DE LA RECHERCHE À L'INDUSTRIE

ANALYSE MULTI-ÉCHELLE DE CÂBLES SUPRACONDUCTEURS

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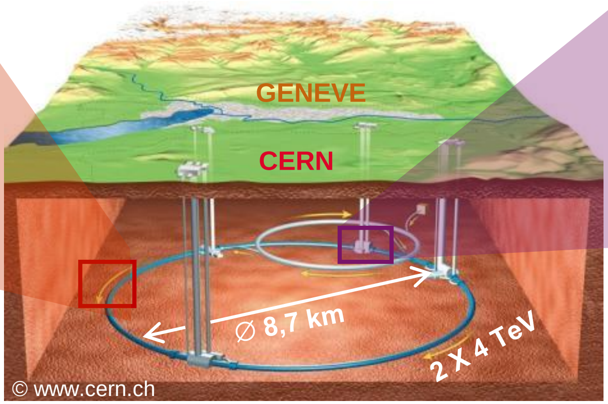
Club Cast3m 2018 - Paris
04/02/2019

PARTICLE COLLIDER : THE NEED FOR HIGH FIELD MAGNETS

<u>Circular particle accelerators magnet</u> :

Dipole & Quadrupole LHc (NbTi) → $\mathbf{B_{max}}$ < 9T



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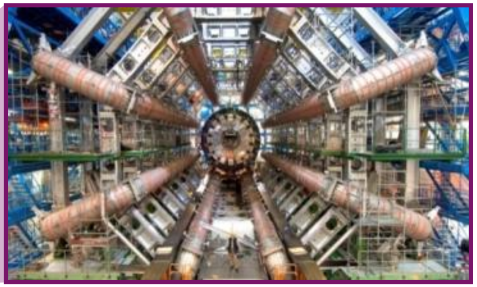


<u>Detector magnet</u> :

ATLAS (NbTi) → $\mathbf{B_{max}}$ **< 4T**

04 juillet 2012

Sciences

SCIENCES Archéologie Biologie Cosmos Géologie Mathématiques Médecine Paléontologi

Le boson de Higgs découvert avec 99,9999 % de certitude

Le Monde.fr | 04.07.2012 à 09h26 • Mis à jour le 04.07.2012 à 13h39

Par David Larousserie Genève, envoyé spécial

Principle of a circular accelerator, to ensure the collision of the 2 beams :

❶ accelerate the particles

→ *radiofrequency cavities* : $\vec{F} = q\vec{E}$

❷ deviate the particules (bend the trajectory)

→ *dipolar magnets* : $\vec{F} = q\vec{V} \wedge \vec{B}$

❸ focus the beam (concentrate the bunches)

→ *quadripolar magnets*

❹ reduce aberrations

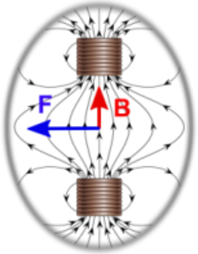
→ *multipolar magnets*

The LHc today :

- ~ 1200 dipole magnets (L=14m)
- ~ 400 quadrupole magnets (L=3m)

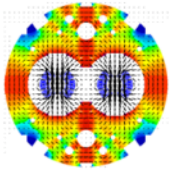
The futur of LHc :

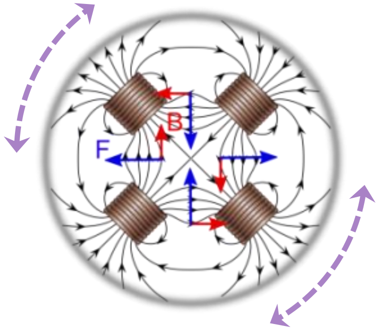
- **HL-LHc (luminosity upgrade X 10) → 2022**
- HE-LHc (energy upgrade X 2,5) → 2035

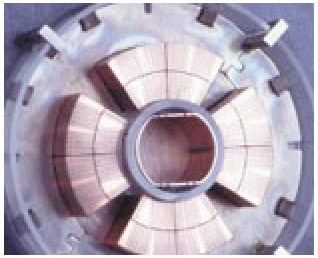


EUCARD

Increase $\vec{B}$





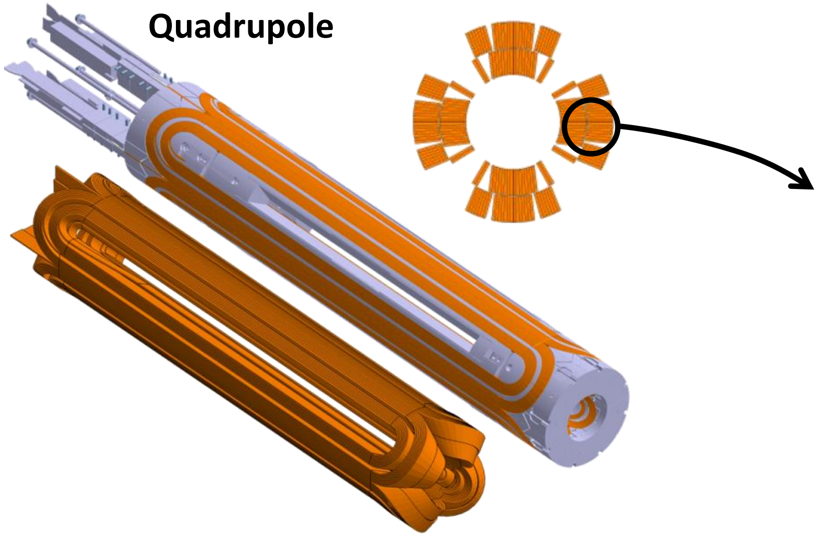


Dipoles are used to bend the beam trajectory

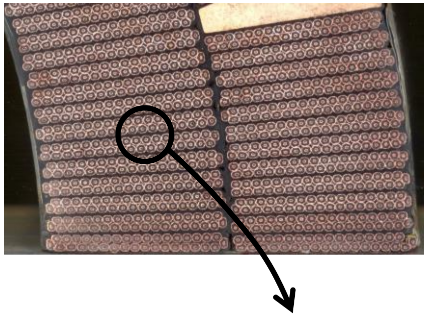
Quadrupoles are used for beam focusing

A MULTISCALE STRUCTURE …

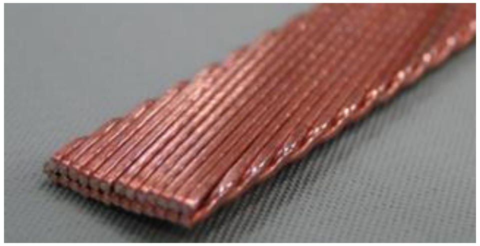
Quadrupole



Winding – stack (≈ m/cm)

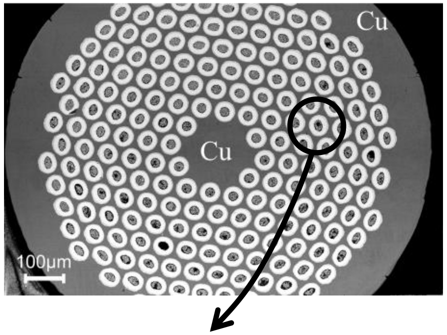


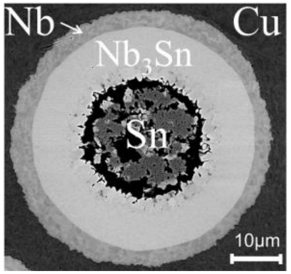
P. Ferracin, www.uspas.fnal.gov
Fermilab, http://td.fnal.gov
G. Lenoir, PhD thesis



Rutherford cable (≈ cm/mm)

Strand
(≈ mm/µm)





FILAMENT
(≈ mm/µm)

- State of the art
  - NbTi alloy currently used can reach 9/10T
  - LHC's upgrade aims beyond 10 T
- Development of Nb_3Sn based conductor
  - Complex manufacturing process
  - Brittle material
  - Electrical performances depends on mechanical state (strain)

➡ Influence of local phenomena must be understood ⇨ relevant criterion

➡ Superconductor behaviour should be anticipated ⇨ predictive approach

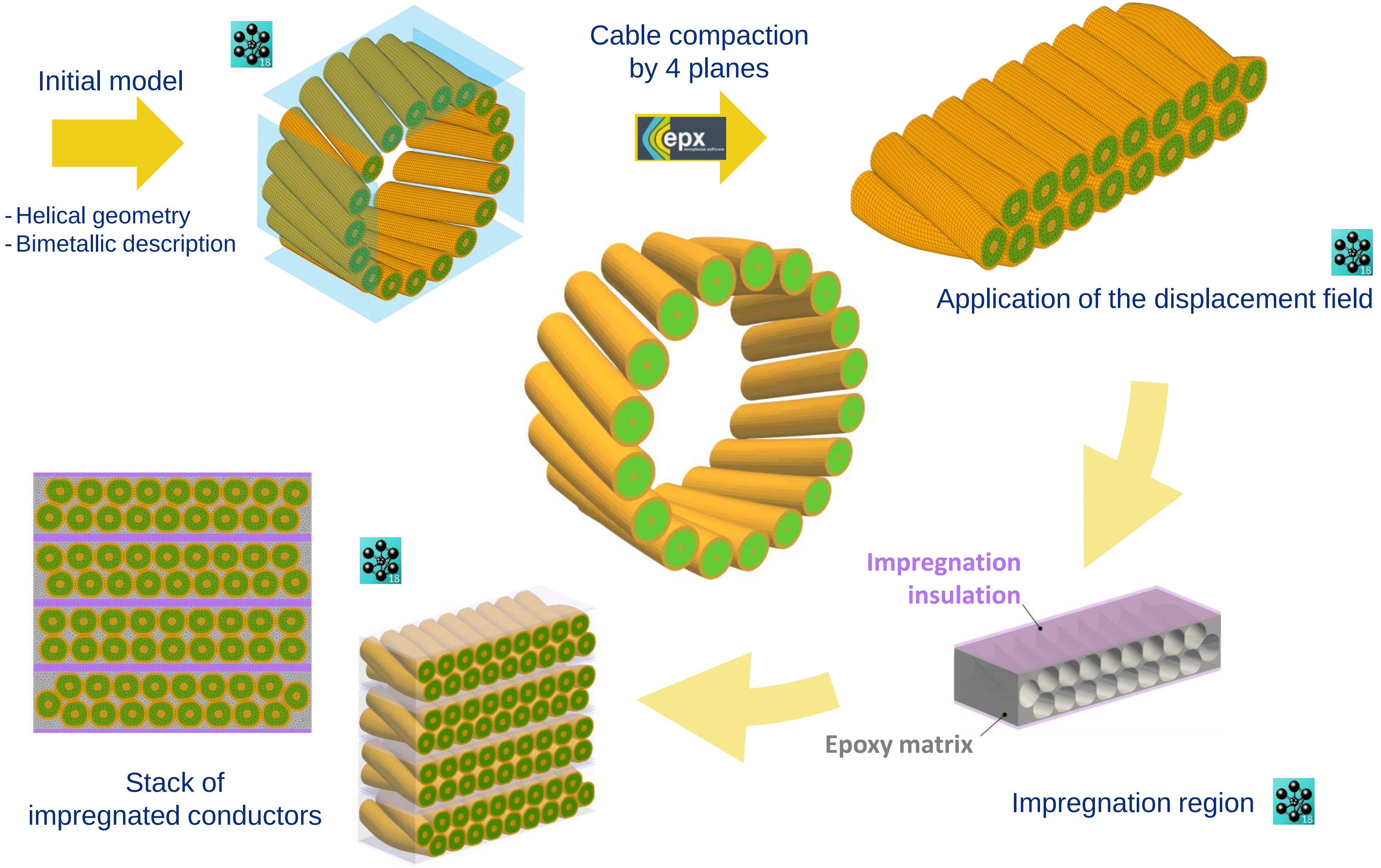
➡ Cable features should be optimized mechanically

OUTLINE

- GEOMETRIC MODEL (F. NUNIO)
  - ↳ Rutherford cables considering bi-metallic model
  - ↳ impregnation region
  - ↳ stack of conductors

- MECHANICAL MODEL (G. LENOIR)
  - ↳ Bi-metallic strand model based on RVE at the µ-scale
  - ↳ Inverse identification of material parameters
  - ↳ Validation of the model

CABLING MODEL METHODOLOGY



Initial model

- Helical geometry
- Bimetallic description

Cable compaction by 4 planes

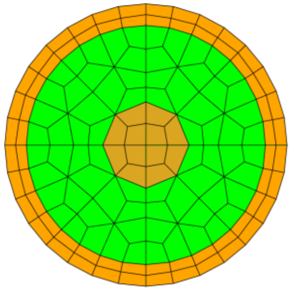
Application of the displacement field

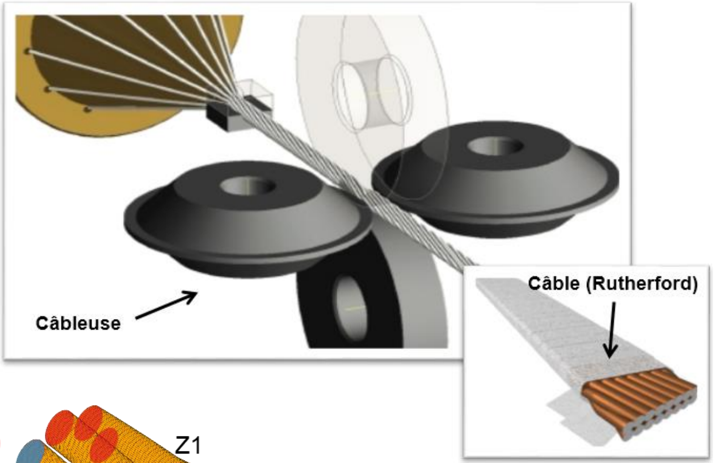
Impregnation region

Stack of impregnated conductors

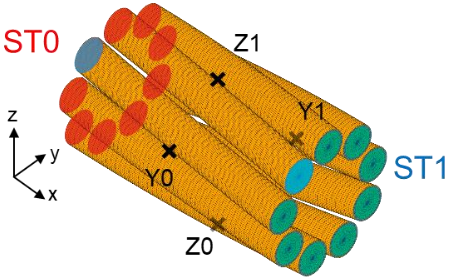
CABLING MODEL

- ☐ Parametrization of the model :
  - Strand parameters
  - Cable parameters
    - Number of strands
    - Twist pitch P
    - Final size of the Rutherford shape W x H

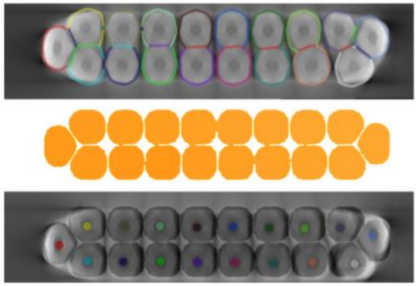




- ☐ Benefits :
  - Cast3m script generates EPx input file
  - Persistence of the model’s hierarchical structure during all modeling steps



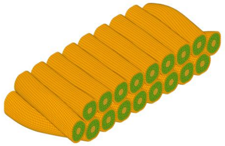
⇨ **Adaptative tool for the prediction of the cable geometry**



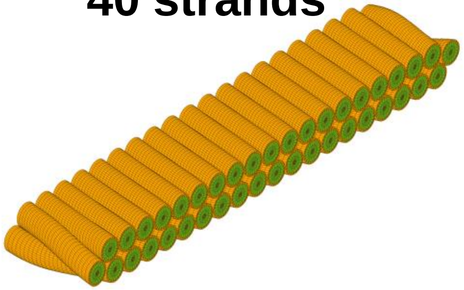
CT scan comparison

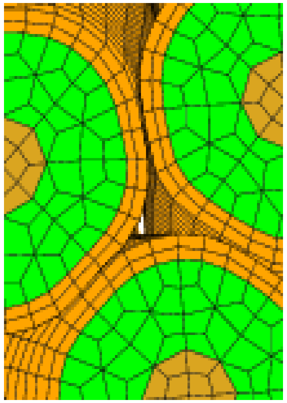
9 strands

18 strands



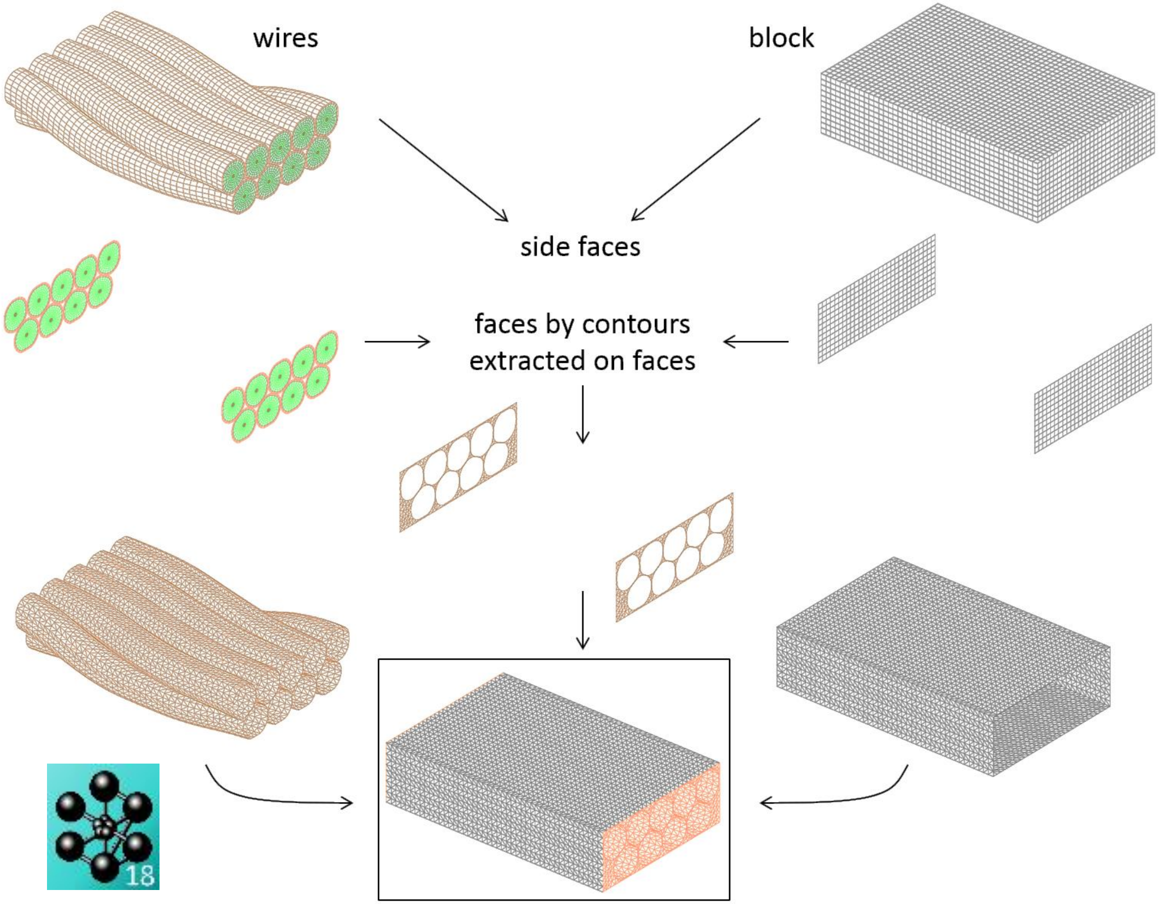
40 strands





IMPREGNATION MODEL

- Matrix filler construction :
  - not fully successful with reverse engineering methods (surface reconstruction, Boolean operators …)
  - no improvements with direct Boolean cut at the level of the mesh
  - **method** : rebuild the skin of the matrix filler by a “sewing” technique, and mesh the volume

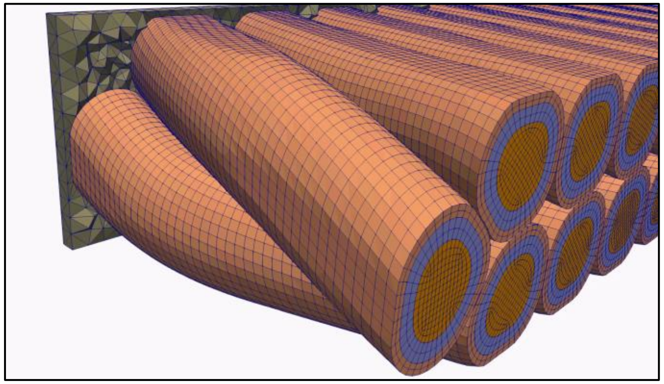


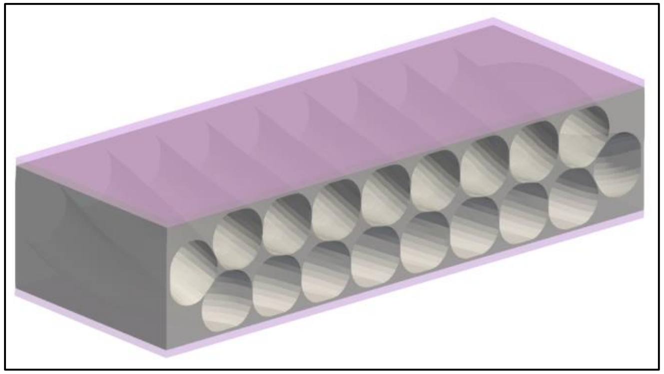
wires

block

side faces

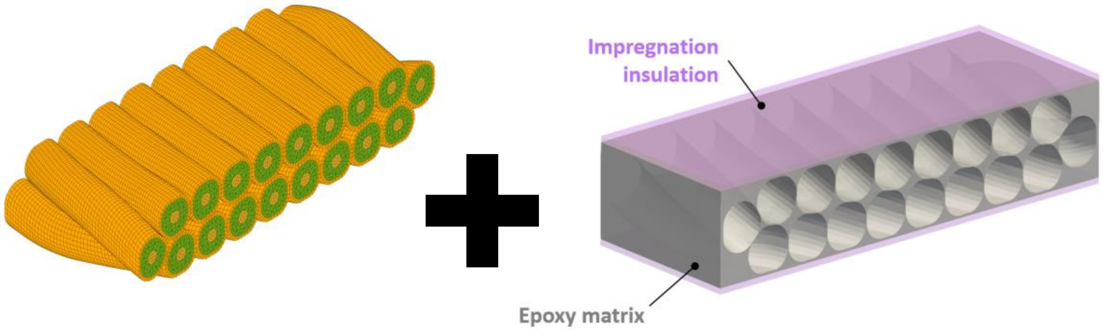
faces by contours extracted on faces

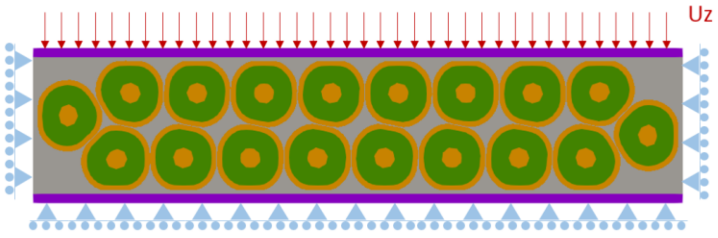




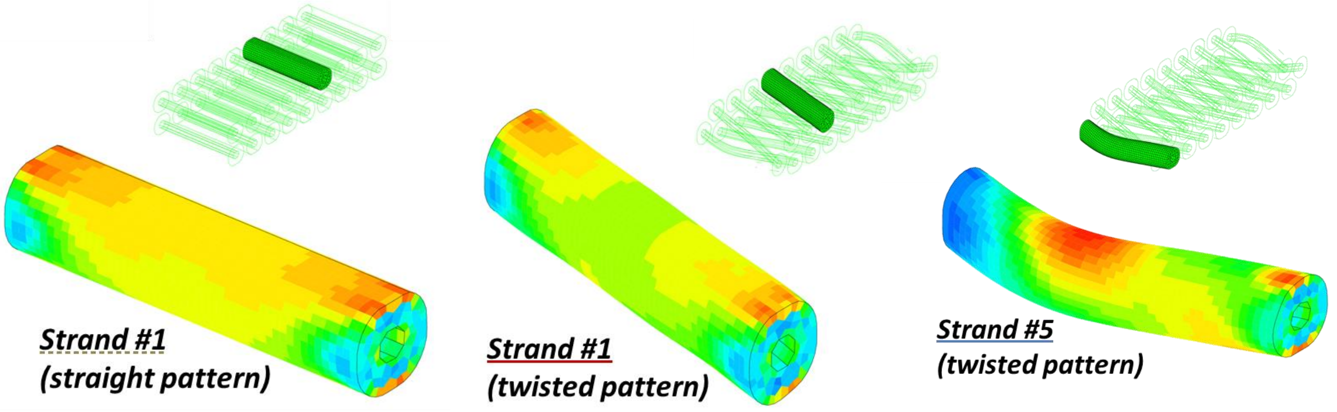
SUMMARY OF CABLING MODEL

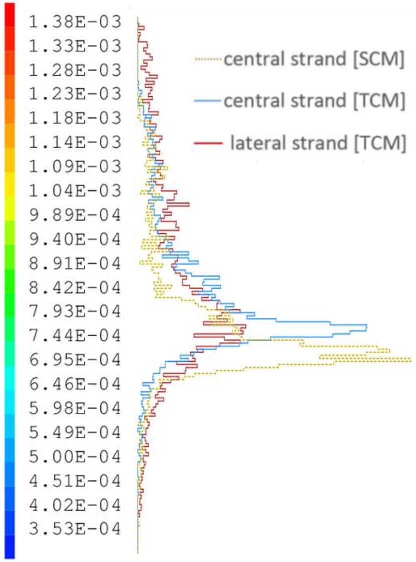
☐ Model of impregnated Rutherford cable

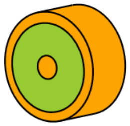




☐ Analysis of numerical compressive test on one stack







Bi-metallic model

⇨ Representative results of cable requires adapted mechanical model at the strand scale

OUTLINE

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  - ↳ Validation of the model

THE BI-METALLIC MODEL

☐ Detailled mesh of strands in cable model numerically too expansive

⇨ Simplified representation of the strands

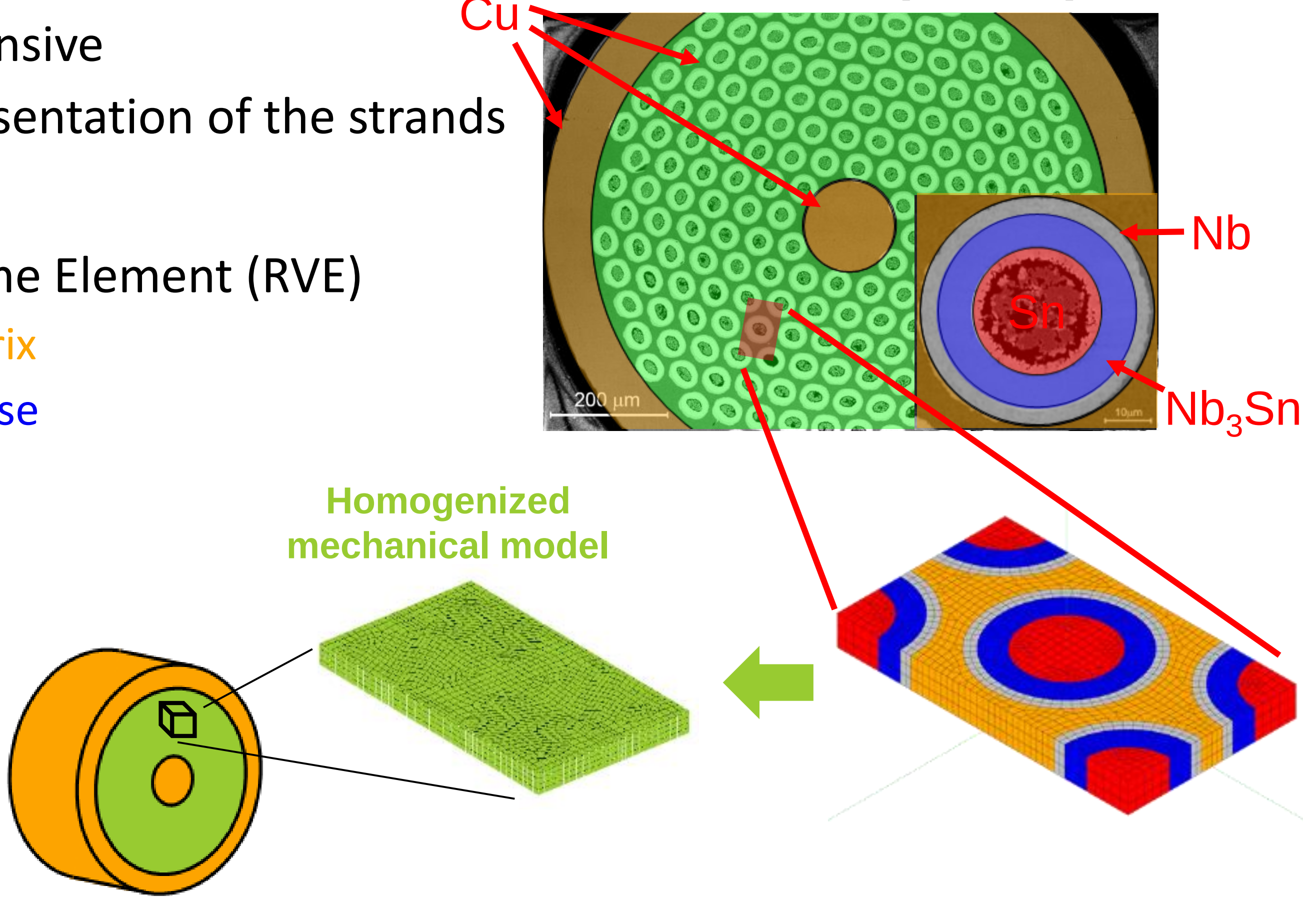
☐ Filament scale
Representative Volume Element (RVE)

- Interfilamentary matrix
- Superconducting phase
- Filament Barrier
- Filament Core

☐ Strand scale

- Filamentary Region
- Outer Layer
- Strand Core

SEM transverse observation of a Powder-In-Tube strand [Lenoir 17]



[Lenoir 17] G. Lenoir, PhD Thesis, Ecole CentraleSupélec, MSSMat laboratory, 2017

⇨ Definition the composition of the bi-metallic model sets and their mechanical behavior

FEATURES - ELASTO-PLASTIC BEHAVIOR LAWS

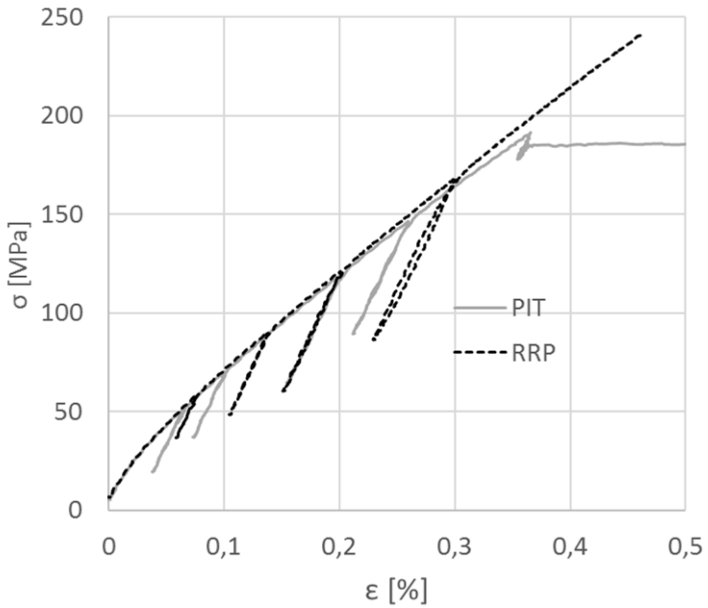
- ☐ Non-linear behavior of strands
  - ⇨ Adapted constitutive equation for elasto-plastic materials
  - ⇨ Predictibility of non-monotonic behavior

- ☐ Mechanical modeling *[Lemaître 94]*
  - ◘ Von Mises yield criterion $f(\sigma, X, R)$
  - ◘ Elasticity with Hooke's law: $\sigma = \mathrm{E} * \varepsilon$
  - ◘ Elasto-plasticity with hardening [Armstrong 66] [Lemaître 94]

Isotropic: $\dot{R} = \mathrm{b} * (\mathrm{Q} - R) * \dot{p}$

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

Hardening
Plasticity
Parameters



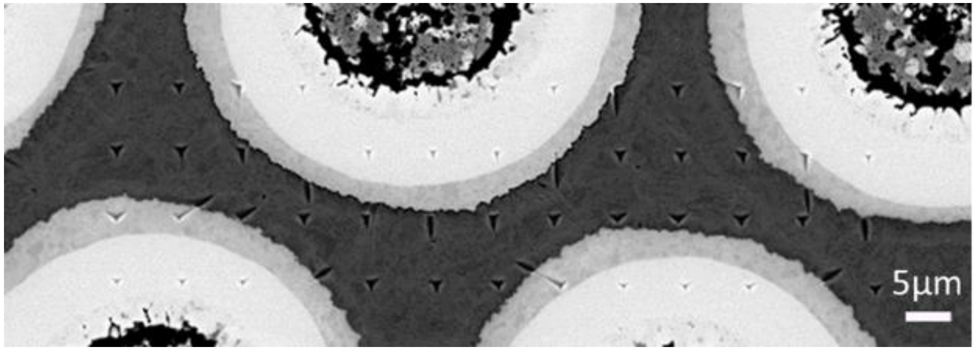
Tensile test on Nb_3Sn strands
[Lenoir 17]

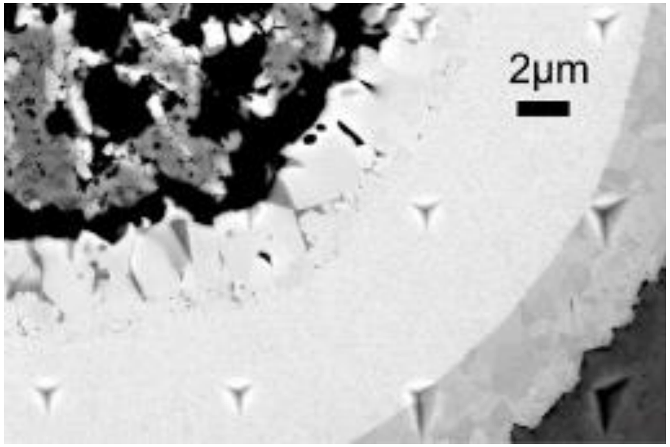
3D-model based on **internal variables** of individual components

[Lemaître 94] J. Lemaitre and J.-L.Chaboche, U.K.: Cambridge Univ. Press, 1994.
[Armstrong 66] P.-J. Armstrong, C.-O. Frederick, Board Report, Berkeley Nuclear Laboratories, 1966.

LOCAL PROPERTIES - NANO-INDENTATION *[LENOIR 17]*

- ☐ Observations

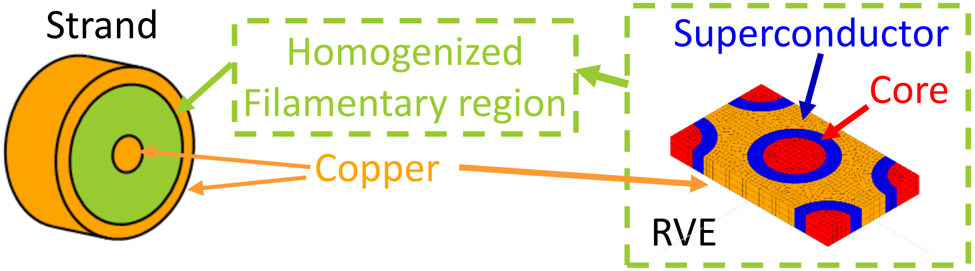




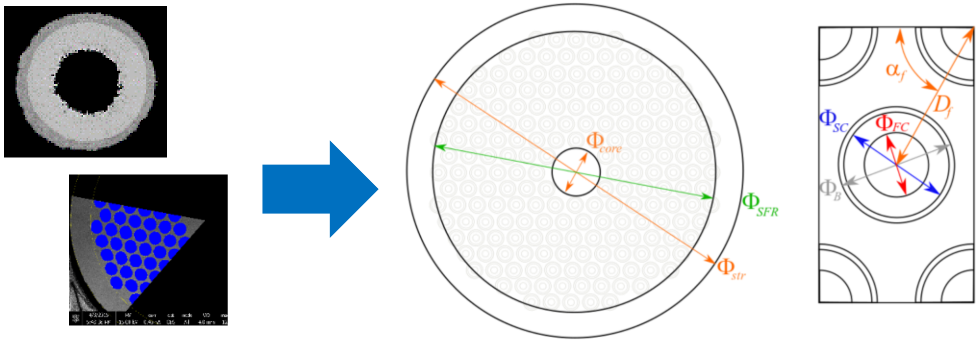
PIT	Indents number	E [GPa]	H [GPa]
Cu OL	18	133 ±5	1,25 ±0,08
Cu CO	15	125 ±4	1,14 ±0,07
Cu IF	92	132 ±6	1,33 ±0,13
Nb	13	125 ±13	1,69 ±0,43
Nb_3Sn SG	35	171 ±6	13,1 ±0,56

- ☐ Results
  - **Copper** considered as homogeneous
  - **Niobium** behavior close to copper’s
  - **Nb_3Sn**
    - Small grain phase purely elastic
    - Large grain phase not characterized
  - **{Tin, porosities}** not characterized

SUMMARY OF THE PIT BI-METALLIC MODEL



- Composition & mechanical parameters
  - Strand Core, Outer-layer & Interfil. Matrix – Copper
    - ⇨ Elasto-plastic with hardening - $E_{Cu}, \nu_{Cu}, \sigma_{y\,Cu}, b_{Cu}, Q_{Cu}, C_{Cu}, \gamma_{Cu}$
  - Supercond. – Nb_3Sn
    - ⇨ Elastic - E_{SC}, ν_{SC}
  - Filament Core - Sn / Porosities
    - ⇨ Elastic - E_{FC}, ν_{FC}
- Geometrical parameters from Image analysis using ImageJ software
  - Strand: $\O_{str}$, $\O_{SFR}$, $\O_{core}$
  - RVE: $\O_{SC}$, $\O_{FC}$, D_f, α_f



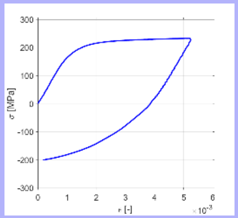
⇨ Model parameters identify by direct measurements & inverse identification

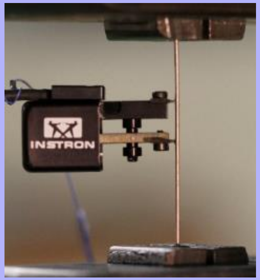
INVERSE IDENTIFICATION OF MATERIAL PARAMETERS

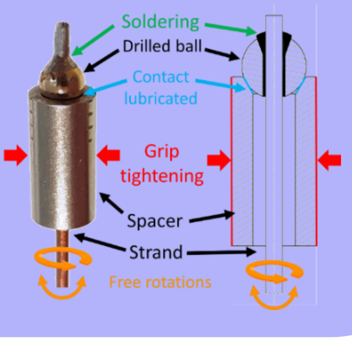
⇨ Finding the parameters which minimize the error between a model response and experimental data

Tensile tests

- ◘ Performed at CEA
- ◘ SCUTT device [Lenoir 17]
- ◘ Room temperature
- ◘ Reacted strands







Tensile tests model

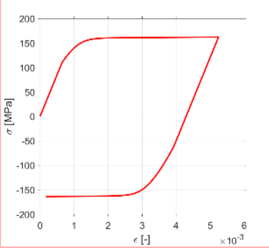
- ◘ Parallel materials
  - ■ Homogeneous strain

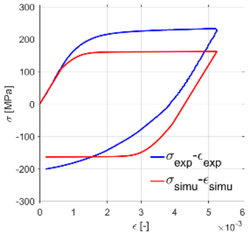
$$\varepsilon = \varepsilon_{SC} = \varepsilon_{FC} = \varepsilon_{Cu}$$

  - ■ Stress distribution

$$\sigma = f_{vSC} * \sigma_{SC} + f_{vFC} * \sigma_{FC} + f_{vCu} * \sigma_{Cu}$$

- ◘ Behavior of the sets
  - ■ Copper ⇨ $E_{Cu}, \nu_{Cu}, \sigma_{y\,Cu}, b_{Cu}, Q_{Cu}, C_{Cu}, \gamma_{Cu}$
  - ■ Supercond ⇨ E_{SC}, ν_{SC}
  - ■ Filament Core ⇨ E_{FC}, ν_{FC}
- ◘ Mech. differential system solved using a Runge-Kutta method





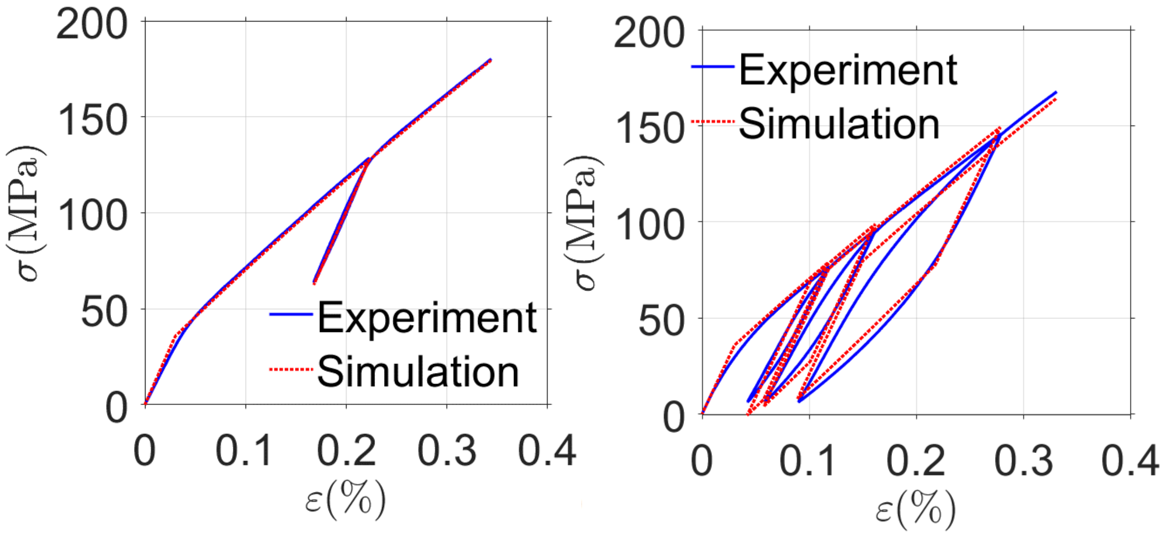
⇨ Optimization process

- ◘ Iteratively generate a set of parameters
- ◘ Compare the responses with a least square error
- ◘ Choose the set of parameters which minimize the error

} Genetic & gradient-based algorithms

INVERSE IDENTIFICATION RESULTS OF PIT

☐ Comparison with the tensile tests used to identify the parameters



☐ Fixed parameters

E_{Cu}, E_{SC}

☐ Optimized parameters

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

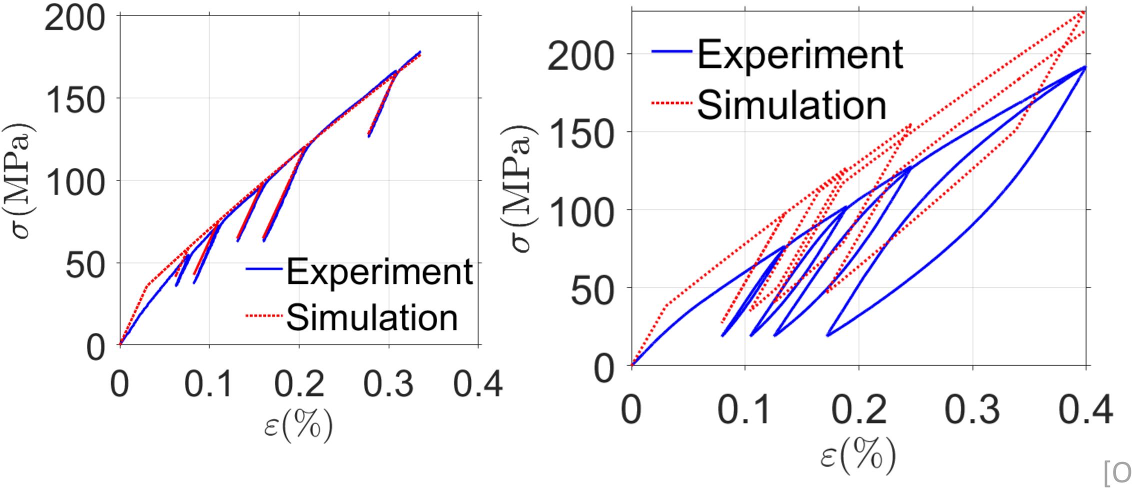
☐ Comments

- Elastic moduli
- Loading plastic behavior
- Elasto-plastic unloading
- Initial slope / high $\sigma_{y\ Cu}$

☐ Improvments

- Copper data
- Transverse tests on strand
- Adding kinematic hardening *[Ohno 94]*

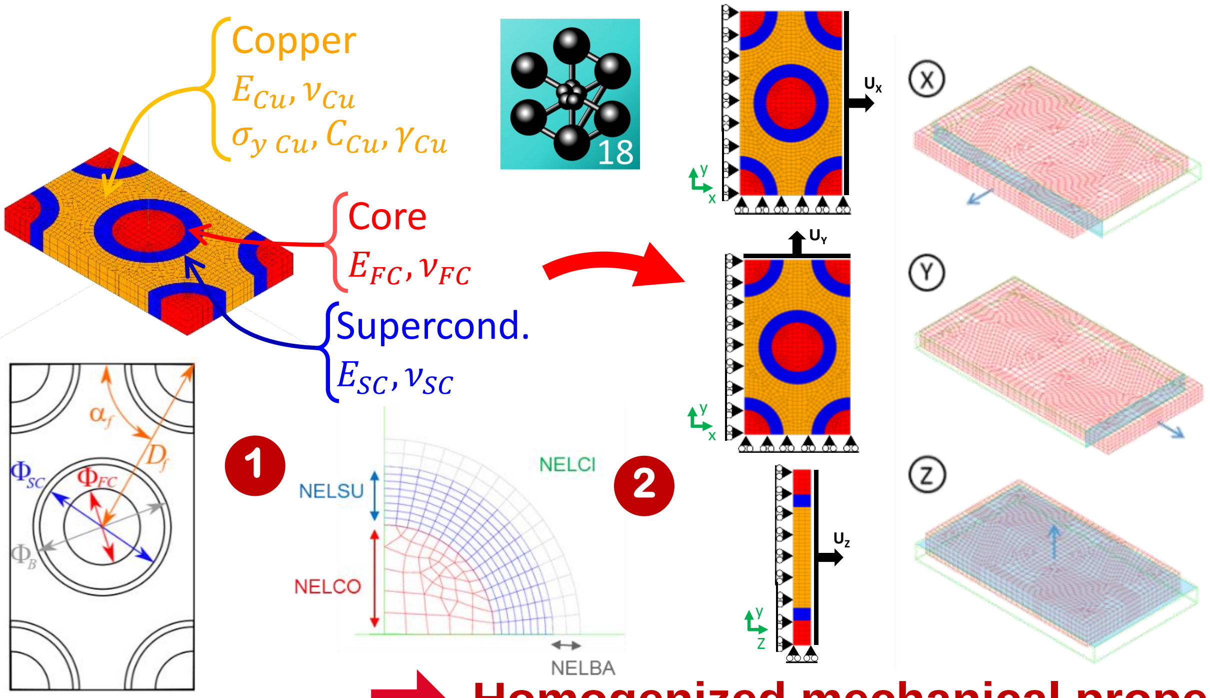
☐ Comparison with independant tests

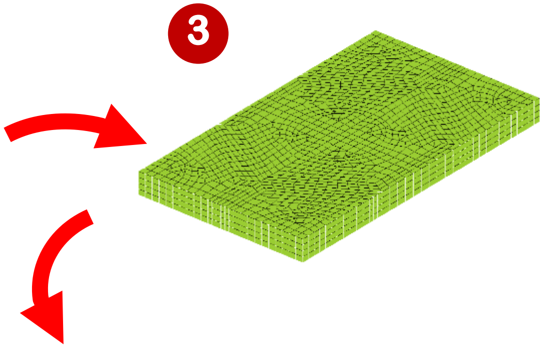


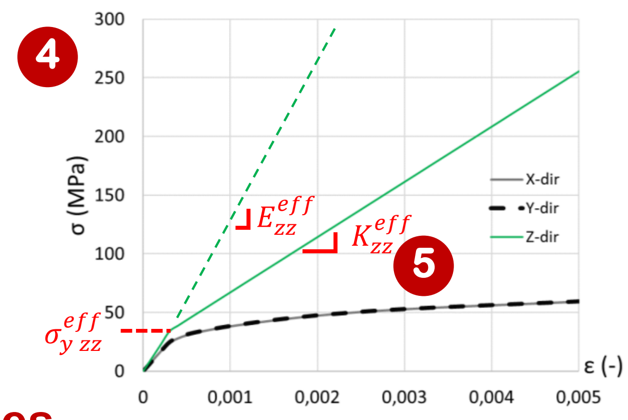
[Ohno 94] N. Ohno & J.-D. Wang, *Eur. J. Mech. A/Solids*, 1994.

BI-METALLIC MODEL - RVE HOMOGENIZATION IN CAST3M

1. Definition of the geometry and the materials parameters from the identification process
2. Numerical tests in the different directions
3. Integration of stress and strain in the total volume
4. Plot of stress-strain curve in the total volume on the aimed direction
5. Extraction of the bi-linear model in the different directions





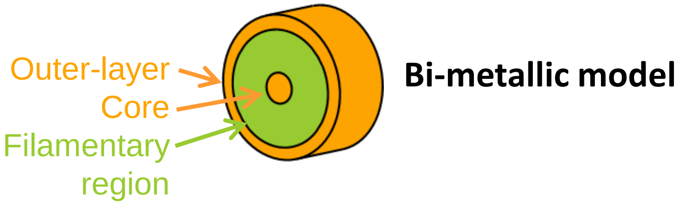


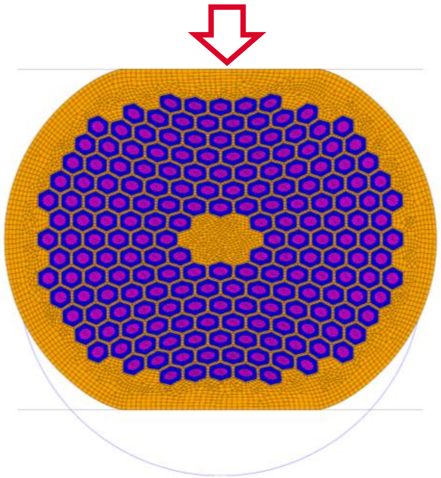
Homogenized mechanical properties (bi-linear model in each direction)

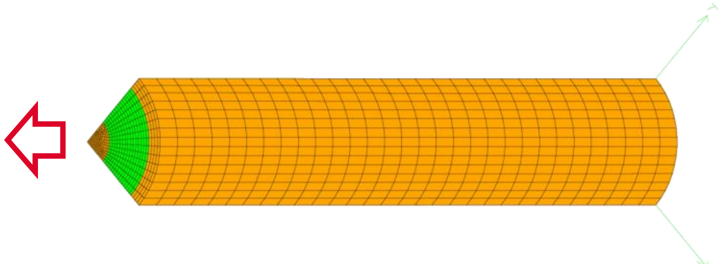
FUTURE VALIDATION OF THE MODEL

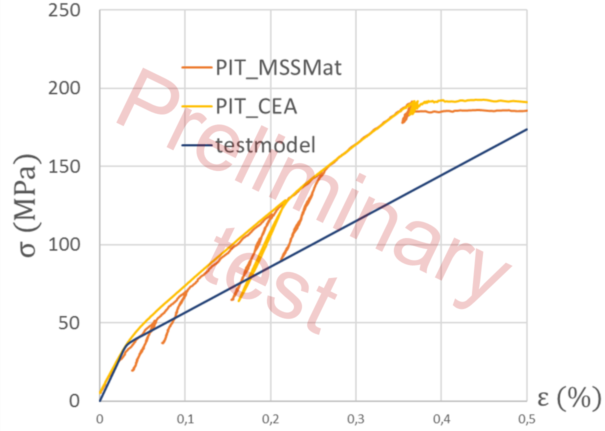
⇨ Comparison of the bi-metallic model response, detailed strand models & experimental data

- ☐ Mechanical behavior
  - Copper
    - ↳ behavior laws from identification process
  - Filamentary area
    - ↳ bi-linear model from homogenization process
- ☐ Numerical tests
  - Transverse direction
  - Tensile direction

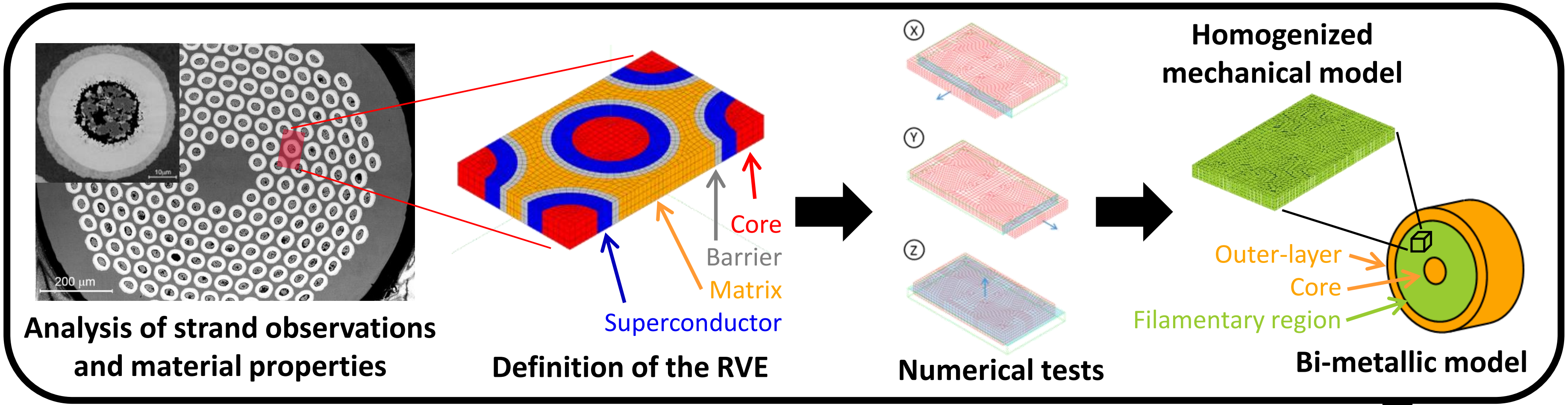








SUMMARY OF THE MODEL



Analysis of strand observations and material properties

Core
Barrier
Matrix
Superconductor

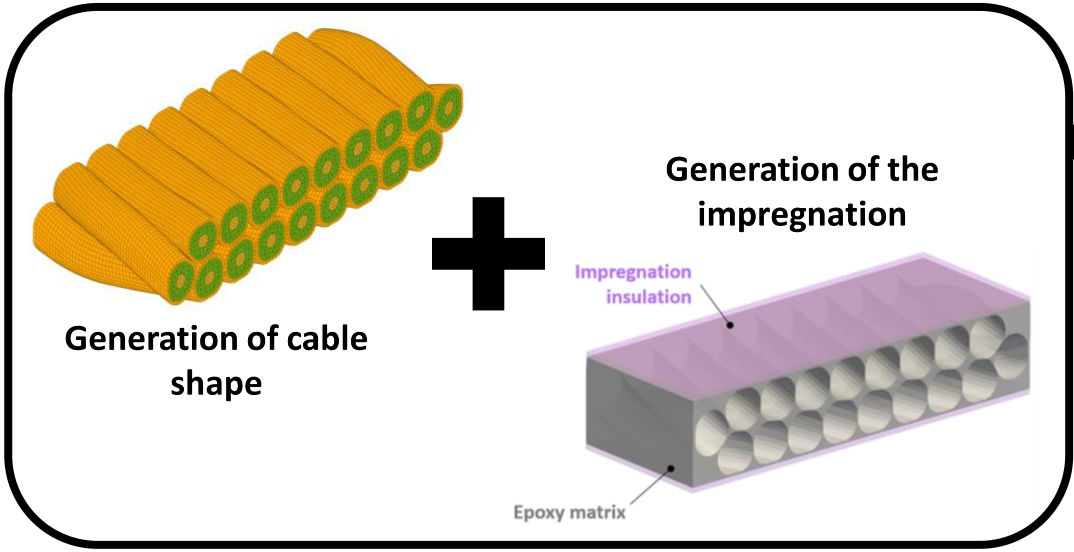
Definition of the RVE

Numerical tests

Homogenized mechanical model

Outer-layer
Core
Filamentary region

Bi-metallic model

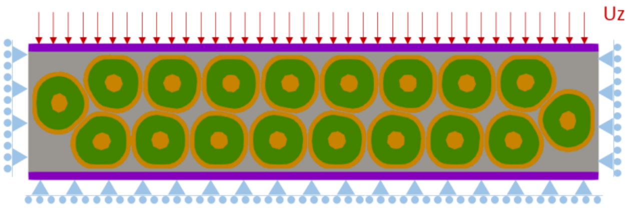


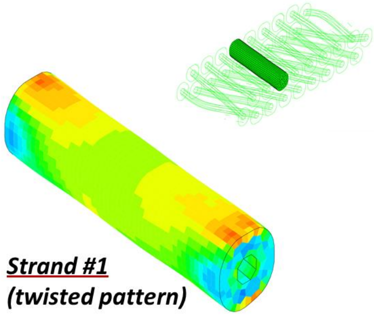
Generation of cable shape

Generation of the impregnation

Impregnation insulation

Epoxy matrix



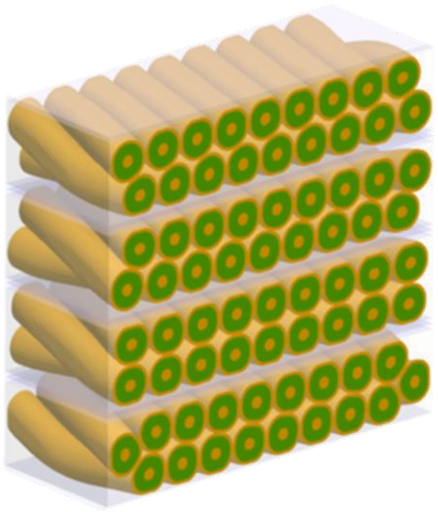


Strand #1
(twisted pattern)

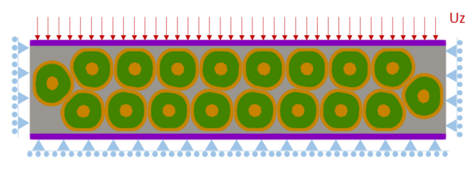
SUMMARY

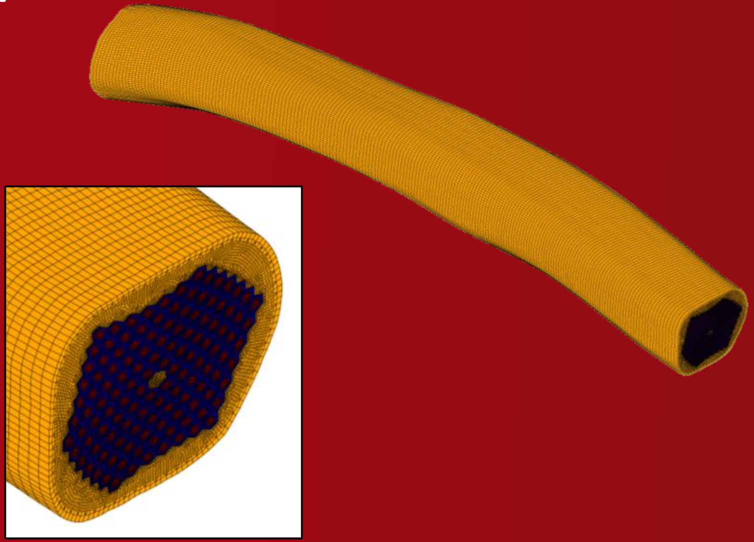
- GEOMETRIC MODEL
  - ↳ **Predictable** definition of the geometry of **Rutherford cables** considering **bi-metallic** model
  - ↳ **Robust and automated** creation of the **impregnation region**
  - ↳ Mechanical modelling of a **representative stack** of conductors
- MECHANICAL MODEL
  - ↳ **Bi-metallic strand model** based on **RVE at the µ-scale**
  - ↳ Elasto-plastic behavior with **internal variables**
  - ↳ Can be used for **predictable modeling** of cables

PERSPECTIVES



- **Electrical prediction**





- **Tensile tests at cryogenic temperature (on-going)**
- Nano-indentation at cryogenic temperature
- Enrichment of the experimental database with **transverse tests** and **copper data (on-going)**
- **Validation** of model prediction on experimental tests at **strand scale** & **cable (stack) scale**
- Add initial residual stress to account for strand heat treatment (experimental data needed)
- Improve the behavior law
- CoCaSCOPE platform

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SPECIAL THANKS TO DEN/DM2S/SEMT/DYN (V. FAUCHER, O. JAMOND, T. LAPORTE)

Analyse multi-échelle de câbles supraconducteurs

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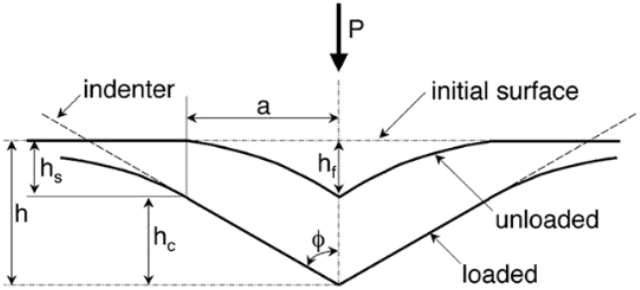
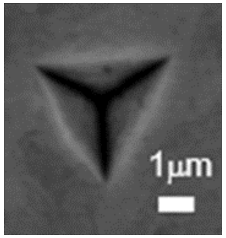
LOCAL PROPERTIES – NANO-INDENTATION TEST

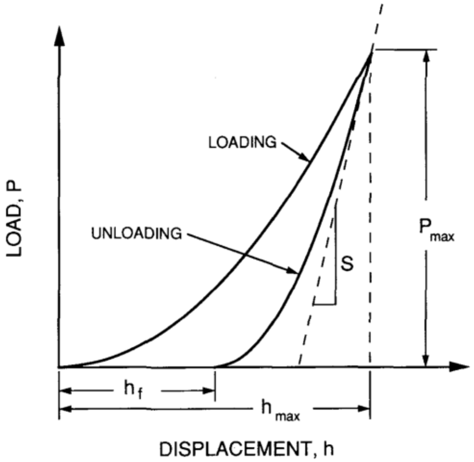
☐ Principle [Oliver 04]

- Mark (indentation) on the material surface realized with a tip (indenter)
- Load and displacement measured during indentation
- Contact stiffness and indenter properties

  ⇨ local elastic modulus and nano-hardness of the material







☐ Procedure

- MTS-XP nano-indenter (MSSMat - CentraleSupélec)
  (*Continuous/Dynamic Stiffness Measurement* technique)
- Dimension: Imposed depth 200nm

  Indents size ≈1,4µm
- Indents grid for statistical results
- Transverse cross-section of strands

  ↳ Surface preparation by manual and vibratory polishing of epoxy impregnated strand [Bajas 11]

- Validation of each indents
  - Contact stiffness and elastic modulus with penetration depth curves
  - SEM observations

[Oliver 04] W. C. Oliver and G. M. Pharr, *J. Mat. Res.*, 2004.
[Bajas 11] H. Bajas, PhD Thesis, Ecole Centrale Paris, MSSMat laboratory, 2011.

ELASTIC PROPERTIES DATABASE IN COMMUNITY

Material	E (GPa)	Reference
Copper	80	[Bajas 11]
	108	[Scheuerlein 17]
	116	[Alknes 16]
	118	[Sugano 16]
	128-137	[Mitchell 05]
Nb_3Sn	124	[Dylla 16]
	127	[Hojo 06]
	132	[Bussiere 80]
	135-100	[Mitchell 05]
	136	[Scheuerlein 15]
	137	[Keller 67]
	144	[Poirier 84]
	150-65	[Bray 97]
	165	[Easton 80]
	179-168	[West 79]
Niobium	92	[Alknes 16]
	103	[Sugano 15]
	105-110	[Mitchell 05]

$E_{\text{Nano-ind.}}$

129GPa

171GPa

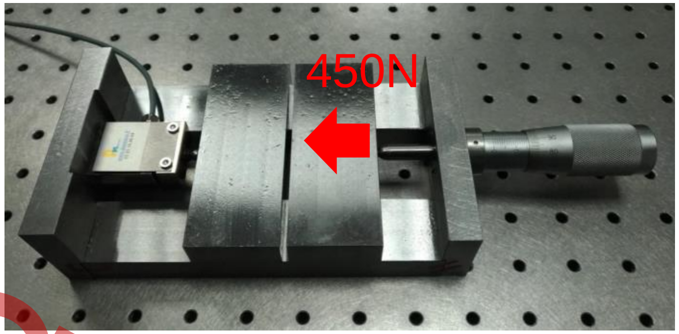
125GPa

- ☐ Differences in
  - Manufacturing process
    - Of materials
    - Of strands
  - Measured object
    - Complete strand
    - Filaments bundles (w/o matrix)
    - Single filament
    - Tapes (ex: Nb_3Sn layers/ductile substrate)
    - Single cristal
  - Measurement methods
    - Axial extensometer and load cell
    - Optical extensometer
    - Resonant Ultrasound Spectroscopy
    - Cristallographic orientation
  - Direct measurement vs Mixture laws
- ☐ Based on literature values

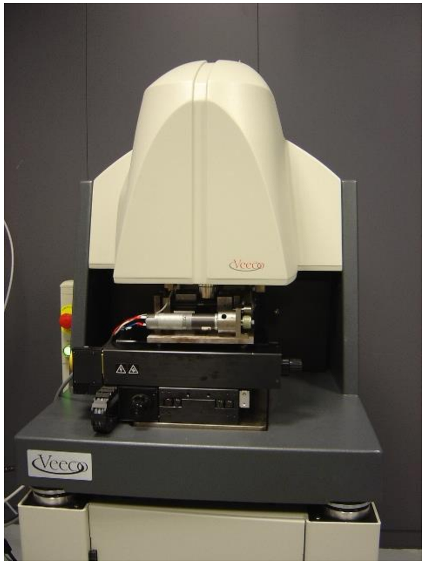
(E_{Nb}, single cristal properties, ASM International)

TRANSVERSE COMPRESSION ON STRANDS

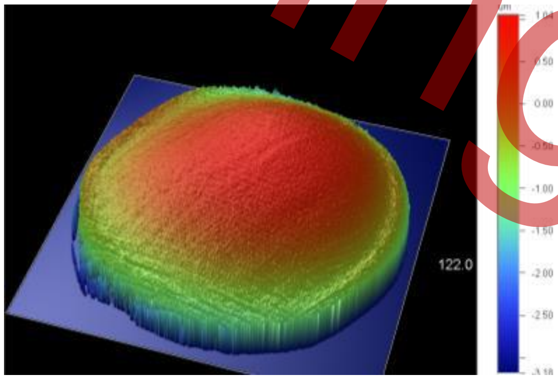
- ☐ Collaboration with ENSAM Châlons (R. Rotinat, R. Moulart, L. Fouilland, C. Person)
  - Digital Image Correlation during an *in-situ* transversal compression test
  - Objective
    - Quantify anisotropy
    - Include additional data for behavior laws identification



Compression device



Compression device inside the interferometric microscope



Planeity analysis of a copper wire and a strand