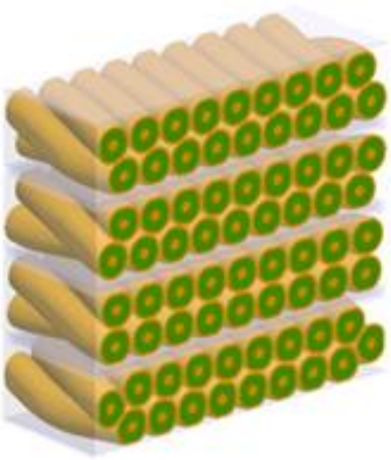
DE LA RECHERCHE À L'INDUSTRIE

CoCaSCOPE approach

for multiscale modelling of Nb_3Sn Rutherford cables



P. Manil, F. Nunio, K. Pirapakaran, G. Lenoir*
+ contributors listed at the end

CEA Paris-Saclay
Institute of research into the fundamental laws of the Universe
Systems engineering division

*currently at CERN

14 October 2021

OUTLINE

- CONTEXT
  - ↳ High field magnet program at Saclay
  - ↳ Technological R&D for Nb_3Sn
- COCASCOPE APPROACH
- COCASCOPE « BRICKS »
  - ↳ Preprocessor
  - ↳ Mesh validation
  - ↳ Bi-metallic homogeneized model
  - ↳ Computation and post-treatment
- RESULTS
- CONCLUSIONS & PERSPECTIVES

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IRFU'S LONG-TERM INVOLVEMENT IN SC MAGNETS

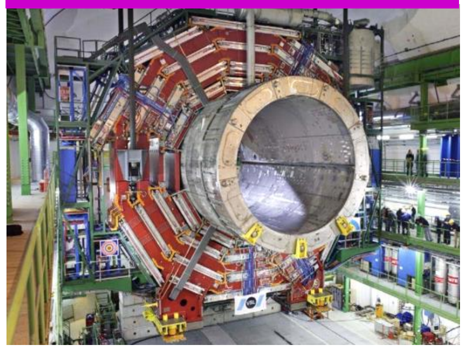
- Irfu's superconduting magnet program is piloted by **DACM division** with engineering support from DIS

2006

LHC interaction quadrupoles for CERN

2007

CMS solenoid integration for CERN



2009

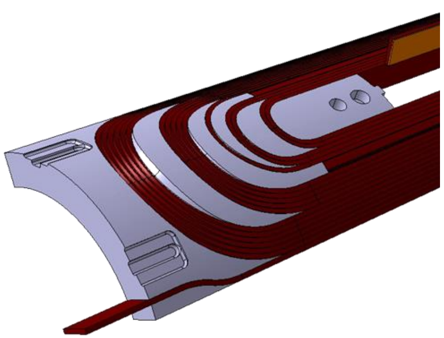
CARE-NED / SMC (12.6T)

2012

R3B spectrometer For GSI/FAIR

2014

MQXC quadrupoles for CERN



2018

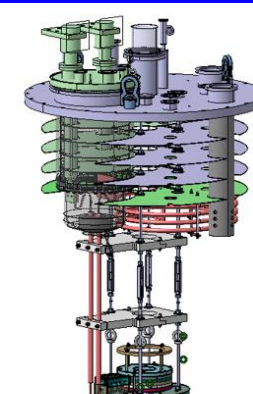
JT-60SA toroidal magnets tests at Saclay

2019

42 T hybrid magnet for LNCMI

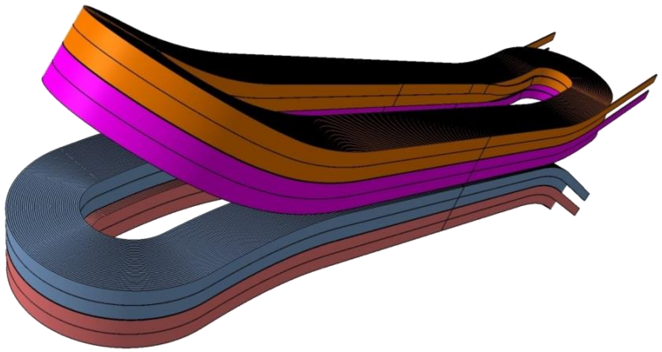
2021

MQYYM for HL-LHC

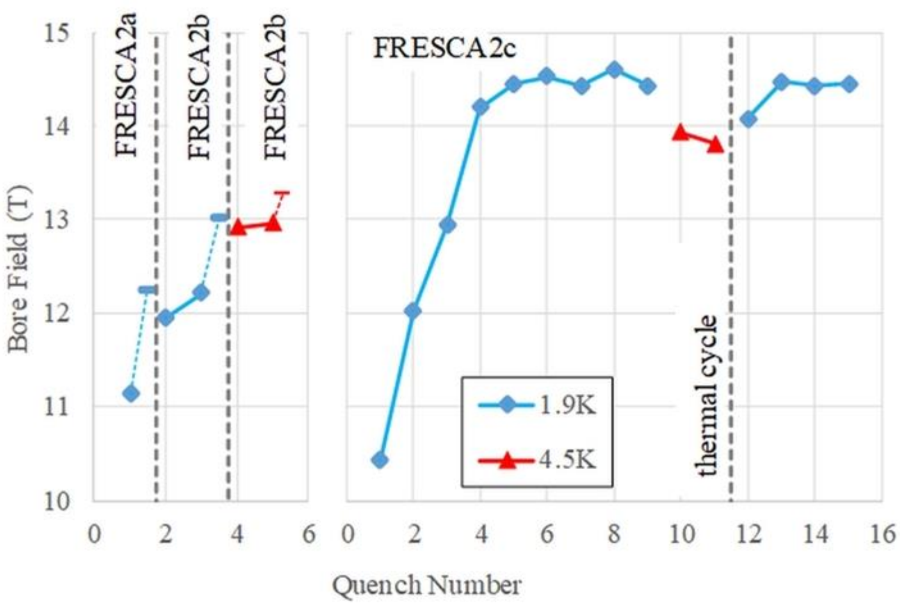


HIGHLIGHT #1: FRESCA2

- Nb_3Sn dipole in view of FCC
- 100mm aperture for test station upgrade



- Record field of 14.6 T in 2018

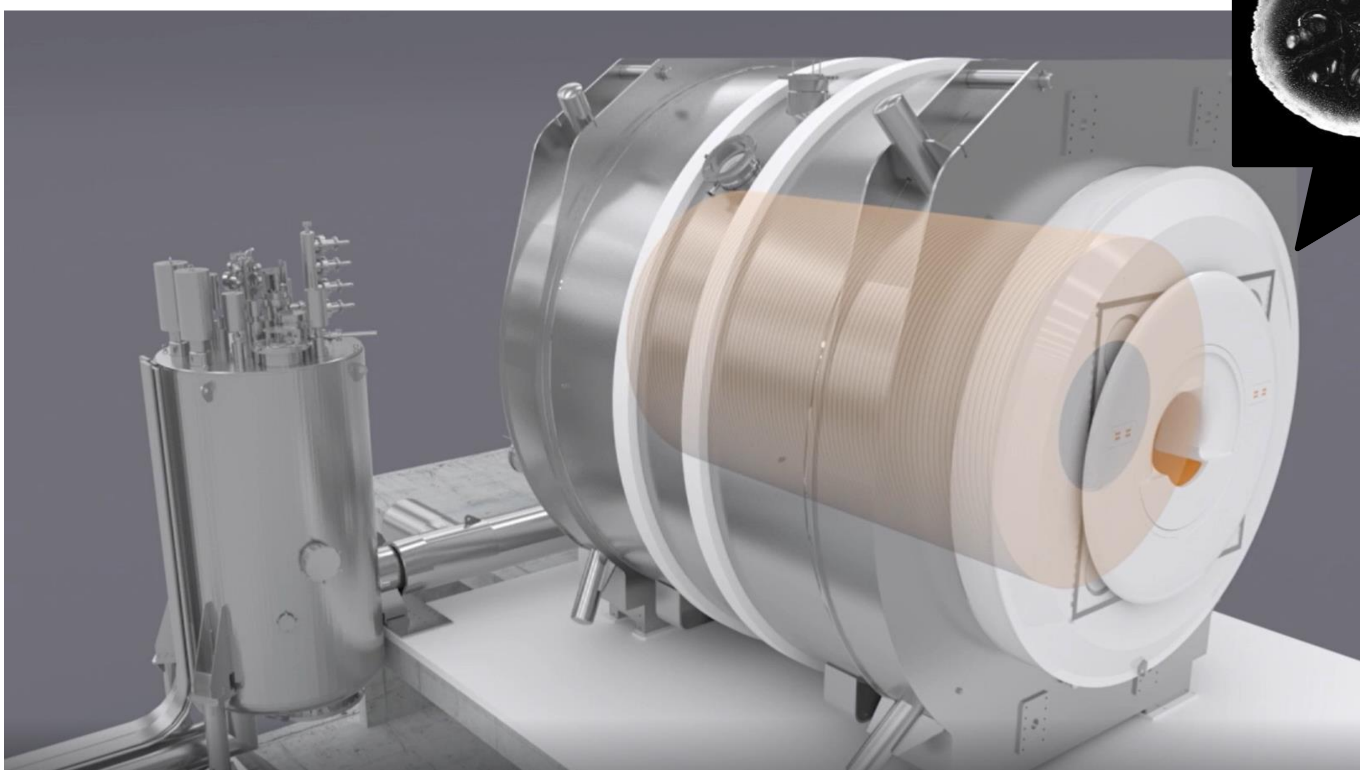


Courtesy G. Willering, CERN

Picture from CERN Website

Highlight #2: ISEULT

- NbTi MRI solenoid for human brain imaging
- 900mm aperture
- Record field of 11.7 T, very high homogeneity
- First image published last week!



Courtesy ISEULT project team, CEA (PL L. Quettier)

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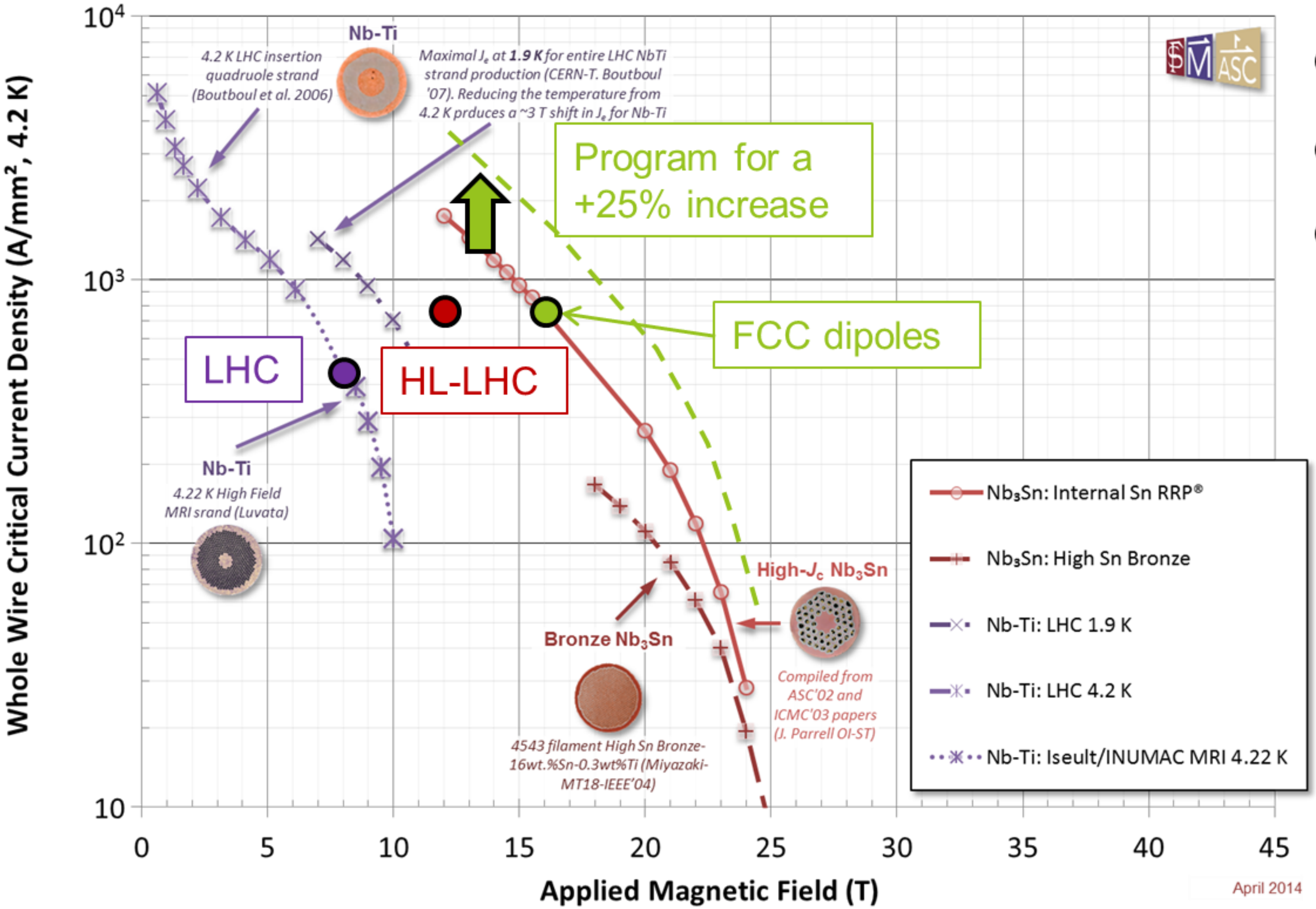
HIGHER MAGNETIC FIELDS IN VIEW OF FCC



Magnet operating points :

- LHC
- HL-LHC
- FCC

Courtesy E. Rochepault, CEA

CEA-CERN COLLABORATION FOR Nb_3Sn

CEA Nb_3Sn TECHNOLOGICAL R&D PROGRAM

NED-SMC
Experience
Racetrack ~13 T

FRESCA2
Experience
Dipole ~15 T

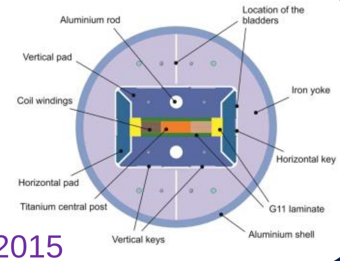
+Grading

CoCaSCOPE is here!

SMC

Demonstrate

Nb_3Sn technology ≥ 12 T



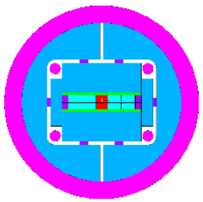
J.C. Perez et al., IEEE TAS 2015

+Grading

R2D2

Demonstrate grading ≥ 12 T

1.5 m, no bore



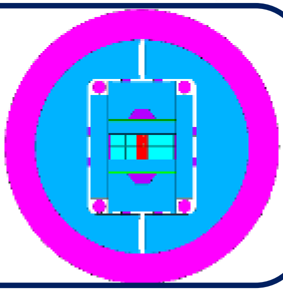
V. Calvelli et al., IEEE TAS 2021

+Flared ends

FD Demonstrator

Grading + **Flared-ends ≥ 14 T**

1.5 m, No bore

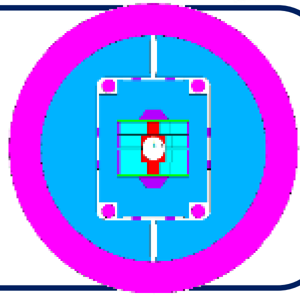


+Aperture

F2D2 Short model

Grading + Flared-ends + **Aperture = 16 T**

1.5 m, 50 mm bore



E. Rochepault et al., IEEE TAS 2020

CEA-CERN collaboration

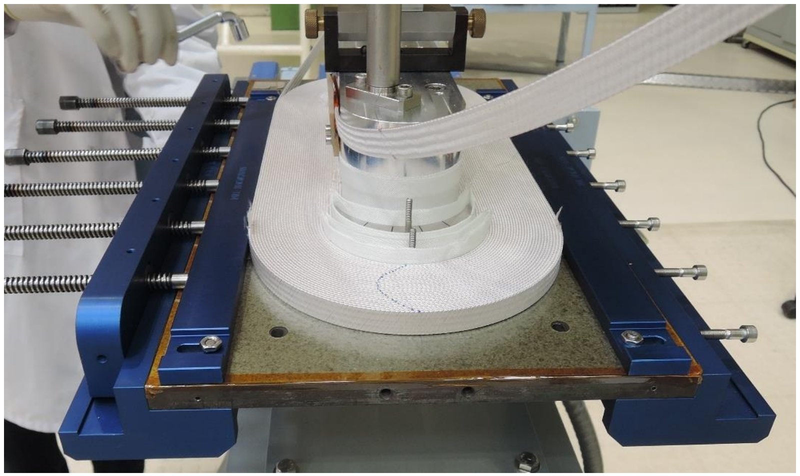
CEA-CERN Future Collaboration

Adapted from E. Rochepault, CEA

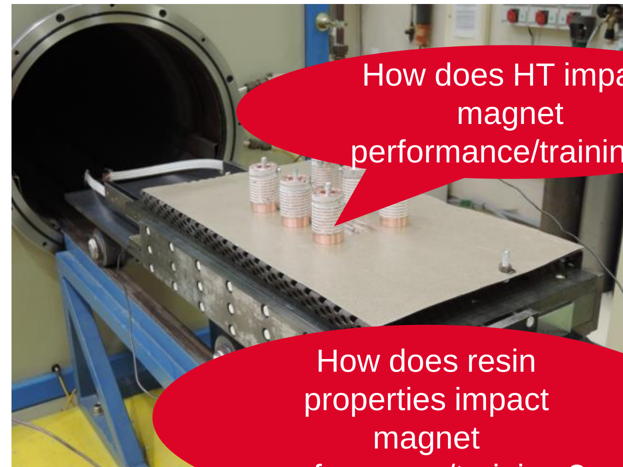
SMC program at Saclay

- Goal = Gaining experience on the full fabrication process of Nb_3Sn coils

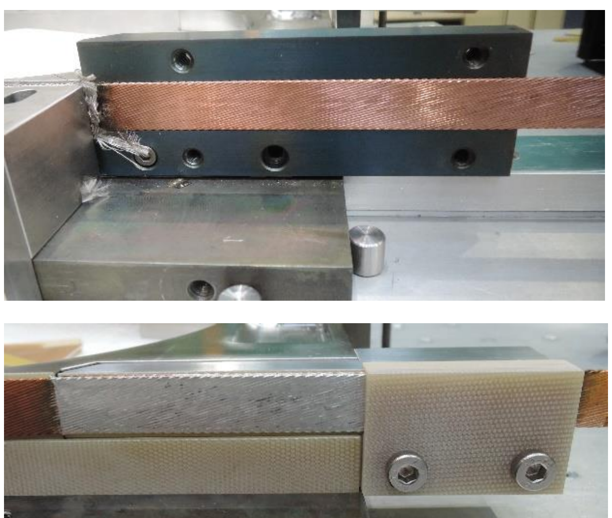
1. Winding



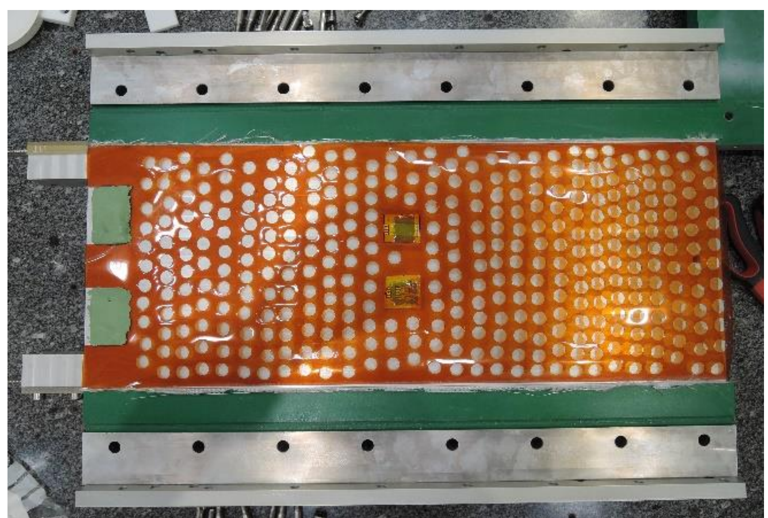
2. Heat treatment



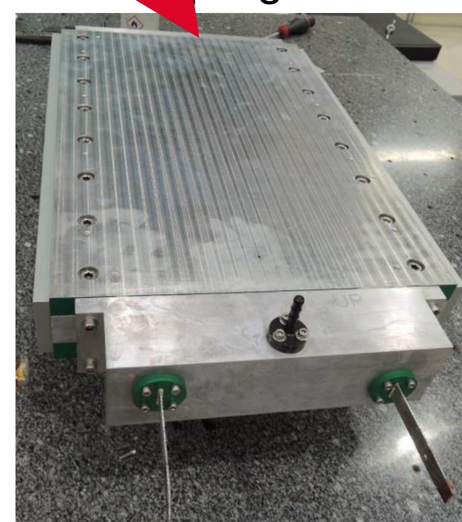
3. Splicing



4. Instrumentation/insulation



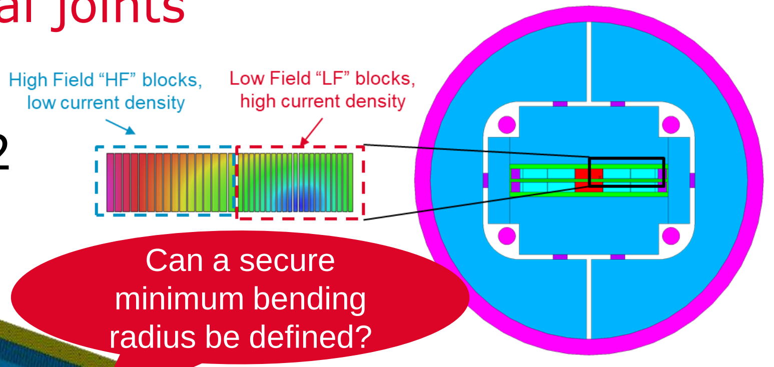
5. …pregnation

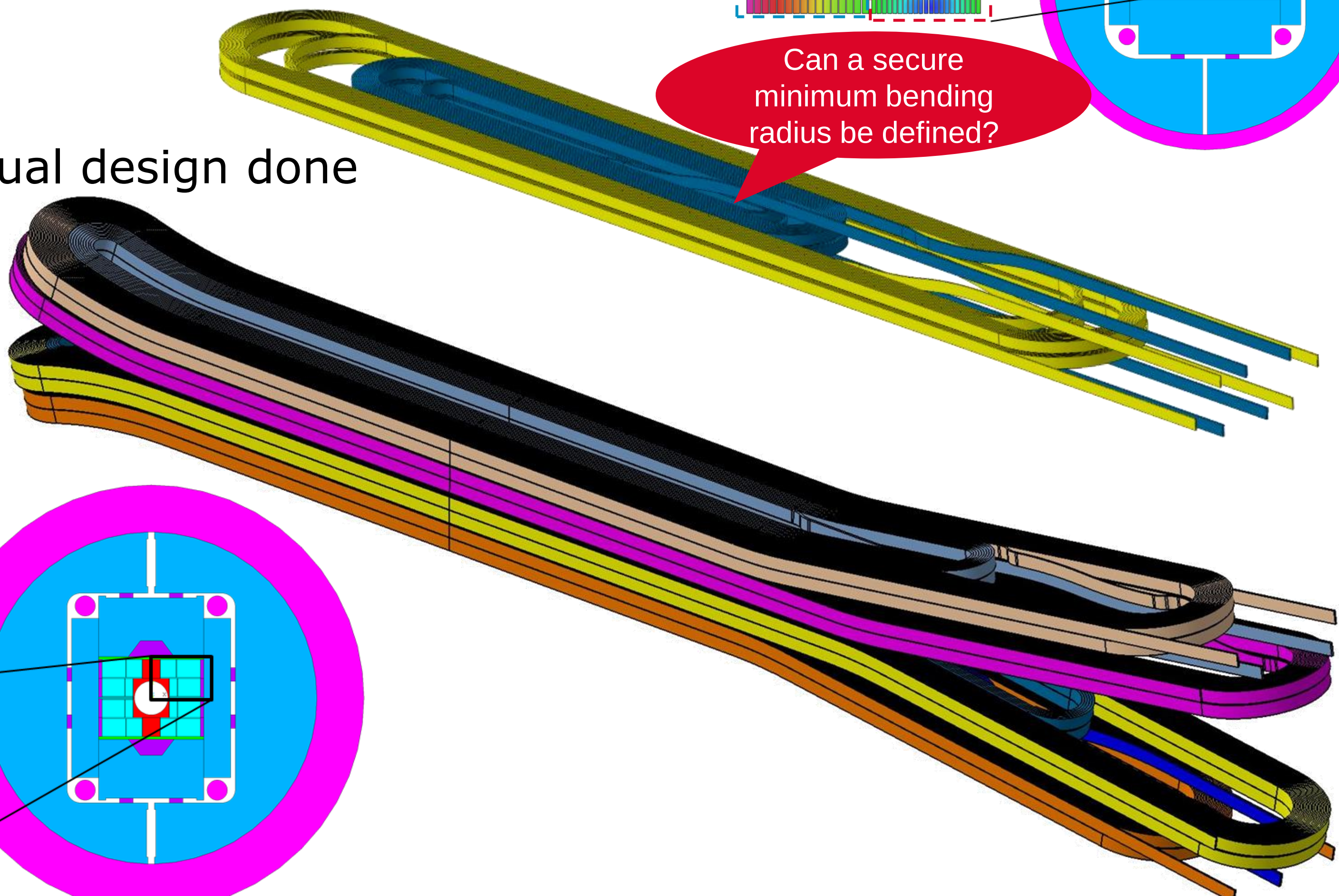


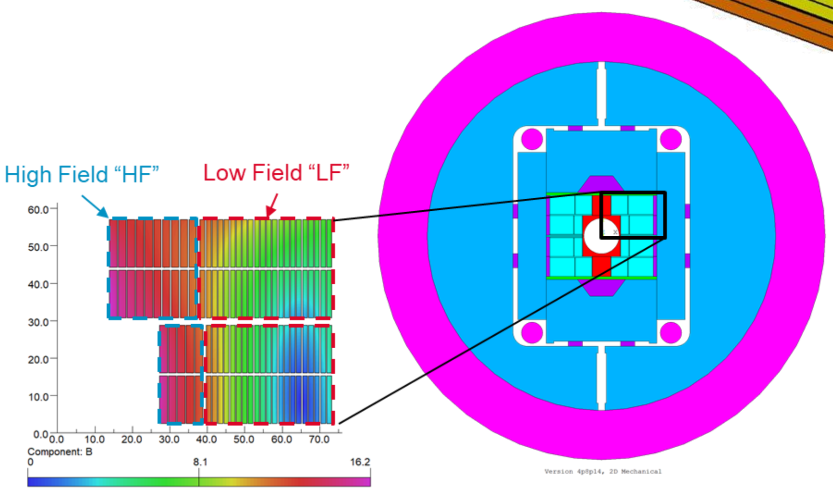
Courtesy F. Rondeaux, E. Rochepault, CEA

R2D2 / F2D2 PROGRAMS

- Goal = Demonstrating grading with external joints
- R2D2: design on-going, fabrication in 2022
- F2D2: conceptual design done



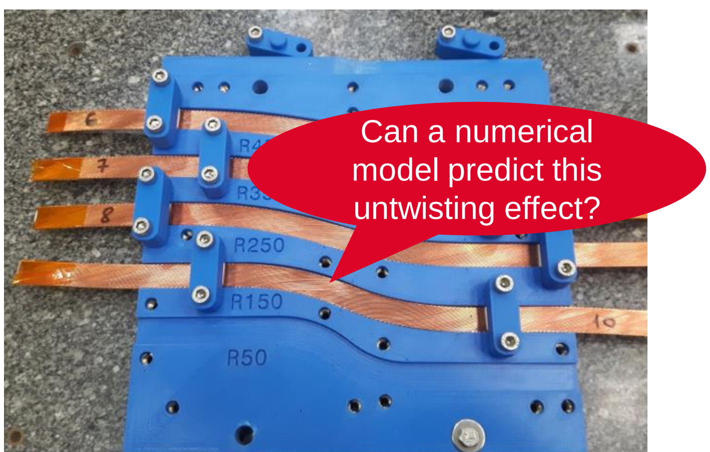


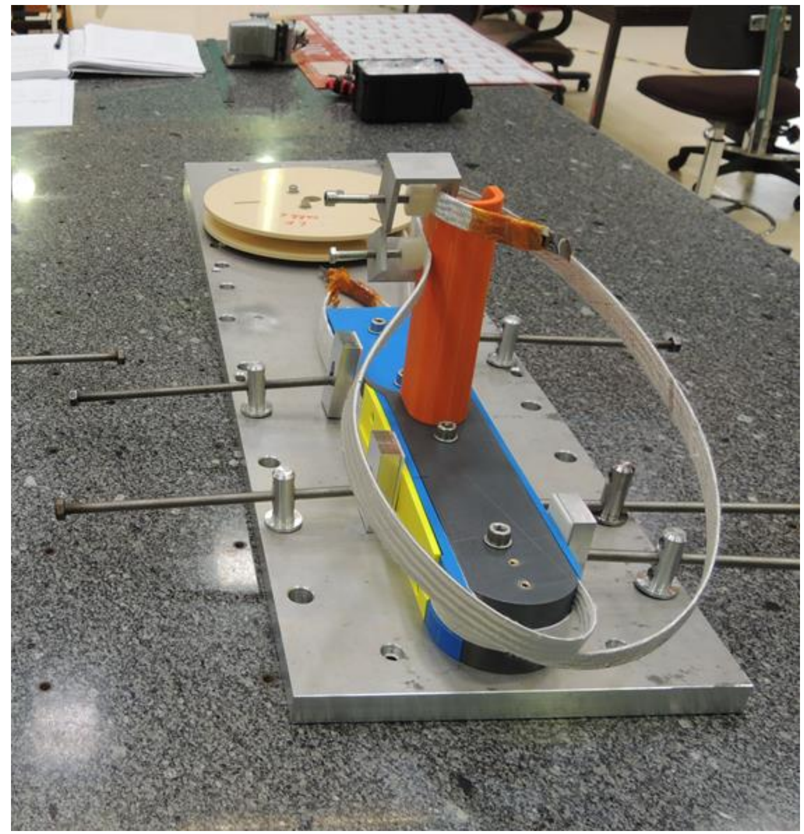


Courtesy V. Calvelli, G. Minier, CEA

WINDING TEST PROGRAM

- Goal = Gaining practice on winding / improving tooling concepts





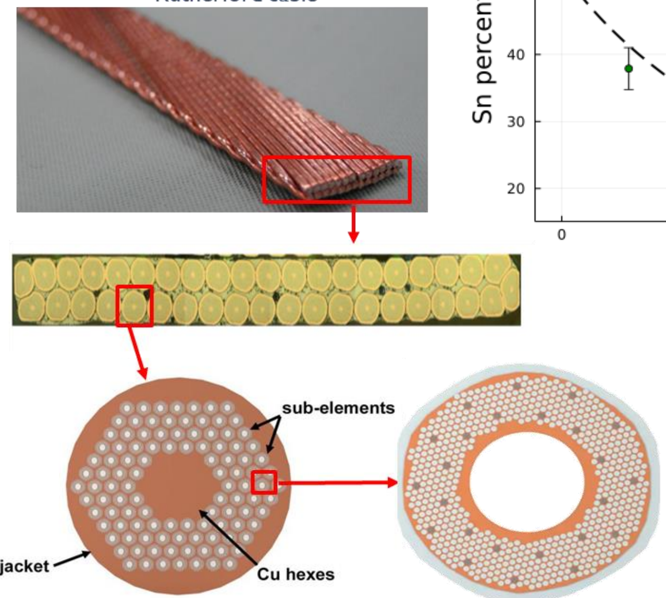
Courtesy F. Rondeaux, M. Durante, E. Rochepault, CEA

Nb_3Sn HEAT TREATMENT R&D

- Goal = Understanding / modeling phenomena occuring during reaction
  - Phase transformations
  - Dimensional changes
  - Mechanical state of Nb_3Sn filaments

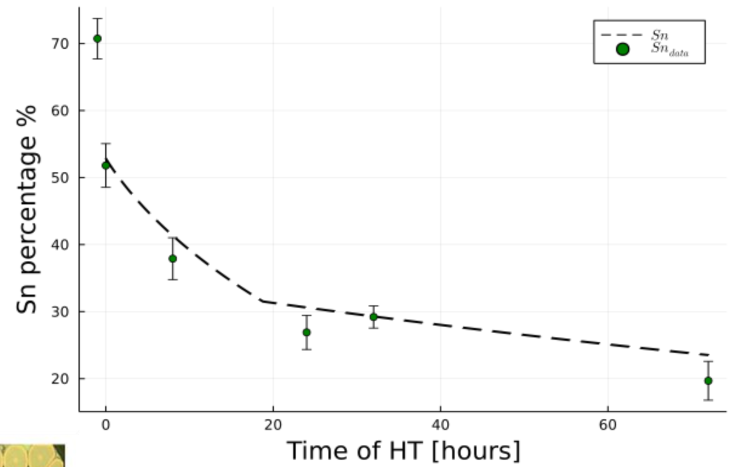
How does HT impact magnet performance ?

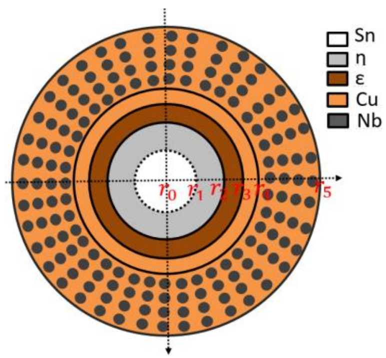
Rutherford cable

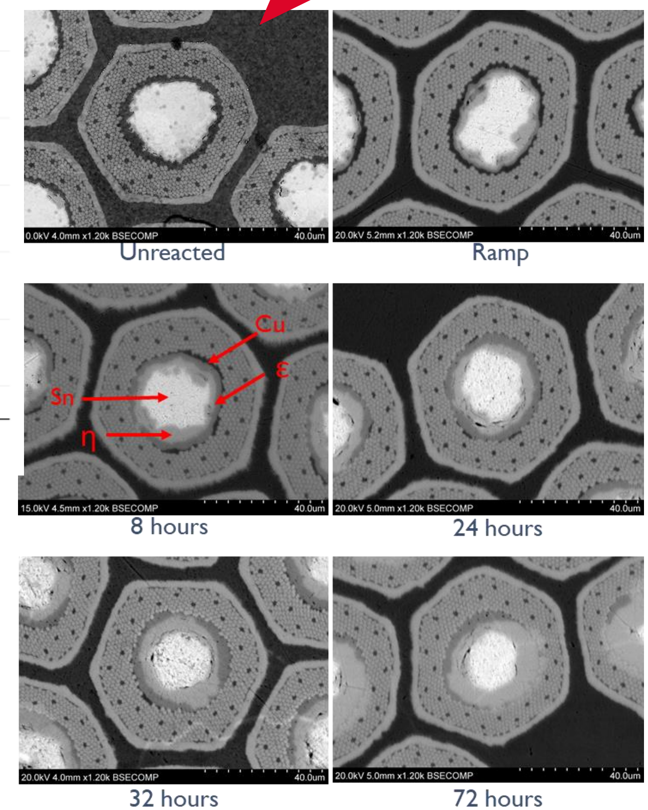


RRP strand cross-section

RRP sub-element cross-section



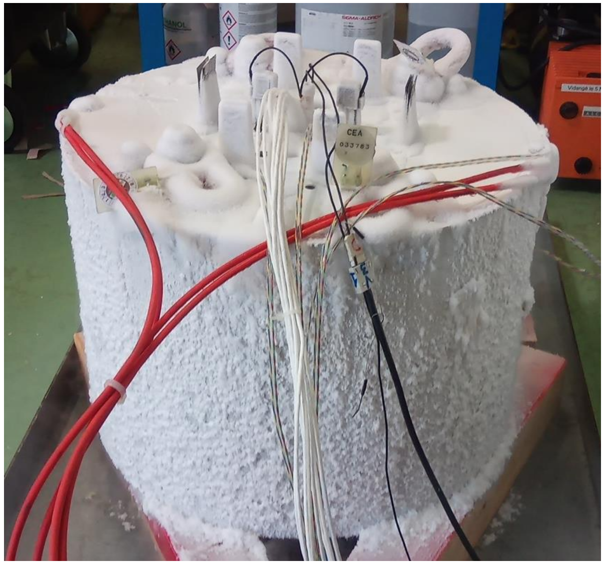


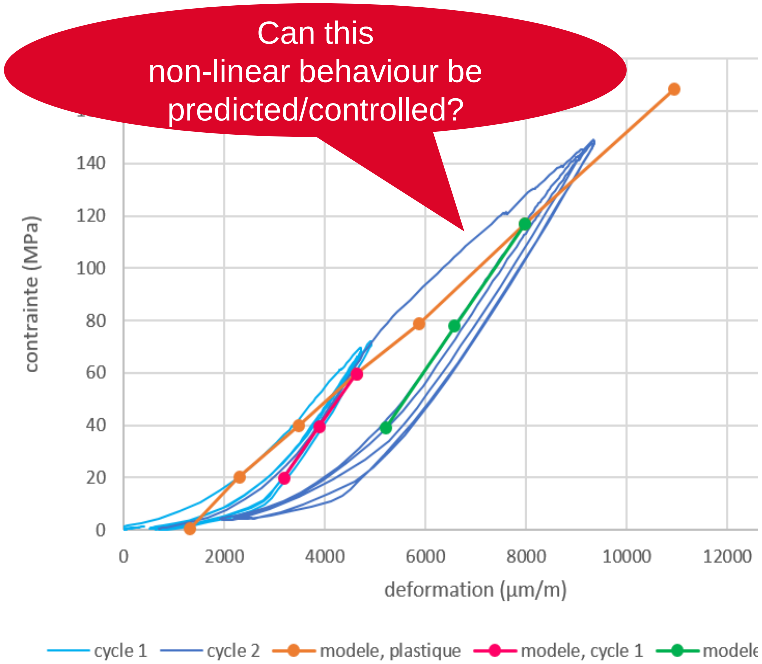


Courtesy Arsenii Gorynin, CEA

- Goal = Understand magnet thermo-mechanical behaviour during preload and thermal cycles

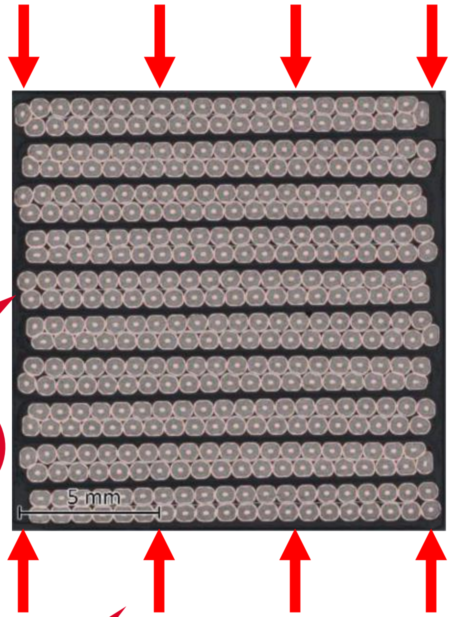
- Joint R&D with LMT (Normale Paris-Saclay) and MSSMAT (CentraleSupélec)
- New characterization methods





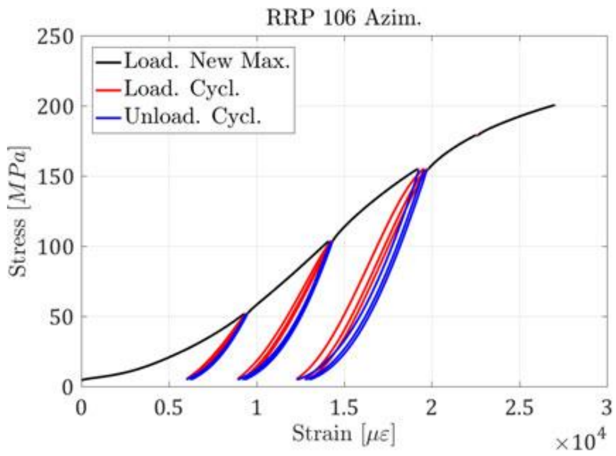
Courtesy E. Rochepault, G. Campagna, CEA

- Ten-stack experimental tests are often used to characterize magnets thermo-mechanical behaviour



How representative are stacks from the real magnet?

Setup-dependant?



Courtesy G. Vallone, CERN

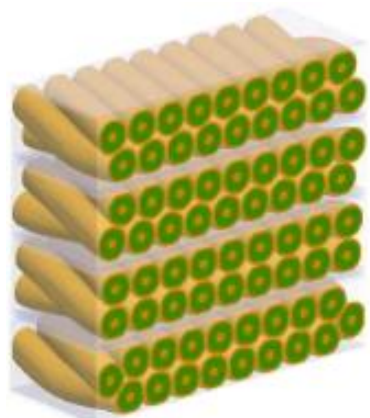
How integrate the results in a numerical model?

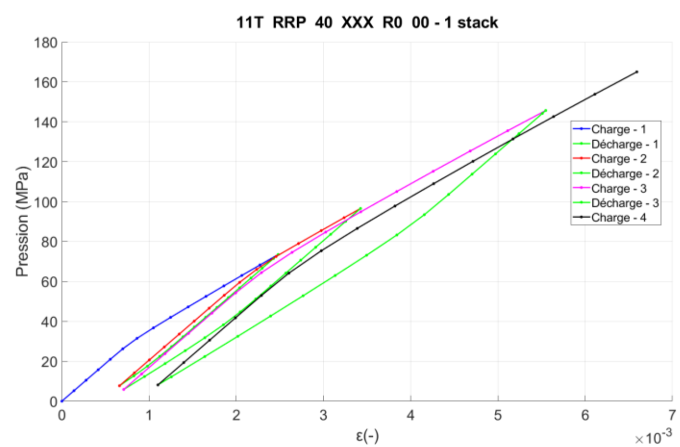
Multiscale Modeling

To adress these questions, Irfu has launched in 2012 with several partners (including CERN) a multiscale modeling program: CoCaSCOPE.

- Goal = **Multipurpose multiscale 3D model of Rutherford cables**

- CoCaSCOPE = *modélisation du Comportement de Câbles SupraConducteurs pour l'Optimisation de leurs Performances Electriques*
  - ✓ Predictive approach
  - ✓ Includes geometrical modeling, strand characterization, homogeneization
  - ✓ Non linear (with plasticity and hardening)





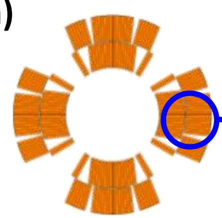
Courtesy K. Pirapakaran, CEA

Outline

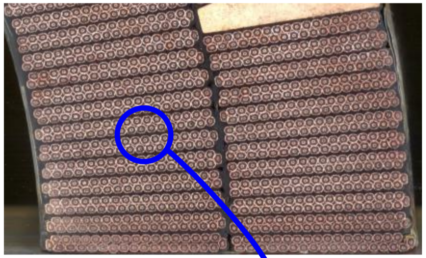
- Context
  - ↳ High field magnet program at Saclay
  - ↳ Technological R&D for Nb_3Sn
- CoCaSCOPE approach
- CoCaSCOPE « bricks »
  - ↳ Preprocessor
  - ↳ Mesh validation
  - ↳ Bi-metallic homogeneized model
  - ↳ Computation and post-treatment
- Results
- Conclusions & perspectives

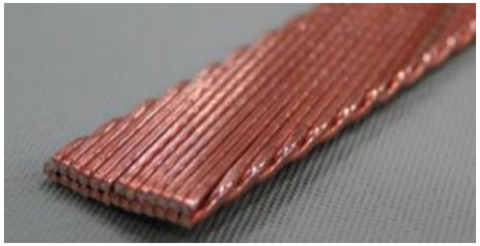
MULTISCALE APPROACH

Magnet (≈ 10m)

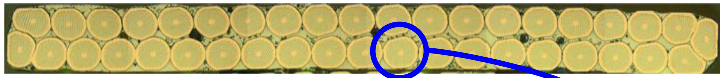


Winding – stack (≈ m/cm)

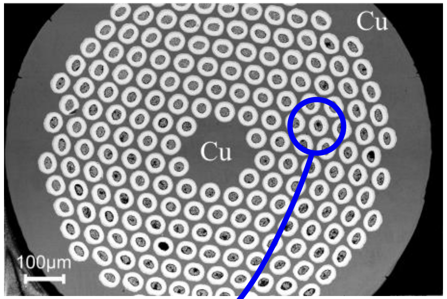


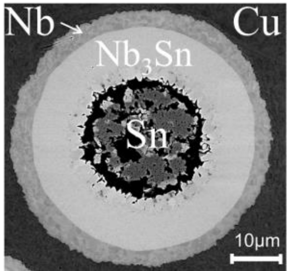


Rutherford cable (≈ cm/mm)



Strand (≈ mm)



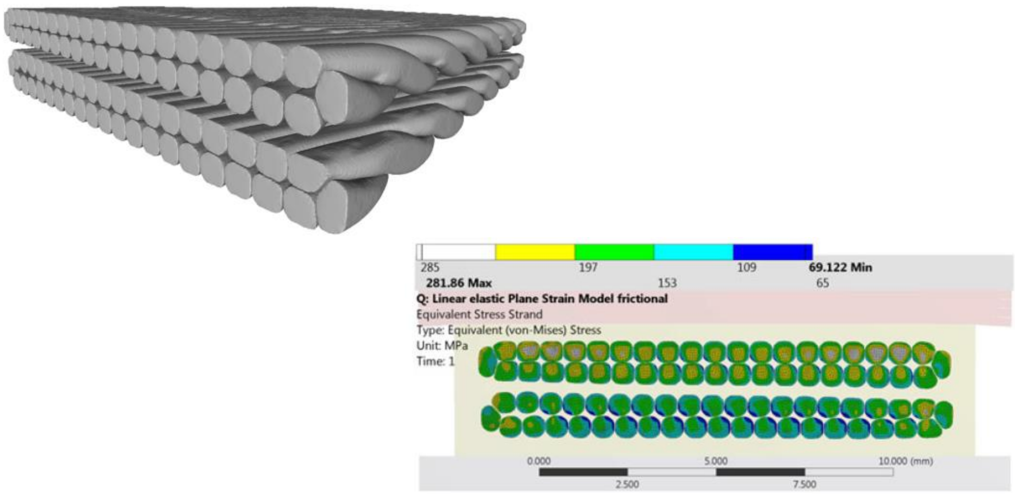


FILAMENT (≈ mm/10µm)

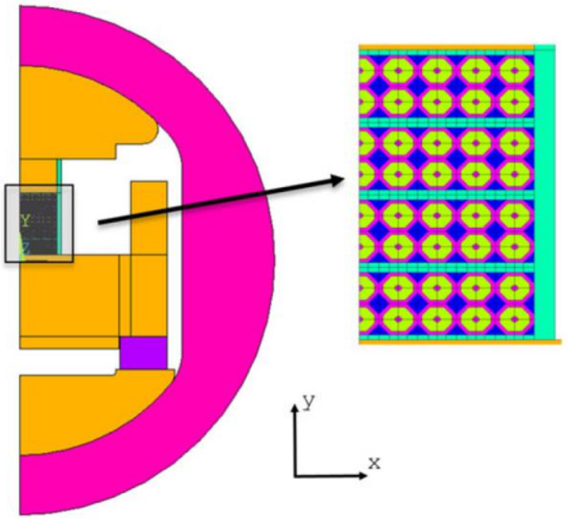
Courtesy P. Ferracin, Fermilab, G. Lenoir, CERN

STATE OF THE ART 1/2

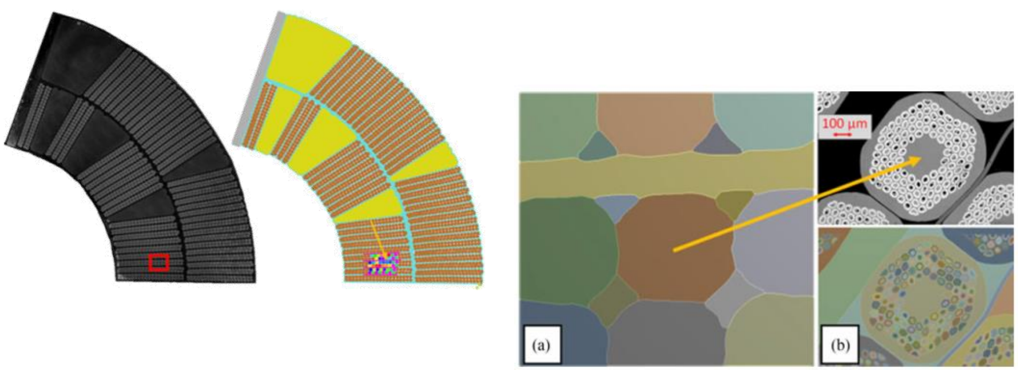
FE model based on RX tomographic images [Wolf 18]



FE model of compression test on cable stack [Vallone 18]



FE sub-modeling model based on HD optical image of coil [Daly 18]

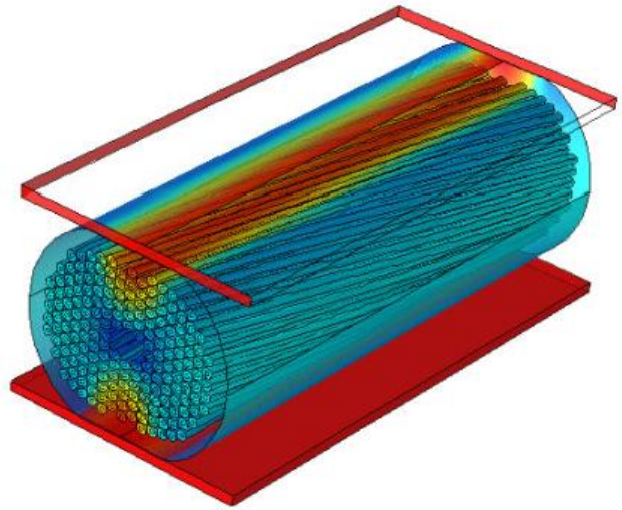


Existing approaches are

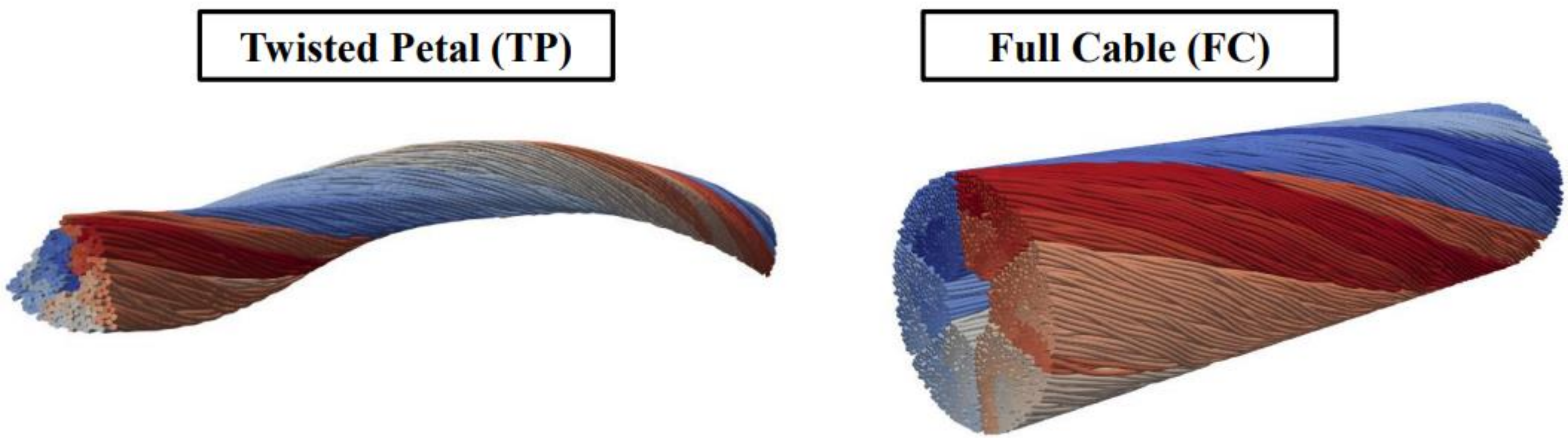
- ⇨ 2D FE model
- ⇨ Simple geometry
- ⇨ Limited mechanical model (Elastic or curve fit)
- ⇨ Non predictive

Courtesy F. Wolf, G. Vallone, M. Daly, CERN

State of the art 2/2



3D FE model of reversible critical current reduction [Cattabiani 19]

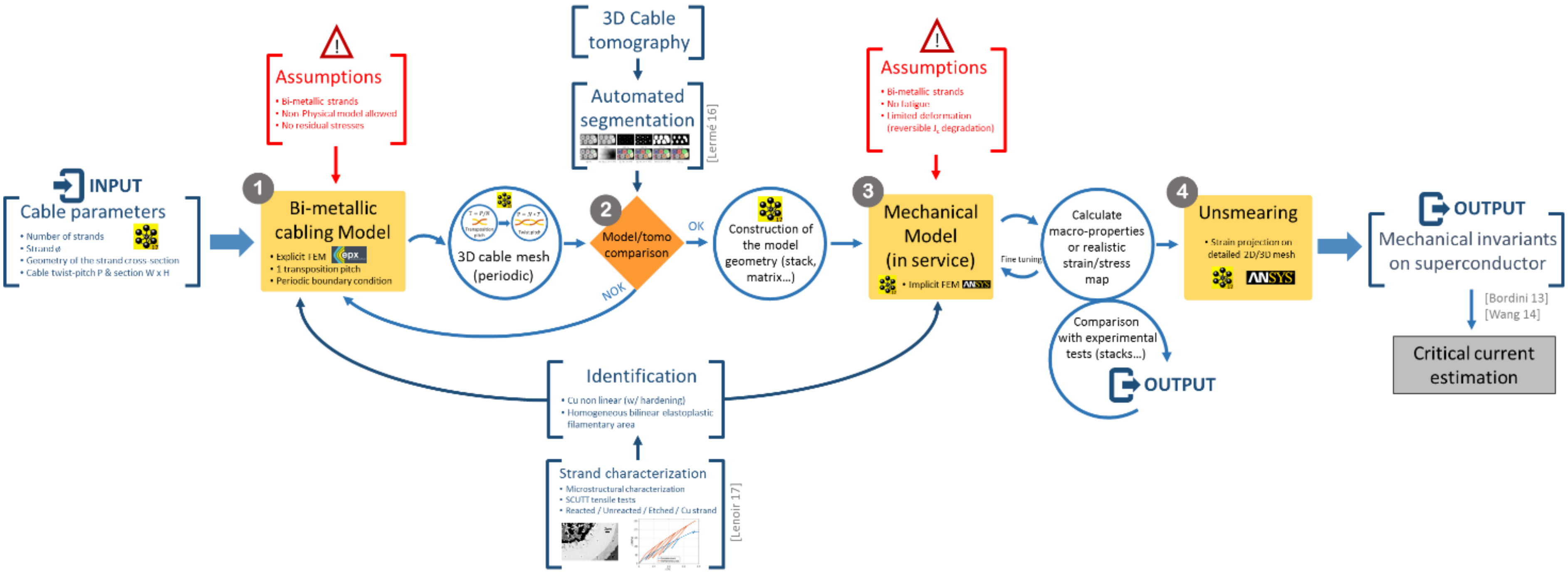


3D FE model of CICC cable based on Multifil [Riccioli 21]

Courtesy A. Cattabiani, CERN, R. Riccioli, CEA

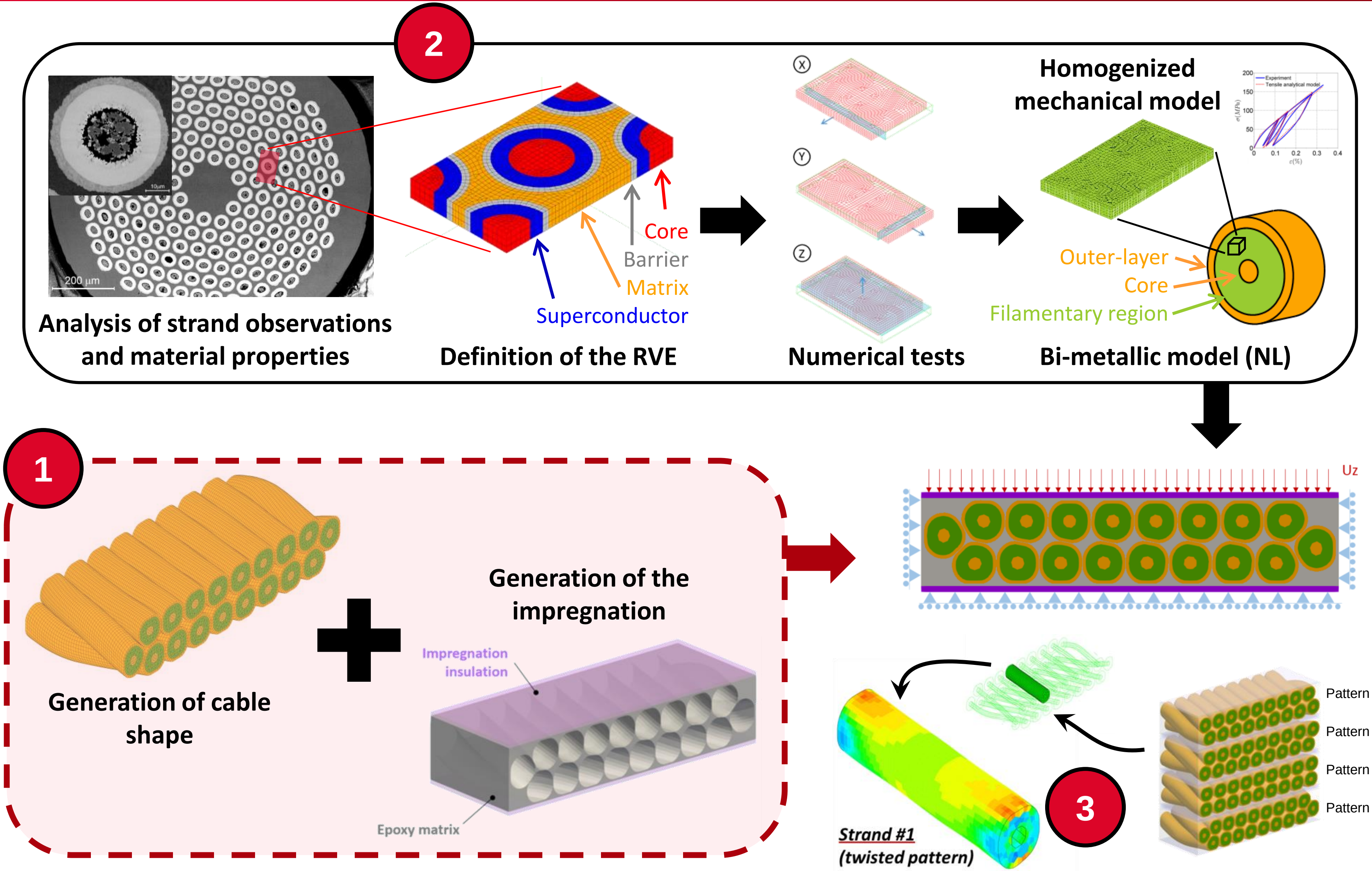
OVERVIEW OF COCASCOPE APPROACH

- CoCaSCOPE is a multipurpose tool for magnet designers



P. Manil *et al.*, "A Numerical Approach for the Mechanical Analysis of Superconducting Rutherford-Type Cables Using Bimetallic Description," in *IEEE Transactions on Applied Superconductivity*, vol. 27, no. 4, pp. 1-6, June 2017

Overview of CoCaSCOPE approach



Slide by F. Nunio, CEA

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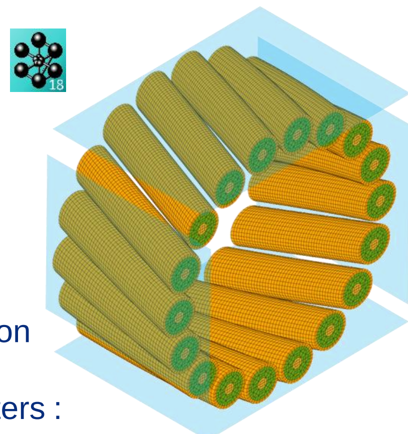
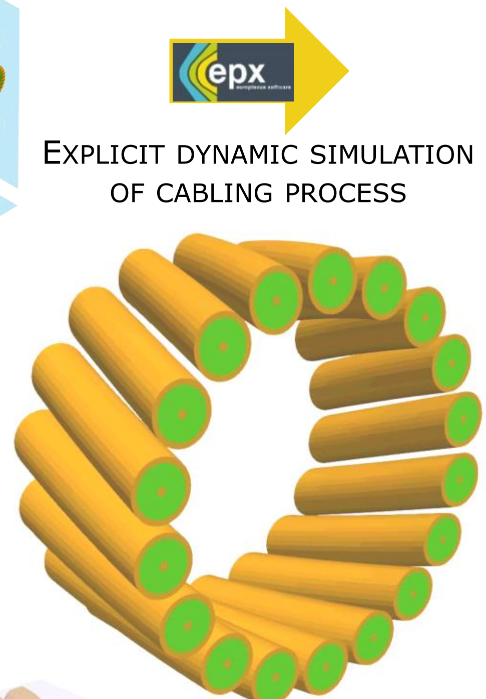
Overview of the Cabling Model Methodology

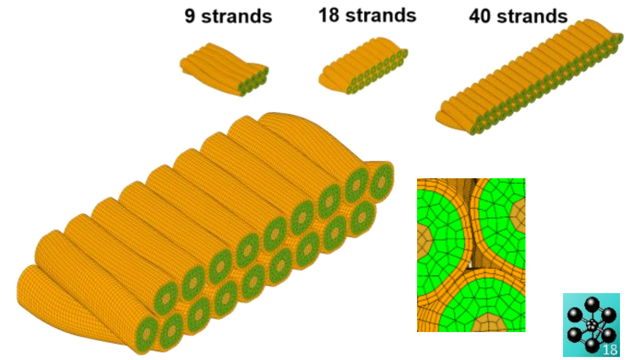
Initial model

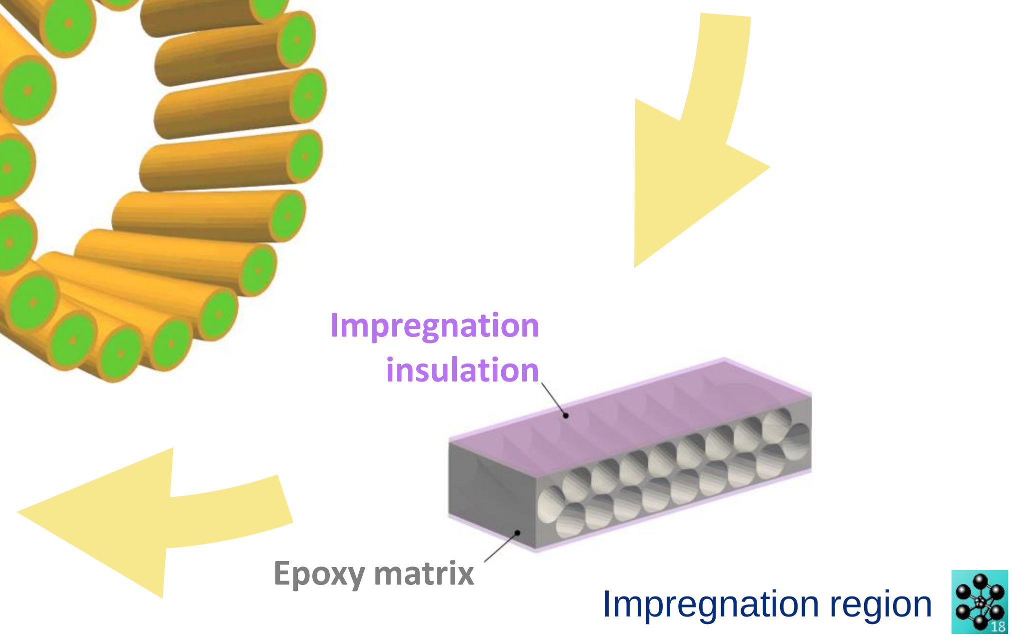


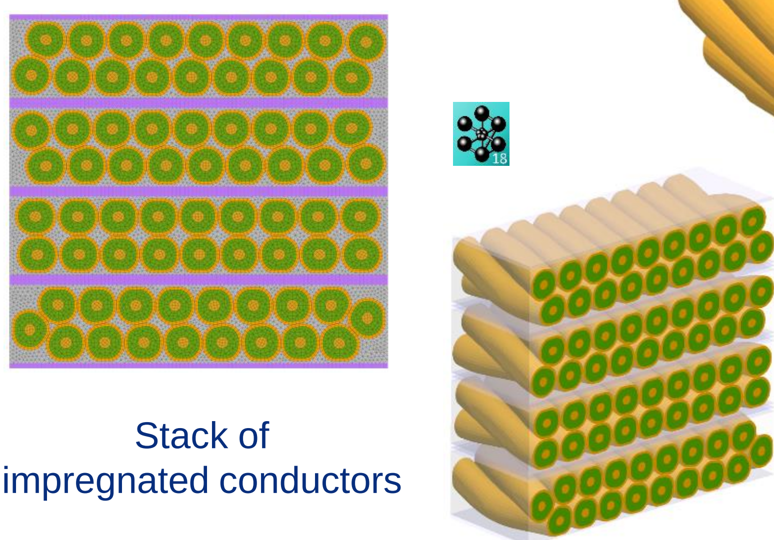
- Helical geometry
- Bimetallic description
- Parameters :
  - Strand parameters :
    - Inner core / outer core
  - Cable parameters :
    - # of strands / twist pitch P / size W x H

Cable compaction
by 4 planes









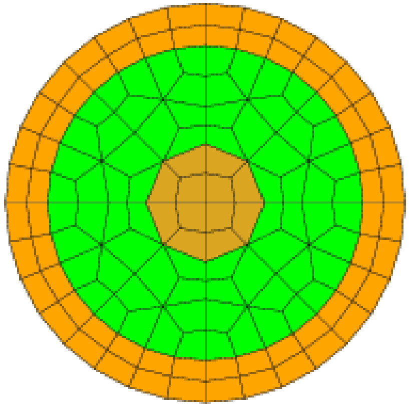
Stack of
impregnated conductors

Slide by F. Nunio, CEA

F. Nunio, P. Manil and G. Lenoir, "3-D Mechanical Finite Element Analysis of Impregnated Rutherford Cable Stacks," in *IEEE Transactions on Applied Superconductivity*, vol. 29, no. 5, pp. 1-6, Aug. 2019

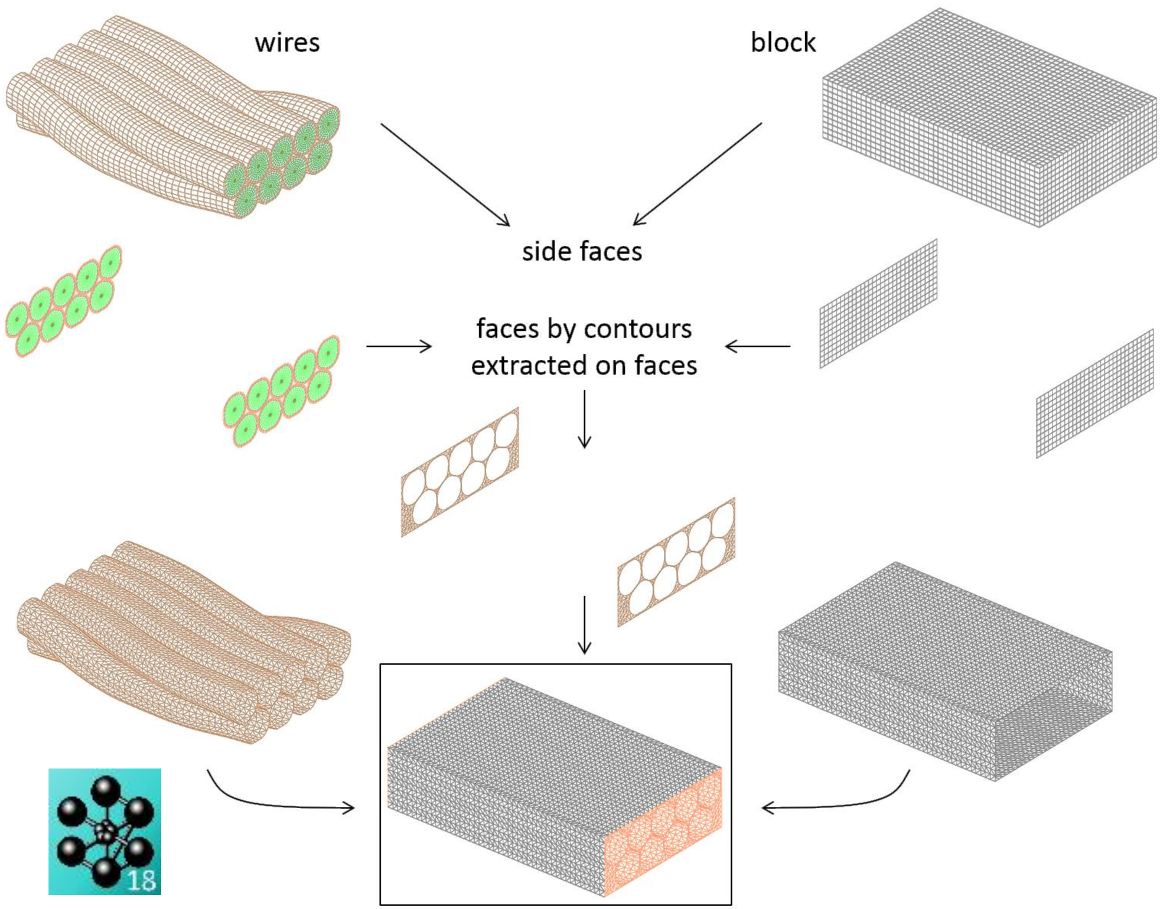
STRAND SECTION MESH

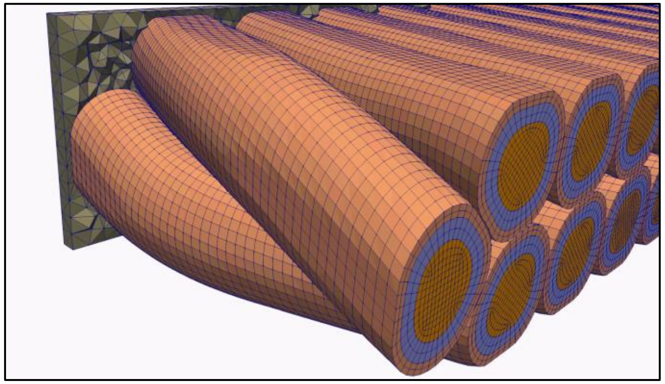
- Optimized to allow projection to the lower scale

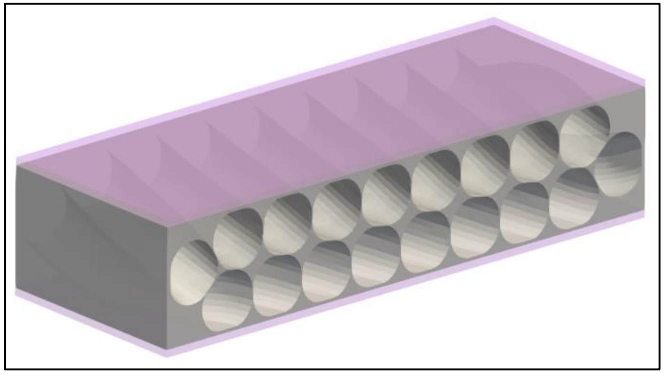


IMPREGNATION MATRIX MODEL

- Boolean operators have been tried → not fully successfully
- Skin of the matrix is rebuilt by a sewing technique, then volume meshed





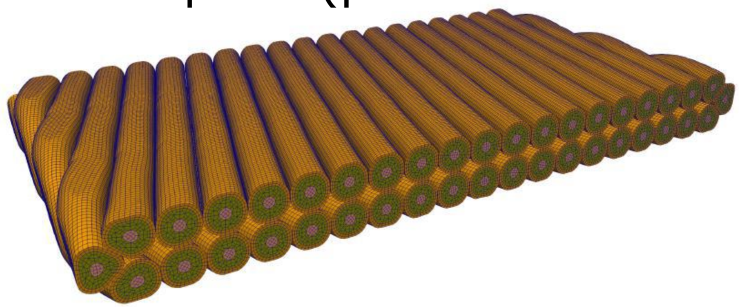


Slide by F. Nunio, CEA

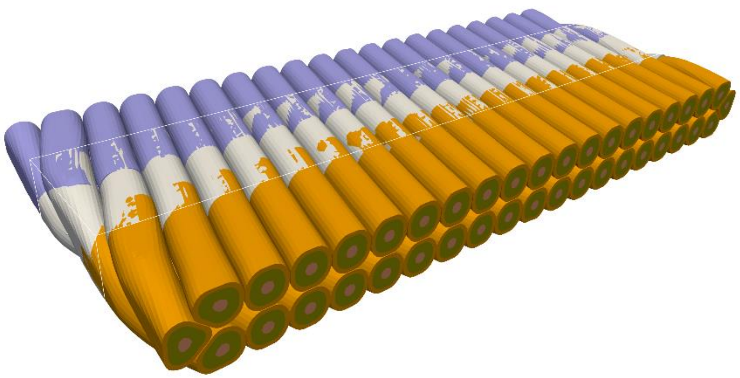
Ouput mesh typology

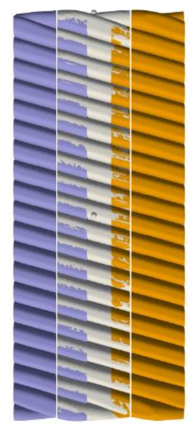
- Periodic mesh over 1 transposition pitch (periodic boundary conditions)

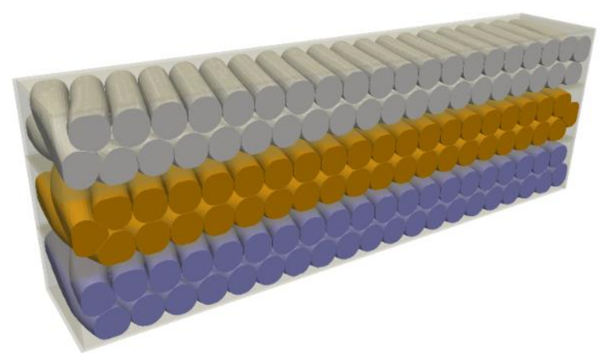
3 periodic meshes glued



- Different twist patterns can be generated (avoid stacking of cables with similar overlapping)



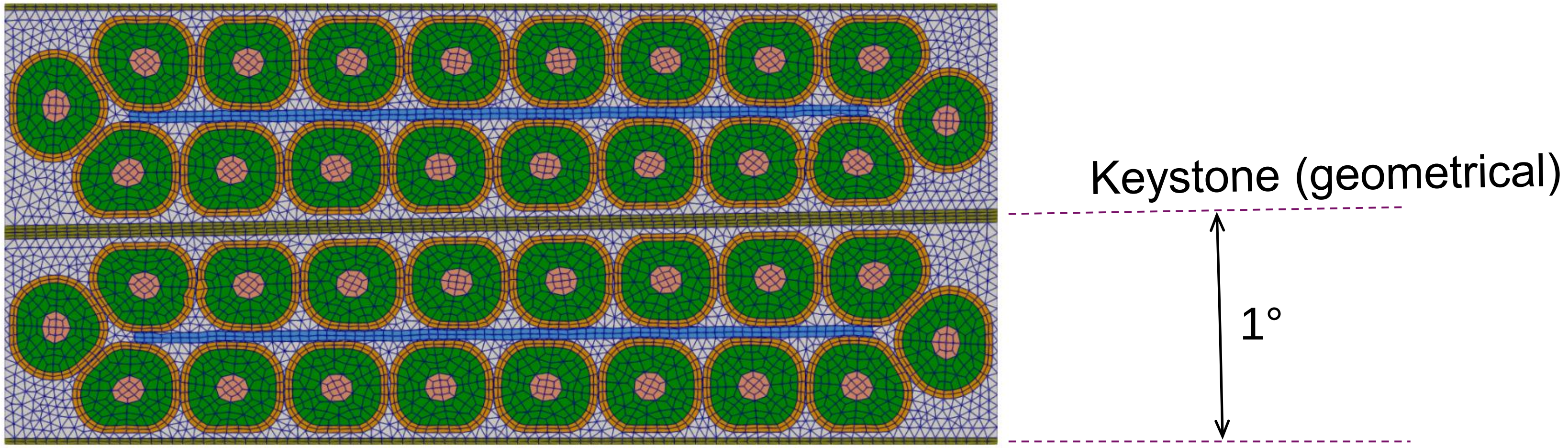




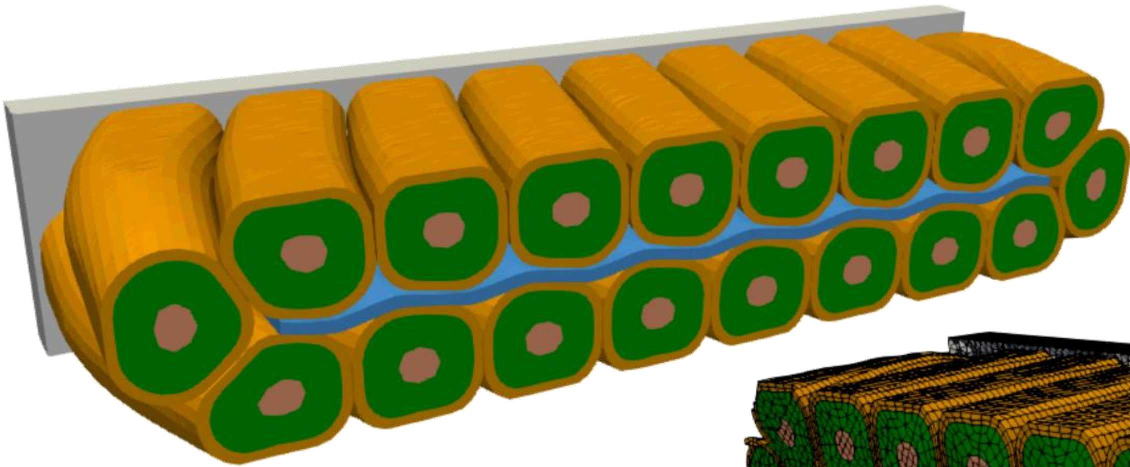
- Linear mesh elements:
  - hexahedrons (strand/core)
  - tetrahedrons (matrix)
  - wedges (insulation)

KEYSTONE

- Obtained by geometric tranformation

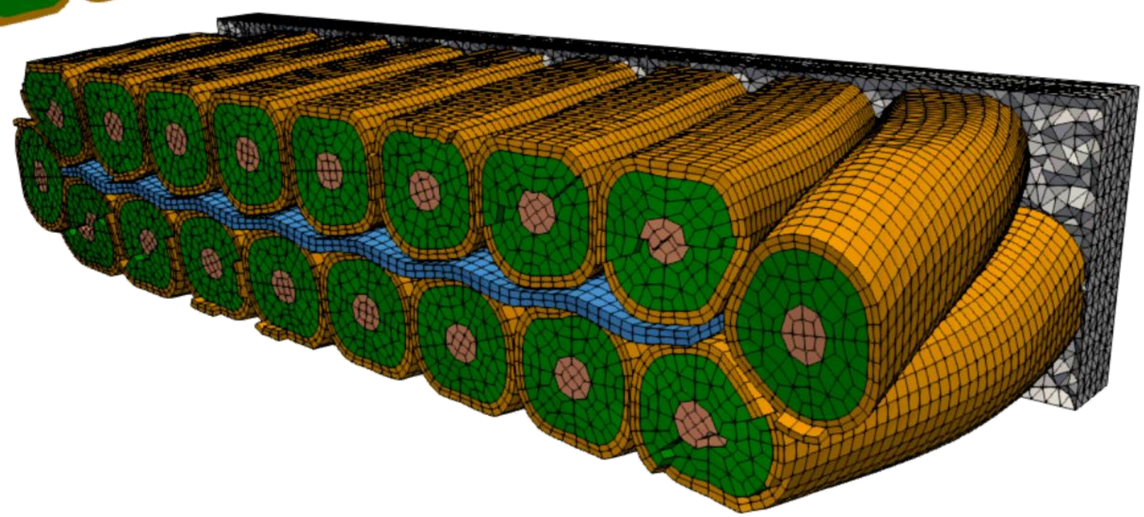


CORE



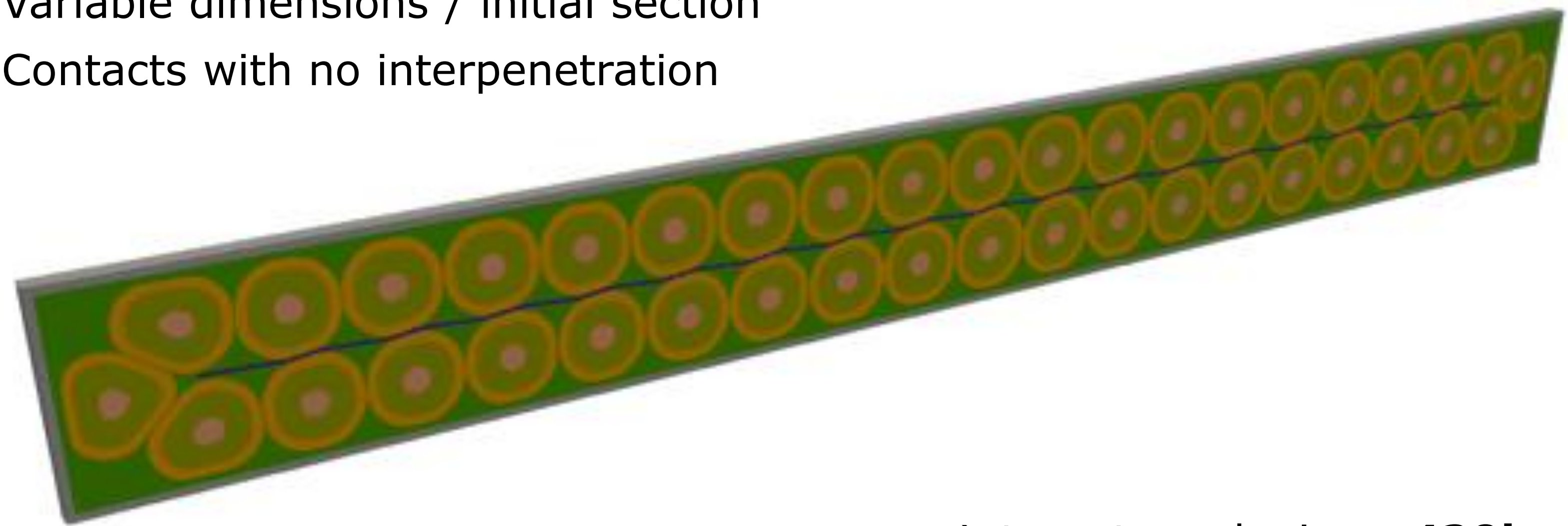
Each domain of the cable and strands is identified

Meshes are consistent across the interfaces



MAIN FEATURES OF COCASCOPE MESH

- 3D mesh
- Bi-metallic model → intrinsic description of anisotropy
- Periodic mesh (can be stacked *in any direction*)
- Impregnation included
- Keystone / core can be included
- Fully conformal mesh with partition (strands/impregnation/insulation)
- Variable dimensions / initial section
- Contacts with no interpenetration

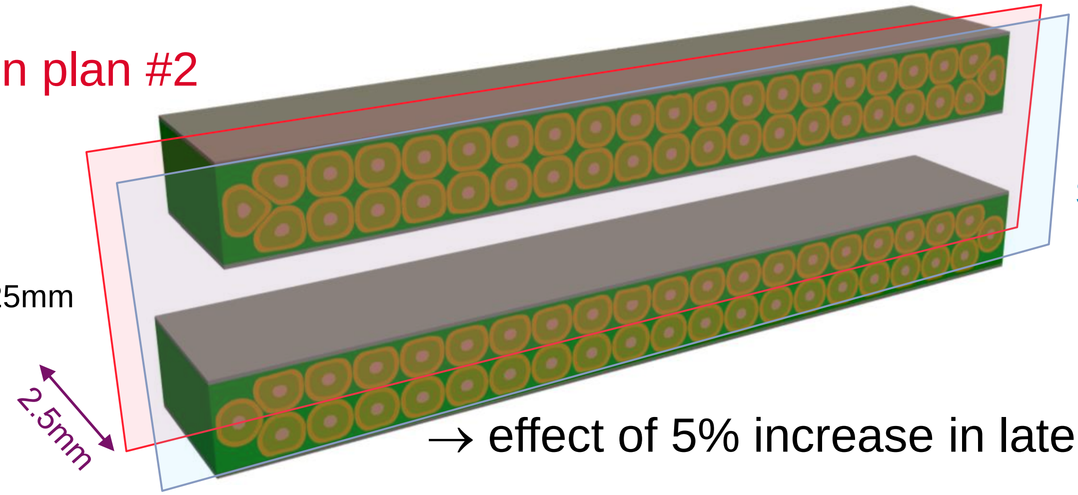


→ target mesh size **~420k nodes** for one transposition pitch

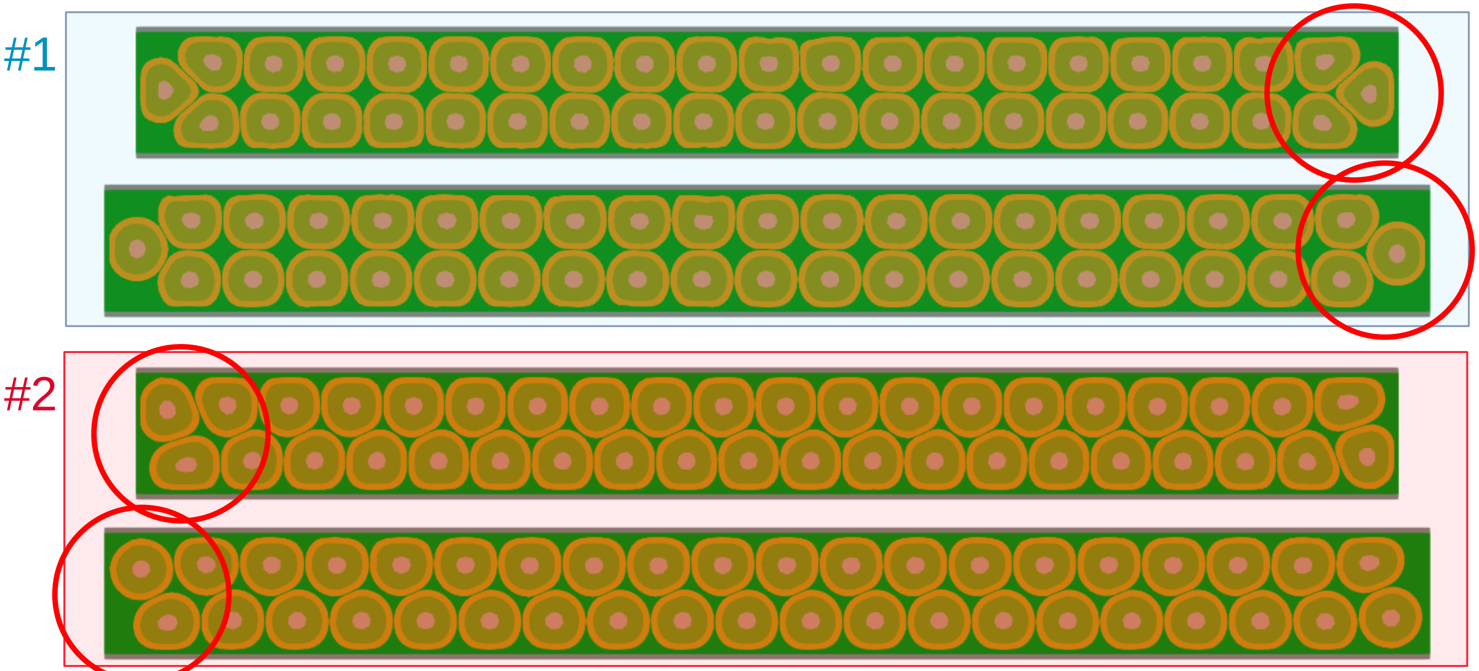
- Warning: it remains a non-physical model!

40 STRANDS : EFFECT OF CABLE ASPECT RATIO 1/2

Parameters :
- 40 strands
- twist pitch = 100mm
- target cable section = 14 x 1.25mm
- strand diameter = 0.7mm



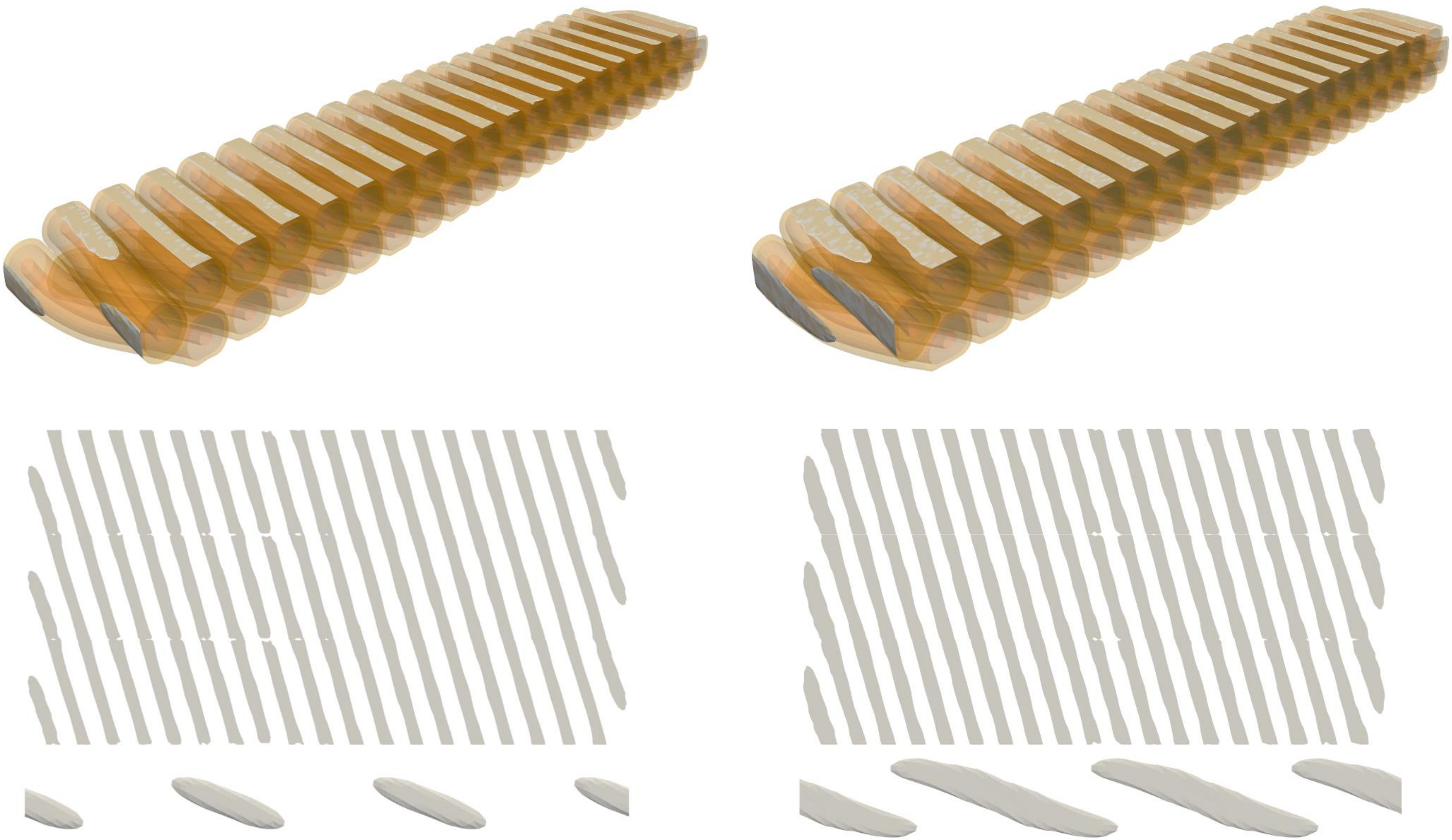
→ effect of 5% increase in lateral compaction



Slide by F. Nunio, CEA

40 STRANDS : EFFECT OF CABLE ASPECT RATIO 2/2

→ effect of 5% increase in lateral compaction



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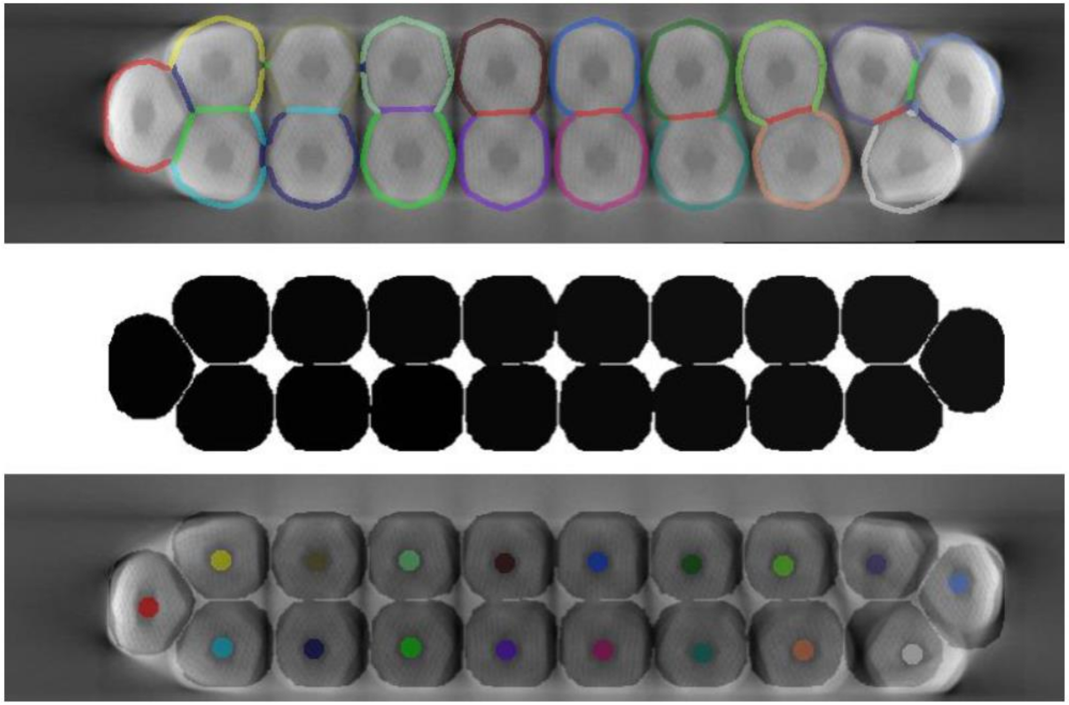
- COCASCOPE APPROACH
- COCASCOPE « BRICKS »
  - ↳ Preprocessor
  - ↳ Mesh validation
  - ↳ Bi-metallic homogeneized model
  - ↳ Computation and post-treatment
- RESULTS
- CONCLUSIONS & PERSPECTIVES

MODEL VS TOMOGRAPHY 1/2

- Tomographies of existing 18- and 40-strand cables are used to check the model (15 microns, done at MATEIS)

- Analytical tools have been developped at Armines to get automatically the centroid/shape of each strands



Tomography
+ identified strand shapes

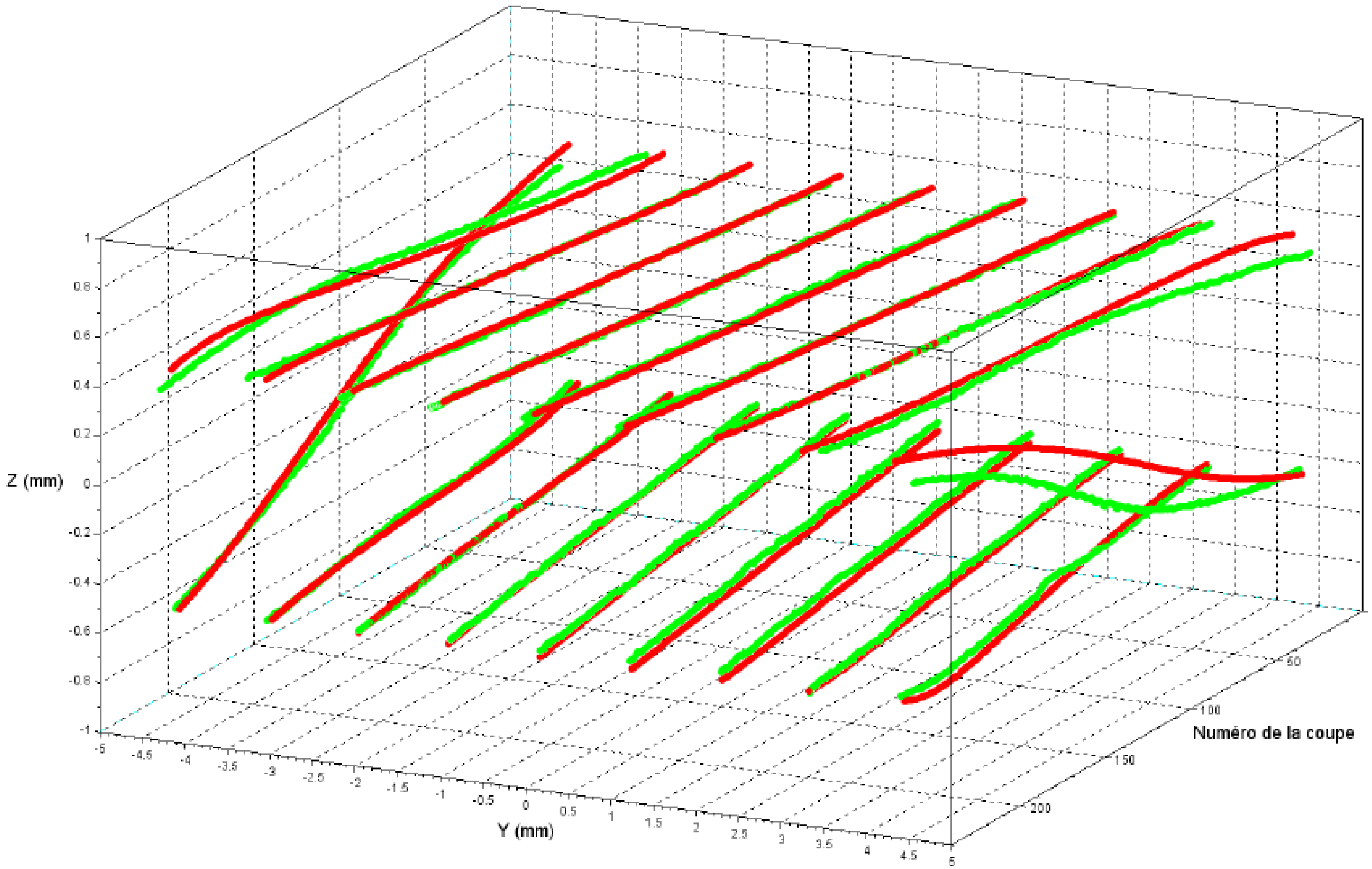
Strand shapes extracted
from CoCaSCOPE model

Superimposition
of model and tomography

Tomography by E. Maire, Y Buffière, INSA Lyon

MODEL VS TOMOGRAPHY 2/2

- Centroid of each strand extracted from tomography (green) compared to computed mesh (red)



Courtesy C. Carlé, CEA

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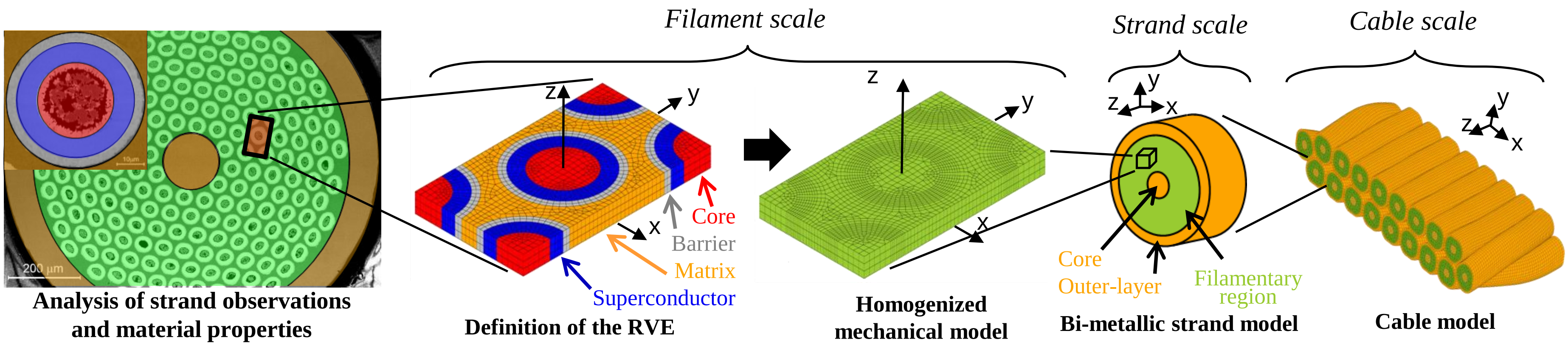
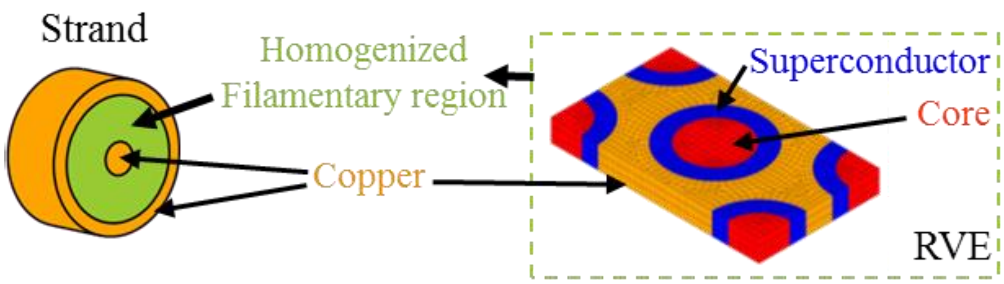
Strand Bi-Metallic Model 1/2



→ Intrinsic anisotropic model

→ Niobium barrier is included in copper region (similar modulus)

STRAND BI-METALLIC MODEL 2/2



- Copper ⇨ Elasto-plastic with hardening
  $E_{Cu}, \nu_{Cu}, \sigma_{y\ Cu}, b_{Cu}, Q_{Cu}, C_{Cu}, \gamma_{Cu}$

- 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}

Bi-metallic model is defined by 11 parameters:

$E_{Cu}, \nu_{Cu}, \sigma_{y\ Cu}, b_{Cu}, Q_{Cu}, C_{Cu}, \gamma_{Cu}, E_{SC}, \nu_{SC}, E_{FC}, \nu_{FC}$

+ 3 volume fractions

G. Lenoir, P. Manil, F. Nunio and V. Aubin, "Mechanical Behavior Laws for Multiscale Numerical Model of Nb3Sn Conductors," in IEEE Transactions on Applied Superconductivity, vol. 29, no. 5, pp. 1-6, Aug. 2019

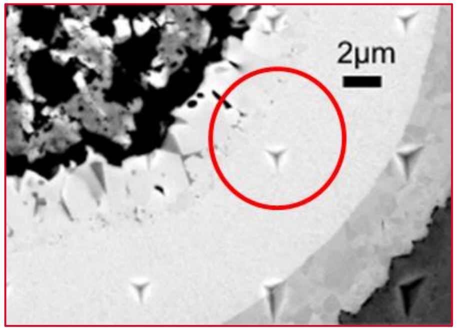
Identification of Material Parameters

Bi-metallic model is defined by 11 parameters:

$E_{Cu}, \nu_{Cu}, \sigma_{y\,Cu}, b_{Cu}, Q_{Cu}, C_{Cu}, \gamma_{Cu}, E_{SC}, \nu_{SC}, E_{FC}, \nu_{FC}$

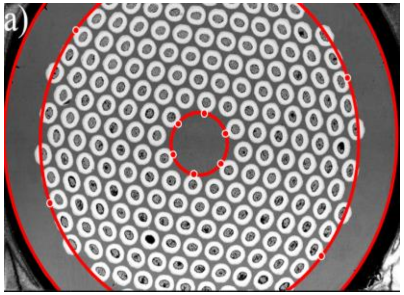
+ volume fractions

- Direct identification (at RT)
  - E_{Cu}, E_{SC} are identified by nanoindentation
  - $\nu_{Cu}, \nu_{SC}, \nu_{FC}$ are taken from litterature



Courtesy G. Lenoir, CentraleSupélec

- Numerical identification
  - $\sigma_{y\,Cu}, b_{Cu}, Q_{Cu}, C_{Cu}, \gamma_{Cu}, E_{FC}$ are obtained using ILCO code (next slide)

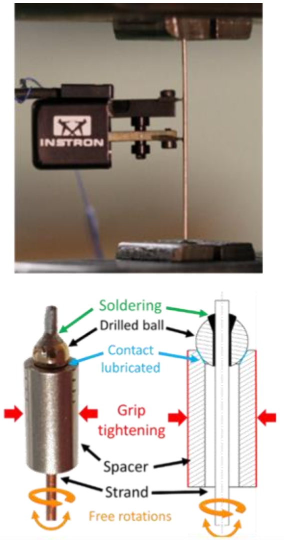


- Volume fractions are measured from SEM images

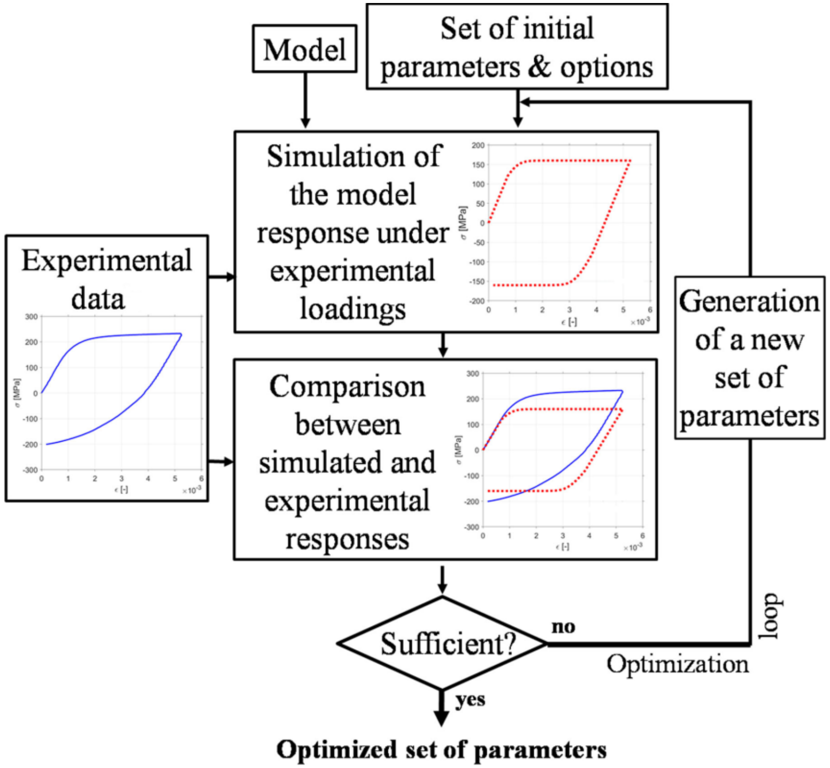
→ At cryogenic temperature, more parameters are identified numerically

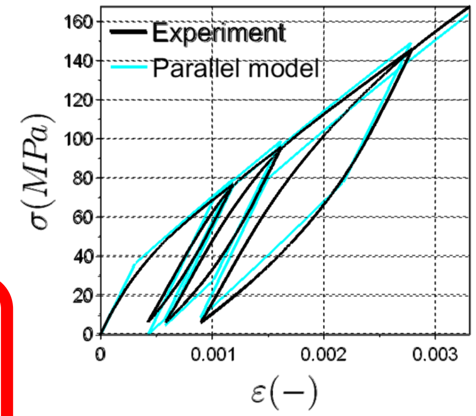
NUMERICAL IDENTIFICATION USING ILCO

$\sigma_{y\ Cu}, b_{Cu}, Q_{Cu}, C_{Cu}, \gamma_{Cu}, E_{FC}$ are obtained using ILCO code (optimization-based identification)



SCUTT setup
for harmless strand characterization at RT/77K





Courtesy G. Lenoir, CentraleSupélec

All parameters of our bi-metallic model are now identified:

$E_{Cu}, \nu_{Cu}, \sigma_{y\ Cu}, b_{Cu}, Q_{Cu}, C_{Cu}, \gamma_{Cu}, E_{SC}, \nu_{SC}, E_{FC}, \nu_{FC}$

Identification of Material Parameters

- An example of identified parameters: FRESCA2 PIT strand
- Room temperature / 77K

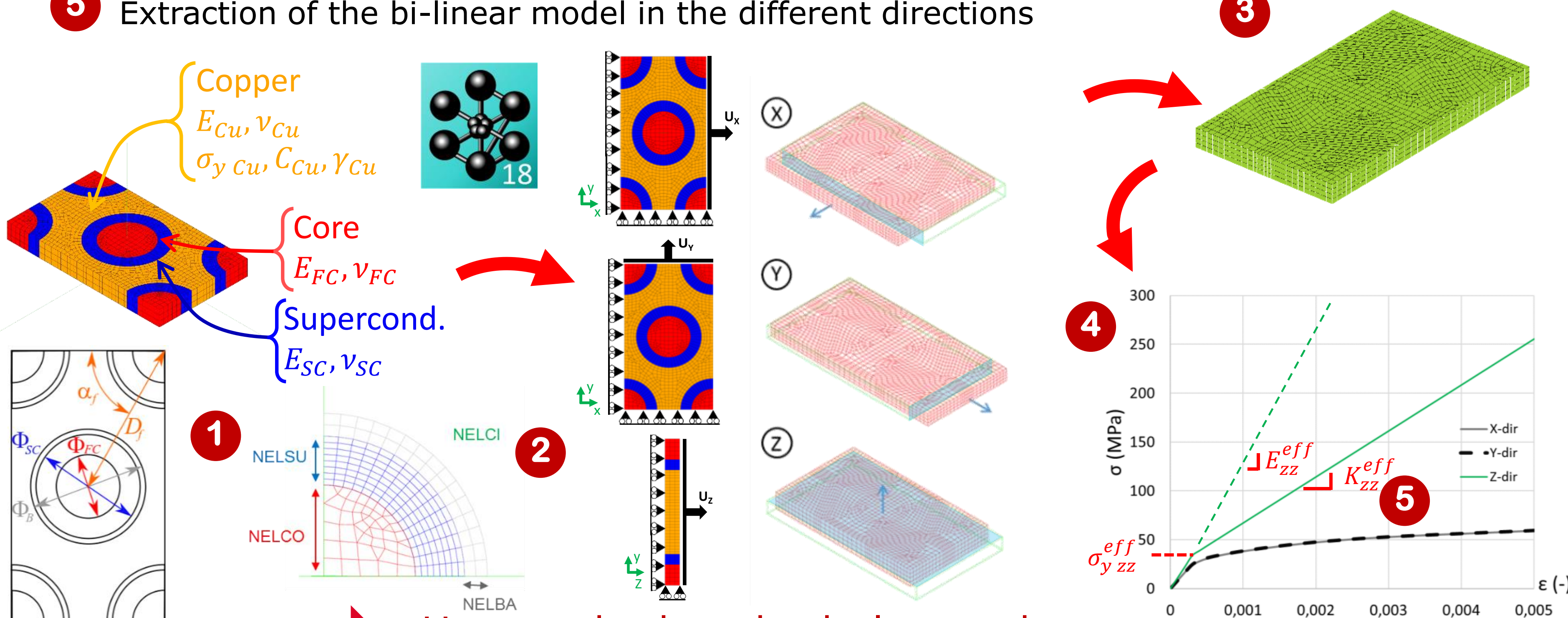
Identified Parameters of the PIT Bi-metallic model at room temperature / 77K

Components	Model	*E*(GPa)	σ_y(MPa)	*C(MPa)*	γ
Copper	Chaboche hardening	129/135	39/30	35960/25600	310/64
Barrier	Identical to copper				
Filament Core	Elastic	3/3	-	-	-
SC region (Nb_3Sn SG)	Elastic	171/145	-	-	-

- This set of parameters can be used for predictive simulations, even for load cases significantly different from the ones used during the identification process.

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)

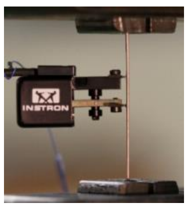
Slide by F. Nunio, CEA

BI-METALLIC MODEL VS EXPERIMENTAL RESULTS

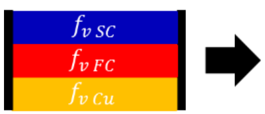
- Tensile test over a strand:

  Experimental / Analytical / FEM results are compared

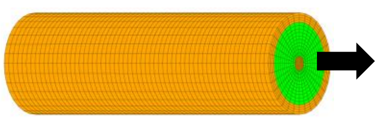
—— Experiment



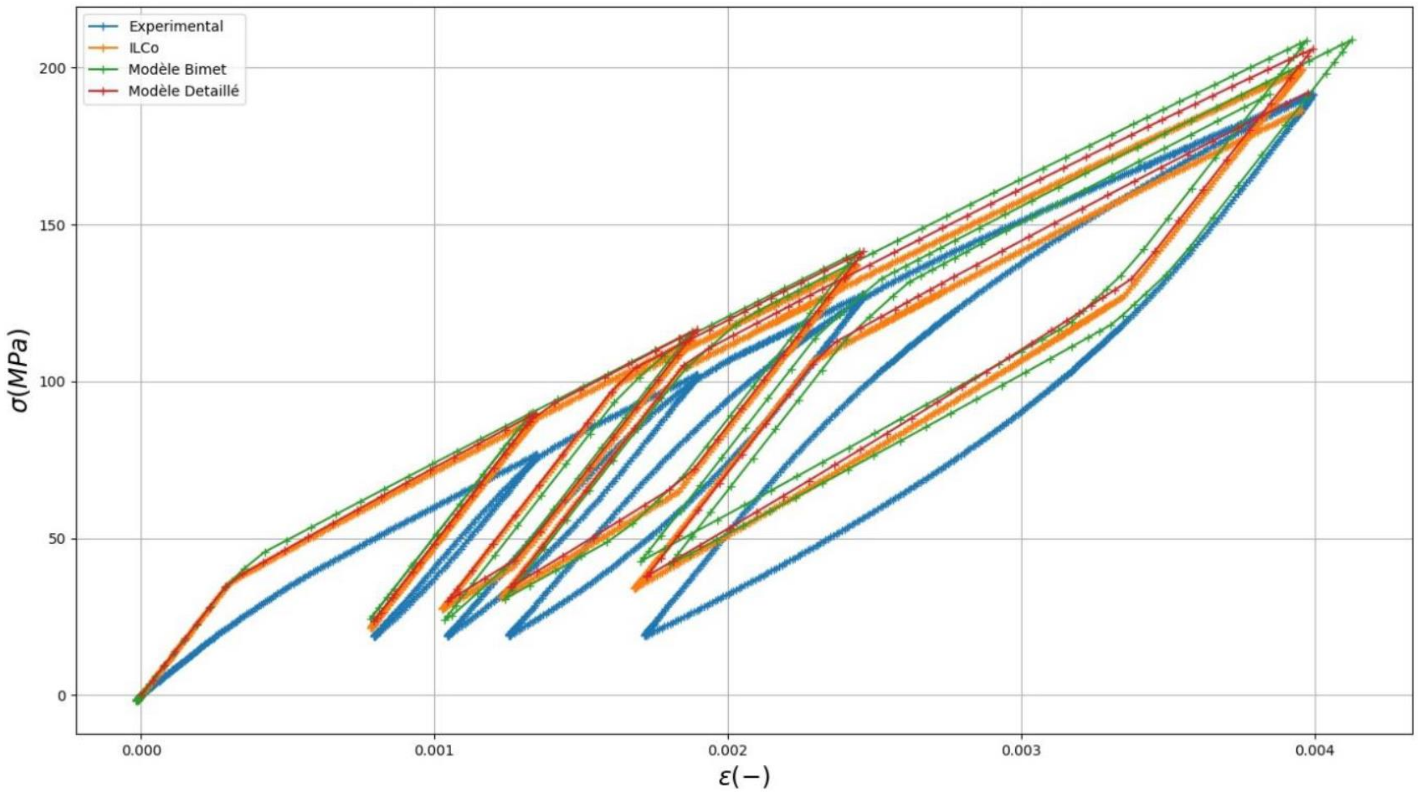
—— Tensile model



—— FE Bi-met



—— FE detailed



This comparison is done on a load case independent from ILCO identification

Courtesy M. Pouliquen, G. Lenoir, CEA

OUTLINE

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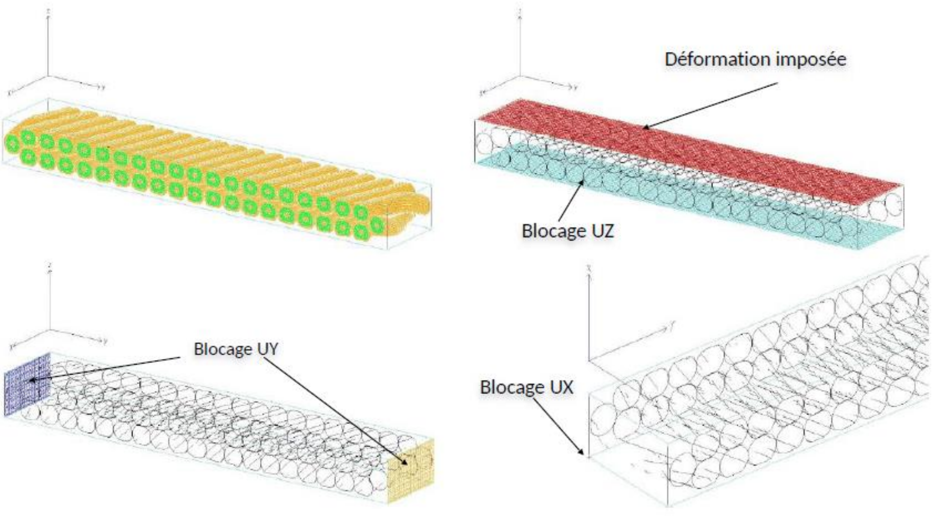
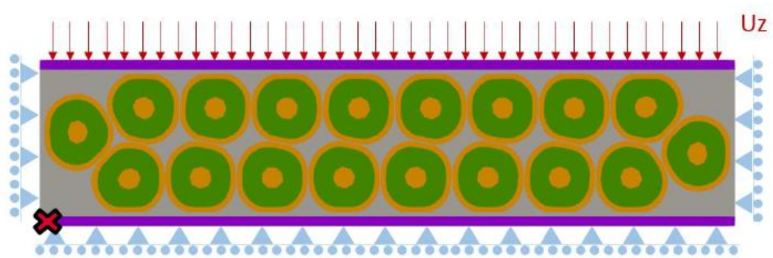
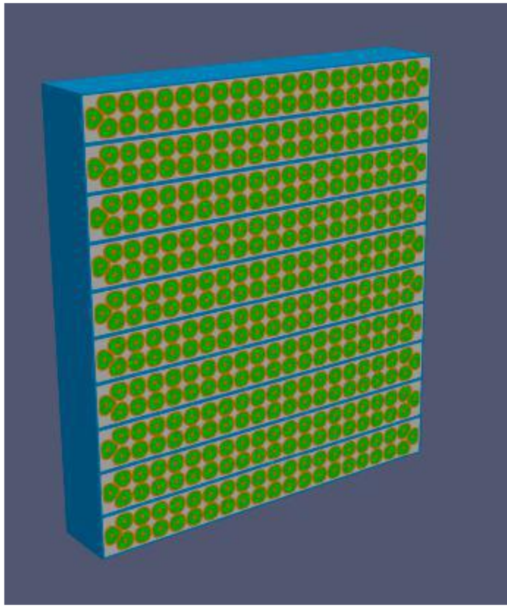
MECHANICAL CALCULATION

- CoCaSCOPE mesh/material properties is used in FEM model
- First tests with uniform transverse compression (up to 0.3%)

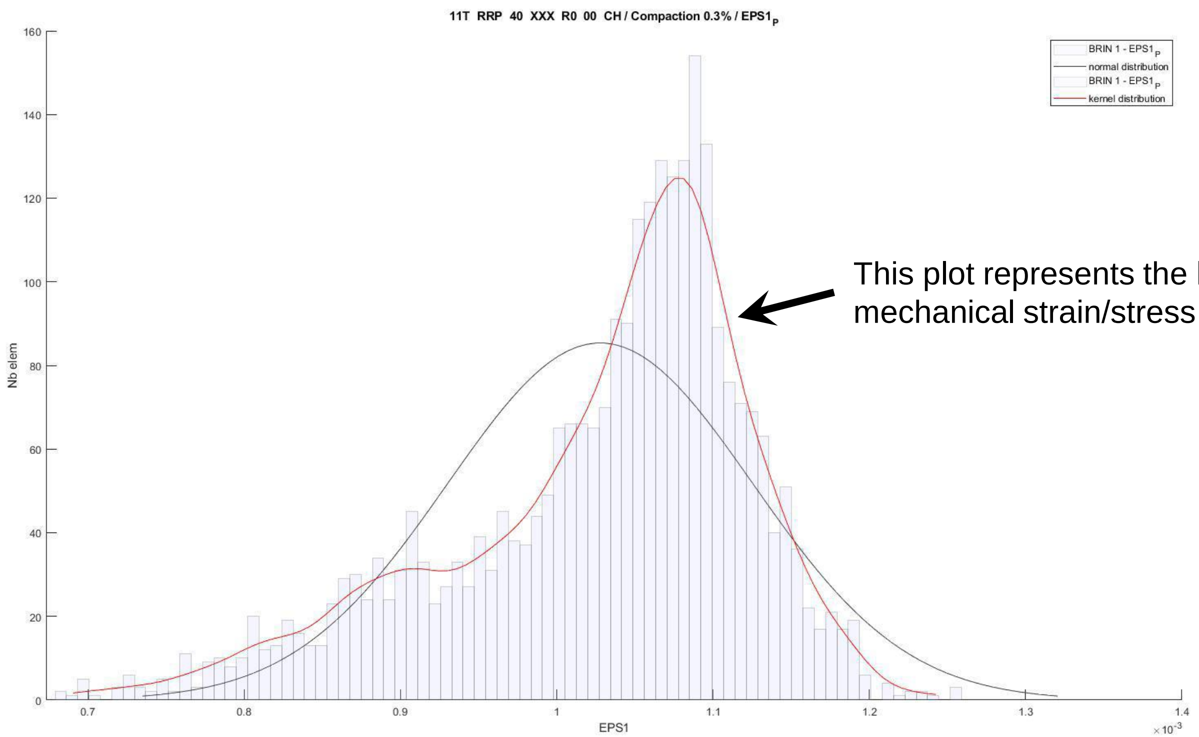






DATA VISUALIZATION 1/2

- In view of mechanical / electromagnetic scaling laws, data must be analyzed at the **local scale** (filamentary region)
- Need for convenient plot allowing easy comparison
- Mechanical parameters distribution is plotted for each strand:

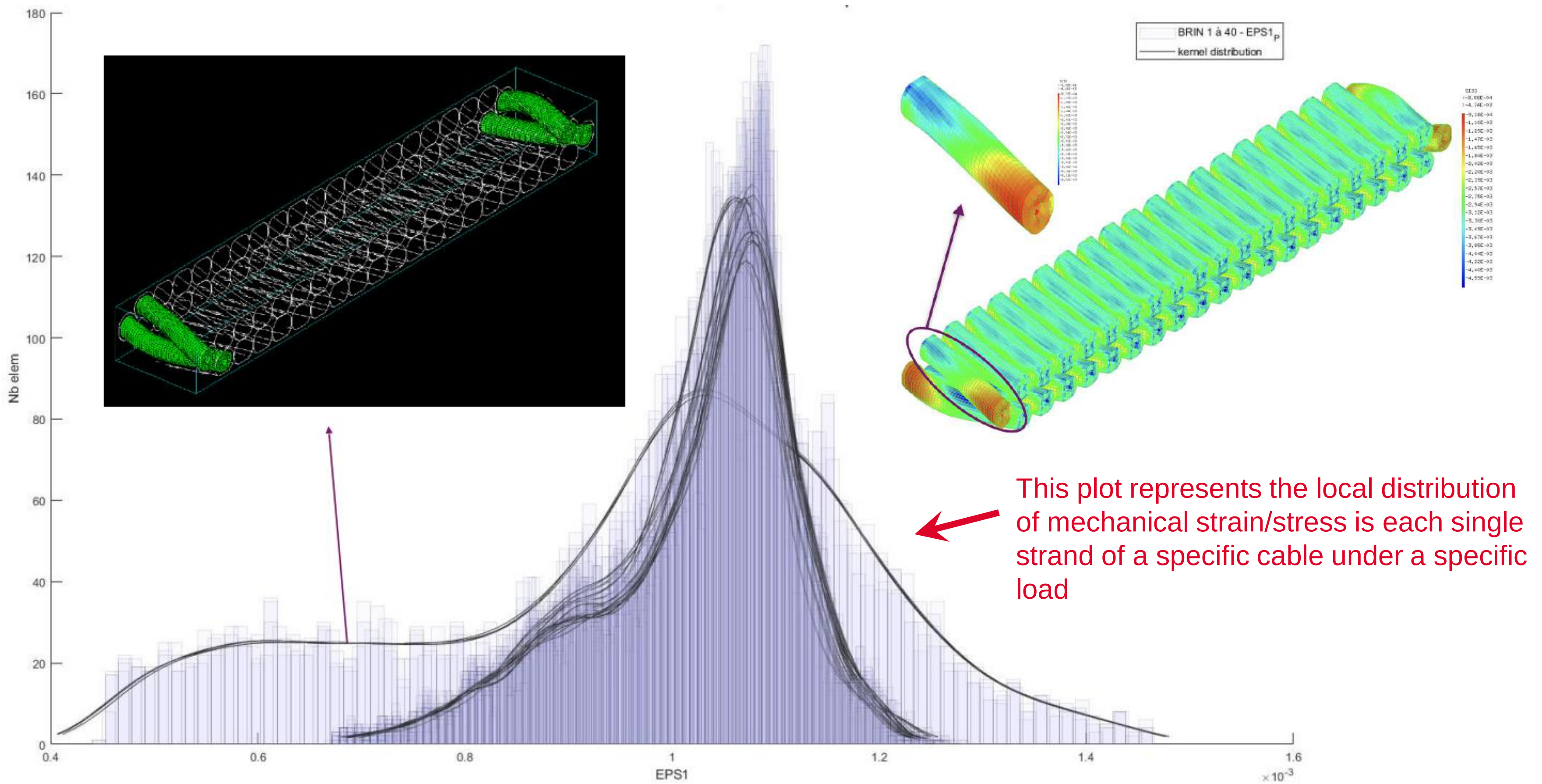


This plot represents the local distribution of mechanical strain/stress is one strand

Courtesy K. Pirapakaran, CEA

DATA VISUALIZATION 2/2

- Mechanical parameters distribution can plotted for all strands of a cable:



Courtesy K. Pirapakaran, CEA

→ potential benefits :

- **estimate the cable current transport capability**, thanks to the existing scaling laws
- allows easy comparison between cable configurations
- provide guidelines for Rutherford cable optimisation

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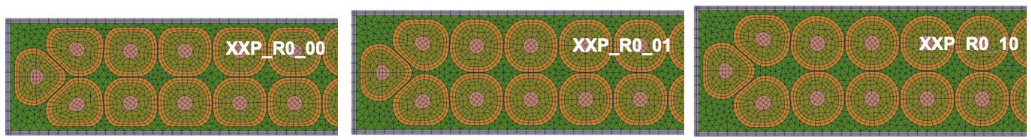
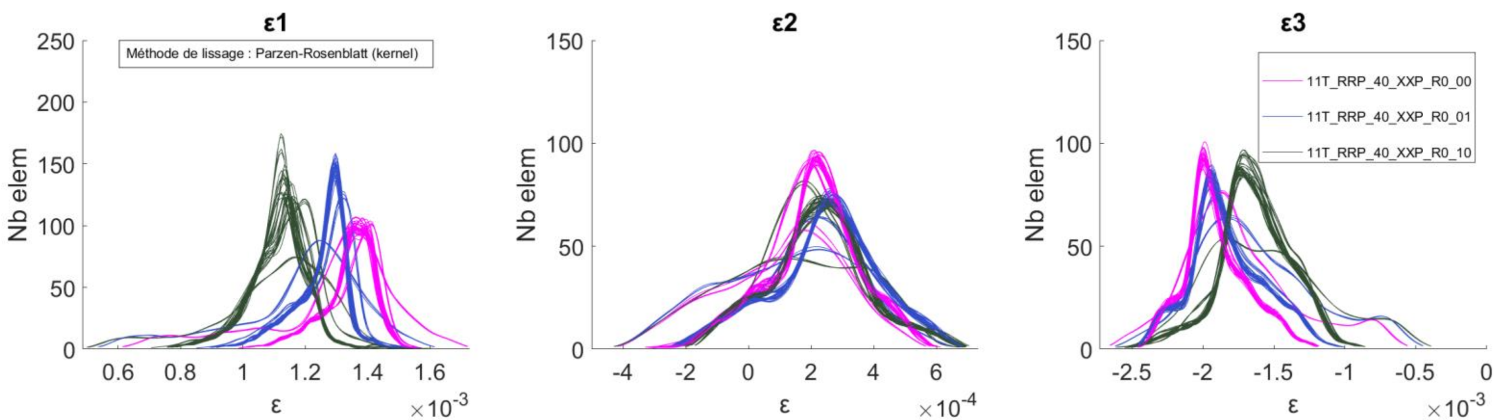
Results presented today are preliminar and given for illustration of the potentiality of CoCaSCOPE tool

IMPACT OF TRANSVERSE COMPACTION OF CABLE

Warning: preliminar results!



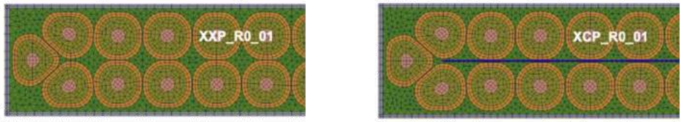
High compaction   Medium compaction   Low compaction



→ Impact on the stack/lateral directions

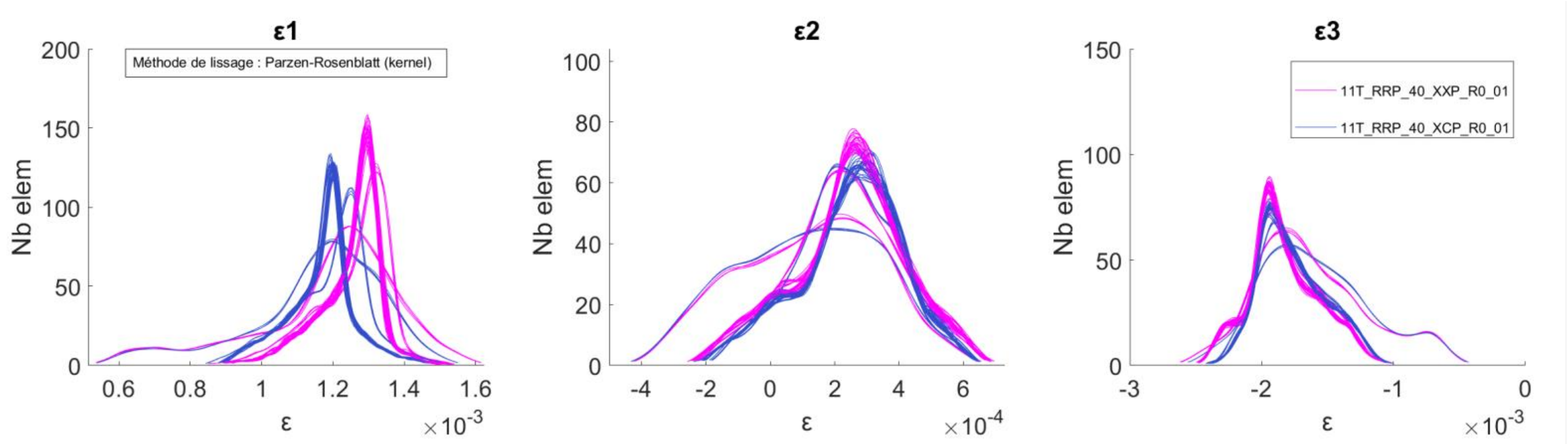
IMPACT OF STEEL CORE

Warning: preliminar results!



No core

Steel core

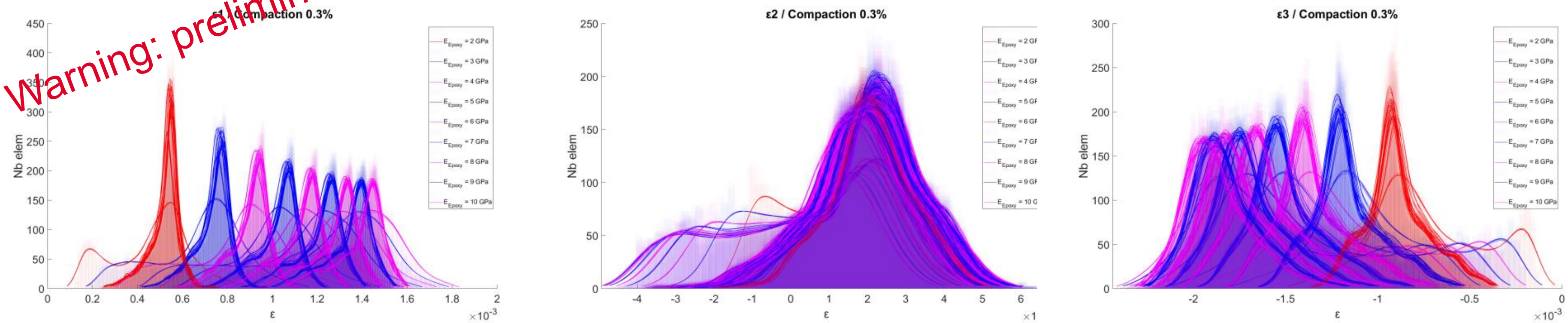


→ Limited impact on local strains (for a fixed compaction rate)

Impact of matrix stiffness

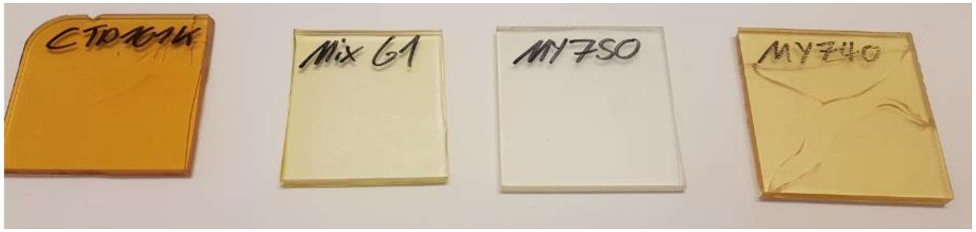
Warning: preliminar results!

Epoxy matrix modulus from 2 to 10 Gpa

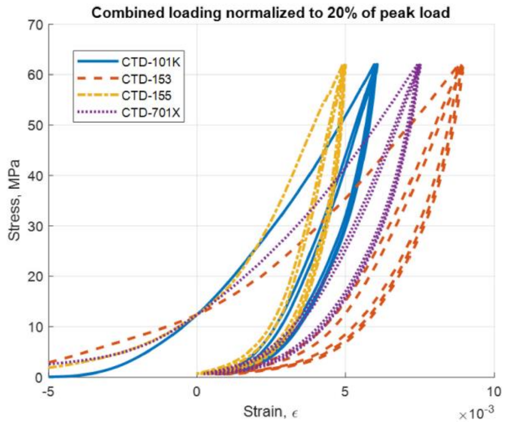


→ Strong impact on local strains

→ Further studies are planned based on experimental data



Courtesy A. Brem, ETHZ

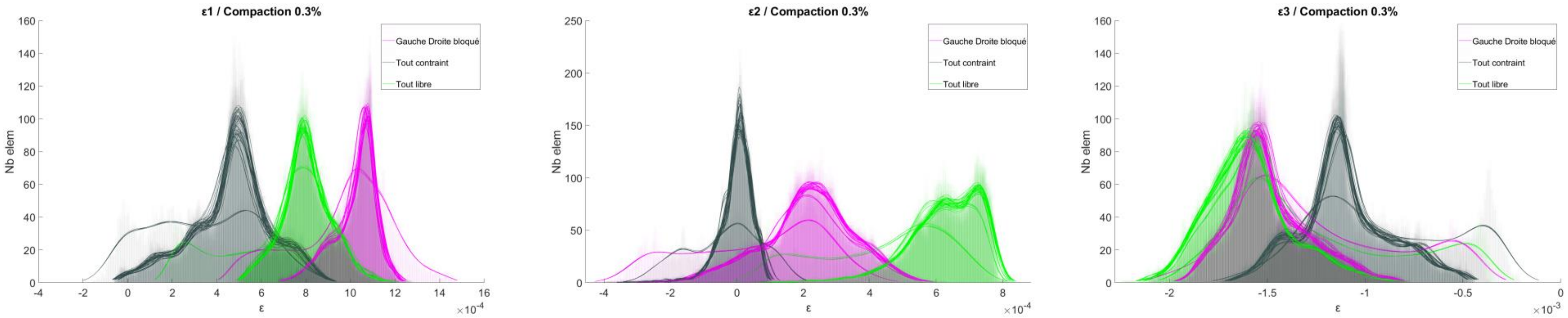


Courtesy S. Krave, Fermilab [Krave 20]

IMPACT OF BOUNDARY CONSITIONS

Warning: preliminar results!

Blocked in lateral direction / Blocked in 3 directions / Free in 3 directions

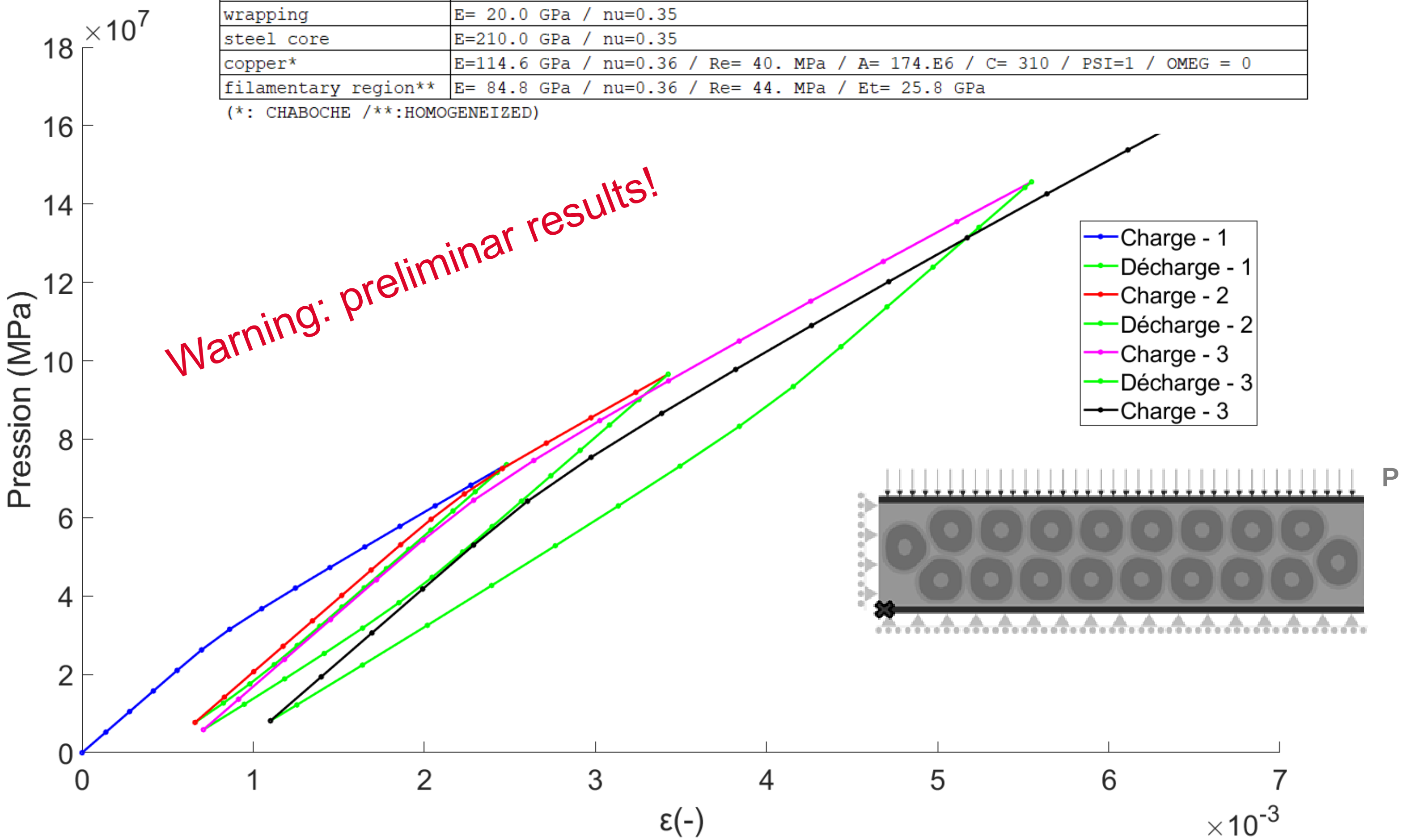


→ Major impact on local strains

CYCLIC TRANSVERSE LOADING 1/2

impregnation	E= 5.0 GPa / nu=0.35
wrapping	E= 20.0 GPa / nu=0.35
steel core	E=210.0 GPa / nu=0.35
copper*	E=114.6 GPa / nu=0.36 / Re= 40. MPa / A= 174.E6 / C= 310 / PSI=1 / OMEG = 0
filamentary region**	E= 84.8 GPa / nu=0.36 / Re= 44. MPa / Et= 25.8 GPa

(*: CHABOCHE /**:HOMOGENEIZED)

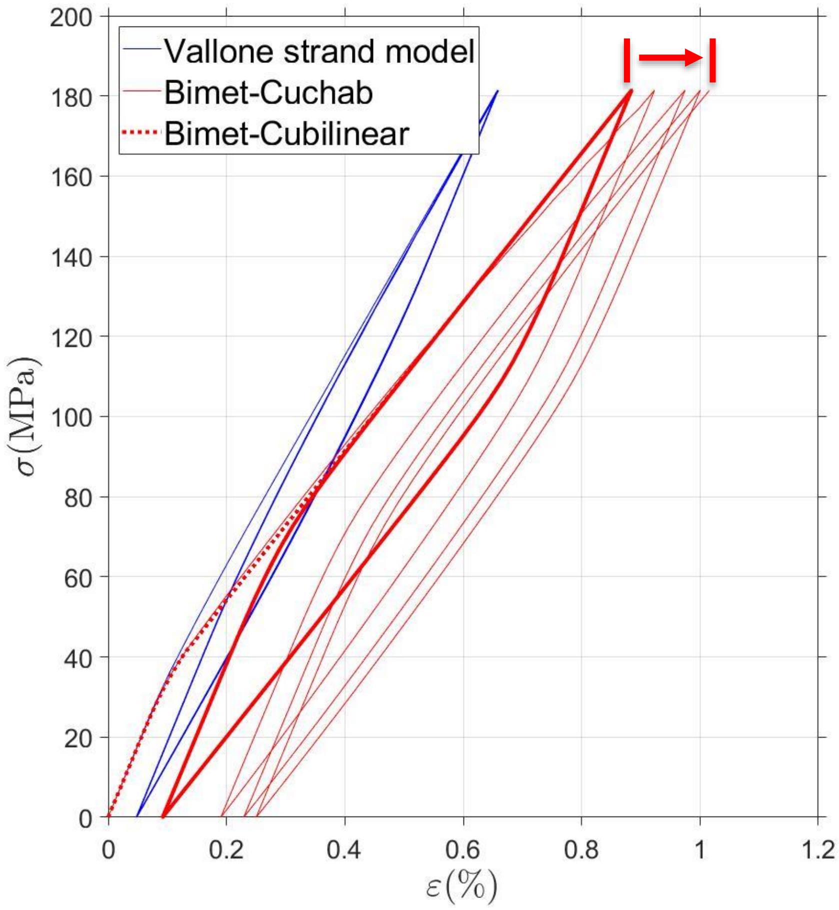


→ potential benefits :

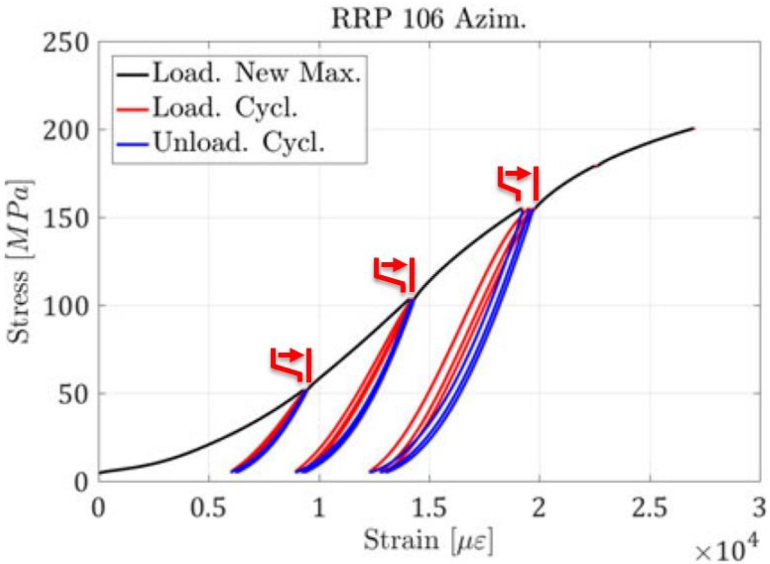
- Accounts for hardering / **strain accumulation** (not the case with bilinear plasticity)
- comparison with stack samples tests for models validation
- assist in the interpretation of experimental results

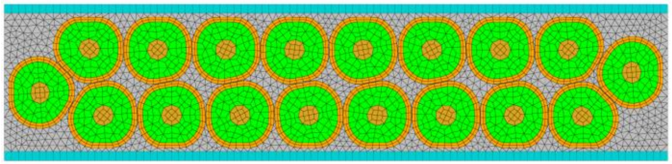
CYCLIC TRANSVERSE LOADING 2/2

Gilles Lenoir (CERN) shows that strain accumulation occurring in real magnets is not represented by bilinear plasticity models. Hardening model is necessary.



Courtesy G. Lenoir, CERN





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NEXT STEPS 1/4

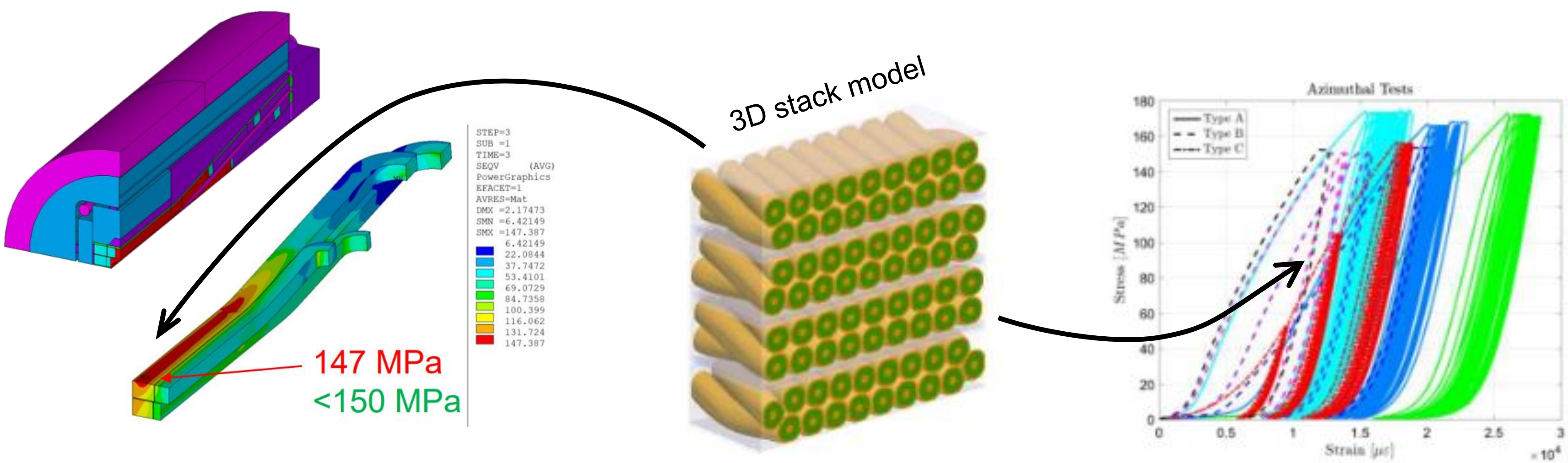
→ implement the **strain function** and **scaling laws** in the filamentary region in order to estimate the current transport degradation (B. Bordini 2014, G. Vallone 2018)

→ make the link with the stresses at the winding scale (implement stack model in magnet simulations as sub-model)

→ build 10-stack and “sample holder” models (including setup)

→ implement thermo-mechanical phenomena induced by the process of metallurgy

→ improve computation time as 3D stack models are heavy (> 1 million nodes)

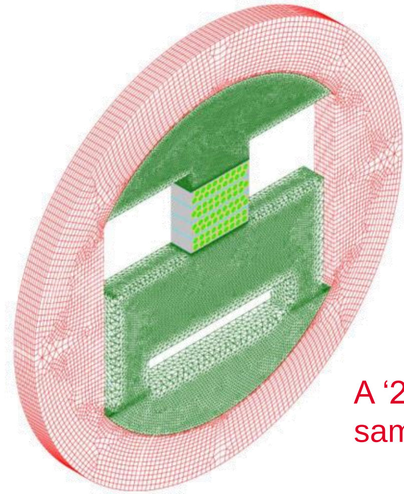


E. Rochepault, IEEE TAS 2020

C. Fichera, IEEE TAS 2019

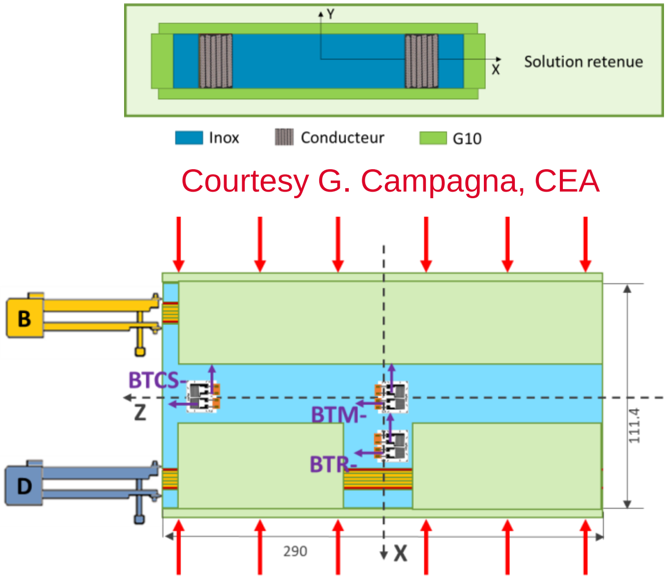
NEXT STEPS 2/4
CORRELATION WITH EXPERIMENTAL DATA

→ Possibility to model the characterization tooling in order to take into account its compliance

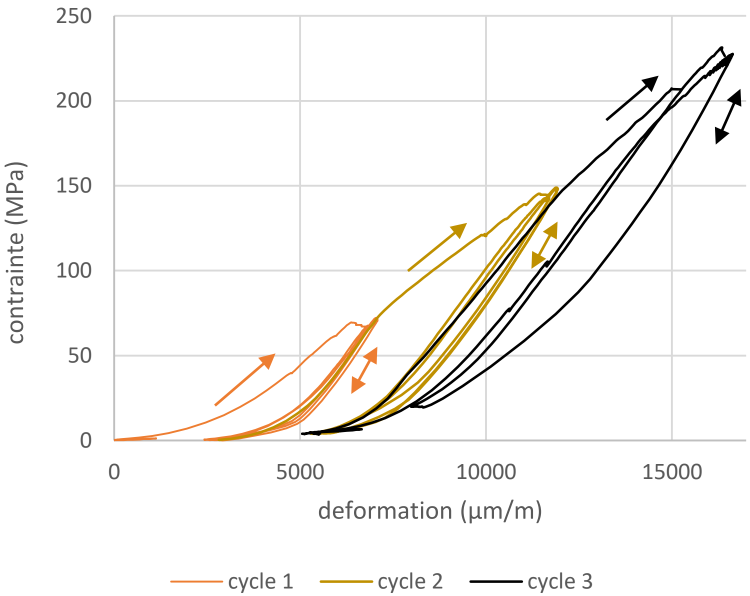


A '2D+ slice' of CERN's sample holder

→ Simulating simple experimental devices such as the dummy coil of DACM



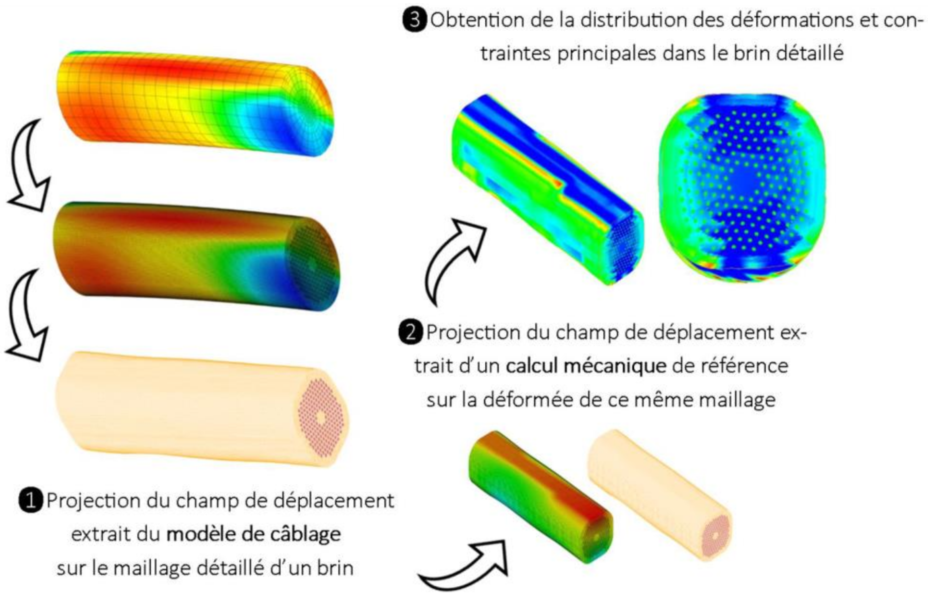
Courtesy G. Campagna, CEA



NEXT STEPS 3/4

LINK WITH THE MICROSTRUCTURE SCALE

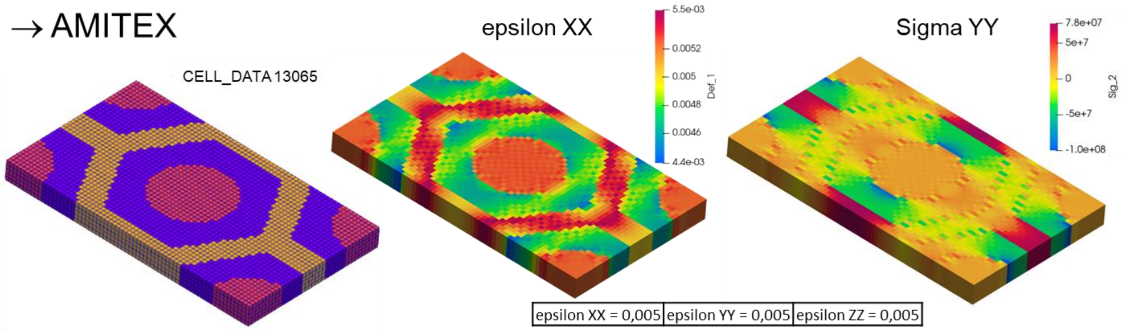
→ The results obtained at the strand level can be **projected to the filament level** if needed for the electromagnetic post-treatment (scaling laws)



NEXT STEPS 4/4
TRYING FFT METHOD INSTEAD OF FEM

→ Using a FFT method (AMITEX) instead of FEM at the REV level will be investigated next year in order to gain efficiency in the identification/computation process

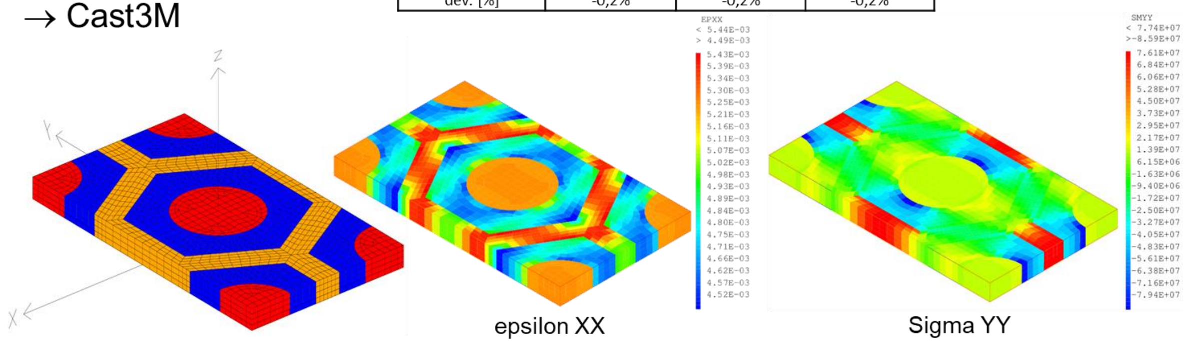
→ AMITEX



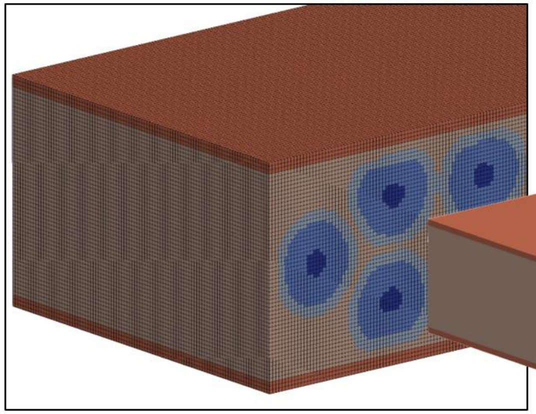
(3 x uniaxial traction X/Y/Z)
(elastic Cu and SC)

	epsilon XX = 0,005	epsilon YY = 0,005	epsilon ZZ = 0,005
	Sigma ~ XX	Sigma ~ YY	Sigma ~ ZZ
Cast3M [MPa]	610,04	610,06	612,03
AMITEX [MPa]	609,11	609,09	611,00
dev. [%]	-0,2%	-0,2%	-0,2%

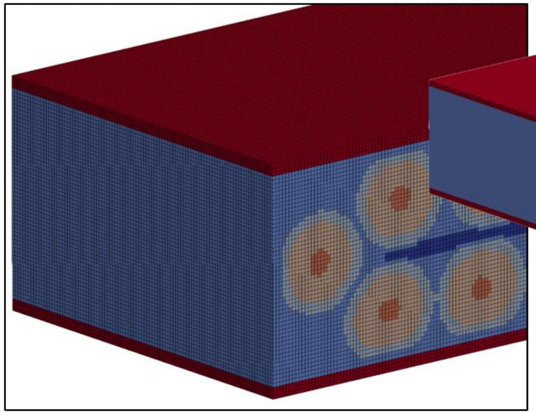
→ Cast3M



Without steel strip



With steel strip



Slide by F. Nunio, CEA

Conclusions

- CoCaSCOPE offers a multipurpose approach for **multiscale 3D modelling of Rutherford cables**
- Bi-metallic model allows a simple formulation accounting for **copper hardening**
- allows **comparisons of cable configurations** early in the design process
- provides conformal mesh bricks that can be assembled together
- enables transition between scales

PERSPECTIVES

- Modeling large deformations of cable

- Adding fracture mechanics

- Improving data at cryogenic temperatures by using cold nano-indentation or other experimental techniques (micropillars…)

- **CEA is open for collaborations around CoCaSCOPE!**

DE LA RECHERCHE À L'INDUSTRIE

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