# Modelling of magnetization currents and AC loss in coated conductor coils of the 10000 turn class and other 3D situations

**Enric Pardo**,
M Kapolka, J Souc, M Solovyov, L Frolek,
F Gomory

Institute of Electrical Engineering
Slovak Academy of Sciences

# How far can you go in 10 hours?

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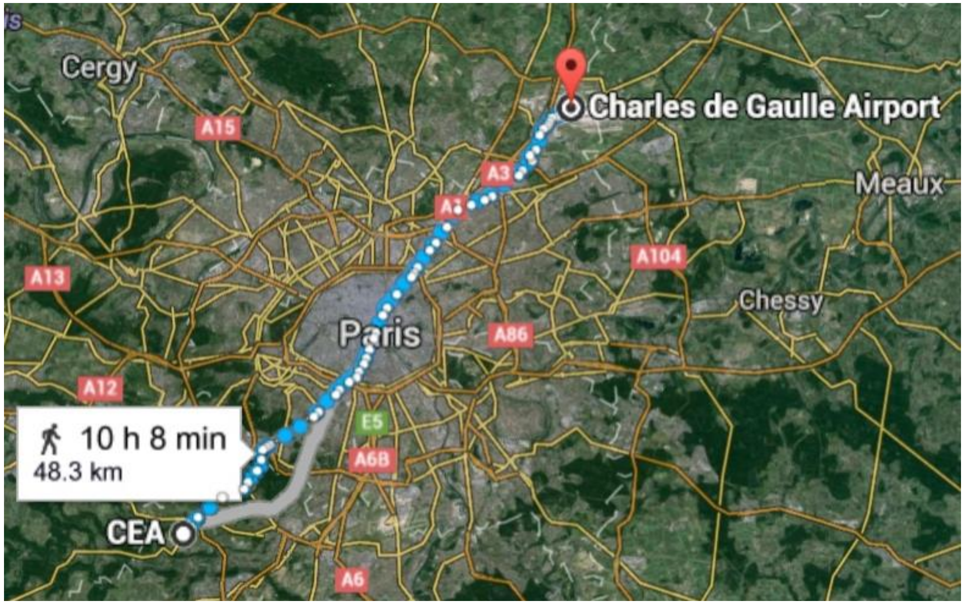
on foot




to the airport (luckily)

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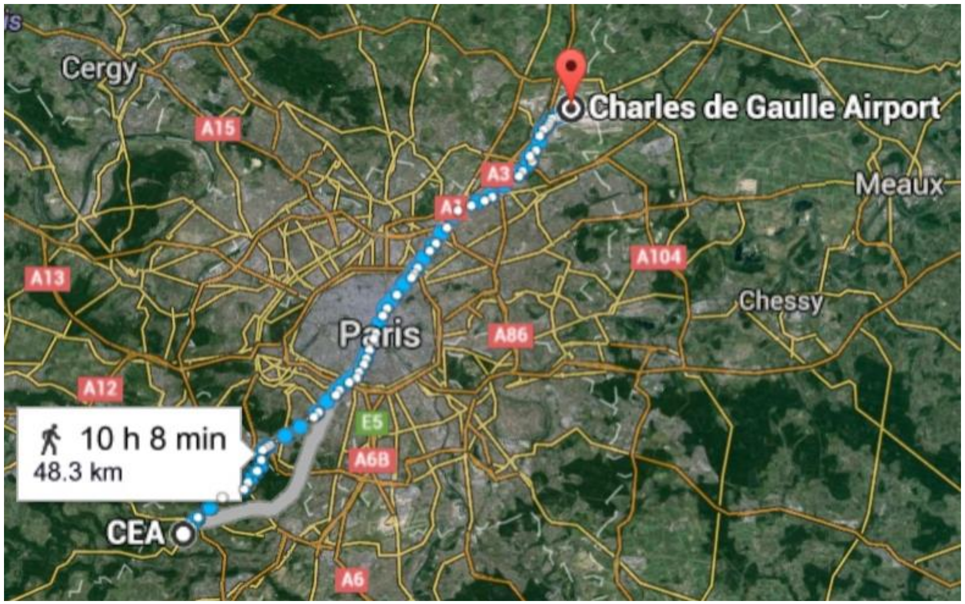


to the airport (luckily)

by plane

almost the whole World

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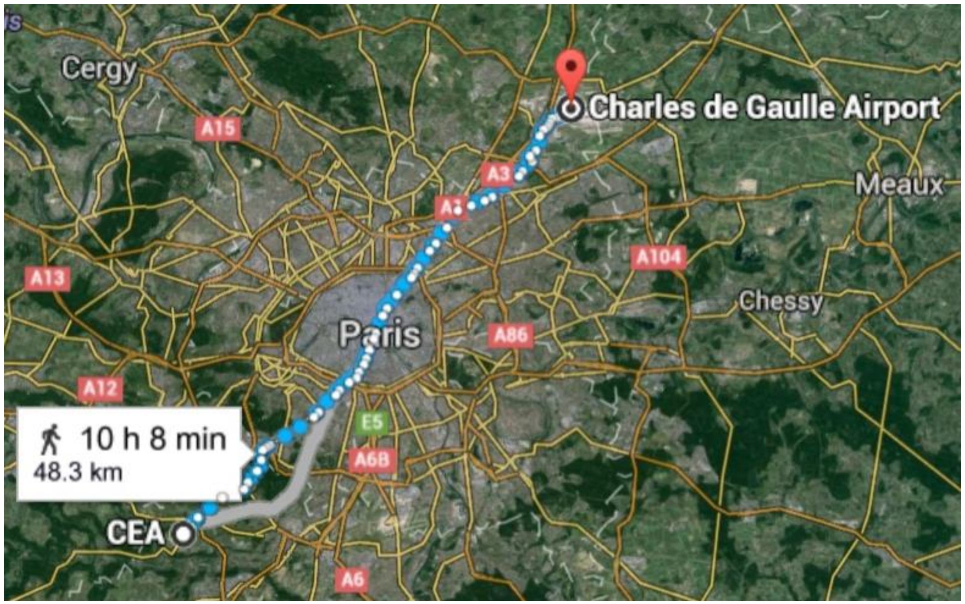


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almost the whole World

**Faster transportation opened new possibilities**

# Faster computations open new possibilities

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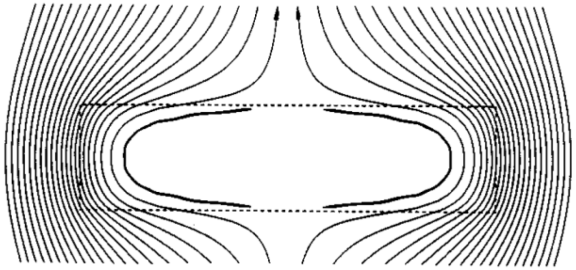
1 tape



Brandt 1996 PRB

# Faster computations open new possibilities

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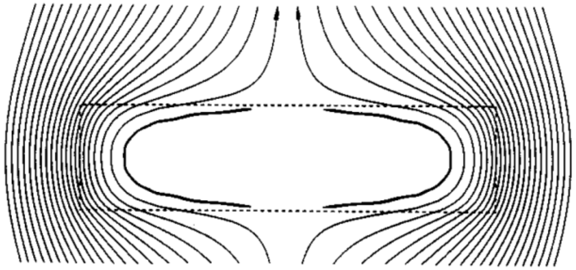
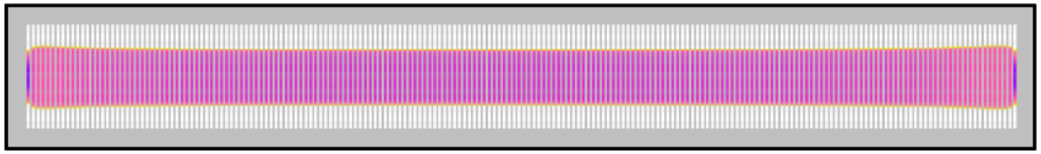


Brandt 1996 PRB

100 tapes



Pardo 2008 SuST

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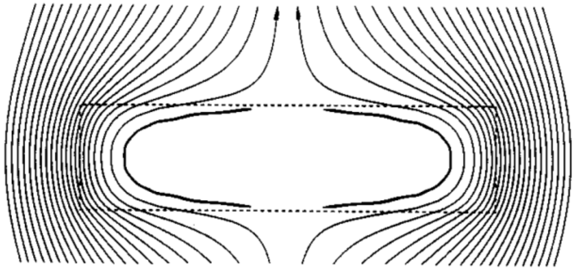

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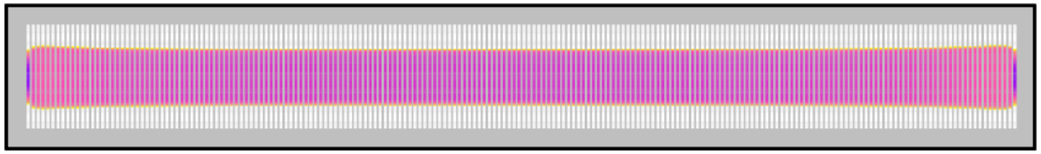
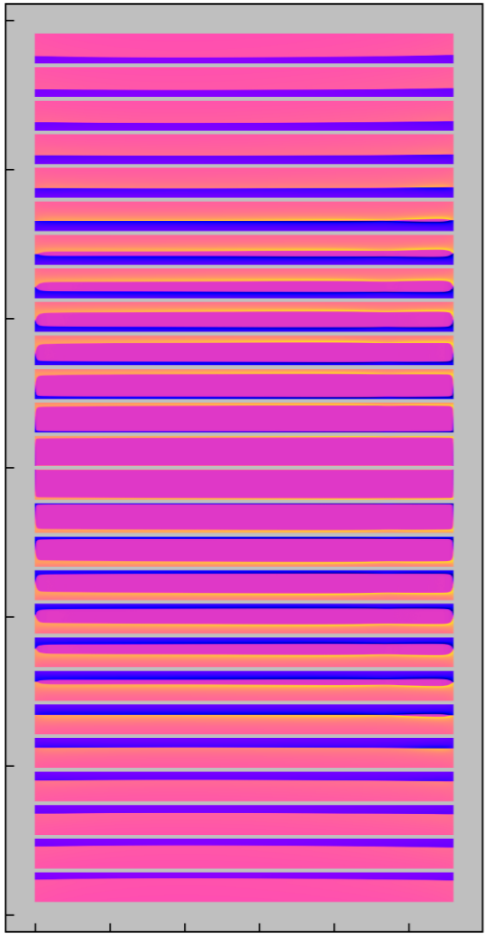


Pardo 2008 SuST

**This talk**



**10 000 tapes**

# Large scale applications with windings of many turns

**Transformers**
up to 2000 turns

Staines et al. 2012
SuST

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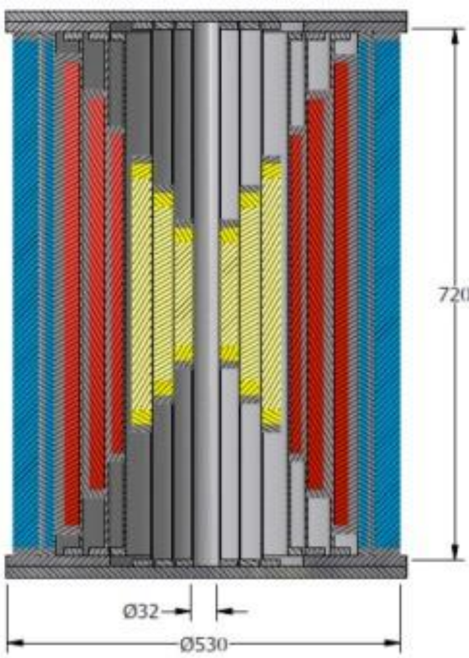
**Magnets**
up to 30000 turns




Trociewitz et al. 2011
Appl. Phys. Lett.

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**Transformers**
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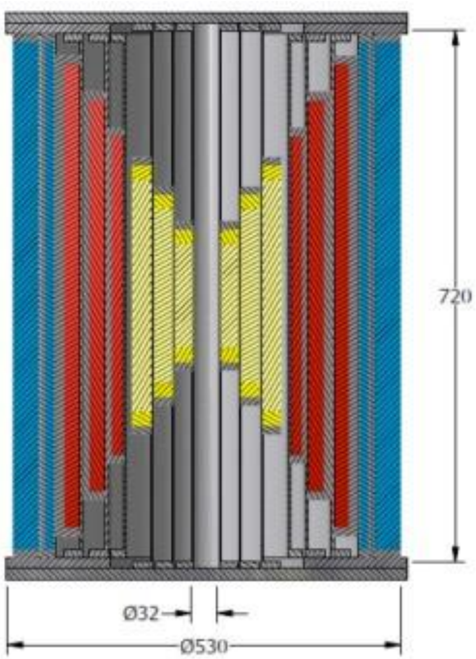
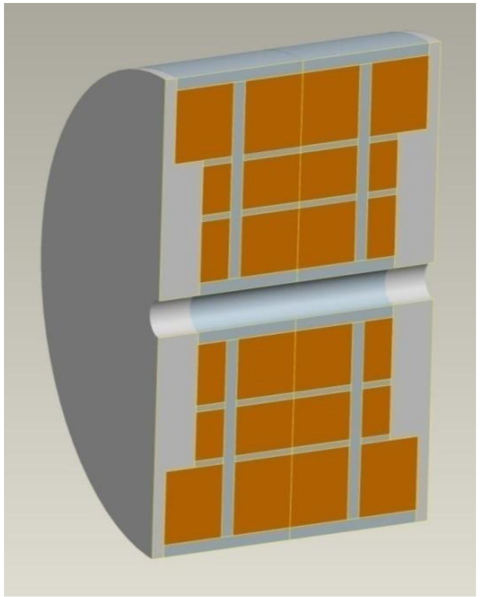



Trociewitz et al. 2011 Appl. Phys. Lett.

**SMES**



DOE, Brookhaven NL, ABB, SuperPower, University of Houston

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**Model**

**Validation with experiments**

**Magnet-size coils**

**3D modelling**

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# General model

**Maxwell equations**

**Any vector E(J) relation of the material**

# General model

**Maxwell equations**

**Any vector E(J) relation of the material**

Assumption:

**Negligible electromagnetic radiation**

Low frequencies

1 m wire: **below 3 MHz**

# Novel variational principle

**J**-q formulation

q: charge density

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**J**-q formulation

q: charge density

We find **J** by minimzing fuctional
at constant q

$$\mathbf{L}_J = \int_V \left( \frac{1}{2} \Delta \mathbf{J} \cdot \frac{\Delta \mathbf{A}_{SJ}}{\Delta t} + \Delta \mathbf{J} \cdot \frac{\Delta \mathbf{A}_a}{\Delta t} + U(\mathbf{J}) + \nabla \phi \cdot \Delta \mathbf{J} \right) dV$$

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We find q by minimzing fuctional
at constant **J**

$$\mathbf{L}_q = \int_V \left( \frac{1}{2} \Delta q \cdot \Delta \phi - \nabla \phi \cdot (\mathbf{J}_0 + \Delta \mathbf{J}) \right) dV$$

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$$\mathbf{L}_q = \int_V \left( \frac{1}{2} \Delta q \cdot \Delta \phi - \nabla \phi \cdot (\mathbf{J}_0 + \Delta \mathbf{J}) \right) dV$$

**We minimize both functionals iteratively**

# Novel variational principle

Takes inductive and capacitive effects into account

**Reduces computation volume to the superconductor**

High potential to reduce computing time

**Model**

**Validation with experiments**

**Magnet-size coils**

**3D modelling**

Model

Validation with experiments

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- Small coil
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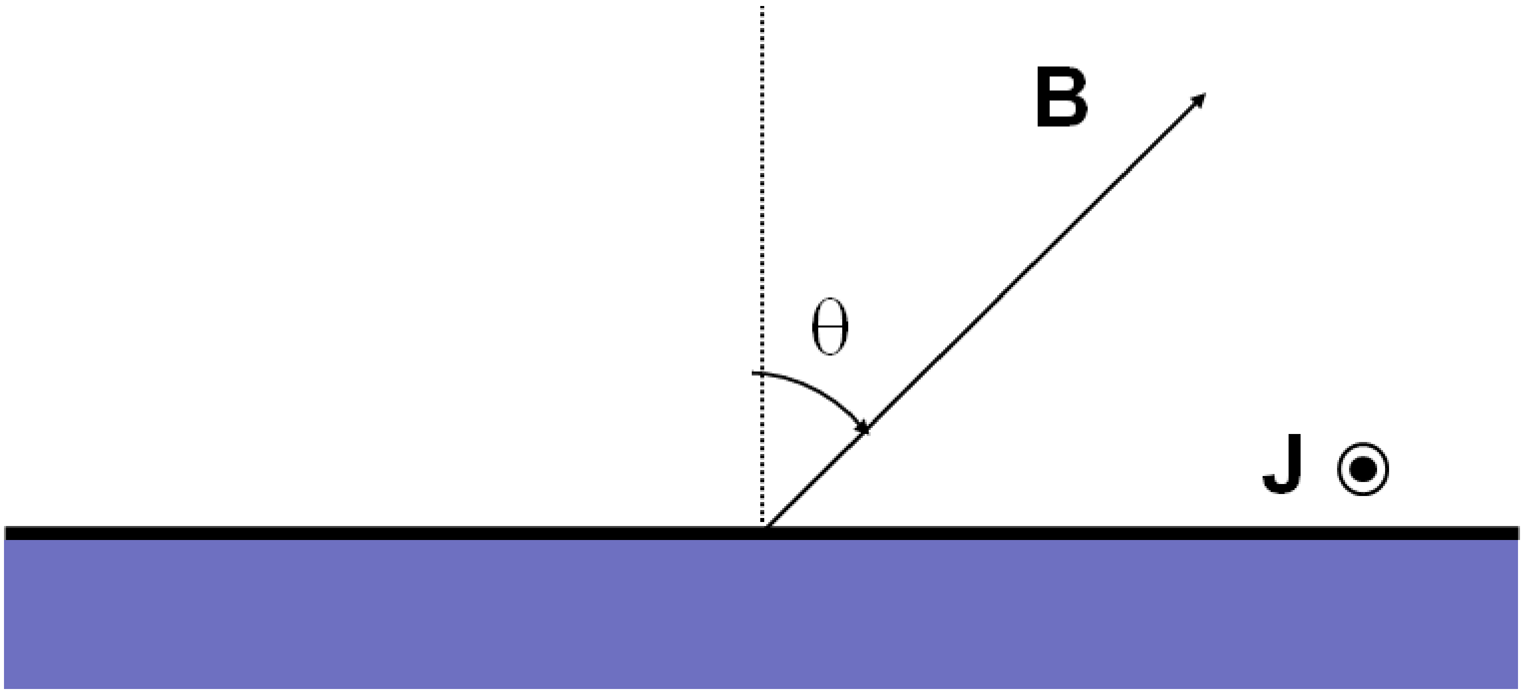
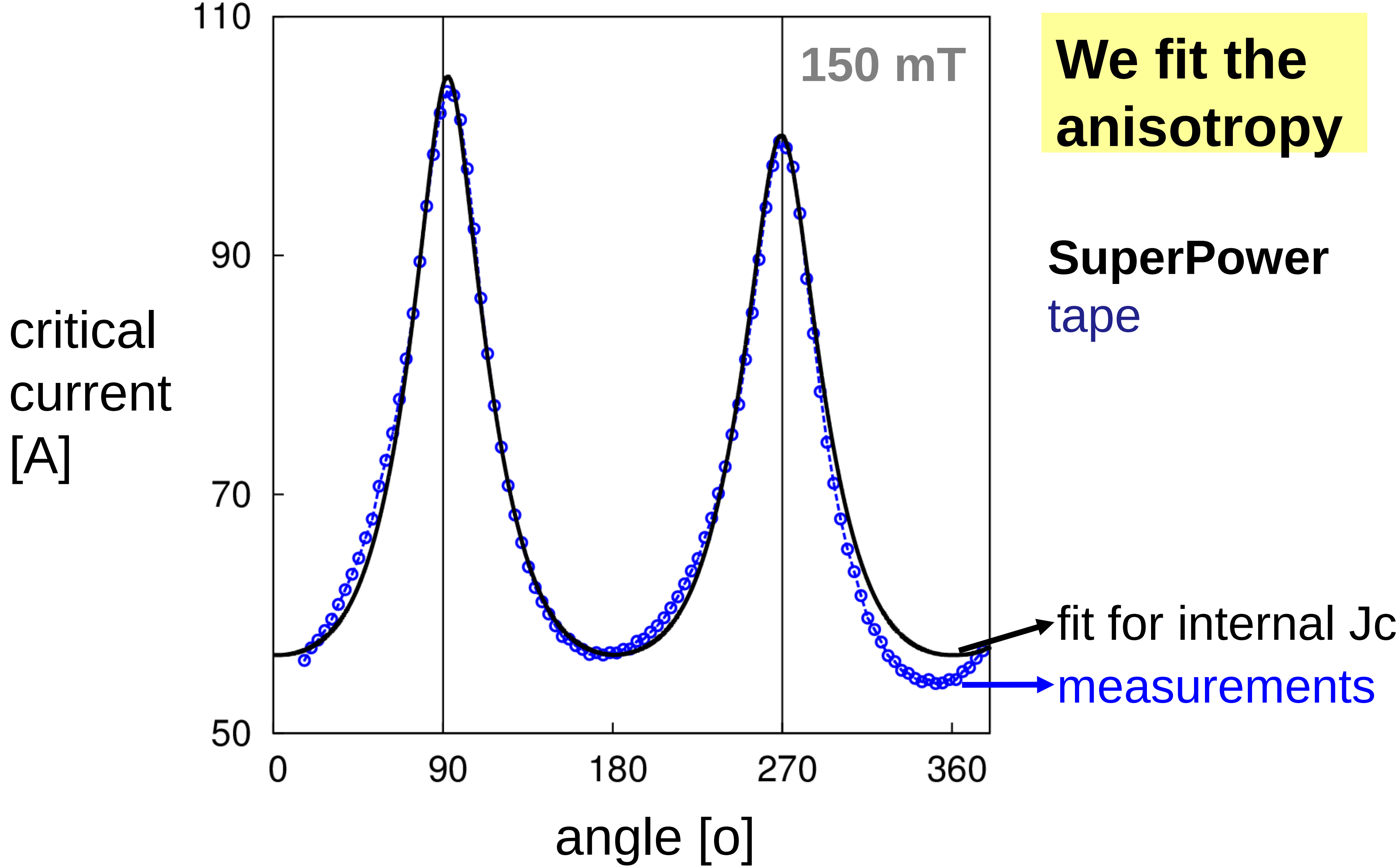
# Anisotropy measurements



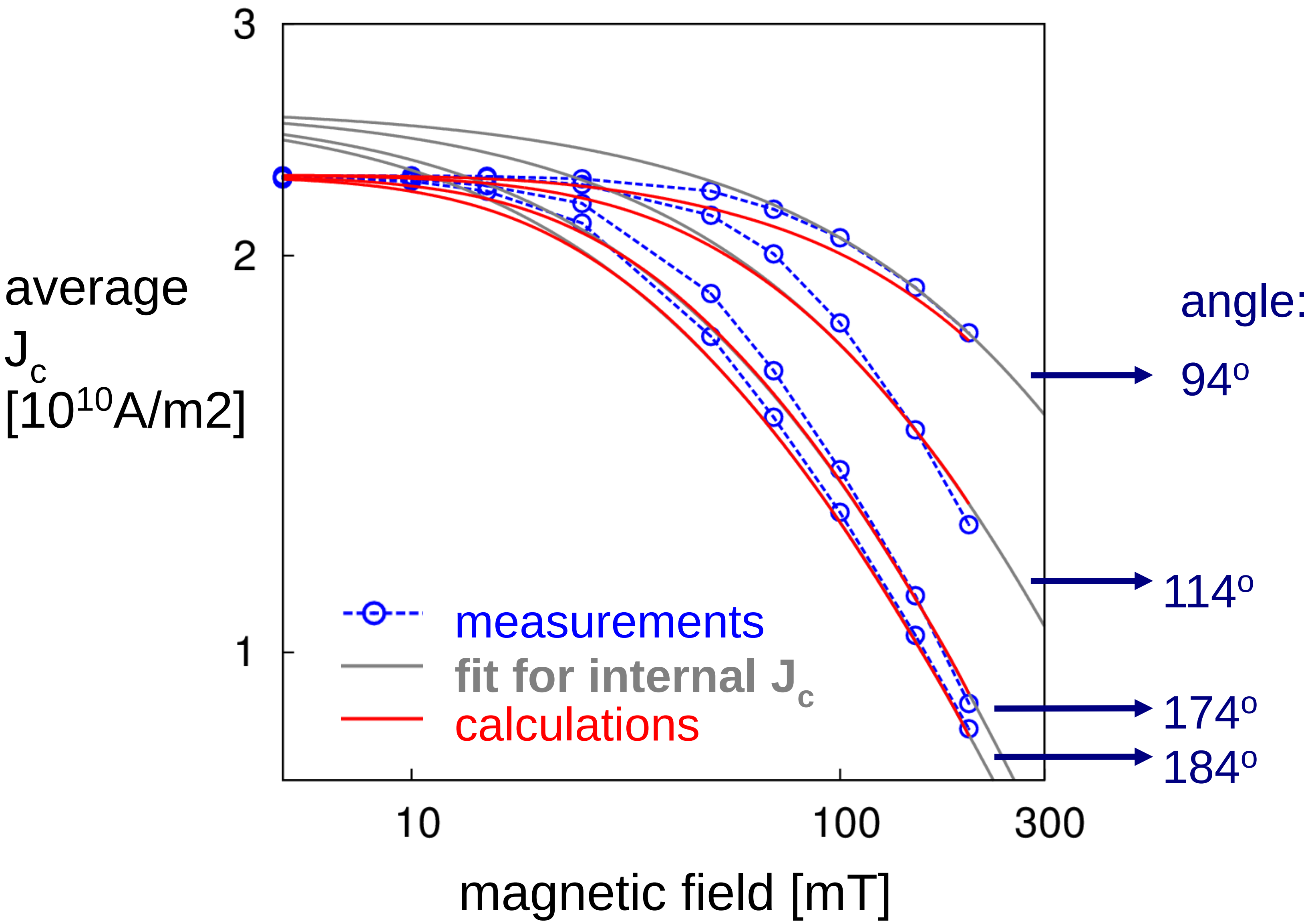
# Asymmetric anisotropy




**We fit the anisotropy**

**SuperPower**
tape

# Calculations correct self-field



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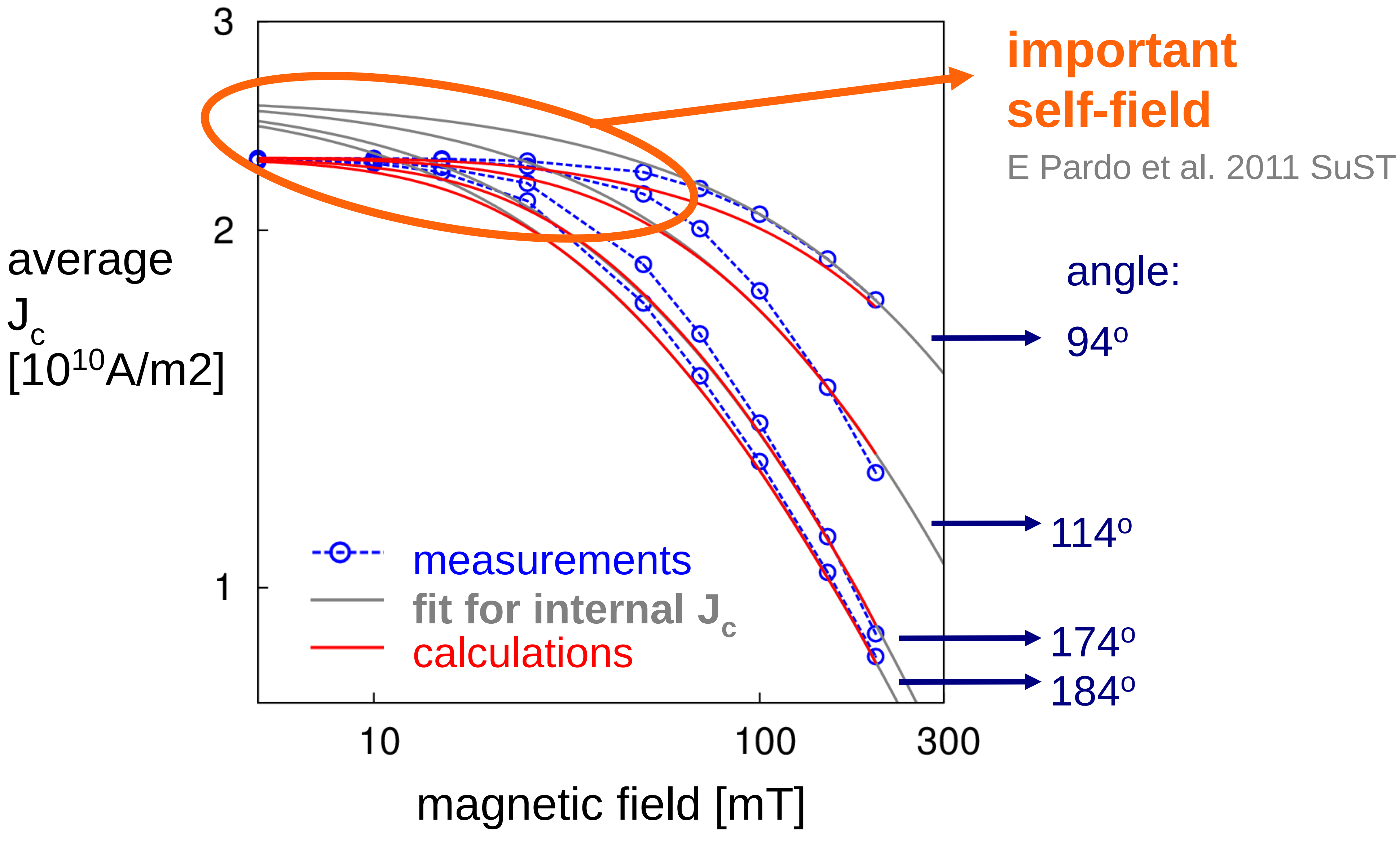
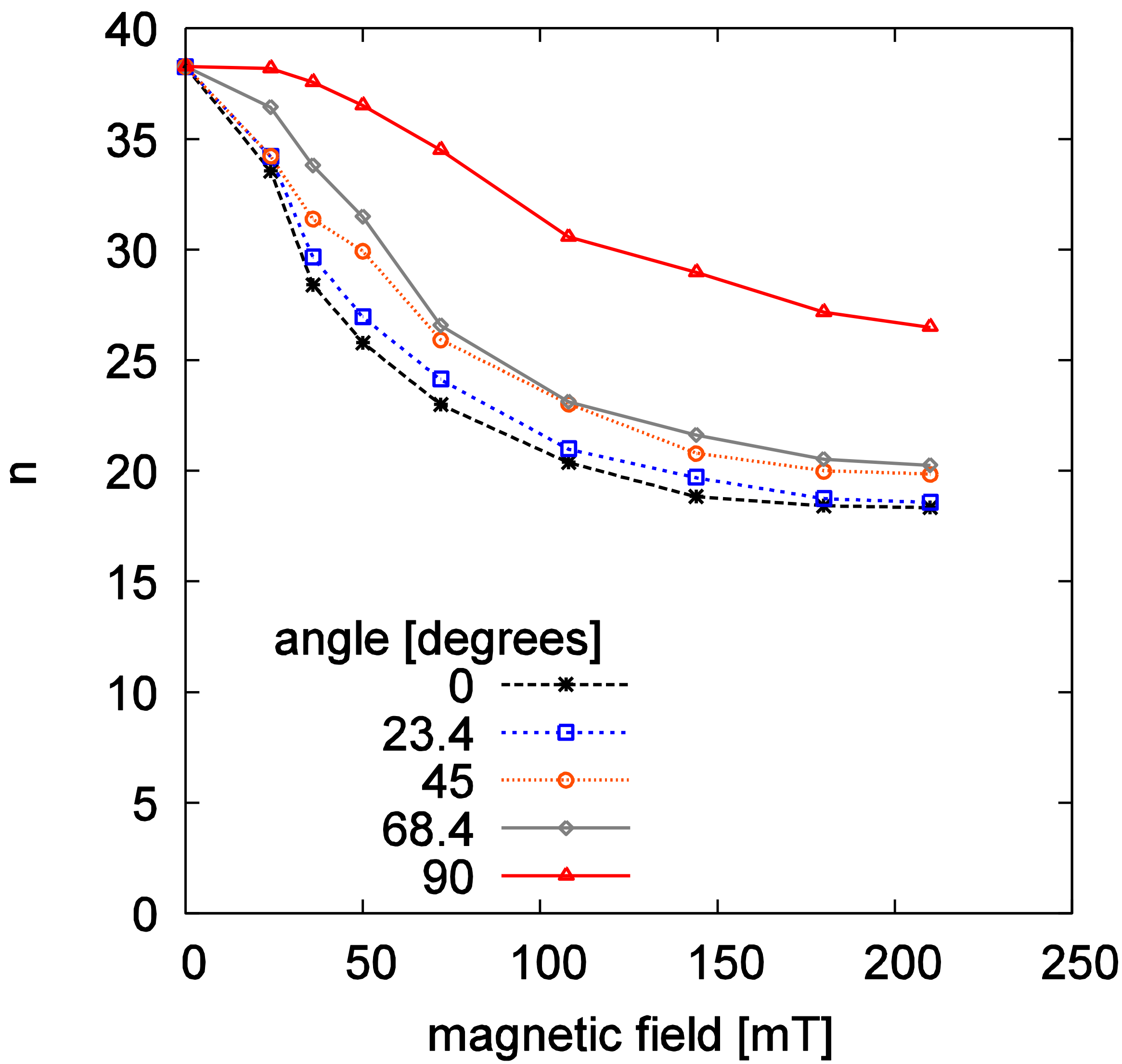
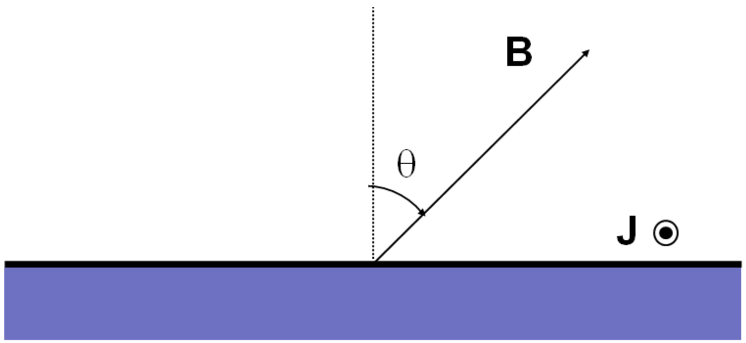
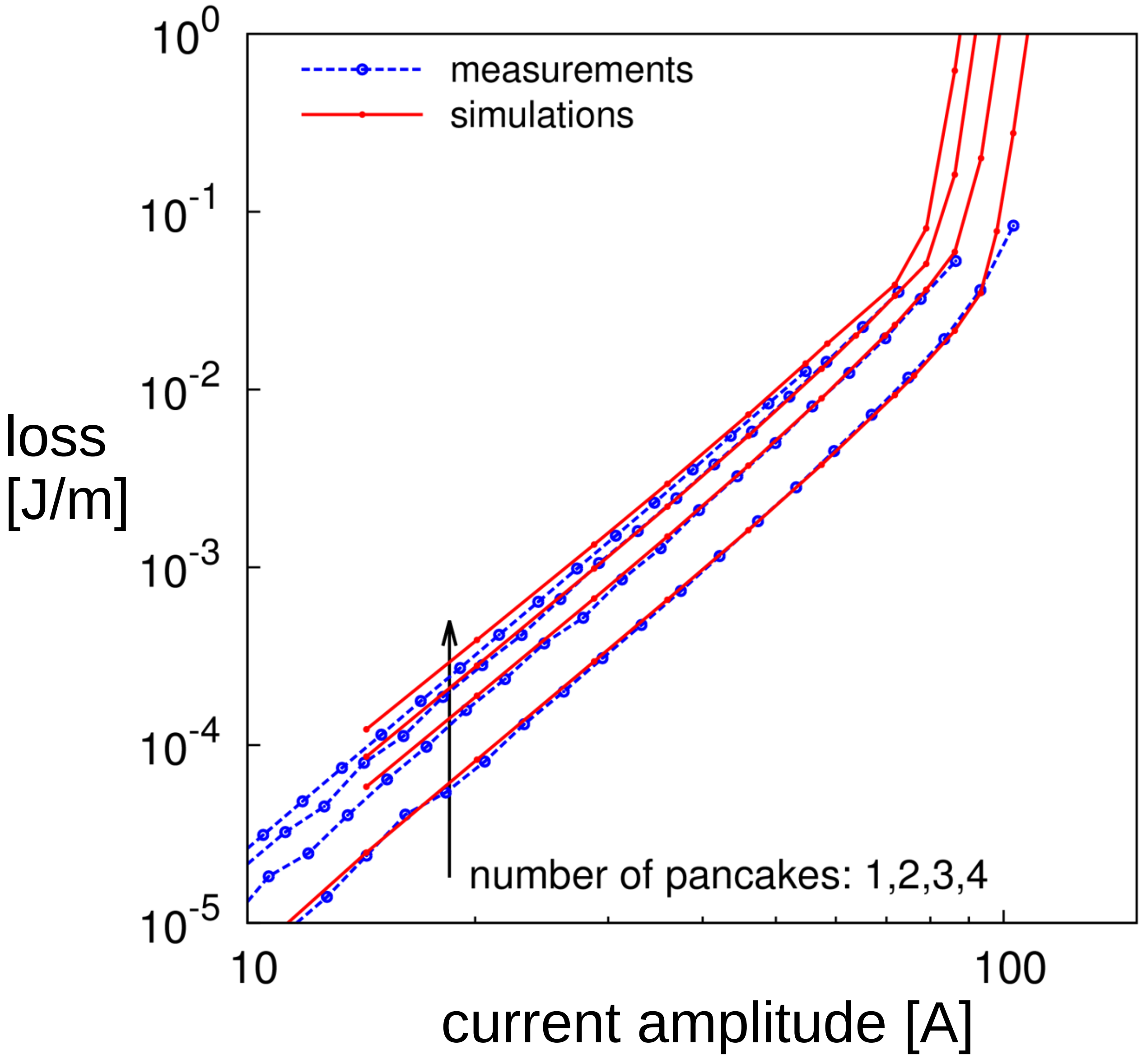


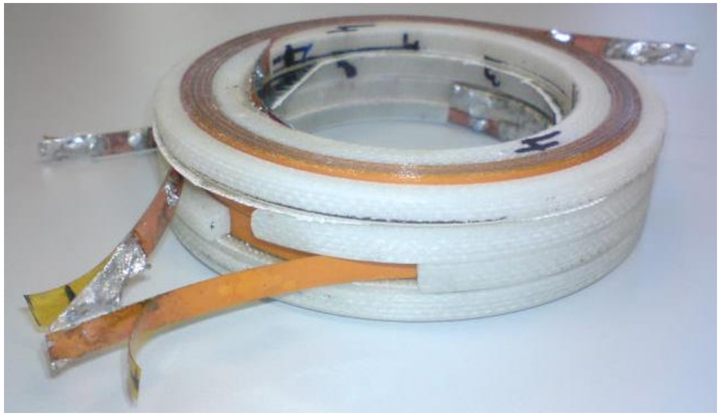
# Power-law exponent depends on magnetic field



# AC loss in test coils agrees with experiments



Magnetic field dependent $J_c$

Magnetic field dependent power-law exponent

**Model**

**Validation with experiments**

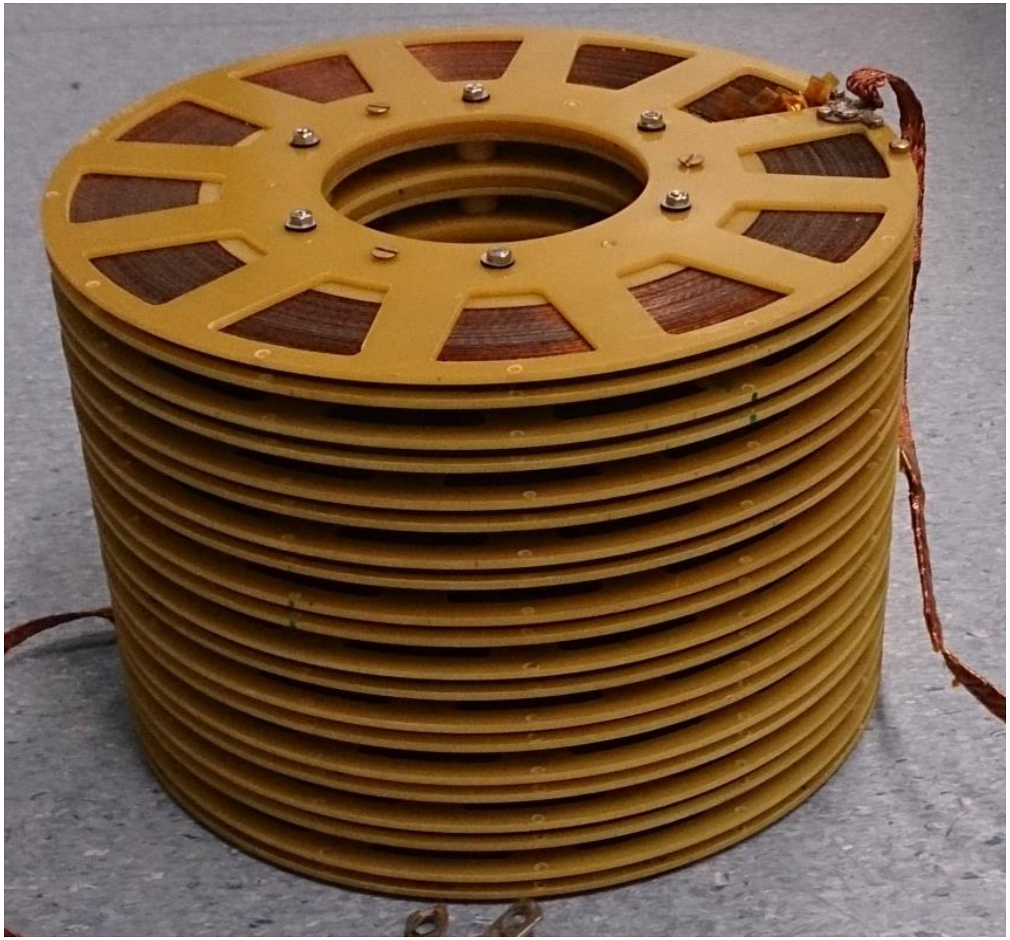
- Small coil
- Medium size coil
- Transformer

**Magnet-size coils**

**3D modelling**

# Constructed coil with optimum parameters

SuNAM tape



**670** turns

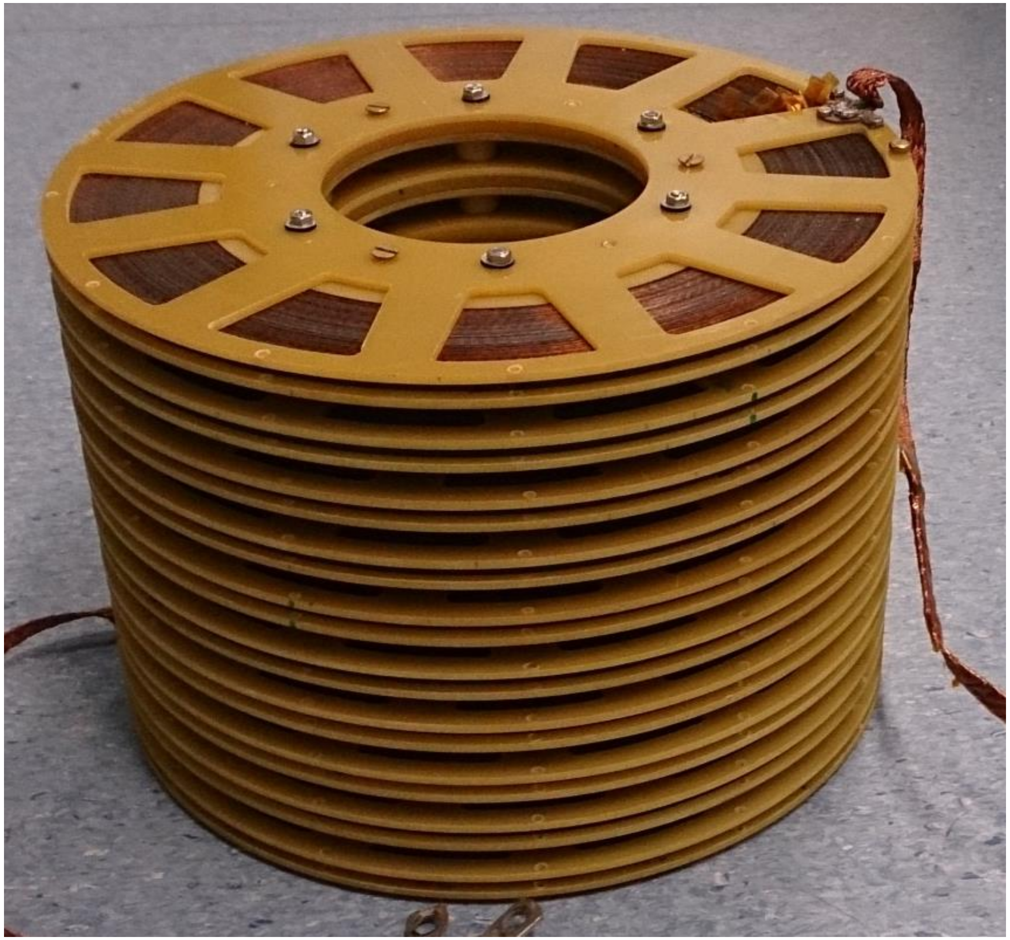
around **500** m of tape

**10** pancakes

**Coil design for maximum stored energy**

# Constructed coil
# with optimum parameters

SuNAM tape



**670** turns
around **500** m of tape
**10** pancakes

**Coil design**
**for maximum stored energy**

Similar coils may be used for:

- **High-voltage winding of transformers**
- **Inductors for passive filters**
- **Resonators for high-voltage generation**

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**3D modelling**

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Medium size coil

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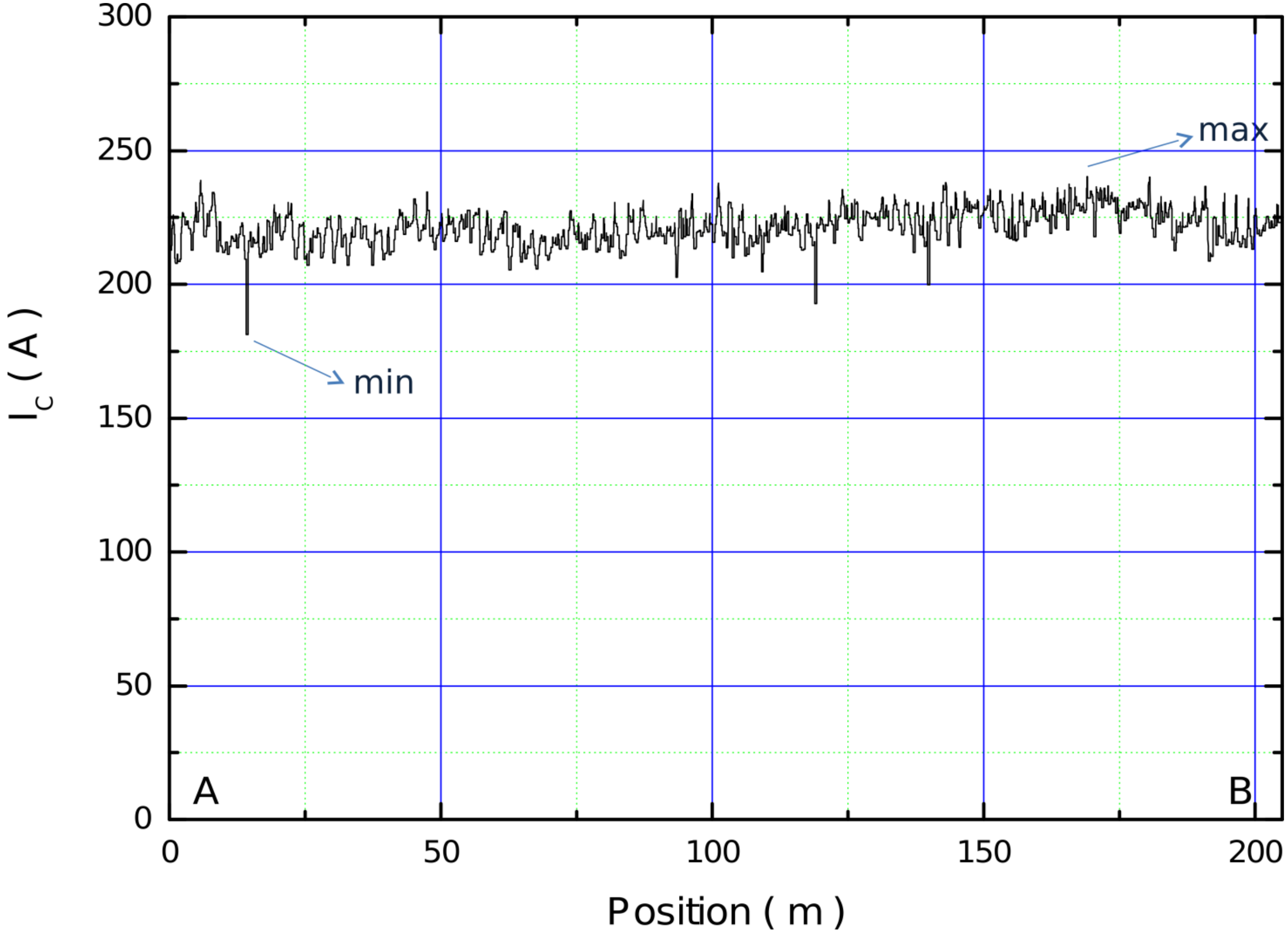
# Tape is inhomogeneous in length

## SuNAM tape

## Self-field critical current



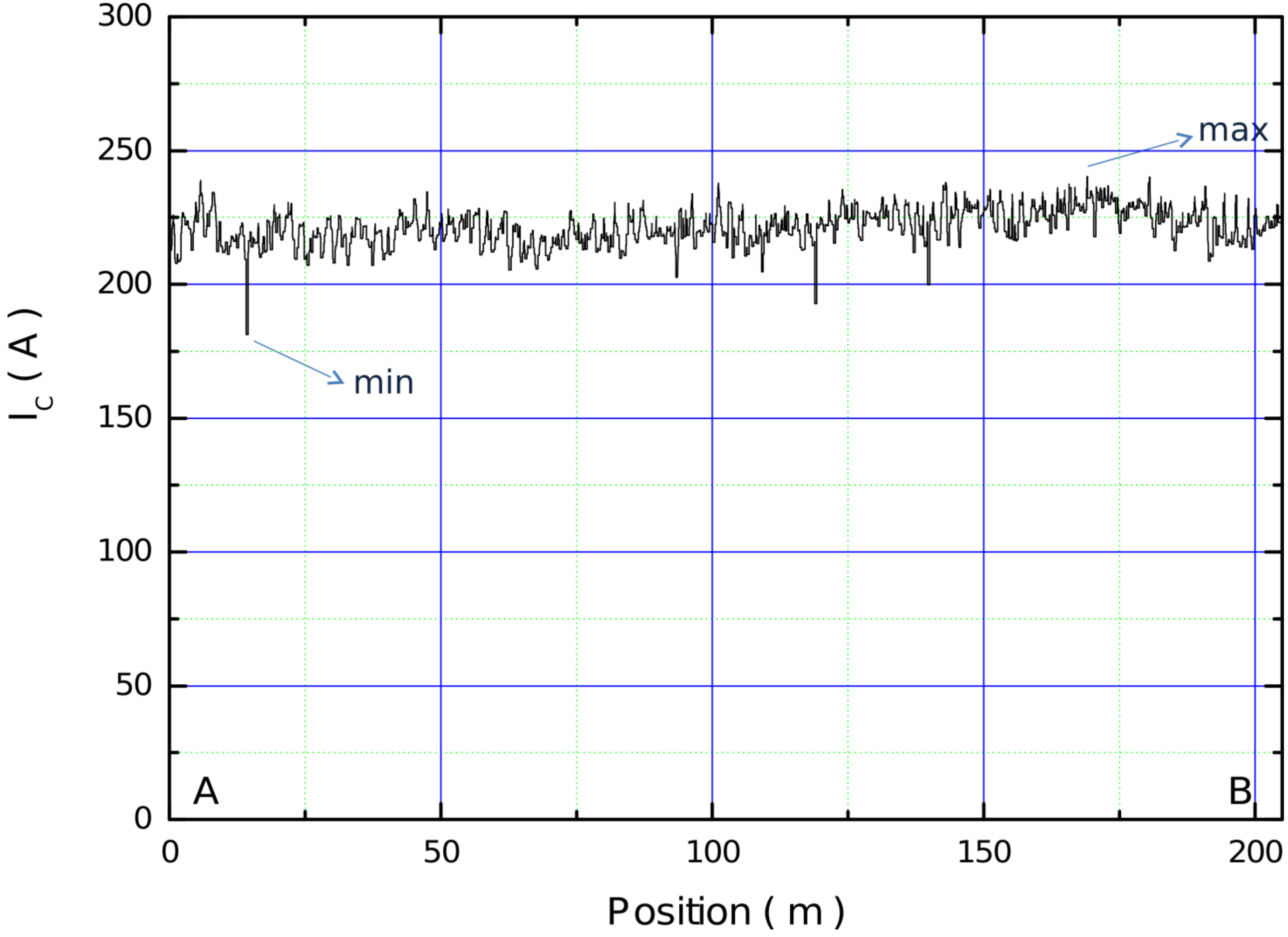

Inhomogeneity introduces uncertainty in model

Graph provided by SuNAM

# Tape is inhomogeneous in length

**SuNAM tape**

**Self-field critical current**

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**Which is the relevant value?**

Graph provided by SuNAM

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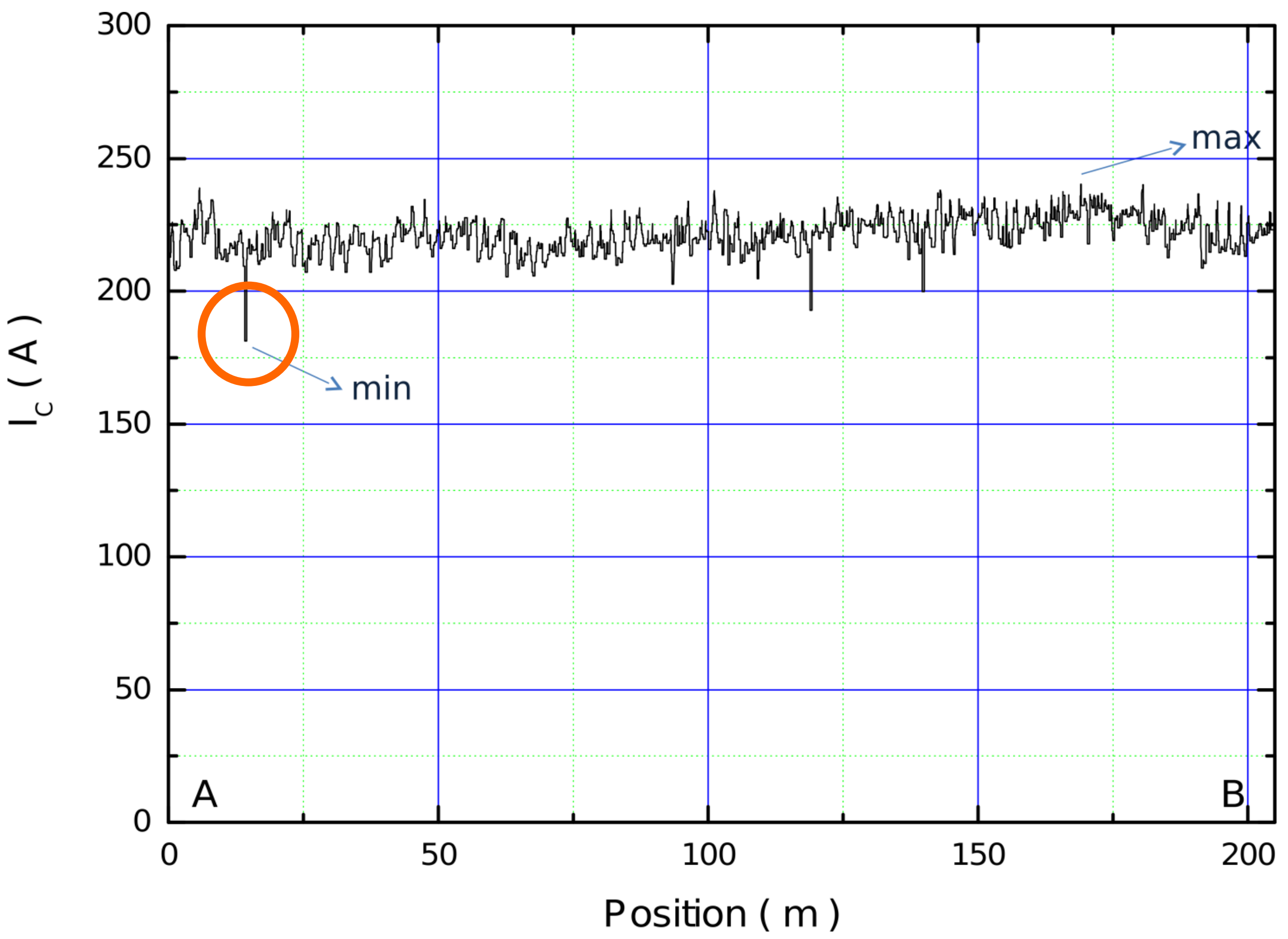



Inhomogeneity introduces uncertainty in model

**Which is the relevant value?**

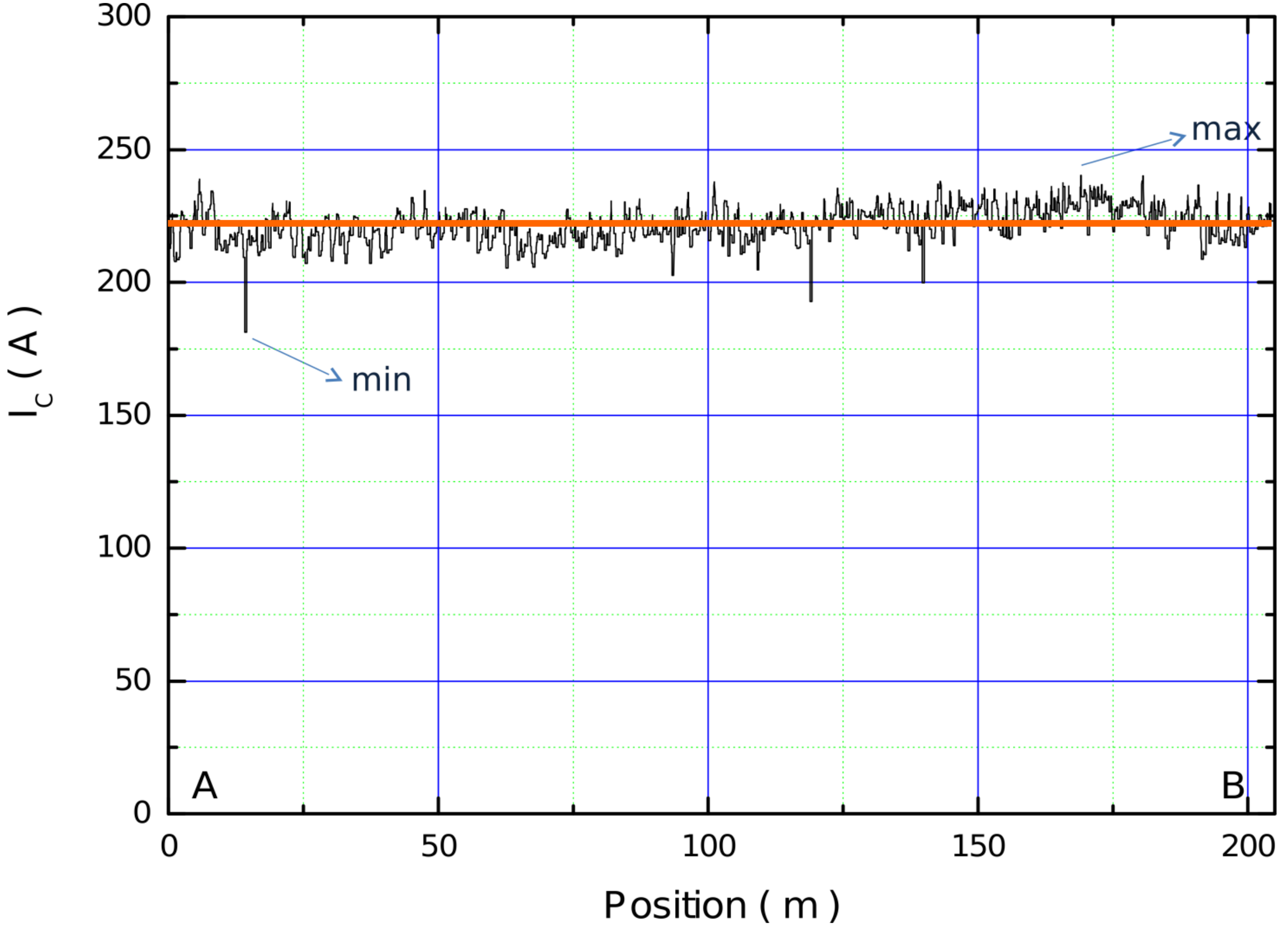
**Coil critical current dominated by minimum $I_c$**

Graph provided by SuNAM

# Tape is inhomogeneous in length

## SuNAM tape

## Self-field critical current




Inhomogeneity introduces uncertainty in model

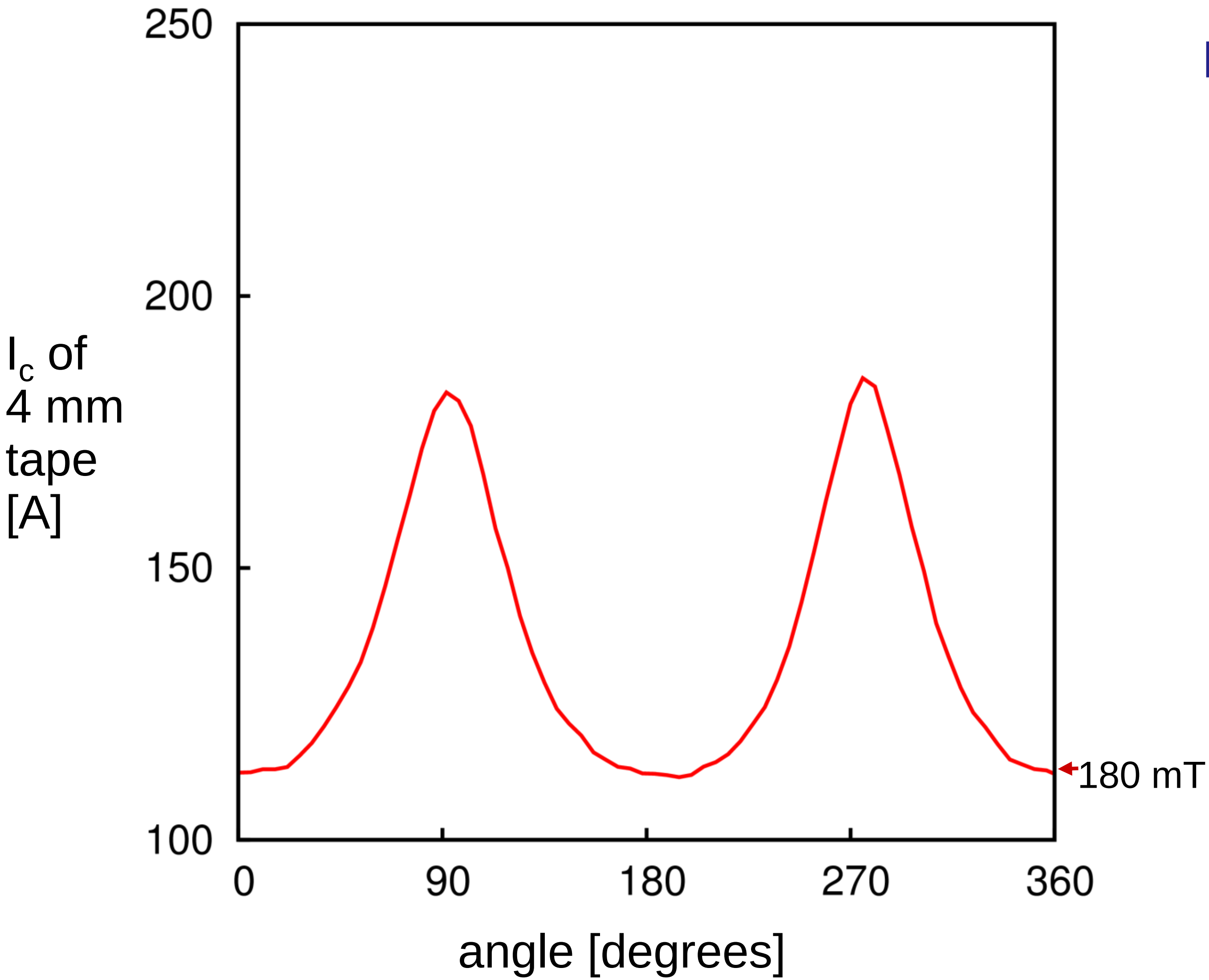
**Which is the relevant value?**

**Coil critical current dominated by minimum $I_c$**

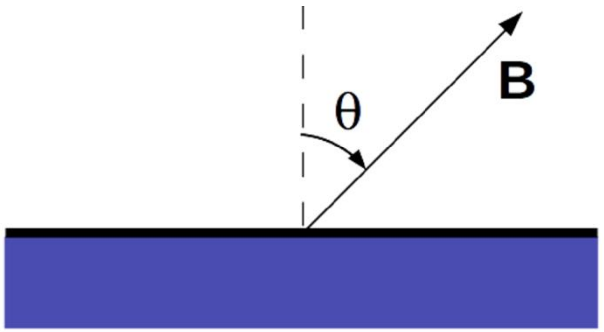
**Loss dominated by average $I_c$**

Graph provided by SuNAM

# Anisotropic field dependence of $I_c$




Roughly 180º symmetry



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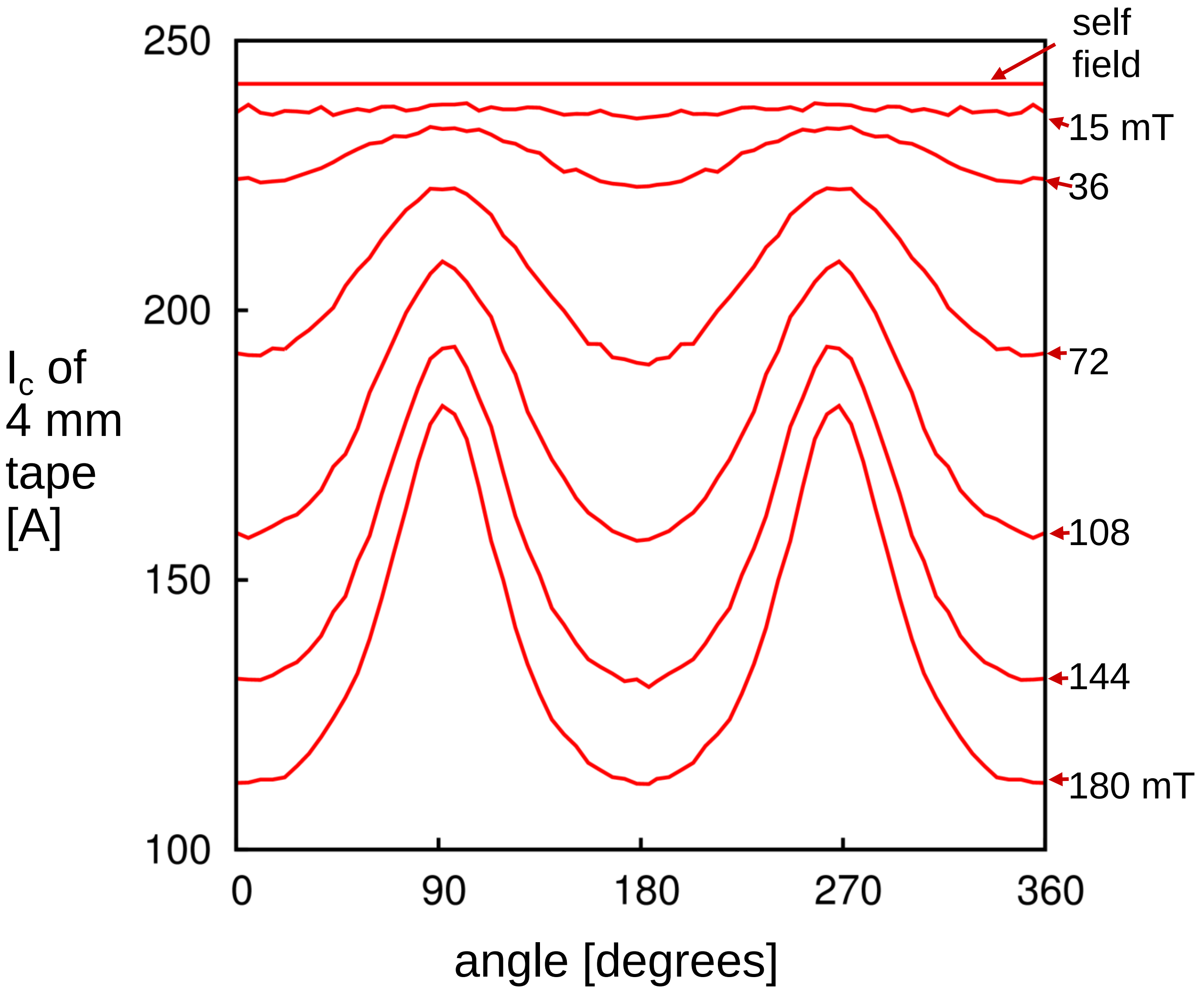
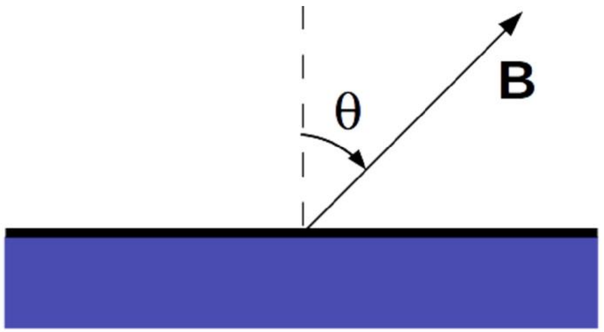



we assume
$180^o$ symmetry
for all applied fields



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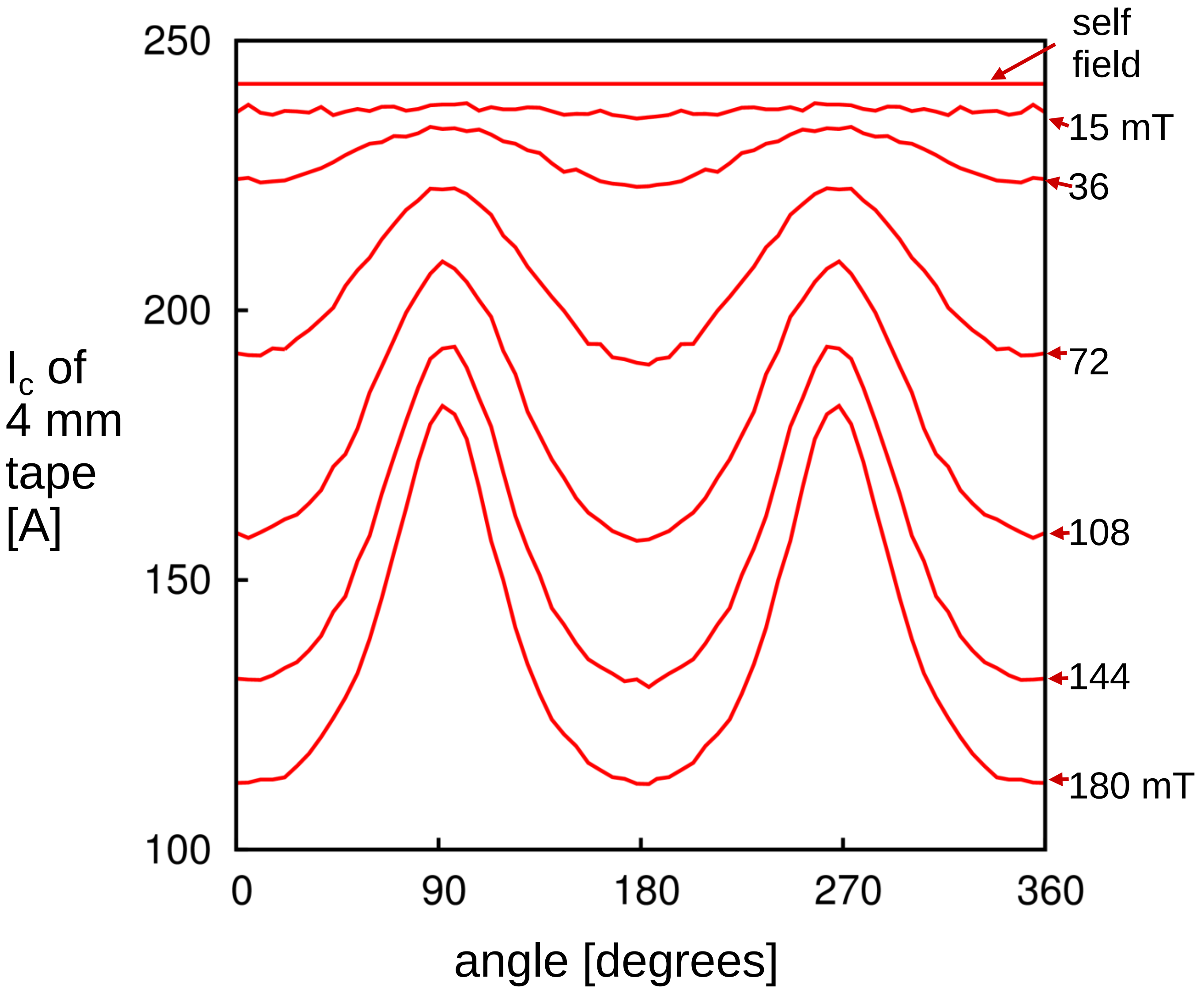
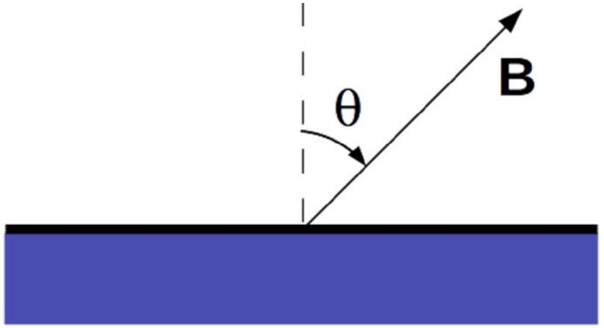
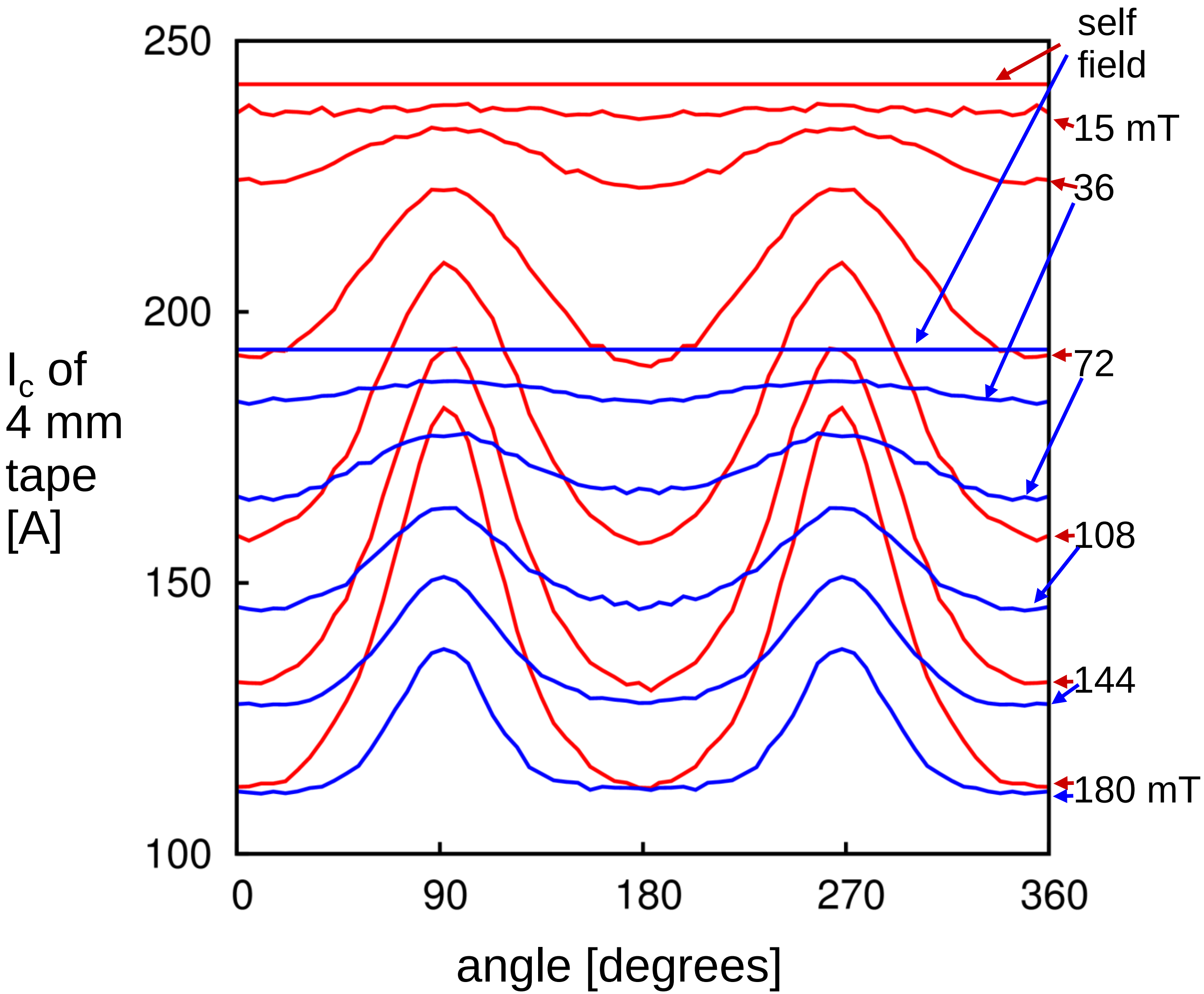



we assume
180º symmetry
for all applied fields

**How does $I_c$ change with different batches?**

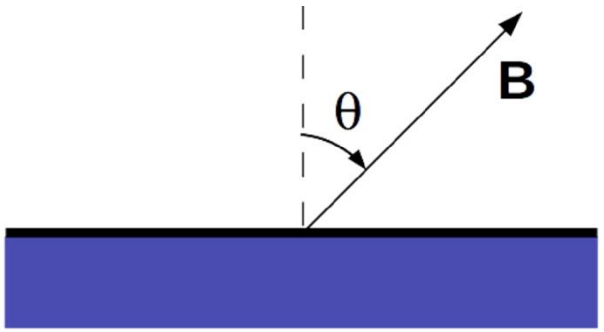


# Under magnetic fields, different batches are more similar




Good:

**In-field $I_c$ maybe good also for low self-field $I_c$**



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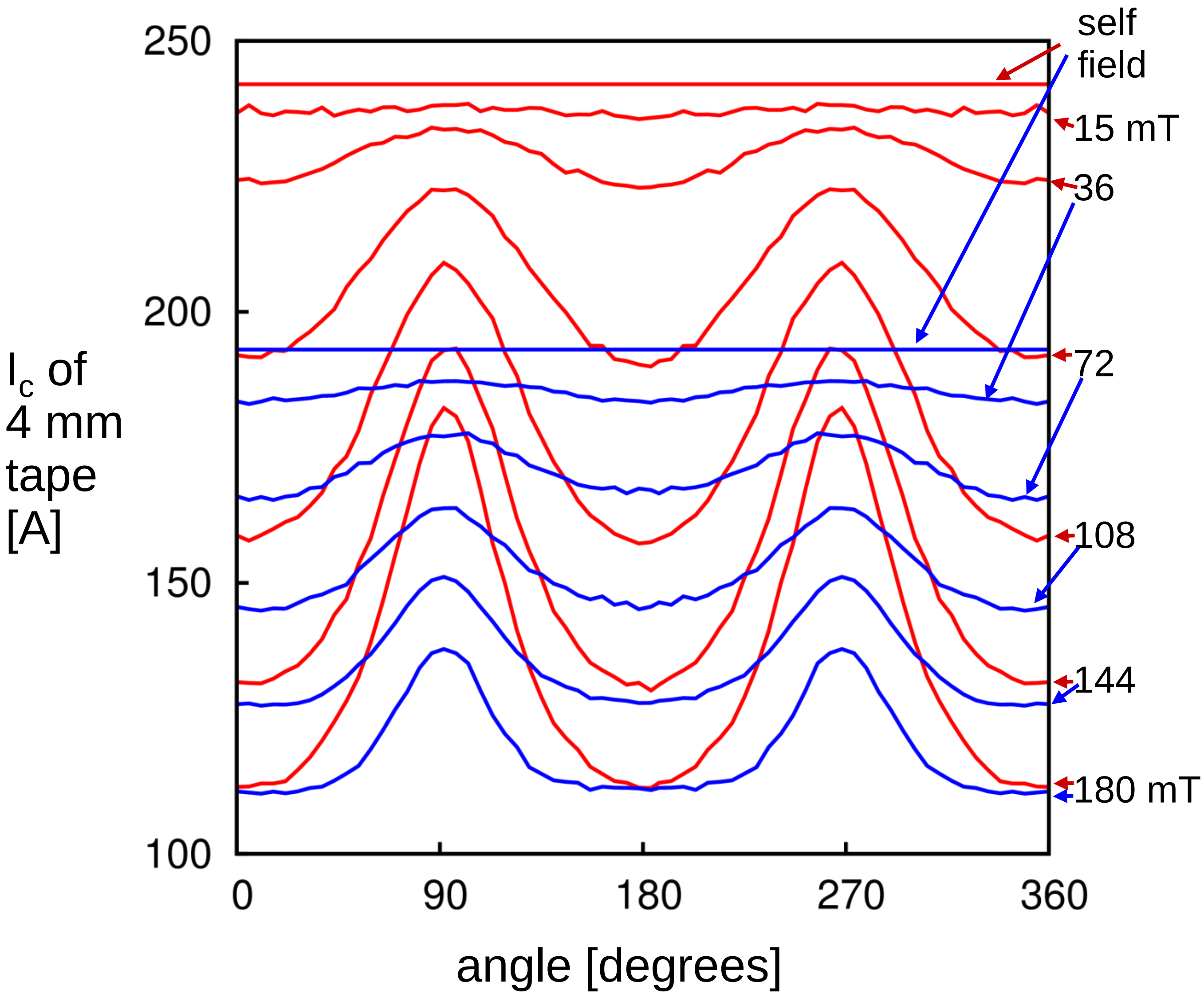
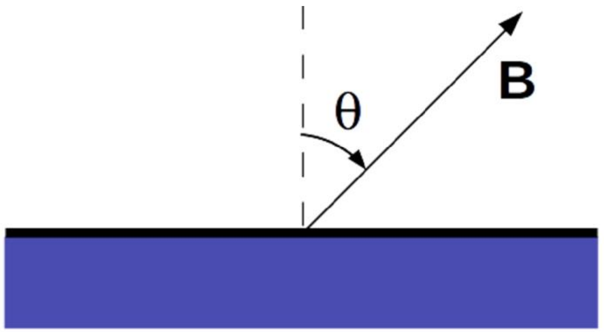



Good:

**In-field $I_c$ maybe good also for low self-field $I_c$**

Bad:

**Self-field inhomogeneity measurements not always useful**



**Model**

**Validation with experiments**

Small coil

Medium size coil

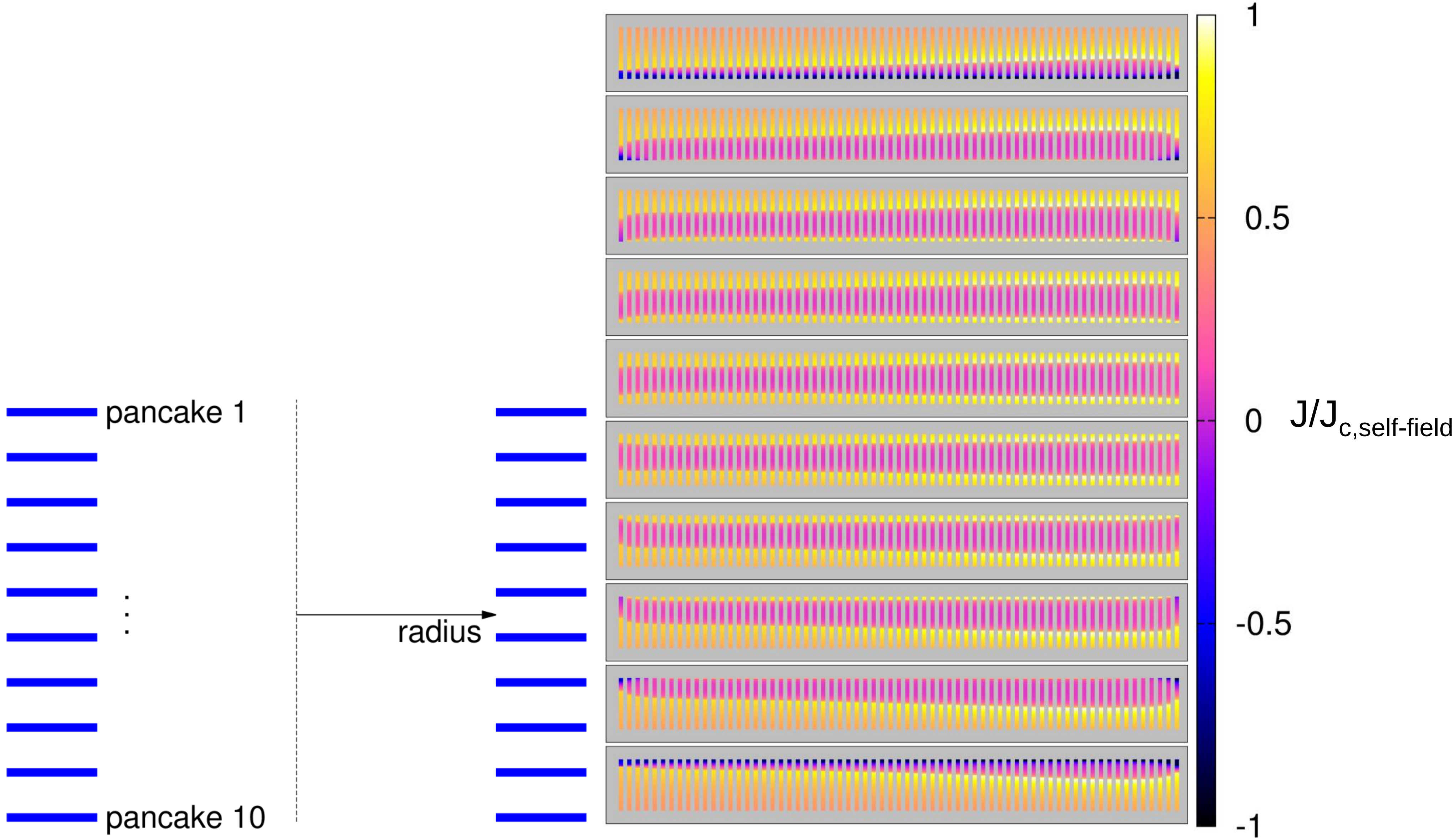
- Tape properties
- Screening currents
- Comparison to experiments

Transformer

**Magnet-size coils**

**3D modelling**

# Detailed current density in all turns



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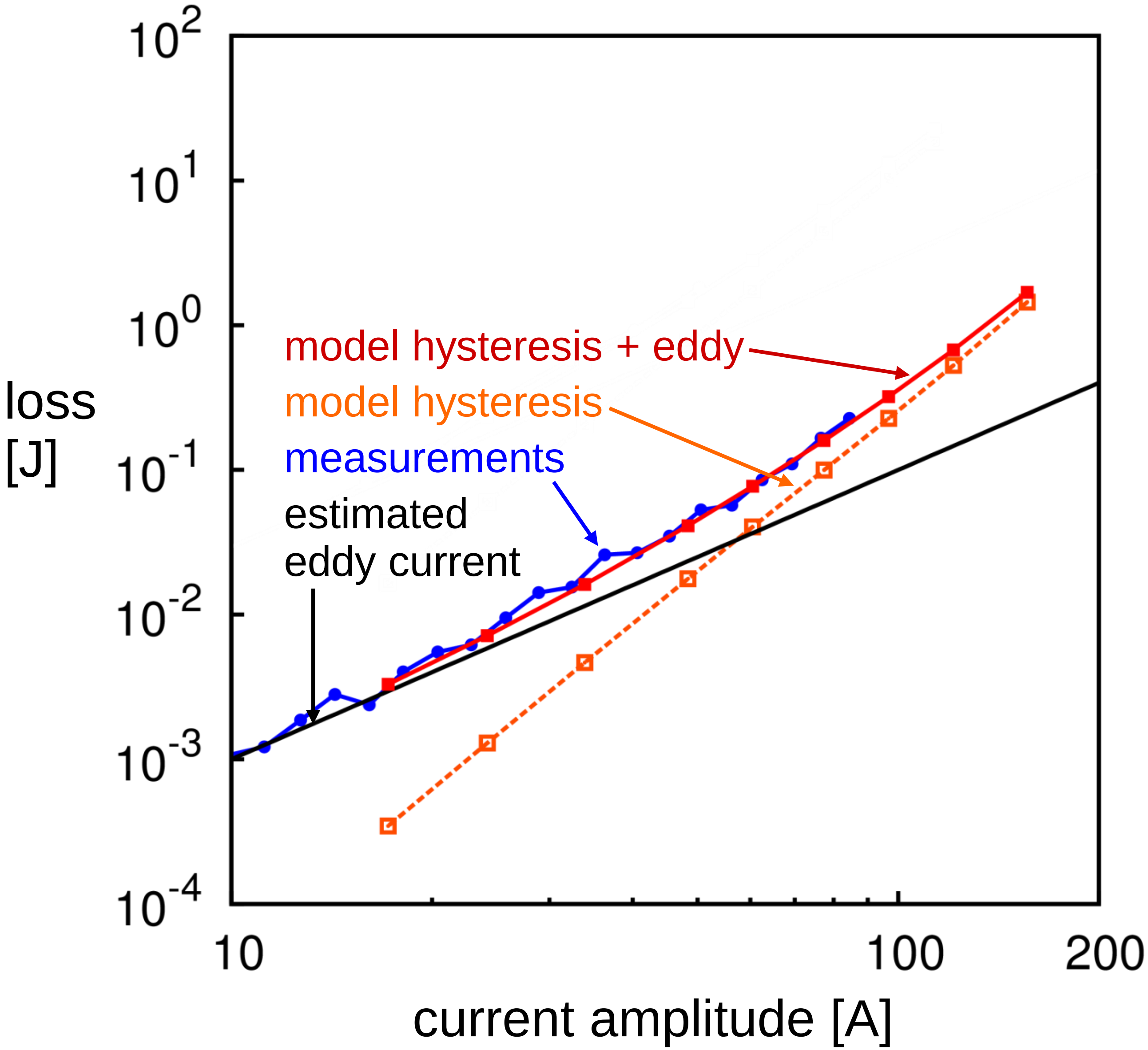
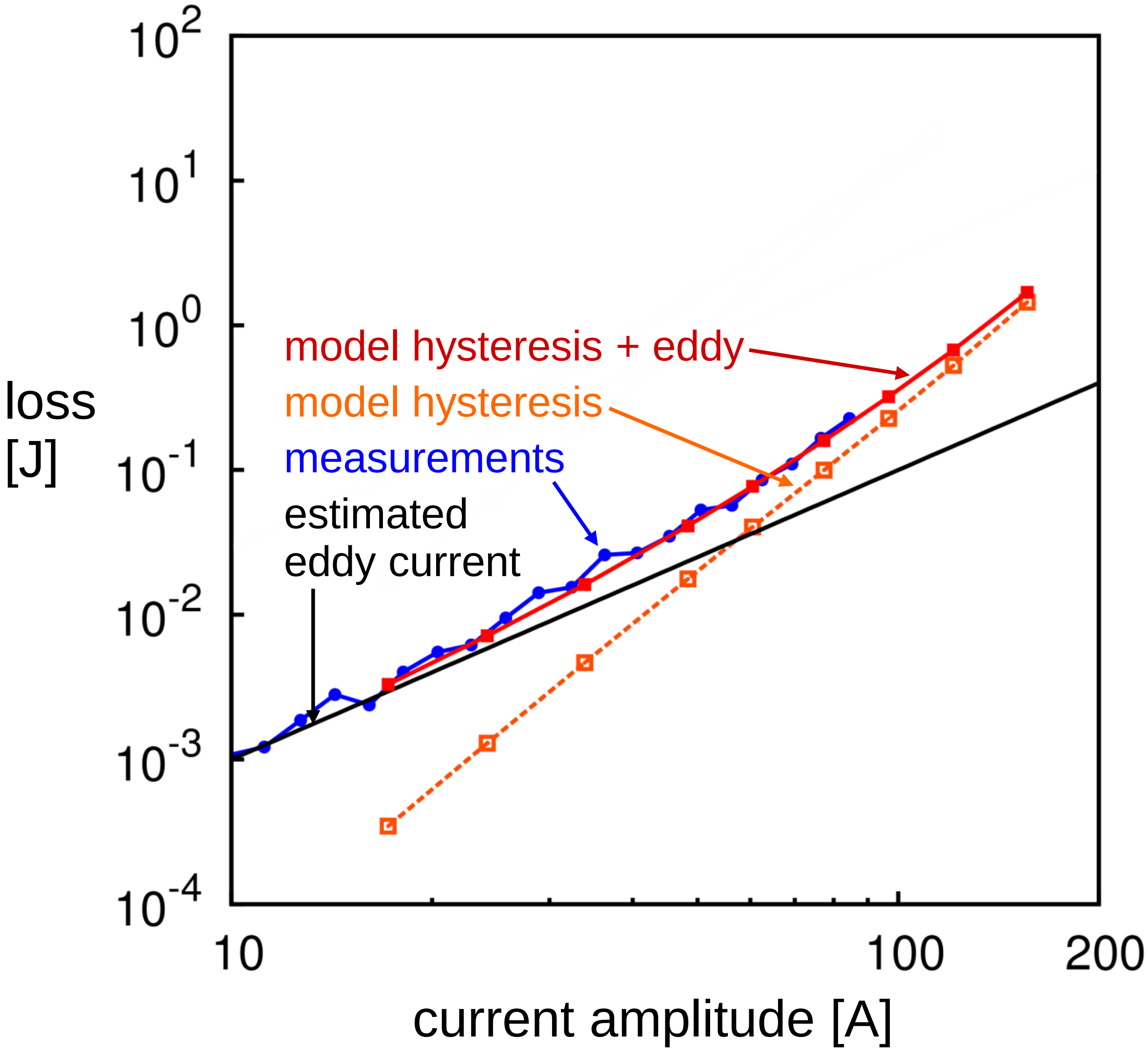
# Calculated AC loss agrees with experiments




**Single pancake**

Measurements
by electrical means

# Calculated AC loss agrees with experiments



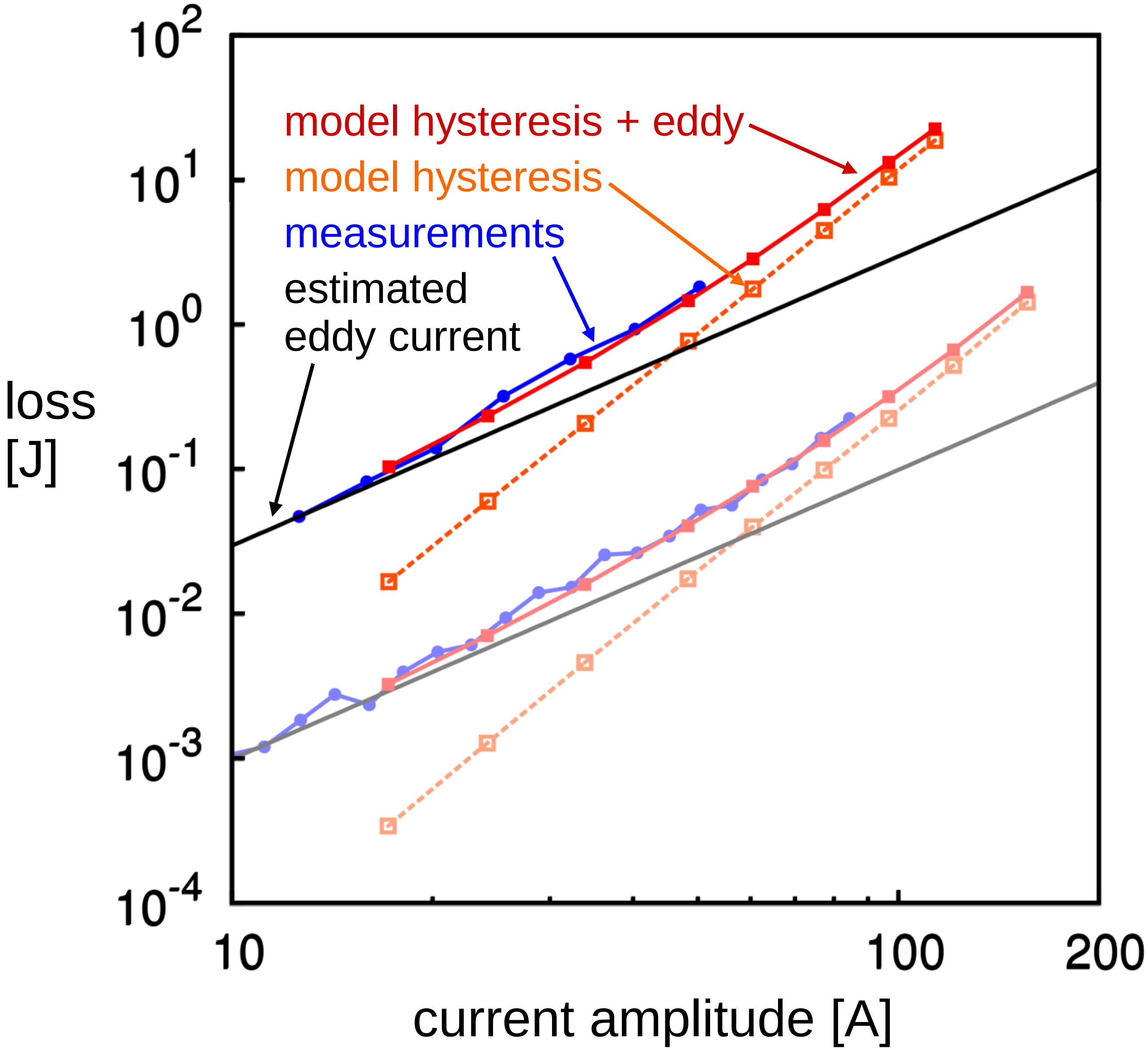

**Single pancake**

Measurements by electrical means

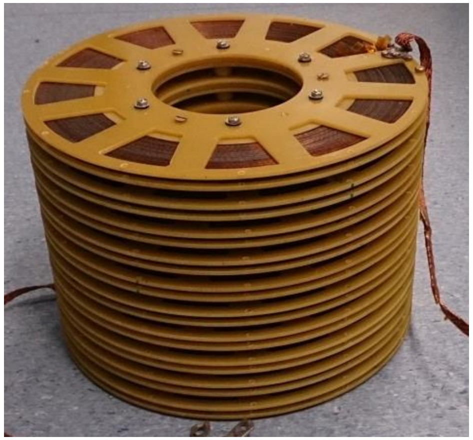
**Low currents:**

eddy current loss at current leads dominates

# Calculated AC loss agrees with experiments




**Whole coil**



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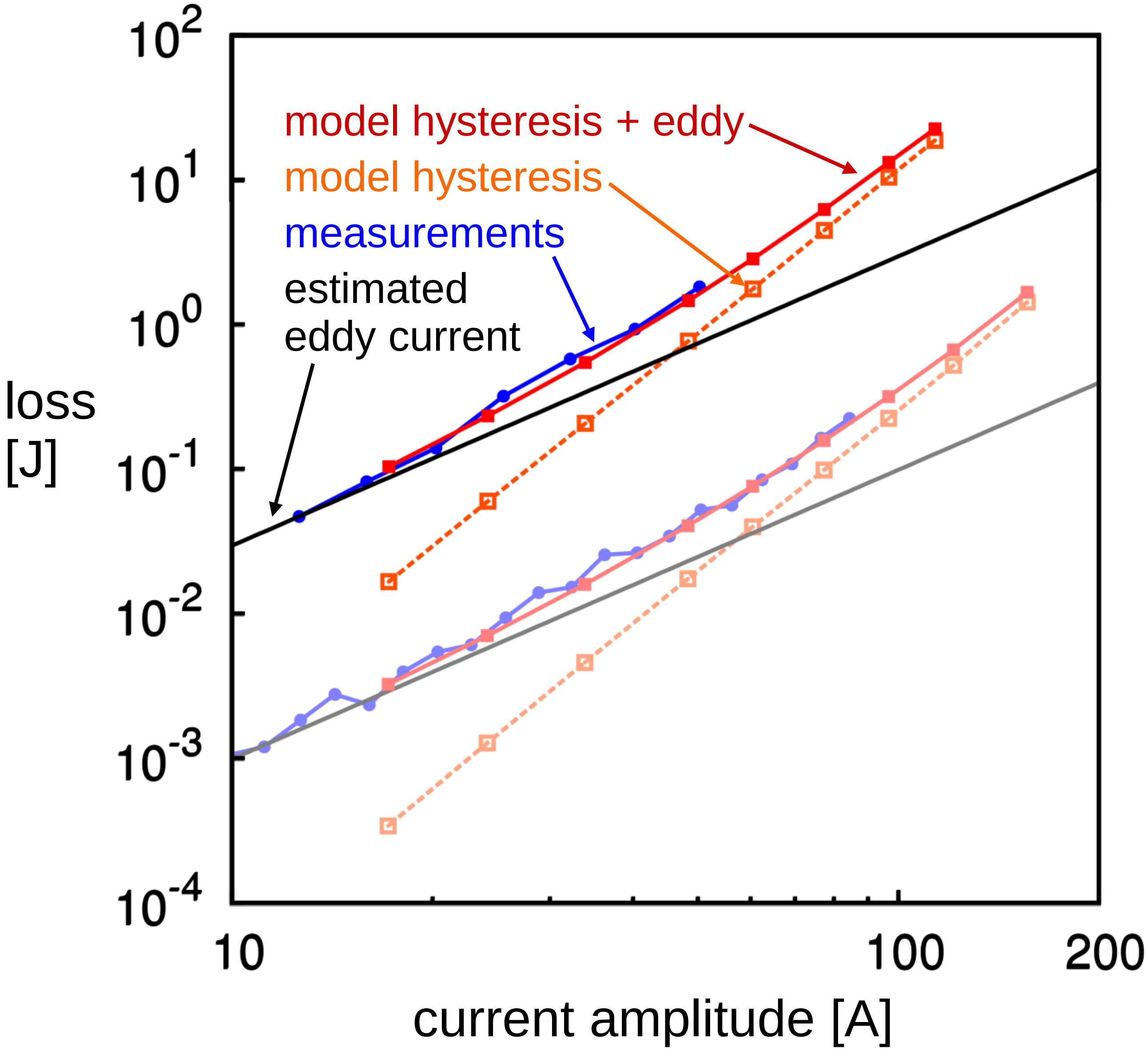
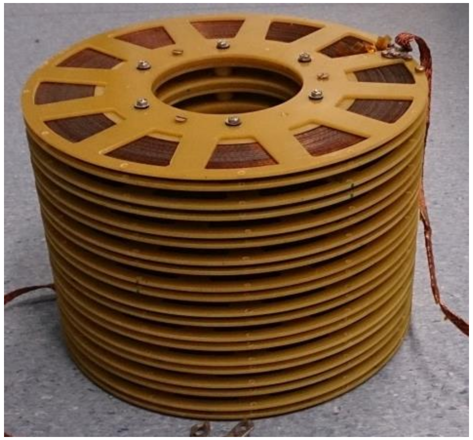



**Whole coil**

Measurements
by boil-off method



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- Medium size coil
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**Magnet-size coils**

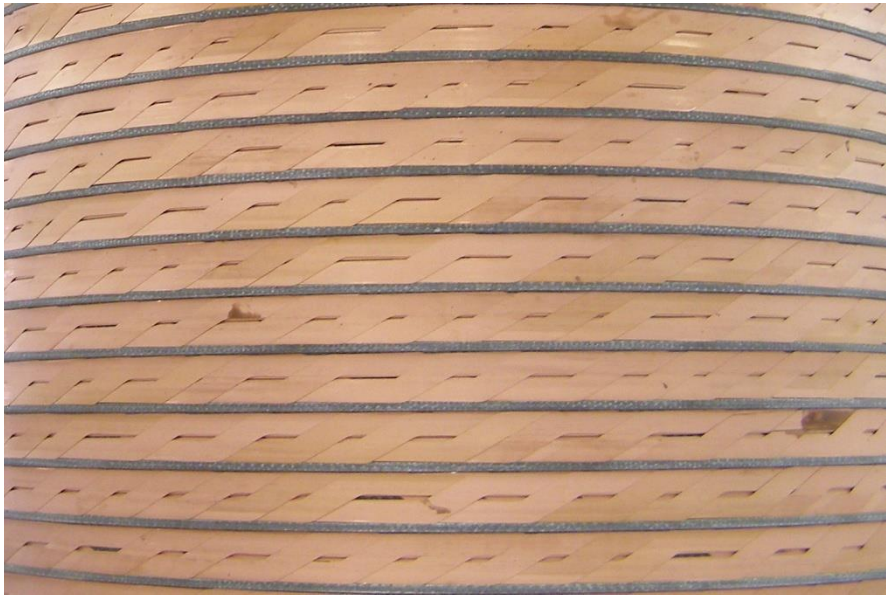
**3D modelling**

# Transformer with Roebel cable in low-voltage winding

1 MVA 11 kV/415 V 3 phase transformer

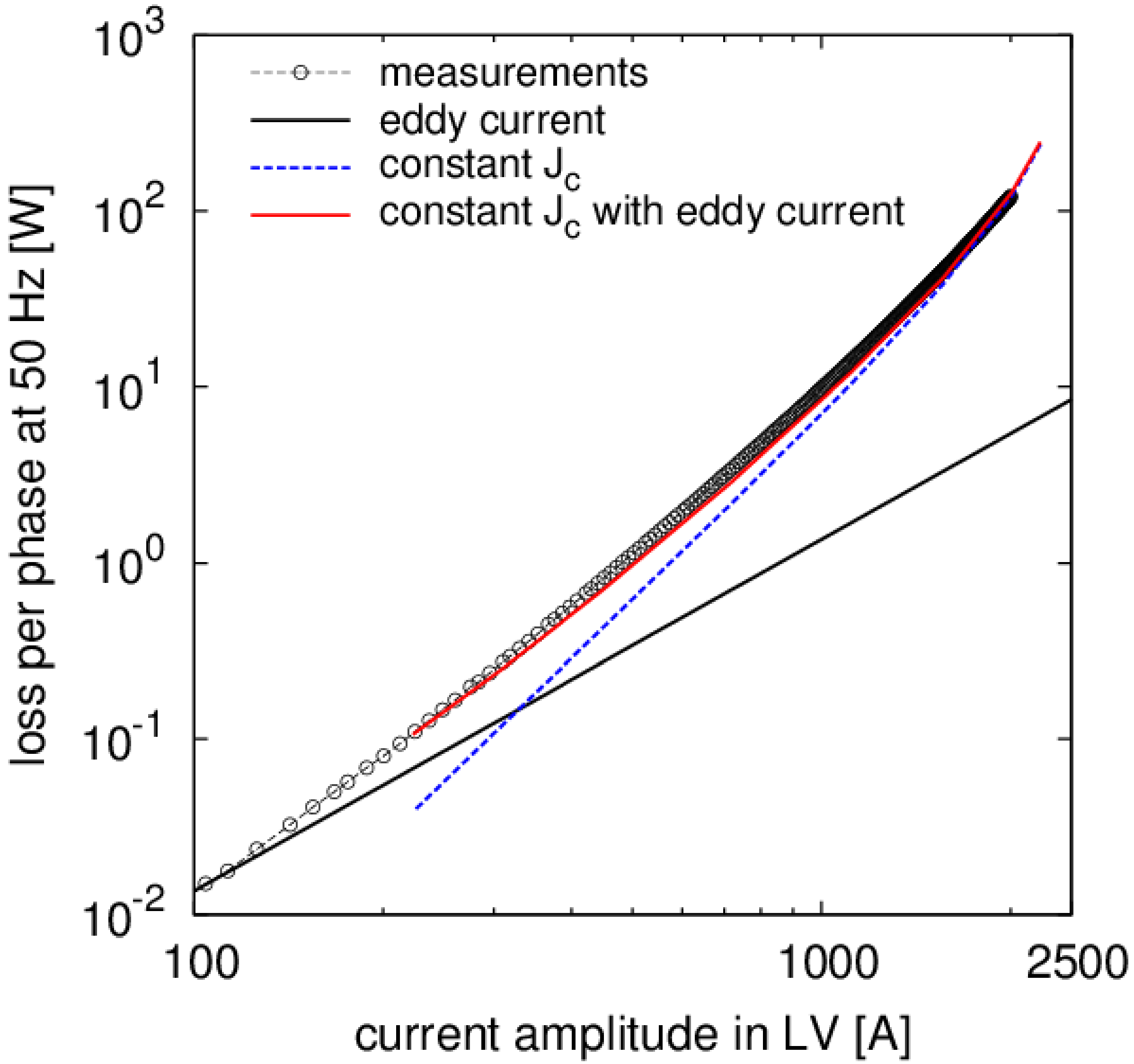
**Robinson Research Institute in Wellington and industrial partners**

**Roebel cable in low voltage winding**



# AC loss agrees with model

E Pardo et al 2015 SuST, November




**Copper current leads cause eddy current loss**

consistent with estimations

**Real large scale application**

~1200 turns or strands

**Model**

**Validation with experiments**

**Magnet-size coils**

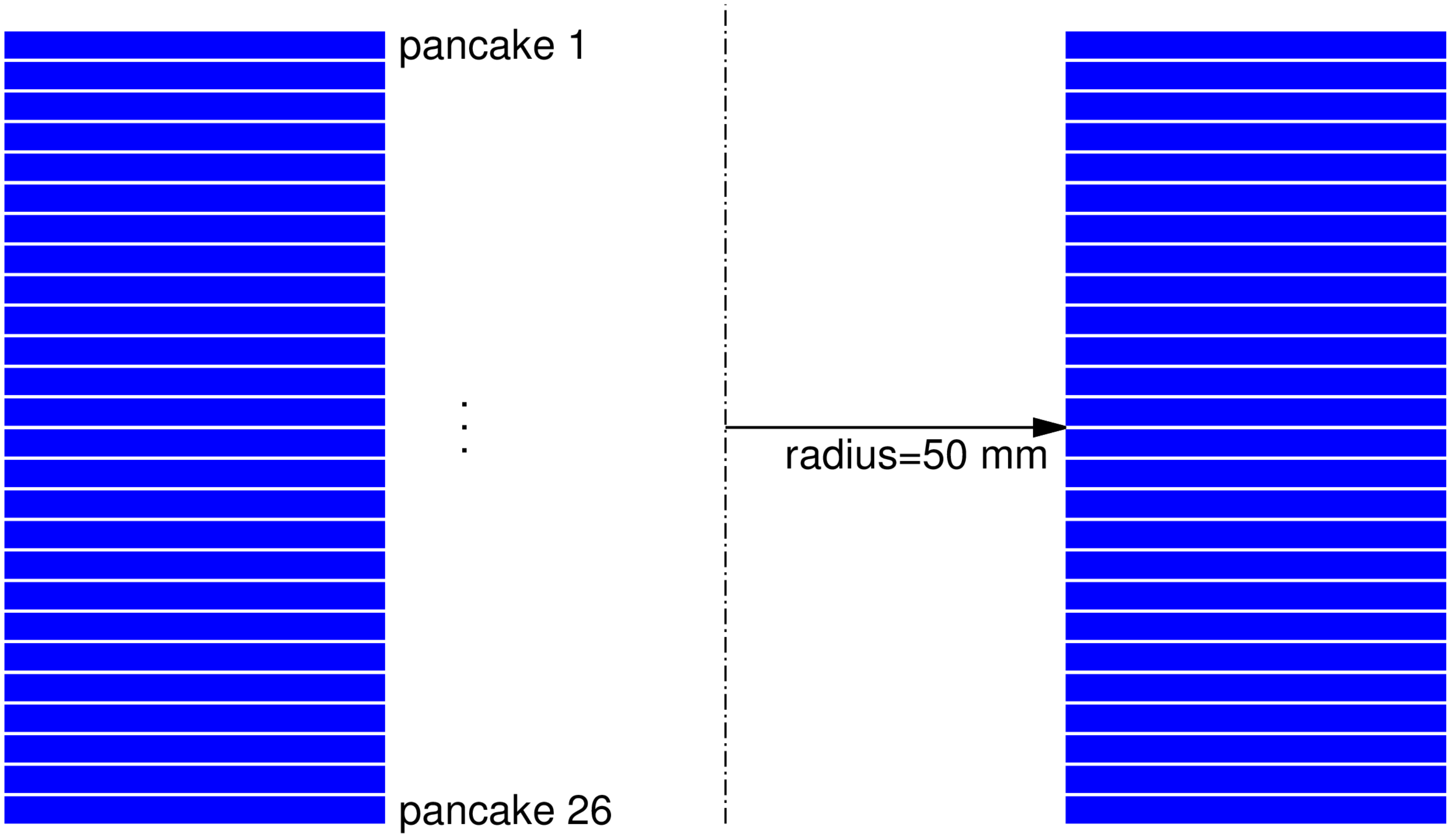
**3D modelling**

# Example winding

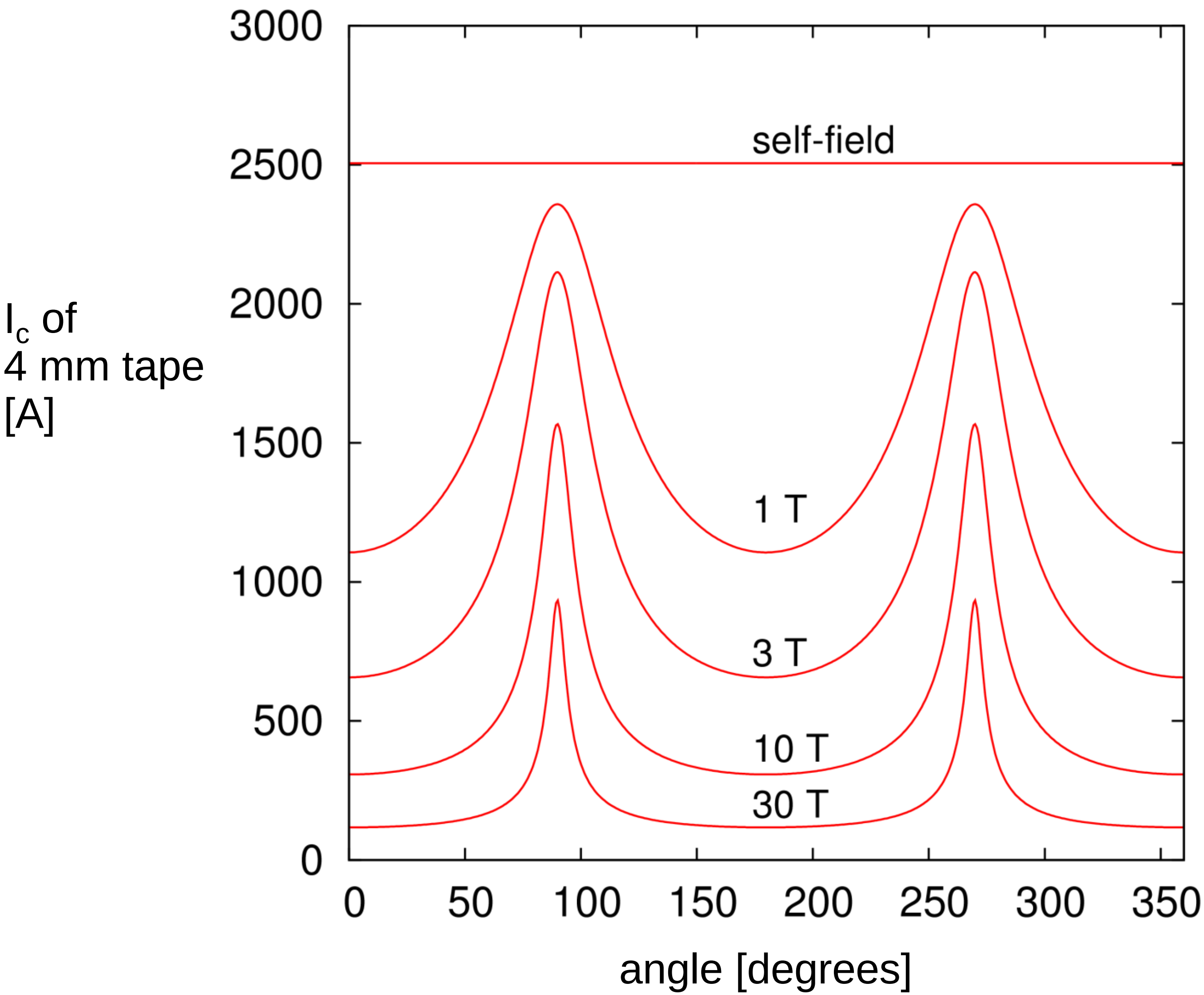
26 pancakes

400 turns per pancake

**more than 10000 turns**



# Anisotropic field dependent $J_c$

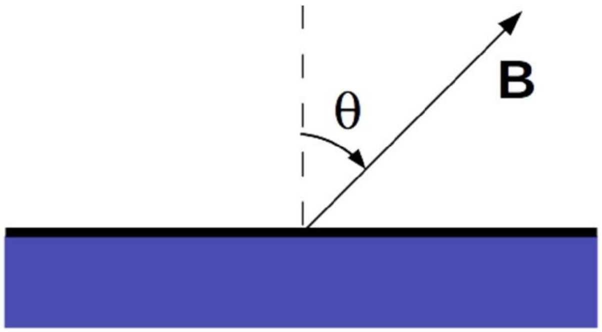



SuperPower tape

Fit of $J_c$ from measurements at **4.2 K**

D K Hilton et al. 2015 SuST

**Results useful for high-field magnets**



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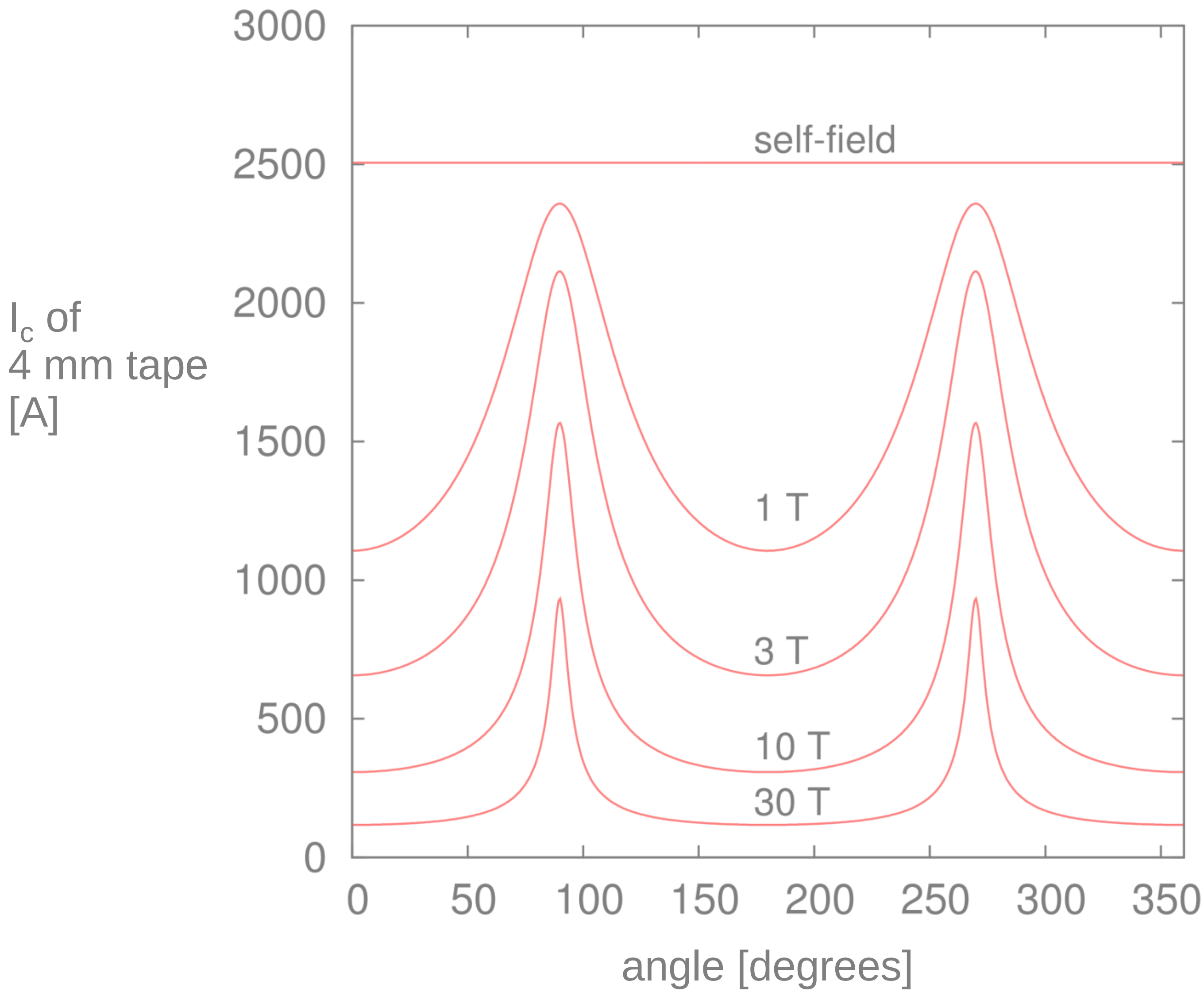


Power-law exponent: **30**

SuperPower tape

Fit of $J_c$ from measurements at **4.2 K**

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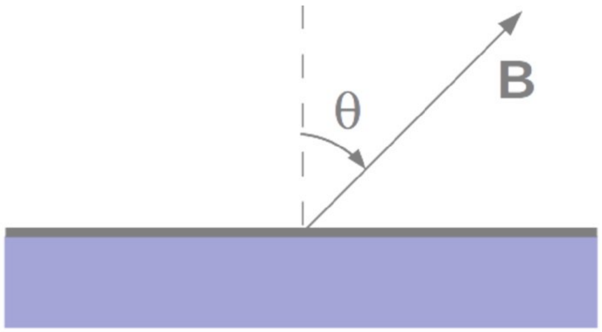


**Model**

**Validation with experiments**

**Magnet-size coils**

**3D modelling**

**Model**

**Validation with experiments**

**Magnet-size coils**

- Screening currents
- Magnetic field distortion
- AC loss

**3D modelling**

**Model**

**Validation with experiments**

**Magnet-size coils**

- Screening currents
  - Real geometry
  - Continuous approximation
- Magnetic field distortion
- AC loss

**3D modelling**

**Model**

**Validation with experiments**

**Magnet-size coils**

Screening currents

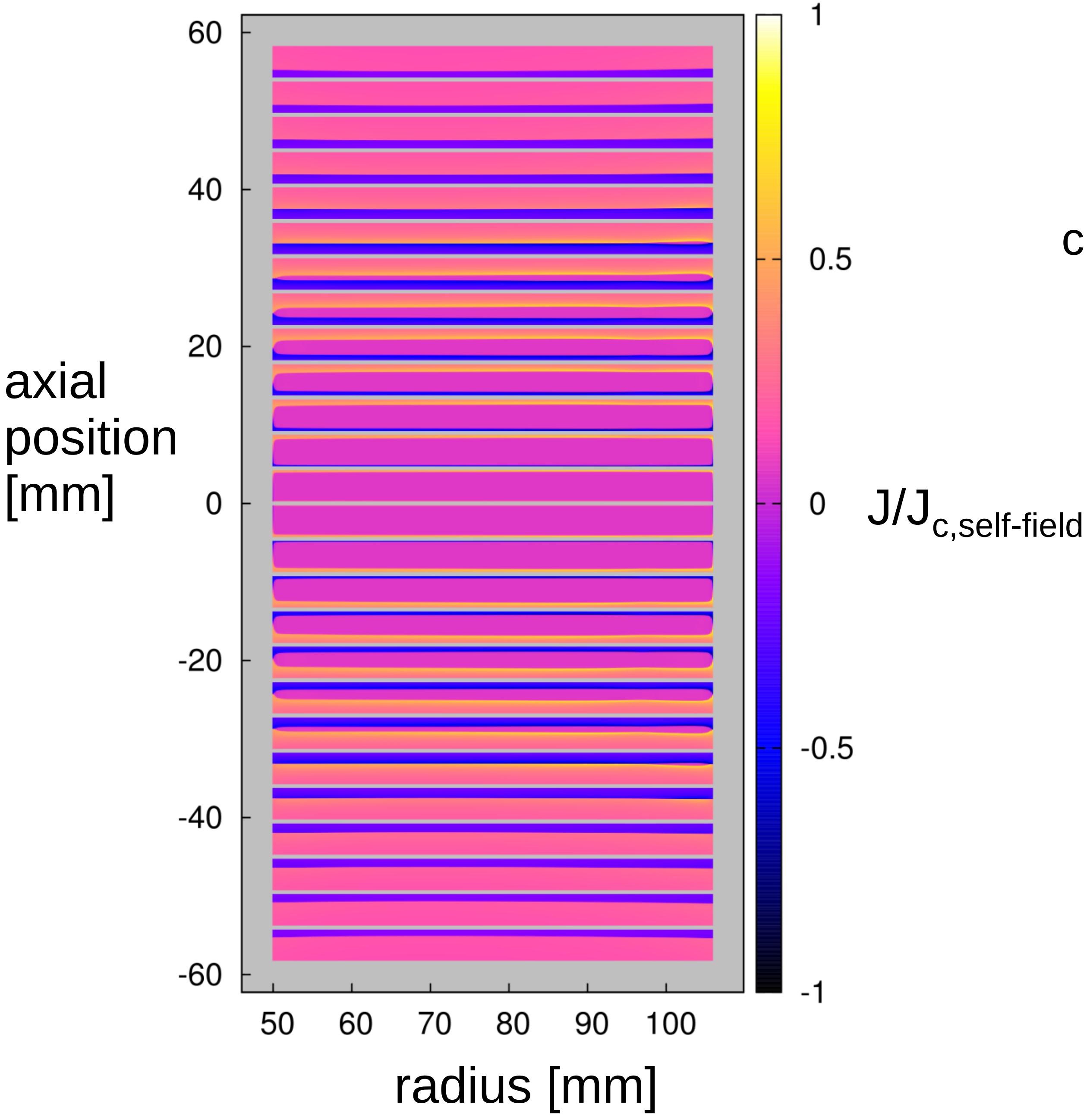
- Real geometry
- Continuous approximation

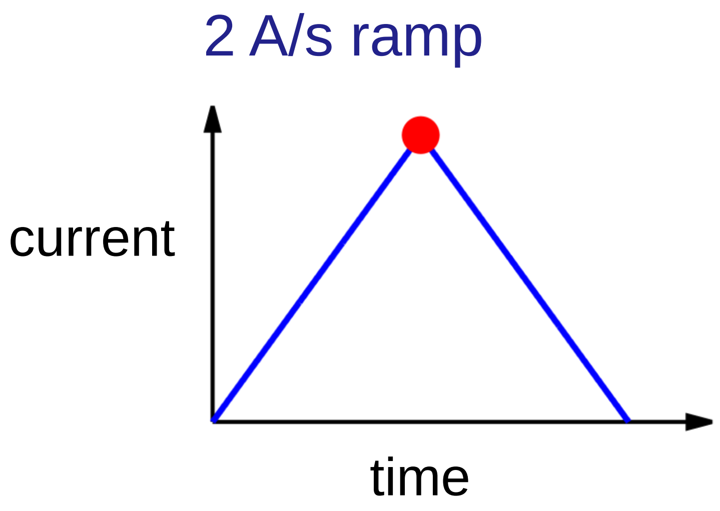
Magnetic field distortion

AC loss

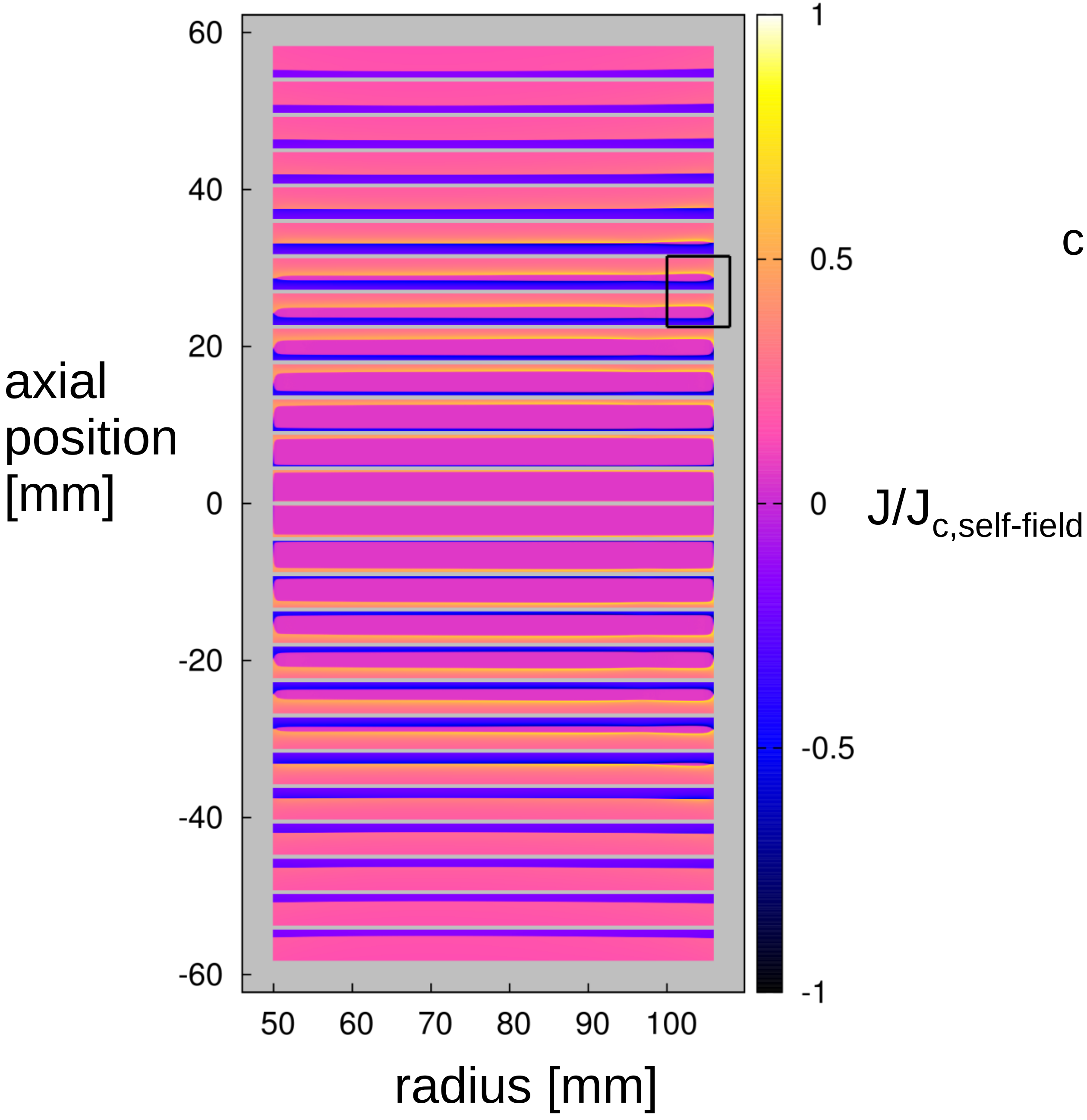
**3D modelling**

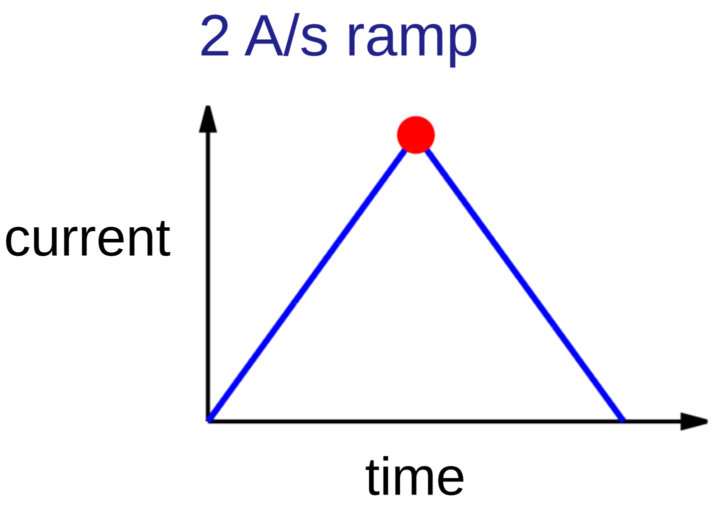
# Important screening currents



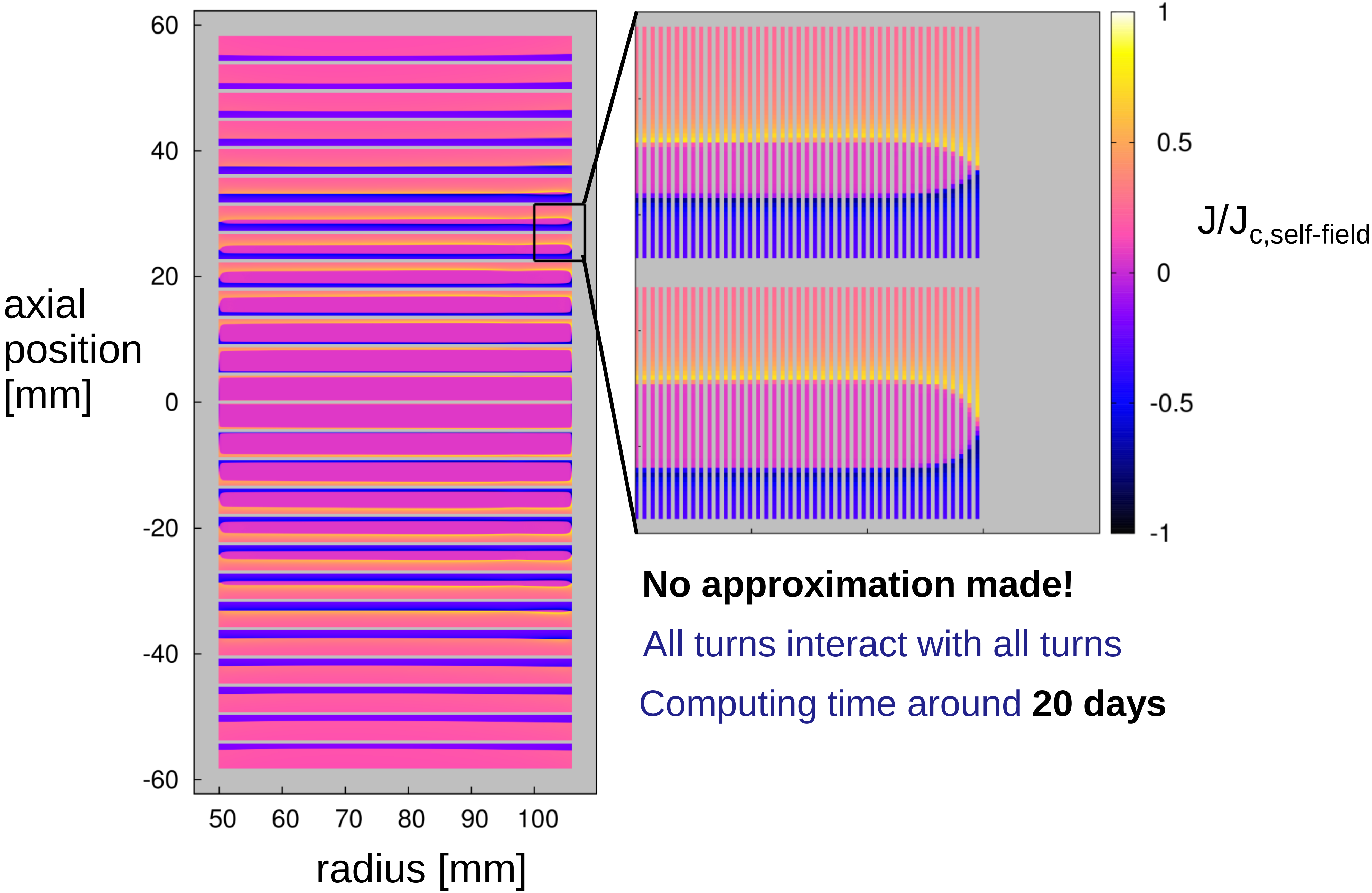



# Detailed current density at all turns



# Detailed current density at all turns

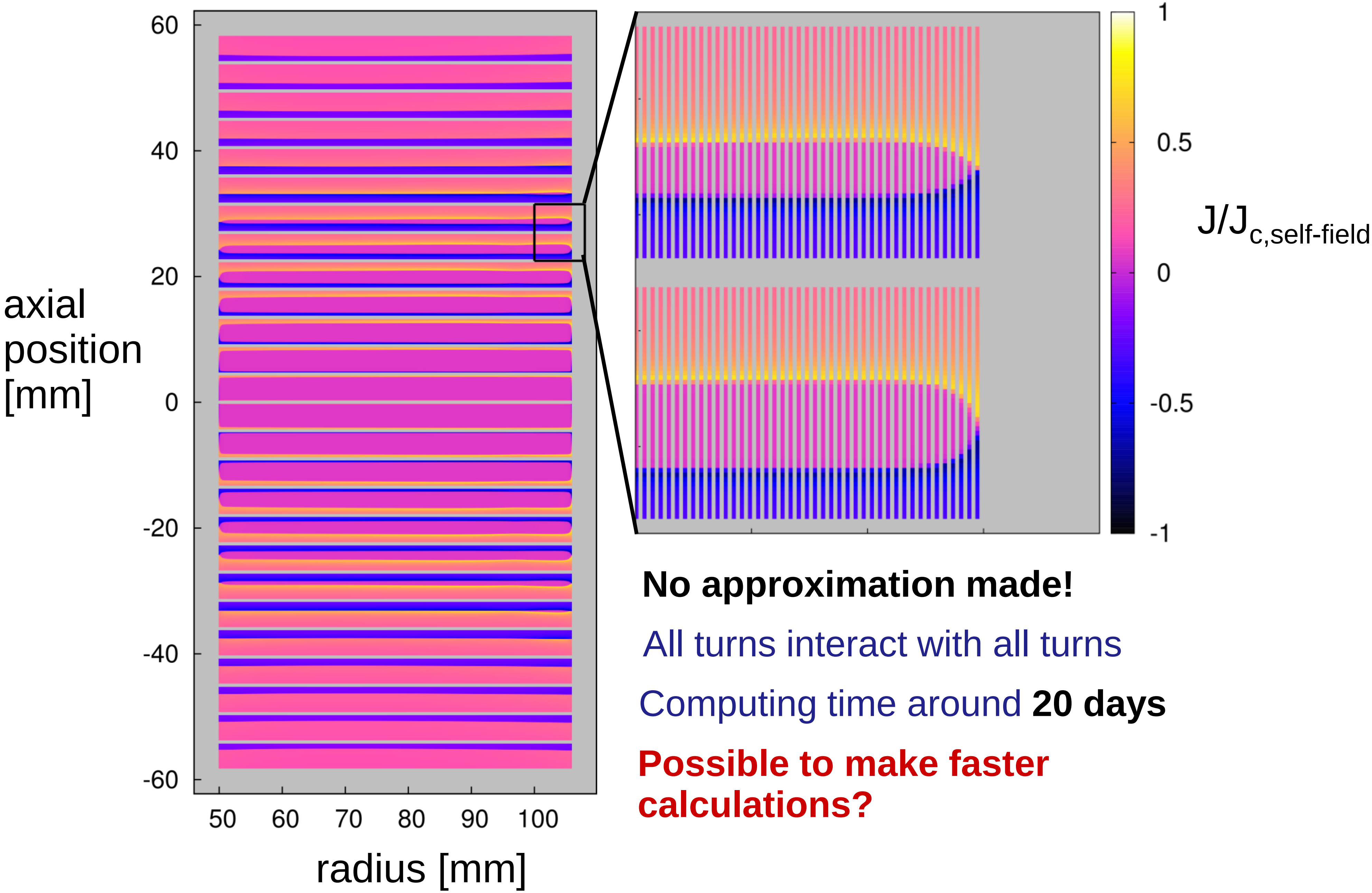



**No approximation made!**

All turns interact with all turns

Computing time around **20 days**

# Detailed current density at all turns




**No approximation made!**

All turns interact with all turns

Computing time around **20 days**

**Possible to make faster calculations?**

**Model**

**Validation with experiments**

**Magnet-size coils**

Screening currents

- Real geometry
- Continuous approximation

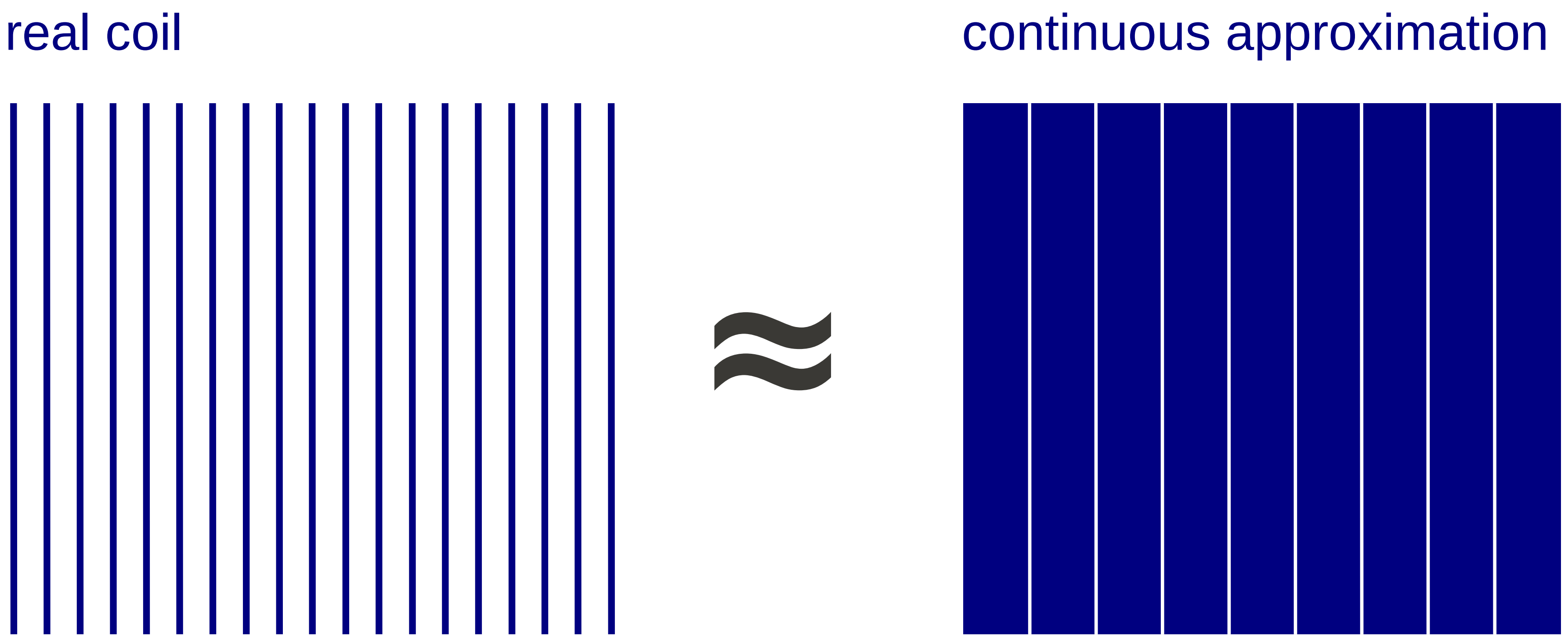
Magnetic field distortion

AC loss

# Continuous approximation

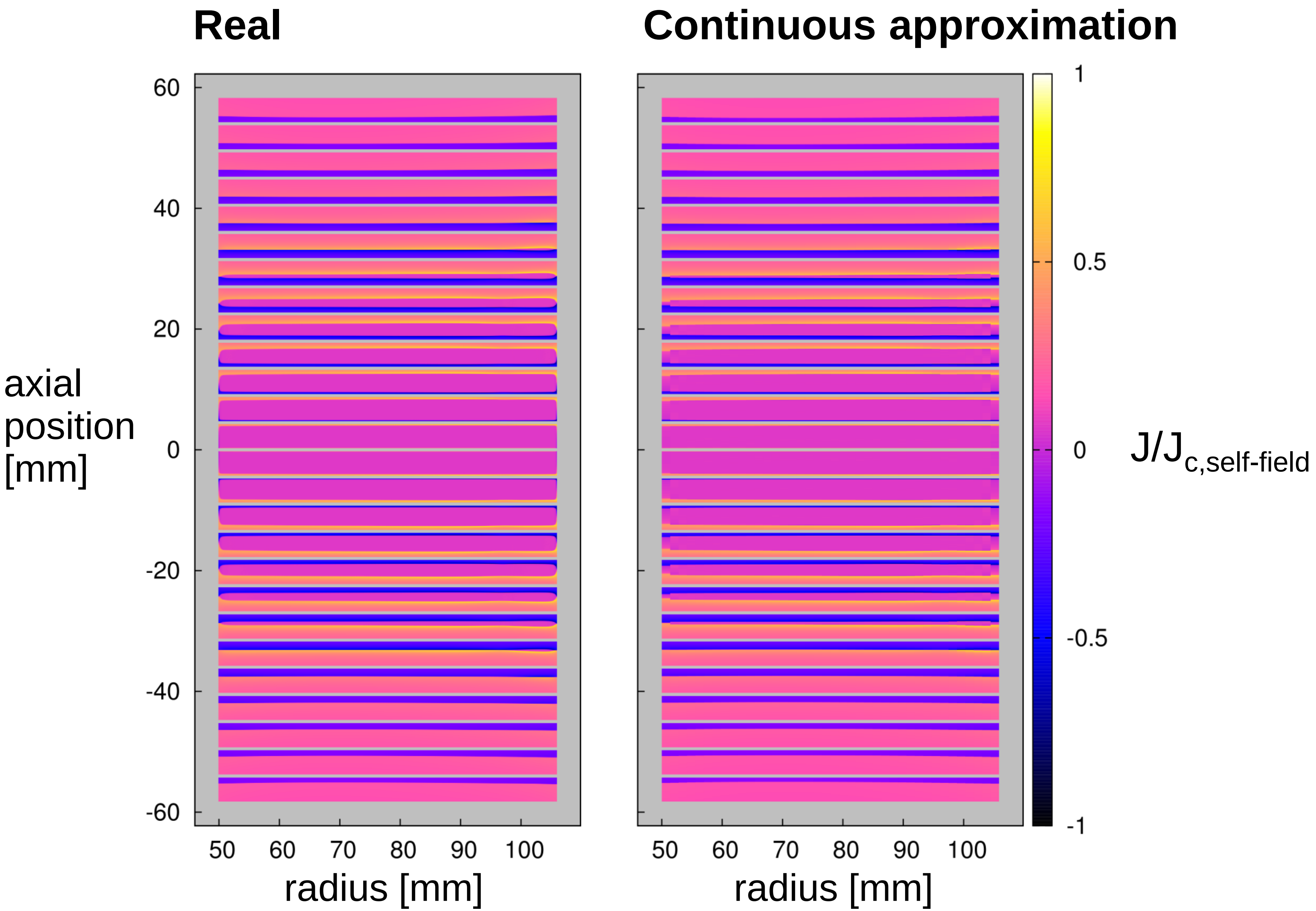
Pancake coil approximated by taking:

- **Less turns**
- **No separation between turns**

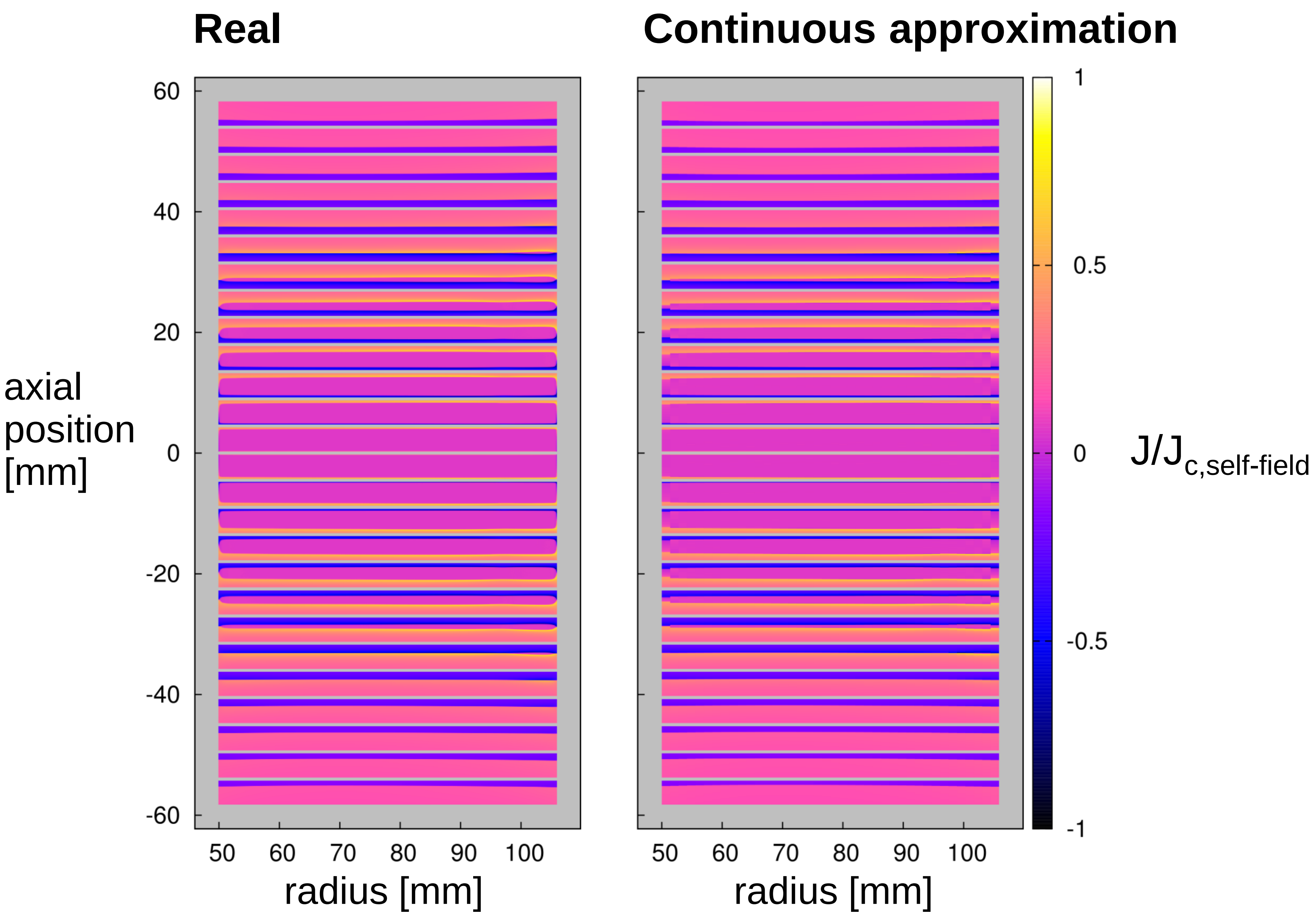



[Prigozhin and Sokolovsky 2011 SuST]

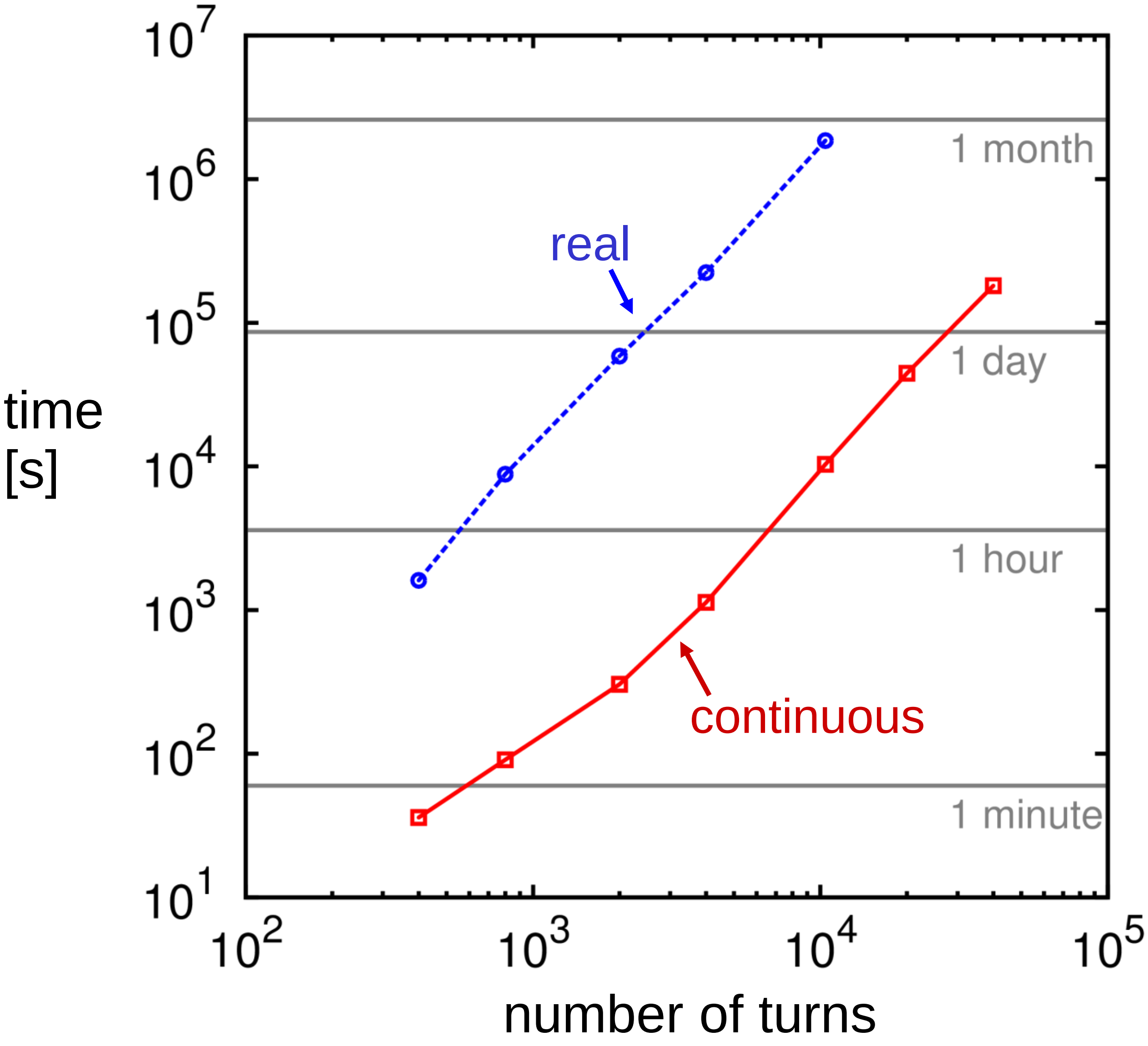
# Practically the same results



# Practically the same results **but faster!**



# We computed up to 40000 turns




10000 turns: **2.7 hours**

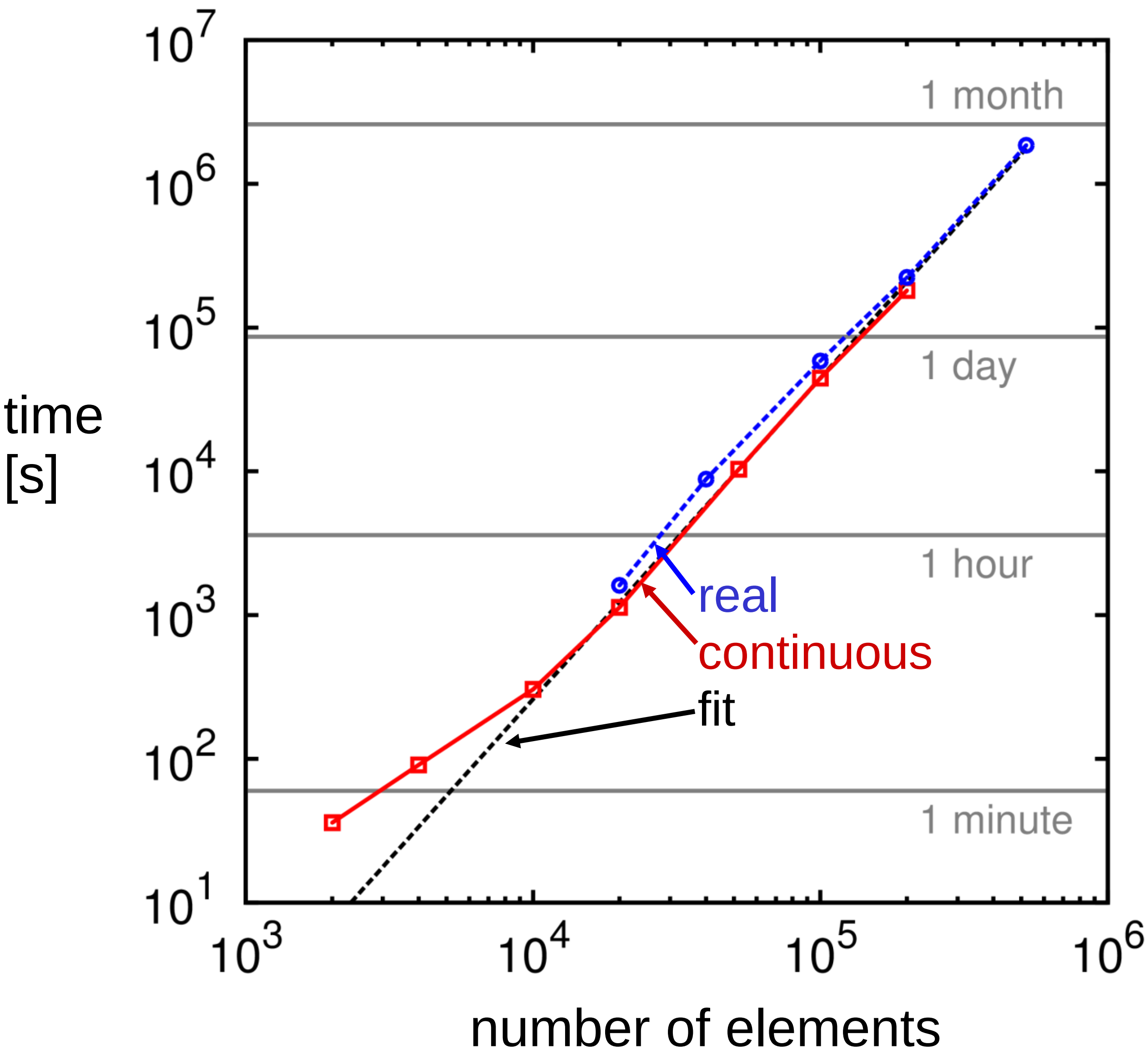
40000 turns: **2 days**

**fulfills requirements for high-field magnets**

H W Weijers et al. 2014 IEEE TAS

S Awaji et al. 2014 IEEE TAS

# Up to 500 000 elements in the superconductor




**Computing time scales as second power**

**Model**

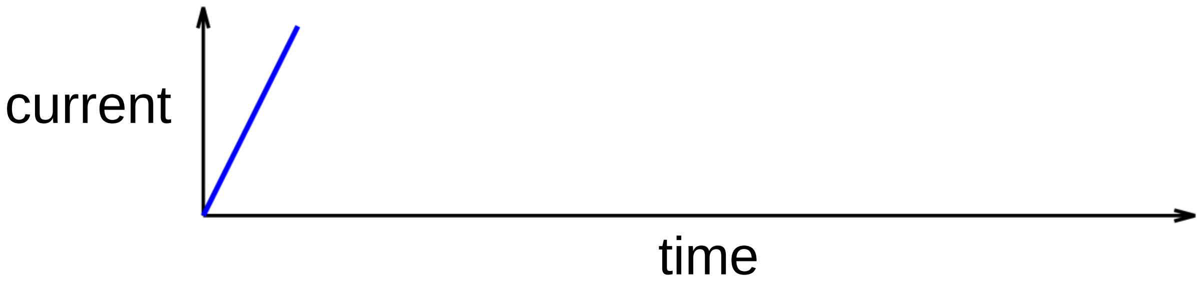
**Validation with experiments**

**Magnet-size coils**

- Screening currents
- Magnetic field distortion
- AC loss

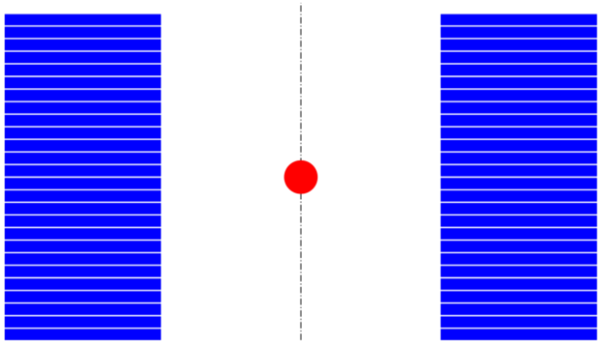
**3D modelling**

# Screening currents are important

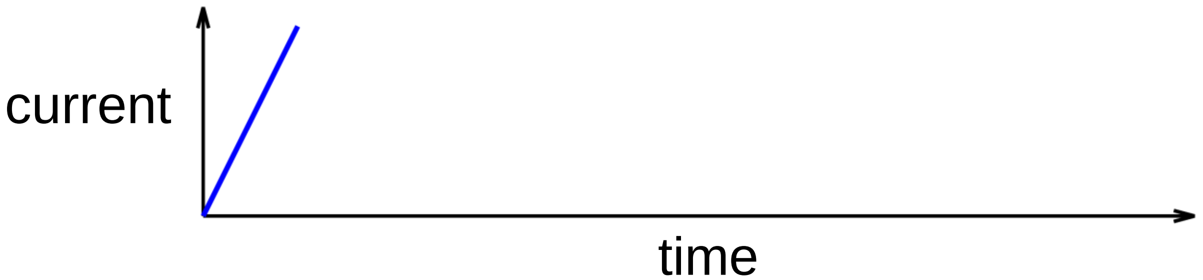



generated field
at maximum current **15 T**

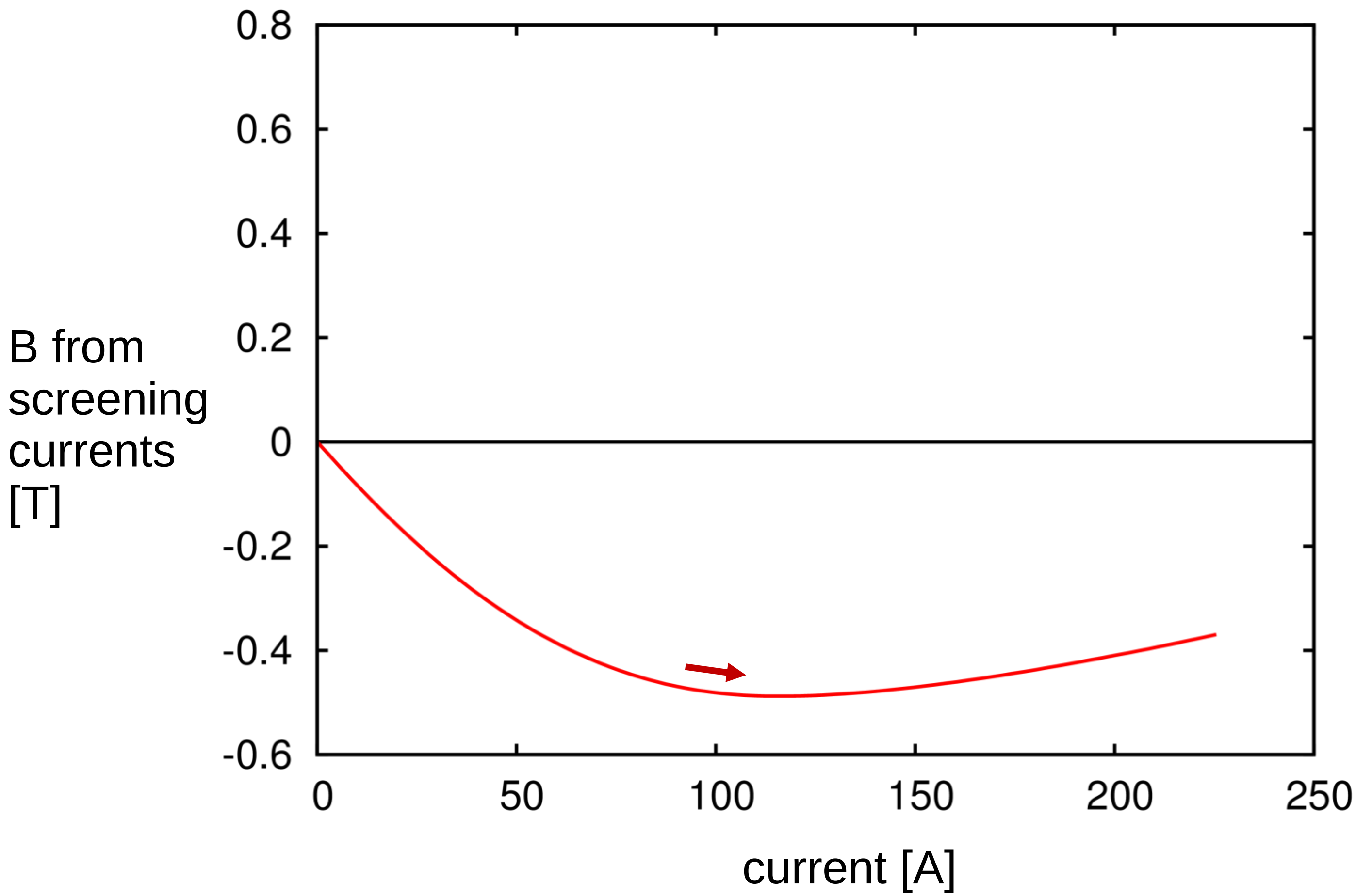
magnetic field
at bore center



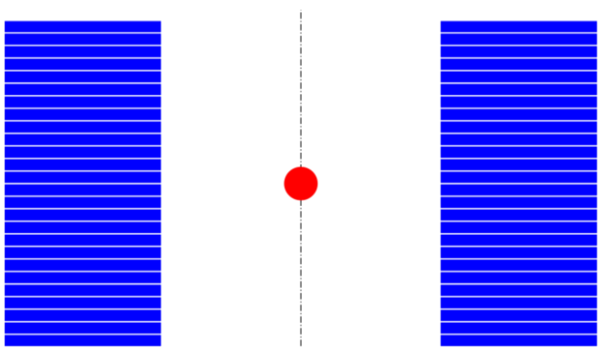
# Screening currents are important



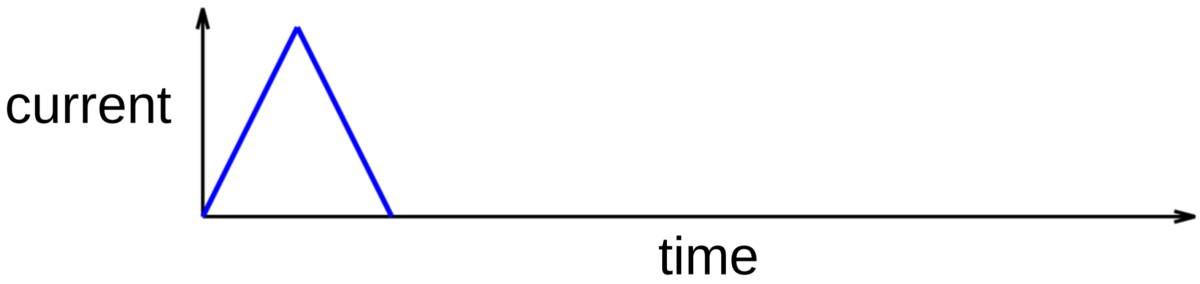

generated field
at maximum current **15 T**



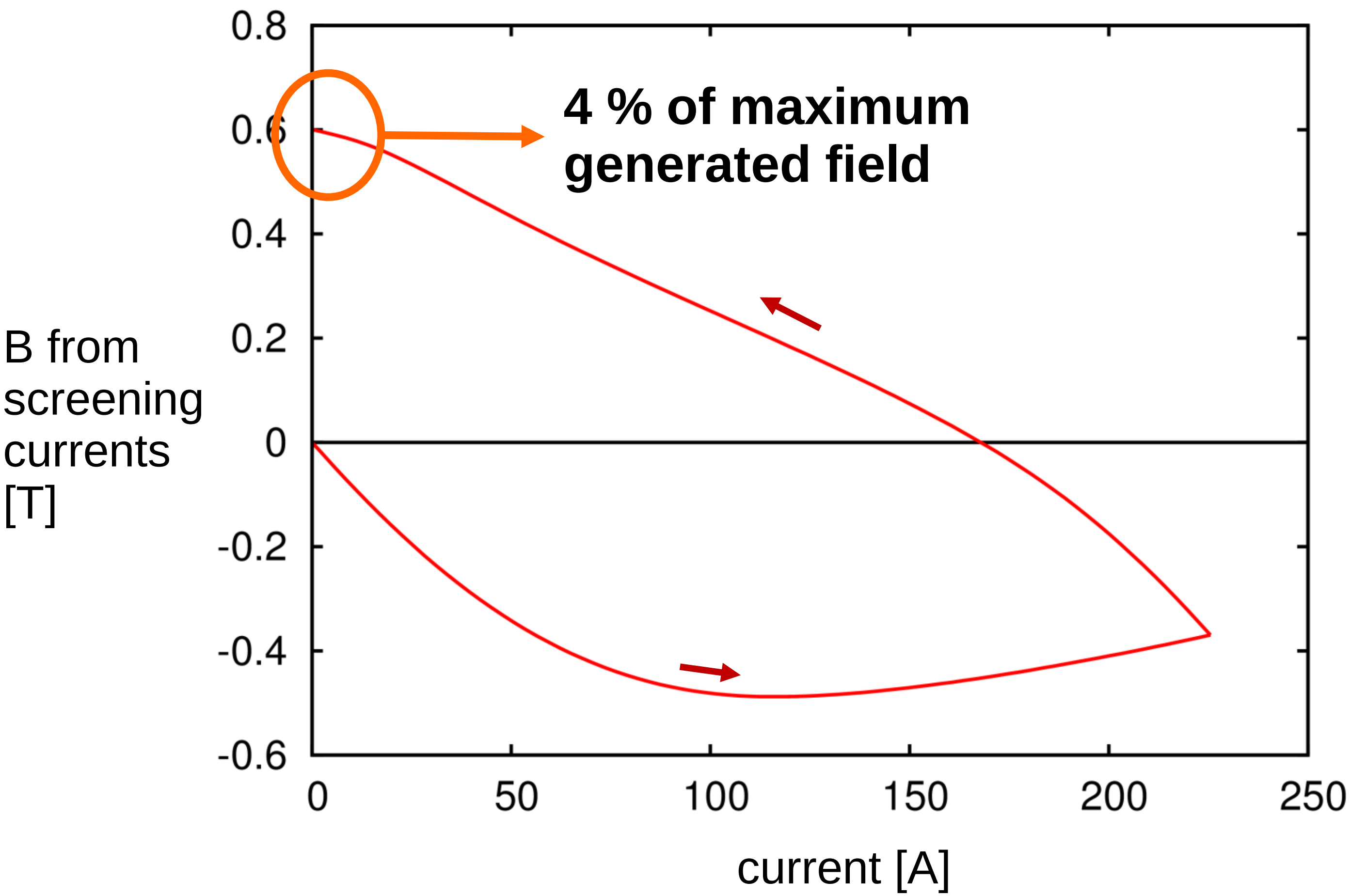

magnetic field
at bore center



# Screening currents are important

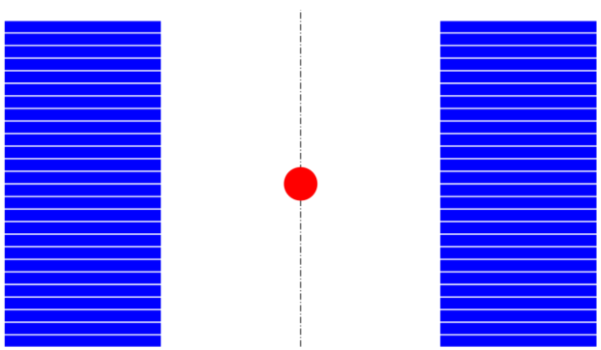



generated field
at maximum current **15 T**

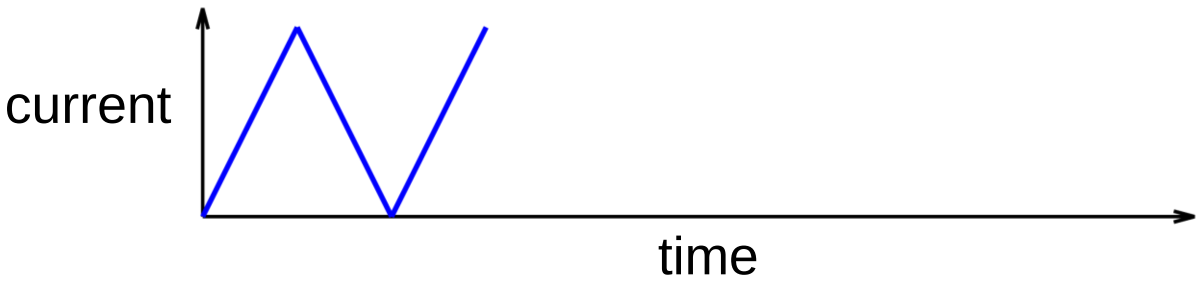



**Important for
MRI and NMR**

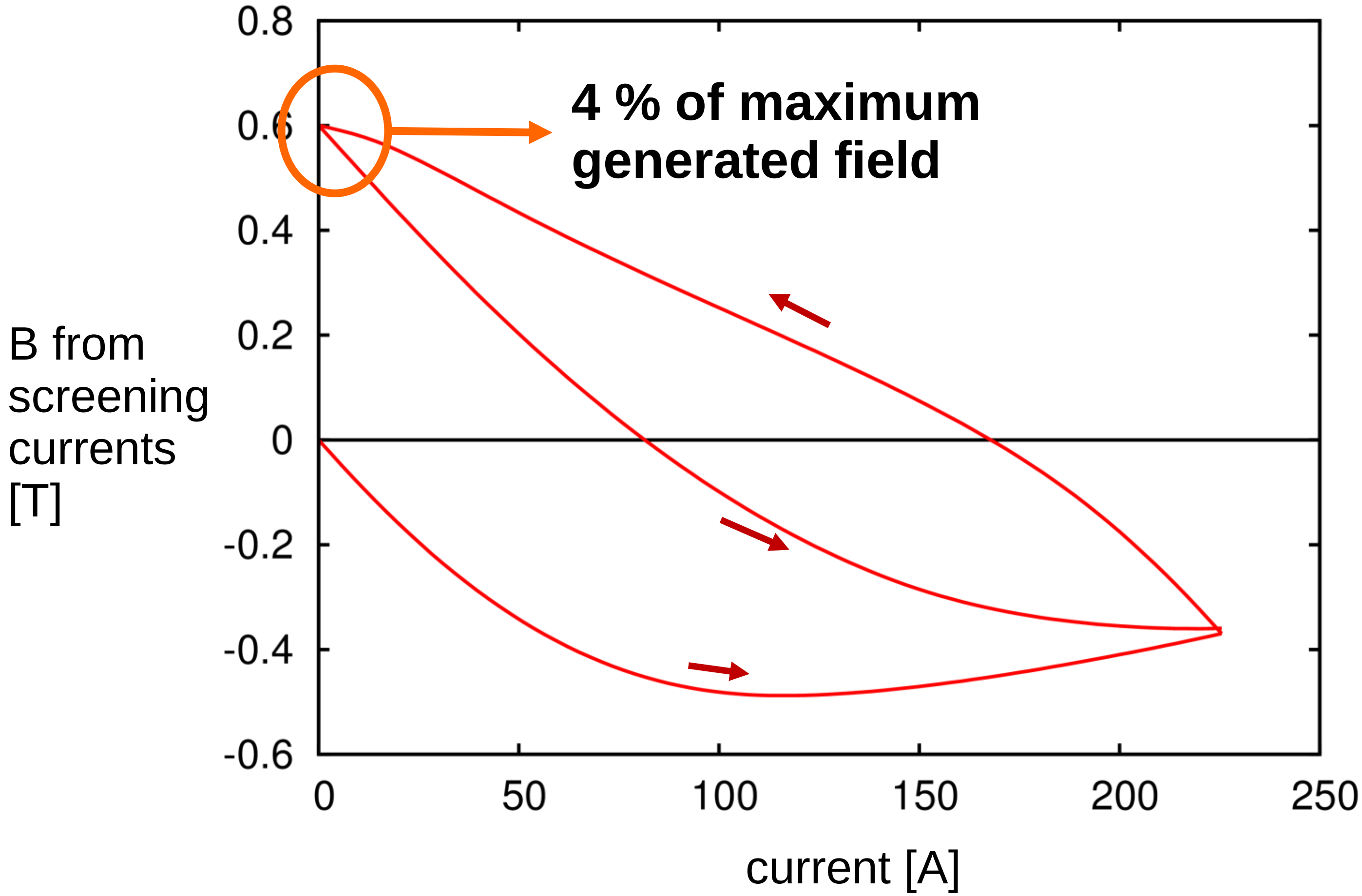
magnetic field
at bore center



# Screening currents are important




generated field
at maximum current **15 T**




**Important for**
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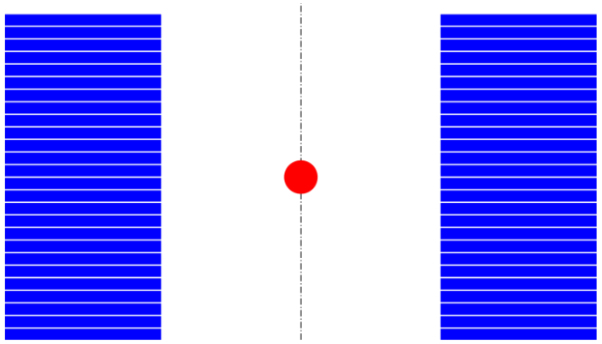
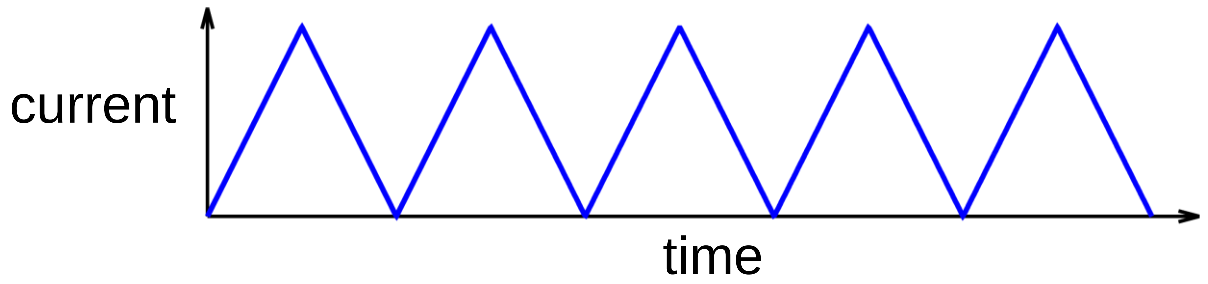
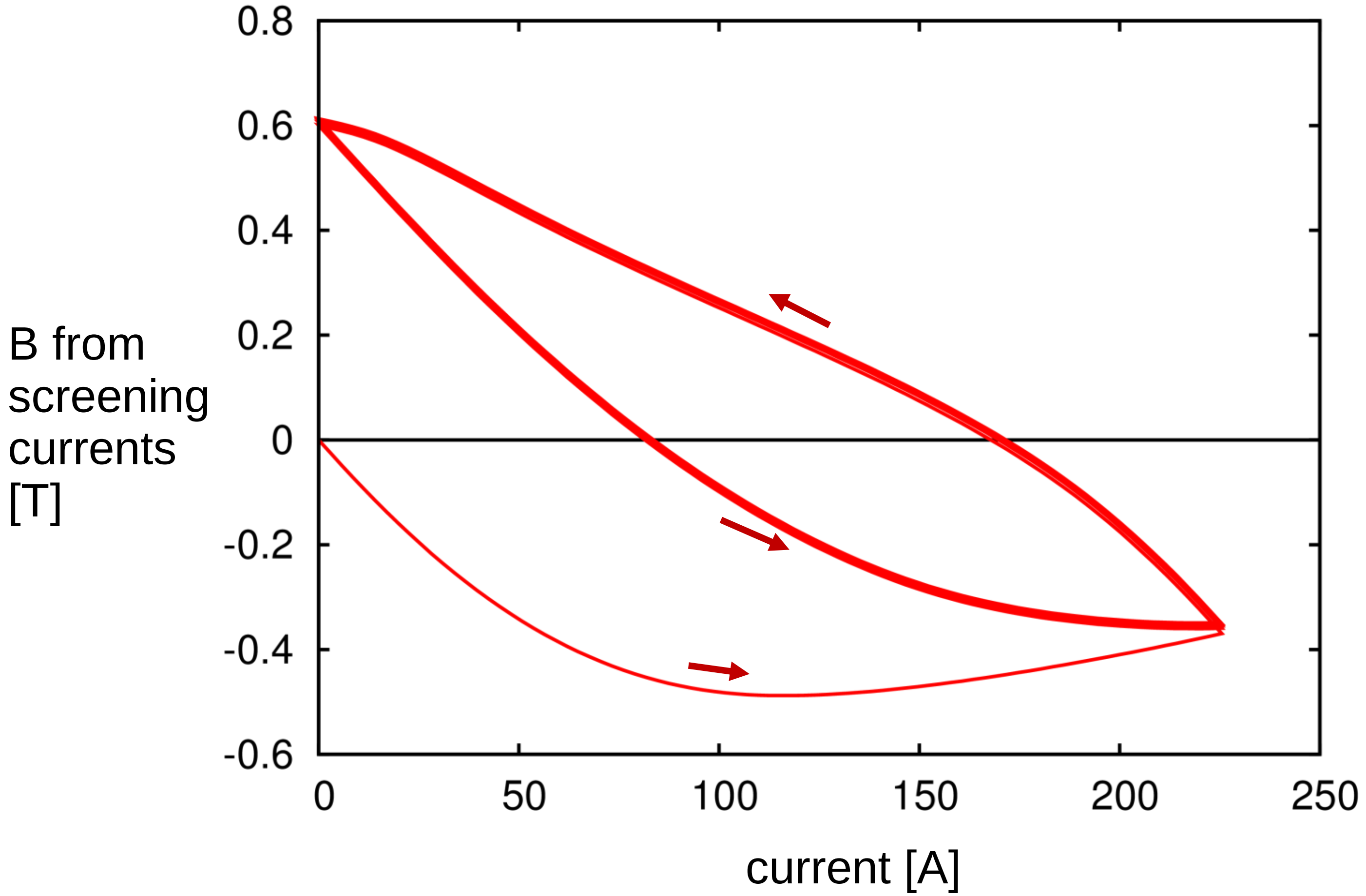
magnetic field
at bore center



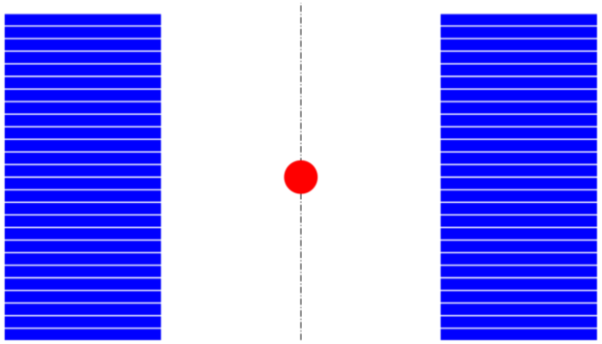
# Screening currents are important



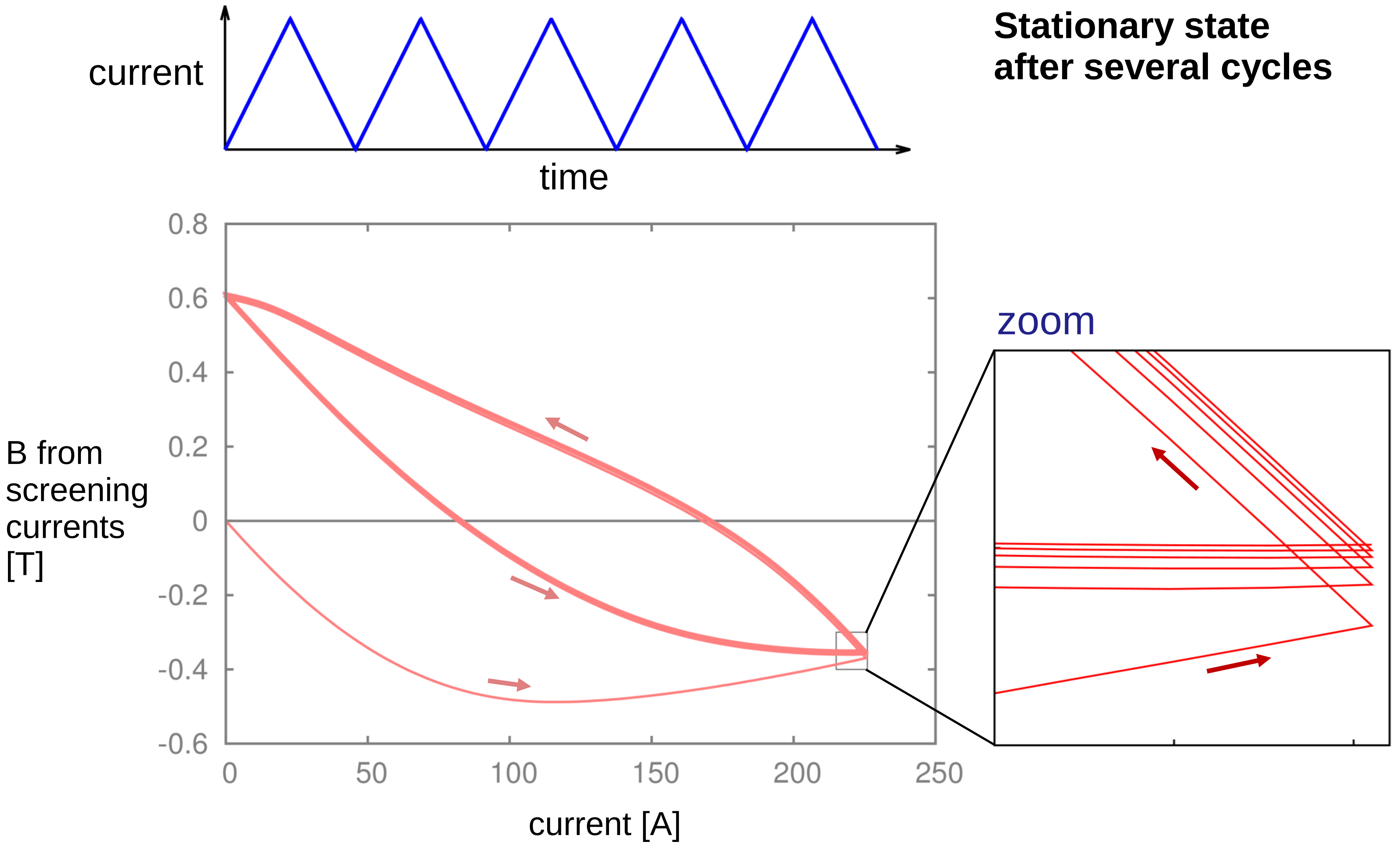

**Stationary state after several cycles**

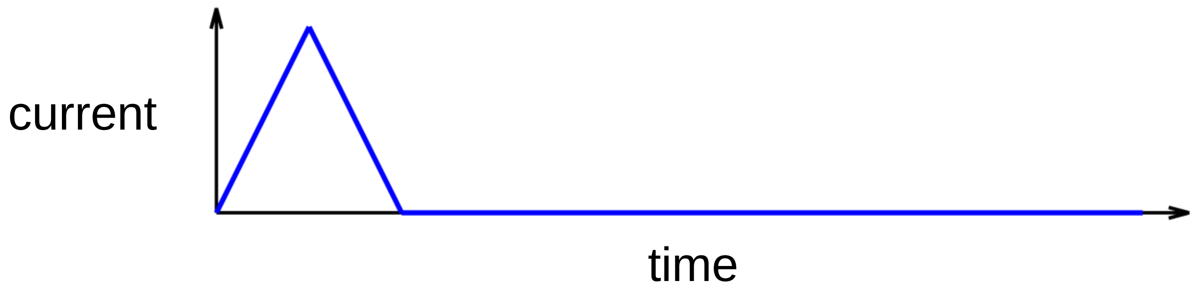



magnetic field at bore center



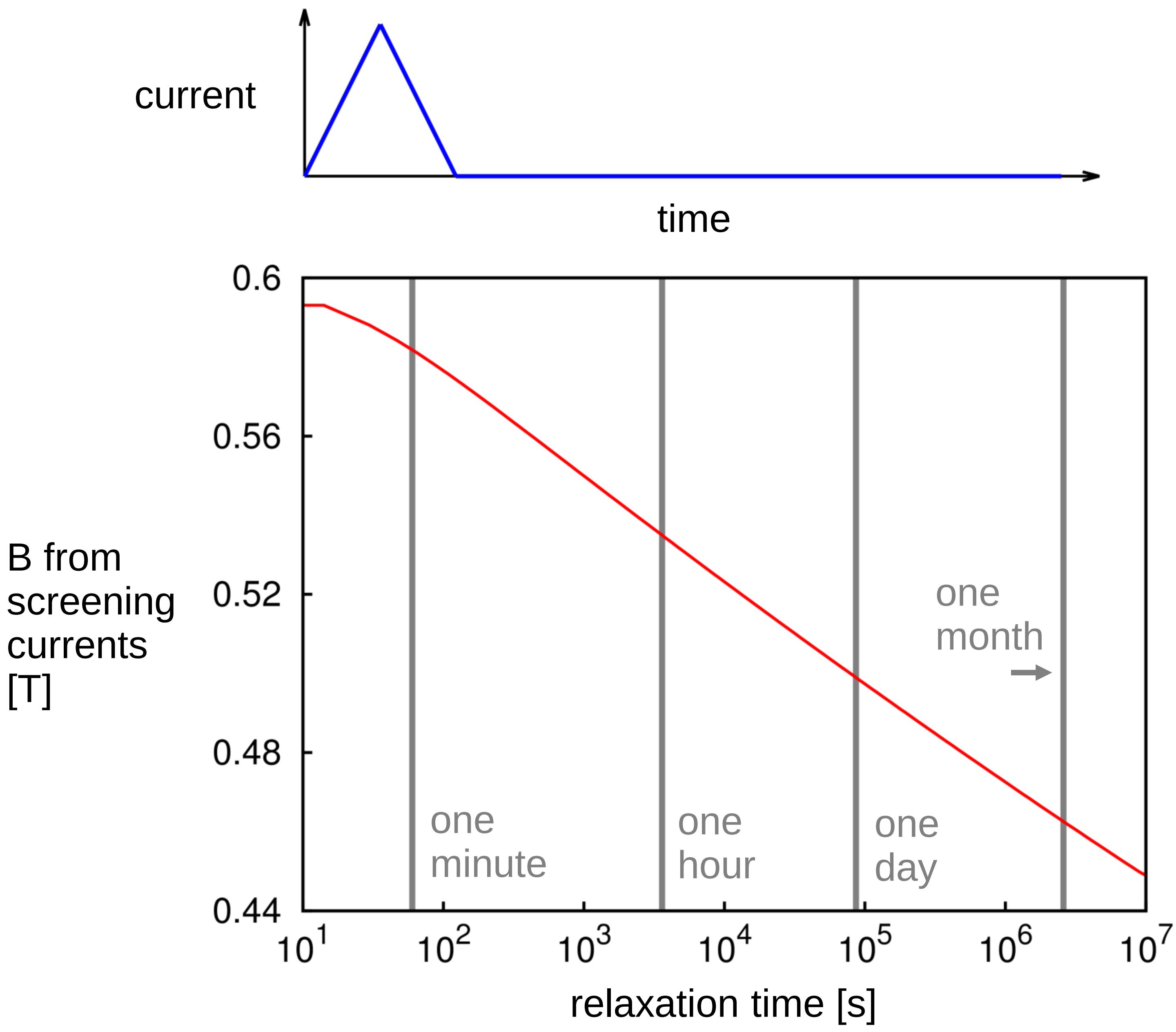
# Stationary state after several cycles





current
time

# Important change after relaxation

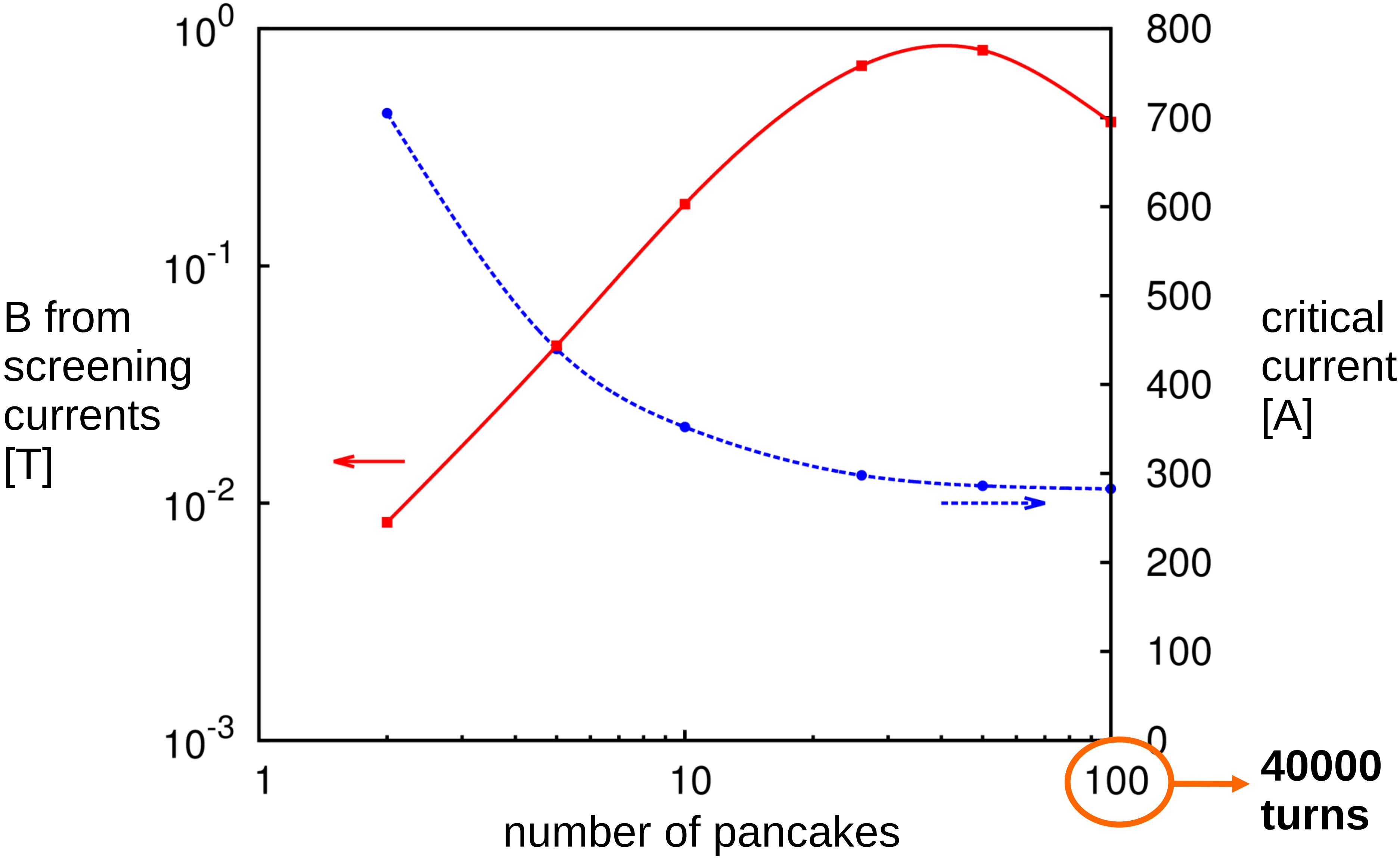



after one day:

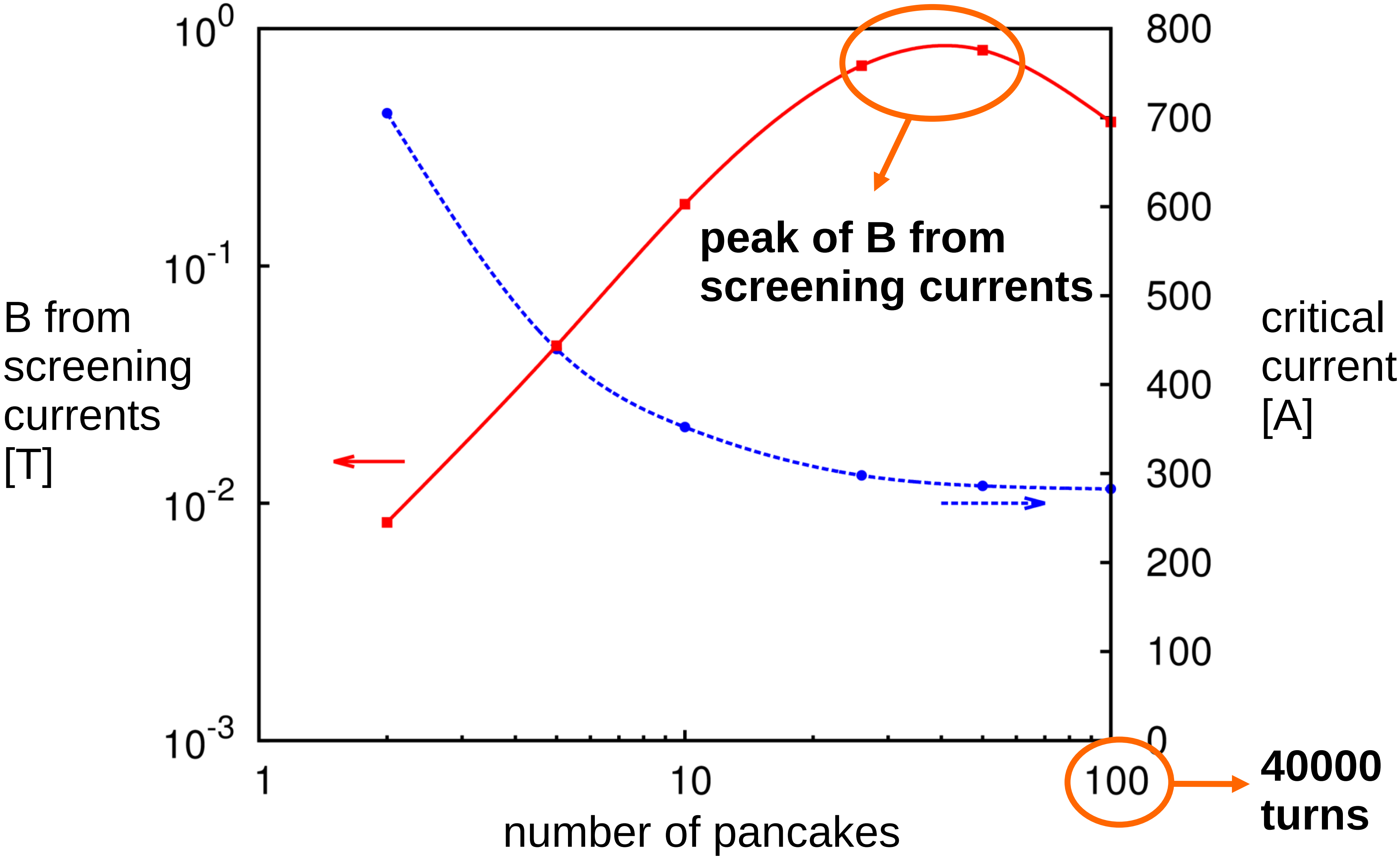
**15 % change**

**0.6 % change**
**compared to**
**total magnetic field**

# Dependence on number of pancakes



# Dependence on number of pancakes



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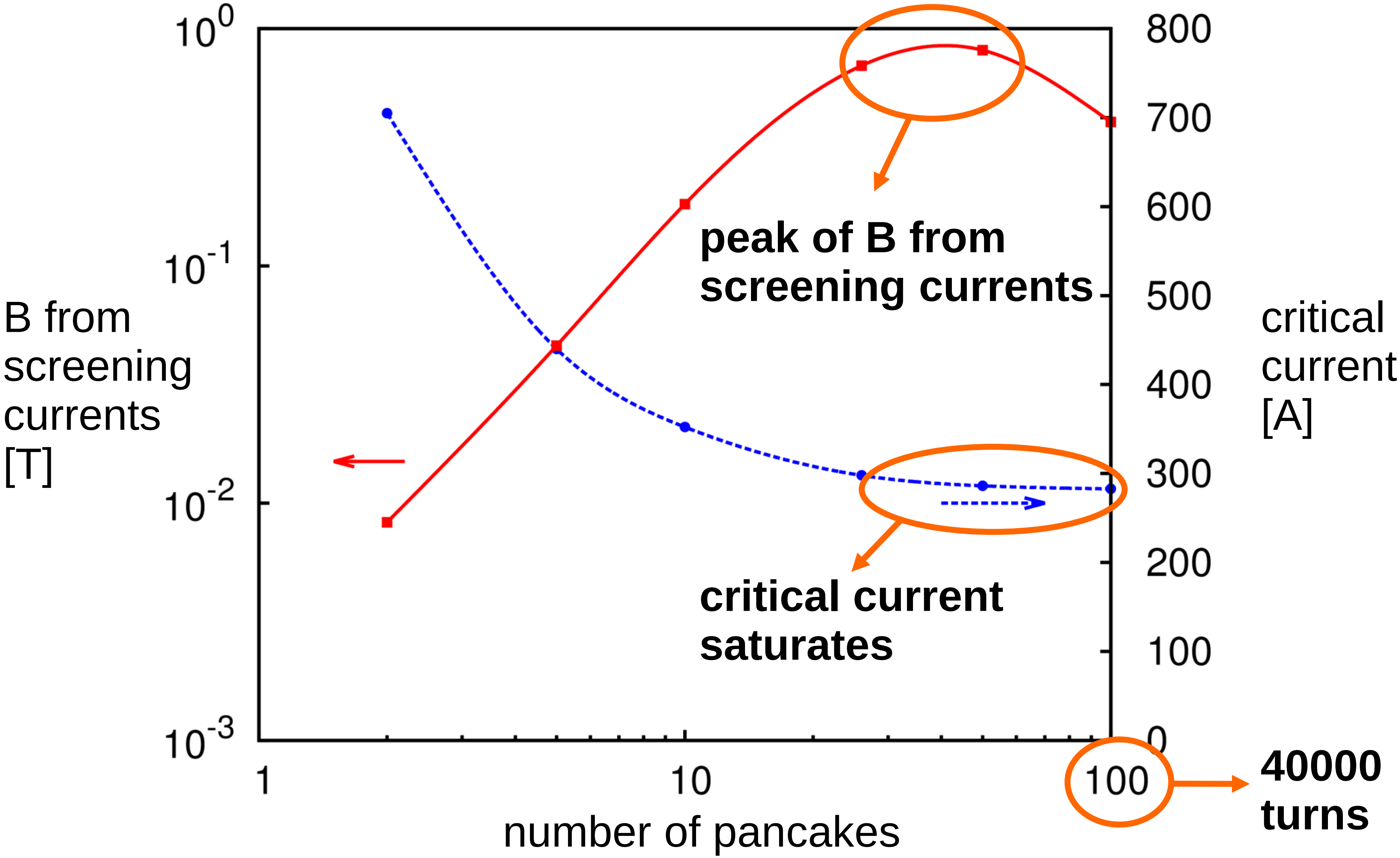


**Model**

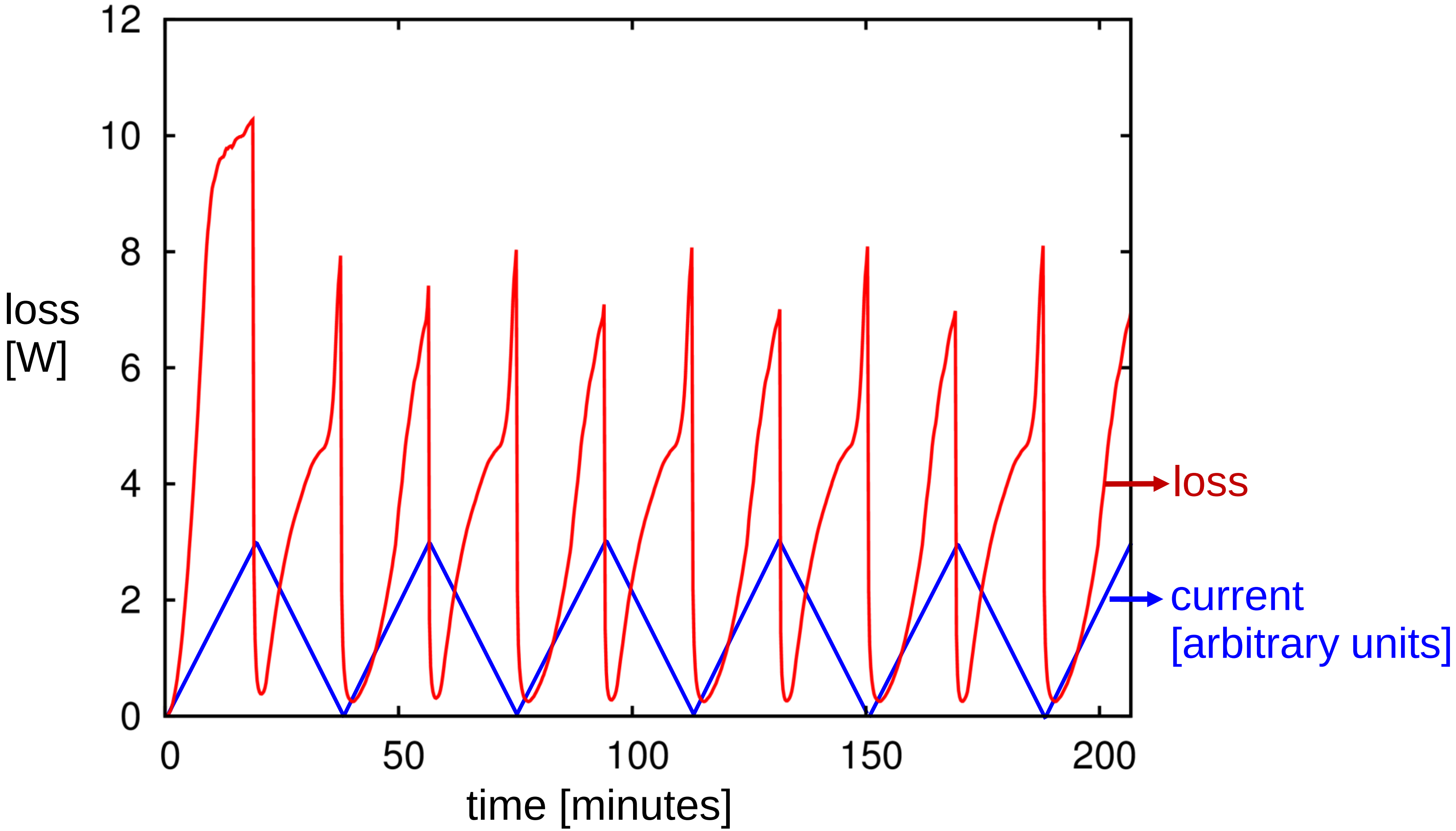
**Validation with experiments**

**Magnet-size coils**

- Screening currents
- Magnetic field distortion
- AC loss

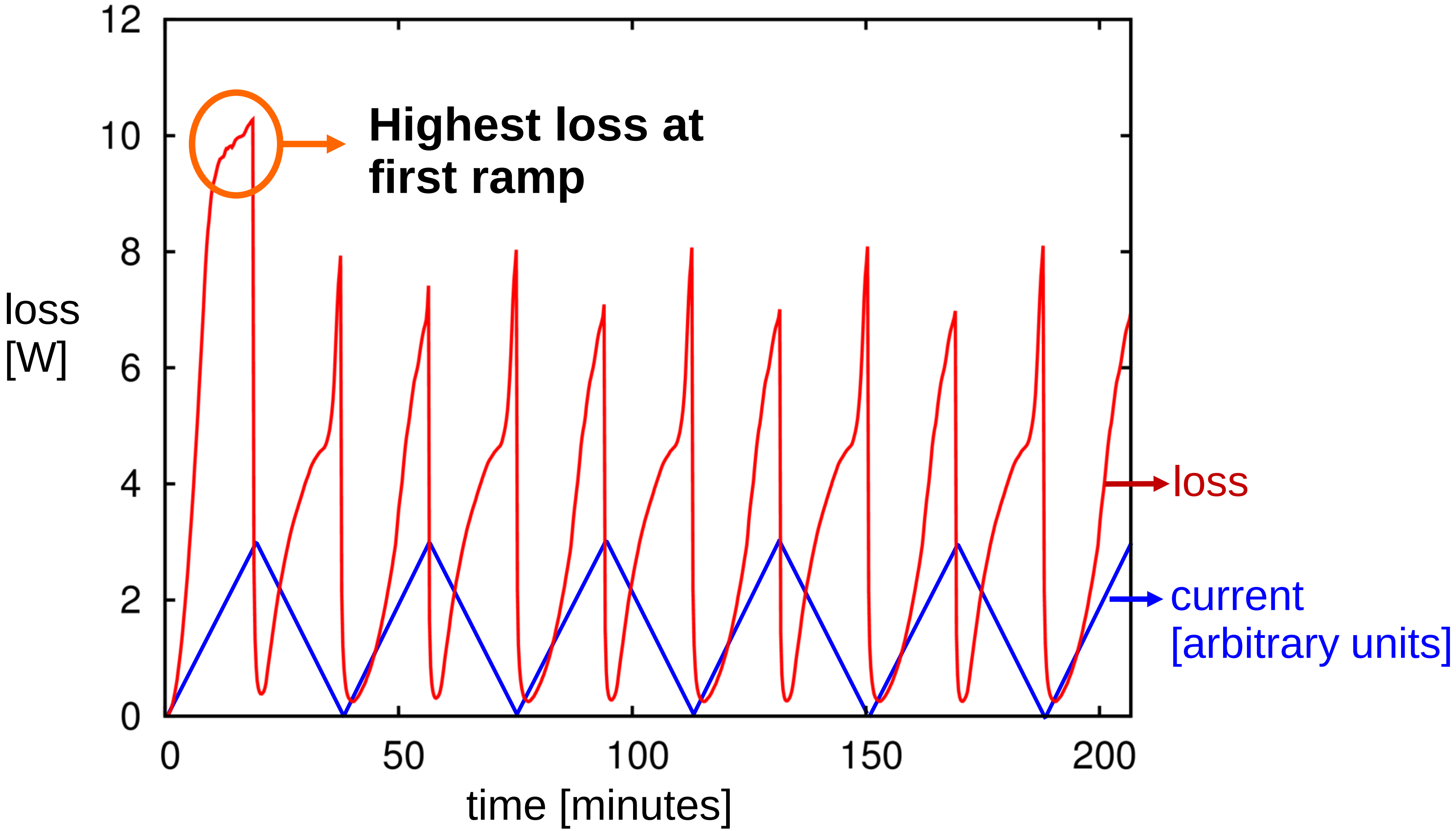
**3D modelling**

# Power loss



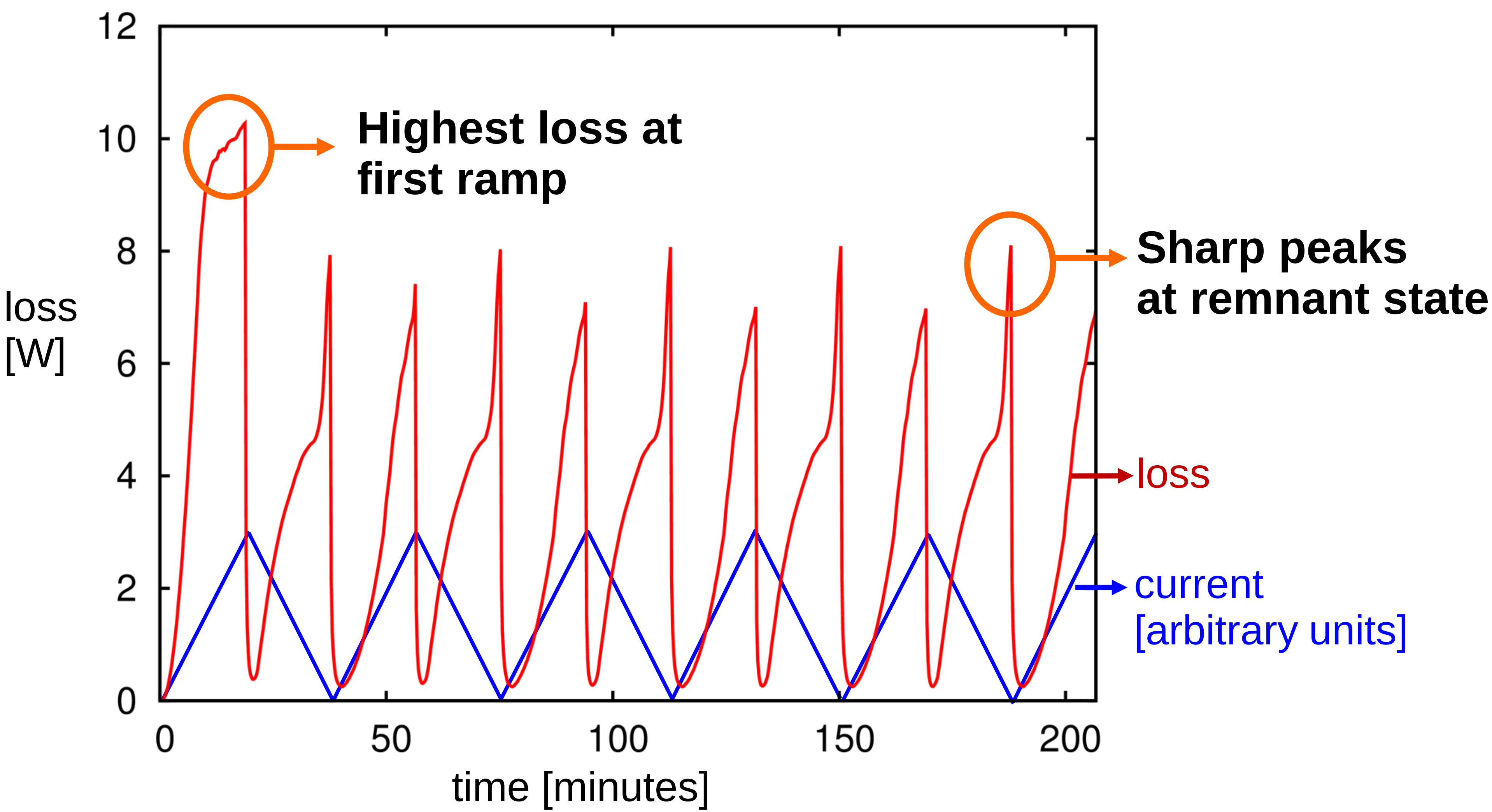
loss
[W]
12
10
8
6
4
2
0
0
50
100
150
200
time [minutes]
loss
current
[arbitrary units]

# Power loss



Highest loss at
first ramp
loss
[W]
12
10
8
6
4
2
0
0
50
100
150
200
time [minutes]
loss
current
[arbitrary units]

# Power loss



12
10
8
6
4
2
0
loss
[W]
0
50
100
150
200
time [minutes]
Highest loss at
first ramp
Sharp peaks
at remnant state
loss
current
[arbitrary units]

**Model**

**Validation with experiments**

**Magnet-size coils**

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- AC loss

**3D modelling**

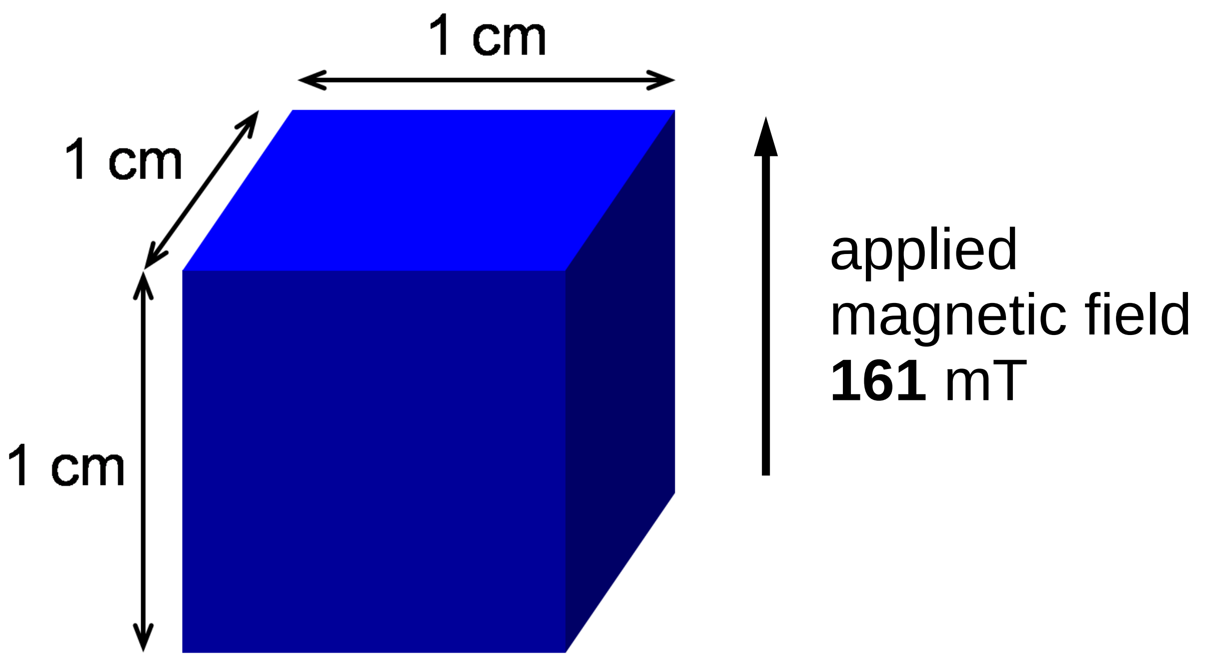
# Parameters

Isotropic power-law **E(J)** relation

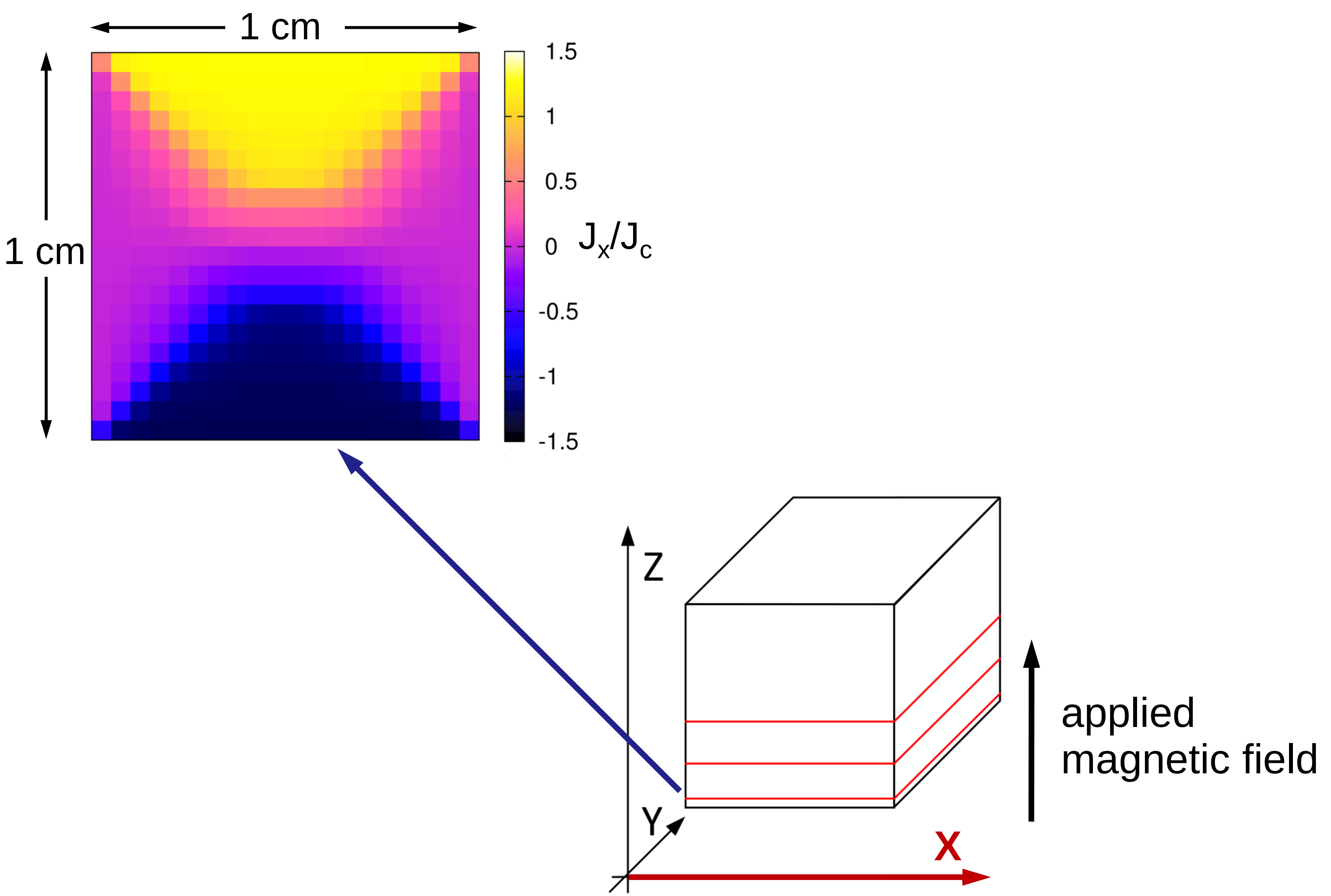
$$\mathbf{E}(\mathbf{J}) = E_c \left( \frac{|\mathbf{J}|}{J_c} \right)^N \frac{\mathbf{J}}{|\mathbf{J}|}$$

$J_c = 10^8$ A/m$^2$

**N=30**



# Current density: x component



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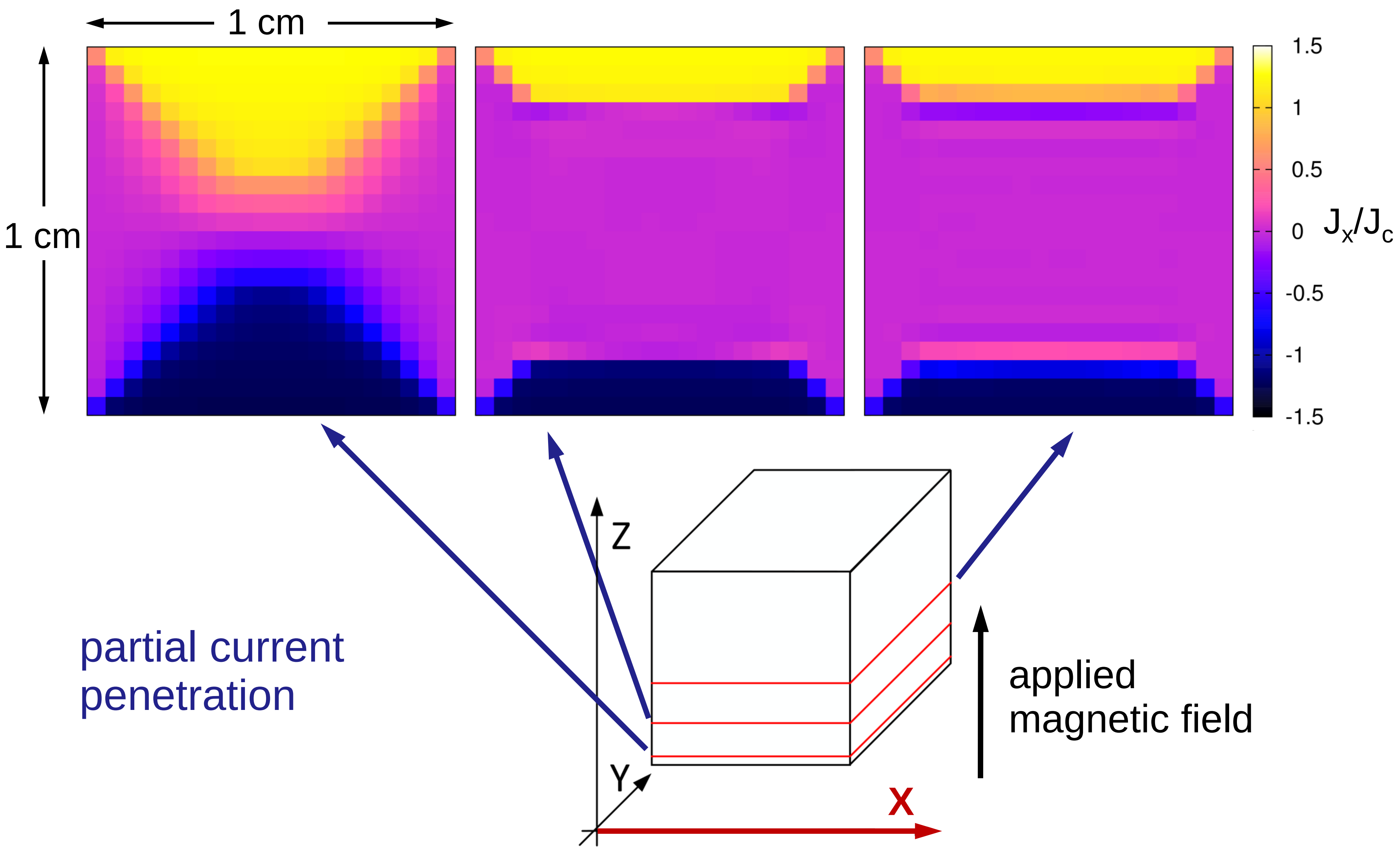
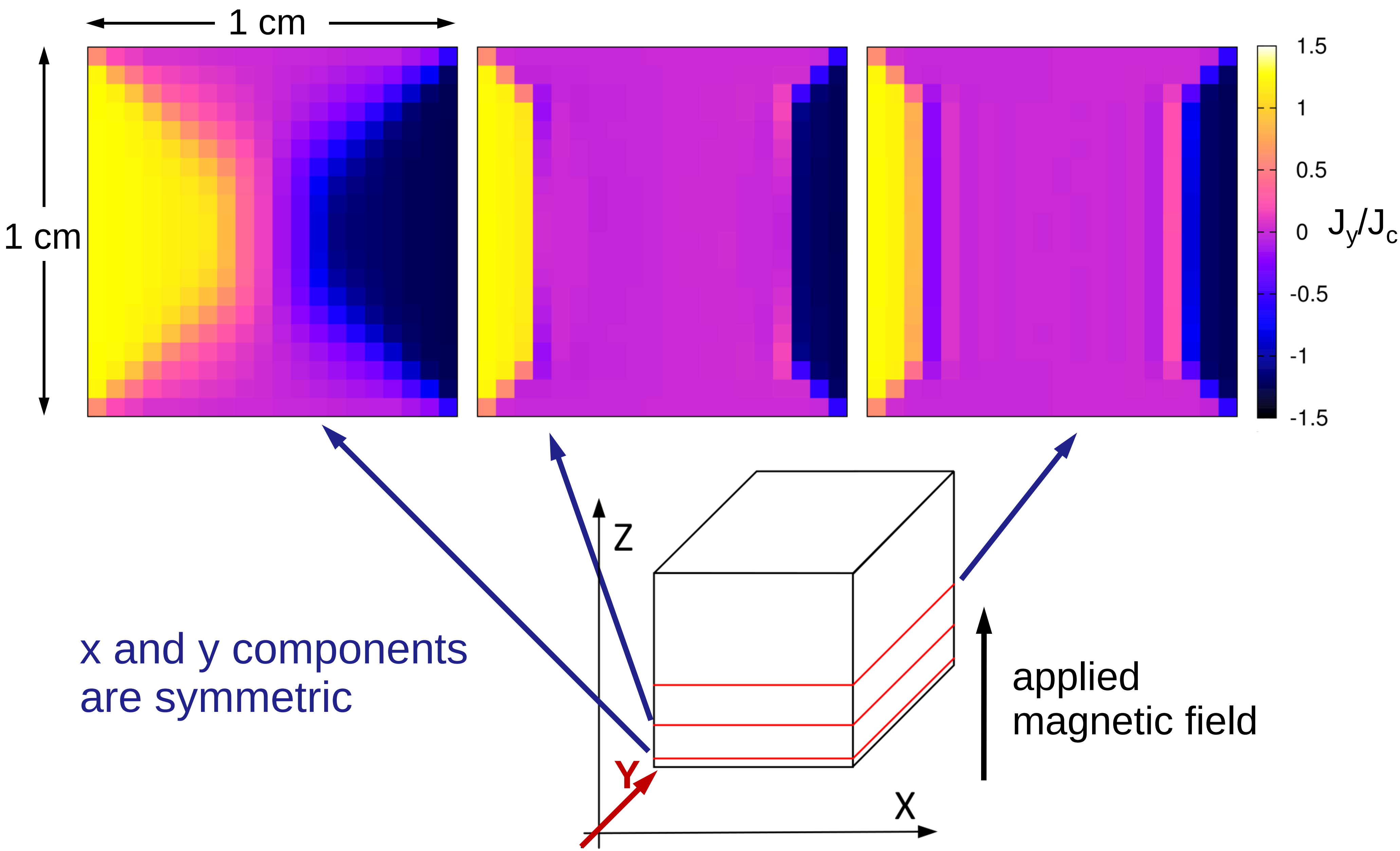


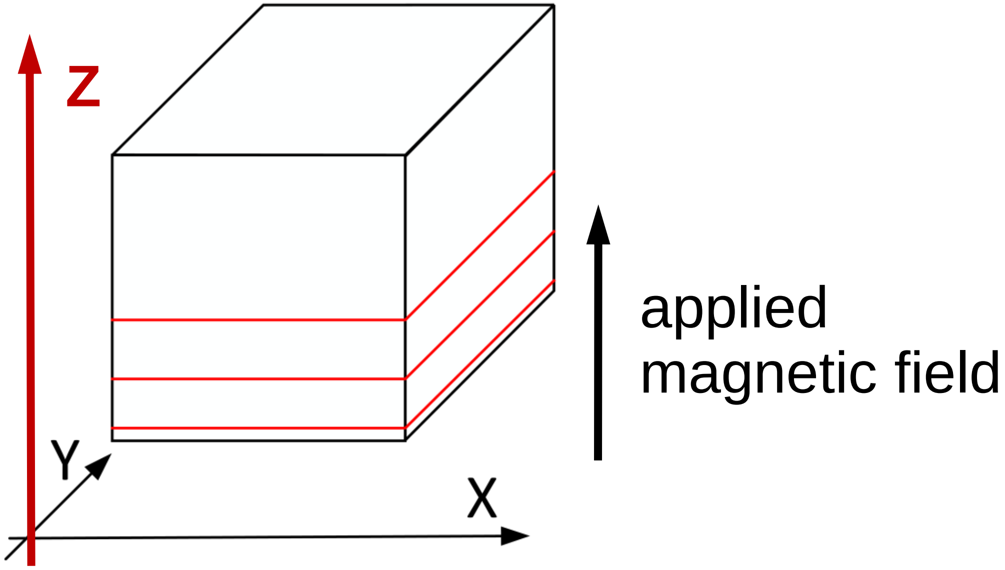

partial current penetration

# Current density: y component

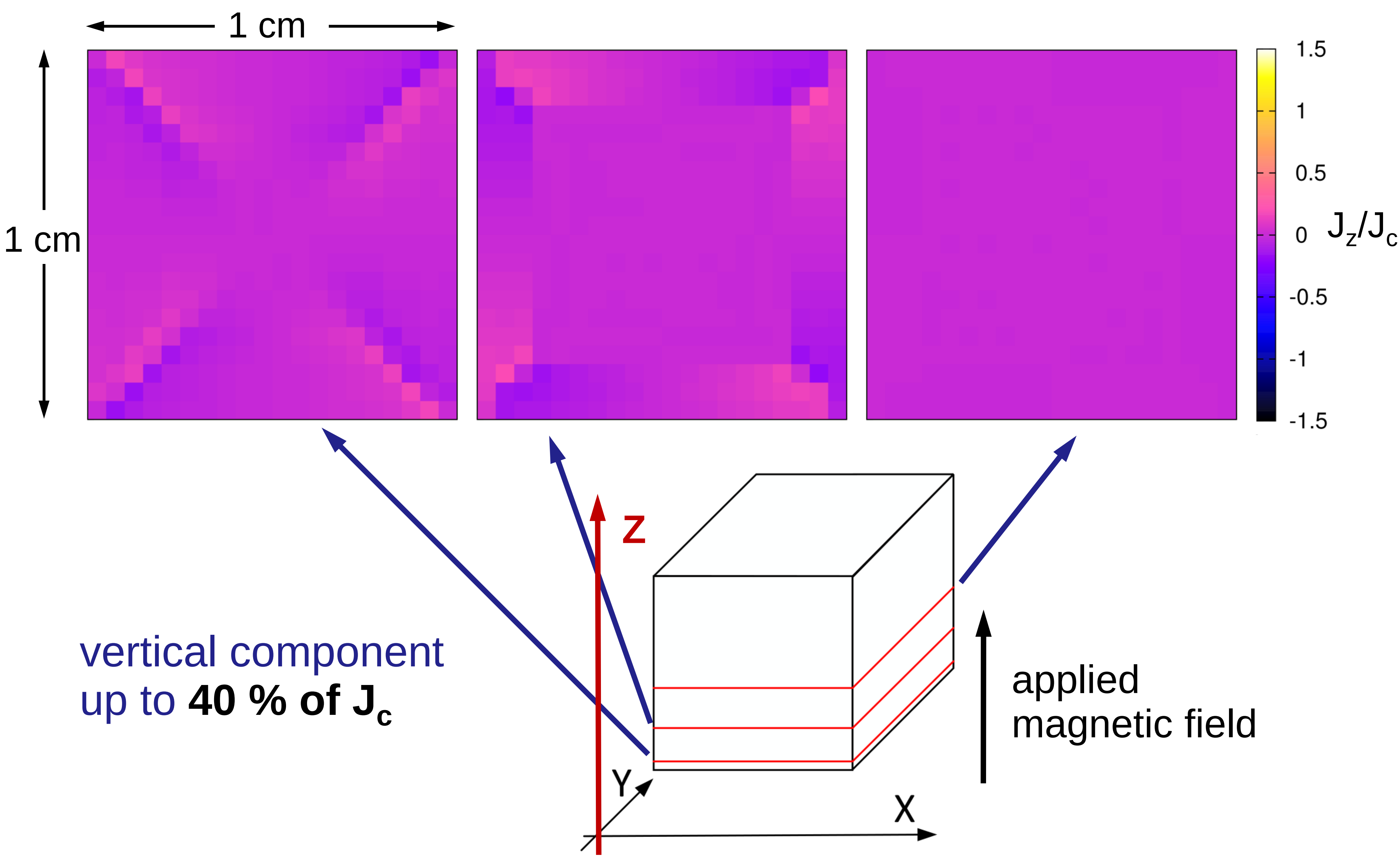



x and y components
are symmetric

# Is there vertical component?



# There is current with vertical component




vertical component
up to **40 % of $J_c$**

# Conclusions

# 3D model

## Superconducting cube in applied field

**First 3D solution by a variational principle**

**Significant current density in applied field direction**

# 3D model

Superconducting cube in applied field

**First 3D solution by a variational principle**

**Significant current density in applied field direction**

**Possible to model stacks of tapes**

# 3D model

Superconducting cube in applied field

**First 3D solution by a variational principle**

**Significant current density in applied field direction**

**Possible to model stacks of tapes**

**High potential for complex situations**

Once optimised
like the axi-symmetric model

# Modelling and measurement of coils

Constructed coil with

**670** turns

**500** m of tape

# Modelling and measurement of coils

Constructed coils up to

**670** turns

**500** m of tape

**Measured AC loss** by

electrical means

boil-off methods

# Modelling and measurement of coils

Constructed coil with

- **670** turns
- **500** m of tape

**Measured AC loss** by

- electrical means
- boil-off methods

**Modelling agrees with experiments**

**Loss dominated by average in-field critical current of the tape**

# Modelling of coils with many turns

Time efficient method allows modelling:

**Up to 10000 turns with no approximation**

**Up to 40000 turns with continuous approximation**

# Modelling of coils with many turns

Time efficient method allows modelling:

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- **Up to 40000 turns with continuous approximation**

Fulfills requirements for:

- **Transformers**
- **High-field magnets**
- **SMES**

# Modelling of coils with many turns

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**High-field magnets**

**SMES**

# Modelling of coils with many turns

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Further possible situations:

**HTS magnet as insert coil**

**Partial charge or discharge of magnet or SMES**

# Modelling of coils with many turns

Further possible situations:

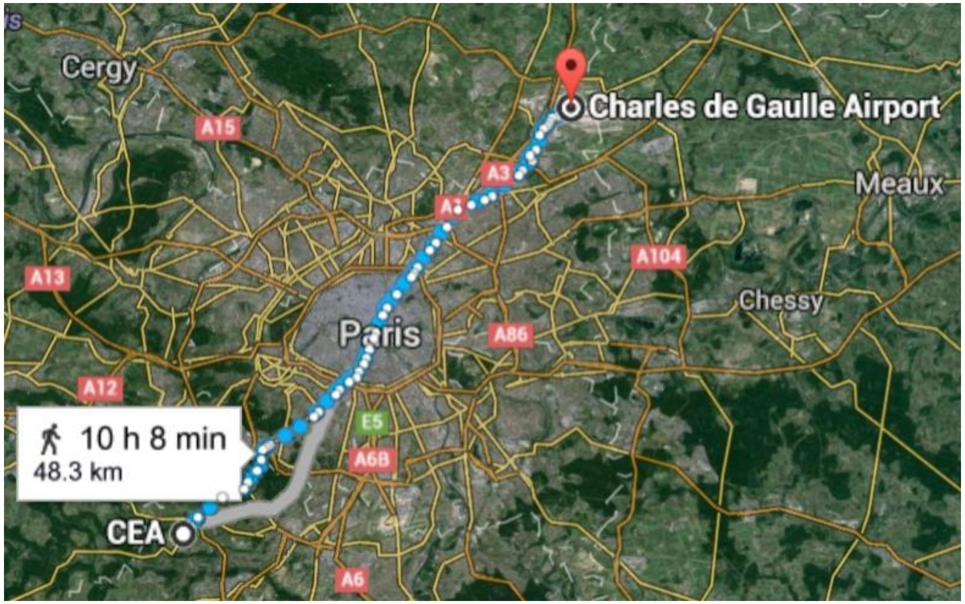
**HTS magnet as insert coil**

**Partial charge or discharge of magnet or SMES**

**Looking forward to collaborating with you!**

# How far can you go in 10 hours?

on foot




to the airport (luckily)

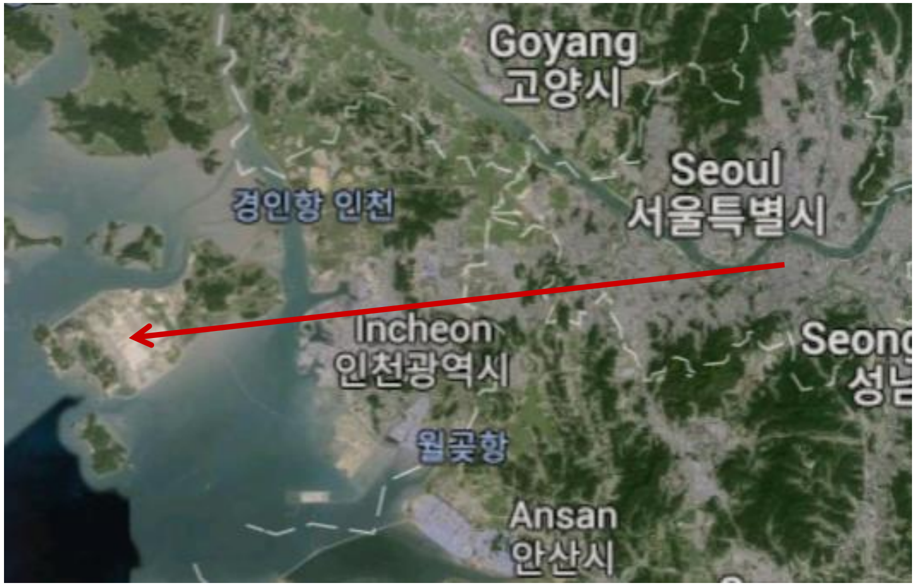
by plane

almost the whole World

**Faster transportation opened new possibilities**

# How far can you go in 10 hours?

on foot




to the airport (luckily)

by plane

almost the whole World

**No need to go so far for lunch!**

**Thank you**
**for your attention!**

# Would you like to know more?

# Stack of pancakes with maximum energy

## Optimization of 3 parameters

Repeat until no change

**Find maximum energy by changing:**

1. External radius
2. Turn separation
3. Pancake separation

**Constrains**

Total tape length: **500 m**

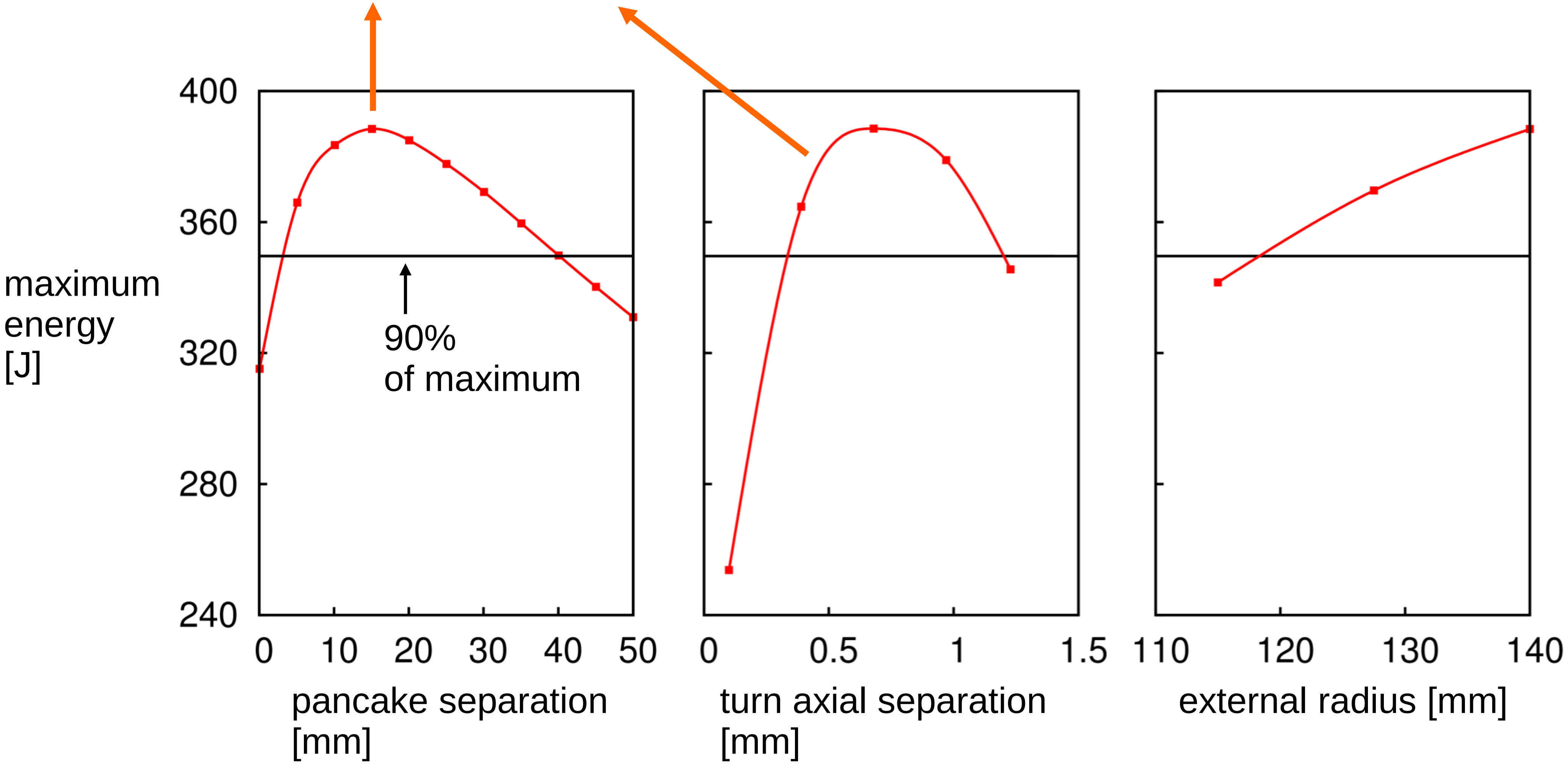
Maximum external radius: 14 cm

Minimum internal radius: 1.5 cm

Maximum tape length in pancake: 50 m

# Optimum values

**wide peak in turns and pancake separations** ⇒ **good for coil construction**



# Functional minimization for J

E Pardo et al. 2015 SuST

## Equation

$$\mathbf{E} = -\dot{\mathbf{A}} - \nabla\phi$$

# Functional minimization for J

E Pardo et al. 2015 SuST

Equation

$$\mathbf{E} = -\dot{\mathbf{A}} - \nabla\phi$$

is the Euler-Lagrange equation of

$$\mathbf{L}_J = \int_V \left( \frac{1}{2}\Delta\mathbf{J} \cdot \frac{\Delta\mathbf{A}_{SJ}}{\Delta t} + \Delta\mathbf{J} \cdot \frac{\Delta\mathbf{A}_a}{\Delta t} + U(\mathbf{J}) + \nabla\phi \cdot \Delta\mathbf{J} \right) dV$$

# Functional minimization for J

E Pardo et al. 2015 SuST

Equation

$$\mathbf{E} = -\dot{\mathbf{A}} - \nabla\phi$$

is the Euler-Lagrange equation of

$$\mathbf{L}_J = \int_V \left( \frac{1}{2}\Delta\mathbf{J} \cdot \frac{\Delta\mathbf{A}_{SJ}}{\Delta t} + \Delta\mathbf{J} \cdot \frac{\Delta\mathbf{A}_a}{\Delta t} + U(\mathbf{J}) + \nabla\phi \cdot \Delta\mathbf{J} \right) dV$$

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

Term with the material **E(J)** relation

# Functional minimization for J

E Pardo et al. 2015 SuST

Equation

$$\mathbf{E} = -\dot{\mathbf{A}} - \nabla\phi$$

is the Euler-Lagrange equation of

$$\mathbf{L}_J = \int_V \left( \frac{1}{2}\Delta\mathbf{J} \cdot \frac{\Delta\mathbf{A}_{SJ}}{\Delta t} + \Delta\mathbf{J} \cdot \frac{\Delta\mathbf{A}_a}{\Delta t} + U(\mathbf{J}) + \nabla\phi \cdot \Delta\mathbf{J} \right) dV$$

For given scalar potential,
we obtain **J** by minimizing the functional

# Functional minimization for J

E Pardo et al. 2015 SuST

Equation

$$\mathbf{E} = -\dot{\mathbf{A}} - \nabla\phi$$

is the Euler-Lagrange equation of

scalar potential

$$\mathbf{L}_J = \int_V \left( \frac{1}{2}\Delta\mathbf{J} \cdot \frac{\Delta\mathbf{A}_{SJ}}{\Delta t} + \Delta\mathbf{J} \cdot \frac{\Delta\mathbf{A}_a}{\Delta t} + U(\mathbf{J}) + \nabla\phi \cdot \Delta\mathbf{J} \right) dV$$

For given scalar potential,
we obtain **J** by minimizing the functional

**How to obtain the scalar potential?**

# Functional minimization for the charge density

The continuity equation

$$\nabla \cdot \mathbf{J} + \dot{q} = 0$$

# Functional minimization for the charge density

The continuity equation

$$\nabla\cdot\mathbf{J} + \dot{q} = 0$$

is the Euler-Lagrange equation of

$$\mathbf{L}_q = \int_V \left( \frac{1}{2}\Delta q \cdot \Delta\phi - \nabla\phi \cdot (\mathbf{J}_0 + \Delta\mathbf{J}) \right) dV$$

Given **J**,
we obtain charge density by minimizing functional

**We minimize both functionals iteratively**

# Minimum Electro-Magnetic Entropy Production (MEMEP)

[Pardo et al. 2015 SuST, April]

Self-programmed code

Computes detailed current density

Does no need to mesh the air

**Very fast**

**Very low RAM memory**

**Can use any vector E(J) relation**

This talk:

$$\mathbf{E}(\mathbf{J}) = E_c \left( \frac{|\mathbf{J}|}{J_c} \right)^N \frac{\mathbf{J}}{|\mathbf{J}|}$$

# 3D variational principle

We find **J** by minimizing functional

$$\mathbf{L}_J = \int_V \left( \frac{1}{2} \Delta\mathbf{J} \cdot \frac{\Delta\mathbf{A}_{SJ}}{\Delta t} + \Delta\mathbf{J} \cdot \frac{\Delta\mathbf{A}_a}{\Delta t} + U(\mathbf{J}) + \nabla\phi \cdot \Delta\mathbf{J} \right) dV$$