Analytical modeling of coupling losses in CICCs, extensive study of the COLISEUM model

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OUTLINES

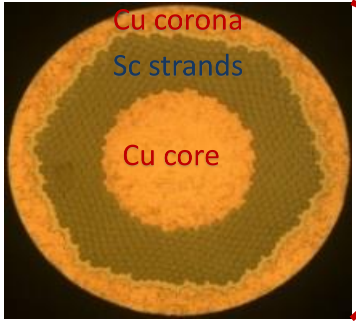
I – GENERAL CONTEXT

II – EXTENSIVE STUDY OF THE COLISEUM MODEL

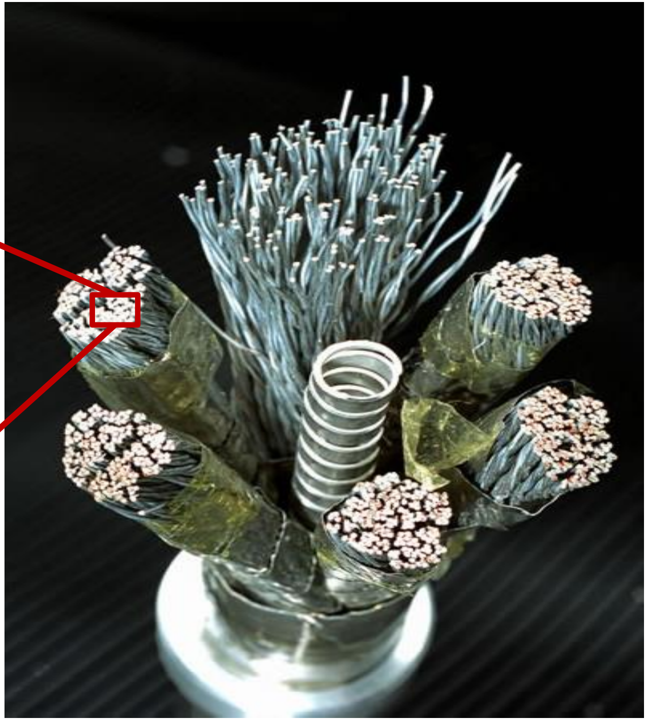
III – ANALYTICAL DEVELOPMENTS

IV – CONCLUSION

CICC (Cable in Conduit Conductor)



Superconducting strand

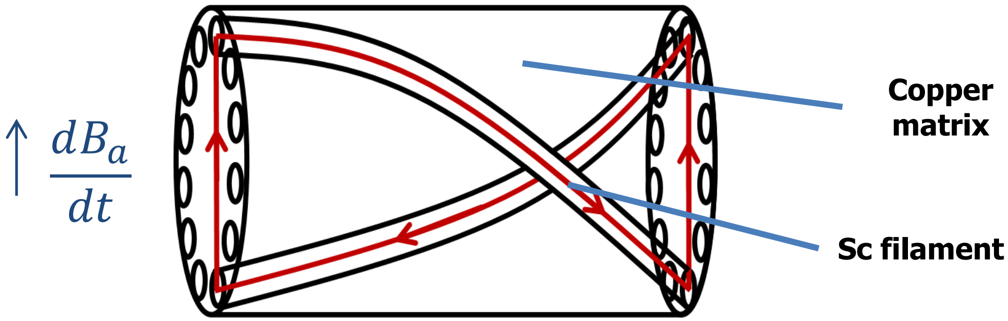


ITER TF cable

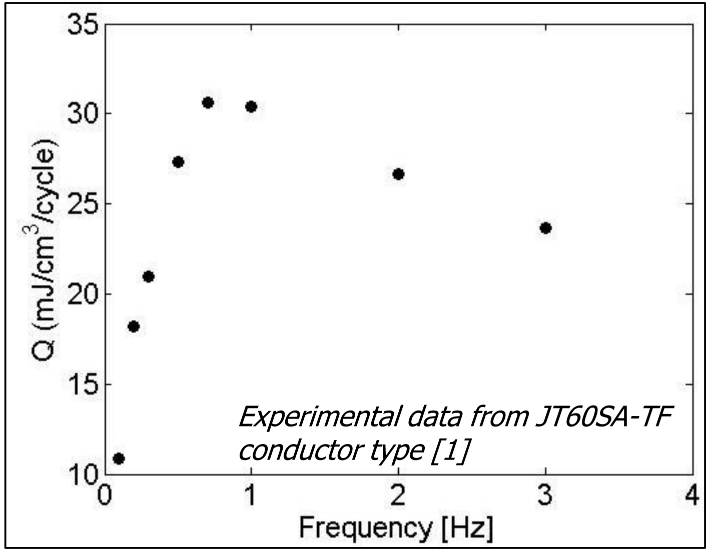
ITER CS cable

Superconducting strands twisted to form stages

CICC and coupling losses



- Induced current loop characterized by their time constant, τ **[ms]**
- Shielding coefficient, **$n\kappa$ [-]**



Coupling losses

$$P = \sum_j \frac{n\kappa_j \tau_j}{\mu_0}\left(\frac{dB_i}{dt}\right)^2$$

where

> τ, the time constant of the current loop [ms]

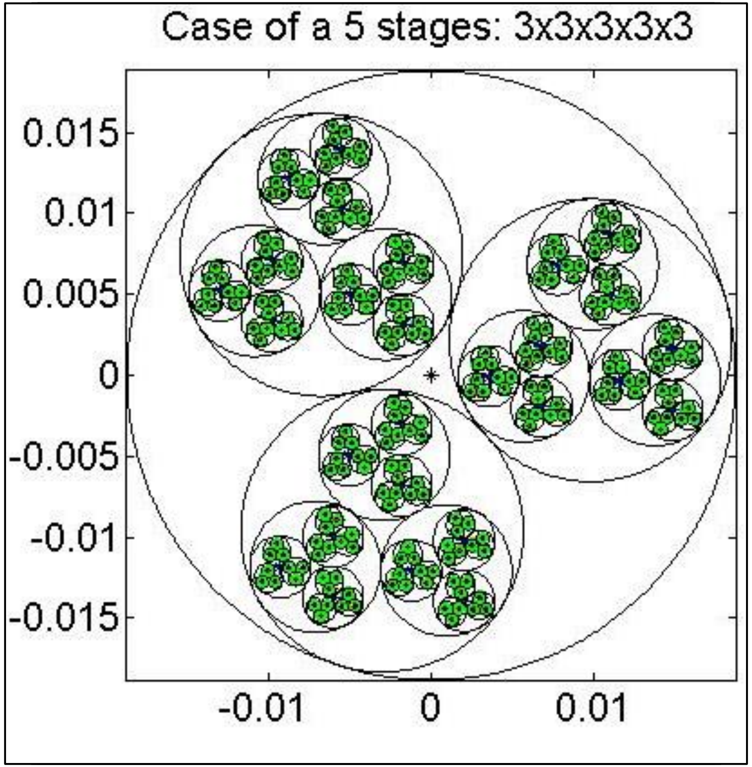
> $n\kappa$, the shielding coefficient [-]

[1] M. Chiletti, PhD thesis, 2020.

COLISEUM (**CO**upling **L**osses analyt**I**cal **S**taged cabl**E**s **U**nified **M**odel)

Key features of the model

- **Analytical**
- **Predictive**
- **At various scale**
  - Geometrical parameters
  - Inter-stages transverse conductances
- **One (nκ,τ) couple per stage**



I – GENERAL CONTEXT

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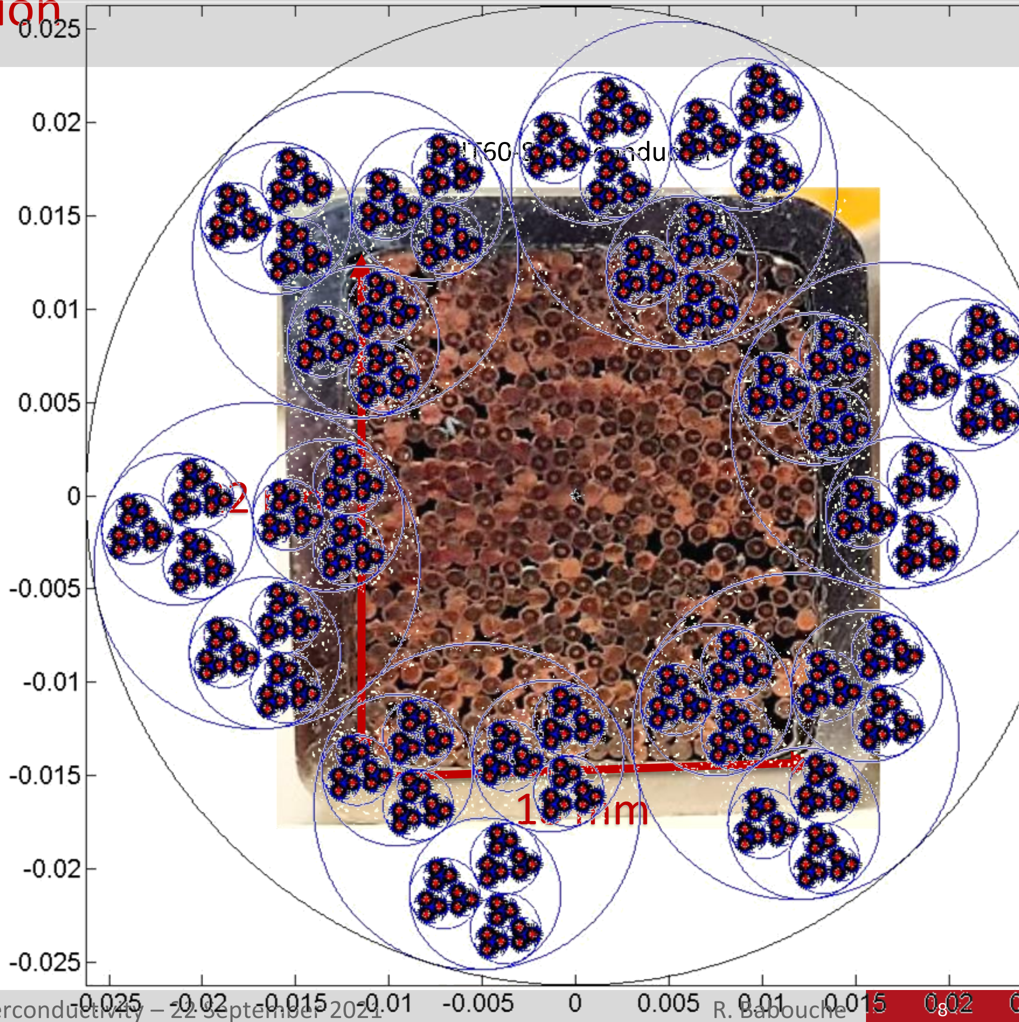
II. Study in non tangential condition

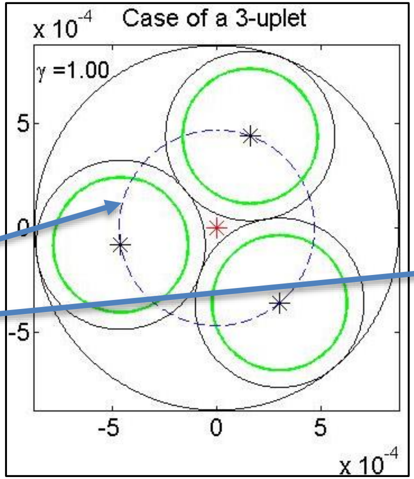
- **Until now**
  - The COLISEUM model considered unrealistic virtual cables: simulation with tangent tubes

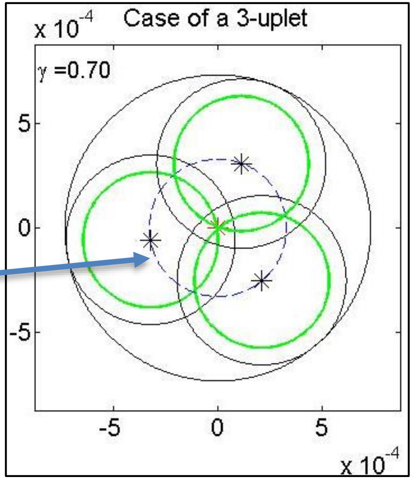
- **From now**
  - Study of the model in non tangential conditions. Getting closer to real compacted cables



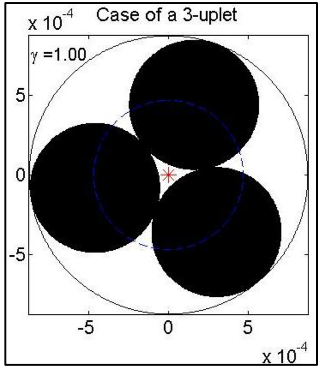
- **Each stage is characterized by a penetration coefficient γ**
  - $\gamma \in [0;1]$
  - $\gamma = 1$: tangential condition
  - $\gamma = 0$: fully penetrated

$$\gamma = \frac{R_{c\ tangent}}{R_c}$$





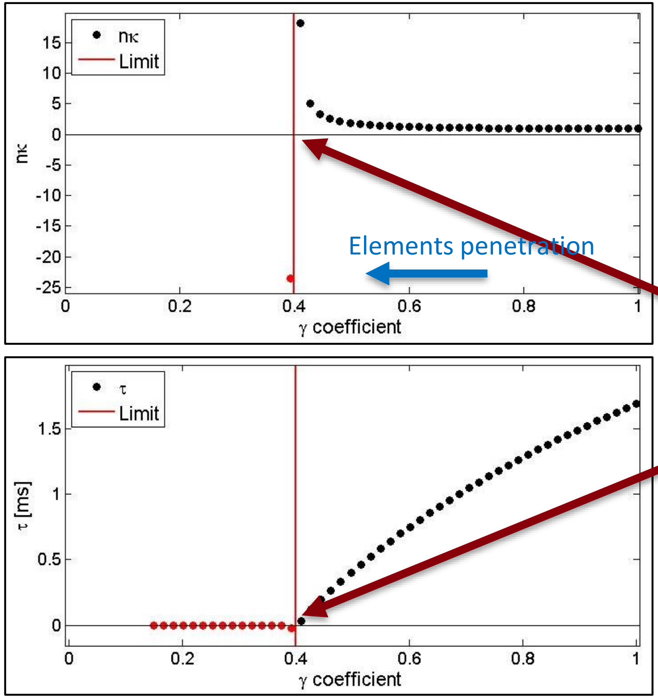
- **Void rate indicator**
  - VR ∈ [0;100] %
  - Practical indicator
  - Ratio of the circumscribed area and the area occupied by the elements



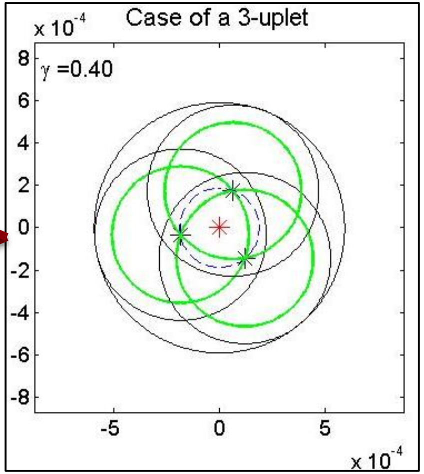
Parametric study on
Shielding coefficient, $n\kappa$ [-]
Time constant, τ [ms]

II. Study in non tangential condition

- We will consider that the model reached its limit if $n\kappa$ and/or τ are negative or null
  - Case of a one stage cable, x3
  - Parametric study on $n\kappa$ and τ

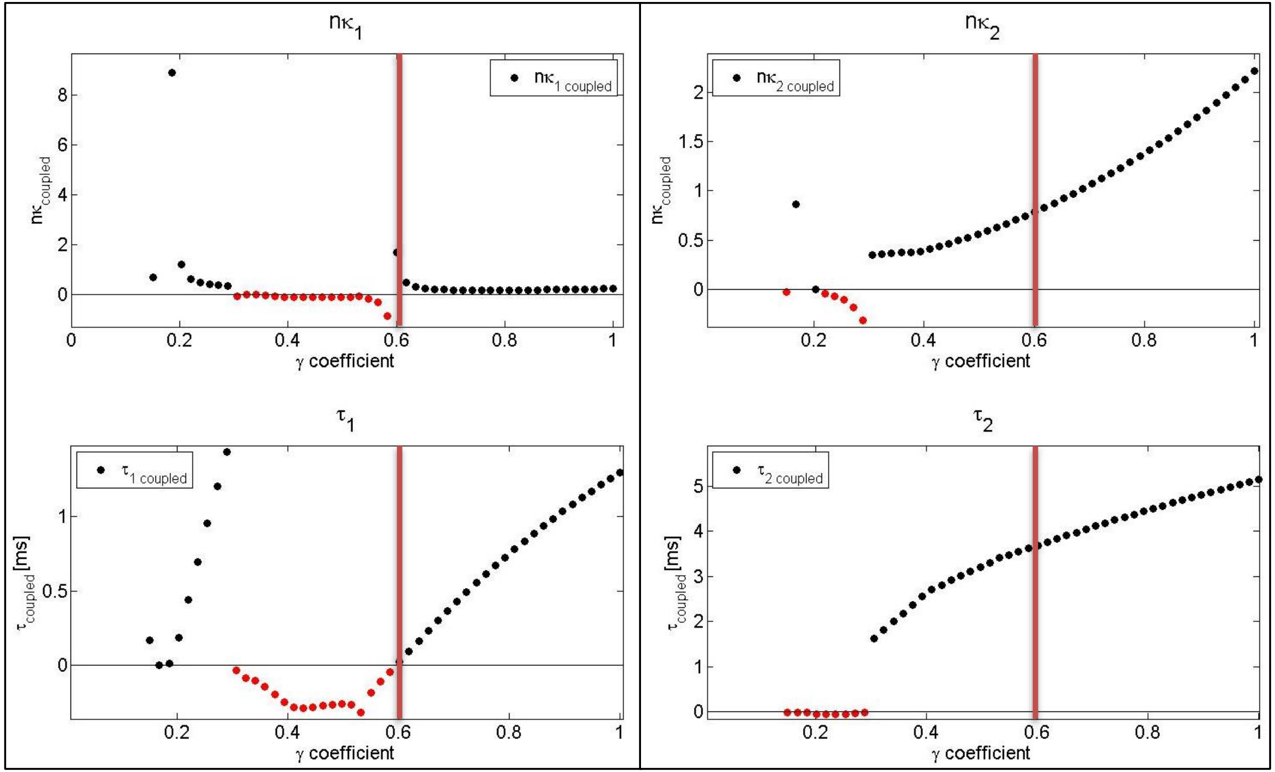


- Looking for specific limit

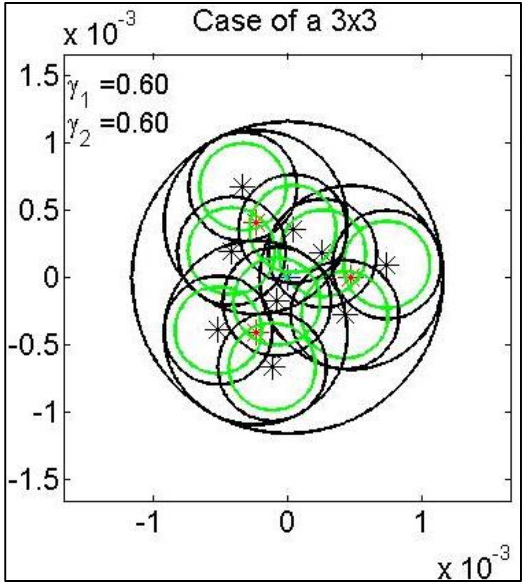


II. Study in non tangential condition

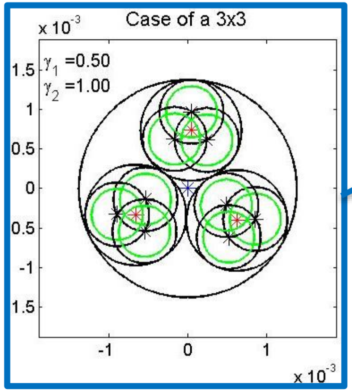
- We will consider that the model reached its limit if $n\kappa$ and/or τ are negative or null
  - Case of a two stages cable, 3x3



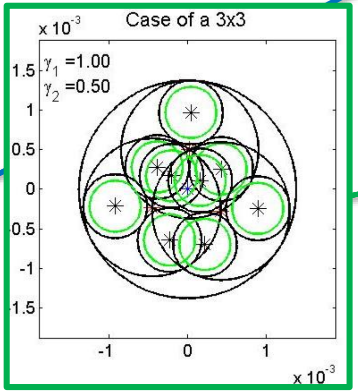
- Peculiar case for $\gamma_1 = \gamma_2$
- Looking for specific limit



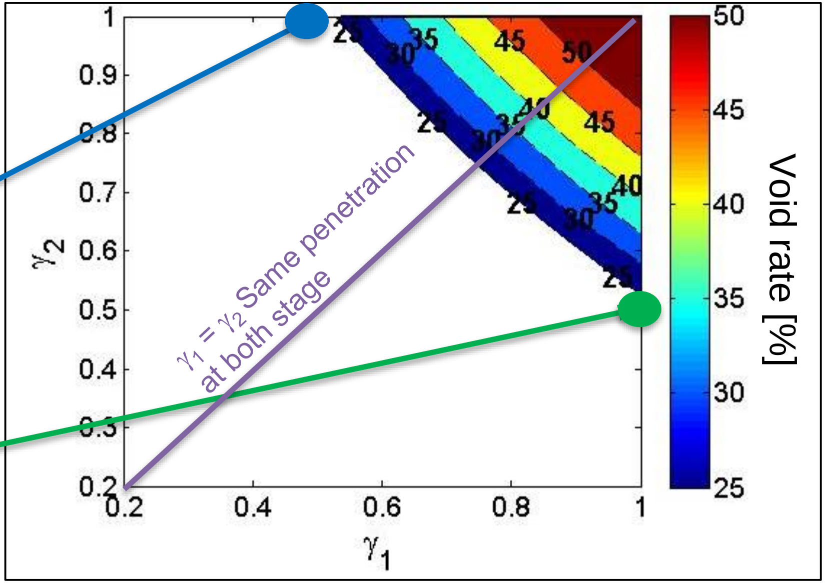
- Application of typical void rate value
  - Case of a two stages cable, 3x3
  - One γ coefficient per stage
    - Uncoupling γ_1 and γ_2
  - VR between 25 and 50 %



γ_1 affected

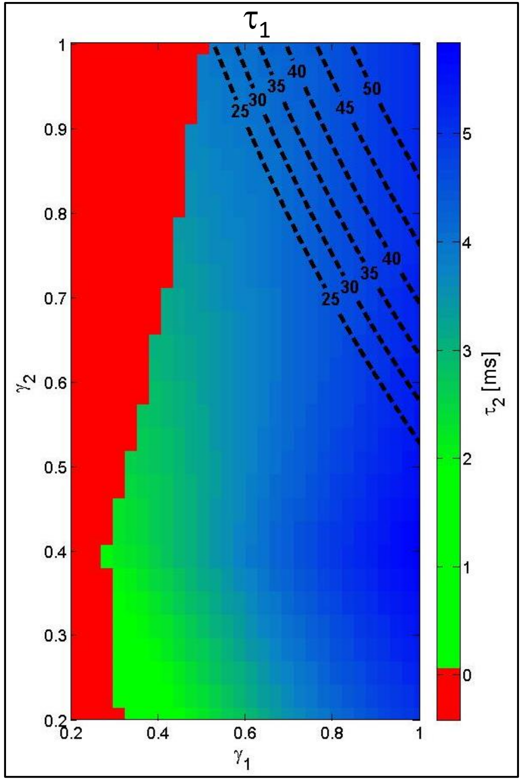


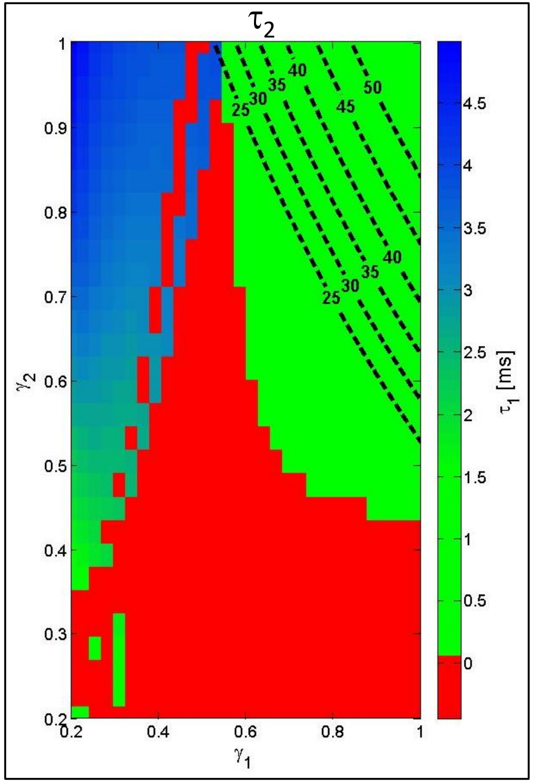
γ_2 affected



Void rate as a function of the penetration coefficients combinations

- Behaviour of the magnetic parameters
  - Case of a two stages cable, 3x3
  - Time constant, τ [ms]

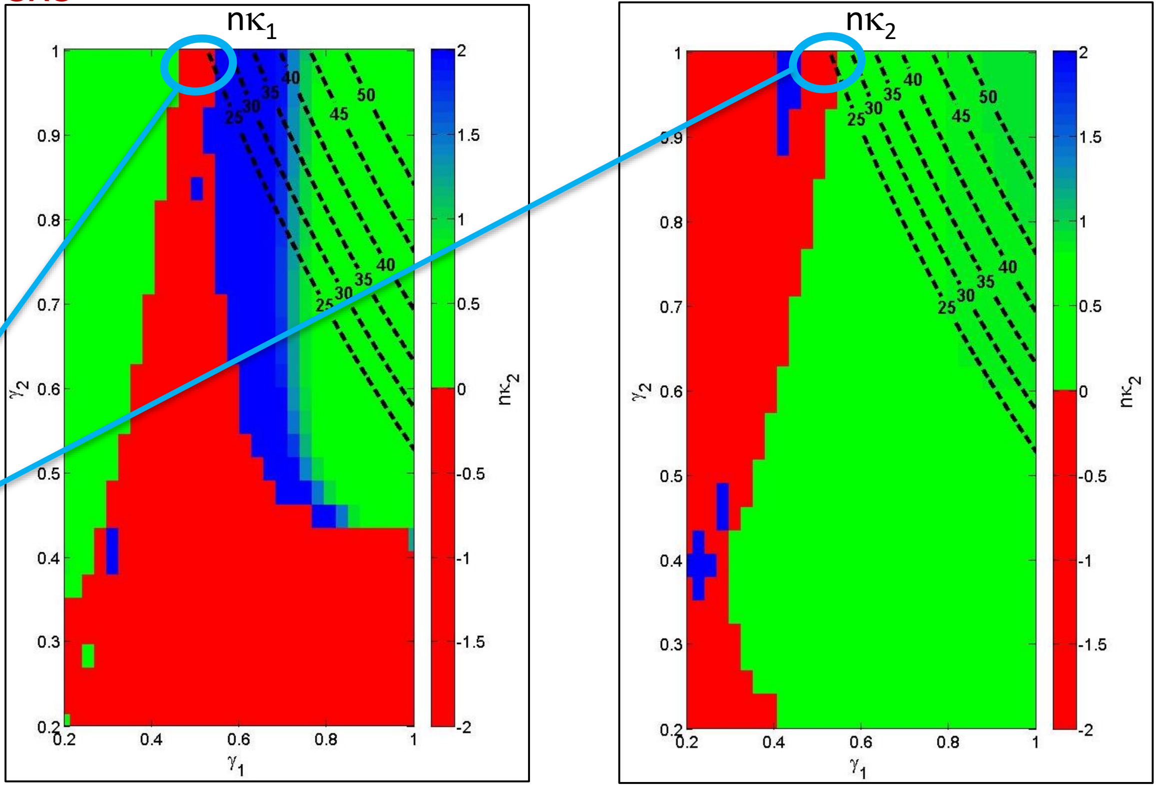




- Map of the time constants, τ_1 and τ_2
- Void rate overlap
- Negative values of τ are overlapped in red

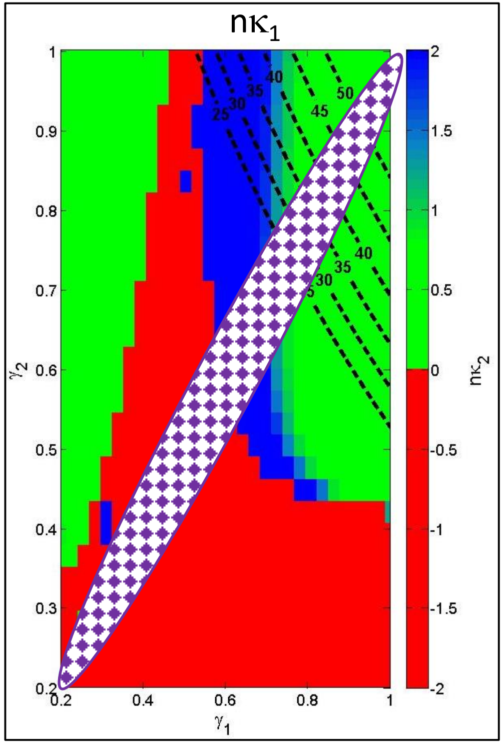
- Behaviour of the magnetic parameters
  - Case of a two stages cable, 3x3
  - Shielding coefficient, nκ [-]

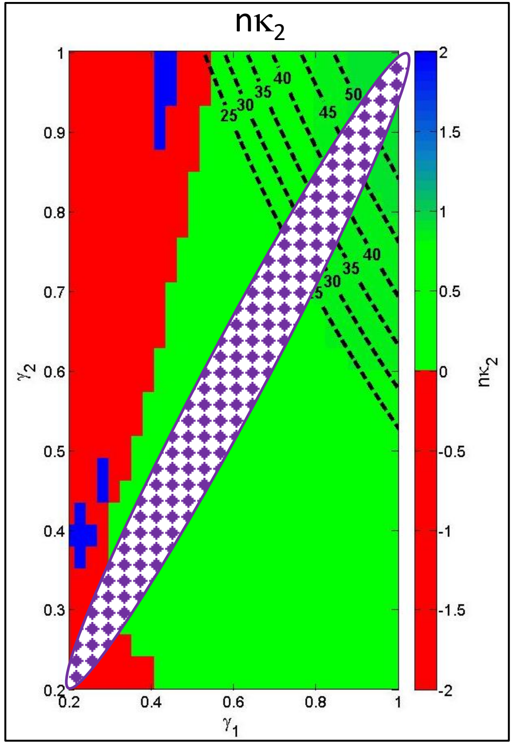
- Map of the shielding coefficients, $n\kappa_1$ and $n\kappa_2$
- Negative values of nκ are overlapped in red
- Extreme cases are crossing critical areas



Conclusion

- In reality, void rate should not be far from the $\gamma_1 = \gamma_2$ area
- Consecutive stages should have similar penetration coefficients
- For typical values of void rate, the COLISEUM model stays far from the critical areas





❖ Confident in the results obtained in non-tangential condition
❖ This will be generalized up to the n^th^ stage

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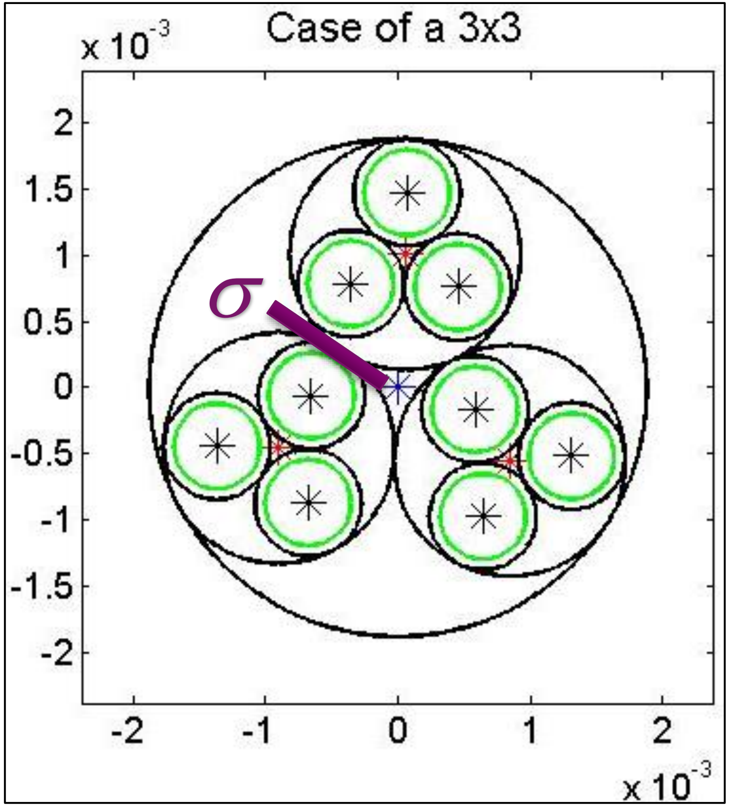
COLISEUM model output

Coupled results and ranks

- Coupled result means that stages are interacting with each other
- The transverse conductance σ is ≠ 0
- No more possible to attribute one (nκ,τ) couple per stage
- Speak about coupled ranks

❖ **Find an indicator to determine the influence of each stage in each coupled rank**



III. Development of the current influence indicator

Method

- Calculation made on current combinations

Analytical background

$$[I_p]_j + [\tau_c]_j\,[\dot{I}_p]_j = [W]_j[Y]_j\dot{B}_a$$

$$where,\quad [I_p]_j = [W]_j[I] = \sum_{k=1}^{n} W_{jk}I_k$$

Choosen convention to express the contribution

Normalized coefficient C_{jk}

$$C_{jk} = \left(\frac{W_{jk}}{\sqrt{\sum_{k=1}^{n}(W_{jk})^2}}\right)^2 = \frac{(W_{jk})^2}{\sum_{k=1}^{n}(W_{jk})^2}$$

- W_{jk} can be seen as combination coefficient
- C_{jk} refers to the influence of the current of the k^{th} stage to the j^{th} coupled rank

Application

- 3x3x3x3x3 layout

Red: Dominant stage

Coupled ranks

nκ	τ_c [ms]	Current influence [%]				
0.05	1.19	97.6	2.4	0.0	0.0	0.0
0.08	4.11	61.8	37.6	0.7	0.0	0.0
0.17	12.09	5.2	58.1	35.8	1.0	0.0
0.11	32.62	0.1	6.3	58.2	34.7	0.7
0.90	93.40	0.0	0.0	3.9	46.1	49.9

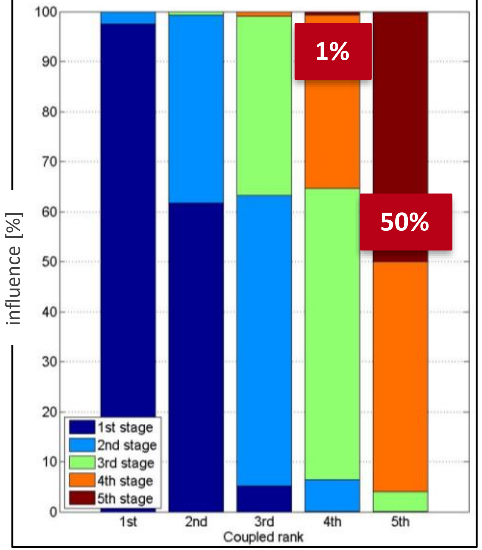
- Current influence not directly linked to the magnetic coefficients nκ and τ, but to the currents.
- Dominant stages exist

Parametric studies conducted on the current influence indicator

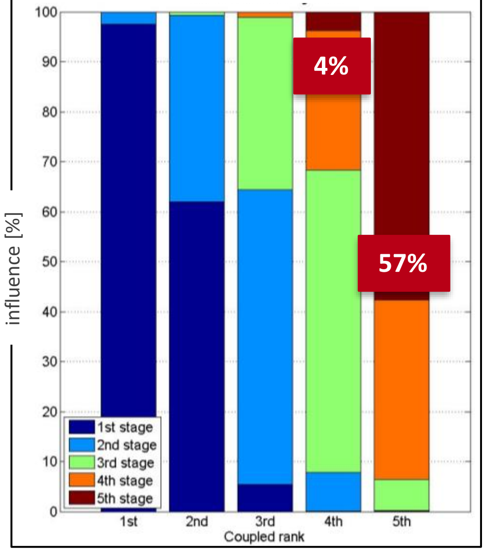
Current influence as a function of the multiplicity

- Example of a 5 stages cable
- Dominant stages exist
- The higher, the larger the contribution

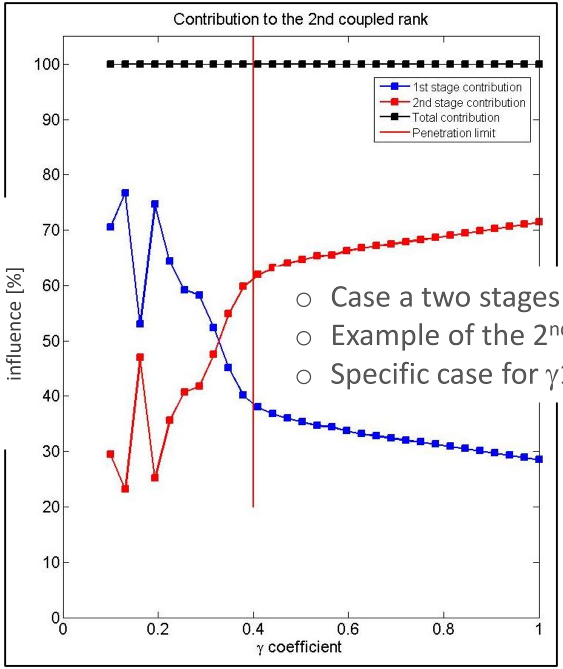
3x3x3x3x3 layout



3x3x3x3x6 layout



Current influence behaviour in non tangential conditions



- Case a two stages cable, 3x6 layout
- Example of the 2nd coupled rank
- Specific case for $\gamma 1 = \gamma 2$

Conclusion and perspectives

Conclusion

- Study of the model in non-tangential conditions
  - Limit identified
  - Far from the usual cases. Confident in the model to generalized this study for a n stages cable
- Analytical developments
  - A new indicator of the current influence
  - A new tool to be explored and developed

COLISEUM future developments

- Background work on the model
- Crosscheck with experimental data
- Use of effective geometrical and electrical inputs (tomography, inter-stage conductance measurement)
- Experimental campaign on various CICCs design at the JOSEFA test station @Cadarache

Thank you for your attention

BACK UP SLIDES

Analytical background

Real space

$$[I]+[\tau][\dot{I}]=[Y]\dot{B_a}$$

$[\tau]$: n − by − n time constant matrix

$\dot{B_a}$: fist derivative of an exiter term

Eigen space

$$[I]+[V][\tau_c][V]^{-1}[\dot{I}]=[Y]\dot{B_a}$$

where, $[\tau]=[V][\tau_c][V]^{-1}$

$$[I_p]+[\tau_c][\dot{I_p}]=[W][Y]\dot{B_a}$$

where, $[V]^{-1}[I]=[I_p]$
$[V]^{-1}=[W]$

$$[I_p]_j+[\tau_c]_j\,[\dot{I_p}]_j=[W]_j[Y]_j\dot{B_a}$$

where, $[I_p]_j=[W]_j[I]=\sum_{k=1}^{n}W_{jk}I_k$

Choosen convention to express the influence

$$C_{jk}=\left(\frac{W_{jk}}{\sqrt{\sum_{k=1}^{n}\left(W_{jk}\right)^2}}\right)^2=\frac{\left(W_{jk}\right)^2}{\sum_{k=1}^{n}\left(W_{jk}\right)^2}$$

C_{jk} is the contribution of the k^{th} uncoupled stage to the j^{th} coupled rank