Electro-thermal Analysis of quench in High Field HTS coils

Marco Breschi, **Lorenzo Cavallucci**, Pier Lugi Ribani,
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Outline

- NHMFL prototype coil: configuration and quench test
- Magnetic flux density analysis
- 2D COMSOL model
- Results
- Model development
- Conslusion

NHMFL Prototype Coil: Configuration *[1]*

- **Six double pancake** modules (each with 244 **YBCO** turns) were stacked on a bore tube alterned with tree **heater spacers**.

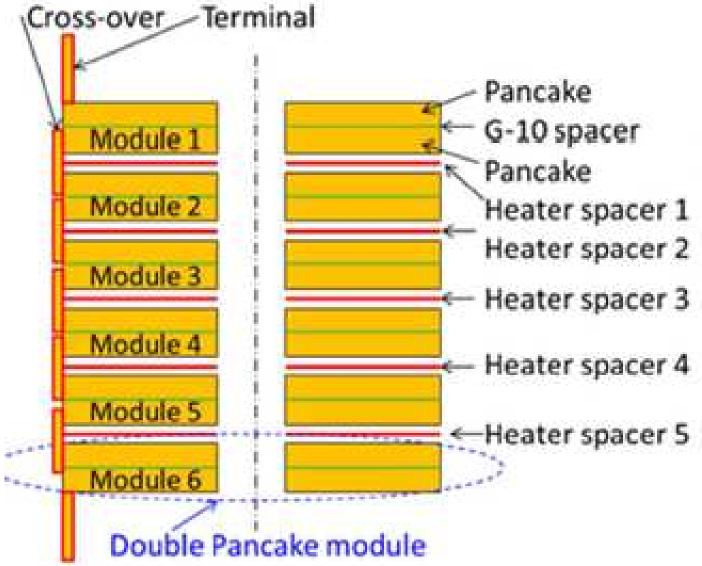
  Inner radius = 20 mm

  Outer radius = 70 mm

- Dry-wound double pancake coil modules with uninsulated conductor and **insulated stainless steel cowind**.

- The cowind serves both as **turn to turn insulation** and reinforcement. It is insulated by a 2-3 µm **alumina layer.**

- Electrical stand-off between the two pancakes of a module is provided by a thin **G-10 sheet** sandwiching the quench heater elements.



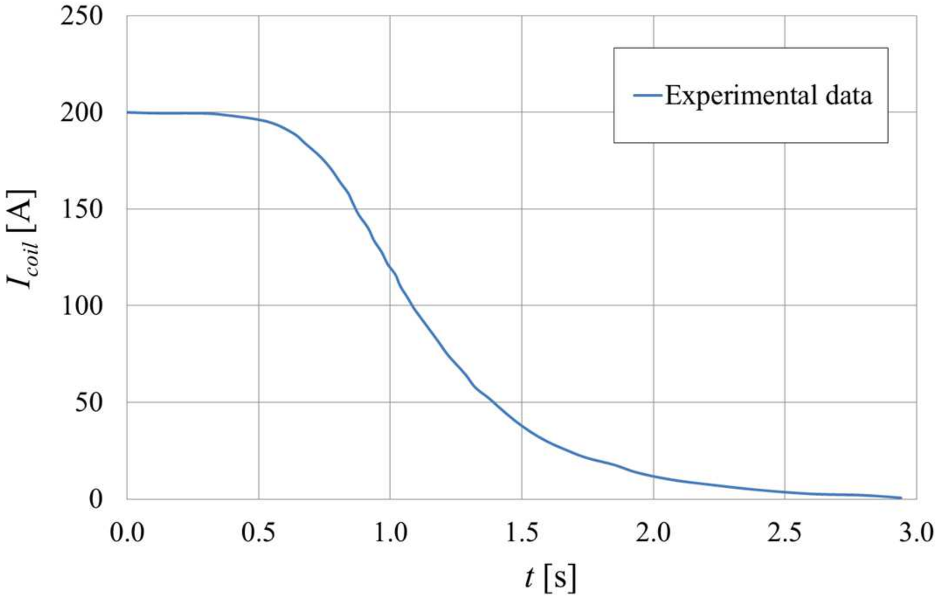
Heater spacer

[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.

NHMFL Prototype Coil:

Quench test

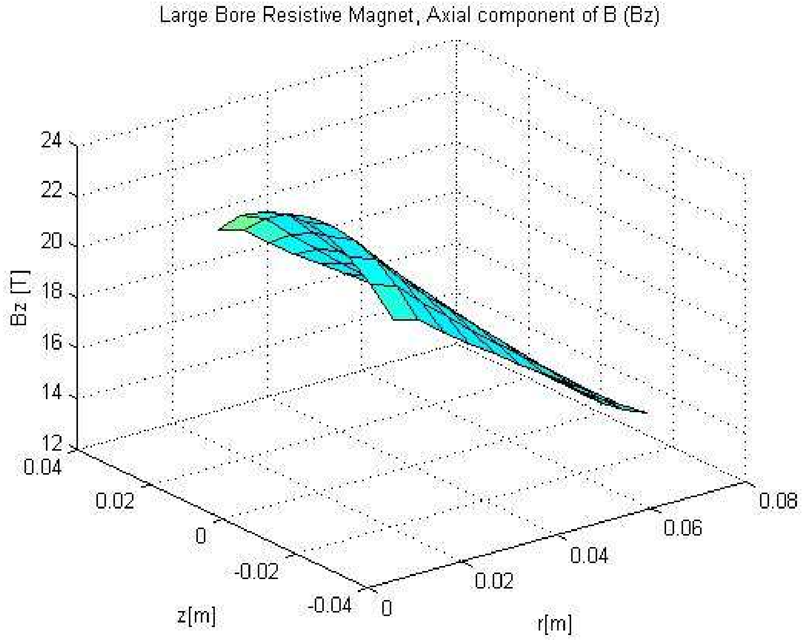
- The test was performed at **4.2 K** in **self-field** and in a **background magnetic field of 15 T.**
- The prototype coil was initially powered by a **200 A** constant current
- **Two out of three heaters of each module** were energized simultaneously for **0.8 s**. The coil was discharged across the normal zones without energy extraction.

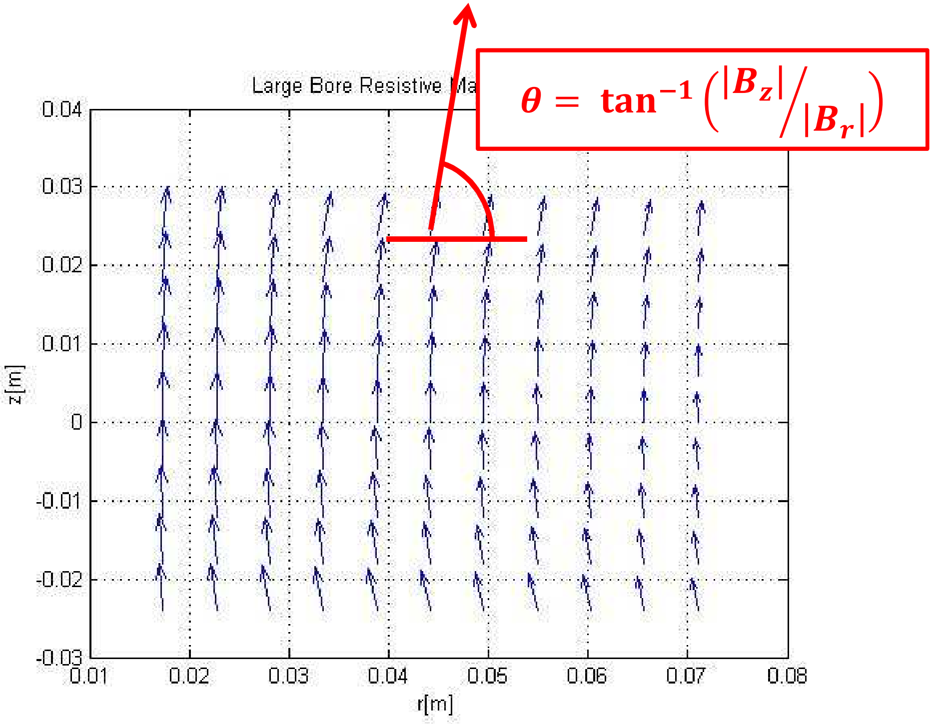


Magnetic flux density analysis:

Prototype coil

External and self magnetic flux density on prototype coil

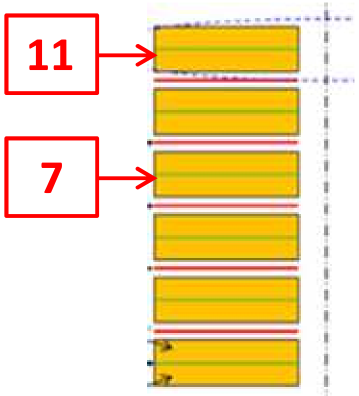




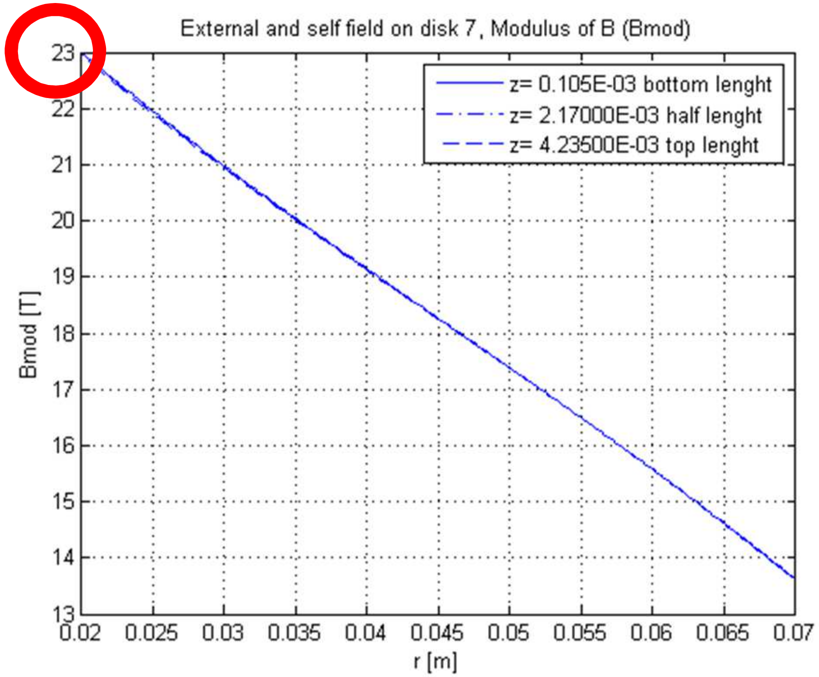
$$\theta = \tan^{-1}\left({|B_z|}/{|B_r|} \right)$$

Magnetic flux density analysis:
Pancake **7** *vs* Pancake **11**

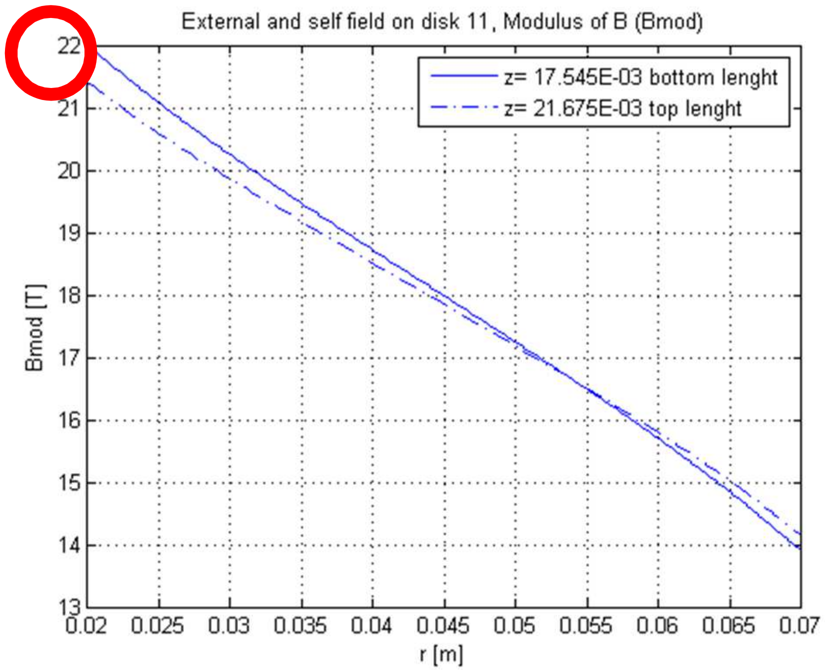
Magnetic flux density modulus
comparison between pancake 7 and 11



Pancake 7

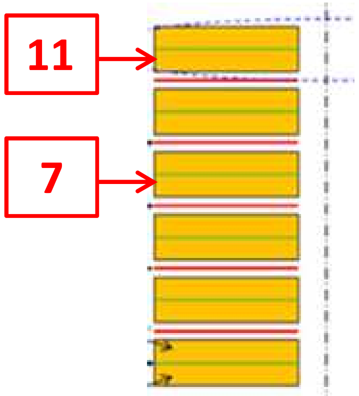


Pancake 11



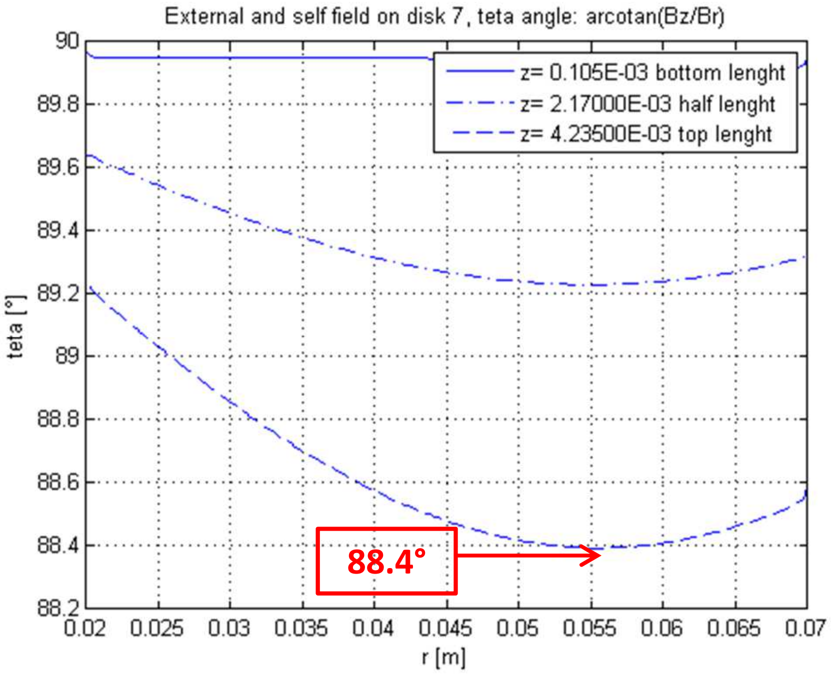
Magnetic flux density analysis:

Pancake **7** *vs* Pancake **11**

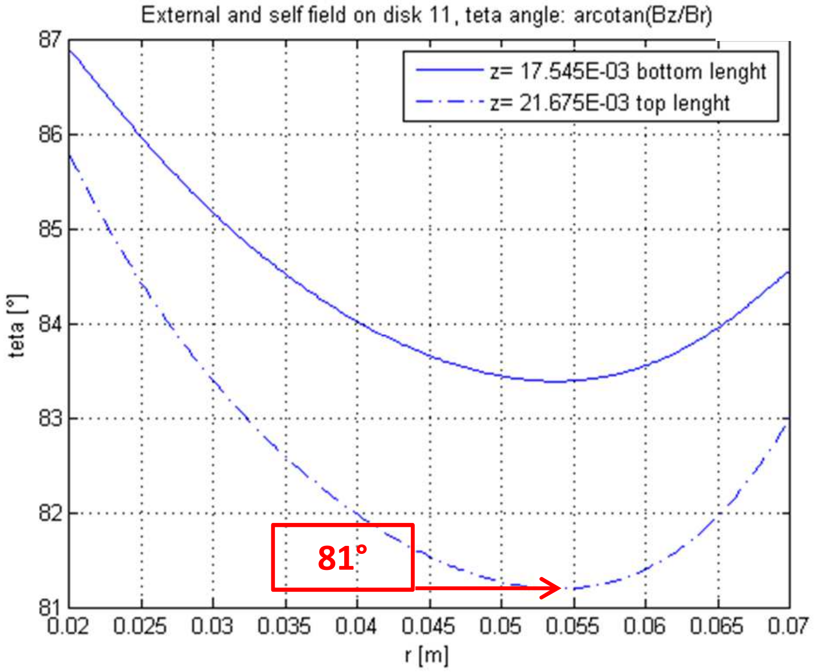


Teta angle comparison between pancake 7 and 11

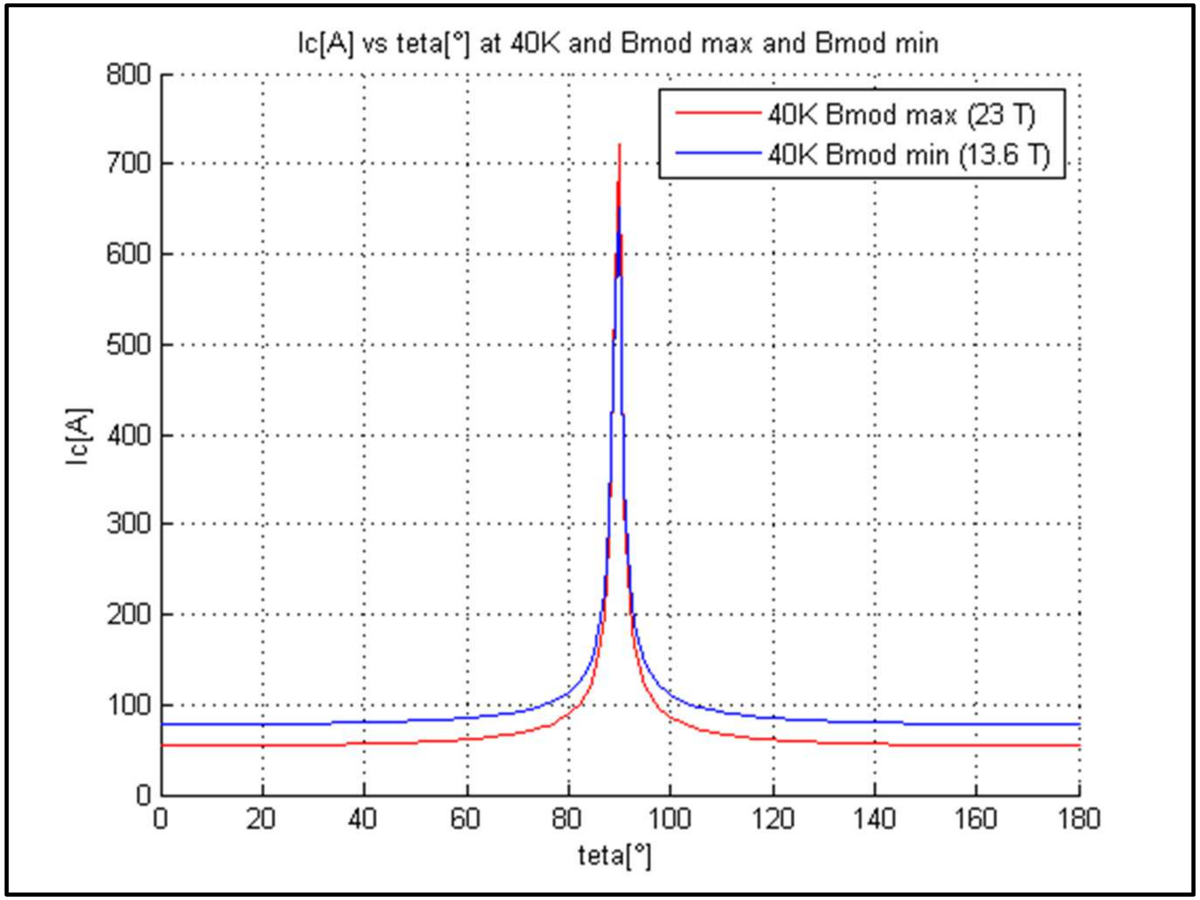
Pancake 7

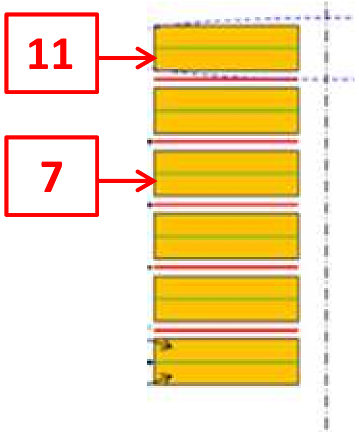


Pancake 11



Magnetic flux density analysis:
Pancake **7** *vs* Pancake **11**

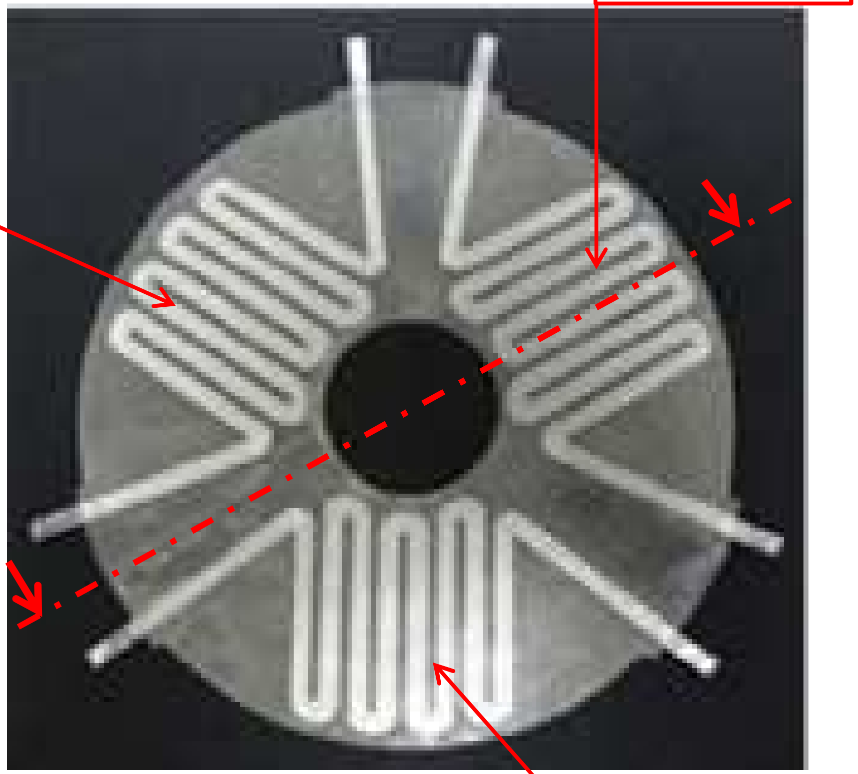




2D FEM Model

Simmetry condition

During quench test, only **two heater** subelements out of three on each disk are simultaneously energized (pulse duration **0.8 s)**. The simmetry condition allows one to decrease the number of degrees of freedom



heater OFF

heater ON

heater ON

2D FEM Model

Equation

Heat Balance Equation

$$\rho \cdot C_p \frac{dT}{dt} - \nabla \cdot (k(T)\nabla T) = Q_{joule}$$

$$Q_{joule} = \sigma(T, |\boldsymbol{B}|, |\boldsymbol{E}|)\nabla V \cdot \nabla V$$

Current Density Continuity Condition

The slowly varying time-derivative term of the magnetic potential $^{\partial A}/_{\partial t}$ is ignored *[2]*

$$\nabla \cdot \mathbf{J} = \mathbf{0}$$

$$\nabla \cdot (-\sigma(T, |\boldsymbol{B}|, |\boldsymbol{E}|)\nabla V) = 0$$

Magnetic Flux Density components

$$B_r = b_r(x,y,z) \cdot i + Br^{ext}$$

$$B_z = b_z(x,y,z) \cdot i + Bz^{ext}$$

Coil Constitutive Law

$$V_{term} = R_{joint} i + R_{NZ} i + L \frac{di}{dt}$$

where

$L = 0.44\ [H]$ prototype coil inductance

$V_{joint} = R_{joint} \cdot i(t = 0s)$

R_{NZ} integration of local Joule loss.

$$R_{NZ} i^2 = \mathbf{12} \cdot \mathbf{2} \cdot \int_V \vec{E} \cdot \vec{J} dV$$

Assumption: the whole prototype coil resistance is obtained by multiplying the resistance of pancake 11 by a factor 12.

[2] W. K. Chan, J. Schwartz, "A Hierarchical Three-Dimensional Multiscale Electro-Magnetic-Thermal Model of Quenching in REBa$_3$Cu$_3$O$_{7-\delta}$ Coated-Conductor-Based Coils ," *IEEE Trans. Appl. Supercond.*, vol. 22, no. 5, Oct. 2012.

2D FEM Model

YBCO tape homogenization

- **Longitudinal electrical conductivity $\boldsymbol{\sigma^L}$**

If coil current flows along the tape, the tape layers are assumed in parallel.

$$\sigma_L\,[{}^{S}/_{m}] = \frac{d_{Cu}}{d_{tot}}\cdot\sigma_{Cu} + \frac{d_{Ag}}{d_{tot}}\cdot\sigma_{Ag} + \frac{d_{Sub}}{d_{tot}}\cdot\sigma_{Sub} + \frac{d_{YBCO}}{d_{tot}}\cdot\sigma_{YBCO}$$

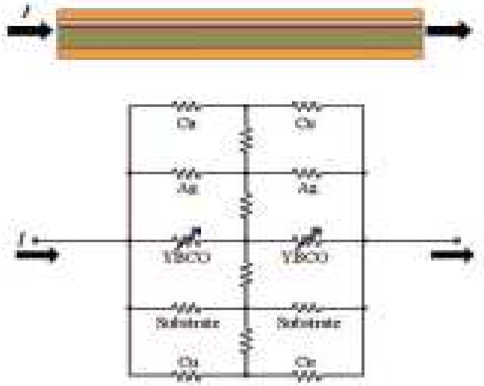
- **Transversal electrical conductivity $\boldsymbol{\sigma^T}$**

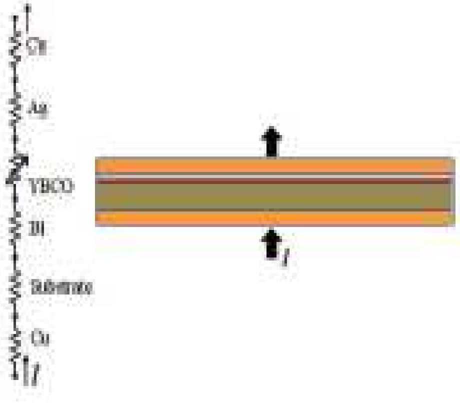
If coil current is longitudinal to the tape, the tape layers are in series.

$$\sigma_T[{}^{S}/_{m}] = \frac{d_{tot}}{d_{Cu}/\sigma_{Cu}} + \frac{d_{tot}}{d_{Ag}/\sigma_{Ag}} + \frac{d_{tot}}{d_{Sub}/\sigma_{Sub}} + \frac{d_{tot}}{d_{YBCO}/\sigma_{YBCO}}$$

- **Longitudinal and transversal thermal conductivity $\boldsymbol{k_L, k_t}$**

If heat flux is longitudinal or transversal, equivalent homogenization technique is applied for longitudinal k_L and transversal k_T thermal conducibilility.

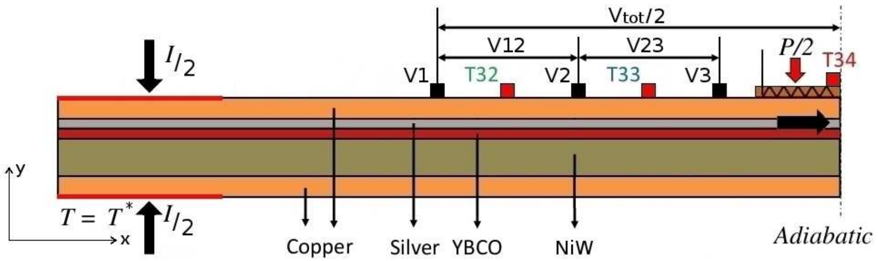


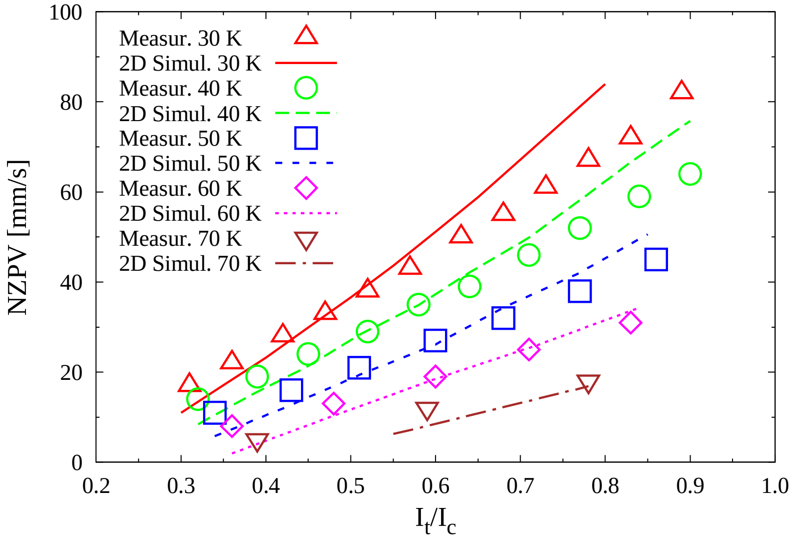


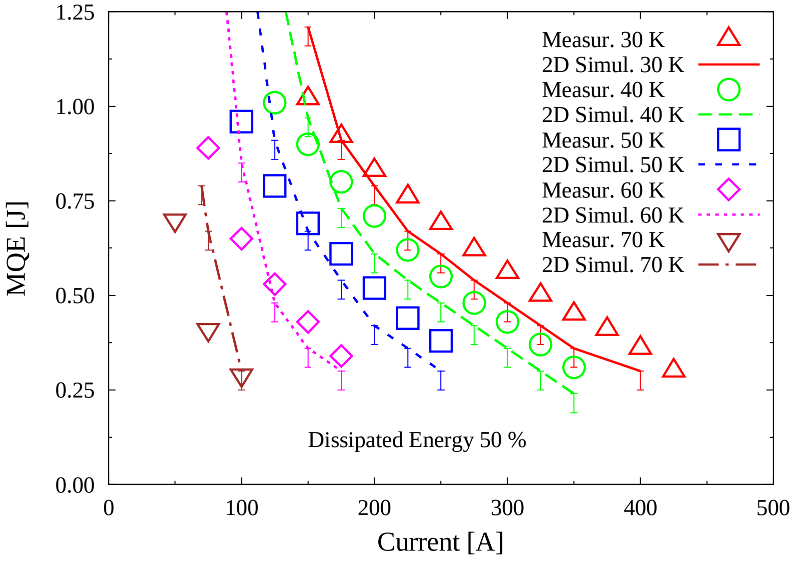
2D FEM Model

Tape model validation

- The tape model was previously validated versus experimental results on a HTS tape manufactured by AMSC [3]







[3] M. Casali, M. Breschi, P. L. Ribani, "Two-Dimensional anisotropic model YBCO coated conductors ," *IEEE Trans. Appl. Supercond.*, vol. 25, no. 1, Feb. 2015.

2D FEM Model

Critical current fit function

- In homogenization tecnique, **YBCO electrical conductivity $\boldsymbol{\sigma_{YBCO}}$** is evaluated by power law

$$\sigma_{YBCO} = \left(\frac{J_c}{J}\right)^n \frac{J}{E_c}$$

- Critical current density $\boldsymbol{J_C}$ is calculated by **critial current parametrization $\boldsymbol{I_c(B, \theta, T)}$** *[4]*

$$I_c(B,\theta) = \frac{b_0}{(B+\beta_0)^{\alpha_0}} + \frac{b_1}{(B+\beta_1)^{\alpha_1}}\left[\omega^2(B)\cdot cos^2(\boxed{\theta} - \varphi_1) + sin^2(\boxed{\theta} - \varphi_1)\right]^{-1/2}$$

where

$$\omega_1(B) = c_1\left[B + \left(\frac{1}{c_1}\right)^{1/\varepsilon_1}\right]^{\varepsilon_1}$$

coefficients $b_0,\ b_1, \alpha_0, \alpha_1, \beta_0, \beta_1, \varphi_1$ are temperature dependent.

[4] D. K. Hilton, A. V. Gavrilin, U. P. Trociewitz, "Practical fit function for transport critical current versus field magnitude and angle data from (RE)BCO coated conductors at fixed low temperature and in high magnetic fields ," *Supercond. Sci. Technol. 28 (2015) 074002 (9pp)*

2D FEM Model

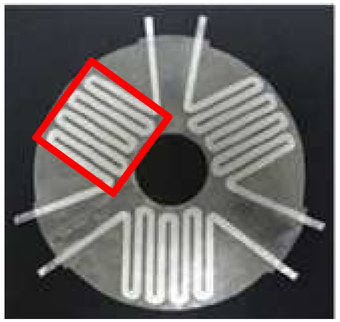
Boundary condition - Temperature

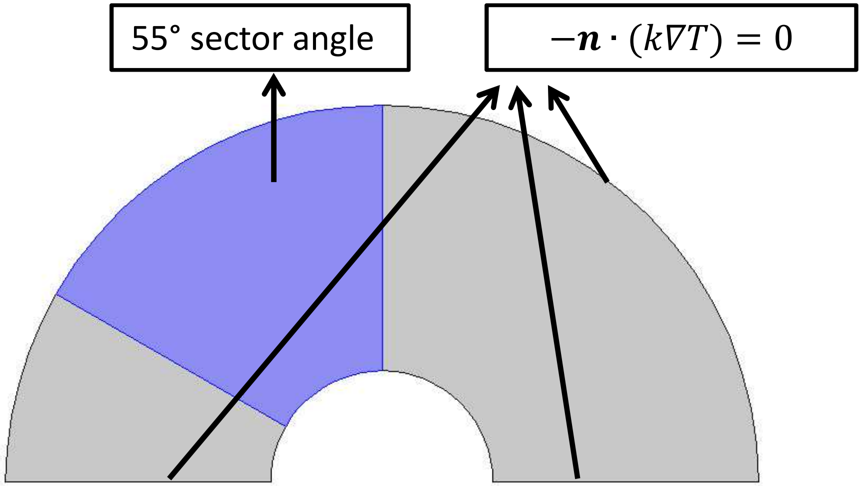
$$\boldsymbol{\rho \cdot C_p \frac{dT}{dt} - \nabla \cdot (k(T)\nabla T) = Q_{joule}}$$

- **Heater Area**

The area of a 55° sector angle is equal to heater area (as rectangle). Then **correction parameter** to take in accaunt real heater shape

$$S_{heater} = S_{55°}$$





55° sector angle

$-\boldsymbol{n} \cdot (k\nabla T) = 0$

Initial condition: $T\ (t = 0\ s) = \ 4.2\ \mathrm{K}$

- **Heater Power**

In a 2D model the surperficial heater power [W/m^2] has to be modelled as a volumetric power density [W/m^3]. To reach the same temperature as in the real case a **correction parameter** is introduced.

$$P_{Vol.}\left[\frac{W}{m^3}\right] = 2.3\ \frac{P_{heater}(t)[W]}{coil\ height\ [m] \cdot\ S_{60°}\ [m^2]}$$

correction parameter = 2.3

2D FEM Model

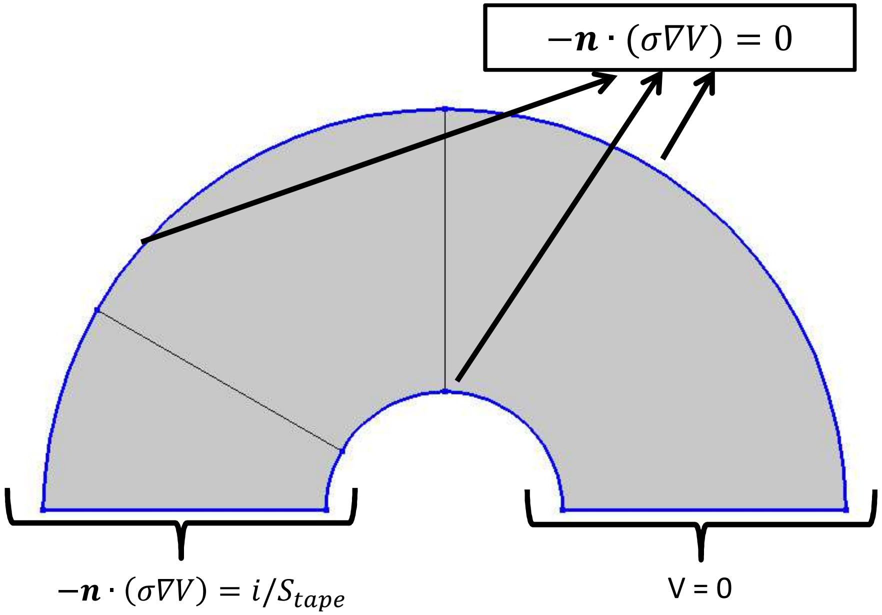
Boundary condition-Voltage-Current

$$\boxed{\boldsymbol{\nabla} \cdot (-\boldsymbol{\sigma}(\boldsymbol{T}, |\boldsymbol{B}|, |\boldsymbol{E}|)\boldsymbol{\nabla V}) = \mathbf{0}}$$

$$\boxed{\boldsymbol{V_{sc}} + \boldsymbol{V_{joint}} = \boldsymbol{R_{joint} i} + \boldsymbol{R_{sc} i} + \boldsymbol{L} \frac{\boldsymbol{di}}{\boldsymbol{dt}}}$$

- Voltage, **initial condition**
  $V\ (t = 0s) = 0\ V$
- **Zero current density flux** on external surfaces
  $-\boldsymbol{n} \cdot (\sigma \nabla V) = 0$
- **Inlet current density** equal to single tape current density
  $-\boldsymbol{n} \cdot (\sigma \nabla V) = \frac{i}{S_{tape}}$
- **Dirichlet** Boundary Condition
  $V = 0\ V$

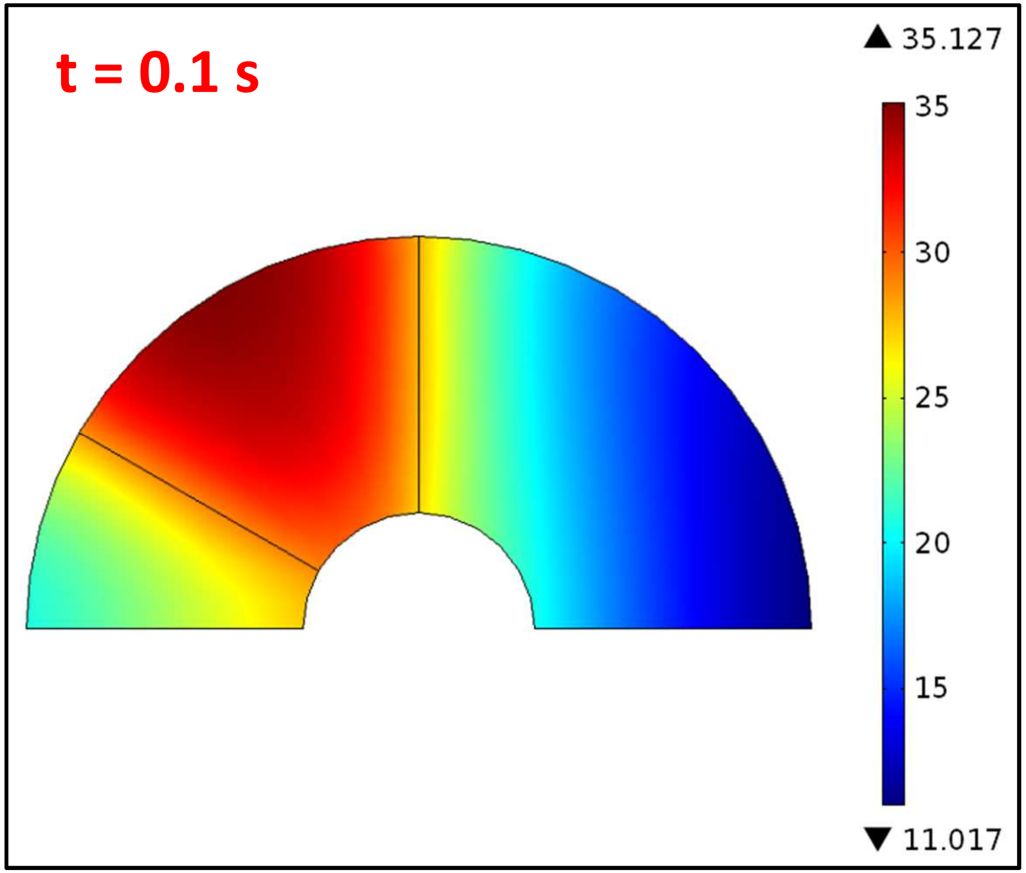
- Current, **initial condition**
  $i\ (t = 0s) = 200\ A$



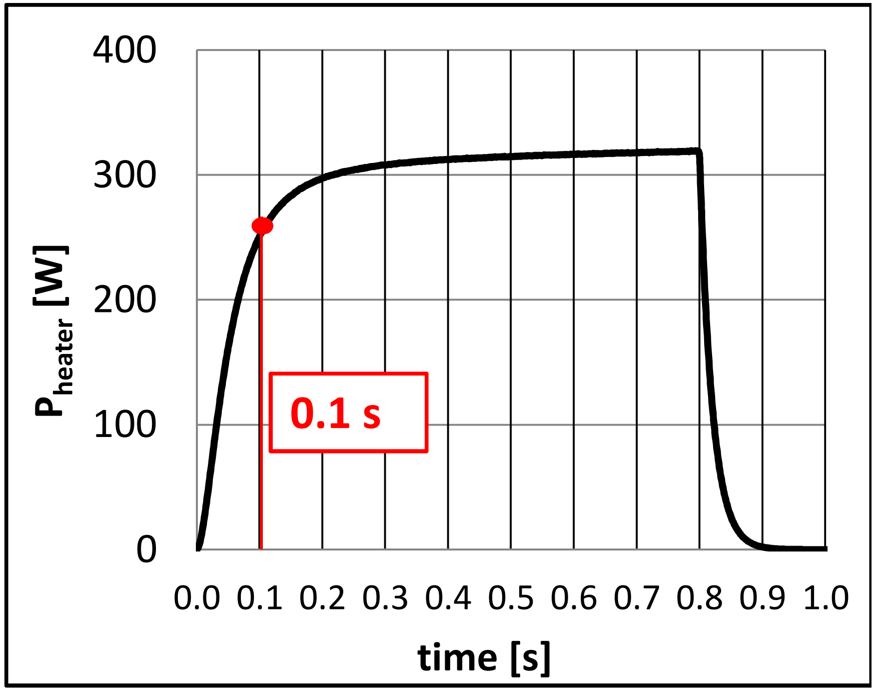
2D FEM Model

Temperature evolution

Heater ON



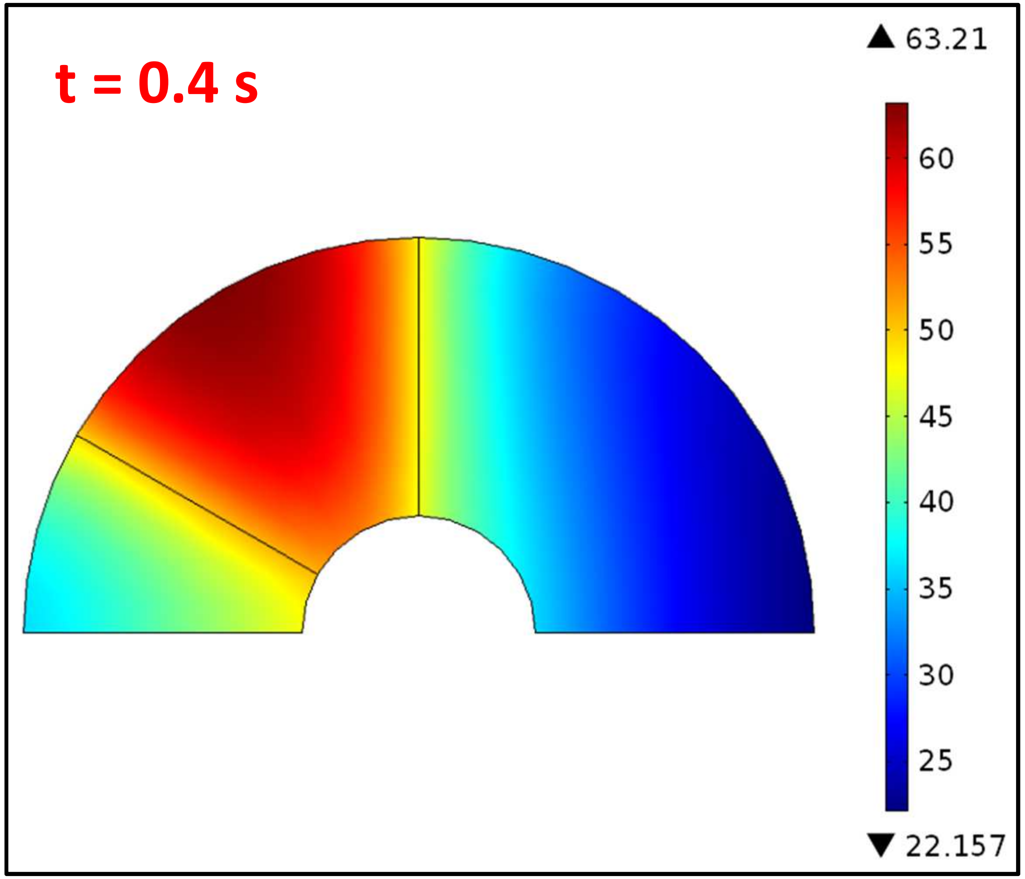
Single heater pulse



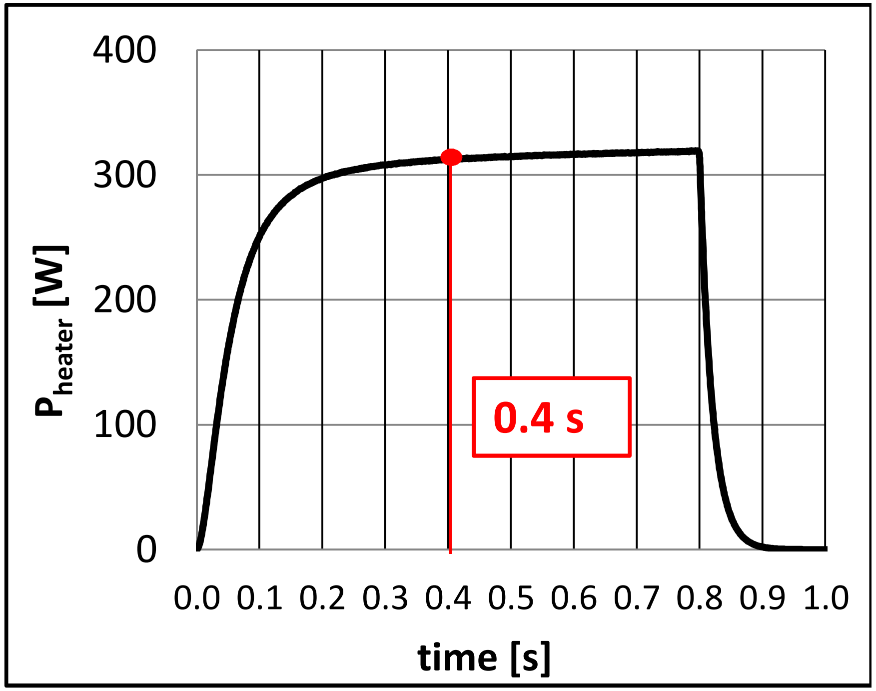
2D FEM Model

Temperature evolution

Heater ON



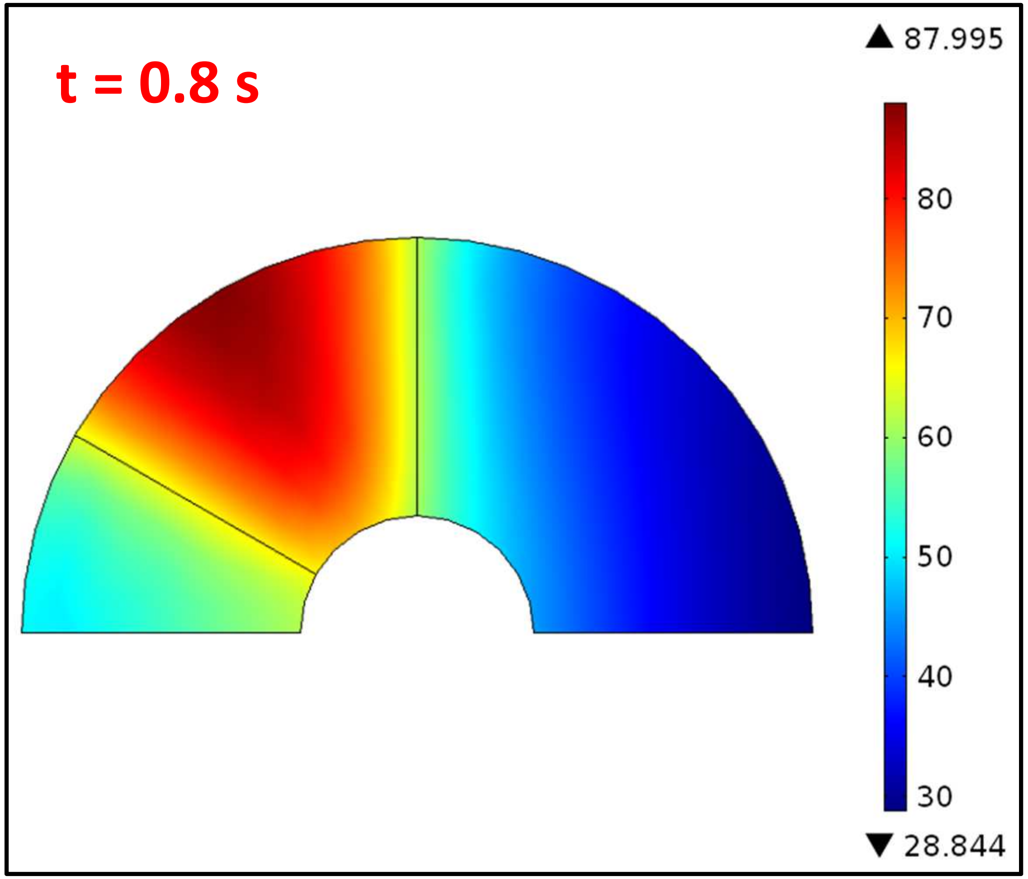
Single heater pulse



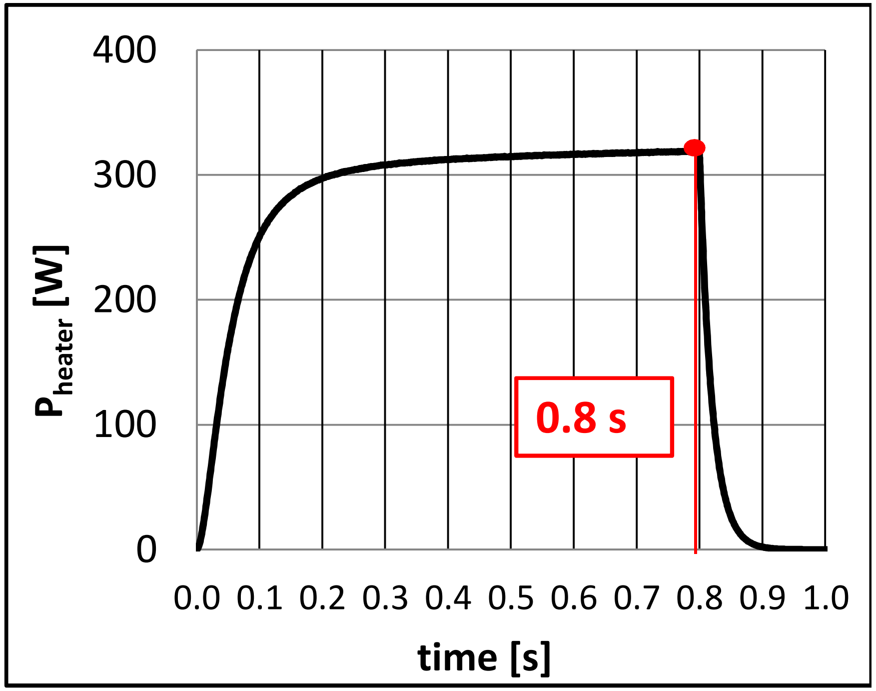
2D FEM Model

Temperature evolution

Heater ON



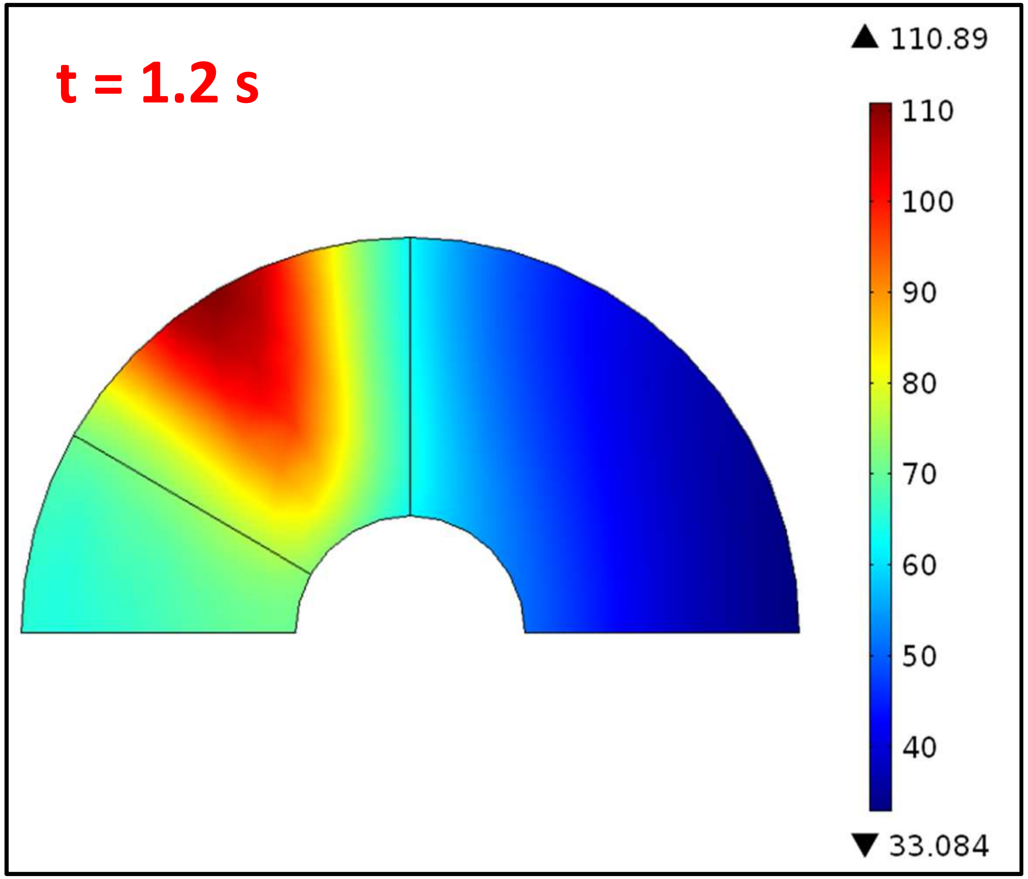
Single heater pulse

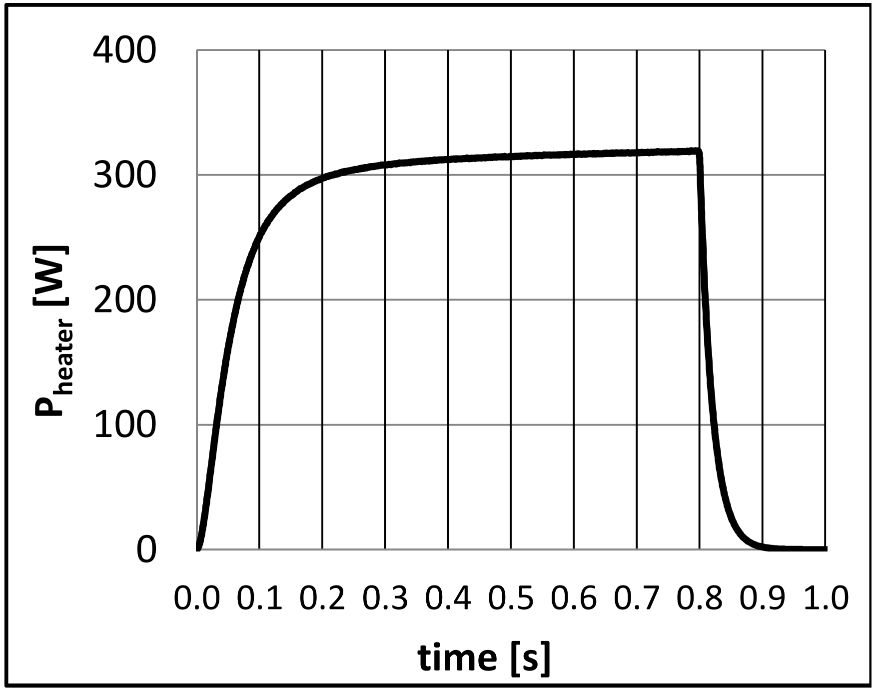


2D FEM Model

Temperature evolution

Heater OFF

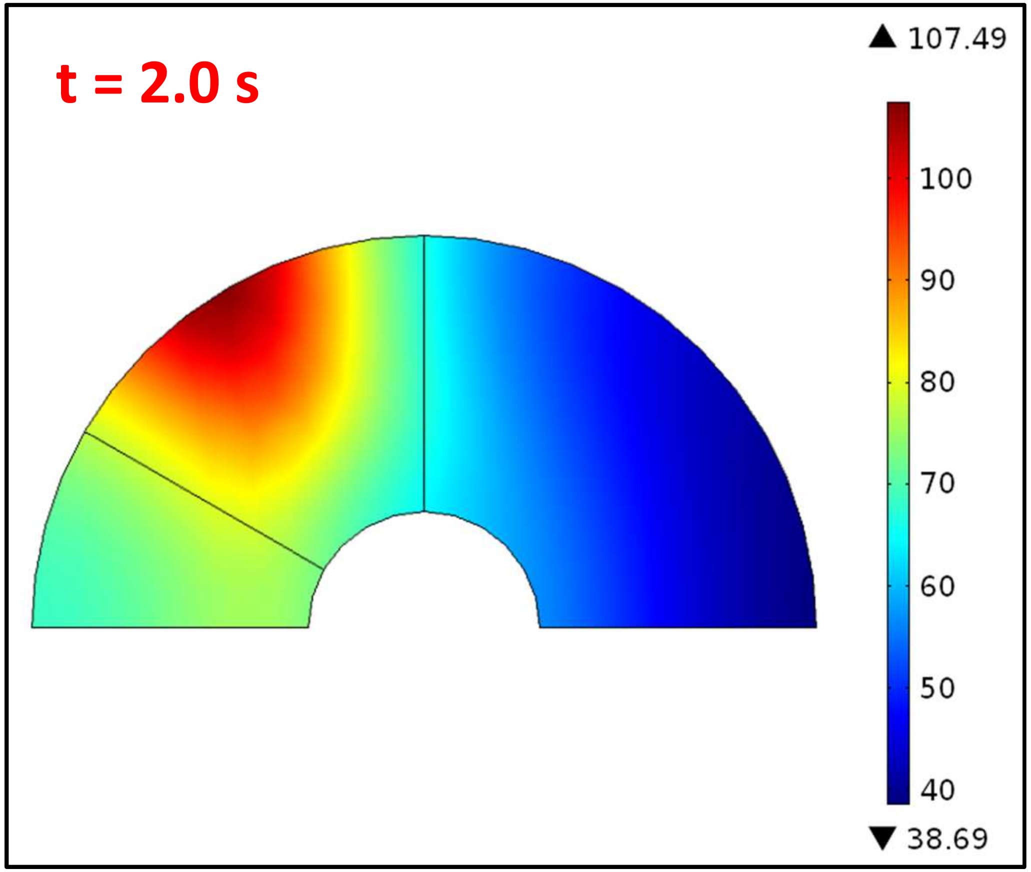



Single heater pulse

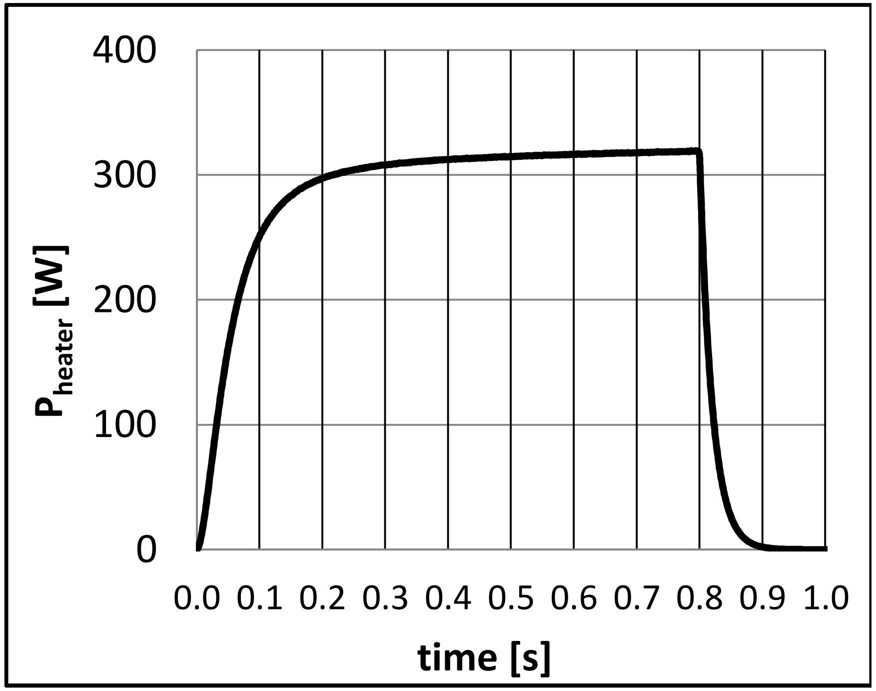
2D FEM Model

Temperature evolution

Heater OFF



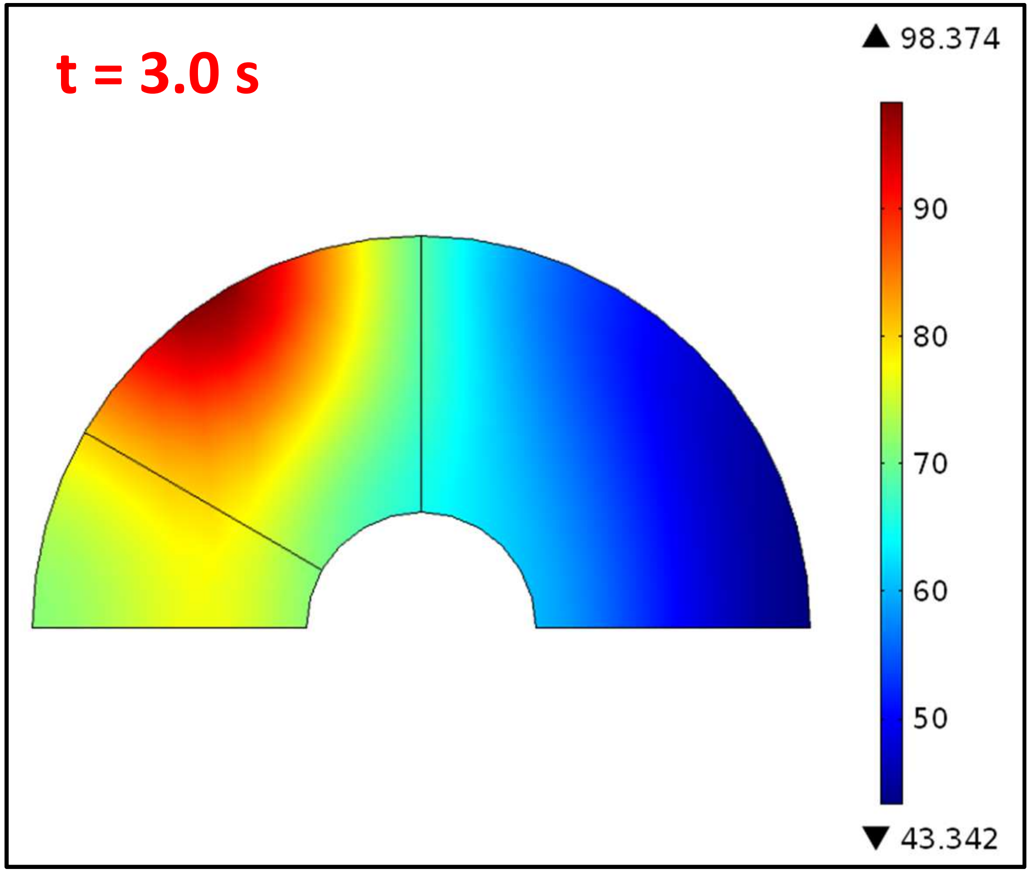
Single heater pulse



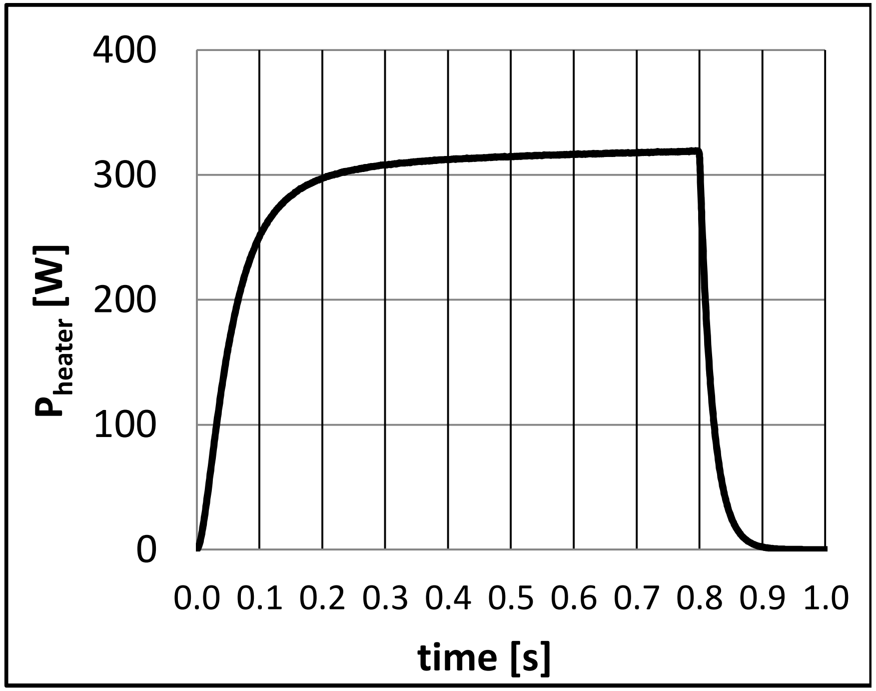
2D FEM Model

Temperature evolution

Heater OFF



Single heater pulse

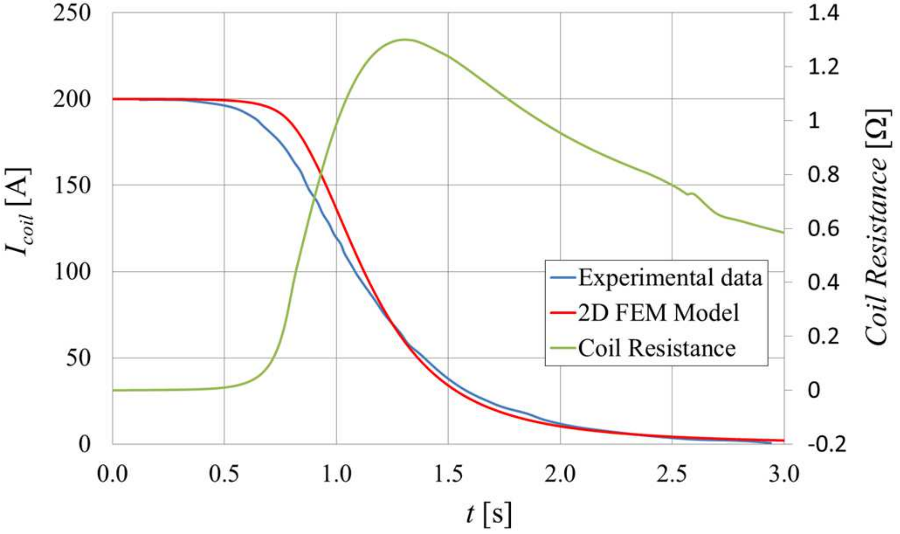


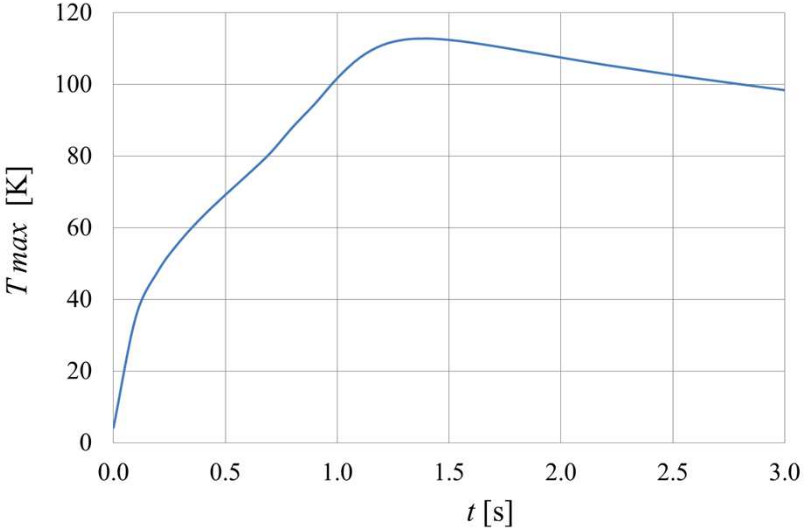
Comparison between the 2D model and the experimental data: coil current evolution

- The coil current damping due to the increasing resistance of the normal zone can be represented by the 2D model

- The normal zone propagation increases the coil resistance

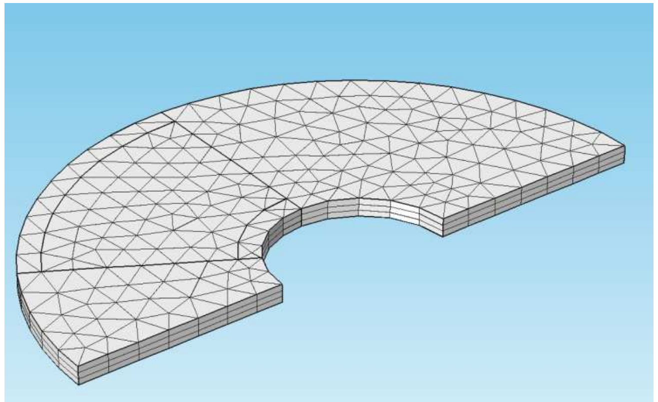
- The reduction of the coil resistance is due to the decreasing temperature related to the current decay.



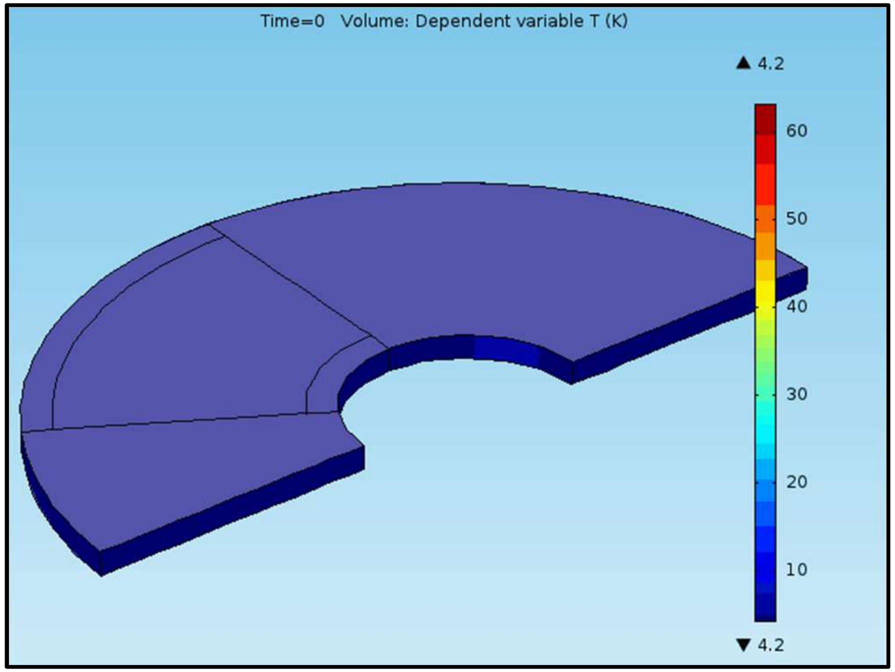


Model development

3D Model



- In order to improve the analysis of the quench propagation, a 3D model is under development.
- A heat disturbance is applied with a uniform flux density to the upper surface in the heater region.
- Adiabatic condition are imposed on the lower pancake surface.
- Long computational time (at the moment)



Conclusion

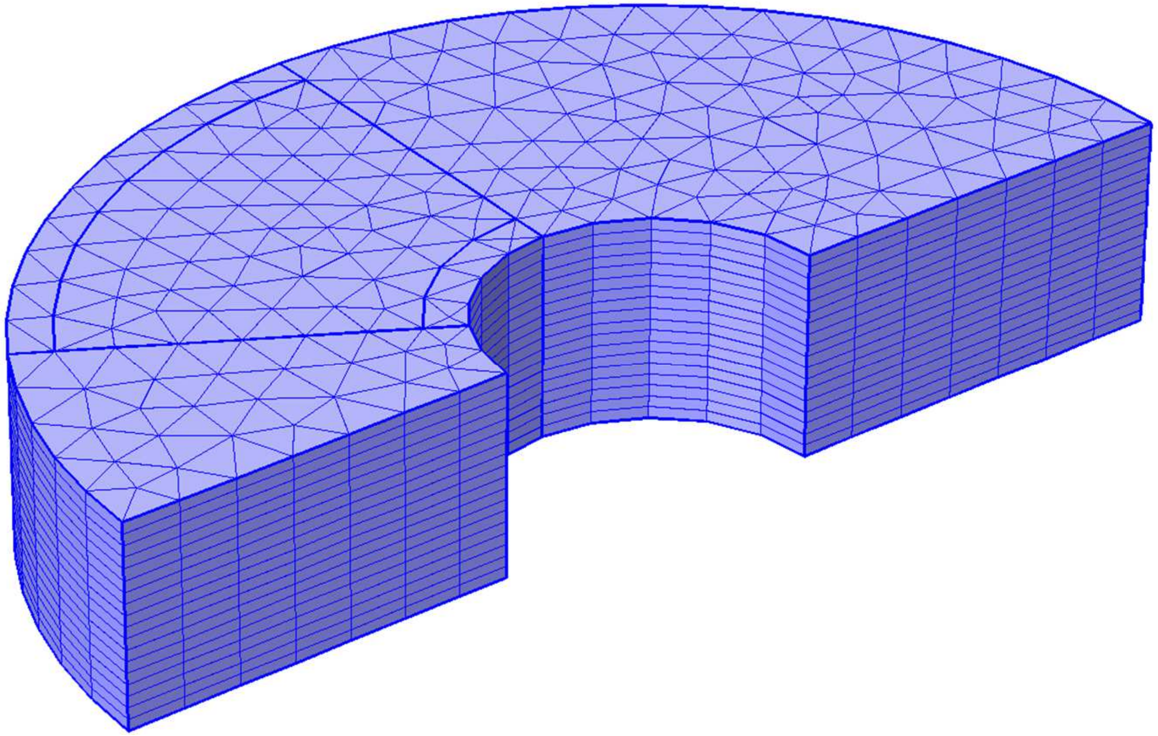
- A 2D model of quench propagation in coated conductors has been developed
- The model describes one pancake of the coil by means of a homogenized anisotropic material
- The main features of the experimental results can be reproduced but further investigations are required to reach a quantitative agreement
- A 3D model of the pancake is under development

The End

Model development

3D Model

Assumption 12



2D FEM Model

Equation

Heat Balance Equation

$$\rho \cdot C_p \frac{dT}{dt} - \nabla \cdot (k(T)\nabla T) = Q_{joule}$$

$$Q_{joule} = \sigma(T, |\boldsymbol{B}|, |\boldsymbol{E}|)\nabla V \cdot \nabla V$$

Current Density Continuity Condition

The slowly varying time-derivative term of the magnetic potential $\partial A / \partial t$ is ignored *[2]*

$$\nabla \cdot \mathbf{J} = \mathbf{0}$$

$$\nabla \cdot (-\sigma(T, |\boldsymbol{B}|, |\boldsymbol{E}|)\nabla V) = 0$$

Magnetic Flux Density components

$$B_r = b_r(x, y, z) \cdot i + Br^{ext}$$

$$B_z = b_z(x, y, z) \cdot i + Bz^{ext}$$

Coil Constitutive Law

$$V_{sc} + V_{joint} = R_{joint} i + R_{NZ} i + L\frac{di}{dt}$$

where

$$L = 0.44\ [H]$$

$$V_{joint} = R_{joint} \cdot i(t = 0s)$$

$$= 8.06\ [\mu\Omega] \cdot 200\ [A]$$

$$V_{sc} = 10^{-100}\ [\mathrm{V}]$$

R_{NZ} evaluated by *joule power* relation.

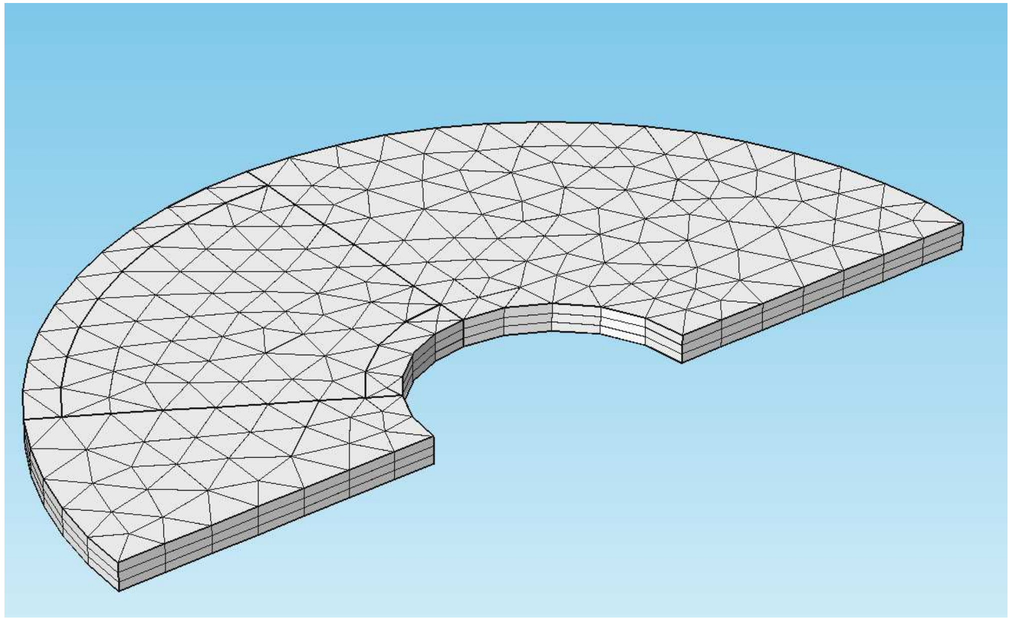
Assumption: the prototype coil is supposed as composed by pankace 11, then multiplication factor 12 is introduced

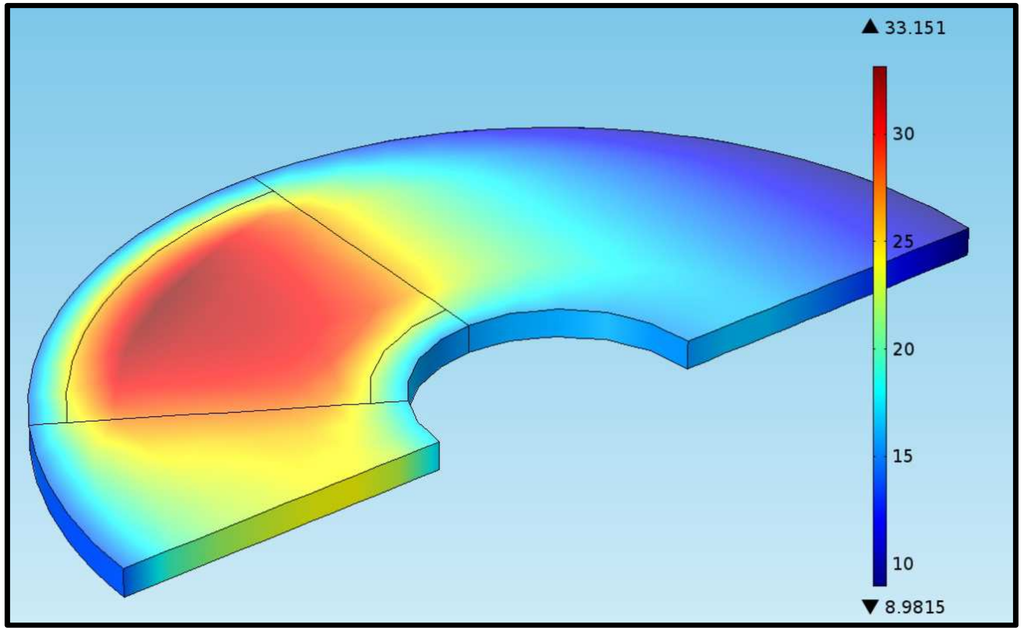
$$R_{NZ} i^2 = \mathbf{12} \cdot 2 \cdot \int_V \vec{E} \cdot \vec{J} dV$$

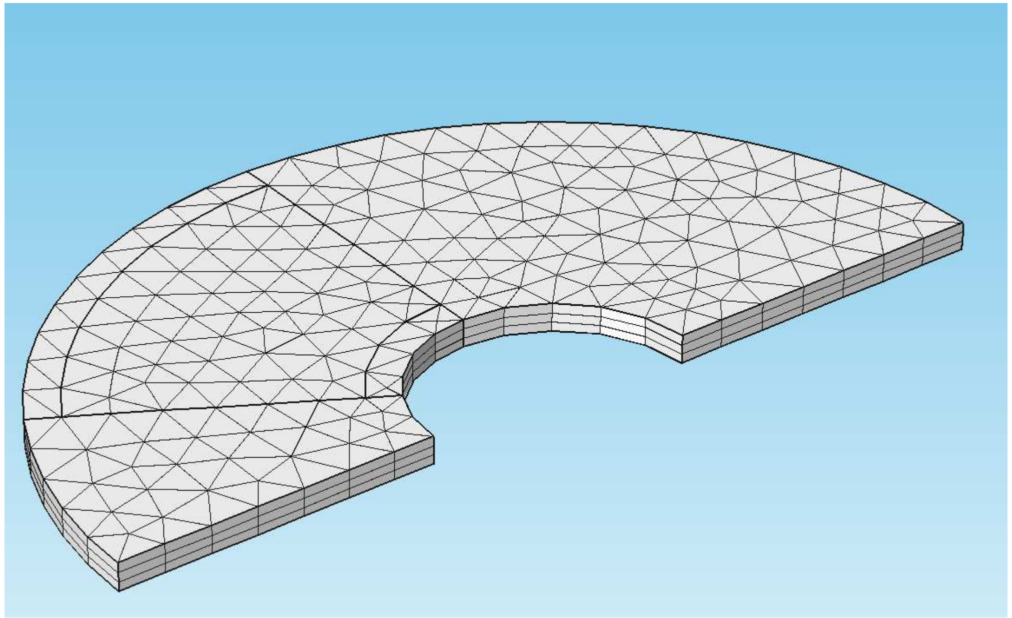
[2] W. K. Chan, J. Schwartz, "A Hierarchical Three-Dimensional Multiscale Electro-Magnetic-Thermal Model of Quenching in $REBa_3Cu_3O_{7-\delta}$ Coated-Conductor-Based Coils ," *IEEE Trans. Appl. Supercond.*, vol. 22, no. 5, Oct. 2012.

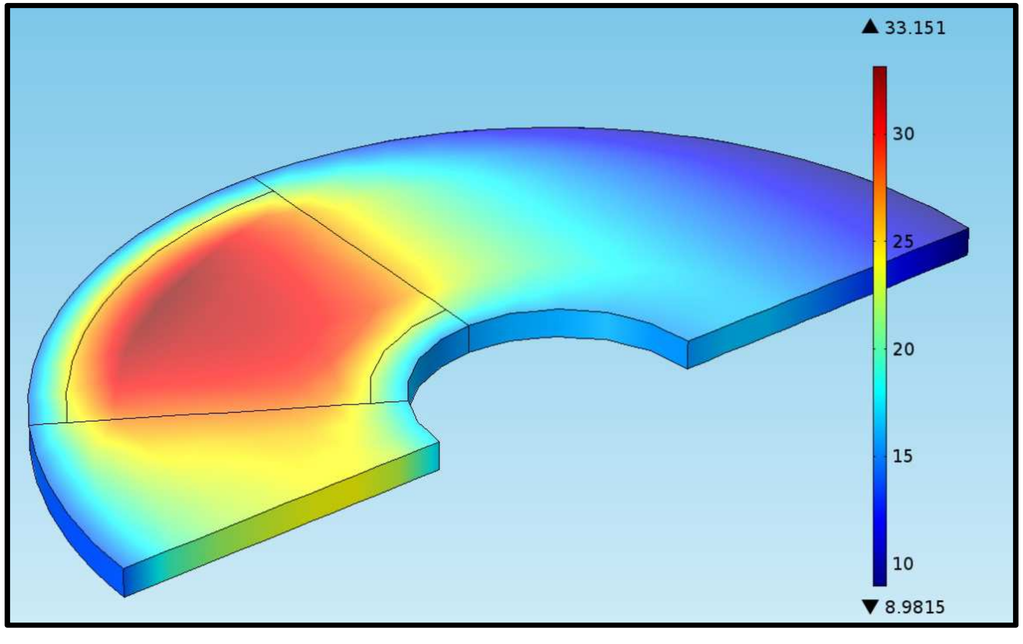
Future development

3D





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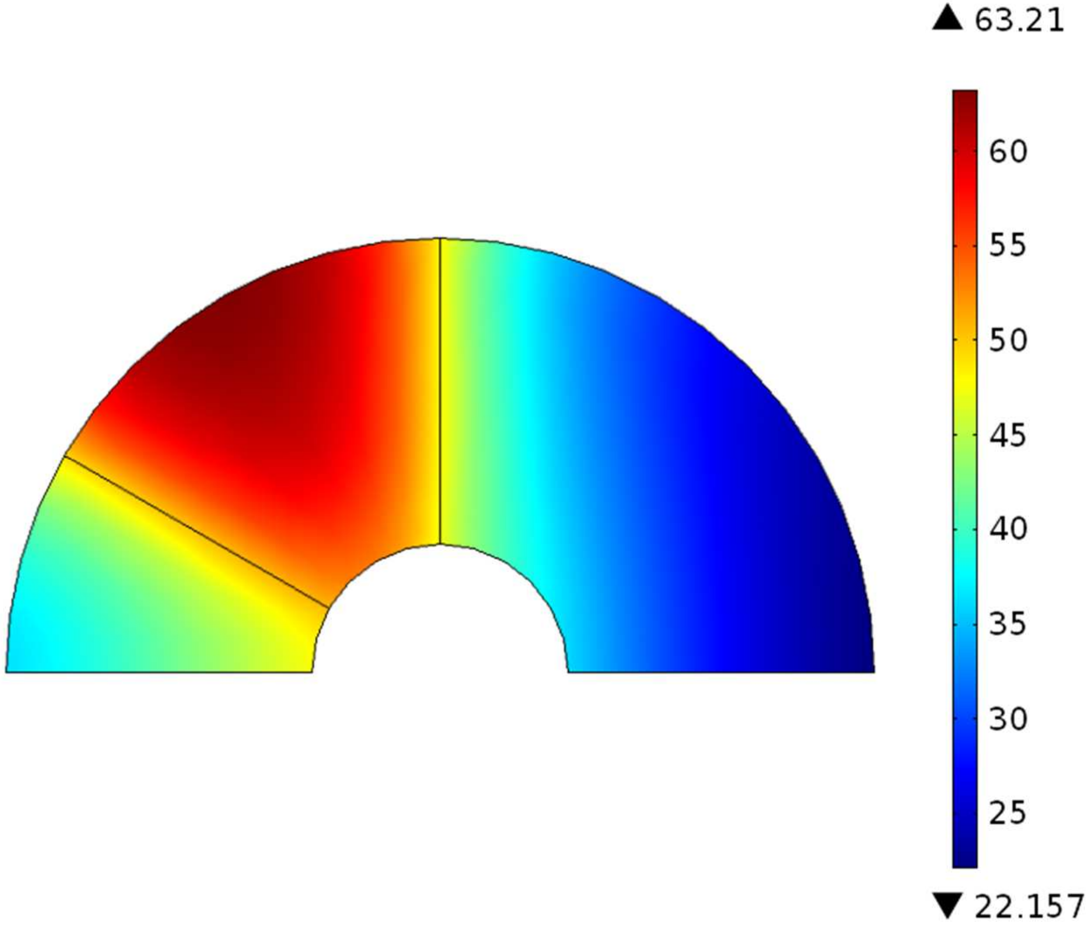
2D FEM Model

Temperature evolution

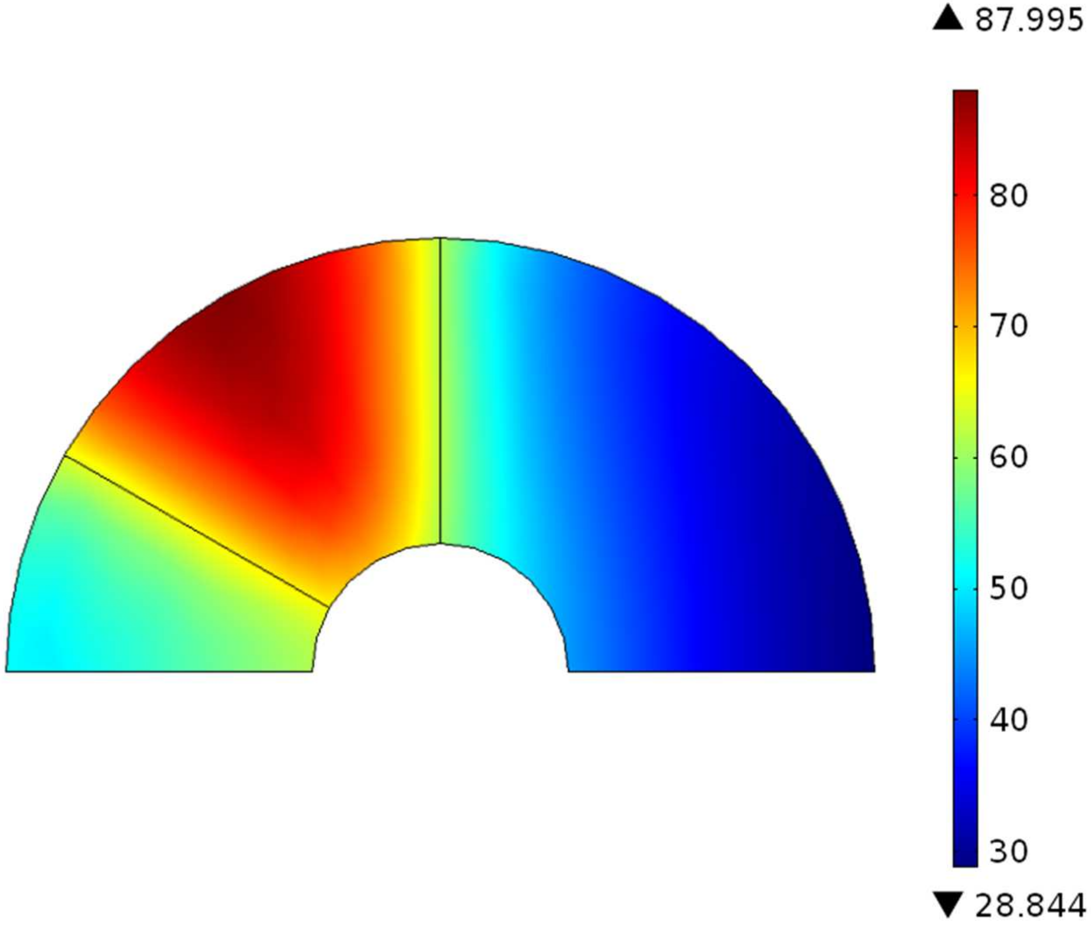
t = 0.4 s



2D FEM Model

Temperature evolution

t = 0.8 s



2D FEM Model

Boundary condition - Temperature

$$\boxed{\rho \cdot C_p \frac{dT}{dt} - \nabla \cdot (k(T)\nabla T) = Q_{joule}}$$

- **Initial condition**

$$T\ (t = 0\ s) = 4.2\ K$$

- **Adiabatic condition** on all external surfaces

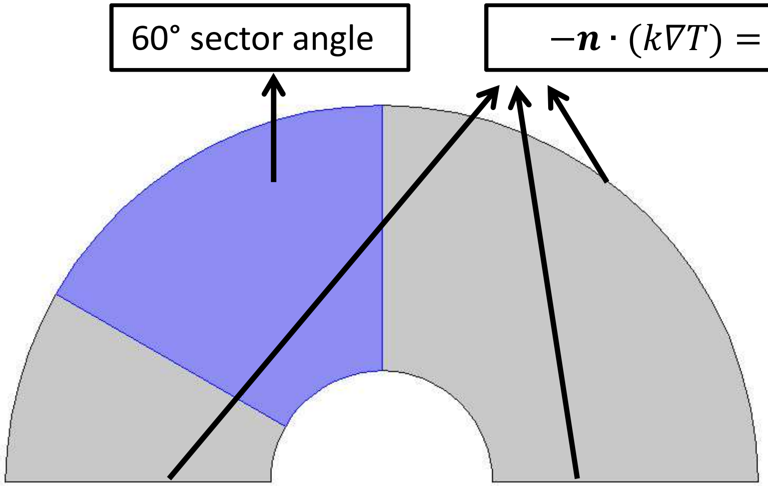
$$-\boldsymbol{n} \cdot (k\nabla T) = 0$$

- **Heater heat flux** on a 60° sector angle area.

In a 2D model the surperficial heater power *[W/m²]* has to be modelled as a volumetric power density *[W/m³]*. The same power is introduced in a lerger volume then, to reach the same temperature as in the real case a fitting parameter is introduced.

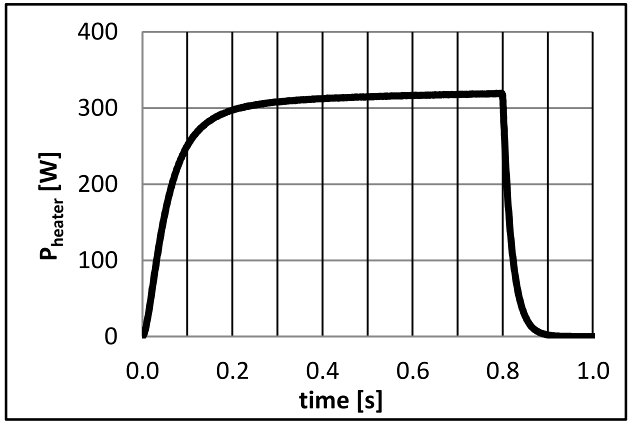
$$P_{Vol.}\left[\frac{W}{m^3}\right] = 2.5\ \frac{P_{heater}(t)[W]}{coil\ height\ [m] \cdot S_{60°}\ [m^2]}$$

fitting parameter = 2.5



60° sector angle

$-\boldsymbol{n} \cdot (k\nabla T) = 0$



2D FEM Model

Boundary condition - Temperature

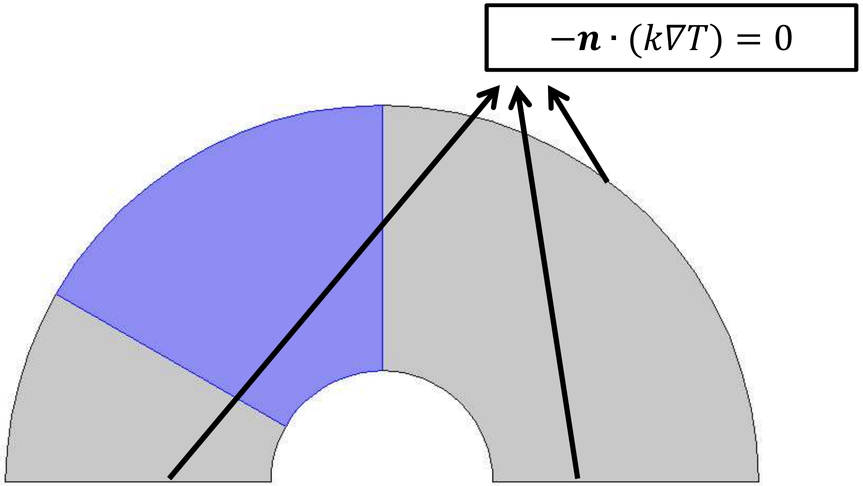
$$\boxed{\boldsymbol{\rho \cdot C_p \frac{dT}{dt} - \nabla \cdot (k(T)\nabla T) = Q_{joule}}}$$

- **Initial condition**

  $T\ (t = 0\ s) = 4.2\ K$

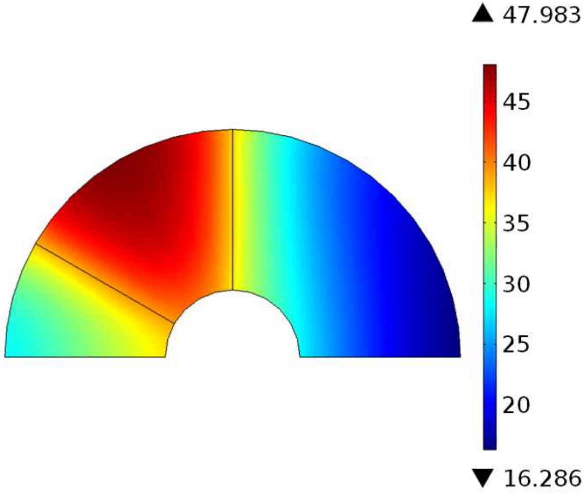
- **Adiabatic condition** on all external surfaces

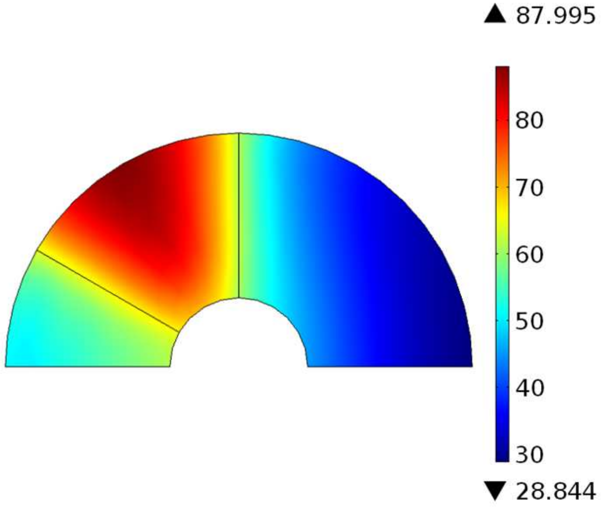
  $-\boldsymbol{n} \cdot (k\nabla T) = 0$

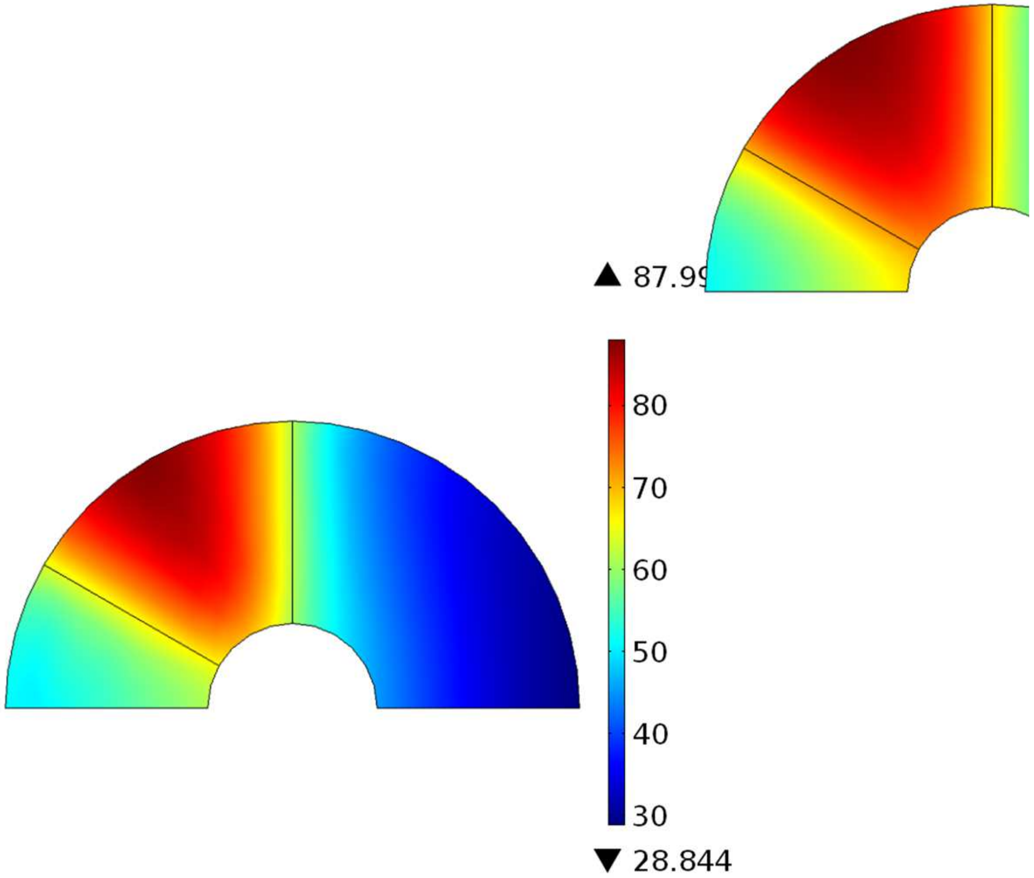


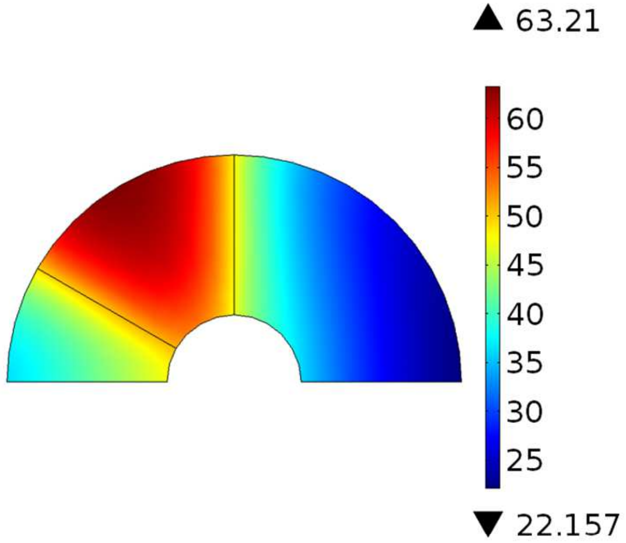
2D FEM Model

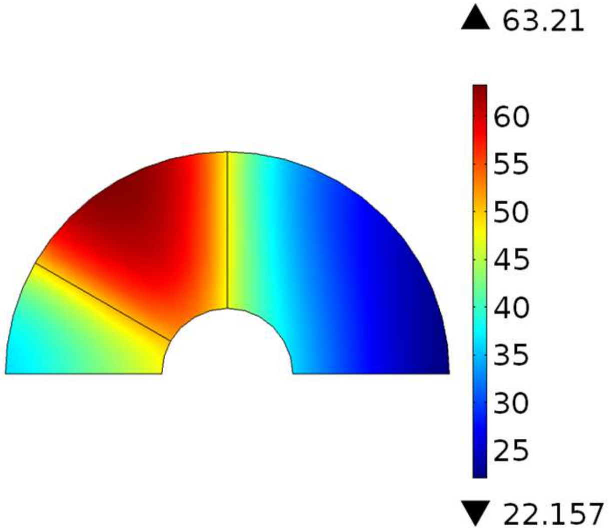
Temperature evolution








▲ 63.21
60
55
50
45
40
35
30
25
▼ 22.157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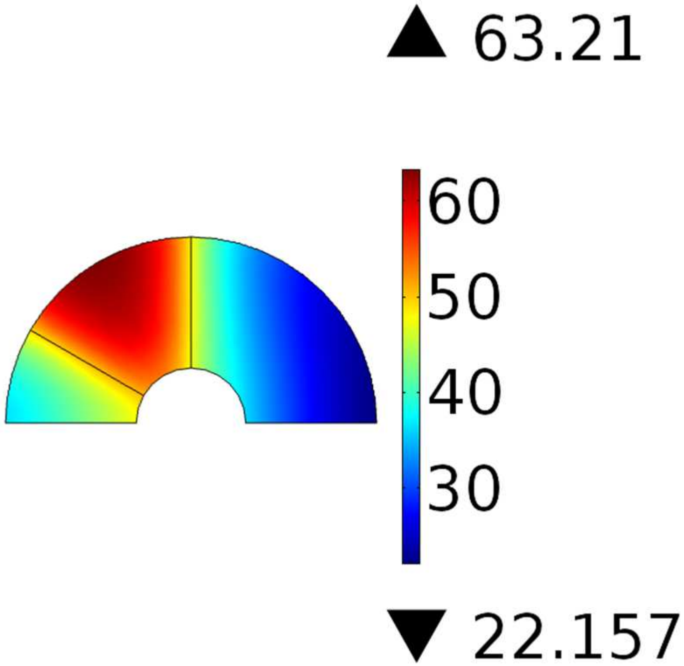
▲ 63.21
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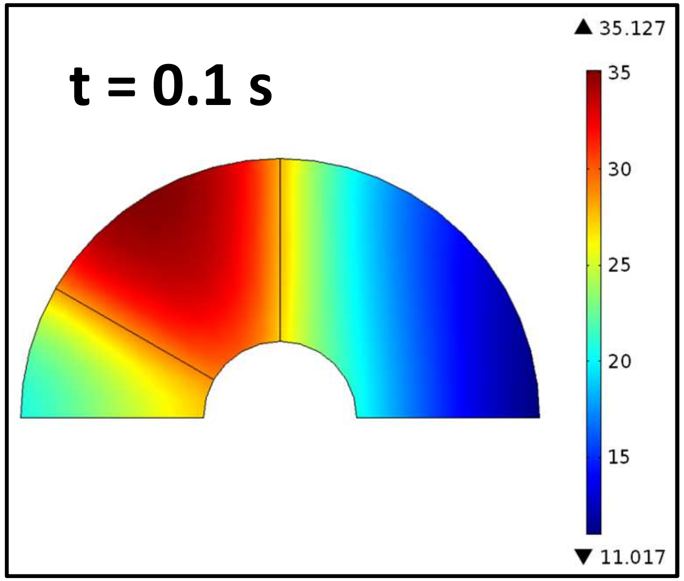
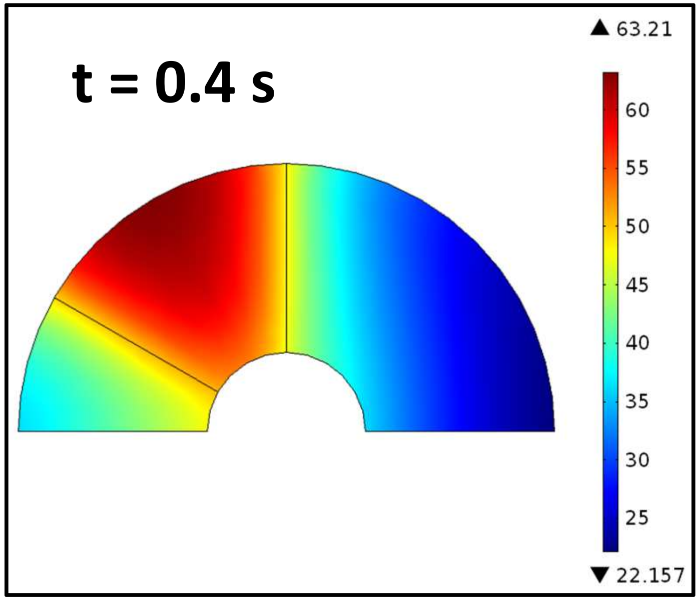
▼ 22.157

2D FEM Model

Temperature evolution

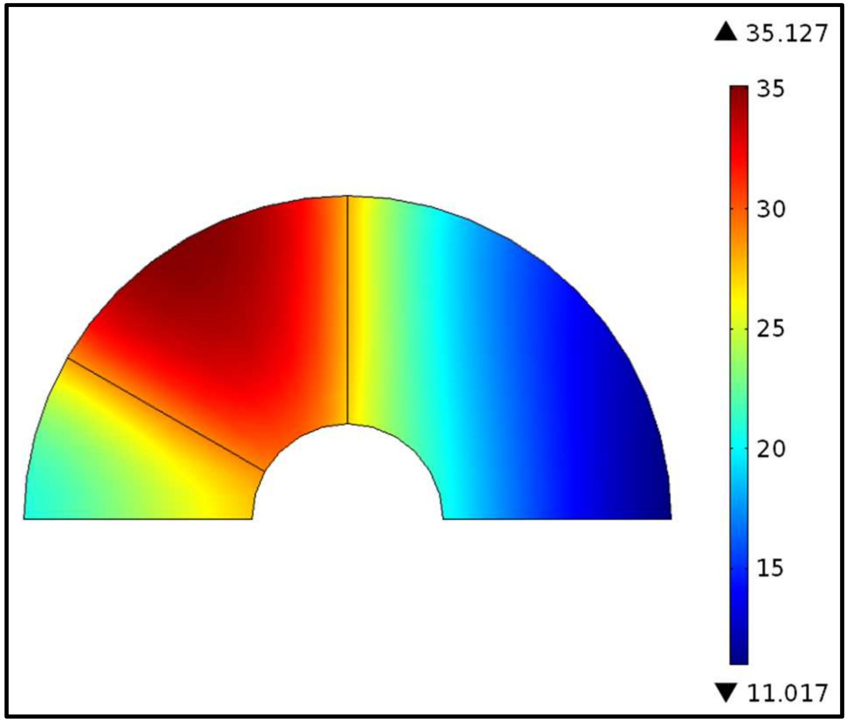




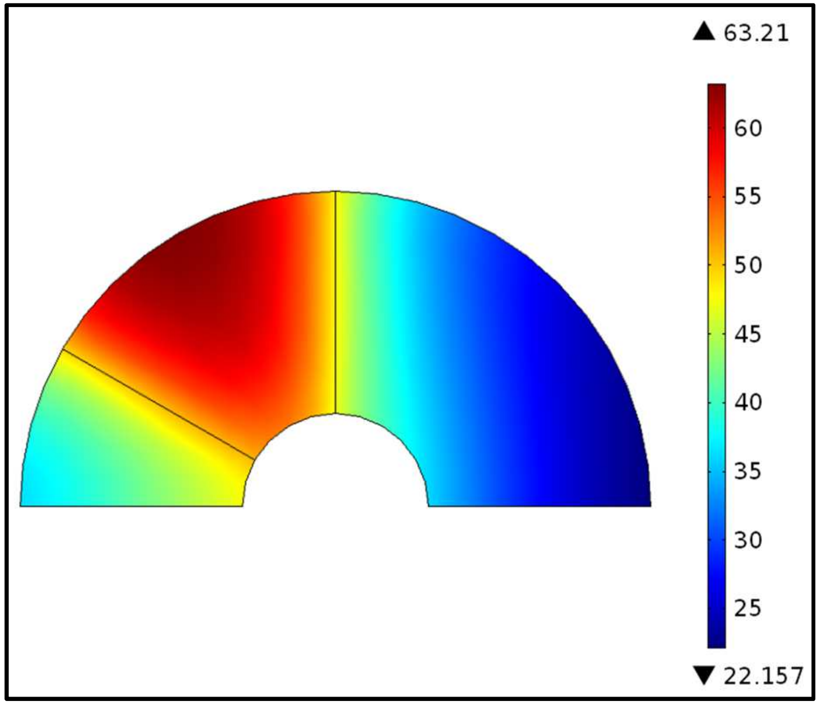
2D FEM Model

Temperature evolution

t = 0.1 s



t = 0.4 s



Magnetic flux density evolution during coil current damping

Coil current damping effect on
magnetic flux density and teta angle