Analysis of the quench propagation along Nb_3Sn Rutherford cables with the THELMA code

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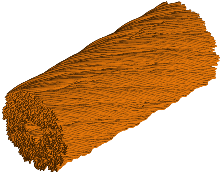
2015 CHATS-AS Workshop, Bologna, Italy, Sept. 14, 2015

Summary

- Introduction.
- The Rutherford cable models:
  - geometrical,
  - electromagnetic.
- The thermal model
  - The thermal model of the Rutherford cable
- Analysis of the quench propagation in Short Model Coil 3
- Conclusions
- Acknowledgements

Introduction

- THELMA is a numerical analysis code developed for the coupled thermal and electromagnetic analysis of cable-in-conduit conductors and joints.



- To model Nb_3Sn Rutherford cables with THELMA :
  - a new geometrical model has been implemented to describe the Rutherford cables;
  - a new thermal model has also been implemented, applicable the Rutherford cables, for the coupled electromagnetic-thermal analysis;
  - a first validation of these models has been given by the analysis of the quench longitudinal propagation velocity in the Nb_3Sn prototype coil SMC-3.

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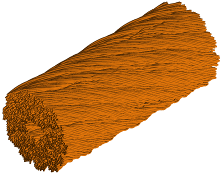

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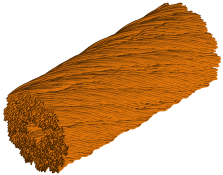

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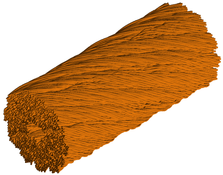

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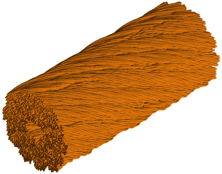

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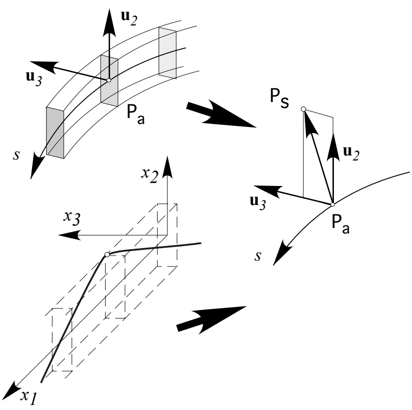
The Rutherford cable geometrical model - I



- In THELMA, the SC cable is a 3D object characterised by its curvilinear axis, around which strands are built:

$$\mathbf{OP}_s = \mathbf{OP}_a + x_2\mathbf{u}_2 + x_3\mathbf{u}_3,$$

- For a Rutherford cable, $x_2(s)$, $x_3(s)$ correspond to the cartesian coordinates of a rectilinear cable whose strand axes are described analytically as a set of straight and circumference arc segments.

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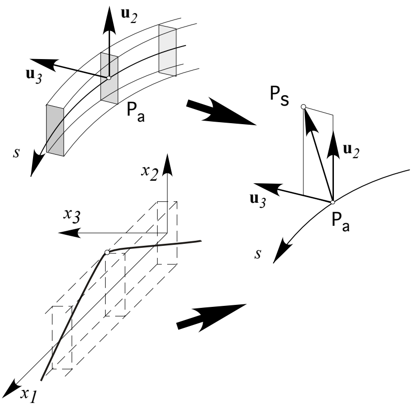

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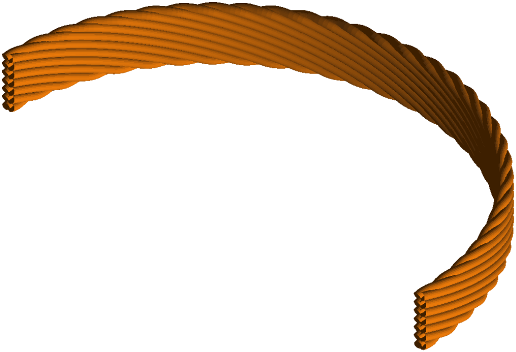

Pictorial view of a curved segment of a 14 strands non-keystoned Rutherford cable.

Go to Rutherford geometrical model details

The THELMA electromagnetic model of Rutherford cables

- The THELMA distributed parameter electromagnetic (EM) cable model, developed by Bologna University, has been used;
- the model considers a non linear resistive-inductive network and its unknowns are the strand current imbalances with respect to the cable transport current uniformly distributed;
- along the cable, each strand is divided into N_{el} longitudinal strand elements suitably set according to the desired level of space resolution ⇒ no constraint from the cable band length.
- All the Rutherford cable strands are individually represented.

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Go to EM model details

The Rutherford cable electrical resistances

In literature, to describe the electrical resistances of a Rutherford cable, the cross-over R_c and the adjacent R_a resistances are used:

- R_c corresponds directly to the series of the THELMA spot resistances of the two strands.

$$R_{c_{i,j}} = R_{s_i} + R_{s_j}$$

- R_a is associated to the length of the crossover between two strands $\ell_a \approx \ell_{Tr}/(2(N_{st}-1)\sin\varphi)$, being N_{st} the number of cable strands, and is related to the THELMA distributed resistances.

$$R_{a_{i,j}} = (R_{d_i} + R_{d_j})/\ell_a$$

☞ The THELMA contact resistances are determined from the model of the cable DC resistance measurements.

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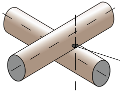

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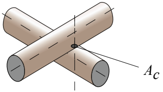

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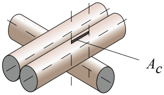

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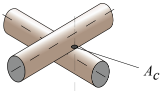

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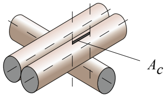

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The thermal model

A brand-new thermal (TH) analysis model has been implemented:

- based on a lumped thermal network ⇒ unknowns: nodes temperatures T_k and branches heat currents Φ_k;
- alternative to the original THELMA thermal-hydraulic module, which is focused on the CICC strand-helium heat exchange;
- general-purpose library of thermal components, including temperature and heat current generators, linear and non linear thermal conductances and capacitances;
- network equations written with the modified node approach and solved numerically in time domain.

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The thermal model of the Rutherford cable - I

- Usually, no forced-flow He cooling is present ⇒ thermal non linear conduction only is considered;
- in the cable, both distributed and concentrated heat currents are present;
- a mixed distributed and lumped model should therefore be considered.

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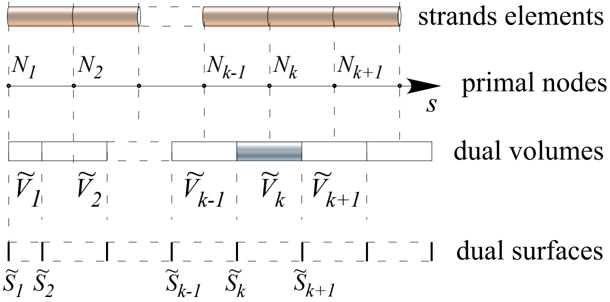

- the temperatures T_k are associated to the primal nodes N_k,
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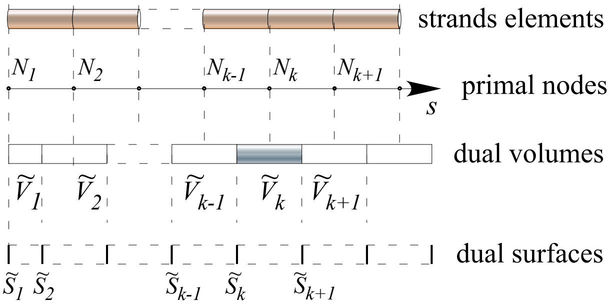

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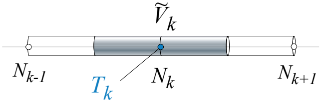

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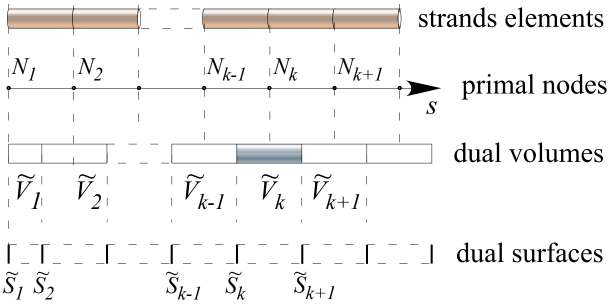

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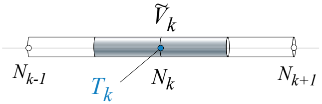
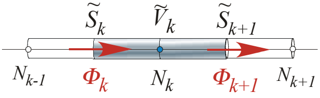
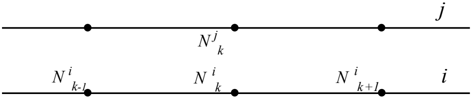
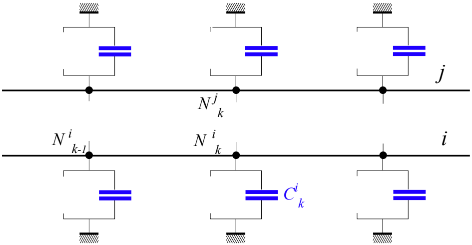






To build the lumped network:

- the i-th strand primal mesh nodes correspond to the network nodes N^i_k;
- each dual volume corresponds to a thermal capacitance C^i_k;
- each dual boundary surface corresponds to a longitudinal thermal conductance $G^l_{k-1,k}$;
- losses are represented by heat current generators $P^{g,i}_k$;
- the inter-strand thermal conductances $G^{i,j}_k$ are also considered.



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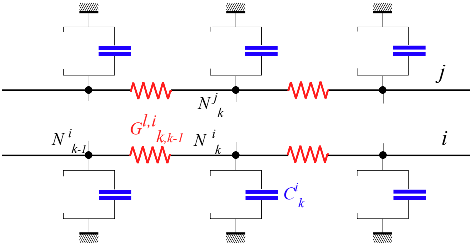

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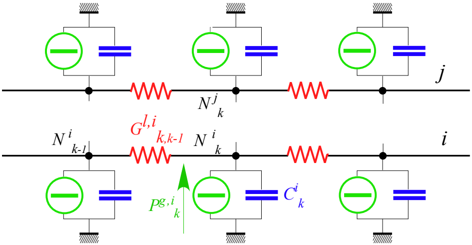

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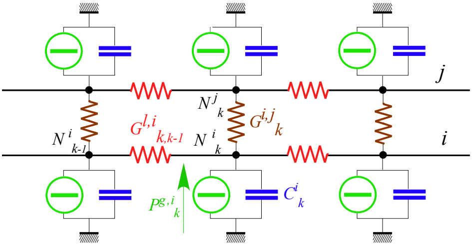

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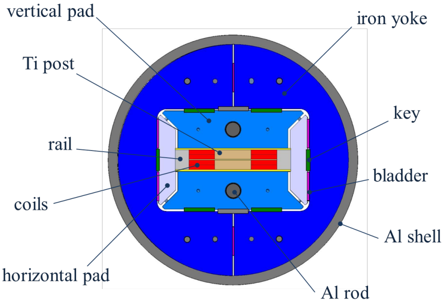
Model validation:

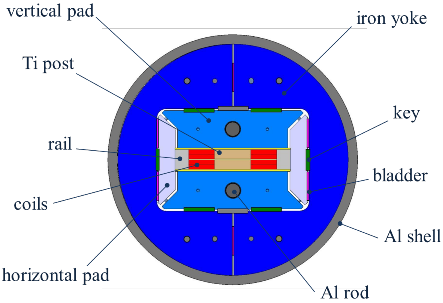
Analysis of the quench longitudinal propagation in Short Model Coil 3

Short Model Coil 3



- Short racetrack coil made with Nb_3Sn, developed in the frame of the Next European Dipole Joint Research Activity.
- Coil target: magnetic field of 12 T on the conductor;
- Two double pancake coils.

Short Model Coil 3



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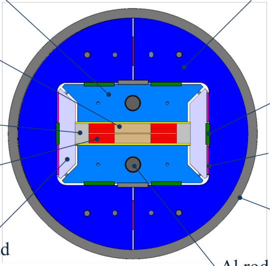

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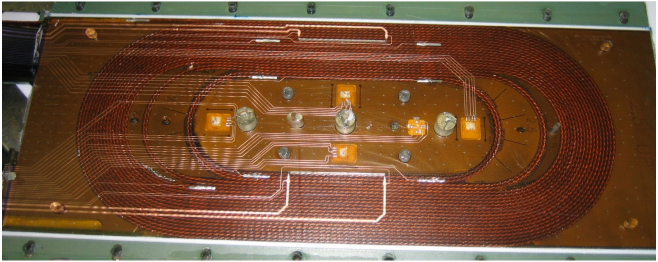
The Short Model Coil 3 pancake



- Each pancake is made of 21 turns divided into 3 groups of 17, 2 and 2 turns;
- Rutherford cable:
  - 14 Nb_3Sn PIT strands with a diameter of 1.25 mm, no keystoning;
  - cross-section 10 mm wide and 2.2 mm thick, transposition pitch: 60 mm;
- I_{css}=15400 A @ 4.2 K and 18500 A @ 1.9 K.

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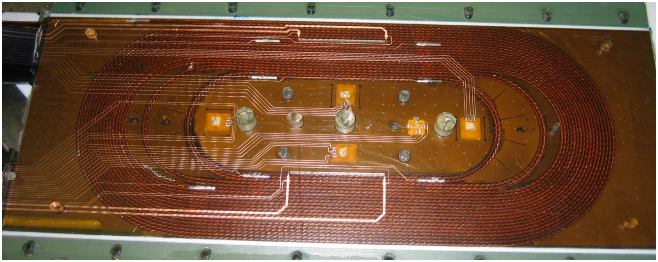

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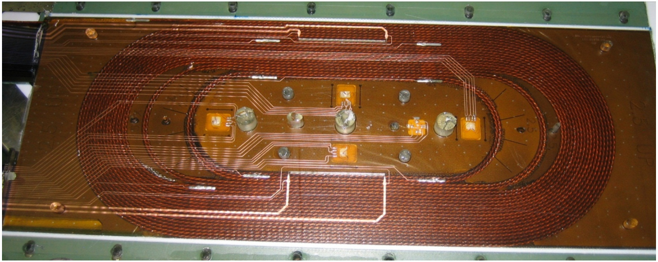

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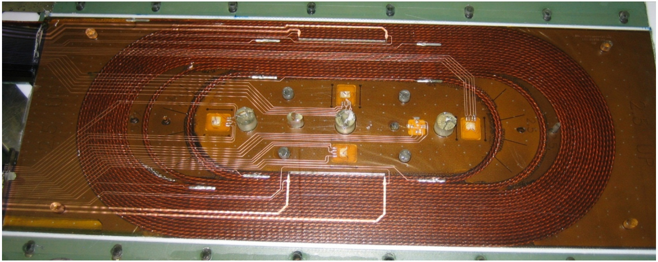
Experimental set-up



- voltage distribution along the coil conductor measured by eight voltage taps per pancake; Go to voltage probes location details
- magnetic field measured by a Hall probe;
- all probes, the coil strain gauges and two spot heaters connected by traces obtained with a technique similar to that of printed boards;
- voltages along the conductor measured as differences between these taps signals ⇒ 15 longitudinal voltage signals available.

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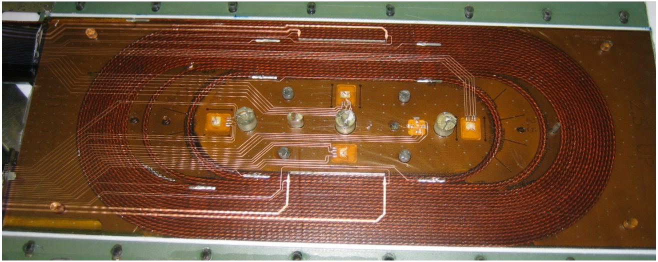

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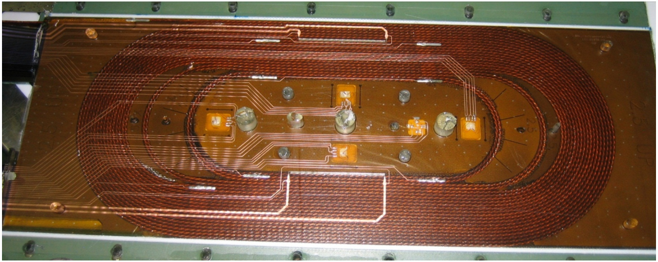

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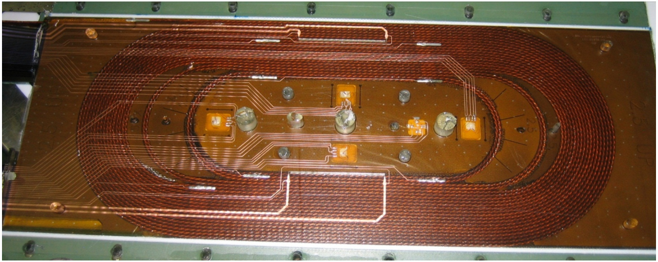

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Tests

- The voltage data used for the model validation have been collected @ 4.2 and 1.9 K, with the coil fed with current ramps at 10 or 20 A/s.
- During training, two plateau current values have been reached, at 95% and 92% of the load line, respectively at 4.2 and 1.9 K, which correspond to 12.5 T on the conductor.
- The large majority of the quenches was detected in the straight part of the innermost turn, 13 cm long, between taps 102 and 72 located in the coil 1 lower layer.

Go to voltage probes location details

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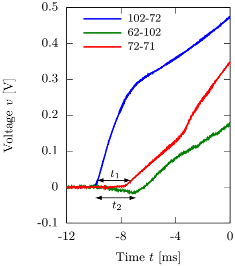
Quench propagation velocity measurements



The propagation velocity was measured with the Time-of-Flight (ToF) method, using the voltage waveform along one or three consecutive coil segments.

$$v_q^{ToF} = d_{taps}/(t_1 + t_2)$$

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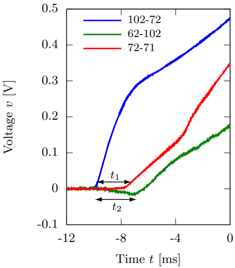

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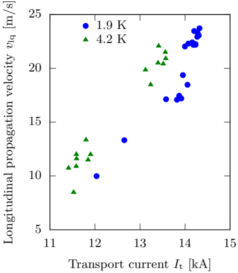

Measured quench propagation velocities along coil segment 72-102 from tests at 4.2 and 1.9 K.

The THELMA model of SMC3

- Modelled part: the 15 cm long coil straight part which includes the 72-102 coil segment;
- discretisation step along the cable: 1 mm;
- Twente/ITER SC strand scaling law;
- EM model boundary conditions: at both ends strands fed by equal constant current generators with two polygons of inter-strand resistances ⇒ current redistribution possible up to the ends;
- TH model boundary conditions: adiabatic;
- quench triggered by a heat pulse (0.1 : few mJ) applied to a single strand in the highest field zone @ the cable middle length.

▸ Go to THELMA SMC3 model details ▸ Go to SMC3 iron model details

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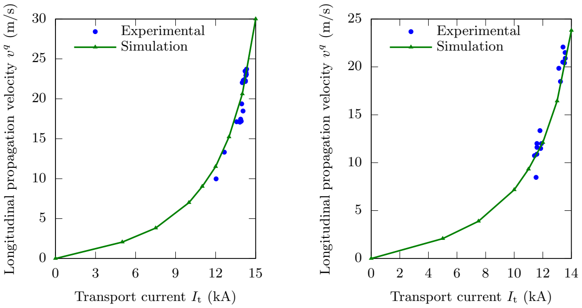
Comparison between measured and computed velocities

The quench propagation velocity v^q has been studied as a function of the cable transport current I_t at two initial temperatures $T_0 = 1.9$ (left) and 4.2 K (right).



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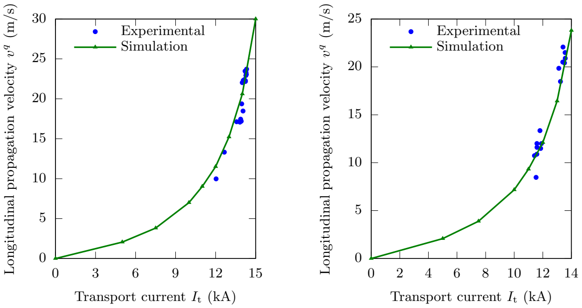

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Further results - I

(Loading smc_profile)

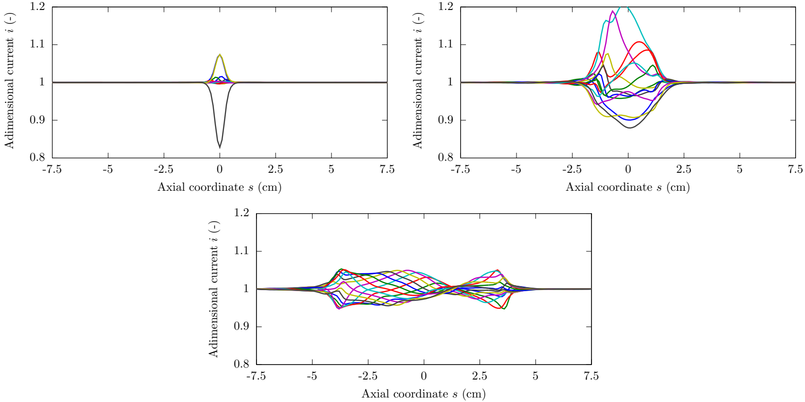
View of the strands temperature along the cable.

Further results - II

(Loading smc_cross_section)

View of the strands temperature in the cross-section where the heat pulse was applied and two close cross-sections

Further results - III



View of the strands adimensional currents along the cable at $T_0 = 4.2$ K, $I_t = 14$ kA. Above, left: $t = 0.3$ ms, above, right: $t = 1$ ms, below: $t = 2.5$ ms after the disturbance.

Conclusions

- A new THELMA model of the Rutherford cables has been developed.
- This model makes use of the new THELMA thermal model, coupled with the existing electromagnetic module.
- THELMA can analyse the Rutherford cable behavior at a very detailed level, showing electromagnetic and thermal diffusion effects both along and among strands.

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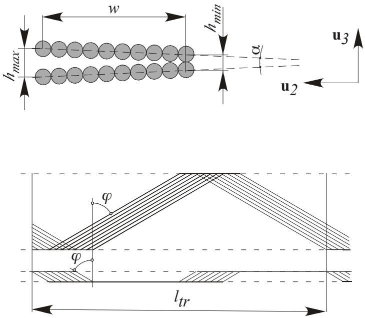
Acknowledgements

The research leading to these results has received funding from the European Commission under the Transnational Access activity of the FP7 Research Infrastructures project EUCARD-2, grant agreement no. 312453.

Thanks for your attention!

Go to to Rutherford geometrical model
Go to Rutherford geometrical model details
Go to EM model
Go to EM model details
Go to Rutherford electrical contact resistances
Go to contact resistances details
Go to TH module
Go to TH module details
Go to EM and TH modules coupling details
Go to voltage probes location details
Go to THELMA SMC3 model
Go to SMC3 model details

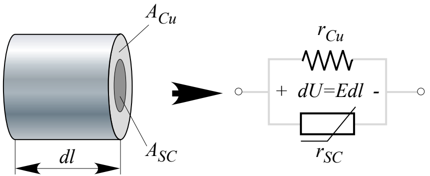


- Keystoning can be taken into account.
- The twisting angle φ, used for both the in-plane and the out-of-plane transpositions, is:

$$\varphi \approx \tan^{-1}\left(\frac{l_{tr}}{2\left(h_{med}+\frac{w}{\cos\alpha/2}\right)}\right)$$

▸ Return to Rutherford geometrical model ▸ Back to hub

- Different strand scaling laws are available.
- Strand cross-section ⇒ electrical parallel of the Cu stabilizer and the SC material



- The following equation is numerically solved in terms of I_{SC}:

$$I_{st} = I_{SC} + \frac{A_{Cu}}{\varrho_{Cu}} E_c \left(\frac{I_{SC}}{I_c} \right)^n ,$$

Return to electromagnetic model
Back to hub

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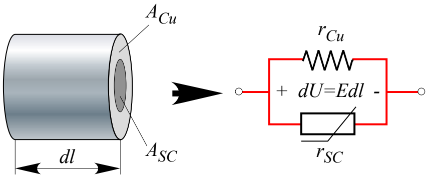

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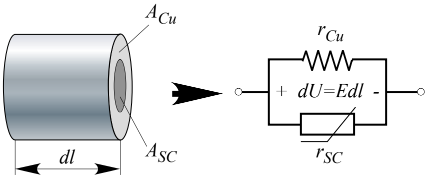

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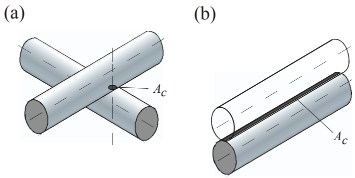
Return to electromagnetic model   Back to hub

Details of the EM and TH contact resistances models



In THELMA:

(a) the spot R_s (Ω or K/W) and

(b) the distributed R_d (Ω·m or K·m/W)

contact resistances can be individually assigned to the cable strands.

- the cable geometry is scanned and the single local conductances are computed.
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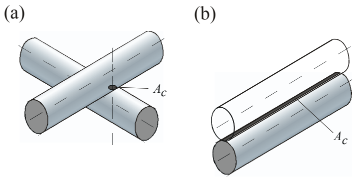
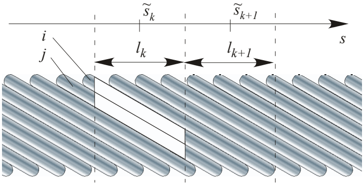
Return to Rutherford electrical contact resistances
Back to hub





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Return to Rutherford electrical contact resistances
Back to hub

Details of the new THELMA TH model - I

- The resulting system of algebraic-differential equations can be written as:

$$\begin{pmatrix} \mathbf{A}_r^T & \mathbf{R}_{th} \\ \mathbf{G}_{th} & \mathbf{A}_r \end{pmatrix} \begin{pmatrix} \mathbf{T} \\ \mathbf{\Phi} \end{pmatrix} + \begin{pmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{C}_{th} & \mathbf{0} \end{pmatrix} \frac{\mathrm{d}}{\mathrm{d}\,t} \begin{pmatrix} \mathbf{T} \\ \mathbf{\Phi} \end{pmatrix} = \begin{pmatrix} \mathbf{T}^i \\ \mathbf{\Phi}^i \end{pmatrix}$$

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Details of the new THELMA TH model - II

The final form of the system is:

$$\begin{pmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{F}^{th}_{d,d} & \mathbf{0} \end{pmatrix} \frac{\mathrm{d}}{\mathrm{d}\,t} \begin{pmatrix} \mathbf{X}_a \\ \mathbf{X}_d \end{pmatrix} + \begin{pmatrix} \mathbf{D}^{th}_{a,a} & \mathbf{D}^{th}_{a,d} \\ \mathbf{D}^{th}_{d,a} & \mathbf{D}^{th}_{d,d} \end{pmatrix} \begin{pmatrix} \mathbf{X}_a \\ \mathbf{X}_d \end{pmatrix} = \begin{pmatrix} \mathbf{Y}_a \\ \mathbf{Y}_d \end{pmatrix}.$$

These two equation systems are obtained, which are solved at each iteration:

$$\begin{cases} \mathbf{X}_a = {\mathbf{D}^{th}_{a,a}}^{-1}\mathbf{Y}_a - \mathbf{U}^{th}_{a,d}\mathbf{X}_d \\ \frac{\mathrm{d}}{\mathrm{d}\,t}\mathbf{X}_d = {\mathbf{F}^{th}_{d,d}}^{-1}\mathbf{Y}_d - \mathbf{U}^{th}_{d,a}\mathbf{X}_a - \mathbf{U}^{th}_{d,d}\mathbf{X}_d, \end{cases}$$

where:

$\mathbf{U}^{th}_{a,d} = {\mathbf{D}^{th}_{a,a}}^{-1}\mathbf{D}^{th}_{a,d}$, $\mathbf{U}^{th}_{d,a} = {\mathbf{F}^{th}_{d,d}}^{-1}\mathbf{D}^{th}_{d,a}$, $\mathbf{U}^{th}_{d,d} = {\mathbf{F}^{th}_{d,d}}^{-1}\mathbf{D}^{th}_{d,d}$.

▸ Return to the thermal module ▸ Back to hub

EM and TH models coupling

The EM and the TH models are coupled in an explicit way. At each adaptive time step a loop is followed:

- the currents and losses are computed by the EM module starting from the initial temperatures and currents;
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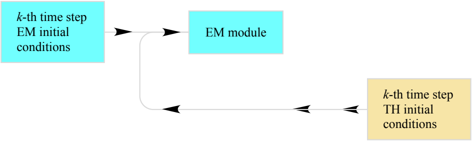

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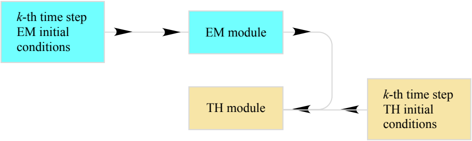

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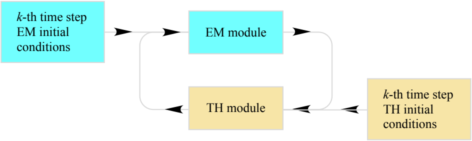

Return to the thermal module
Back to hub

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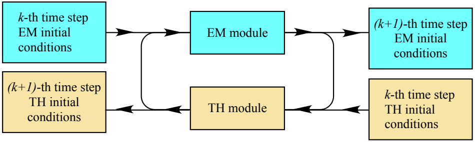
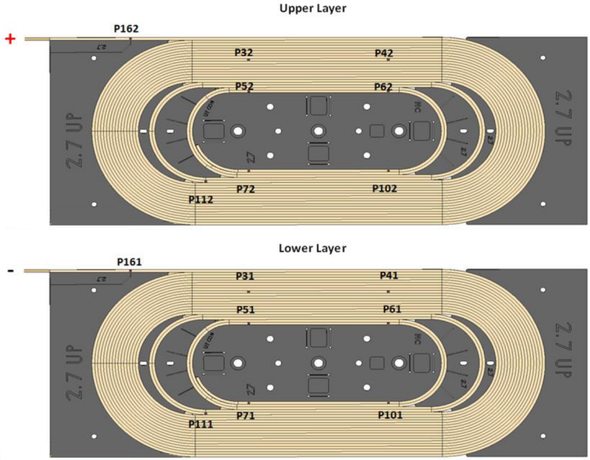


Return to the thermal module
Back to hub

Voltage probes location details



Detail of the voltage probes location on the two layers of each SMC3 coil. Return to experimental set-up Return to tests Back to hub

Details of the THELMA SMC3 model

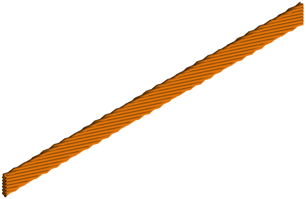
- Twente/ITER SC strand scaling law:

p	q	C	$B_{c20,max}$ (T)	$T_{c0,max}$ (K)	$C_{n,1}$	$C_{n,2}$	$\varepsilon_{0,a}$ (%)	ε_m (%)
0.5	2	$2.118 \cdot 10^{11}$	29.452	16.973	45.062	4.256	0.286	0

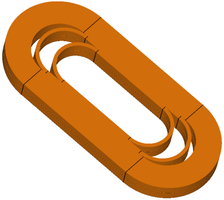
- applied strain $\varepsilon_{appl} = -0.2\%$ and I_c degradation 16.3%;
- $n = 1 + r\, I_c^s = 1 + 2.20\, I_c^{0.47}$ (rescaled); Cu RRR=75 (NIST model);
- $R_c = 1$ mΩ and $R_a = 9.4\ \mu\Omega \Rightarrow R_d = 10.4$ n$\Omega\cdot$m and $R_s = 0.5$ mΩ in THELMA.
- distributed thermal conductances (from NbTi): $G_d = \alpha\, T^\beta = 0.545\, T^{1.54} \quad \mathrm{W/m \cdot K}$
- spot thermal conductance done by considering the strand diameter.

Return to THELMA SMC3 model
Back to hub

Details of the iron model of SMC3 - I



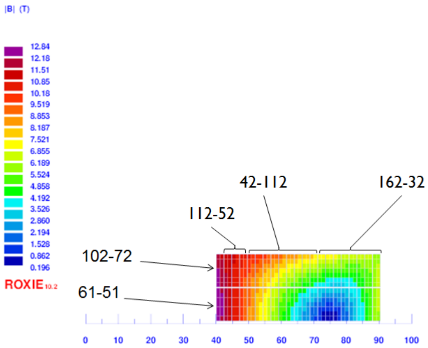
All the strands of the modelled Rutherford cable segment are individually represented;



the rest of the coil is represented by a sequence of solid blocks;

☞ However iron gives a non negligible contribution to the total field (up to 2 T).

Details of the iron model of SMC3 - II



A ROXIE code 2D model has been developed to get the iron contribution.

▸ Return to THELMA SMC3 model ▸ Back to hub