ALMA MATER STUDIORUM
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Analysis of Current Distribution during Quench in a Pancake coil wound with REBCO Roebel cable

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Chats 2019
Applied Superconductivity

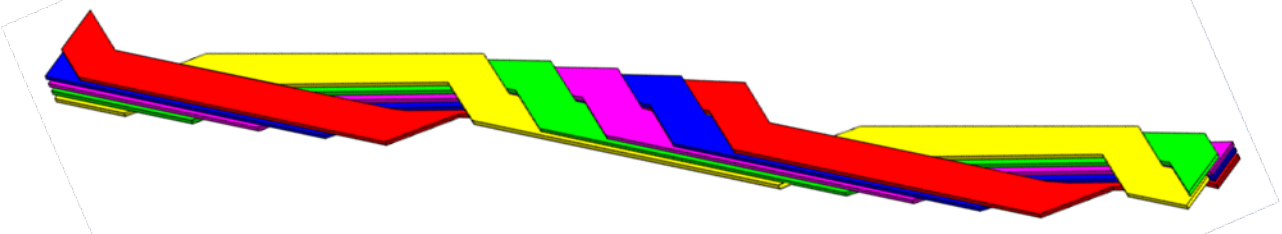
THE REBCO ROEBEL CABLE: Introduction

- The Roebel bar technique was applied in superconductivity for the first time to reduce the AC losses in the **NbTi Roebel** cable of the **EURATOM toroidal** field magnet
- The advantages of the Roebel cables are related to their **ability to carry high transport currents** with a **compact design** and **mechanical flexibility**.
- The **quench models of REBCO cables** available in the literature are based on various approaches, usually 0D, 2D or 3D approaches
- The motivation for this work is to test the feasibility of a **reduced dimensionality approach in the frame of a 1D model**

[1] E. Härö et al., «Hot Spot Temperature in an HTS Coil: Simulations With MIITs and Finite Element Method», IEEE Trans. Appl. Supercond., vol. 25, n. 2, 2015

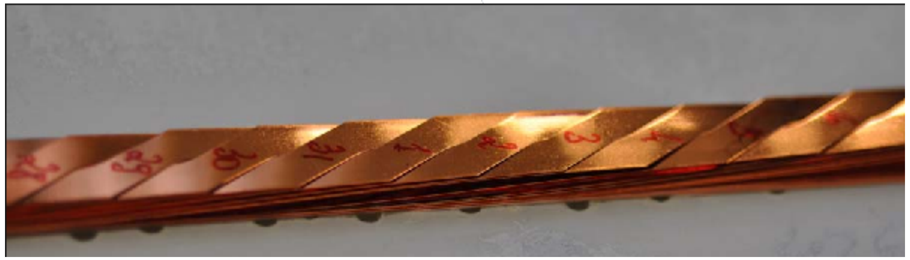
[2] G. Kirby et al., «Status of the Demonstrator Magnets for the EuCARD-2 Future Magnets Project», IEEE Trans. Appl. Supercond., vol. 26, n. 3, 2016

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



Mechanical flexibility

Compact Design



OUTLINE

INTRODUCTION

ROEBEL COIL Model

- **Experimental Setup Description**
- **Model Description**
  - **Thermal Model**
  - **Electrical Model**
- **Validation and Results**
  - **Voltage Measurements**
  - **Temperature Distribution**
  - **Current Distribution**
  - **Impact of Heater Pulse on QE**

CONCLUSIONS

THE REBCO ROEBEL COIL: Experimental Setup

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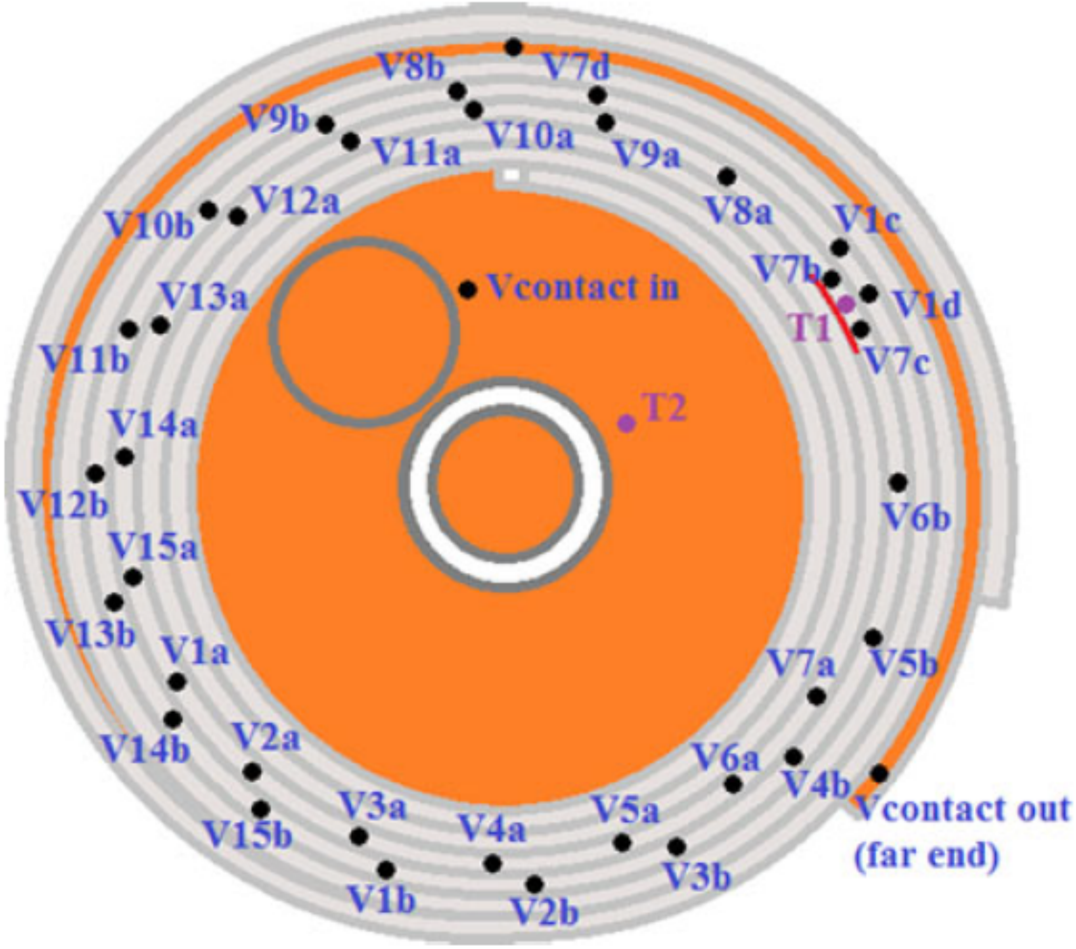
- A piece of **2 m long** Roebel cable with **15 strands** of punched **2G YBCO tapes** (Bruker EST) was wound into a pancake coil of **7 turns** with 72 mm inner diameter.
- The **critical current** for the tape in self field of the coil is about **33 A**.
- The cable, with a **transposition pitch** of **226 mm,** was assembled at KIT (Germany).
- A length of **200 µm** thick **fiberglass ribbon** was co-wound as the 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 (between turns #4 and #3).
- A set of quench measurements for this Robel pancake coil was performed in **LN2** with a **transport current around 450 A.**



[4] Q. Zhang, *et. al*. «Performance and Quench Characteristics of a Pancake Coil Wound With the 2G YBCO Roebel Cable,» *IEEE Trans. Appl. Supercond., vol. 28, no. 4, Jun. 2018.*

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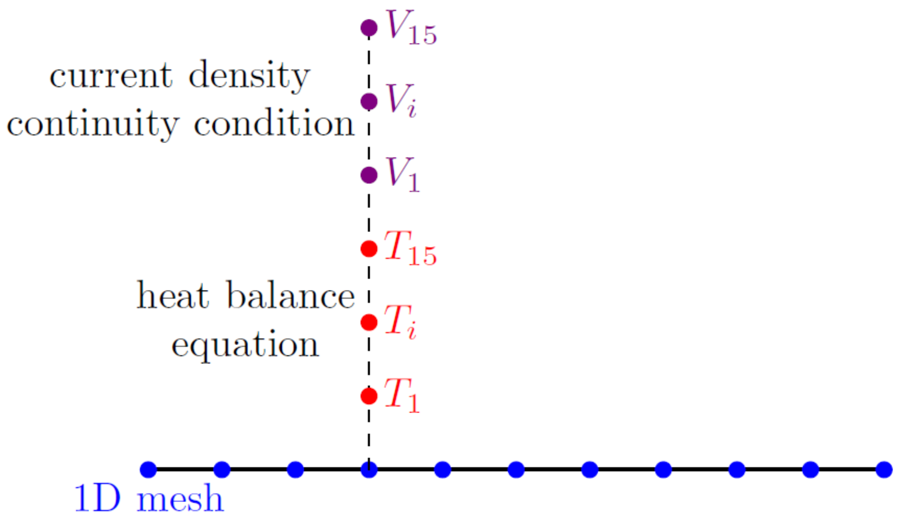
THE REBCO ROEBEL CABLE: Finite Element Model Description

1D MESH PATTERN

The ROEBEL cable tapes are 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**

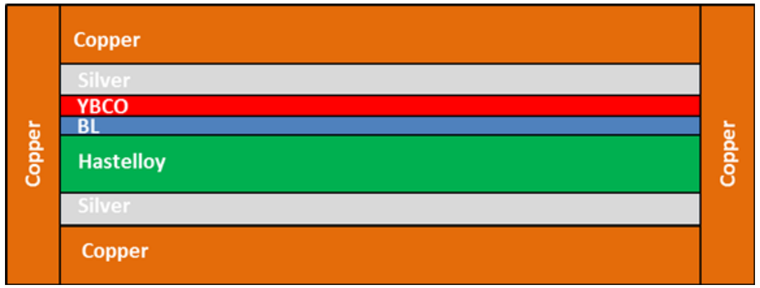
$$\mathbf{T} = (T_i, \dots, T_{N_t}) \qquad \forall i = 1 \dots N_t$$
$$\mathbf{V} = (V_i, \dots, V_{N_t}) \qquad \forall i = 1 \dots N_t$$



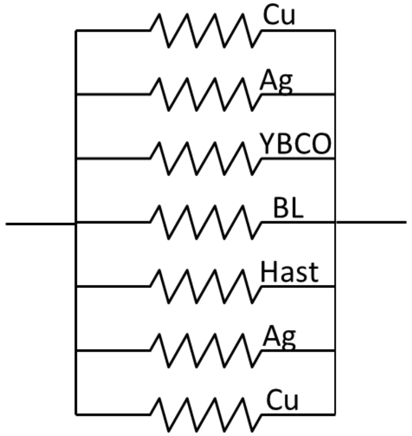
HOMOGENIZATION PROCEDURE

- The tape is modeled as an uniform conducting material with **homogenized properties**
- The tape layers are assumed in **parallel** and the longitudinal electrical conductivity $\boldsymbol{\sigma_i}$ is computed as:

$$\sigma_i = \frac{I_c(T_i)}{E_c\ S_{tot}} \underbrace{\left(\frac{1}{E_c}\frac{\partial V_i(x,t)}{\partial x}\right)^{\frac{1-n}{n}}}_{\textbf{power law}} + \sum_{j=1}^{N_l} \sigma_j(T_i(x,t))\,\frac{S_j}{S_{tot}} \qquad \forall i = 1 \dots N_t$$



REBCO layers



$Ic(77\,\mathrm{K}, \mathit{self\ field}) = 65\ \mathrm{A}$ for the punched 5.5 mm wide Bruker tape

THE REBCO ROEBEL COIL: Thermal Model

THERMAL CONTACT BETWEEN TURNS

- **A set of coupled equations** is solved to determine the temperatures of all the **N_t tapes**.
- A further thermal element is added to represent the **insulation between turns: T_{ins}**

$$\mathbf{T} = [T_1 \ldots T_{Nt}, T_{ins}]$$

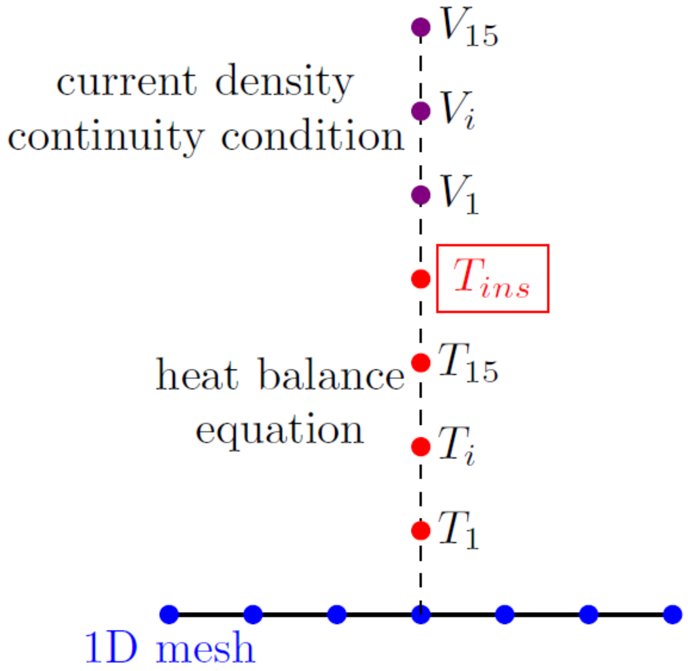
$$\rho\, C_p(T_i(x,t))\, \frac{\partial T_i(x,t)}{\partial t} - \frac{\partial}{\partial x}\left(k(T_i)\, \frac{\partial T_i(x,t)}{\partial x}\right) = \sigma_i\left(T_i(x,t), E_i(x,t)\right)\left(\frac{\partial V_i(x,t)}{\partial x}\right)^2 + \boxed{\sum_j^{N_t} Q^J_{i,j}(x,t)} + \boxed{\sum_j^{N_t} Q^c_{i,j}(x,t)} + \boxed{Q^h_i(x,t)} + Q^{\mathrm{out}}_i(x,t) + Q^{\mathrm{in}}_i(x,t)$$

Joule power of current between tapes in contact

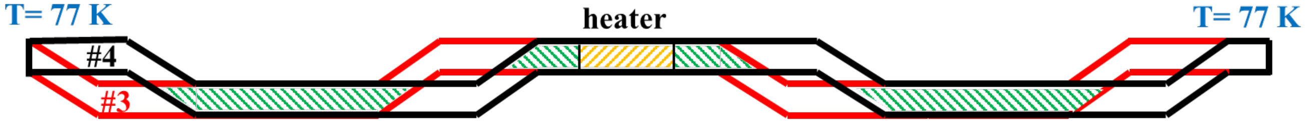
thermal conduction between the *i*-th and *j*-th tapes in contact

heater thermal disturbance

***i* = 1, …, N_t+1**

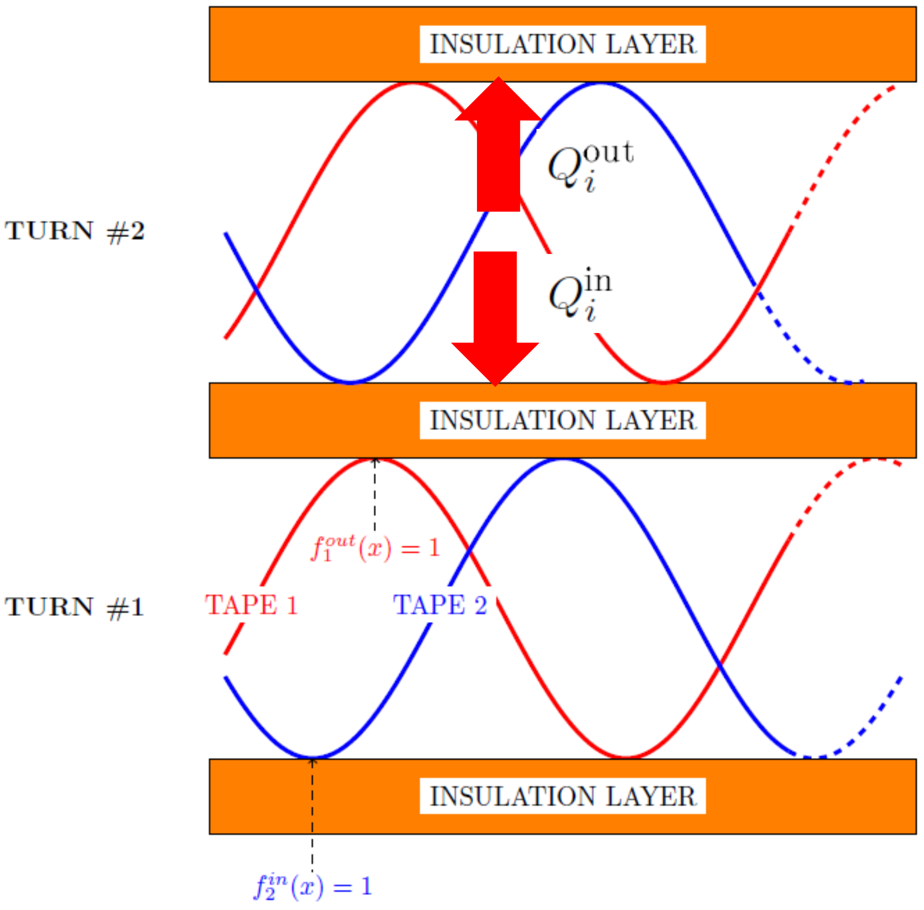


- The **thermal contact between turns** is described through the heat fluxes **Q_i^{in}** and **Q_i^{out}** towards the insulation located towards the inner part of the coil and the outer one respectively.
- As **boundary conditions**: **fixed temperature** of **77 K** at the terminals of the cable



THE REBCO ROEBEL COIL: Thermal Model

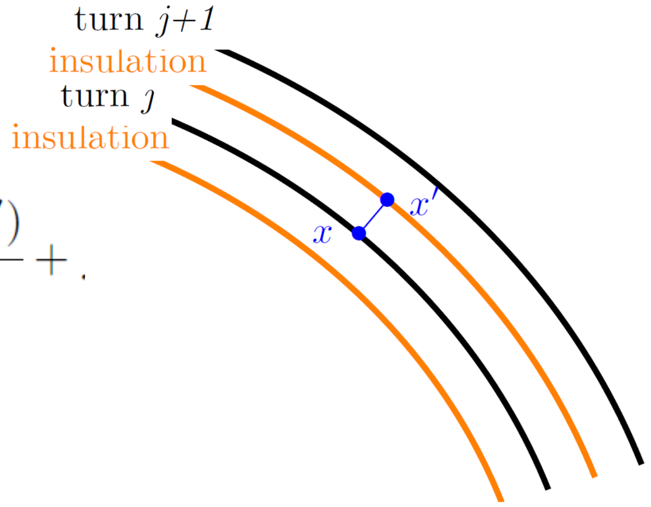
THERMAL CONTACT BETWEEN TURNS



- The f_i^{out} and f_i^{in} functions describe the contact between the considered tape and the insultation towards the outer and inner turns respectively.

$$f_i^{out} = \begin{cases} 1 & \text{contact with the insulation} \\ 0 & \text{no contact with the insulation} \end{cases}$$

- For the ***i*-th** tape, the **heat exchange** with the insulation layer is computed at the **contact positions *x* and *x'***.



$$Q_i^{\text{out}}(x) + Q_i^{\text{in}}(x) = f_i^{\text{out}}(x)\,\frac{T_i(x) - T_{ins}(x')}{R_{th}^{c-ins}\,t} + \, . \\ + f_i^{\text{in}}(x)\,\frac{T_i(x) - T_{ins}(x')}{R_{th}^{c-ins}\,t}$$

where

$R_{th}^{c-ins} = 0.005\,\frac{\mathrm{m^2\,K}}{\mathrm{W}}$ determined considering the thickness of the fiber glass layer

t tape thickness

THE REBCO ROEBEL COIL: Thermal Model

LIQUID NITROGEN COOLING BATH

- The liquid nitrogen bath is modeled as

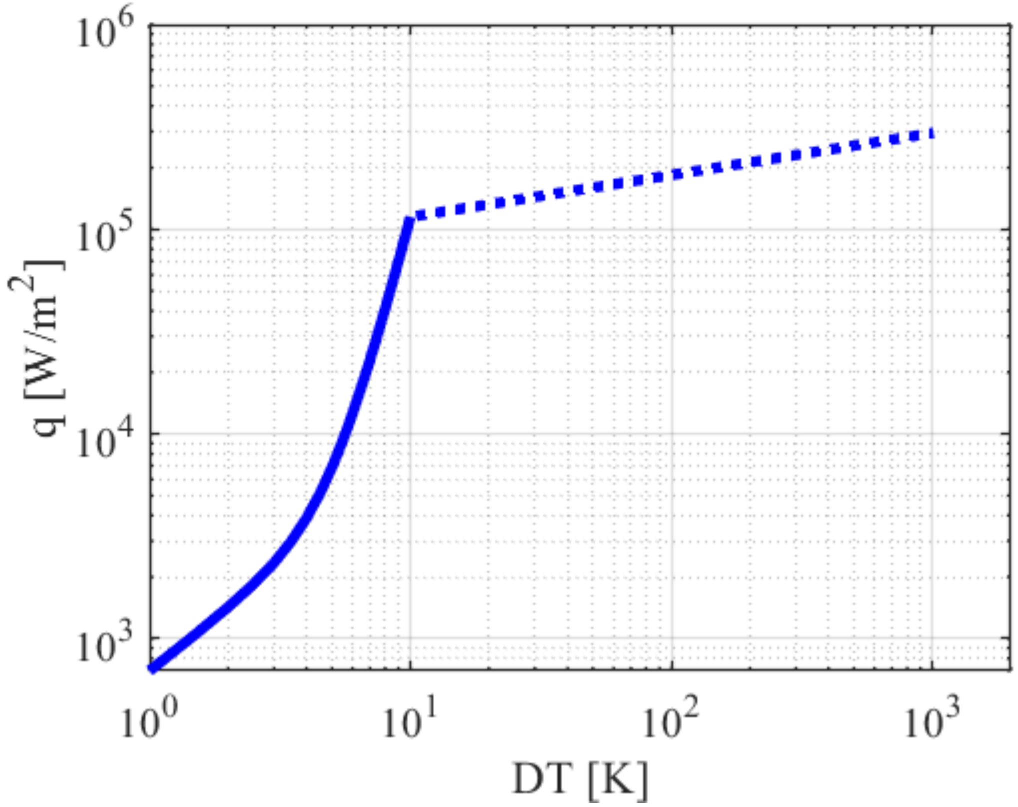
$$Q_i^{LN}(\xi,t) = \frac{h\,(T_i(\xi,t)-T_0)\,(T_i(\xi,t)-T_0)}{w}$$

where T_0 is set at 77 K and w is the tape width.

- The **nucleate boiling** contribution is supposed dominant and is implemented as

$$h(\Delta T_i) = a + b\Delta T_i^4 \qquad \text{nucleate boiling}$$

where $a = 0.6953\frac{\mathrm{kW}}{\mathrm{m^2K}}$ and $b = 1.079\frac{\mathrm{W}}{\mathrm{m^2K^5}}$



[4] LM. Kida, Y. Kikuchi, O. Takahashi and I. Michiyoshi, «Pool-Boiling Heat Transfer in Liquid Nitrogen» *J. Nucl. Sci. Technology*, *vol.* 28, *no.* 7, *pp.* 501-503 (1981).

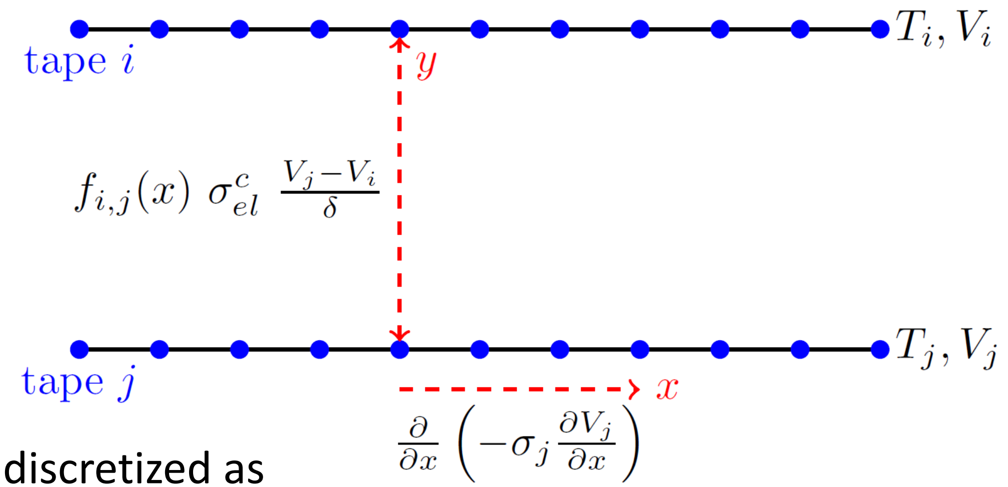
[5] M. Sumption, M. Majoros, C. Kovacs and E. W. Collings «Stability, quench and current sharing in Roebel and CORC cables for HEP magnets» presented at the 13th European Conference on Applied Superconductivity EUCAS 2017, Geneva, Swiss, Sept. 17–21, 2017.

THE REBCO ROEBEL COIL: Electrical Model

CURRENT DENSITY CONTINUITY CONDITION

- A set of equations is solved for an **array of electric potentials** representing the voltages **[V_1 … V_{Nt}]** of all tapes with respect to the **electric potential reference** located at the terminal of the cable.

$$\mathbf{V} = [V_1 \ldots V_{Nt}]$$



- The **current density continuity** condition is written for the ***i*-th** tape as

$\nabla \cdot \mathbf{J_i} = 0$ since $\mathbf{J_i} = -\sigma_i \nabla V_i$

$$\frac{\partial}{\partial x}\left(-\sigma_i \frac{\partial V_i}{\partial x}\right) + \frac{\partial}{\partial y}\left(-\sigma_i \frac{\partial V_i}{\partial y}\right) = 0$$

In the 1D discretization, the term corresponding to the y direction can be discretized as

$$\frac{\partial}{\partial y}\left(-\sigma_i \frac{\partial V_i}{\partial y}\right) = -\sum_j f_{i,j}(x)\ \underbrace{\sigma_{el}^c}\ \frac{V_j - V_i}{\delta} \Rightarrow \boxed{\frac{\partial}{\partial x}\left(-\sigma_i\left(T_i(x,t), E_i(x,t)\right) \frac{\partial V_i(x,t)}{\partial x}\right) = \sum_j f_{i,j}(x)\ \sigma_{el}^c\ \frac{V_j(x,t) - V_i(x,t)}{\delta}}$$

the **contact conductance** between tapes is within the range presented in [1]

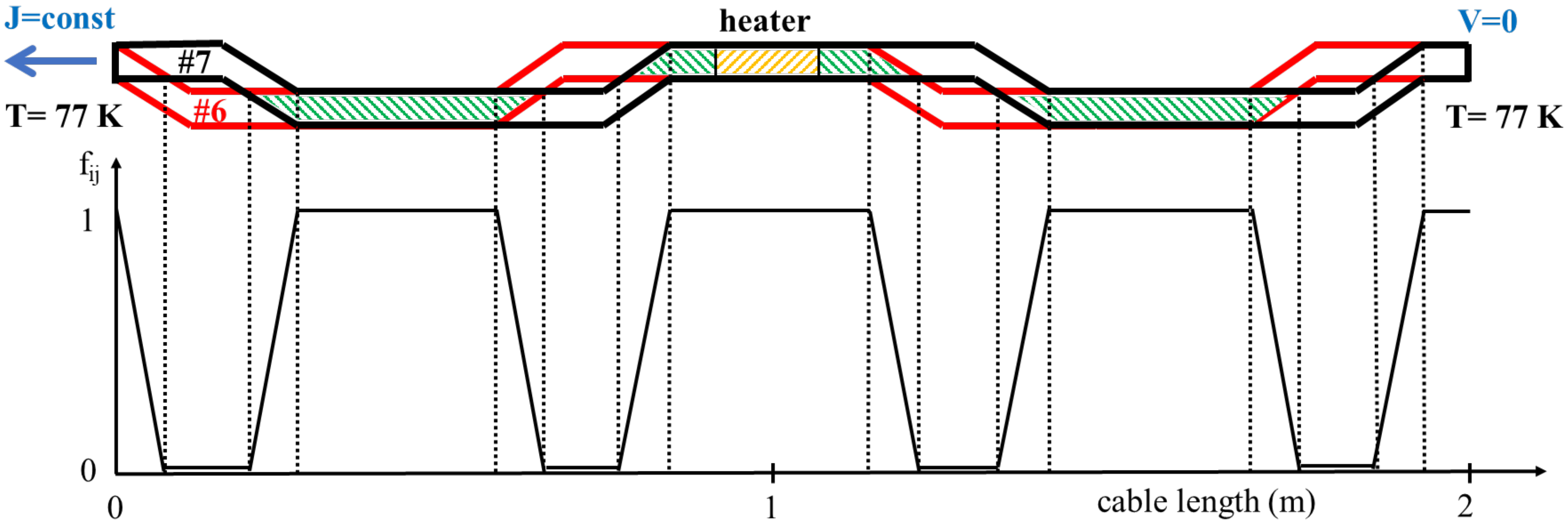
$$\sigma_{el}^c = 0.5 \times 10^8\ \frac{\mathrm{S}}{\mathrm{m}^2}$$

[1] S. Otten et al., «Inter-strand resistance in REBCO Roebel cables and effect on AC loss», presented at EUCAS 2017

THE REBCO ROEBEL COIL: Electrical Model

f_{ij} FUNCTIONS

- f_{ij} accounts for the **contact area** between the *i*-th and the *j*-th tape.
- The function is set to **1** if the two tapes overlap and to **0** if they are not in contact



BOUNDARY CONDITIONS

- **Electric Potential** at the reference terminal of the cable

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

- The **current** is set **uniform** on each tape at the other terminal
- The **current** at the terminal x = 0 is imposed according to the **joint resistance** determined by experimental data.

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

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

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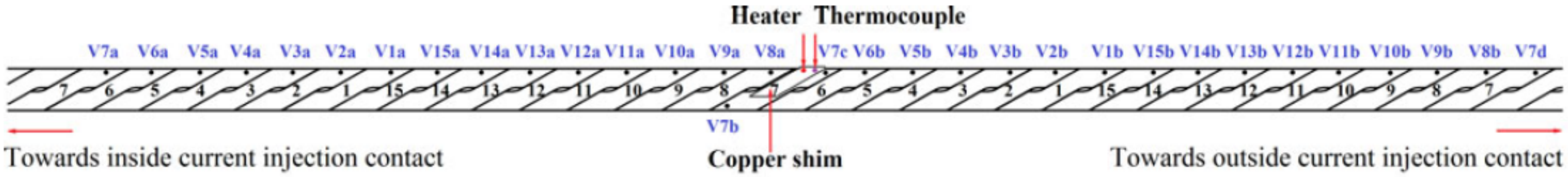
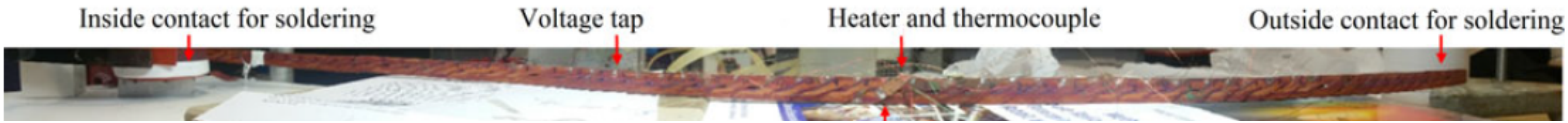
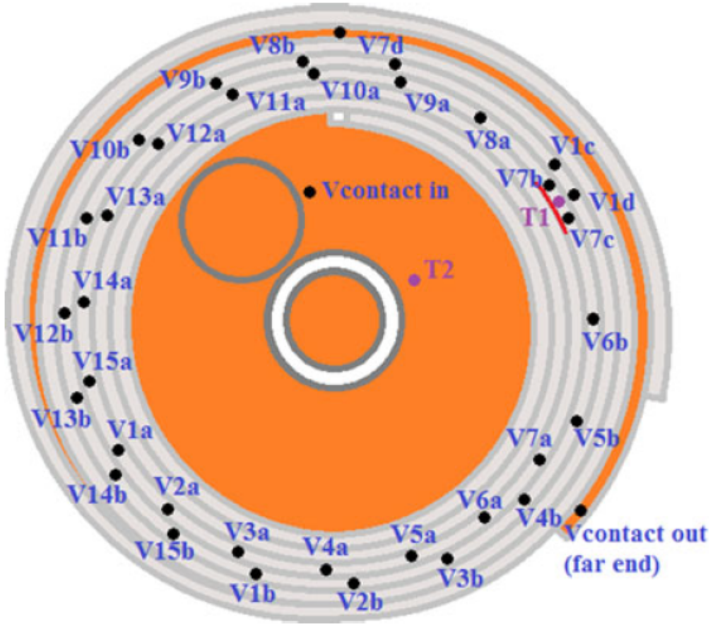




- Two voltage taps (**V7b** and **V7c**) were soldered on the tape at either side of the transposition section enclosing the heater.
- A further pair of taps (**V7a** and **V7d**) were soldered one pitch length away from V7b and V7c towards the inner and outer contacts.
- For each of the remaining strands, a voltage-tap pair (**Vna** and **Vnb**, n = 1 ... 15) separated by one pitch length was soldered on either side of the heater.

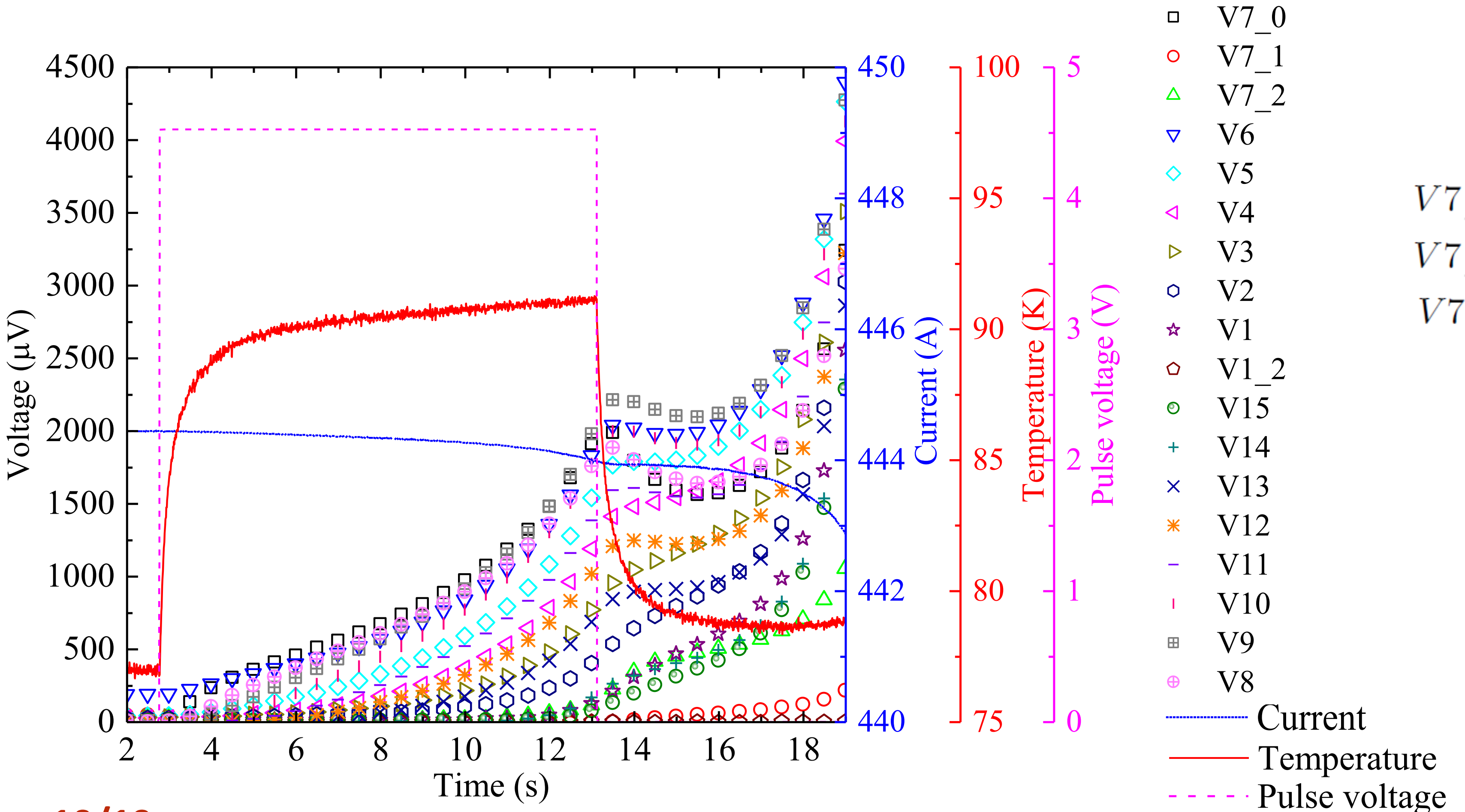
$$Vn = Vna - Vnb \qquad \forall n = 1 \cdots 15$$

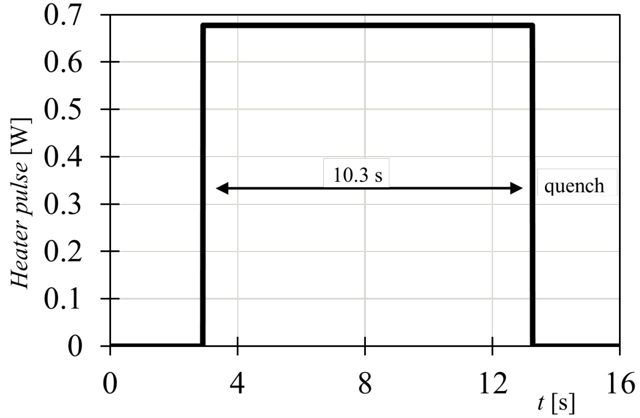


[3] Q. Zhang, *et. al*. «Performance and Quench Characteristics of a Pancake Coil Wound With the 2G YBCO Roebel Cable,» *IEEE Trans. Appl. Supercond., vol. 28, no. 4, Jun. 2018.*

THE REBCO ROEBEL COIL: Voltage Measurements

- The voltage signals measured during quench show the differences between the various tapes



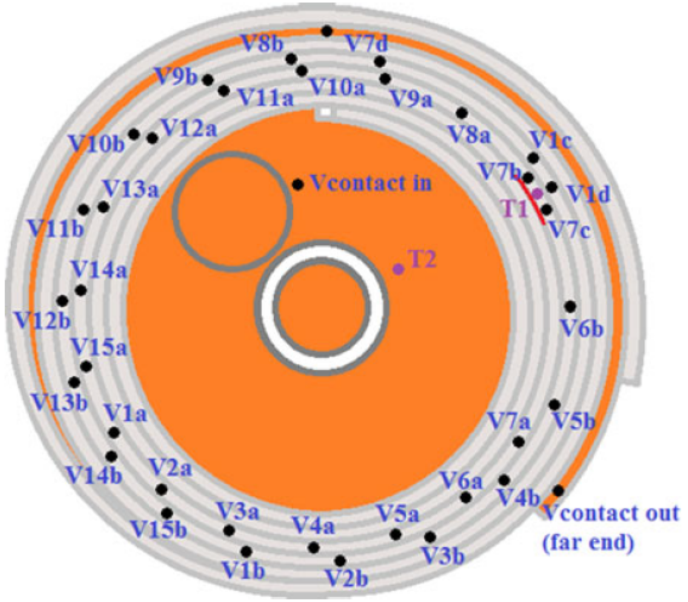


$$V7\_1 = V7a - V7b$$

$$V7\_2 = V7c - V7d$$

$$V7\_0 = V7b - V7c$$

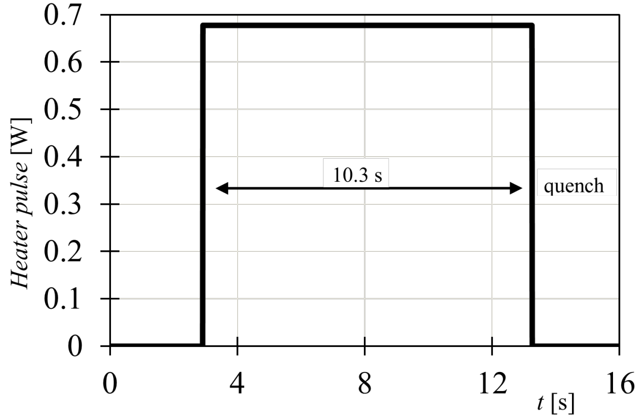
$$Vn = Vna - Vnb$$



THE REBCO ROEBEL COIL: Voltage Measurements

QUENCH CASE

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



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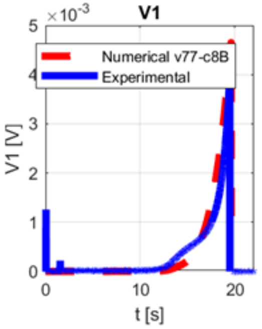
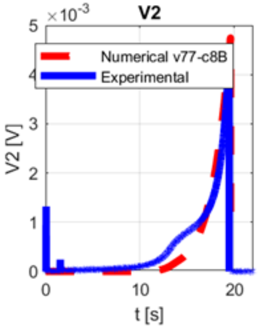
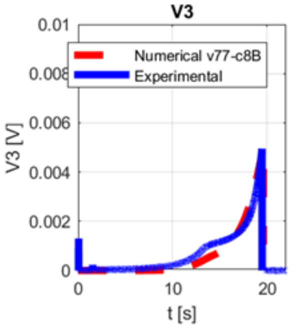
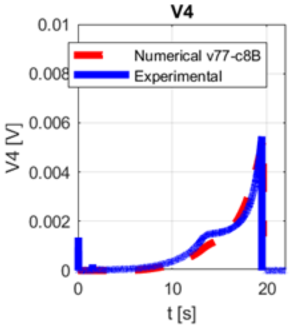
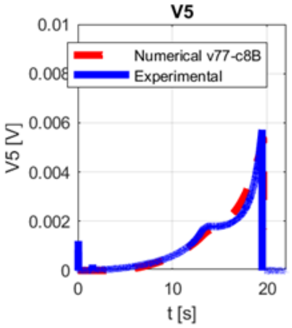
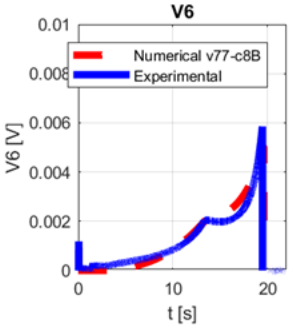


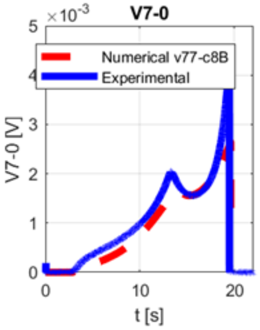


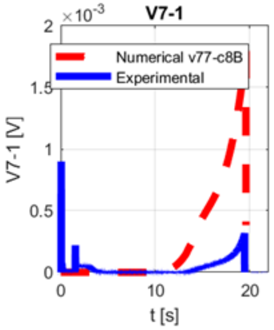


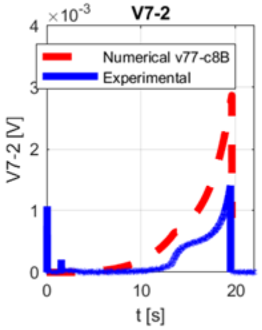


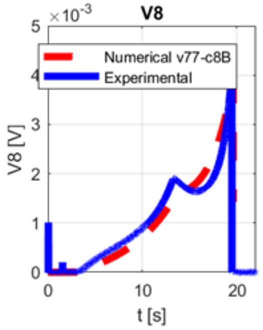


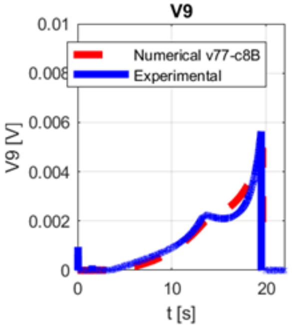


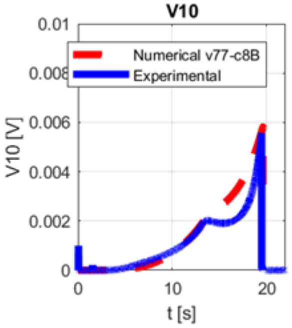


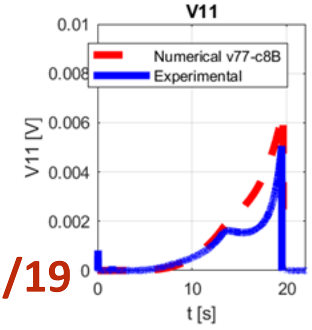


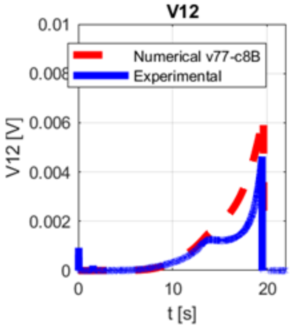


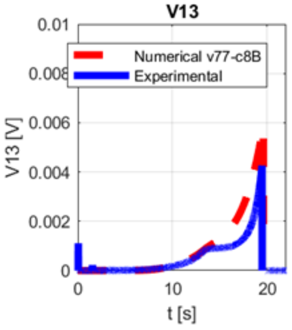


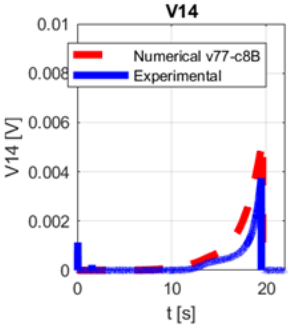


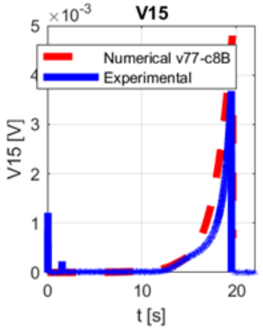


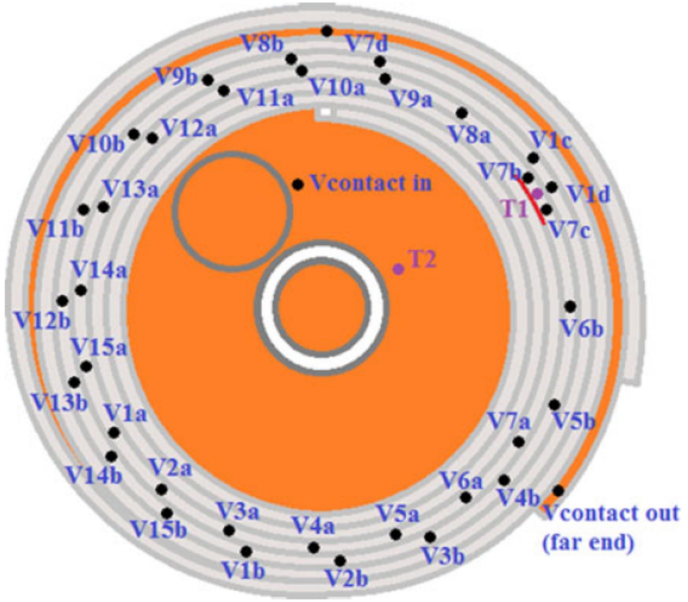








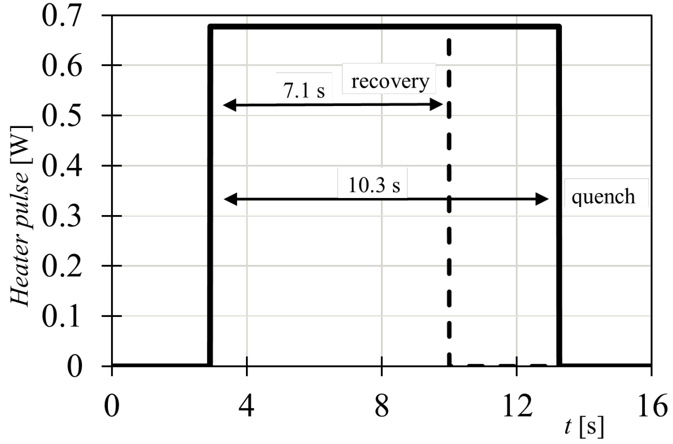




THE REBCO ROEBEL COIL: Recovery Case

RECOVERY CASE

- The heat pulse duration was reduced (with the same power), obtaining a recovery. The computed **QE** is about **15-20 %** less than the measured value.



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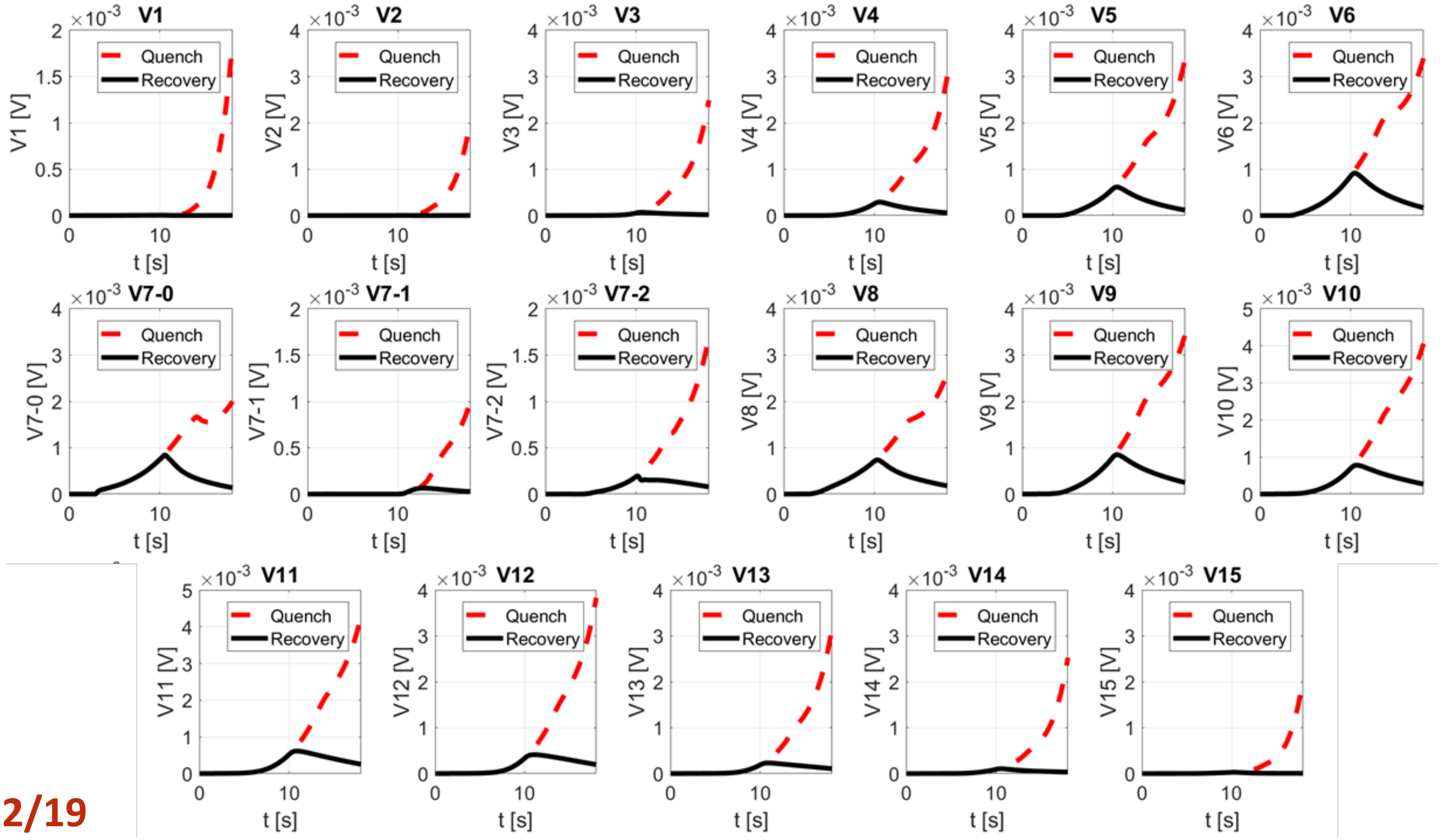
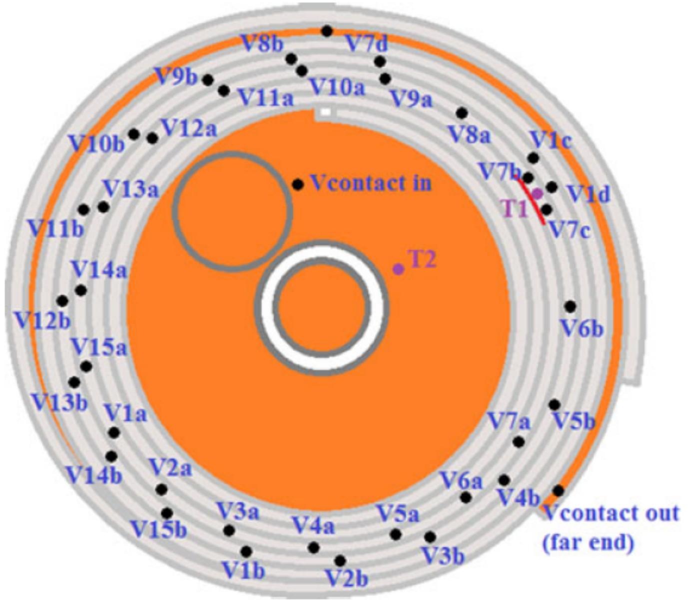
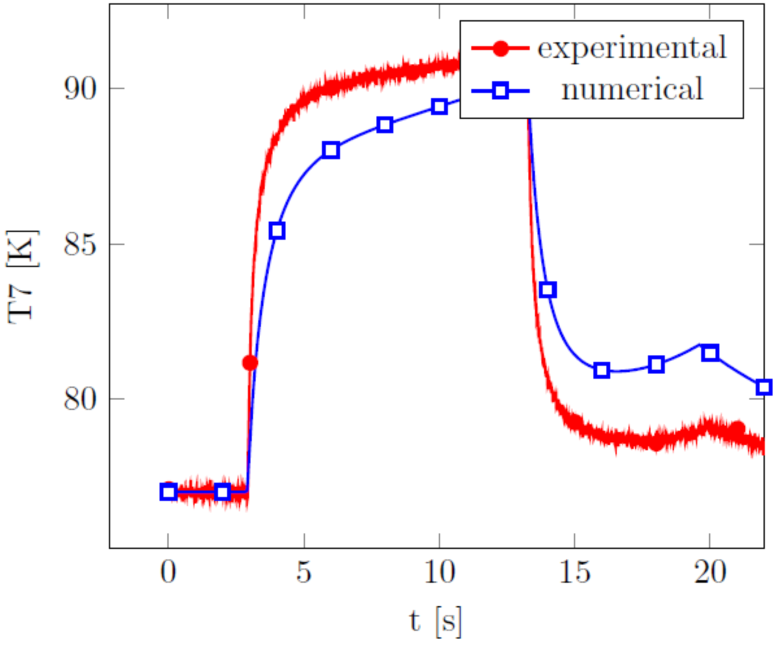


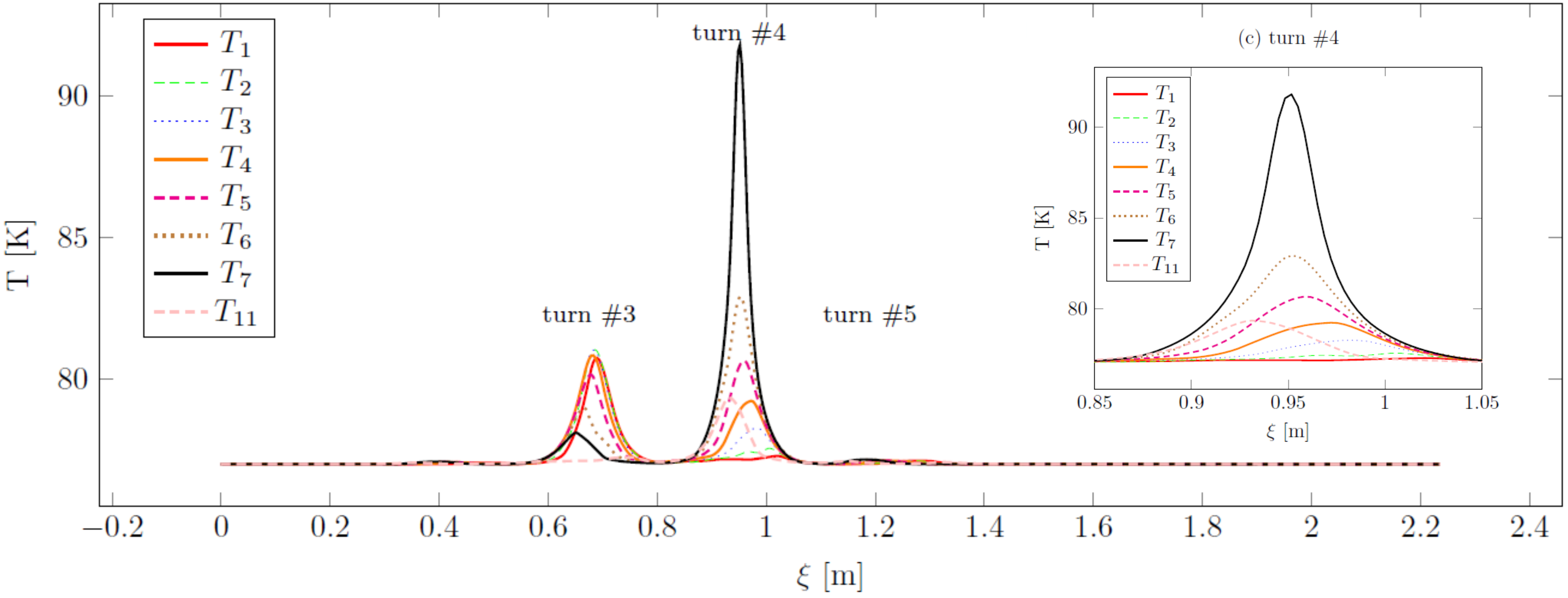


THE REBCO ROEBEL COIL: Temperature Distribution

QUENCH CASE

- A thermocouple located on the **heater** measures the temperature during the heater pulse.
- The **temperature distribution** of the tapes at the **end of the heater pulse** shows the redistribution inside the cable and between the various turns of the coil.

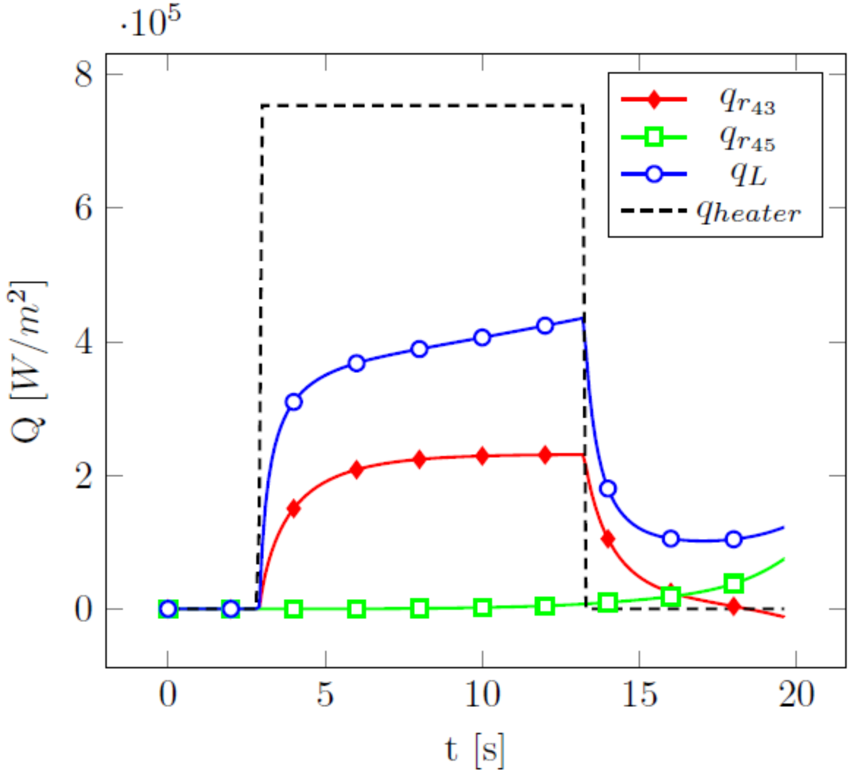




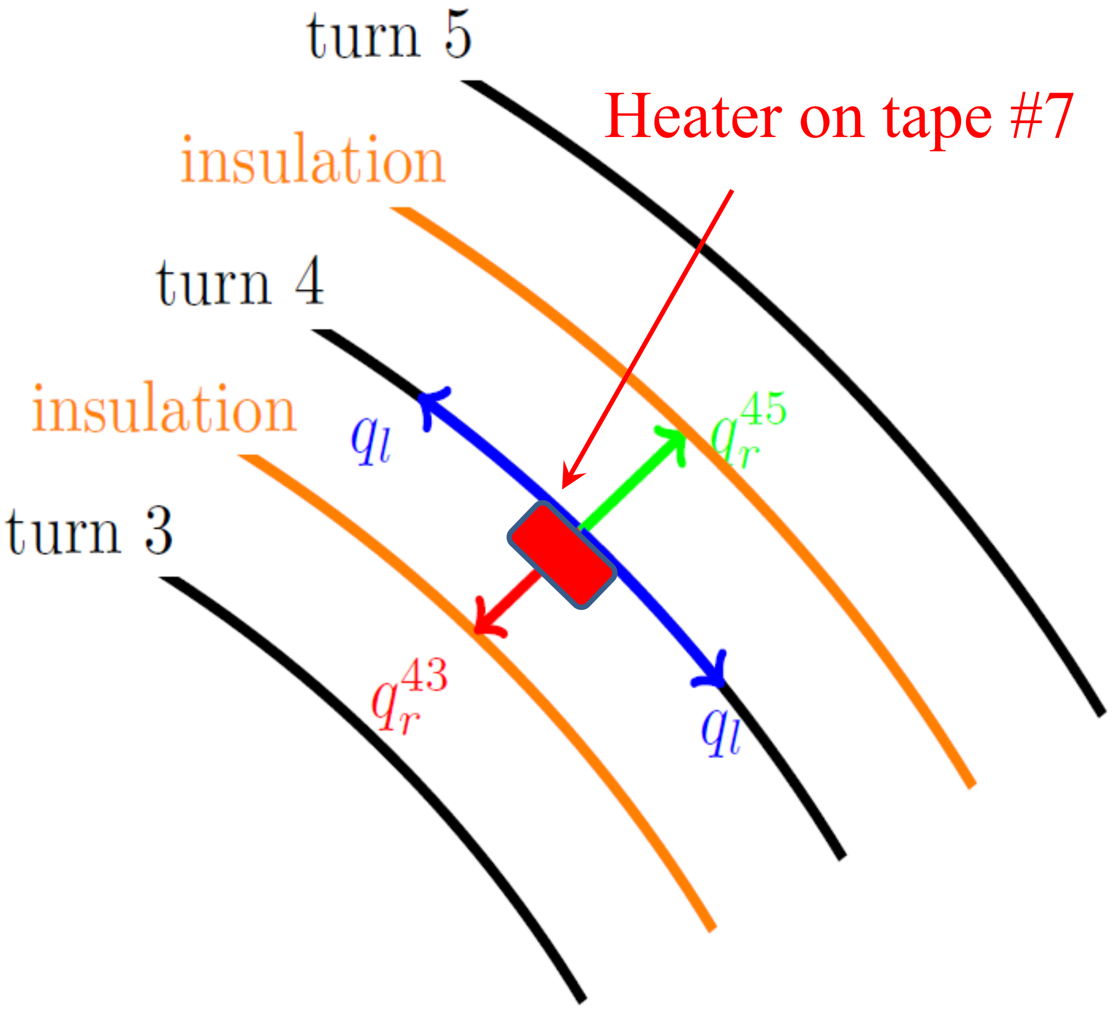
THE REBCO ROEBEL COIL: Radial and Longitudinal Heat Flux

QUENCH CASE

- The **heat flux of the cable** in the **longitudinal** and **radial directions** is computed at the **heater location**.
- The heat flux in the longitudinal direction is greater than the heat flux in radial direction, which is however significant.


HEAT FLUX

IN THE LONGITUDINAL AND RADIAL DIRECTION

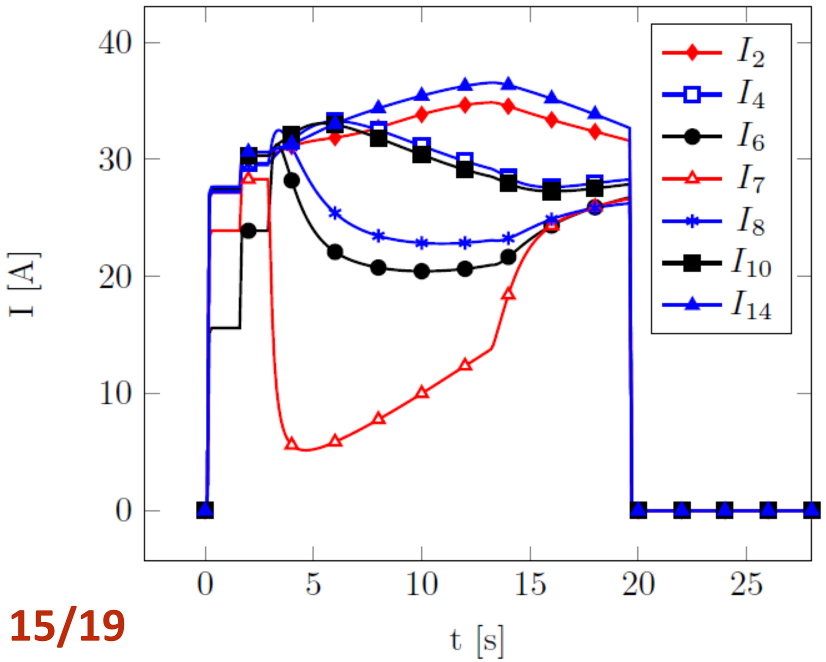


THE REBCO ROEBEL COIL: Current Distribution between Strands

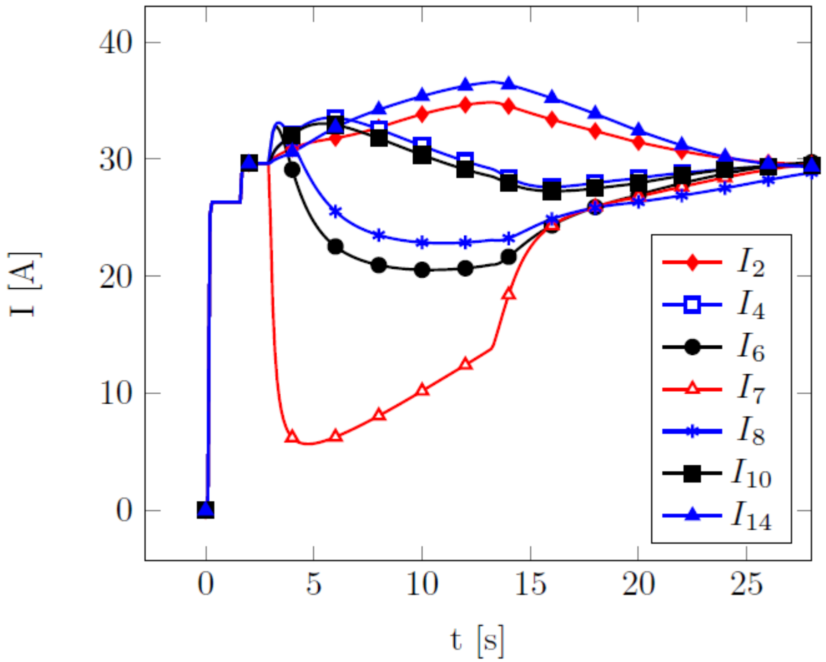
QUENCH CASE

- The current density at the heater location on the strands #2, #4, #6, #7, #8, #10 and #14 is shown for two cases:
- CASE #1
  a) as boundary condition, **different current entering** the strands at the terminal due to different **terminal joint resistance**;
  b) **current cut-off** at t = 20 s
- CASE #2:
  a) as boundary condition, the **same current inletting** the strands at the terminal;
  b) **no current cut-off**.

CASE #1



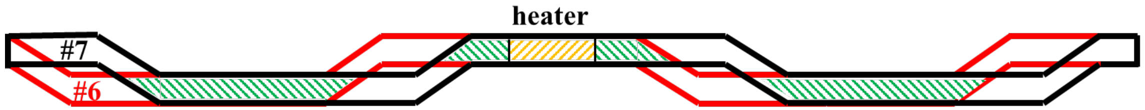
CASE #2

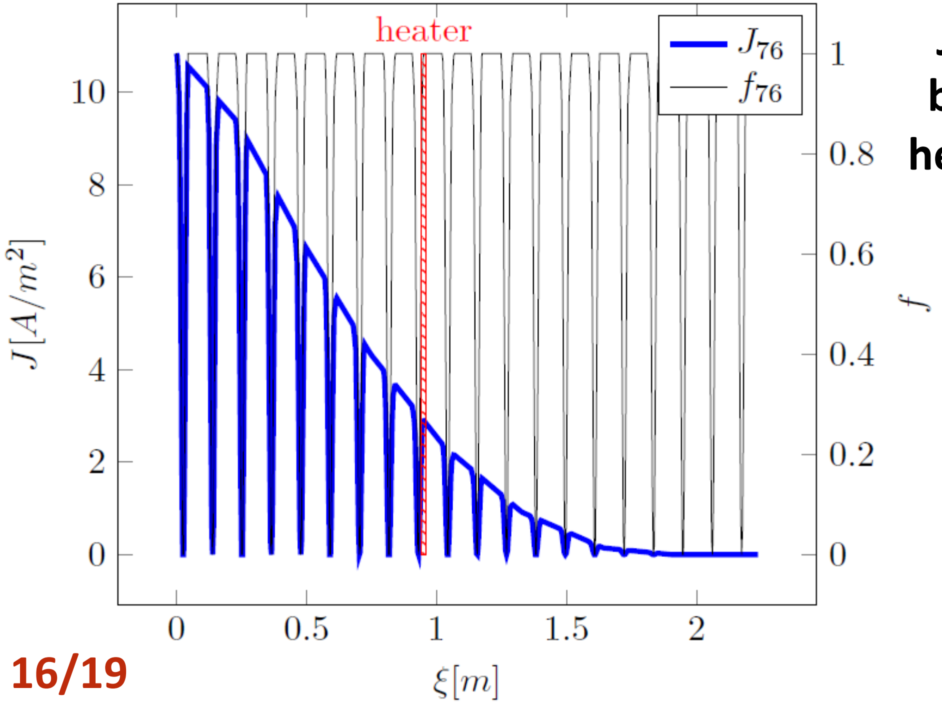


- The boundary conditions have no remarkable impact on the current redistribution.
- CASE #2 shows that the **current distribution time** is about **10 s – 15 s**.

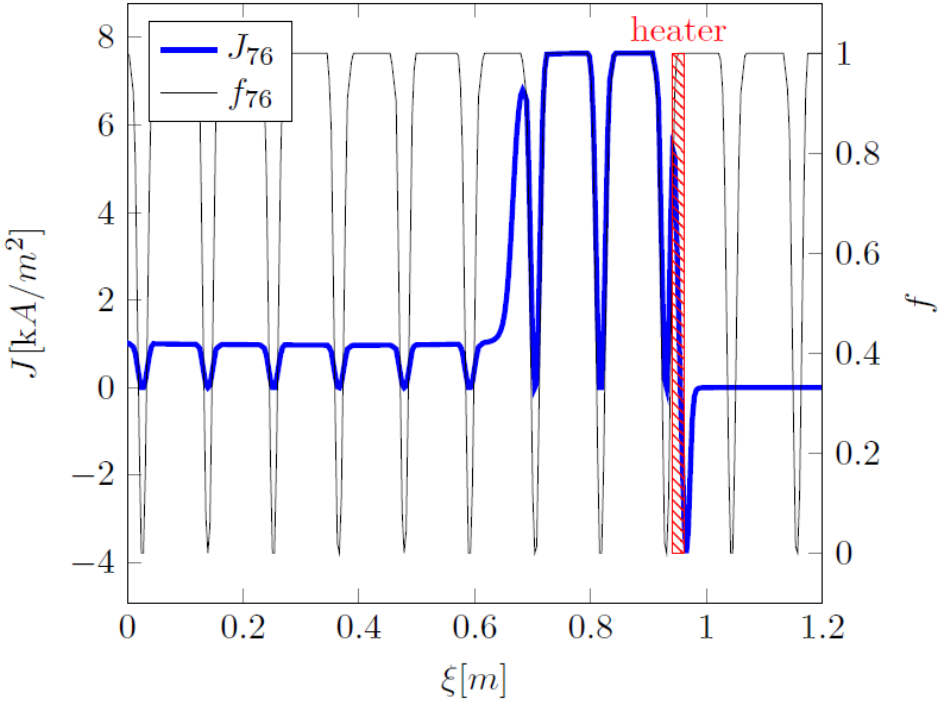
THE REBCO ROEBEL COIL: Current Distribution between Strands

- The **current density J_{76}** between strands #7 and #6 as a function of the position is shown before and during the heater pulse
- J_{76} is **null** if the **strands #7** and **#6** are **not in contact** and has a maximum if the strands overlap.
- The **terminal joint resistances** at the terminal x = 0 impose **different currents on the strands** at the boundaries. This affects the **current redistribution along the whole coil length**.
- The current redistribution due to the terminal joint resistance of about 0.01 kA/m^2 is **negligible** with respect to the redistribution during the heater pulse between -4.0 kA/m^2 and 8.0 kA/m^2





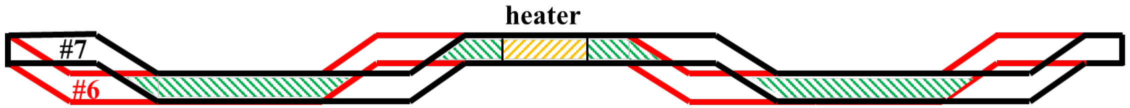
J_{76} -*vs*- f_{76}
before the
heater pulse
***t* = 1.0 s**



J_{76} -*vs*- f_{76}
during the
heater pulse
***t* = 10.0 s**

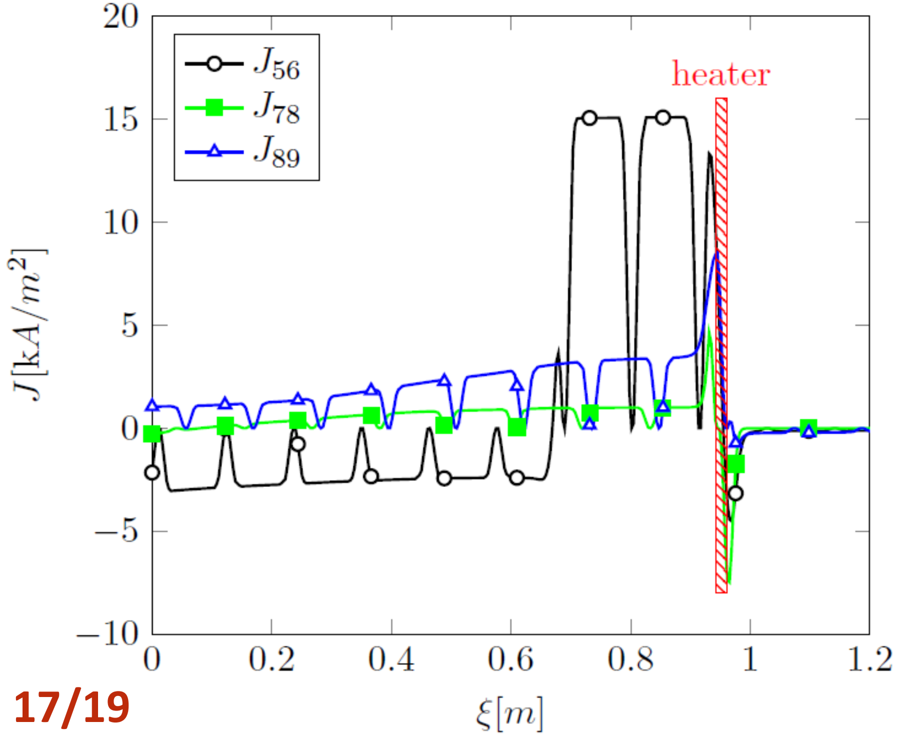
THE REBCO ROEBEL COIL: Current Distribution between Strands

- The transverse currents between strands #5 and #6, #7 and #8. #8 and #9 are compared here.
- Between **0.0 m** and **0.7 m**, the current distribution is due to the **terminal joint resistance**.

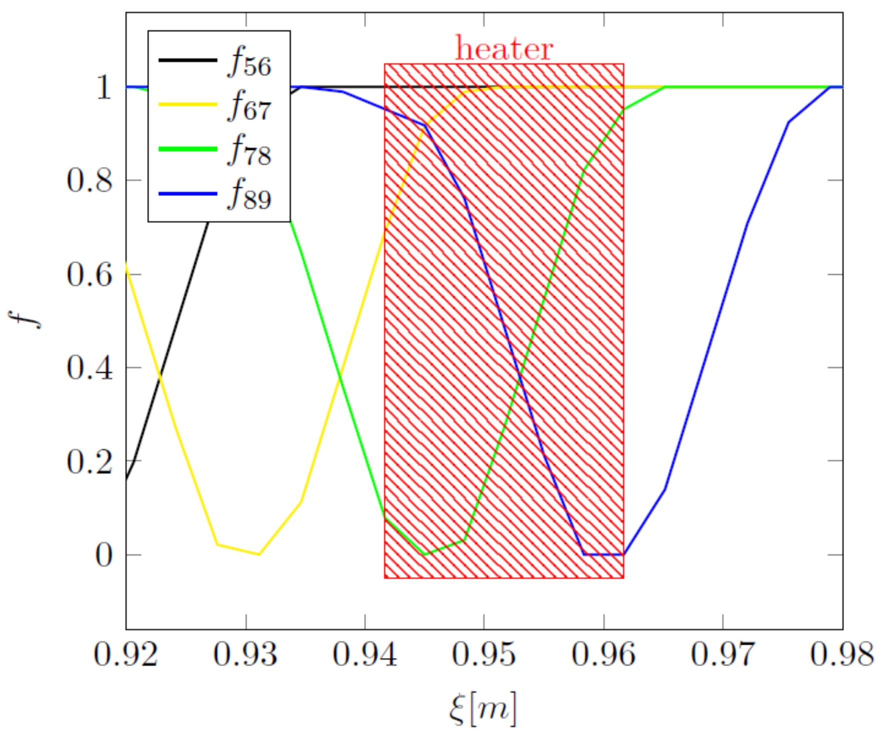


- Between **0.7 m** and **1.0 m**, the transverse currents are higher and are due to the **heater disturbance** around 1.0 m.
- The current density J_{56} is higher than J_{78} although the strands #7 and #5 are not directly in contact.

J_{56} , J_{78} and J_{89} at *t* = 10.0 s



Contact Function *f*

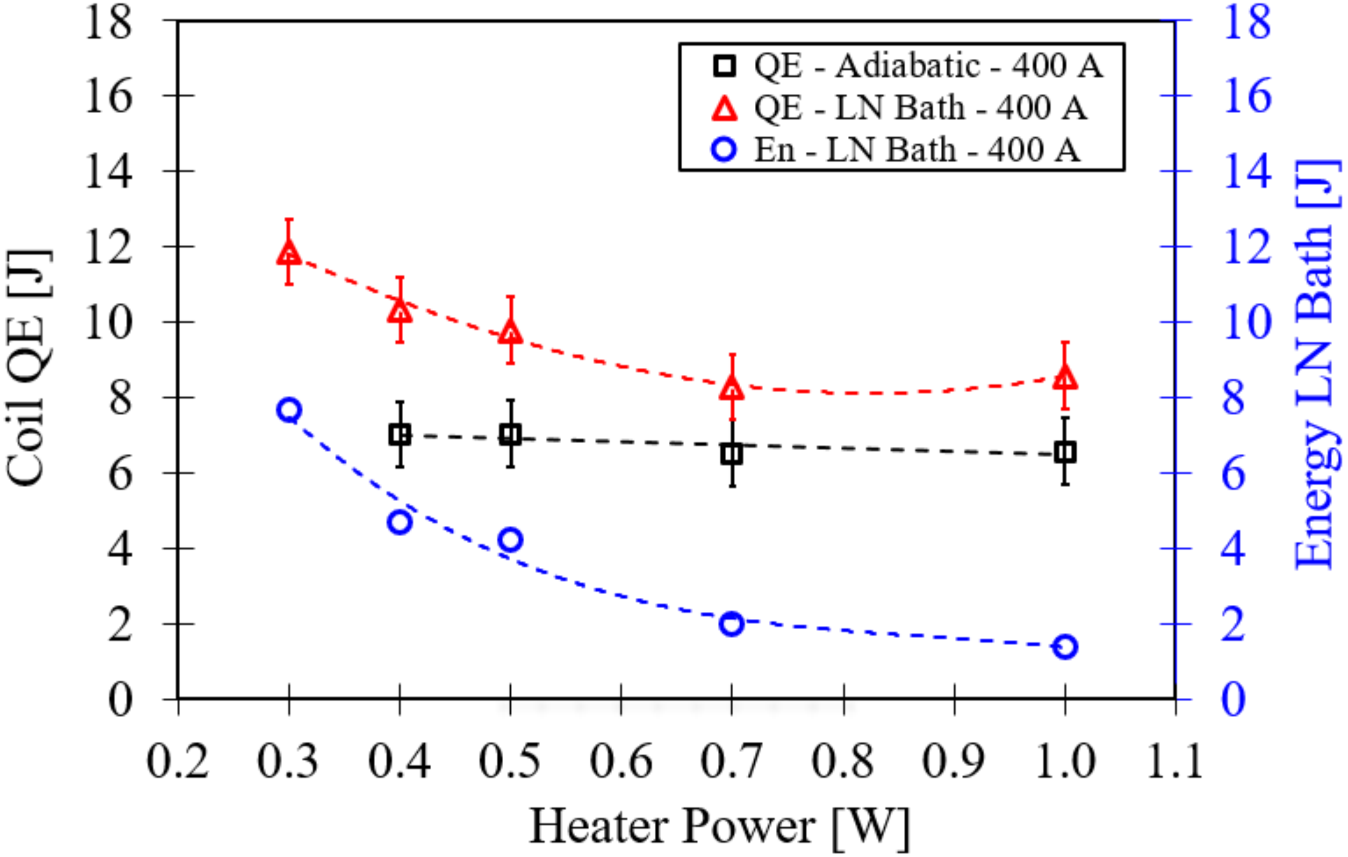


- The strands #6-#7 and #6-#5 overlap at the heater location.
- The strands #7-#8 are not in contact at the heater location.
- The heat flux from the heater can reach strand #5 more easily than strand #8.

THE REBCO ROEBEL COIL: Impact of Heater Pulse on QE

- If the coil is supposed **adiabatic**, the QE remains stable at around **7 J.**
- If the **liquid nitrogen bath** is introduced, the QE tends to increase from 7 J for the 1 W case to 12.6 J for 0.3 W case.
- At 1 W heater power, only 1.4 J out of 7 J introduced by the heater are removed by the LN bath.
- At 0.3 W heater power, 40 % of the energy of the heater is removed by the LN bath (7.7 J out of 11.9 J).
- At **low heater power, the LN bath has more impact on the cooling of the coil**. Longer heater pulses allow greater amounts of energy to be removed by the bath.

Numerical Results
Adiabatic -*vs*- NON-Adiabatic



OUTLINE

INTRODUCTION

ROEBEL COIL Model

- Experimental Setup Description

- Model Description
  - Thermal Model
  - Electrical Model

- Validation and Results
  - Voltage Measurements
  - Temperature Distribution
  - Current Distribution
  - Impact of Heater Pulse on QE

CONCLUSIONS

CONCLUSIONS

- An electro-thermal model for the analysis of quench in Roebel cable is applied to study a **7 turns pancake** wound with of a **2 m long** cable made of **15 strands.**
- Based on a **homogenization procedure**, and a **single 1D mesh**, the electro-thermal model is able to describe consistently the **heat** and **current redistribution** between tapes during quench.
- The computed voltages and temperatures are in good agreement with the experimental results; the heat exchange in transverse direction **across the cable** and **from turn to turn** can be described
- The current redistributes along the whole coil length due to the terminal contact resistances. The heater disturbance determines a redistribution current of about 8.0 kA/m^2 mainly located in a **0.3 m long region around the heater**.
- The impact of the heater power pulse on quench energy was analyzed. **The conduction seems the dominant mechanism in the cooling of the heated region**. At low values of the heater power, the QE of the coil increases since the liquid nitrogen bath has more impact on the cooling balance.
- Given the reduced dimensionality of this 1D (quasi-2D) approach, **the computational burden is reduced relative to 2D or 3D models**, still retaining a good description of the main physical phenomena

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Thanks for your attention !

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