Modeling of screening currents in non-insulated REBCO magnets: fast and accurate 2D approach

Enric Pardo

Institute of Electrical Engineering,
Slovak Academy of Sciences

Philippe Fazilleau

CEA, Saclay, France

Super EMFL

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Model

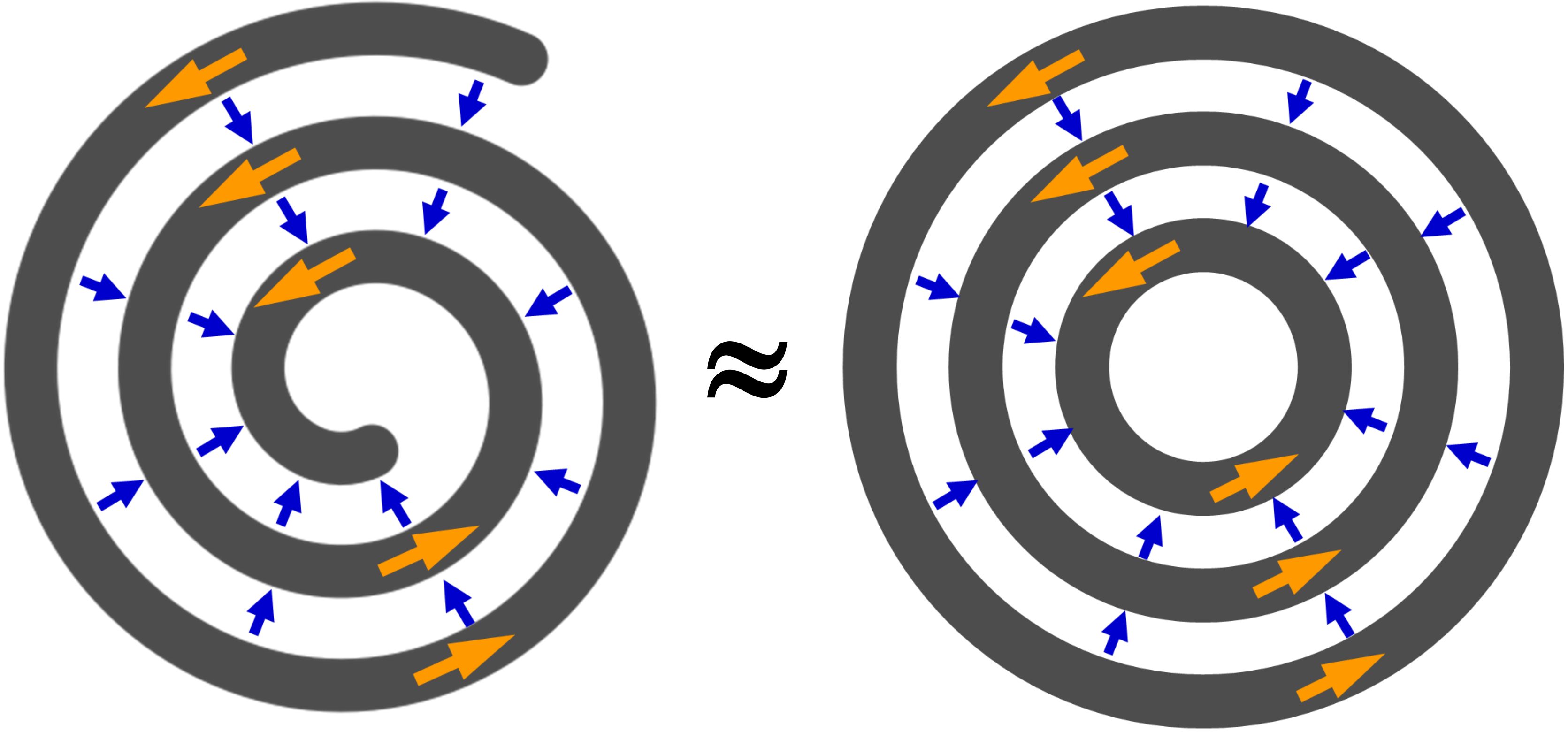
Magnet results

Model

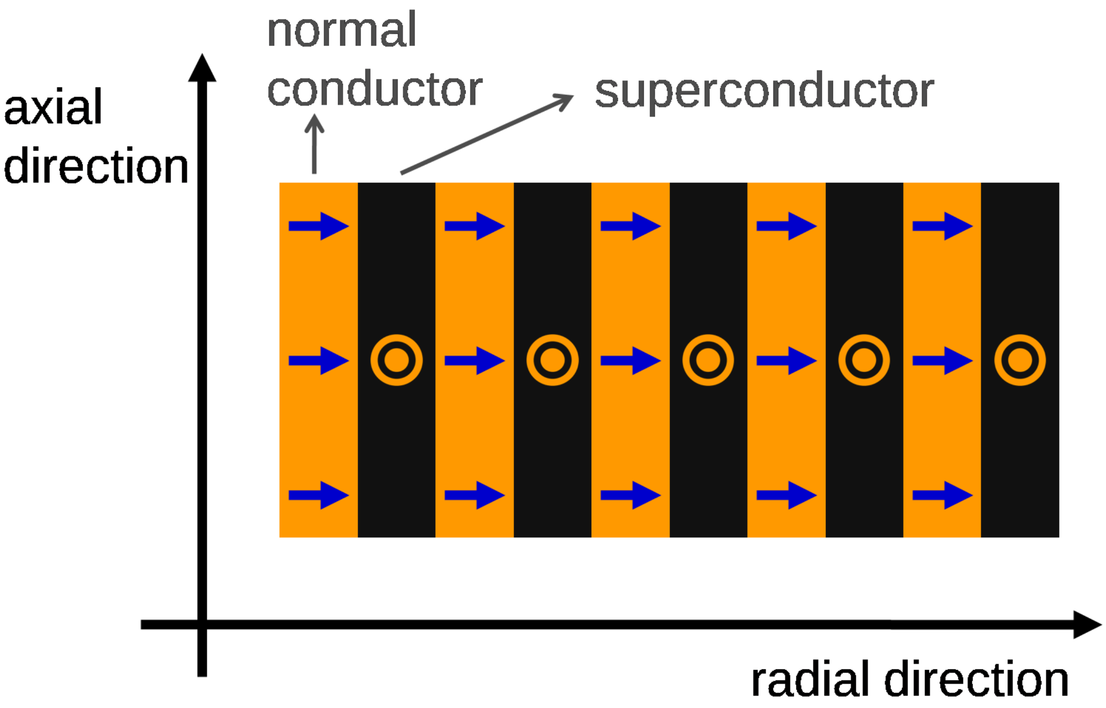
- Axi-symmetric approach
- Solver
- Benchmark

Magnet results

Spiral coil behaves almost like axi-symmetric



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

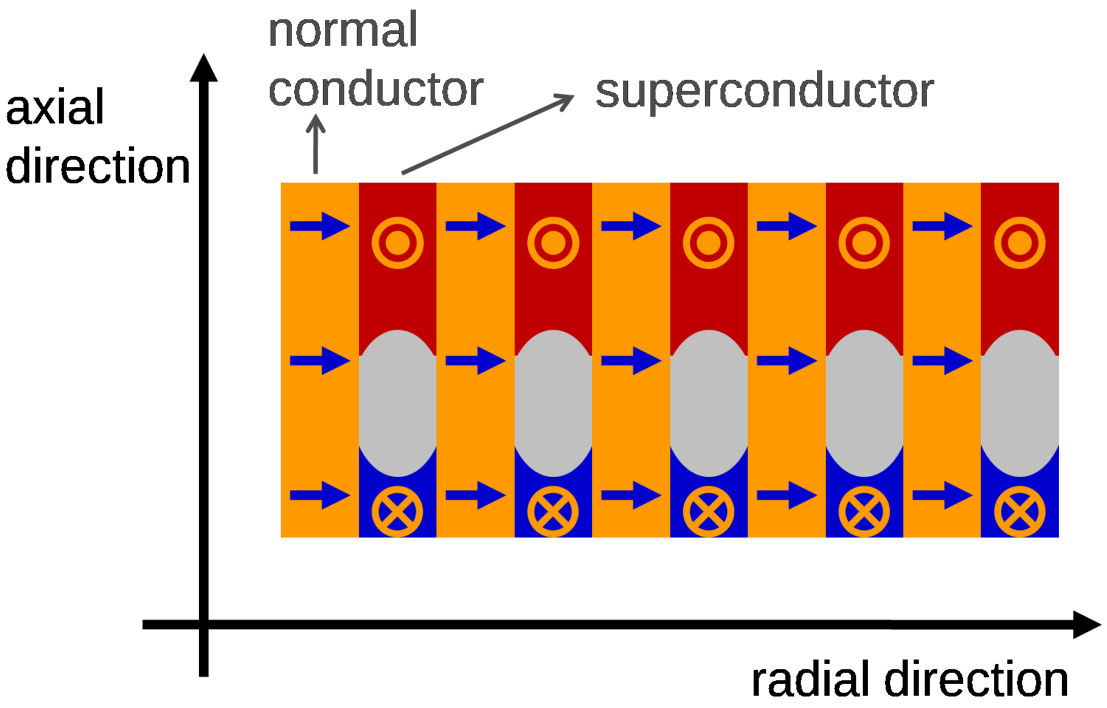


At each turn:

$$I = I_r + I_\varphi$$

input current

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



At each turn:

$$I = I_r + I_\varphi$$

input current

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

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Magnet results

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

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

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

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

E Pardo, M Kapolka 2017 J Comp. Phys.

Model

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Benchmark double pancake coil

Number or turns per pancake: **200**

Radial resistance between turns: **50 μΩ cm^2**

Ramp rate: **1 A/s**

Input current: **400 A**

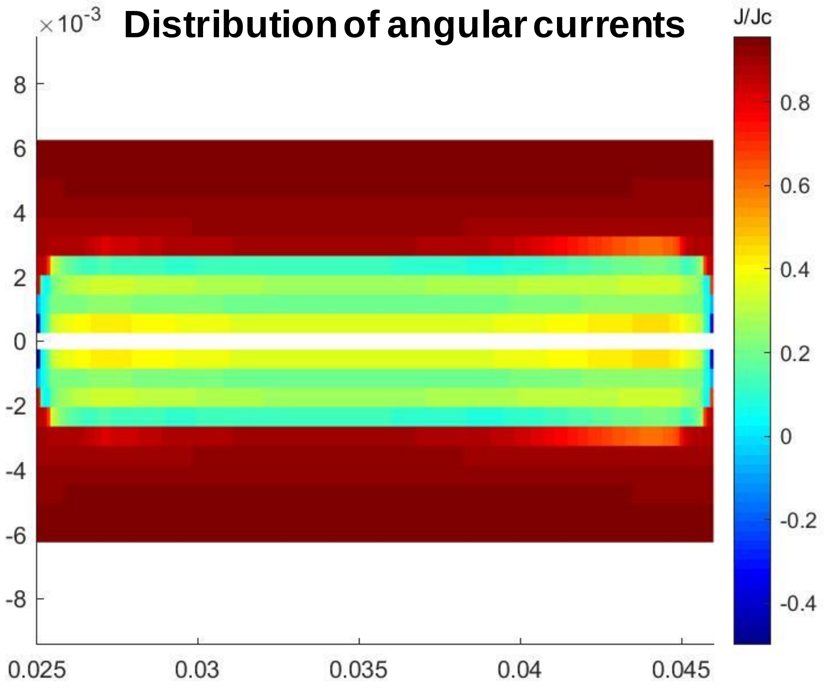
Pancake separation: **500 μm**

Numerical models:

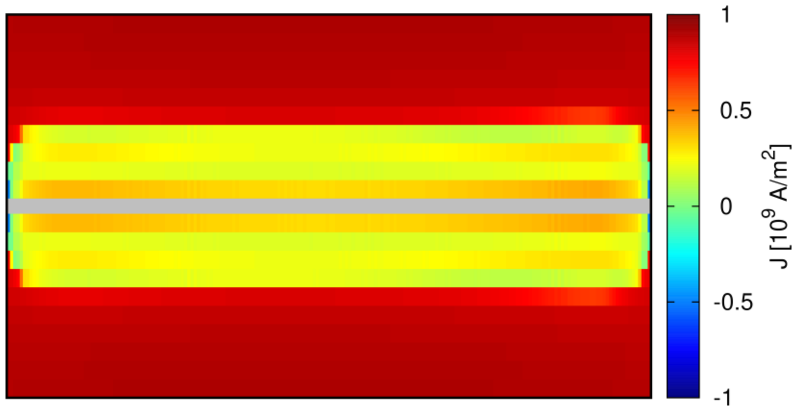
- **MEMEP (IEE Slovakia)**
- **MATLAB with ODE coupling (CEA France)**

Results between models agree

MATLAB ODE

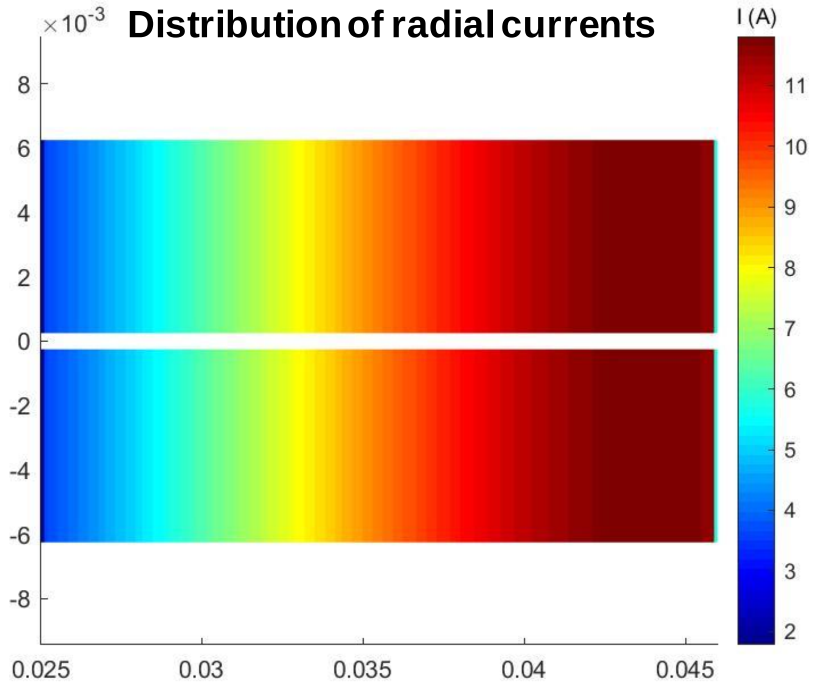


MEMEP

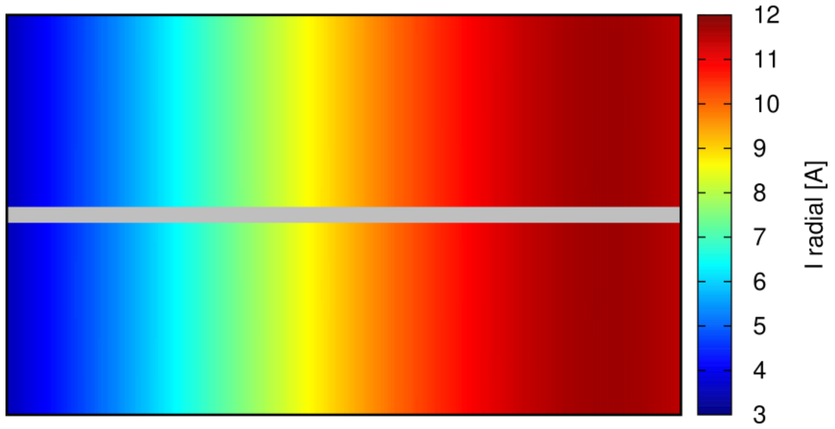


Results between models agree

MATLAB ODE



MEMEP



Model

Magnet results

Model

Magnet results

- Inputs
- Low currents
- High currents
- Generated magnetic field

Parameters

Inner radius: **25 mm**

Outer radius: **46 mm**

Number of pancakes: **20**

Number of turns per pancake: **200**

Background magnetic field: **20 T**

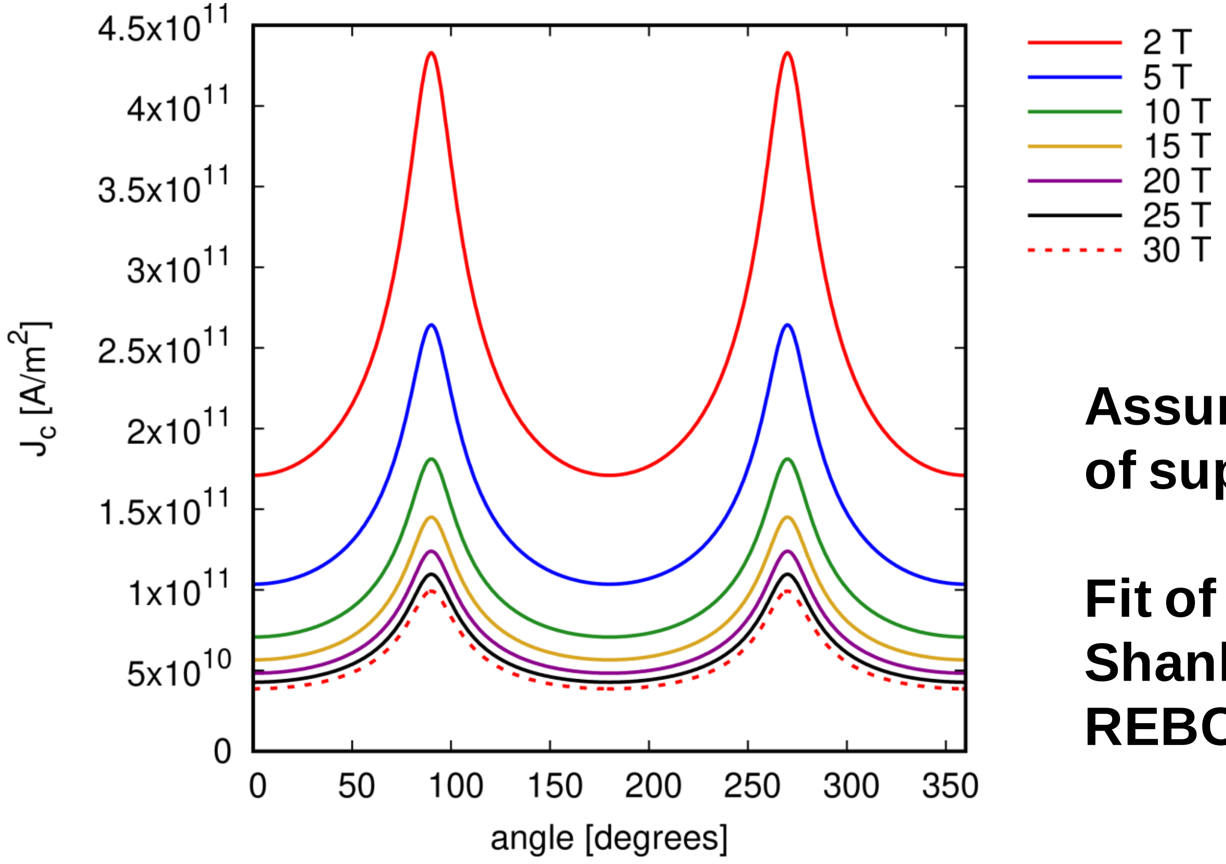
Turn-to-turn resistance: **10 000, 50, 5 $\mu\Omega$ cm^2**

metal-insulated

soldered

non-insulated

Input $J_c(B,\theta)$



Assumed 1 μm thickness of superconductor

Fit of measurements of Shanhai Superconductors REBCO tape

Model

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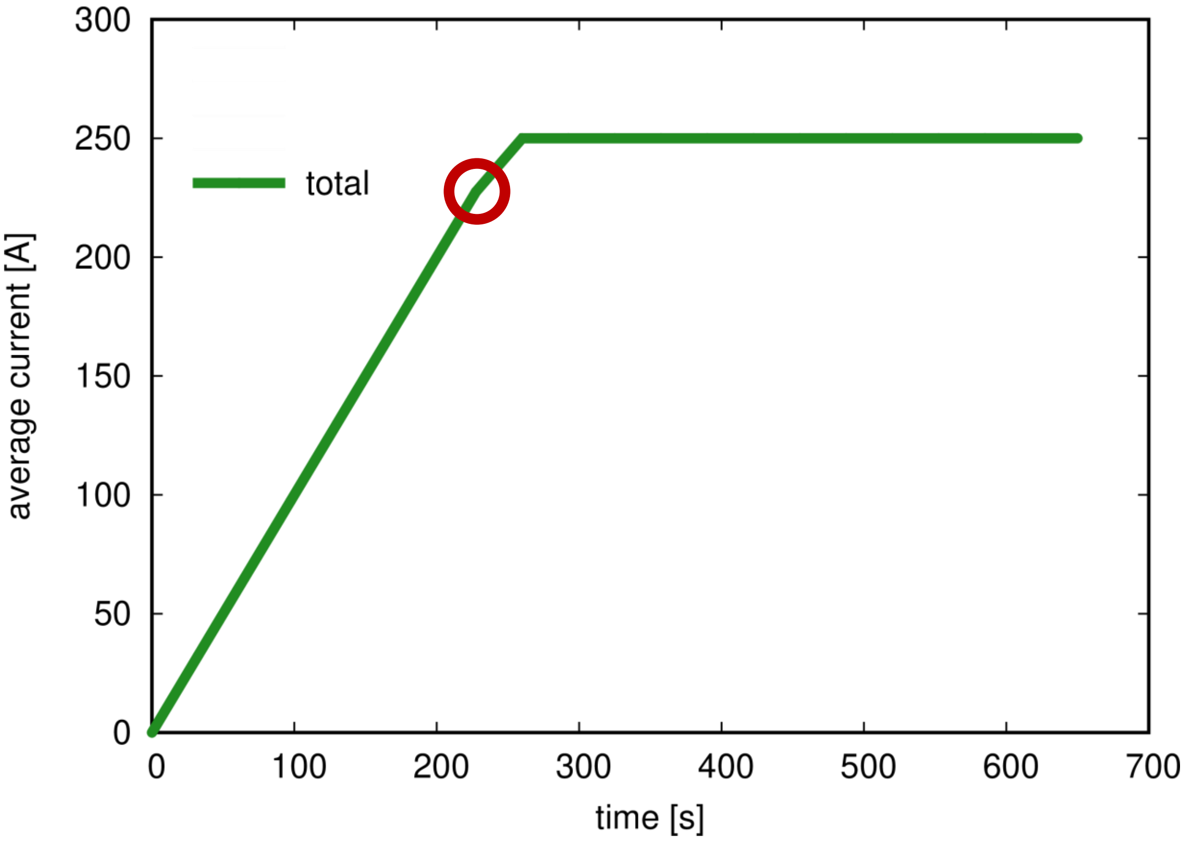
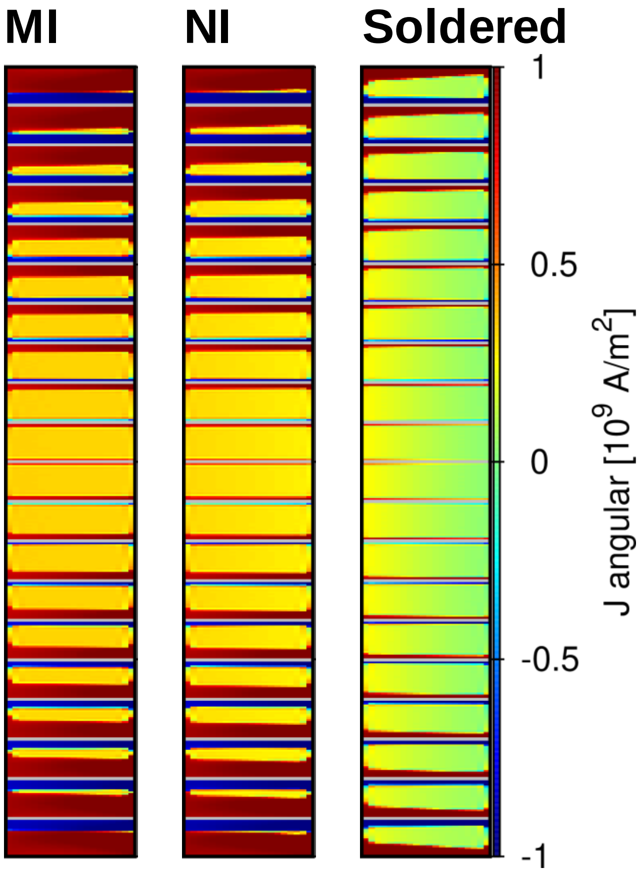
Ramp increase

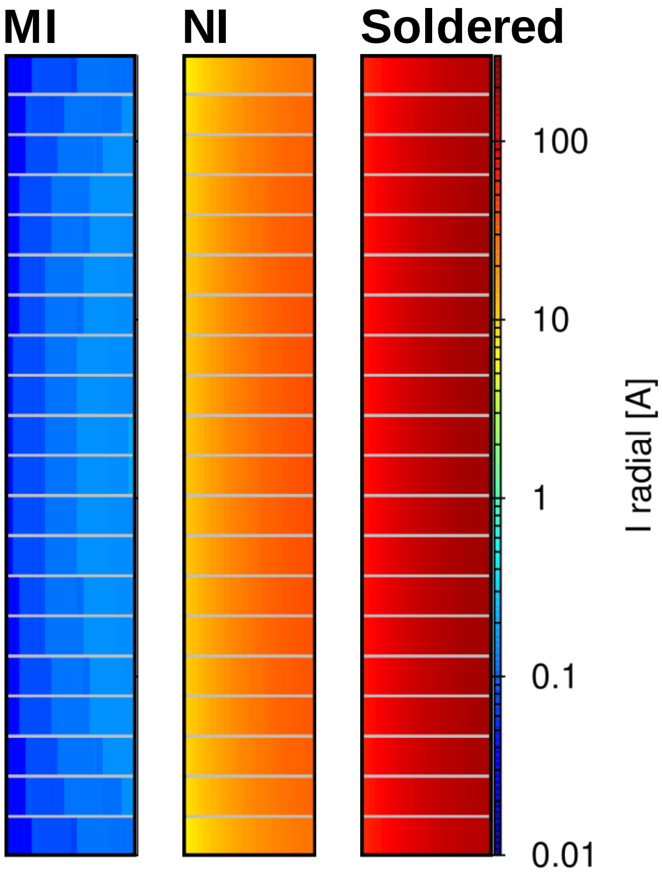


Input current: **250 A**

What happens here?

Superconducting screening currents increase with radial resistance

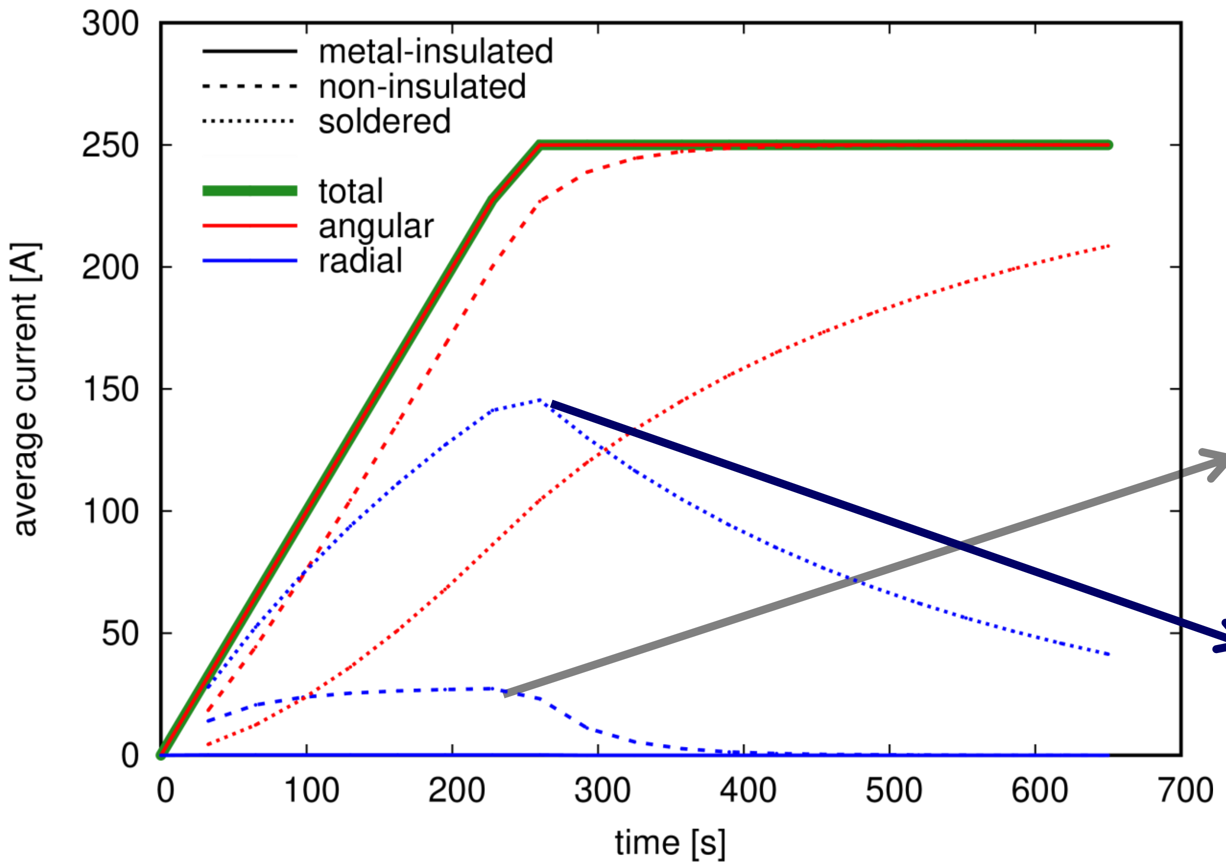




Input current: **250 A**

End of ramp increase

Radial current evolution



Input current: **250 A**

No radial current for metal-insulated

Radial current significant at ramp increase

Huge radial current

Computing time
of non-insulated coil

Mutual inductances:

210 s

Time evolution inlcuding relaxation:

150 s

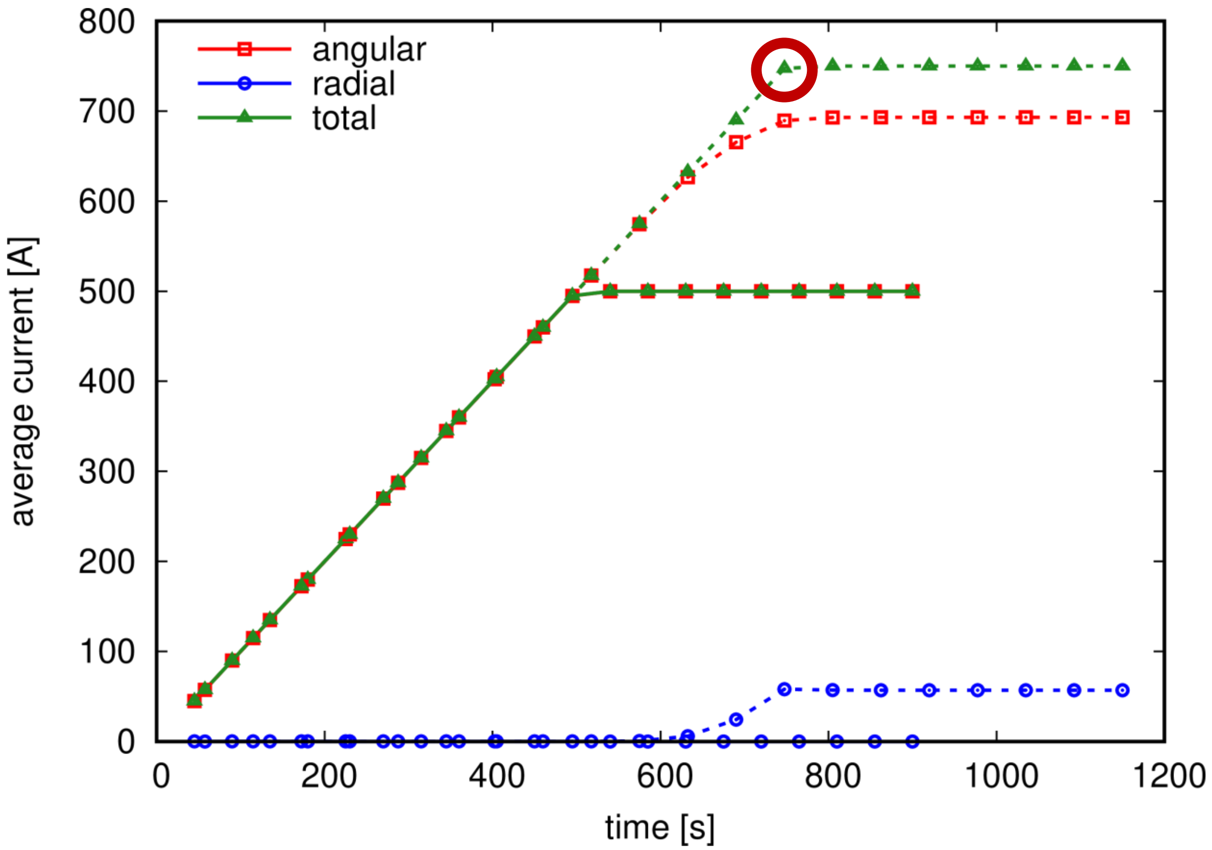
Faster than real-time opearation!

Model

Magnet results

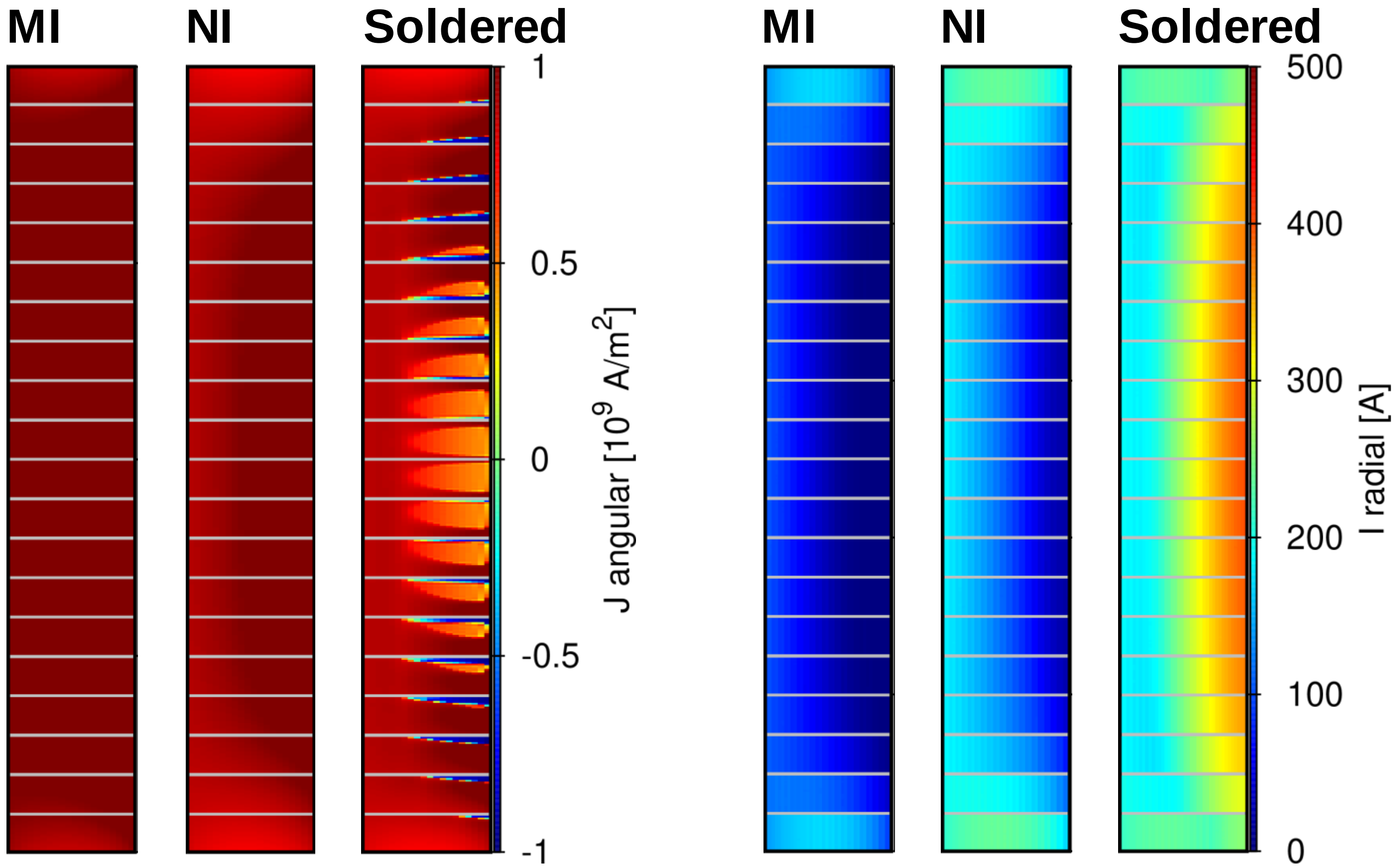
- Inputs
- Low currents
- High currents
- Generated magnetic field

Over-critical current transfers to radial direction



Metal-insulated

Over-critical tapes transfer current to radial direction

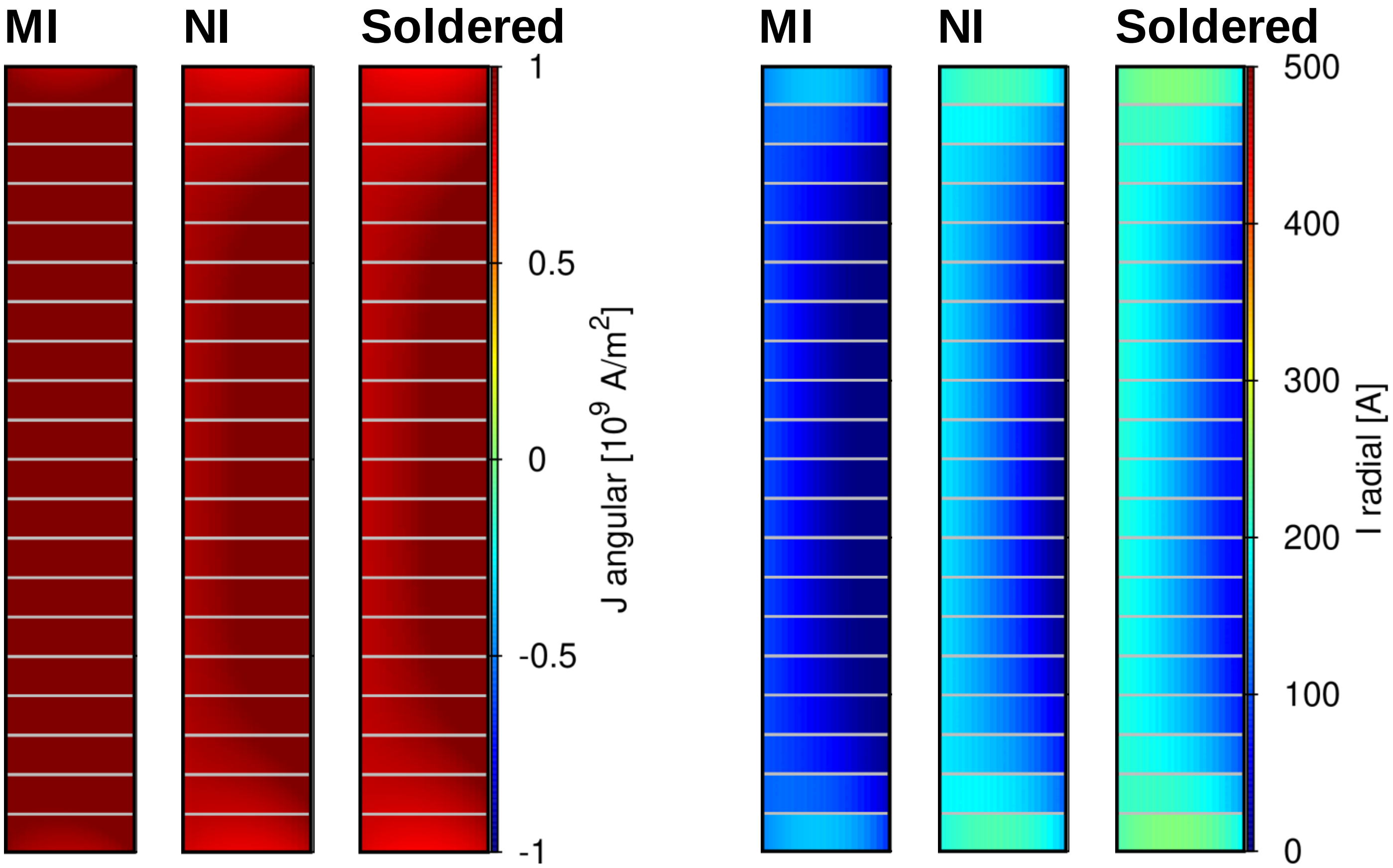


Input current: **750 A**

End of ramp increase

Soldered coil still presents screening currents

Relaxation eliminates screening currents



Input current:
750 A

400 s
relaxation

Model

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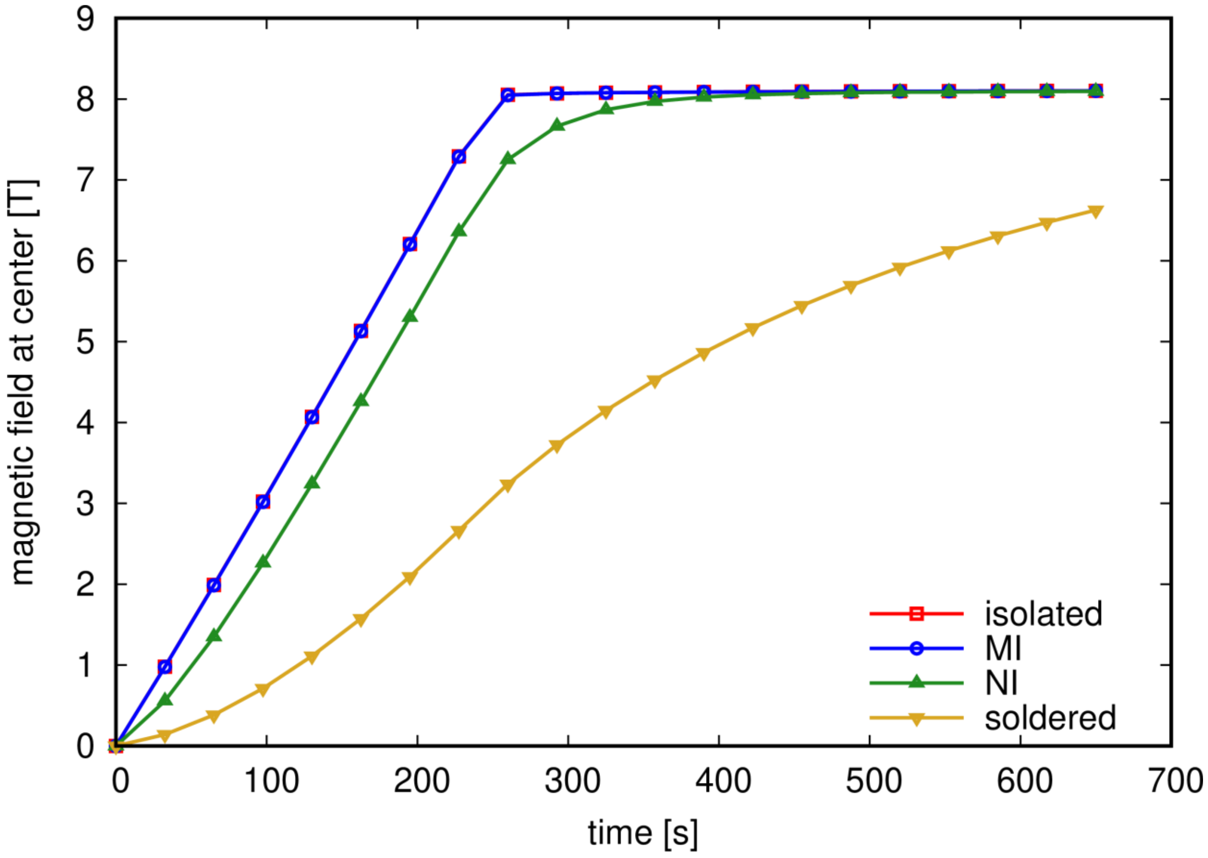
- High currents
- Generated magnetic field

Magnetic field at bore center

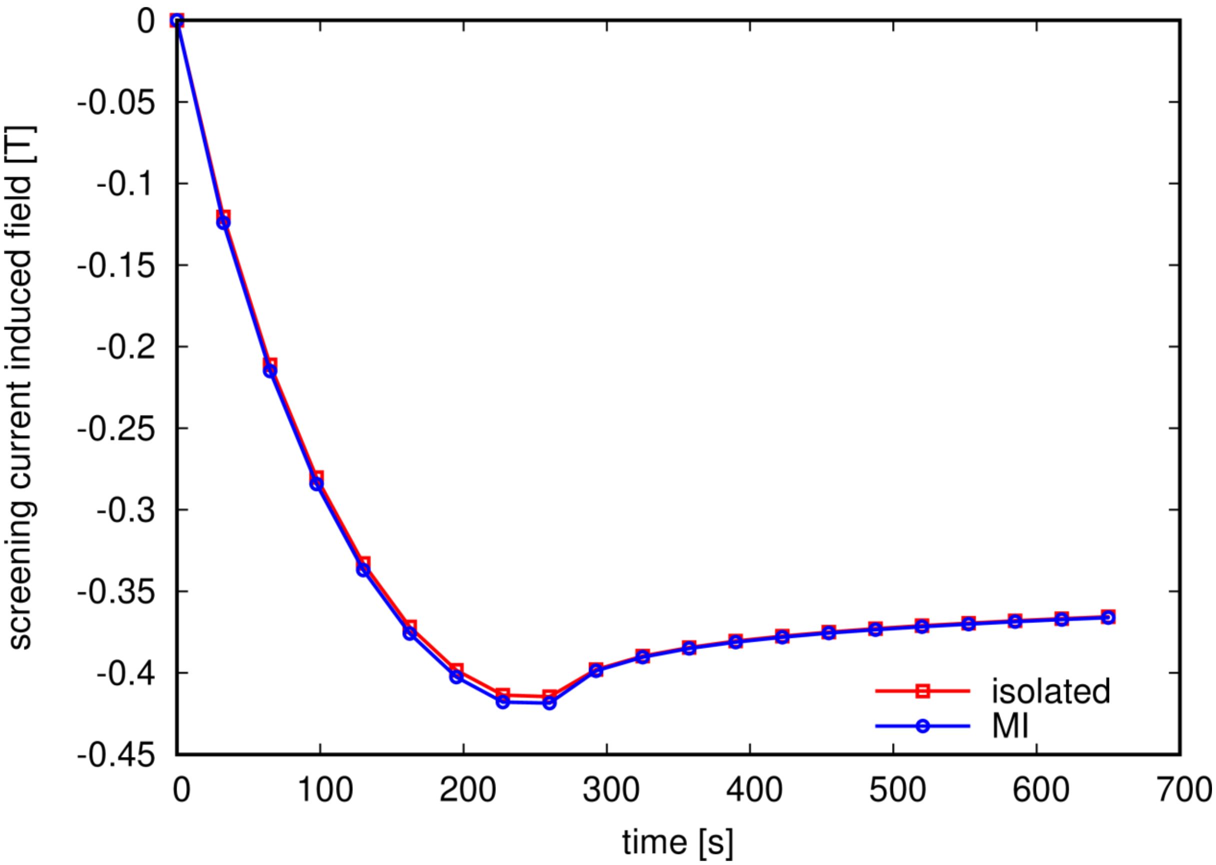


Metal-insulated is almost the same as isolated

Non-insulated stabilizes after relaxation

Soldered magnets will need long relaxation times

Screening current induced field



Metal-insulated behaves almost like insulated

Conclusion

Fast and accurate modeling of non-insulated magnets

Axi-symmetric moded describes all electro-magnetic proerties of the magnet

- Screening currents in superconductor
- Radial current at each turn

Computing time faster than real operation

Screening current induced field from metal-insulated magnet is the same as isolated

Thank you for your attention!