Multi-physics modeling of metal-insulated REBCO magnets with screening currents

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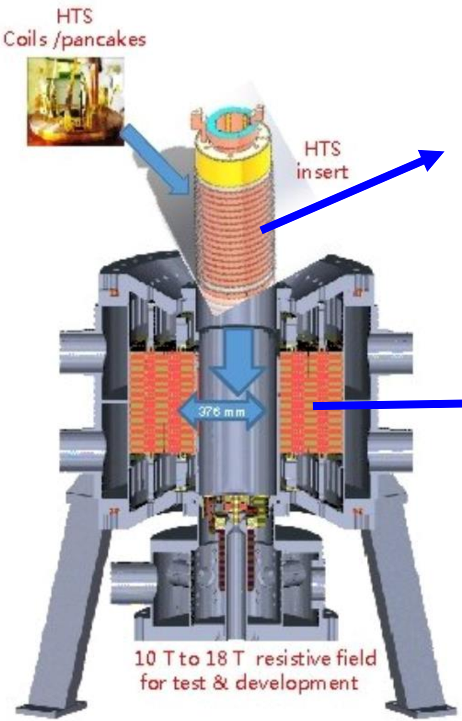
Many superconducting applications contain coils

High magnetic field magnets

- MRI
- Material research
- Fusion

Resistive high-field magnets are highly energy-consuming

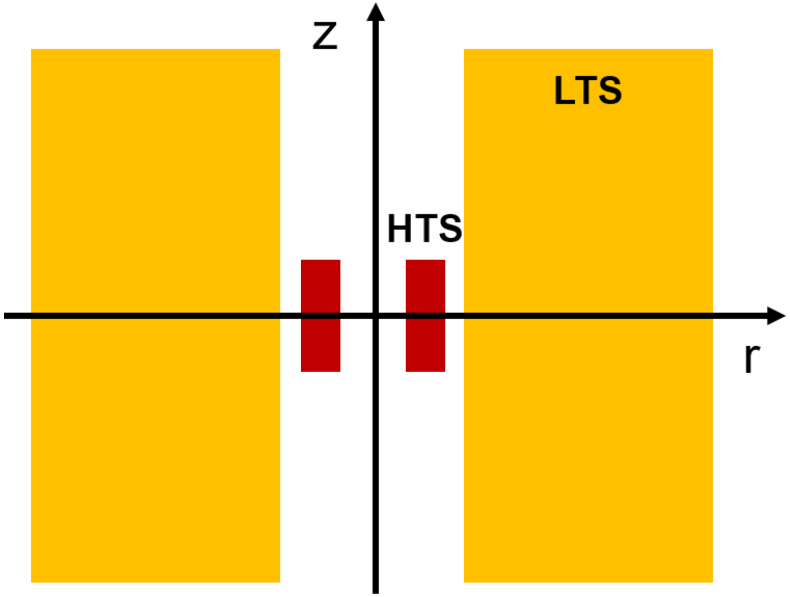


REBCO superconducting insert

Resistive outsert

High-field magnet
from CNRS Grenoble

Full superconducting magnets have advantages



With LTS outsert:

Low energy consumption

High field stability

BiLFINGER

cnrs

LNCMI

HLD.

HELMHOLTZ
ZENTRUM DRESDEN
ROSSENDORF

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EMFL
European Magnetic Field Laboratory

UNIVERSITY
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DE GENÈVE

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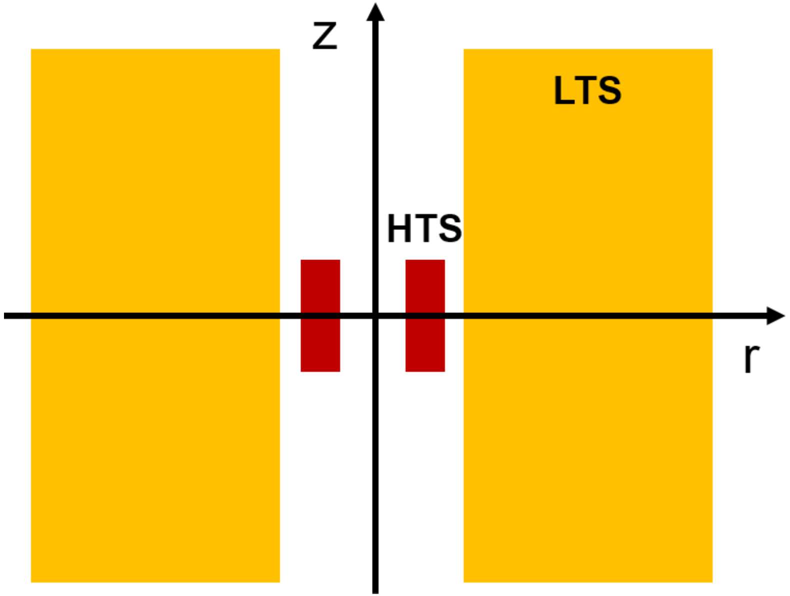
We also acknowledge national funding

VEGA Grant no. 2/0098/24

Full superconducting magnets have advantages



With LTS outsert:

- **Low energy consumption**
- **High field stability**

SuperEMFL project designs:

- **32 T magnet**
- **40 T magnet**

Design requires fast and accurate computer modelling

Electromagnetic response and screening currents

Thermal quench stability

Mechanical properties during quench

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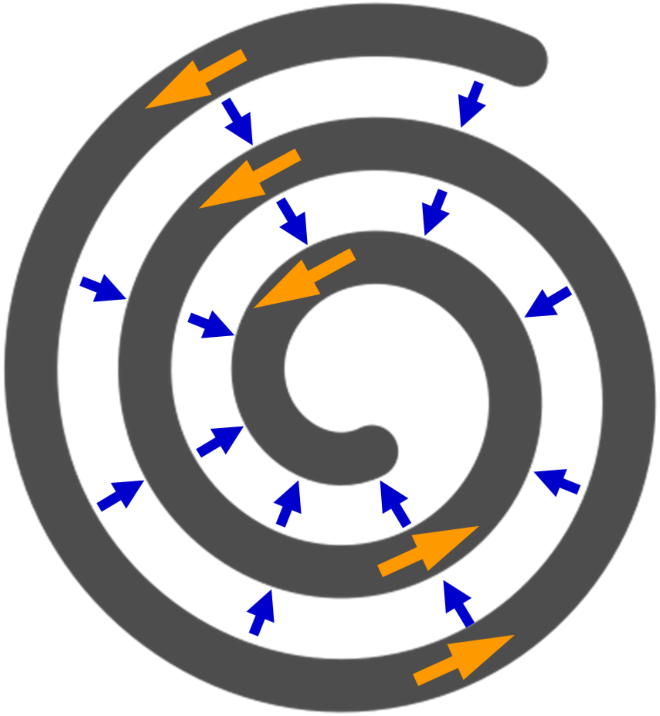
Metal-insulated enables radial currents



Radial currents prevent damage during electrothermal quench

Electromagnetic modelling

Electro-thermal quench

Mechanical stress during quench

Electromagnetic modelling

Electro-thermal quench

Mechanical stress during quench

Electromagnetic modelling

- Axi-symmetric variational method
- Benchmark
- REBCO insert

Electro-thermal quench

Mechanical stress during quench

Electromagnetic modelling

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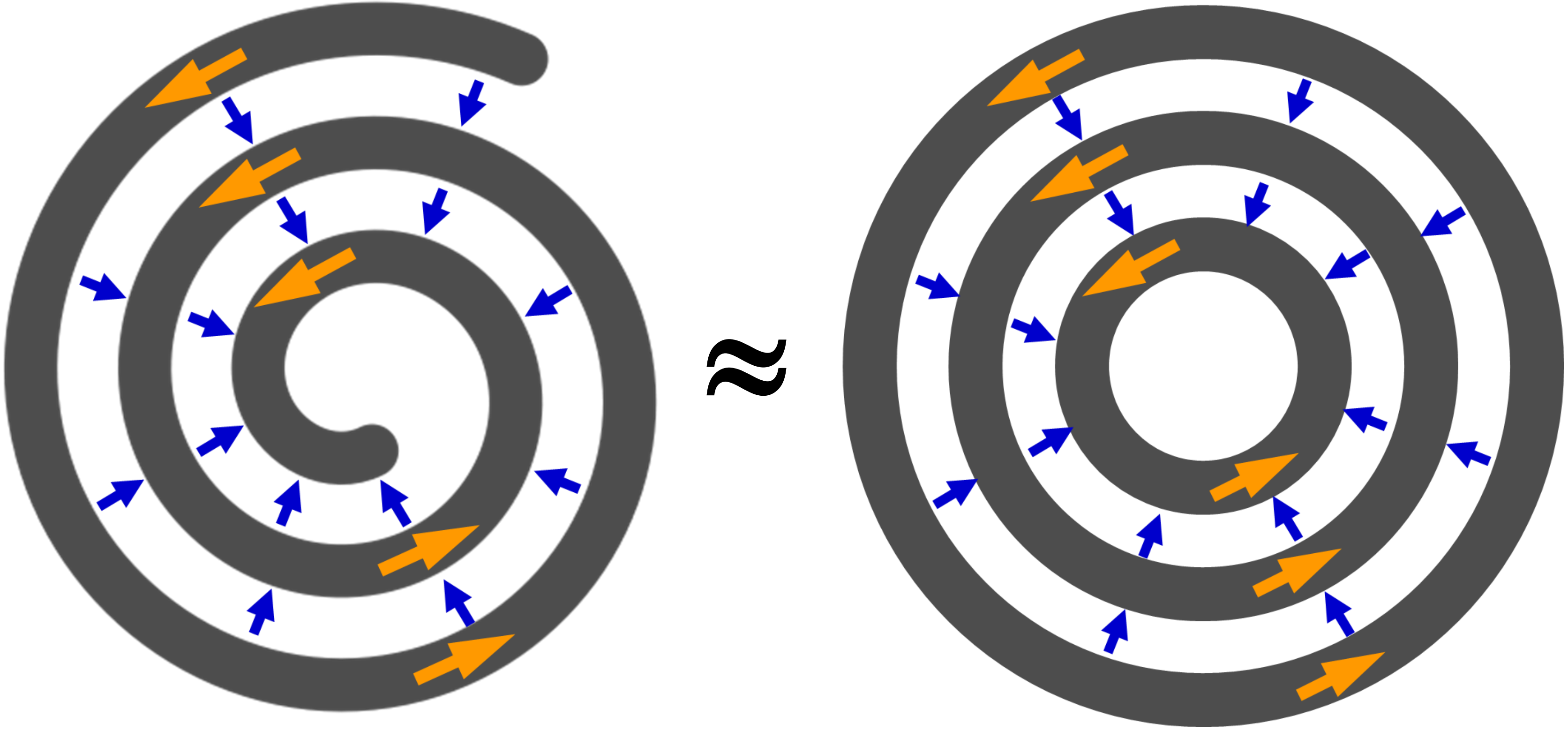
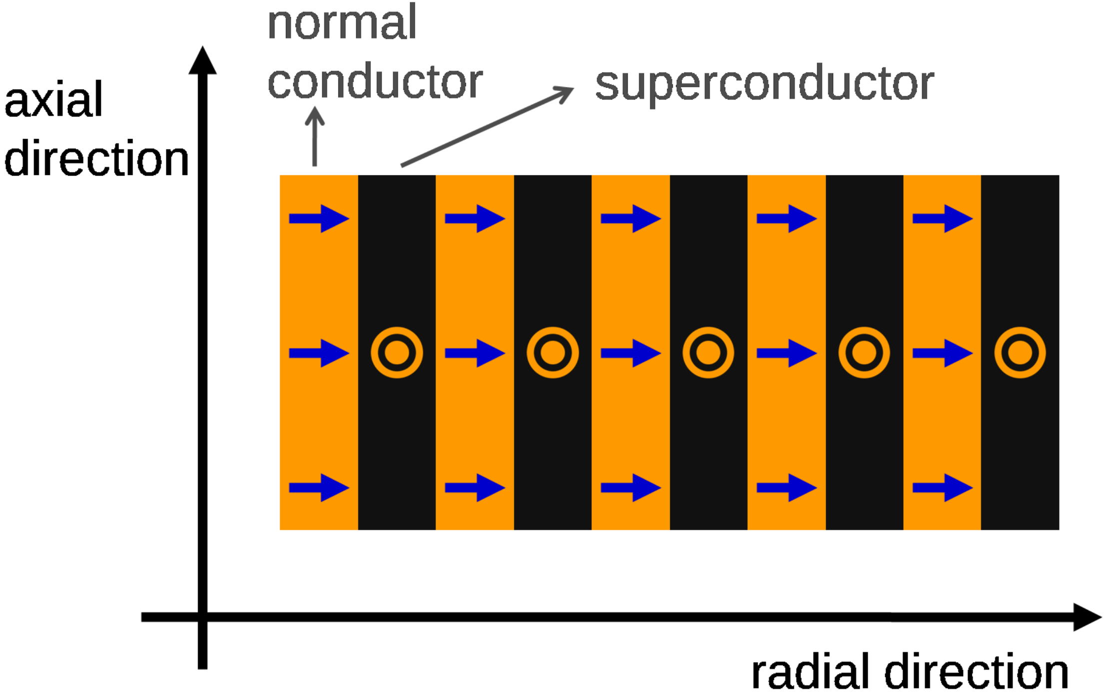
Spiral coil behaves almost like axi-symmetric



How to model non-insulated coils in 2D: we impose current conservation

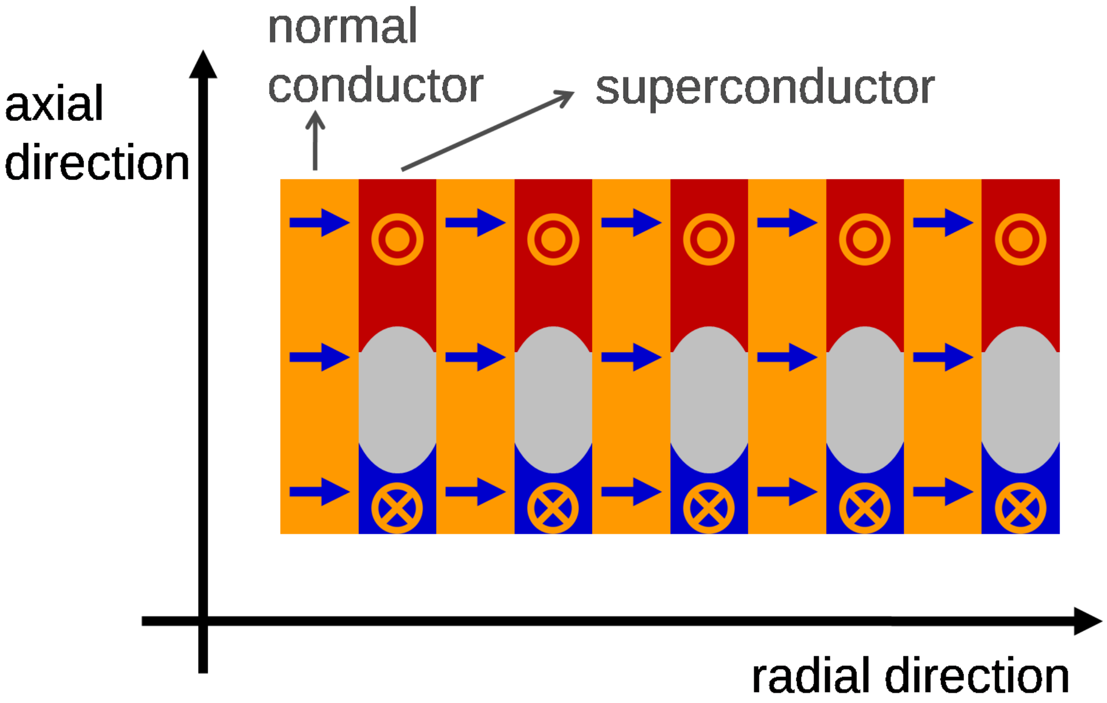


At each turn:

$$I = I_r + I_\varphi$$

input current

How to model non-insulated coils in 2D: we impose current conservation



At each turn:

$$\underset{\text{input current}}{\underset{\downarrow}{I}} = I_r + I_\varphi$$

We enable screening currents

Homogenized model element by element

In angular direction:

Superconductor in parallel with metal

In radial diection:

Superconductor in series with metal

Enables to model either:

all turns one by one

or

homogenized pancake coil

Minimum Electro Magnetic Entropy Production (MEMEP)

Solving the equations

$$\mathbf{E}(\mathbf{J}) = -\frac{\Delta \mathbf{A}}{\Delta t} - \nabla\phi \qquad\qquad \nabla\cdot\mathbf{J} = 0$$

is the same as minimizing the functional

J change between two time instants

$$L = \int_V \mathrm{d}V \left[\frac{1}{2}\boxed{\Delta\mathbf{J}}\cdot\frac{\Delta\mathbf{A}_J}{\Delta t} + \Delta\mathbf{J}\cdot\frac{\Delta\mathbf{A}_a}{\Delta t} + \boxed{U(\mathbf{J})} + \nabla\phi\cdot\mathbf{J}\right]$$

Non-linear **E**(**J**) relation

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

E Pardo, M Kapolka 2017 J Comp. Phys.

Electromagnetic modelling

- Axi-symmetric variational method
- Benchmark
- REBCO insert

Electro-thermal quench

Mechanical stress during quench

Benchmark double pancake coil

Number or turns per pancake: **200**

Radial resistance between turns: **$5 \cdot 10^{-9}$ Ωm^2**

Ramp rate: **1 A/s**

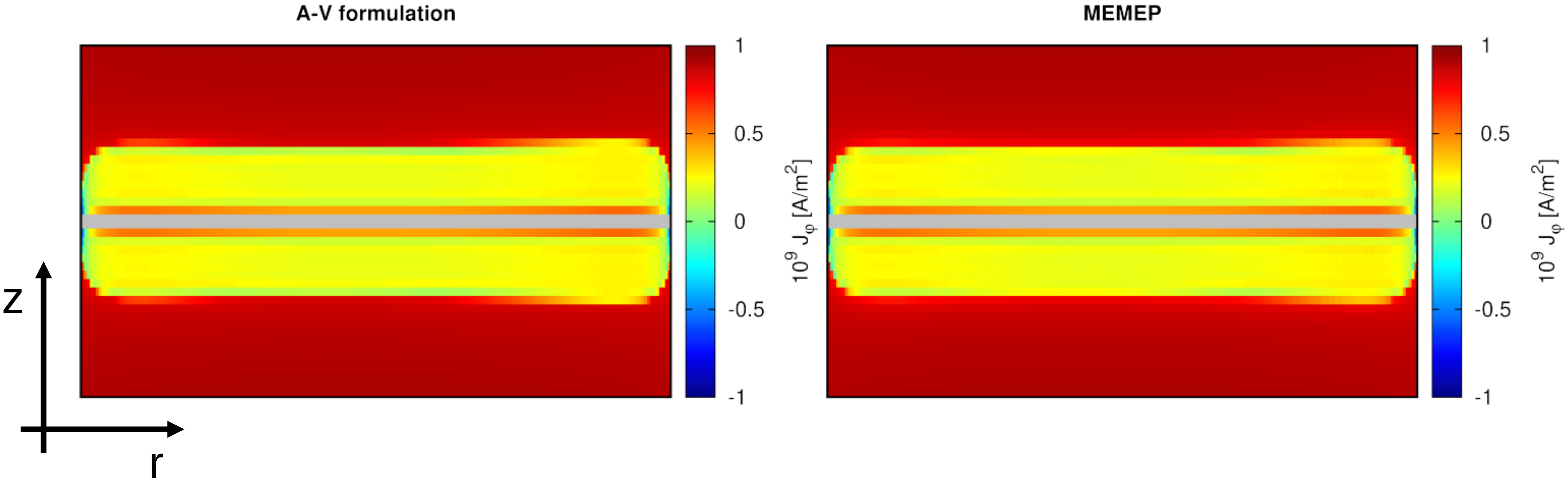
Input current: **400 A**

Pancake separation: **500 μm**

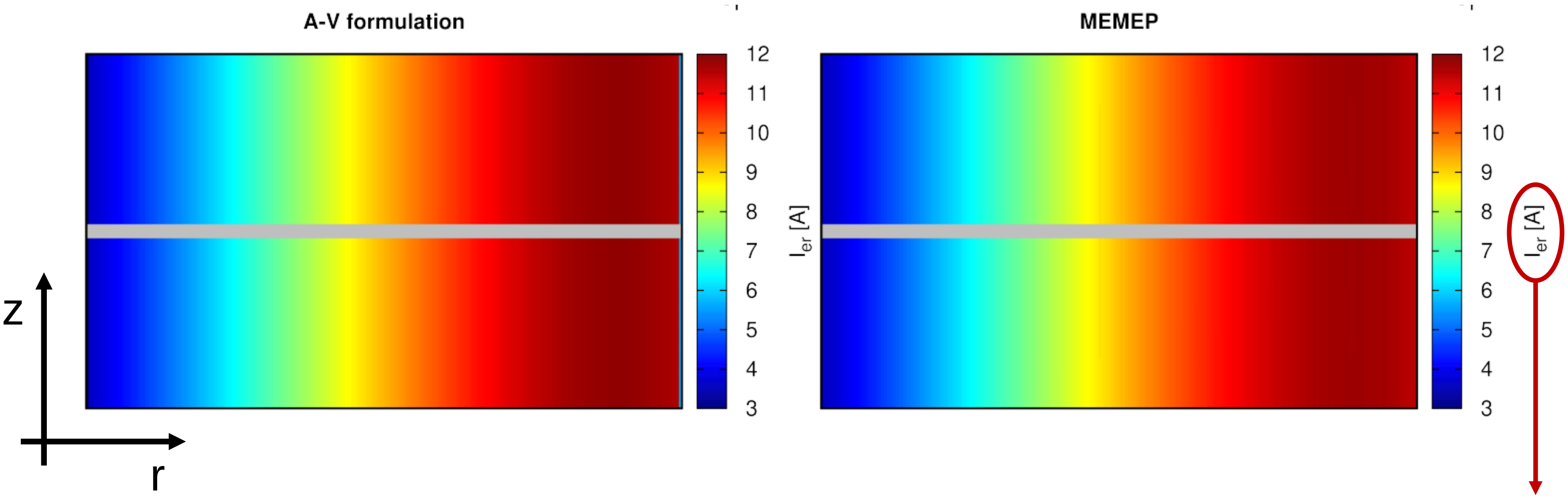
Numerical models:

- **MEMEP (IEE Slovakia)**
- **MATLAB with ODE coupling (CEA France)**

Results between models agree



Results between models agree



$$I_{er} = 2\pi r \times (\text{tape width}) \times J_r$$

Electromagnetic modelling

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32 T insert baseline design

Inner diameter: **25 mm**

Outer diameter: **102.5 mm**

Number of pancakes: **16**

Number of turns per pancake: **250**

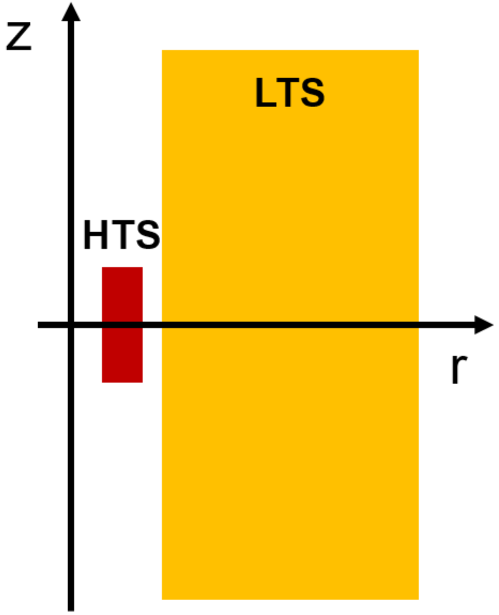
Background magnetic field: **19 T**

Turn-to-turn resistance: **10^{-6}, 10^{-7}, 10^{-8}, 10^{-9} Ω m^2**

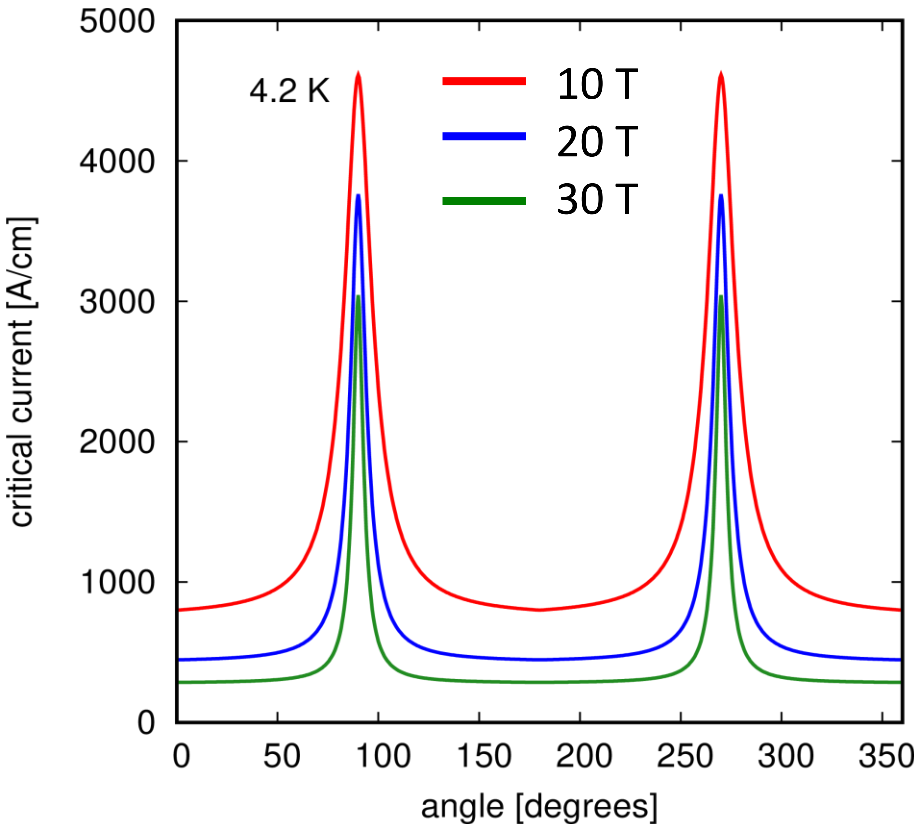
metal-insulated

non-insulated

soldered



Input $J_c(B,\theta)$



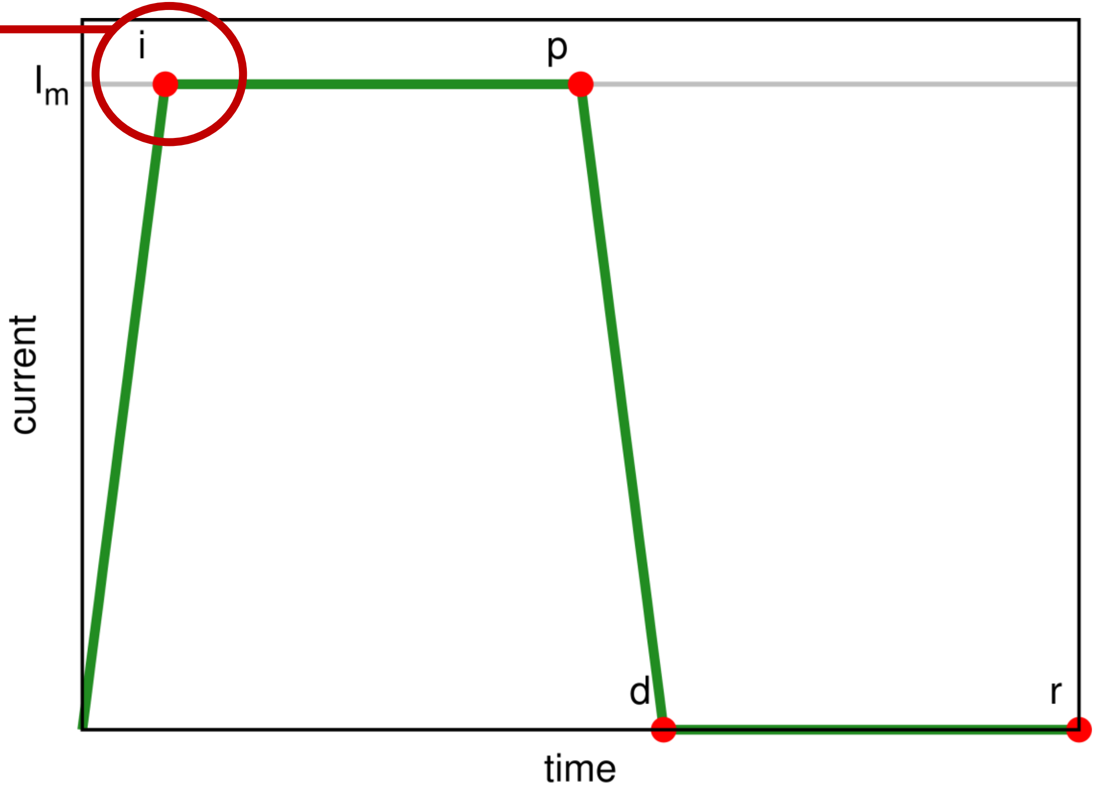
Fujikura tape

Fit from measurements

Critical current
per unit width

Magnet charge and discharge profile

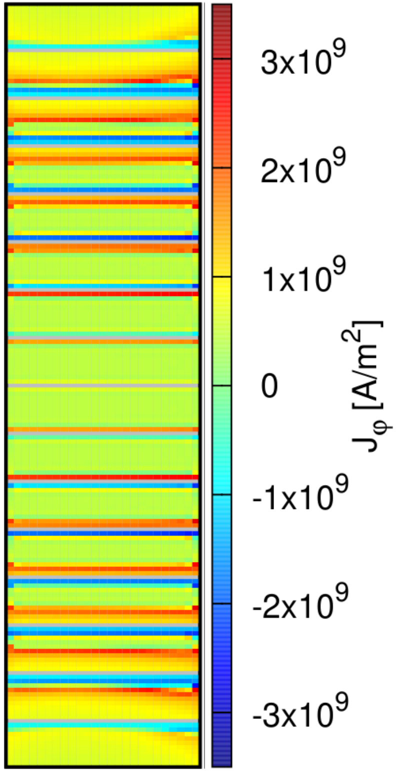
End of initial charge



Screening currents are significant

MI

10^{-6}



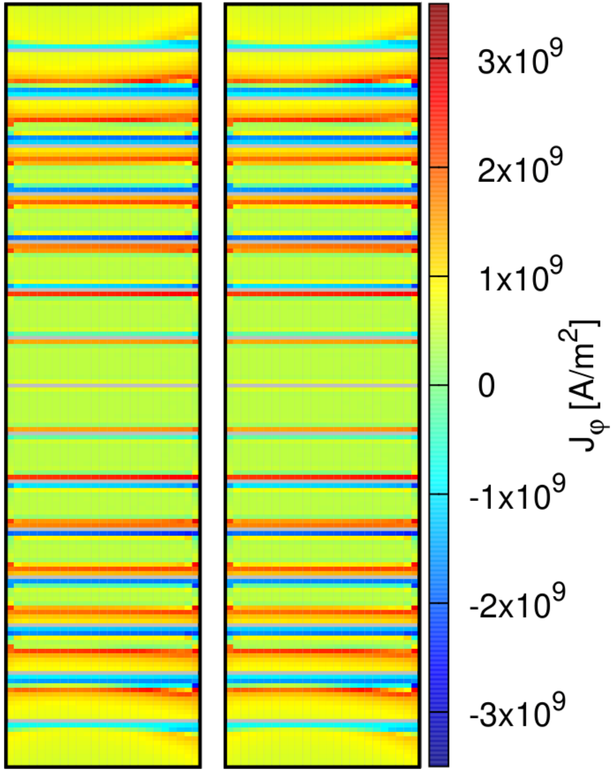
Input current:

333 A

Screening currents are significant

MI

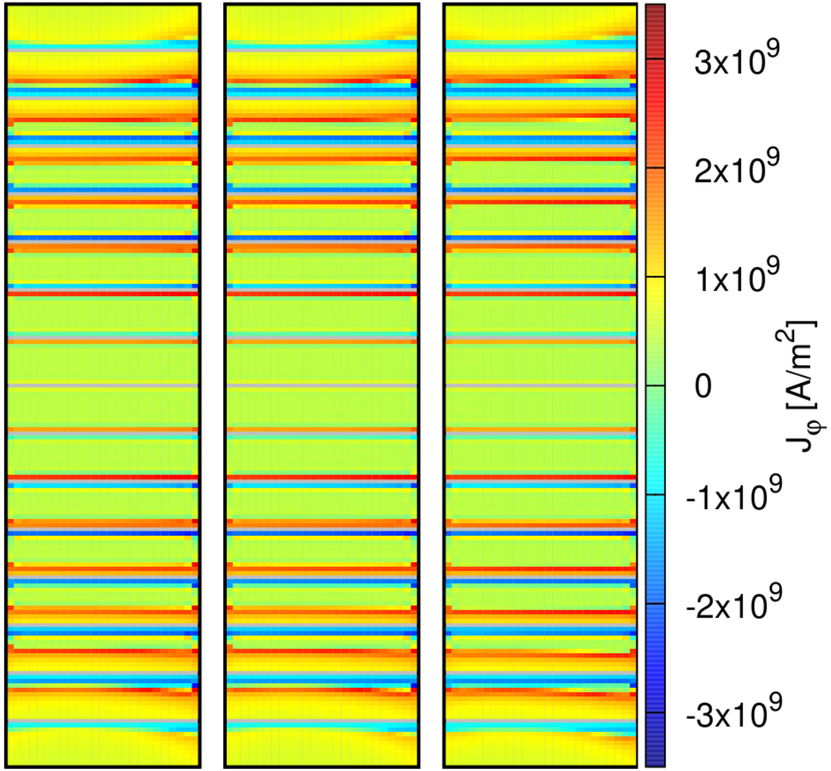
10^{-6} 10^{-7}



Input current:

333 A

Screening currents are significant



MI **NI**

10^{-6} 10^{-7} 10^{-8}

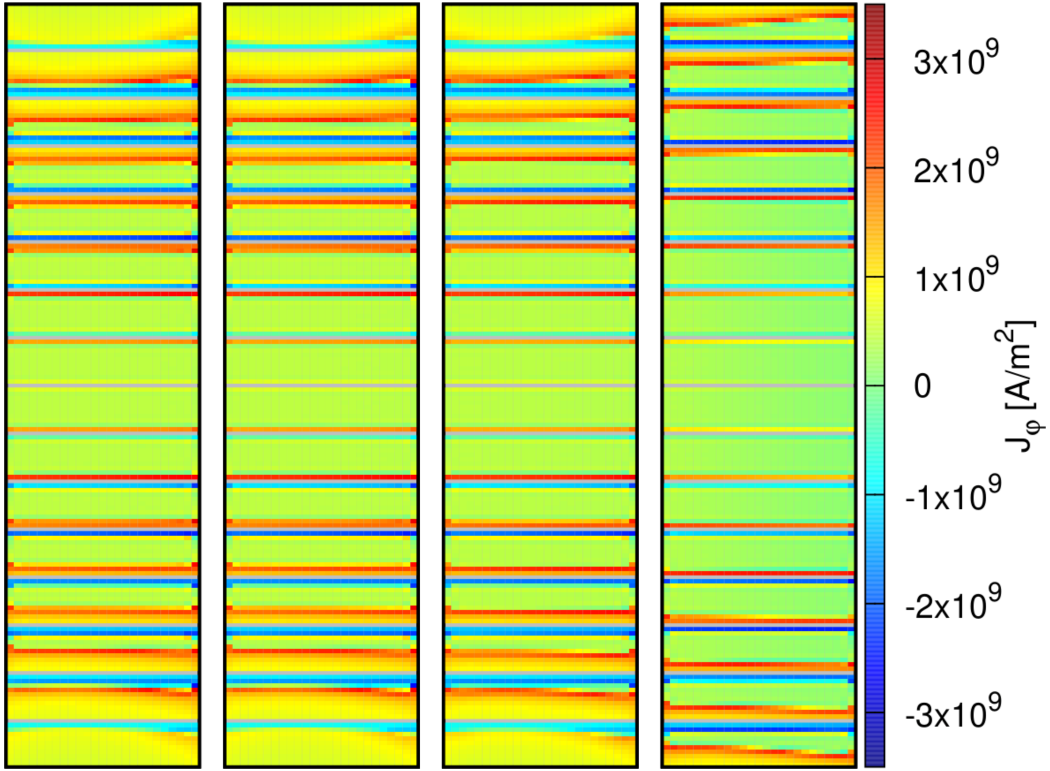
Input current:

333 A

Screening currents are significant

MI **NI** **Soldered**

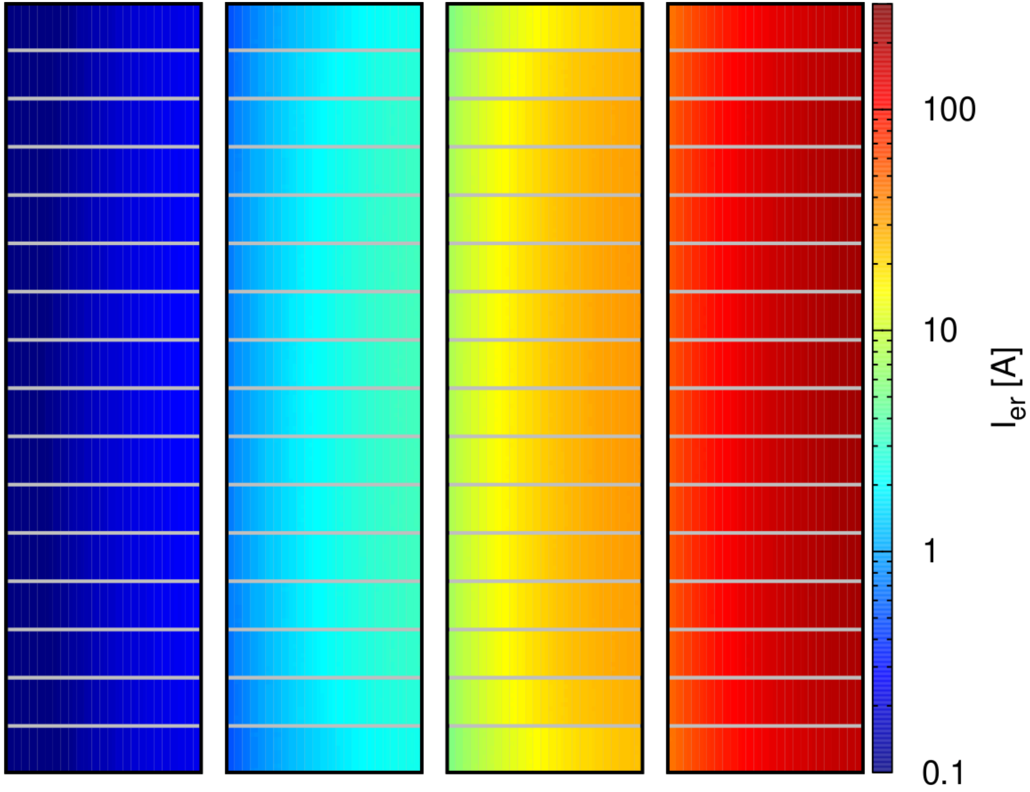
10^{-6} 10^{-7} 10^{-8} 10^{-9} Ωm



Input current:
333 A

Screening currents increase with contact resistance

Radial currents are present



MI **NI** **Soldered**

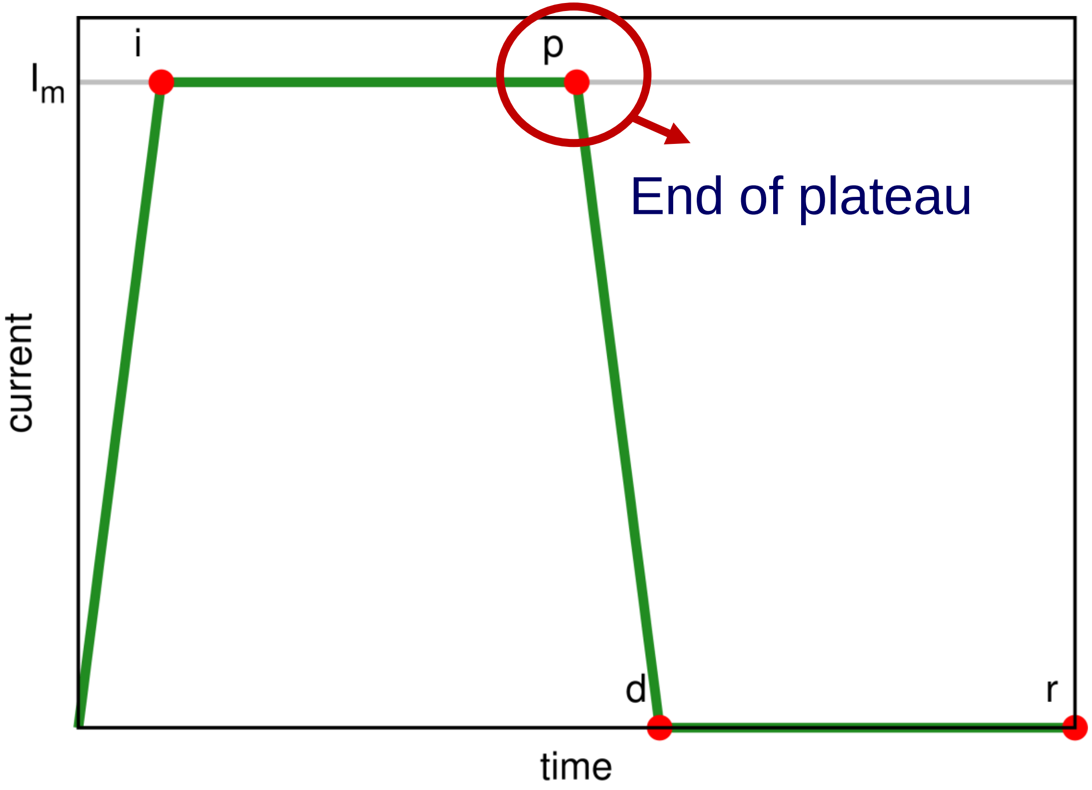
10^{-6} 10^{-7} 10^{-8} 10^{-9} Ωm

Input current:
333 A

Radial currents decrease with contact resistance

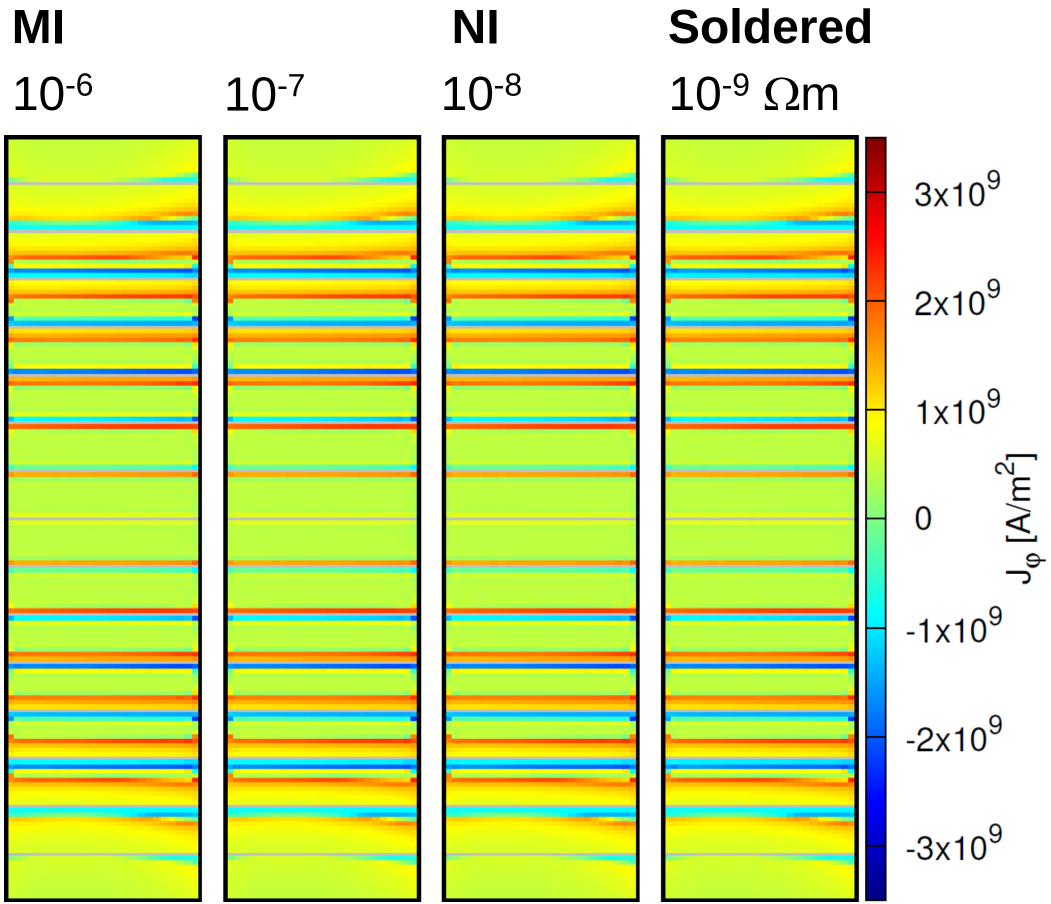
E Pardo, P Fazilleau 2024
SuST

Magnet charge and discharge profile



End of plateau

Screening currents are the same

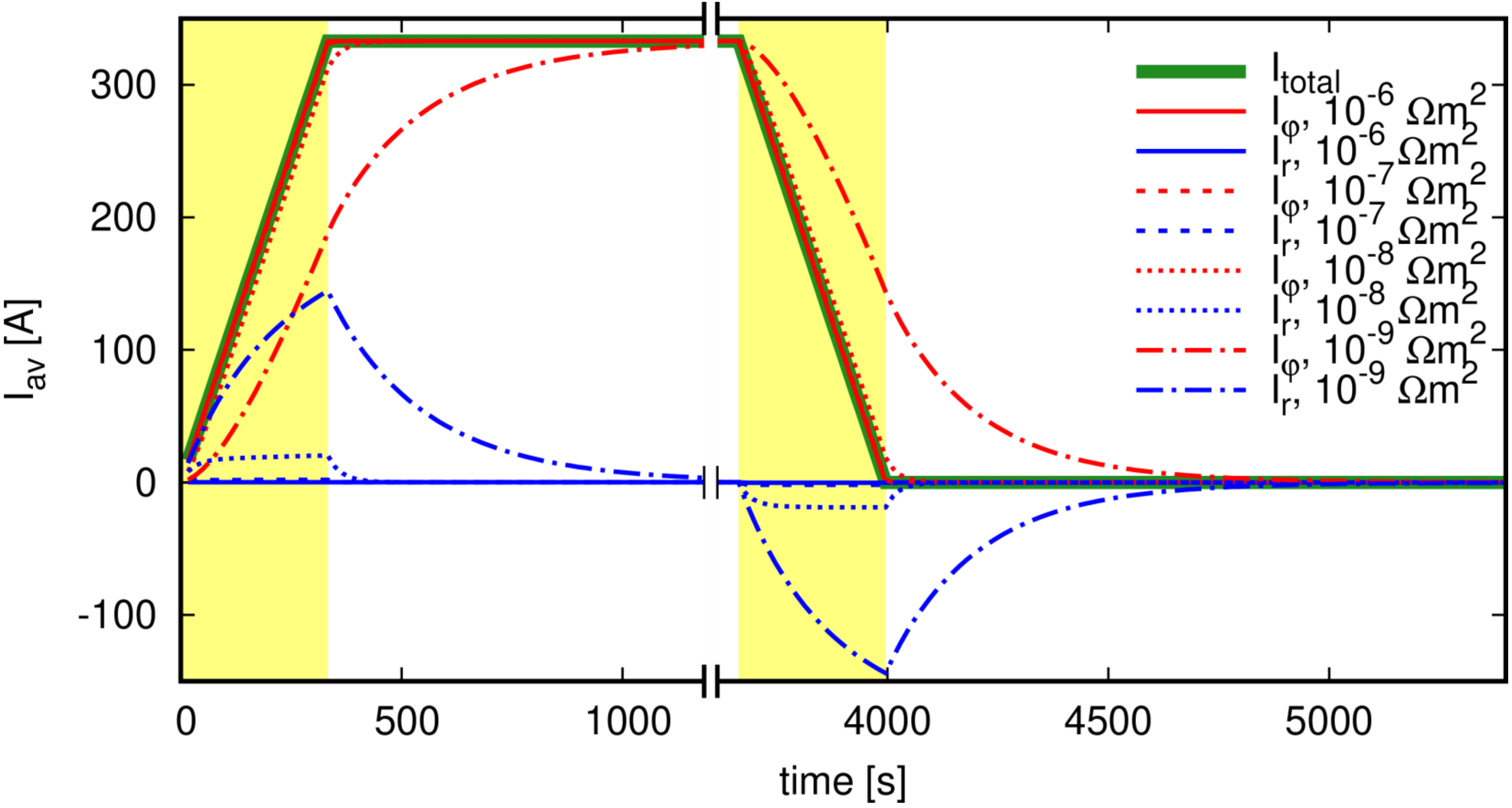


Input current: **333 A**

After relaxation:

Screening currents independent from contact resistance

Radial current reduces angular current



Computing time of non-insulated coil

Mutual inductances:

210 s

Time evolution inlcuding relaxation:

150 s

Faster than real-time opearation!

Electromagnetic modelling

Electro-thermal quench

Mechanical stress during quench

Electromagnetic modelling

Electro-thermal quench

- Finite difference method
- Electro-thermal quench
- Force on LTS outsert

Mechanical stress during quench

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Electro-thermal quench

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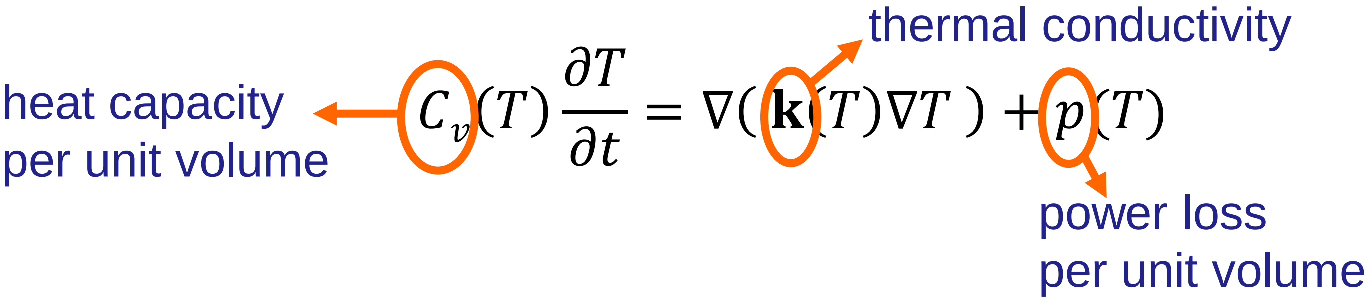
Mechanical stress during quench

Finite Difference method (FD)

Heat diffusion equation



$$C_v(T)\frac{\partial T}{\partial t} = \nabla(\mathbf{k}(T)\nabla T) + p(T)$$

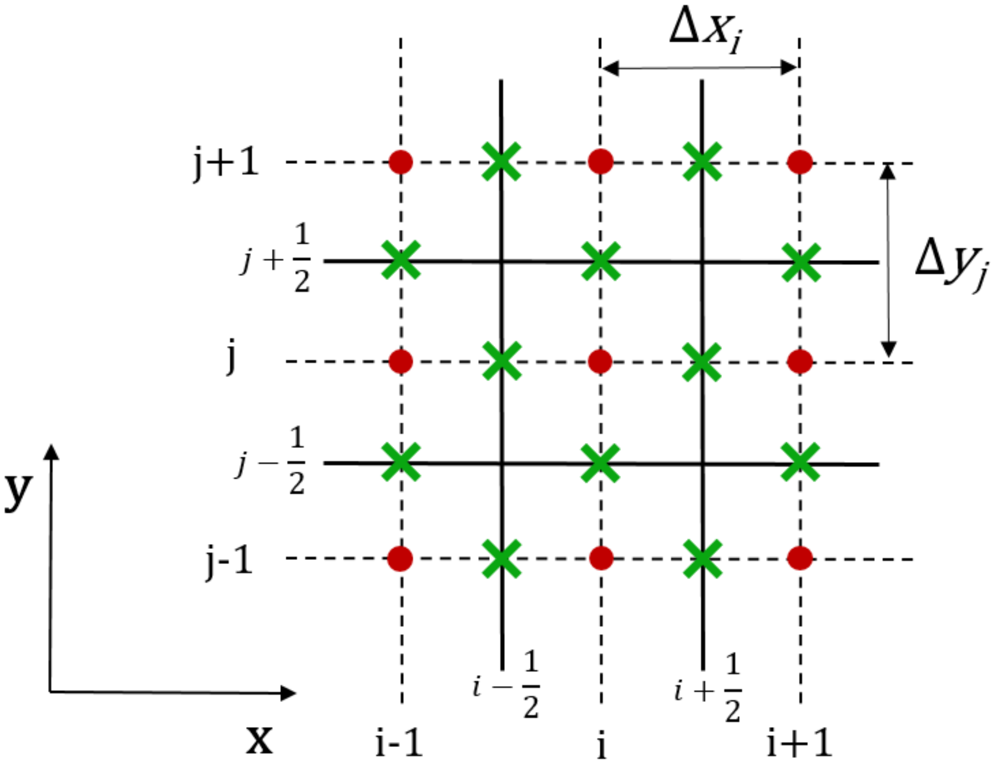
heat capacity
per unit volume

thermal conductivity

power loss
per unit volume

Solved using **Explicit Discretization**
and Euler’s time integration

Discretization



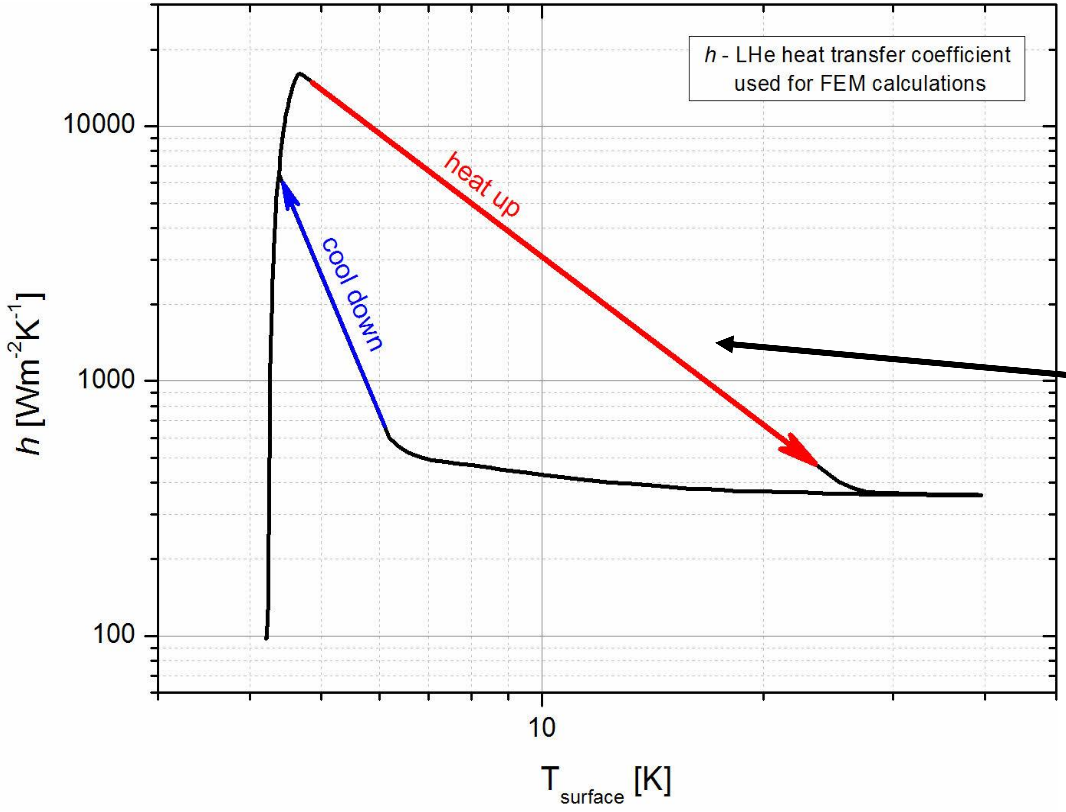
Variables:

temperature at cells

Heat conductivity evaluated at surfaces

We also take liquid helium cooling into account

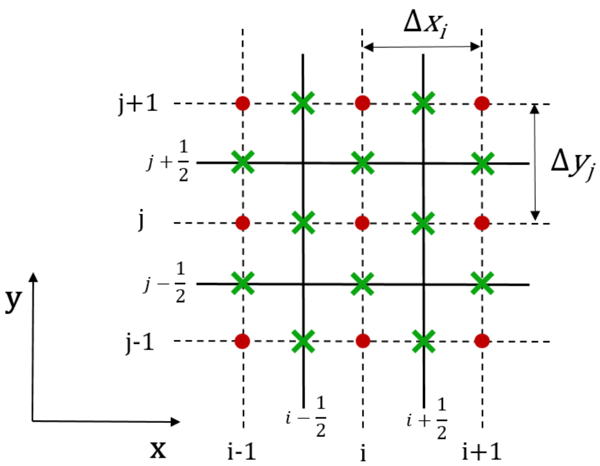
Cooling by liquid Helium



We use ‘up’ curve for now

Reference:
G. Vandoni, CERN
L. Kopera, IEE-SAV

Discretization



We find temperature from those at previous time step

$$\begin{aligned}
T_{ij}^{n+1} = T_{ij}^{n} &+ \frac{\Delta t}{c^{n}_{v,i,j}\Delta r_{i,j}}\left[\frac{r_{i+\frac{1}{2},j}}{r_{i,j}} k_{r,i+\frac{1}{2},j}\frac{T^{n}_{i+1,j}-T^{n}_{i,j}}{r_{i+1,j}-r_{ij}} - \frac{r_{i-\frac{1}{2},j}}{r_{i,j}} k_{r,i-\frac{1}{2},j}\frac{T^{n}_{i,j}-T^{n}_{i-1,j}}{r_{i,j}-r_{i-1,j}}\right] \\
&+ \frac{\Delta t}{c^{n}_{v,i,j}\Delta z_{i,j}}\left[k_{z,i,j+\frac{1}{2}}\frac{T^{n}_{z,i,j+1}-T^{n}_{z,i,j}}{z_{i,j+1}-z_{i,j}} - k_{z,i,j-\frac{1}{2}}\frac{T^{n}_{z,i,j}-T^{n}_{z,i,j-1}}{z_{i,j}-z_{i,j-1}}\right] \\
&+ \frac{\Delta t p^{n}_{i,j}}{c_{v,i,j}}.
\end{aligned}$$

A Dadhich et al. arXiv:2402.04034

Stability condition

$$dt \le \frac{C_v(T) \cdot \min\left(\Delta x^2, \Delta y^2\right)}{2k(T)}$$

May require many timesteps!

Why Finite difference?

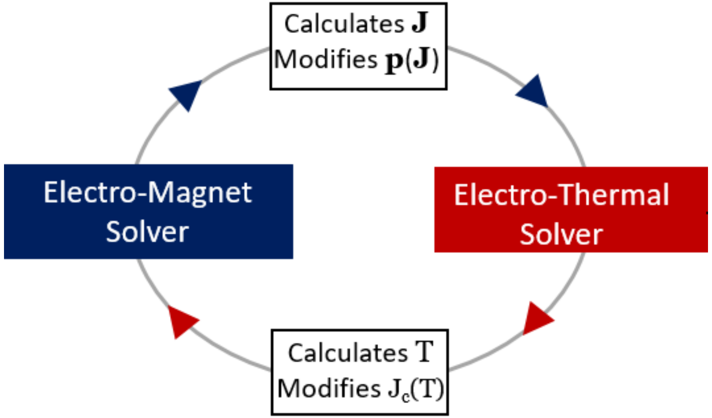
Explicit Finite Difference is fast and simple to implement

Lot of timesteps required, but MEMEP is fast!

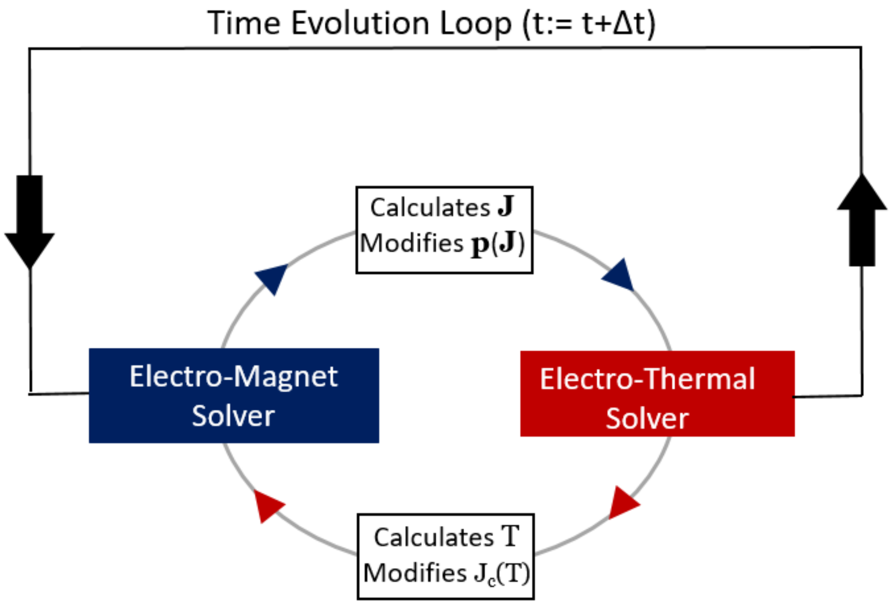
Our in-house software in C++

Variable timestepping: Different timesteps for MEMEP & FD!

Coupling Electro-Magnetic and Electro-Thermal Models



Coupling Electro-Magnetic and Electro-Thermal Models



Time Evolution Loop (t:= t+Δt)

Calculates $\mathbf{J}$
Modifies $\mathbf{p}(\mathbf{J})$

Electro-Magnet Solver

Electro-Thermal Solver

Calculates T
Modifies $\mathrm{J_c(T)}$

Electromagnetic modelling

Electro-thermal quench

- Finite difference method
- Electro-thermal quench
- Force on LTS outsert

Mechanical stress during quench

HTS insert interacting with LTS outsert

Geometry of NOUGAT insert

Pancakes: **18**

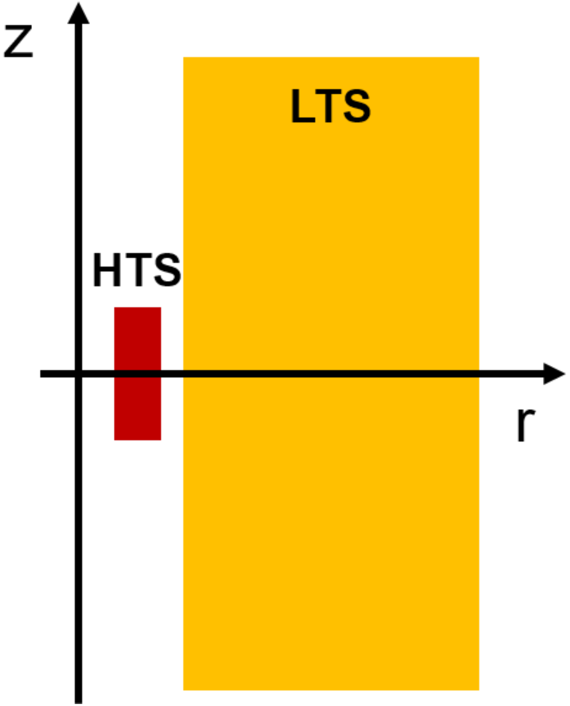
Turns per pancake: **290**

REBCO tape: **Fujikura**

Turn-to-turn resistance: **10^{-6} Ωm^2**

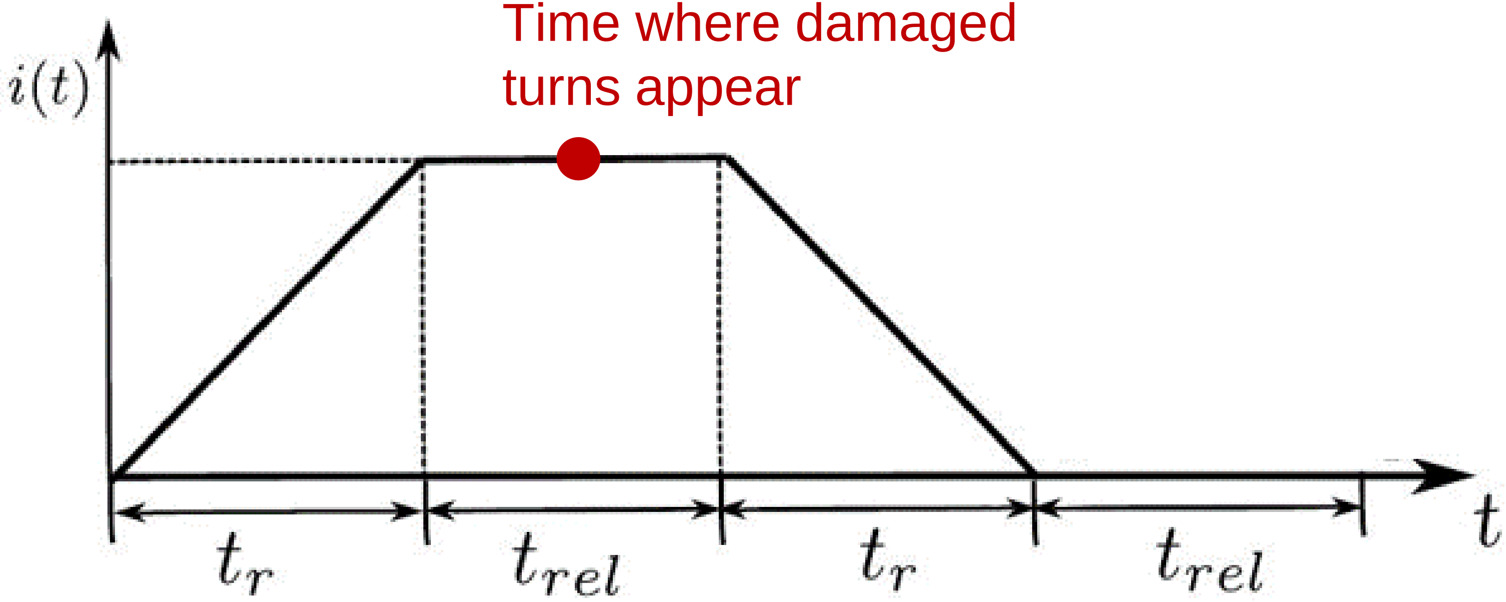
Operating current: **314.3 A**

Voltage limitation: **1 V**



LTS outsert: OXFORD **19 T**, 150 mm bore

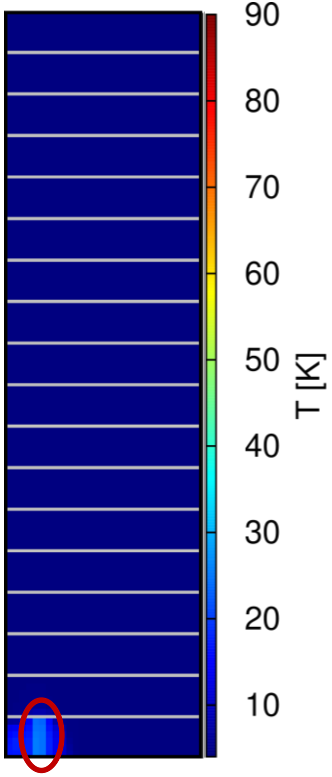
Damaged turns appear after charging the magnet



Time where damaged turns appear

Temperature evolution after degradation

4.5 ms



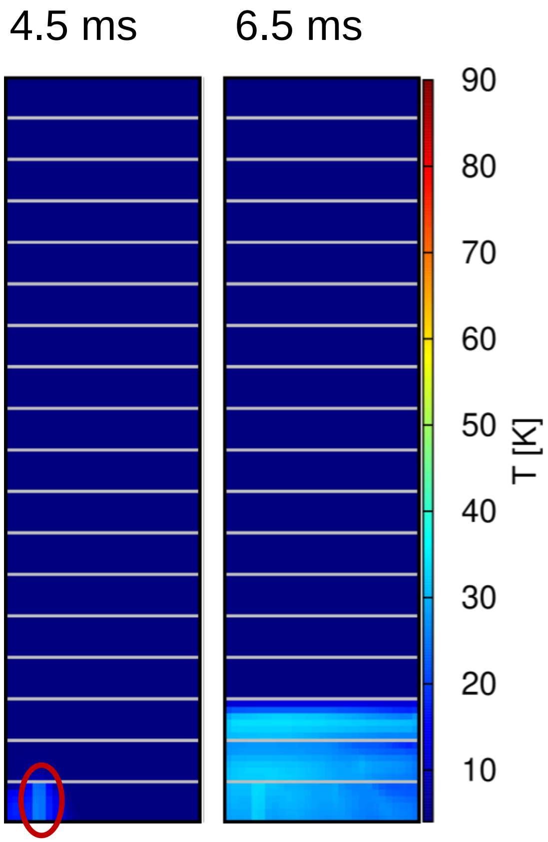
Damaged homogenized turn: 90 % reduction of J_c

Voltage limitation:

1 V

Operating current:
314.3 A

Temperature evolution after degradation



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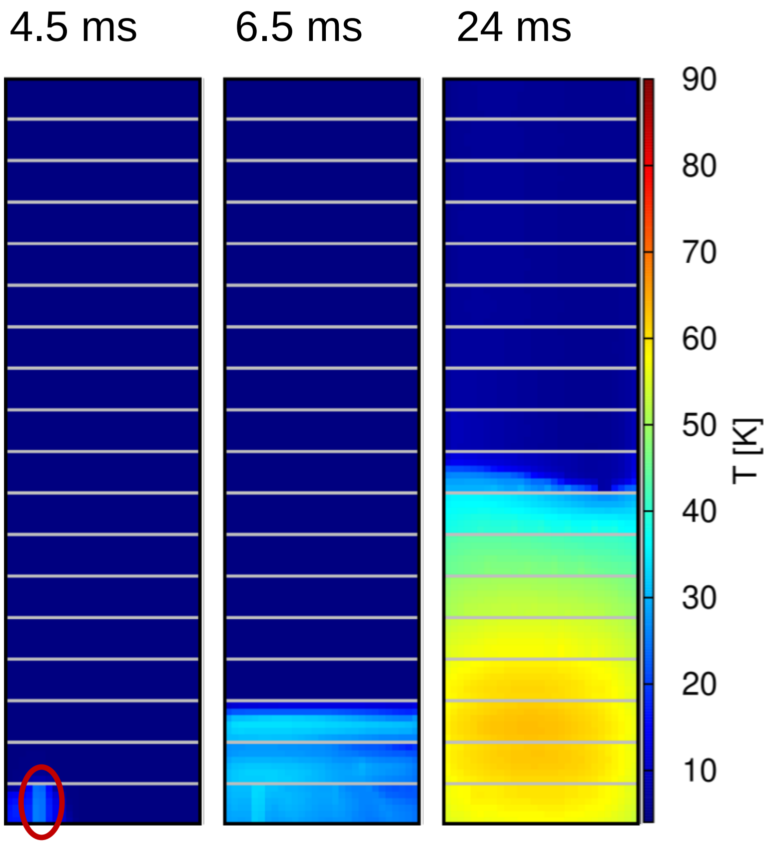

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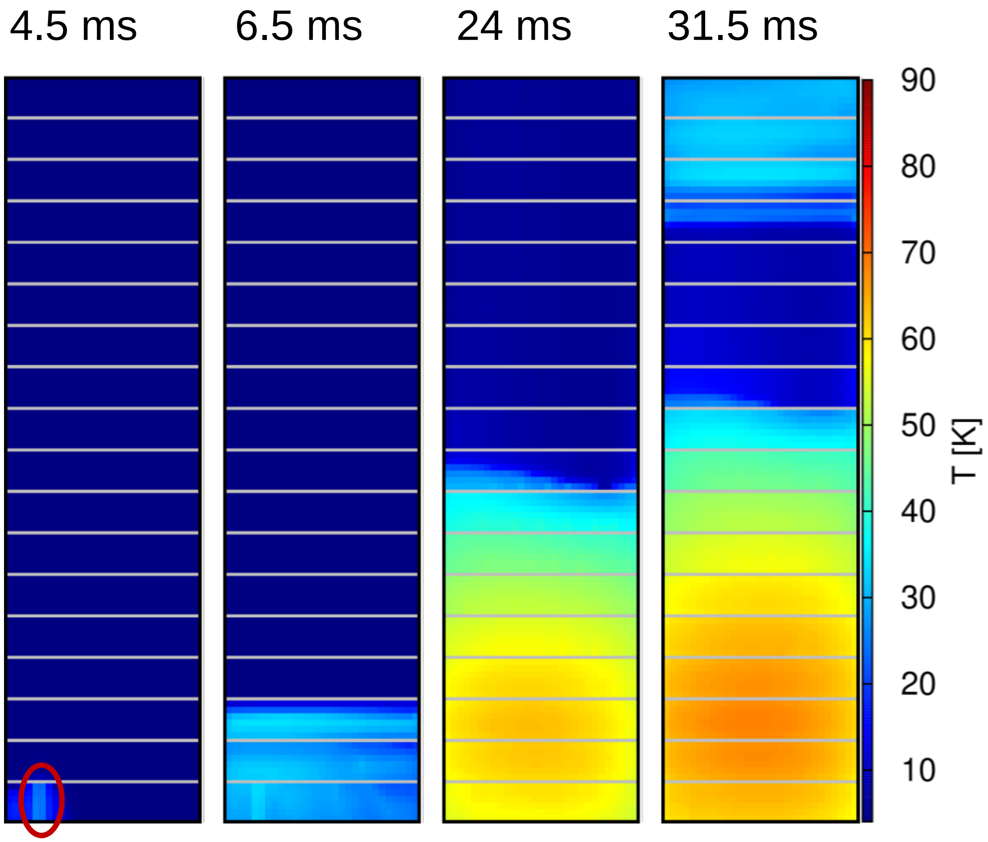

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314.3 A

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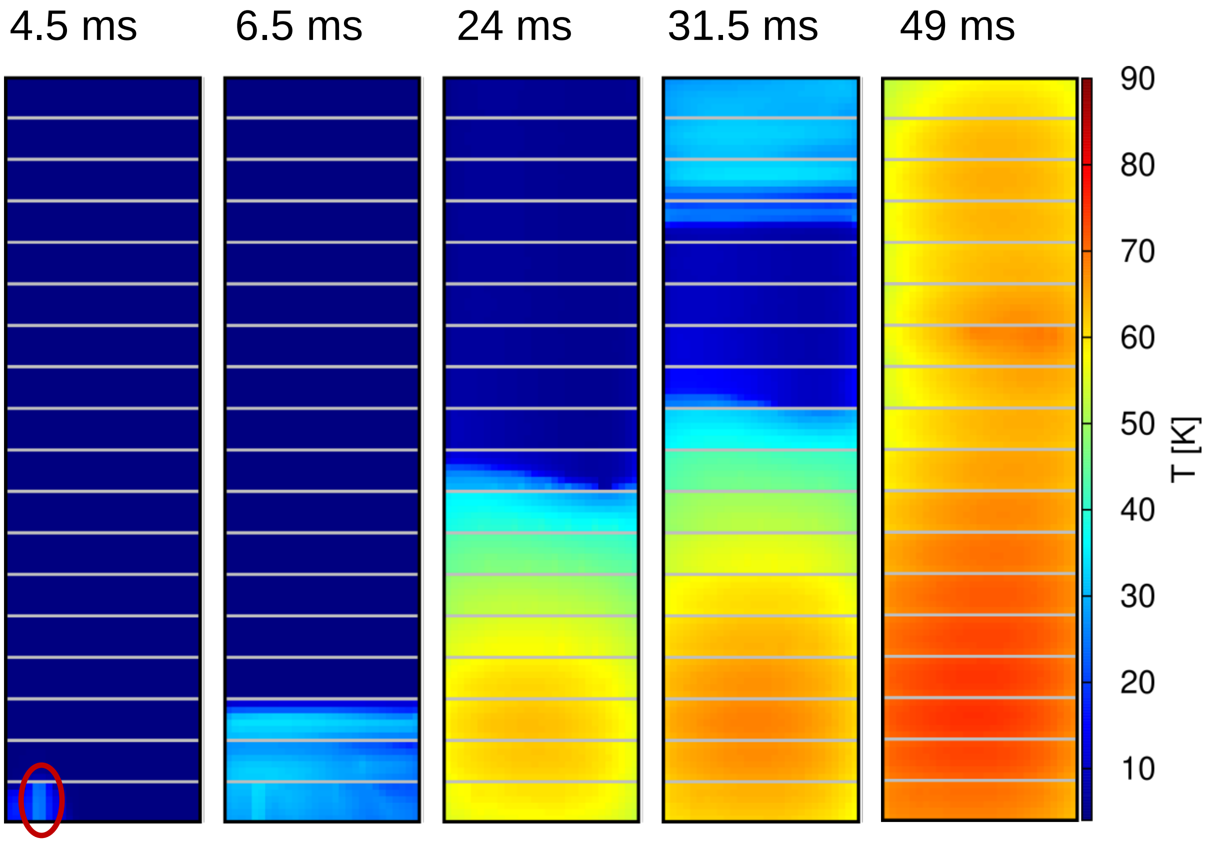


Damaged homogenized turn: 90 % reduction of J_c

Voltage limitation:

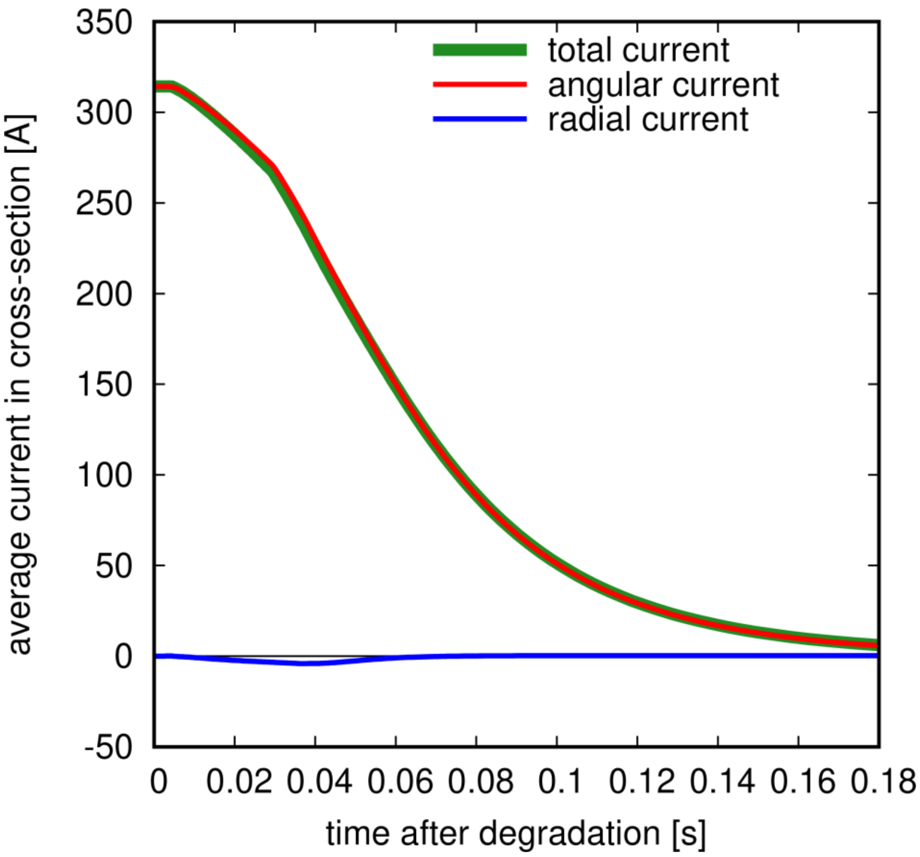
1 V

Operating current:

314.3 A

Fast quench due to electromagnetic coupling

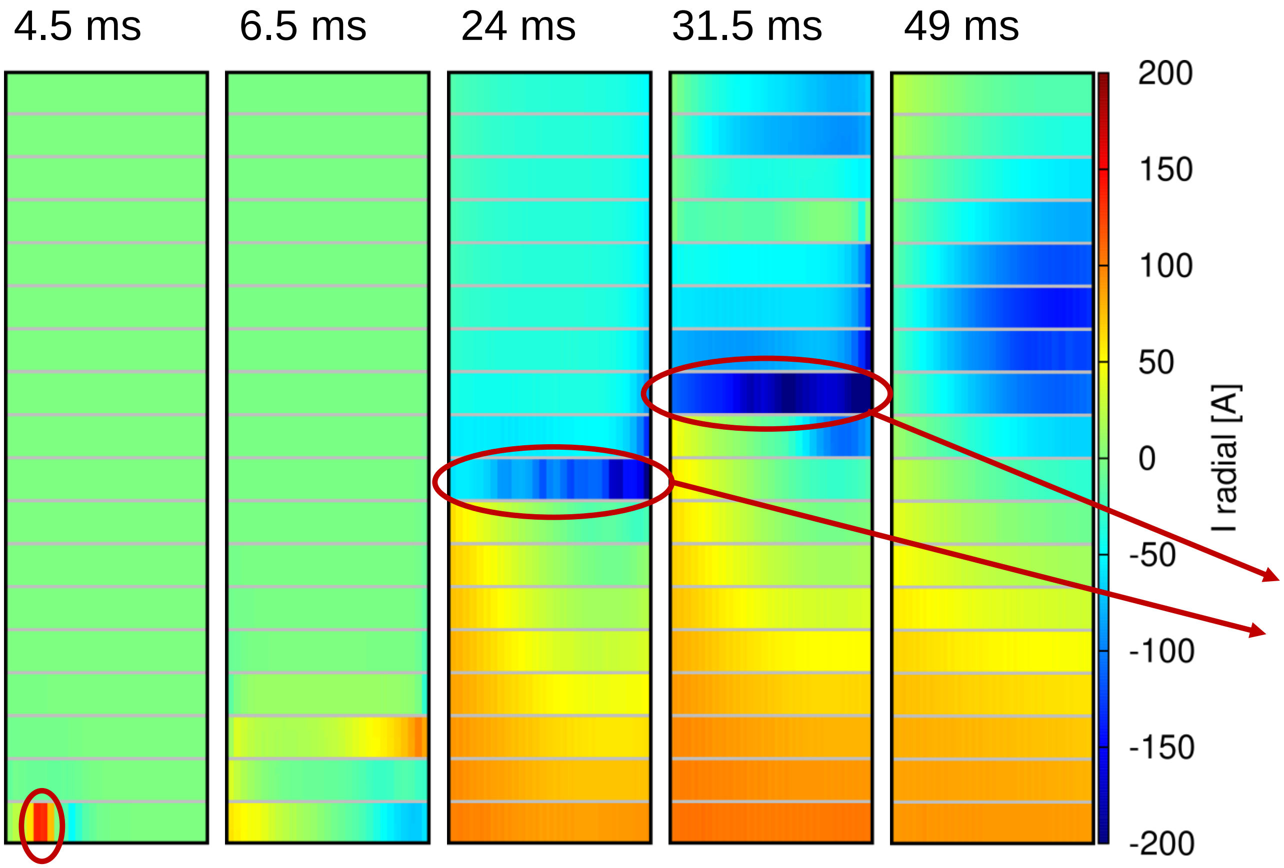
Voltage limitation reduces total current



Voltage limitation:

1 V

Radial currents



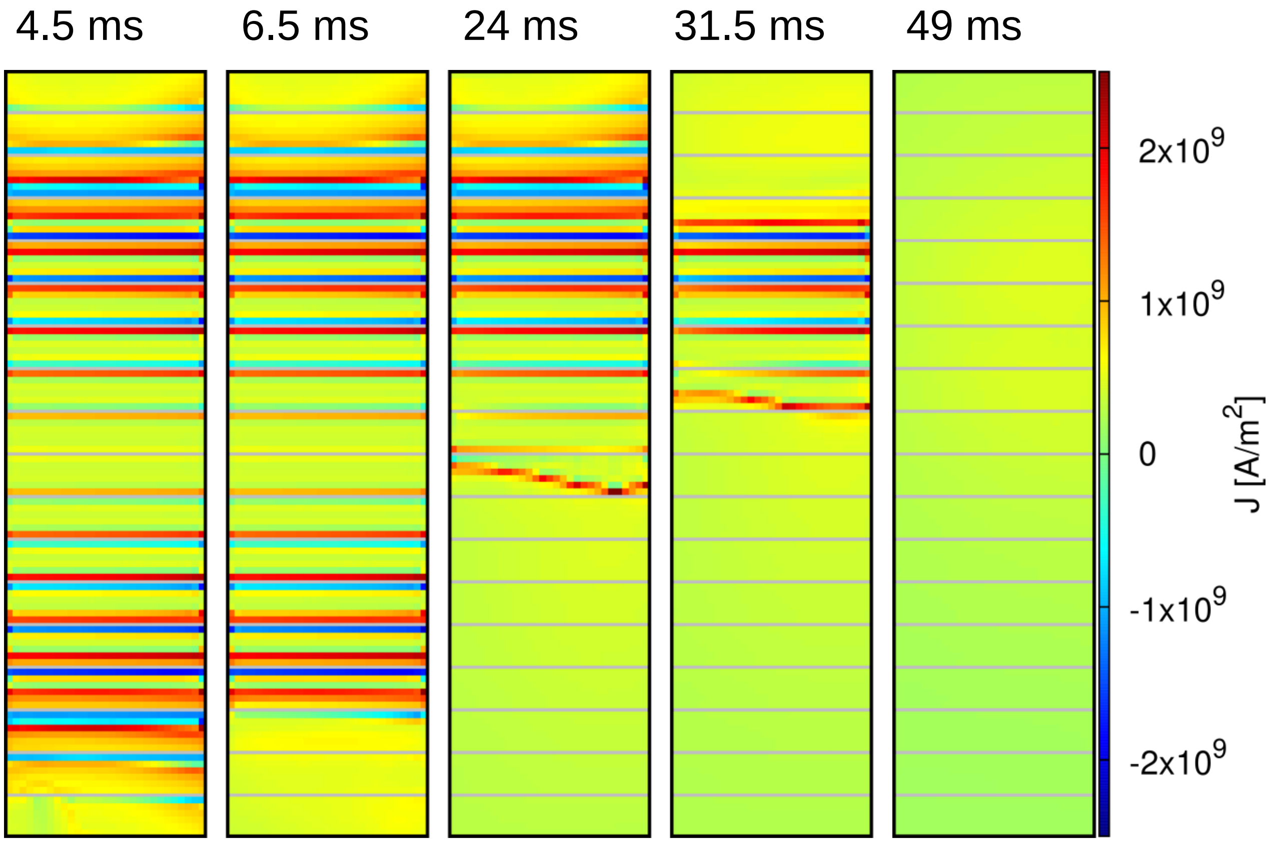
Voltage limitation:

1 V

Transfer to radial current at damaged turn

Strong negative radial currents due to decrease in magnetic flux

Angular current density



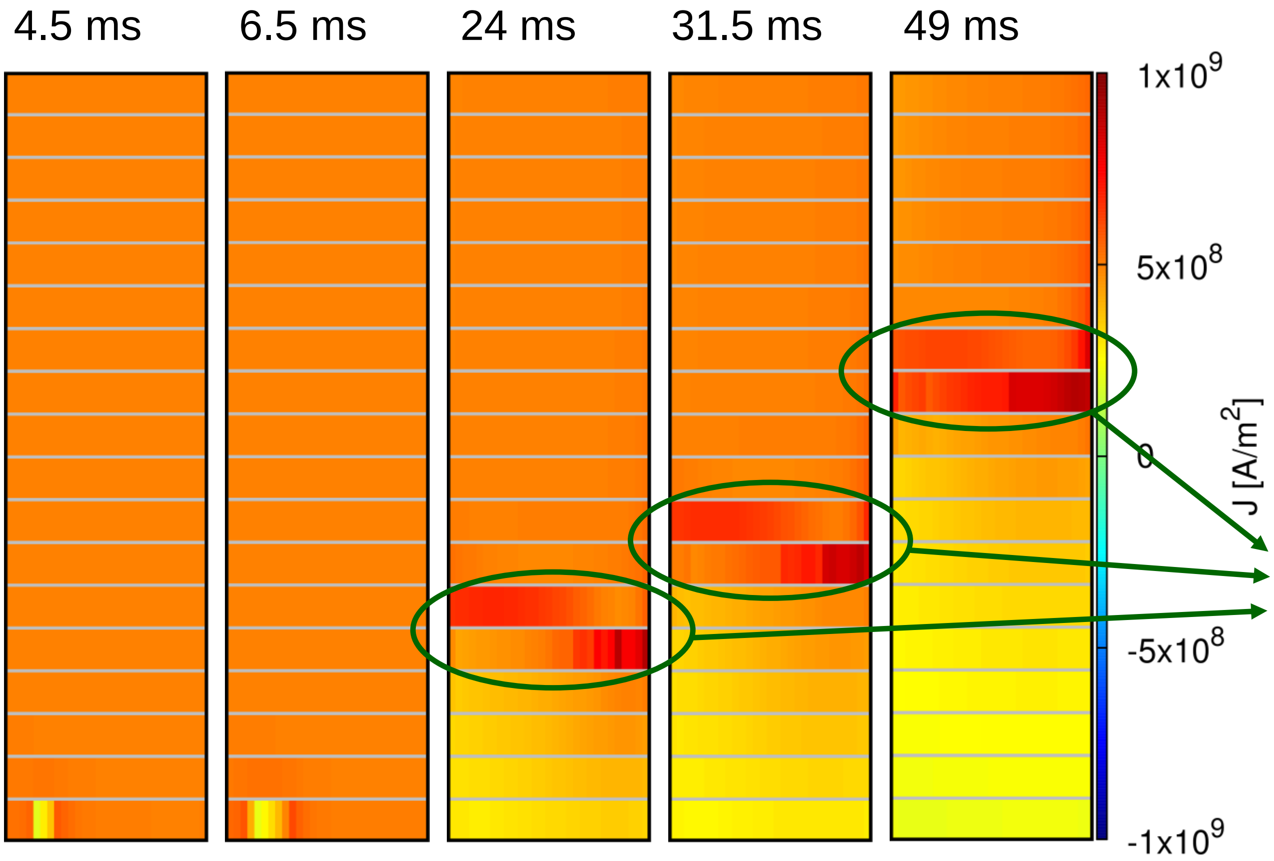
Voltage limitation:

1 V

Screening currents speed-up quench

They cause additional AC loss

What happens without screening currents?



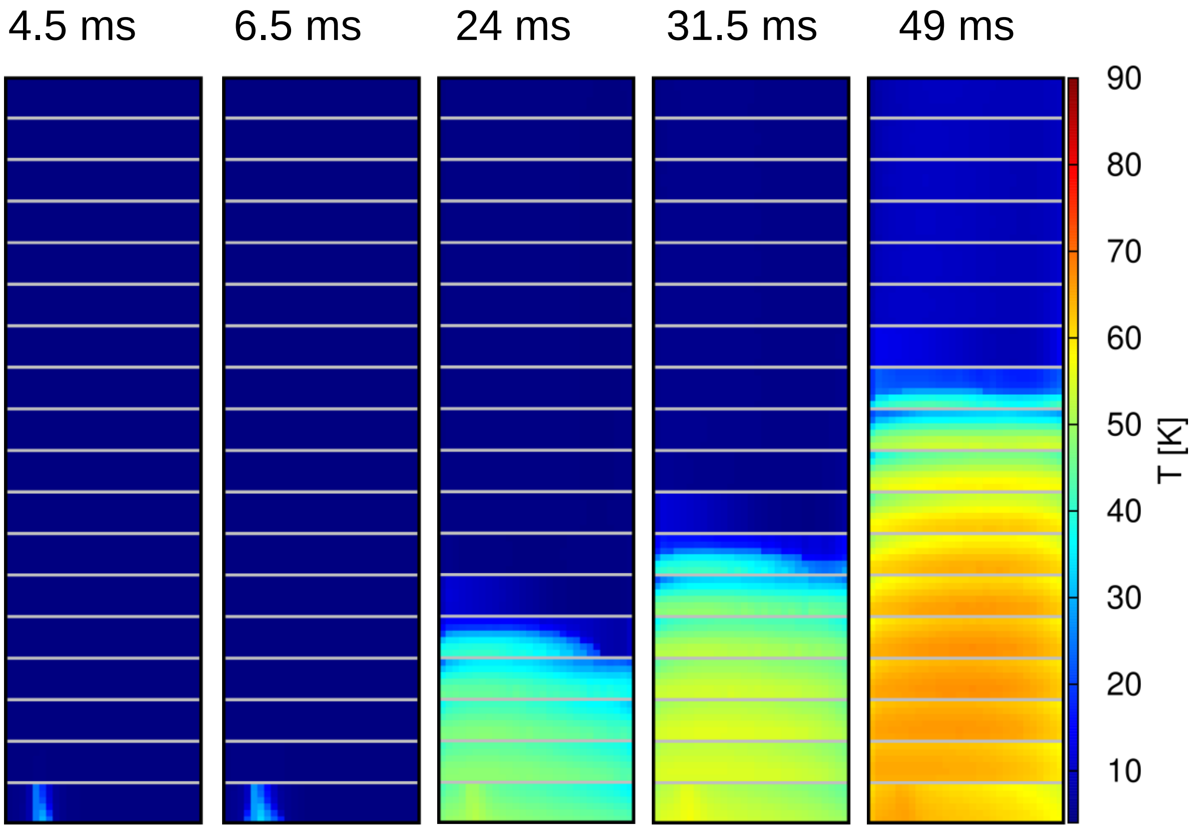
Voltage limitation:

1 V

Quench propagates slower

Increase in current at pancakes where quench propagates

Temperature evolution after degradation

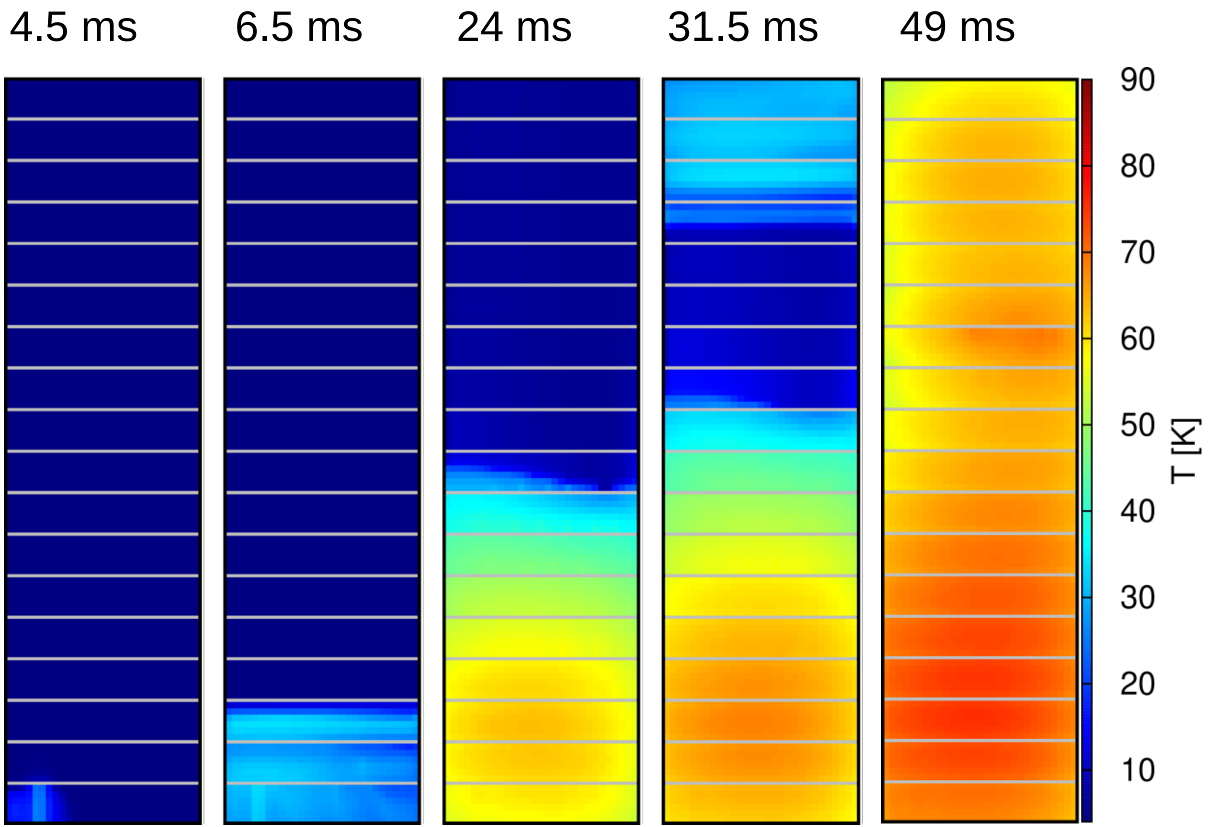


Voltage limitation:

1 V

Quench propagates slower

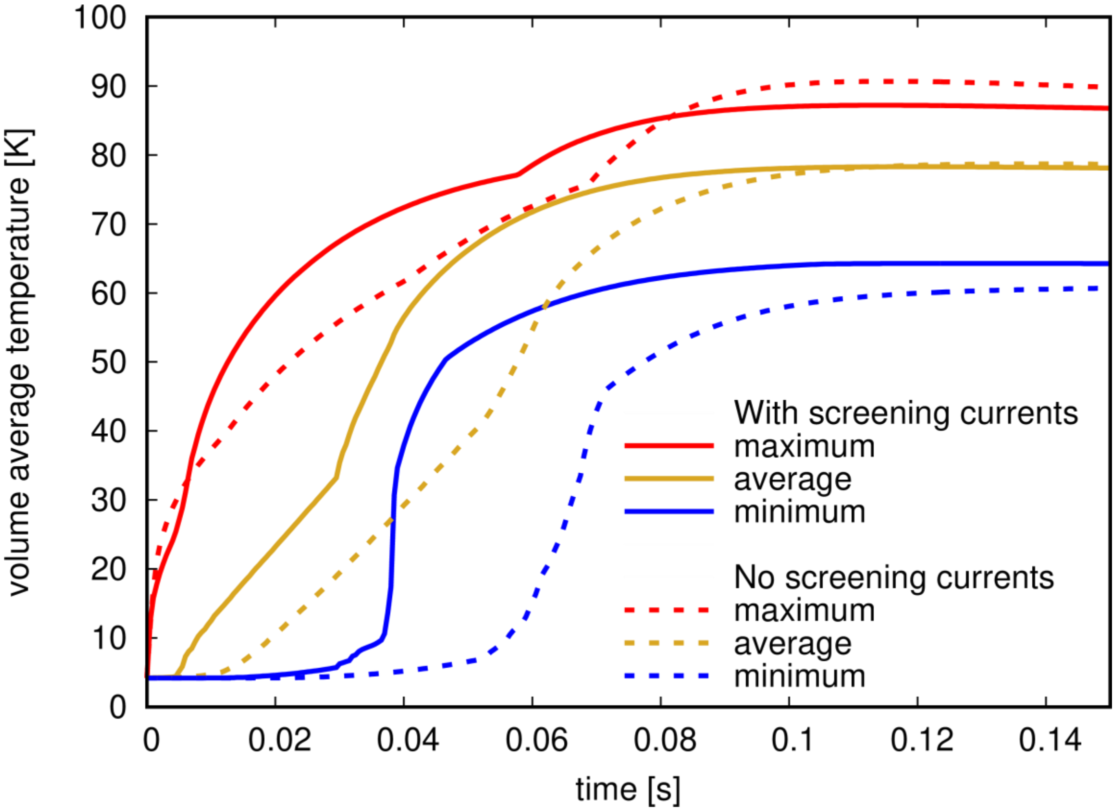
Faster quench with screening currents



Voltage limitation:

1 V

Quench propagates faster with screening currents



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- Finite difference method
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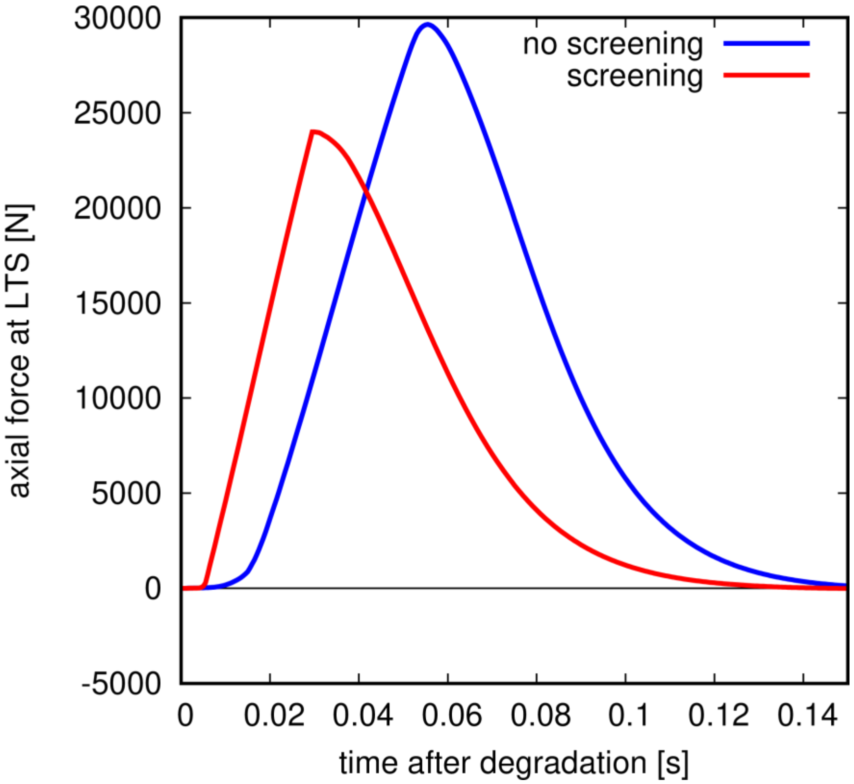
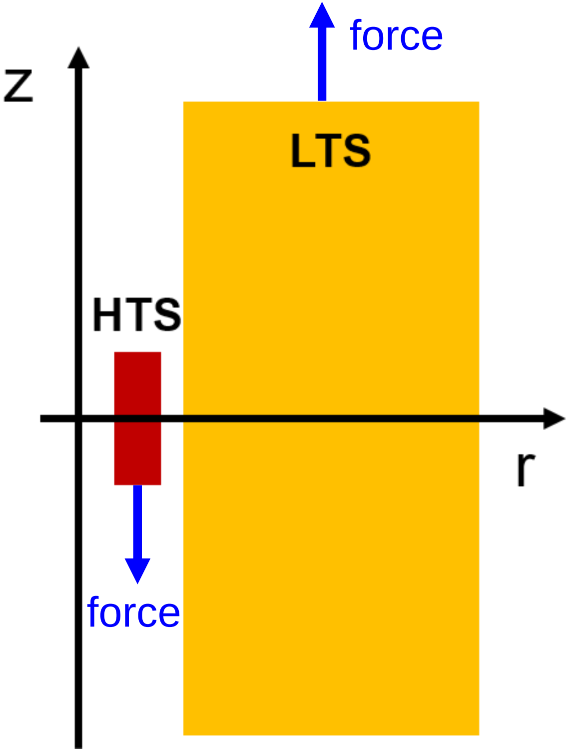
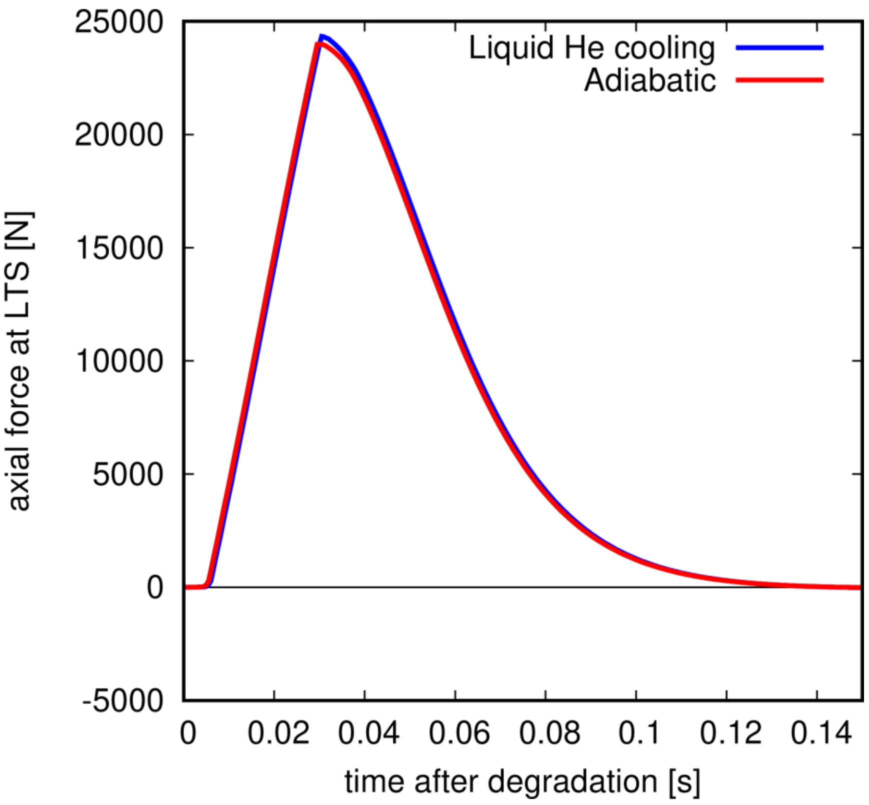
Mechanical stress during quench

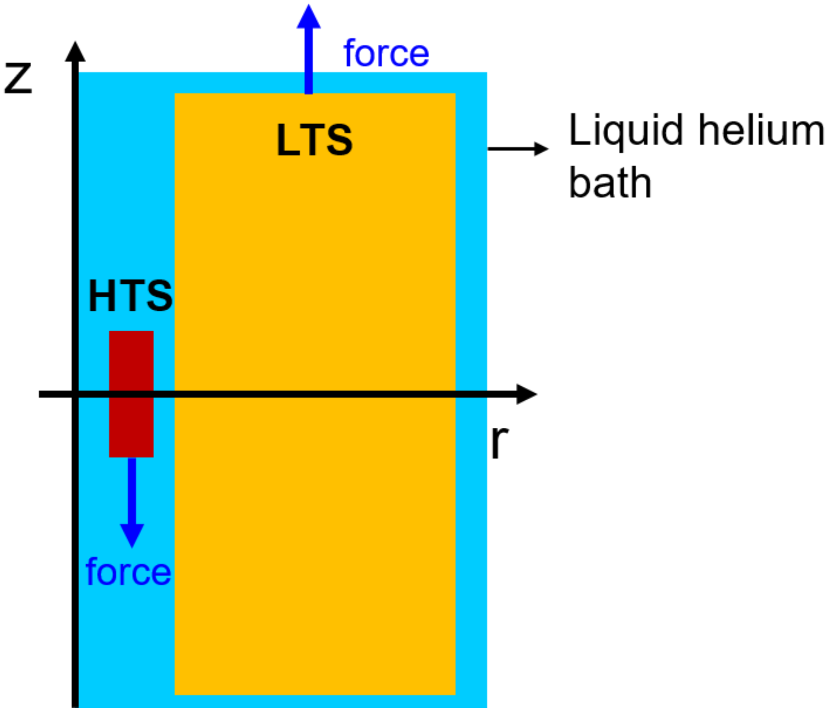
Screening currents reduce force on LTS during quench





Cooling by liquid helium has no impact





Electromagnetic modelling

Electro-thermal quench

Mechanical stress during quench

Electromagnetic modelling

Electro-thermal quench

Mechanical stress during quench

- Finite elements method
- Results during quench

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General equations

Governing equation: $\nabla \cdot (\underbrace{D}_{\text{stiffness matrix}}\underbrace{\varepsilon}_{\text{strain}}) + \underbrace{\boldsymbol{f}}_{\text{body force density}} = 0$

Lorentz force: $\boldsymbol{f}_L = \boldsymbol{J} \times \boldsymbol{B}$

Thermal stress: $\boldsymbol{f}_t = -\nabla \cdot (D\underbrace{\varepsilon_t}_{\text{thermal strain}})$

With axial symmetry

Governing equations:

$$\frac{\partial \sigma_r}{\partial r} + \frac{\partial \sigma_{rz}}{\partial z} + \frac{\sigma_r - \sigma_\phi}{r} + f_r = 0$$

$$\frac{\partial \sigma_z}{\partial z} + \frac{\partial \sigma_{rz}}{\partial r} + \frac{\sigma_{rz}}{r} + f_z = 0$$

Elastic assumption:

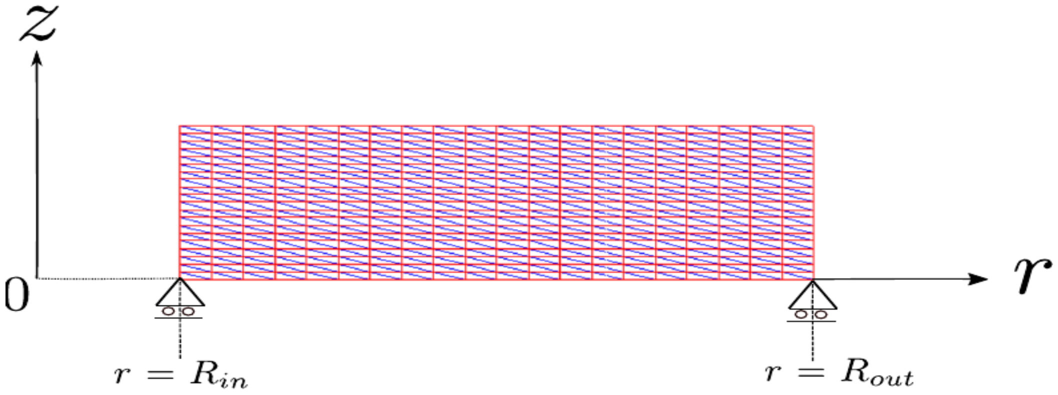
$$\sigma = D\,\varepsilon$$

Strains and displacements:

$$\varepsilon_r = \frac{\partial u_r}{\partial r}, \varepsilon_\phi = \frac{u_r}{r}, \varepsilon_z = \frac{\partial u_z}{\partial z}, \varepsilon_{rz} = \frac{\partial u_r}{\partial z} + \frac{\partial u_z}{\partial r}$$

Displacements are state variables

Our own finite element method



Boundary conditions:

Fixed lower axial displacement

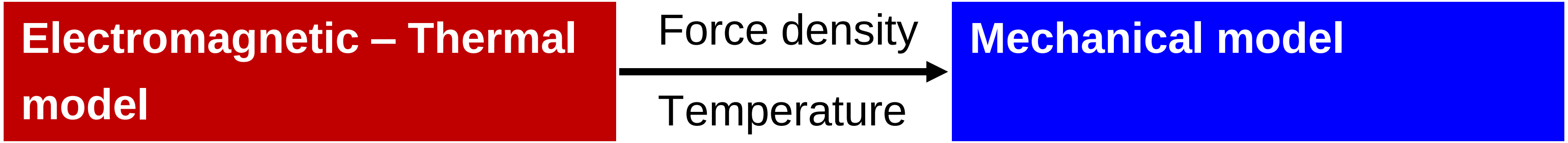
Programmed in MATLAB

Very fast

Only few seconds!

AK Srivastava, E Pardo 2024 SuST

Mechanical model coupled one-way



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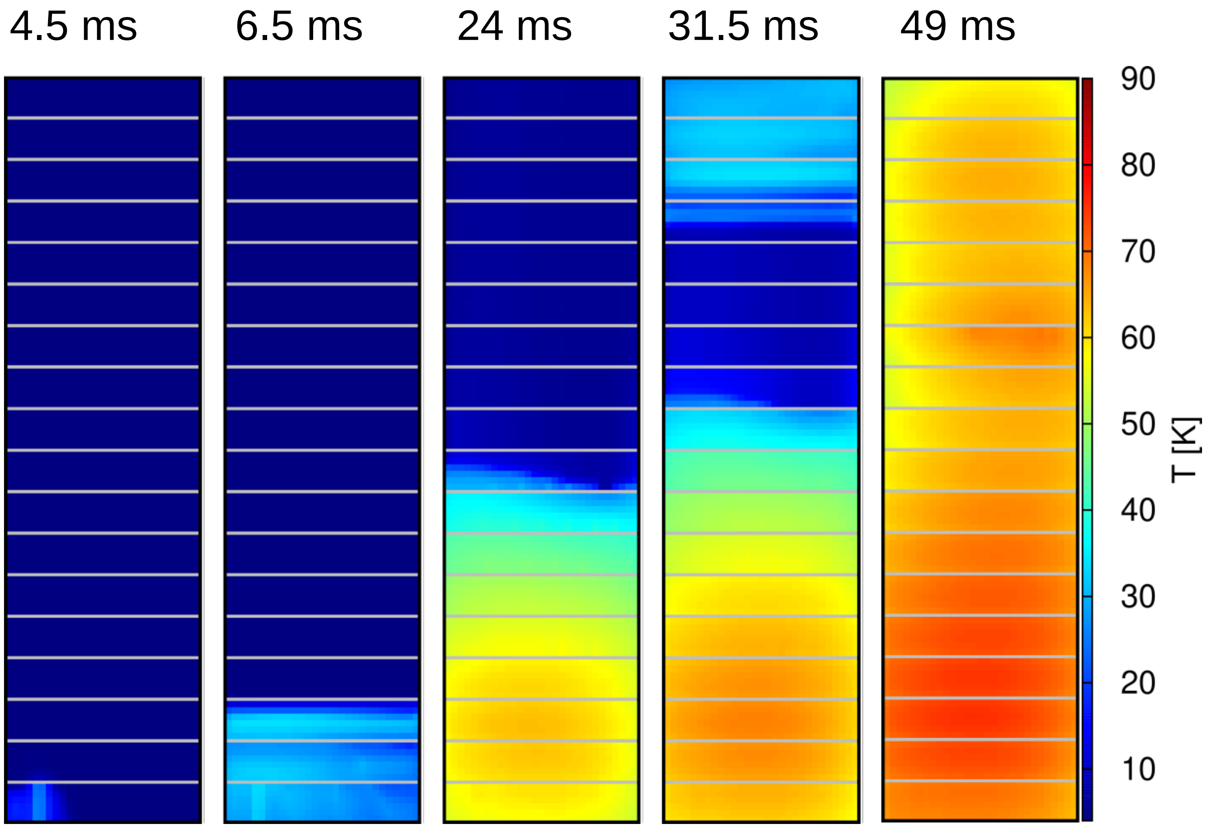
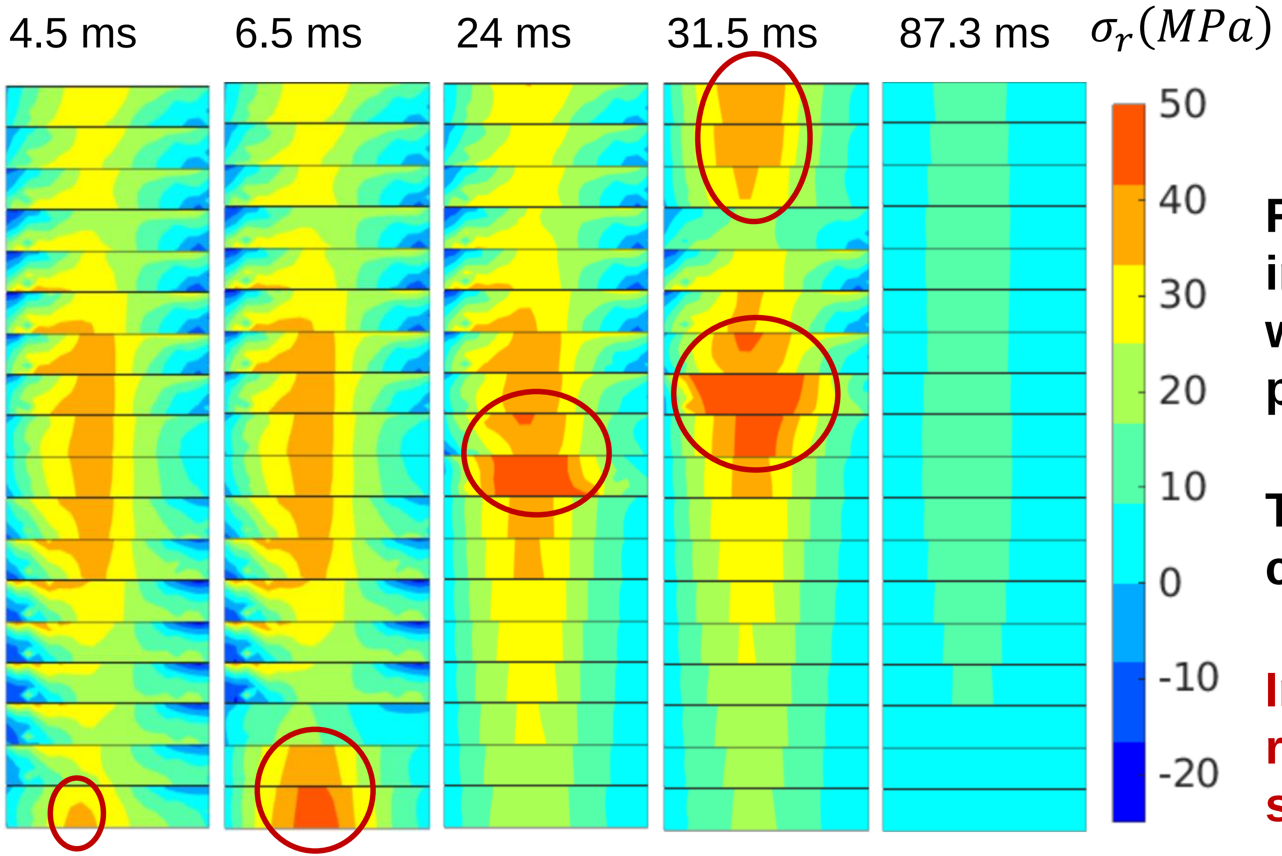
Faster quench with screening currents



Voltage limitation:

1 V

Radial stress evolution

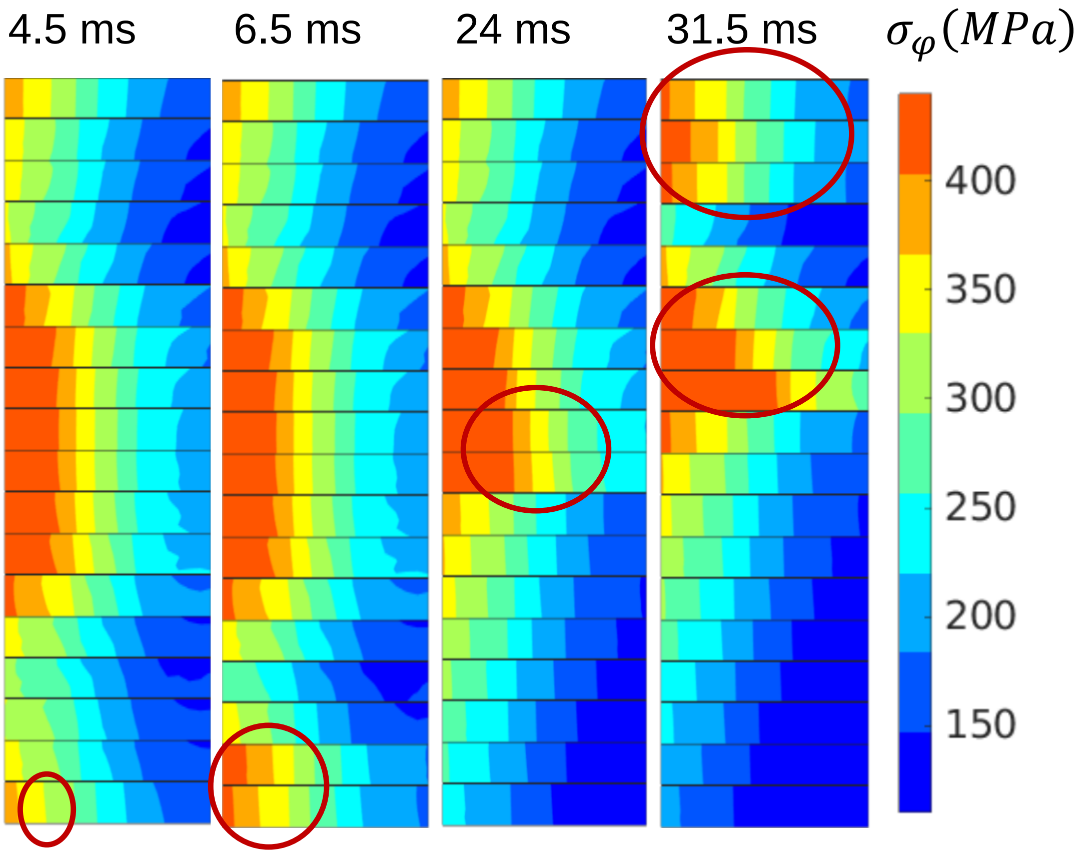


Radial stress increases at pancakes where quench propagates

Tensile radial stress could detach turns

Increased radial stress at quench should be compensated

Hoop stress evolution



Hoop stress increases at pancakes where quench propagates

Maximum hoop stress is roughly the same

Conclusion

Multi-physics modelling of high-temperature superconductors

You can use axi-symmetric model for metal-insulated coils

Fast and accurate electromagnetic modeling

Fully coupled electro-thermal model **with screening currents**

Effect of strongly damaged turn:

- **Electrothermal quench propagates electromagnetically**
- **Screening currents speed-up electrothermal quench**

Multi-physics modelling of high-temperature superconductors

Fast and accurate electro-thermo-mechanical modelling

Increased stress due to screening currents

Thermal stress during quench could be problematic if not compensated

Thank you for your attention!

Would you like to know more?

enric.pardo@savba.sk

Baseline 32 T pre-design

REBCO tape: **Fujikura**

Number of pancakes: **16**

Turn-to-turn resistance: **10^{-7} Ωm^2**

Background magnetic field: **from 19 T LTS**

Thermal expansion coefficient: **10^{-6} K^{-1}**

G-10 pancake spacer: **0.5 mm**

General equations

Governing equation:

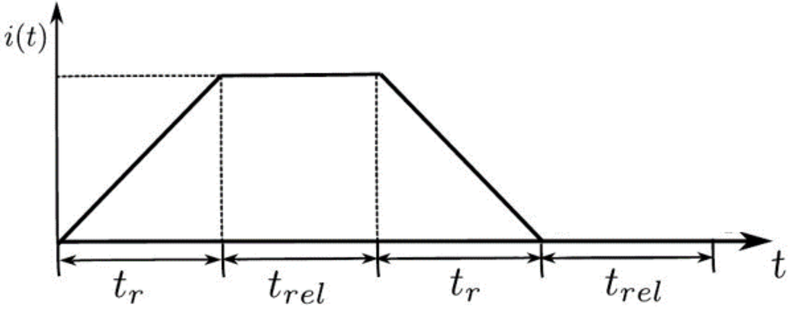
$$\nabla \cdot (D\varepsilon) + \boldsymbol{f} = 0$$

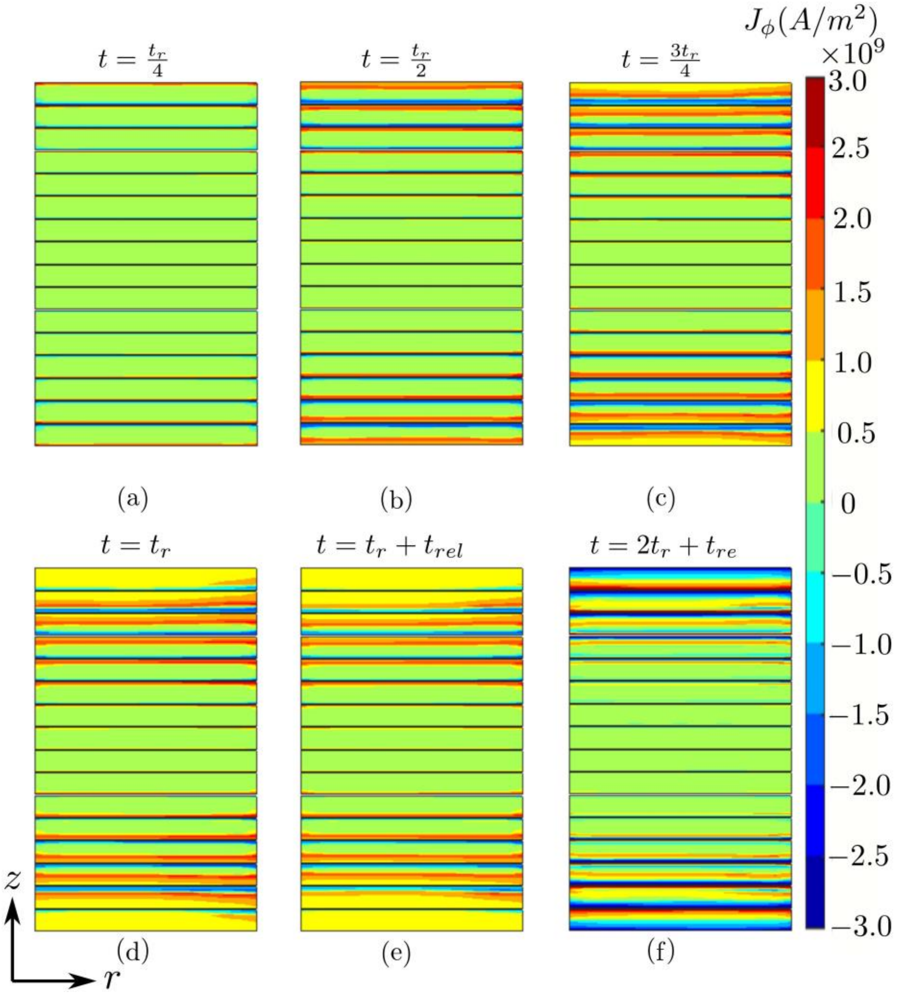
stiffness matrix strain body force density

Lorentz force:

$$\boldsymbol{f}_L = \boldsymbol{J} \times \boldsymbol{B}$$

Current density with screening currents

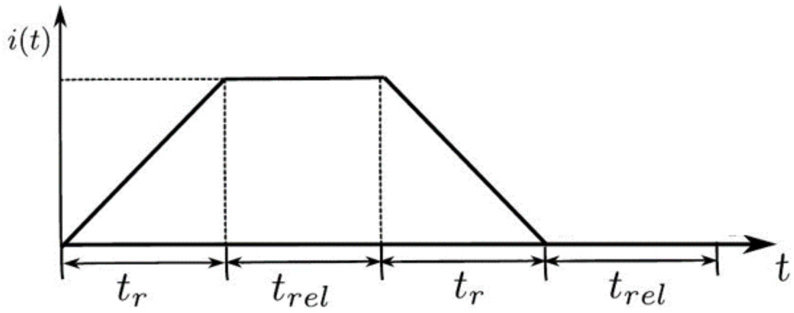


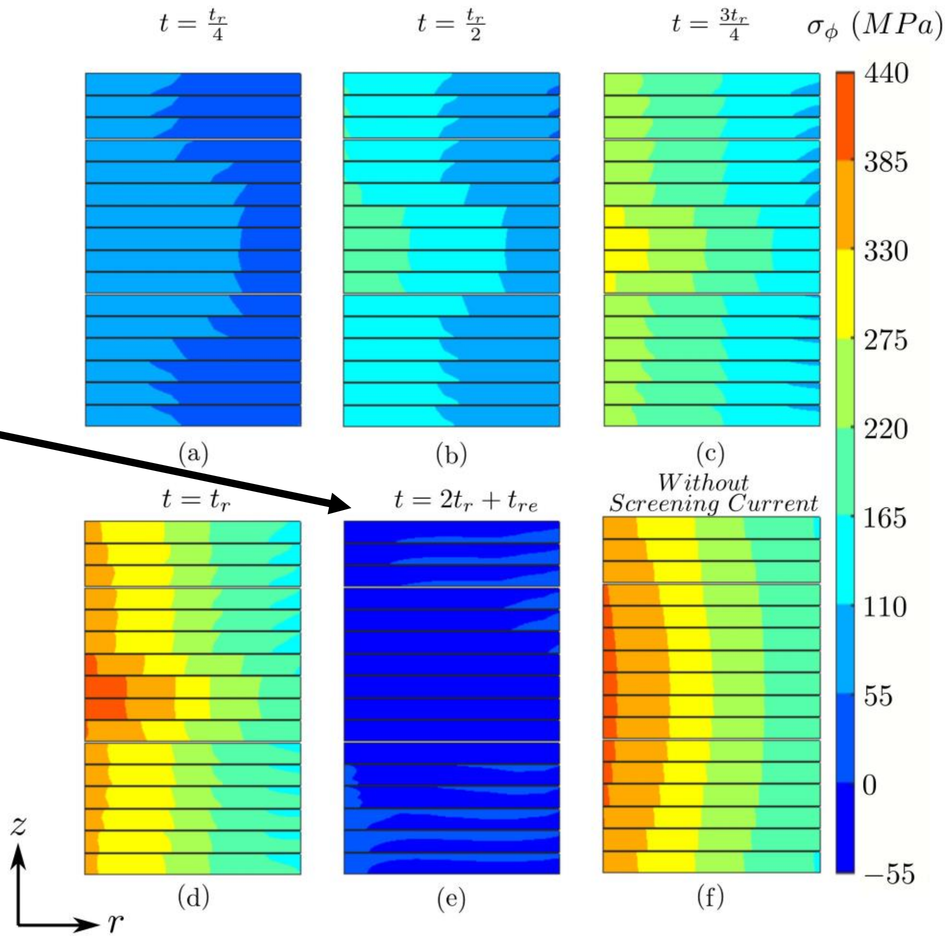


Screening currents increase stress

Negative hoop stress regions at remanence

Might cause buckling

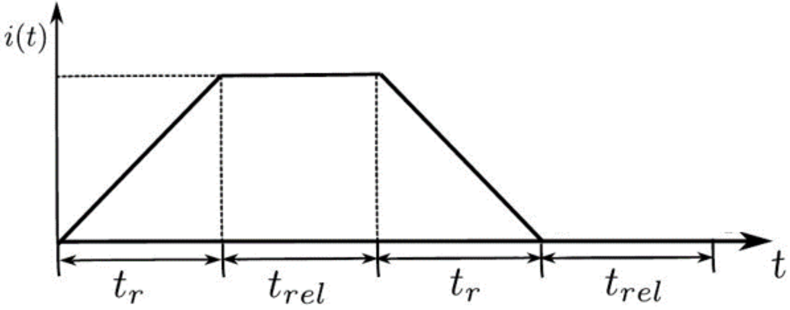


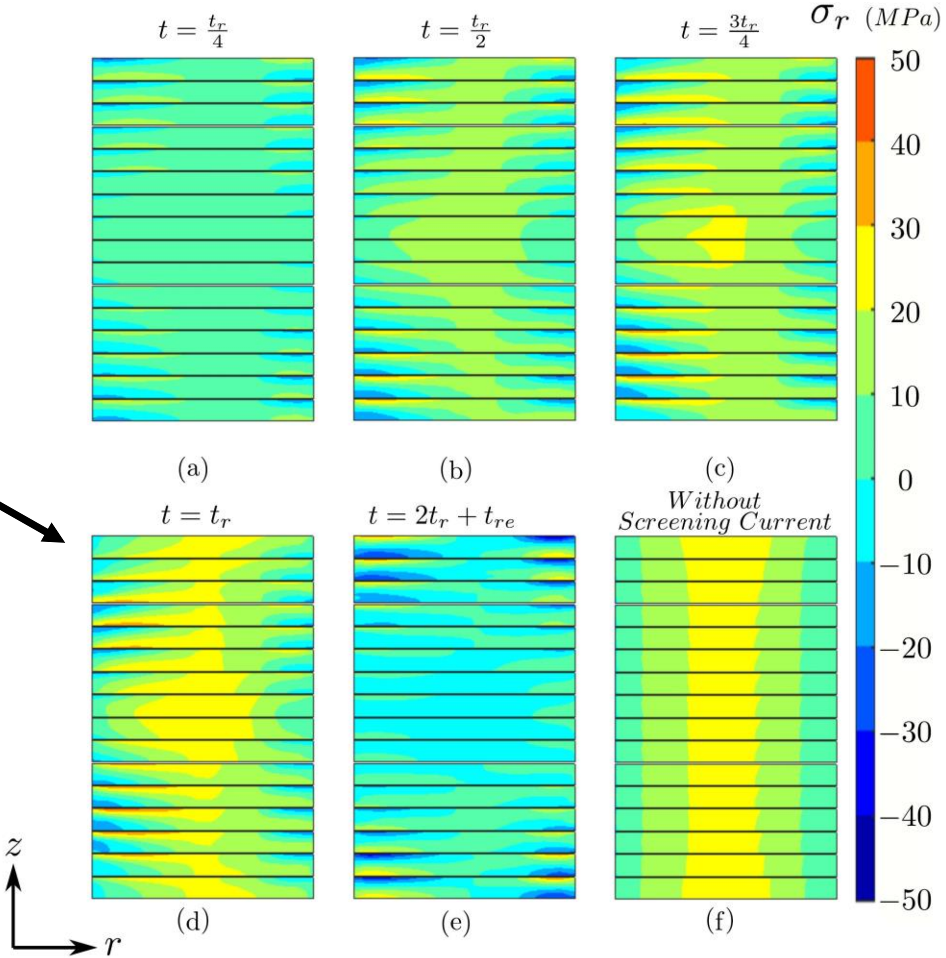


Screening currents increase stress

Tensile radial stress regions

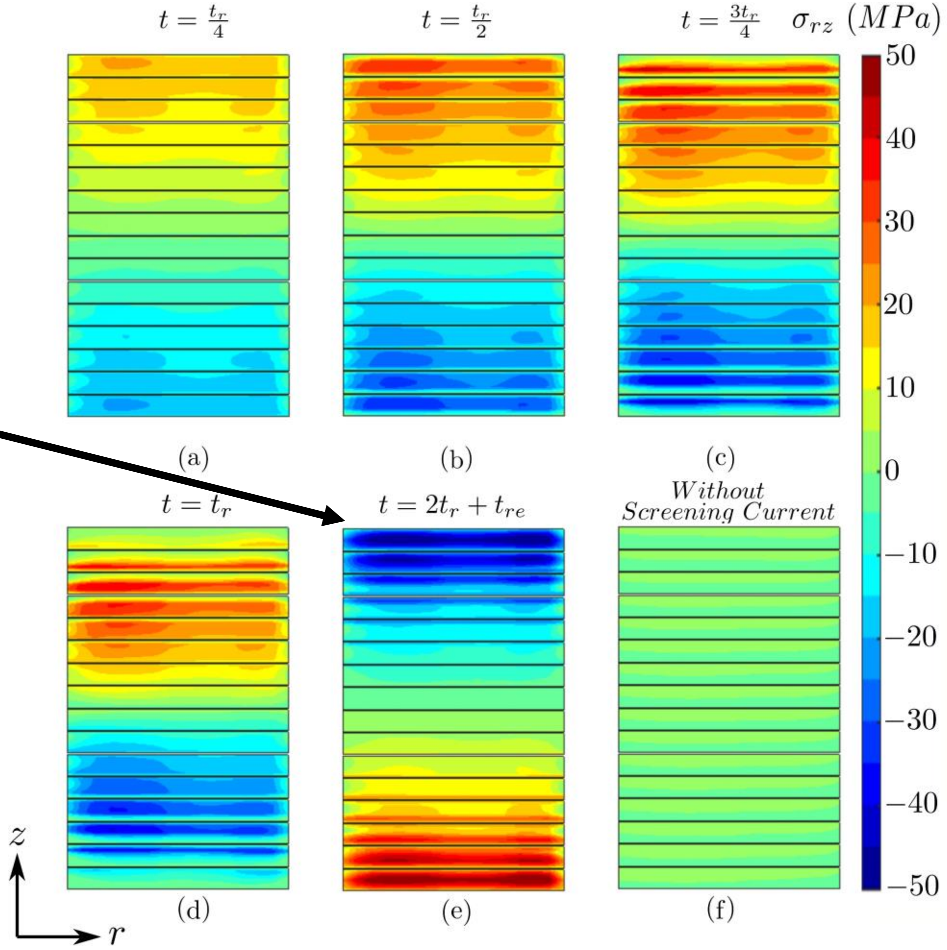
Might lose contact between tapes

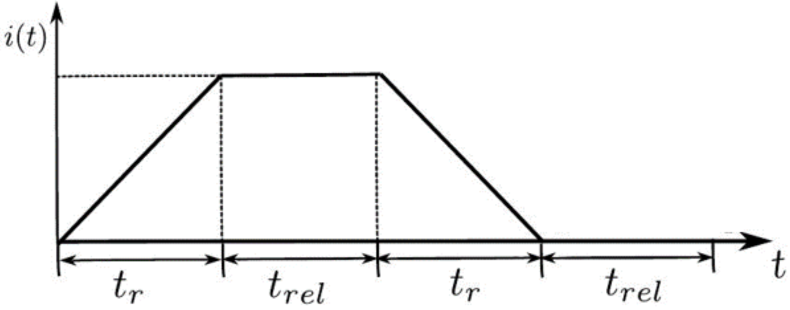




Shear stress might be problematic

Maximum shear stress at remanence

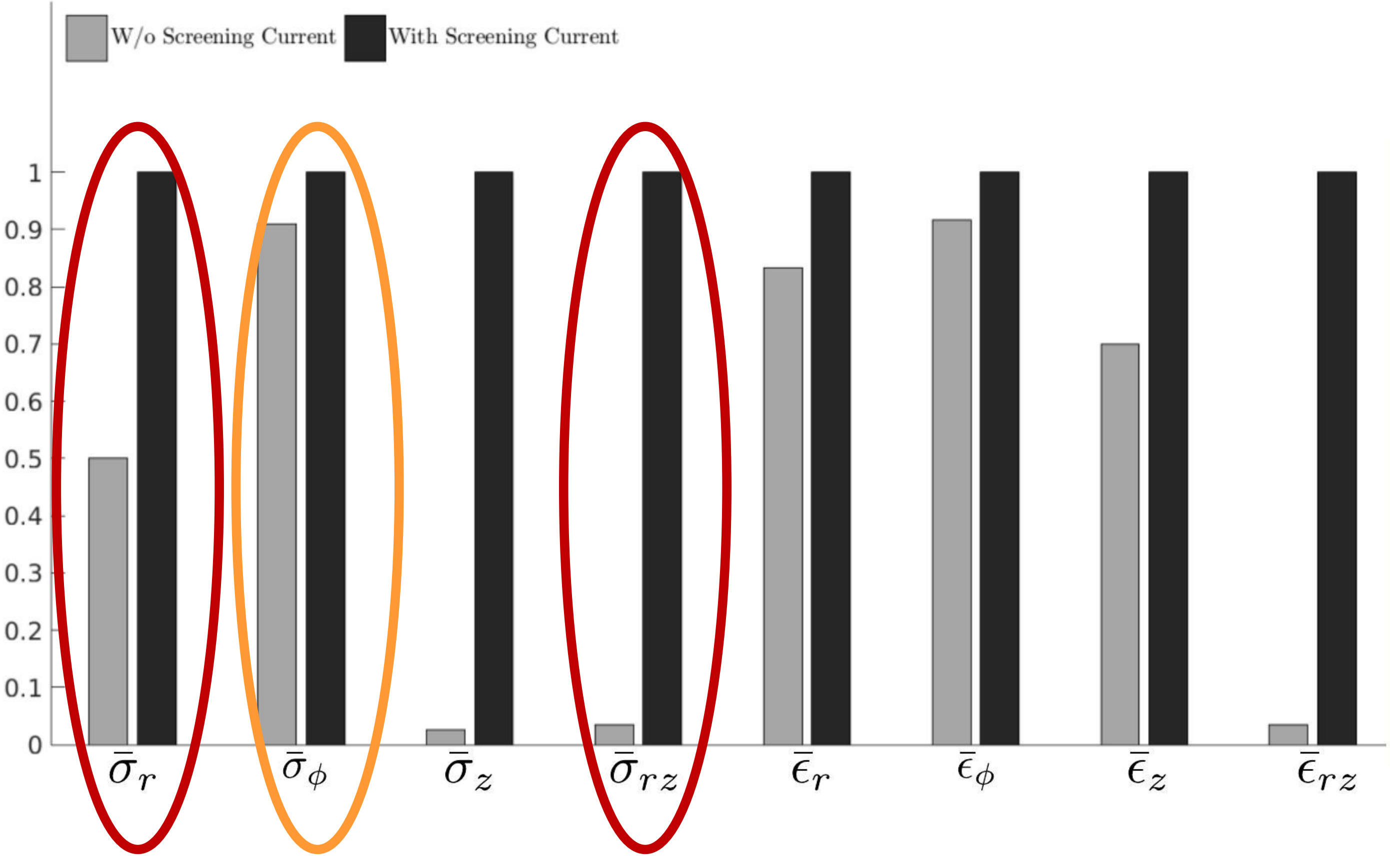




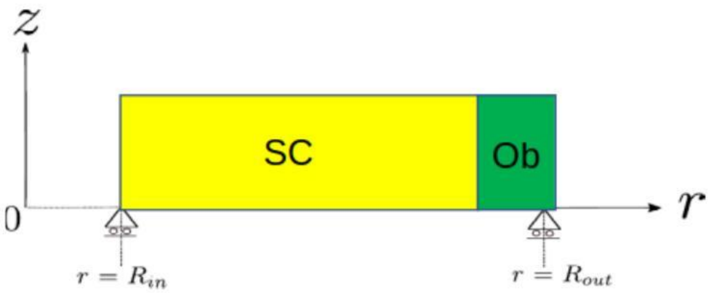
Screening currents are important

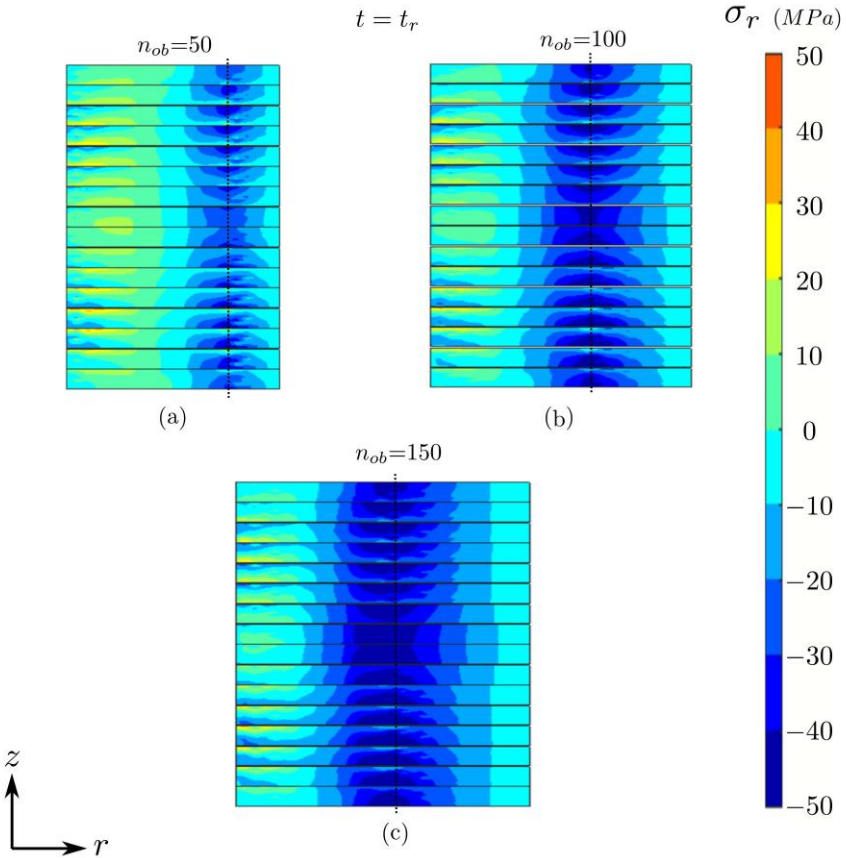
maximum
at winding

[normalized
quantity]

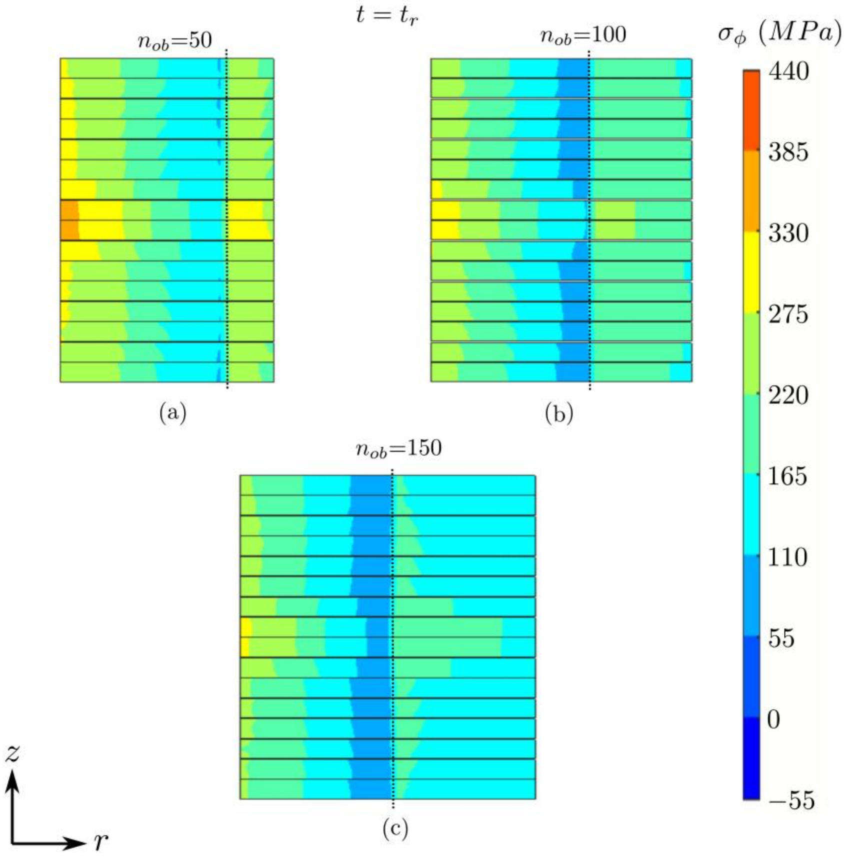


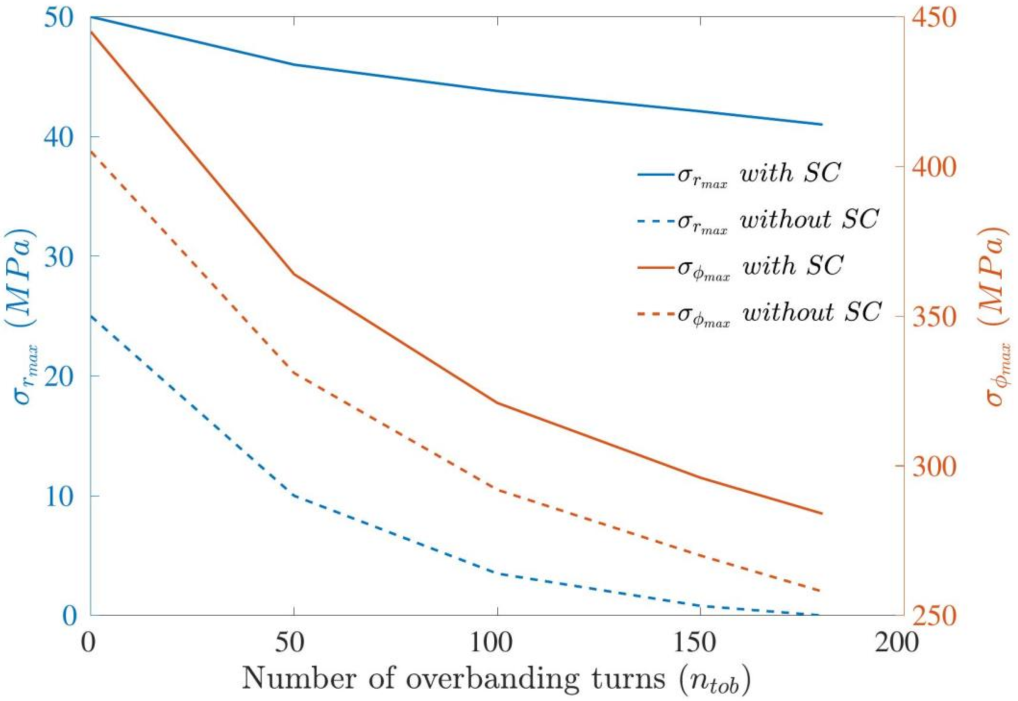
Overbanding reduces radial stress

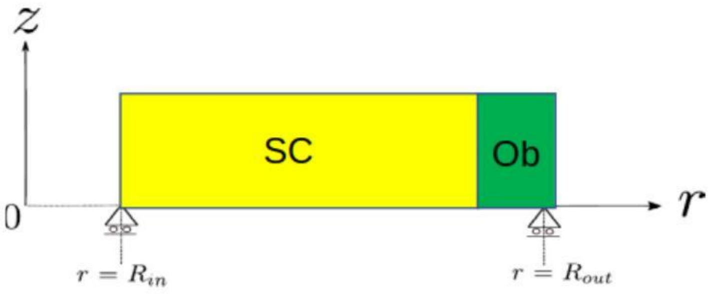




Overbanding reduces hoop stress

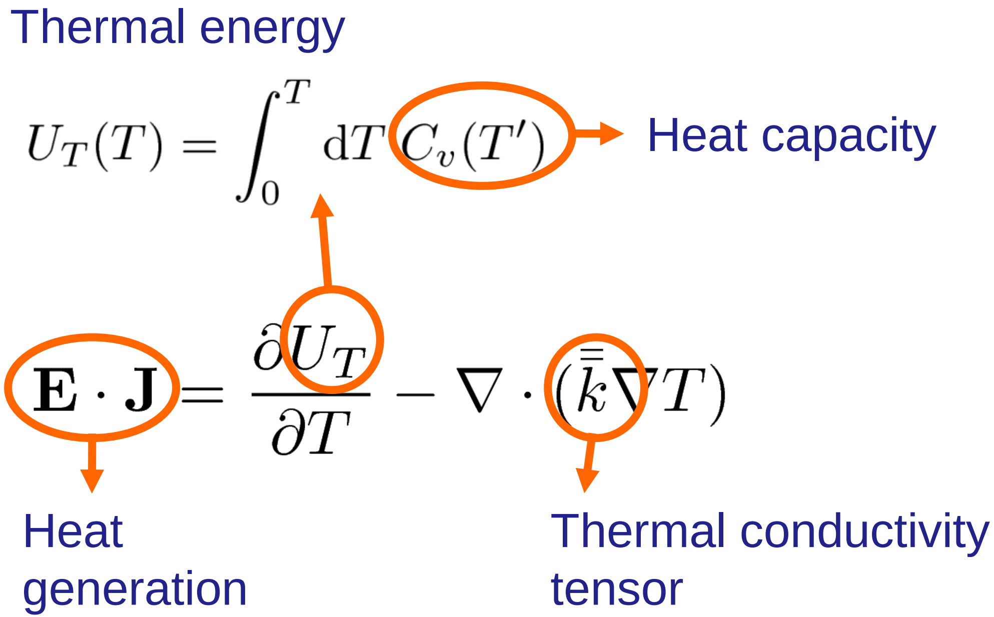






BC: Lower axial displacement fixed

Thermal diffusion equation



Thermal energy

$$U_T(T) = \int_0^T \mathrm{d}T\, C_v(T')$$

Heat capacity

$$\mathbf{E}\cdot\mathbf{J} = \frac{\partial U_T}{\partial T} - \nabla\cdot(\bar{\bar{k}}\nabla T)$$

Heat generation

Thermal conductivity tensor

Variational principle

Solving

$$\mathbf{E}\cdot\mathbf{J} = \frac{\partial U_T}{\partial T} - \nabla\cdot\left(\bar{\bar{k}}\nabla T\right)$$

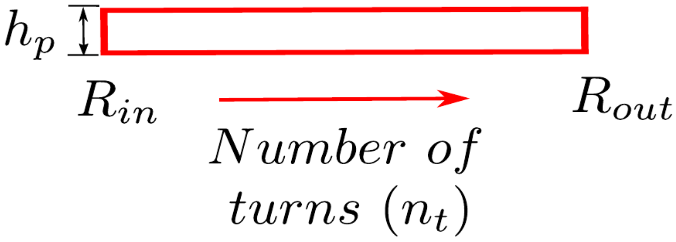
is the same as minimizing

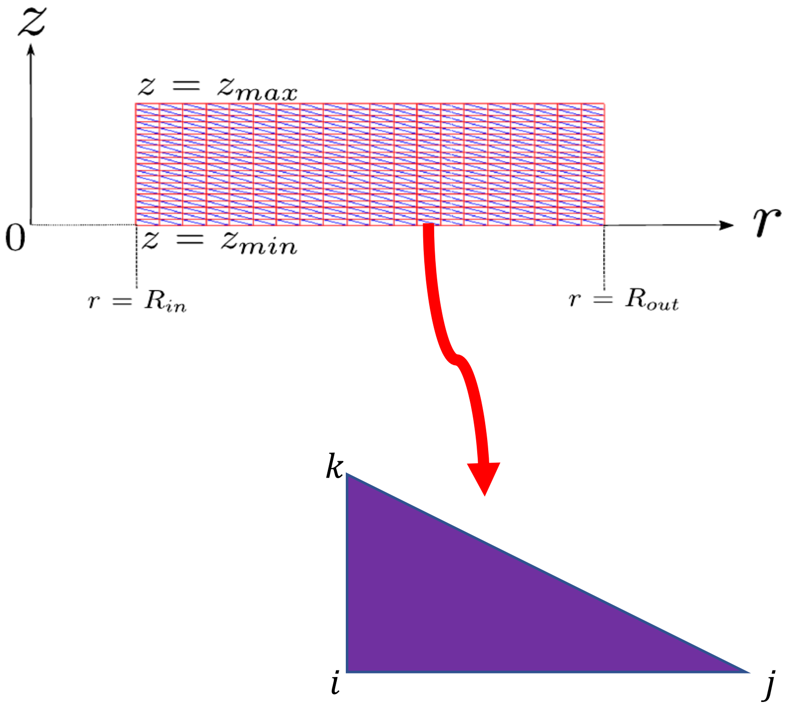
$$L_T = \int_V \mathrm{d}V \left\{ \left[\boxed{h(T)} - U_T(\boxed{T_0})T\right]\frac{1}{\Delta t} + \frac{1}{2}\nabla T\bar{\bar{k}}\nabla T - T\,\mathbf{E}\cdot\mathbf{J} \right\}$$

$$h(T) = \int_0^T \mathrm{d}T' U_T(T')$$

Temperature
at previous time step

Finite Element Model





Electromagnetic modelling

- Axi-symmetric variational method
- Benchmark
- REBCO insert

Electro-thermal quench

- Finite difference method
- Electro-thermal quench
- Force on LTS outsert

Mechanical stress during quench

- Finite elements method