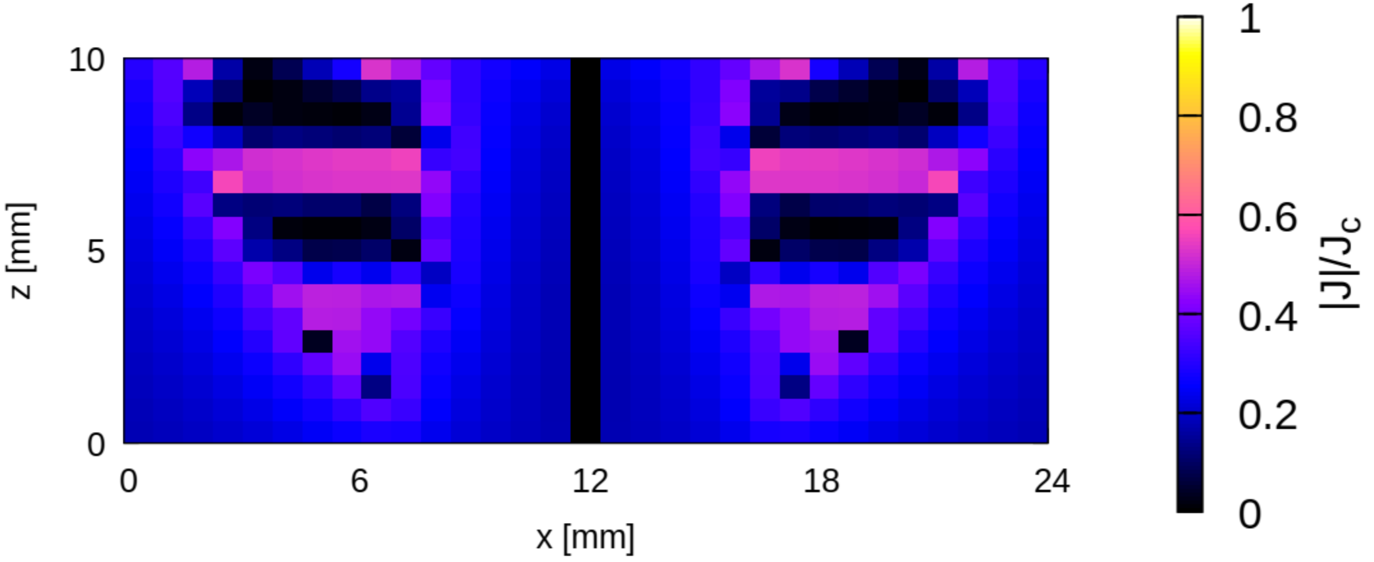
y = 0.4 mm

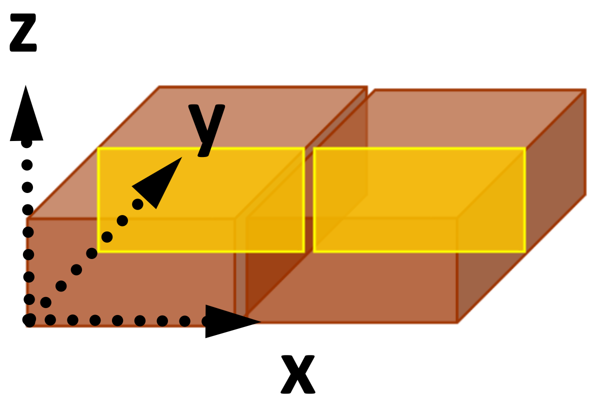




Screening current distribution in y-plane

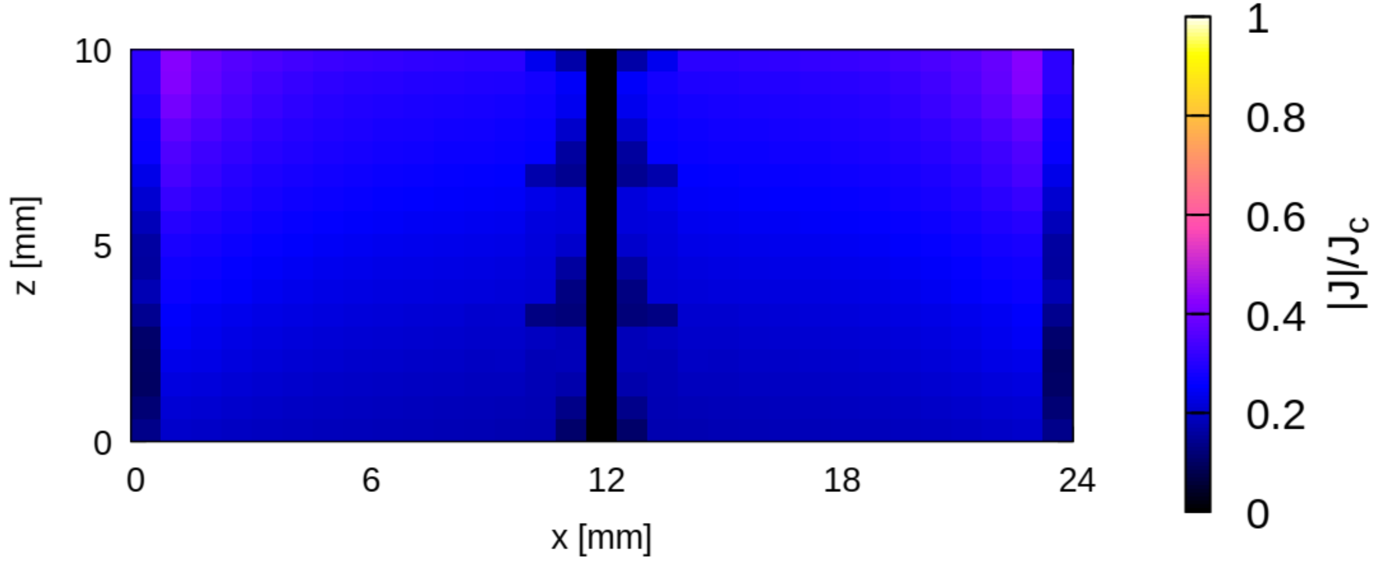
y = 12 mm

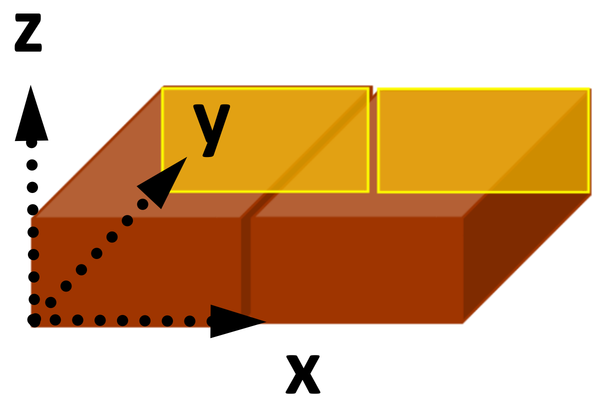




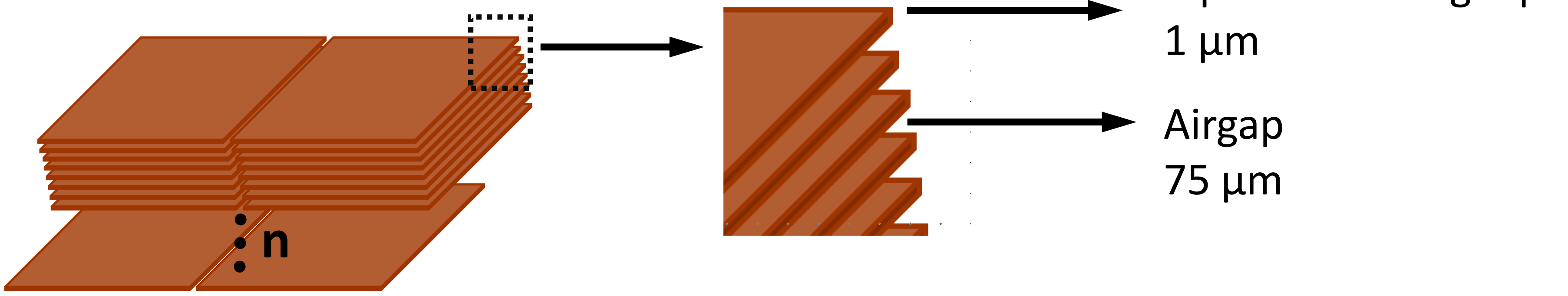
Screening current distribution in y-plane

y = 23.6 mm





Modeling tape stack with multiple tapes with real thickness



$I_c = 400$ A

Gap was considered as a material with ρ = 1

One element in the thickness for each tape and gap

Constant J_c was assumed for simplicity

This model is especially practical for investigating the impact of tape substrate thickness in levitation force

Modeling tape stack with multiple tapes with real thickness

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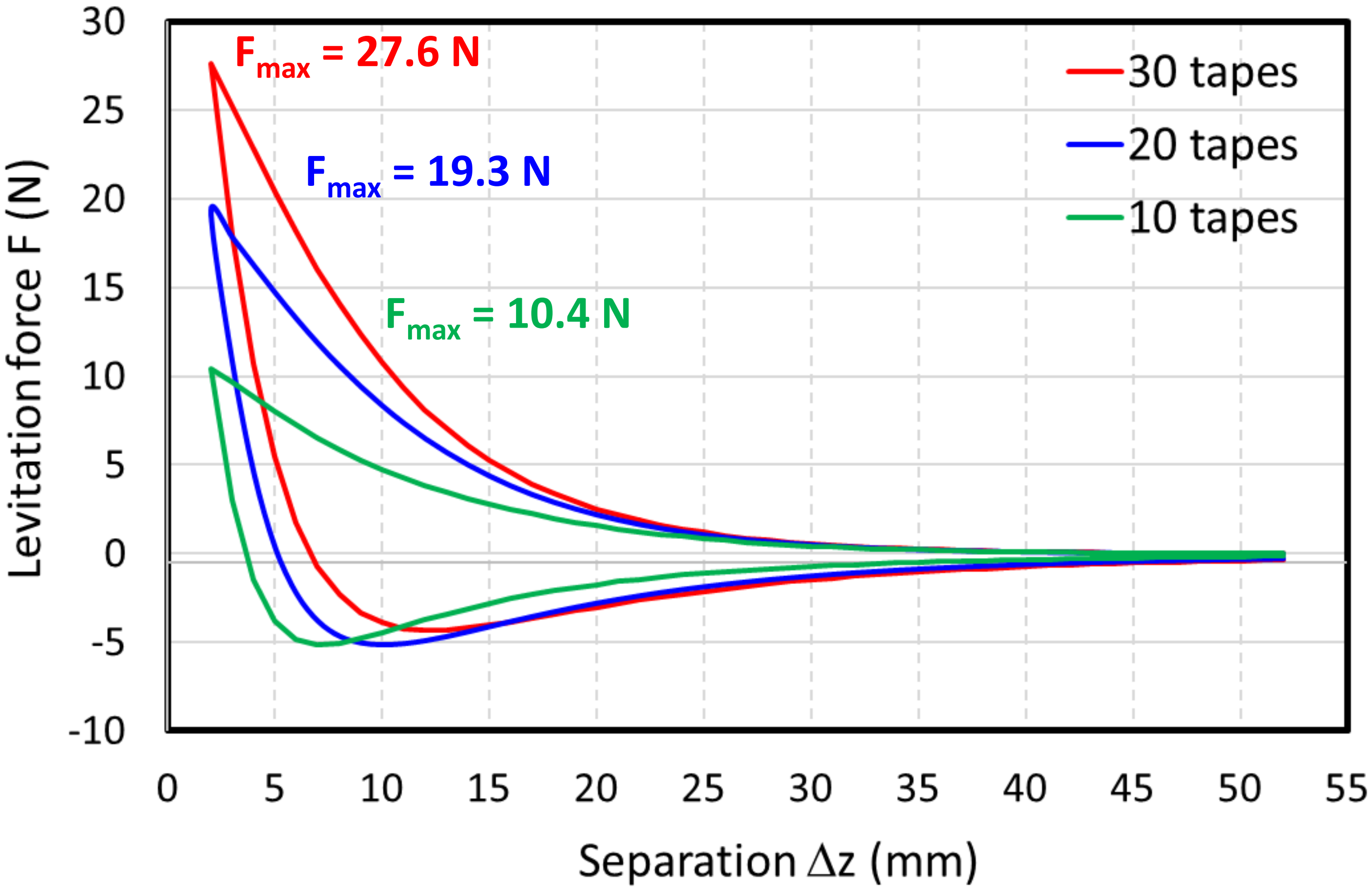

The forces are overcalculated compared to their real value because of assuming constant J_c

Calculation time

x × y × z elements

10 tapes → 25×25×19 → 2.5 hours

20 tapes → 25×25×39 → 10 hours

30 tapes → 25×25×59 → 30 hours

Modeling tape stack with multiple tapes with real thickness

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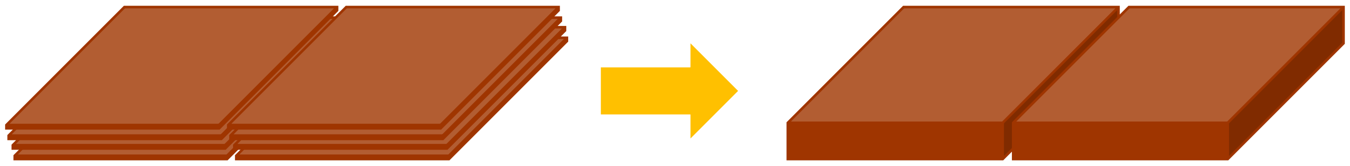
Calculation time

30 tapes $\xrightarrow{25\times25\times59}$ 30 hours

132 tapes $\xrightarrow{25\times25\times263}$ **Can take up to weeks!**

A possible solution



$I_{c,\ tape}$ → $I_{c,\ homo}$

Summary

A model based on MEMEP 3D was presented for modeling the magnetization of HTS tape stacks

MEMEP 3D employs some features to increase the efficiency and calculation speed

A good agreement between the homogenized model and experiment was obtained

Using Kim like model can lead to acceptably good agreement

Modeling each individual tape separately is not a practical method for modeling tape stacks in 3D

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Thanks for your attention!