THELMA Analyses of ITER NbTi Cable-in-Conduit Conductors

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Outline

- Introduction
- The THELMA model:
  – Joints and terminations (EM)
  – CICC (EM)
  – Joints + CICC (TH)
- Applications
- Conclusion

Introduction-1

- Analysis of transients in the ITER CICCs is a multi-physics (thermal-hydraulic + electromagnetic) problem in a multi-stage and multichannel structure
- Phenomena peculiar to NbTi conductors such as the 'sudden quench' [Bruzzone_IEEE_J_ASC_2005] have been qualitatively explained as the combined effect of magnetic field and thermal gradients on the conductor cross section, with possible current non-uniformity [Wesche_IEEE_J_ASC_2004, Wesche_Cryogenics_2005]
- THELMA implements **coupled thermal-hydraulic and electromagnetic models** of a CICC, validated against different kind of transients

Introduction-2

- THELMA showed the capability to capture the qualitative features of these transients, **spikes, sudden and premature nature of the quench**:

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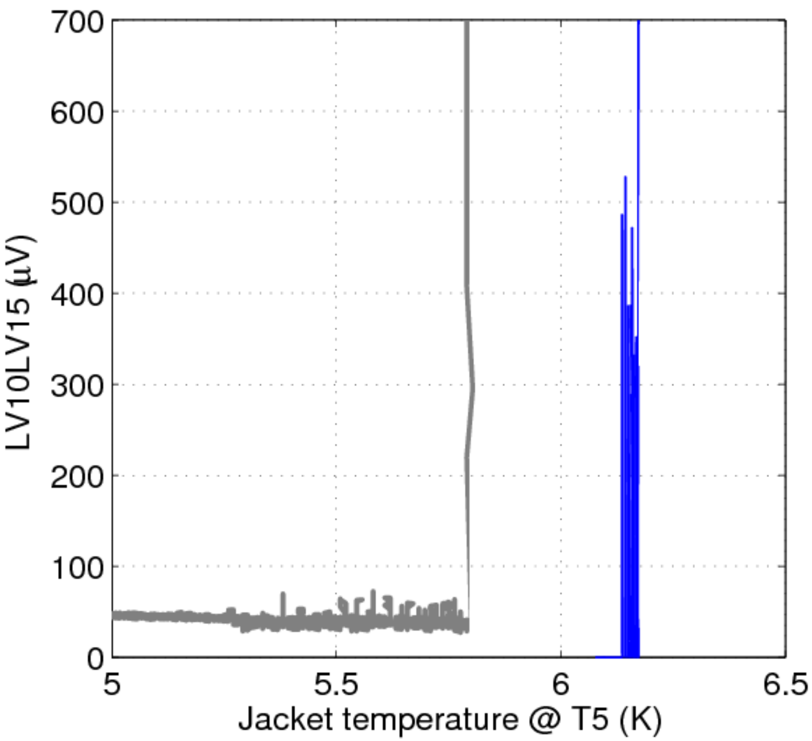
Analysis of sudden quench of an ITER superconducting NbTi full-size short sample using the THELMA code

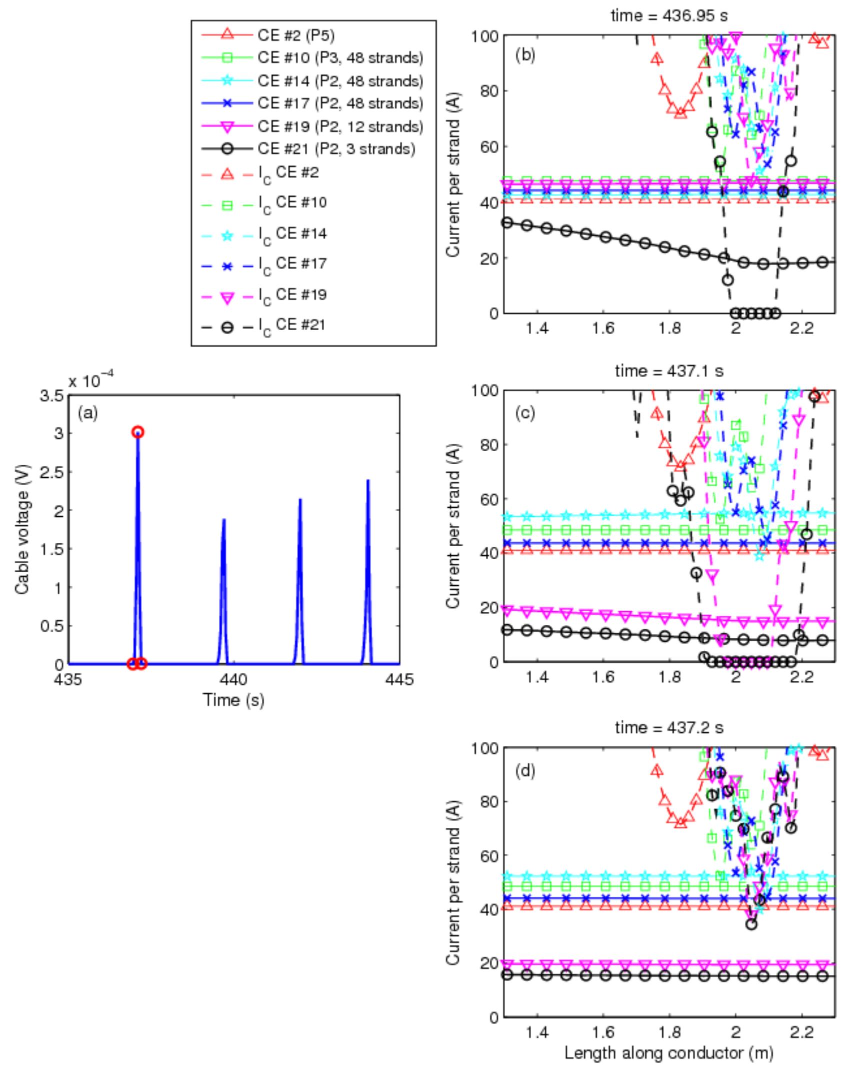
R Zanino[1], F Bellina[2], P L Ribani[3] and L Savoldi Richard[1]

Introduction-3

Spikes, sudden quench

Tcs overestimated





The THELMA model: Joints and terminations

- Electromagnetic (EM) model
- Contact resistances
  - Random resistance distribution
  - Defects

Joint EM model-1

- A lumped linear model is used for the joint area:
  - The cable elements (CE) are discretised into *sections*:

QuickTime™ e un decompressore
sono necessari per visualizzare quest'immagine.

  - A linear conductive N-pole is created in between adjacent sections:

QuickTime™ e un decompressore
sono necessari per visualizzare quest'immagine.

Joint EM model-2

- The joint saddle and sleeves are modelled as equivalent resistors.
- The inter-cable element and the saddle-cable element contacts are automatically computed.
- Two types of contacts are considered: the *spot* and the *distributed* contact.

QuickTime™ and a decompressor are needed to see this picture.

Details

Contact resistances

- Additional layers are considered, around the cable elements or the bundles:

QuickTime™ and a
decompressor
are needed to see this picture.

Random effects on the contact resistances-1

- The accurate computation of the contact resistance is almost impossible:
  - the cable exact geometry is almost unpredictable:
    - simplified geometrical models (e.g.[1-2] [Chen_IEEE_J_MAG_1996] [Van_Lanen_Cryogenics_2010])
    - non linear structural analyses (e.g. [Bajas_IEEE_J_ASC_2010]
  - the strand and saddle/sleeve surface conditions are not known [Ilyin_IEEE_ASC_2005]

Random effects on the contact resistances-2

- Contact resistances with random values have been implemented in THELMA:

$$G_{ij} = G_{ij}^{det} X$$

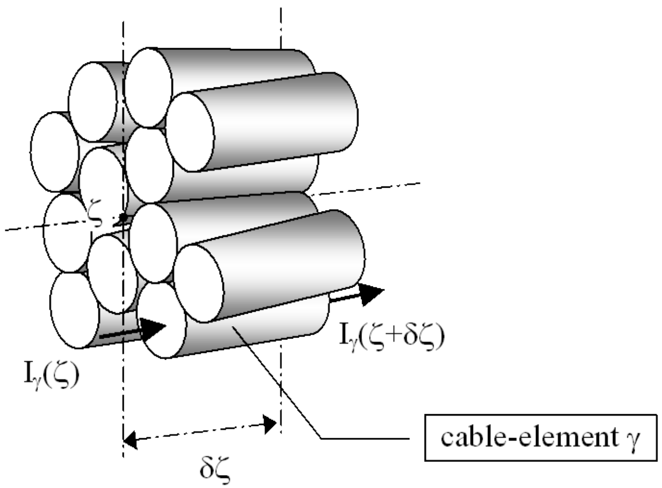
- A log-normal probability distribution has been considered:

$$x \in (0, \infty) \quad f(x, \mu, \sigma) = \frac{1}{x\sigma\sqrt{2\pi}} e^{-\frac{(\ln x - \mu)^2}{2\sigma^2}}$$

The THELMA model: CICC (EM)

- CICC:
  - Cable model
  - Jacket model
  - Transverse conductances

Cable EM model



$$i\_c_k(\zeta,t) = I\_c_k(\zeta,t) - \frac{N_k}{N\_st} I(t)$$

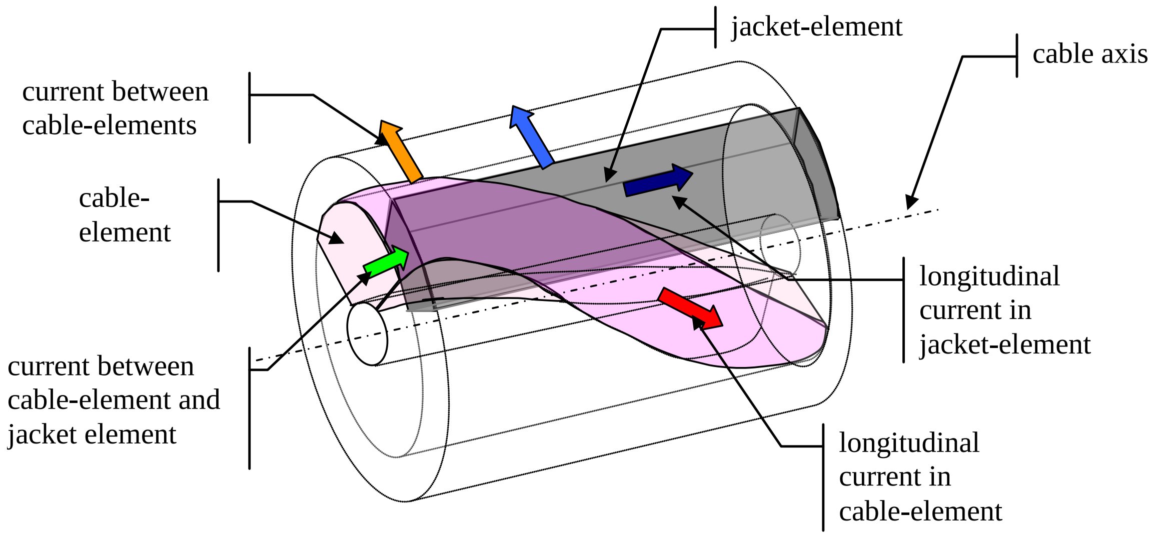
- The strands of the cable are grouped in *N_ce* cable-elements:
- a CE can be a single strand or a group of strands (it is possible to model a cable with non-homogeneus cable-elements: strands, triplets, ... , *petals*),
- the current density is uniform in each CE and directed parallel to the axial line of the CE
- the currents unbalances are the unknowns of the problem

Details

$$\mathbf{B}(\mathbf{P},t) = \sum_{k=1}^{N\_ce} \int_0^L \mathbf{b\_c}_k(\mathbf{P},\zeta)\, i\_c_k(\zeta,t)\, d\zeta + \mathbf{B\_u}(\mathbf{P}) I(t) + \sum_{h=1}^{N\_ext} \mathbf{B\_ext}_h(\mathbf{P})\, I\_ext_h(t)$$

Jacket EM model

- The model for the jacket is similar to the model for the cable.
- The jacket is modeled by means of *N_je* jacket-elements (JE)
- The current density is uniform in each JE and is directed parallel to the axial line of the JE



- the currents in the JEs are unknowns of the problem, but are supposed negligible with respect to transport current in CEs
- The magnetic flux density generated by the currents in JEs is negligible (no self and mutual induction effects between the JEs)

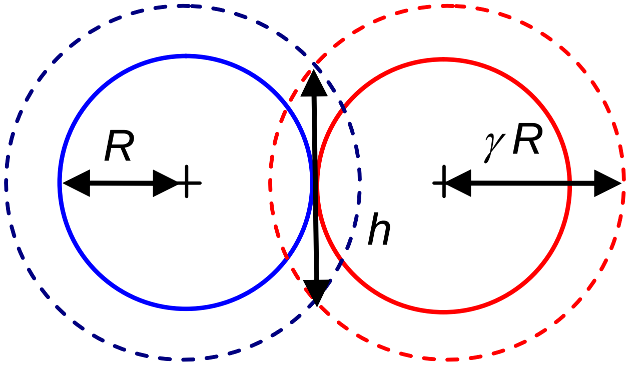
Transverse conductances

• One of the most crucial parameters of the model is the per unit length conductance *G* between two CEs or a CE and a JE.

• The model utilizes two fitting parameters (which must be determined by experimental data) for the calculation of *G* from the geometrical model of the CE trajectories in the cable:

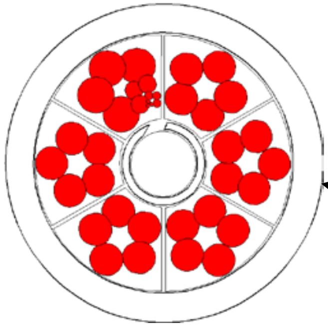
- the geometrical amplification factor γ
- the per unit surface conductivity σ

$$G = \sigma\, h$$

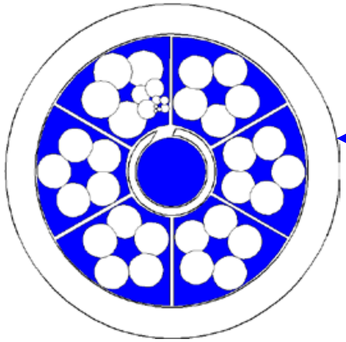


The THELMA model

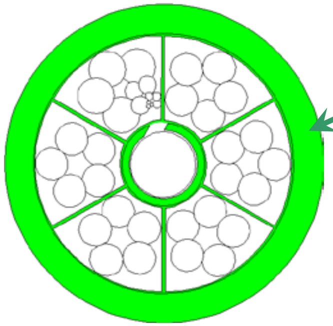
Joint+CICC (TH)



•Transient 1D heat conduction equation for **M** current carrying **Cable Elements** (refinement down to the strand level allowed)



• 1D Euler-like set of equations for **N** hydraulic channels



• Transient 1D heat conduction equation for **K** "**jacket**"-like components (jacket, wrapping, spiral,…)

[L. Savoldi Richard_FED_2007]

M

+

3N

+

K

M+3N+K

equations

Applications

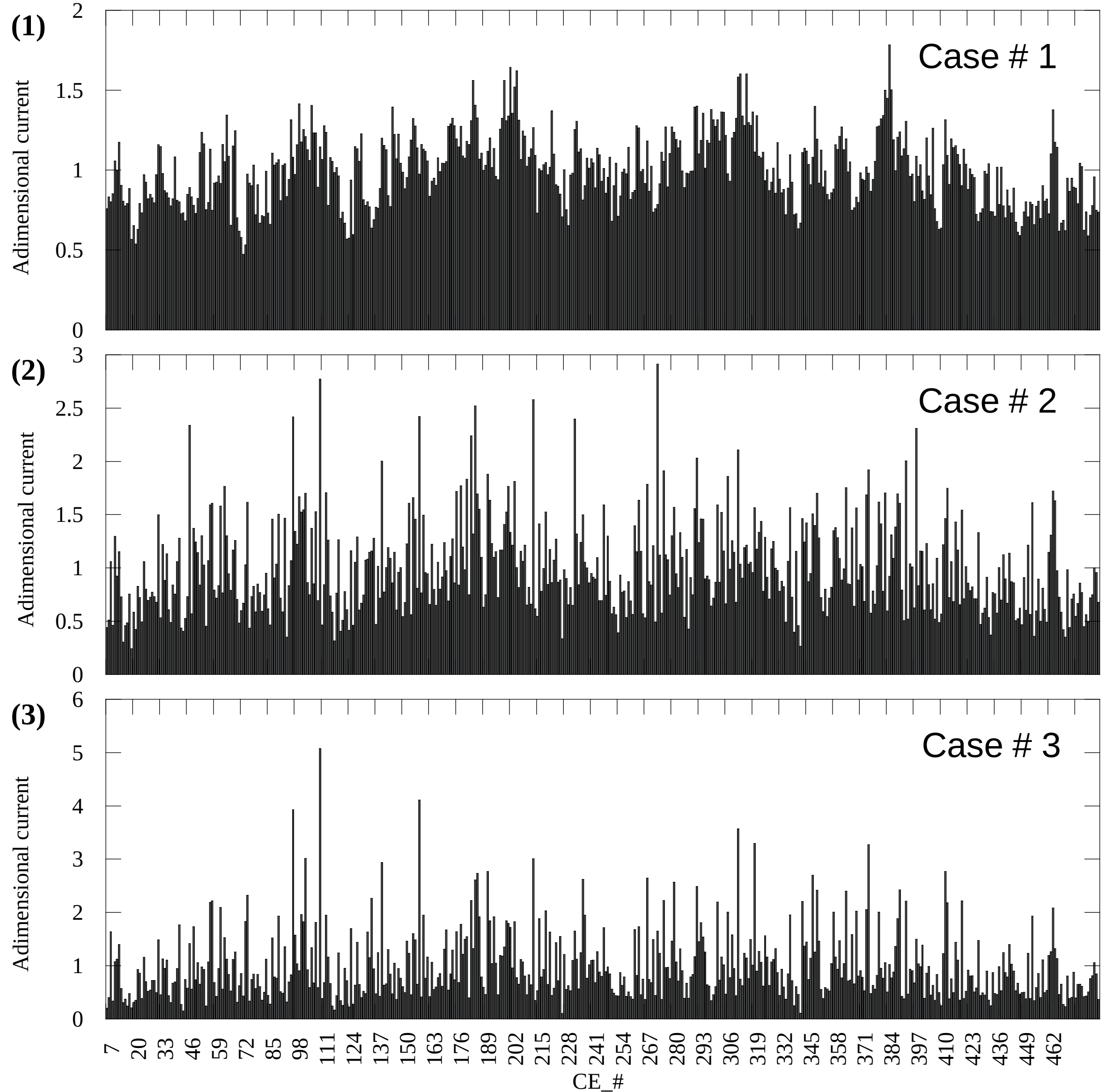
- The original, deterministic contact resistance model (**case # 1**) has been compared with one or two random contact resistance distributions (**cases # 2 and 3**) for:
  - –analysis of DC current distribution,
  - –analysis of sudden quench and Tcs of full size NbTi CICCs
  - –analysis of joint inter-cable element contact self resistances
  - –analysis of joint/termination defects on the sample performances.

Details

Details

DC current distribution

- The random contact resistance increases the current imbalances among the CEs.
- The CE current is almost constant along the CE (not shown).
- The leg overall voltage can increase (+30%), as well as decrease (-10%).



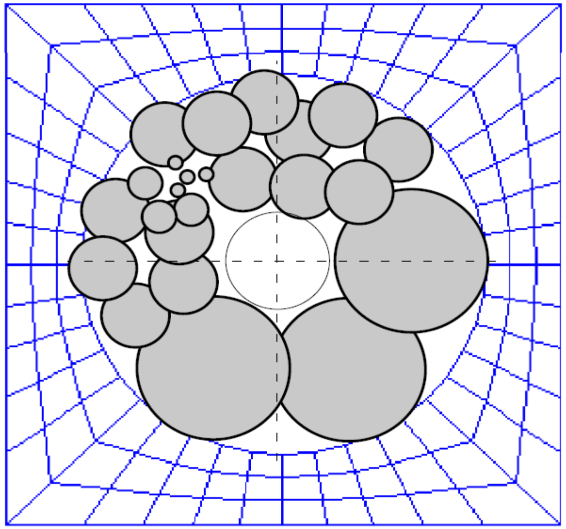
Analysis of sudden quench and Tcs

- Tests PDC070409 (60 kA) **and PDC070405 (20 kA)** have been considered:
- The analysis of the two tests have been done with different discretizations of the cable.
- The effects of the transverse conductance between CEs has been studied with a parametric analysis.
- The effects of the random contact resistance distributions have been studied (**case # 2**)

PFCI Iq data

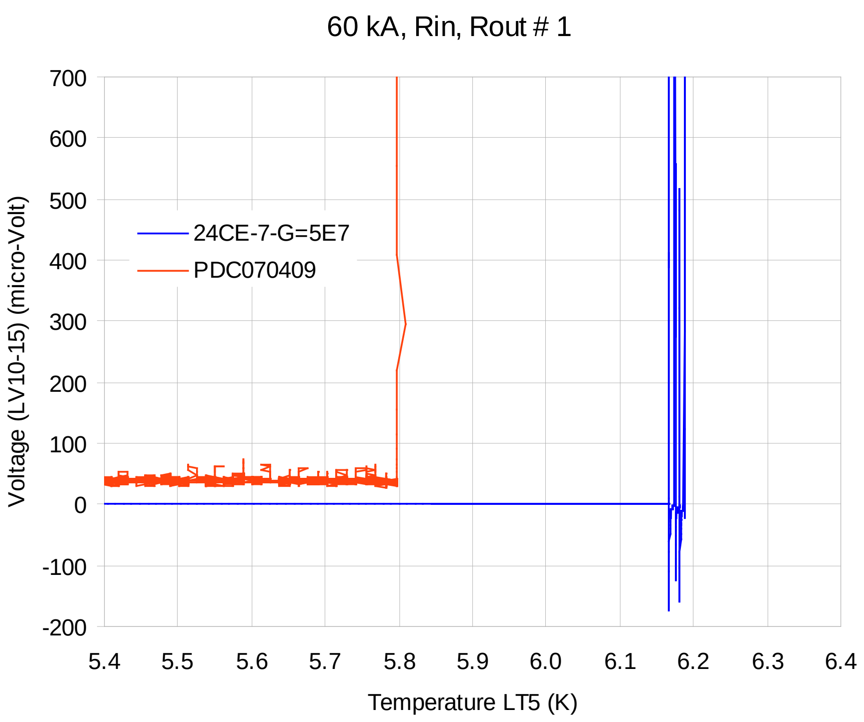
CICC discretization

- A simplified model of the cable has been adopted with 24 CEs.
- The model considers the “most loaded” sub-petal discretized with 3 sub-sub-petals, and 4 triplets [Zanino_SUST_2011].
- For each CE, the spatial dependence of the unknown current was discretized by means of 201 equally spaced nodes, which are sufficient to guarantee the convergence of the method.



Analysis of sudden quench-1

- A reference set for the simulation parameters has been defined (# 1 of contact resistance values, G_{cc} = 5×10^7 S/m^2, G_{cj} = 4.5×10^4 S/m^2).
- Spikes and sudden quench are reproduced.
- Spikes are too high
- T_q is too high

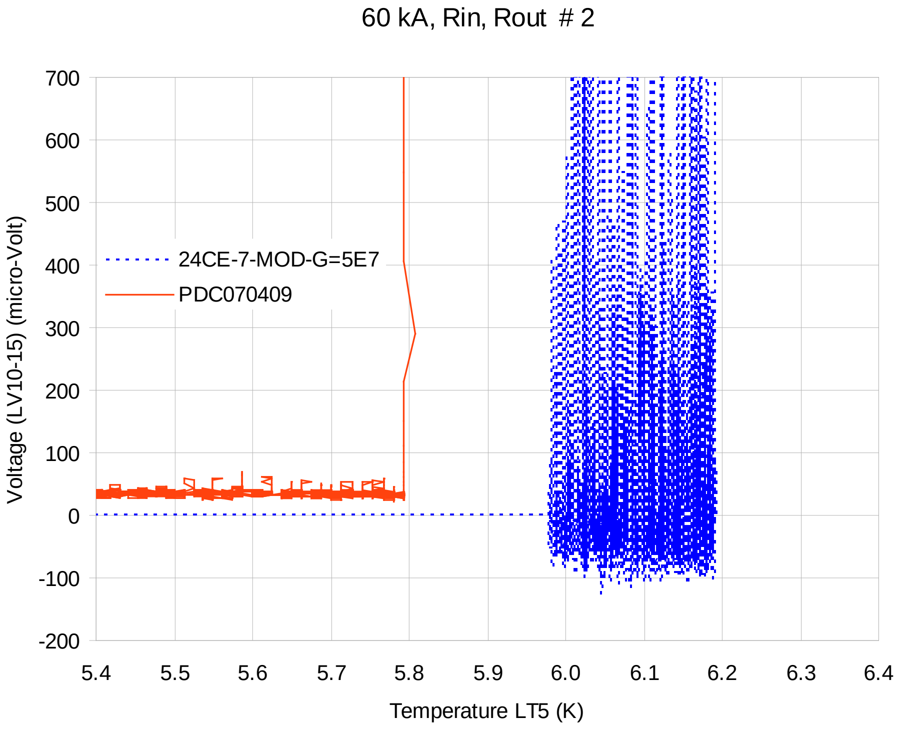


Analysis of sudden quench-2

- **Why T_q is too high ?**

Is current distribution too uniform ?

- The simulation has been done with the same cable model but **set # 2** of contact resistance values (random effects)
- The current imbalances increase
- Spikes start at lower temperature
- T_q is not reduced



Analysis of sudden quench-3

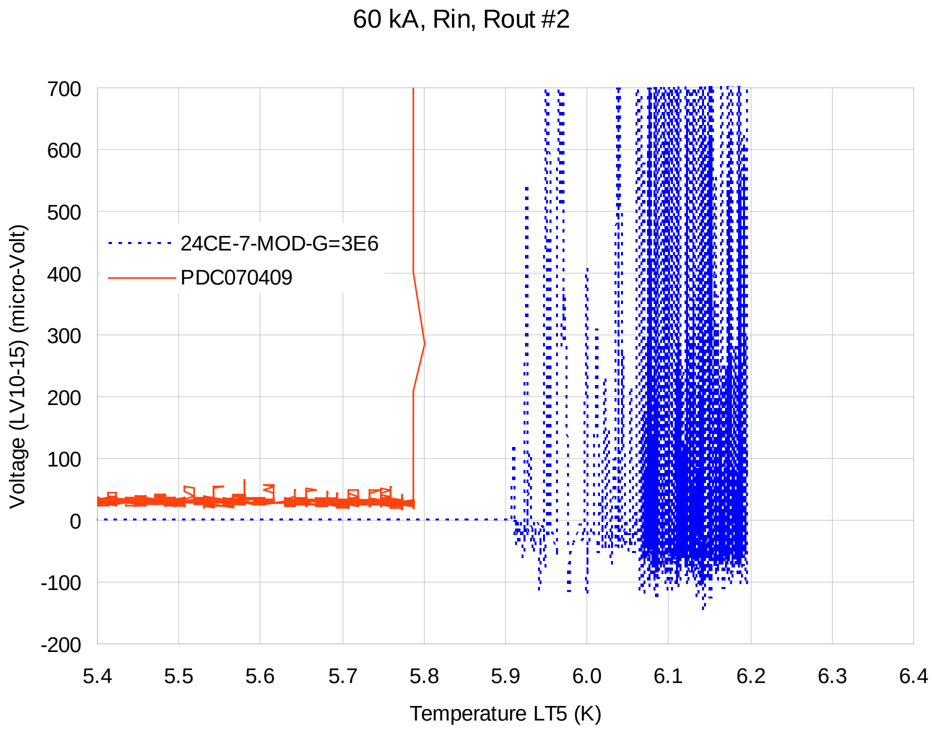
•Why T_q is too high ?

Is transverse conductance in the cable too high ?

•The simulation has been done with #2 of contact resistance value and **Gcc reduced by factor ~ 10 to 3×10^6 S/m^2**

• only 0.1 K difference between experimental T_q and the temperature where the first spike is present

•T_q is not reduced

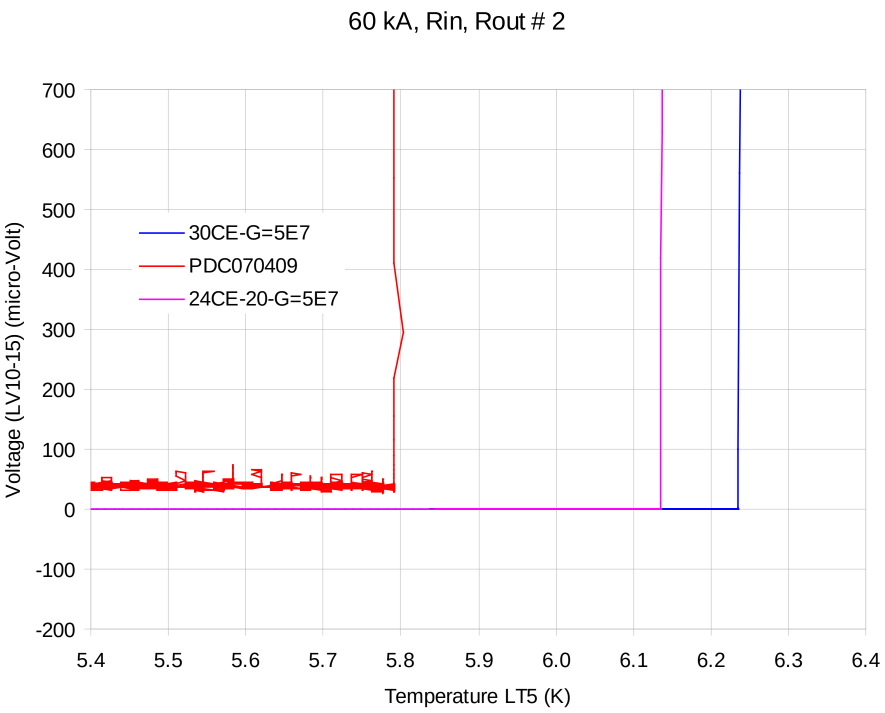


Analysis of sudden quench-4

- **Why T_q is too high ?**

Is discretization not sufficient ?

- The simulation has been done with set # 2 of Joint contact resistance, $G_{cc} = 5\times10^7$ S/m^2, but **different discretizations**
- Sub-petal 20 (instead of sub-petal 7) is discretized
- T_q is reduced
- Spikes are not present

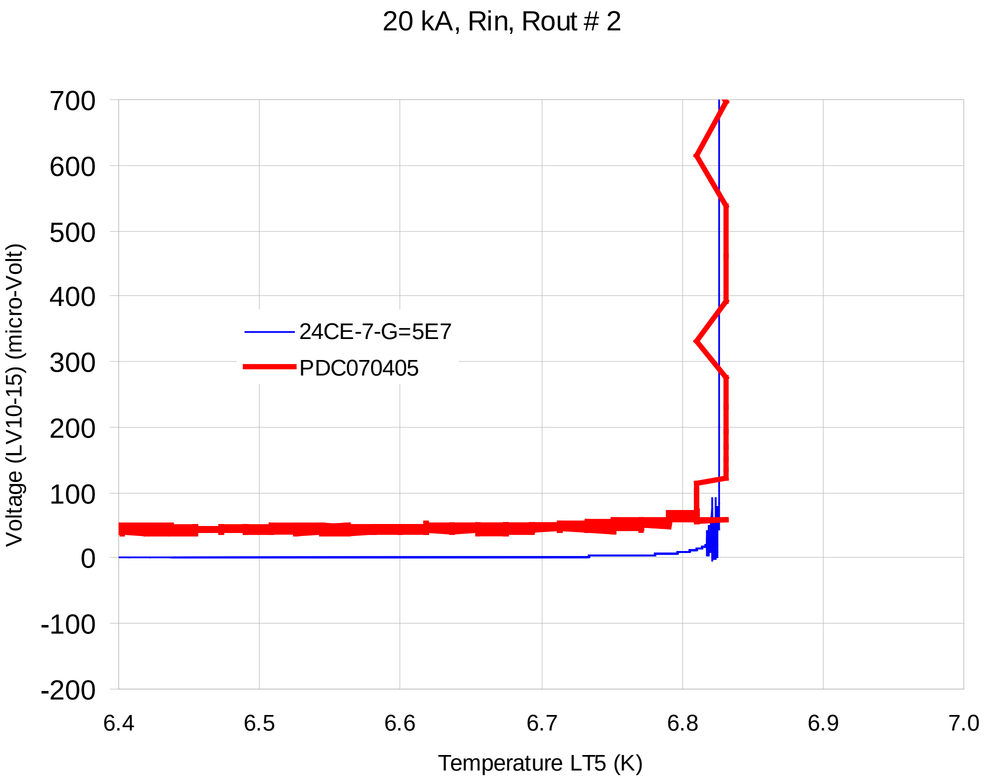


Analysis of Tcs @ 20 kA

- **Why T_{quench} is too high ?**

 Is scaling law wrong ?

- The simulation has been done with set # 2 of Joint contact resistance, $G_{cc} = 5 \times 10^7$ S/m^2, but with a 20 kA transport current
- Calculated Tcs fits well with the experimental one. Some small spikes are present only after T_{cs} is reached ($E > 10\ \mu V/cm$)



Conclusion and perspectives

- The multiphysics THELMA code has been used to self-consistently simulate the transition of full-size NbTi ITER CICC.
- @ low transport current the smooth transition is accurately reproduced.
- @ high transport current:
  - the sudden nature of the transition of is reproduced
  - the thermo-electrical nature of the voltage spikes precursors is explained and qualitatively captured
  - The effect of different uncertainties in the model (conductance values, random effects, local temperature distribution) is presently under investigation to explain the discrepancy in Tq

Thank you very much

Summary of PCI-FSJS DC data

Table 2.1: PFCI-FSJS, Strand data

	Left leg	Right leg
Strand diameter (mm):	0.733	0.733
Barrier nature:	Nickel Coating	Nickel Coating
Strand Manufacturer	VNIIKP	VNIIKP

Table 2.3: PFCI-FSJS, left leg cable, measured contact resistance values (from [22])

Measurement type		R_c under full load (nΩ·m)		
		ne	ne	op
Inter-strand	$R_{c_{is}}$	9180	-	-
Inter-subpetal	$R_{c_{ib}}$	2570	2920	3360
Inter-petal	$R_{c_{ip}}$	16590	13570	16320

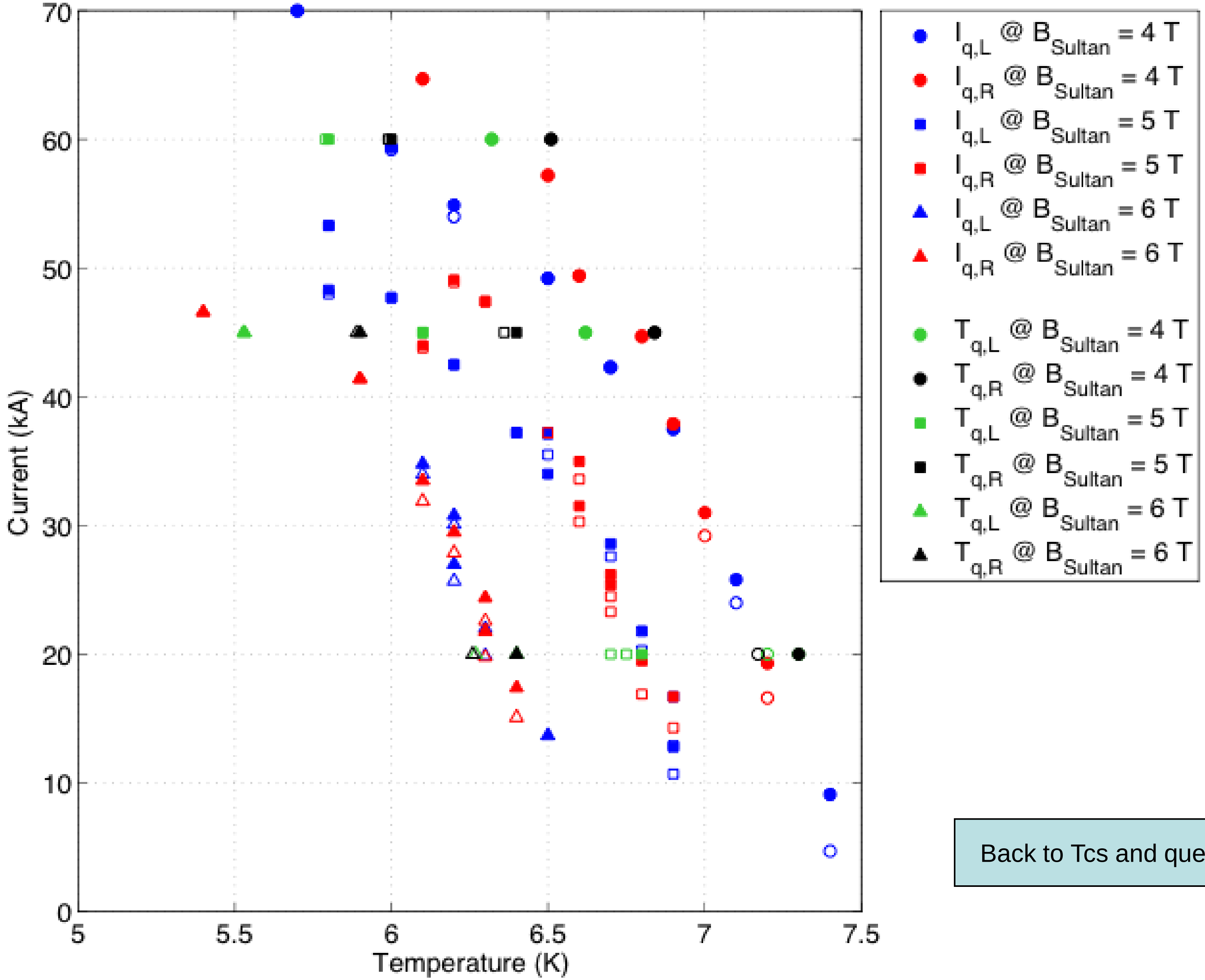
Table 2.12: PFCI-FSJS joint and terminations main geometrical, electrical and measured data

	Inlet termination	Lower joint	Outlet termination
Elementary saddle net length (mm)	420	89.6	420
N. of elementary saddles per termination and joint	1	5	1
N. of saddle insulating breaks	0	4	0
Intermediate insulating gap thickness (each) (mm)	-	1	-
Total joint and termination length (mm)	420	452	420
Saddle out-of-plane length (mm)	39	39	39
Saddle in-plane length (mm)	17.6	35.2	17.6
Sleeve inner diameter (mm)	34	34	34
Sleeve outer diameter (mm)	42	42	42
In-plane distance of sleeve centre (mm)	17.4	17.4	17.4
Saddle resistivity @ 4.5 K (nΩ· m)	0.207	0.352	0.207
Sleeve resistivity @ 4.5 K (nΩ· m)	9.60	9.60	9.60
Joint/termination measured resistance (nΩ)	18	9	7

Table 2.2: PFCI-FSJS, THELMA cable bundles geometrical data

		Left leg (with petal wrappings)	Right leg (without wrappings)
First stage (triplet) (1x3)	Twisting pitch (mm):	42	42
	Void fraction:	-1	-1
	Innermost bundle diameter (mm):	0.0	0.0
	Average bundle diameter (mm):	0.846	0.846
	Outermost bundle diameter (mm):	1.39	1.39
	Overall net bundle perimeter (mm):	6.91	6.91
	Overall net bundle area (sqmm):	1.26	1.26
Second stage (1x3x4)	Twisting pitch (mm):	86	86
	Void fraction:	0.42	0.42
	Innermost bundle diameter (mm):	0.0	0.0
	Average bundle diameter (mm):	2.2	2.2
	Outermost bundle diameter (mm):	3.33	3.33
	Overall net bundle perimeter (mm):	27.6	27.6
	Overall net bundle area (sqmm):	5.06	5.06
Third stage (subpetal) (1x3x4x4)	Twisting pitch (mm):	122	122
	Void fraction:	0.42	0.42
	Innermost bundle diameter (mm):	0.0	0.0
	Average bundle diameter (mm):	4.33	4.33
	Outermost bundle diameter (mm):	6.67	6.67
	Overall net bundle perimeter (mm):	110.5	110.5
	Overall net bundle area (sqmm):	20.25	20.25
Fourth stage (petal) (1x3x4x4x5)	Twisting pitch (mm):	158	158
	Void fraction:	0.42	0.42
	Innermost bundle diameter (mm):	0.0	0.0
	Average bundle diameter (mm):	7.45	7.45
	Outermost bundle diameter (mm):	14.91	14.91
	Overall net bundle perimeter (mm):	552.6	552.6
	Overall net bundle area (sqmm):	101.27	101.27
Fifth stage (cable) (1x3x4x4x5x6)	Twisting pitch (mm):	489	540
	Void fraction:	0.36	0.36
	Innermost bundle diameter (mm):	12	12
	Average bundle diameter (mm):	24.4	24.4
	Outermost bundle diameter (mm):	36.8	36.8
	Overall net bundle perimeter (mm):	2810	2810
	Overall net bundle area (sqmm):	608	608

Summary of PCI-FSJS results



Back to Tcs and quench analysis

Joint contact resistances-1

- *Spot* and the *distributed* contact:

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decompressor
are needed to see this picture.

QuickTime™ and a
decompressor
are needed to see this picture.

Back to joint model

Cable model - 3

- The model of the cable is derived from Maxwell Equations in the form of a distributed parameter model.
- After a finite element discretization in the space variable the equations of the model have the following form:

$$\mathbf{M}\frac{d\mathbf{v\_c}}{dt}=\mathbf{F}(\mathbf{v\_c},\mathbf{v\_T},t) \qquad \mathbf{R}\cdot\mathbf{v\_j}=\mathbf{F\_j}(\mathbf{v\_c},\mathbf{v\_T},t)$$

v_c = vector of current unbalances of all but last the CEs in each node along the cable: (N_ce-1)×N_node components

v_j = vector of currents in the JEs in each node along the cable: N_je×N_node components

v_T = vector of temperature of all the CEs in each node along the cable: N_ce×N_node components

- The system of ordinary differential equations is numerically solved, at each time step, with the actual value of the temperature vector, by means of an implicit 2nd order method.
- The algebraic equation is solved by means of LU decomposition.

Back to EM model

Scaling law

- For each CE the parallel electrical connection between normal matrix and SC material is considered

$$\begin{cases} E = E_c \left(\dfrac{J_s}{J_c(B,T)} \right)^{n(B,T)} = \rho_m(B,T)\, J_m \\ J_s \dfrac{1}{1+\chi} + J_m \dfrac{\chi}{1+\chi} = J \end{cases}$$

- The Bottura scaling law for the NbTi is considered with the parameters as in [Zani et Al., IEEE Trans. **15** 3506-9]

$$t(T) = \frac{T}{T_{c0}}, \qquad B_{c2}(T) = B_{c20}\left(1 - t(T)^{\delta}\right), \quad b(B,T) = \frac{B}{B_{c2}(T)}$$

$$J_c(B,T) = \frac{C_0}{B} b^{\alpha} (1-b)^{\beta} \left(1-t^{\delta}\right)^{\gamma}$$

α= 1.95, β = 2.1, δ = 1.7, γ = 2.1, T_{c0} = 9.03 K,

B_{c20} = 15.06 T, C_0 = 4.1505×10^{11} A T/m^2

- The n-value is a function of Jc

$$n(B,T) = 1 + \left(\frac{Jc(B,T)}{n_1} \right)^{n_2}$$

n_1 = 4.581×10^6 A/m^2

n_2 = 0.5925

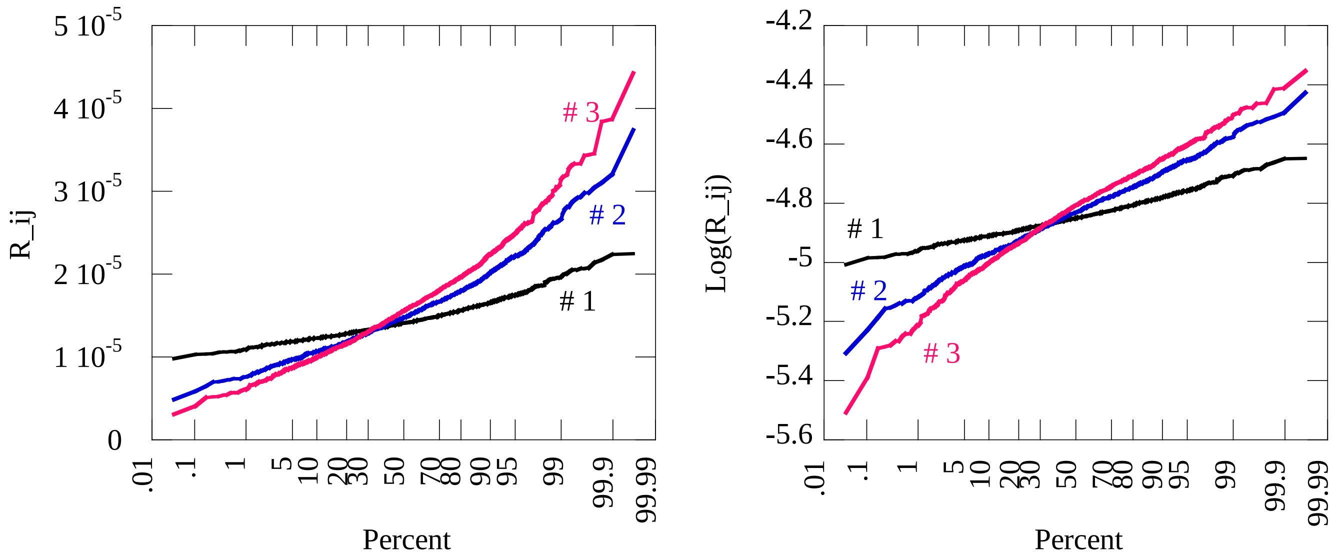
Back to EM model

Inter-cable element equivalent self resistances - 1

- The model has been used to simulate the inter-cable element contact resistances as done by Twente University for the strands of TFPRO2 [Bruzzone_IEEE_J_ASC_2008]-[Van_Lanen_IEEE_J_ASC_2010].

- The upper termination has been considered the cable elements are fed by two, and the corresponding *self resistances Rii* are measured.

Inter-cable element equivalent self resistances - 2

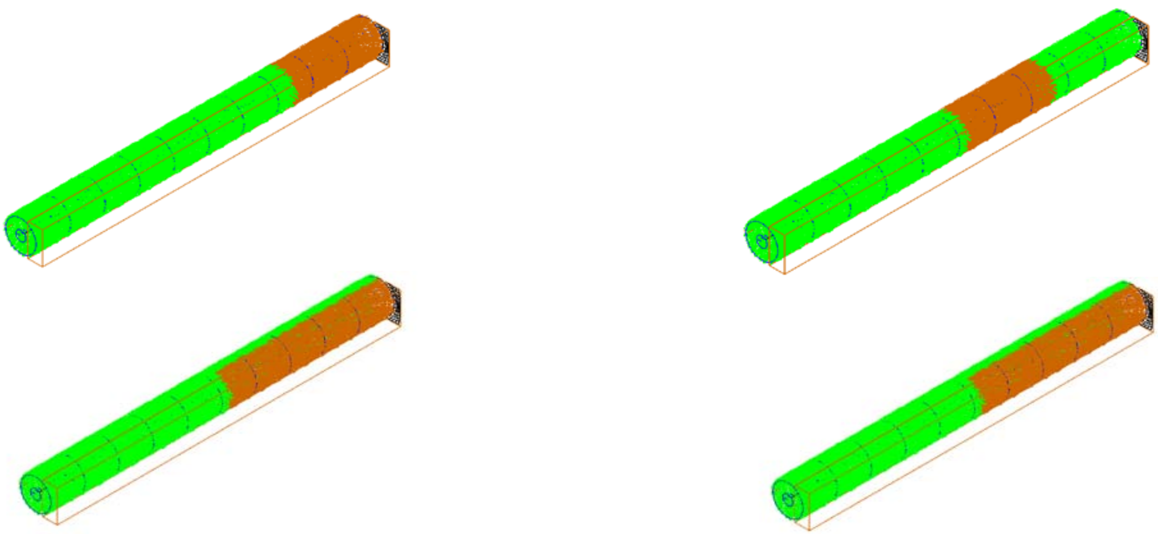


- Both in the absence and in presence of random effects, the computed self resistances are log-normally distributed, as found from Twente measurements [Van_Lanen_IEEE_J_ASC_2010].

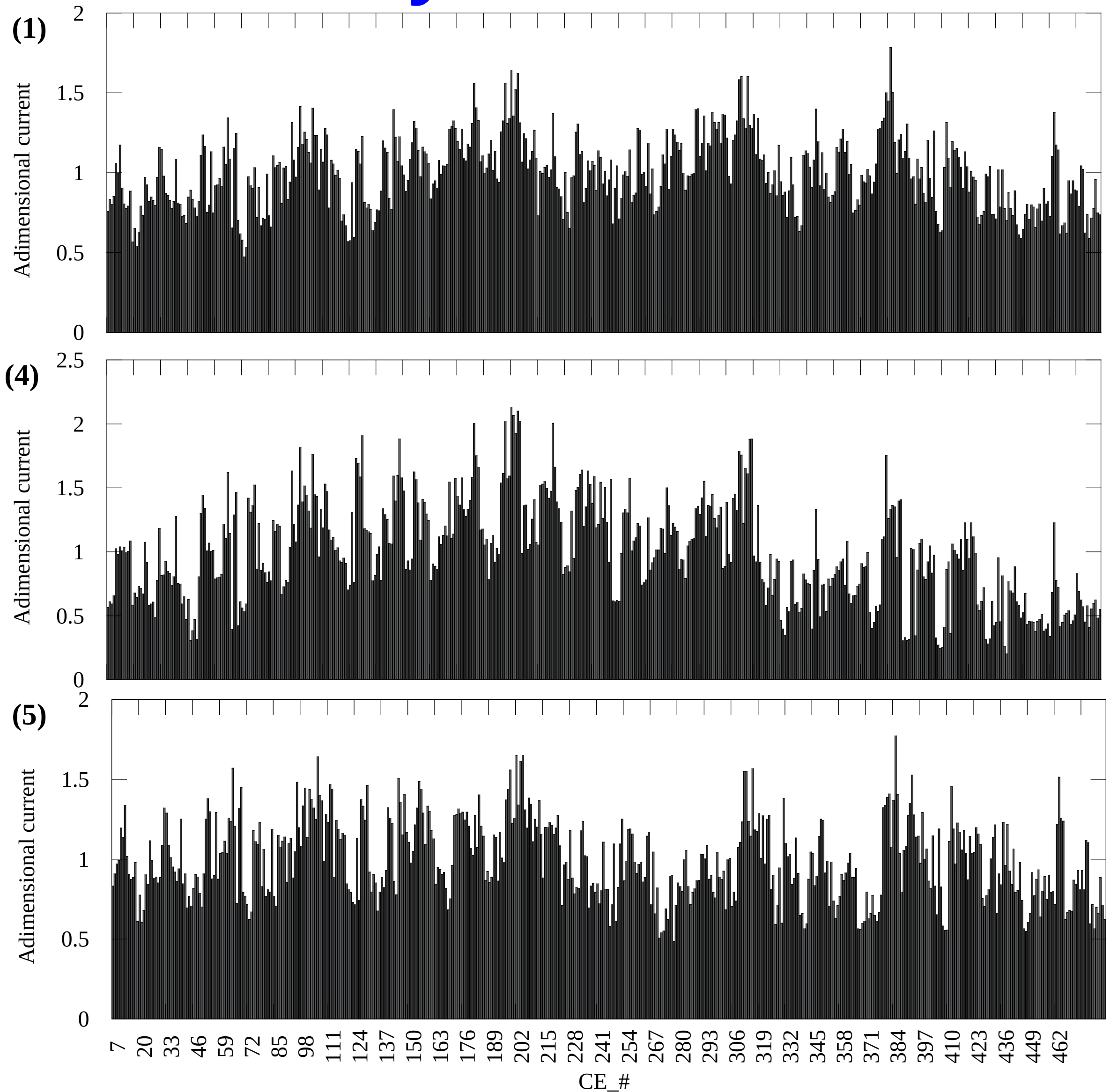
Back

Analysis of joint/termination defects on the sample performances.

- The effect of non conductive zones at the cable-sleeve interface of the termination has been considered also.
- Four defects have been considered:



Analysis of defects-2

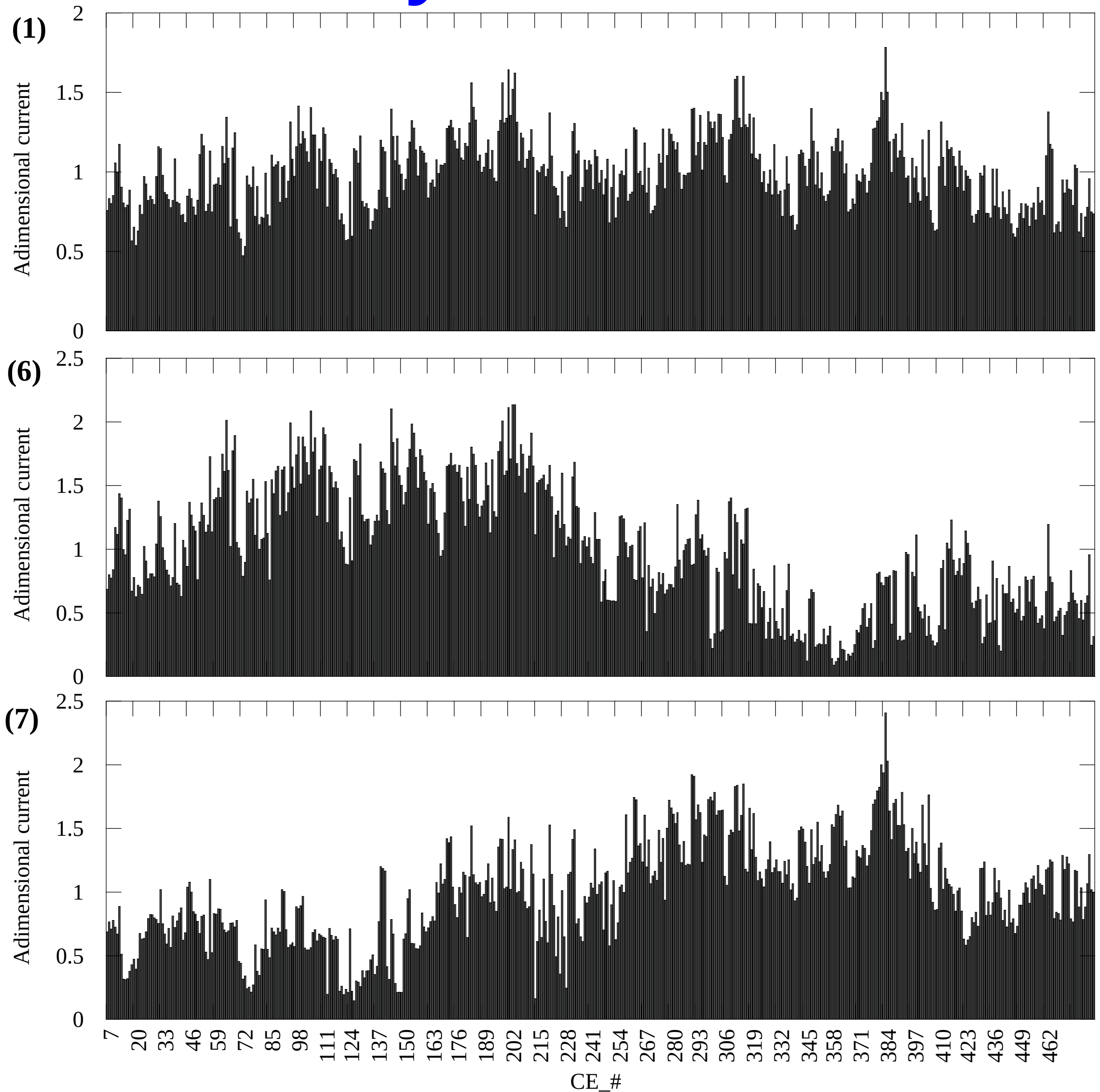


Healthy term.

Defect # 1

Defect # 2

Analysis of defects-3



Healthy term.

Defect # 3

Defect # 4

Back to applications