Quench Analysis of Coupled Insert/Outsert Magnet Systems of the NHMFL

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Outline

- **HTS Insert Description**

- **NHML high field HTS coils**

  1) Test case 1: HTS insert + Resistive Magnet
  2) Test case 2: double HTS insert + 17-section LTS ousert with constant current
  3) Test case 3: double HTS insert + 17-section LTS ousert with variable current

- **2D FEM**

  1) Thermal Model Equation
  2) Coil constitutive law
  3) Anisotropic homogenization

- **Comparison between simulation and experimental data**

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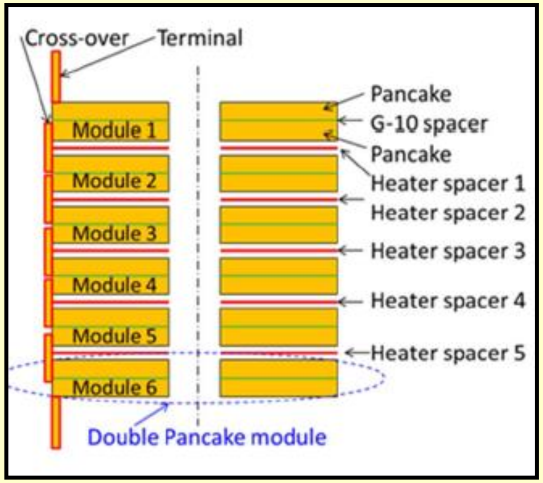
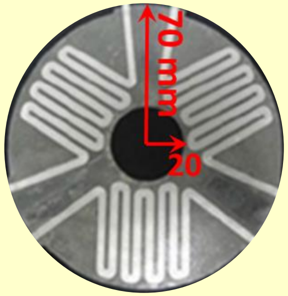
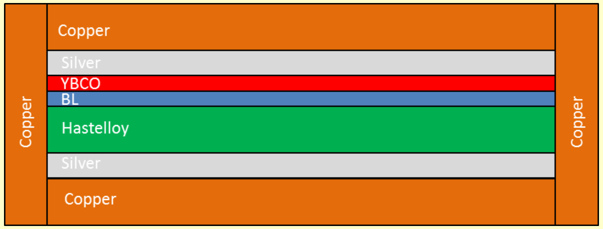
HTS Insert Description

- **Six double** **YBCO pancake** modules stacked alternated with five **heater spacers**.
- Double pancake coil modules with un-insulated conductor and **insulated stainless steel cowind**.
- The cowind serves both as **turn to turn insulation** and reinforcement. It is insulated by a 5-7 μm **alumina layer.**
- Electrical stand-off between the two pancakes of a module is provided by a **G-10 sheet.**





Heater elements



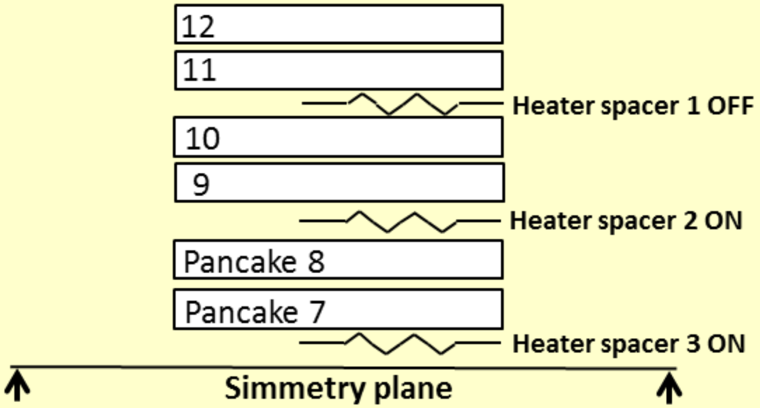
SuperPower SCS4050

[1] H. W. Weijers *et al.*, "Progress in the development of a superconducting 32 T magnet with REBCO high field coils," *IEEE Trans. Appl. Supercond.*, vol. 24, no. 3, Jun. 2014, Art. ID. 4301805.

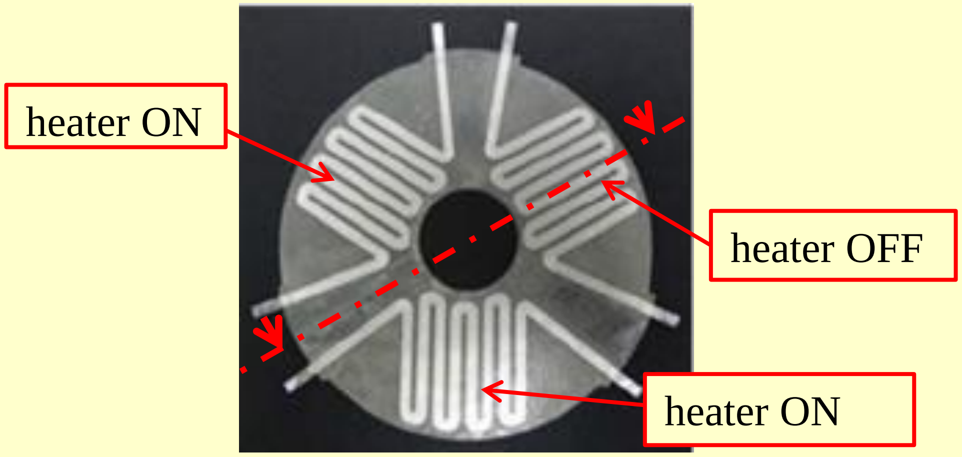
Test case 1: HTS insert + Resistive Outsert

- Test performed at **4.2 K** in **self-field** and in a **background magnetic field of 15 T** (Large Bore Resistive magnet)**.**
- Prototype coil energized at a **200 A** current
- **Two out of three heaters of each module** energized simultaneously for **0.8 s**.
- Coil discharged across the **normal zones without energy extraction.**
- The **symmetry condition** allows one to decrease the number of degrees

Symmetry condition 1



Symmetry condition 2



Test case 2: double HTS insert + 17-section LTS outsert with constant current

- Set-up composed of:
  a) 2 **HTS insert** coils
  b) 17-section **LTS outsert**

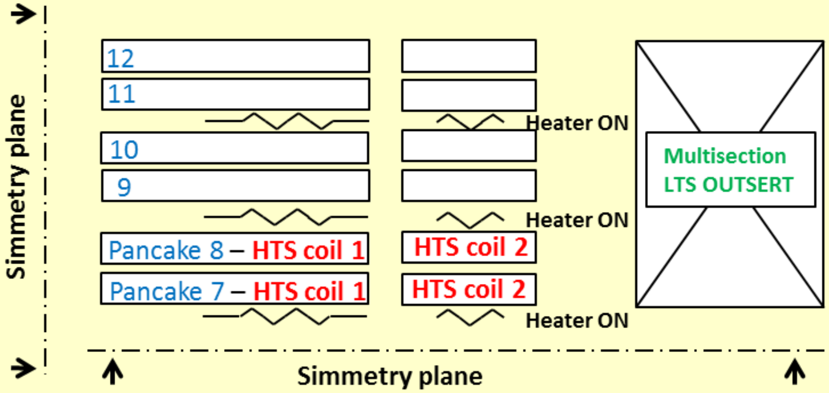
- **HTS insert** energized at a **173 A** constant current

- **LTS outsert** of the **32 T magnet project**: transport current **134 A**

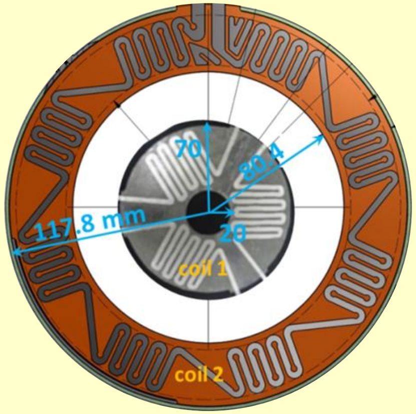
- **All heaters** fired simultaneously with **19 A** heater current. New design for heater electrical insulation

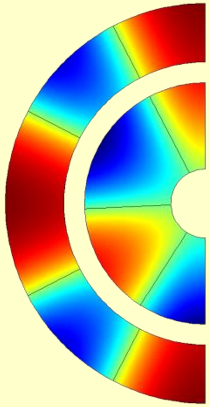
- The **outsert quench detection system** reacts on the voltage induced on the outsert. The **outsert quench protection system is not triggered**: outsert current constant

Symmetry condition 1



Symmetry condition 2





Test case 3: double HTS insert + 17-section LTS outsert with variable current

- Magnet composed of:
  - a) **2 HTS insert** coils
  - b) **17-section LTS outsert**

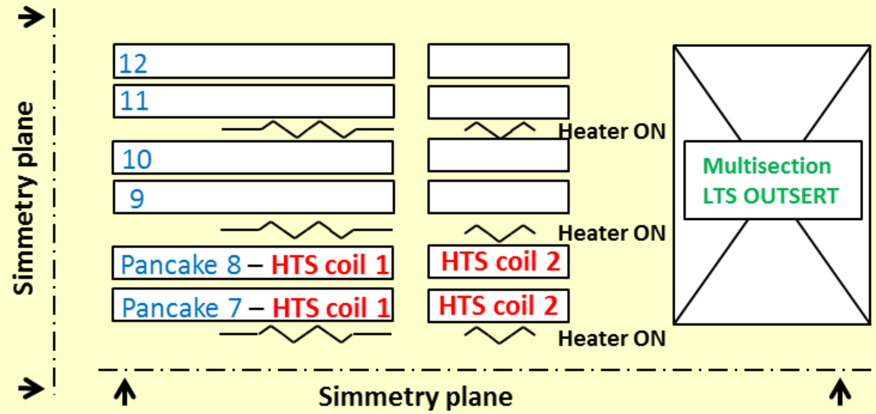
- The **HTS insert** is energized at a constant current of **222 A**.

- **LTS outsert** of the **32 T magnet project** at **214 A**

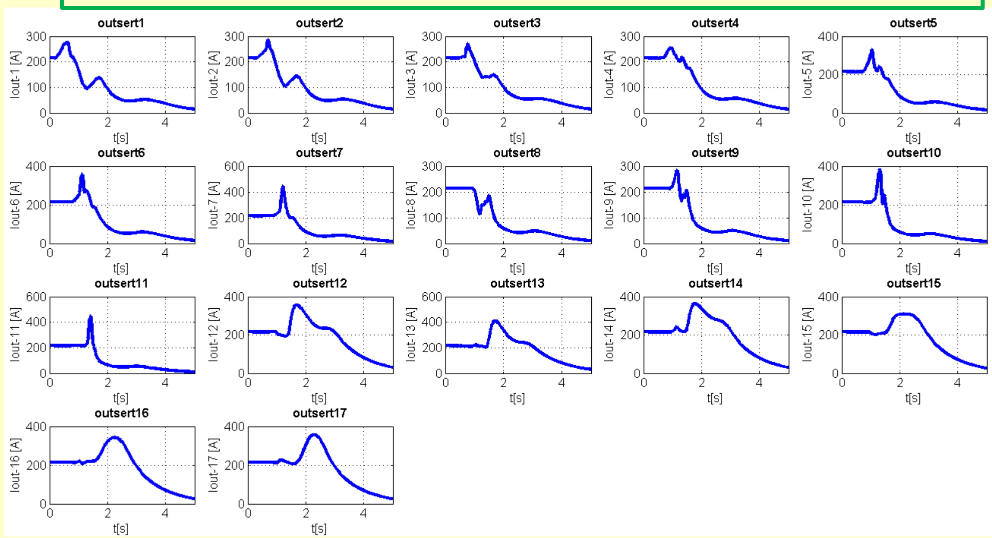
- **All heaters** are fired with **19 A** heater current

- The induced voltages in the outsert meet the criterion, **the outsert quench protection system is triggered** resulting in the outsert fast discharge.

Symmetry condition 1



Variable current in the 17-sections outsert



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2D FEM Thermal Model Equations

HEAT BALANCE EQUATION

- $\frac{\partial T}{\partial z}$ in each pancake assumed negligible
- The heat balance equation is solved on each pancake:

➡ $\boldsymbol{T_i(x, y, t)}$ temperature evolution on the $\boldsymbol{i^{th}}$ **pancake**

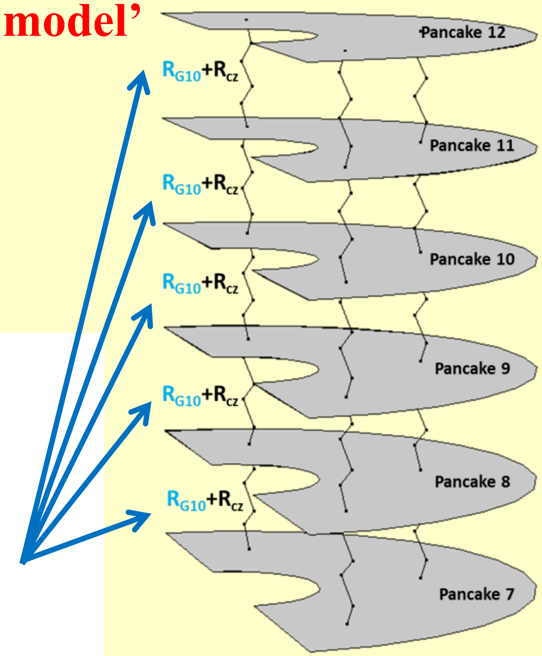
$$\rho(T_i)C_p(T_i)\frac{dT_i(x,y,t)}{dt} - \nabla\cdot(\boldsymbol{k}(T_i)\nabla T_i) \qquad \forall\, i = 7 \ldots 12$$

$$= \underbrace{\frac{J^2}{\sigma_i(T_i, B_i, E_i)}}_{\text{Joule heating}} + Q_{heat,\,i}(x,y,t) + \underbrace{Q^{cond}_{axial,i}(x,y,t)}_{\text{Axial conduction between pancakes}}$$

Joule heating

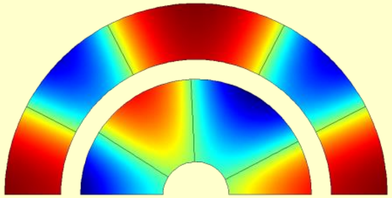
Axial conduction between pancakes

Conceptual scheme of the 'quasi 3D model'



Boundary conditions:

- Adiabatic conditions
- Heater pulse $Q_{heat,i}(x,y,t)$ on the heater area



Initial condition

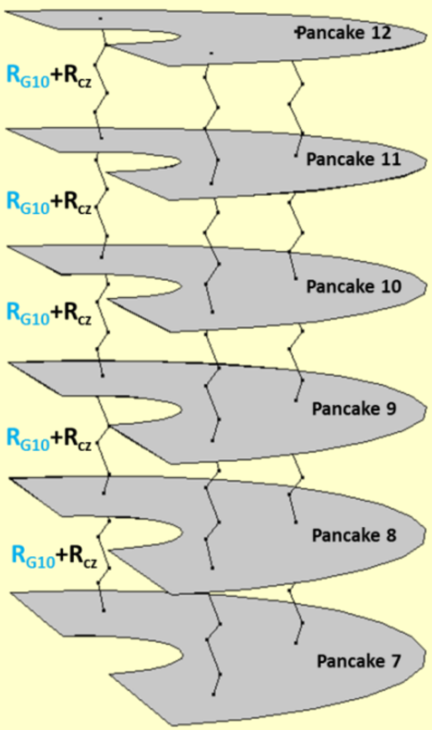
$T(t = 0\ \text{s}) = 4.2\ \text{K}$

2D FEM Thermal Model Equations

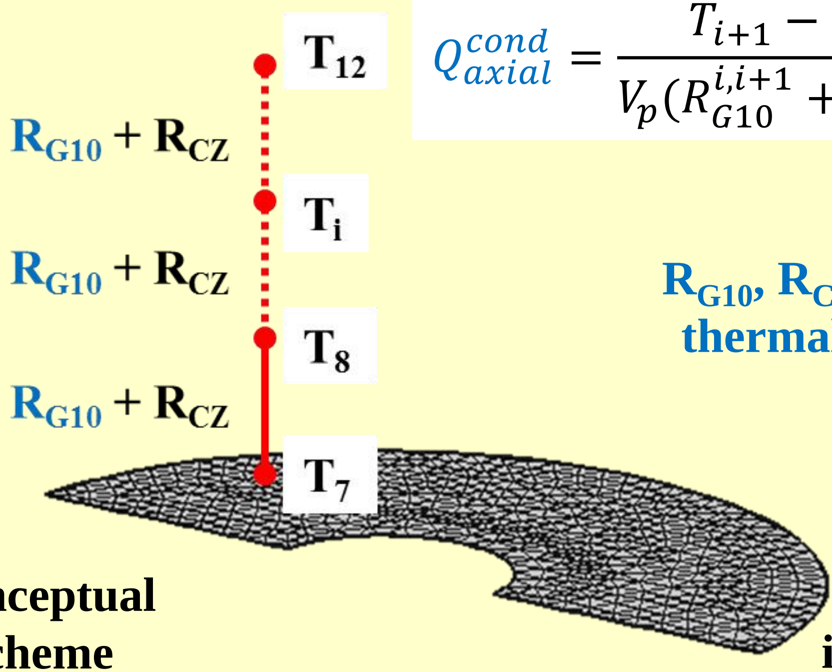
ONE 2D MESH INSTEAD OF 6

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**

$$\boldsymbol{T} = [T_7(x,y) \quad \dots \quad T_i(x,y) \quad \dots \quad T_{12}(x,y)]$$



Conceptual scheme



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

R_{G10}, R_{CZ} distributed thermal resistances

2D COMSOL implementation

[2] M Breschi, L Cavallucci, P L Ribani, A.V. Gavrilin and H. W. Weijers, "Analysis of quench in the NHMFL REBCO prototype coils for the 32T Magnet Project", Supercond. Sci. Technol., 29, 055002, 2016

2D FEM: Coil Constitutive Law

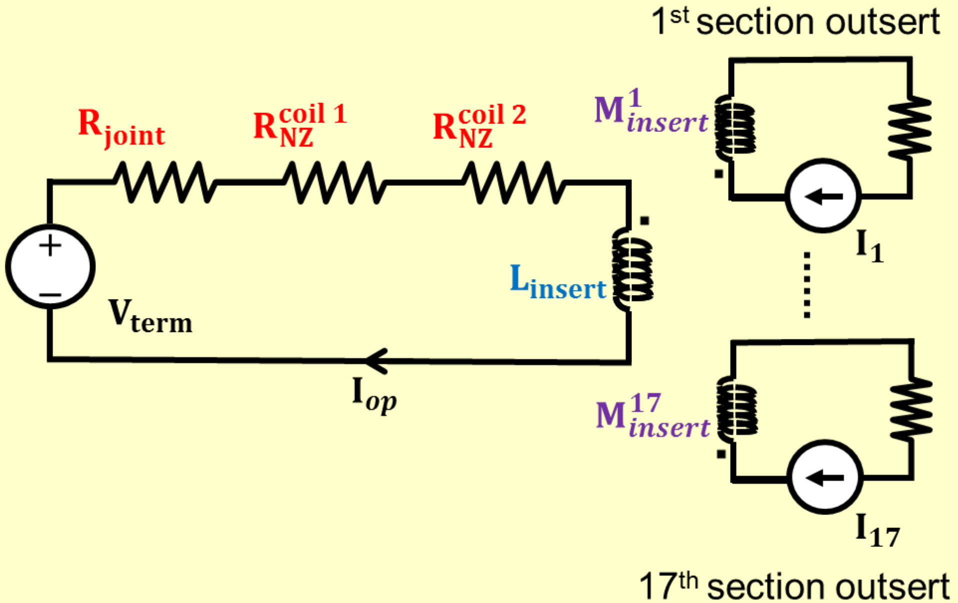
- The operation current I_{op} in the insert is obtained from the **lumped parameter circuit** describing the mutual induction coupling between the insert and ousert

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

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

$$R_{NZ}^{coil\,2} = \frac{4}{{I_{coil}}^2}\sum_{i=7}^{12}\int_{V_i}\frac{J^2}{\boldsymbol{\sigma}_{\boldsymbol{i}}^{\mathbf{coil\,2}}(x,y)}dV_i$$

$$R_{NZ}^{coil\,1} = \frac{4}{{I_{coil}}^2}\sum_{i=7}^{12}\int_{V_i}\frac{J^2}{\boldsymbol{\sigma}_{\boldsymbol{i}}^{\mathbf{coil\,1}}(x,y)}dV_i$$



2D FEM: Anisotropic homogenization

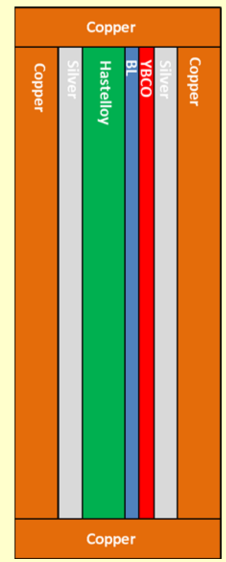
- **Longitudinal electrical conductivity σ^L**

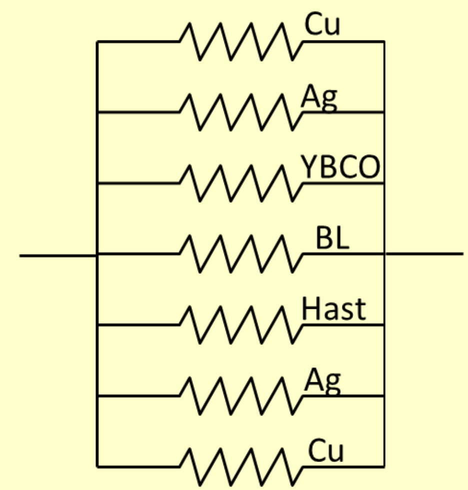
The tape layers are assumed in **parallel** and the current that flows in YBCO layer (I_{YBCO}) is evaluated by:

$$E_c\left(\frac{I_{op}}{I_c}\right)^n = \frac{I_{op}-I_{YBCO}}{\sum_i^{i\neq YBCO}\sigma_i(T_i,|\boldsymbol{B}_i|,|\boldsymbol{E}_i|)S_i} \Rightarrow I_{YBCO}$$

bisection method

$$\Rightarrow E = \frac{I_{op}-I_{YBCO}}{\sum_i^{i\neq YBCO}\sigma_i S_i} \Rightarrow \boxed{\sigma_{Hom} = \frac{I_{op}}{\left(\sum_i S_i\right)\cdot E}}$$





- **Transversal electrical conductivity σ^T**

In general, the tape layers are assumed in **series**, accounting for the alumina insulation layers between the turns.

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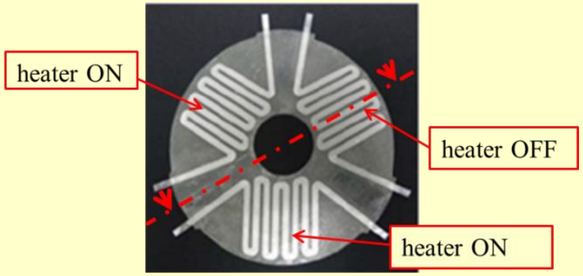
Model vs experiment: case study 1

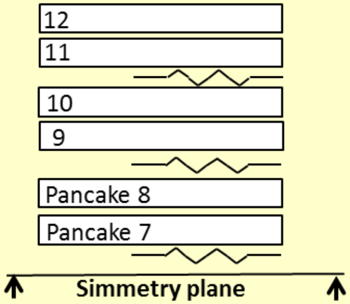
- Comparison of measured and computed **coil currents** during the quench test at **14 A**, **16 A** and **19 A** maximal heater current

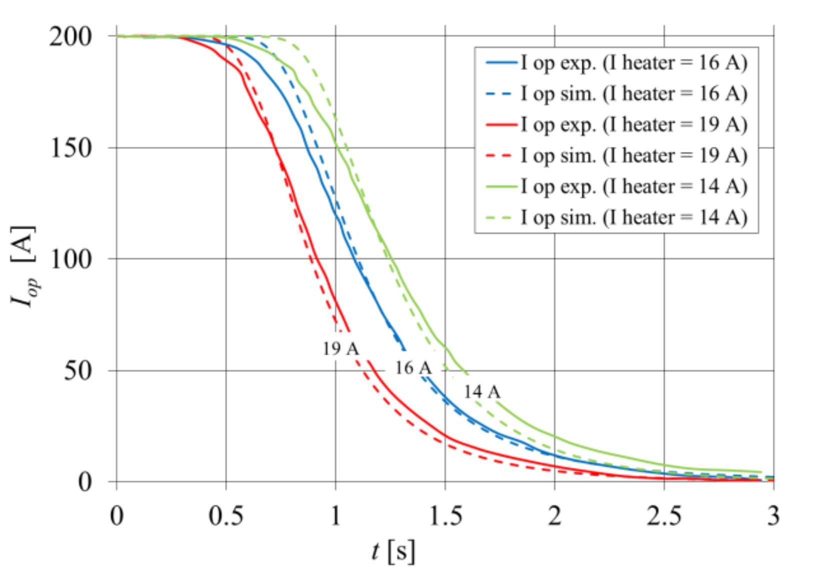
- Comparison of measured and computed coil **overall resistance** during the quench test at **16 A** maximal heater current

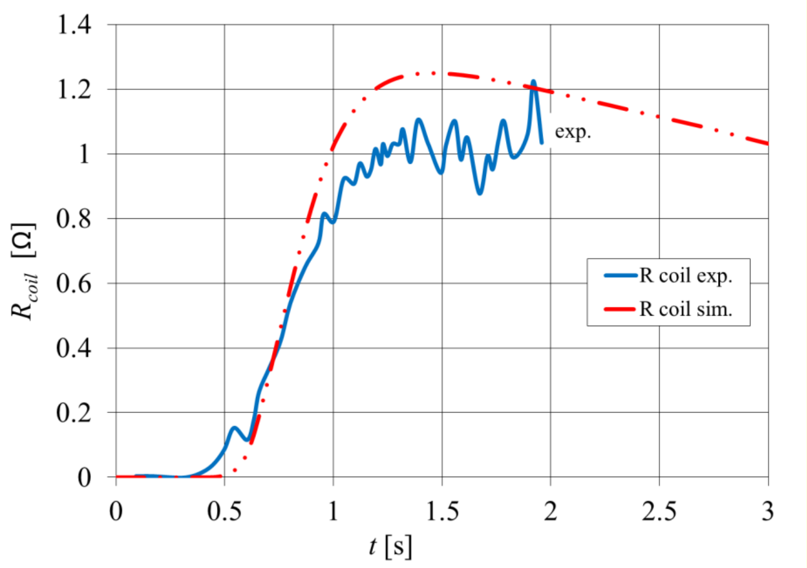
Experimental set-up

- I coil (t=0s) = 200.0 A
- **background magnetic field 15 T**





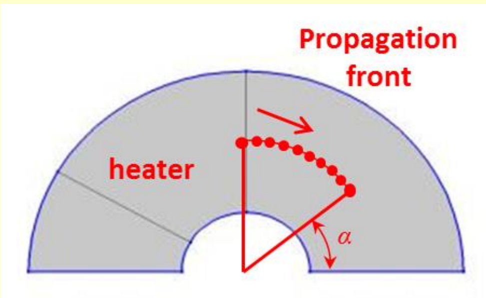




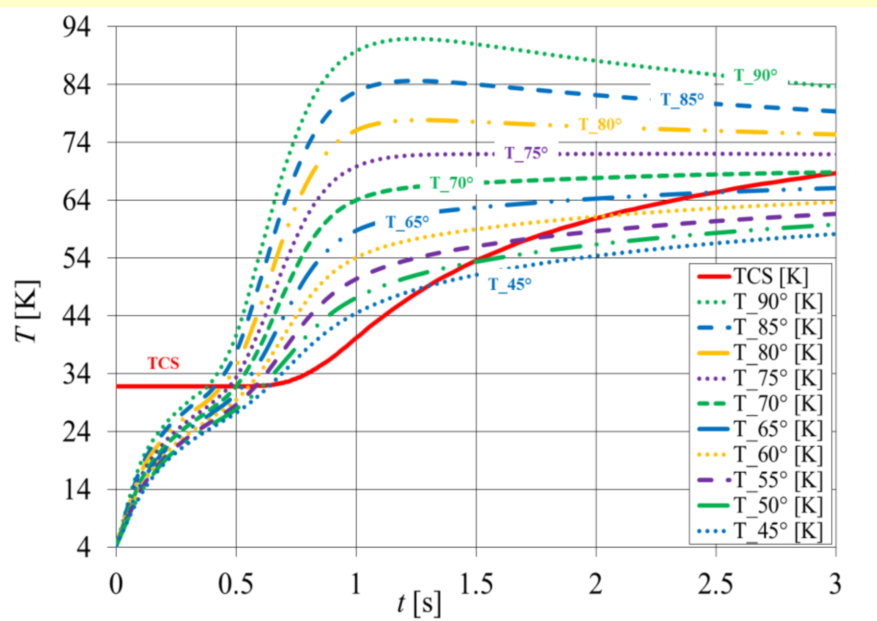
Model vs experiment: case study 1

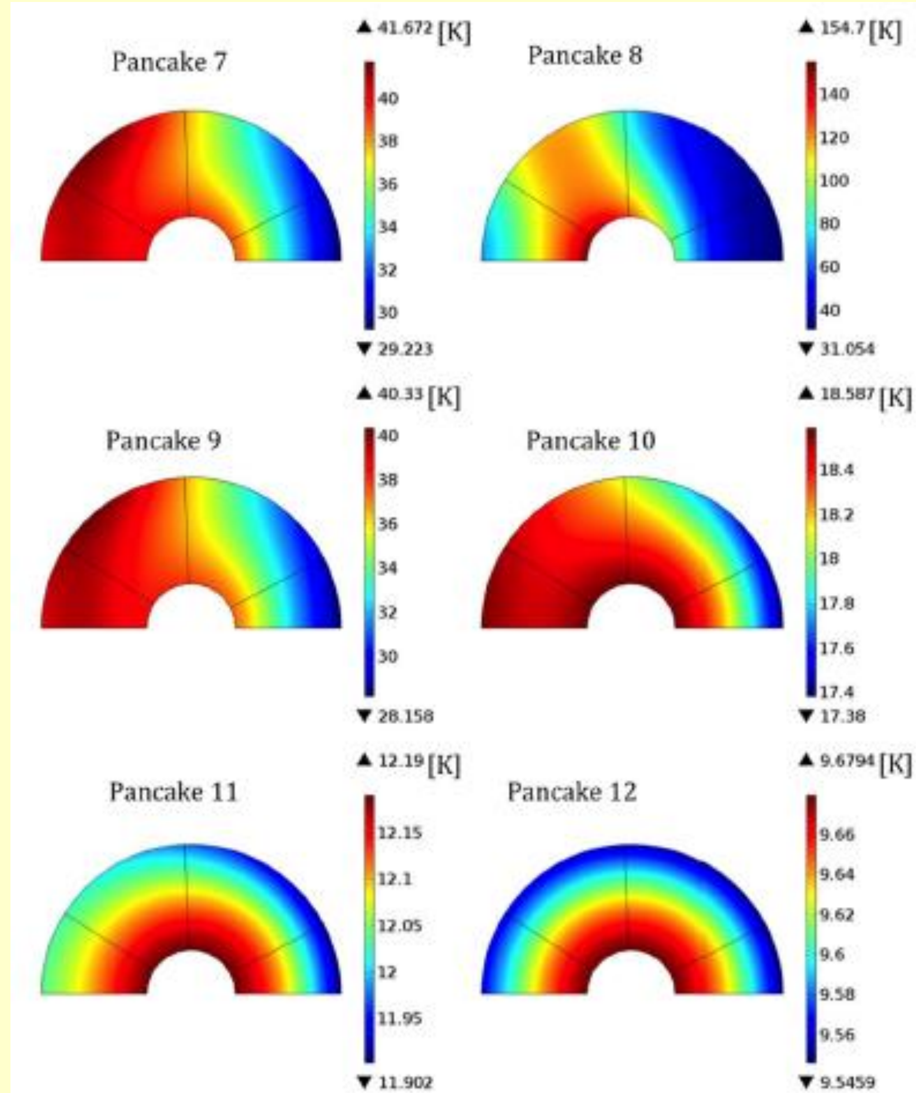
Normal Zone Propagation Velocity

- NZPV defined as the azimuthal **propagation velocity** of the front at temperature T_{cs}.



NZPV
9.0 ÷ 15 [cm/s]

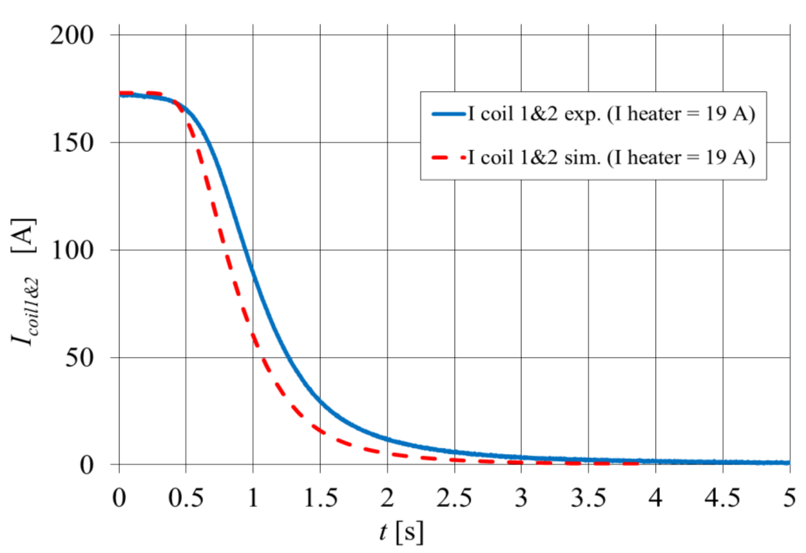




t = 1.5 s - 16 A heater current

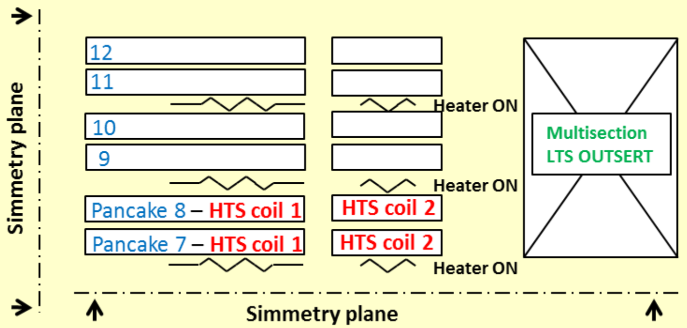
Model vs experiment: case study 2

- Measured vs computed **insert currents:** heater current of **19 A**

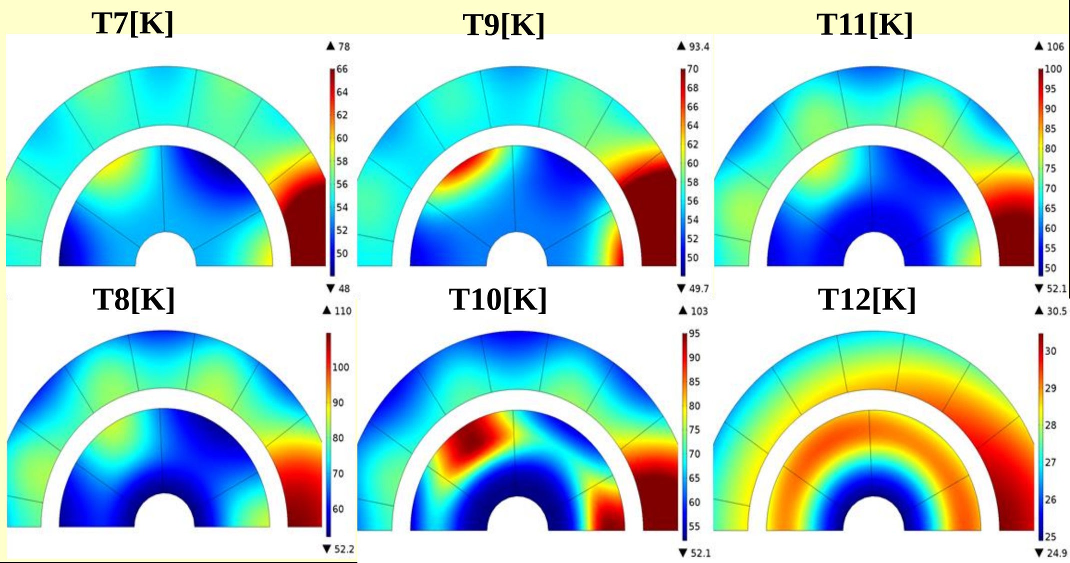


Experimental set-up

- I coil 1&2 = 173.0 A
- I outsert = 134.0 A (constant in time)

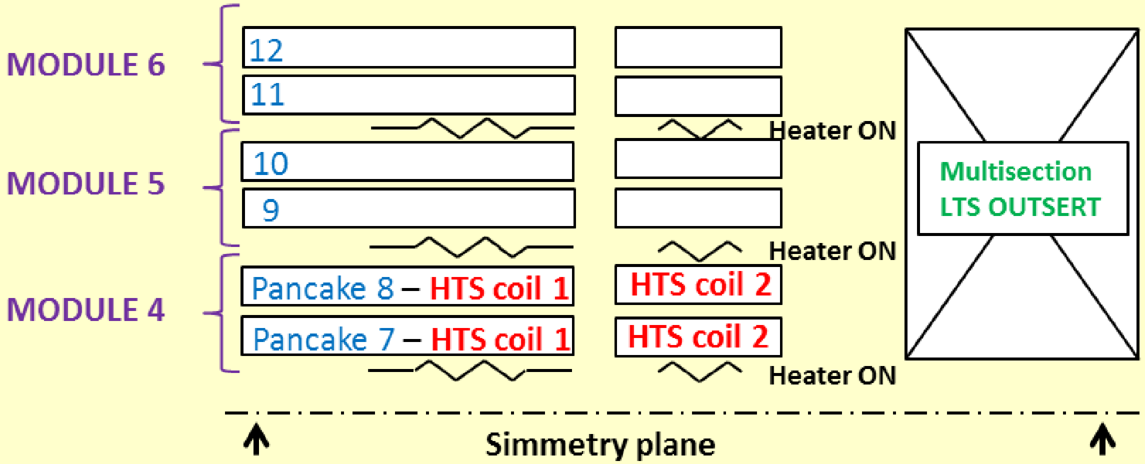


Temperature distribution on pancakes at *t* = 2s

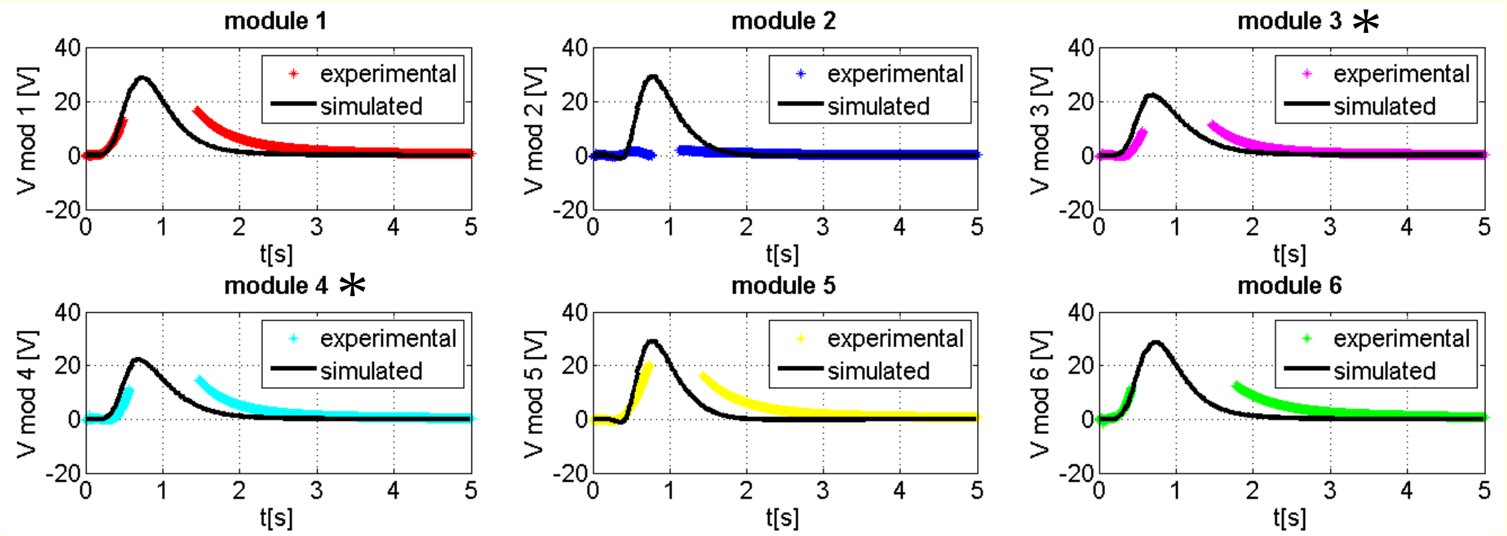


Model vs experiment: case study 2

- Measured vs computed **teminal voltages of modules of coil 1** with heater current of **19 A**
- Experimental acquisition system cannot measure voltages above **10.5 V**

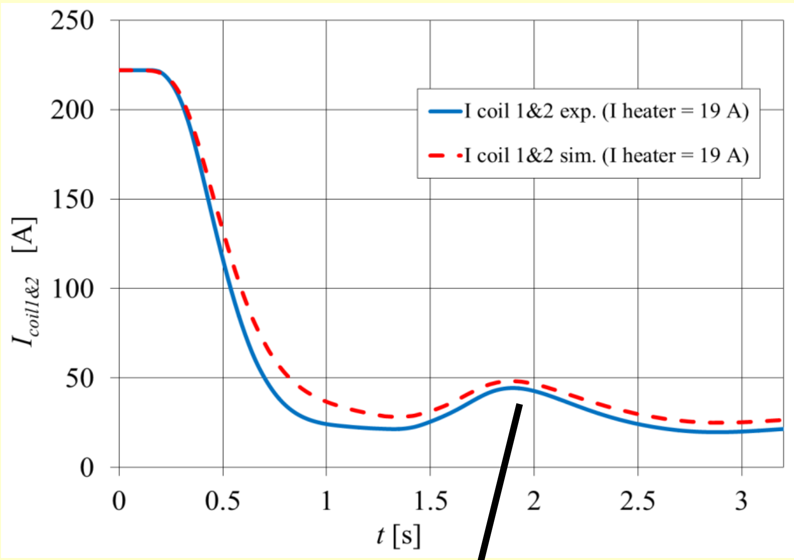


coil 1



Model vs experiment: case study 3

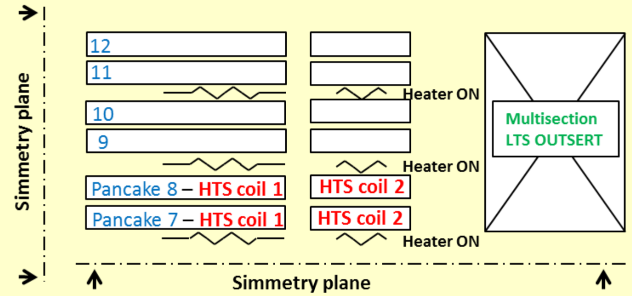
- Measured vs computed **insert currents:** heater current of **19 A**



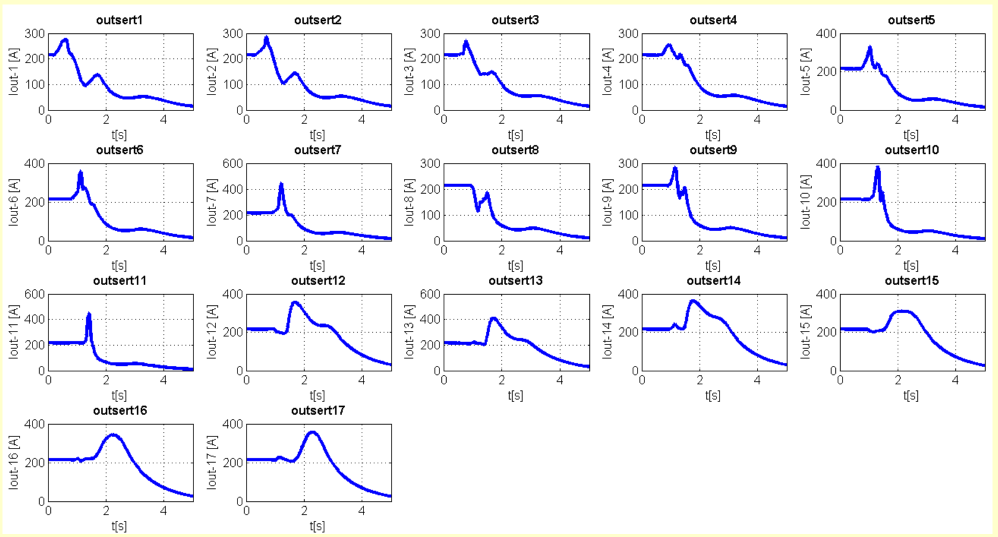
Peak related to the **inductive coupling** between the insert and the outsert

Experimental set-up

- I coil 1&2 = 222.0 A
- I outsert = 214 A (variable in time)

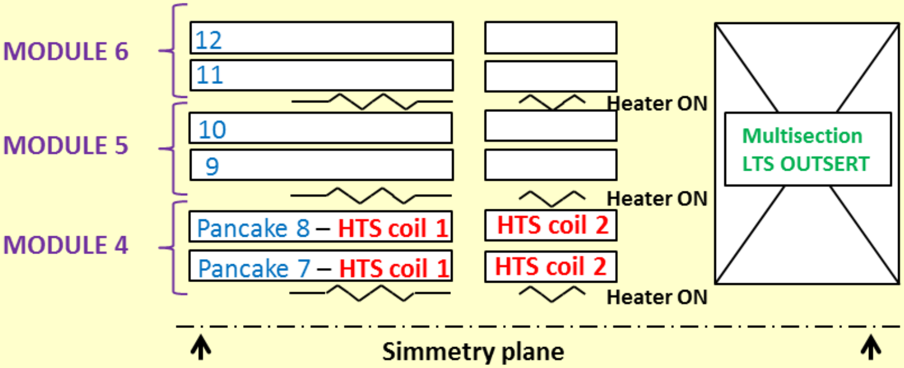


Variable current in the 17 sections outsert

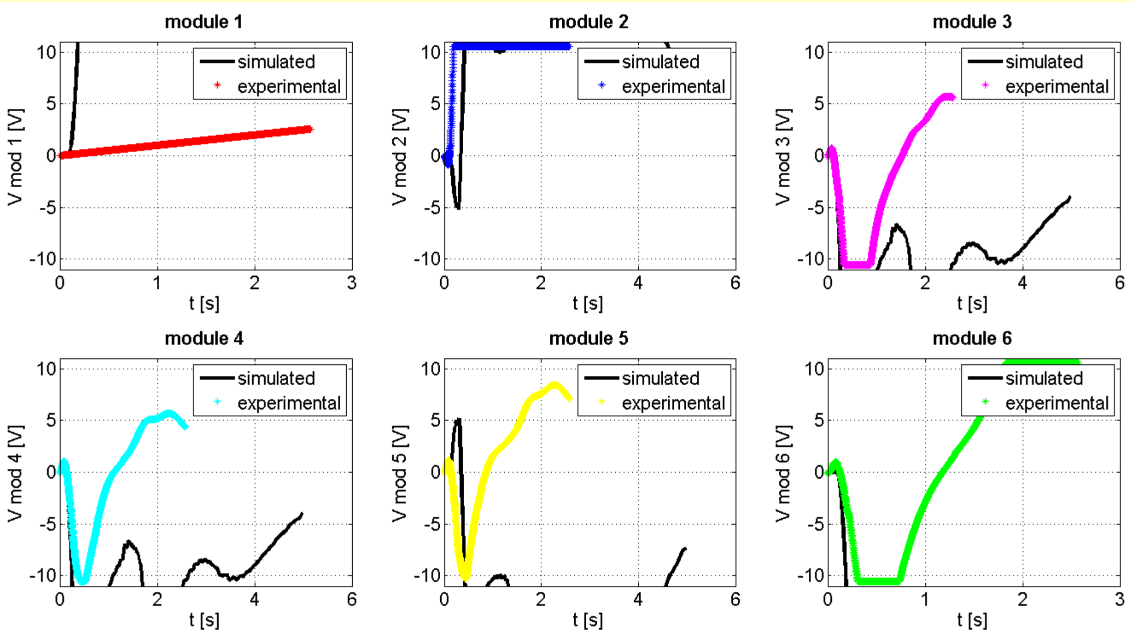


Model vs experiment: case study 3

- Measured vs computed **teminal voltages of modules of coil 1** with **19 A** heater current
- Experimental aquisition system can measure voltages that exceed **10.5 V**



coil 1



- The **agreement** is **not yet satisfactory,** possibly due to inhomogeneities of the critical current. Specific measurements on these tapes at different locations show **I_c-values higher or lower than those implemented, in a +/- 20% range.**

⬇

further work required

Conclusion

- A ‘quasi 3D FEM model’ is developed in **COMSOL** Multiphysics environment to simulate **quench** in HTS coils.
- Only **one 2D pancake** is discretized with a mesh. A set of heat balance equations is written for an **array of temperatures** $\boldsymbol{T} = [T_7(x,y) \quad \ldots \quad T_i(x,y) \quad \ldots \quad T_{12}(x,y)]$
- All pancakes interact with each other through **distributed thermal resistances.**
- An **anisotropic homogenization procedure** is applied to reduce the degrees of fredom in the model
- Quench experiments on **NHMFL prototype** coils developed in the frame of the **32 T magnet project** have been analyzed:

  1) A **good agreement** between simulated and experimental **decay of the current** in the HTS insert coils.

  2) A **rather good agreement** between simulated and experimental teminal voltages in the modules is obtained for constant current in the outsert between; the agreement is still **not satisfactory** for variable current in the outsert

Thanks for your attention