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Invited poster presentation 3A-LS-O1.8 given at EUCAS 2015; Lyon, France, September 6 – 10, 2015.
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3D modeling and measurement of coupling AC loss in soldered tapes and striated coated conductors

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3A-LS-O1.8

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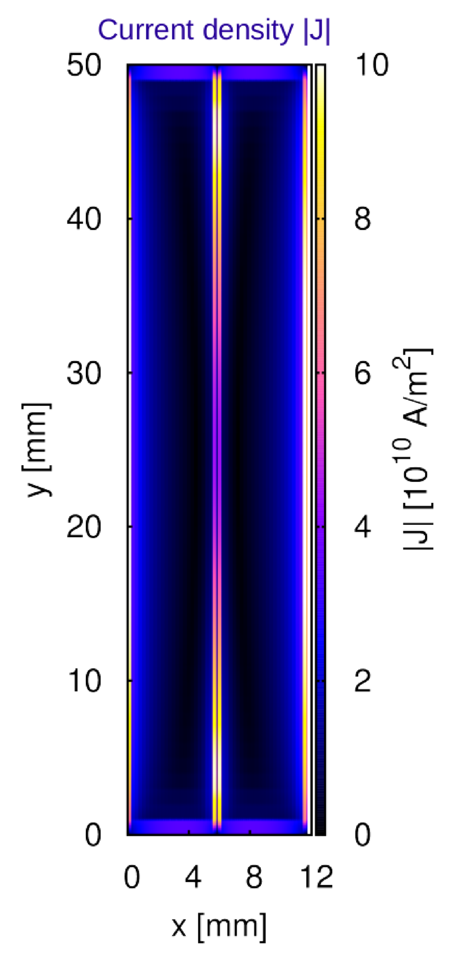
Introduction

Coated conductors experience high AC loss
Striation reduces hysteresis loss
There appear coupling loss

Measurements of AC loss in striated and soldered tapes



Linear model

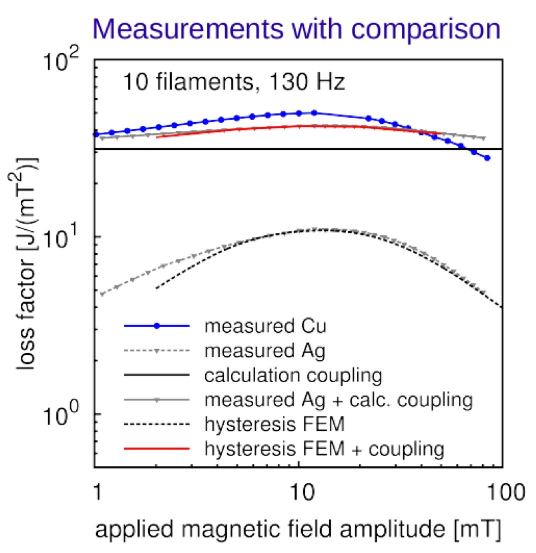
assumes linear materials
zero resistivity in superconductor
calculates J and q in steady state

Basic equations:

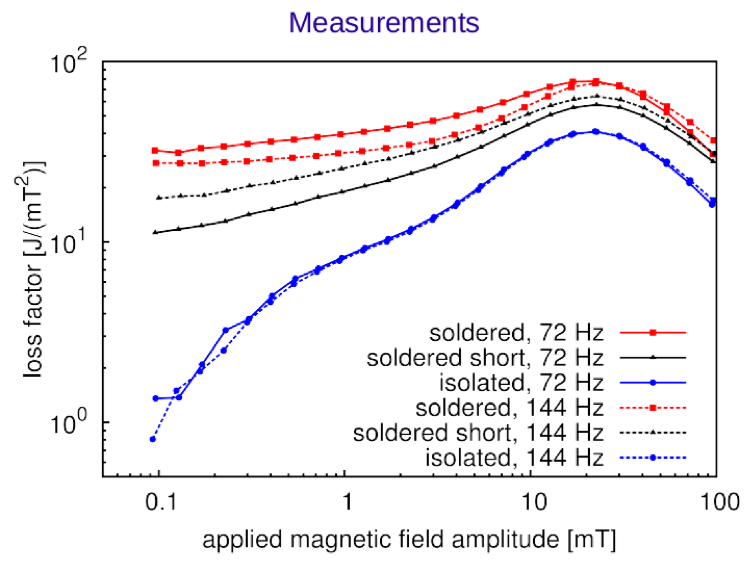
$$\rho\mathbf{J} = -\dot{\mathbf{A}} - \nabla\phi$$

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

charge density



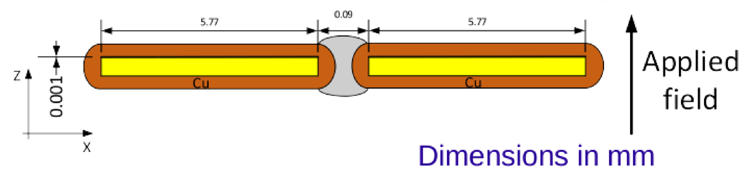
Cross section of striated tapes



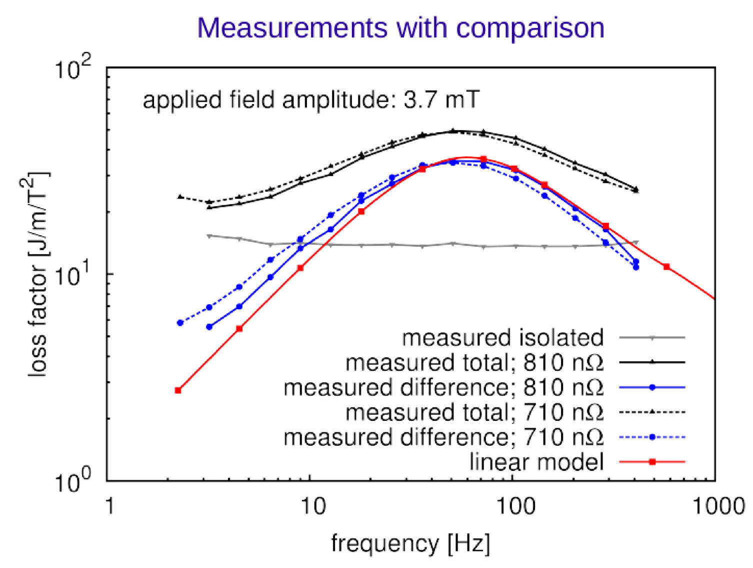
Soldered tapes

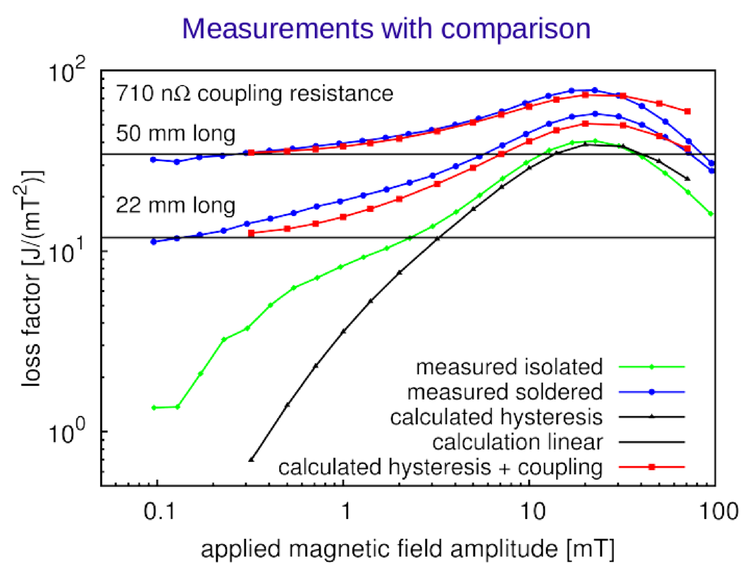
6 mm	widht, two soldered tapes (SuperPower)
50 mm	lenght
1 μm	superconductor thickness
J_c	2.72×10^{10} A/m^2 I_c =157 A
ρ	39.4×10^{-11} Ωm (linear material)

Cross section of soldered tapes



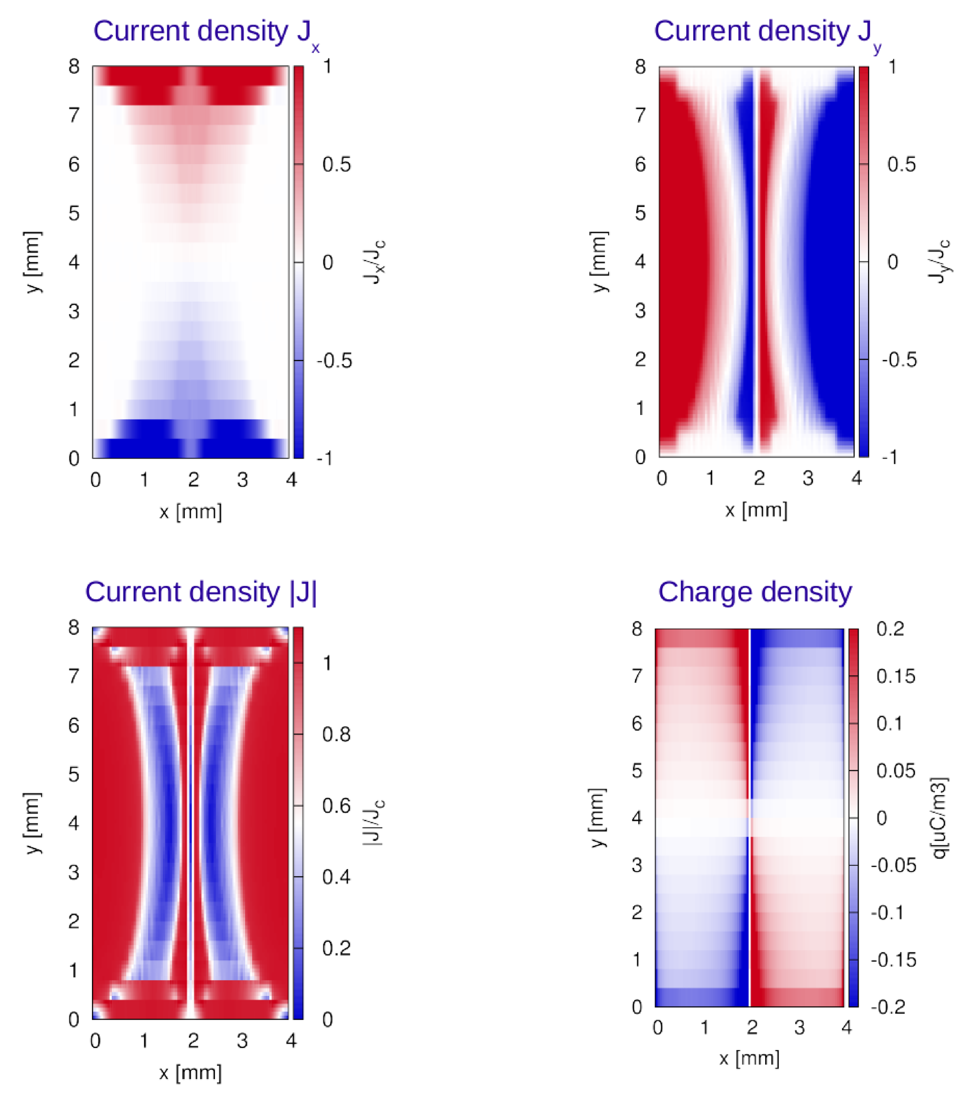
Dimensions in mm





Comparison of two calculation methods

MEMEP – minimum electro-magnetic entropy production

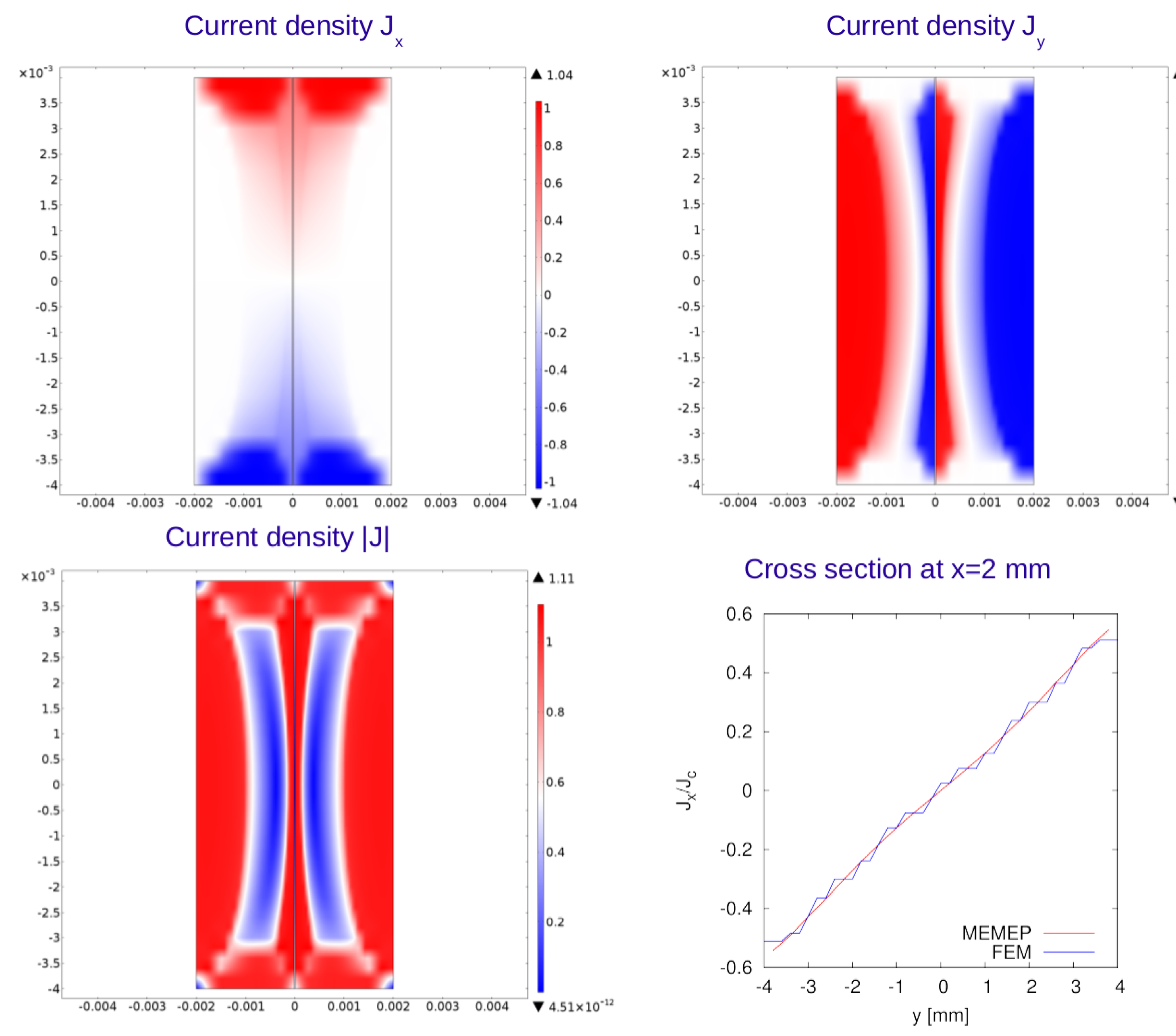


3D modeling based on minimum electro-magnetic entropy production (MEMEP)

Isotropic power law

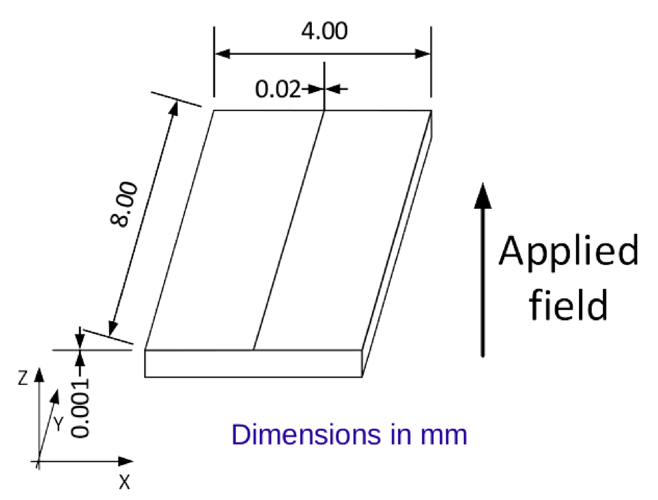
$$\mathbf{E}(\mathbf{J}) = E_c\left(\frac{|\mathbf{J}|}{J_c}\right)^N \frac{\mathbf{J}}{|\mathbf{J}|}$$

FEM – finite element method



Geometry of simulations:

4x8mm	tape with two striations
1 μm	thickness
20 μm	width of linear material at striation
Frequency	50 Hz
B_{Amax}	20 mT
J_c	3×10^{10} A/m^2
$\rho_{effective}$	2.4×10^{-11} Ωm (20μm linear material)
N	30



Dimensions in mm

CONCLUSION

Model for linear materials agrees with measurements at low amplitudes

At low frequencies (few Hz) soldered tapes present low coupling losses: important for magnets

MEMEP simulations agree with FEM

MEMEP requires further development for long samples

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3D electromagnetic modeling of practical superconductors for power applications

3A-LS-O1.8

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Introduction

Current has 3D behavior
Computation volume restricted to superconductor volume

3D formulation

Vector and scalar potential

Coulomb's gauge

$$\mathbf{E} = -\dot{\mathbf{A}} - \nabla\phi \qquad \nabla\cdot\mathbf{A} = 0$$

charge density

$$\nabla\cdot\mathbf{E} = \frac{q}{\epsilon_0}$$

$$\Phi(\mathbf{r}) = \frac{1}{4\pi\epsilon_0}\int_{V'}\frac{q(\mathbf{r})}{|\mathbf{r}-\mathbf{r}'|}dV'$$

$$\nabla\times\mathbf{B} = \mu_0\mathbf{J} + \frac{\dot{\mathbf{E}}}{c^2}$$

$A_s(\mathbf{r})$

$$\mathbf{A}(\mathbf{r}) = \frac{\mu_0}{4\pi}\int_{V'}\frac{\mathbf{J}(\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|}dV' + \frac{1}{4\pi c^2}\int_{V'}\frac{\dot{\mathbf{E}}(\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|}dV'$$

Low frequencies: Neglect terms with second derivatives of E and B (no electromagnetic radiation)

$$\text{(1)} \quad \mathbf{E} = -\dot{\mathbf{A}} - \nabla\phi \approx -\dot{\mathbf{A}}_S - \nabla\phi$$

$$\mathbf{B} = \nabla\times\mathbf{A} \approx \nabla\times\mathbf{A}_S$$

Continuity equation

$$\text{(2)} \quad 0 = \nabla\cdot\mathbf{A} = \nabla\cdot\mathbf{A}_S + \frac{\dot{\phi}}{c^2} \Leftrightarrow \nabla\cdot\mathbf{J} + \dot{q} = 0$$

For given **E**(**J**) relation, solving equations (1) and (2) same as minimizing (3) and (4)

A_s due to ΔJ; change in applied vector potential; $\mathbf{J}=(\mathbf{J}_0+\Delta\mathbf{J})$; $\mathbf{J}_0$: **J** at the beginning of time step

$$\text{(3)} \quad L_J = \int_V\left(\frac{1}{2}\Delta\mathbf{J}\cdot\frac{\Delta\mathbf{A}_{SJ}}{\Delta t} + \Delta\mathbf{J}\cdot\frac{\Delta\mathbf{A}_a}{\Delta t} + U(\mathbf{J}) + \nabla\phi\cdot\Delta\mathbf{J}\right)dV$$

$\Delta\mathbf{J}$ change in **J** in 1 time step

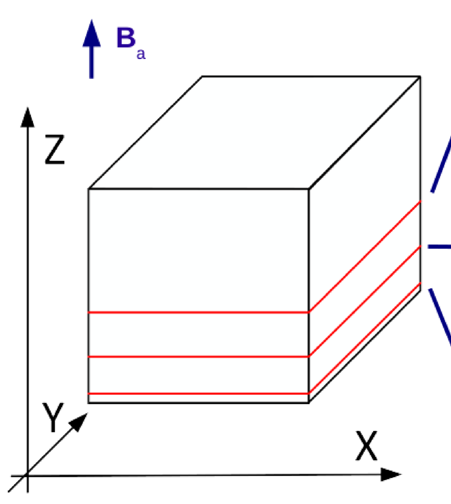
$$U(\mathbf{J}) = \int_0^{\mathbf{J}}\mathbf{E}(\mathbf{J}')\cdot d\mathbf{J}'$$

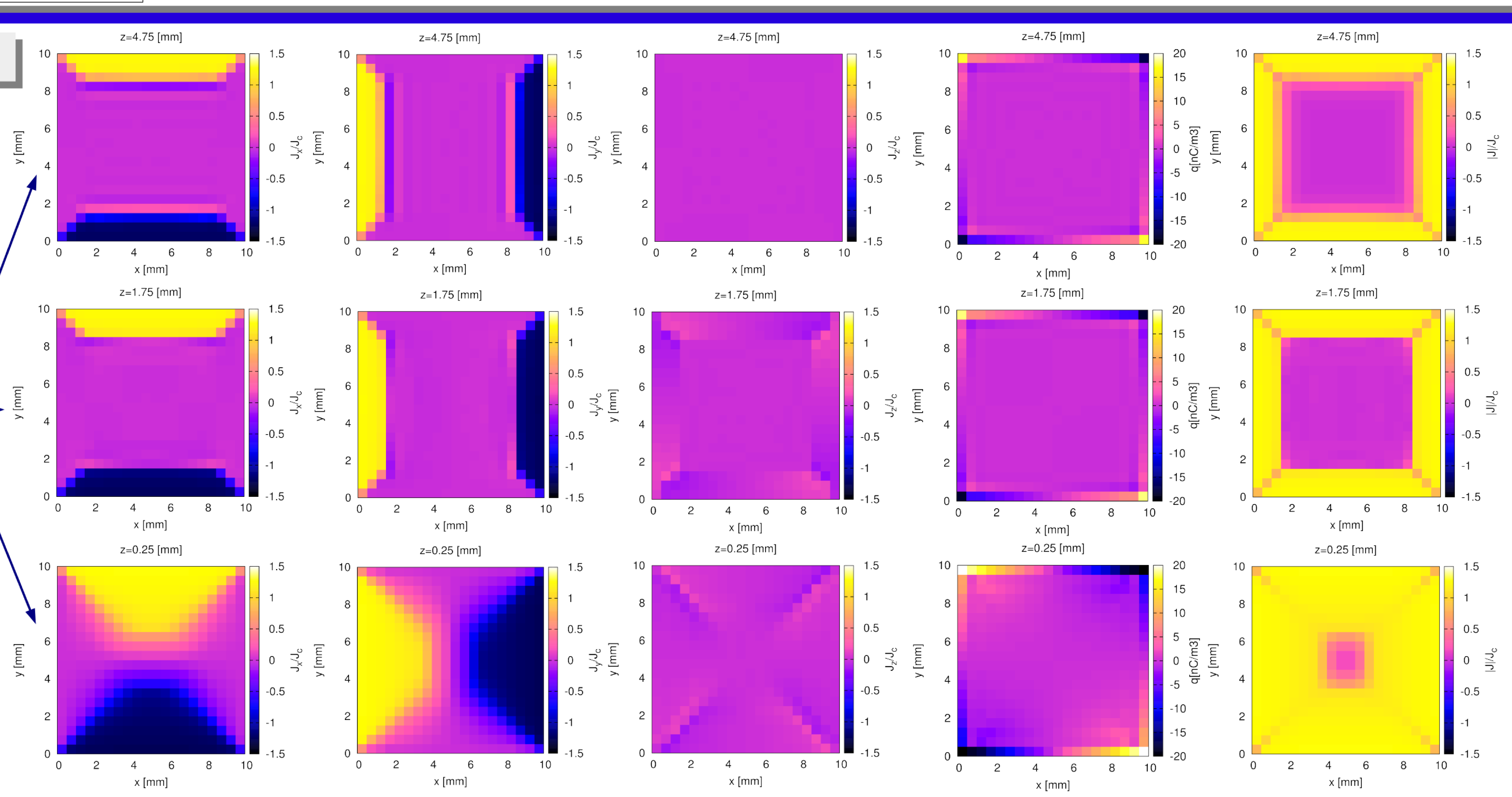
$$\text{(4)} \quad L_q = \int_V\left(\frac{1}{2\Delta t}\Delta q\cdot\Delta\phi - \nabla\phi\cdot(\mathbf{J}_0+\Delta\mathbf{J})\right)dV$$

change in q in 1 time step; $\phi=(\phi_0+\Delta\phi)$; ϕ_0: ϕ at the beginning of time step

3D solution

10x10x10	mm
Frequency	50 Hz
B_a	161 mT
J_c	10^8 A/m^2
N	30



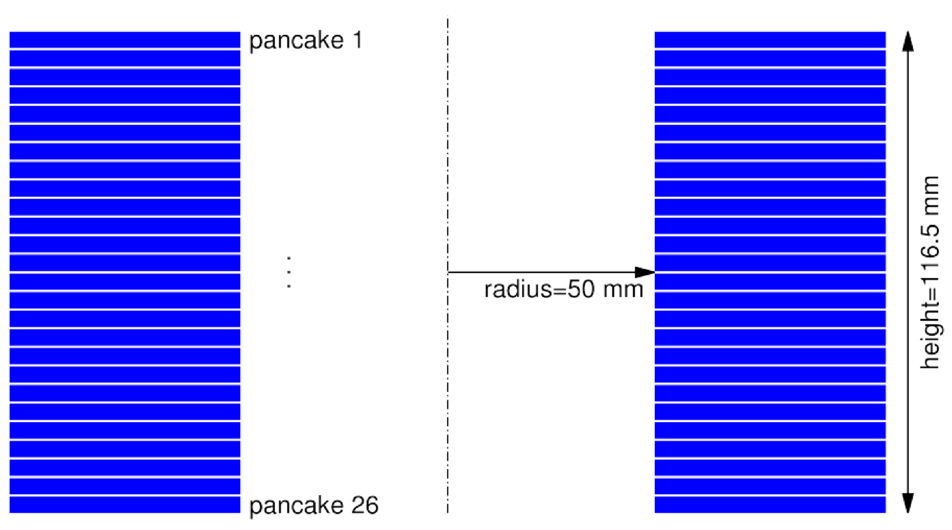


Isotropic power law

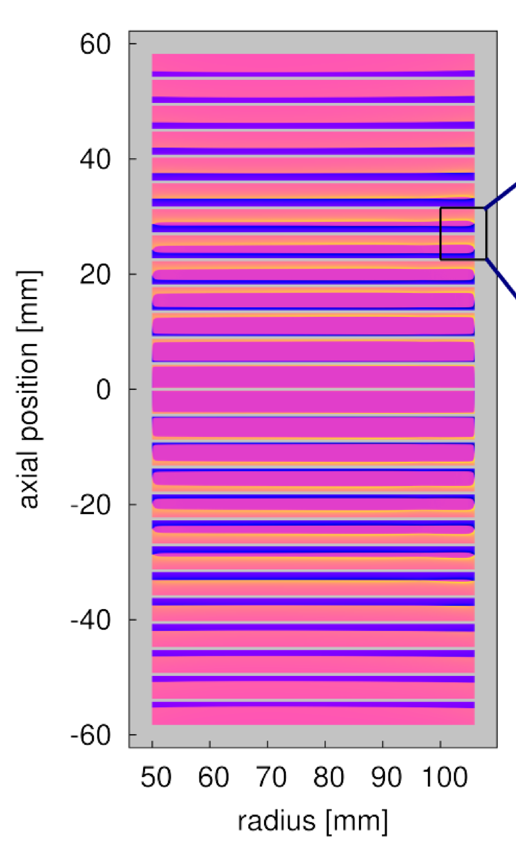
$$\mathbf{E}(\mathbf{J}) = E_c\left(\frac{|\mathbf{J}|}{J_c}\right)^N\frac{\mathbf{J}}{|\mathbf{J}|}$$

2D solution for coils

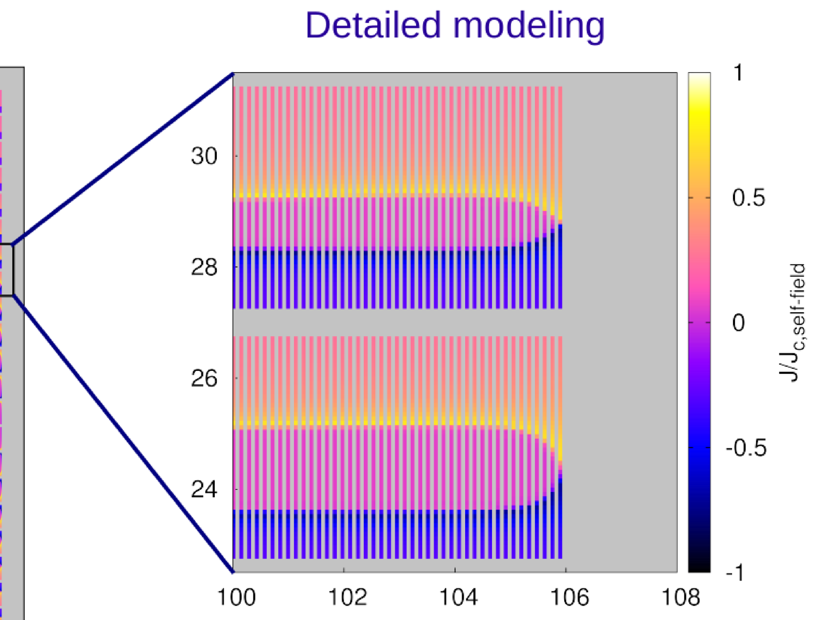
More than 10000 turns
Cross section of coil



Up to 40000 turns with continuous approximation



Detailed modeling

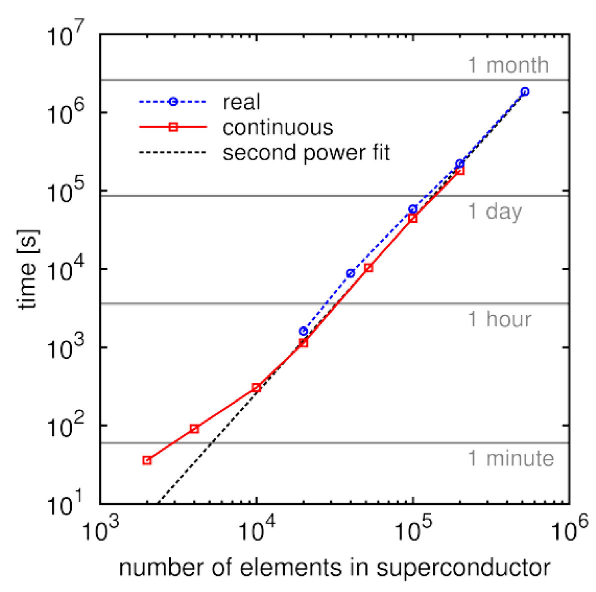


N=30

$J_c(\mathbf{B},\theta)$
from measurements
at 4.2 K up to 30 T

[DK Hilton et al SuST 28 (2015) 074002]

Calculation time



CONCLUSION

3D model has potential for fast calculations