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Karlsruhe Institute of Technology

Numerical Modelling of HTS Applications

Francesco Grilli

Institute for Technical Physics - ITEP

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"Numerical modeling of HTS" is a vast field.

Several different aspects can be modeled

- Electromagnetic effects
- Thermal effects
- Mechanical forces
- Network behavior
- Cryogenics (CFD)
- …

Focus on electromagnetics: motivation

- The electromagnetic behavior of HTS is very peculiar → specific modeling approaches need to be devised
- Superconductors' performance determined by the way magnetic flux penetrates and moves
- This is strongly determined by
  - The superconductor's non-linear electrical behavior
  - The superconductor's shape
  - The presence of other materials
- Particular interest for applications: AC losses

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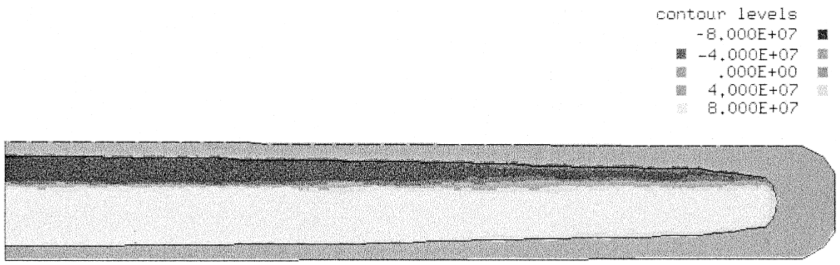
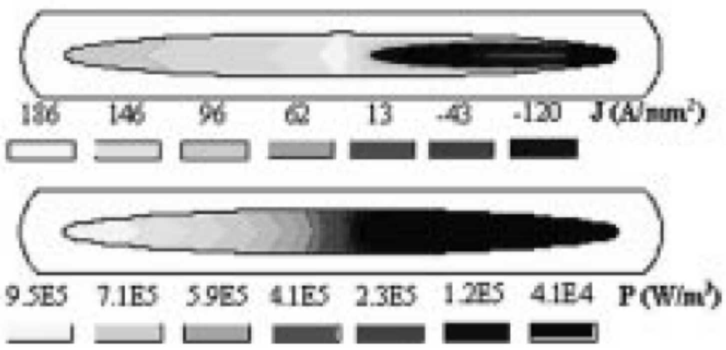
Models for individual tapes date back to the end of 1990s.



Amemiya et al., 1998 Physica C **310** 30-35

T-ϕ formulation

Home-made code

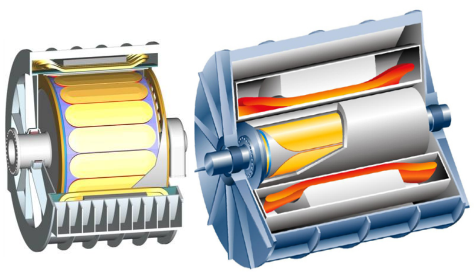


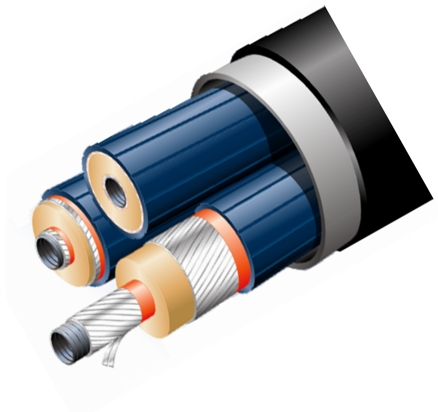
Stavrev et al., 2002 IEEE TAS **3** 1857-1865

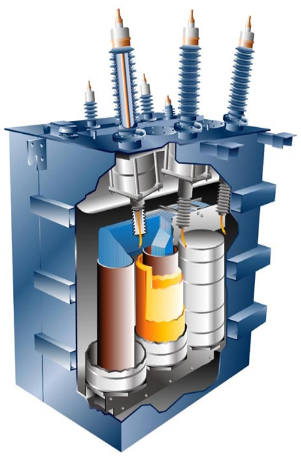
A-V formulation

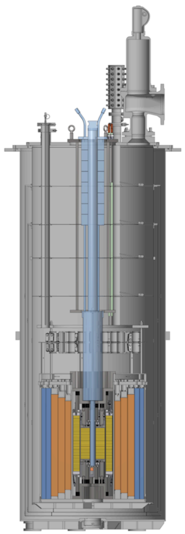
Flux 2D, commercial code

We have now complex HTS applications.







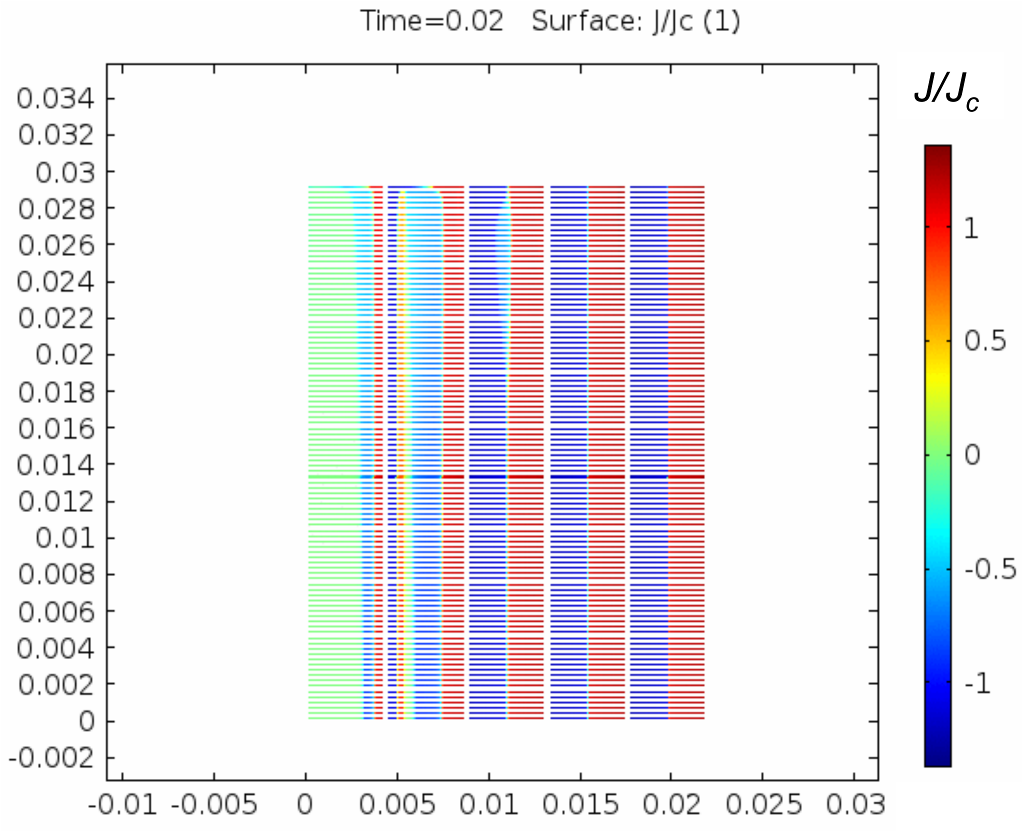


Motors & generators | Cables | Transformers | Magnets

How have models evolved to handle the simulation of such devices?

Increased computing power has helped.

E.g. 500 coated conductors, current distribution at each instant of a cycle



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What is the purpose of this presentation?

1. **Evolution.** To give a glimpse at what it is possible to do now
   - Not a review - apologies in advance for the examples I didn't show
2. **Applications.** To show some examples of how the models have been used to simulate HTS applications
3. **Discussion.** To suggest a few possible topics to the discussion that will follow.

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Evolution

A variety of models has flourished.

8001920 IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 23, NO. 2, APRIL 2013

Analytical Methods and Formulas for Modeling High Temperature Superconductors

Grigorii P. Mikitik, Yasunori Mawatari, Andy T. S. Wan, and Frédéric Sirois, *Senior Member, IEEE*

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 24, NO. 1, FEBRUARY 2014 8200433

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*

IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2015.
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Those models can now handle complex situations.

1. Interacting superconductors

2. 3-D modeling

3. Magnetic materials

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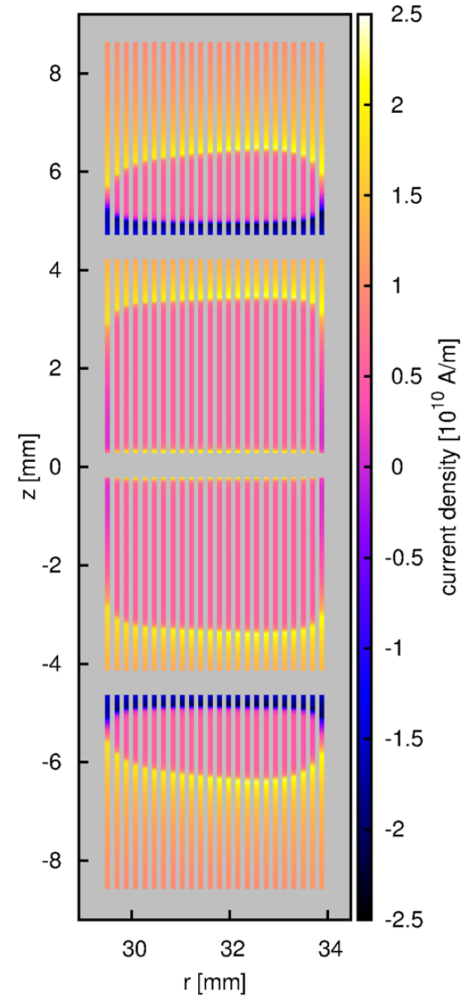
Then, models have been adapted for complex situations.

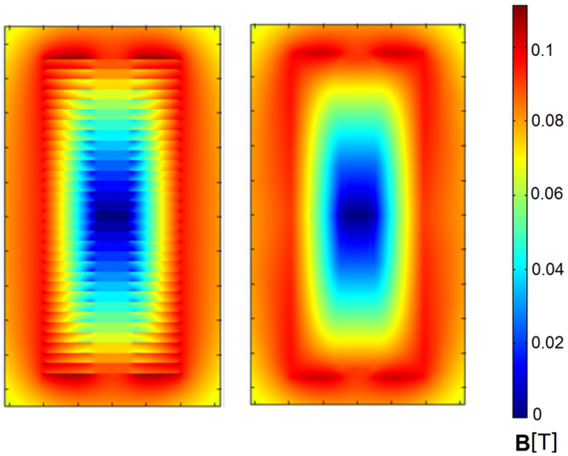
1. Interacting superconductors
   - Simulation of individual tapes



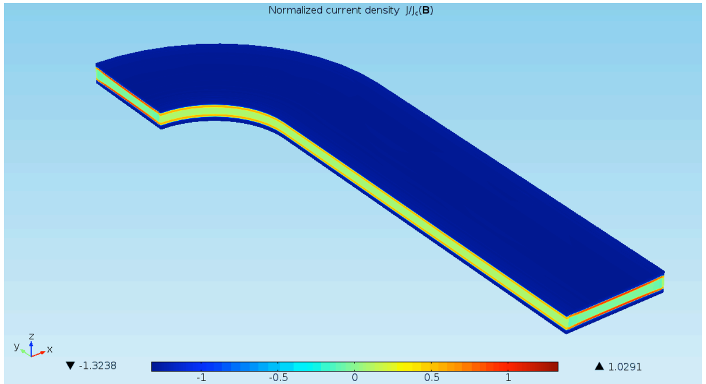
Pardo et al. 2012 SuST **25** (3) 035003

Then, models have been adapted for complex situations.

1. Interacting superconductors
   - Simulation of individual tapes
   - Homogenization



Clem et al., 2007 SuST **20** 1130
Prigozhin et al., 2011 SuST **24** 075012
Yuan et al., 2010 SuST **23** 085011
Zermeno et al., 2013 JAP **114** 173901



Zermeno, Grilli, 2014 SuST **27** 044025

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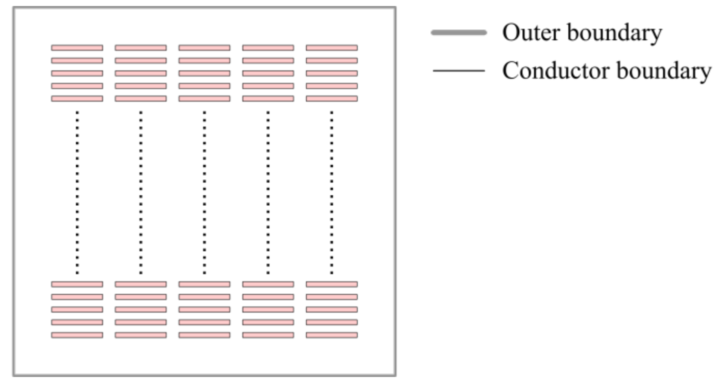
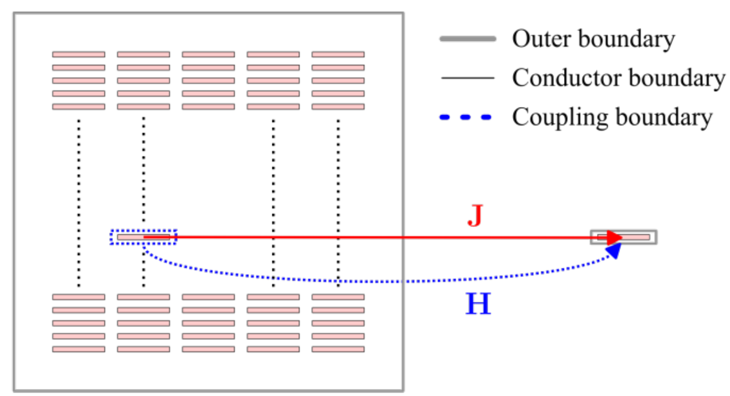
Then, models have been adapted for complex situations.

1. Interacting superconductors
   - Simulation of individual tapes
   - Homogenization
   - Multi-scale





Coil sub-model
A-formulation

Tape sub-model
H-formulation

Queval 2013 IEEE TAS **23** (3) 5201905

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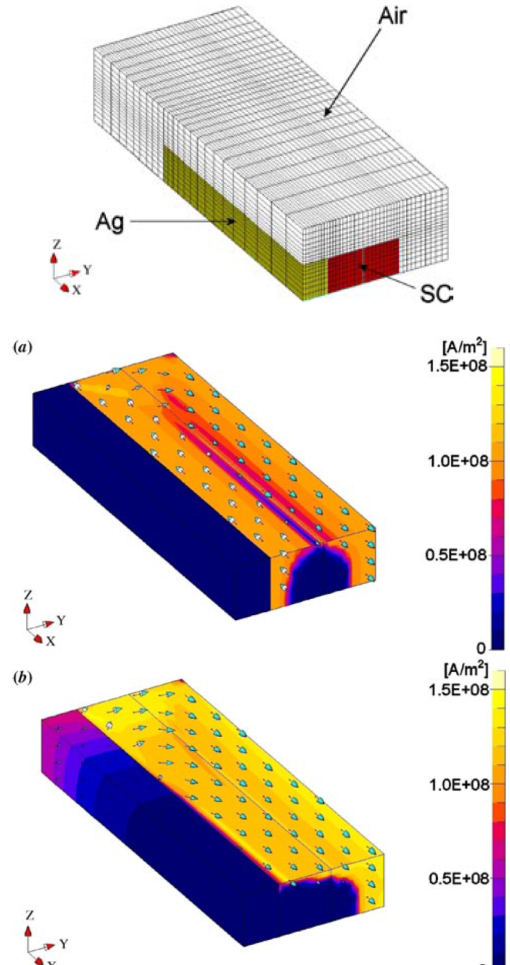
Then, models have been adapted for complex situations.

1. Interacting superconductors
   - Simulation of individual tapes
   - Homogenization
   - Multi-scale
2. 3-D modeling
   - Full 3-D

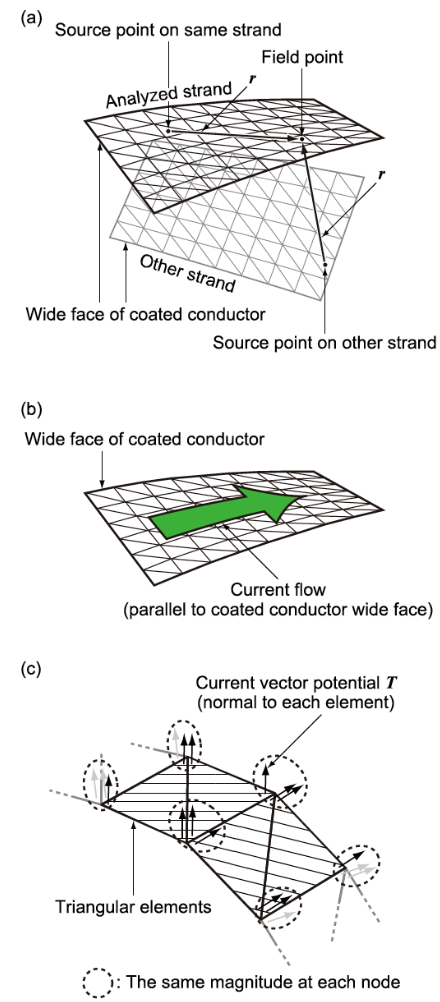


See also E. Pardo's poster in this session

Grilli et al., 2003 SuST **16** 1228

Then, models have been adapted for complex situations.

1. Interacting superconductors
   - Simulation of individual tapes
   - Homogenization
   - Multi-scale
2. 3-D modeling
   - Full 3-D
   - Infinitely-thin-tape approximation



Nii et al., 2012 SuST **25** 095011

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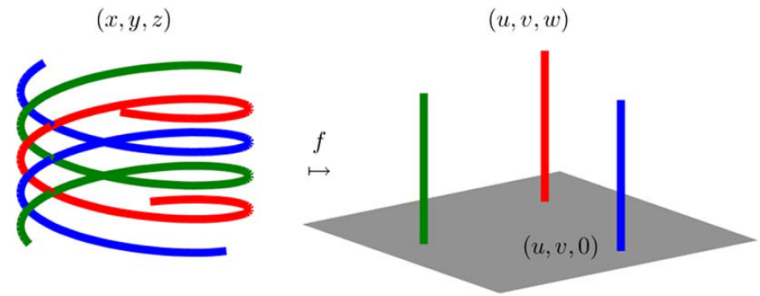
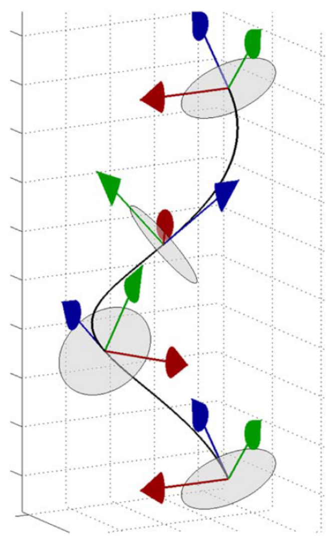
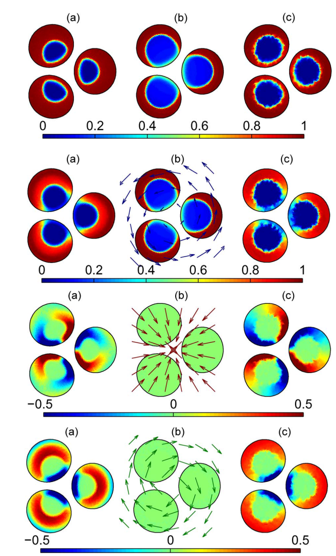
   - Simulation of individual tapes
   - Homogenization
   - Multi-scale
2. 3-D modeling
   - Full 3-D
   - Infinitely-thin-tape approximation
   - Change of coordinates







Stenvall et al., 2013 IEEE TAS **23** (3) 8200105

Then, models have been adapted for complex situations.

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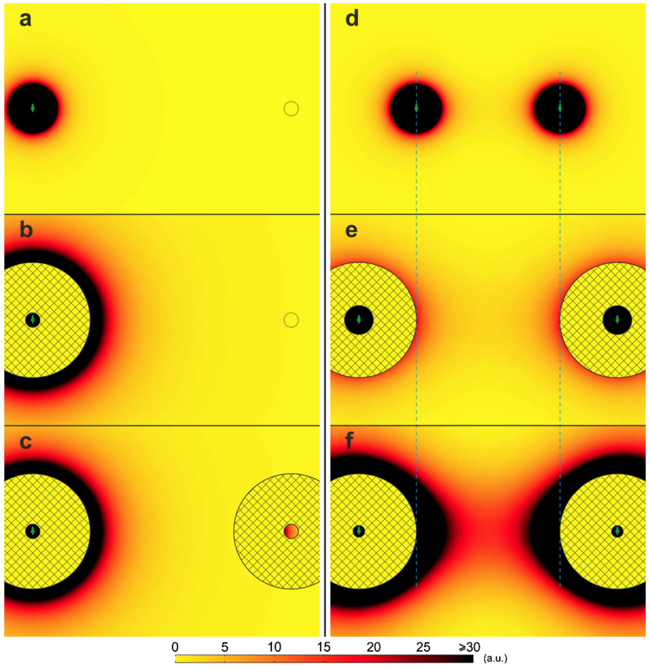
   - Simulation of individual tapes
   - Homogenization
   - Multi-scale
2. 3-D modeling
   - Full 3-D
   - Infinitely-thin-tape approximation
   - Change of coordinates
3. Magnetic materials
   - Flux concentration/transportation



Navau et al., 2012 PRL **109** 263903

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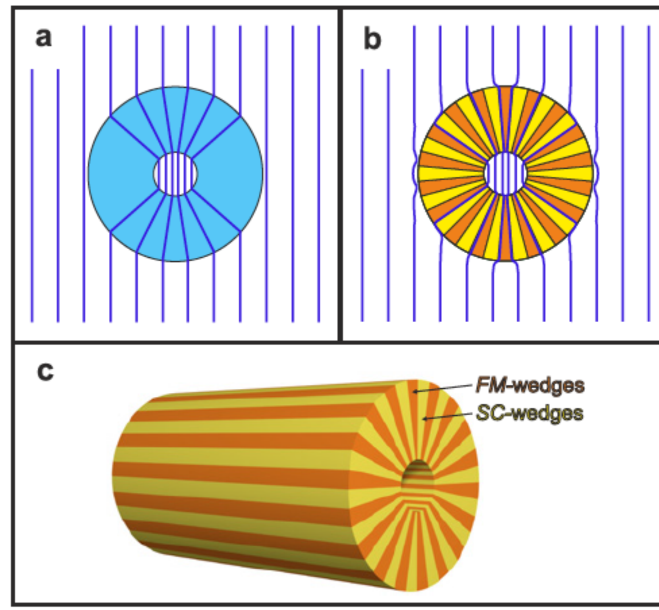

Prat-Camps et al., 2013 SuST **26** 074001

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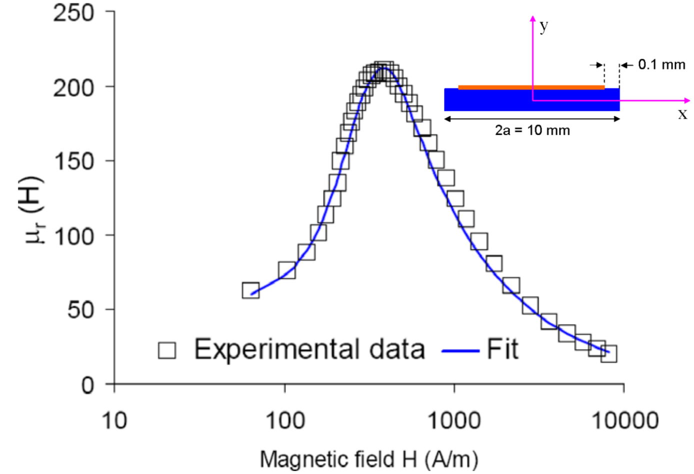
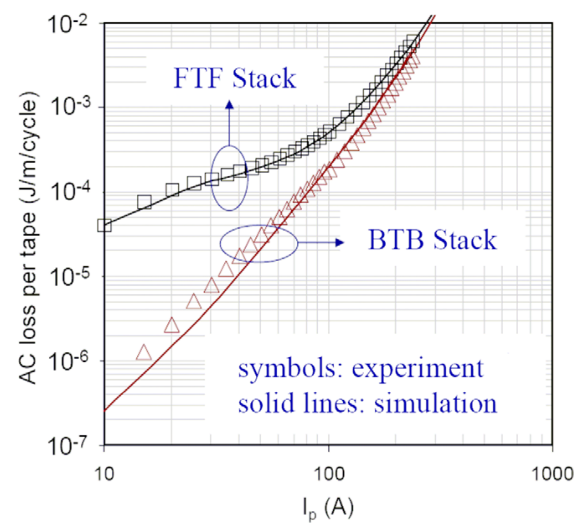
   - Multi-scale
2. 3-D modeling
   - Full 3-D
   - Infinitely-thin-tape approximation
   - Change of coordinates
3. Magnetic materials
   - Flux concentration/transportation
   - Handling two non-linearities





Nguyen et al., 2010 SuST **23** 025001

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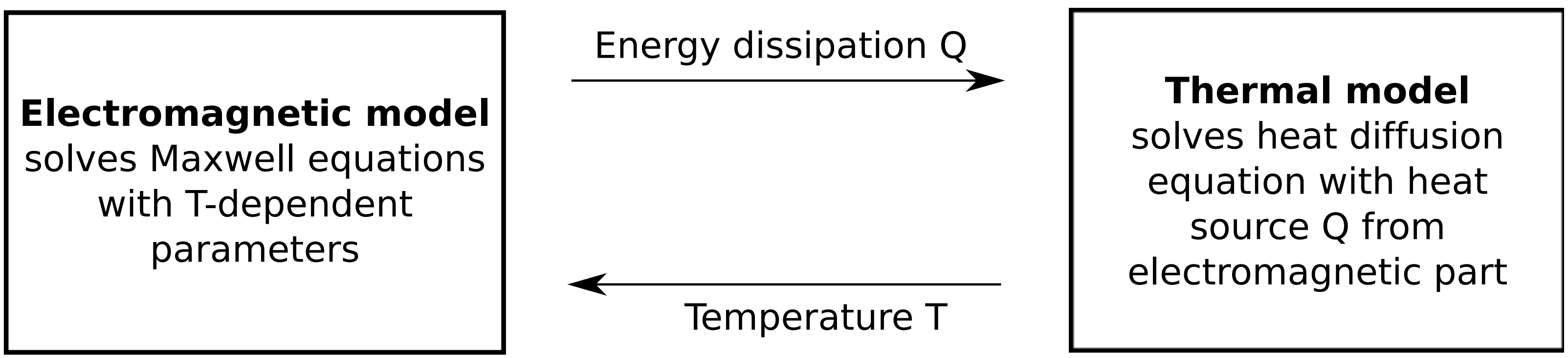
Beyond electromagnetics: thermal models

Electromagnetic-thermal coupling



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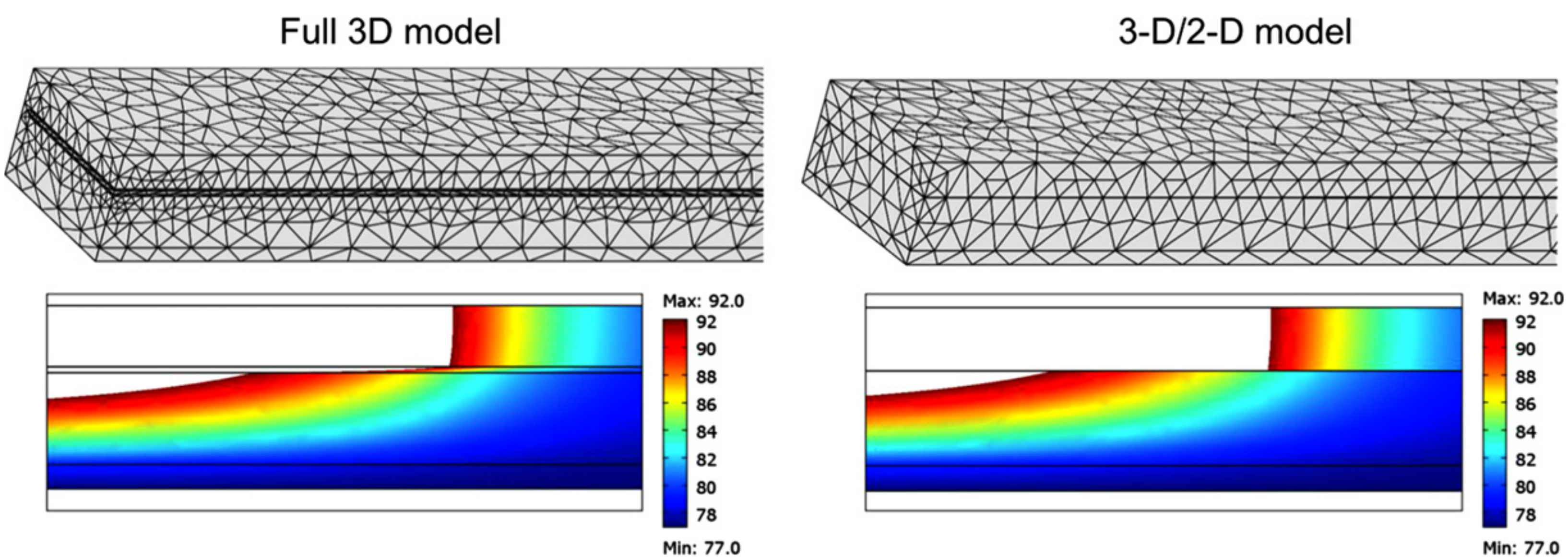
Beyond electromagnetics: thermal models

- Electromagnetic-thermal coupling

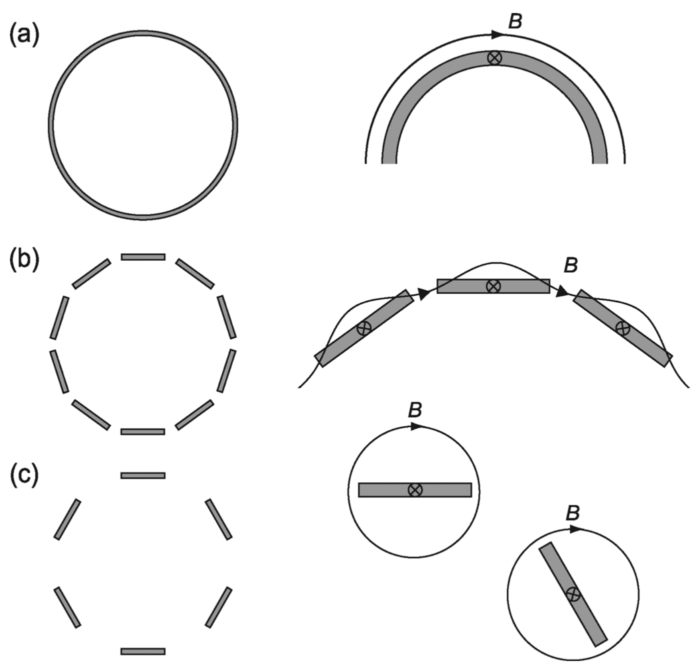


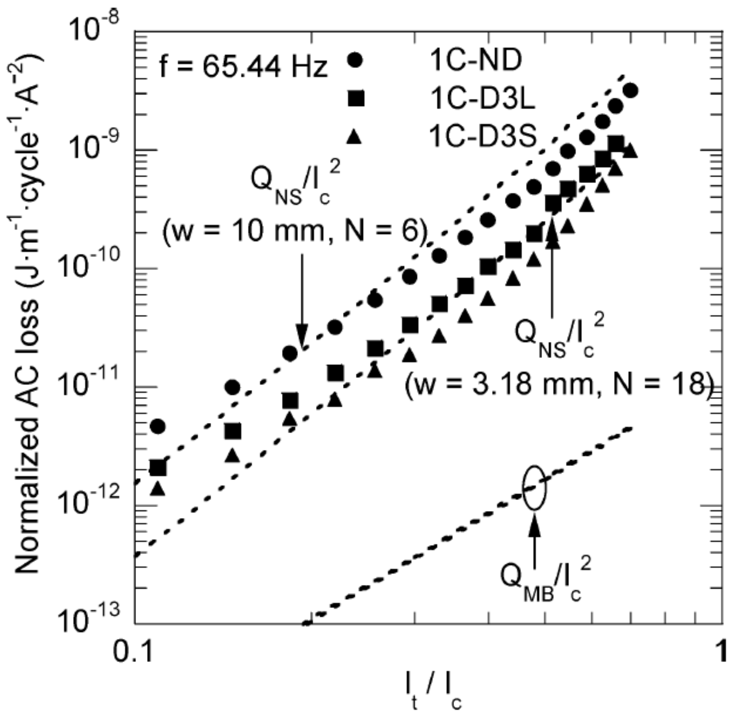
Chan et al., 2012 IEEE TAS **22** (5) 4706010

Applications

Cables (for power transmission)

- Generally simulated in 2-D, axial field neglected
- Good agreement with experimental data

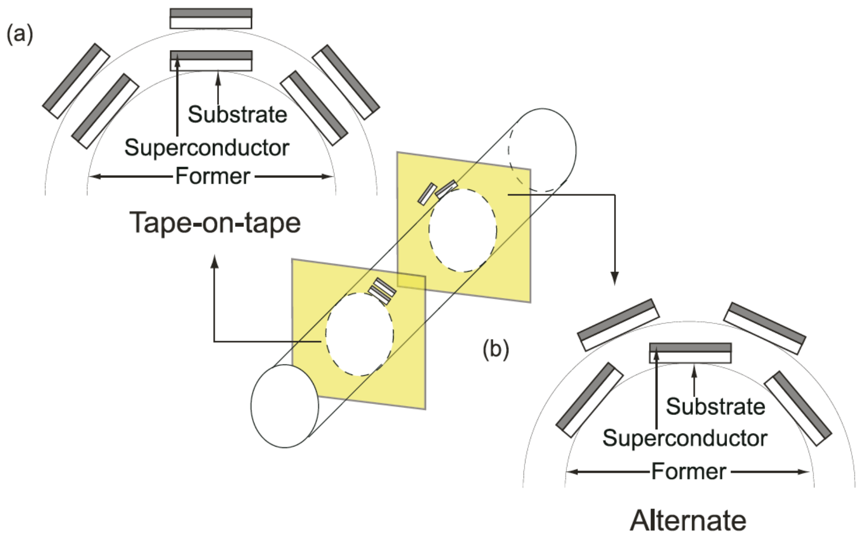


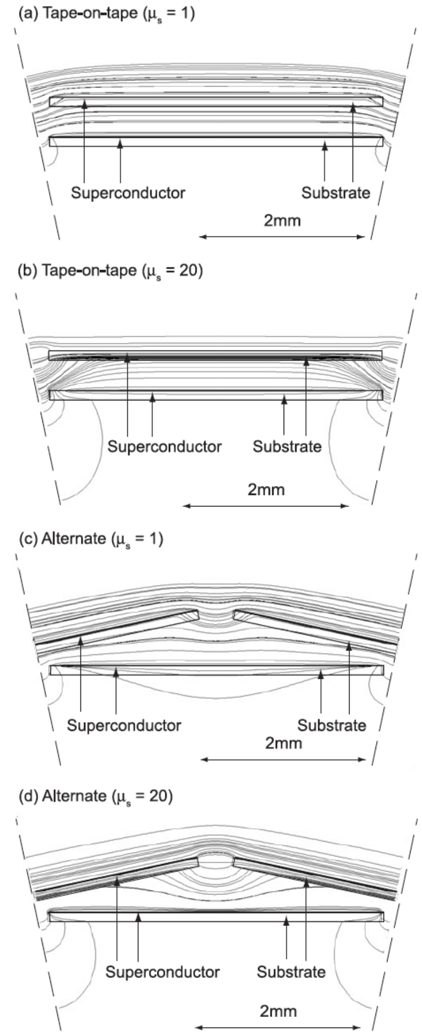


Amemiya et al., 2012 IEEE TAS **17** (2) 1712

Cables (for power transmission)

- “2.5-D” to handle changing relative tape position in multi-layer cables

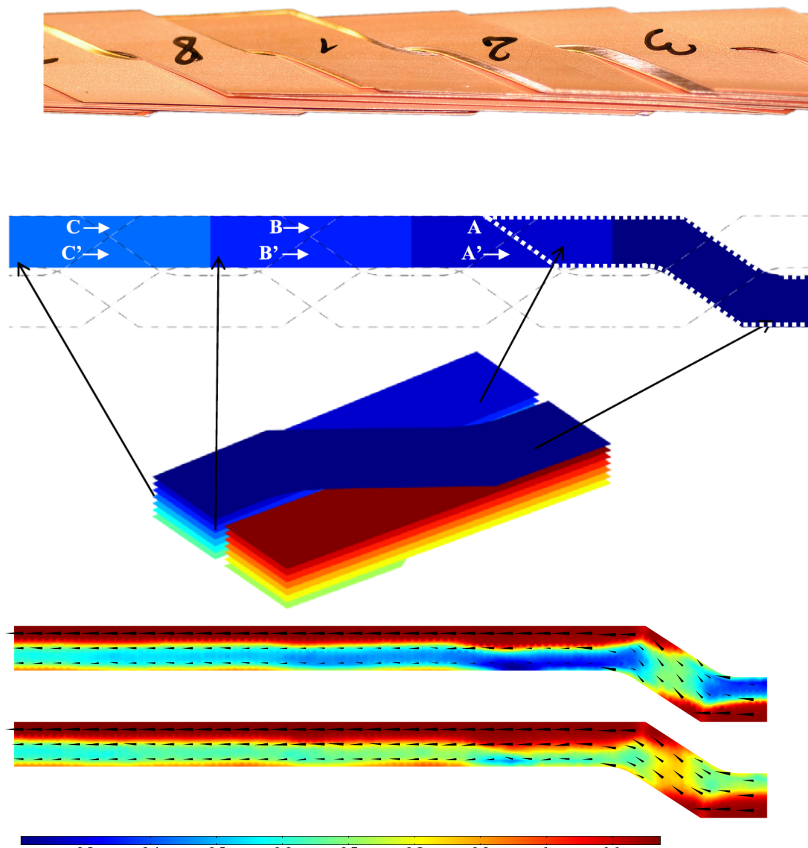




Nakahata and Amemiya, 2008 SuST **21** 015007

Cables (Roebel)

Full 3-D model: x00,000 DOFs, days of simulations



Zermeno et al., 2013 SuST **26** 052001

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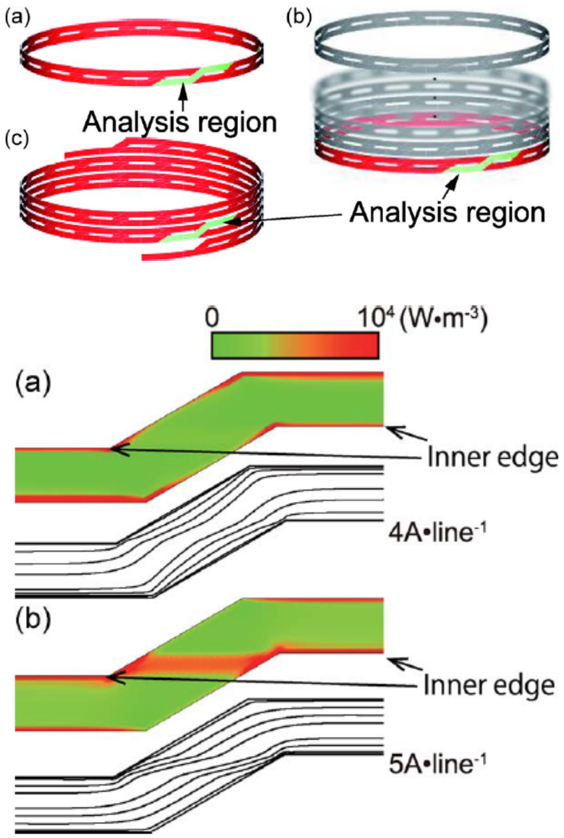
Cables (Roebel)

Infinitely thin tape approximation



Nii et al., 2012 SuST **25** (9) 095011
Sogabe et al., 2014 IEEE TAS **24** (3) 4803005

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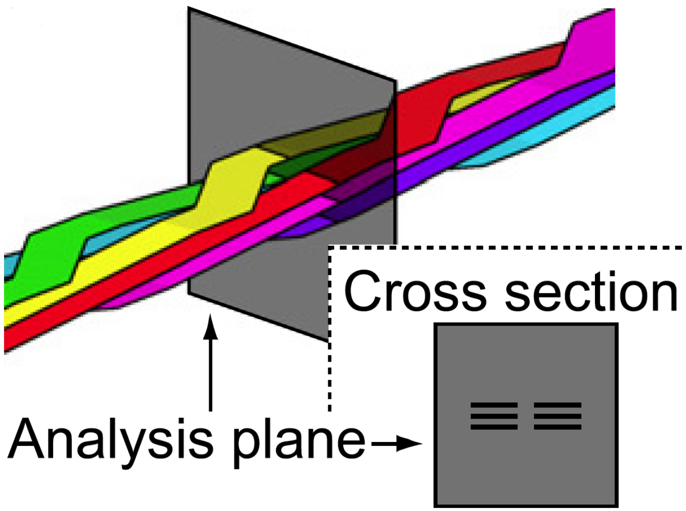
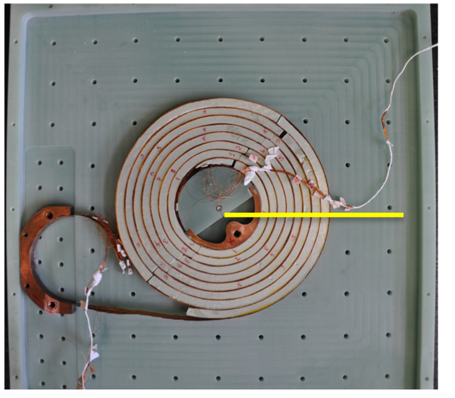
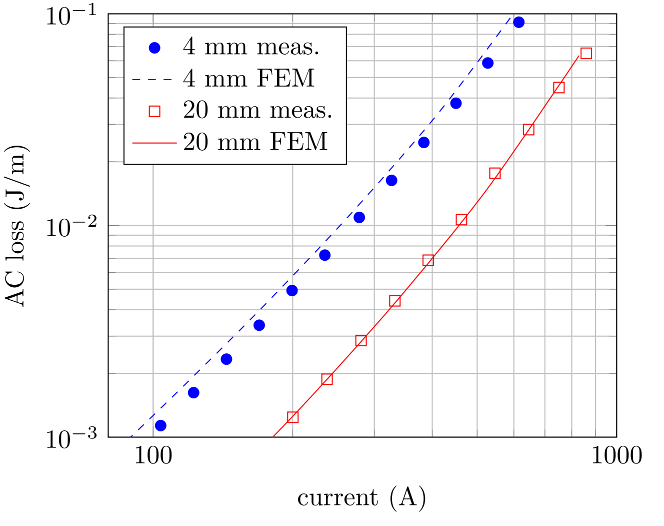
Cables (Roebel)

For many purposes, simulation of the 2-D cross-section is sufficient

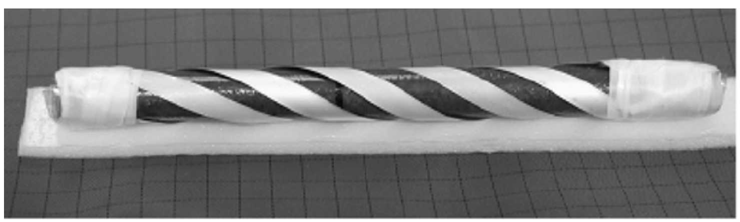


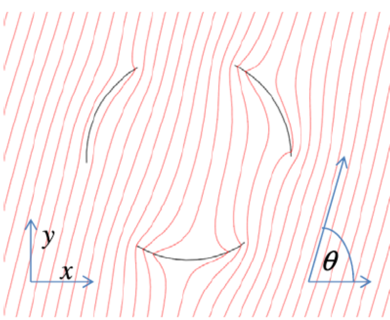




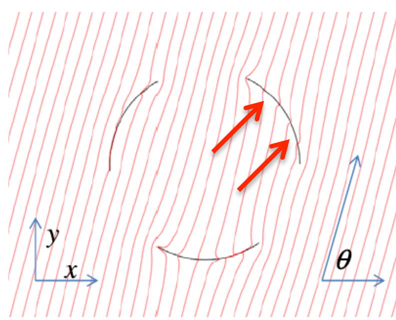
Cables (CORC)

- In principle, the axial field cannot be neglected
- Magnetization losses of a 1-layer cable (with filaments) were reproduced by successive 2-D simulations.

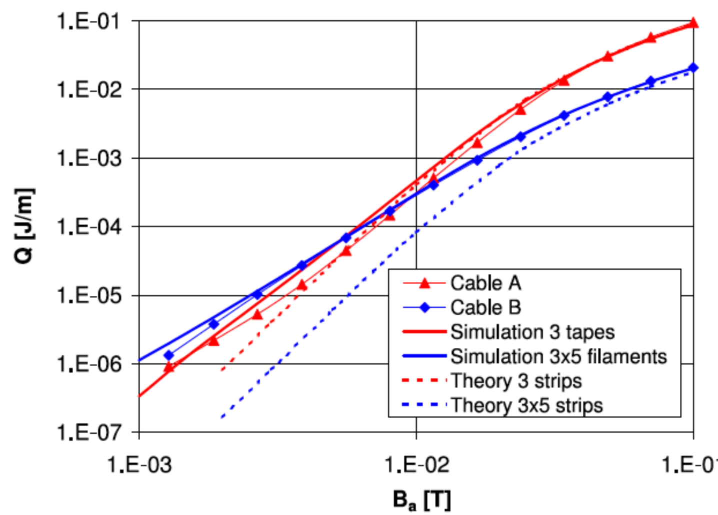




3 tapes, no filam.



3 tapes, 3 filam.



Souc et al., 2013 SuST **26** (7) 075020

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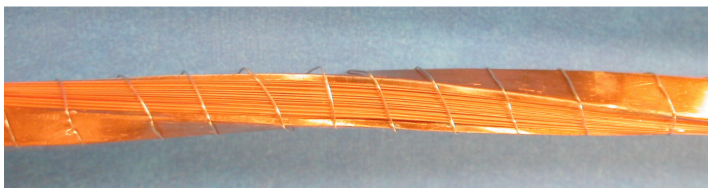
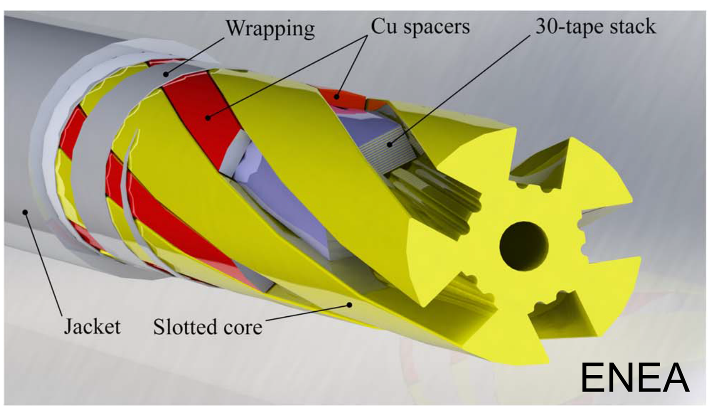
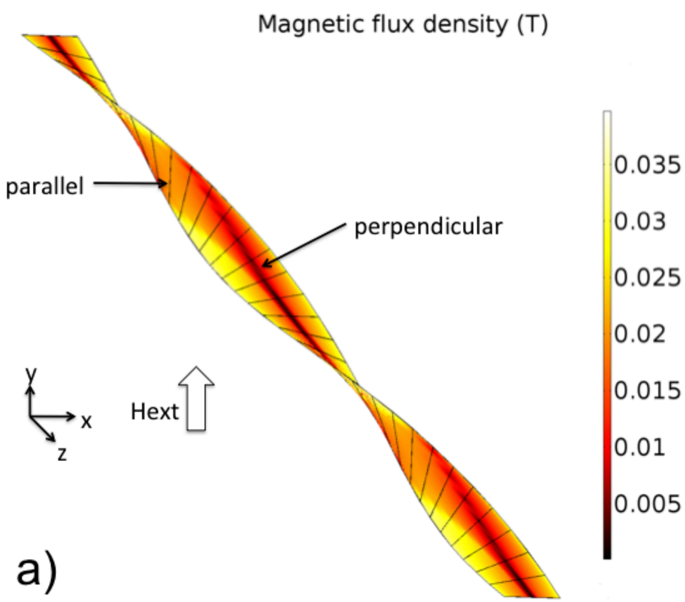
Cables (TSTC): complex, generally 3-D

In principle, they can be simulated by a series of 2-D slices

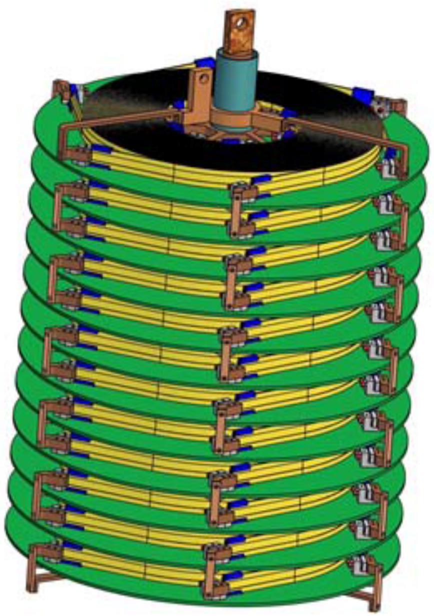


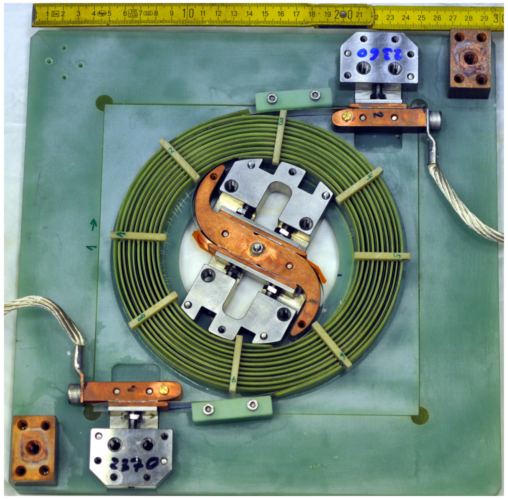


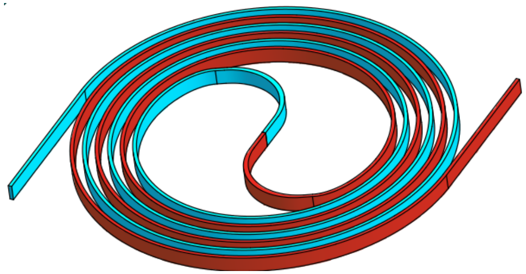


Fault current limiters

- Resistive FCLs: (bifilar) coils
- Simulation of electromagnetic behavior: no particular problems

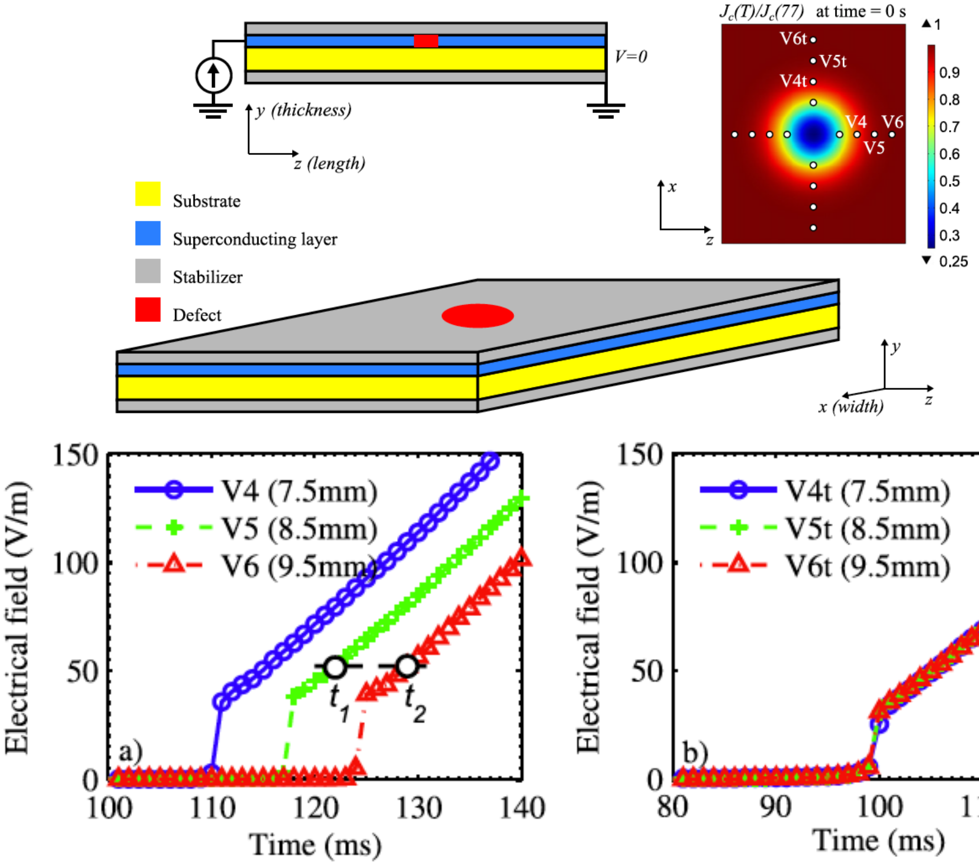






Fault current limiters

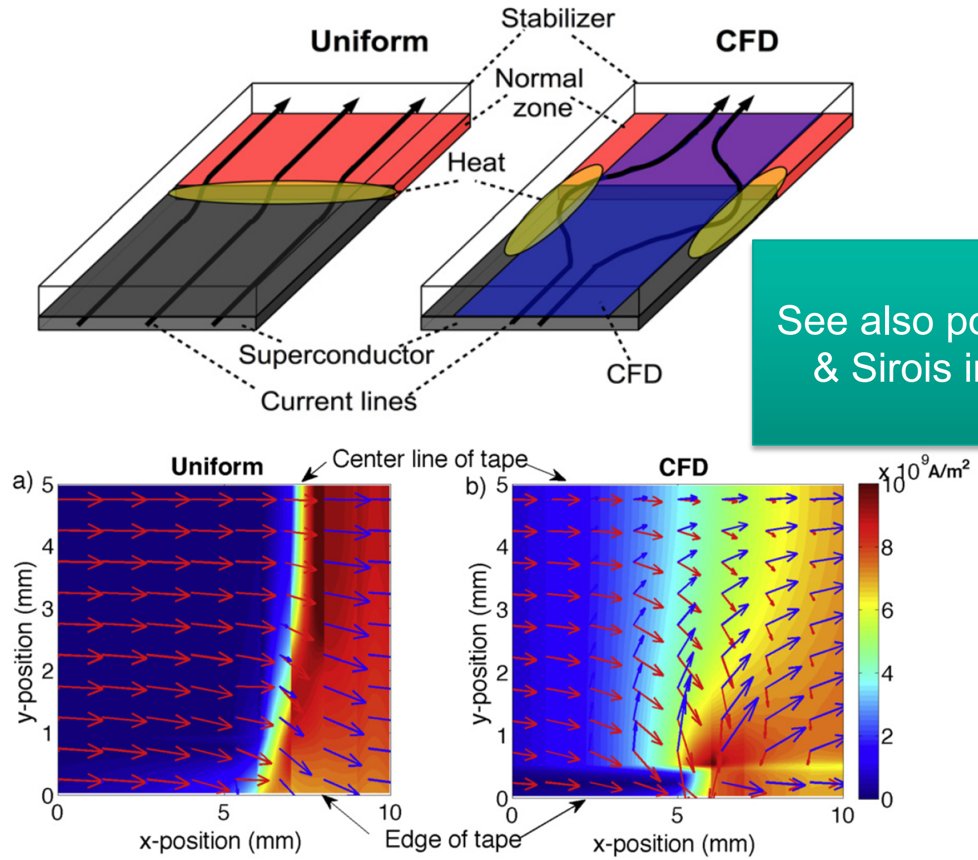
Quench propagation → normal zone propagation velocity (NZPV)



Colangelo and Dutoit, 2014 SuST **27** 124005

Fault current limiters

New tape architecture with higher NZPV (current flow diverter)

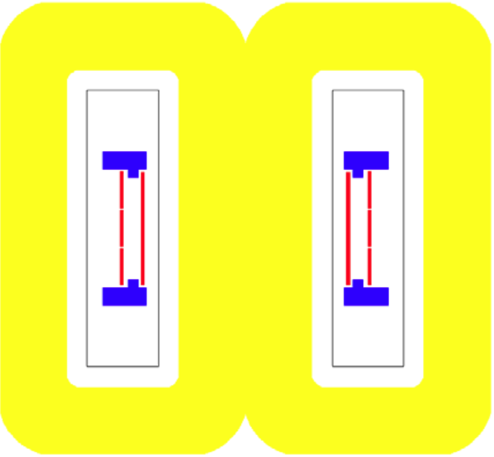


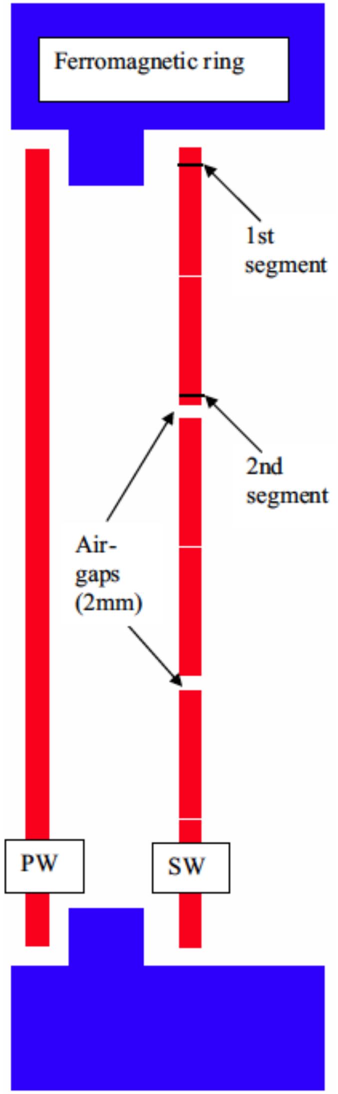
See also poster by Lacroix & Sirois in this session

Lacroix and Sirois, 2014 SuST **27** 035003

Transformers

- Axisymmetric models with multiple tapes

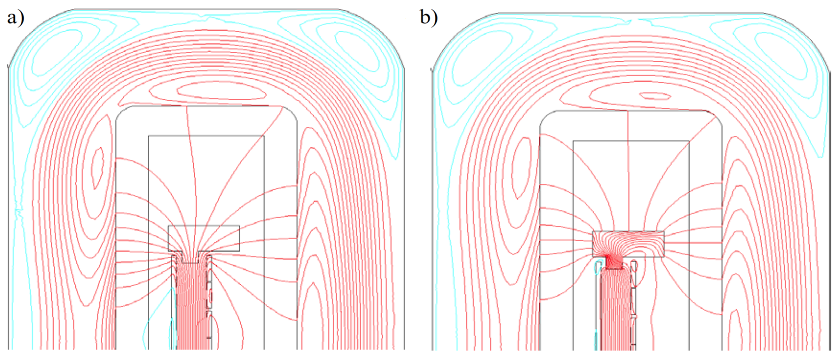


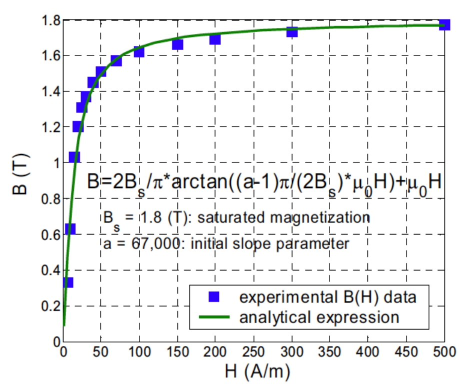


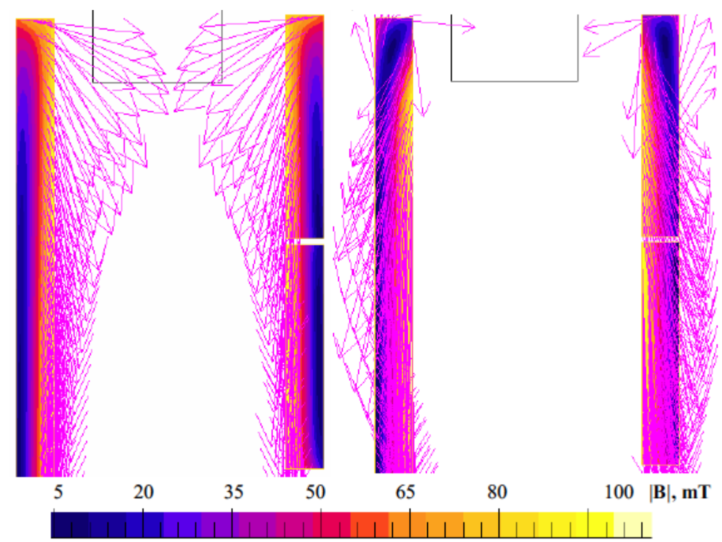
Stavrev et al., 2004 IOP Conf. Ser. **181** 1083

Transformers

- Axisymmetric models with multiple tapes







Stavrev et al., 2004 IOP Conf. Ser. **181** 1083

IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2015.
Invited keynote presentation 3A-LS-O1.2 given at EUCAS 2015; Lyon, France, September 6 – 10, 2015.
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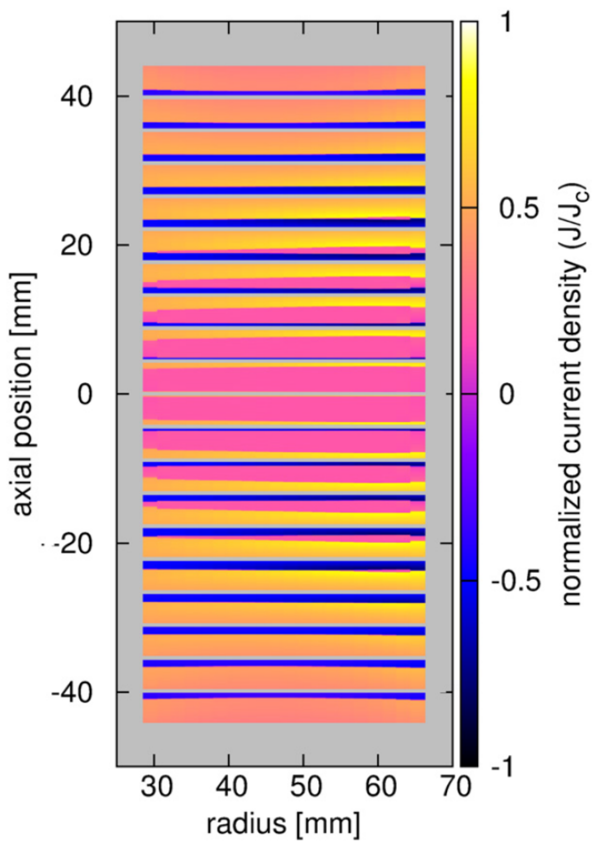
Large coils and magnets

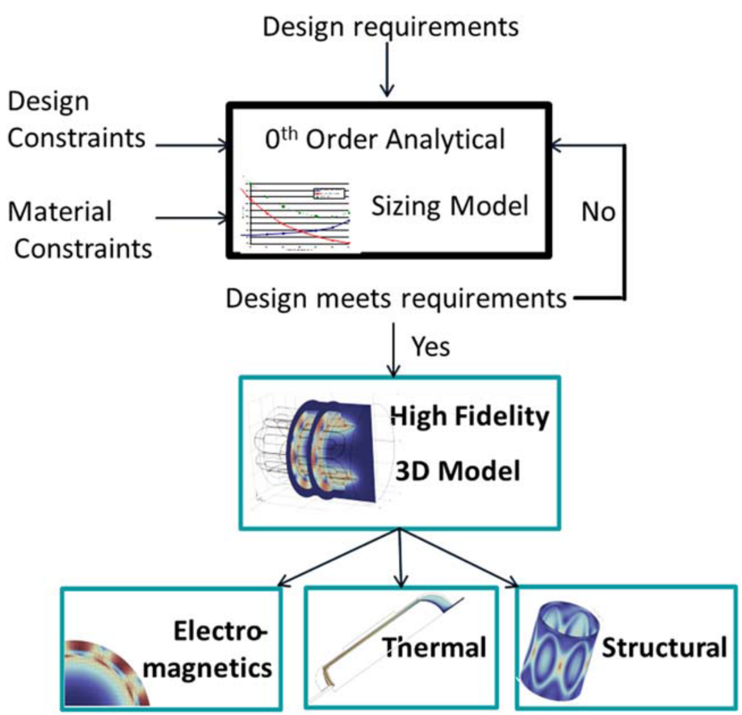
- Very large number of turns, simulation of all 1000+ turns demonstrated
- Homogenization technique: valid alternative to reduce problem size

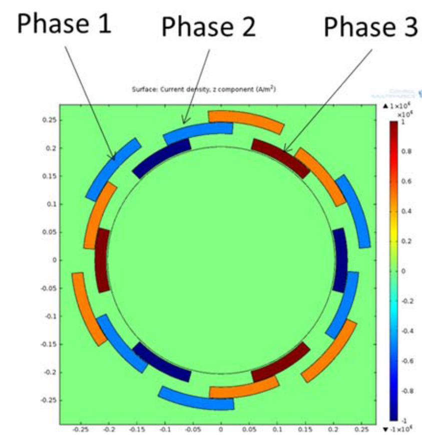


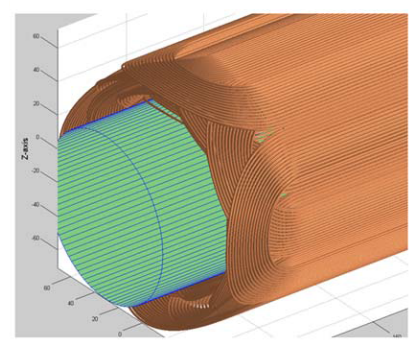
20 pancakes, 200 turns each

Pardo et al., 2015 SUST **28** (4) 044003

Electrical machines







Masson et al., 2013 IEEE TAS **23** (3) 3600805

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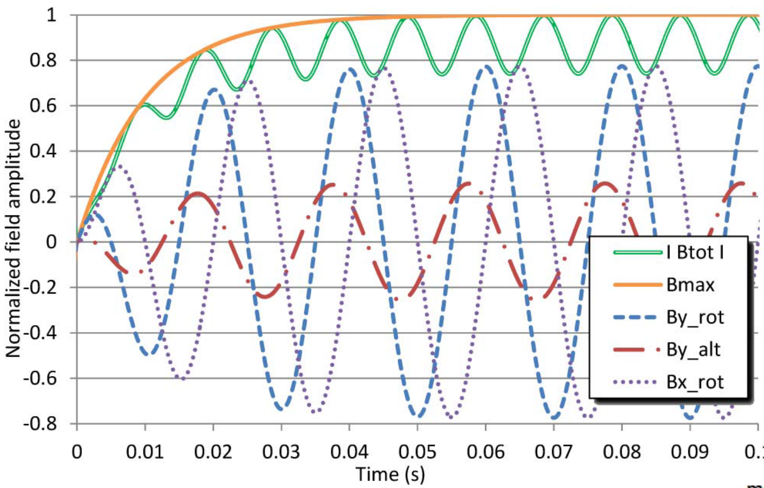
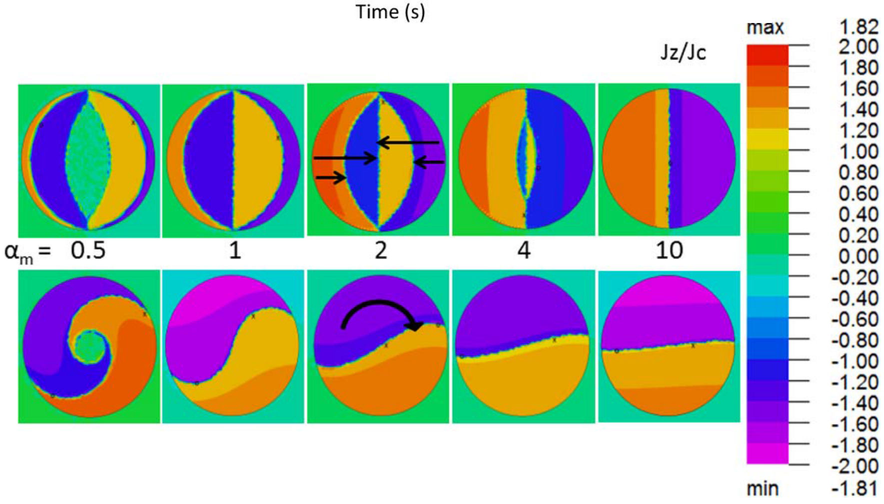
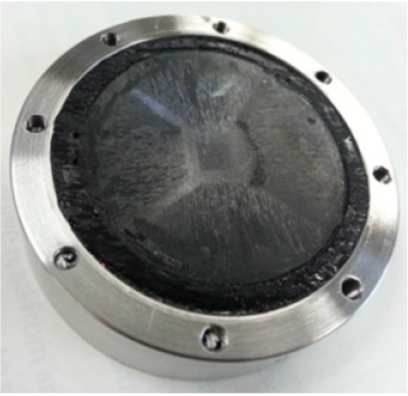




Lorin and Masson, 2013 IEEE TAS **23** (3) 8201405

Numerical modeling of bulks

- Magnetization pulses → Full electromagnetic-thermal model necessary
- Simple geometry allows for 3-D



$$\rho \cdot C \frac{\mathrm{d}T}{\mathrm{d}t} = \nabla \cdot (k \nabla T) + Q$$

$$J_{c0}(T) = \alpha \left[1 - \left(\frac{T}{T_c} \right)^2 \right]^{1.5}$$

Ainslie et al., 2014 SuST **27** 065008

REVIEW: Ainslie et al., 2015 SuST **28** 053002

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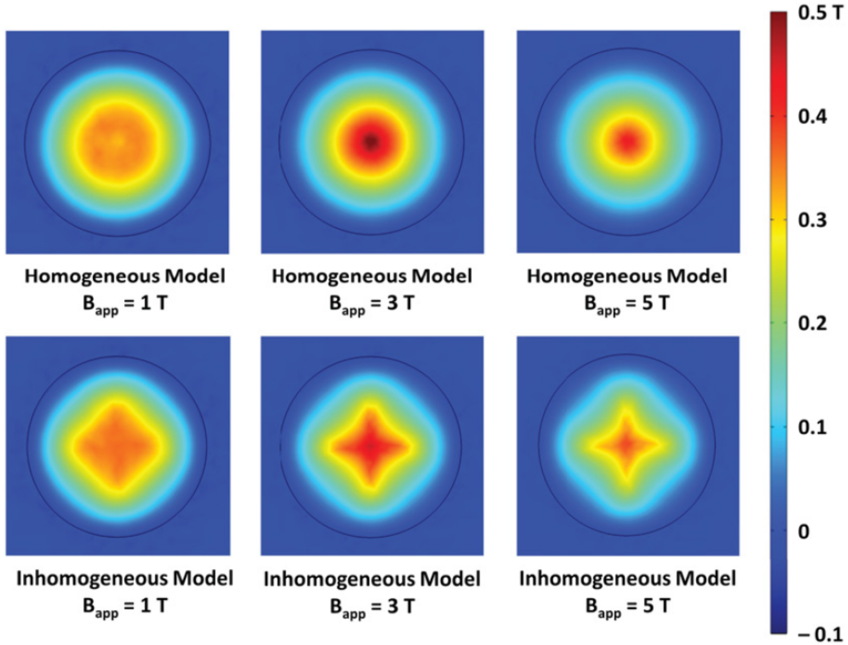
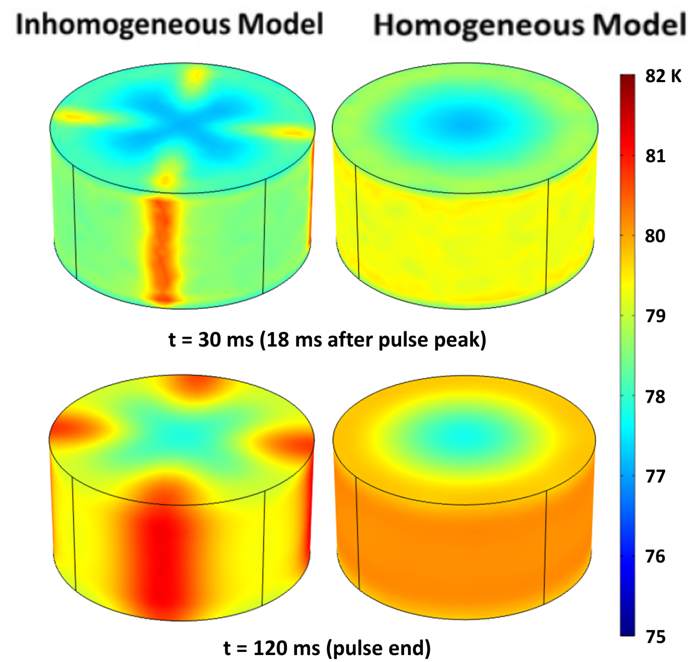


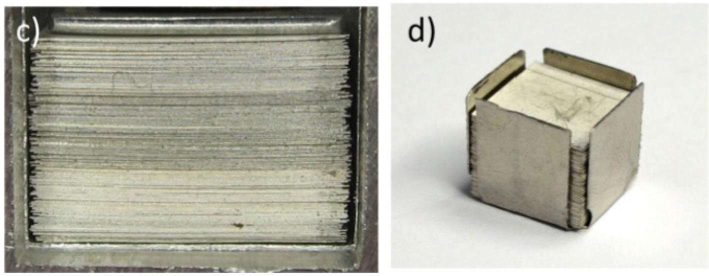


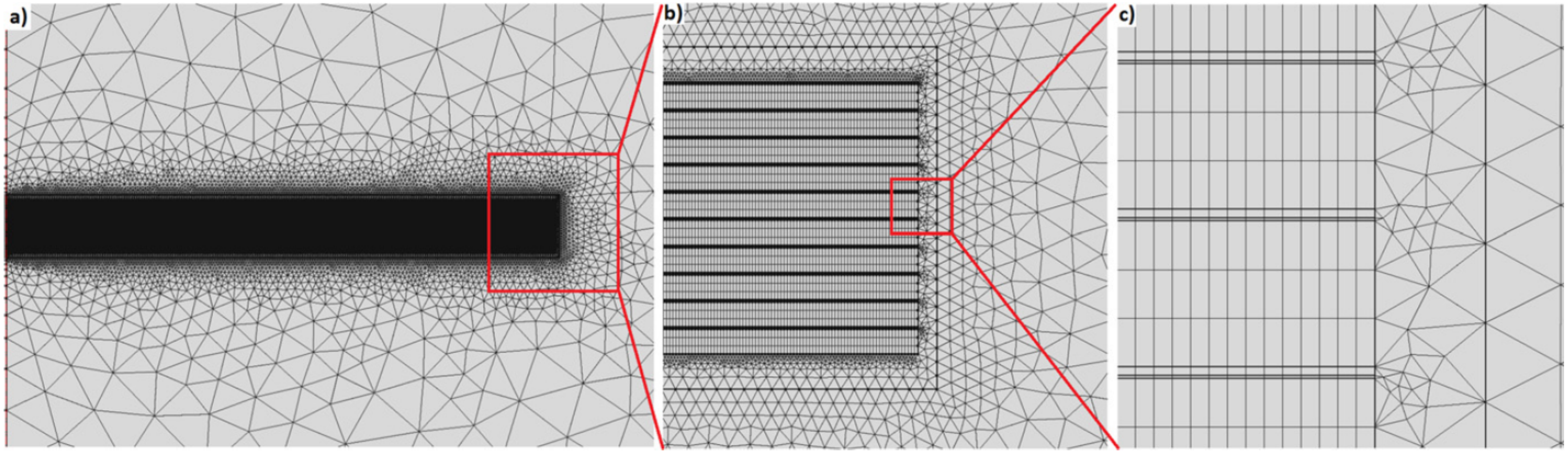
Ainslie et al., 2014 SuST **27** 065008

REVIEW: Ainslie et al., 2015 SuST **28** 053002

What about stacks of HTS as permanent magnets

Similar approach to bulks, but more challenging geometry → 2-D only





Patel et al, 2013 SuST **26** 032001   Page et al., 2015 SuST **28** (2) 053002

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Open challenges & possible topics for discussion

- To make the modeling palette complete:
  - Basic aspects (e.g. flux cutting, top/bottom losses,…)
  - Complexity: modeling of multi-layer cables in 3-D (HTS CORC / MgB_2)
  - New modeling approaches still necessary and welcome!
- To make the models useful for designing actual devices
  - Materials' properties available in wide range of temperatures and fields
  - Improvement of computation speed (adaptive solvers etc.)
- To avoid work duplication and advance faster
  - Sharing models
  - Sharing materials' properties

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Share & Collaborate

HTS MODELLING WORKGROUP

Modelling of high temperature superconductors (HTS)

WELCOME! | BOARD | MODEL FILES | BENCHMARKS | WORKSHOPS | PUBLICATIONS

Shared models

See also poster by V. Zermeño in this session

This page contains the following shared examples of numerical models:

1. Integral equation for thin conductors solved by finite-elements (Comsol);
2. 2-D H-formulation of Maxwell's equations with edge elements (Comsol, FlexPDE);
3. 2-D homogeneous model to estimate AC losses in coated conductor stacks and coils (Comsol);
4. 3-D homogeneous model to estimate AC losses in coated conductor stacks and coils (Comsol);
5. 2-D Campbell's model to estimate magnetization losses in a wire in the critical state (FreeFem++);
6. 2-D model for magnetization of superconducting bulks (Comsol)
7. 3-D model for magnetization of superconducting bulks (Comsol)

Feel free to download the files and use them!

If you use them for your presentations/publications, please cite the related references.

Thank you for listening!

I also would like to thank the people who helped me put together the material for this talk and clarify some aspects:

Frederic Sirois, Daniele Colangelo, Victor Zermeno, Mark Ainslie,
Enric Pardo, Michal Vojenciak, Antti Stenvall