Advances in HTS Modeling

WAMHTS-5, Budapest, April 11th 2019

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Acknowledgement: L. Cavallucci, F. Grilli, P. L. Ribani

Outline

- Introduction
- HTS tape modeling
- From tapes to cables
  - Twisted Stacked Tape Cable
  - Roebel cables
- Scaling up: coils and magnet systems
- Discussion

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Main issues and problem scales...

Issues

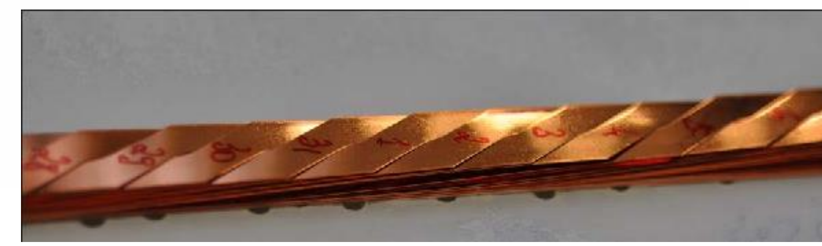
- High aspect ratio
- Anisotropy
- Strong non-linearity
- Inhomogeneity of critical current
- Interface properties
- Problem dimensions (3D)
- Multiphysics

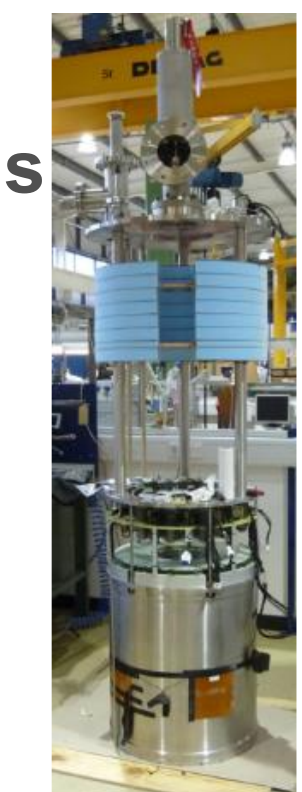
Scale

- Layer/filament
- Tape
- Cable
- Coil
- Magnet systems

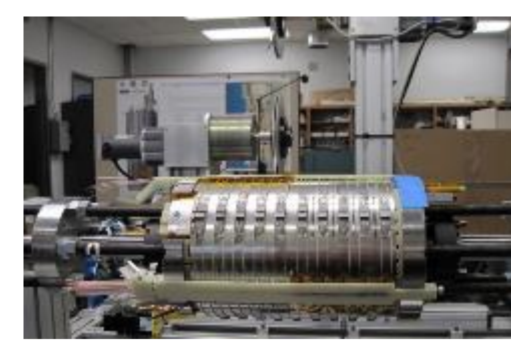
REBCO tape

Roebel Cable





Hybrid 32 T NHMFL magnet



DIPARTIMENTO
INGEGNERIA DELL'ENERGIA ELETTRICA
E DELL'INFORMAZIONE "GUGLIELMO MARCONI" - DEI

...and modeling solutions

Modeling techniques

- Field models (FEM, FEM-BEM, variational methods..)
  - Homogenization
  - Multi-scale
  - Change of coordinates
  - Reduced dimensionality
  - Statistical approach (for I_c longitudinal variations)
- Circuit models
  - Lumped parameters
  - Distributed parameters
- Hybrid models (field model + circuit model)

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- Introduction
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  - CORC
  - Twisted Stacked Tape Cable
  - Roebel cables
- Scaling up: coil and magnet systems
  - Insulated coils
  - Non insulated coils
- Discussion

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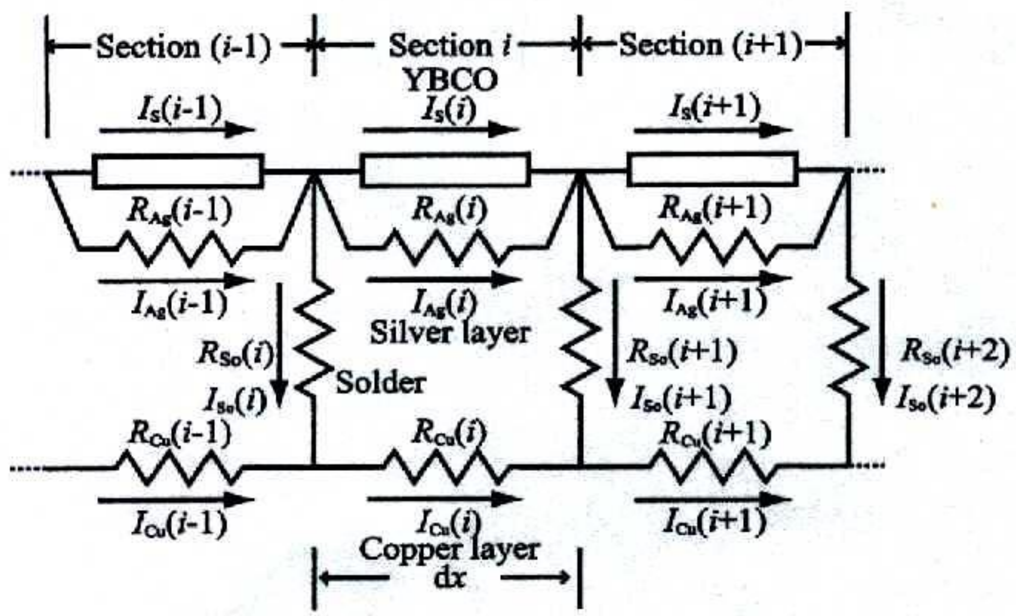
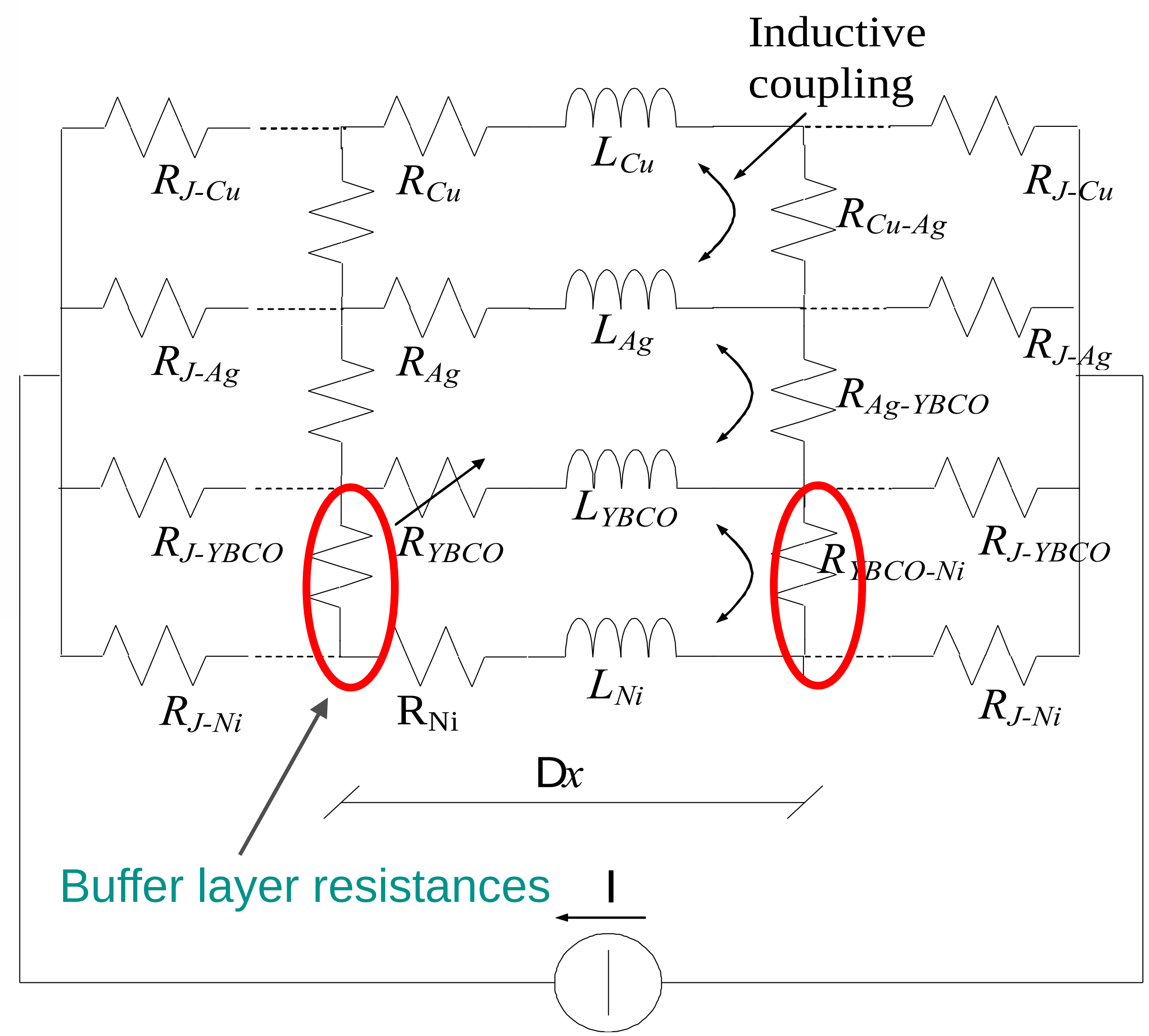
HTS tape modeling: circuit models

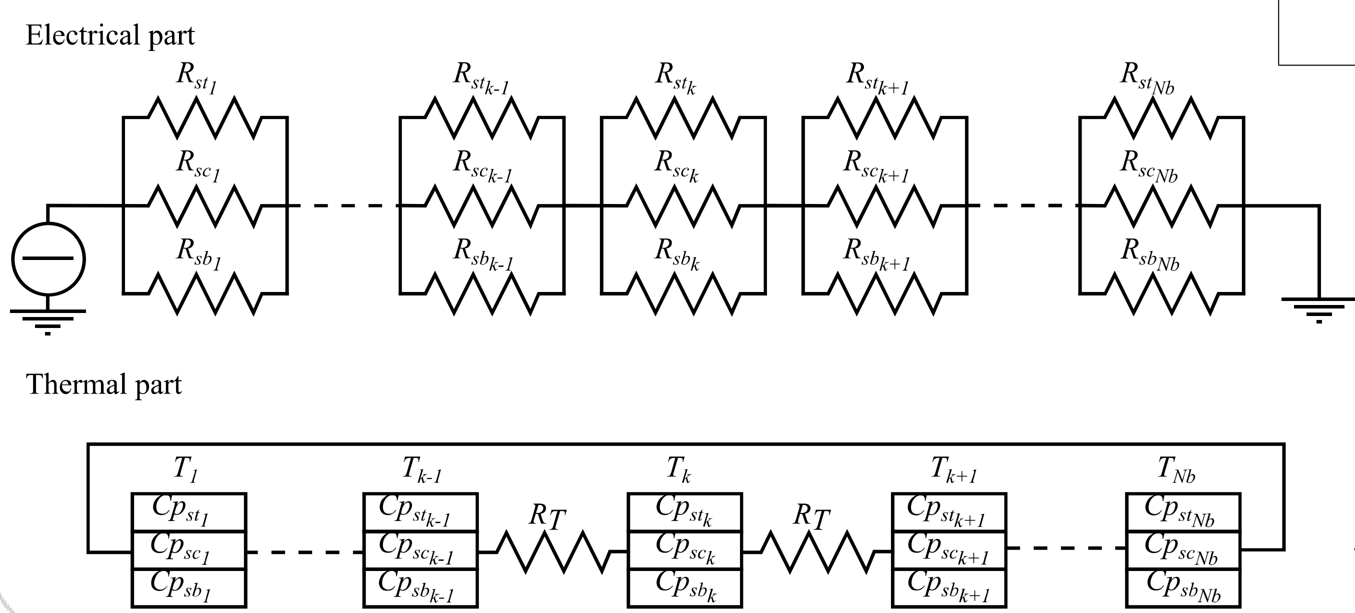
Lumped or distributed parameter circuit models



[1] Y. Fu, O. Tsukamoto, M. Furuse, *IEEE Trans. Appl. Supercond.*, Vol. 13, pp. 1780 – 1783, 2003.



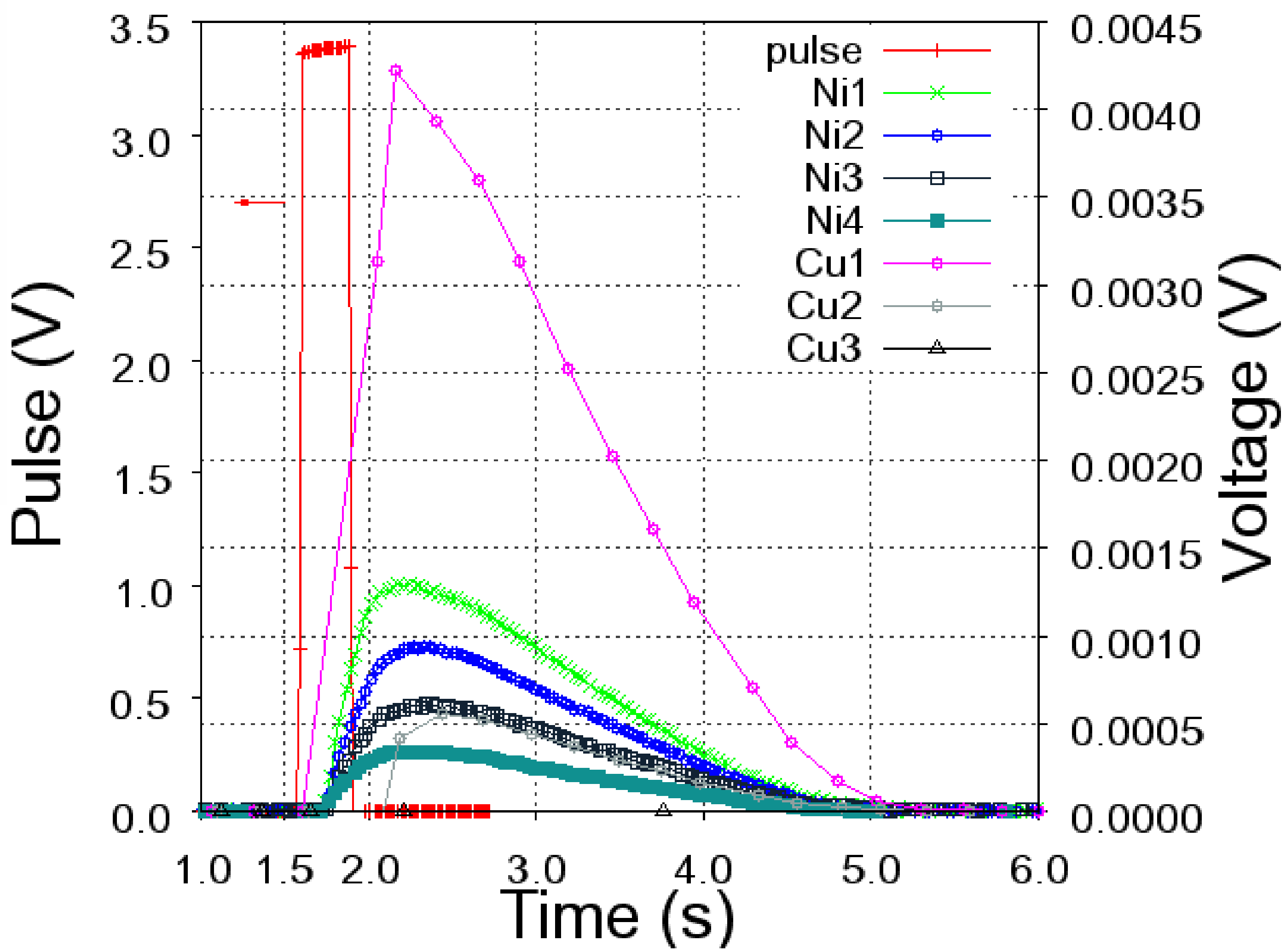
[2] M. Breschi, P. L. Ribani, X. Wang, J. Schwartz, *Supercond. Sci. Technol., Vol.* 20, L9 – L11, 2007.

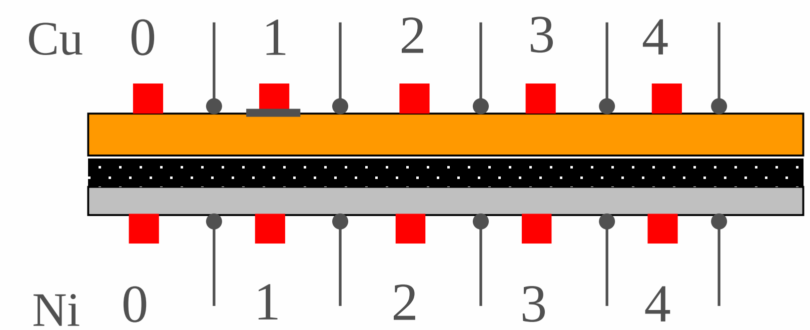


[3] D. Colangelo, B. Dutoit, Supercond. Sci. Technol., Vol. 27, 124005, 2014

HTS tape modeling: circuit models

Lumped or distributed parameters circuit models





- **Resistive heater pulses applied on the copper side of the tape**

[2] X. Wang, A. Caruso, M. Breschi, G. Zhang, U. Trociewitz, H. Weijers, J. Schwartz, *IEEE Trans. Appli. Supercond.*, Vol. 15, n. 2, pp. 2586 – 2589, 2005.

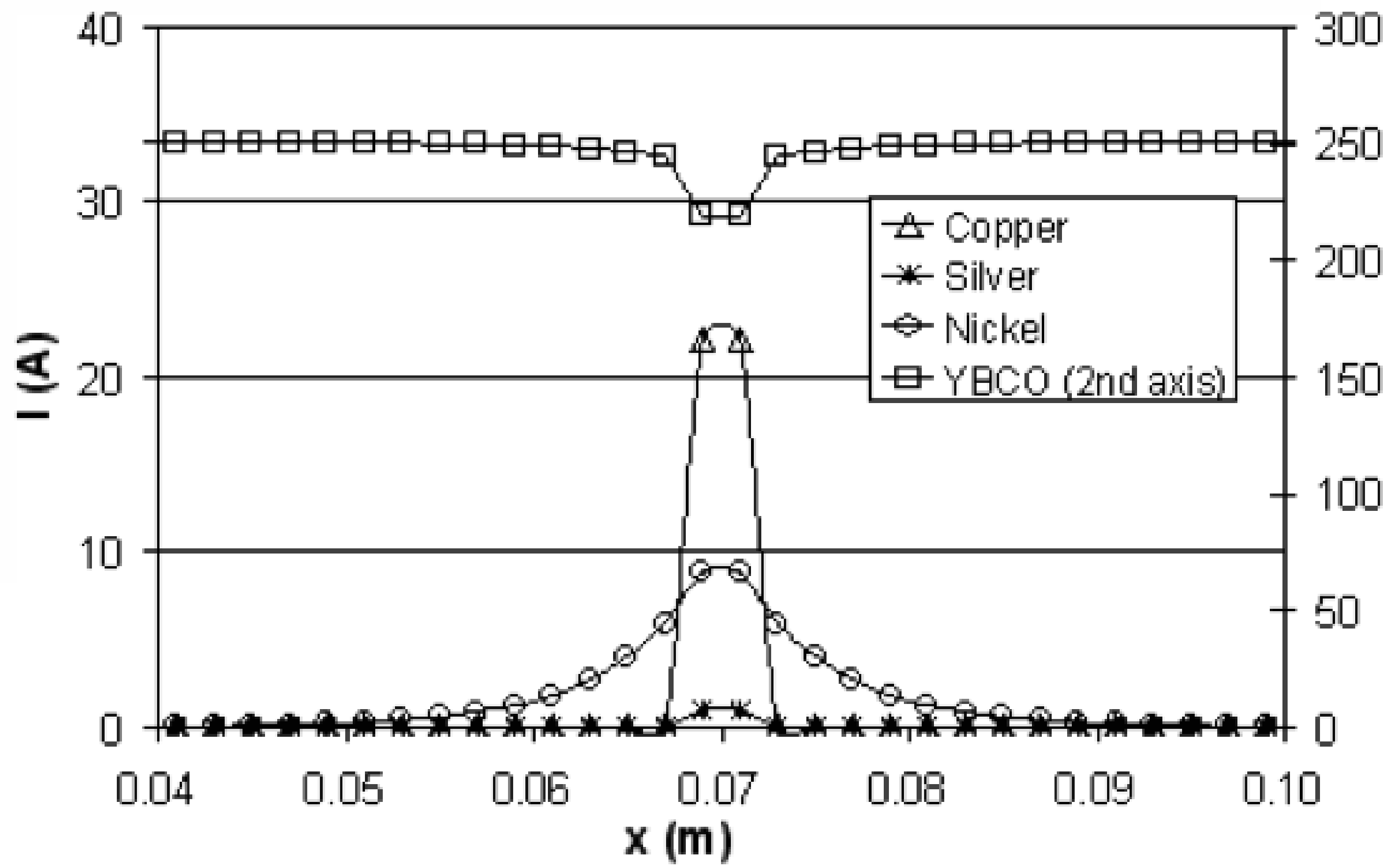
- **Measured at 77 K, I_t = 58 A (40% I_c), pulse height = 3.42 V**
- **Nickel substrate and copper not equipotential**
- **Different voltages measured on the two sides of the tape**

HTS tape modeling: circuit models

Current redistribution during quench

- The resistance of the buffer layer is **greater** than the transverse resistances between YBCO and Ag layers
- Current redistribution length (4 cm – 10 cm) towards the substrate greater than towards the Ag and Cu layers (1 cm - 2 cm)

$$\lambda_T = \frac{1}{\sqrt{rG}}$$



- Tuning the contact resistances can affect the quench propagation velocity

[2] M. Breschi, P. L. Ribani, X. Wang, J. Schwartz, *Supercond. Sci. Technol.* 20 L9 – L11, 2007.

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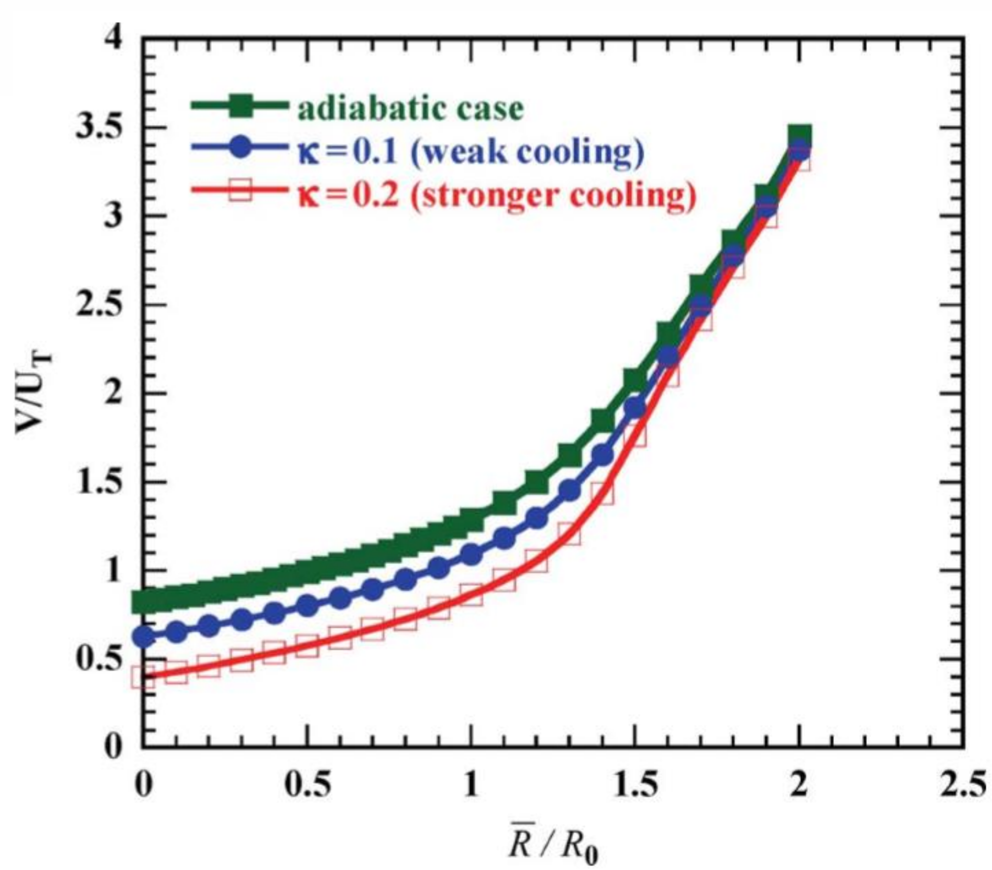
HTS tape modeling: different architectures

New tape architectures with higher NZPV

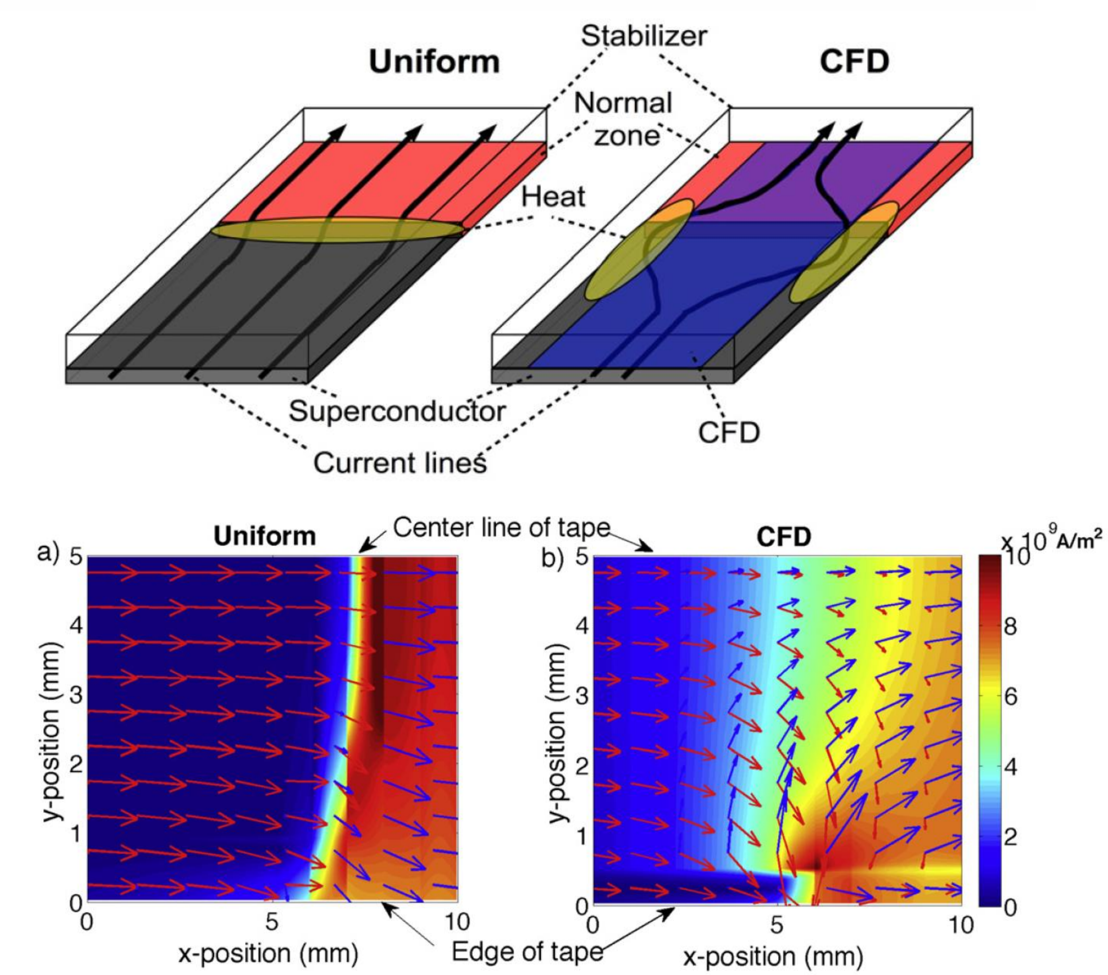
- Understanding the crucial role of transverse resistances in the quench development led to alternative **tape architectures**

Increasing NZPV with increasing interfacial resistance



[4] Levin GA, Barnes PN, Rodriguez JP, Connors JA, Bulmer JS., *IEEE Trans. Appl. Supercond., Vol. 19,* 2009

Current flow diverter



[5] C. Lacroix, F. Sirois, *Supercond. Sci. Technol.,* 035003, 2014.

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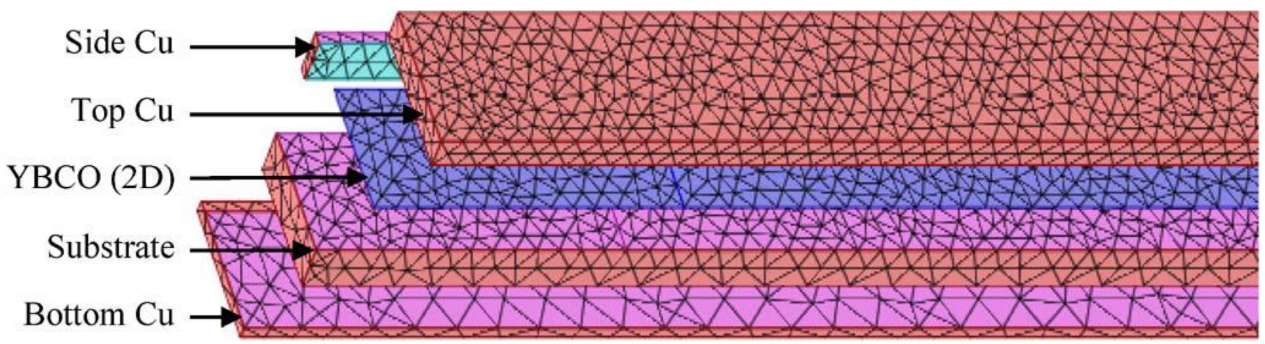
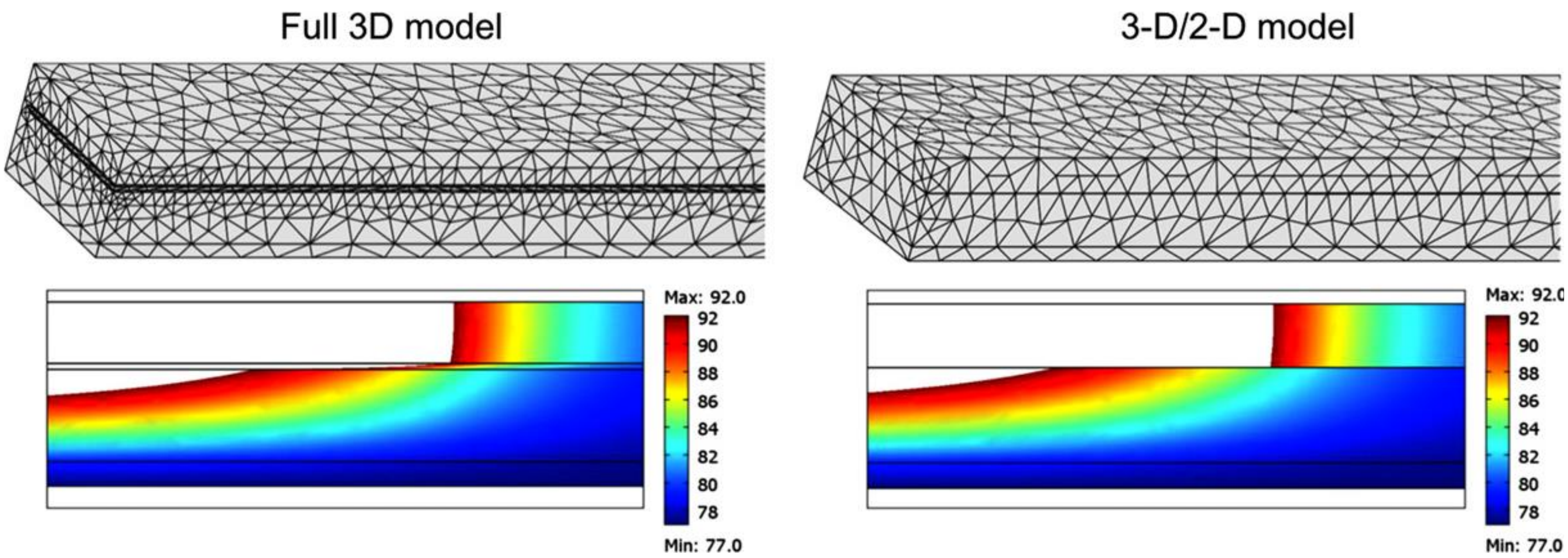
HTS tape modeling: field models

3D model and mixed dimensional method (2D – 3D)



- Copper stabilizers and substrate meshed in 3-D, YBCO layer meshed as a 2-D shell.



[6] W. K. Chan, P. J. Masson, C. Luongo., *IEEE Trans. Appl. Supercond.*, Vol. 20, pp. 2370 - 2380, 2010

HTS tape modeling: field models

2D model with change of coordinates

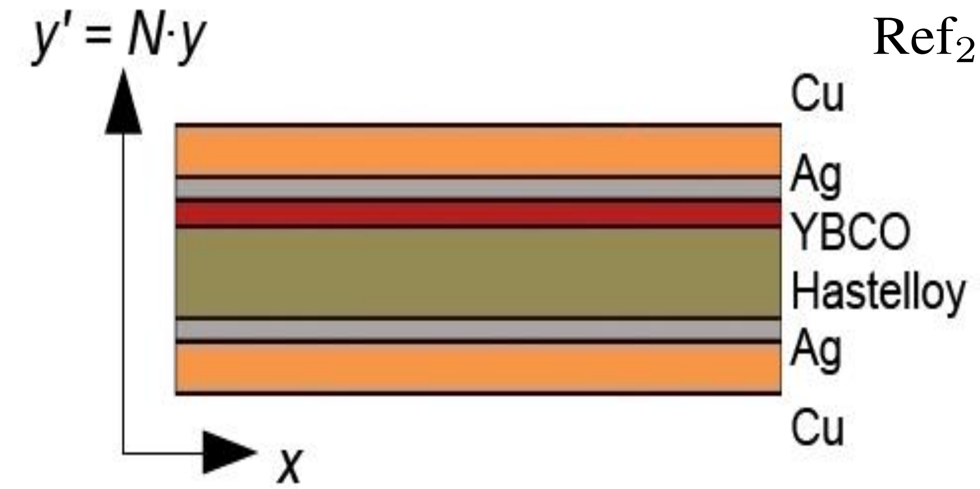
Ref$_1$

- To cope with the high aspect ratio, the tape thickness is multiplied by a constant parameter ***N***

Equation	Material Properties
$\rho c_p \frac{\partial T}{\partial t} = N \rho' c_p' \frac{\partial T}{\partial t}$	$c_p'(T) = c_p(T)$ $\rho' = \rho / N$
$-\frac{\partial k_x}{\partial T}\left(\frac{\partial T}{\partial x}\right)^2 = -N \frac{\partial k_x'}{\partial T}\left(\frac{\partial T}{\partial x}\right)^2$ $-k_x \frac{\partial^2 T}{\partial x^2} = -N k_x' \frac{\partial^2 T}{\partial x^2}$	$k_x' = k_x / N$
$-\frac{\partial k_y}{\partial T}\left(\frac{\partial T}{\partial y}\right)^2 = -\frac{\partial k_y'}{N \partial T}\left(\frac{\partial T}{\partial y}\right)^2$ $-k_y \frac{\partial^2 T}{\partial y^2} = -k_y' \frac{\partial^2 T}{N \partial y^2}$	$k_y' = k_y \cdot N$
$\sigma_x \left(\frac{\partial V}{\partial x}\right)^2 = N \sigma_x' \left(\frac{\partial V}{\partial x}\right)^2$	$\sigma_x' = \sigma_x / N$
$\sigma_y \left(\frac{\partial V}{\partial y}\right)^2 = \sigma_y' \left(\frac{\partial V}{\partial y}\right)^2 \frac{1}{N}$	$\sigma_y' = \sigma_y \cdot N$

[7] M. Casali, M. Breschi, P. L. Ribani, *IEEE Trans. Appl. Supercondu.*, vol. 25, n. 1, 6862876, 2015

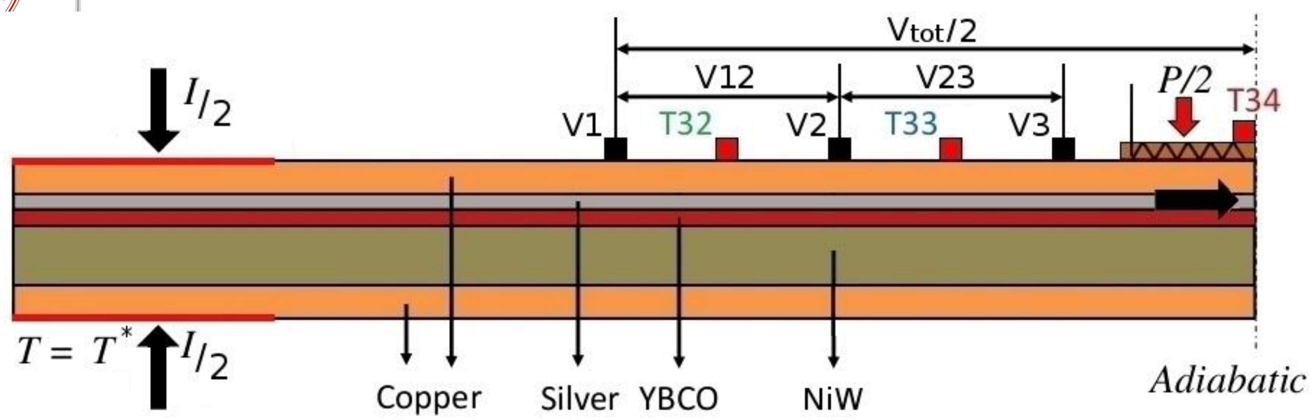
Ref$_2$

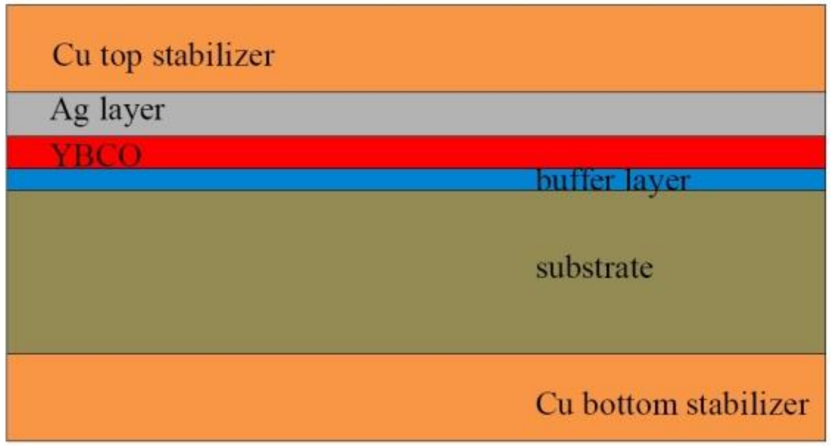


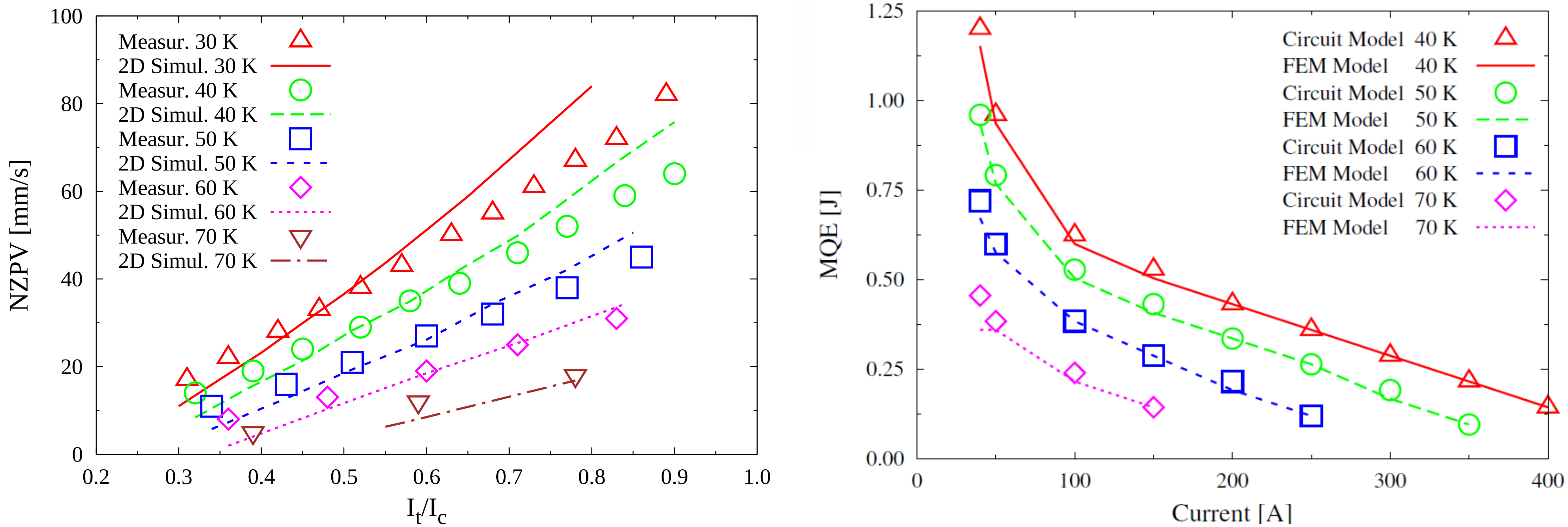
Triangular mesh

N	Free Triangular	
	Mesh elements	*Computation time [s]*
1	420000	-
50	20000	5423
100	10000	2792

HTS tape modeling: field vs circuit model







- Significant reduction of computation time with **circuit model** relative to **field model**

Computation time [s]	RECOVERY	QUENCH
Circuit	188	89
FEM	6329	1371

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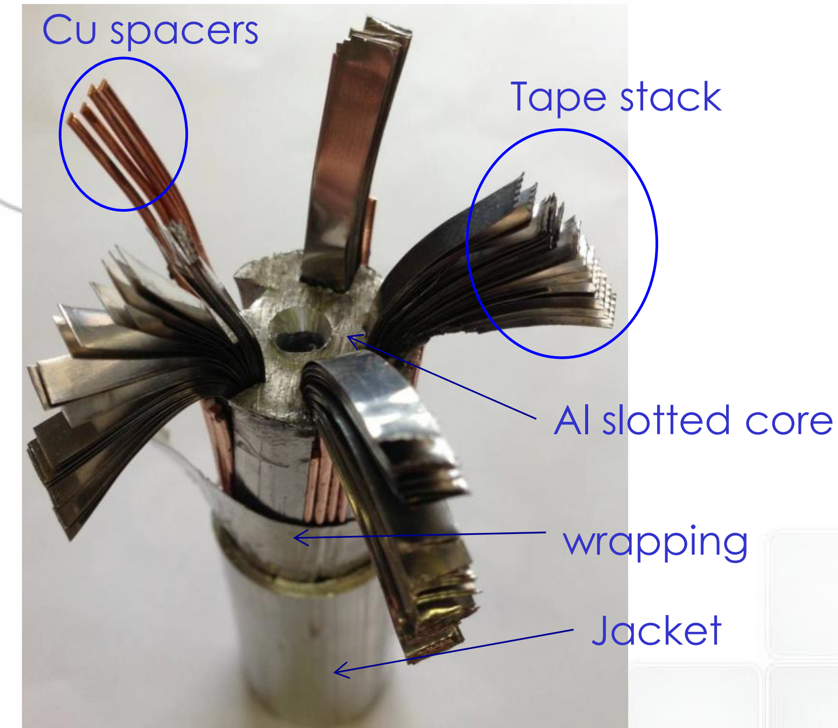
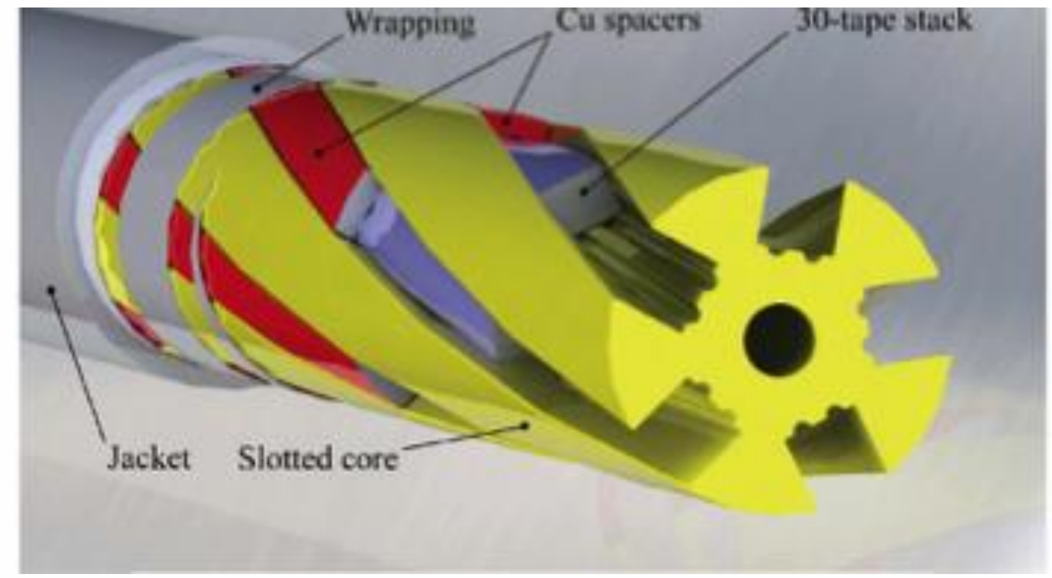
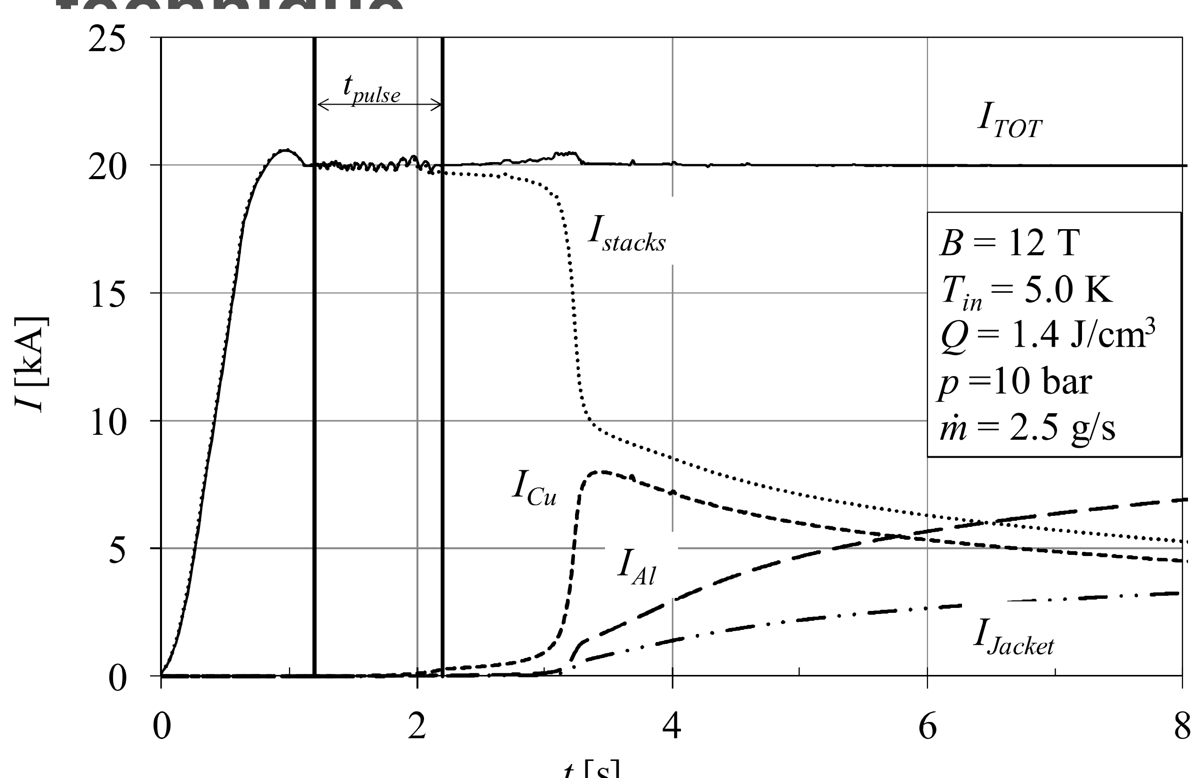
From tapes to cables: twisted stacked tape cable (slotted core)

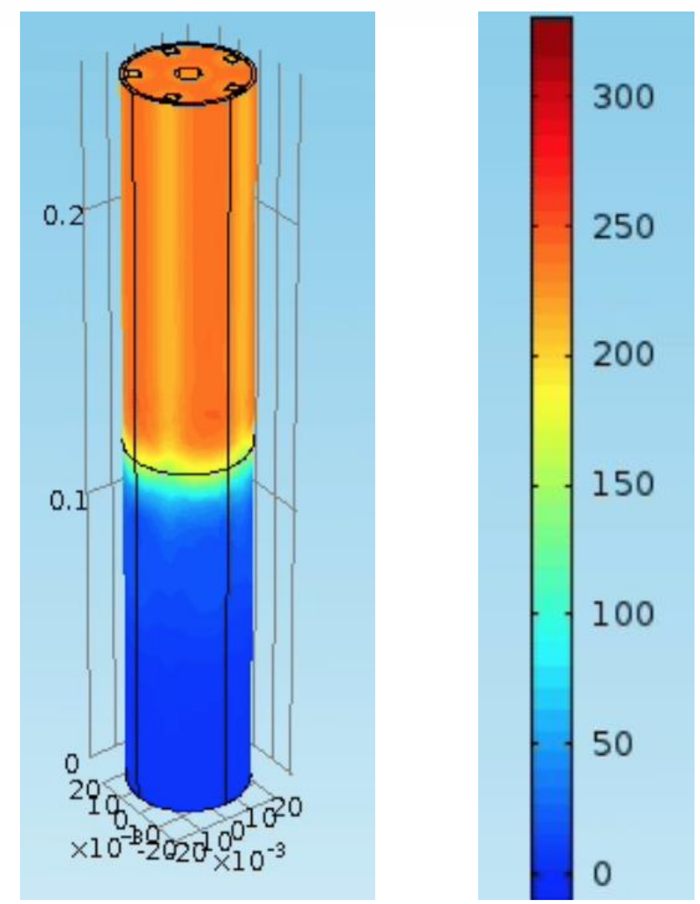


Twisted stacked cable (ENEA Frascati)



- **Electro-thermal field model based on homogenization technique**

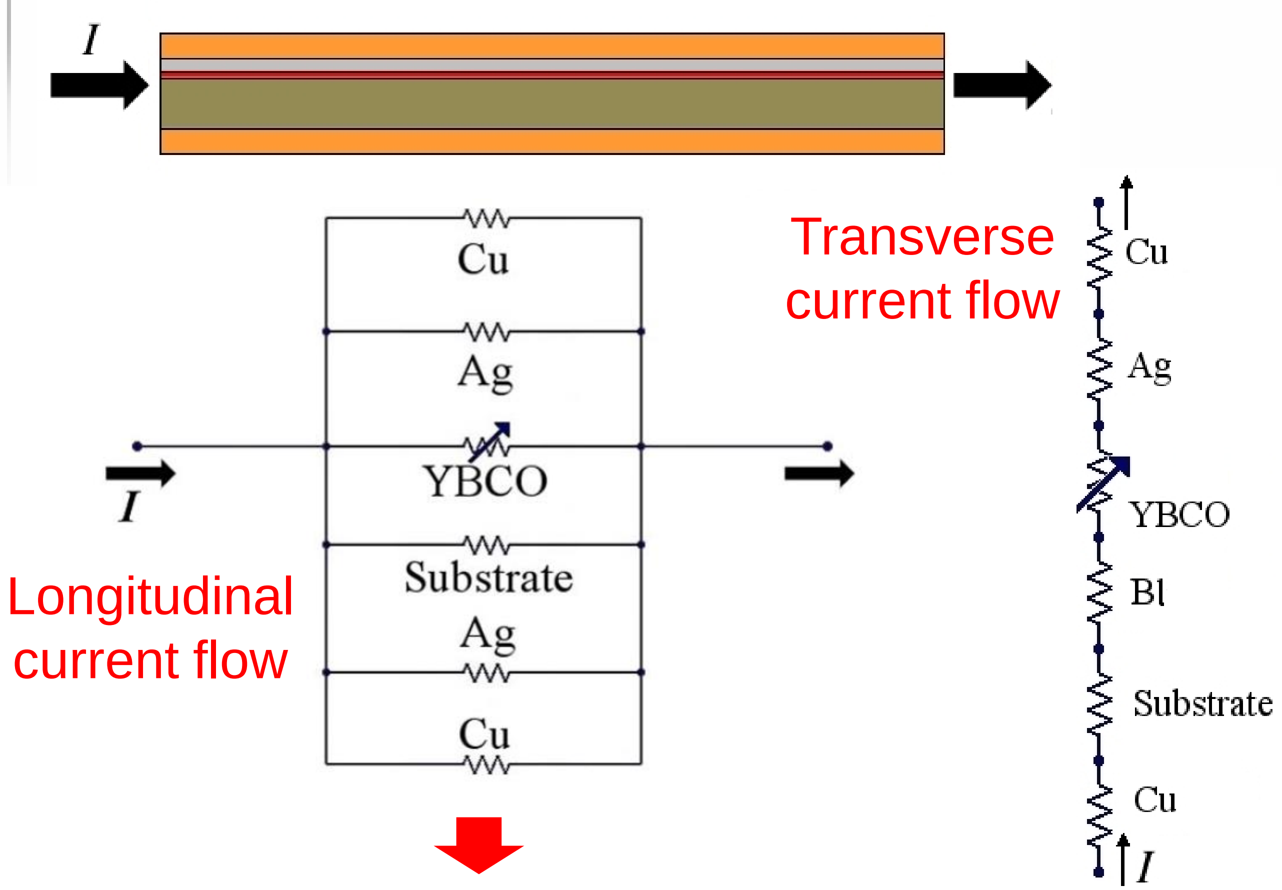




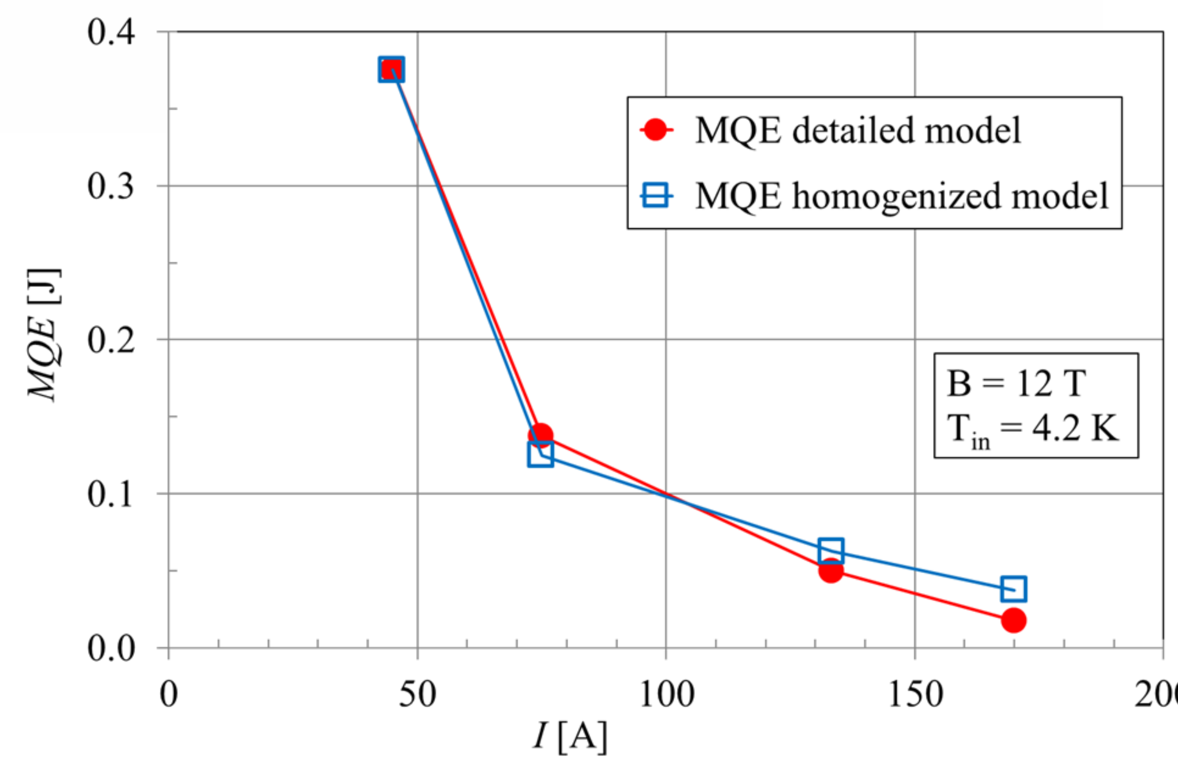
[8] M. Breschi, et al., *IEEE Trans. Appl. Supercondu.*, vol. 25, n. 3, 4800505, 2015

From tapes to cables: homogenization

- Increasing the number of degrees of freedom, modeling stacks requires **homogenization** techniques
- Resistances are taken in parallel for the longitudinal flow, and in series for the transverse flow, obtaining **anisotropic** properties



$$\sigma_l = \frac{I_c(T,B)}{E_c\ S_{tot}} \left(\frac{E}{E_c}\right)^{\frac{1-n}{n}} + \sum_{j=1}^{N_l} \sigma_j(T,B)\ \frac{S_j}{S_{tot}}$$

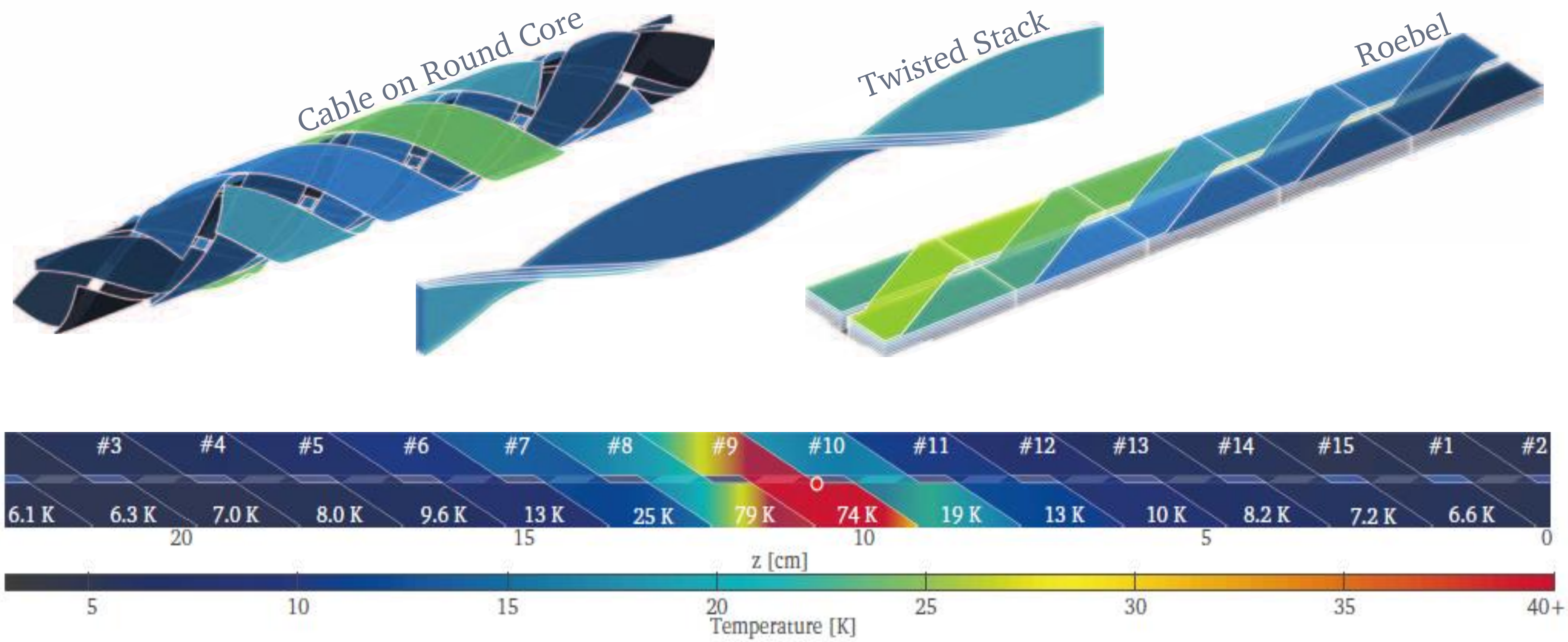


- The error on MQE due to homogenization **can reach 30 %**

[8] M. Breschi, et al., *IEEE Trans. Appl. Supercondu.*, vol. 25, n. 3, 4800505, 2015

From tapes to cables: 3D - thin strip

- **Electromagnetic and thermal network model for quench analysis, AC loss and field quality**



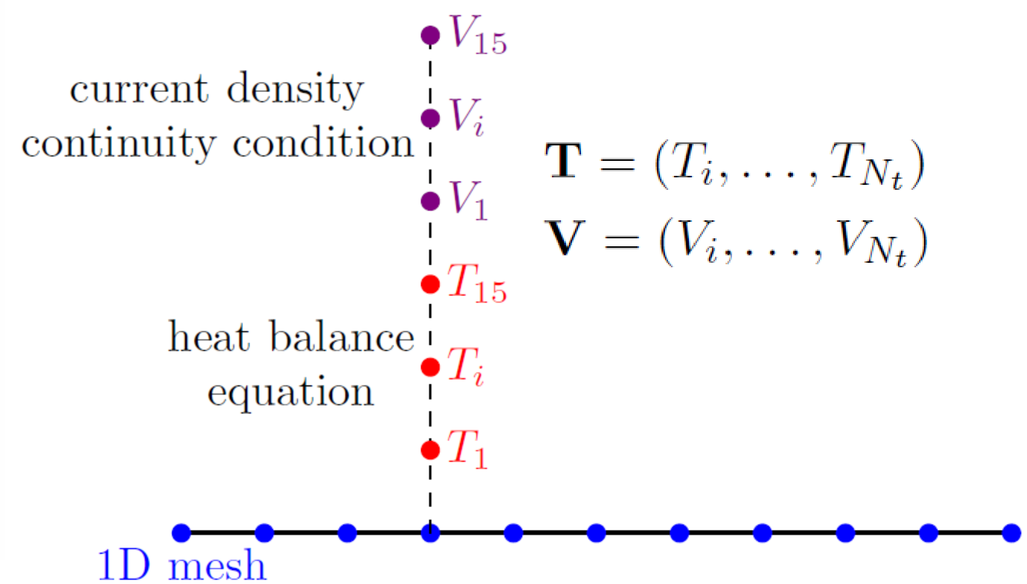
- **Computation of current and temperature distribution during quench.**

[9] J. Van Nugteren., «High Temperature Superconductors Accelerator Magnets», Ph.D. dissertation, University of Twente, 2016

From tapes to cables: Roebel cable reduced dimensionality approach

Electrothermal model for quench calculation

- The Roebel cable is described by means of a 1D FEM model.
- At each mesh point, the model unknowns are the temperatures T_i and voltages V_i of each tape



$$\mathbf{T} = (T_i, \ldots, T_{N_t}) \qquad \forall i = 1 \ldots N_t$$

$$\mathbf{V} = (V_i, \ldots, V_{N_t}) \qquad \forall i = 1 \ldots N_t$$

- The **heat diffusion equation** can be written for the i-th tape as

$$\rho\, C_p(T_i(x,t))\, \frac{\partial T_i(x,t)}{\partial t} - \frac{\partial}{\partial x}\left(k(T_i(x,t))\, \frac{\partial T_i(x,t)}{\partial x}\right) =$$

$$= \sigma_i\left(T_i(x,t), E_i(x,t)\right)\left(\frac{\partial V_i(x,t)}{\partial x}\right)^2 + \sum_j Q^J_{i,j}(x,t) + \sum_j Q^c_{i,j}(x,t) + Q^h_i(x,t)$$

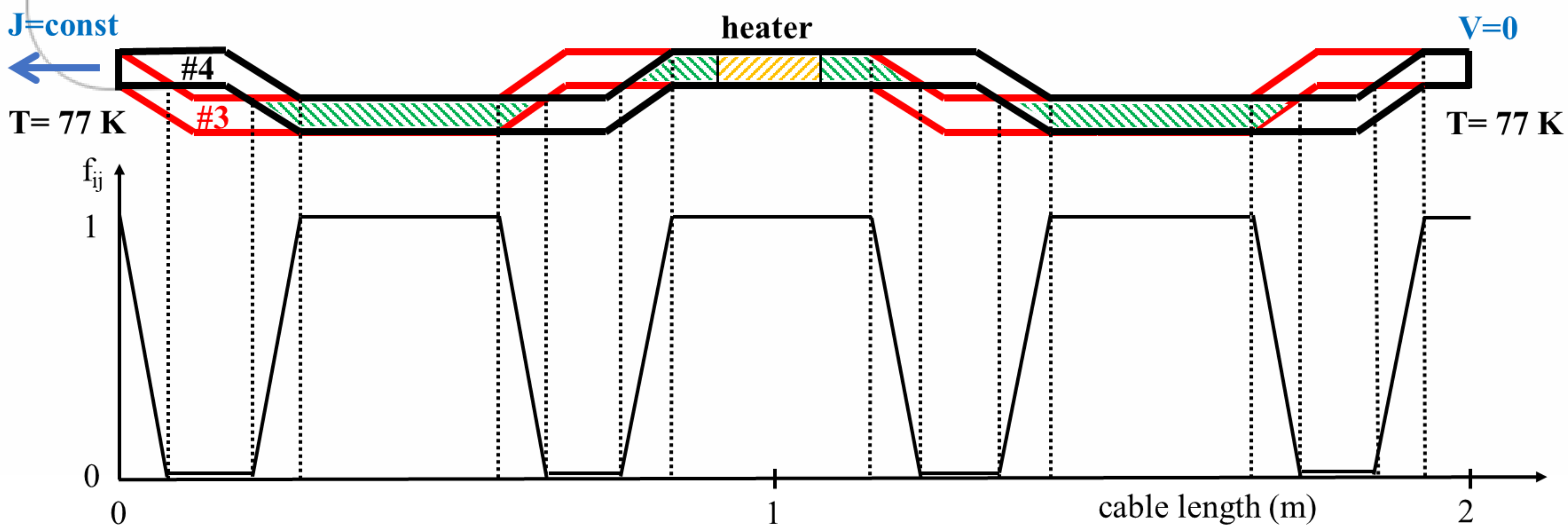
Joule power due to the current exchange between the *i*-th and *j*-th tapes in contact ($\sum_j Q^J_{i,j}$)

thermal conduction between the *i*-th and *j*-th tapes in contact ($\sum_j Q^c_{i,j}$)

heater thermal disturbance (Q^h_i)

[10] L. Cavallucci, M. Breschi, P. L. Ribani and Y. Yang, *IEEE Trans. Appl. Supercond.*, vol. 28, no. 4, Jun. 2018.

From tapes to cables: Roebel cable reduced dimensionality approach



- The contact between different tapes is described through **non-uniform conductances**
- The electric potential at the reference terminal of the cable is set to 0

$$V_i = 0 \qquad \forall i = 1 \dots N_t$$

- The current distribution is set on each tape at the other terminal

$$I_i(t) = k_i(t) \qquad \forall i = 1 \dots N_t$$

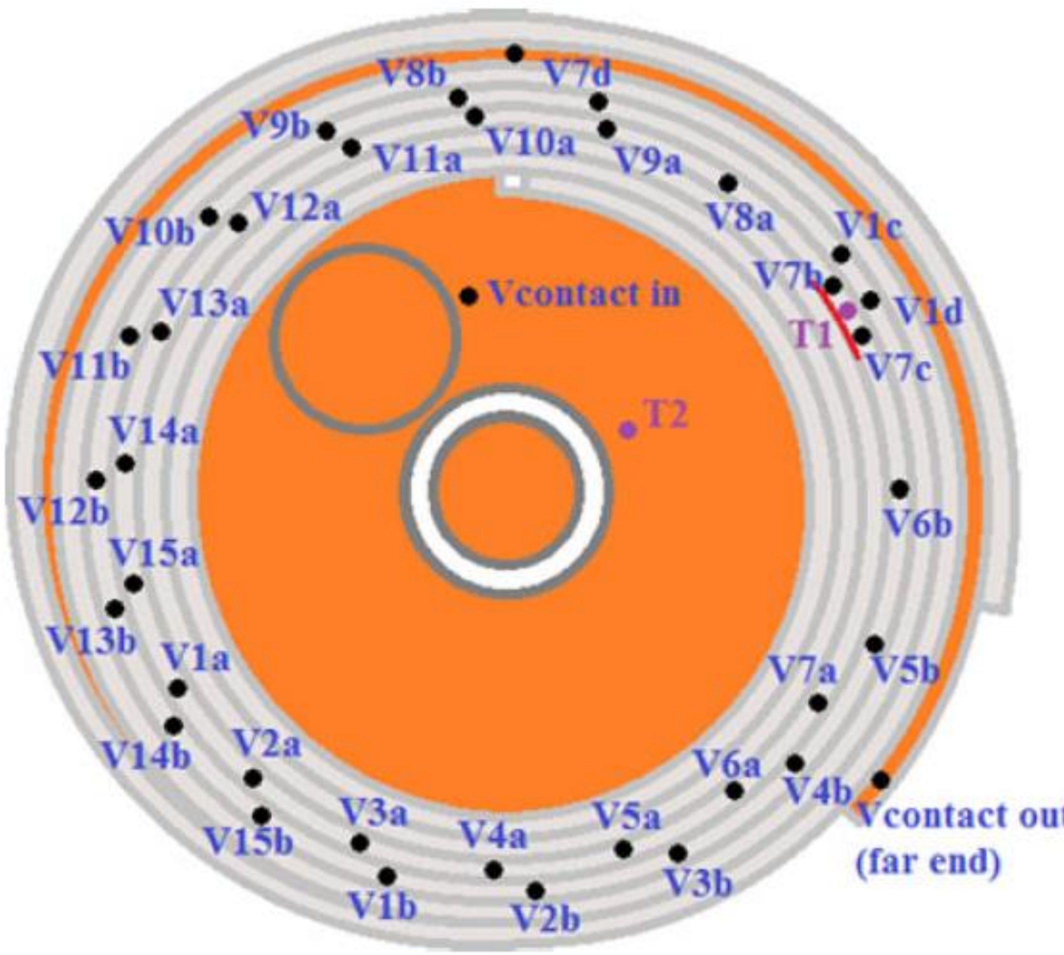
$$\sum_{i=1}^{N_t} I_i(t) = I_{op}(t)$$

- Coupling with the **thermal model**

From tapes to cables: Roebel cable reduced dimensionality approach

Experiment at the University of Southampton

- A 2 m long Roebel cable with 15 strands YBCO tapes (Bruker EST) was wound into a **pancake coil of 7 turns** with 72 mm inner diameter.
- A length of **fiberglass ribbon** was co-wound as electrical insulation layer; the coil was then impregnated with epoxy resin.
- At the 4th turn of the coil, a **miniature heater** was attached to tape #7 at the inner face of the turn
- Quench experiments were performed at **77 K**, 450 A transport current

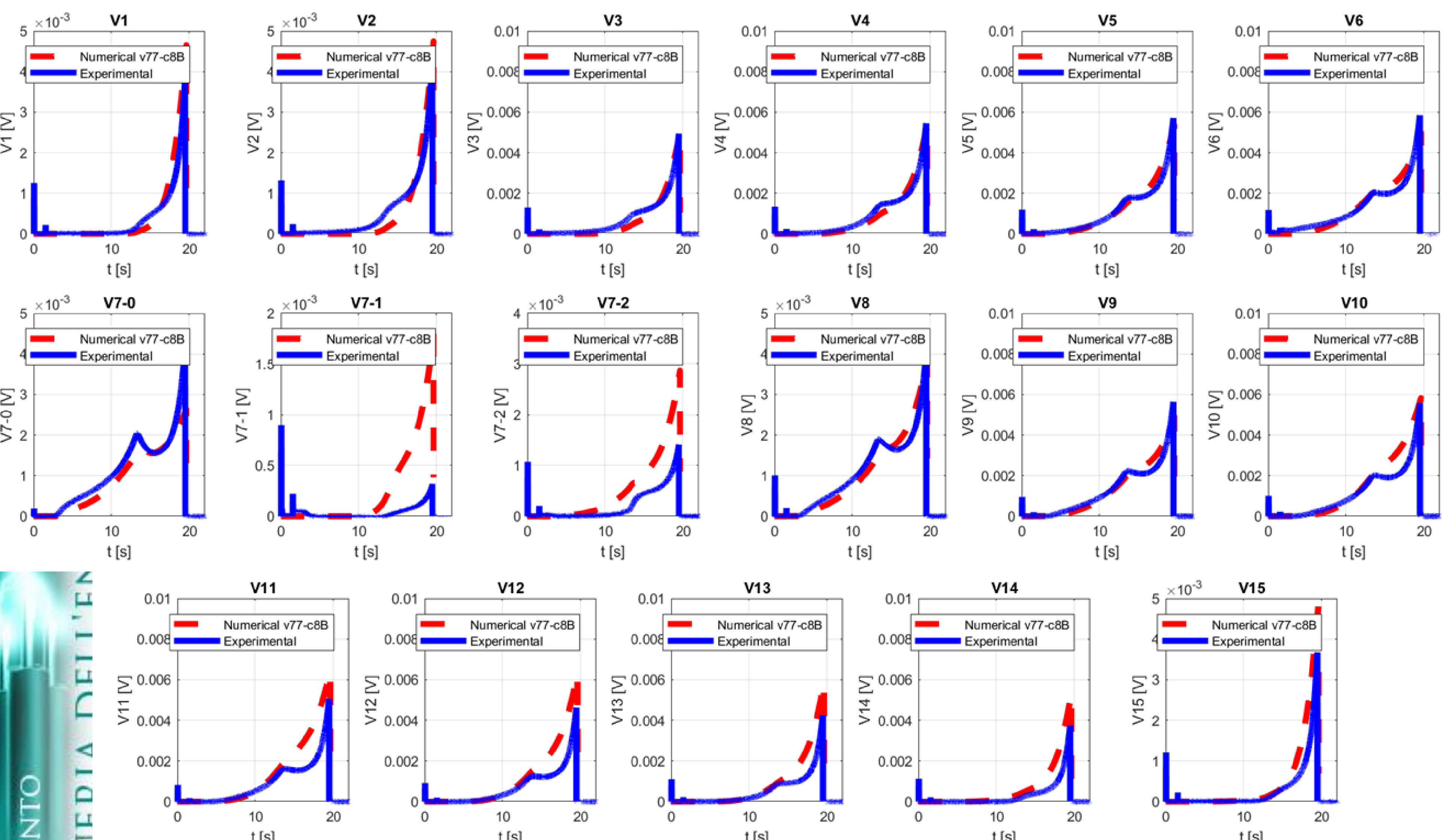


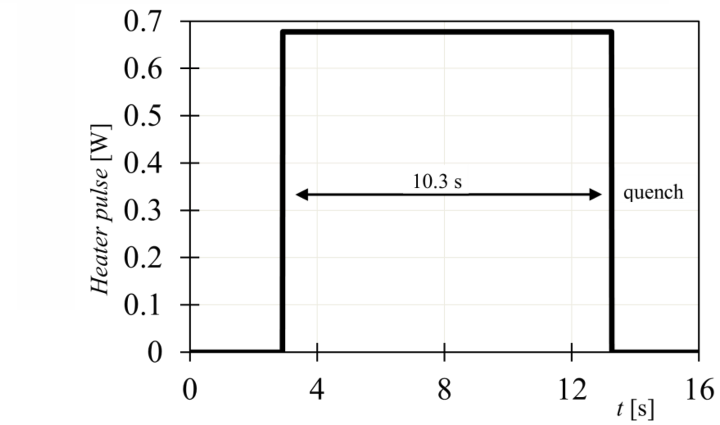
[11] Q. Zhang, et. al., *IEEE Trans. Appl. Supercond.*, vol. 28, no. 4, Jun. 2018.

From tapes to cables: Roebel cable reduced dimensionality approach

Model vs experiment

- A good agreement was found between the experimental and numerical results

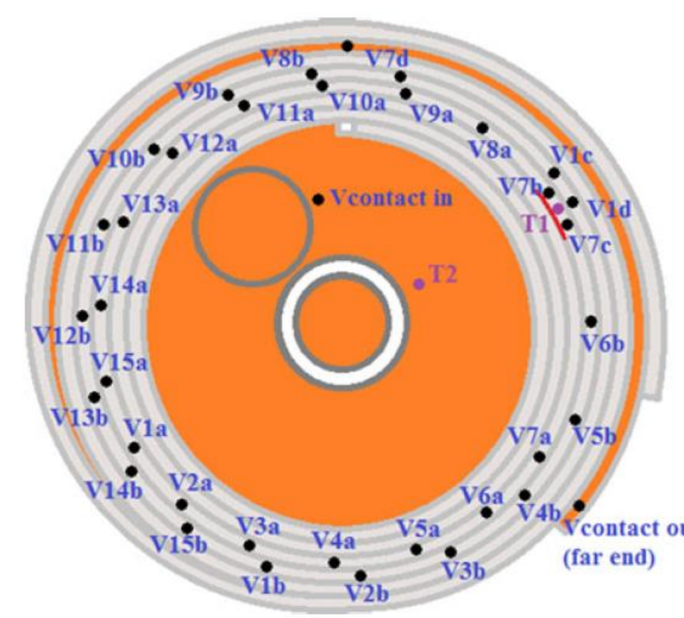




$$V7\_1 = V7a - V7b$$

$$V7\_2 = V7c - V7d \quad Vn = Vna - Vnb$$

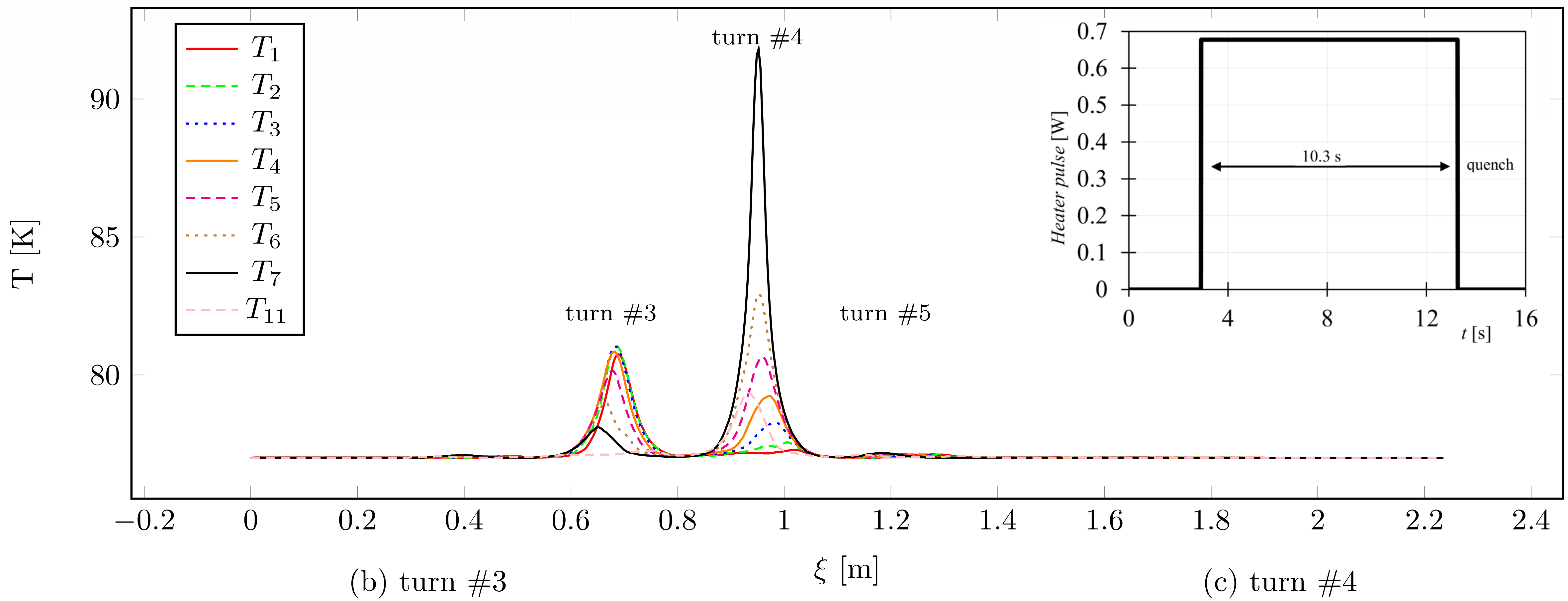
$$V7\_0 = V7b - V7c$$



From tapes to cables: Roebel cable reduced dimensionality approach

Quench propagation in the longitudinal and radial direction

- The temperature distribution *at the end of the heater pulse* shows the effects of the heat transverse **between tapes** of the cable and from **turn to turn**



- For some tapes, the heat redistribution **between turns** is faster than within the same turn

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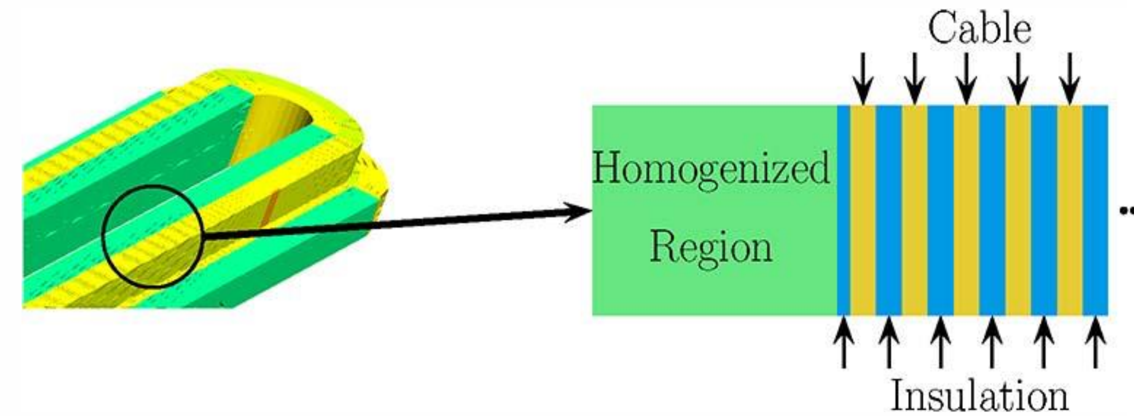
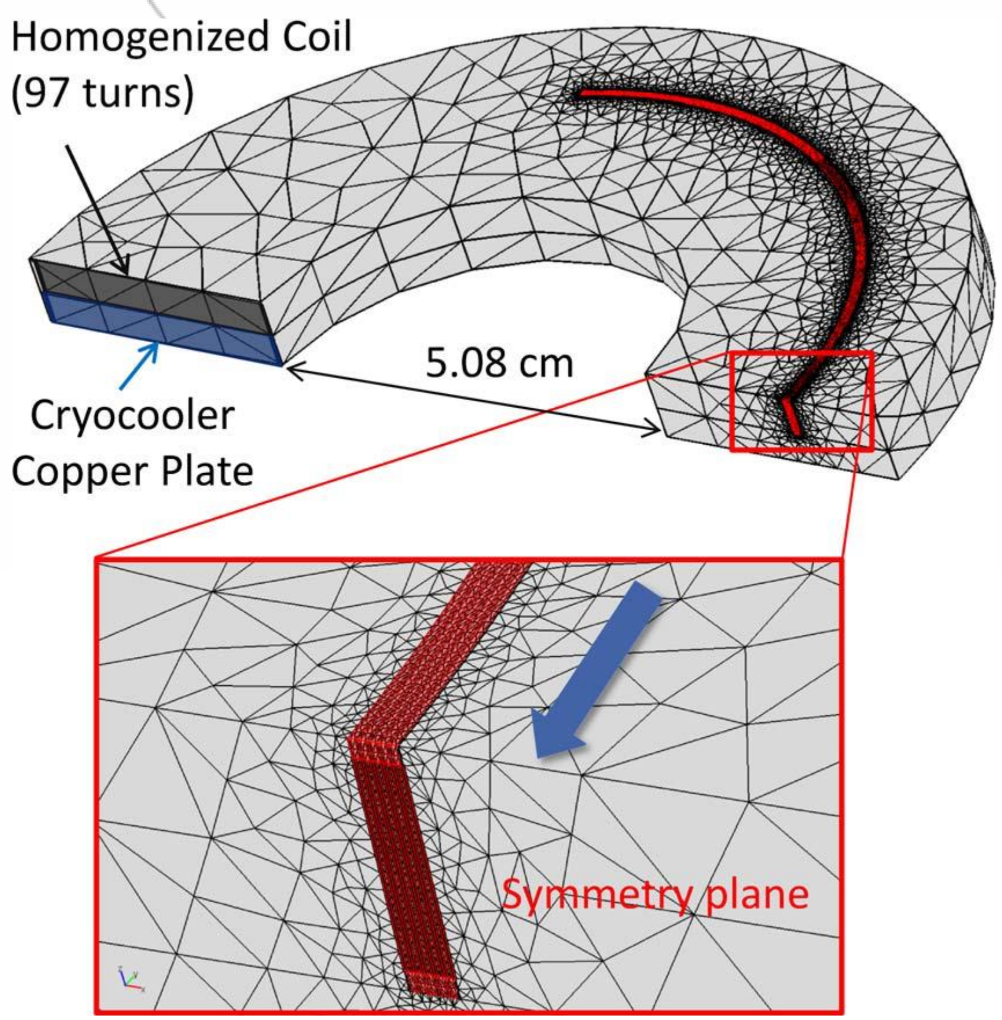
Scaling up: full coil models



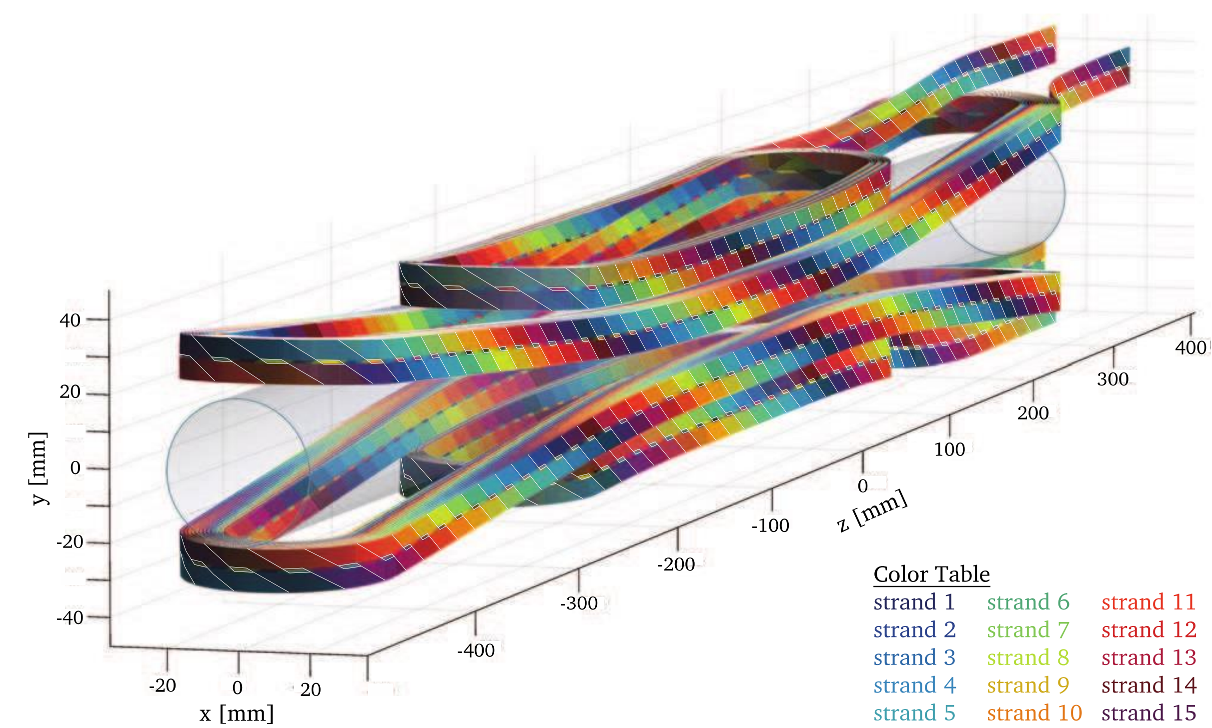
- Coil represented in some parts as a homogenous **mixture of cable and insulation**, in other parts as structur including cable and insulation layer

[13] E. Härö and A. Stenvall, *IEEE Trans. Appl. Supercond.*, vol. 24, no. 3, 4900705, 2014.



- Multiscale coil model composed of a homogenized coil and a localized embedded **multilayer tape module** (inset)

[12] W. K. Chan, J. Schwartz, *IEEE Trans. Appl. Supercond.*, vol. 22, no. 5, 4706010, 2012.



[9] J. Van Nugteren., Ph.D. dissertation, University of Twente, 2016

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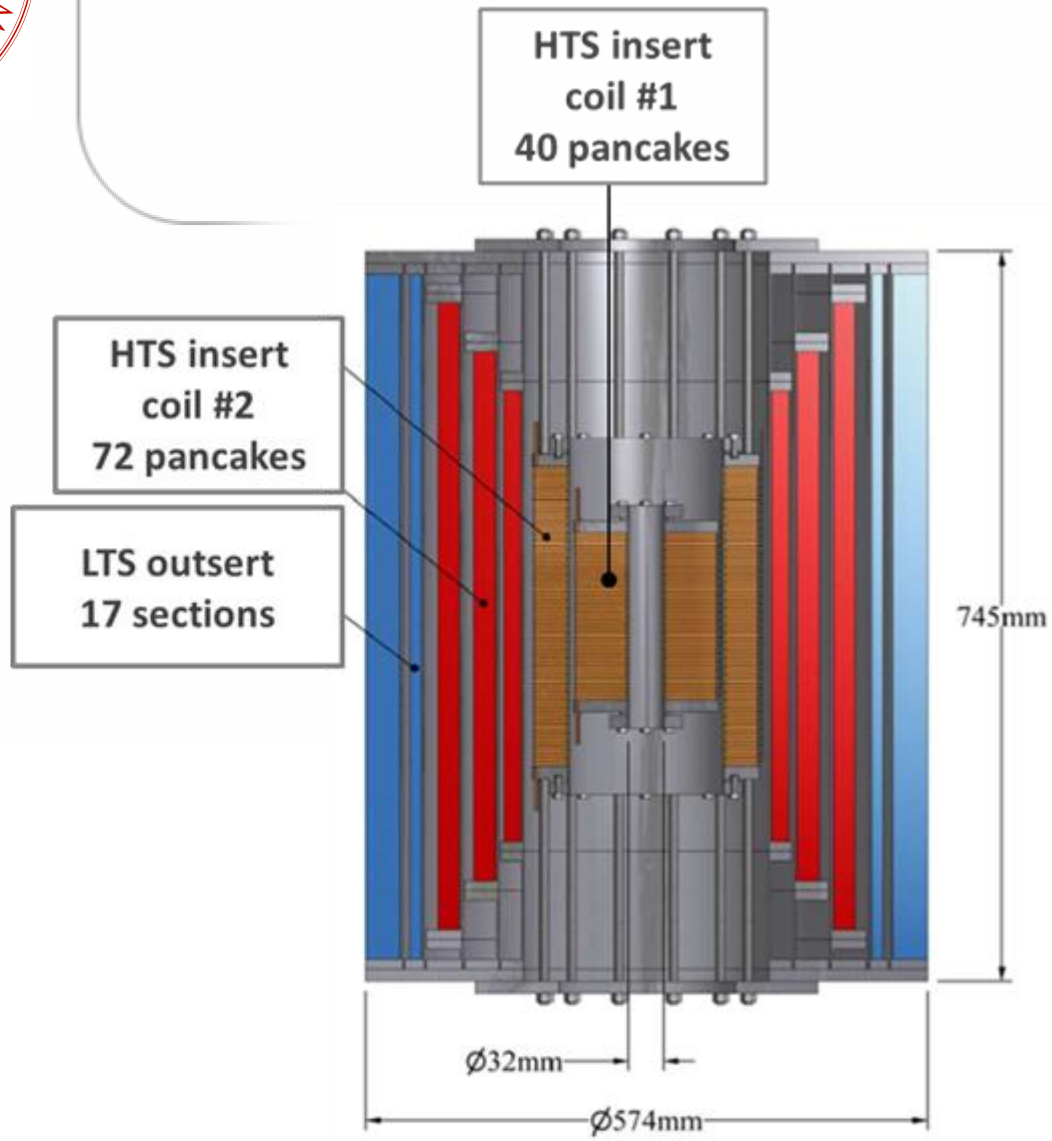
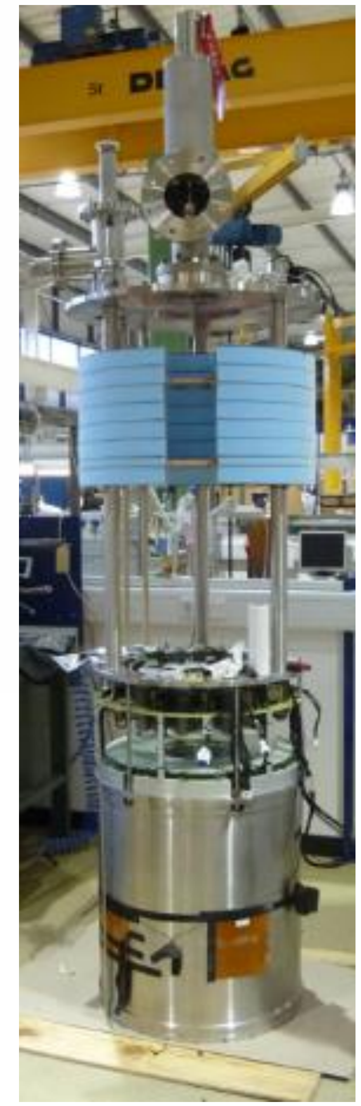
Scaling up: 32 T NHMFL magnet model



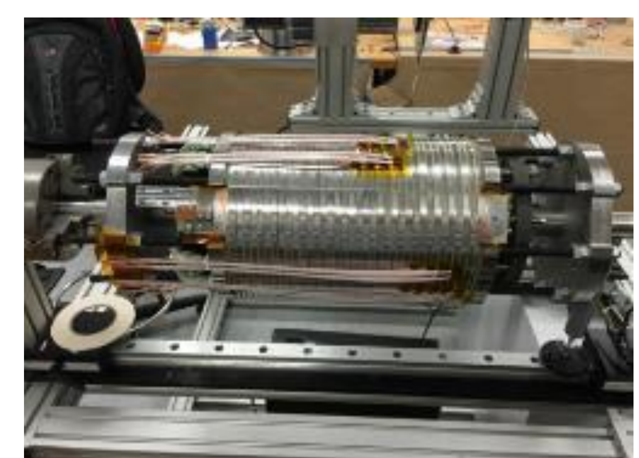


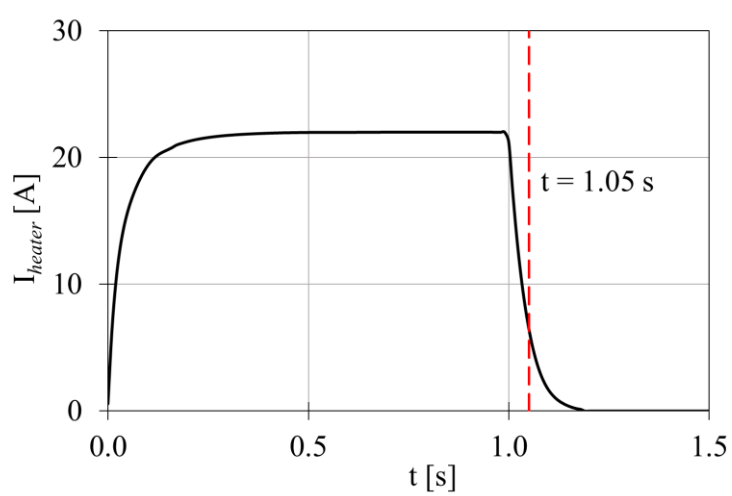
32 T MAGNET

Parameter	Value
Central Field	32 T
LTS Outsert Field	15 T
HTS Insert Field	17 T
Central Bore	34 mm
Ramp time	1 h
Operating temperature	4.2 K
Stored Energy	8.3 MJ
System weight	2.6 ton

HTS insert coil #1 (10.7 T)

HTS insert coil #2 (6.3 T)





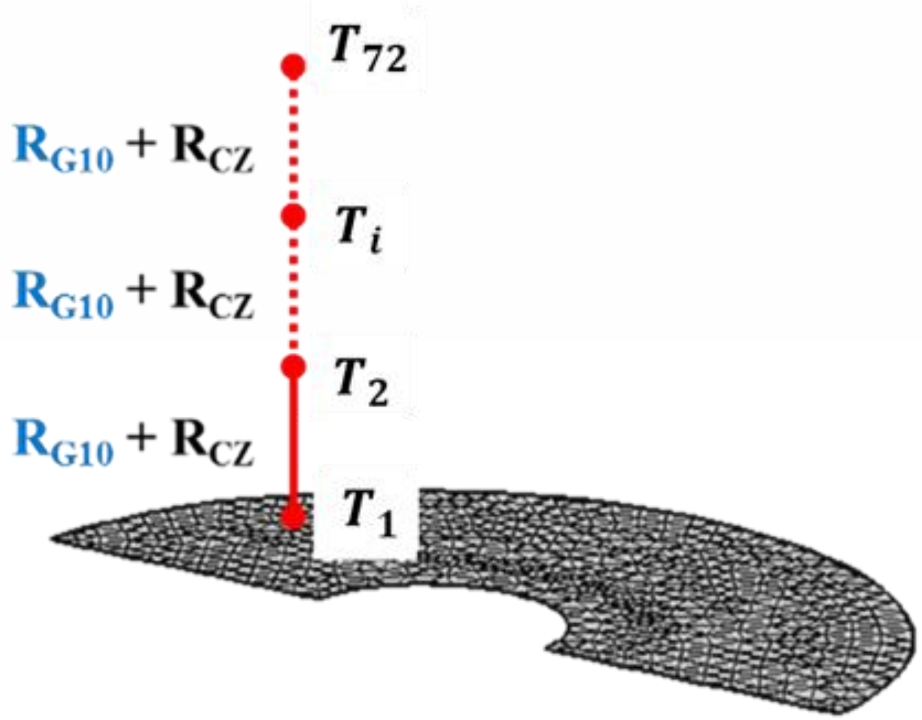
[14] H. W. Weijers et al., *IEEE Trans. Appl. Supercond.*, vol. 24, no. 3, Jun. 2014, Art. ID. 4301805.

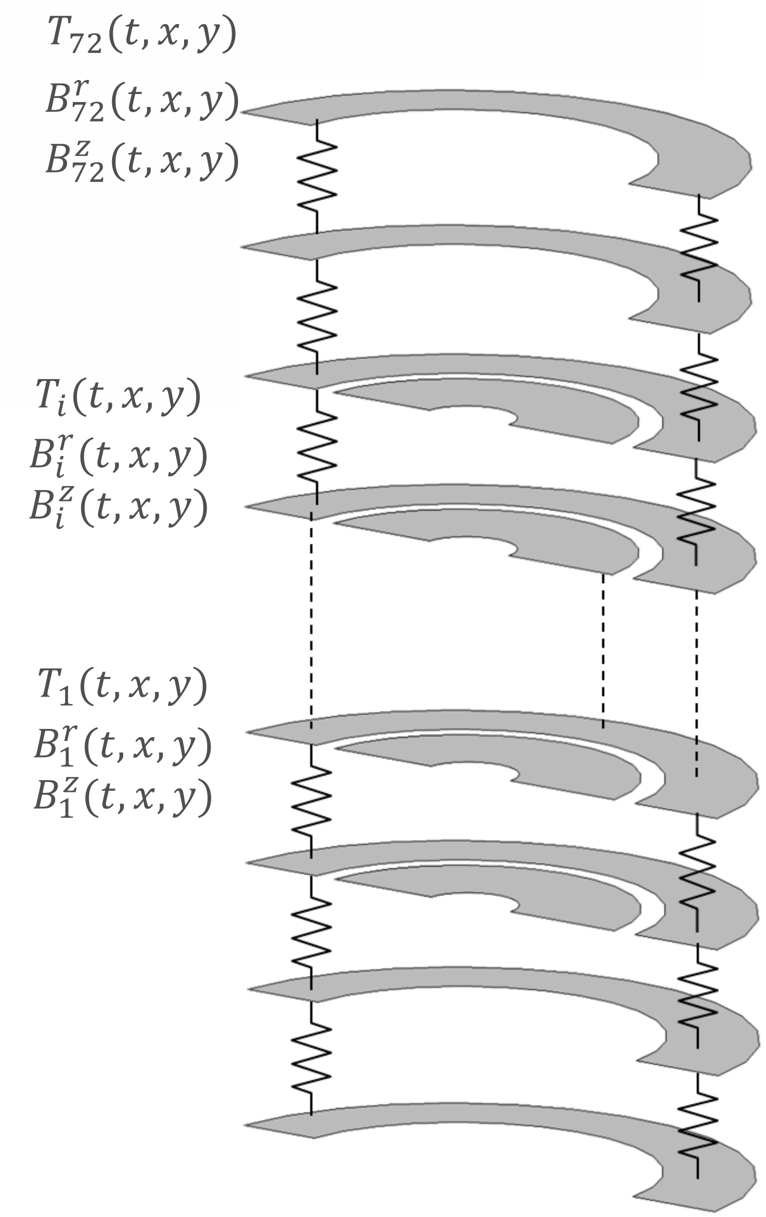
Scaling up: 32 T NHMFL magnet model

- **Only one 2D pancake is discretized with a mesh. At each mesh point, a set of heat balance equations is written for an array of temperatures**

$$\boldsymbol{T} = [T_1(x,y) \quad \dots \quad T_i(x,y) \quad \dots \quad T_{72}(x,y)]$$

R_{G10}, R_{CZ} DISTRIBUTED THERMAL RESISTANCES





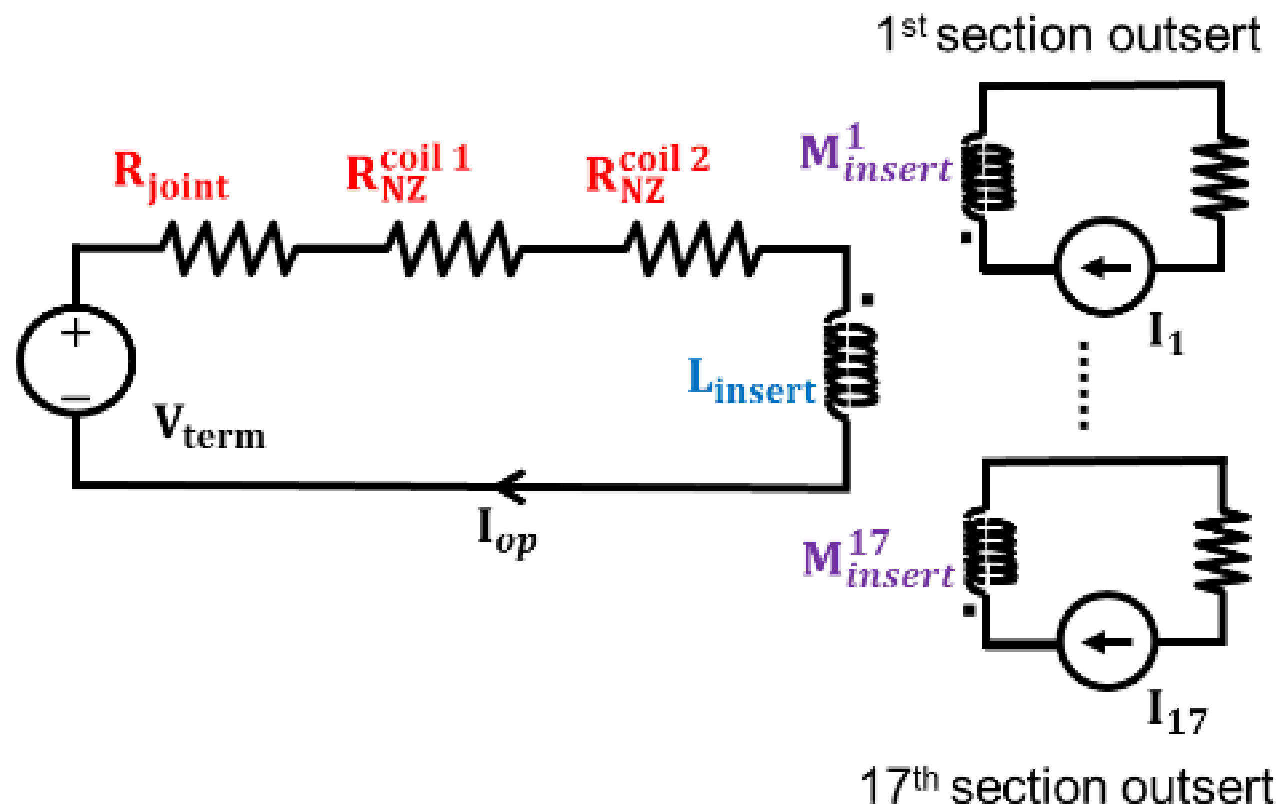
Axial heat flux between pa

$$Q_{axial}^{cond} = \frac{T_{i+1} - T_i}{V_p(R_{G10}^{i,i+1} + R_{cz})} - \frac{T_i - T_{i-1}}{V_p\left(R_{G10}^{i,i+1} + R_{cz}\right)}$$

[15] M Breschi, L Cavallucci, P. L. Ribani, A. V. Gavrilin, and H. W. Weijers, *Supercond. Sci. Technol.*, vol. 29, 2016, Art. no. 055002.

Scaling up: 32 T NHMFL magnet model

Coil constitutive law



- Lumped parameter circuit describing the mutual induction coupling between the insert and the 17-sections outsert

$$V_{ground} = \left(R_{NZ}^{coil\,1}(t) + R_{NZ}^{coil\,2}(t) + R_{joint}\right)I_{op} + L_{insert}\frac{dI_{op}}{dt} + \sum_{j=1}^{17} M_{insert}^{j}\frac{dI_j}{dt}$$

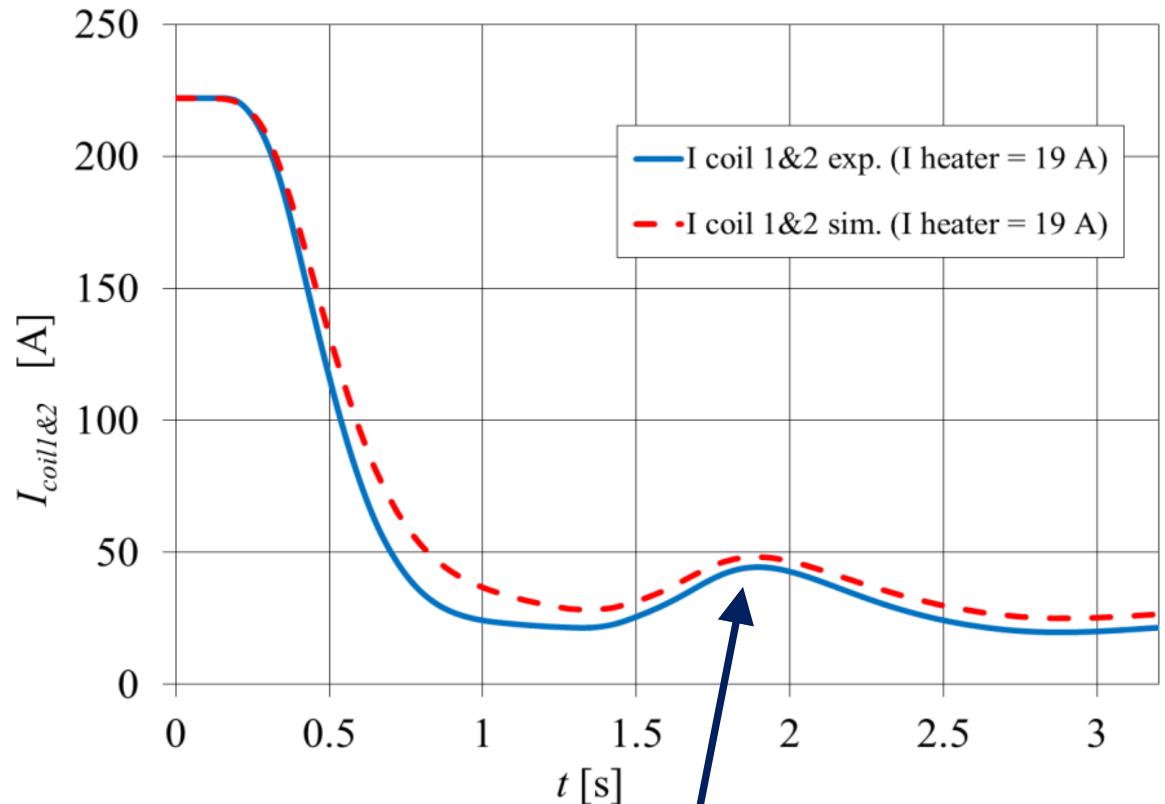
- The resistances of coil 1 and coil 2 can be computed from the power dissipated in all pancakes

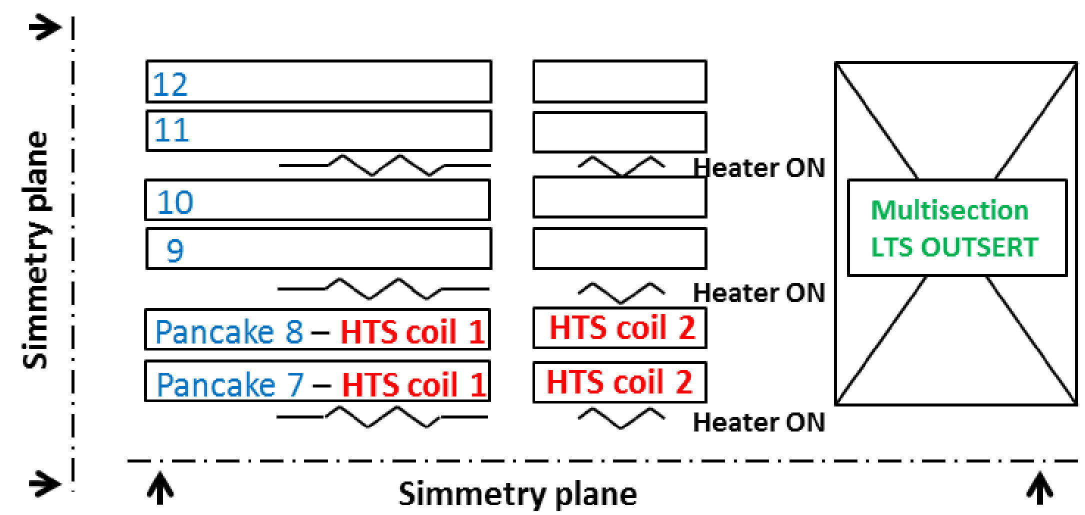
$$R_{NZ}^{coil\,2}(t) = \frac{2}{{I_{op}}^2}\sum_{i=1}^{12}\int_{V_i}\frac{J^2(t)}{\boldsymbol{\sigma_i}\ (t,x,y)}dV_i$$

$$R_{NZ}^{coil\,1}(t) = \frac{2}{{I_{op}}^2}\left(\sum_{i=1}^{16}\int_{V_i}\frac{J^2(t)}{\boldsymbol{\sigma_i}\ (t,x,y)}dV_i + \sum_{i=57}^{72}\int_{V_i}\frac{J^2(t)}{\boldsymbol{\sigma_i}\ (t,x,y)}dV_i\right)$$

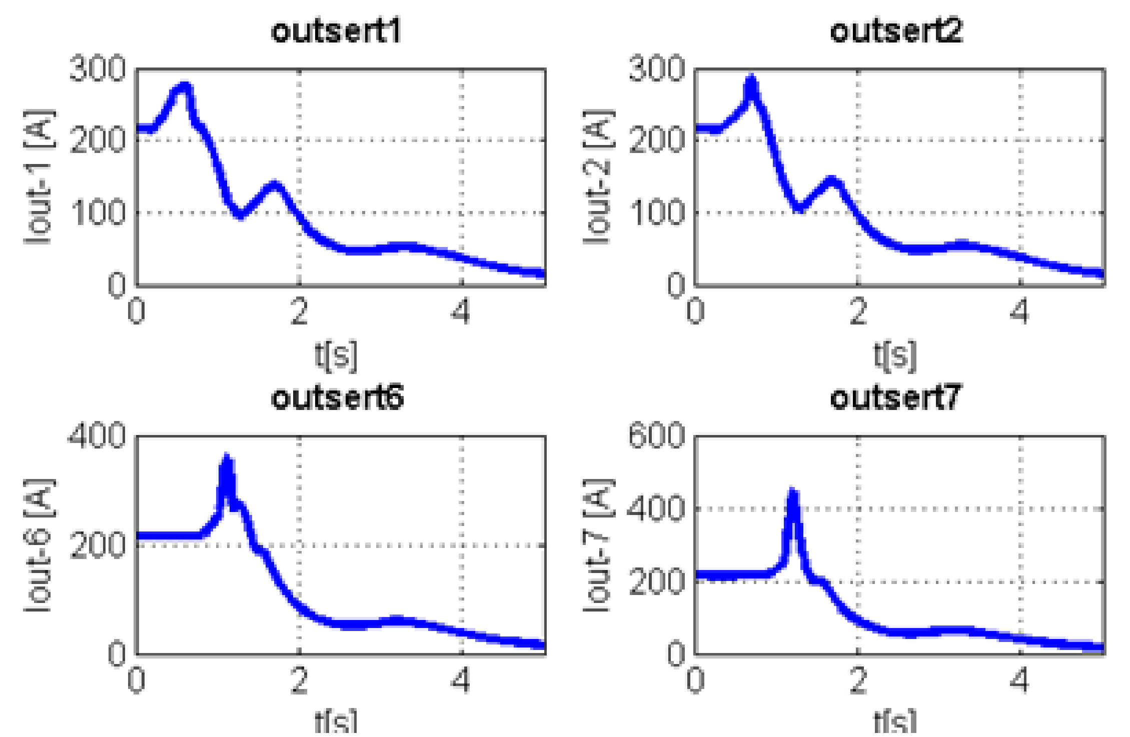
Scaling up: 32 T NHMFL magnet model

- The model was first validated versus the tests of prototype coils made of 12 pancakes





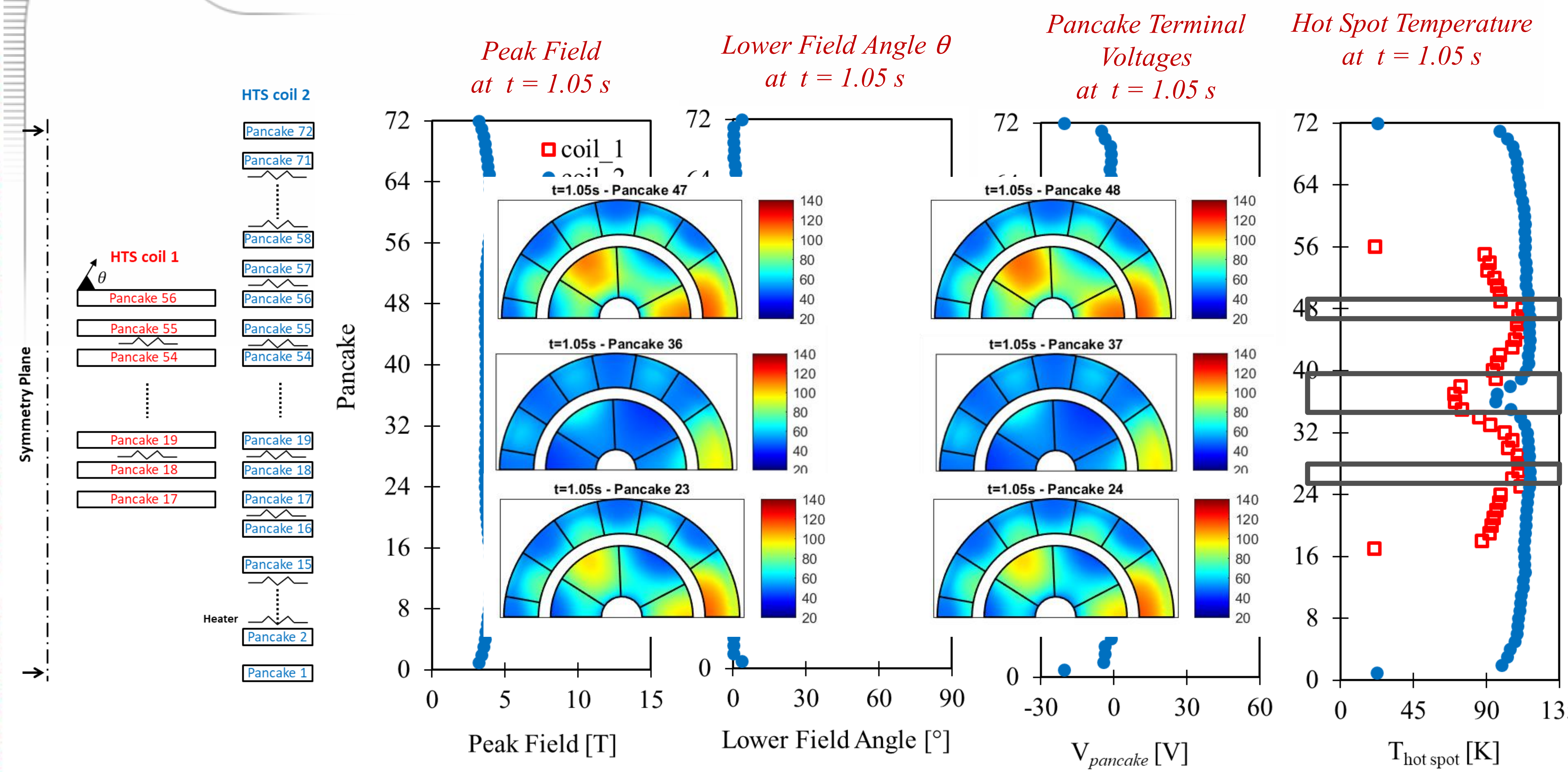
- A local peak of the insert transport current during the discharge is due to the **inductive coupling** between the insert and the outsert



Outsert currents during quench

Scaling up: 32 T NHMFL magnet model

- The model was then applied to analyze the self field quench test of the 32 T magnet (no current in the outsert)



- The most dangerous hot spot locations derive from a trade-off between magnetic field and field angle impacting J_c

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Outline

- Introduction
- HTS tape modeling
- From tapes to cables
  - Twisted Stacked Tape Cable
  - Roebel cables
- Scaling up: coils and magnet systems
- Discussion

Discussion: simulations

- Impressive advances have been made in the last 15 years in the modeling of HTS devices, from single tape to full coils
- The crucial techniques adopted are *homogenization*, *reduced dimensionality* and *multi-scale approach*
- To improve the models as *predictive* tools, we could benefit from:
  - Shared material properties and parameterizations of the critical surface for wide ranges of temperature, field
  - Interface properties (electrical and thermal contact resistances)
  - Improvement of computation speed (parallel computing)
  - Predictive analysis and comparison between models and dedicated experiments

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Discussion: design

- Concerning *quench and current distribution*, much more **analytical work** was performed for LTS than for HTS (different times of the theory development ?)
- Results available for the LTS can be extended to HTS, but not always (NI coils, Roebel cables, etc)
- Analytical formulae for the calculation of current distribution **time constants and lengths, quench energy, propagation velocity,** would be useful for the design *of* HTS based magnets

Thank you for your attention

M. Breschi