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Characterization and modeling of Nb_3Sn conductors for accelerator magnets at CEA Paris-Saclay

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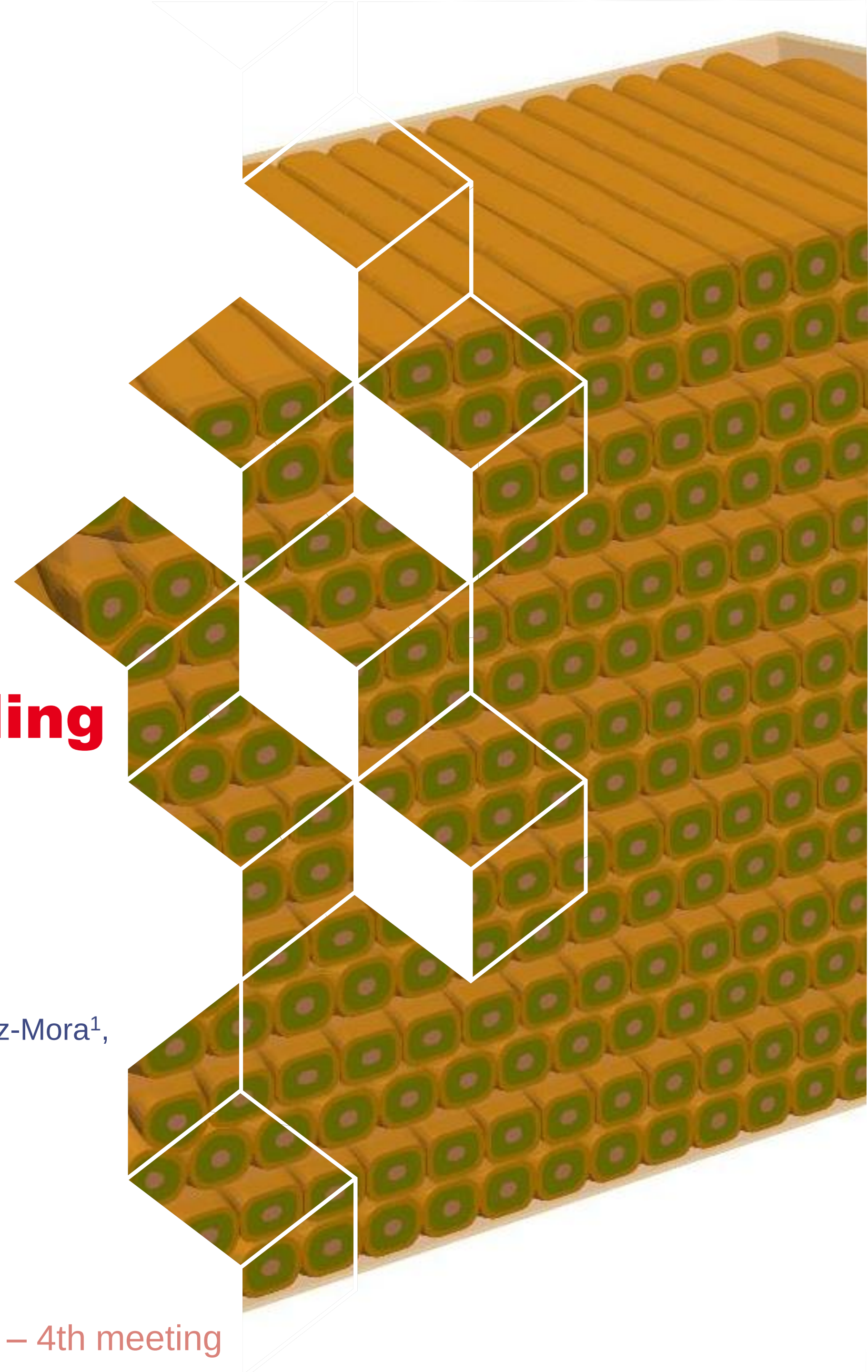
[1] CEA Paris-Saclay
[2] LMPS – Laboratory of Mechanics Paris-Saclay



Outline

1. **Characterization and modeling program for Nb_3Sn conductors @ CEA Paris-Saclay**

2. **CoCaSCOPE**
   Mesh Generator
   Behavior representation
   Experimental characterization
   Single stack simulations

3. **Summary and perspectives**

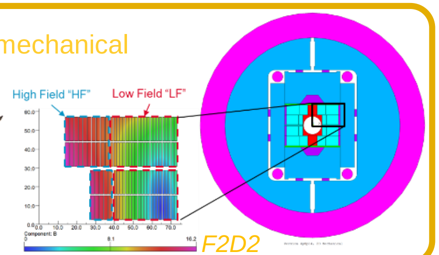
Overview of CEA's Nb_3Sn modeling program

Model | **Experimental**

Magnet scale

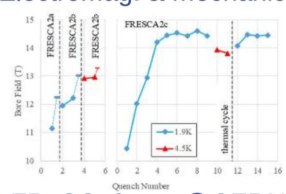
Model — Electromag. & mechanical

FReSCa2

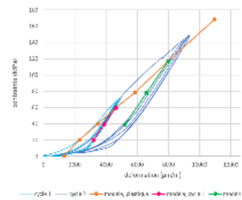


F2D2

Experimental — Electromag. & mechanical



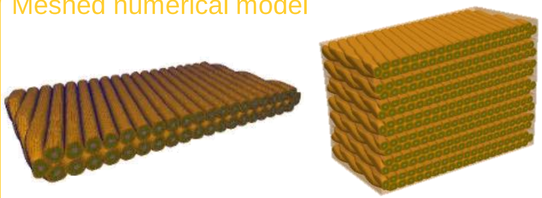
FReSCa2 test @CERN



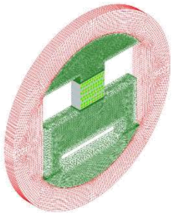
SD program

Cable scale

Model — Meshed numerical model



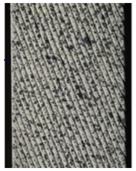
Cable and stack simulation



Numerical twin of stack tests

Experimental

TT-Dimension changes



DIC in-situ

Unreacted or reacted cable behavior

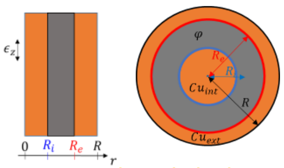
Hard-way bending
Layer jump

10-stack

Strand scale

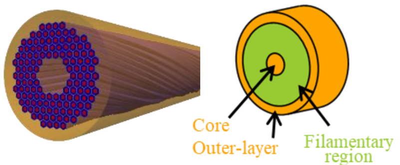
Model

Diffusion



Semi-analytical diffusion model

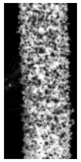
Mechanical



Detailed and bi-metallic strand models

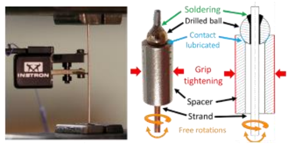
Experimental

TT-Dimension changes



DIC in-situ

Mechanical

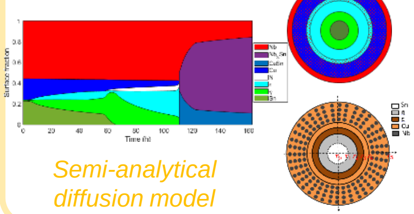


Tensile test

Subelement scale

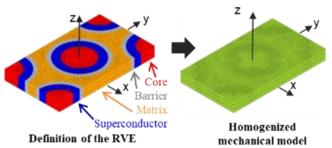
Model

Diffusion



Semi-analytical diffusion model

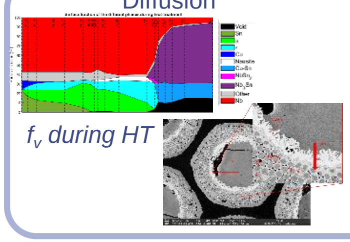
Mechanical



Homogenization of filamentary region

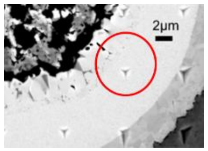
Experimental

Diffusion



f_v during HT

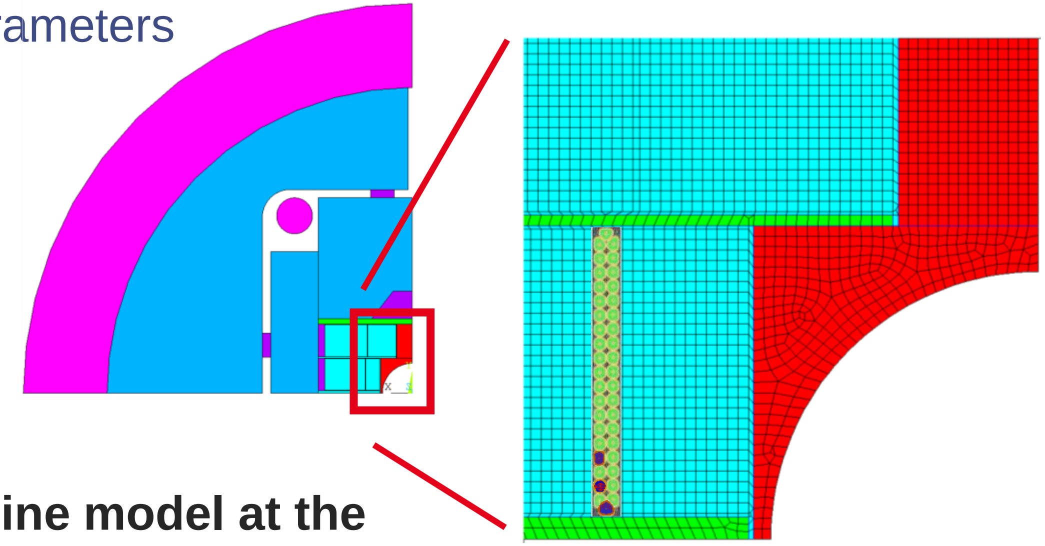
Local mechanical properties



Nano-indentation

Magnet scale and global approach

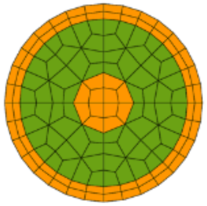
- Magnet model
  - Magnet behavior driven by local parameters
  - Homogenized coil
    - ↳Which behavior ?
    - ↳Which homogenization scheme?
    - ↳Based on which object**(s)** (/scale**(s)**) loaded under which condition**(s)**?



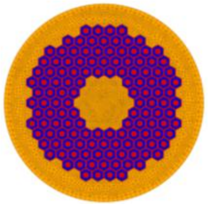
- Approach

⇨ **Multi-scale modeling with baseline model at the cable scale (light mesh & adapted representation)**

  - 2D pre-design steps toward 3D specific models
  - Integration of detailed cable model and detailed strands to access to the local properties
  - **Characterization and modeling of the lower scales to understand and choose relevant level of details (mechanical and geometrical)**



Bi-metallic strand model



Detailed strand model

Outline

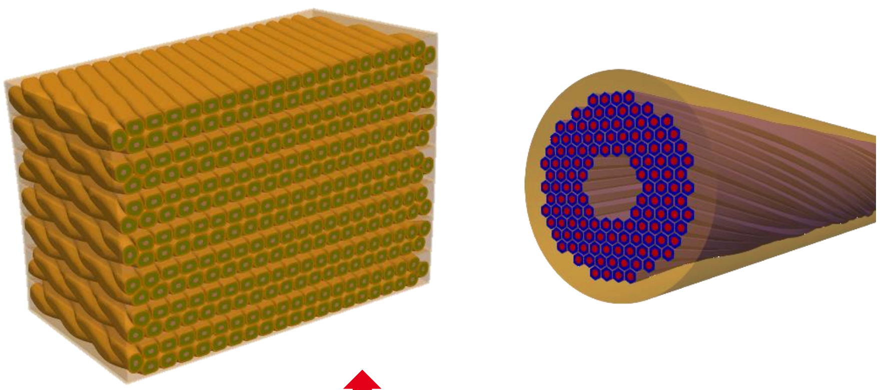
1. **Characterization and modeling program for Nb_3Sn conductors @ CEA Paris-Saclay**

2. **CoCaSCOPE**
   Mesh Generator
   Behavior representation
   Experimental characterization
   Single stack simulations

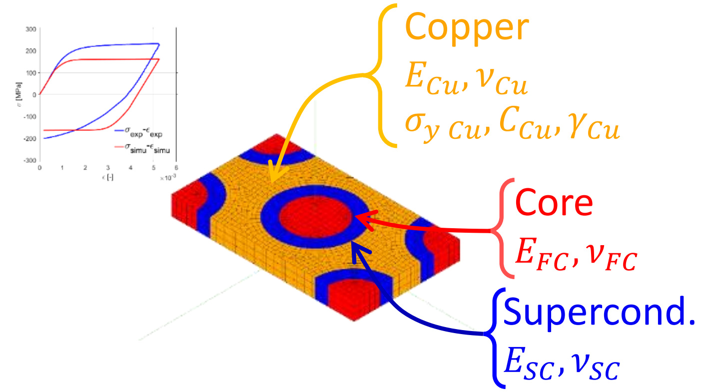
3. **Summary and perspectives**

CoCaSCOPE approach

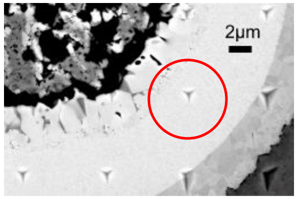
- Mesh Generator - MG
  - ↳Tool for the generation of representative Rutherford cable model and detailed strand



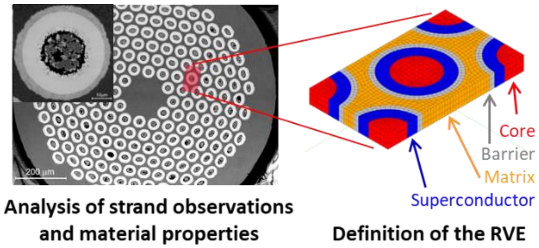
- Behavior Representation - BR
  - ↳Objective oriented representation



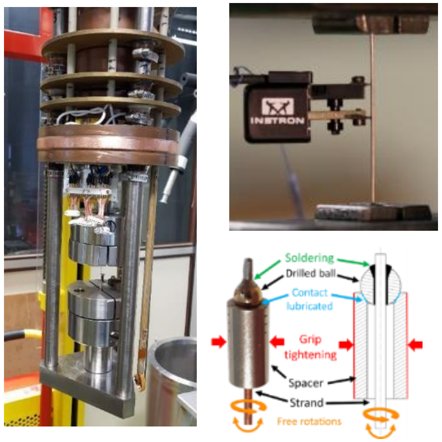
- Experimental Characterization - EC
  - ↳Define modelling strategy
  - ↳Identify models parameters
  - ↳Validate models



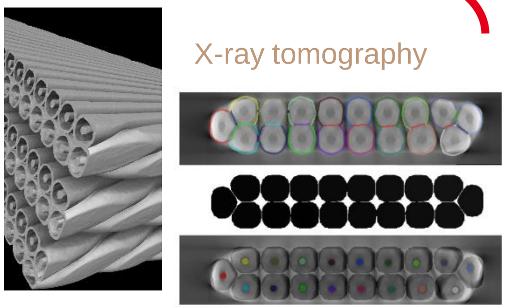
Nano-indentation test



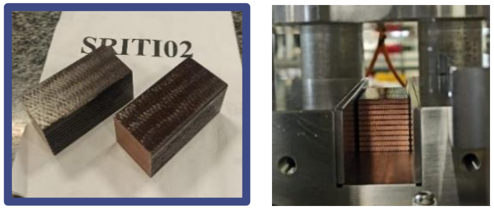
Metallography to define models



Tensile test on strand



X-ray tomography



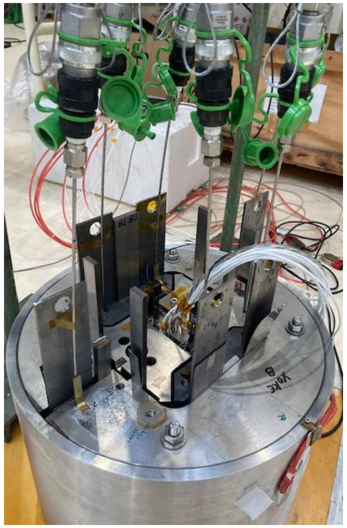
Compressive test on stack

Experimental characterization

- **Objectives**
  - Characterization of the mechanical behavior
    - Strain rate, hold, unloadings, cyclic behavior
    - Investigation of damage (impregnation matrix and conductors)
  - Data for the identification and the validation of mechanical models
- **Available tests and scales**
  - Subscale dipole
  - 10-stack compressive test
  - Strand
    - Nano-indentation
    - Tensile test
- **Perspectives**
  - Transverse tests on strands
  - Nano-indentation @ 77 K
  - Micro and nano-mechanical testing

Instrumented coil segment

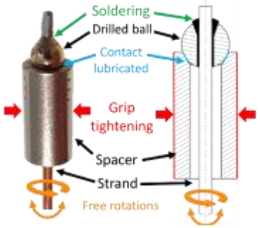
© G. Campagna



Mechanical loading in a structure

Nb_3Sn strand w/ extensometer for tensile test

Setup for clamping strand in machine



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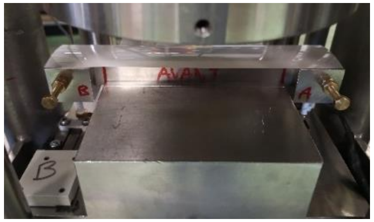
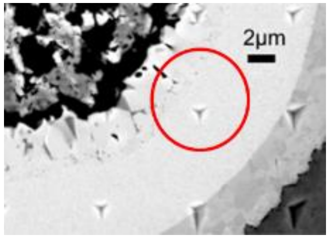
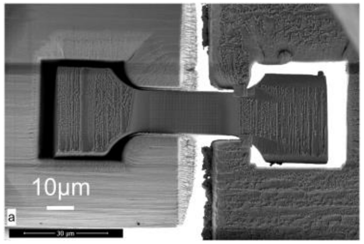
Cryostat & machine for 10-stack test



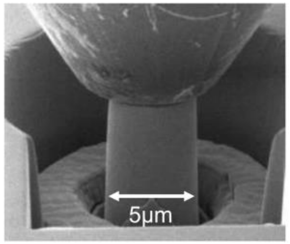
10-stack test setup



Nano-indentation in Nb_3Sn phase of a PIT strand [Lenoir 17]



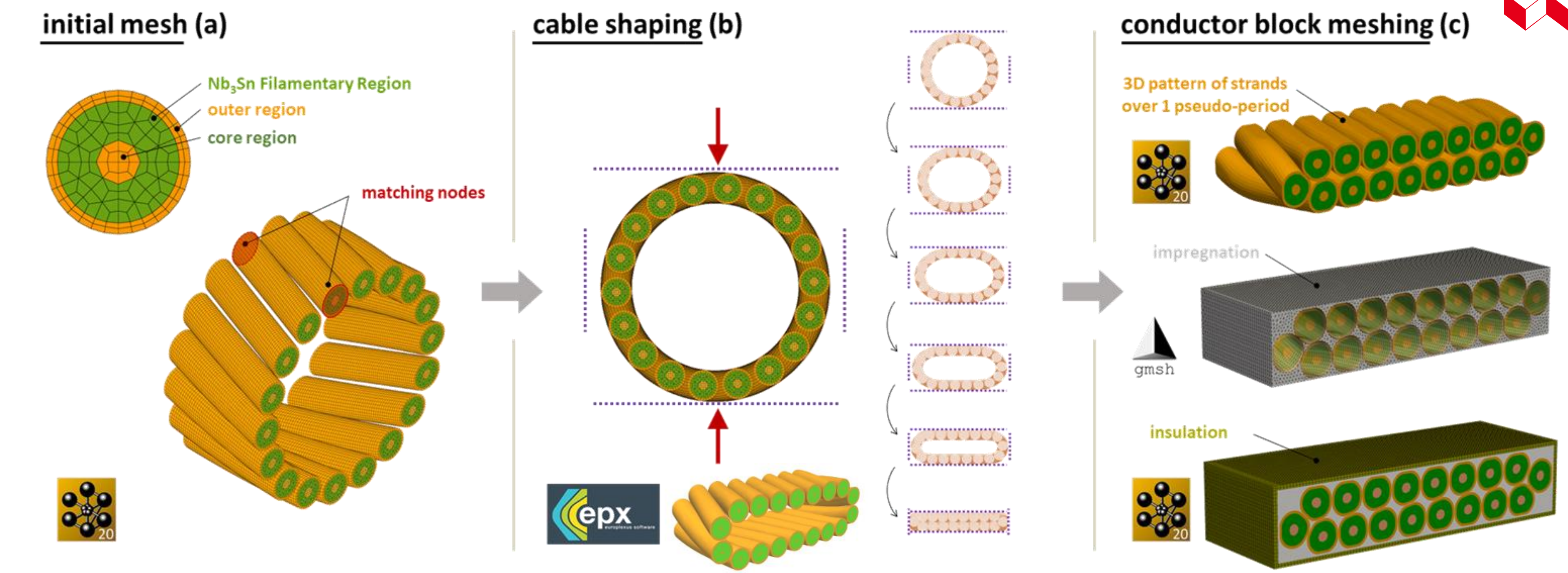
Micro-sample martensitic steel [Ben Salem 19]



Micro-pillar compression [Breumier 20]

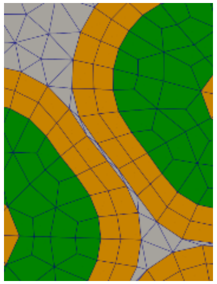
CoCaSCOPE Mesh Generator

F. Nunio et al., IEEE TAS, 2019

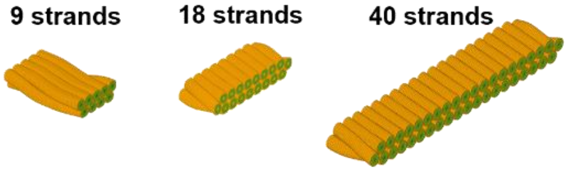


- **Initial model**
  - Helical geometry
  - One pseudo-period
  - Bi-metallic description
  - 8-node brick elements
  - Parameters
    - Strand parameters
      ↳ Diameters (strand, core & filamentary area)
    - Cable parameters
      ↳ # of strands / twist pitch / width & height
    - Mesh density
    - Gap between strands

- **Cable shaping**
  - Simplified cabling process
    ↳ Compaction by 4 rigid planes
  - Parallelized explicit dynamic simulation
  - Coupled displacement of front and rear faces of adjacent strands
  - Clearance gap between strands to avoid interpenetration and ease meshing of impregnation
  - Mechanical state after shaping not considered

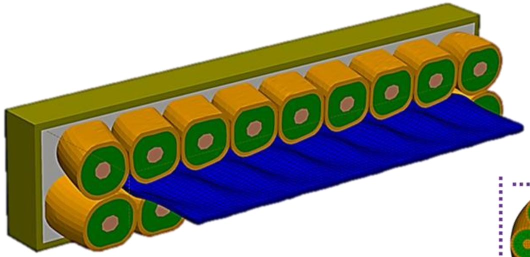


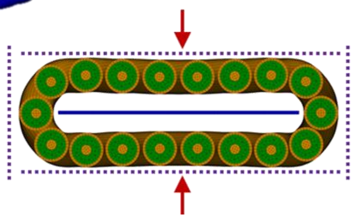
- **Conductor block mesh**
  - Impregnation meshed with 4-node tetrahedral elements
  - Insulation meshed with 6-node pentahedrons elements
  - Node conformal
  - Homeomorphic faces
    ↳ concatenation of blocks



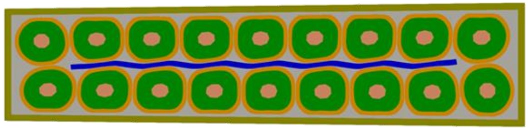
Cable scale - CoCaSCOPE Mesh Generator

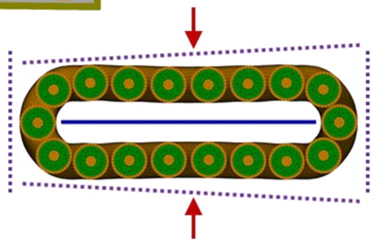
- Options
  - Steel core



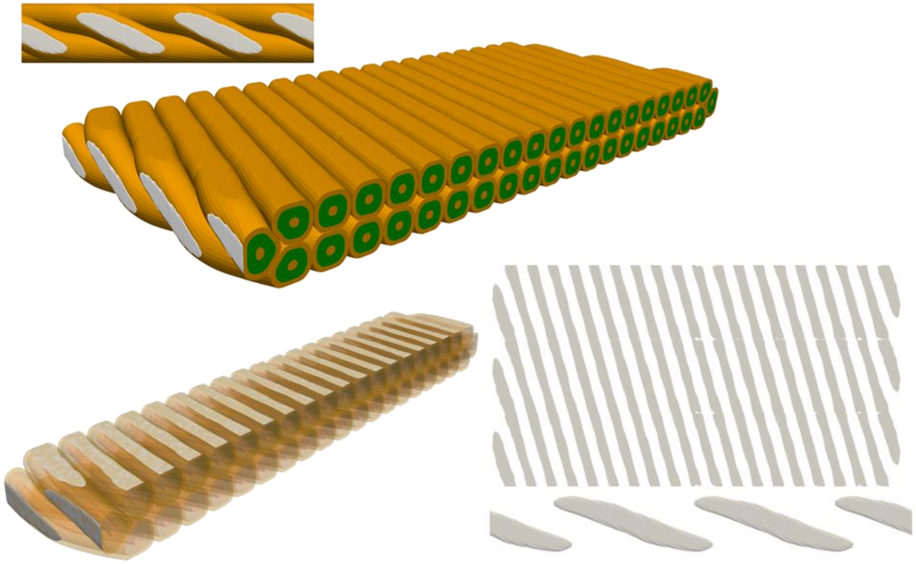


  - Keystone

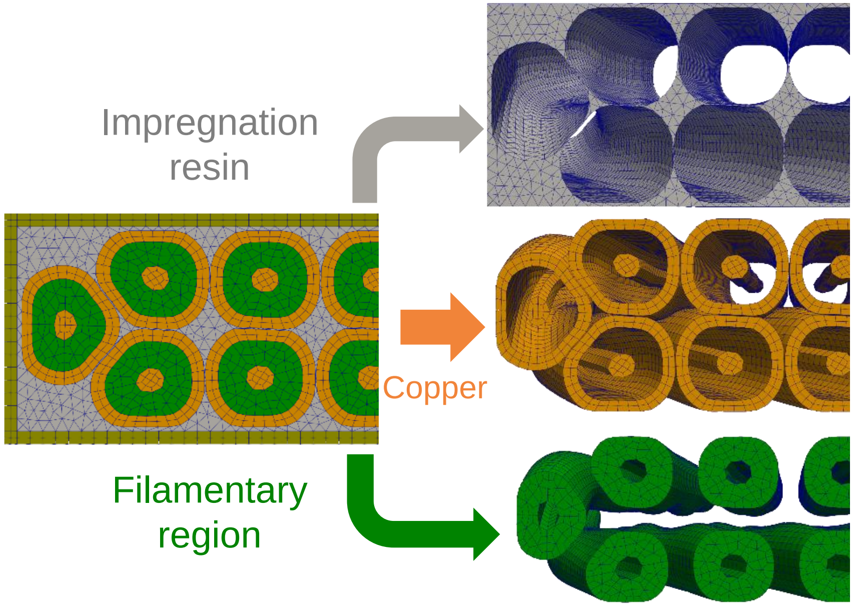




- Features
  - Facets of bare conductor

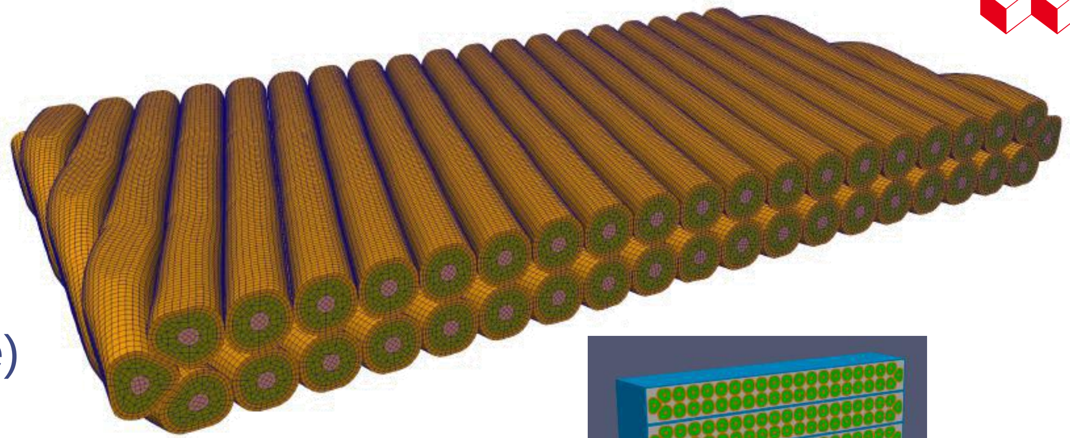


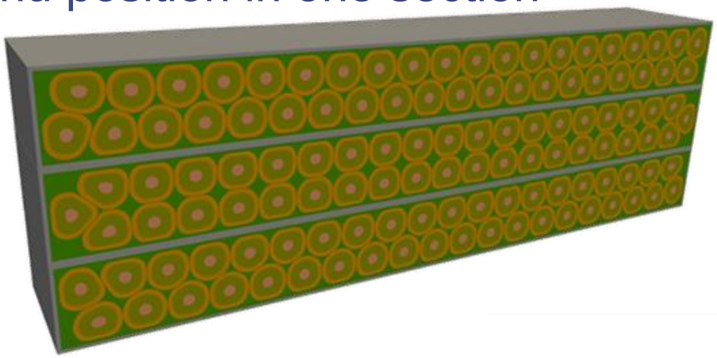
  - Access to the different materials

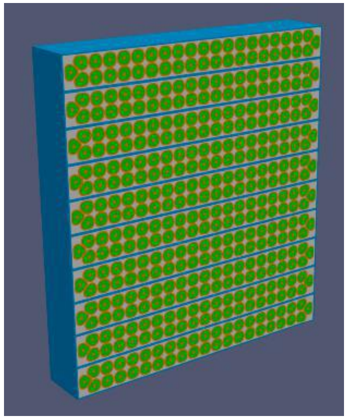


Cable scale - CoCaSCOPE Mesh Generator

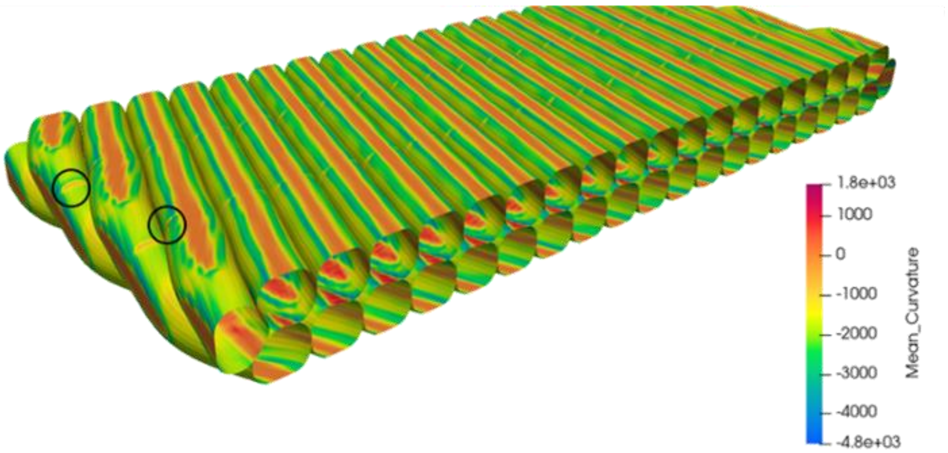
- Concatenation of blocks
  - Mesh block of one pseudo period
    - ↳ twist-pitch divided by # strands
  - Homeomorphic meshes
  - ➔ Concatenation of blocks in length to obtain complete period (or more)
  - ➔ Stacking to reproduce cable stack w/ different strand position in one section





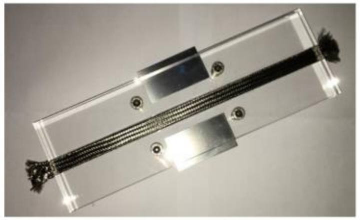


- Discontinuity of the curvature of the outer surface of strands
  - ↳ Poisson effect due to transverse compression concentrated at the ends of the strands



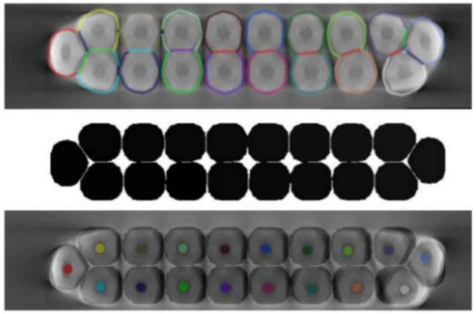
Mesh validation

- Mesh generator validated over X-ray tomographies and image analysis of existing cables

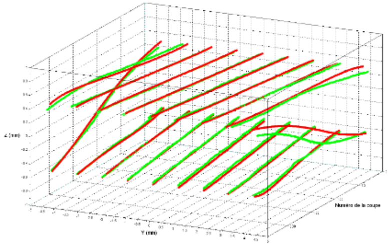


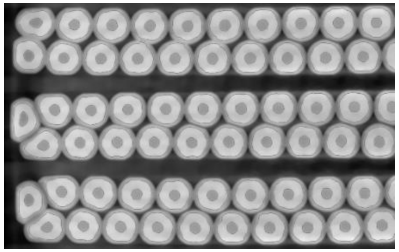
Tomographies performed @ MATEIS lab. INSA Lyon

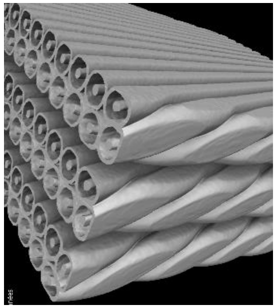
- Overall shape
  - Strand cross-section similar to those from real samples
  - Cable facets consistent with those observed on bare cables



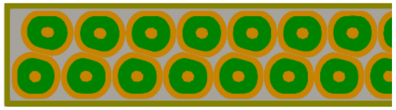
- Strands centroids and cross-section
  - X-ray tomography of cables (15 µm resolution)
    ↳ 9, 18 and 40 strands cables
  - Automatic extraction
    - Centroids
    - Skin of strands
  - Comparison with numerical model
    - Strand by strand centroïd error
    - Inter-strands distance error
    - Global strand deformed shape

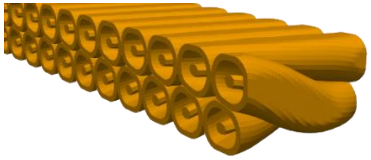


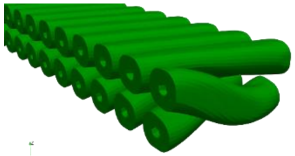




- On-going analysis
  - Imaging of FRESCA2 10-stack & HF/LF R2D2 conductors
  - Quantitative comparison with facets from cabling







Tomographies courtesy of G. Touzé, CEA Paris-Saclay, DES/ISAS/DRMP

CoCaSCOPE – Mesh Generator

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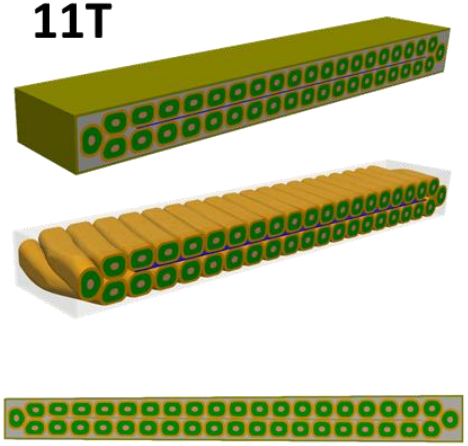
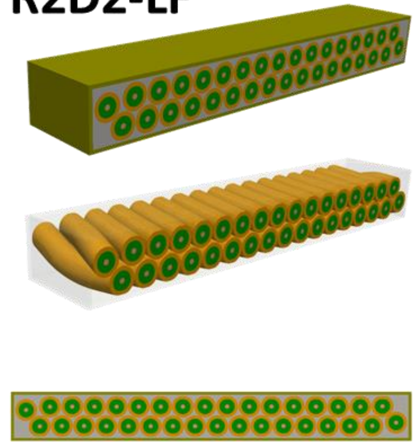
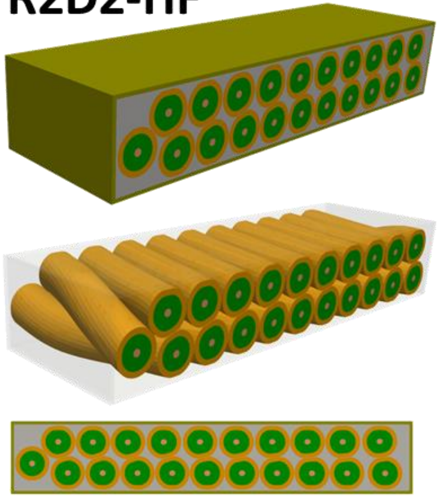


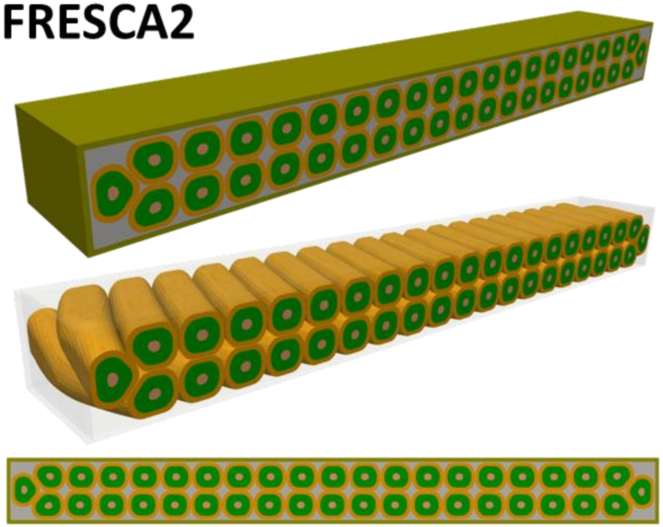
R2D2-LF



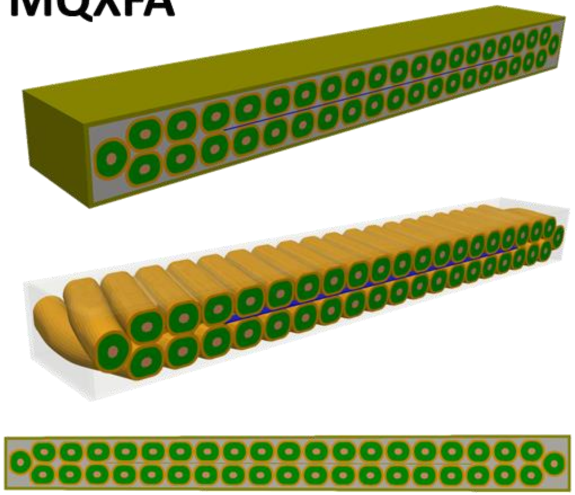
R2D2-HF



FRESCA2

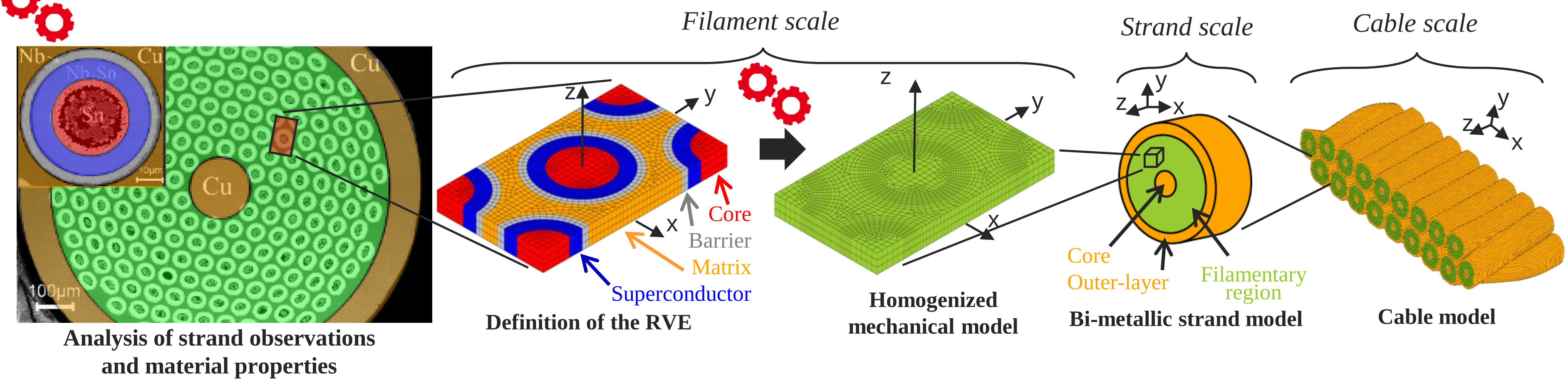


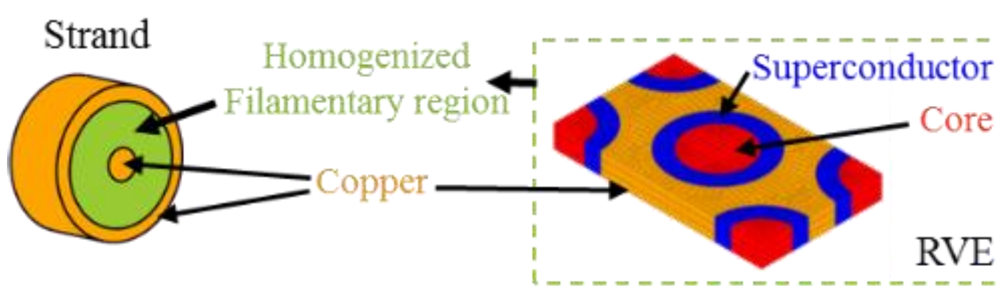
MQXFA



CoCaSCOPE – Behavior Representation
Methodology to build the bi-metallic representation

G. Lenoir, IEEE TAS 2019





Defined by mechanical characterization & image analysis

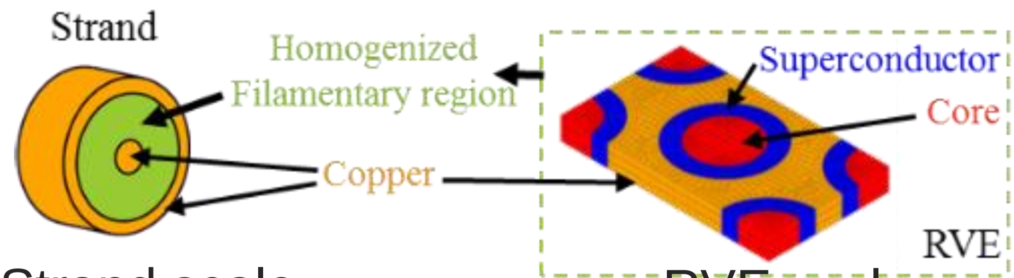
- Strand scale
  - Copper
  - Homogenized FR
- RVE scale
  - Nb_3Sn
  - Filament Core
  - Copper

CoCaSCOPE – Behavior Representation
Methodology to build the bi-metallic representation 2/2

Single material model

- Von Mises yield criterion $f(\sigma, X, R)$
- Elasticity with Hooke's law: $\sigma = \mathrm{E} * \varepsilon$
- Chaboche's model:
  - Isotropic: $\dot{R} = \mathrm{b} * (\mathrm{Q} - R) * \dot{p}$
  - Kinematic: $\dot{X} = \mathrm{C} * \dot{\varepsilon^p} - \gamma * X * \dot{p}$

- Choices & assumptions
  - Based on tensile test ⇨ R = 0 for Nb_3Sn strands
    - ↳ Only one kinematic hardening (simple representation)
    - ↳ Possibility to add several kinematic hardenings (better representation of non-linearities, Ratchetting and shakedown effects, etc.)



Defined by mechanical characterization & image analysis

- Strand scale
- RVE scale

- Copper ⇨ Elasto-plastic with hardening

  $E_{Cu}, \nu_{Cu}, \sigma_{y\ Cu}, C_{Cu}, \gamma_{Cu}$

- Homogenized FR ⇨ Elastio-plastic bilinear (in simulation dir.)

  $E_{zz}^{eff}, \nu_{zz}^{eff}, \sigma_{y\ zz}^{eff}, K_{zz}^{eff}$

- Nb_3Sn ⇨ Elastic - E_{SC}, ν_{SC}
- Filament Core ⇨ Elastic - E_{FC}, ν_{FC}
- Copper ⇨ Elasto-plastic with hardening

  $E_{Cu}, \nu_{Cu}, \sigma_{y\ Cu}, C_{Cu}, \gamma_{Cu}$

⇨ Parameters identify by direct measurements & inverse identification

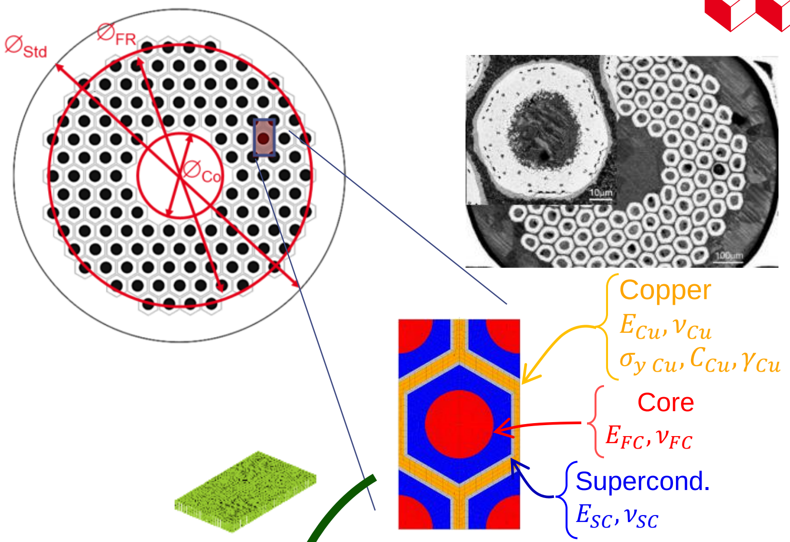
Simulation of single stack - Model description

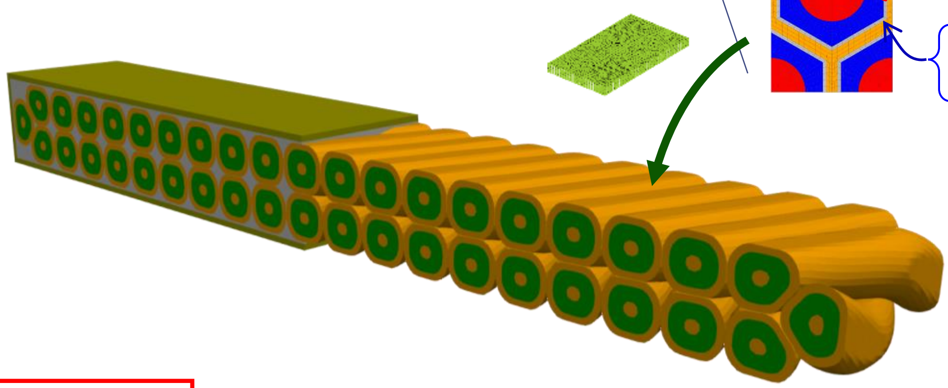
- **FReSCa2 cable model**
- **Materials parameters**
  - Stack scale
    - Impregnated insulation – elastic
      E_{in} = 13 GPa and ν_{in} = 0.35 *[Vallone 18] [Löffler 18]*
    - Impregnation resin – elastic
      E_{re} = 4 GPa and ν_{re} = 0.35 *[Scheuerlein 19], [Sun 22]*
      + test of a value of E_{re} = 1 Gpa
  - Strand scale
    - Copper & Barrier ➔ elasto-plastic
      - E_{Cu} = 129 GPa, ν_{Cu} = 0.33, σ_y= 39 MPa
      - Non-linear kinematic hardening (Chaboche)

$$\dot{X} = C * \dot{\varepsilon^p} - \gamma * X * \dot{p}$$

with C_{Cu} = 35960 MPa and γ_{Cu} = 310
↳ identified on PIT 191 strand *[Lenoir 19]*
    - Superconductor ➔ elastic
      - E_{Su} = 170 GPa, ν_{Su} = 0.3 *[Lenoir 17]*
      - E_{Su} = 129 GPa, ν_{Su} = 0.3 *[Scheuelein 15]*
    - Sub-element core ➔ elastic
      E_{Co} = 3; 50; 100 Gpa

	Model Parameter	Normalized
Bi-metallic	$\varnothing_{Core}$	255 µm
	$\varnothing_{Fil.\ Region}$	785 µm
	$\varnothing_{Strand}$	1000 µm
RVE	D_{subel}	62 µm
	$\varnothing_{Barrier}$	65 µm
	$\varnothing_{Su}$	61 µm
	$\varnothing_{Subel.\ core}$	35 µm





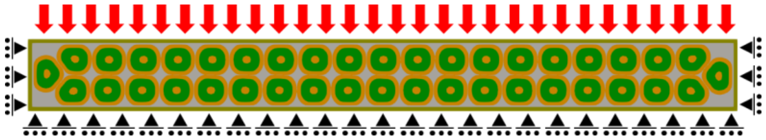
- **Strand models**
  - Homogeneous
    - Bi-linear mechanical model fitted from tensile test at 300 K
    - **kinematic linear hardening** with $H = \frac{E_T * E}{E - E_T}$
  - Bi-metallic – simulations with 3 families of RVE
    - RVE with E_{Su} = 170 Gpa
    - RVE with E_{Su} = 129 Gpa
    - Bimet-Vallone based on [Vallone 18]
      - Copper as bilinear E_{Cu} = 110 GPa, σ_y= 40 Mpa, E_T= 5 Gpa
      - Filamentary region described as Nb_3Sn and matrix with E=100 Gpa

Stack scale simulations with various mechanical descriptions

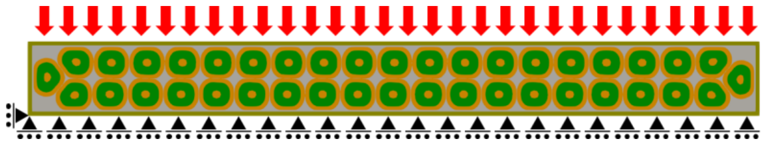
Scale	Component	E [GPa]	σ_y [MPa]	Plastic
Strand	Copper	129 / 110	39 / 40	Chaboche / E_T= 5 GPa
	Supercond.	170 / 129	-	-
	Subel. Core	3 / 50 / 100	-	-
Stack	RVE	74 / 62 / 100	24 / 23	E_T= 32 / 28 GPa
	Impregnation	4 / 1	-	-
	Insulation	13	-	-

Simulation of single stack
Impact of boundary conditions

- Boundary conditions
  - Blocked sides



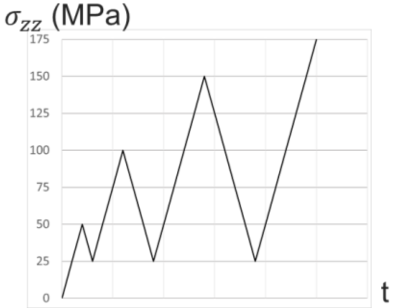
  - Free sides



- Mechanical descriptions

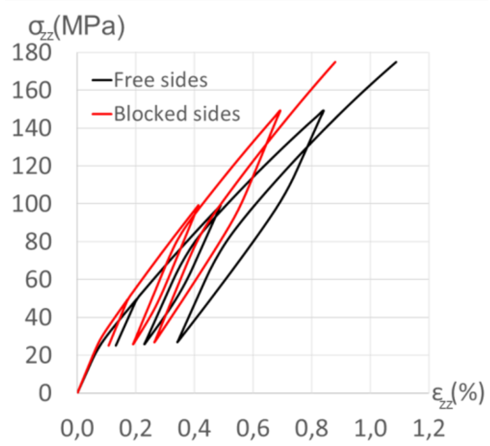
Scale	Component	E [GPa]	σ_y [MPa]	Plastic
Strand	Copper	129	39	Chaboche
	Supercond.	170	-	-
	Subel. Core	3	-	-
Stack	RVE	74	23	E_T=32GPa
	Impregnation	4	-	-
	Insulation	13	-	-

- Loading
  ↳ Monotonic with unloads

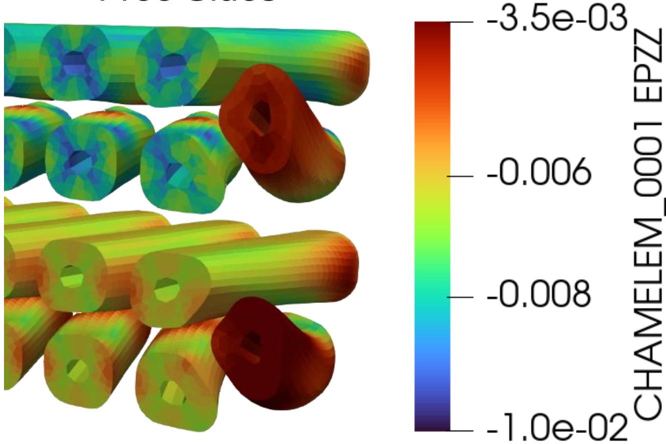


➔ BCs directly impact the global and the local mechanical values

- Results

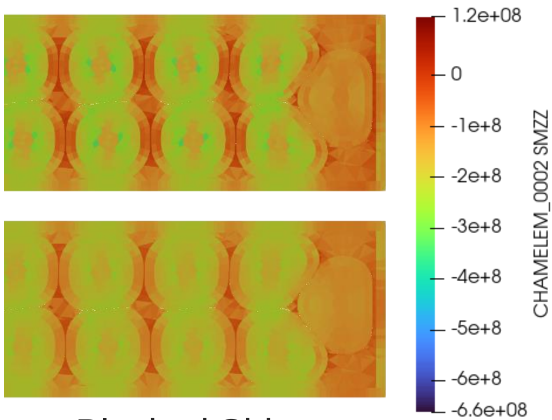


Free Sides



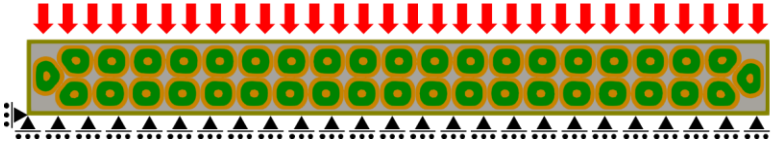
Blocked Sides ε_{zz} in the filamentary region

Free Sides

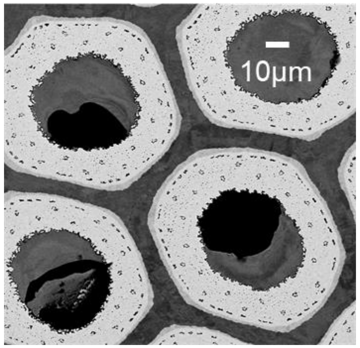


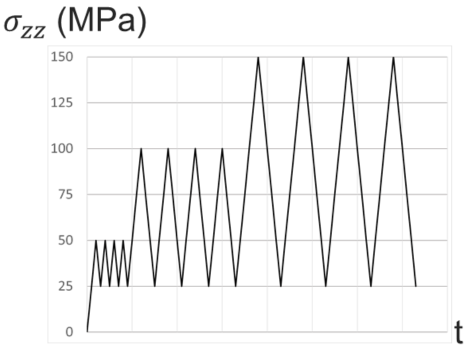
Blocked Sides

Simulation of a single stack
Impact of $E_{subel.\ core}$



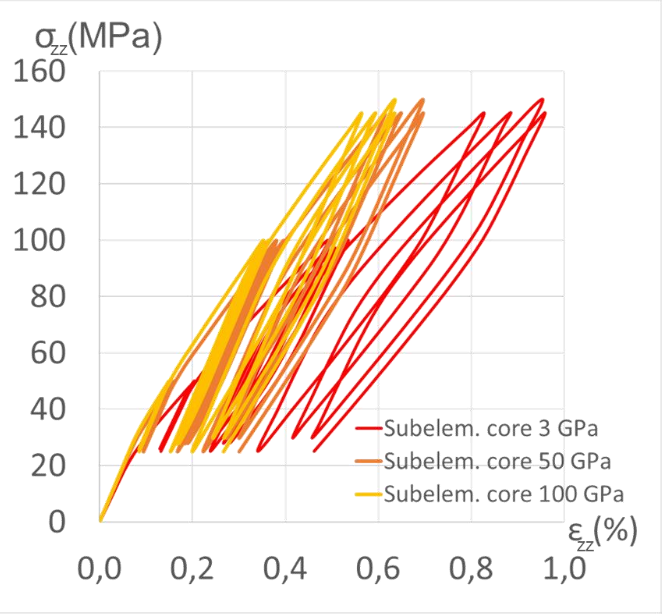
- **BCs**
  - Free sides
  - (Pseudo-)cyclic
    - Increasing unload level
    - 4 cycles / level



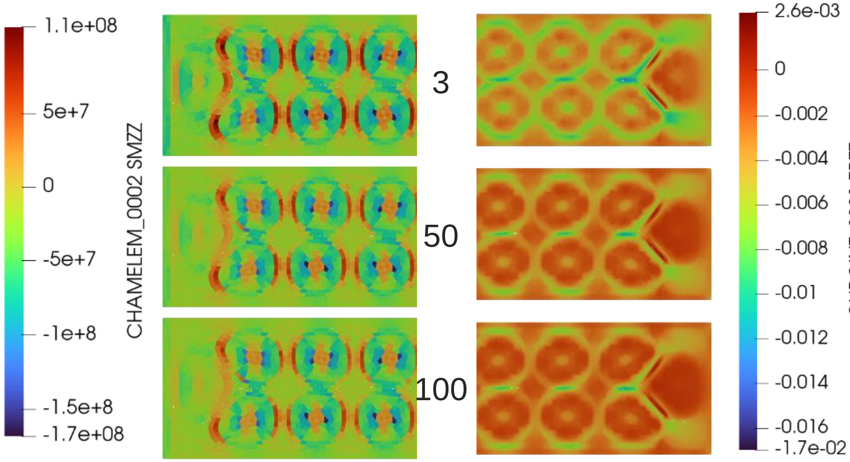


- **Mechanical description**

Scale	Component	E [GPa]	σ_y [MPa]	Plastic
Strand	Copper	129	39	Chaboche
	Supercond.	170	-	-
	Subel. Core	3 /50/100	-	-
Stack	RVE	74/110/133	24/38/45	E_T=32/62/76GPa
	Impregnation	4	-	-
	Insulation	13	-	-



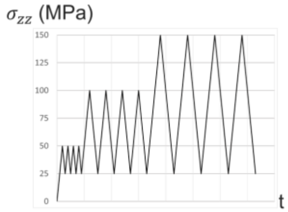
- **Results**

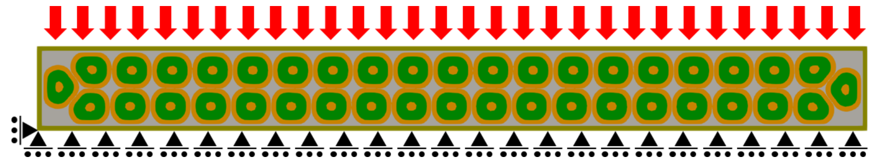


➔ The core of the RRP's subelement require characterization as it can have a large impact on the mechanical behavior of the stack

Simulation of a single stack
Comparison of various mech. models

- BCs
  - Free sides
  - (Pseudo-)cyclic
    - Increasing unload level
    - 4 cycles / level





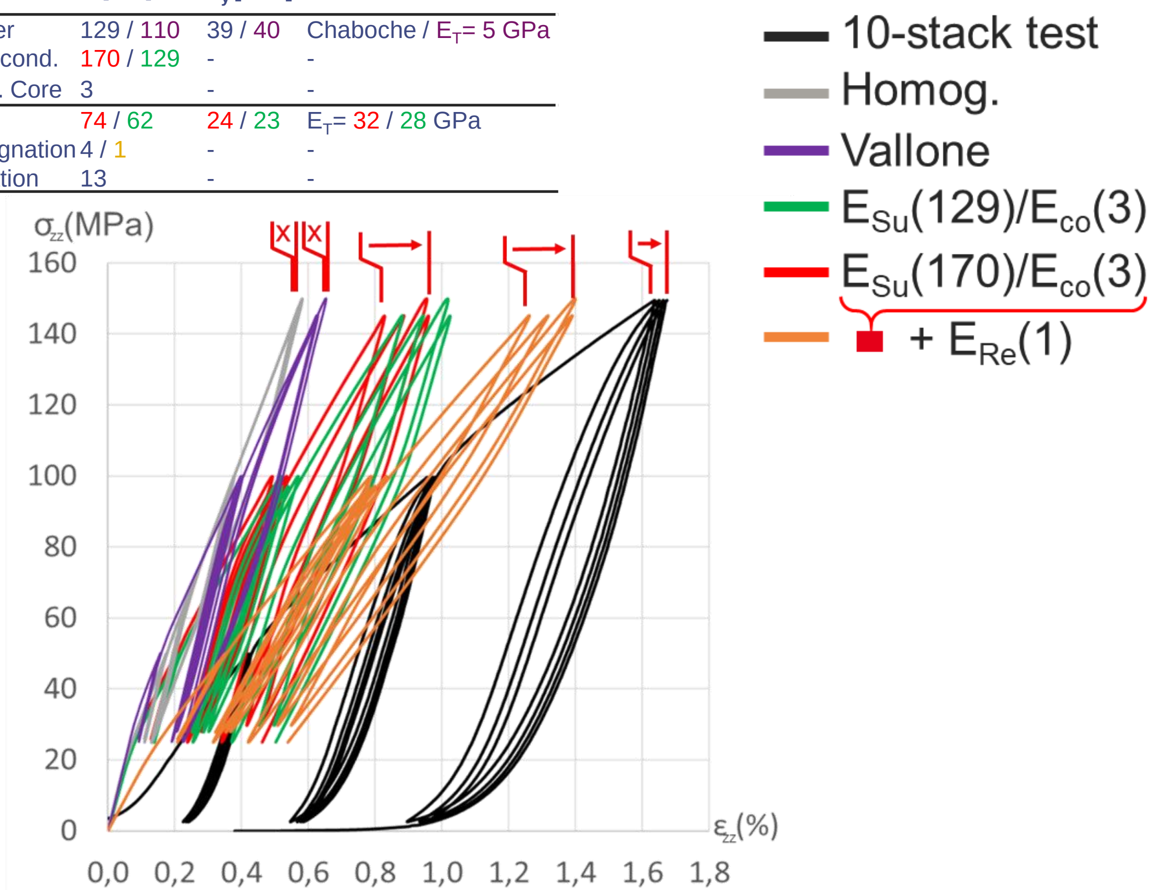
Scale	Component	E [GPa]	σ_y [MPa]	Plastic
Strand	Copper	129 / 110	39 / 40	Chaboche / E_T= 5 GPa
	Supercond.	170 / 129	-	-
	Subel. Core	3	-	-
Stack	RVE	74 / 62	24 / 23	E_T= 32 / 28 GPa
	Impregnation	4 / 1	-	-
	Insulation	13	-	-

- Mechanical description
  - Homog.
    E=127 GPa, ν=0,36,
    σ_y=25 Mpa, E_T=47 Gpa

- Results

Stack equivalent parameters derived from curves

	E^{eq} GPa	σ_y^{eq} MPa	E_T^{eq} GPa
10-stack test	38,7	40	8.3
Homog.	38,9	18	24,6
Vallone	39,1	30	20
Esu(129)/Eco(3)	33,1	36	16,6
Esu(171)/Eco(3)	34,6	35	17,5
Esu(171)/Eco(3) + Ere(1)	17,5	30	11,6



Summary

- Results of simulation
  - Conditions of the simulation has a direct impact
    - ↳ BCs, monotonic/cyclic, 2D / 3D
  - Accurate mechanical properties are required to build robust and predictive models
  - Adapted mechanical descriptions have to be used to reproduce the observed behavior
    - ↳ non linearities / accumulation of strain / damage
- Characterization
  - 10-stack campain
    - ↳ More data for model comparison
    - ↳ Understanding of experimental artefact and representativeness of 10-stack tests for coil behavior
  - Strand scale
    - Core behavior
    - Homogenization scheme
    - Transverse compressive tests & model comparison
- CoCaSCOPE
  - Access to the different entities of the stack
  - Access to various parameters in any geometrical configuration useful to understand the behavior
  - Implementation of various mechanical models
  - Can be used with any Finite Element code

➔ Mesh Generator available for the community to generate any kind of model!

Outline

1. **Characterization and modeling program for Nb_3Sn conductors @ CEA Paris-Saclay**

2. **CoCaSCOPE**
   Mesh Generator
   Behavior representation
   Experimental characterization
   Single stack simulations

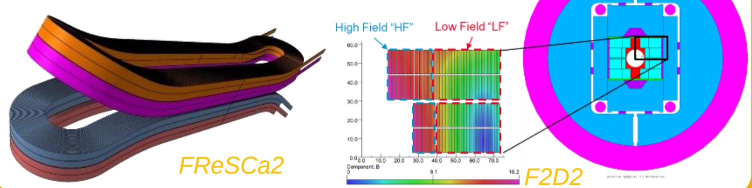
3. **Summary and perspectives**

Overview of CEA's Nb_3Sn modeling program

Model | **Experimental**

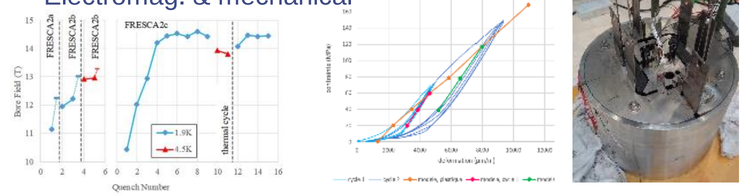
Magnet scale

Model — Electromag. & mechanical



FReSCa2 *F2D2*

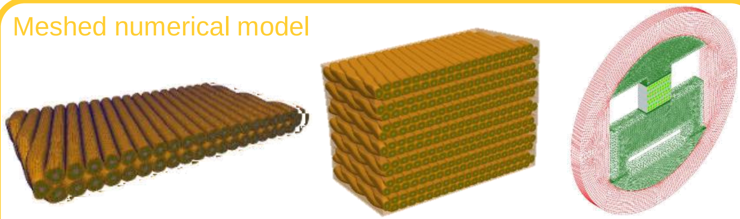
Experimental — Electromag. & mechanical



FReSCa2 test @CERN *SD program*

Cable scale

Model — Meshed numerical model



Cable and stack simulation *Numerical twin of stack test*

Experimental

HT dilatation — Unreacted or reacted cable behavior — Cracks and electromag. perf.

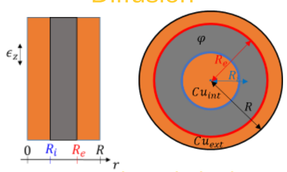
+ Characterization under elementary loadings (Transverse / bending)

DIC in-situ *Hard-way bending* *Layer jump* *10-stack*

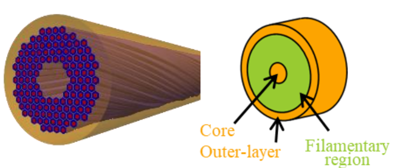
Impact of transverse pressure on a double stack @ CERN

Strand scale

Model — Diffusion / Mechanical

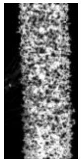


Semi-analytical diffusion model

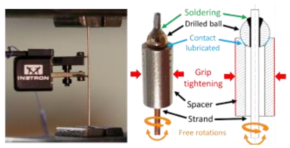


Detailed and bi-metallic strand models

Experimental — HT dilatation / Mechanical



DIC in-situ

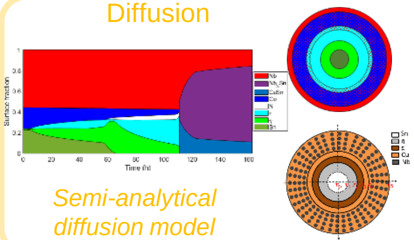


Tensile test

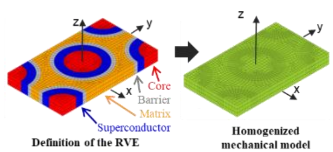
+ Characterization under elementary loadings (Transverse / bending)

Subelement scale

Model — Diffusion / Mechanical

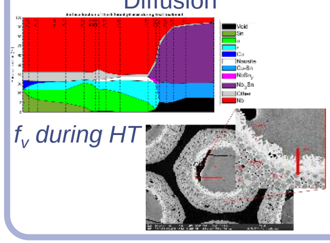


Semi-analytical diffusion model

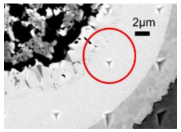


Homogenization of filamentary region

Experimental — Diffusion / Local mechanical properties



f_v during HT

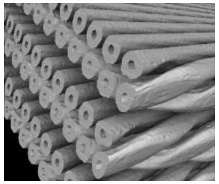


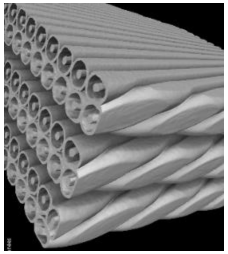
Nano-indentation

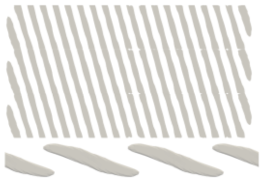
+ µ-sample & µ-pillar

On-going work 11/2023

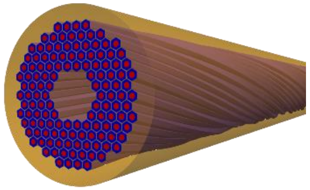
- Comparison of numerical models with real conductors
  - ↳ Facets from cabling QC and extracted from model
  - ↳ X-ray tomographies
  - ↳ Metallographic observations

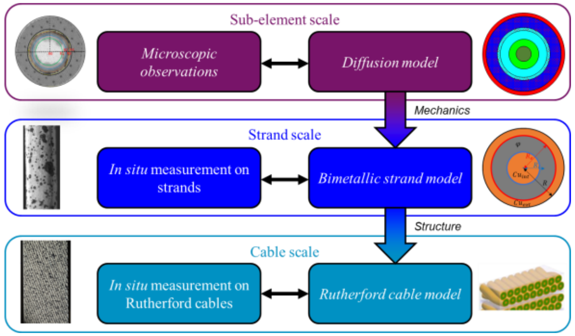






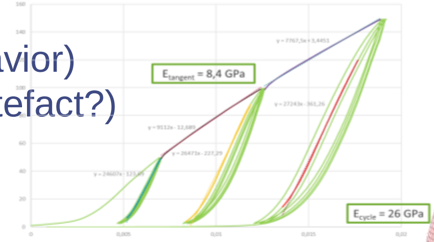
- Identification of material parameters
  - ↳ Tensile data and mechanical representation of other architectures (RRP 108/127 ∅0.7 mm ∅0.85 mm, RRP 132/169 ∅1 mm)
  - ↳ Inverse identification using detailed numerical model of strand w/ twisted sub-elements and experimental data

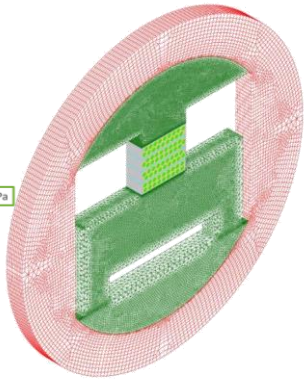




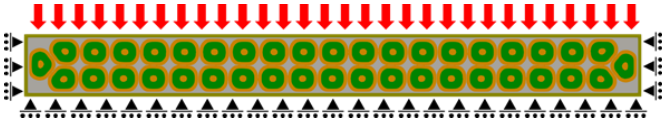
- Thermomechanical
  - ↳ Use of thermomechanical semi-analytical model develoment in cable / stack models
    Following of the PhD of M. Abel-Hafiz

- 10-stack characterization campaign
  - □ Continuity of 10-stack tests @ CEA
  - □ Extend mechanical study (strain rate, hold, unloadings, cyclic behavior)
  - ↳ Highly non-linear behavior at low stress (viscosity, experimental artefact?)





- Simulation program
  - □ 10-stack tests (mechanical)
  - □ FRESCA tests (double-stack & fracture)
  - □ Subscale Dipole – SD
    (coil segment / 5-stack & thermo-mechanic)



Merci !
Thank you !

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