

Advanced 3D Electro-Thermal Modelling of a DC Superconducting Cable Exposed to Overcurrent Conditions

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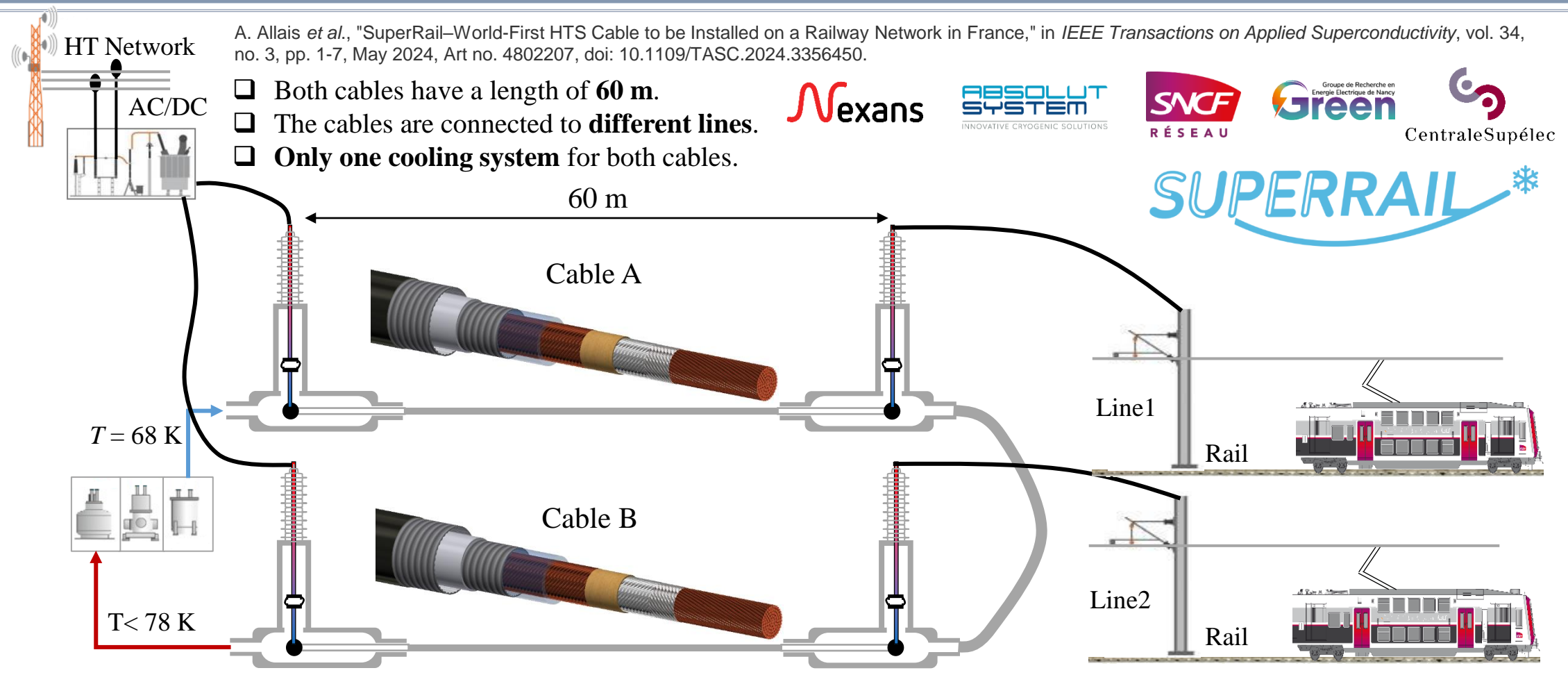
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Session ID & Title: 4Lor2A - Grid Studies with Superconducting Devices II

Presentation ID: 4Lor2A-05



SuperRail project & context



Choice of models and physics

- ❑ E - J power law

$$E(J, B, T) = E_c \left(\frac{J}{J_c(B, T)} \right)^n$$

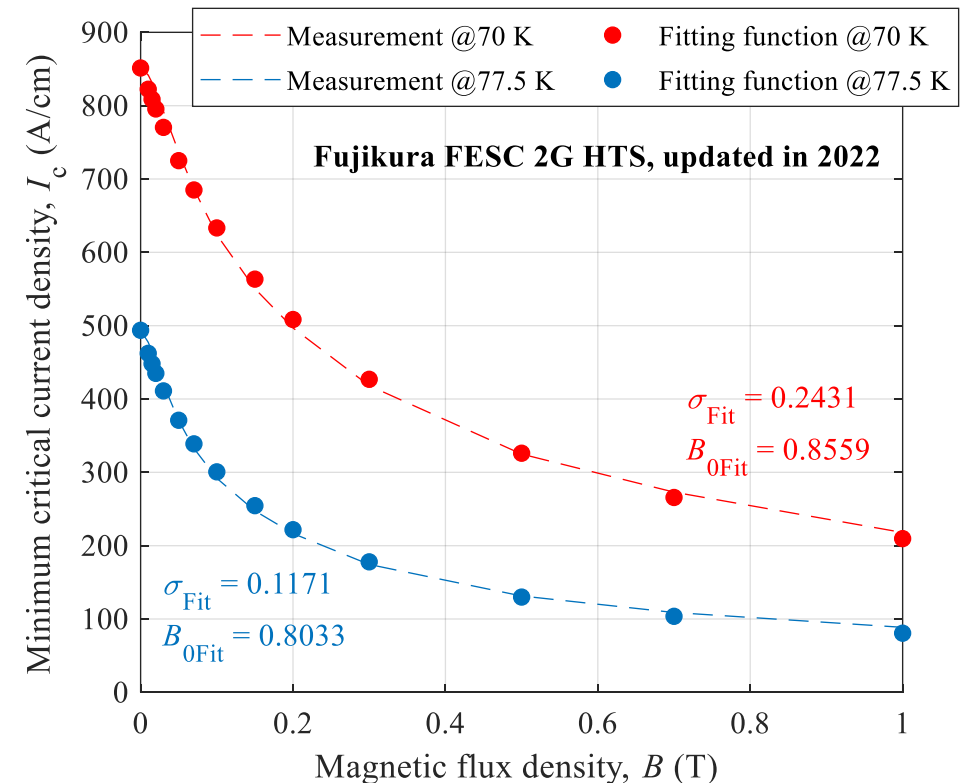
- ❑ Critical current density $J_c(B, T)$

$$J_c(B, T) = J_{c0} \frac{T_c - T}{(T_c - T_0) \left(1 + \frac{B}{B_{0Fit}} \right)^{\sigma_{Fit}}}$$

Where:

- ❑ E_c is the critical electric field
- ❑ J is the current density in the superconducting layer
- ❑ J_c is the critical current density of the tape
- ❑ n is the index of the power law $E(J)$

Need to calculate the **magnetic field** and **thermal effects**, and the **electrical circuit** of the cable that connects it to the electrical network.



Wimbush, Stuart; Strickland, Nick; Pantoja, Andres (2021). Critical current characterisation of Fujikura FESC 2G HTS superconducting wire. figshare. Dataset. <https://doi.org/10.6084/m9.figshare.15095703.v1>

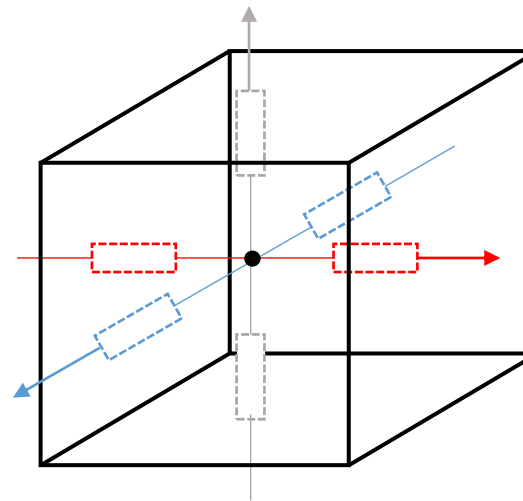
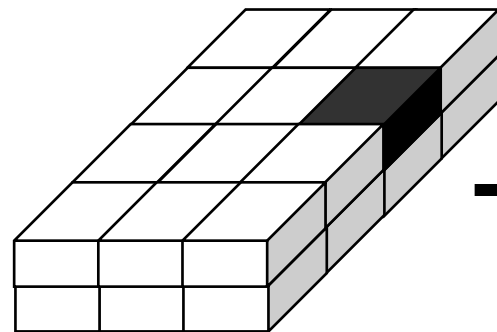
Choice of method

❑ Problem of different scales between the elements of the cable:

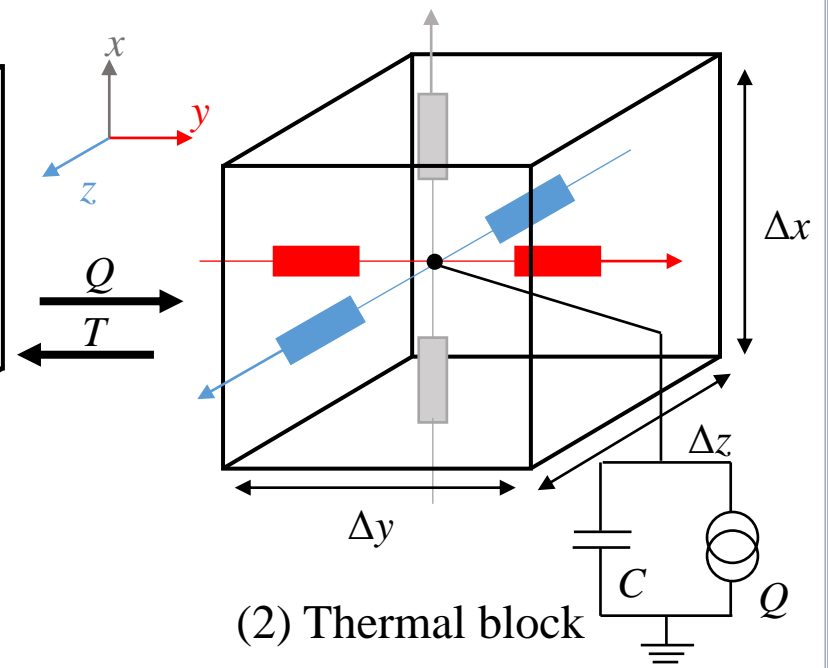
The thickness of the tape is a few **micrometers**, the width of the tape is a few **millimeters**, the radius of the cable is a few **centimeters**, and the length of the cable is a few **kilometers**.

❑ Coupling of the cable model with electrical network equations.

Modeling and discretization of cables into blocks



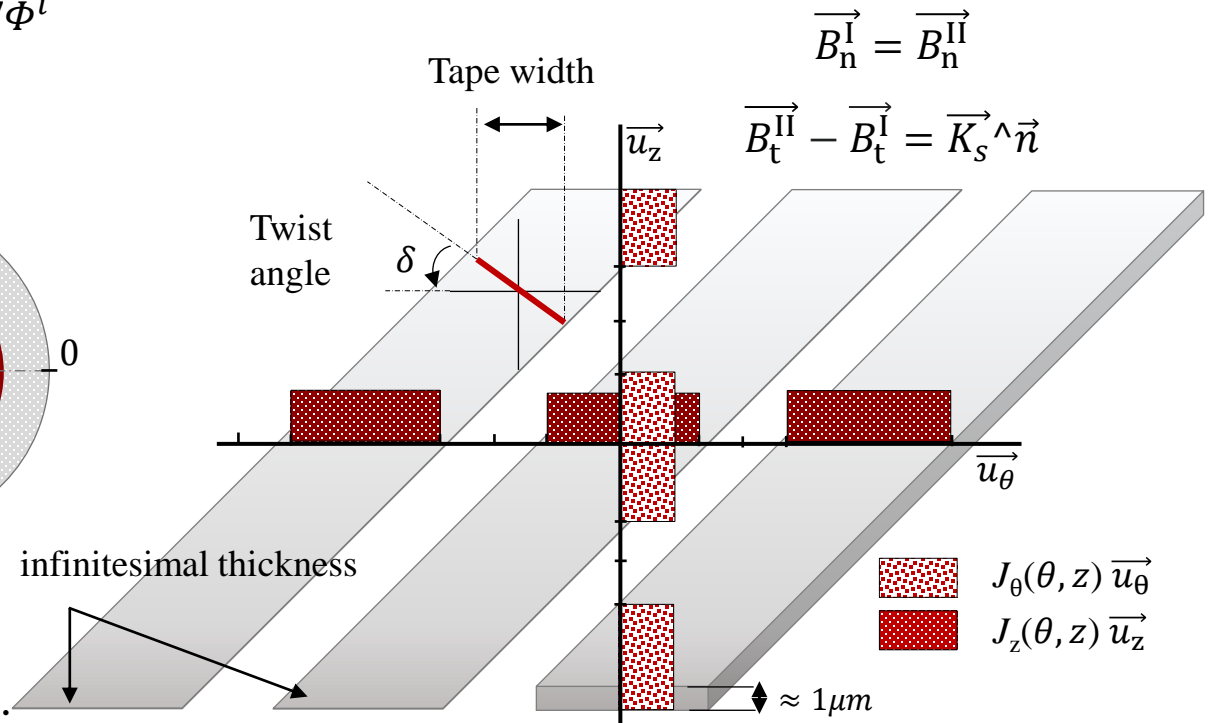
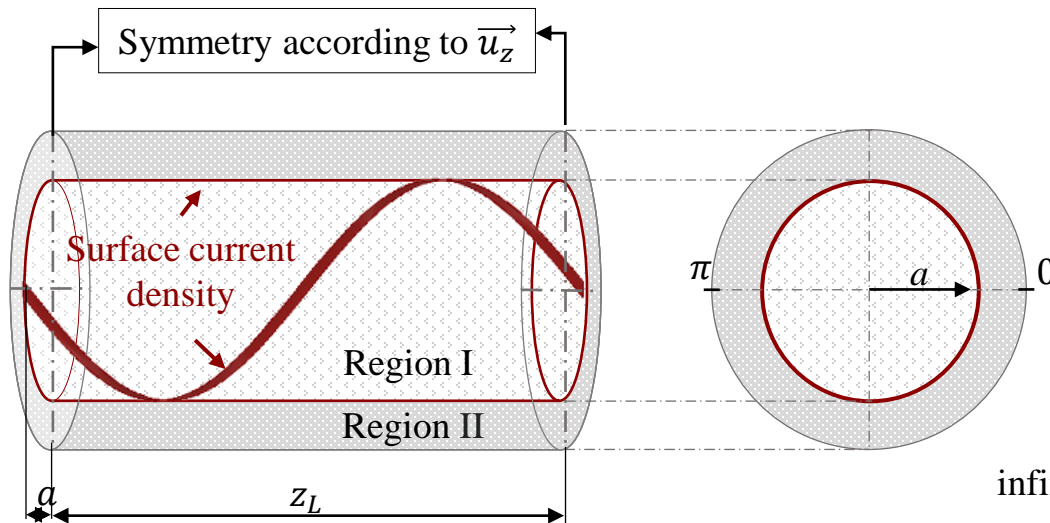
(1) Electrical block



(2) Thermal block

3D electromagnetic analytical modelling

Equations to solve: $\Delta\Phi^i = 0, (i = I \text{ or } II)$ $\vec{H}_i = -\vec{\nabla}\Phi^i$

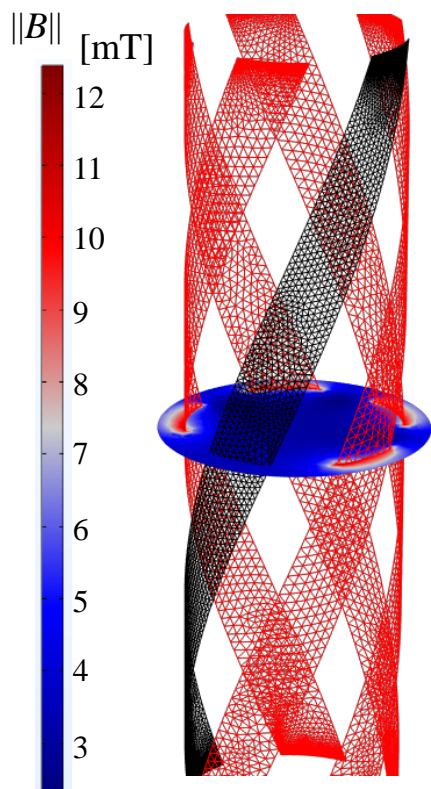


Expression of the radial magnetic field in the region I :

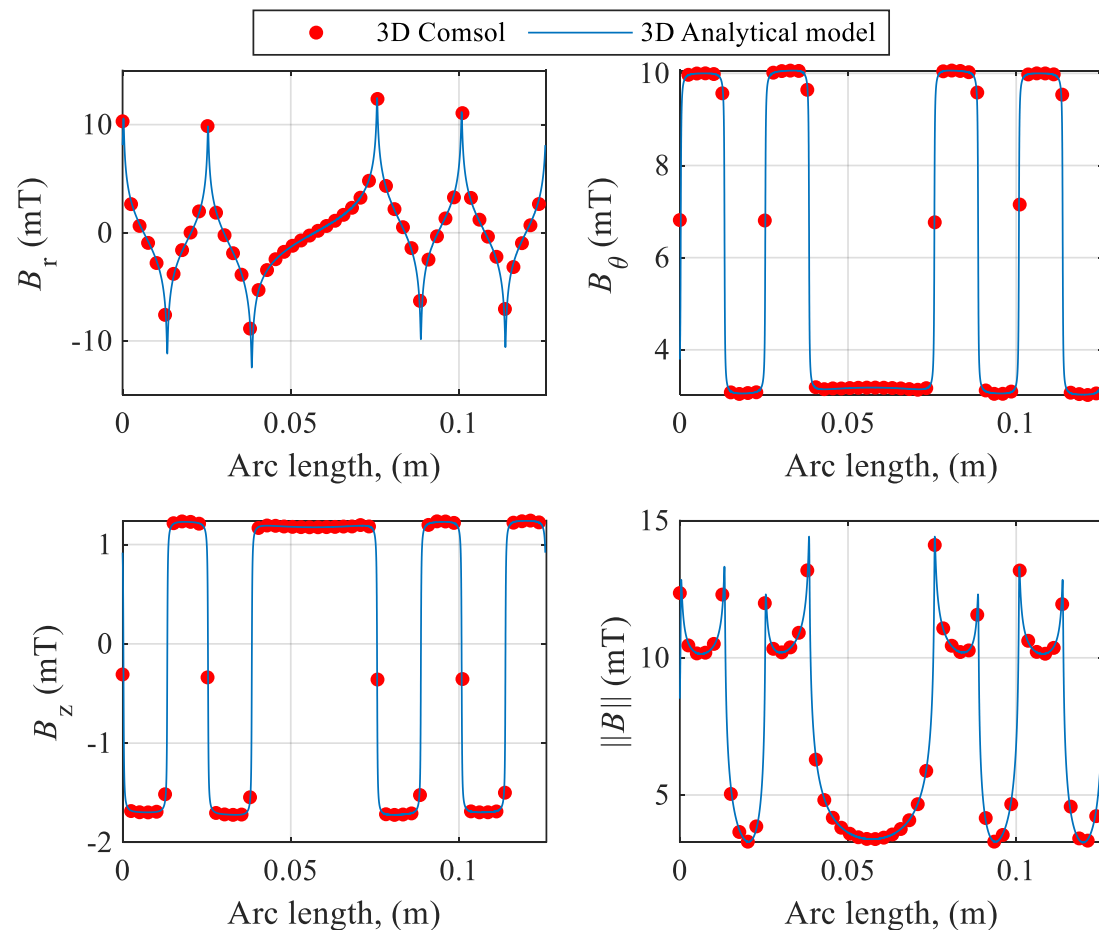
$$\vec{B}_r^I(r, \theta, z) = \frac{2\mu_0 I a^2}{\pi k^2 d} \cos(\delta) \sin\left(\frac{\alpha_z}{\beta_z} \pi k\right) K'_k(k m a) I'_k(k m r) \sin\left(k((\theta - \varphi_0) - m z)\right)$$

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3D Analytical Model vs. 3D Finite Element Model



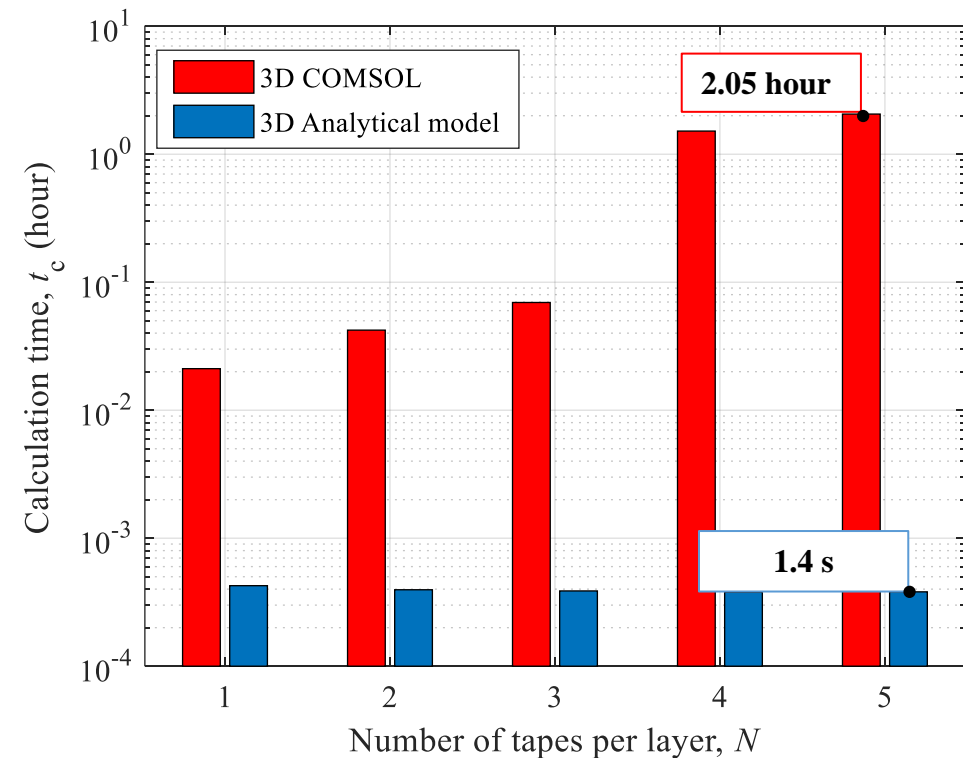
Tape disabled (No Current), $I = 0$
 Tape activated, $I = 150$ A



3D Analytical Model vs. 3D Finite Element Model

- ❑ Error less than **1%** between the **analytical model** and the finite element model in **COMSOL** used as reference.
- ❑ Computation time: the analytical model is **much faster** than COMSOL.

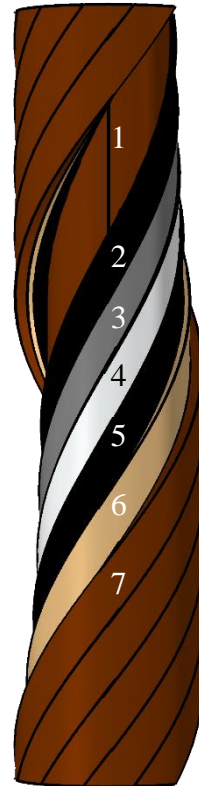
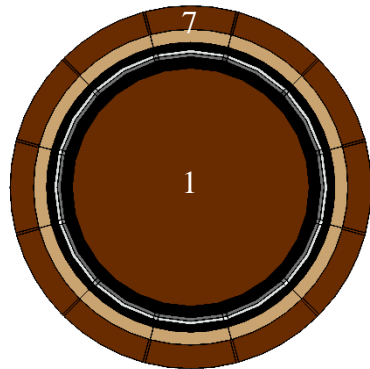
A simulation of a **5-tapes** cable takes **2 hours**. Cables for current transport applications contain more **than twenty tapes**.



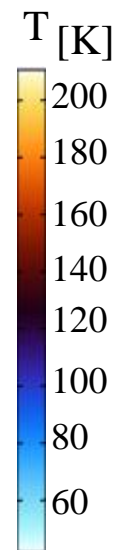
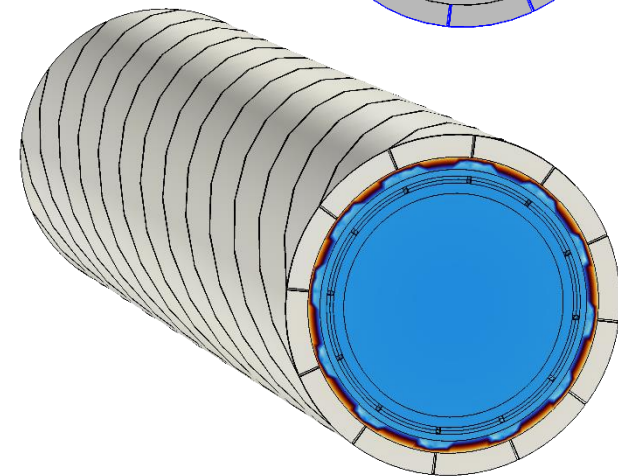
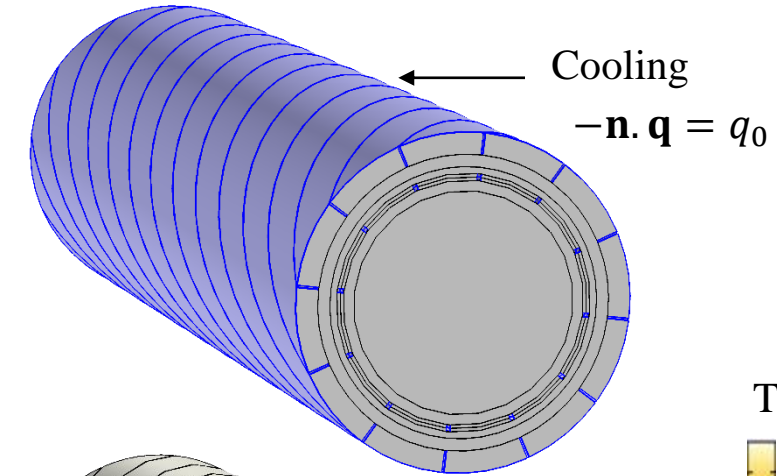
Thermal modelling

Equations to solve: $\rho C_p \frac{dT}{dt} = P + \text{div} (k \cdot \overrightarrow{\text{grad}T})$

Complete cable model developed using FEM in COMSOL



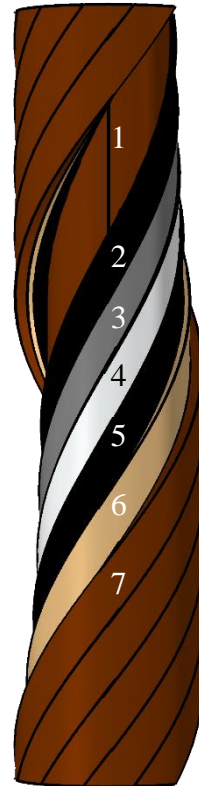
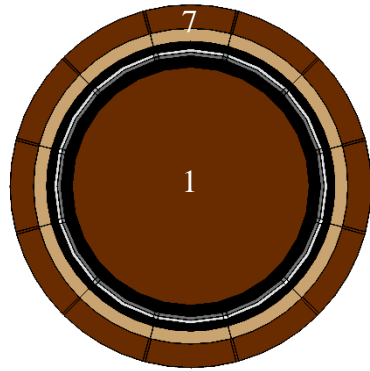
- 1 - Copper core
- 2 - Thin semiconducting layer
- 3 - Layer 1 of the superconducting tape
- 4 - Layer 2 of the superconducting tape
- 5 - Thin semiconducting layer
- 6 - Electrical insulation
- 7 - Cable screen



Thermal modelling

Equations to solve: $\rho C_p \frac{dT}{dt} = P + \text{div} (k \cdot \overrightarrow{\text{grad}T})$

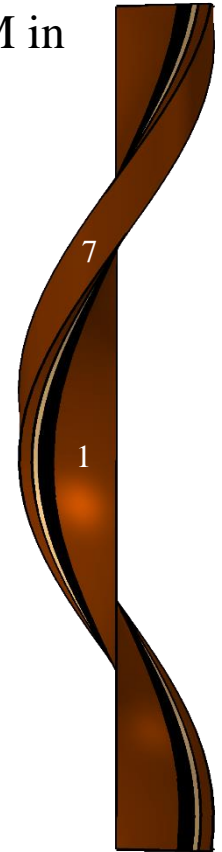
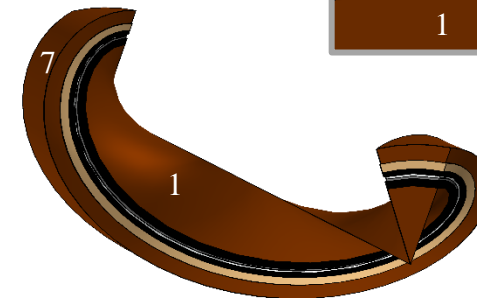
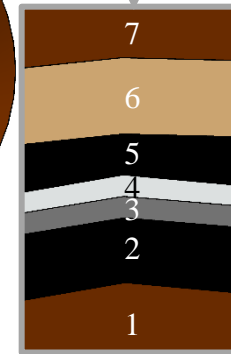
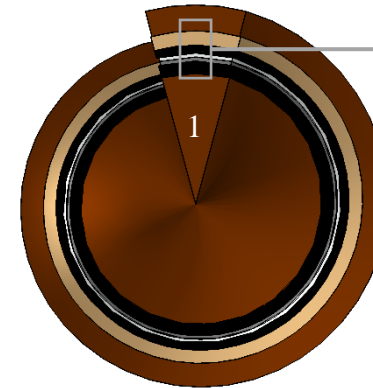
Complete cable model developed using FEM in COMSOL



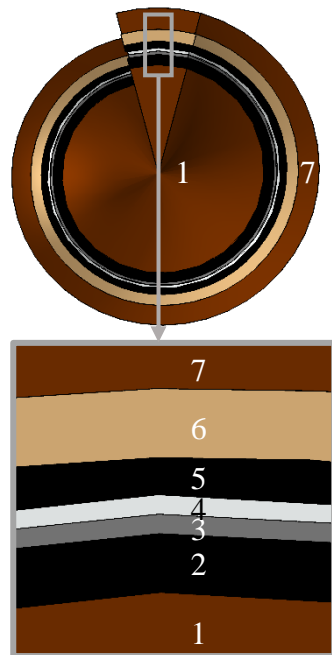
- 1 - Copper core
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- 7 - Cable screen

Reduced cable model developed using FEM in COMSOL

Using symmetries & periodicity



Multi-directional discrete thermal model



7 - Cable screen: Heat exchange in the (x, y, z) directions

6 - Electrical insulation: Heat exchange only in the (r, z) directions

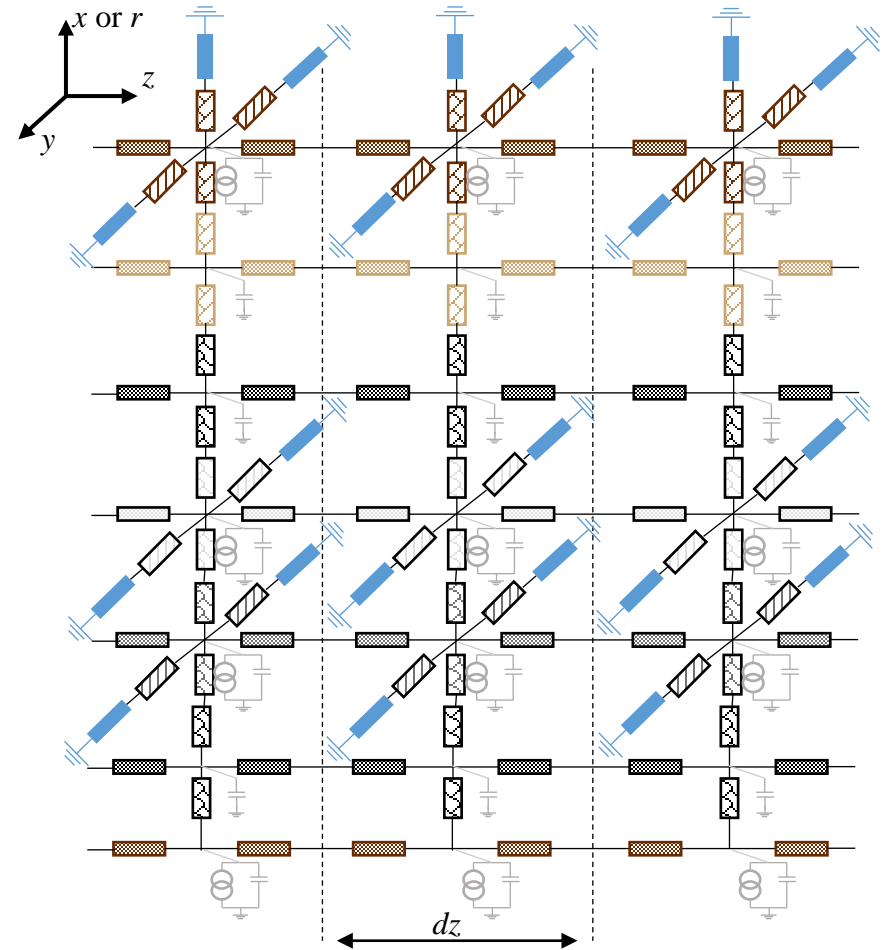
5 - Semi-conductive layer: Heat exchange only in the (r, z) directions

4 - Layer 2 HTS: Heat exchange in the (x, y, z) directions

3 - Layer 1 HTS: Heat exchange in the (x, y, z) directions

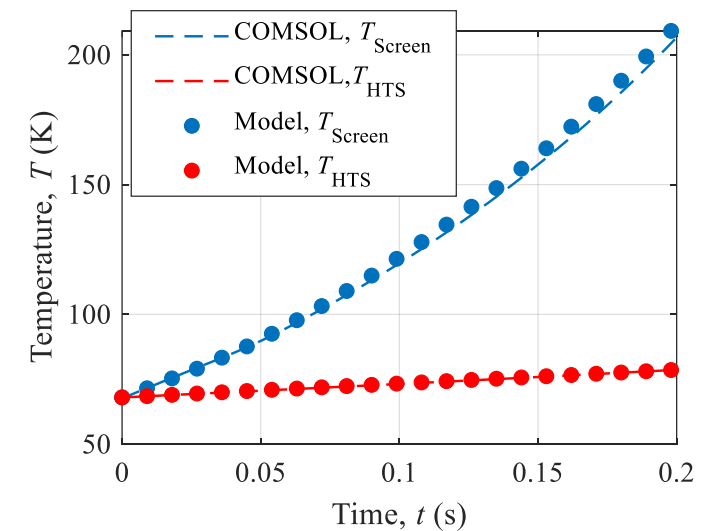
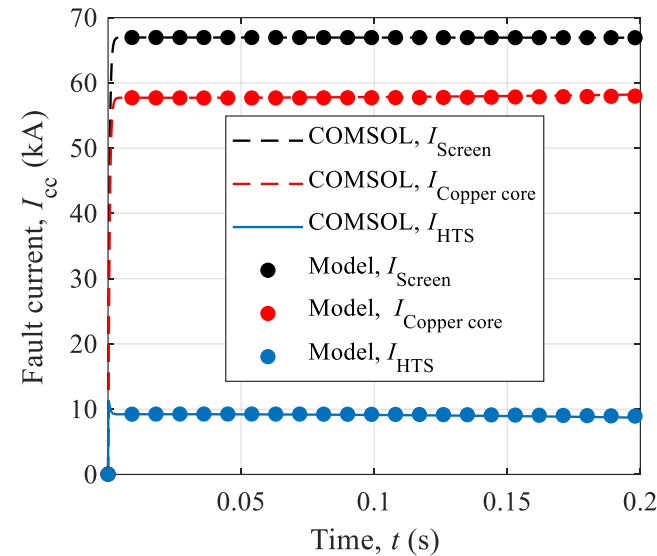
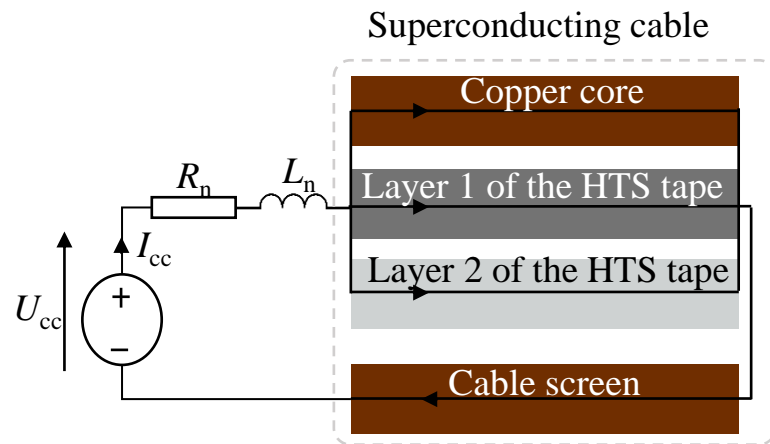
2 - Semi-conductive layer: Heat exchange only in the (r, z) directions

1 - Copper core: Heat exchange in axial directions



Multi-directional Model vs. 3D Finite Element Model

- ❑ Simulation of a direct short circuit on a single cable twist step at **67 kA** for **200 ms**.
- ❑ The screen and the pole of the cable (2 superconducting layers + copper core) are connected in parallel.

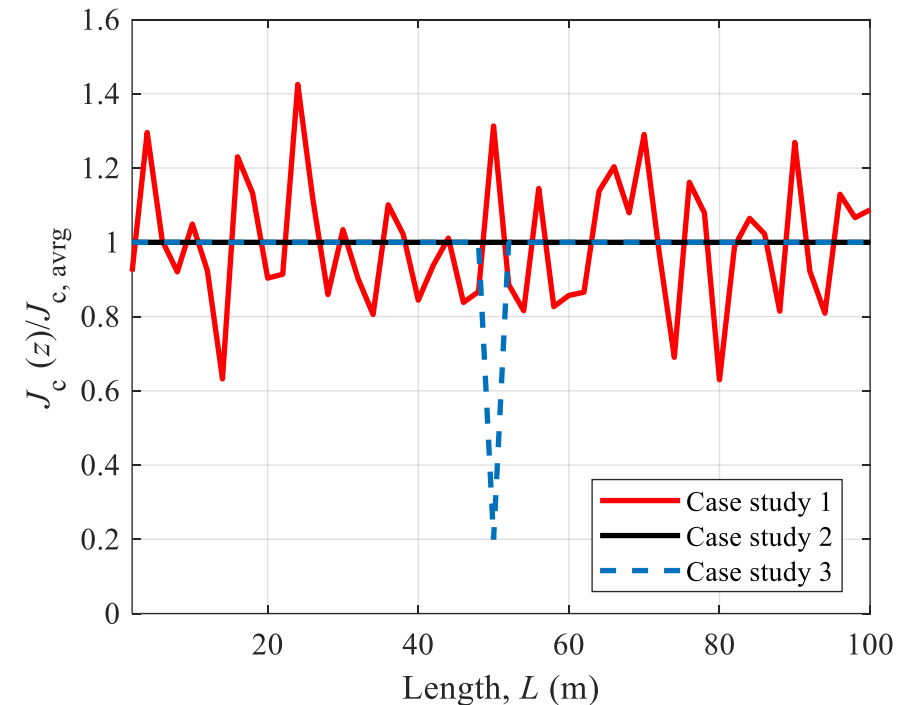


	COMSOL	Multi-directional thermal model
Calculation time (hour : minute : second)	02 :05 :19	00 :00 :02
Relative error (%)		2.60

Cable heating under faults: impact of $J_c(z)$

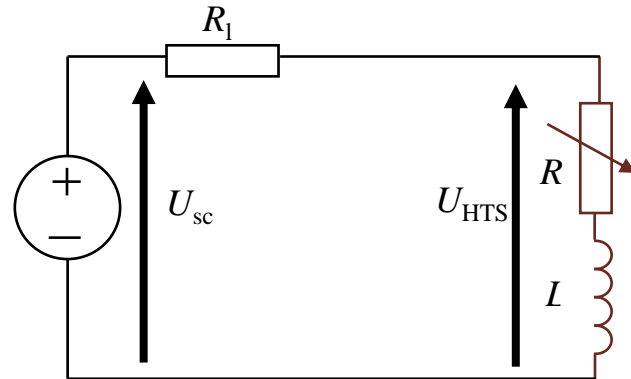
Study on the non-uniform distribution of critical current density along the length

- ❑ **Case Study 1:** Every meter, the critical current density varies by approximately 40% compared to the average critical current density $J_{c, avg}$
- ❑ **Case Study 2:** The critical current density is constant and equal to the average critical current density $J_{c, avg}$ from Case Study 1.
- ❑ **Case Study 3:** Reduction of 80% of the critical current density @ $z = L/2$, i.e., $J_c(z=L/2)=0.2 \times J_{c, avg}$



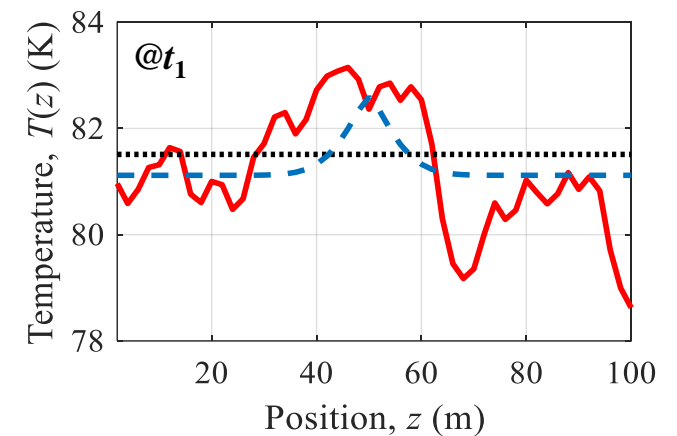
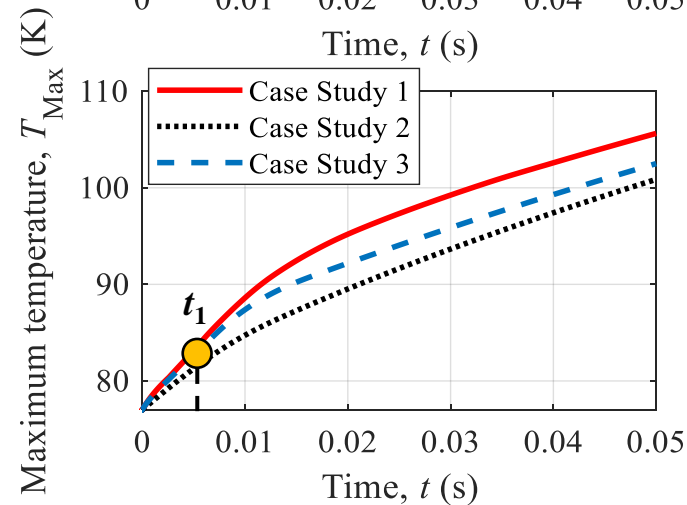
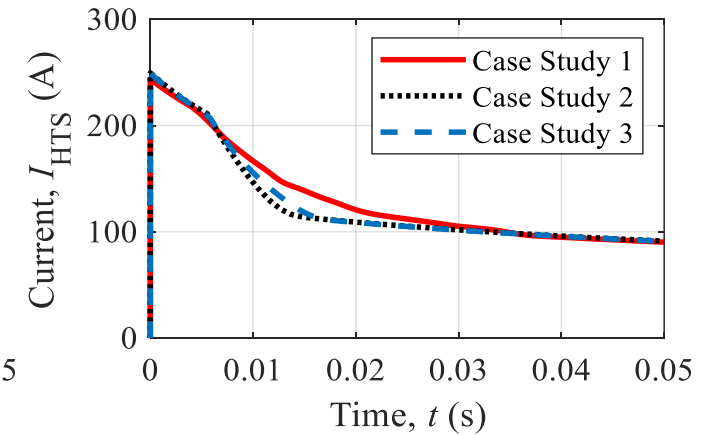
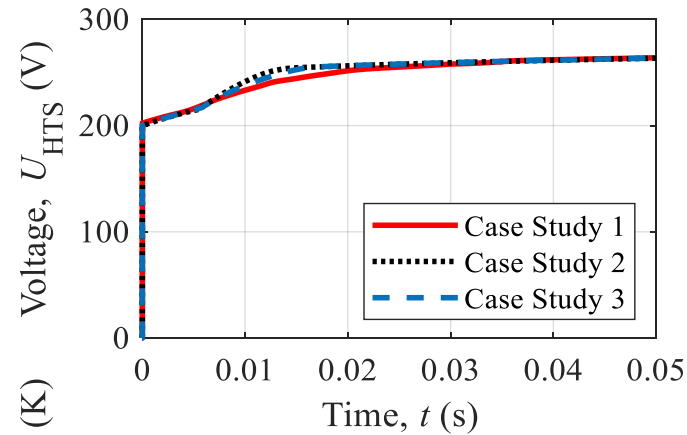
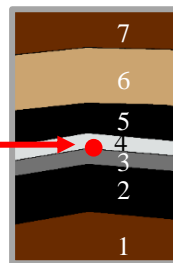
Cable heating under faults: impact of $J_c(z)$

Electrical circuit



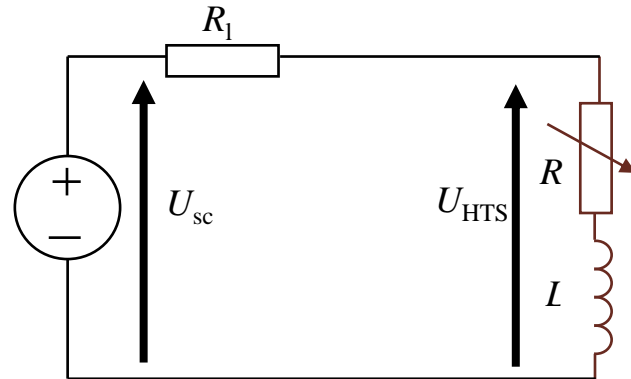
- The length of the tape is 100 m
- Initial temperature is 77 K
- $R_1 = 0.4 \Omega$ (line resistance)
- $U_{sc} = 300 \text{ V}$ (short circuit voltage)

Location of temperature calculation



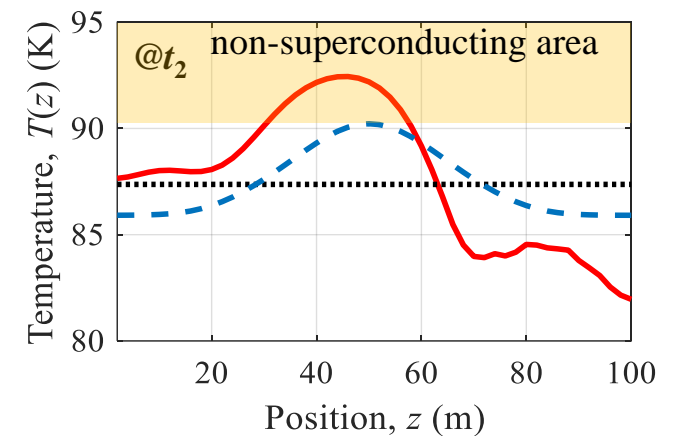
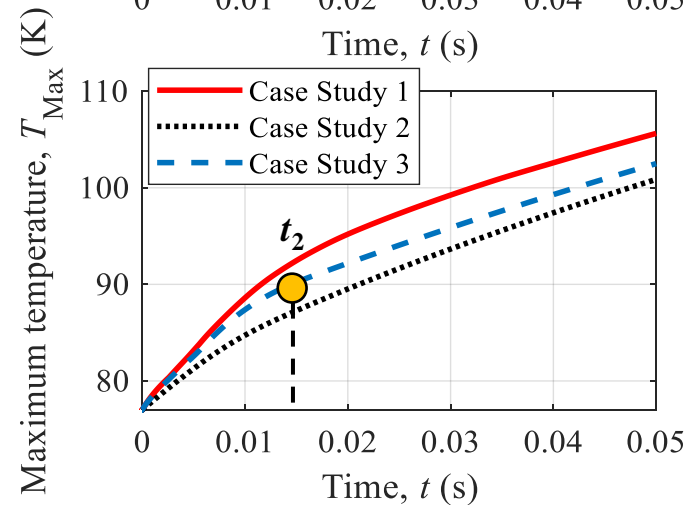
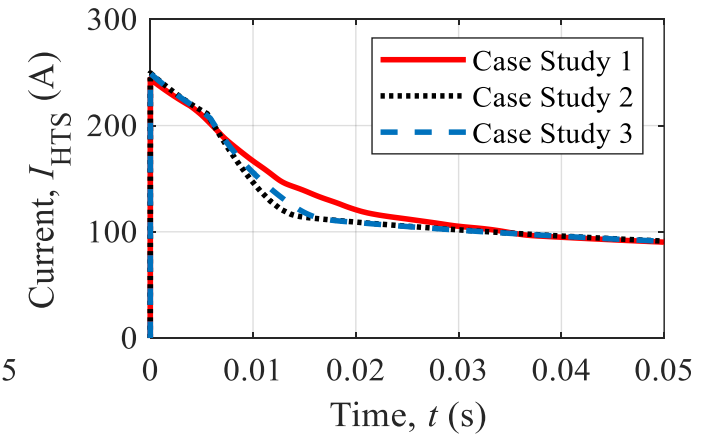
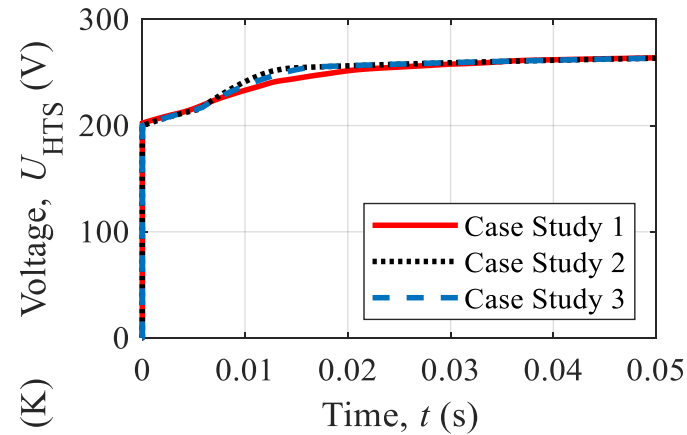
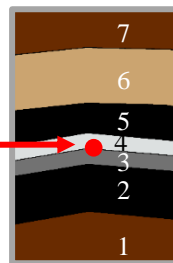
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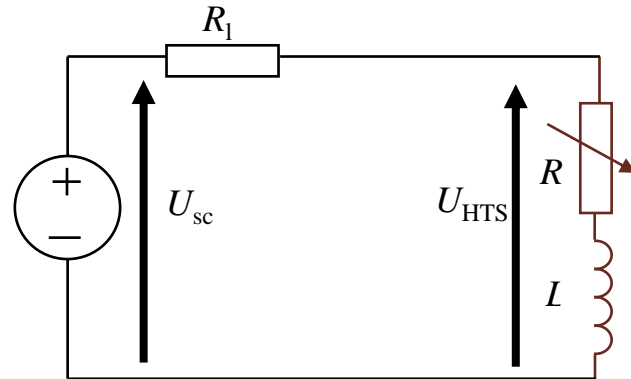
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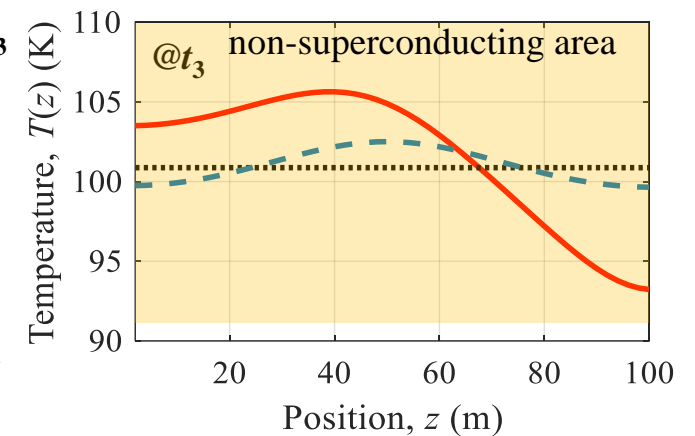
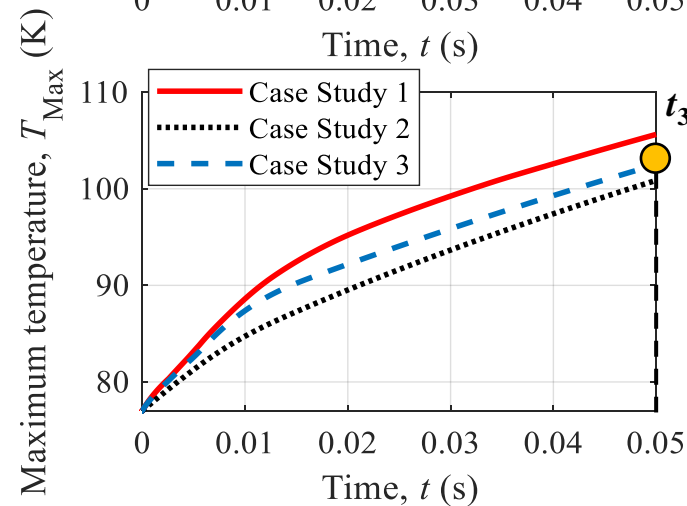
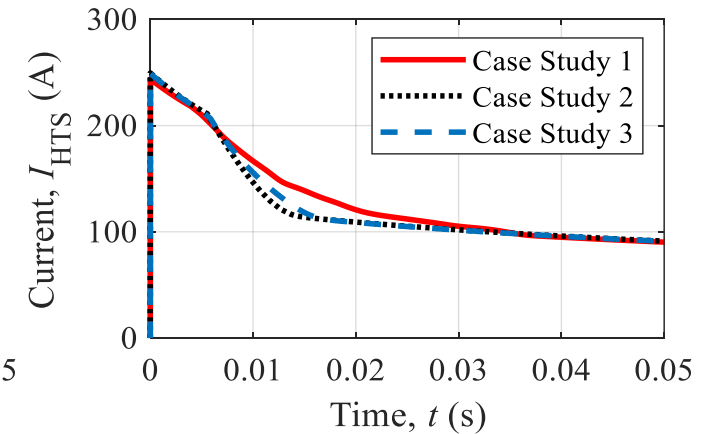
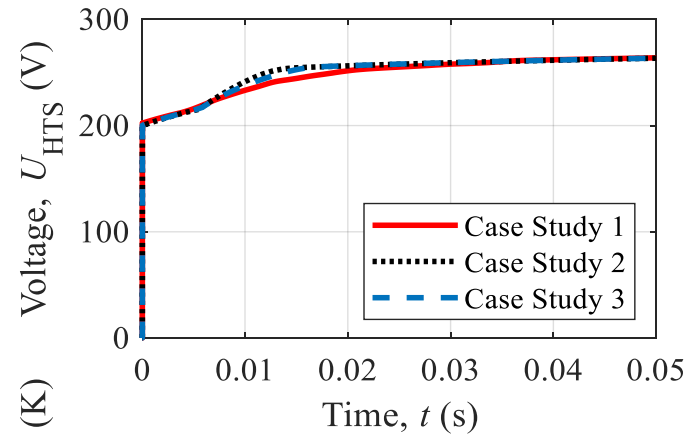
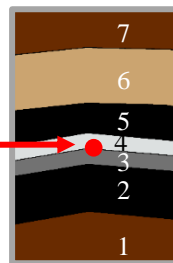
Cable heating under faults: impact of $J_c(z)$

Electrical circuit



- The length of the tape is 100 m
- Initial temperature is 77 K
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- $U_{sc} = 300 \text{ V}$ (short circuit voltage)

Location of temperature calculation



Conclusion and outlook

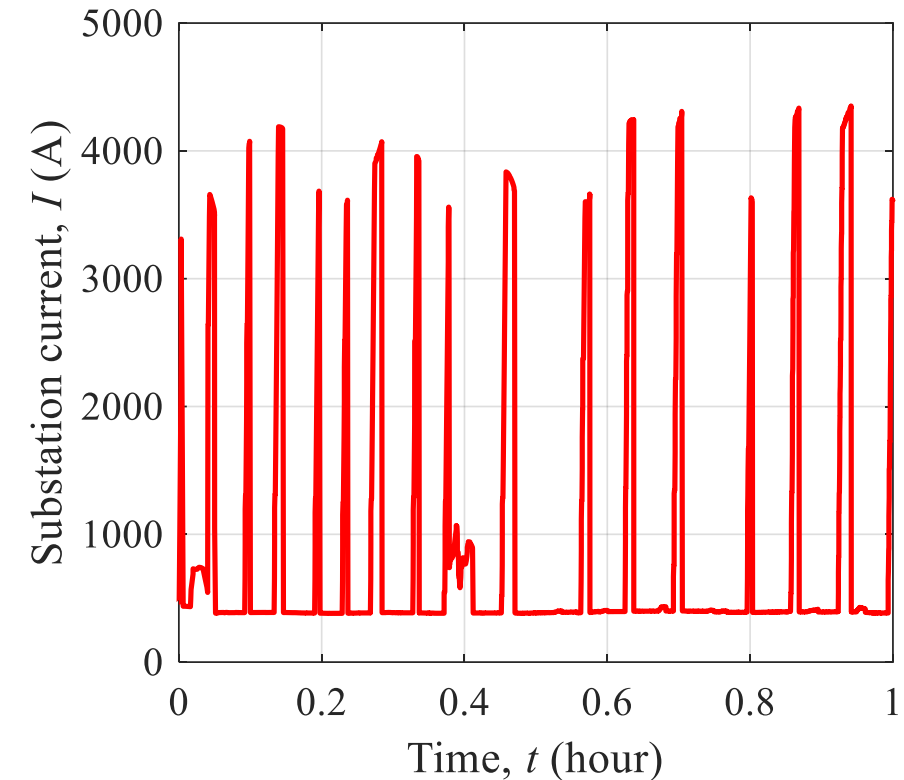
In the railway network, **two types** of faults can occur:

- ❑ The so-called "**brutal**" faults, where the short-circuit current is **much higher** than the critical current of the cable.
- ❑ The so-called "**impedant**" faults, where the fault current is **slightly above** the critical current.

Predict the behavior of superconducting cables in the presence of an **impedant** fault.

Discretize the cable elements to **study heat propagation**.

Account for thermal **contact resistances** between the different layers of the cable in the model.



Thank you for your attention

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The Applied Superconductivity Conference (ASC 2024)
Session ID & Title: 4Lor2A - Grid Studies with Superconducting Devices II
Presentation ID: 4Lor2A-05

References

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Loïc Quéval, S. Abouddrar, Arnaud Allais, Kai Allweins, Kévin Berger, et al.. **Qualification of the SuperRail HTS cable system**. Applied Superconductivity Conference 2024 (ASC 2024), Sep 2024, Salt Lake city, United States. ⟨hal-04748028⟩

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Kévin Berger, Gabriel Hajiri, Arnaud Allais, Jean-Maxime Saugrain, Nicolas Lallouet, et al.. **Progress of the SuperRail Project in Paris and Qualification Results of the 35 m Prototype HTS Cable System**. 4th International Workshop on Cooling Systems for HTS Applications (IWC-HTS), Cryogenics and Superconductivity Society of Japan (CSSJ), Oct 2024, Matsue, Japan. ⟨hal-04752808⟩

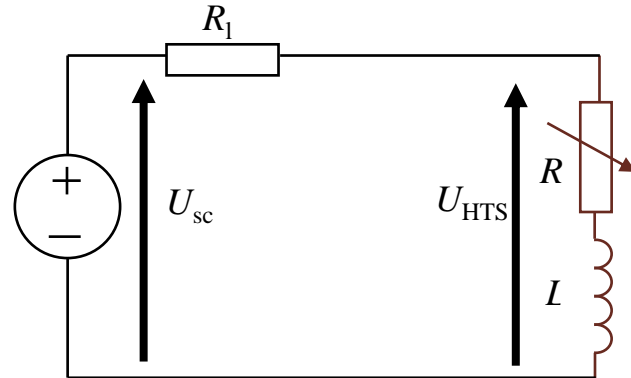
Wimbush, Stuart; Strickland, Nick; Pantoja, Andres (2021). **Critical current characterisation of Fujikura FESC 2G HTS superconducting wire**. figshare. Dataset. <https://doi.org/10.6084/m9.figshare.15095703.v1>



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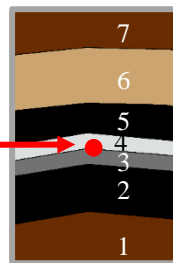
Cable Heating Under Faults: Impact of $J_c(z)$

Electrical circuit



- The length of the tape is 100 m
- Initial temperature is 77 K
- $R_1 = 0.4 \Omega$ (line resistance)
- $U_{sc} = 600 \text{ V}$ (short circuit voltage)

Location of temperature calculation



No significant impact of the inhomogeneity of the critical current density as a function of length.

