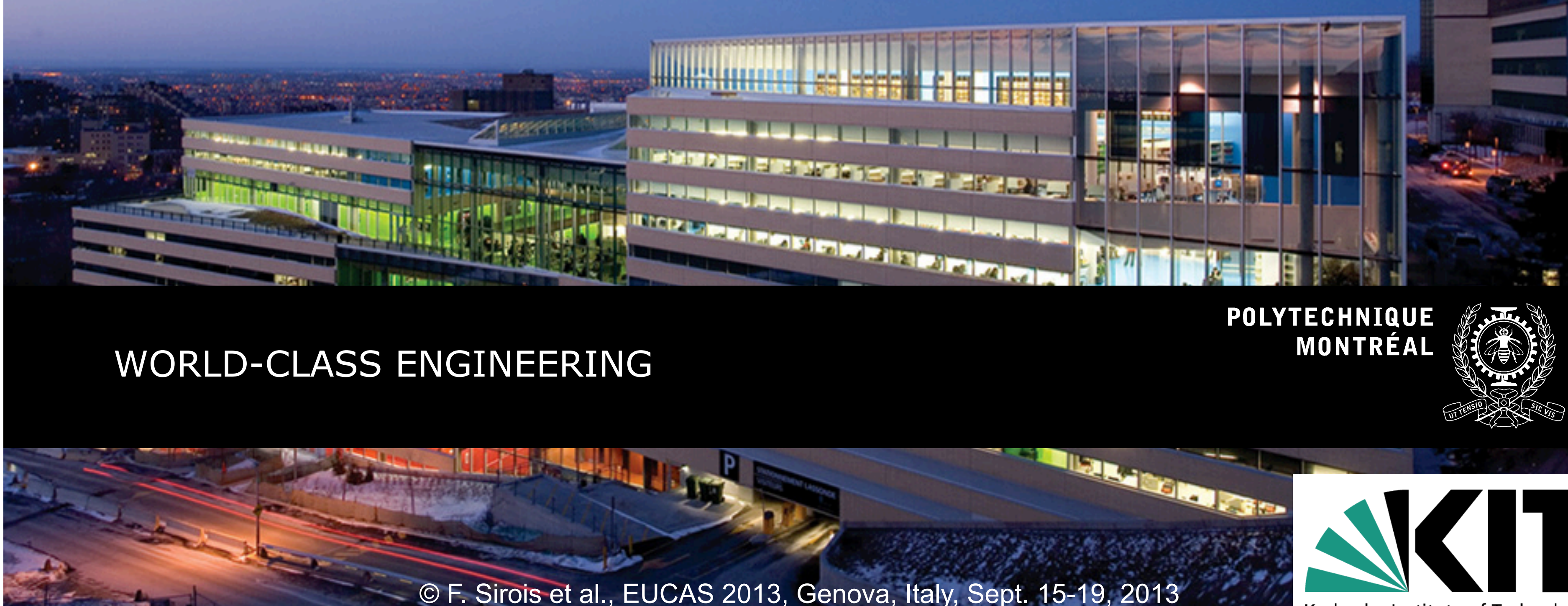
Invited presentation 4M-LS-I1 at EUCAS 2013

Potential and limits of numerical modelling for supporting the development of HTS devices

Frédéric Sirois, Francesco Grilli and many collaborators



WORLD-CLASS ENGINEERING

POLYTECHNIQUE MONTRÉAL

Karlsruhe Institute of Technology

ACKNOWLEDGEMENTS

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PRESENTATION OUTLINE

1) Context and need for numerical modelling

2) Overview of models and numerical methods

3) Paths towards improvement

4) Conclusion

PRESENTATION OUTLINE

1) **Context and need for numerical modelling**

2) Overview of models and numerical methods

3) Paths towards improvement

4) Conclusion

1) CONTEXT AND NEED FOR NUMERICAL MODELLING
→ *EVOLUTION OF HTS DEVICES*

- Status of HTS devices development
    - Good progression, many prototypes over the years
    - Some commercial devices already exist (SFCLs, motors)
    - Still need to reduce the cost of 2G HTS wires
    - A few other things still deserve attention, e.g.
        - cost and reliability of cooling systems
        - mixture of high voltages and cryogenic temperatures
        - etc.
- One common tool can help in addressing many of the above problems:
    - **Numerical modelling**

1) CONTEXT AND NEED FOR NUMERICAL MODELLING
→ *WHY IS NUMERICAL MODELLING REQUIRED?*

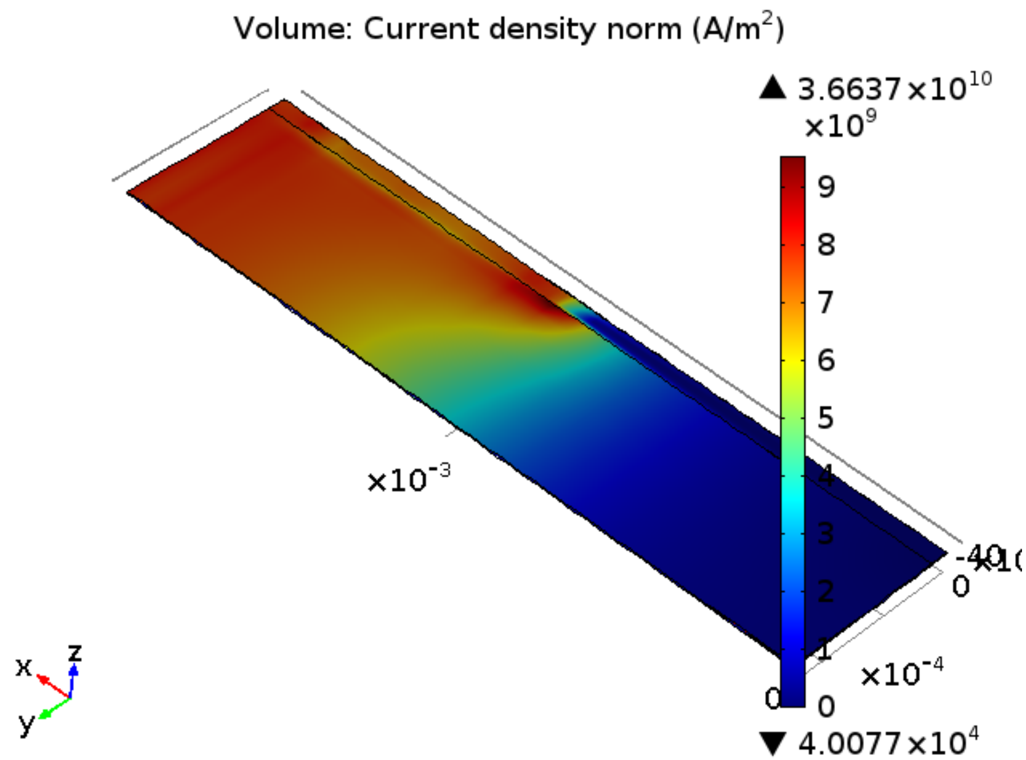
- Generic reasons (true in all fields)
  - Allows optimization of devices + cost reduction by
    - making the best use of materials and components
    - reducing the number of prototypes during the development stage
- Reasons specific to HTS materials and devices
  - Highly nonlinear/anisotropic E-M behaviour
  - Hard to intuitively find
    - geometric arrangements minimizing the losses
    - the most economical configurations of windings
    - etc.

1) CONTEXT AND NEED FOR NUMERICAL MODELLING
→ *WHY IS NUMERICAL MODELLING REQUIRED?*

- From a general/commercial perspective
  - HTS devices performance is conditioned by its environment: notion of system
  - There exists competing technologies
- Numerical modelling can be used to
  - compare performances of different technologies
  - assess the performances of HTS devices, either as
    - individual devices (**physical models**, e.g. FEM)
    - elements of a system (**macroscopic models**, e.g. equivalent circuit models)

1) CONTEXT AND NEED FOR NUMERICAL MODELLING
→ *EXAMPLE OF PHYSICAL MODEL*

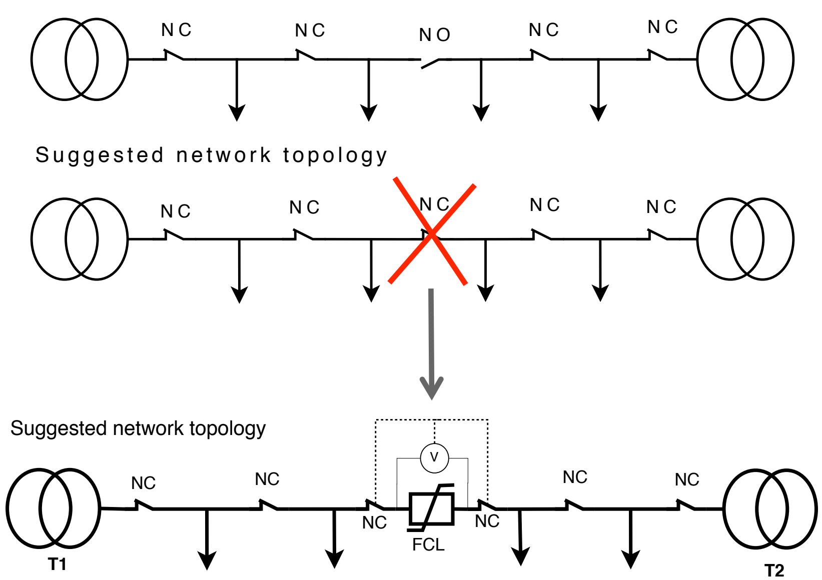
- Modelling of quench in 2-G HTS tapes



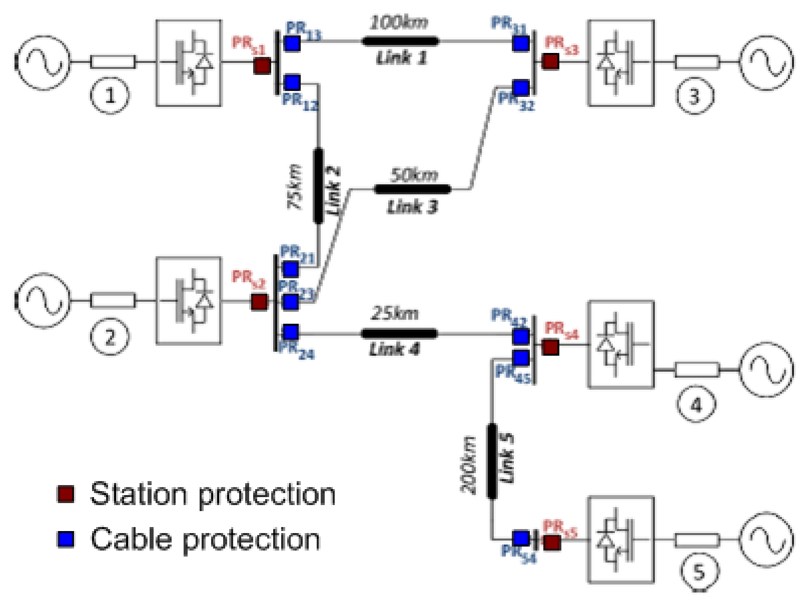
C. Lacroix, 2013.

1) CONTEXT AND NEED FOR NUMERICAL MODELLING
→ *EXAMPLE OF MACROSCOPIC MODEL*

- Impact of SFCL in power systems



a) Meshing of distribution systems

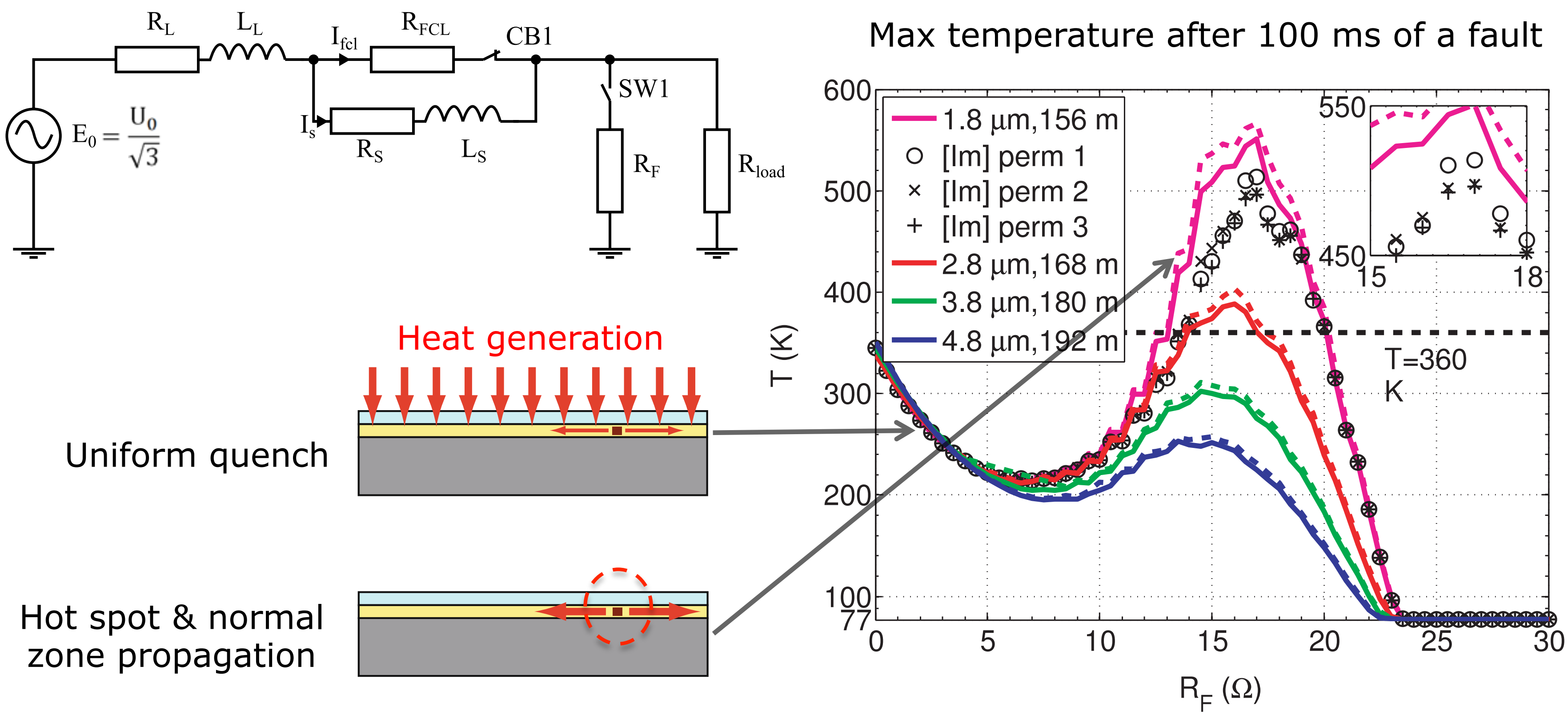


b) Protection of DC multi-terminal systems

C. Gandioli et al., IEEE Trans. Appl. Supercond., 23 (3), 2013

1) CONTEXT AND NEED FOR NUMERICAL MODELLING
→ *EXAMPLE OF DEVICE/SYSTEM INTERACTION*

- Local temperature elevation in SFCL vs. fault impedance



D. Colangelo and B. Dutoit, *Supercond. Sci. Tech.*, 25 (9), p. 095005, 2012.
F. Roy et al., *Physica C*, 469 (15), pp. 1462–1466, 2009.

PRESENTATION OUTLINE

1) Context and need for numerical modelling

2) **Overview of models and numerical methods**

3) Paths towards improvement

4) Conclusion

2) OVERVIEW OF MODELS AND NUMERICAL METHODS
→ *MODEL VS. NUMERICAL METHOD*

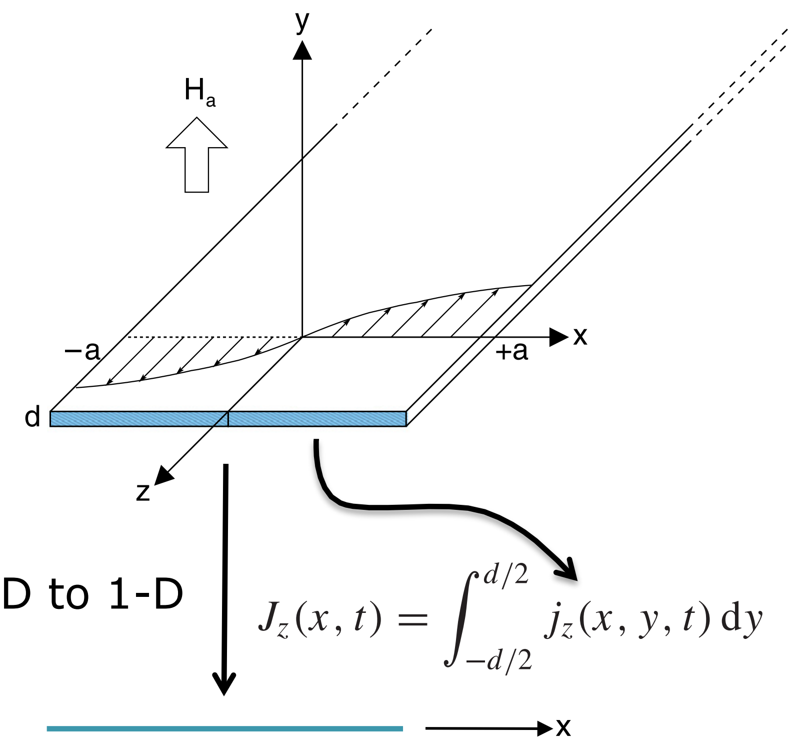
- **Model:**
  - Mathematical representation of a physical (or other) behavior, based on
    - relevant hypothesis
    - simplifying assumptions
  - e.g. *Power-law model* (PLM) vs. *Critical state model* (CSM) (one considers flux creep, the other does not)
- **Numerical method:**
  - Systematic approach to
    - express models in a discrete form
    - solve the resulting system of equations
  - e.g. *Finite element method* (FEM), *point collocation method*, etc.

2) OVERVIEW OF MODELS AND NUMERICAL METHODS
→ *WHAT IS A "GOOD MODEL" ?*

- The quality/effectiveness of a model highly relies on the "smartness" of the assumptions behind it
- Typical considerations:
  - Necessary to simulate the whole device?
    - Symmetries/periodicities?
    - Dimensionality reduction (3D→2D or "2.5D", etc.)?
  - What level of accuracy?
    - Absolute accuracy vs. prediction of trends?
    - How accurate are experiments anyways?
    - Needs of industry vs. academics?

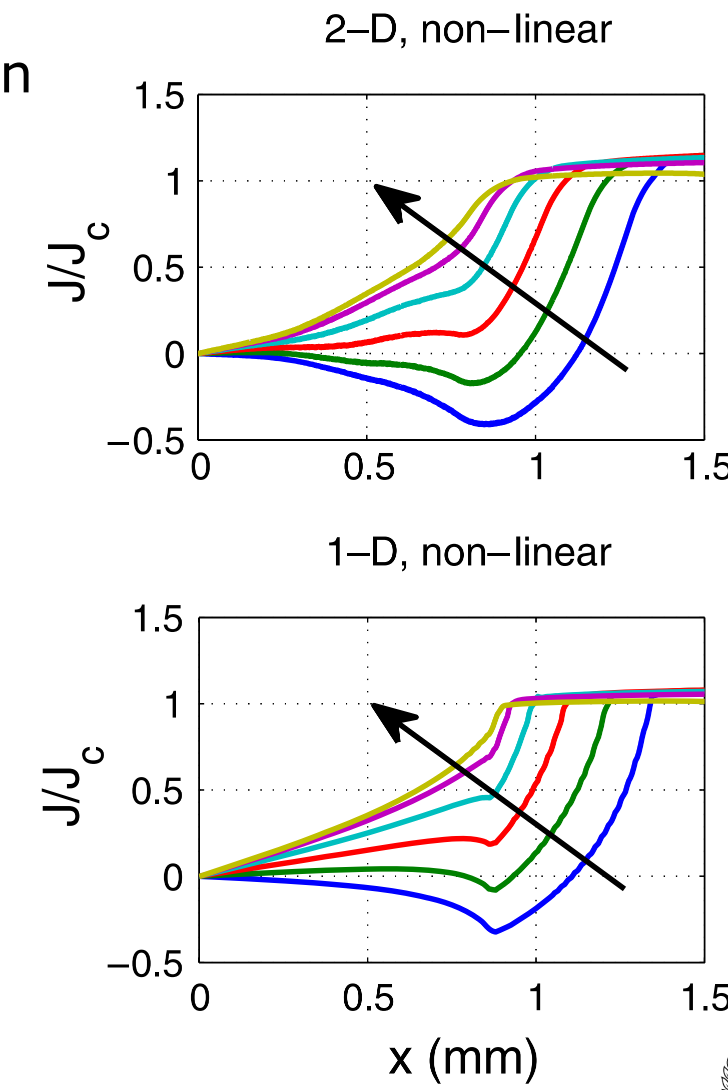
2) OVERVIEW OF MODELS AND NUMERICAL METHODS
→ EXAMPLES OF "SMART" MODELLING APPROACHES

- Infinitely thin film approximation



2-D to 1-D

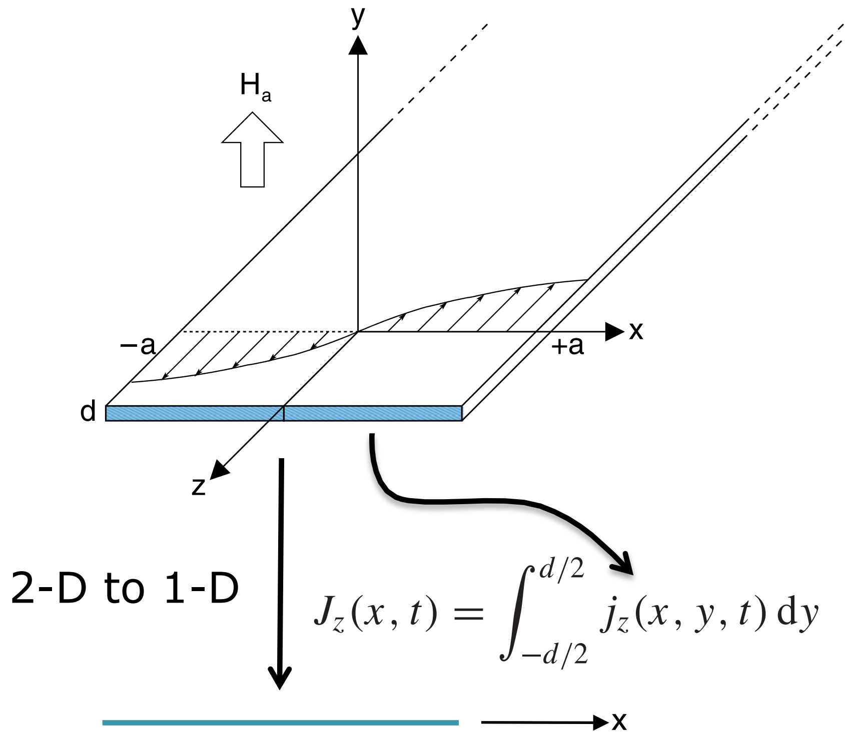
$$J_z(x,t) = \int_{-d/2}^{d/2} j_z(x,y,t)\,\mathrm{d}y$$



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

2) OVERVIEW OF MODELS AND NUMERICAL METHODS
→ *EXAMPLES OF "SMART" MODELLING APPROACHES*

- Infinitely thin film approximation: impact on discretization



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

→ Thickness of tape: 1 μm

→ DOFs:
2,000 (1-D) vs. 50,000 (2-D)

→ Computation time:
2 min. (1-D) vs. 2 h (2-D)

→ Error on AC losses < 2%

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

2) OVERVIEW OF MODELS AND NUMERICAL METHODS → *EXAMPLES OF "SMART" MODELLING APPROACHES*

- Thin interface conditions for quench problems

1/3rd

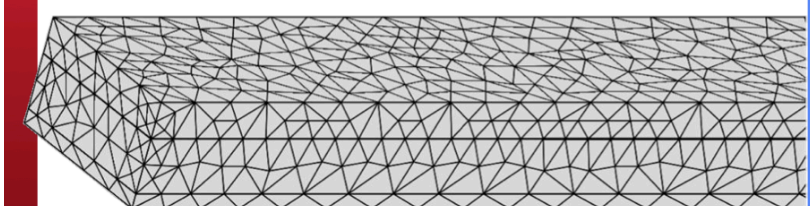
3D/2D Model

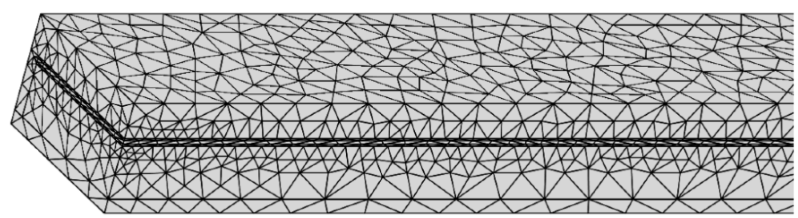
- FE: ~30,000 elements, ~115,000 unknowns.
- Computing time: ~ 3 hrs (0 to 1e-3 s) on a 3.05 GHz quad-core Core i7, 12GB machine.

1/8th

Full 3D Model

- FE: ~130,000 elements, ~360,000 unknowns.
- Computing time: > 24 hrs (0 to 1e-3 s) on the same machine.





21 First HTS Modeling Workshop, Lausanne, CH – May 6th, 2010

Advanced Magnet Lab

 W.-K. Chan et al., 1st HTS modelling workshop, Lausanne, Switzerland, May 2010.

2) OVERVIEW OF MODELS AND NUMERICAL METHODS
→ *EXAMPLES OF "SMART" MODELLING APPROACHES*

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Full 3D Model

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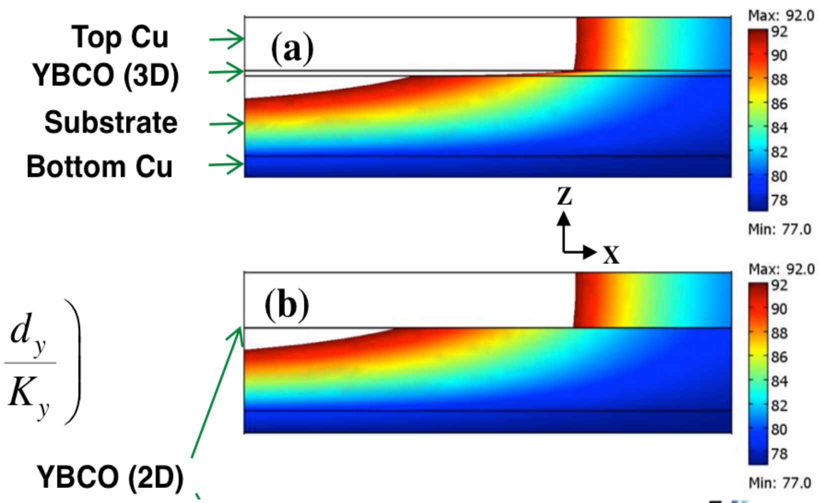
Thermal error Correction:

$$T^{+} = 2\tilde{T} - T^{-} \qquad \tilde{T} = \frac{1}{d_y}\int_0^{d_y} T\,dz$$

$$T^{-} = \left[2\tilde{T} + \left(\frac{K_S}{d_S}(2\tilde{T} - T_{cu}^{-}) - d_y Q_y \right) \frac{d_y}{K_y} \right] \Big/ \left(2 + \frac{K_S}{d_S}\frac{d_y}{K_y} \right)$$



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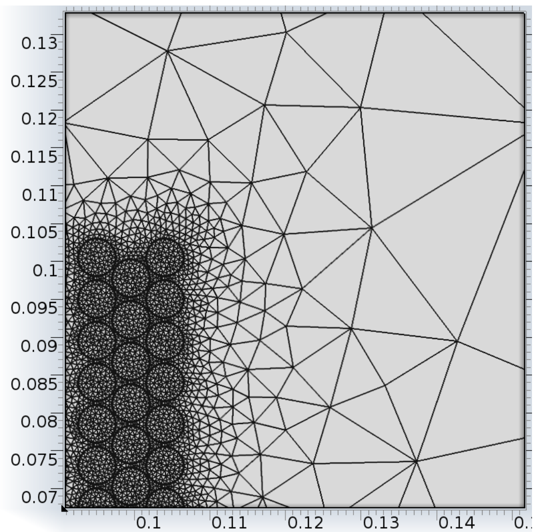
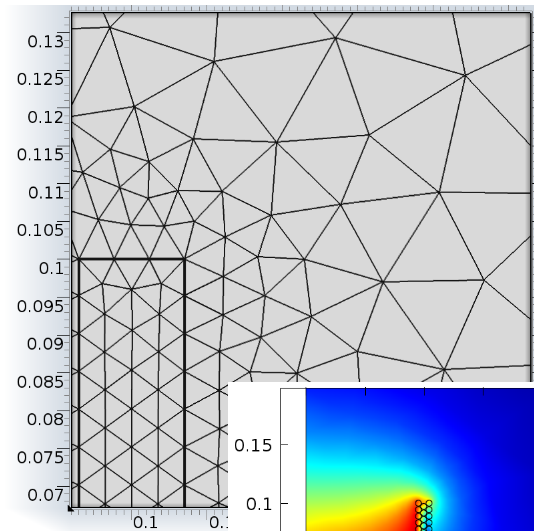
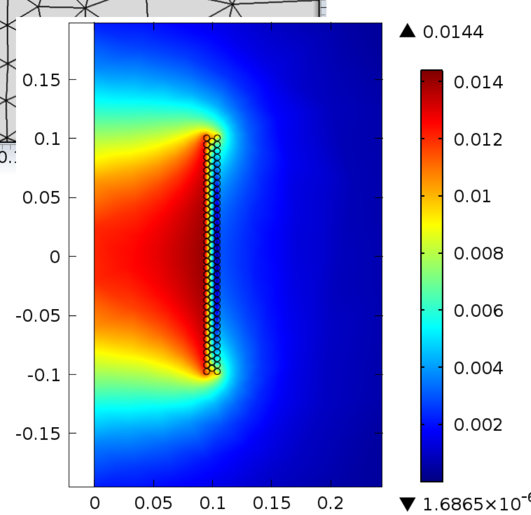
2) OVERVIEW OF MODELS AND NUMERICAL METHODS → *EXAMPLES OF "SMART" MODELLING APPROACHES*

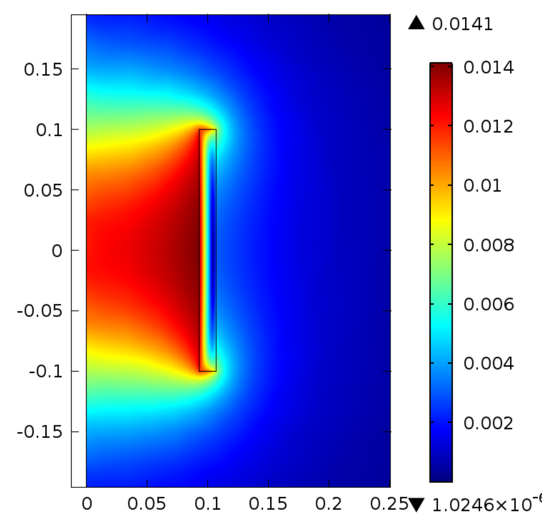
- Current homogeneization in coils: classical version





C.-H. Bonnard, Masters thesis, École Polytechnique de Montréal, October 2012.



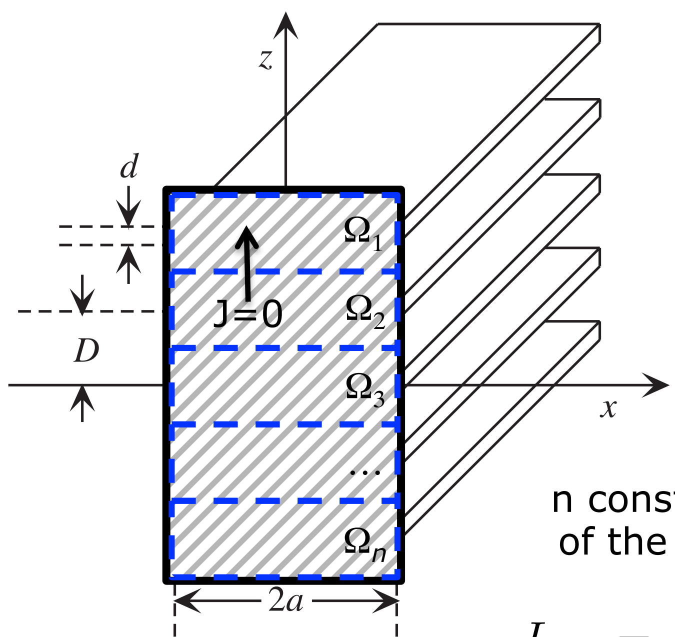


All Ampere-turns in a single macroscopic coil

Field distributions identical, but computation time greatly reduced

2) OVERVIEW OF MODELS AND NUMERICAL METHODS
→ *EXAMPLES OF "SMART" MODELLING APPROACHES*

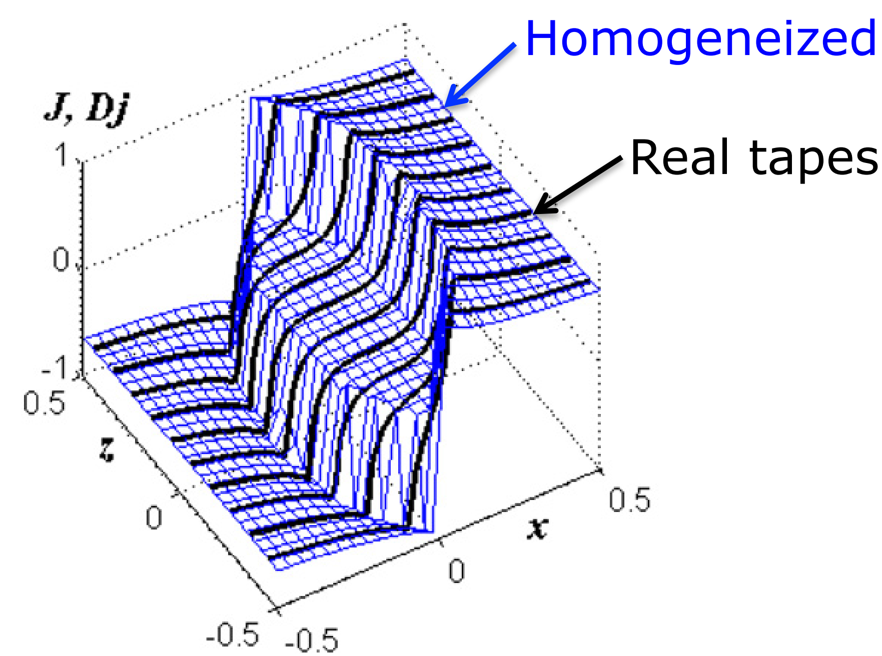
- Current homogeneization in stacks and coils of 2G HTS tapes
  - Concept of "anisotropic superconducting bar" for densely packed tapes



n constraints of the form:

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

(Analytic solution)



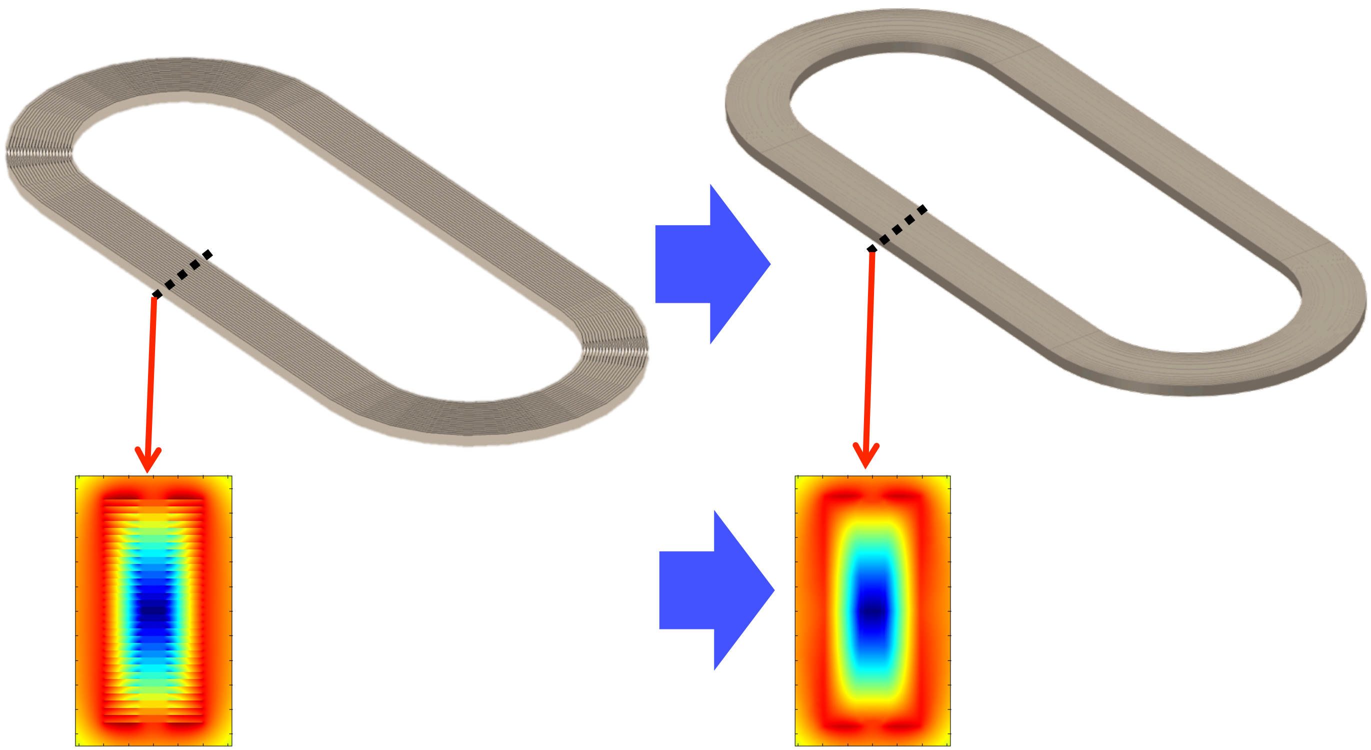
(Refinement and numerical implementation)

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

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

2) OVERVIEW OF MODELS AND NUMERICAL METHODS
→ *EXAMPLES OF "SMART" MODELLING APPROACHES*

- Current homogeneization in stacks and coils of 2G HTS tapes

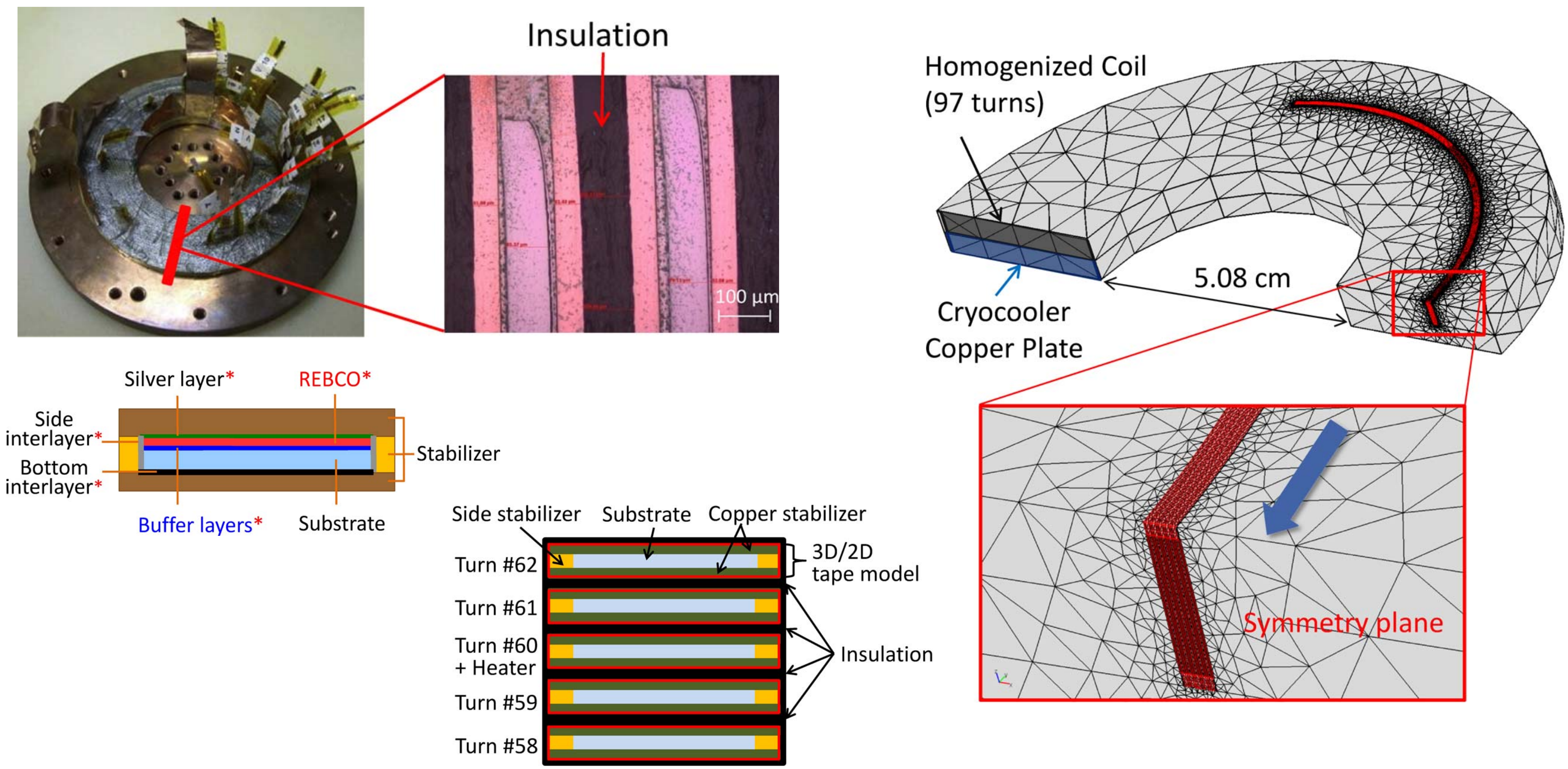


(3-D numerical implementation)

V. Zermeno and F. Grilli, EUCAS 2013, *oral session 4M-LS-O2*

2) OVERVIEW OF MODELS AND NUMERICAL METHODS
→ *EXAMPLES OF "SMART" MODELLING APPROACHES*

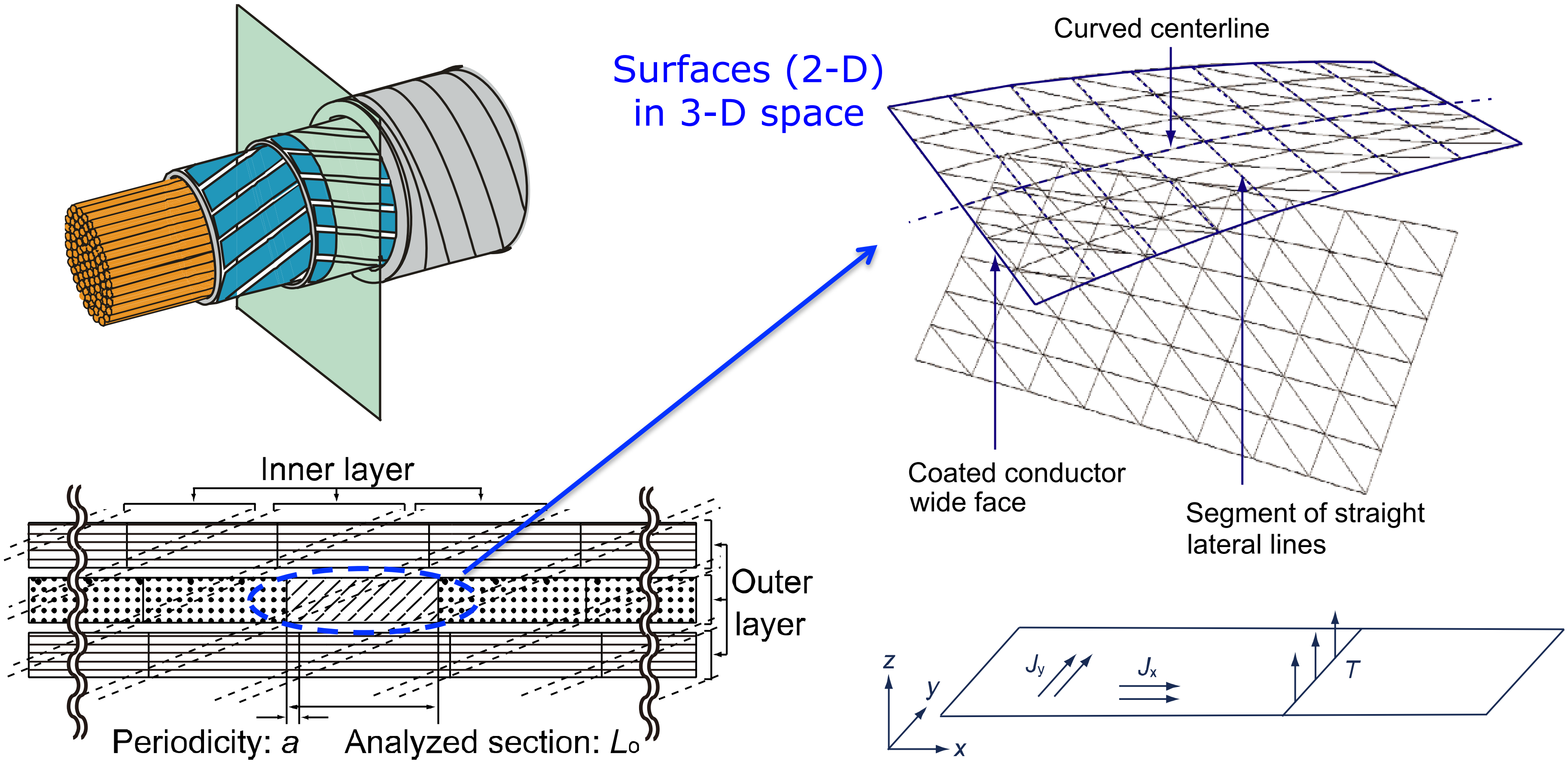
- Hierarchal, 3-D multi-scale tape model for magnets



W. K. Chan and J. Schwartz, *IEEE T. Appl. Supercon.*, 22 (5), p. 4706010, 2012.

2) OVERVIEW OF MODELS AND NUMERICAL METHODS
→ *EXAMPLES OF "SMART" MODELLING APPROACHES*

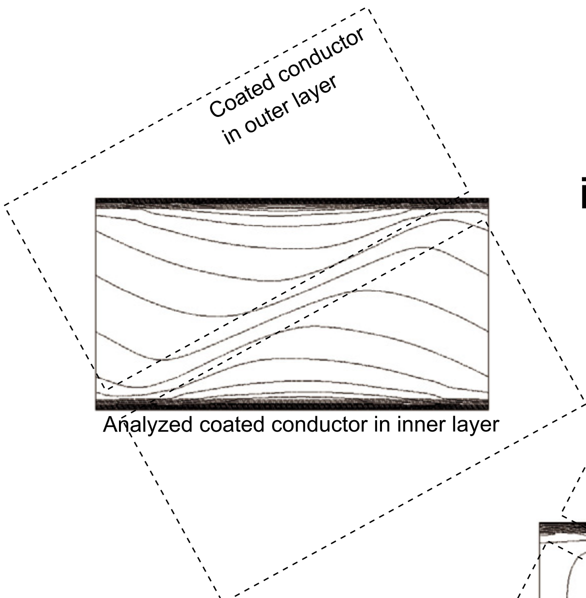
- 3-D modelling of 2-layer cables using a "2.5-D" model



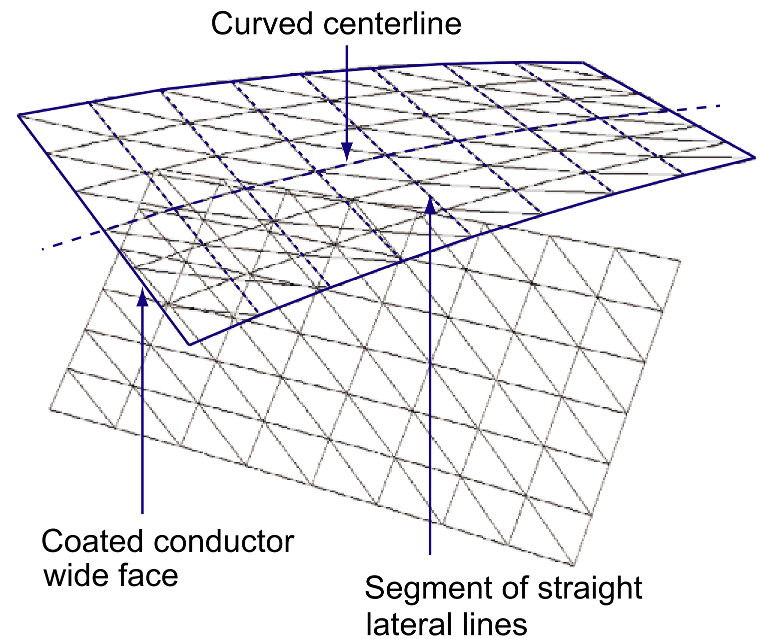
K. Takeuchi, N. Amemiya et al., *Supercond. Sci. Tech.*, 24 (8), p. 119501, 2011.

2) OVERVIEW OF MODELS AND NUMERICAL METHODS
→ *EXAMPLES OF "SMART" MODELLING APPROACHES*

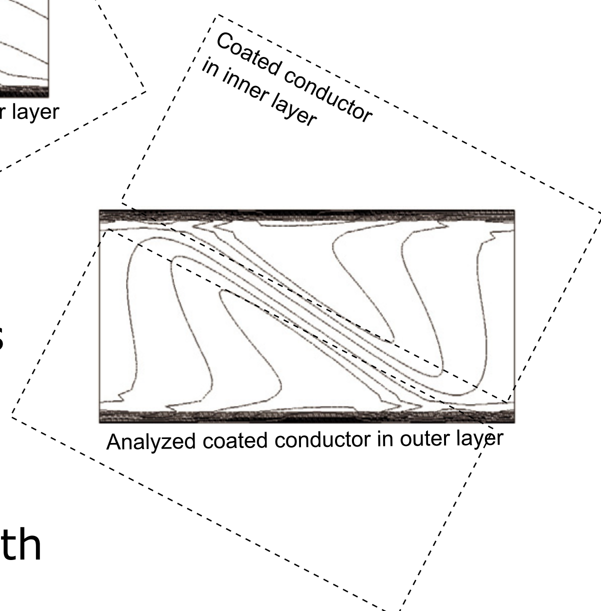
- 3-D modelling of 2-layer cables using a "2.5-D" model



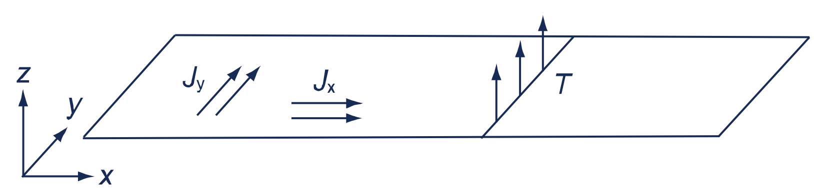
PDEs in superconductors + integral equations at the boundaries



Current path flows



AC losses non uniform along length

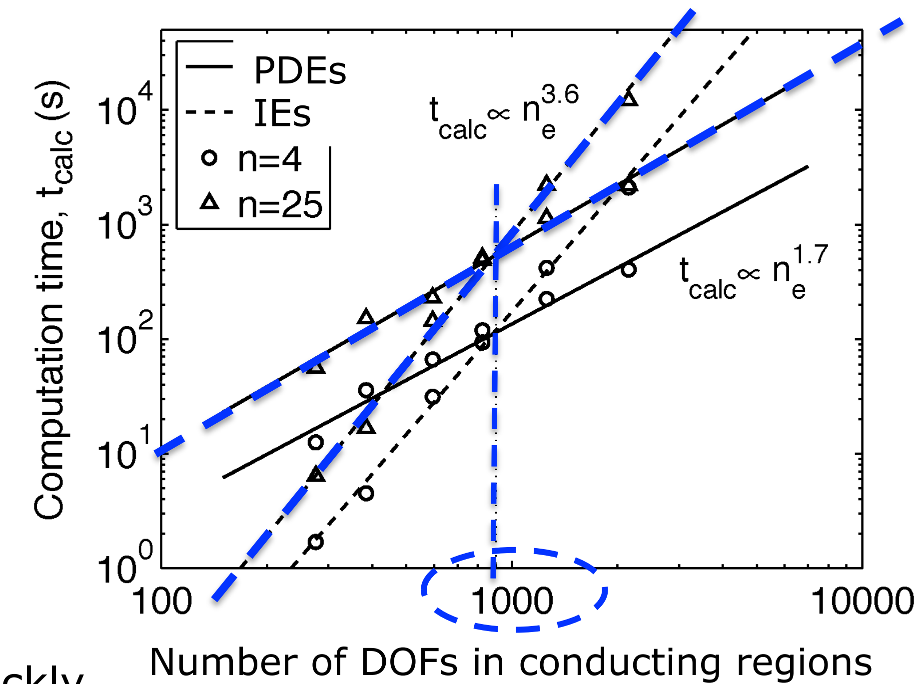


K. Takeuchi, N. Amemiya et al., *Supercond. Sci. Tech.*, 24 (8), p. 119501, 2011.

2) OVERVIEW OF MODELS AND NUMERICAL METHODS
→ *MODELS AND TYPES OF EQUATIONS*

- Models are expressed as equations
  - Ordinary and/or partial differential equations (ODEs / PDEs)
  - Integral equations (IEs)
  - Mixture of PDEs and IEs
  - Algebraic constraints

- <u>IEs</u> vs. PDEs
  - No mesh in air regions (no boundary conditions)
  - **<u>But FULL matrices</u>**
    - Computation time grows quickly
    - Numerically efficient for small number of DOFs



F. Sirois et al. *IEEE T. Appl. Supercon.*, 19 (3), pp. 3600–3604, 2009.

2) OVERVIEW OF MODELS AND NUMERICAL METHODS
→ *MODELS AND CHOICE OF "FORMULATION"*

- Many possible choice of variables ("formulation")
  - Field variables (**H**,**E**) vs. potentials (**A**-V, **T**-Ω, etc.)
    - More intuitive
    - Less DOFS in conducting regions (but more elsewhere)
    - More difficult to couple with electric circuits
    - More difficult to extract some global quantities
      - Inductances, flux linkage, etc.
  - Some models more naturally expressed in a specific formulation
    - e.g. force-displacement method: **A**-V (Campbell, 2007)
- Not discussed any further here
  - too involved for the time allocated
  - ***no systematic benchmarking seems to exist***

2) OVERVIEW OF MODELS AND NUMERICAL METHODS → *MODEL VS. NUMERICAL METHOD*

Reminder…

- **Model:**
  - Mathematical representation of a physical (or other) behavior, based on
    - relevant hypothesis
    - simplifying assumptions
  - e.g. *Power-law model* (PLM) vs. *Critical state model* (CSM) (one considers flux creep, the other does not)
- **Numerical method:**
  - Systematic approach to
    - express models in a discrete form
    - solve the resulting system of equations
  - e.g. *Finite element method* (FEM), *point collocation method*, etc.

2) OVERVIEW OF MODELS AND NUMERICAL METHODS
→ *MODEL VS. NUMERICAL METHOD*

- A given model can be solved by different numerical methods
  - Models and numerical methods are in theory independent
  - Some numerical methods are more suitable than others for a particular model
- Computational performances depends on a proper choice both for
  - <u>the model: compromise between accuracy and complexity</u> (includes materials modelling)
  - the numerical method
- *Model + Numerical method =* **Numerical model**

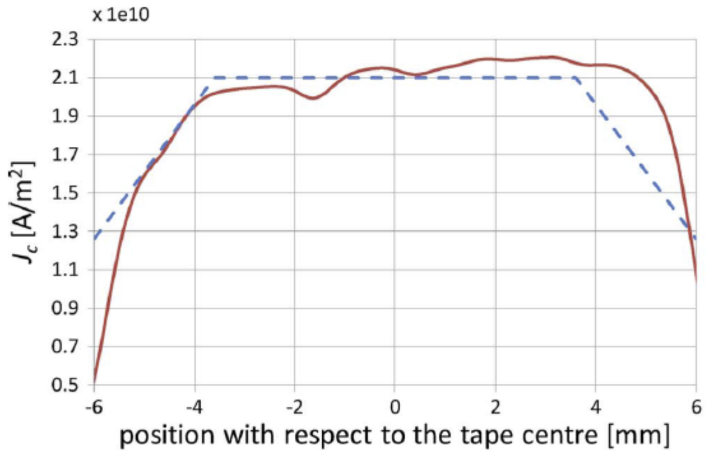
2) OVERVIEW OF MODELS AND NUMERICAL METHODS
→ *NUMERICAL METHODS*

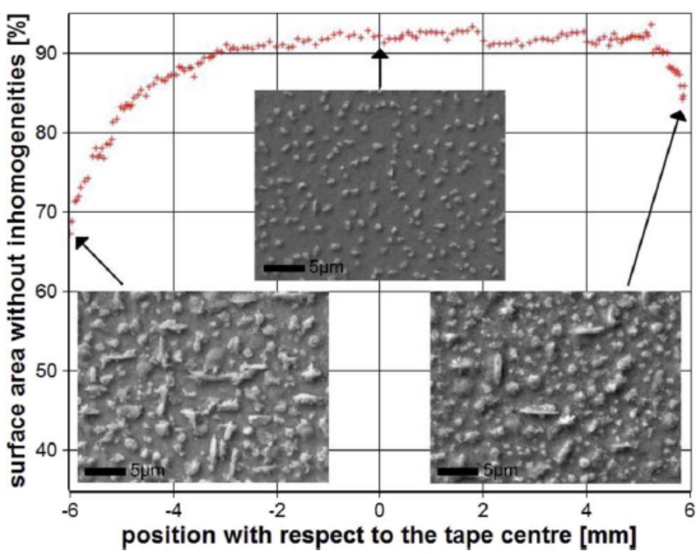
- Numerical methods are numerous
  - Finite element method (FEM), finite difference method, finite volume method, point collocation method, etc.
  - Each method splits into many variants
- Common features of numerical methods
  - Apply to a discretized version of the model
  - Quality of approximation: function of discretization
    - notion of degrees of freedom – DOFs
  - Computation times grow with the number of DOFs
- A suitable numerical method should
  - Maximize accuracy for a given number of DOFs

Obtain a discrete approximation that is as close as possible to the intrinsic accuracy of the model

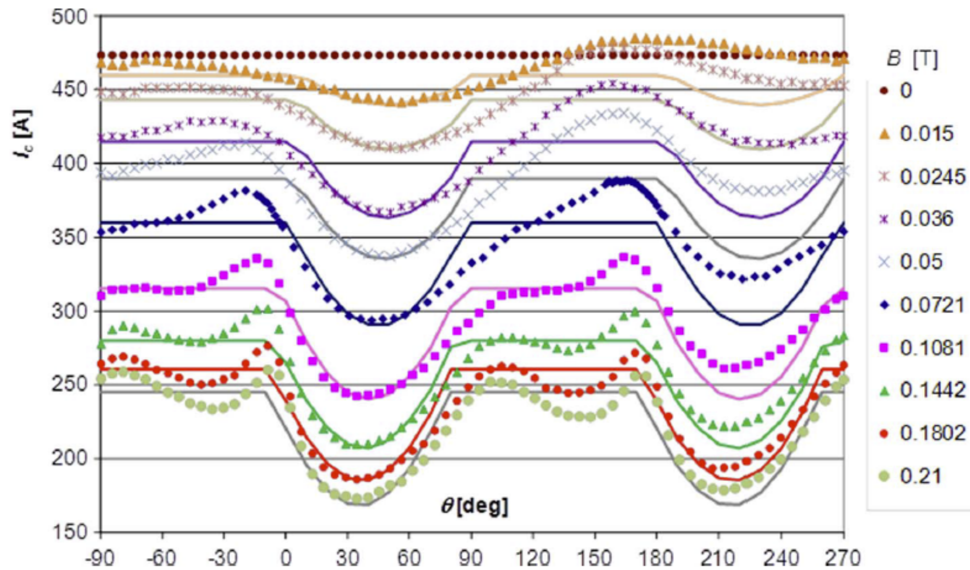
2) OVERVIEW OF MODELS AND NUMERICAL METHODS
→ ACCURACY OF EXISTING NUMERICAL MODELS

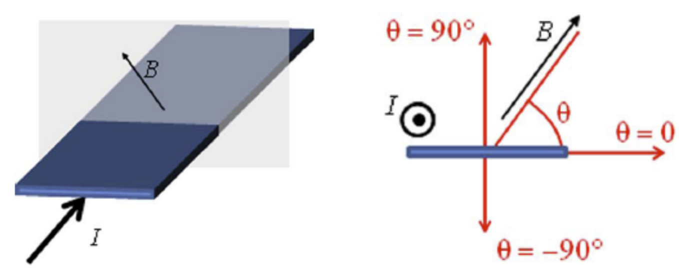
Lateral variation of J_c





Angular dependence $J_c(B,\theta)$

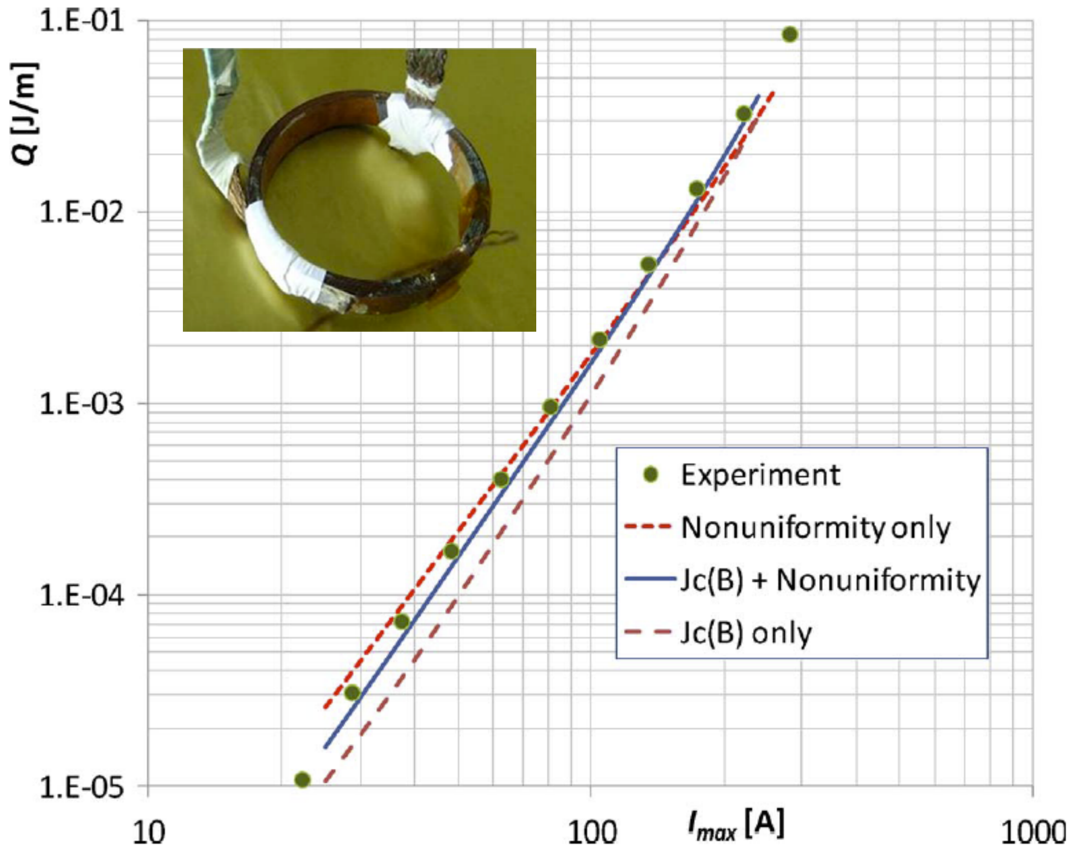




F. Gömöry et al., IEEE TAS, 23 (3), p. 5900406, 2013.

2) OVERVIEW OF MODELS AND NUMERICAL METHODS
→ *ACCURACY OF EXISTING NUMERICAL MODELS*

AC losses in coils using realistic tape models

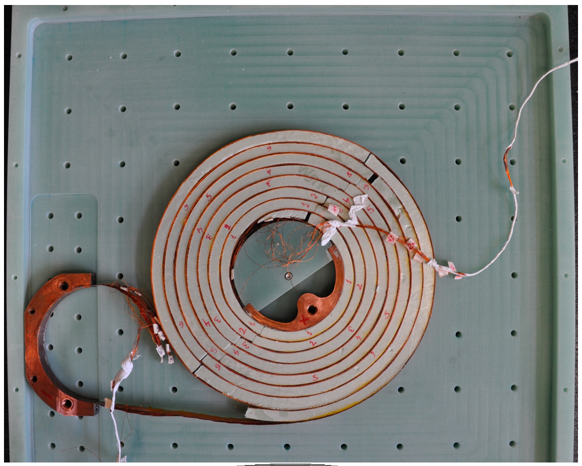


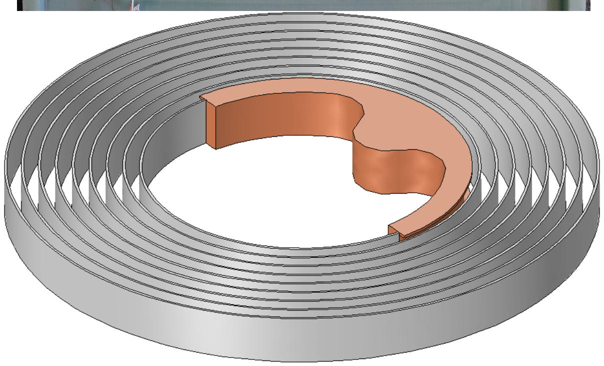
F. Gömöry et al., IEEE TAS, 23 (3), p. 5900406, 2013.

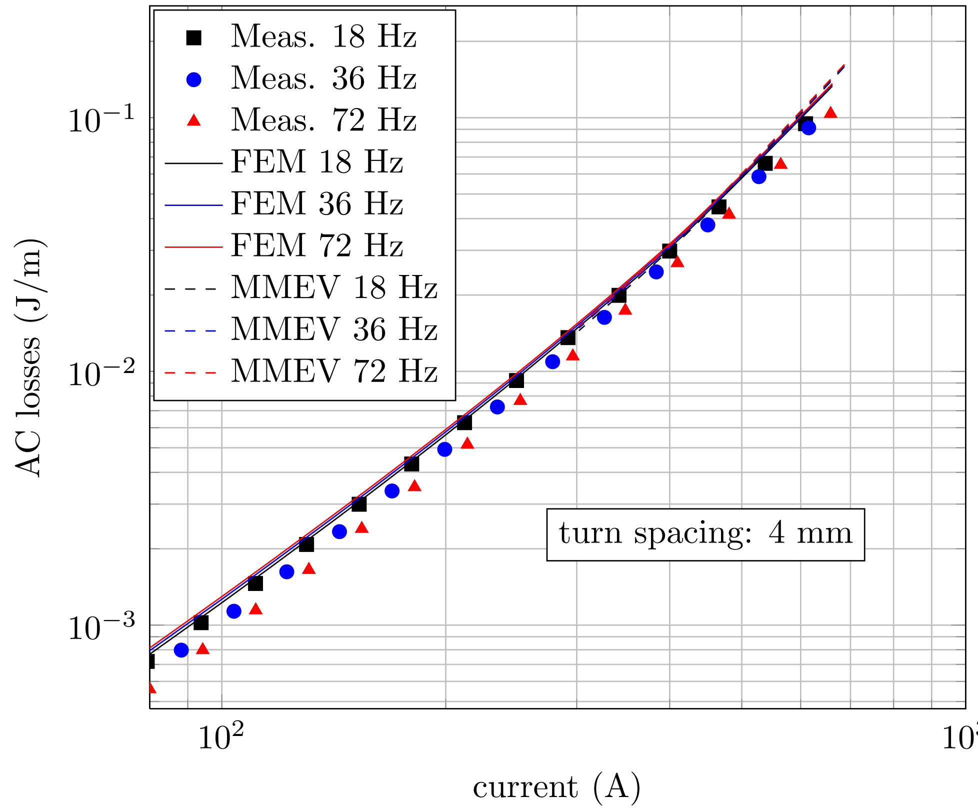
2) OVERVIEW OF MODELS AND NUMERICAL METHODS
→ *ACCURACY OF EXISTING NUMERICAL MODELS*

Roebel pancake coil:

- HTS modelled in 2-D (axisymmetric), copper contact in 3-D



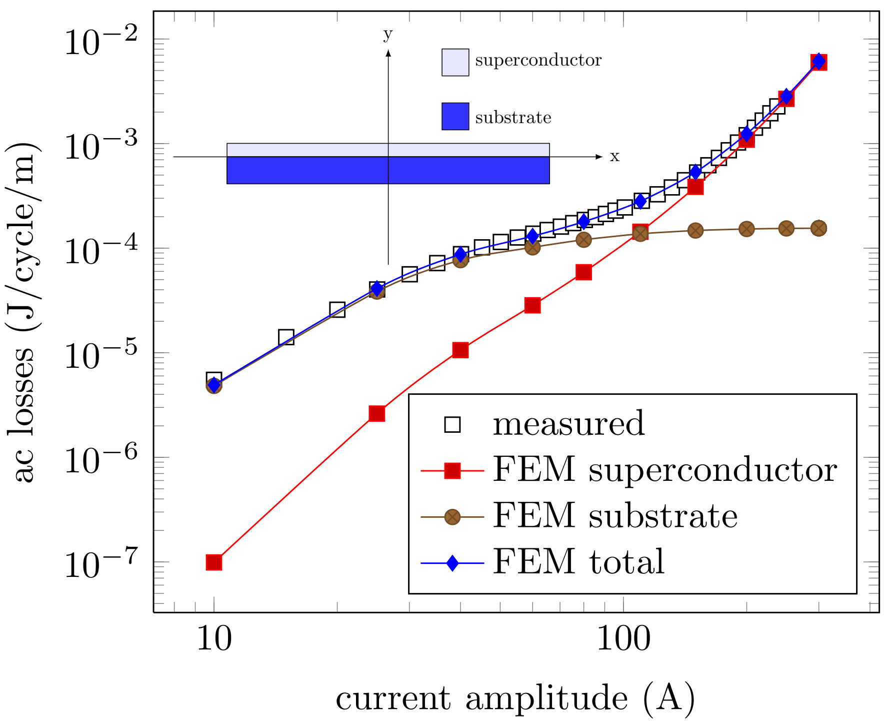




F. Grilli et al., IEEE TAS, at press, 2014.

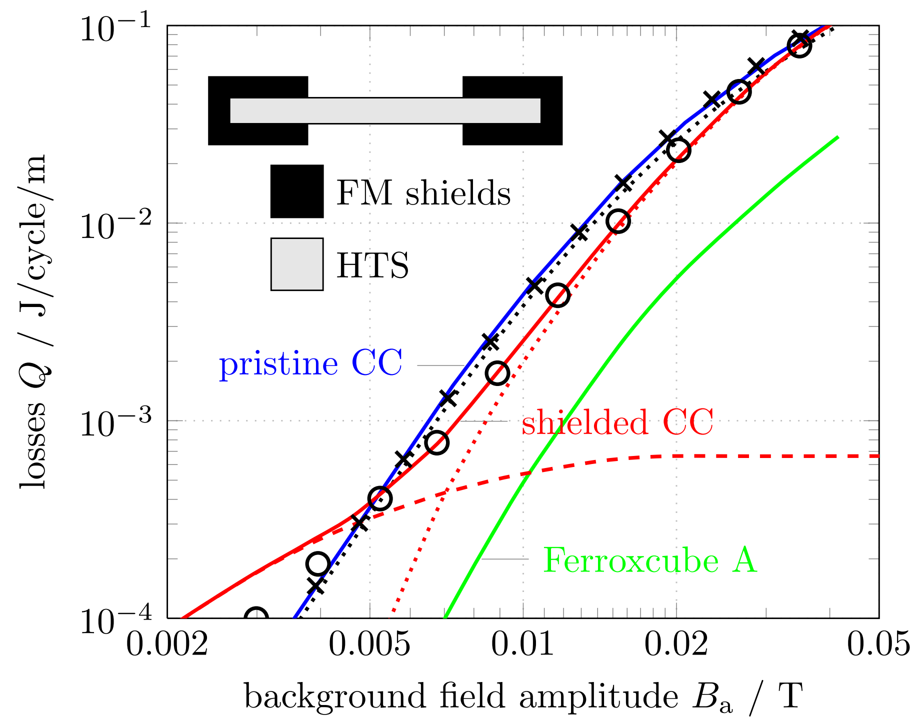
2) OVERVIEW OF MODELS AND NUMERICAL METHODS → *ACCURACY OF EXISTING NUMERICAL MODELS*

CC tapes with Ni-W substrate (ferromagnetic substrate)



D. N. Nguyen et al., *Supercond. Sci. Tech.*, 23 (2), p. 025001, 2010.

Ni-shielding of CC tapes (symbols = experiments)



P. Krüger et al., APL, 102, p. 202601, 2013.

2) OVERVIEW OF MODELS AND NUMERICAL METHODS
→ *TYPICAL COMPUTATIONAL PERFORMANCES*

- Computational performances for simulating a realistic HTS problem (e.g. AC losses vs. transport current) are in the range of:

Dimension	Typical # of DOFs*	Typical solution time
2-D	1000 to X00,000	Minutes to hours
3-D	100,000 to X,000,000	Hours to days

* Based on the use of the FEM

- Computation times are:
  - Acceptable for trying to understand what happens
  - Still too long for optimization of devices (hundreds or thousands of repetitions)

2) OVERVIEW OF MODELS AND NUMERICAL METHODS
→ *AVAILABILITY OF NUMERICAL TOOLS AND MODELS*

- Where do we find simulators for HTS devices?
  - Home made proprietary codes
  - Commercial codes (COMSOL, FLUX, ANSYS, JMAG, MagNet, FlexPDE, etc.)

- Where do we find model files?
  - Everybody has to create his/her own models
  - No file template is publicly available for physical models
  - No library of "HTS devices" exists in power system simulators

2) OVERVIEW OF MODELS AND NUMERICAL METHODS
→ *AVAILABILITY OF NUMERICAL TOOLS AND MODELS*

- At present:
  - Hard to find model templates
  - Poor documentation and availability of home made codes
  - High cost of commercial software licences
  - Long calculation times, not suitable for device optimization
- This leads to a substantial bottleneck:
  - HTS modelling remains a specialized topic, mostly accessible to graduate students or researchers
  - HTS devices remains an obscure object for most manufacturers and power utilities

2) OVERVIEW OF MODELS AND NUMERICAL METHODS → *SUMMARY*

- So, **what is the status of HTS numerical modelling**?
  - In terms of capabilities and accuracy:
    - **Relatively mature and proven**
  - In terms of computational performances (speed):
    - For a single device: **acceptable in 2D, less in 3D**
    - For device optimization: **not fast enough**
  - In terms of availability of model files:
    - Physical models: **not so easily available**
    - Macroscopic models: **even less available**
  - In terms of easiness-of-use:
    - **No modelling environment can be said "easy-to-use"**
- What could/should be improved then?

Performance of numerical methods

Availability and easiness-of-use

PRESENTATION OUTLINE

1) Context and need for numerical modelling

2) Overview of models and numerical methods

3) **Paths towards improvement**

4) Conclusion

3) PATHS TOWARDS IMPROVEMENT

- Two parallel paths to pursue:
  (besides improvement of the models themselves)

  1) Performance of numerical methods

  2) Availability and easiness-of-use of simulation tools

3) PATHS TOWARDS IMPROVEMENT → PERFORMANCE OF NUMERICAL METHODS

- Two parallel paths to pursue:
  1) Performance of numerical methods
     - Use of parallel computing
     - Improved linear algebra solvers for large problems
     - **Develop numerical methods that are better adapted to HTS problems**
       - Requires a good knowledge of the problem
       - To be addressed with specialists in numerical methods

3) PATHS TOWARDS IMPROVEMENT → PERFORMANCE OF NUMERICAL METHODS

- Why are the solution times so long (from a numerical point of view)?

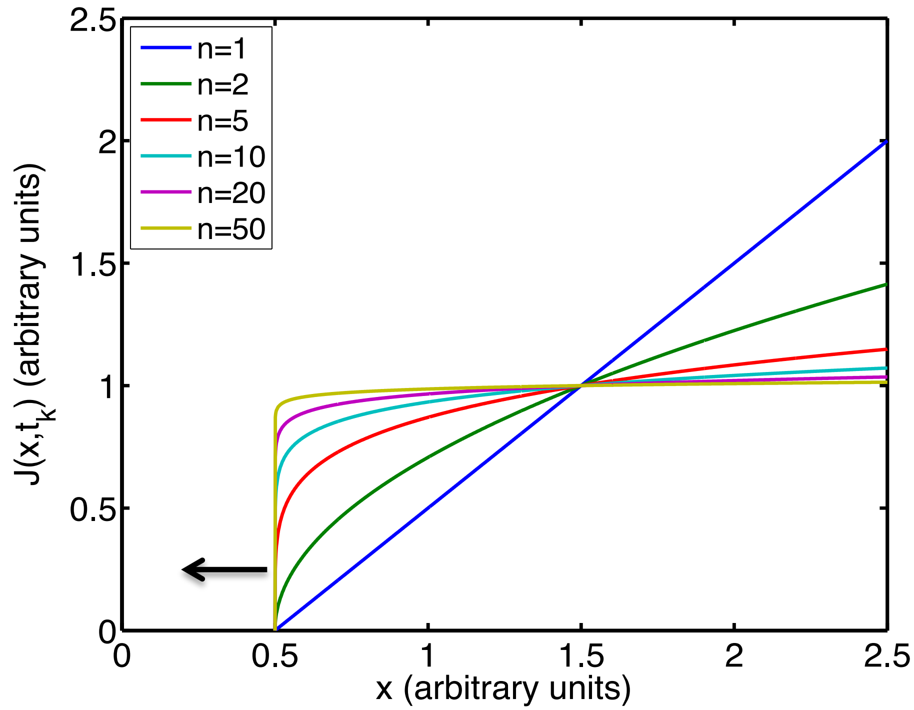
Dimension	Typical # of DOFs*	Typical solution time
2-D	1000 to X00,000	Minutes to hours
3-D	100,000 to X,000,000	Hours to days

* Based on the use of the FEM

- Two main reasons:
  - Large number of DOFs, but many of them "do nothing useful"
  - Highly nonlinear problem → Requires very small time steps
- Solution: use both space and time "adaptivity"

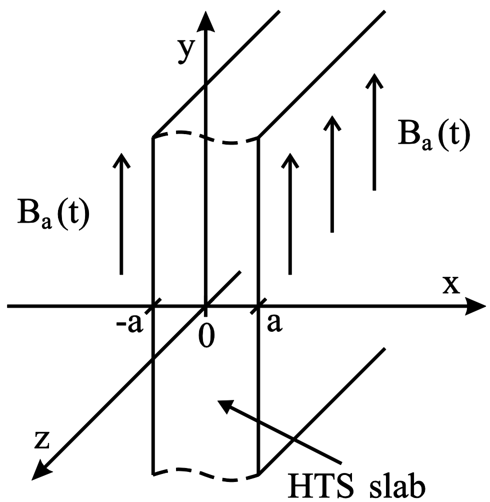
3) PATHS TOWARDS IMPROVEMENT → PERFORMANCE OF NUMERICAL METHODS

- HTS exhibit a singular limit as J→0: sharp and moving current fronts
- Specific behaviour of superconductors …
  - … despite similarities with flux diffusion in ferromagnetic materials (**I. Mayergoyz**, *Nonlinear flux diffusion of electromagnetic fields*, 1998)

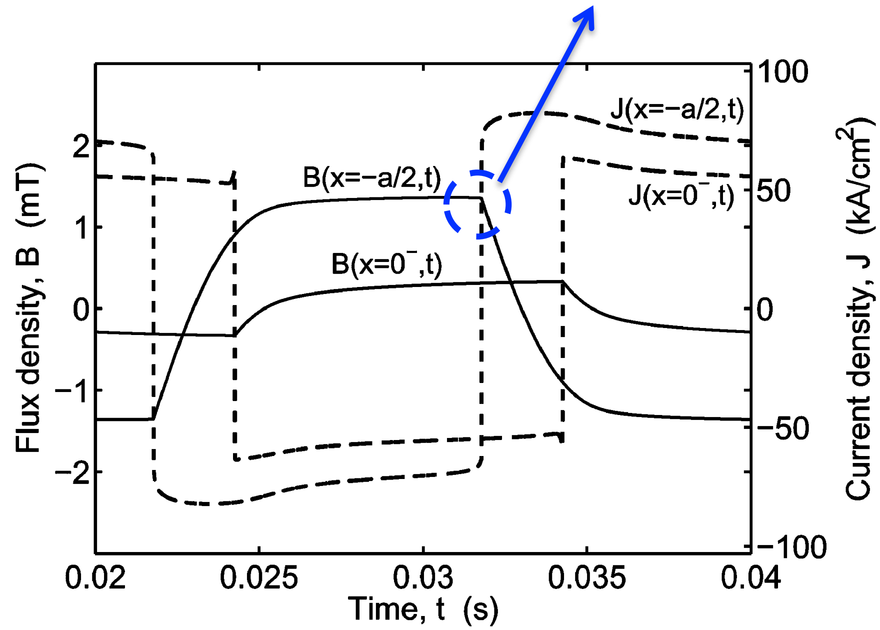


3) PATHS TOWARDS IMPROVEMENT ➔ PERFORMANCE OF NUMERICAL METHODS

- Requirements for stable solution: Sudden change of sign of dB/dt must be captured accurately



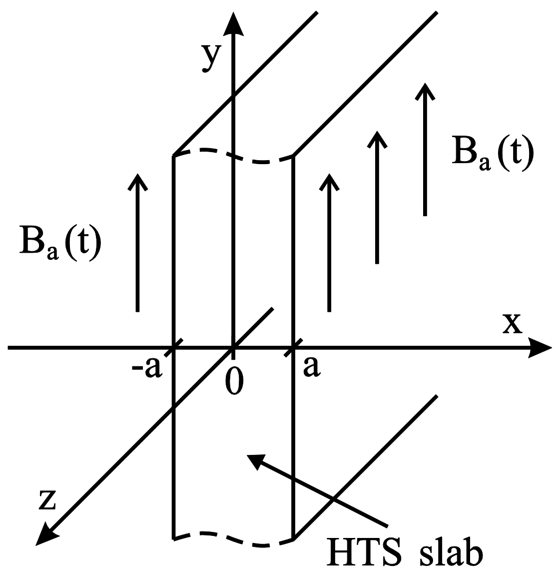
F. Sirois and F. Grilli, IEEE TAS, 18 (3) pp. 1733-1742, 2008.



- Adaptive time stepping algorithms are required
  - e.g. as IDA, DASSL, DASPK, etc. ➔ <u>stabilizes AND accelerates</u> (DASPK available by default in COMSOL)
  - already noticed by **R. Pecher et al.**, Proceedings of EUCAS 2003, Sorrento, Italy.

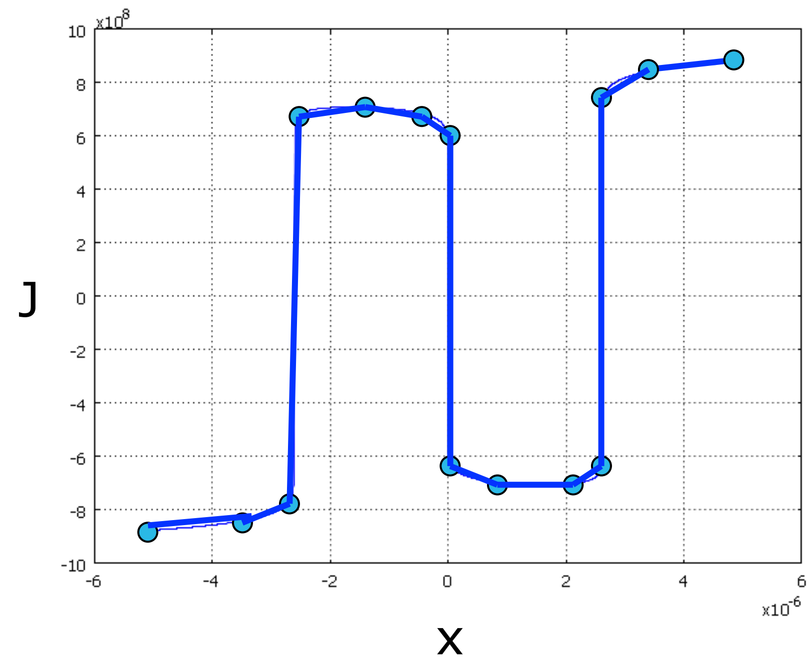
3) PATHS TOWARDS IMPROVEMENT ➔ PERFORMANCE OF NUMERICAL METHODS

- Requirements to further speed-up solution:



Using space adaption can reduce the # DOFs by more than 1 order of magnitude!

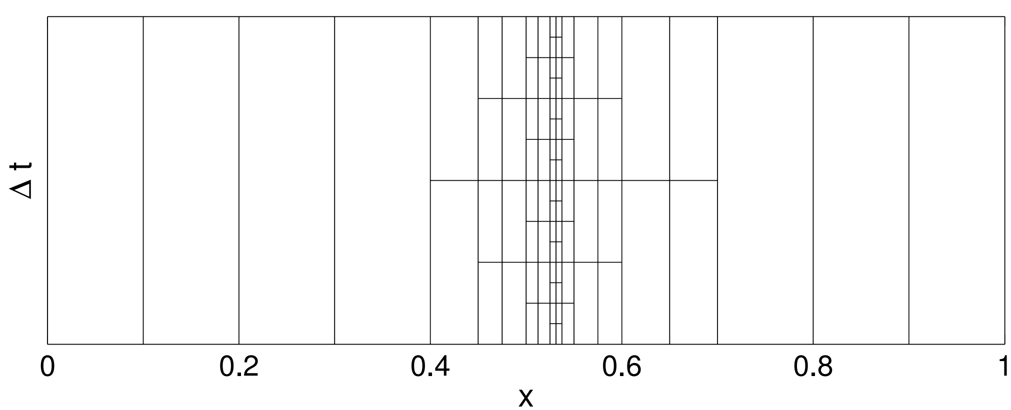
J profile in AC field
2000 elements regularly spaced



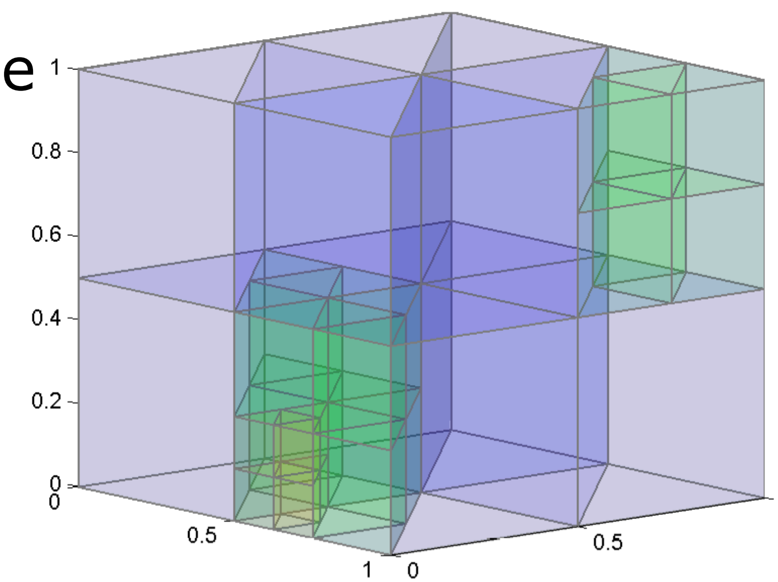
With only 12 interpolating nodes
➔ error < 1%

3) PATHS TOWARDS IMPROVEMENT
➔ PERFORMANCE OF NUMERICAL METHODS

- Adaptive numerical methods are very technical
  - Need to couple with experts in the field
  - Good error estimators must be developed
    - ➔ Requires physical insights of the problem
- Ultimate adaption scheme:
  - Local in both space and time

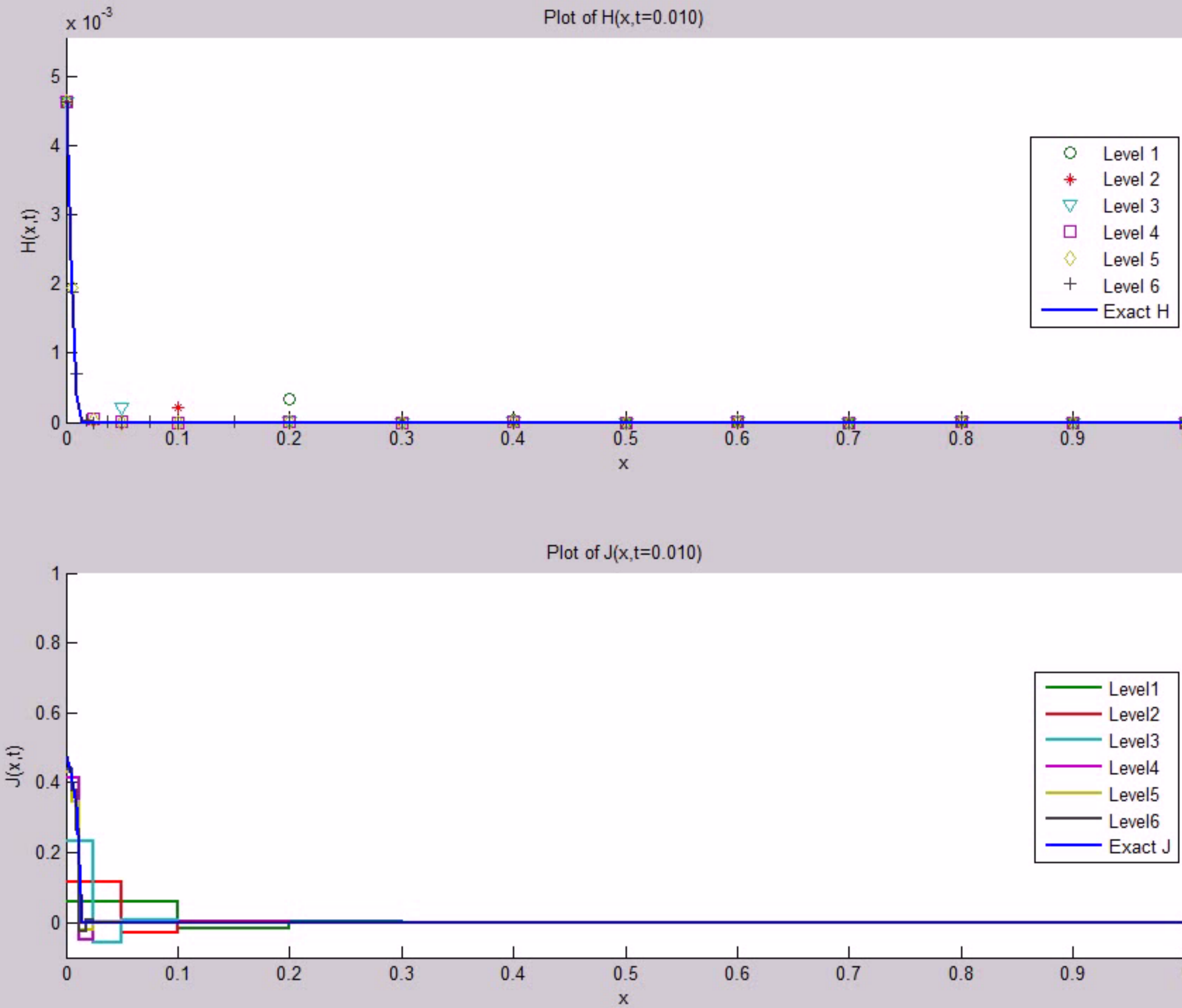


1-D

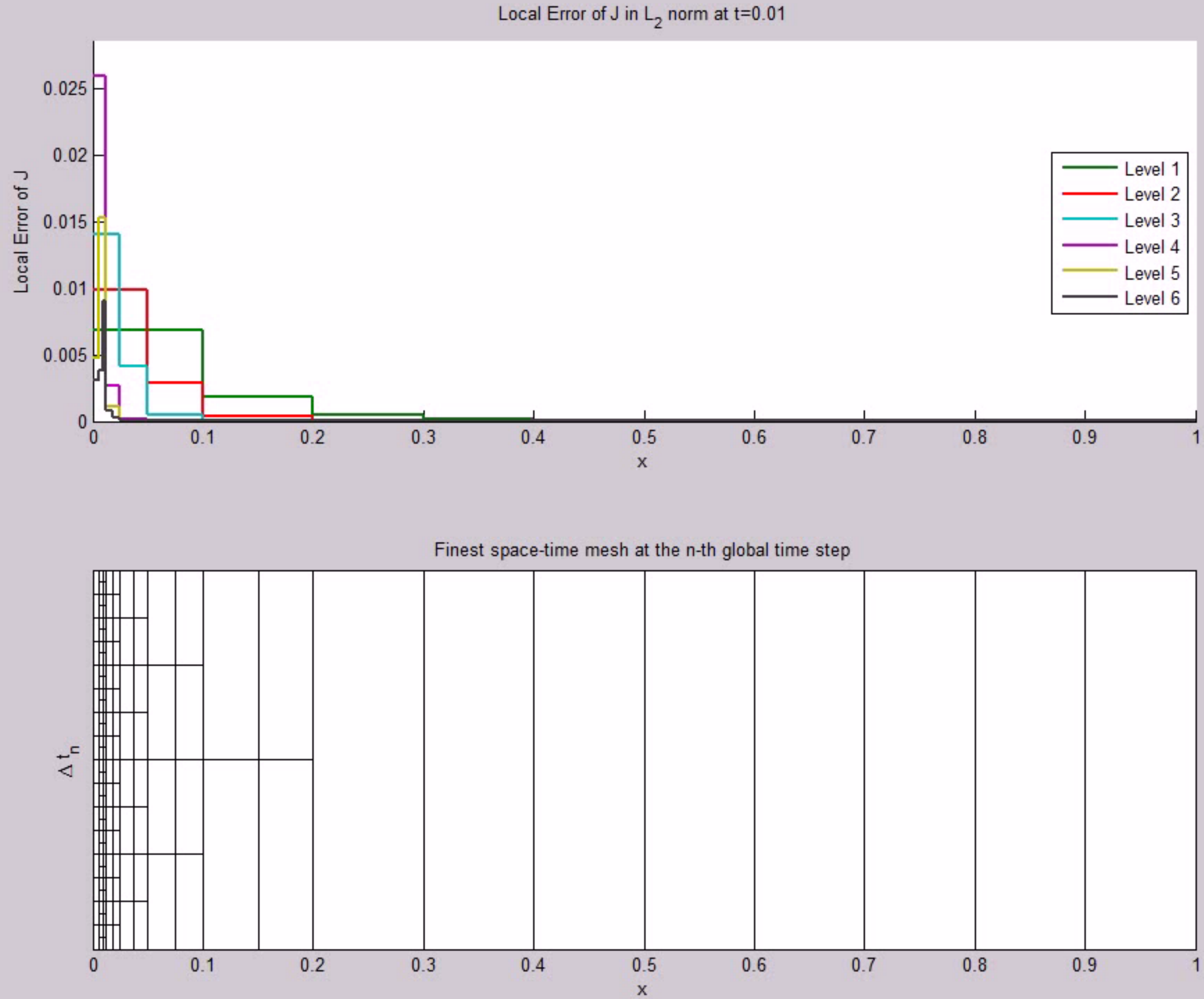


2-D

A. Wan et al., 2012.



A. Wan et al., 2012.



3) PATHS TOWARDS IMPROVEMENT → AVAILABILITY AND EASINESS-OF-USE

- Two parallel paths to pursue:

  1) Performance of numerical methods
     - Use of parallel computing
     - Improved linear algebra solvers for large problems
     - Develop adaptive methods that are well adapted to HTS problems

  2) Availability and easiness-of-use of simulation tools
     - **See next page…**

3) PATHS TOWARDS IMPROVEMENT ➔ AVAILABILITY AND EASINESS-OF-USE

2) Availability and easiness-of-use of simulation tools

- New numerical methods ➔ new computer codes
- Open source format (collaborative development)
- Collective projects should be
  - built on top of existing tools (Sundials, GetDP, etc.)
  - based on a free and reliable platforms (e.g. Python)
  - easily scriptable (no more complex than a Matlab script) ➔ can be used by non-programmers
  - well documented
  - provided with numerous examples and model files
- Develop public libraries of HTS power devices in
  - Simulink, EMTP, ATP, etc.

3) PATHS TOWARDS IMPROVEMENT
→ AVAILABILITY AND EASINESS-OF-USE

2) Availability and easiness-of-use of simulation tools

- Collaborative work commands for
  - a web space/forum for the modellers, where
    - Discussions on common problems are archived
    - Model files in any format could be posted and shared
  - increased networking activities
    - HTS modelling workshops
    - Wider networking actions?
- Good news! A website already exists!

http://www.htsmodelling.com

3) PATHS TOWARDS IMPROVEMENT → WEBSITE OF THE HTS MODELLING WORKGROUP

HTS MODELLING WORKGROUP | Modelling of high temperature superconductors (HTS)

HOME | BOARD | BENCHMARKS | PUBLICATIONS | EVENTS | WORKSHOPS | JOBS

Welcome!

In the past few years numerical modelling has increased in popularity and has been recognized as a powerful tool for investigating the electromagnetic and thermal behaviour of superconductors, and of HTS in particular. Several groups around the world have been working on the development and tests of several models. It has been acknowledged that communication between people involved in this discipline should improve, in order to speed up the advances of this field and also to limit work duplication.

The first step in this direction was taken in 2010, with the organization of a workshop in Lausanne, Switzerland. The large number of attendees and the positive feedback lead to the organization of other workshops in the following years — see Workshop section for more details.

During these workshops, many participants recognized the need of having a permanent platform on the internet for facilitating exchanges between researchers and accessing up-to-date information on the latest developments.
The aim of this website is to be that platform. Please browse through the menu on the top to access the different pages of this website. Do not hesitate to contact us for comments, critics and suggestions.

IMPORTANT NEWS: A special session on numerical modelling will be held at the upcoming European Conference on Applied Superconductivity. Check session *4M-LS: Modeling* in the conference program.

Events List

- Sep. 15, 2013
  European Conference on Applied Superconductivity
- May. 11, 2014
  Fourth International Workshop on Numerical Modelling of HTS
- all events

Events Calendar

<< Sep 2013 >>

M	T	W	T	F	S	S
26	27	28	29	30	31	1
2	3	4	5	6	7	8
9	10	11	12	13	14	15

3) PATHS TOWARDS IMPROVEMENT

- Two parallel paths to pursue:
    1) Performance of numerical methods
    2) Availability and easiness-of-use of simulation tools
- Additional requirement to stimulate positive outcomes in both topics:
    - **Development of benchmark problems that are representative of industrial problems**

3) PATHS TOWARDS IMPROVEMENT → NEED FOR BENCHMARKS

- Benchmarks greatly help in focusing the R&D effort on
  - the most urgent problems to model
  - the most relevant numerical approaches

- Some benchmarks already exist
  - See website http://www.htsmodelling.com
    - High aspect ratio tape, stack of tapes, bulk magnetization, ferromagnetic/SC interaction
  - More complex cases should be defined as well…

3) PATHS TOWARDS IMPROVEMENT → NEED FOR BENCHMARKS

- Invitation to industrials and manufacturers:
  - **Please contribute to benchmark definitions!**
  - Modellers are there, they are creative, they just need to know where you need help!
- 4th international workshop on HTS modelling

HTS MODELLING 2014

Sponsored by:

SuperPower Inc.
A Furukawa Company

May 11 - 14, 2014
Bratislava, Slovakia

http://www.elu.sav.sk/htsmod2014/index.html

PRESENTATION OUTLINE

1) Context and need for numerical modelling

2) Overview of models and numerical methods

3) Paths towards improvement

4) **Conclusion**

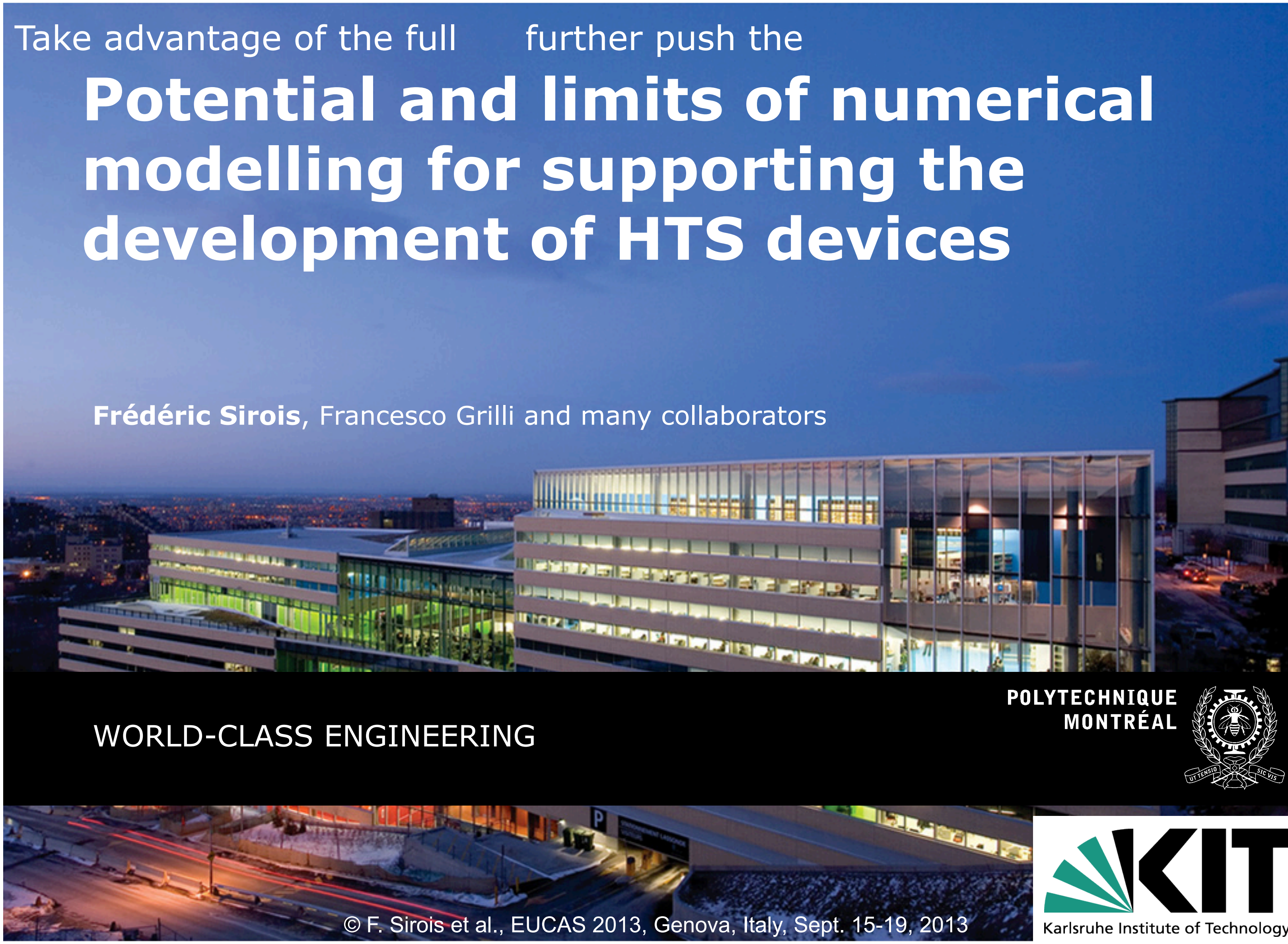
TOPICS DELIBERATELY LEFT OUT

- Analytical solutions
- Materials modelling
  - Important topic, especially for some 3-D configurations that may involve flux cutting
- Modelling for improving our understanding of more fundamental aspects of superconductors

4) CONCLUSION

- Numerical modelling of HTS has reached some maturity
  - Modellers are getting organized in joint projects
- Further progress should aim at providing
  - Easy-to-use models, usable by manufacturers and utilities
  - Faster simulation tools for optimizing devices and systems
- Unifying element between modellers (mostly academics) and device developers/end users
  - Joint definition of benchmarks of industrial relevance

4) CONCLUSION



Karlsruhe Institute of Technology