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Development of a new generic analytical modeling of AC coupling losses in cable-in-conduit conductors

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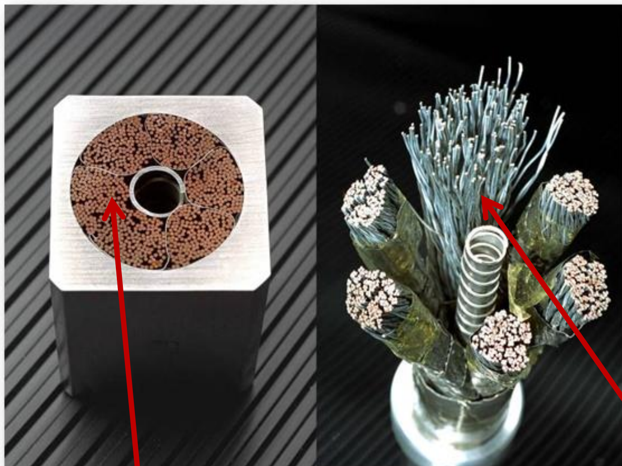
Cable In Conduit Conductor (CICC) architecture

CICC ITER (CS) :



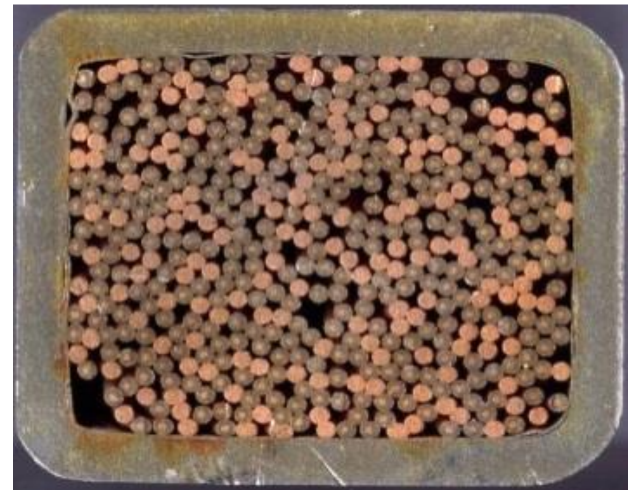
Strands
(Sc composites and Cu)

Strands twisted in several cabling stages (transposition)

- 3 strands twisted together = triplet
- CICC subject to a magnetic field gradient : need for transposition
- Twisting reduces coupling losses
- CICC cooled by supercritical Helium flow at T ~ 4 K

CICC JT-60SA (TF) :

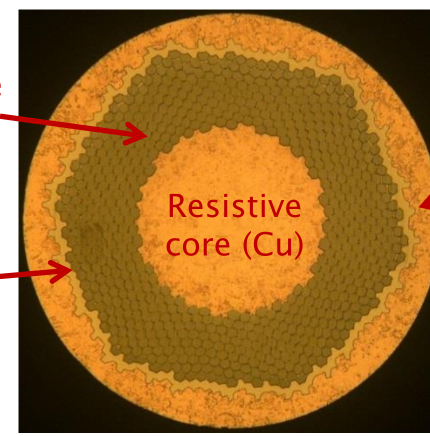
22 mm



26 mm

Filamentary zone
=
NbTi filaments in Cu matrix

Resistive barrier (CuNi)



External resistive shell (Cu)

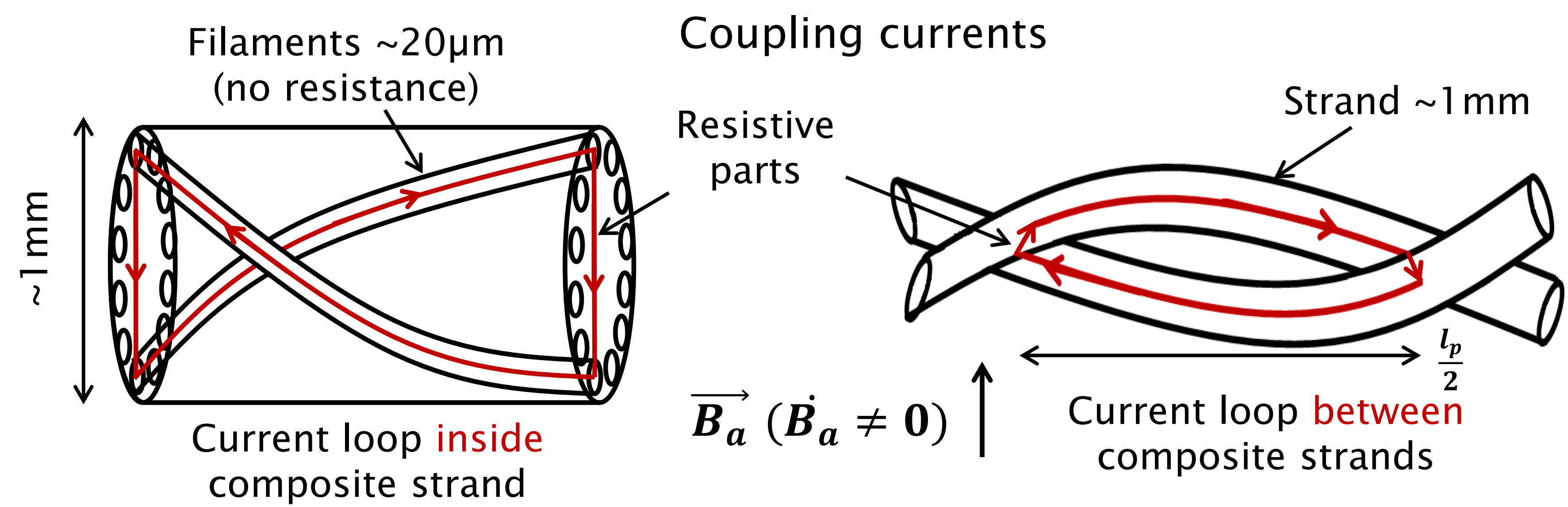
0.81 mm

JT-60SA TF strand

Coupling losses

Inductive phenomenon : time variation of magnetic field induces current loops

→ currents flow through Sc (= no losses) and loop back through Cu (= losses)



Multi-scale phenomenon : coupling currents inside and between strands

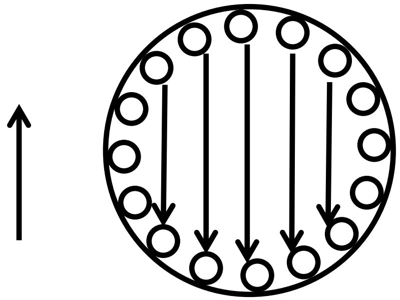
Negative impact on the CICC stability :

- Coupling currents add to the transport current → Sc closer to its critical current
- Coupling losses heat the CICC → Sc closer to its critical temperature

Analytical modeling of coupling losses : existing approaches

At strand scale :

$\overrightarrow{B_a}\ (\dot{B}_a \neq 0)$



Filamentary zone

- Equation : $B_i + \tau \dot{B}_i = B_a$
- Coupling power : $P = \dfrac{2\tau \dot{B}_i^{\,2}}{\mu_0}$
- Time constant : $\tau = \dfrac{\mu_0}{2}\left(\dfrac{l_p}{2\pi}\right)^2 \dfrac{1}{\rho_t}$

B_a : magnetic field created by external source
B_i : internal magnetic field

l_p : filament twist pitch
ρ_t : transverse resistivity

At CICC scale :

- Modeling at strand scale extended to the CICC scale = single time constant approach → insufficient modeling for transient regimes, not predictive
- MPAS model [1] : assumes that each cabling stage taken separately can be represented with only one time constant τ_j and one partial shielding coefficient nk_j

→ For a CICC with N cabling stages, shielding effects are combined and losses are

$$P = \sum_{j=1}^{N} \frac{n\kappa_j \theta_j \dot{B}_{int\,j}^{\,2}}{\mu_0}$$

$n\kappa_j$ and θ_j depend on nk_j and τ_j and are determined from coupling losses measurements → not predictive

[1] : B. Turck, L. Zani, Cryogenics, Vol. 50, 2010

Analytical modeling of coupling losses : our approach

Objective : Build an analytical, predictive and generic model of coupling losses in CICCs

- To enhance the physical understanding of coupling losses (driving parameters ?)
- To create tools which can rapidly be integrated into multiphysics platforms
- To provide fair results with very low CPU consumption

Model developed scale by scale :

- In a previous study [2], we have demonstrated that a cabling stage alone could indeed be represented with one τ and one nk (assumption made by MPAS)

$$\tau_N = \frac{\mu_0}{R\rho_t}\frac{l_c}{\pi}\left(\frac{l_p}{2\pi}\right)^2 \sin^2\left(\frac{\pi}{N}\right)\gamma_N \qquad nk = \frac{N}{\gamma_N}\frac{1}{\left[1+\sin\left(\frac{\pi}{N}\right)\right]^2}$$

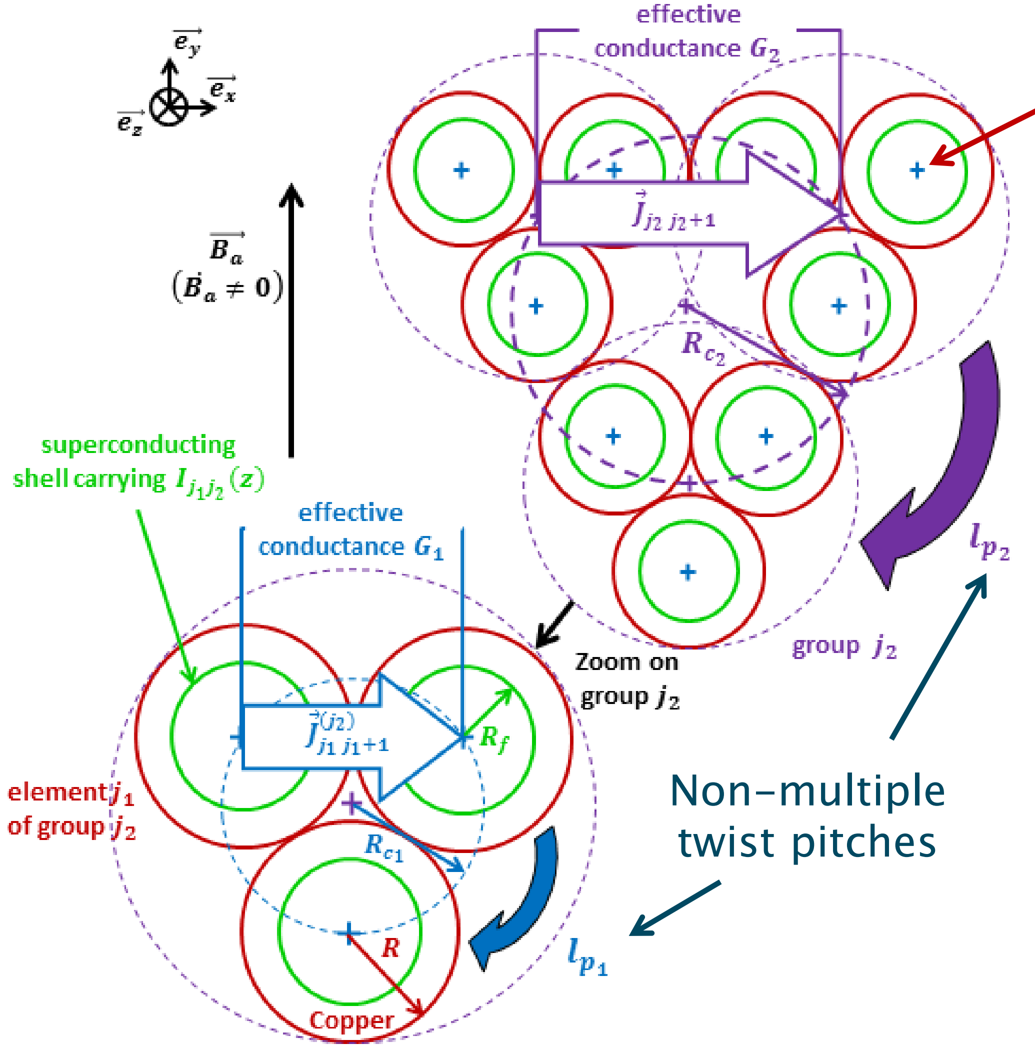
$$\gamma_N = \ln\left(\frac{2R_c}{R_f}\right) - 2\sum_{j=1}^{floor\left(\frac{N-1}{2}\right)} \cos\left(j\frac{2\pi}{N}\right)\ln\left(\sin\left(j\frac{\pi}{N}\right)\right)$$

N : number of elements in stage

- We have now up scaled this study to a two cabling stage conductor (growing complexity due to coupling between two stages) $= N_2$–uplet of N_1–uplets model

[2] : A. Louzguiti et al, I.E.E.E Trans. on App. Superconductivity, 2017

N_2–uplet of N_1–uplets model :



Cross-section of a triplet of triplets of elements
($N_1 = 3$ and $N_2 = 3$)

Element : can be a strand or a simplified sub-petal
=
scale of the element not fixed

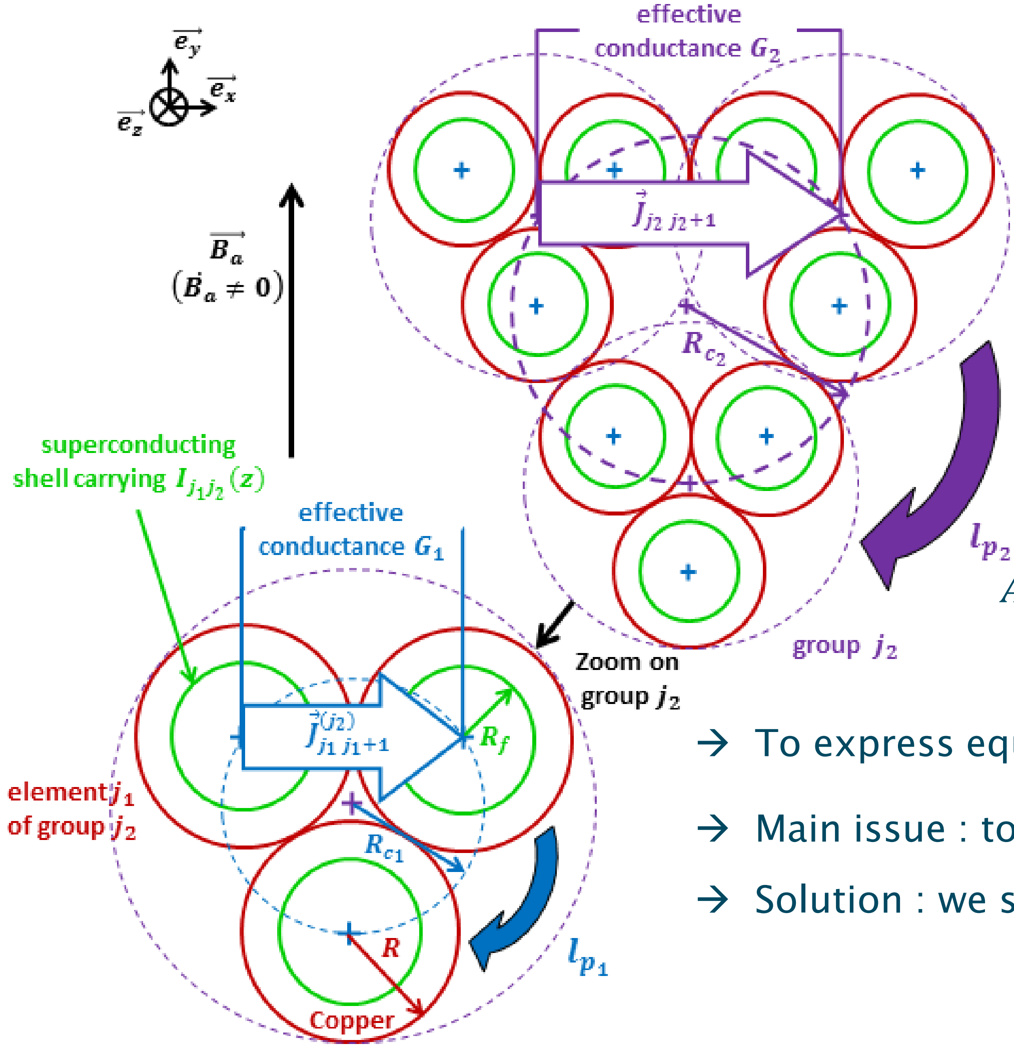
- Our strategy aims at describing the coupling between two consecutive cabling stages
- Longitudinal current $I_{j_1 j_2}$ carried by element j_1 of substage j_2 split as :

$$I_{j_1 j_2} = I^{(1)}_{j_1 j_2} + I^{(2)}_{j_2} / N_1$$

shielding of substage j_2 | shielding of superstage

Analytical modeling of coupling losses : two stage model

N_2−uplet of N_1−uplets model :



Cross−section of a triplet of triplets of elements

$(N_1 = 3$ and $N_2 = 3)$

➢ **Equations :**

Faraday's law of induction + Kirchhoff's current law lead to

$$\frac{d^2 I_{j_1 j_2}}{dz^2} - \sigma_{l_1}\left(2\dot{A}_{z r_{j_1 j_2}} - \dot{A}_{z r_{j_1-1 j_2}} - \dot{A}_{z r_{j_1+1 j_2}}\right) - \frac{\sigma_{l_2}}{{N_1}^2}\sum_{j_1=1}^{N_1}\left(2\dot{A}_{z r_{j_1 j_2}} - \dot{A}_{z r_{j_1 j_2-1}} - \dot{A}_{z r_{j_1 j_2+1}}\right) = 4R_{c_1}\sigma_{l_1}\dot{B}_a e^{i\left[\alpha_1 z + \frac{2\pi(j_1-1)}{N_1}\right]} - 4R_{c_2}\frac{\sigma_{l_2}}{N_1}\dot{B}_a e^{i\left[\alpha_2 z + \frac{2\pi(j_2-1)}{N_1}\right]}$$

with $\alpha_1 = 2\pi/l_{p_1}$ and $\alpha_2 = 2\pi/l_{p_2}$

$A_{z r_{j_1 j_2}}$: magnetic vector potential due to induced currents at center of element j_1 of substage j_2

→ To express equation on $I_{j_1 j_2}$ we need $A_{z r_{j_1 j_2}}$ as function of $I_{j_1 j_2}$

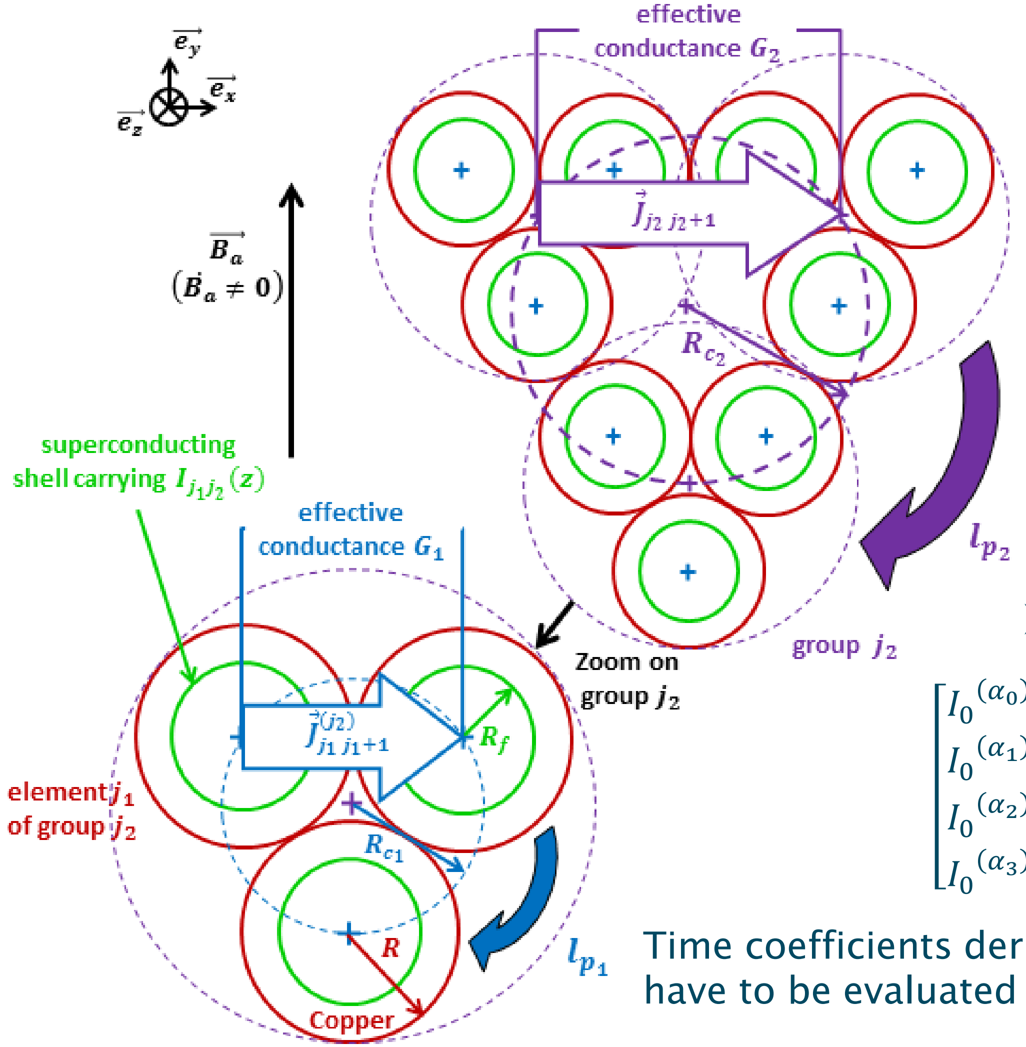
→ Main issue : to use Biot−Savart law, we need $I_{j_1 j_2}(z)$

→ Solution : we suppose

$$I_{j_1 j_2}(z,t) = \sum_{k=1}^{n} I_{0_{j_1 j_2}}^{(\beta_k)}(t)\cos\left(\beta_k z + \varphi_{j_1 j_2}^{(\beta_k)}\right)$$

β_k : spatial frequency

N_2–uplet of N_1–uplets model :



Cross–section of a triplet of triplets of elements
($N_1 = 3$ and $N_2 = 3$)

- ➢ **Search for excited spatial modes :**
  - When $\dot{I}_{j_1 j_2} = 0$ (steady–state) : only two spatial frequencies (α_1 and α_2)
  - Numerical study for a step function shows more spatial frequencies

→ Complex analytical calculation led us to the basis of the spatial frequencies (infinite, linear combinations of α_1 and α_2)

→ But it is possible to keep only four frequencies (other modes negligible according to study in step function)

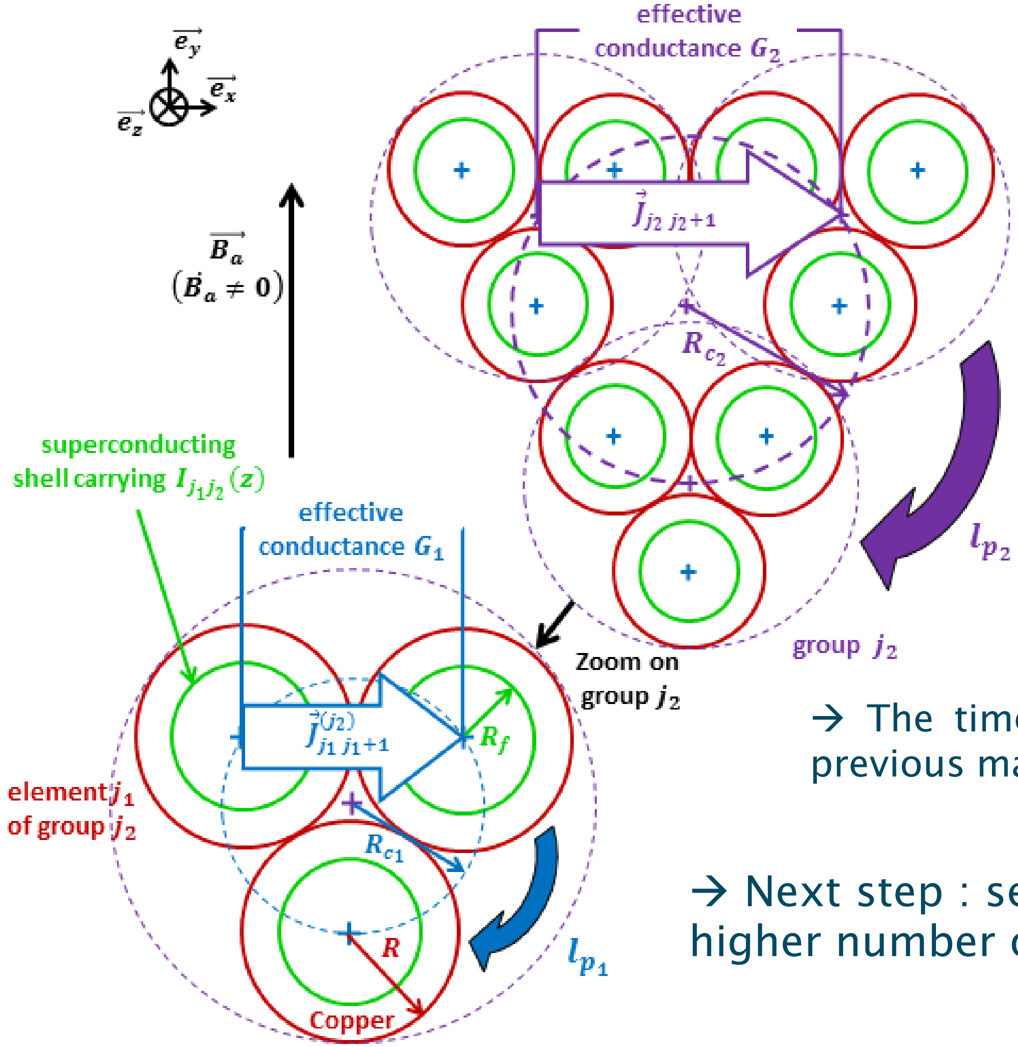
- ➢ **Equation reduced to:**

$$\begin{bmatrix} I_0^{(\alpha_0)} \\ I_0^{(\alpha_1)} \\ I_0^{(\alpha_2)} \\ I_0^{(\alpha_3)} \end{bmatrix} + \begin{bmatrix} \tau_{1\,1} & \tau_{1\,2} & 0 & 0 \\ \tau_{2\,1} & \tau_{2\,2} & \tau_{2\,3} & 0 \\ 0 & \tau_{3\,2} & \tau_{3\,3} & \tau_{3\,4} \\ 0 & 0 & \tau_{4\,3} & \tau_{4\,4} \end{bmatrix} \begin{bmatrix} \dot{I}_0^{(\alpha_0)} \\ \dot{I}_0^{(\alpha_1)} \\ \dot{I}_0^{(\alpha_2)} \\ \dot{I}_0^{(\alpha_3)} \end{bmatrix} = \begin{bmatrix} 0 \\ y_{1\ ext} \\ y_{2\ ext} \\ 0 \end{bmatrix} \dot{B}_a$$

Time coefficients derived analytically but depend on integrals that have to be evaluated numerically

Analytical modeling of coupling losses : two stage model

N_2−uplet of N_1−uplets model :



Cross−section of a triplet of triplets of elements

($N_1 = 3$ and $N_2 = 3$)

- Expression of losses for any time regime :

$$P_l = N_1 N_2 \sum_{k=0}^{3} \frac{\left[\alpha_k I_0^{(\alpha_k)}\right]^2}{\gamma_k}$$

with $\gamma_0 = 32\sigma_{l_1} \sin^2\left(\frac{\pi}{N_1}\right)\cos^2\left(\frac{\pi}{N_1}\right)$,

$\gamma_1 = 8\sigma_{l_1} \sin^2\left(\frac{\pi}{N_1}\right)$, $\gamma_2 = 2\sigma_{l_2} \sin^2\left(\frac{\pi}{N_2}\right)/N_1$

and $\gamma_3 = \gamma_1$

→ We have found four time constants θ_j and partial shielding coefficients $n\kappa_j$ for a two cabling stage conductor

→ The time constants θ_j are the eigenvalues of the previous matrix

→ Next step : search for an iterative process to reach a higher number of cabling stages

Comparison with reference numerical models

Comparison with THELMA (University of Bologna, IT) :

- On a simplified geometry of **ITER CS conductor** (last two cabling stages only) = **6 bundles of 4 elements each** (with diameter of 6.49mm)

- Subject to +/- **0.2T triangular cycles** of transverse magnetic field (**f=0.1 Hz**)

- From geometry **(perfect helicoids)** and conductance network of THELMA, we extract **effective** geometrical and electrical **parameters**

Effective parameters	l_{p_k} (mm)	R_{c_k} (mm)	σ_{l_k} (10^7 S/m)
Substage ($k=1$)	112.5	3.86	2.36
Superstage ($k=2$)	450.0	11.49	6.50

Results :

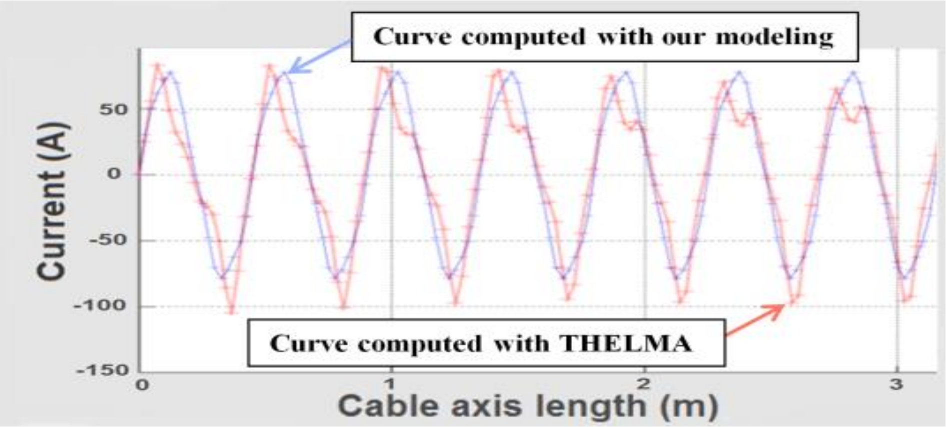
- **Coupling power per unit length of conductor (steady-state) :**

$667\ mW.m^{-1}$ (THELMA) vs $863\ mW.m^{-1}$

→ Agreement within 30%

- **Induced currents :**

→ Agreement within 15%



Comparison with JackPot (University of Twente, NL) :

- On a simplified geometry of **JT60SA TF conductor** (last two cabling stages only) = **6 bundles of 3 elements each** (with diameter of 4.21mm)
- Subject to **+/- 1T sinusoidal cycles** of transverse magnetic field (**f=0.05 Hz**)
- From geometry (**compacted helicoids**) and conductance network of JackPot, we extract **effective** geometrical and electrical **parameters**

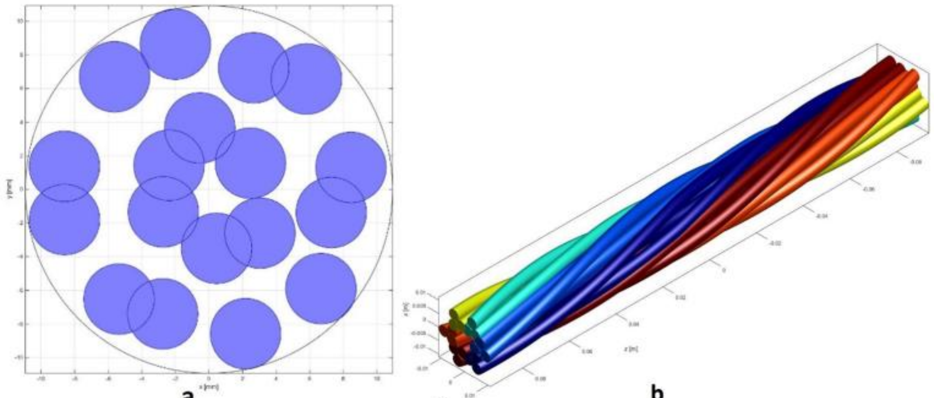
Effective parameters	l_{p_k} (mm)	R_{c_k} (mm)	σ_{l_k} (10^7 S/m)
Substage ($k=1$)	187.0	2.96	1.38
Superstage ($k=2$)	290.2	6.56	5.92

Results :

- **Coupling losses per unit length of conductor per cycle (slowly time-varying regime) :**

$\mathbf{13.35}\ \boldsymbol{J/m/cycle}$ **(JackPot)**
vs $\mathbf{18.94}\ \boldsymbol{J/m/cycle}$

→ Agreement within 40%



Cross-section (a) and 3D geometry (b) produced by JackPot

Discussions:

- **Global agreement between our fully analytical model on two different geometries with two fully numerical models are within ~30/40 % on losses and even better for coupling currents (within 15%) !**

- For both comparisons, our model predicts higher losses :

    - Several numerical effects investigated (changes of spatial discretization, length of conductor and initial phase shifts between elements) but none responsible for the 30-40% discrepancy

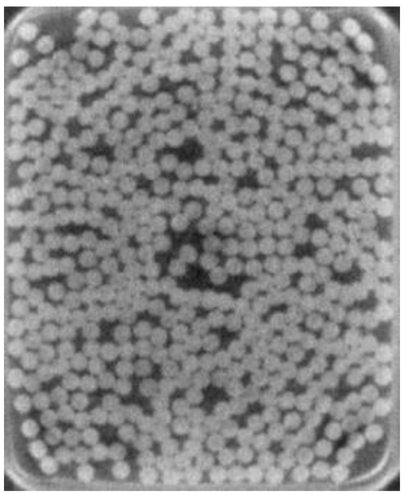
    - Our slight overestimation is very likely to be due to an averaging effect of our modeling at the superstage scale and is not likely to be much higher than 30-40%

- Comparisons with numerical models will go on

X-ray tomography

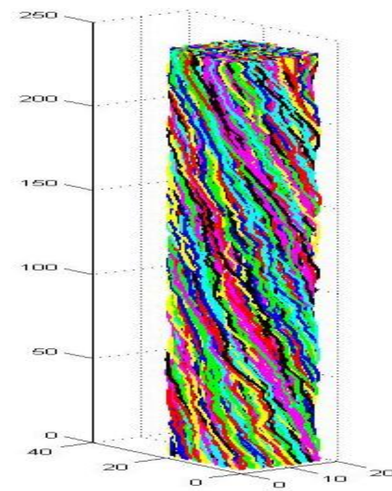
Reconstruction of strand trajectories in a CICC :

- X-ray tomography of JT-60SA TFCS conductor samples made by INFLPR (Bucharest, RO)
- 2D transverse images of CICC obtained every millimeter along its axis
- Development of algorithms for automatic strand detection in every image and 3D reconstruction of strand trajectories



2D transverse image obtained from X-ray tomography

Automatic strand detection + Strand tracking



3D strand trajectories reconstructed

Analysis of Fourier transforms of trajectories

Cabling stage	Cabling radii (mm)	Twist pitches (mm)	Twist pitches (mm) specifications
1	0.49	45.4	45
2	0.82	66.7	70
3	1.62	120.2	120
4	2.31	185.2	190
5	7.75	285.7	290

Effective geometrical parameters

Next steps :

→ Use inter-strand resistivity measurements to deduce the effective electrical parameters of JT-60SA TFCS conductors

→ Compare losses computed with our analytical modeling using effective parameters with losses measured at SULTAN

Conclusions et prospects

Conclusions :

- Previous analytical model of coupling losses on one cabling stage conductor has been **up scaled to a two cabling stage one**

- **Fair agreement** of our approach **with two different reference numerical models** on two **different geometries demonstrates its trustworthiness** (though slightly conservative)

- Methods of calculation of **effective parameters** developed during comparisons with THELMA and JackPot used on **real strand trajectories** to extract **representative effective parameters of JT-60SA TFCS conductor** (in very good agreement with its specifications)

Prospects :

- Set **new comparisons** with numerical models for **different** magnetic **regimes**

- Deduce **effective conductances** for JT-60SA TFCS conductor from resistivy measurements **to compare** losses computed with **our model with** losses **measured** at Sultan

- Search for an **iterative process** allowing to model a **higher number of cabling stages**

Thank you for your attention

Do you have any questions ?

Alexandre LOUZGUITI