

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

Asef Ghabeli, Francesco Grilli, Pengbo Zhou, Jens Hänisch
Günter Fuchs, Oliver de Haas

Since 1969



**German Transrapid TR-07
Electromagnetic Levitation (EML)**



**Japanese Yamanashi
Electrodynamics Levitation (EDL)**

Speed up to 500 km/h!

Full-sized HTS Maglev trains



SupraTrans II
IFW-Dresden, Germany (2011)



Century
Southwest Jiaotong Univ., China (2012)

Can carry up to 15 passengers!



MagLev-Cobra
COPPE/UFRJ, Brazil (2015)

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

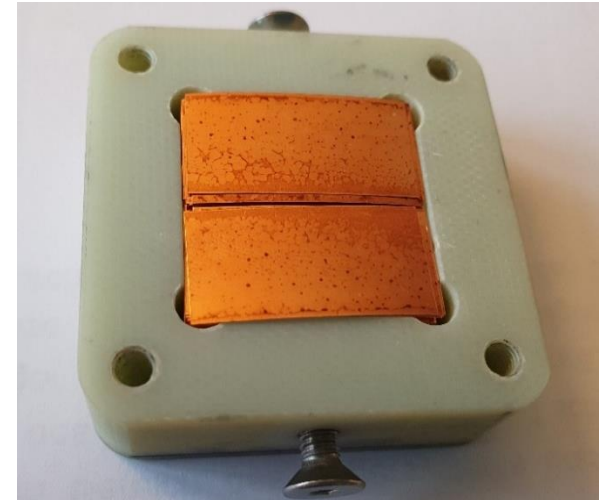
Maglev trains with HTS tape stacks

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



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

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Minimum Electromagnetic Entropy Production method in 3D (MEMEP 3D)

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?

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

Current density
External field

↑
↑

↓
↓

Superconducting or normal conducting region
Dissipation factor
Potential due to transport current

\mathbf{A} is vector potential

Δ is change between two time steps

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

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

How MEMEP 3D solves the problem?

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

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

How MEMEP 3D solves the problem?

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

During Minimization (Open-circuit case)

Is calculated analytically or imported for various sources of external field

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

Known variables
Only unknown variable

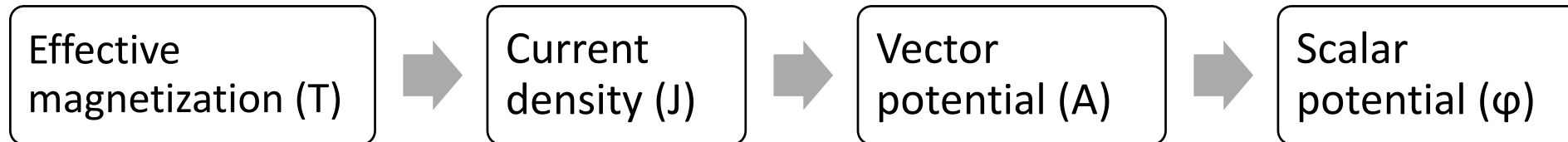
$$\mathbf{A}[\mathbf{J}](\mathbf{r}) = \frac{\mu_0}{4\pi} \int_V dV' \frac{\mathbf{J}(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|}$$

How MEMEP 3D solves the problem?

After Minimization (Open-circuit case)

Become known variable

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

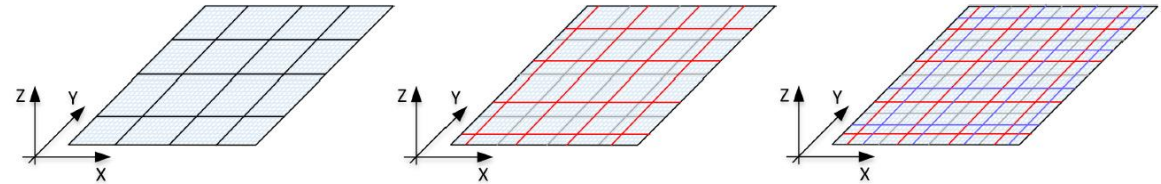


We do not need to solve scalar potential in the functional

Faster calculation speed with MEMEP

MEMEP has some features to speed up the calculation:

Sectors



Parallel programming

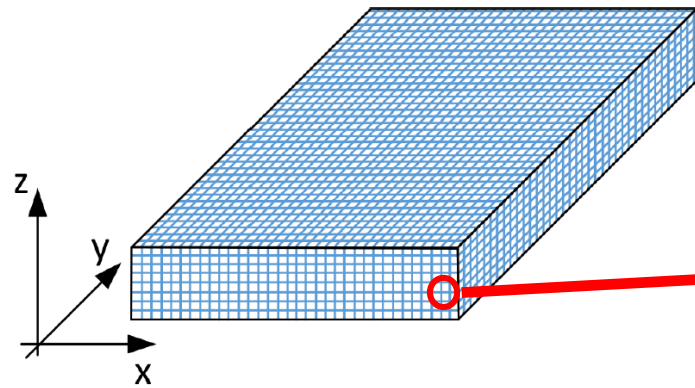
In one computer or in a cluster

Meshing only inside the sample

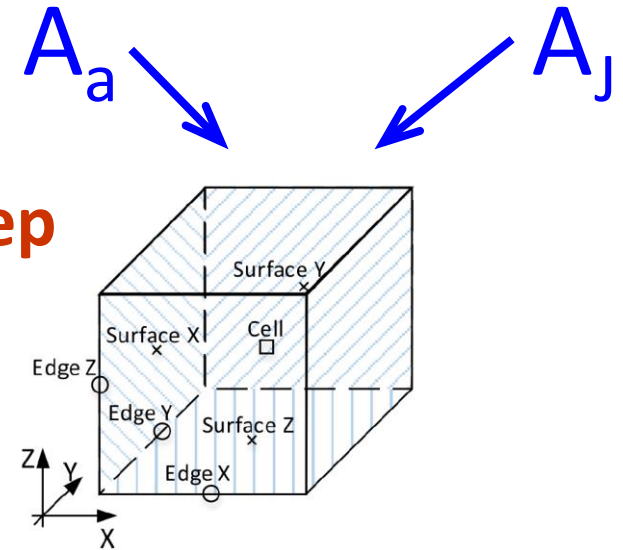
Less number of degrees of freedom and higher computational speed

How to model the movement?

There is no mesh in the air \longrightarrow no moving mesh is needed



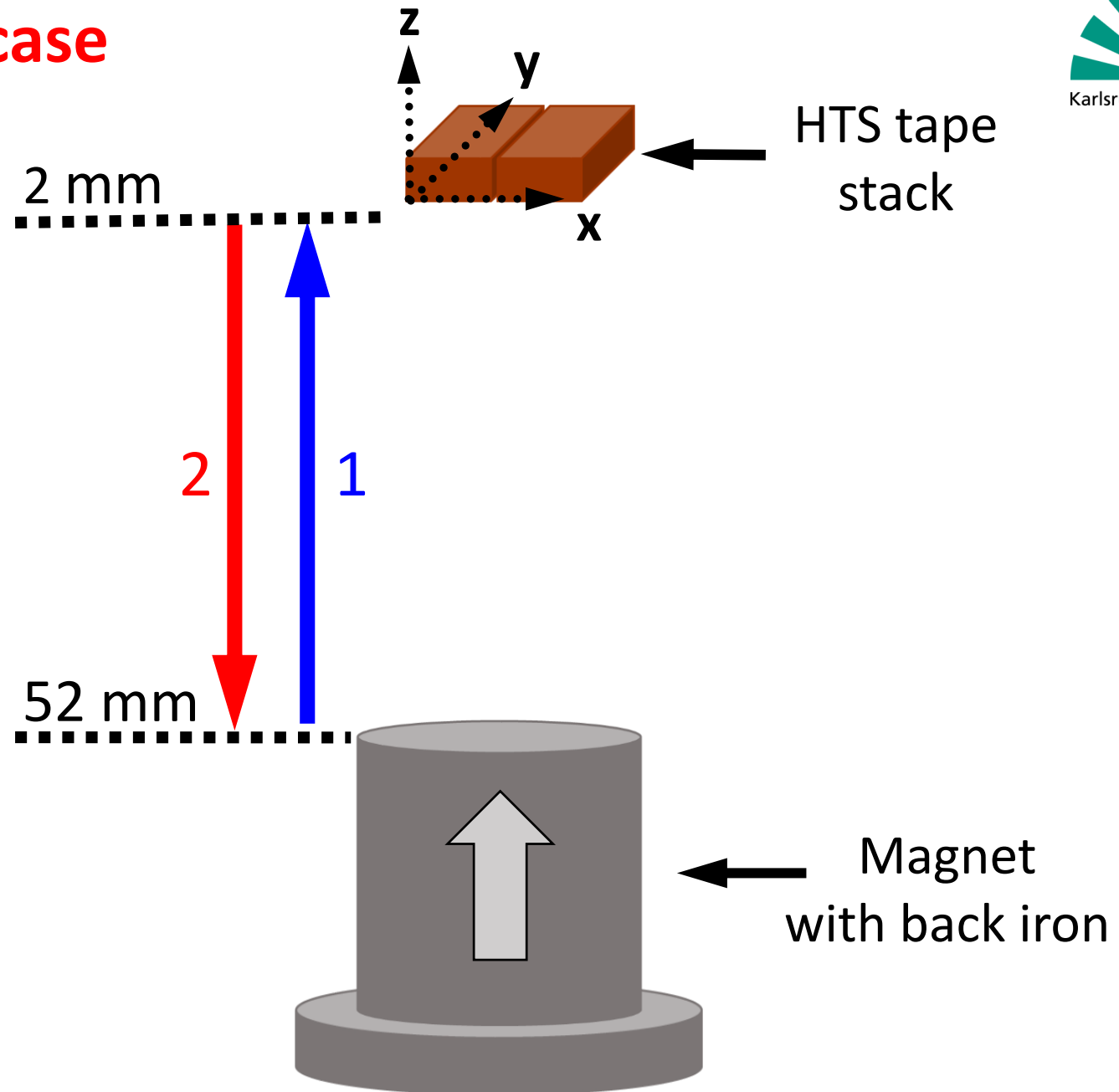
At each time step



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

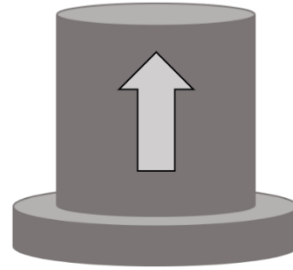
Cylindrical Permanent Magnet with back iron

Diameter = 35 mm

Height = 20 mm

Remanent flux density (B_r) = 1.65 T

Magnet movement speed = 10 mm/s



HTS tape stack

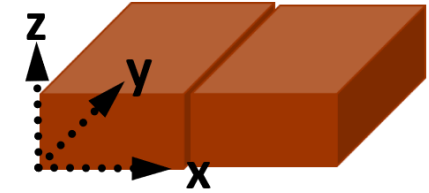
width = 2×12 mm

Depth = 24 mm

Height = 10 mm

Measured tape critical current $I_c = 400$ A

Engineering critical current $I_c = 4.4 \times 10^8$

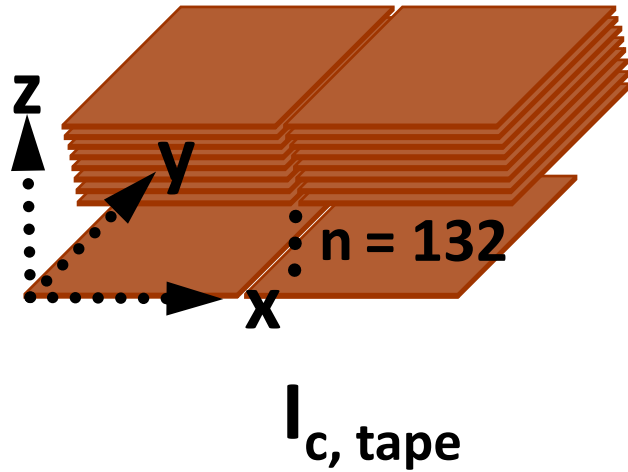


$$I_{c, \text{Bulk}} = I_{c, \text{Tape}} \times \frac{\text{Thickness}_{\text{bulk}}}{132 \times \text{Thickness}_{\text{tape}}}$$

Measured n-value = 32

Homogenization process

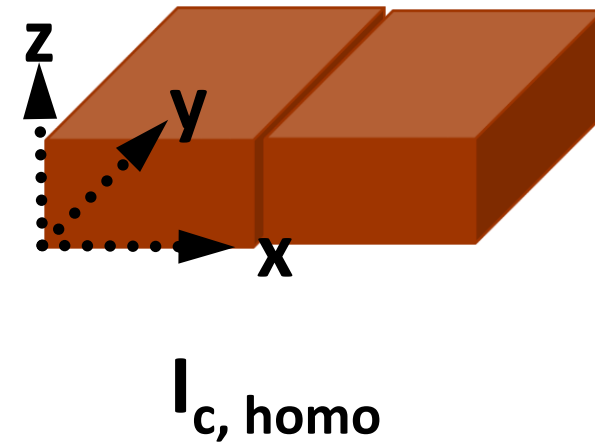
HTS tape stack



Homogenization



Bulk



Current is limited to flow in z direction

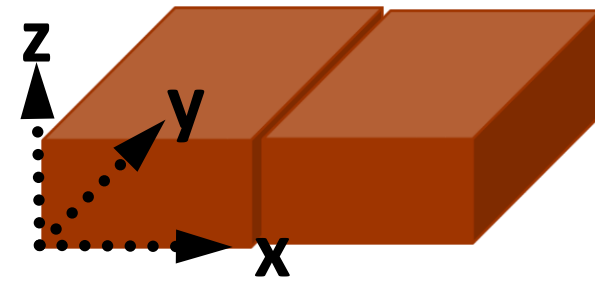
Modeling details

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

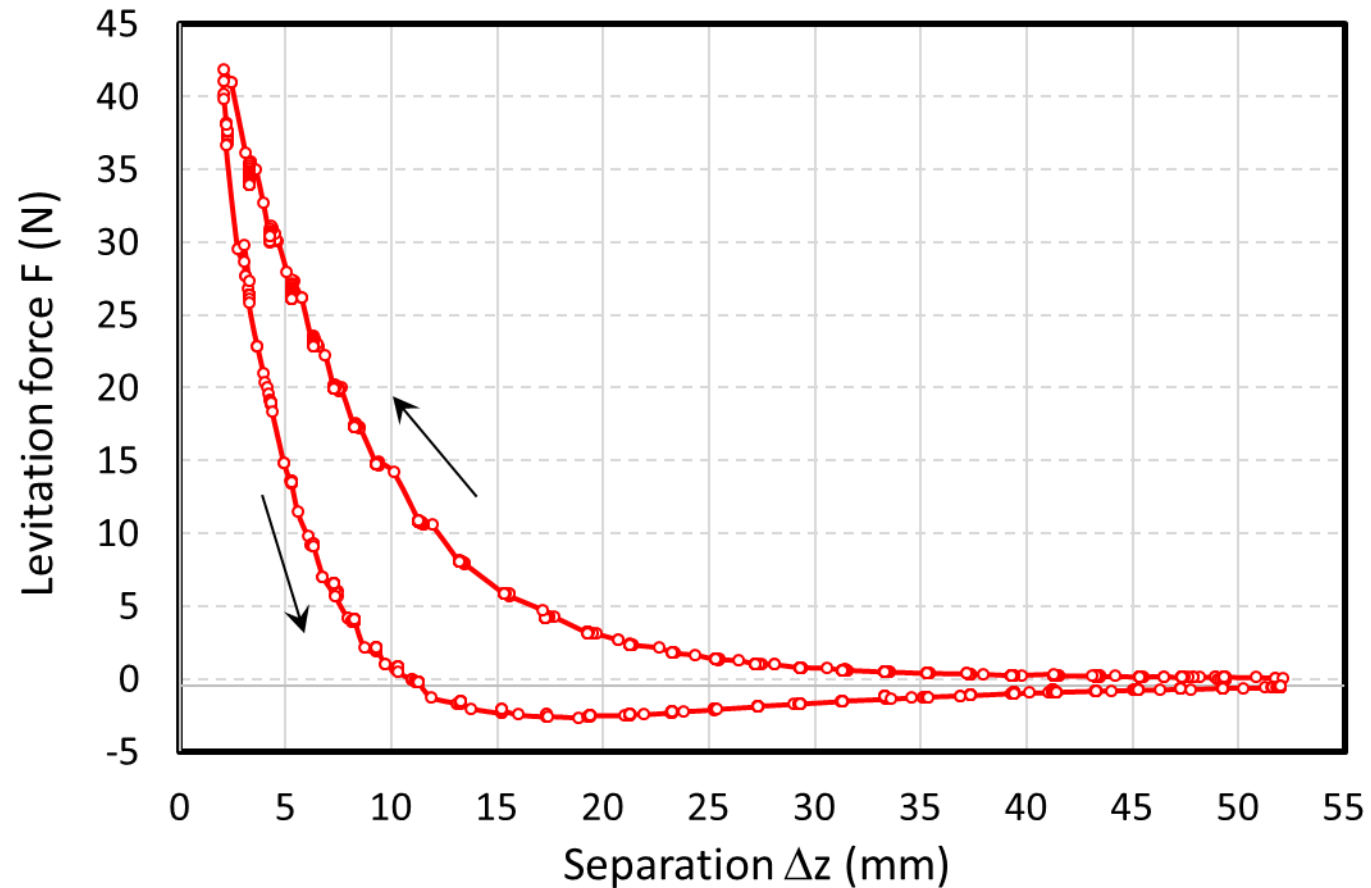
$$F_z(t) = \iiint_{\Omega_{SC}} (J_x \cdot B_y - J_y \cdot B_x) \, dx \, dy \, dz$$



$I_{c, \text{homo}}$

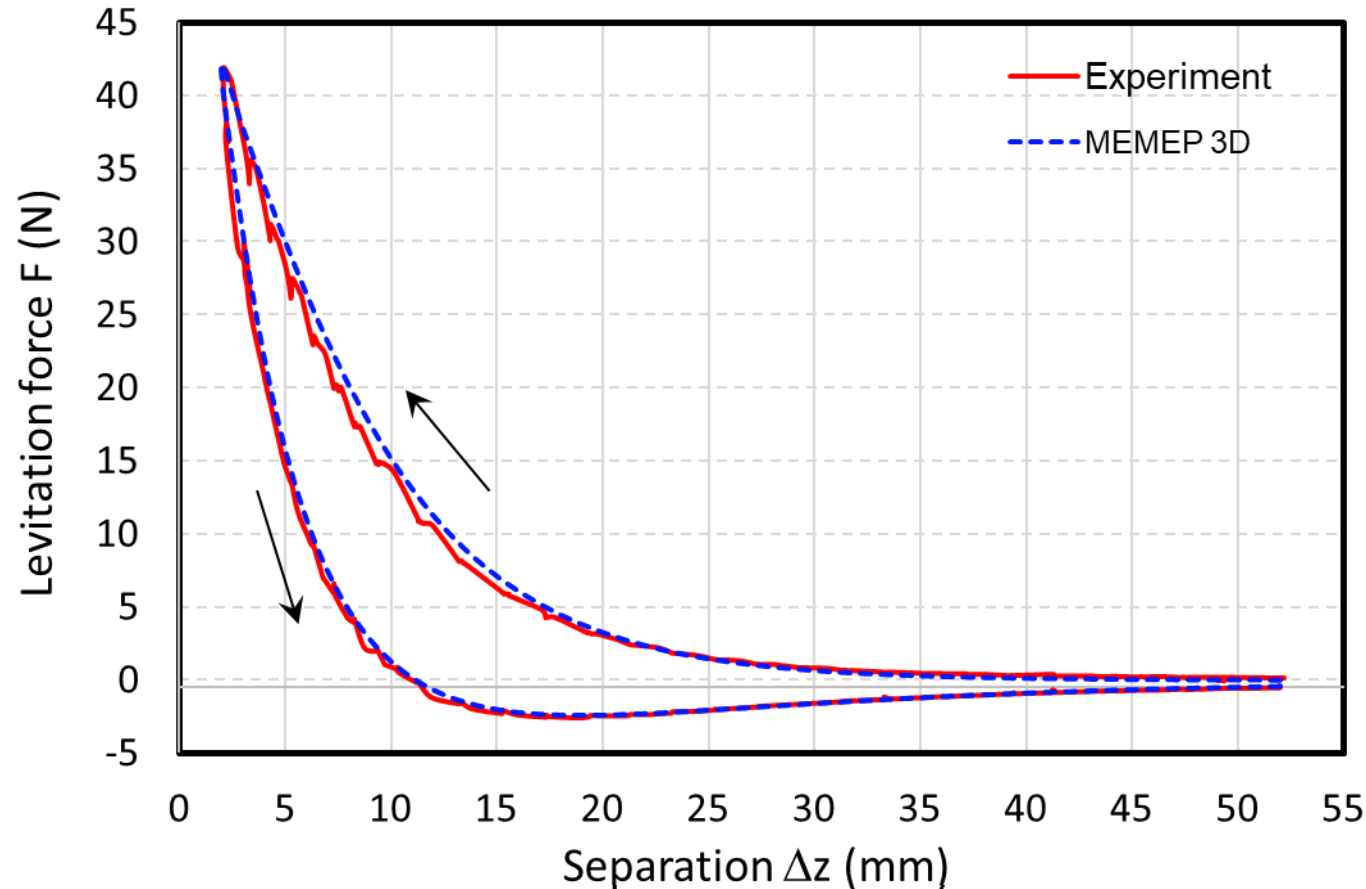
Modeling vs experimental results

Zero field cooling



Modeling vs experimental results

Zero field cooling

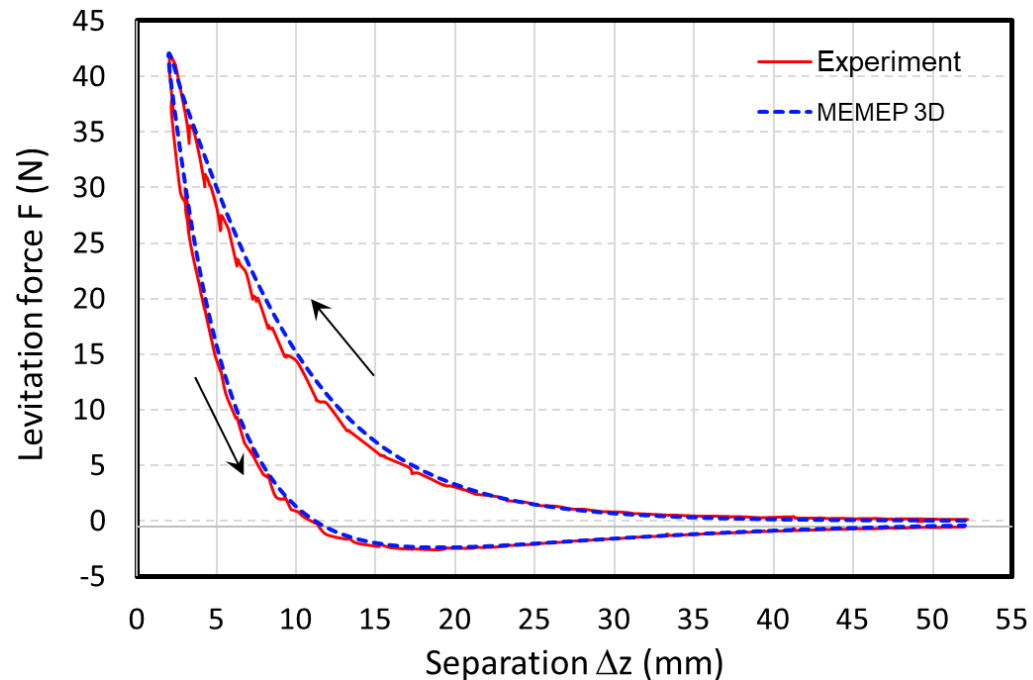


Good agreement between the model and experimental results!

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

Calculation time

Zero field cooling



$31 \times 31 \times 13 = 12,493$ elements

Computer specification

AMD Ryzen threadripper 3970x 32-core processor

128 GB RAM

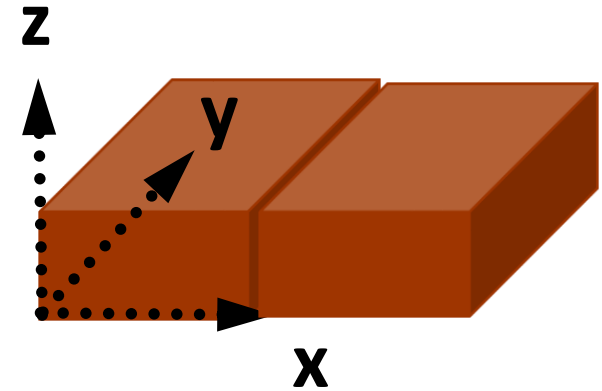
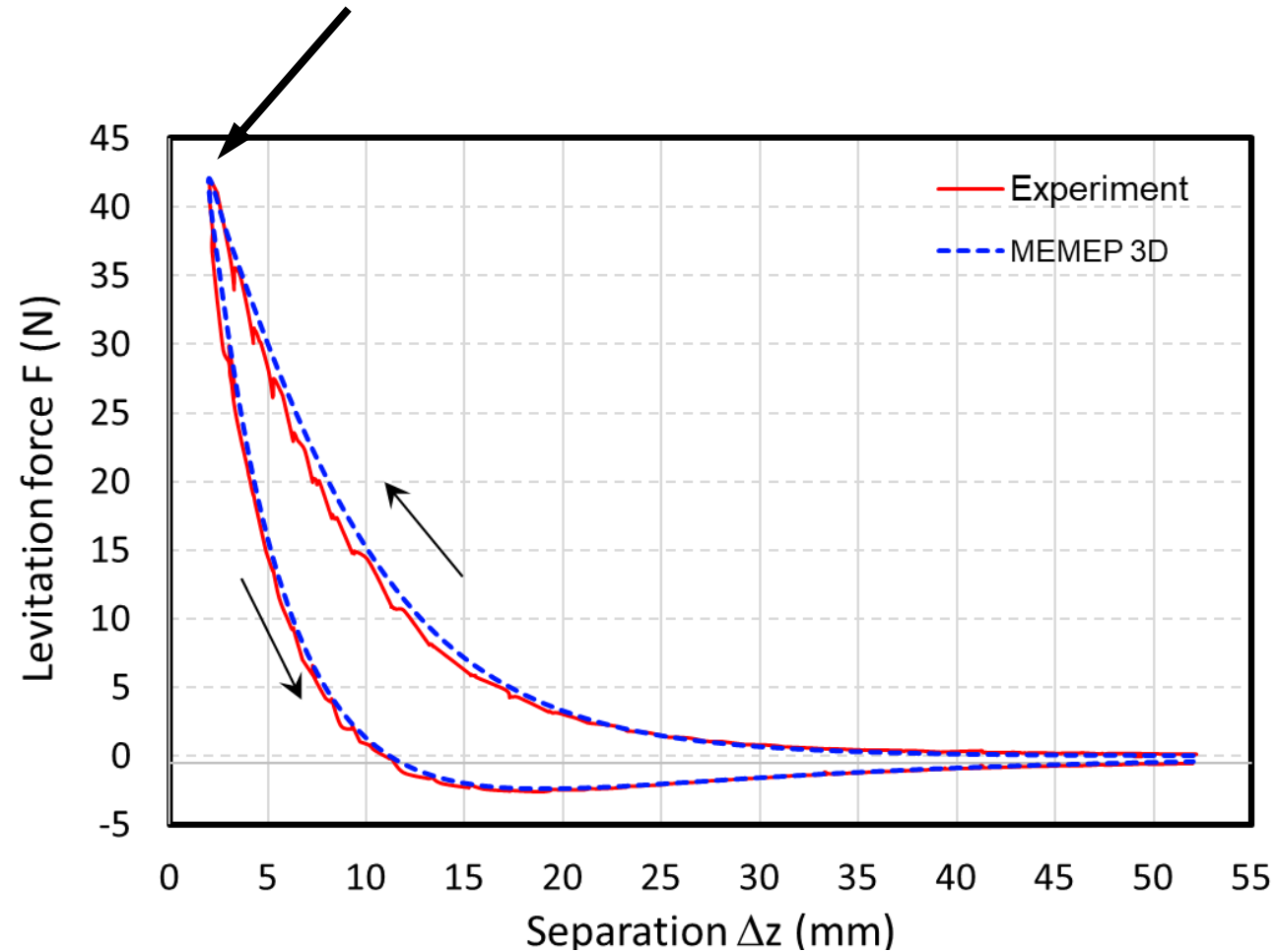
Ubuntu 20.04.4 LTS operating system

Simulation time

1 hours and 36 minutes

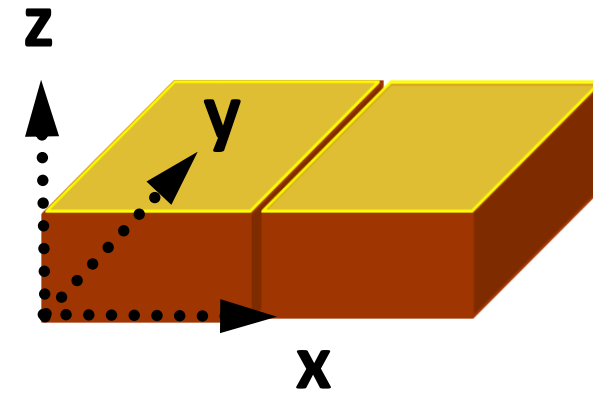
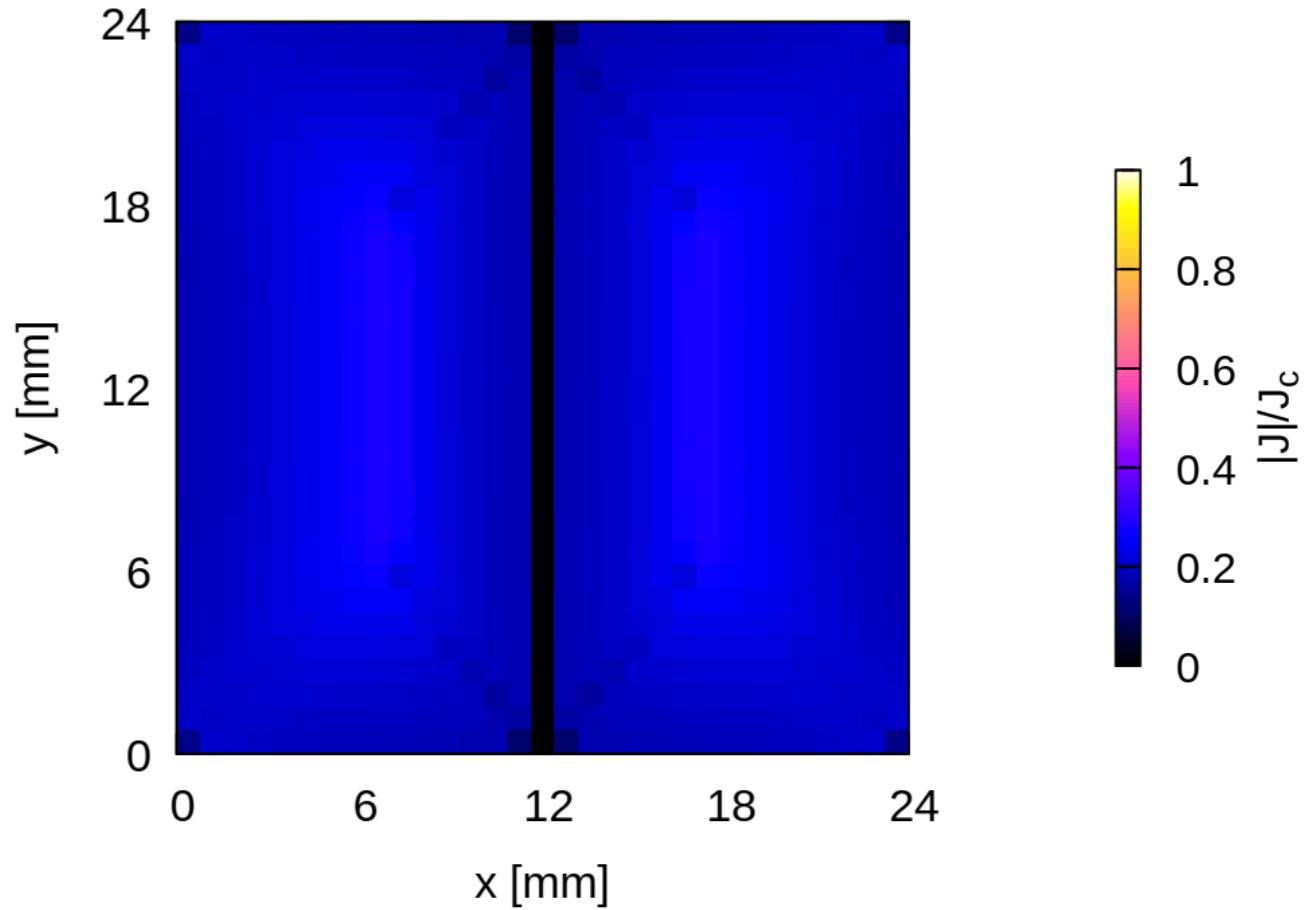
Screening current distribution

At minimum distance of $\Delta z = 2$ mm



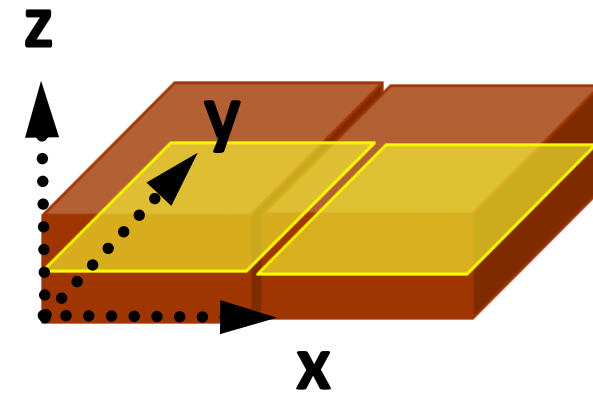
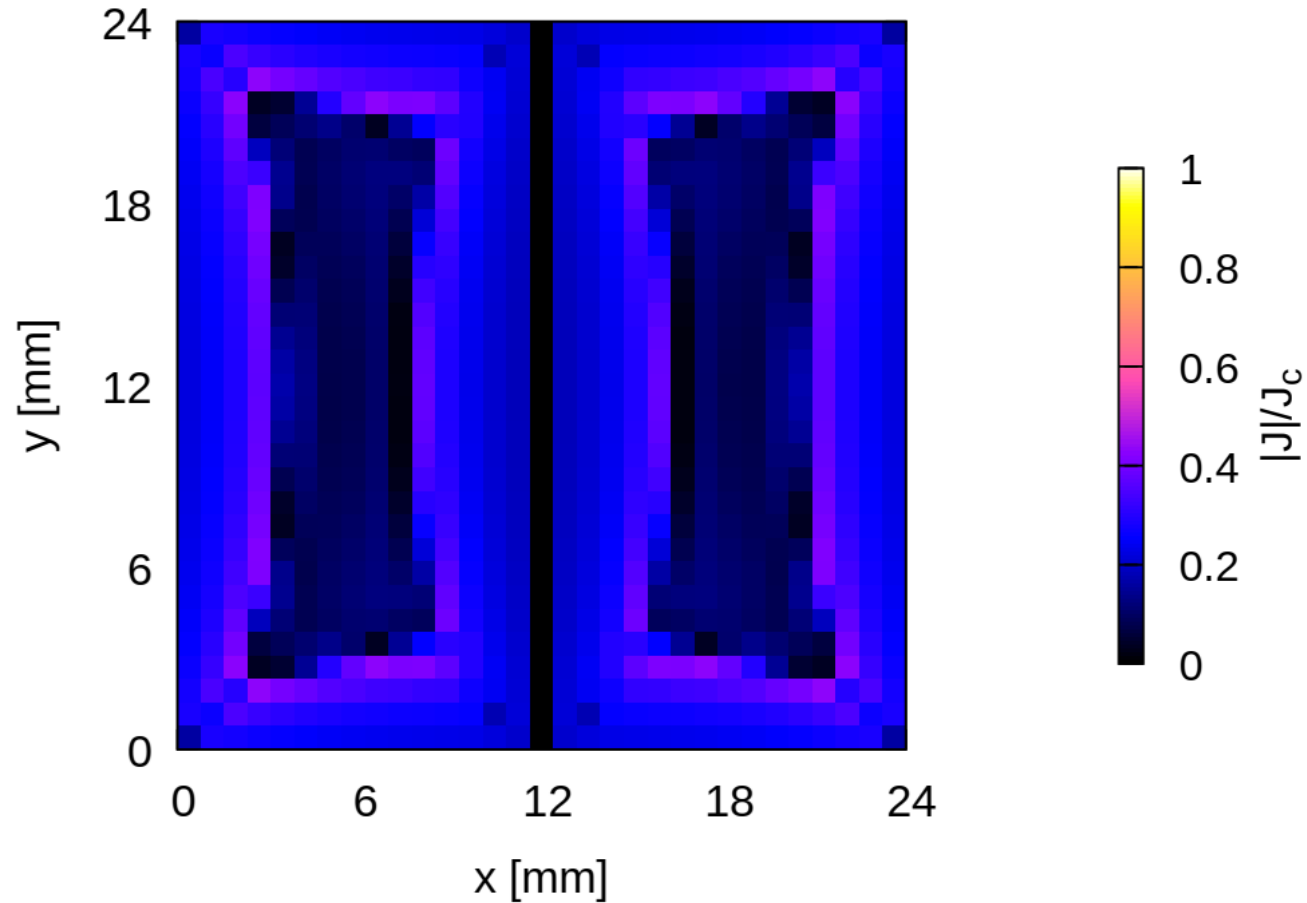
Screening current distribution in z-plane

$z = 0.3 \text{ mm}$



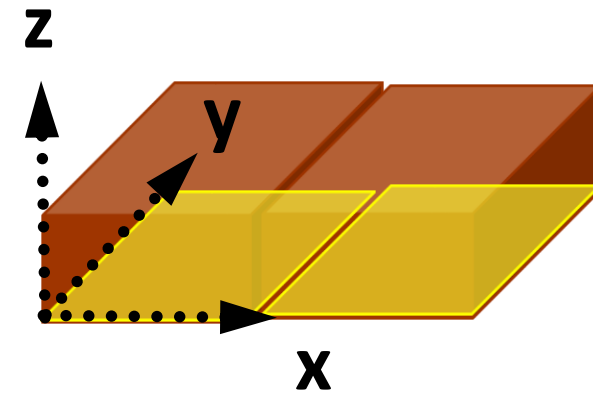
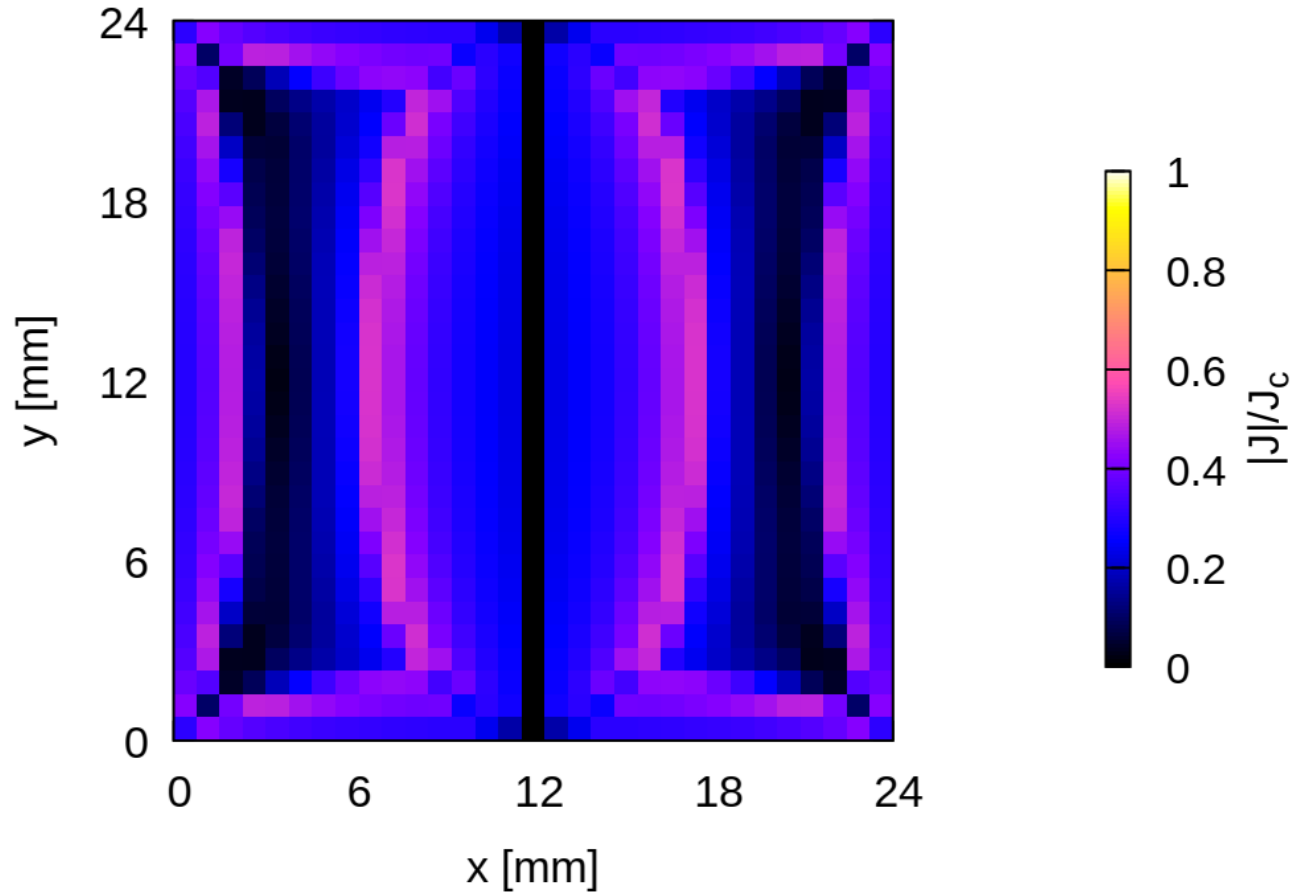
Screening current distribution in z-plane

$z = 5 \text{ mm}$



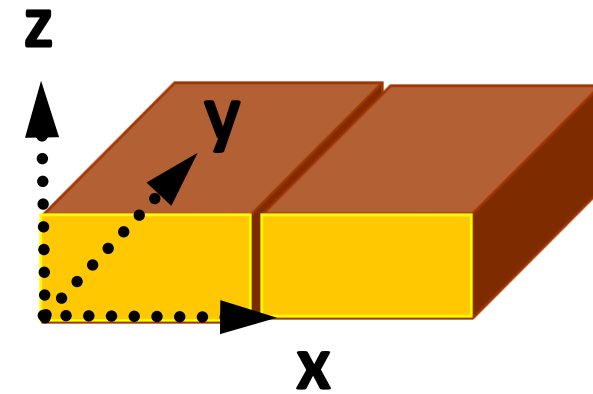
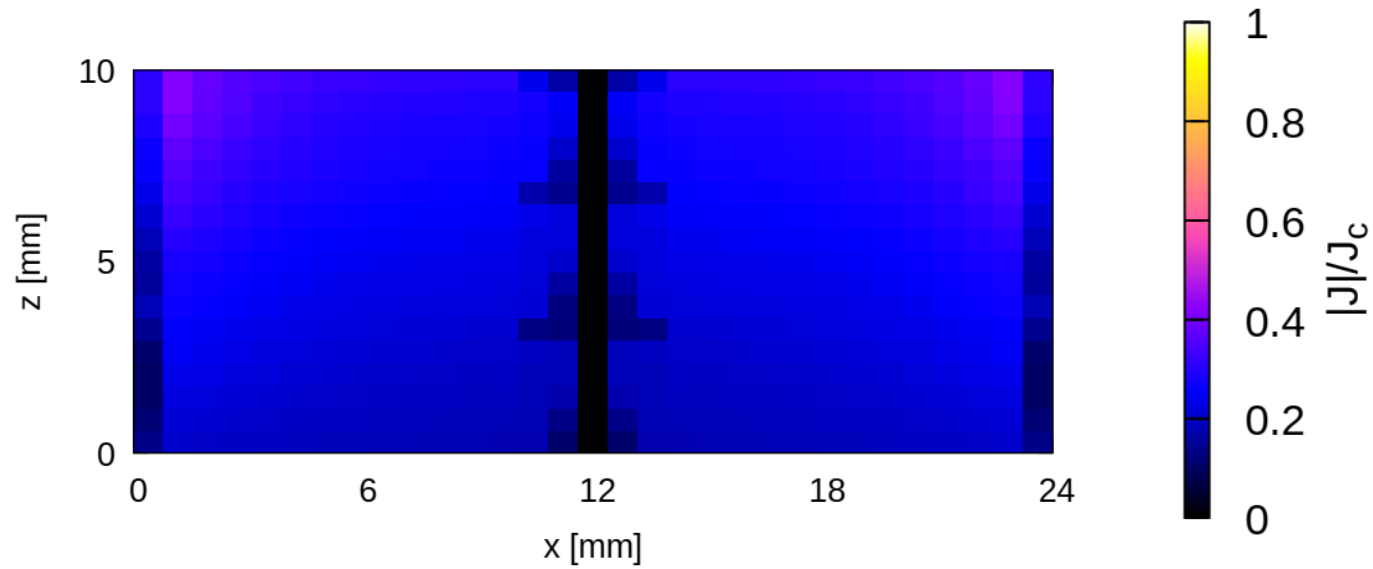
Screening current distribution in z-plane

$z = 9.7 \text{ mm}$



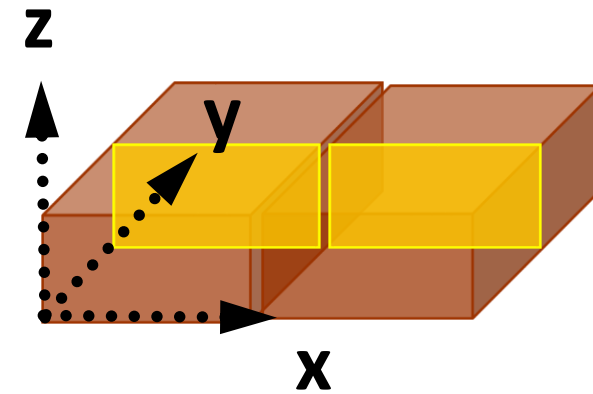
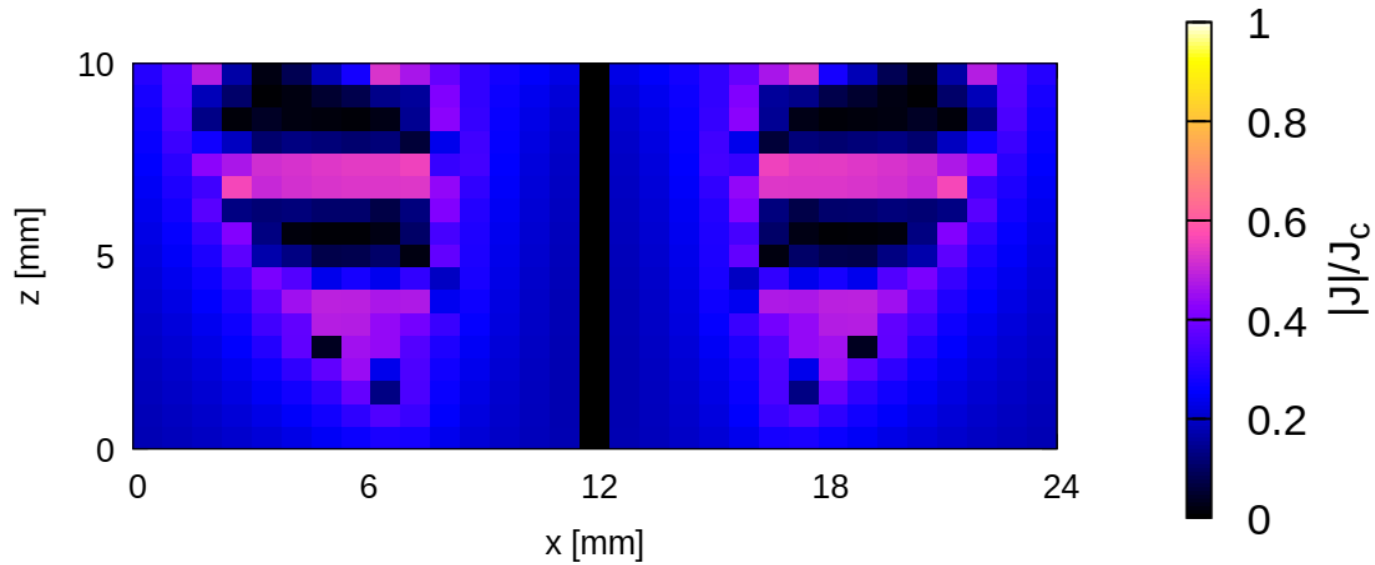
Screening current distribution in y-plane

$y = 0.4 \text{ mm}$



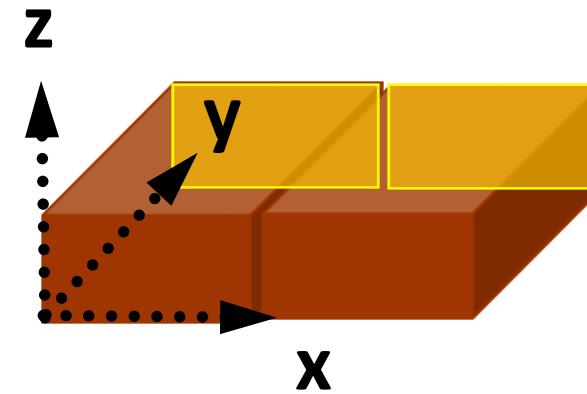
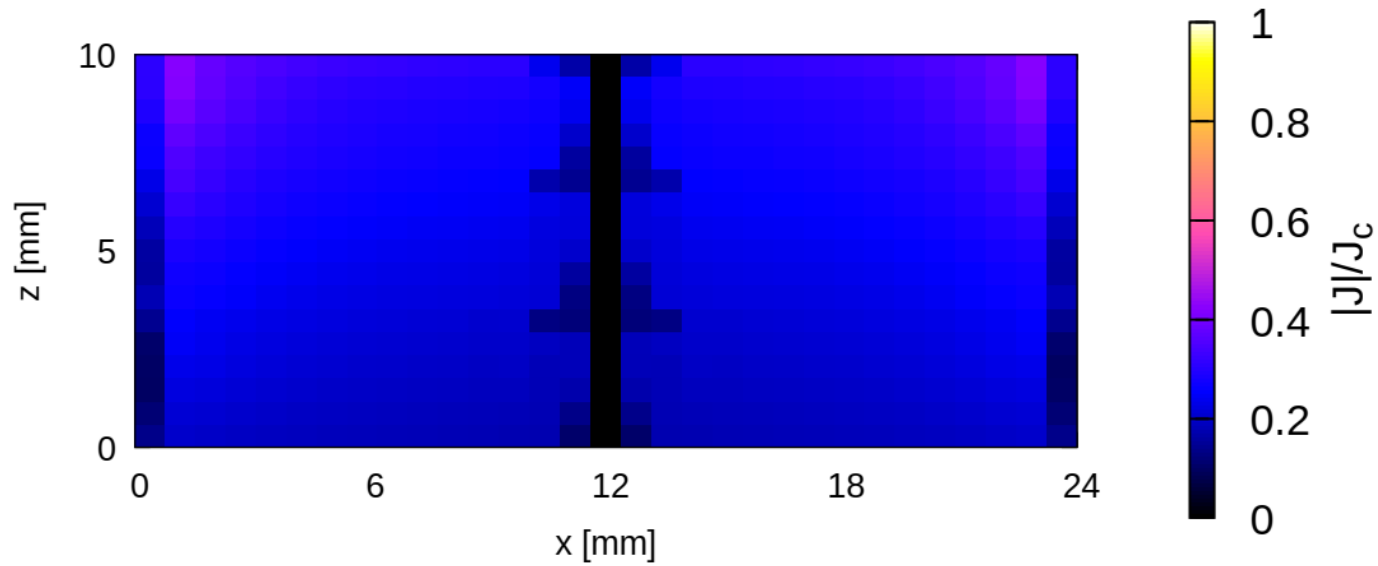
Screening current distribution in y-plane

$y = 12 \text{ mm}$

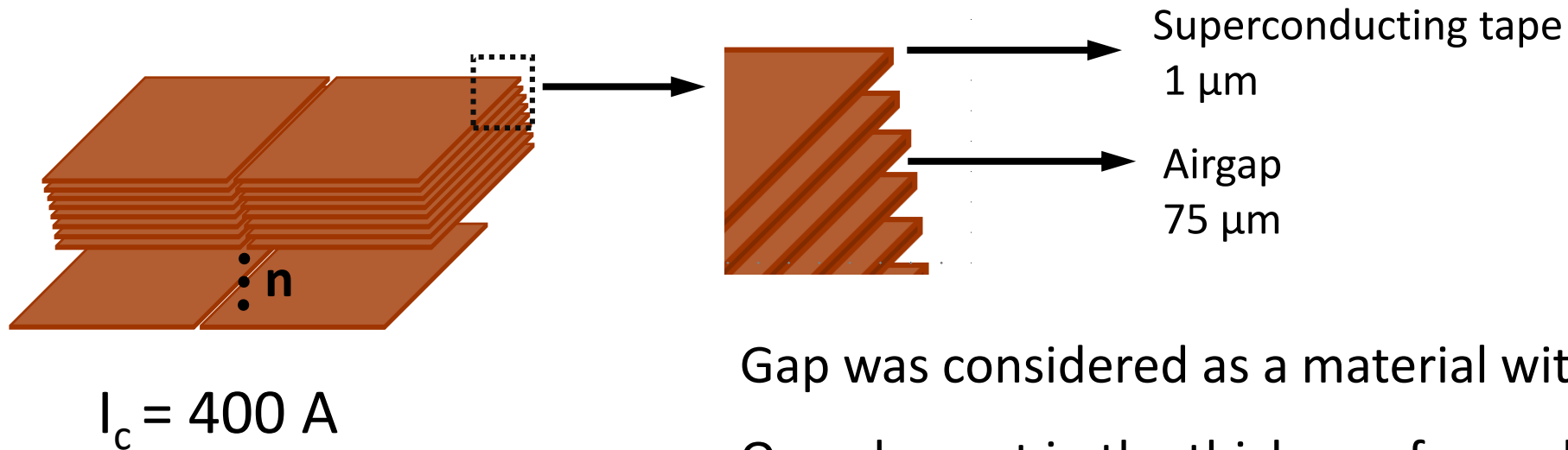


Screening current distribution in y-plane

$y = 23.6 \text{ mm}$



Modeling tape stack with multiple tapes with real thickness



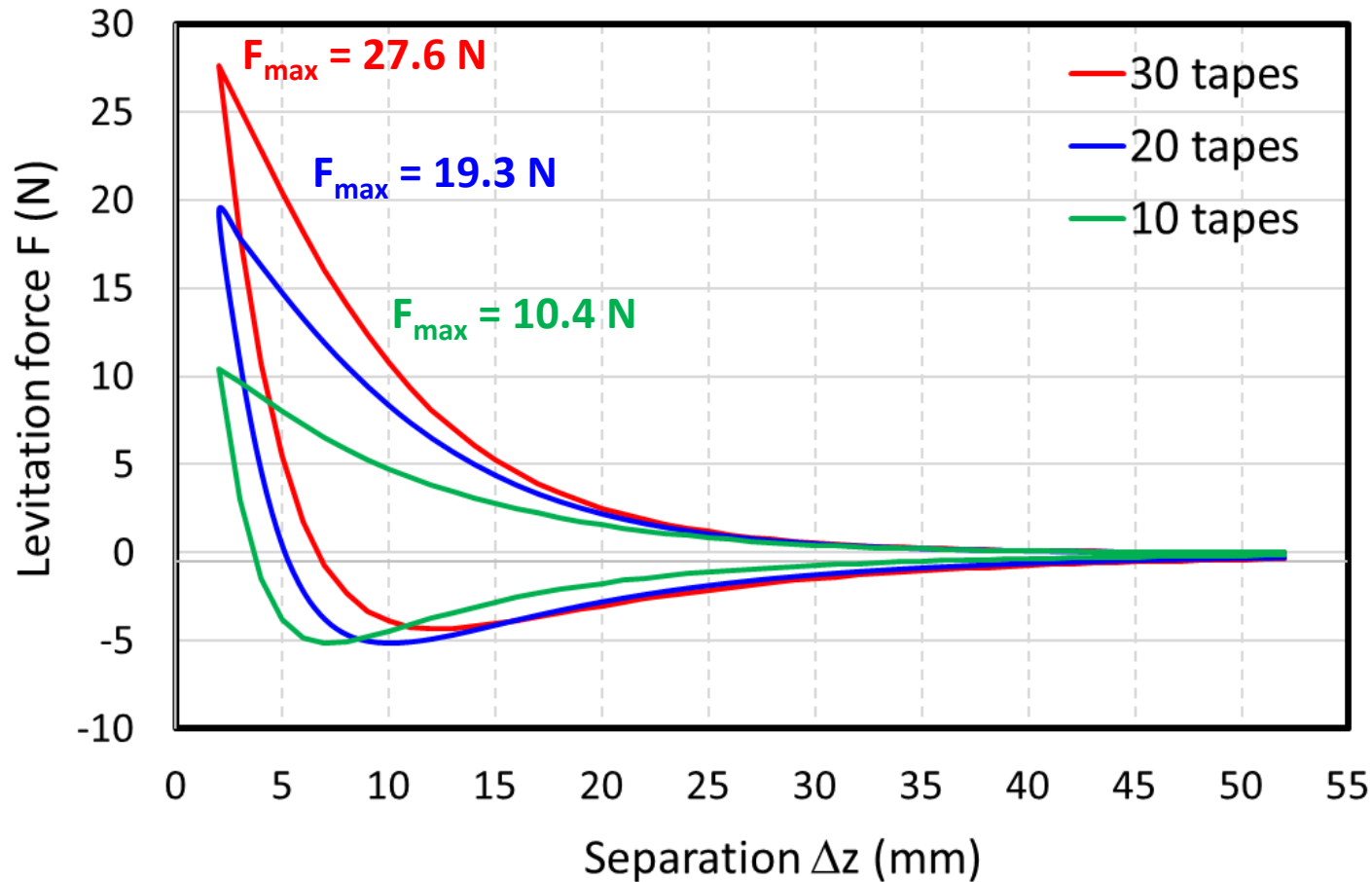
Gap was considered as a material with $\rho = 1$

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



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

Calculation time

	$x \times y \times z$ elements	
10 tapes	$25 \times 25 \times 19$	2.5 hours
20 tapes	$25 \times 25 \times 39$	10 hours
30 tapes	$25 \times 25 \times 59$	30 hours

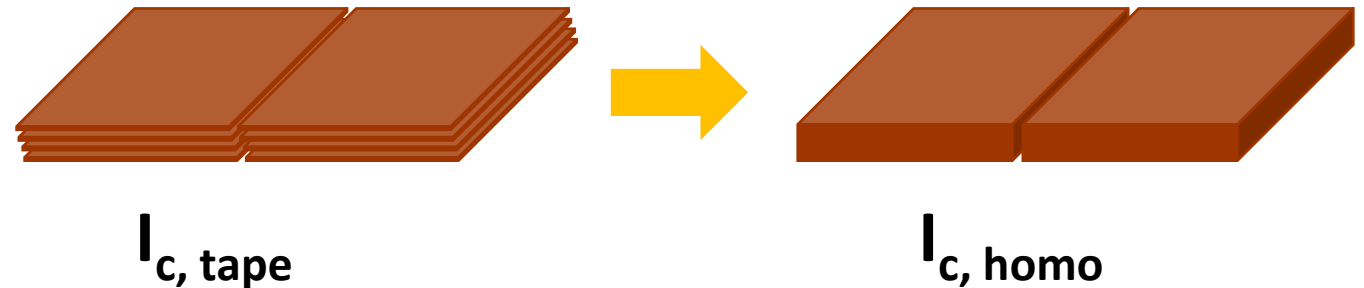
Modeling tape stack with multiple tapes with real thickness

Calculation time

30 tapes $\xrightarrow{25 \times 25 \times 59}$ 30 hours

132 tapes $\xrightarrow{25 \times 25 \times 263}$ **Can take up to weeks!**

A possible solution



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

Thanks for your attention!