Numerical models of HTS for AC loss computation: how far do we need to go?

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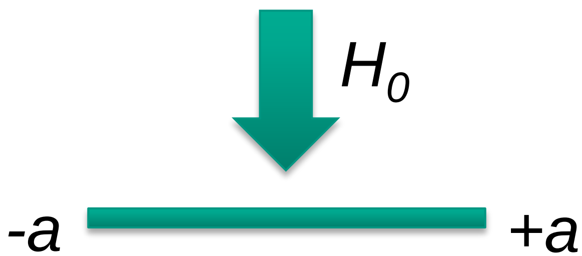
Outline

- Analytical models
  - Applicability and limitations
- Numerical models
  - Overview of the main different approaches
  - Examples of successful application of 2-D models
    - Simulation of realistic HTS devices
    - Comparison with experiments
  - 2-D solutions for 3-D problems
  - Full 3-D models
- Summary and conclusion

Analytical models

- Developed in the framework of the Critical State Model
- Widely used do to their simplicity
  - Example: magnetization losses of a thin superconducting tape



Ingredients:
•Tape's width *2a*
•Tape's critical current I_c
•Amplitude of external field H_0

$$J(y)=\begin{cases}\frac{2J_c}{\pi}\arctan\frac{cy}{(b^2-y^2)^{1/2}}, & |y|<b\\ J_c\,y/|y|, & b<|y|<a\end{cases}$$

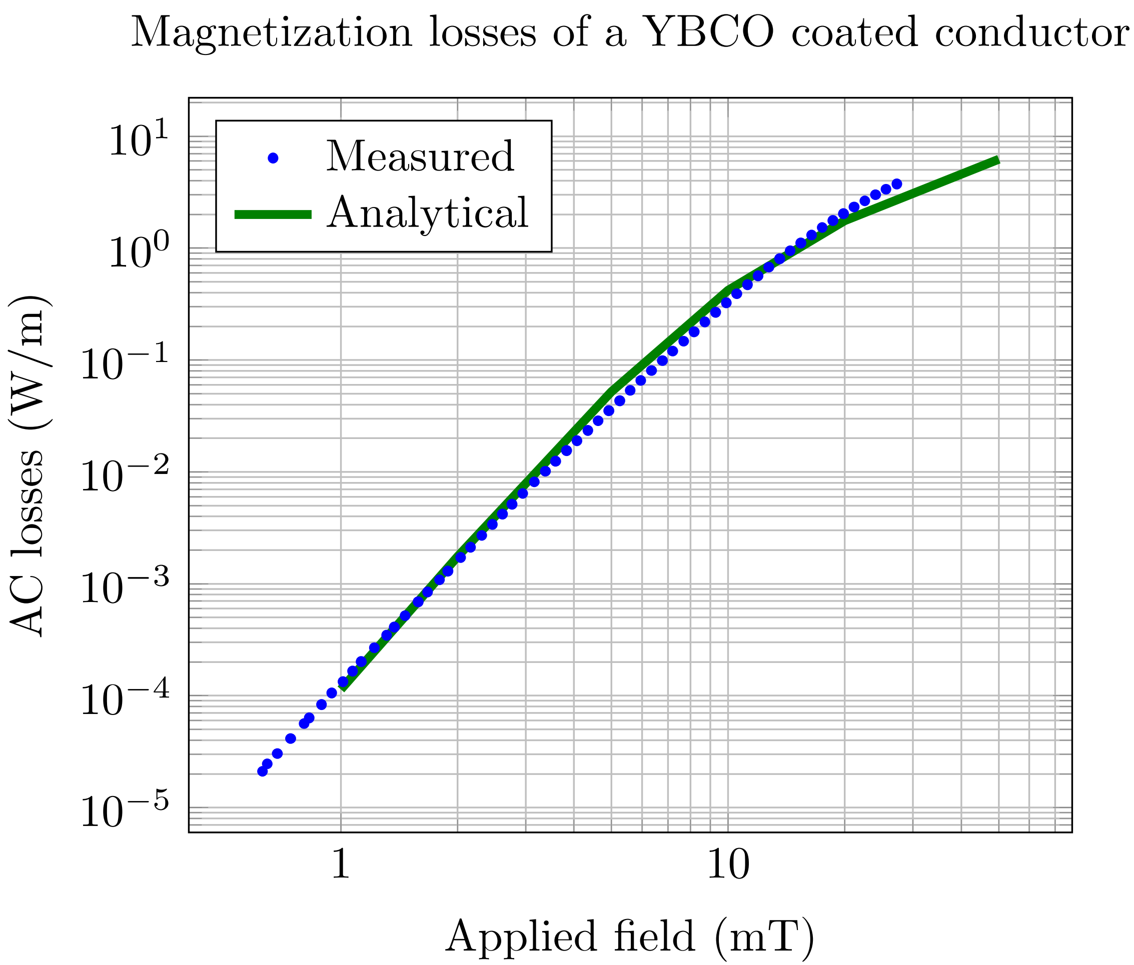
$$H(y)=\begin{cases}0, & |y|<b\\ H_c\,\mathrm{arctanh}\frac{(y^2-b^2)^{1/2}}{c\,|y|}, & b<|y|<a\\ H_c\,\mathrm{arctanh}\frac{c\,|y|}{(y^2-b^2)^{1/2}}, & |y|>a\end{cases}$$

$$P=\nu\mu_0\oint M(H_a)\,dH_a=4\nu\mu_0a^2J_cH_0\,g\left(\frac{H_0}{H_c}\right)$$

$$g(x)=(2/x)\ln\cosh x-\tanh x$$

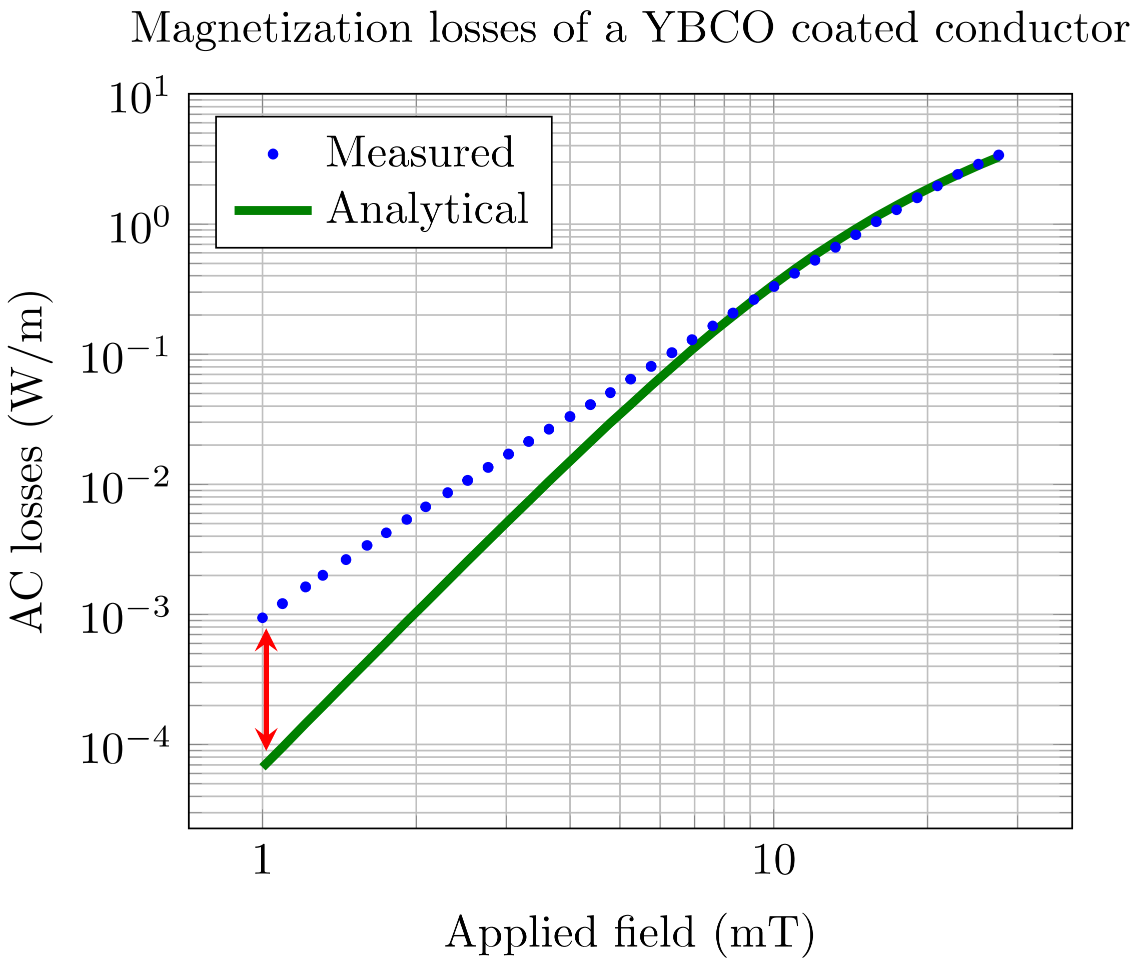
Analytical models

- Sometimes they work well



Analytical models

- Sometimes they don't



Analytical models: limitations

- Simple geometries
  - Difficult to model structured tapes (filaments, stabilizers, magnetic materials,…)
- Tape assemblies: only infinite stacks/arrays
  - No end effects in assemblies with finite number of tapes
- Mostly based on Critical State Model
  - No frequency dependence in AC phenomena
  - No overcritical excursions
  - Difficult to implement J_c(B, theta) and J_c(x,y,z) dependencies
- Uniform fields, simple current/field sources (ramps, AC)

Numerical models can overcome these limitations

Overview of the main different approaches

-Differential (PDE) vs. integral equations
-Many choice of variables: **H**, **E**, **A**-V, **T**-Ω, etc.

Hundreds of possible variants!

Physical model:
-Mathematical equations
-Assumptions & hypothesis
-Materials models
(critical state, power law, etc.)

+

Numerical method:
-Finite element methods
-Point collocation techniques
-Variational methods
-etc.

Numerical model

Implementation environment:
-Home made codes (Matlab, Python, …)
-Commercial packages (Comsol, FlexPDE, …)

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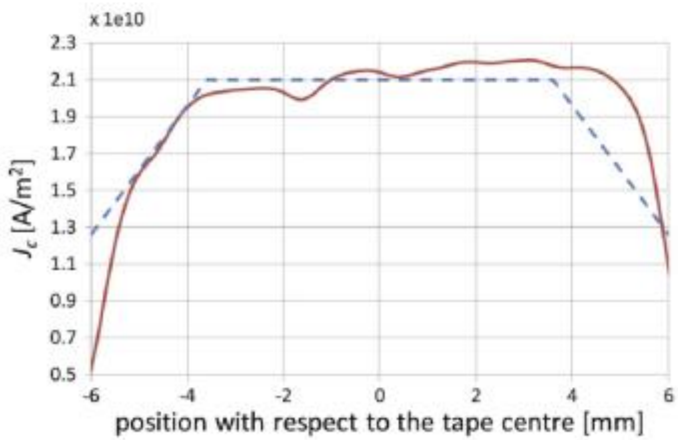
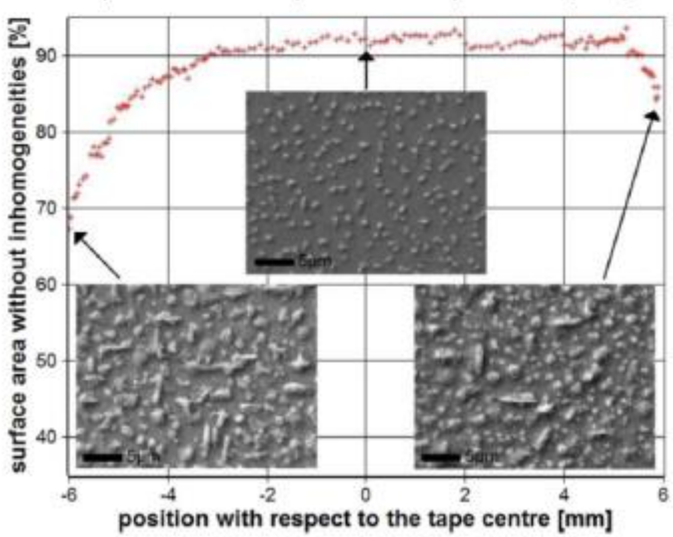
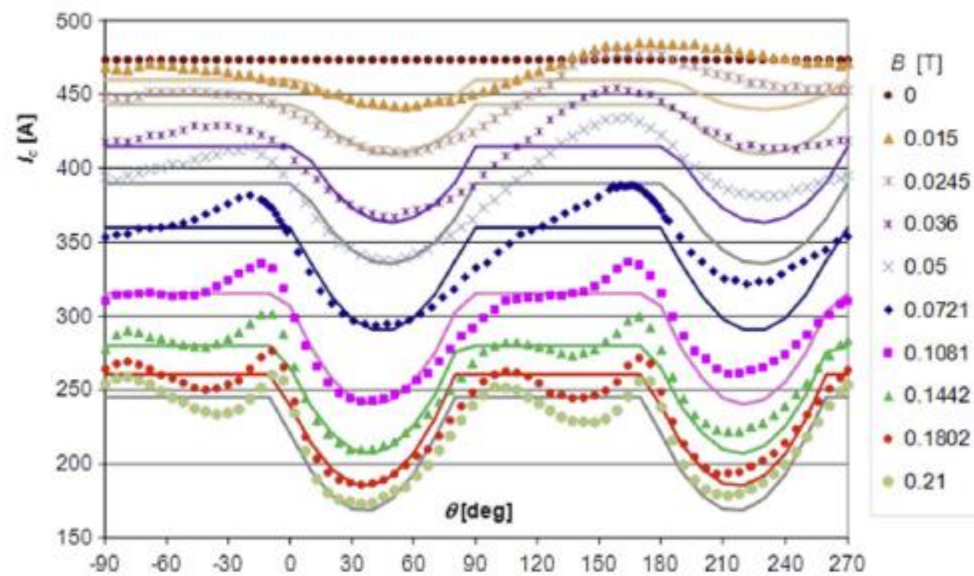
YBCO coated conductors with $J_c(x)$ and $J_c(B,\theta)$

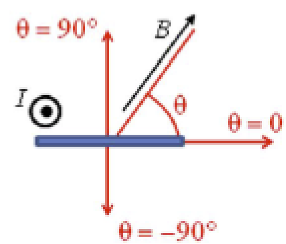
Lateral variation of J_c

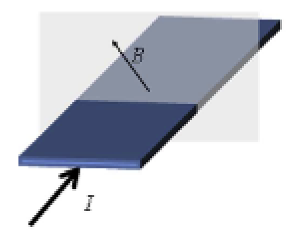




Angular dependence $J_c(B,\theta)$



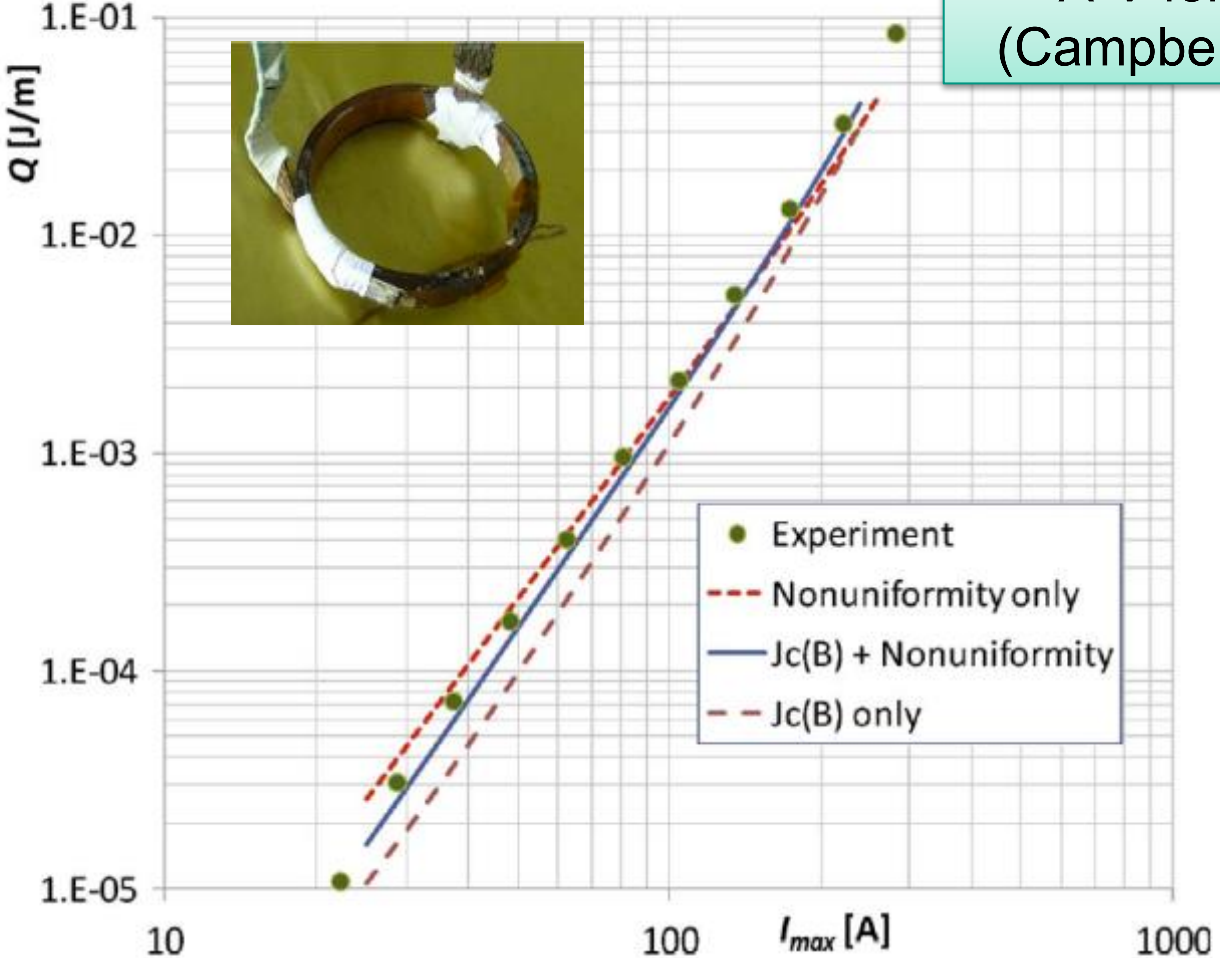




Figures extracted from: F. Gomory et al., “IEEE TAS, VOL. 23, NO. 3, 5900406, 2013”

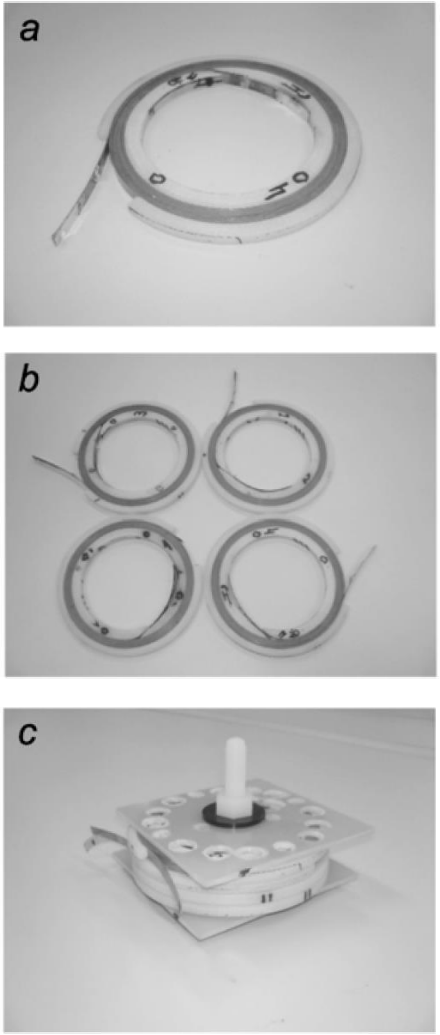
Coil made of YBCO coated conductor

A-V formulation
(Campbell's method)

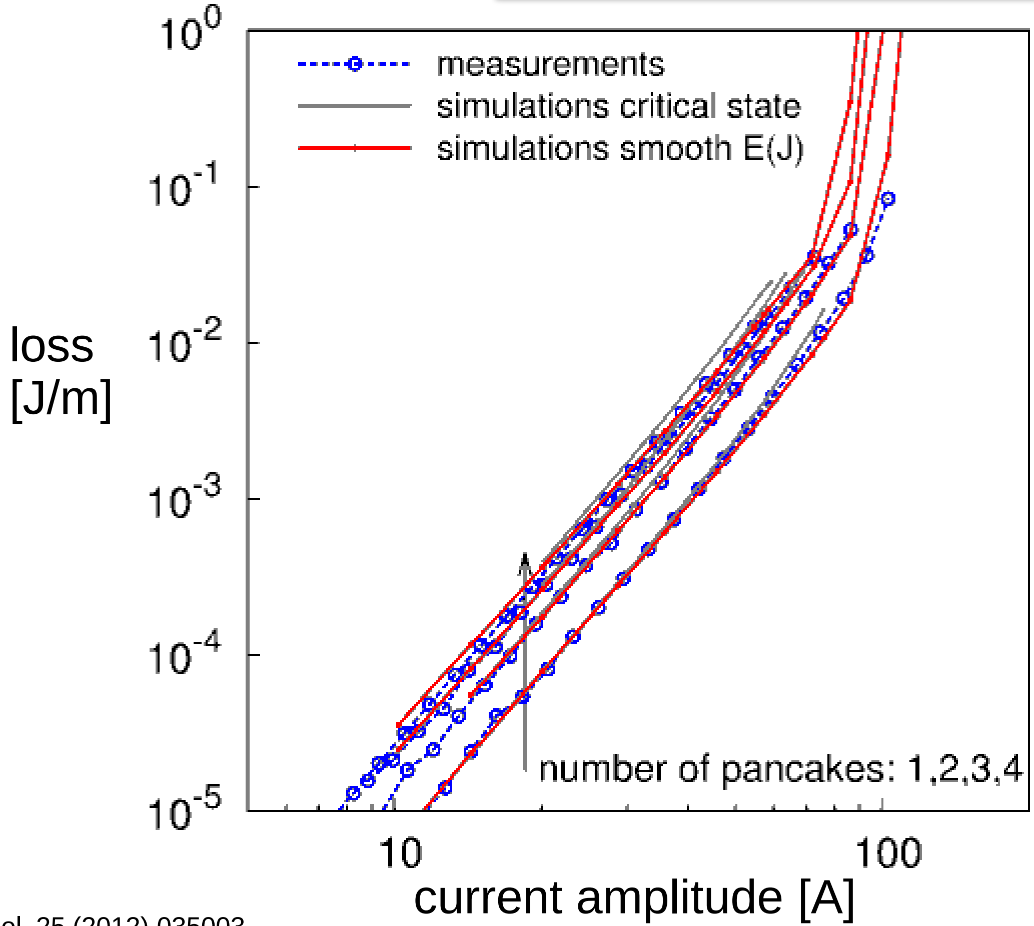


Figures extracted from: F. Gomory et al., "IEEE TAS, VOL. 23, NO. 3, 5900406, 2013"

Stacks of pancake coils of YBCO coated conductors



MMEV method

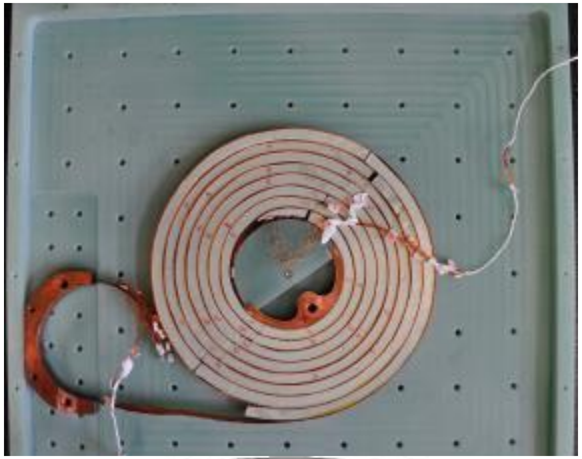


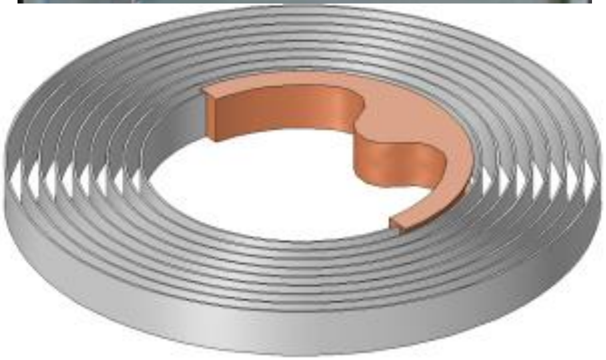
Figures extracted from: E. Pardo et al., Supercond. Sci. Technol. 25 (2012) 035003,
E. Pardo et. al., IEEE TAS, in press

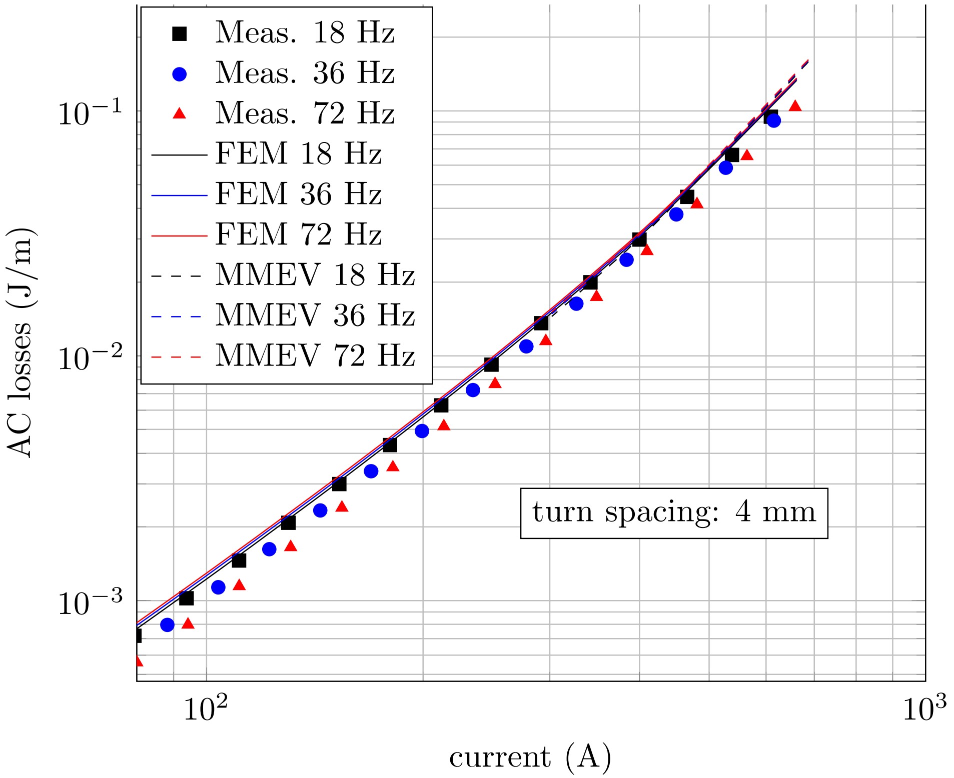
Pancake coils made of Roebel cables

- HTS modelled in 2-D (axis-symmetric model)
- Copper contact in 3-D

H-formulation FEM

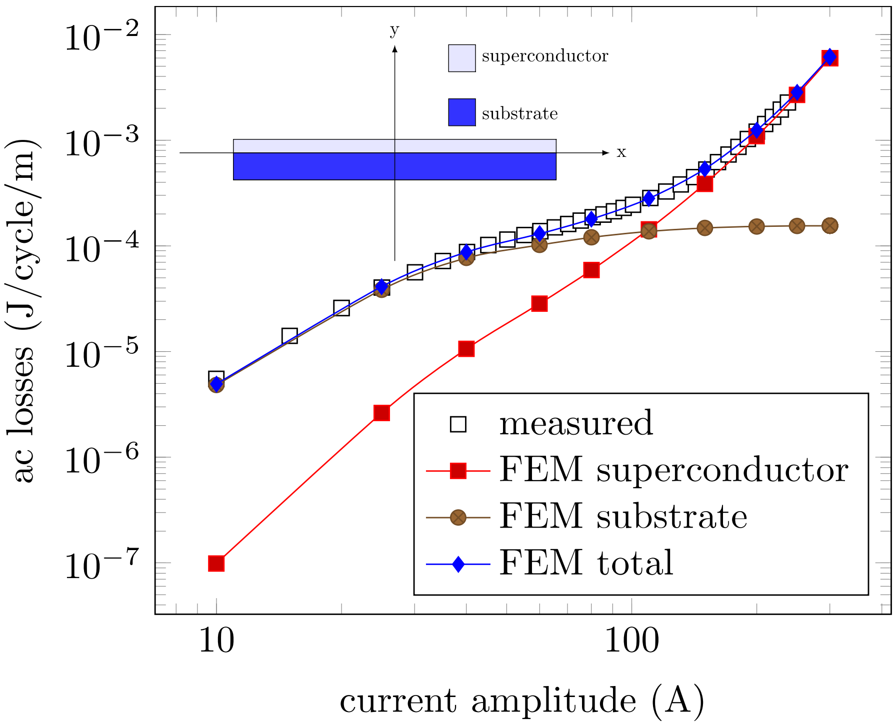




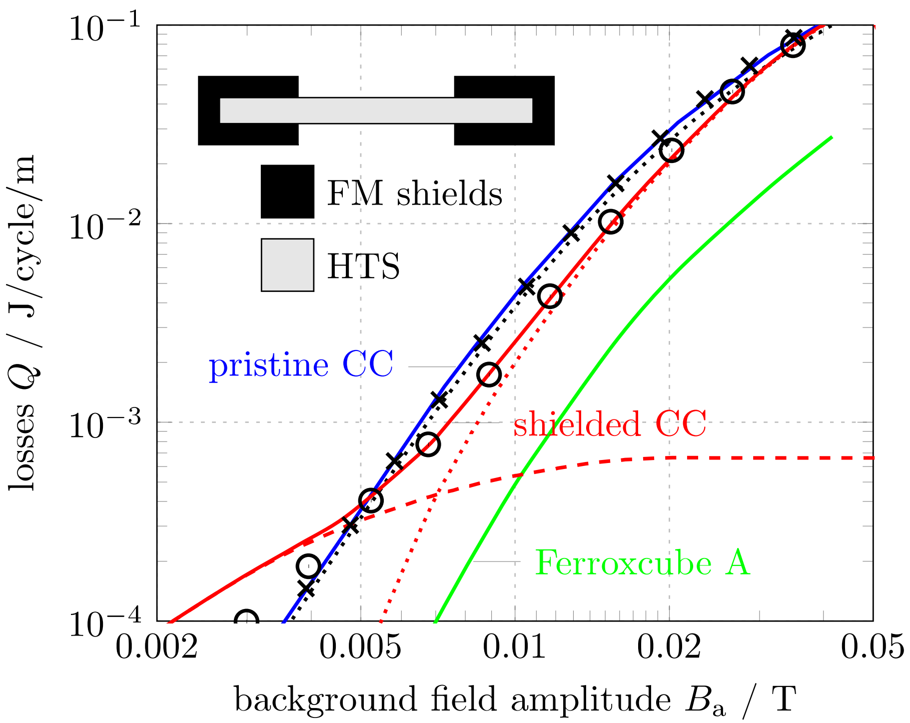


Superconducting and magnetic materials

CC tapes with Ni-W substrate



Ni-shielding of CC tapes

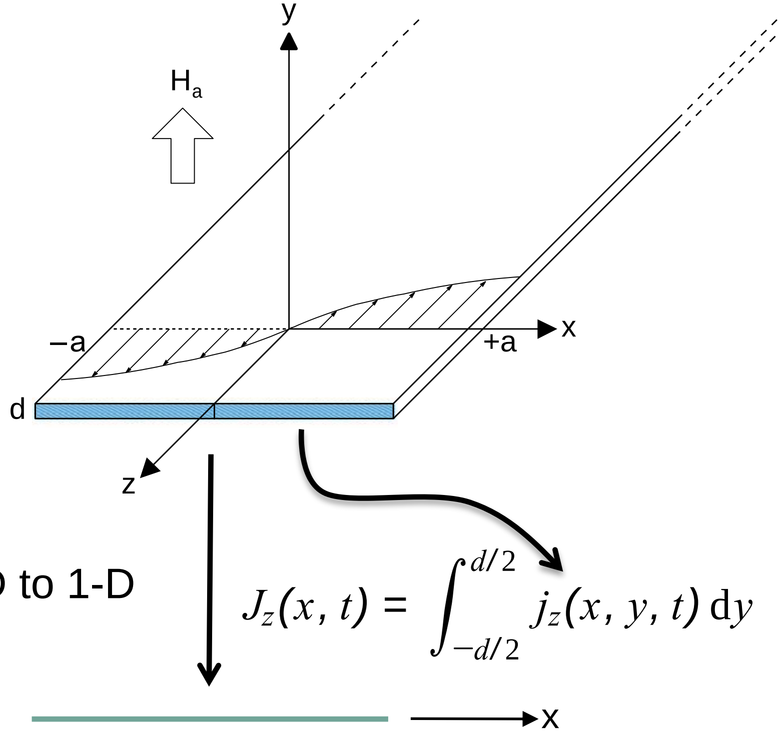


H-formulation FEM

Figure above from: P. Krüger et al., APL 102, 202601 (2013)

Integral equations for thin tapes

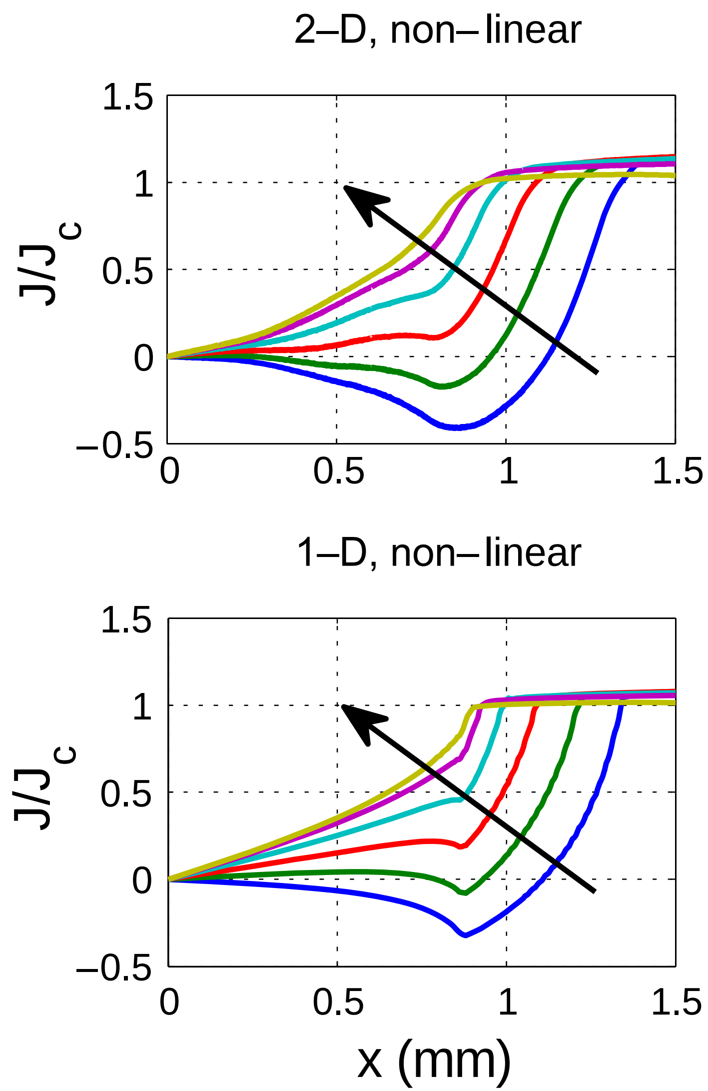
J formulation



2-D to 1-D

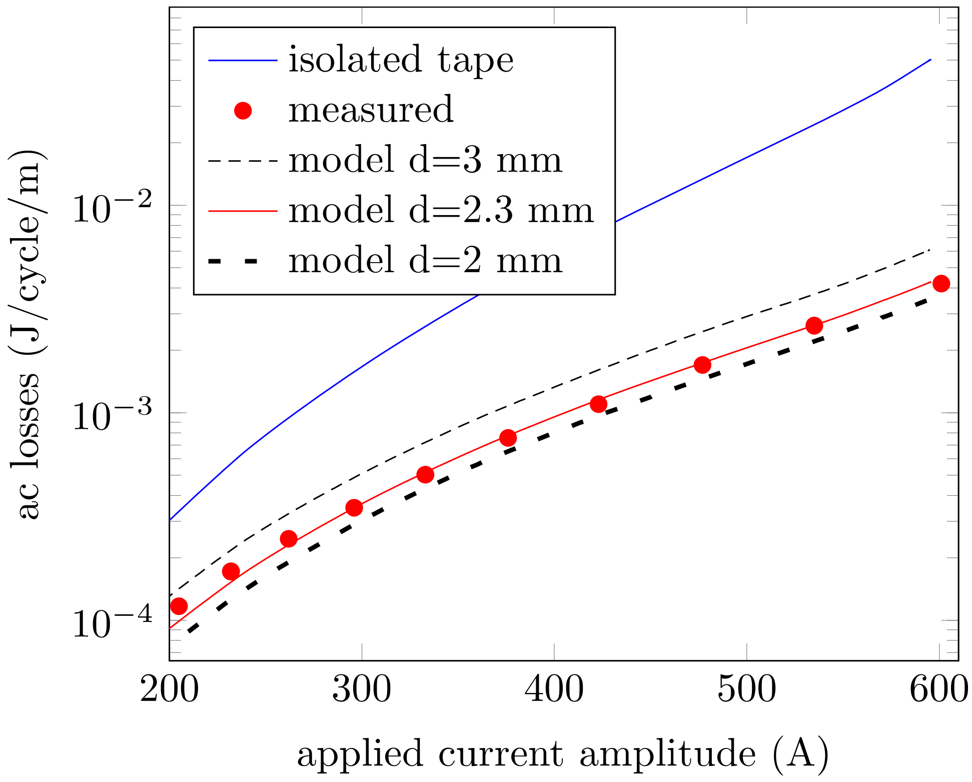
$$J_z(x,t) = \int_{-d/2}^{d/2} j_z(x,y,t)\,\mathrm{d}y$$

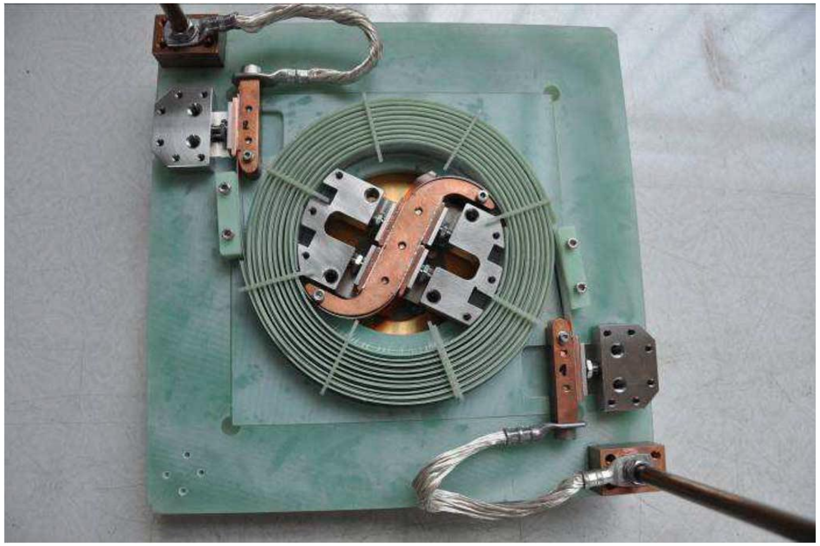
R. Brambilla et al., Supercond. Sci. Tech., 21 (10), p. 105008, 2008.



Integral equations for thin tapes: bifilar coils

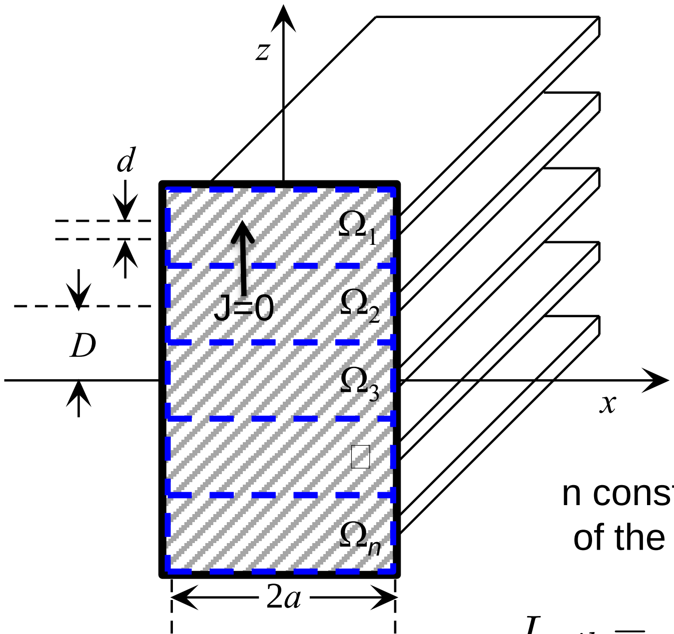
- Fault current limiter applications





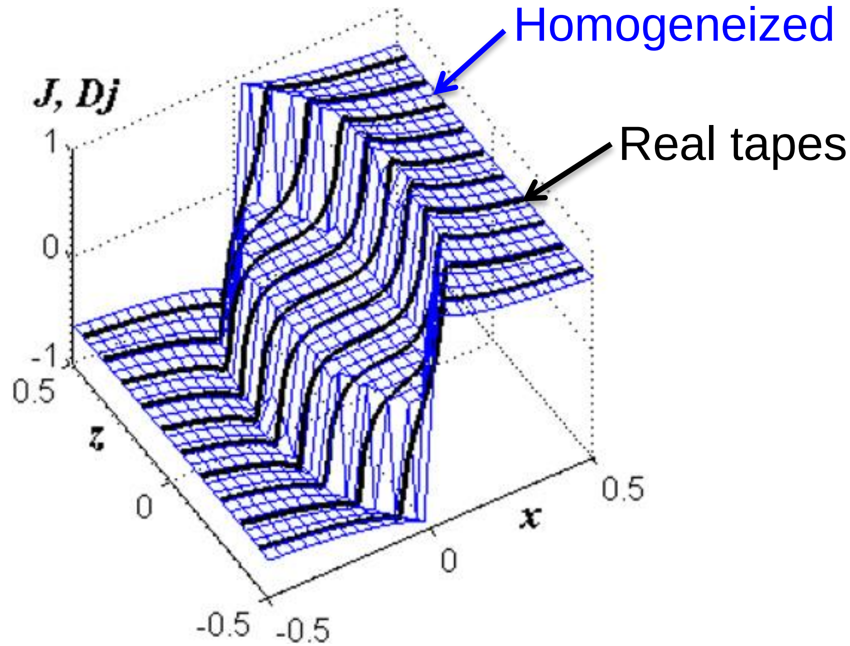
Homogenization technique

- If there are too many tapes to simulate ➔ Homogenization



n constraints of the form:

$$I_{coil} = \int_{\Omega_n} J \,\mathrm{d}S$$



Analytic solution

J. R. Clem et al., Supercond. Sci. Tech., 20 (12), pp. 1130–1139, 2007.

Refinement and numerical implementation

L. Prigozhin and V. Sokolovsky, Supercond. Sci. Tech., 24 (7), p. 075012, 2011.

Homogenization technique

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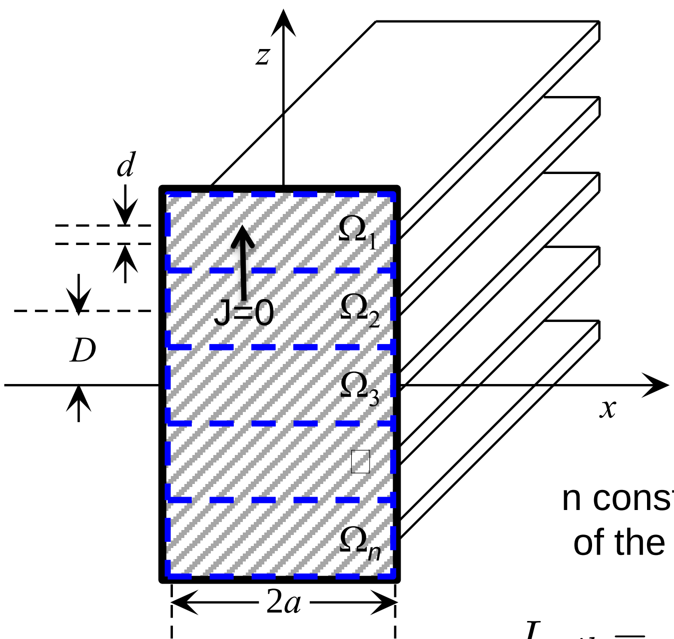

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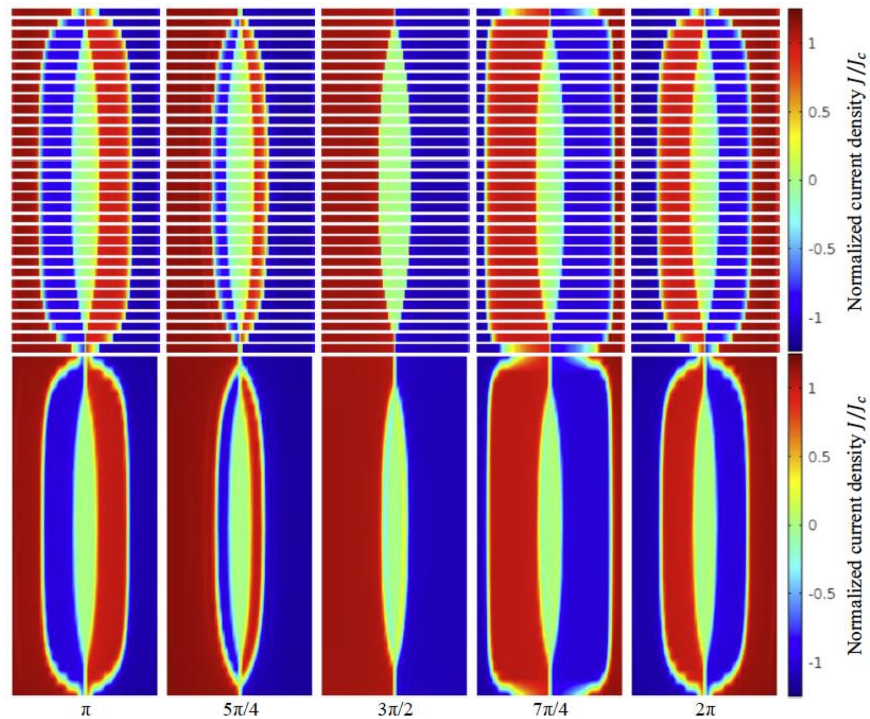


Analytic solution

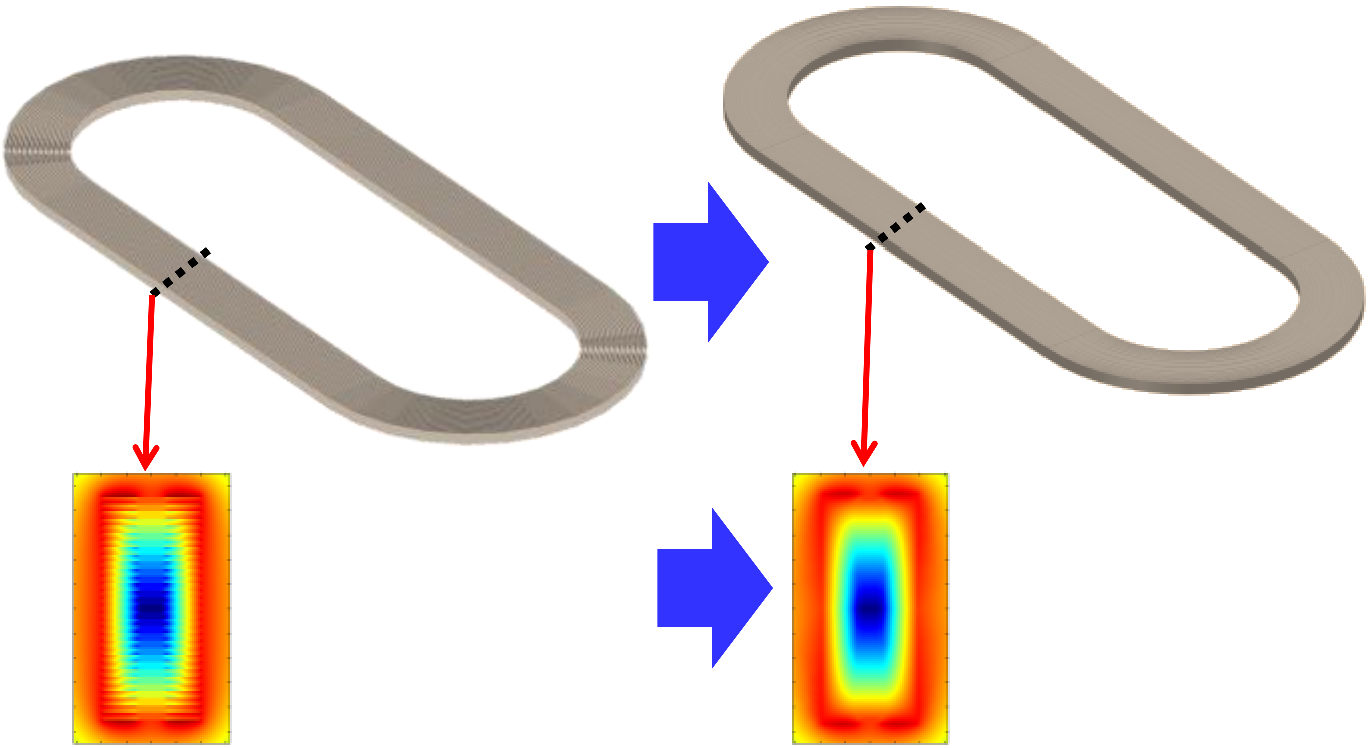
J. R. Clem et al., Supercond. Sci. Tech., 20 (12), pp. 1130–1139, 2007.

Refinement and numerical implementation

V. Zermeno, Journal of Applied Physics, submitted.
Pre-print http://arxiv.org/abs/1308.2568

Homogenization technique: extension to 3-D

- Homogenization in 3-D



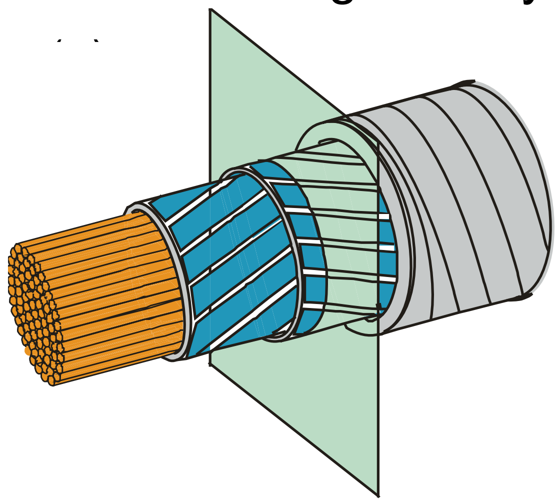
(3-D numerical implementation)

V. Zermeno and F. Grilli, EUCAS 2013

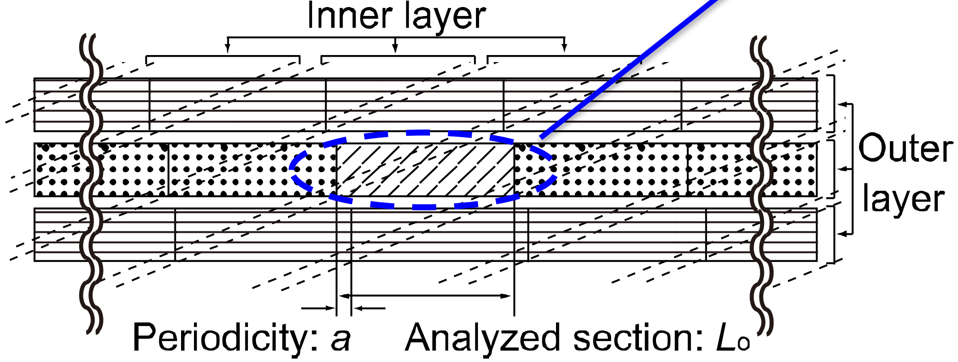
H-formulation FEM

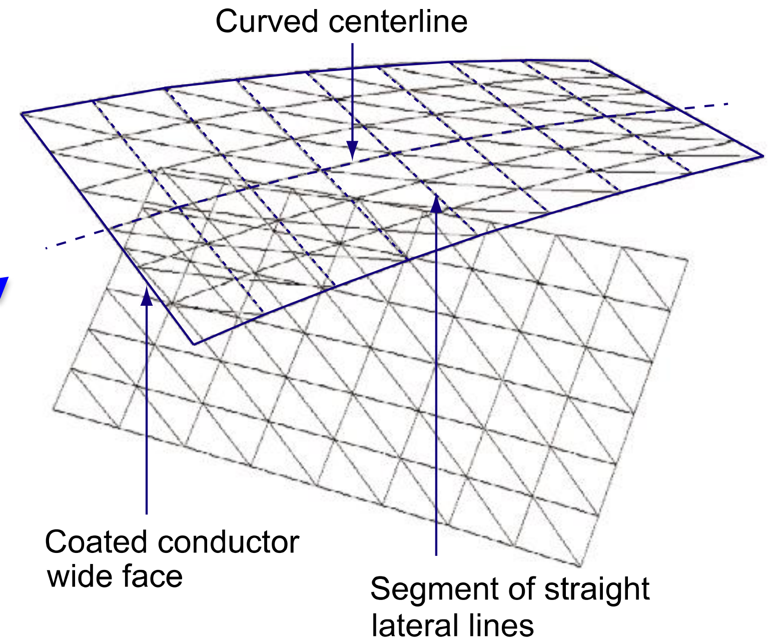
Solutions to avoid full 3-D models (1)

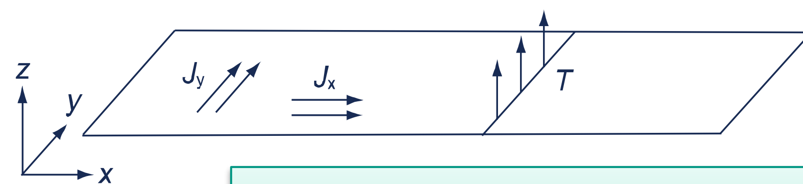
- 3-D modelling of 2-layer cables using a “2.5-D” model



Surfaces (2-D) in 3-D space







T-Ω formulation FEM

K. Takeuchi, N. Amemiya et al., Supercond. Sci. Tech., 24 (8), p. 119501, 2011.

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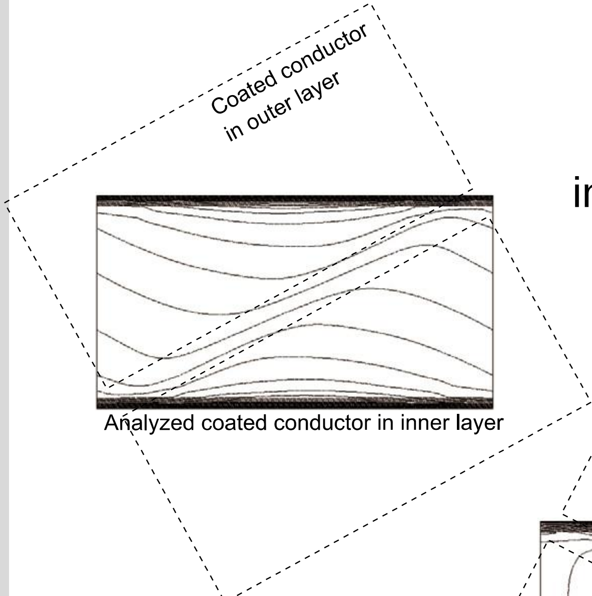
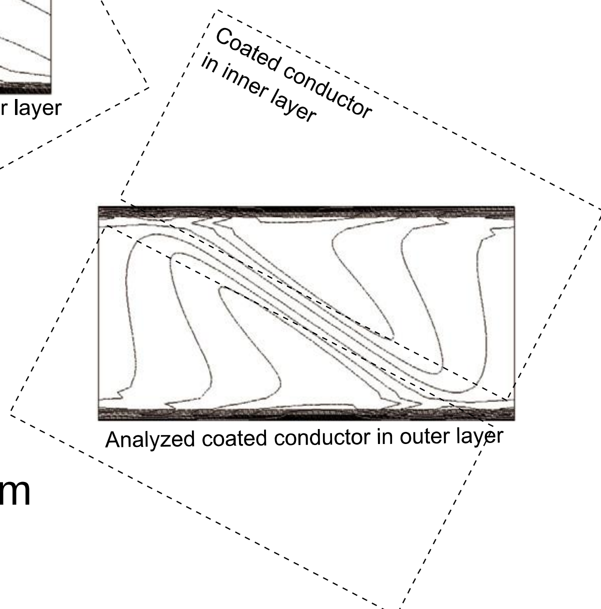
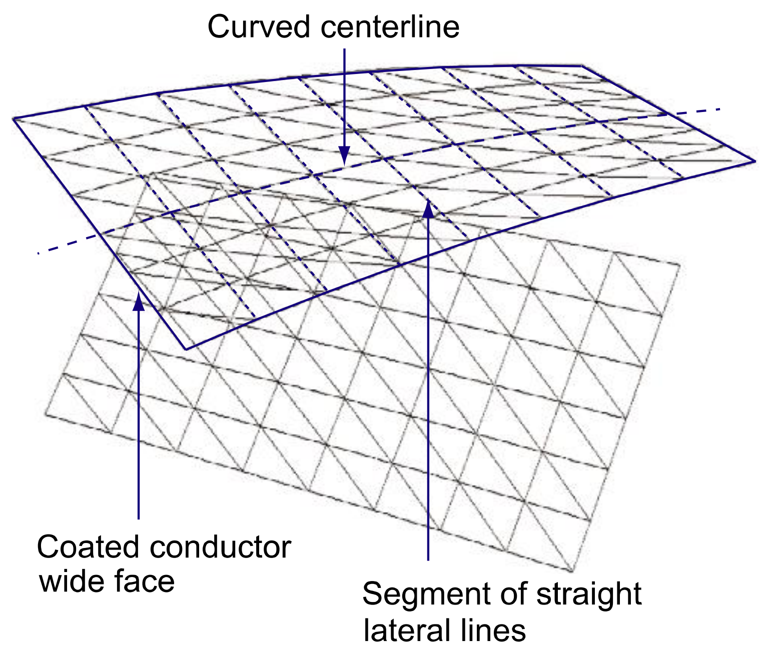


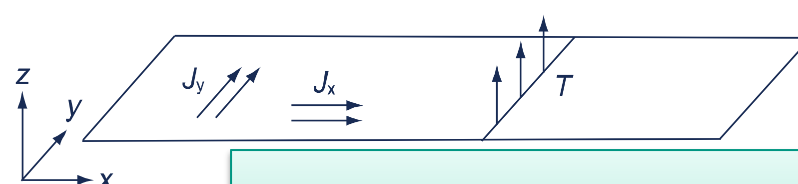
PDEs in superconductors + integral equations at the boundaries



Current path flows

AC losses non uniform along length



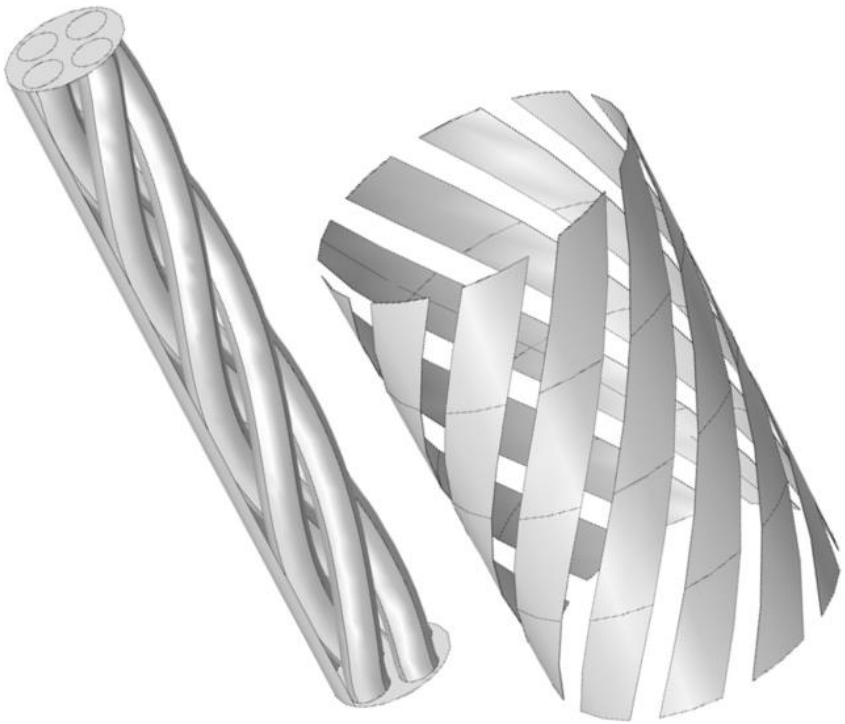


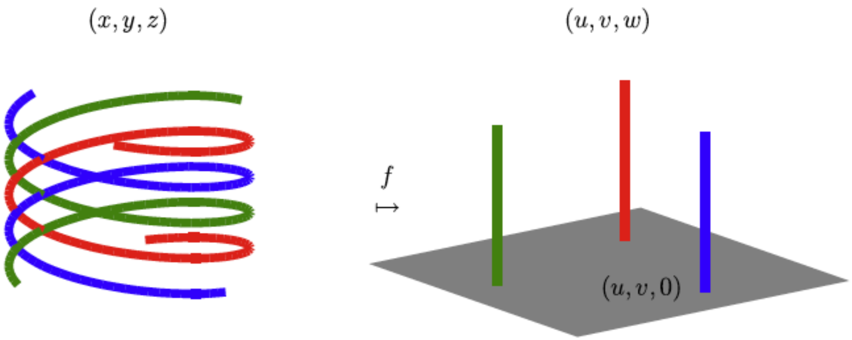
T-Ω formulation FEM

K. Takeuchi, N. Amemiya et al., Supercond. Sci. Tech., 24 (8), p. 119501, 2011.

Solutions to avoid full 3-D models (2)

- Change of coordinates in helical geometries



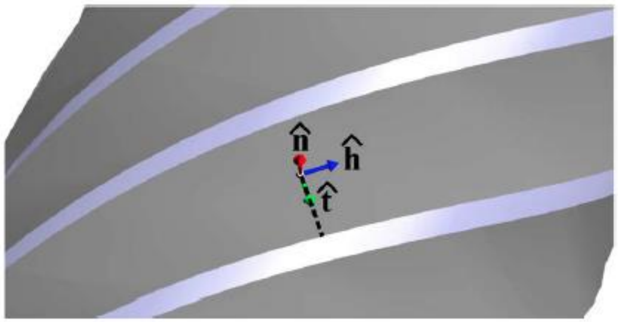


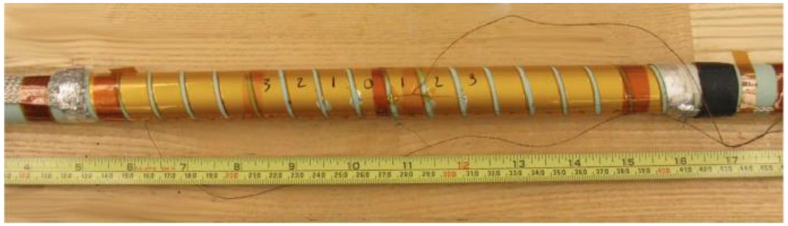
A. Stenvall et al., Supercond. Sci. Tech., 26, p. 045011, 2013.

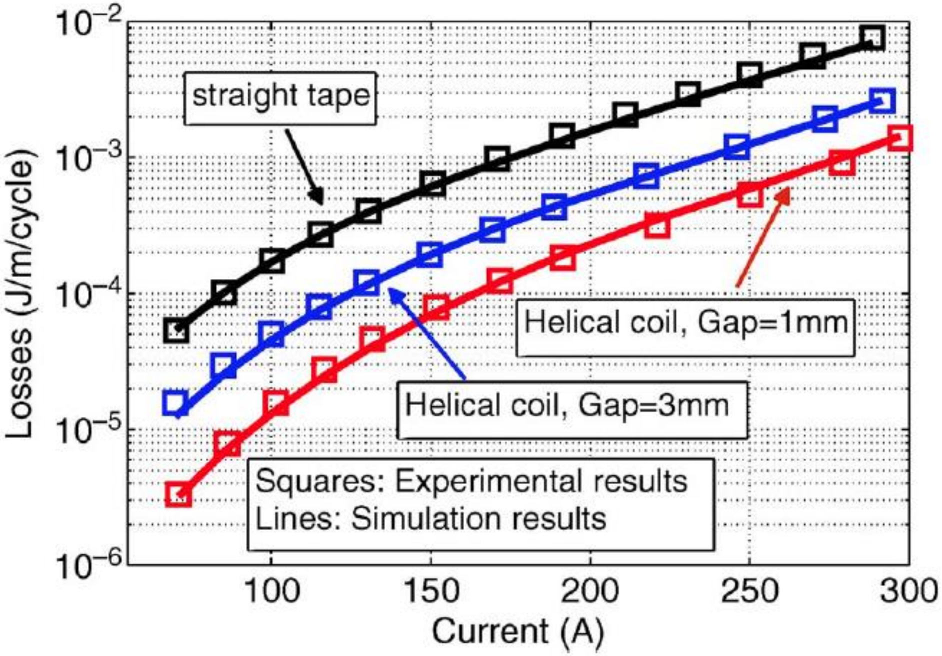
A-V formulation FEM

Solutions to avoid full 3-D models (3)

- Cable made of one helically wound YBCO coated conductor
- Integral equation + helical symmetry
- Thin tape approximation: 3-D problem solved as 1-D



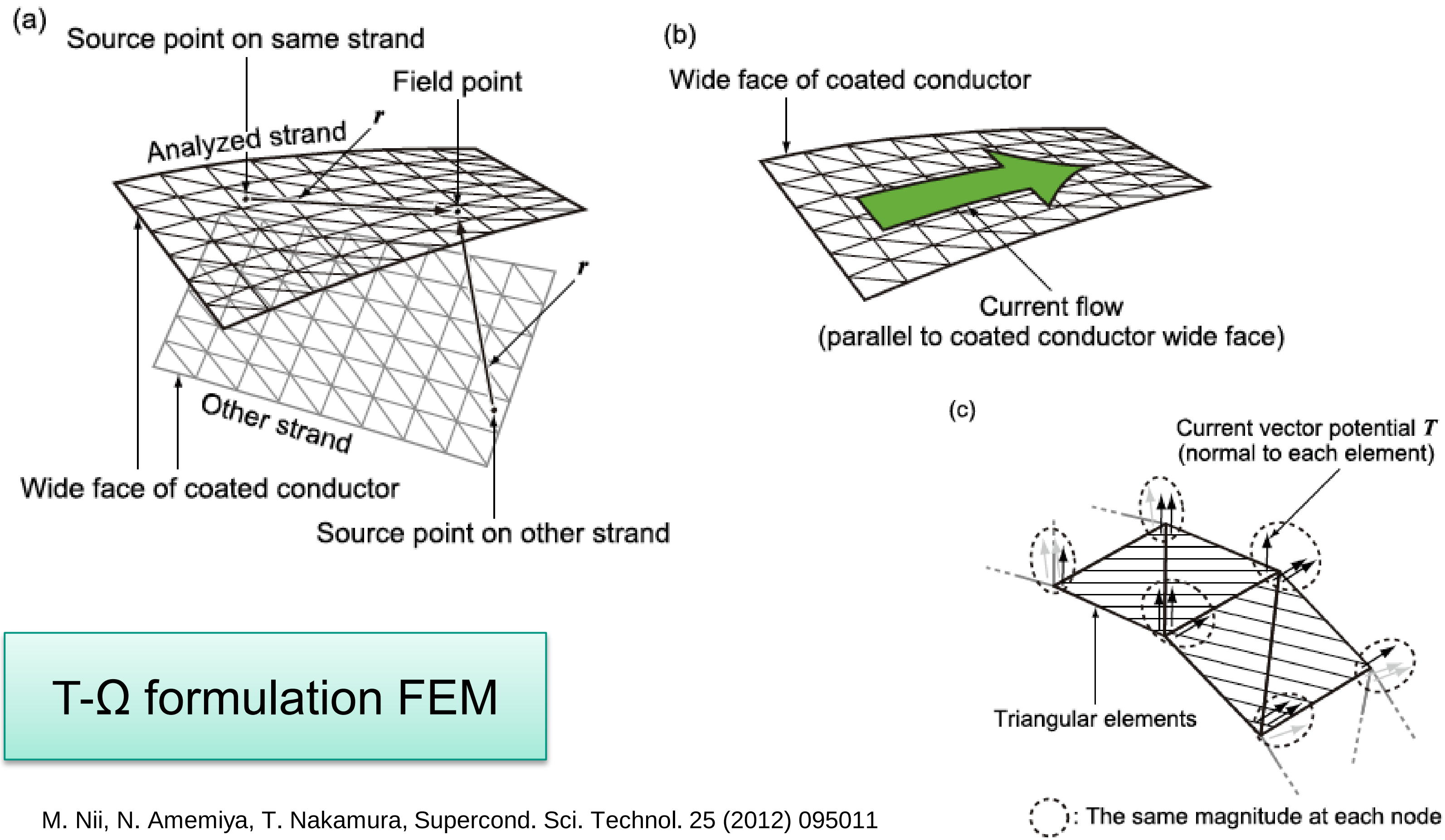




M. Siahrang, F. Sirois, D. N. Nguyen, S. Babic, S. P. Ashworth, IEEE Trans. Appl. Supercond., 20 (6) p. 2381-2389, 2010

Solutions to avoid full 3-D models (4)

- Roebel geometry with infinitely thin tape approximation



T-Ω formulation FEM

M. Nii, N. Amemiya, T. Nakamura, Supercond. Sci. Technol. 25 (2012) 095011

Solutions to avoid full 3-D models (4)

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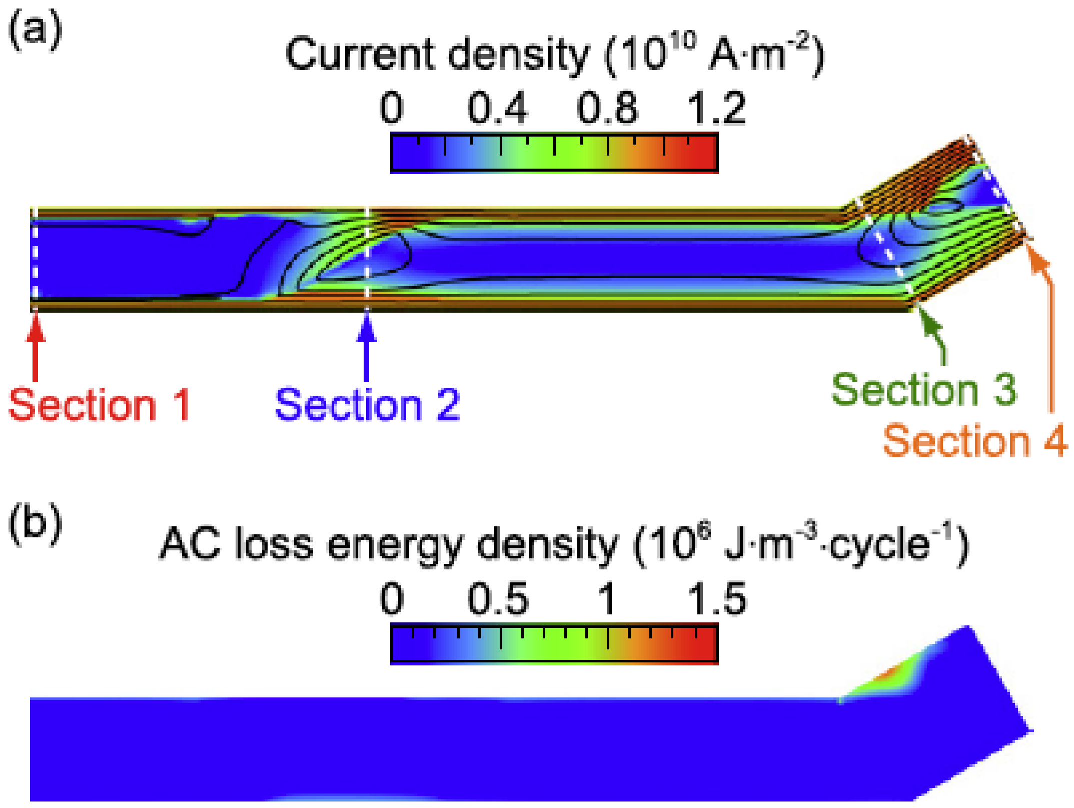
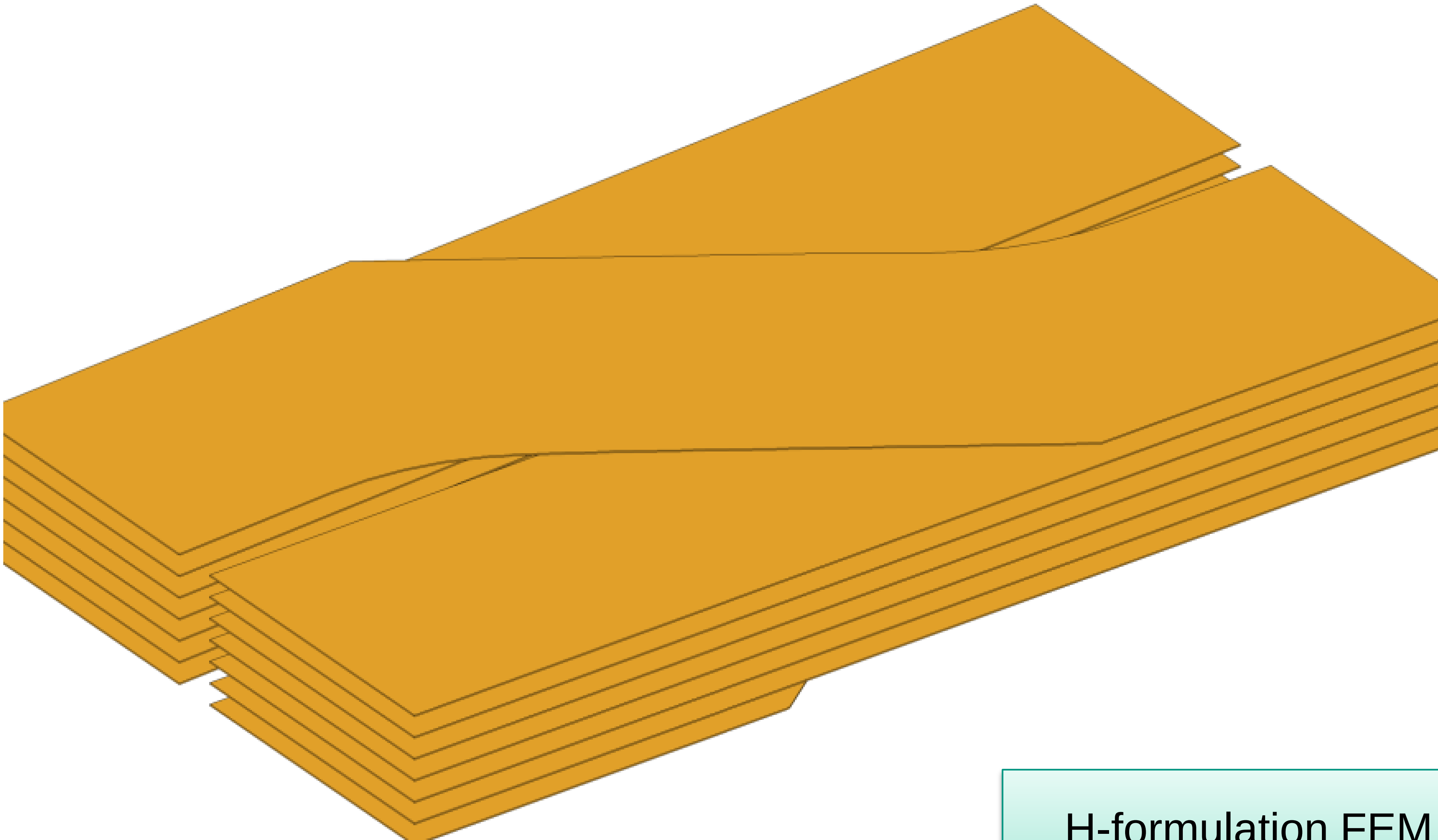


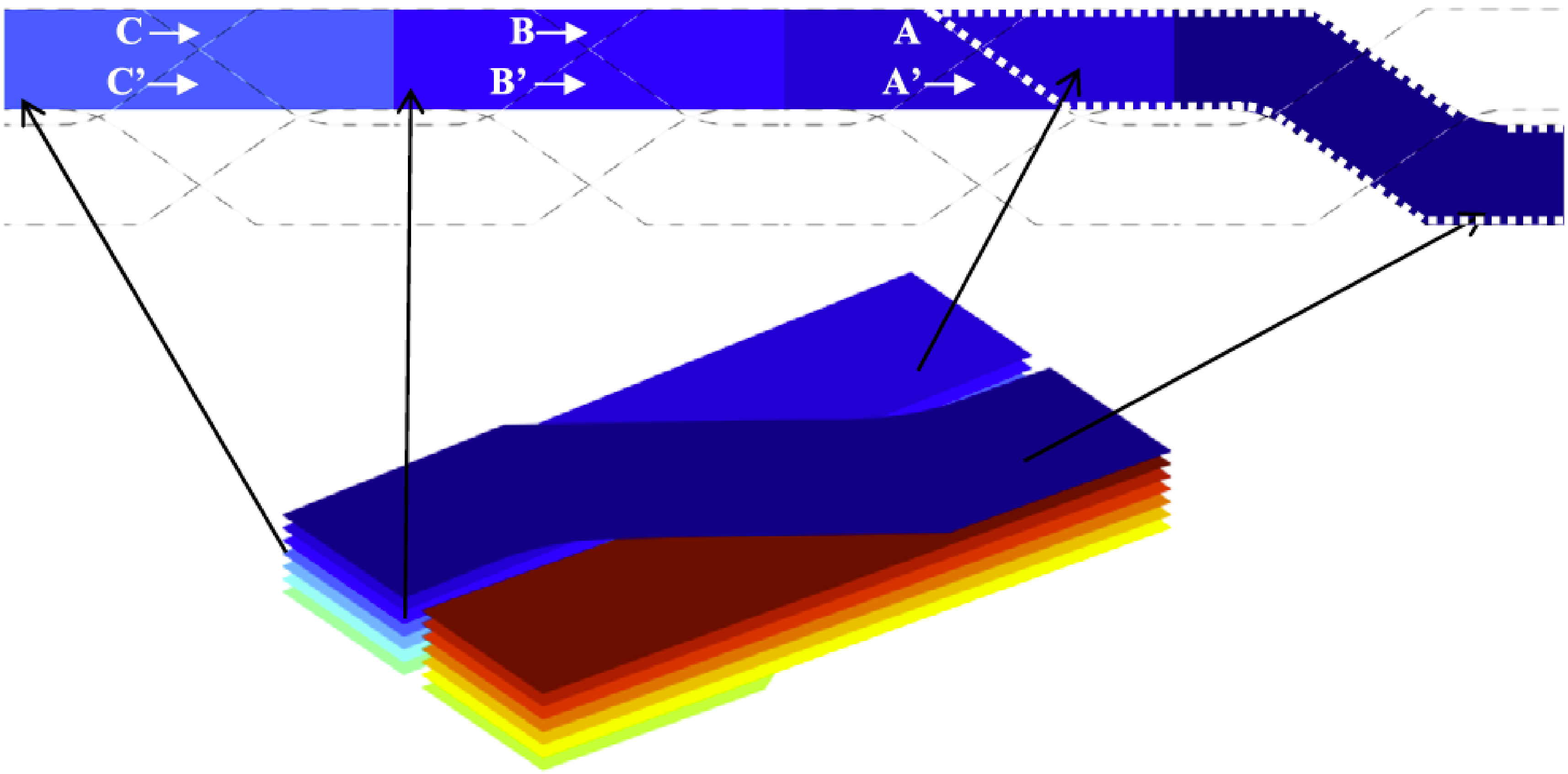
M. Nii, N. Amemiya, T. Nakamura, Supercond. Sci. Technol. 25 (2012) 095011

Full 3-D model of a Roebel

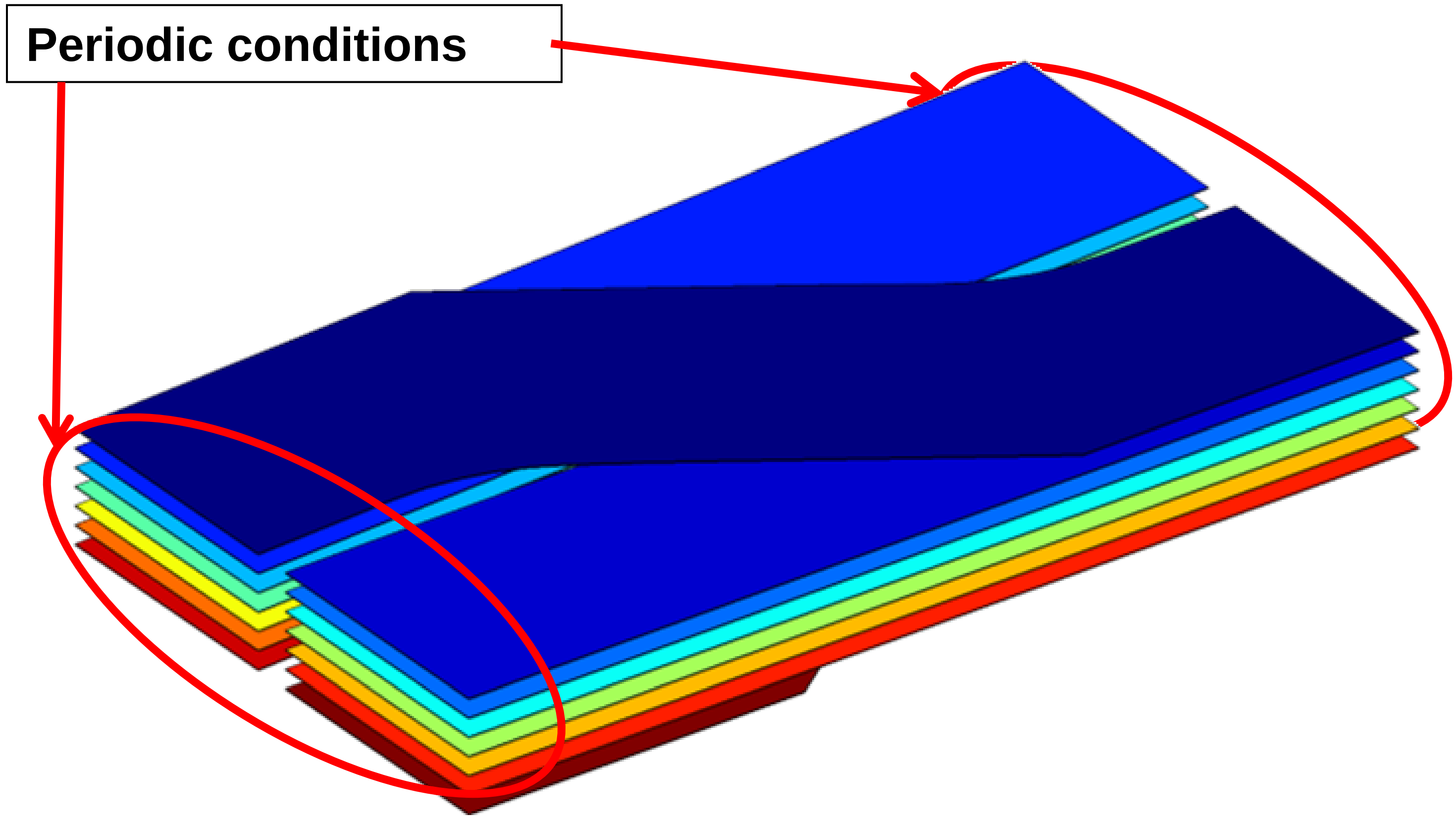


H-formulation FEM

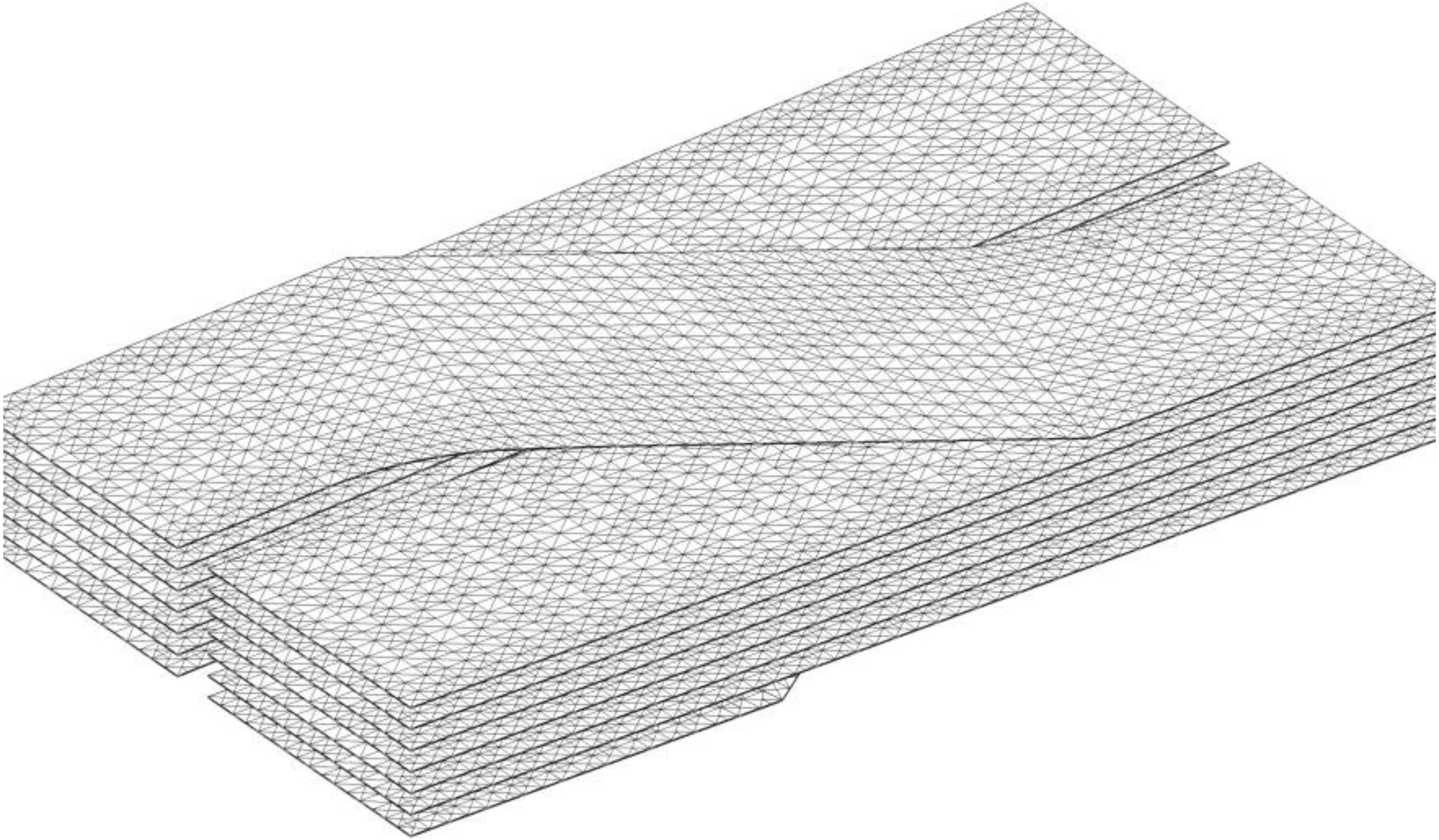
Full 3-D model of a Roebel



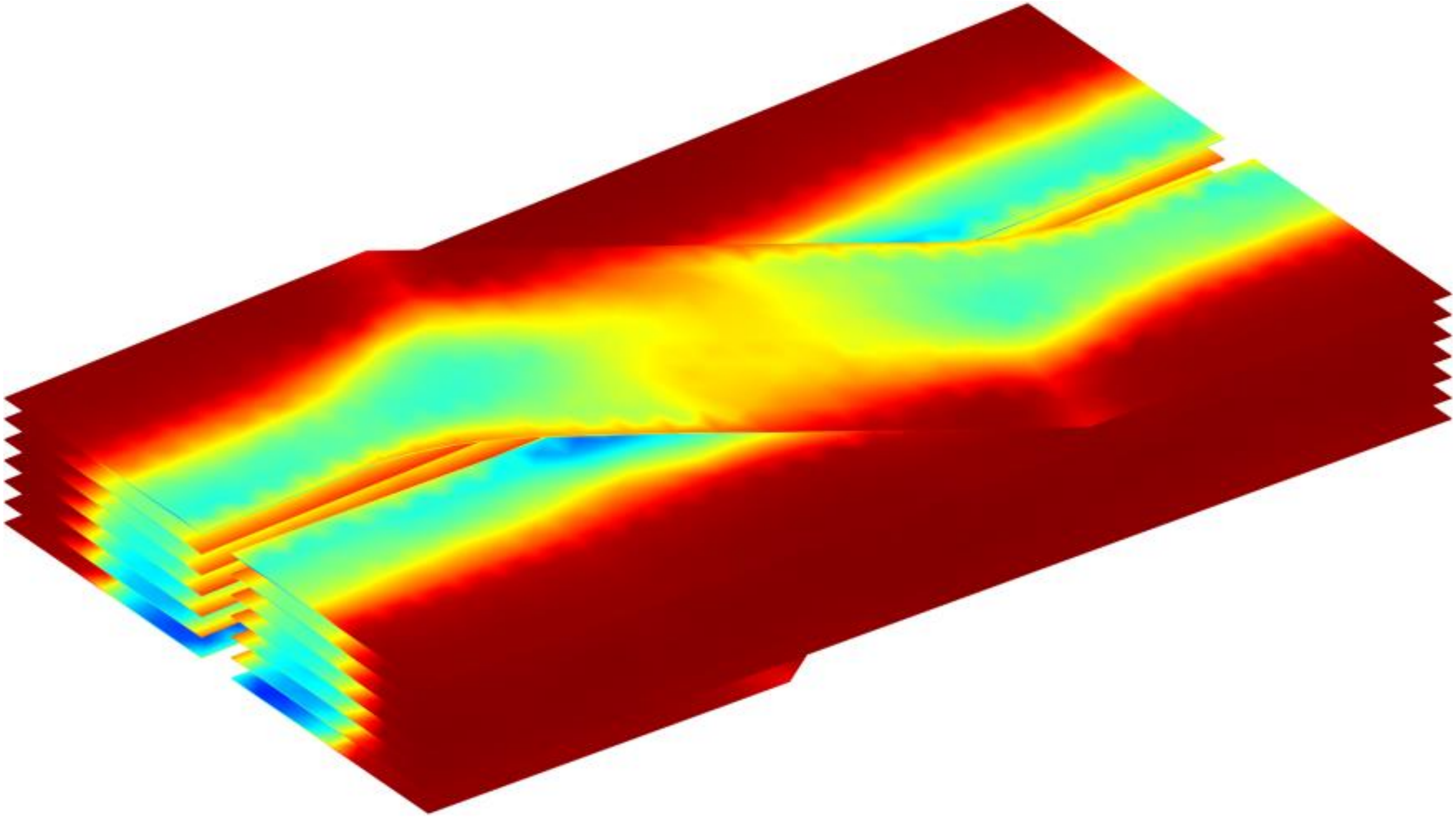
Full 3-D model of a Roebel



Full 3-D model of a Roebel

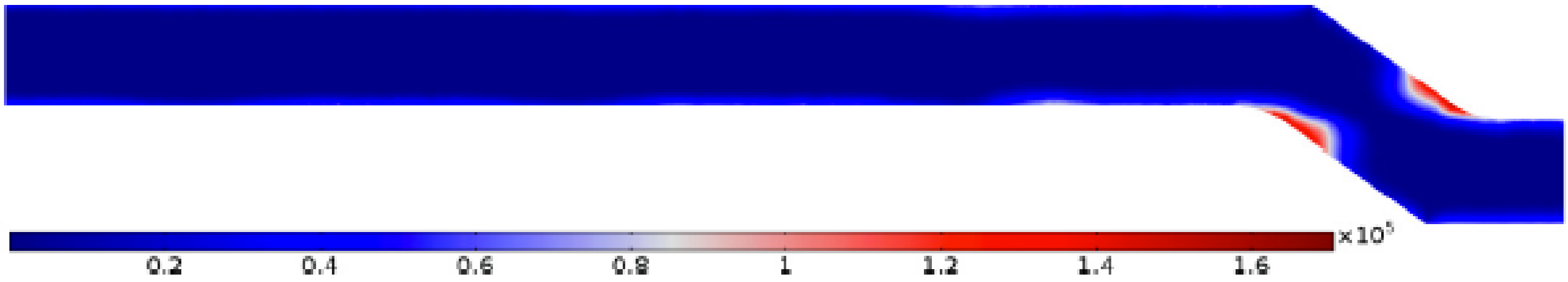


Full 3-D model of a Roebel

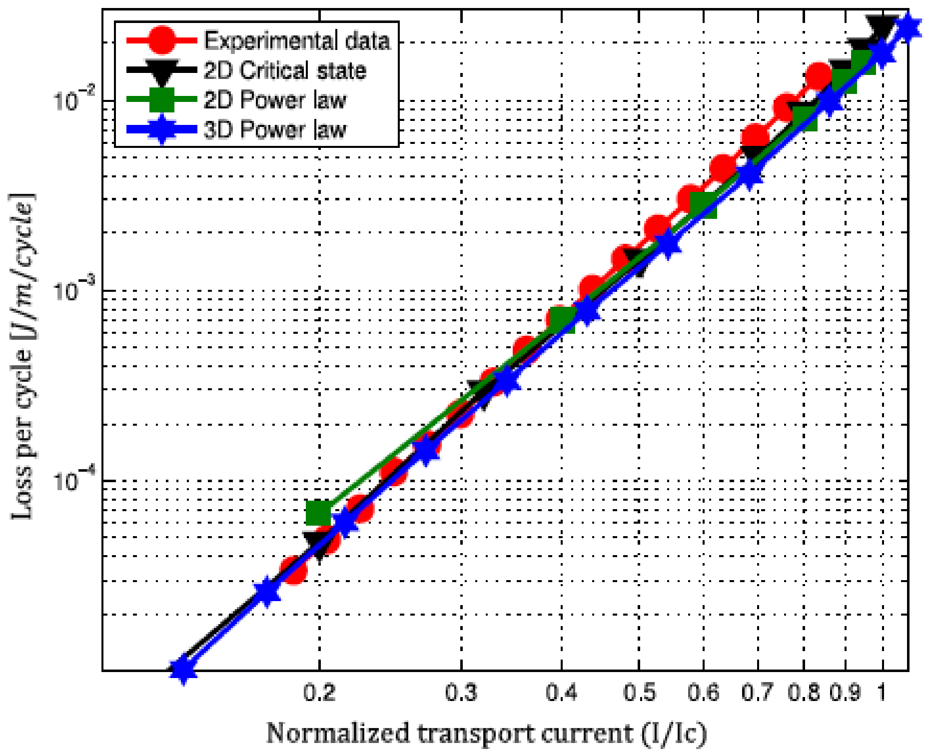


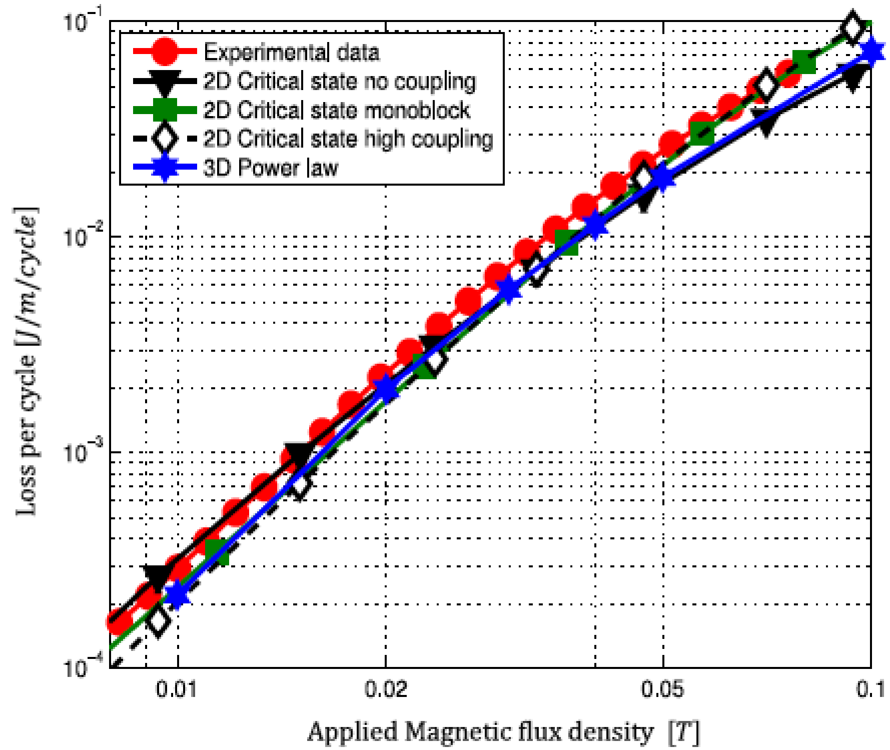
Full 3-D model of a Roebel

- Identification of “critical” zones (highest dissipation)



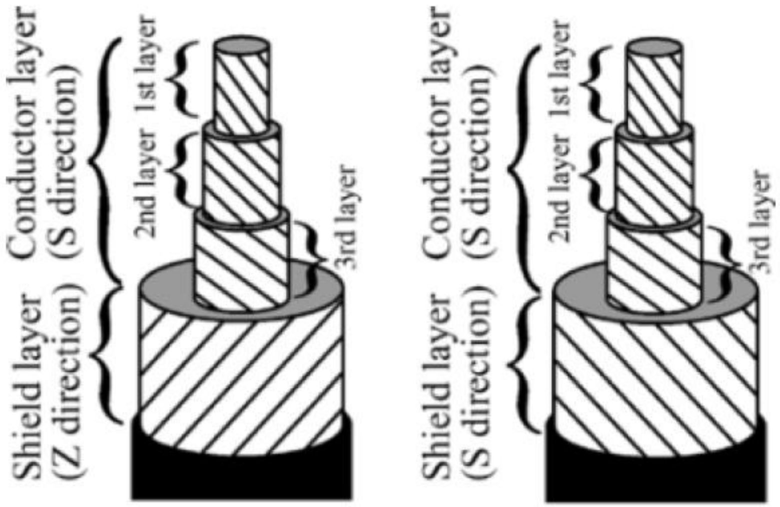
Full 3-D model of a Roebel

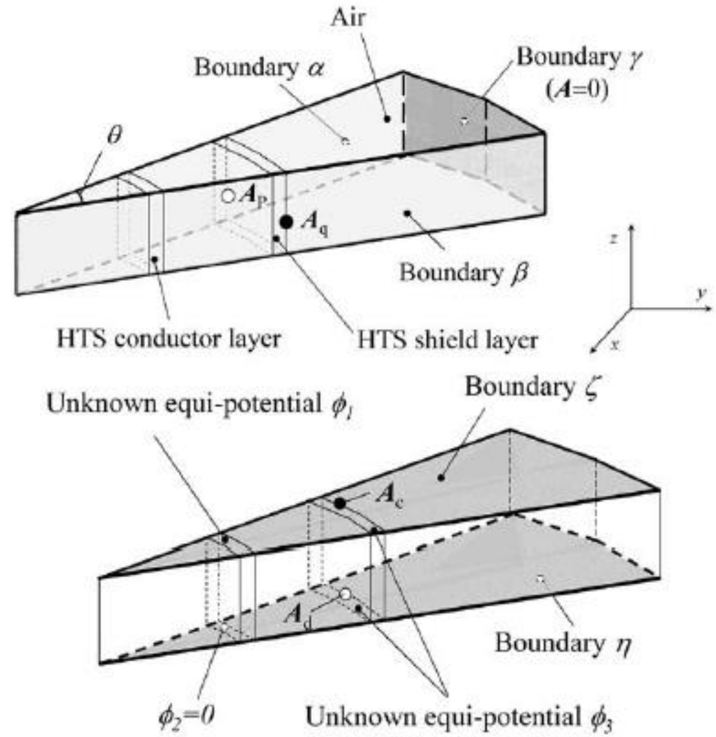




3-D model for a multi-layer HTS power cable

- 3-D FEM with anisotropic conductivity
  - No gaps between tapes





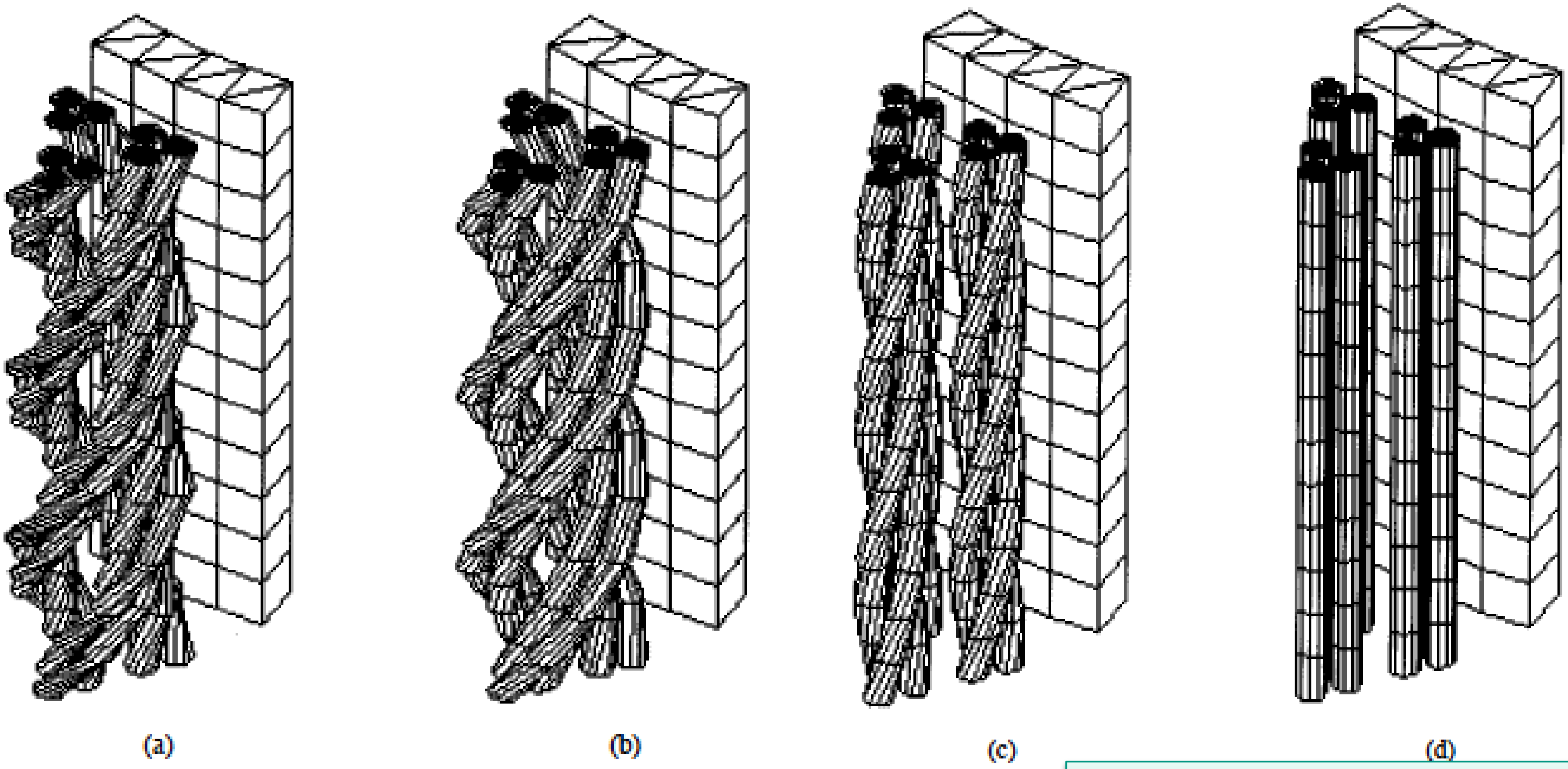
D. Miyagi et al., IEEE Trans. Superc. 40 (2) 908-911, 2004

D. Miyagi et al., IEEE Trans. Magn. 16 (2) 1614-1617, 2006

A-V formulation FEM

3-D model for cable made of twisted wires

- Double-helix geometry



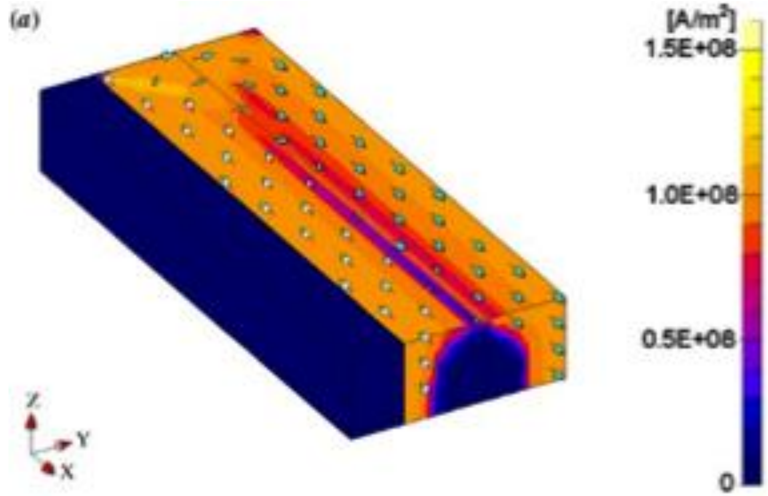
H. Hoshimoto et al. IEEE Trans. Magn. 36 (4) 1205-1208, 2000

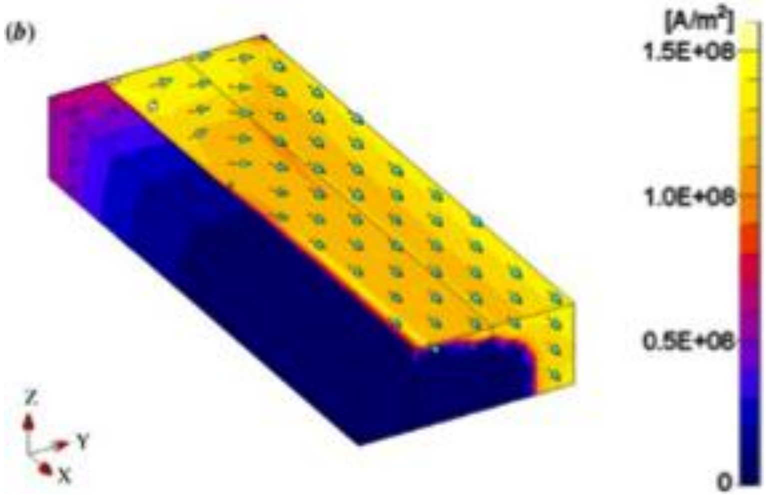
A-V formulation FEM

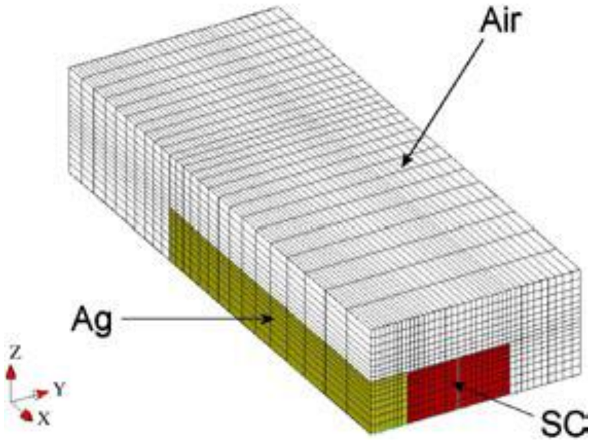
3-D models of coupling between SC filaments

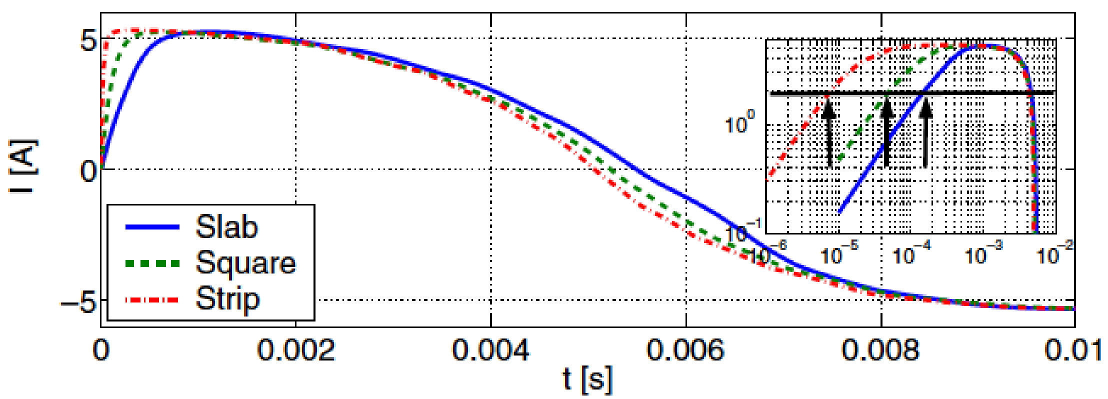
T-Ω formulation FEM

- Influence of the aspect ratio on the onset of coupling





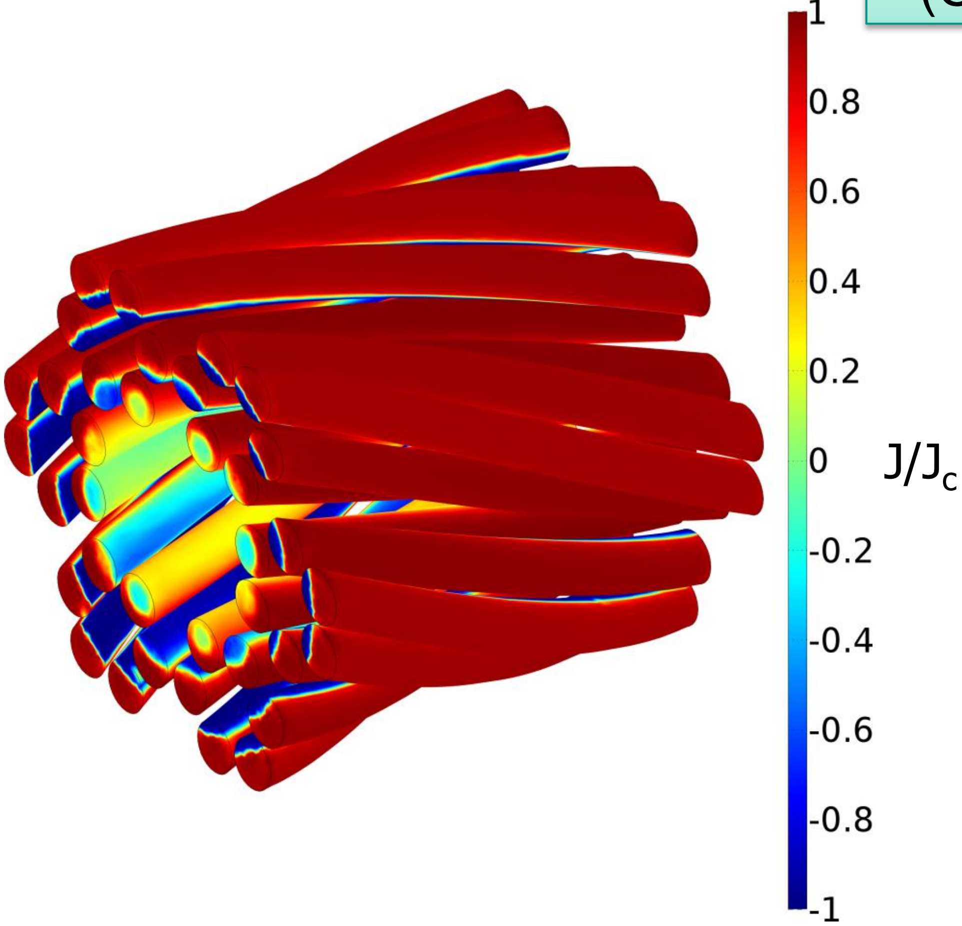




3-D simulation of a CICC

- Details in Victor Zermeno's talk

A-V formulation CSM
(Campbell's method)



Summary

- Many numerical models have been developed in the past few years
- 2-D models have reached a mature status
  - Refined HTS description ($J_c(B)$, $J_c(x,y)$)
  - Structured conductors (filaments, stabilizer, non-linear magnetic materials)
  - Complex devices (hundreds of tapes)
  - Can be adapted to solve 3-D problems
  - Performance still to be improved for device optimization
- 3-D models are far behind
  - Mostly proof-of-concept status
  - Complexity and size of the problem rapidly increases
  - CAD-FEM-SOLVERS more susceptible to problems
  - Scarcely applied for simulating realistic devices
  - Are they really necessary?

Summary

- Review paper on AC loss computation
  - 32 pages, 333 references
  - IEEE Transactions on Applied Superconductivity
  - Pre-print available at http://arxiv.org/pdf/1306.6251.pdf

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY 1

Computation of Losses in HTS Under the Action of Varying Magnetic Fields and Currents

Francesco Grilli, Enric Pardo, *Member, IEEE*, Antti Stenvall, Doan N. Nguyen, Weijia Yuan, and Fedor Gömöry, *Member, IEEE*