Sub-modeling approach of plastically deformed geometries of Nb_3Sn cables and strands for the 11T dipole magnet.

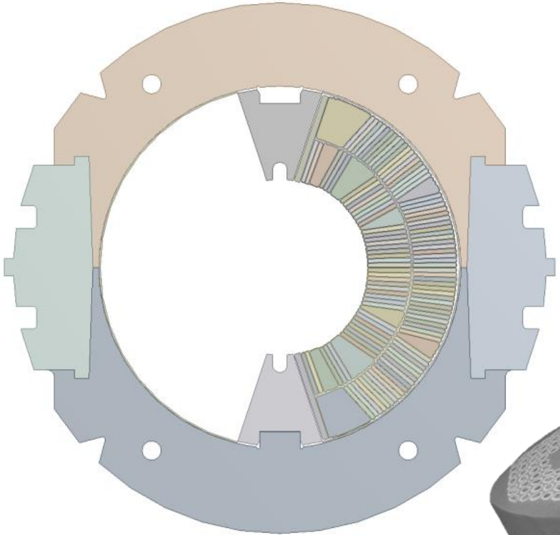
M. Daly, C. H. Löffler, O. Sacristan de Frutos, R. Gauthier, M. Guinchard, A. T. Fontenla, F.Savary.

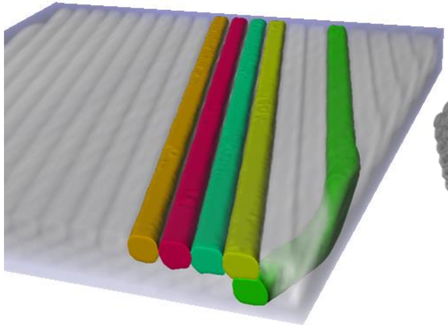
Workshop #2 on Nb3Sn technology for accelerator magnets.

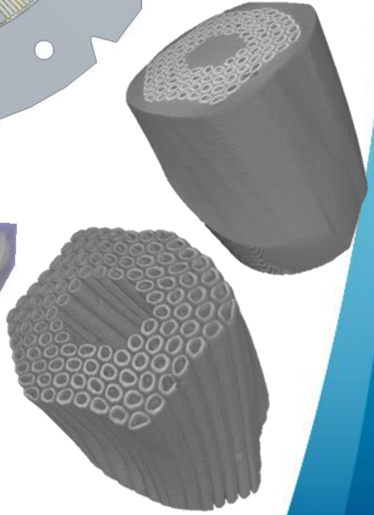
Paris - October 11-12, 2018

Summary

- Overview
- Material characterisation
  - Experimental work
- Validation of material models
  - Calibration
  - Detailed models
- Multi-scale approach
  - From coil to filament
- Linking global coil behaviour to local strands and filaments
  - Stress/Strain/Ic
- Concluding remarks



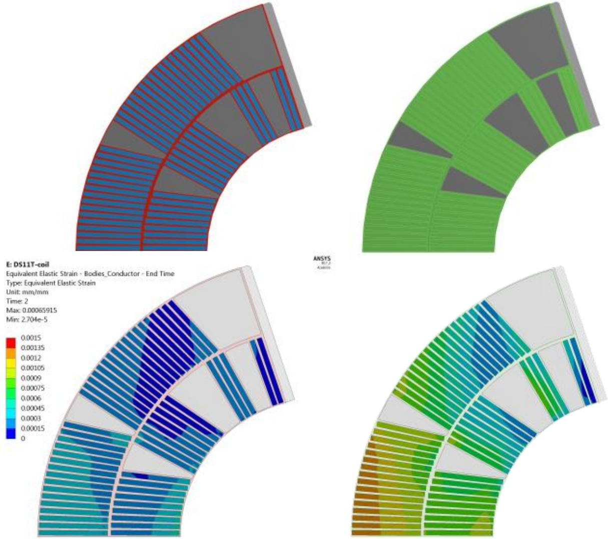




Introduction

- Some gap in knowledge of material properties:
  - Different cable configurations (Including Mica)
  - Large deviation in material properties obtained from 10-stacks
- Mitigated success in short model dipole magnet performances.
  - FE models do not sufficiently capture the stress-strain behaviour of the impregnated 11T dipole coils.
  - Increasing the detail of FE models requires additional material properties.
- No straightforward correlation between strands within test samples (2-stacks) and strands within coil geometries.

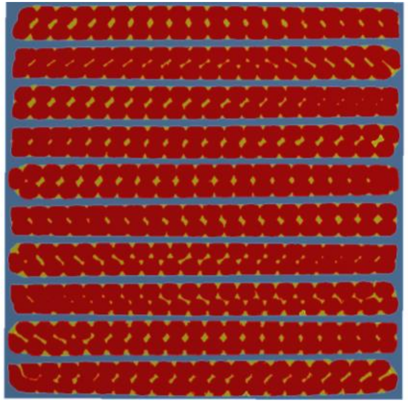
	Loading			
Values in GPa	Monotonic		Cyclic	
D.R Chichili	18 (300 K)	26 (4.2 K)	39 (300 K)	40 (4.2 K)
M. Reytier			33 ± 1 (293 K)	45 ± 1 (4.2 K)
R. Bossert	17 (RT)		37 (RT)	
D. Dell'Orco	38 at 293 K and 43 at 77 K			

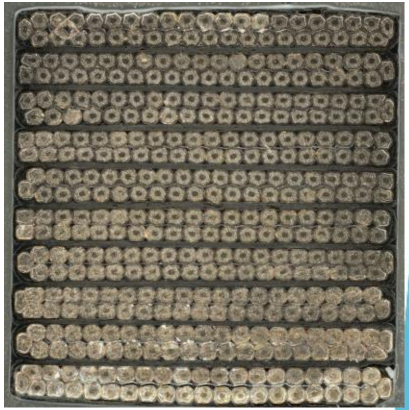


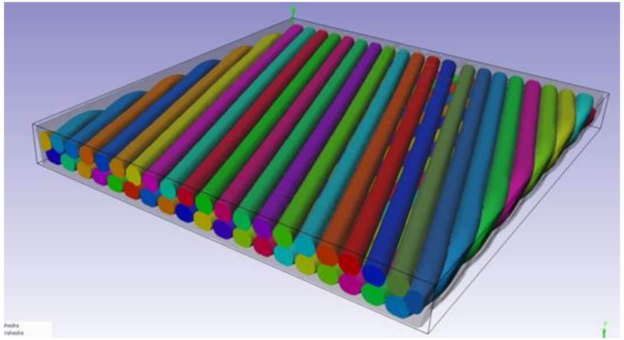
FEA comparison provided by C. H. Löffler

Detailed Characterisation

- Actual 10-stacks have four distinct materials:
  - Pure resin (8%)
  - Reacted S2/Resin/mica composite (13%)
  - Conductor (Nb_3Sn/Cu) (79%)
  - Stainless Steel core (mostly included in 79% conductor)
- Keystone effects.
- Rutherford distribution of conductor.
- Plastified conductor.







Segmentation achieved using ScanIP from Synopsys

CHARACTERISATION PROCEDURE

Material Characterisation

- Fiber Glass Composite (% Vf)
- 10-stack Measurements
- 3-Point Bend Tests

E, ε

σ, ν

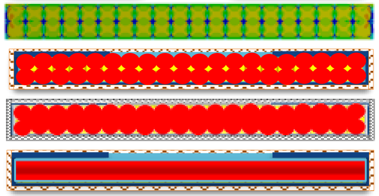
$$[S_{ij}] = \begin{bmatrix} \frac{1}{E_1} & -\frac{\nu_{21}}{E_2} & -\frac{\nu_{31}}{E_3} & 0 & 0 & 0 \\ -\frac{\nu_{12}}{E_1} & \frac{1}{E_2} & -\frac{\nu_{32}}{E_3} & 0 & 0 & 0 \\ -\frac{\nu_{13}}{E_1} & -\frac{\nu_{23}}{E_2} & \frac{1}{E_3} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{23}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{31}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{12}} \end{bmatrix}$$

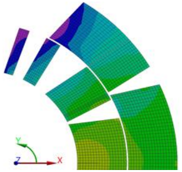
$$\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \gamma_{23} \\ \gamma_{31} \\ \gamma_{12} \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & 0 & 0 & 0 \\ S_{12} & S_{22} & S_{23} & 0 & 0 & 0 \\ S_{13} & S_{23} & S_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & S_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & S_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & S_{66} \end{bmatrix} \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_{23} \\ \tau_{31} \\ \tau_{12} \end{bmatrix}$$

Validate with Measurements

Validate: Stacks, Collaring Press, E-Modulus Press (Digital Imaging Correlation)

2D Model → 3D Model → Coil Model 2D & 3D





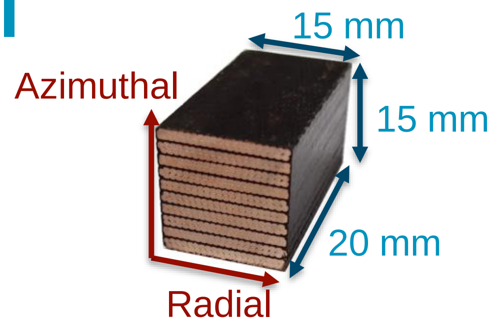
Sample Fabrication and Experimental Work

Finite Element Properties

Modelling and Calibration of Models

Experimental

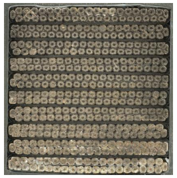
- 10-stack sample preparation
  - Reproduces as best as possible the fabrication of the 11T dipole.
  - Cavity size equivalent to 10 cables in coil cross-section.
- Specific mould design
  - Ease of use/unmoulding
  - Can be used for producing witness samples
- Samples cut to 20 mm lengths
- Samples tested in custom-made rig with 8 LVDTs for producing stress-strain curves and Poisson ratios in all xyz directions.

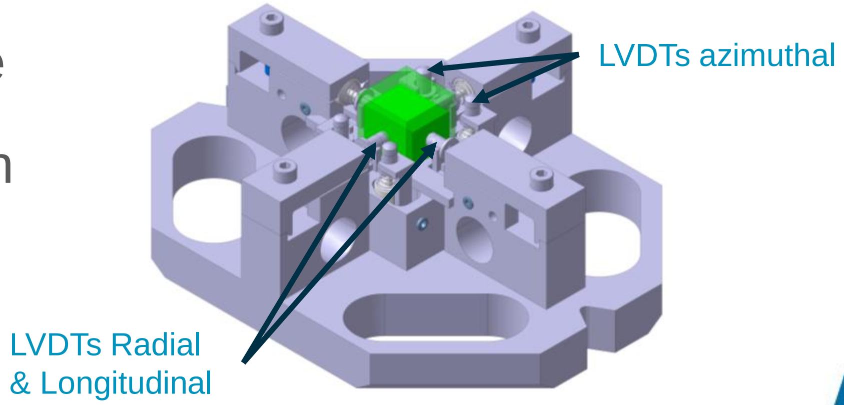



Pure Resin


Bronze + S2/Resin

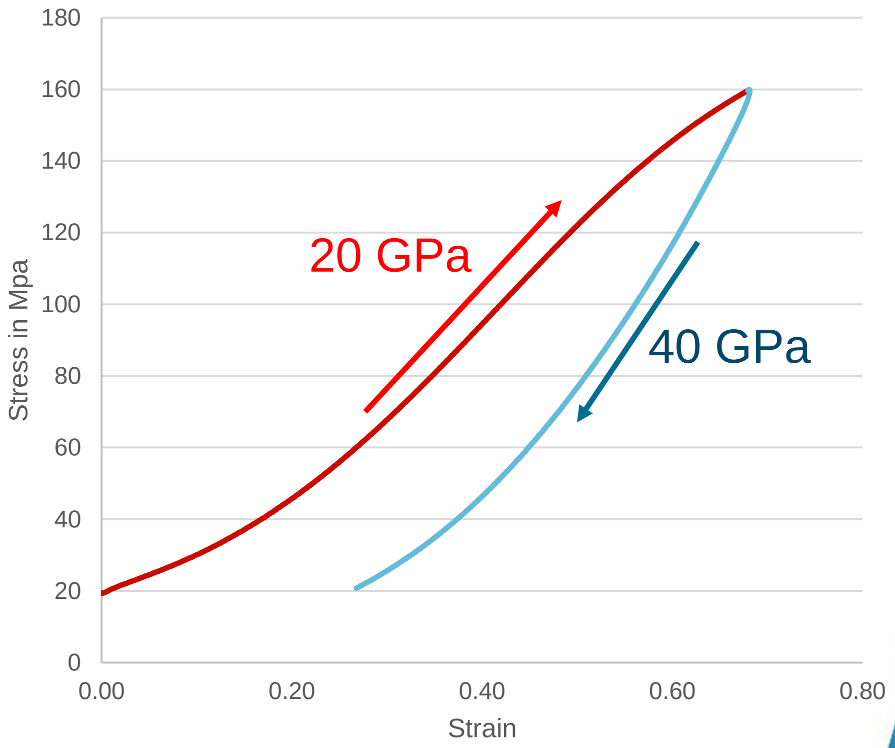

Cu + Mica/S2/Resin


Nb3Sn + Mica/S2/Resin



10-stack Measurements (Azimuthal)

- Compression of 10-stacks in the Azimuthal, Radial and Longitudinal direction:
  - 3 load cycles
  - 12 and 50 cycles
  - Load and 1hr hold
  - Retest 15 days later
- Validation against bronze and insulated copper cables.
- Different stiffness for first loading of samples and subsequent unloading-reloads



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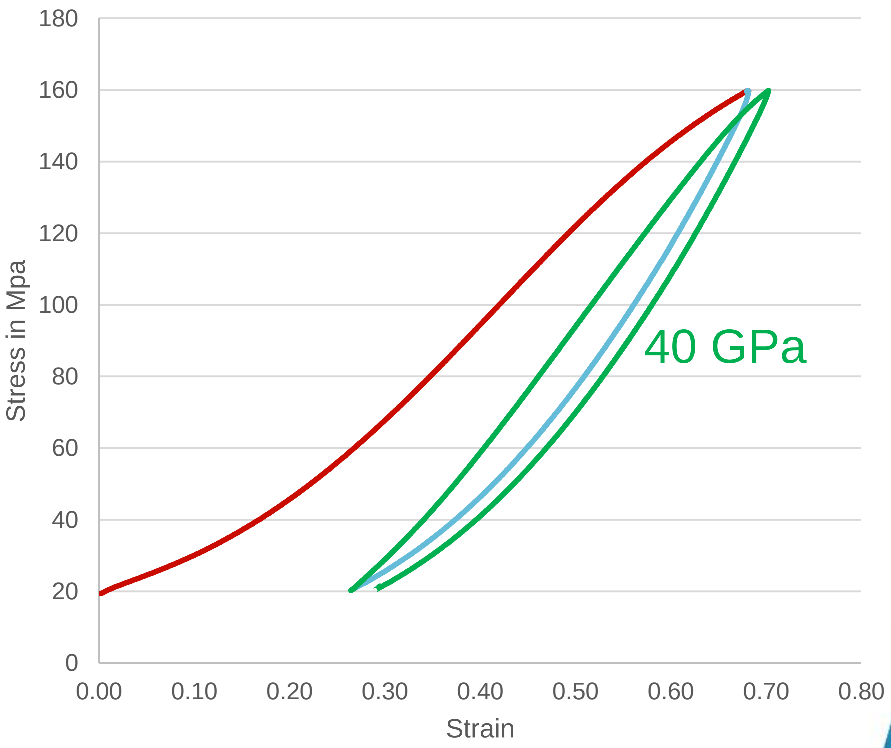
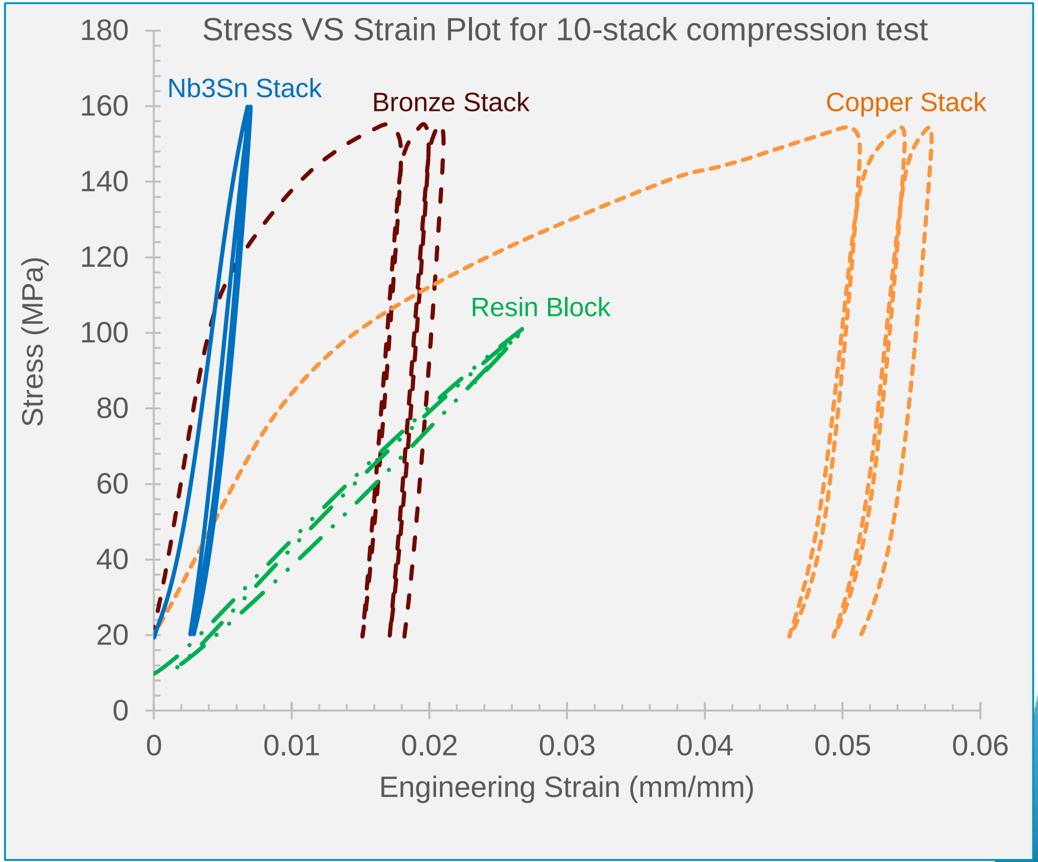


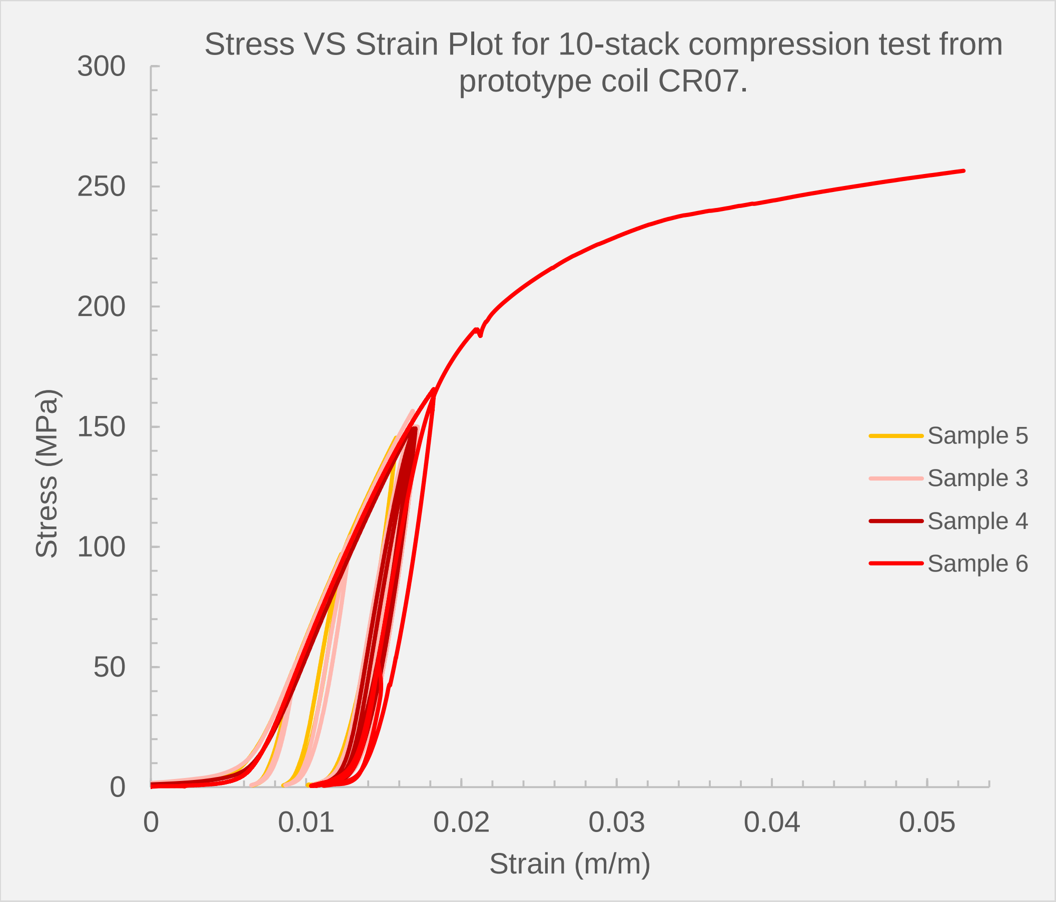
Compression Test Results 01

- 10-stack samples:
  - Tests performed in the azimuthal direction at $3MPa.s^{-1}$
  - Initial pre-compression at **20 MPa**.
  - High repeatability for bronze and copper 10-stacks and resin blocks.
  - Elastic modulus measured after the first loading using the secant method.
  - The modulus can vary depending on the method used for measuring the slope.

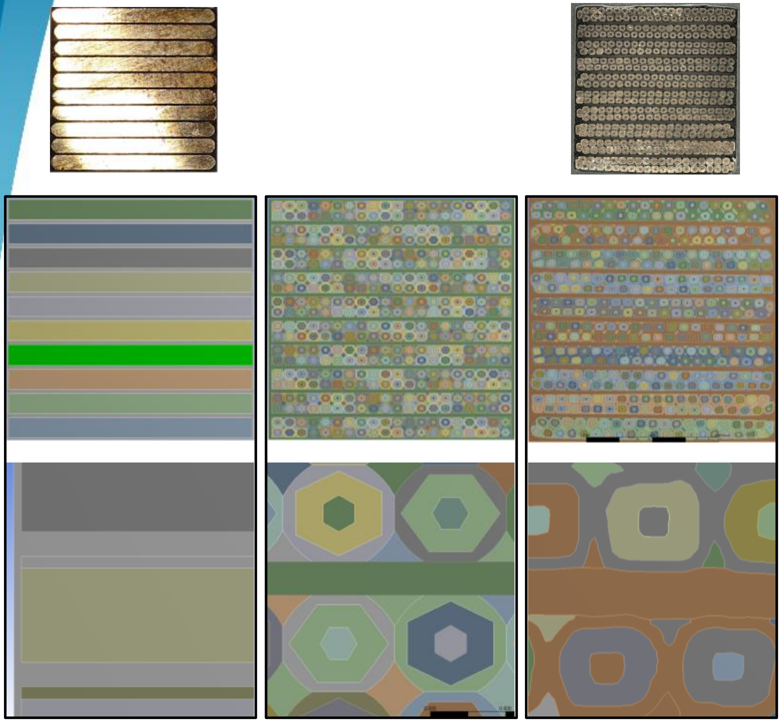


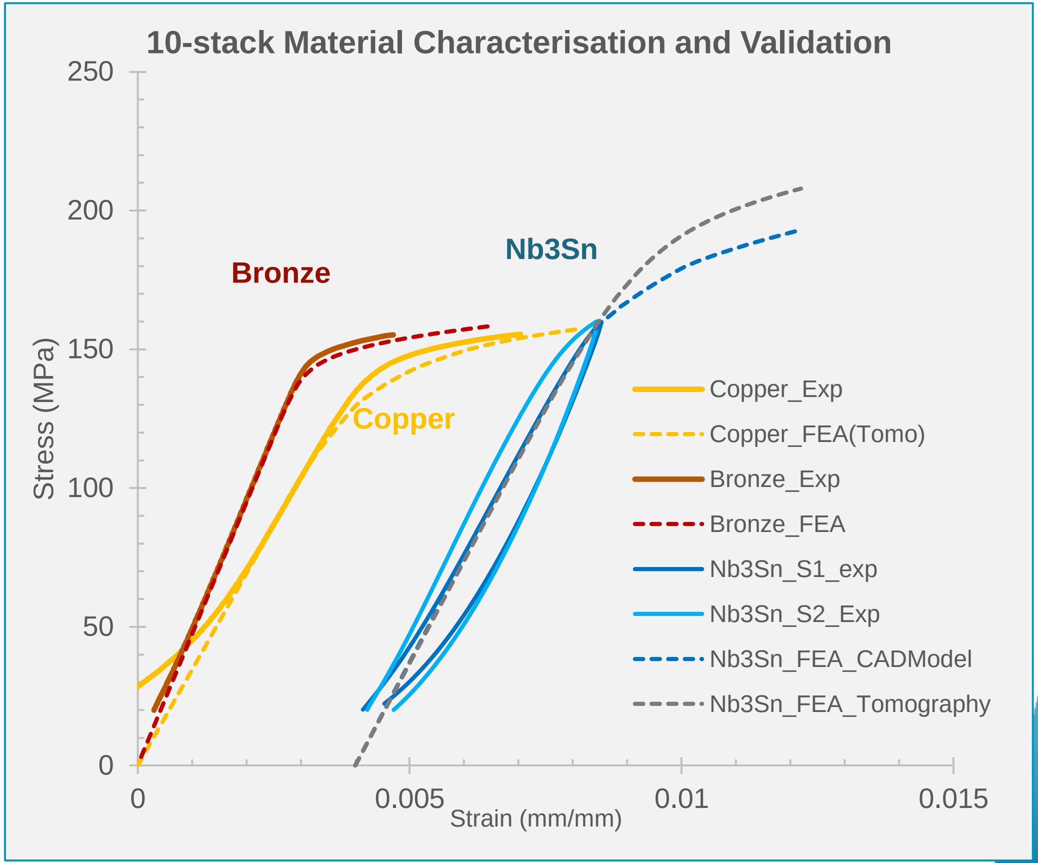
Compression Test Results 02

- 10-stack samples:
  - New results for prototype cable insulation for CR07 coil.
  - Overall behaviour similar to previous tests.
  - Tests performed in the azimuthal direction at 3MPa.s^{-1}
  - Initial pre-compression at **0,2 MPa**.
  - High repeatability for 10-stacks.



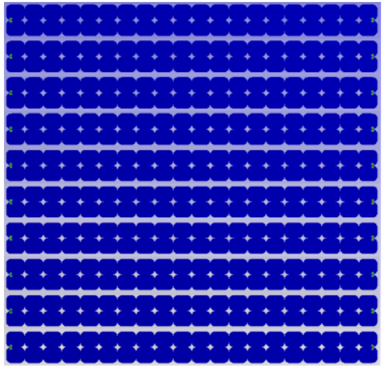
Material Characterisation & Validation

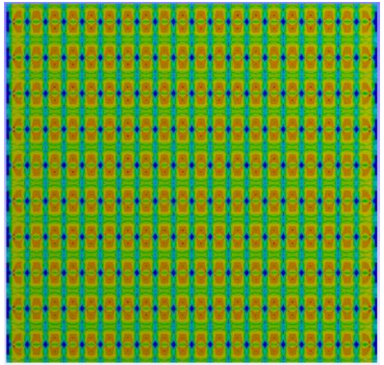


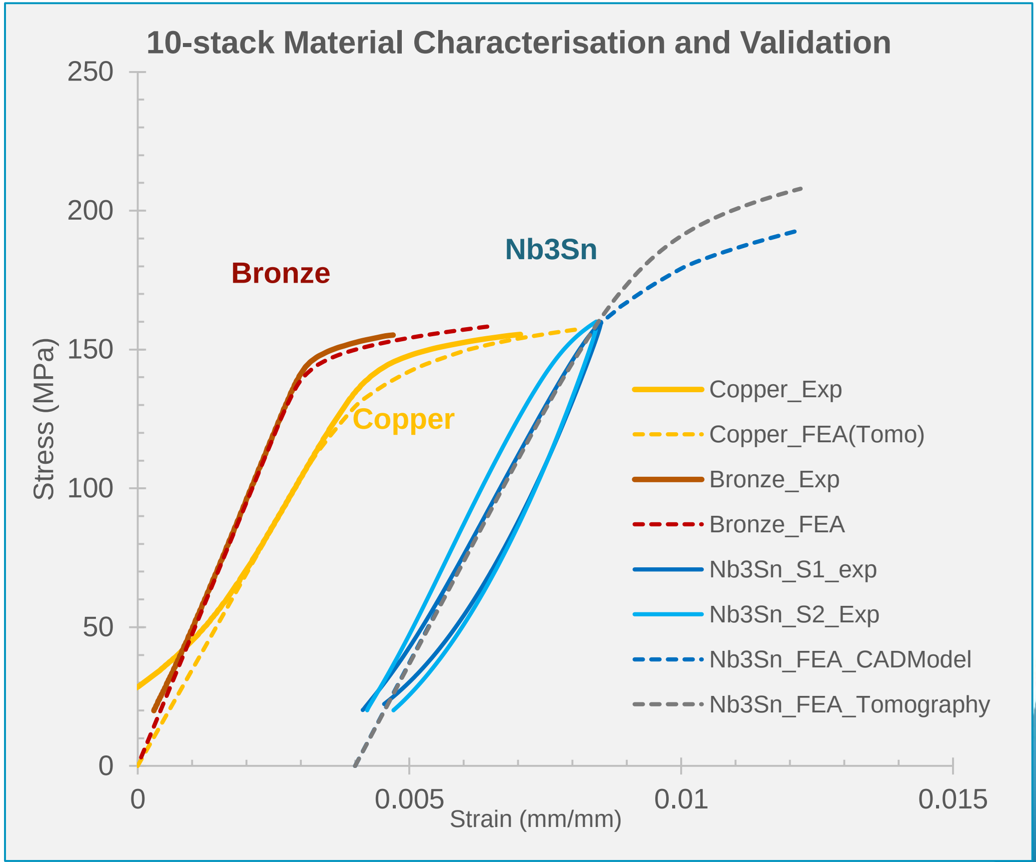


Material Characterisation & Validation

- Stress-strain behaviour of stacks dependent on a number of factors (caveats):
  - Geometry (blunt contours, alignment of strands).
  - Volume fraction of individual materials.
  - Material laws used.
  - Interaction between parts (Friction).



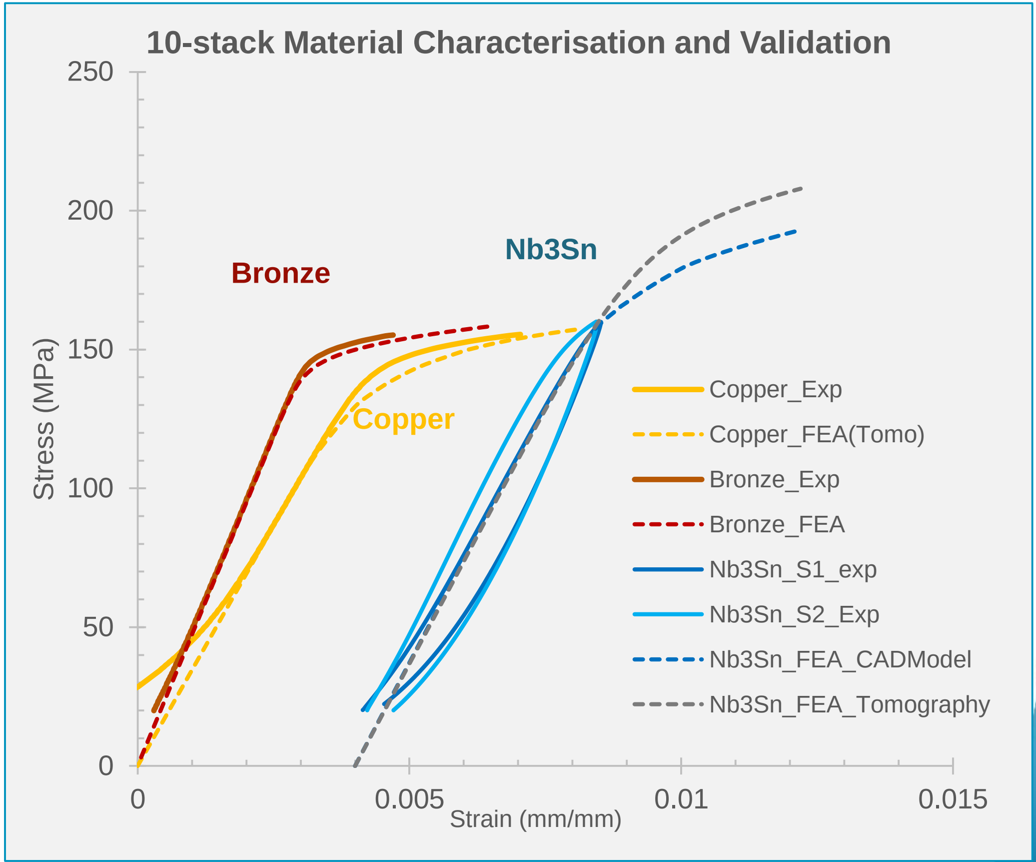




Material Characterisation & Validation

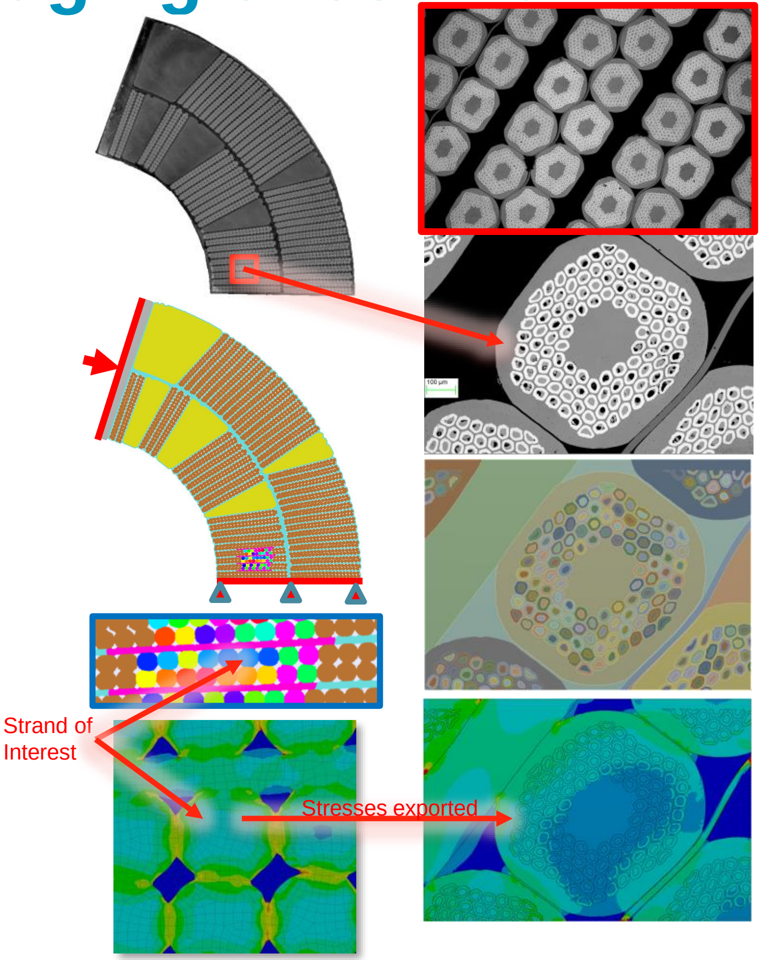
- Material properties estimated through curve-fitting of experimental data.
- Copper annealing point is drastically above experimental measurements.
- Other material models used such as Ramberg-Osgood hardening model.

Material	E (GPa)	σ_{Yield} (MPa)
Resin	3,8	100
Bronze	118	117
Copper	109	250
Fibre/Mica/Resin	11	250
SC (Nb_3Sn) filaments	140	400
SC (Nb_3Sn)/Cu (1:1) composite strand	123	250
SC (Nb_3Sn) 10-stack	36 ± 2	N/A



Multiscale imaging of coil 107

- A region of interest and a strand of interest were chosen within coil 107.
- The same strand was imaged under an SEM in much greater detail including filaments.
- The segmented and meshed (2D) image of Coil 107 was imported from ScanIP into Ansys and simply loaded.
- The stresses on the strand within the coil were exported to the SEM image that was segmented and meshed in ScanIP.
- The stresses applied to the strand are the most representative stresses that would be observed at a strand level (mix of azimuthal & transverse).
- This method also allows us to compute the stresses on the filaments and estimate degradation using scaling laws.



Multiscale imaging of coil 107

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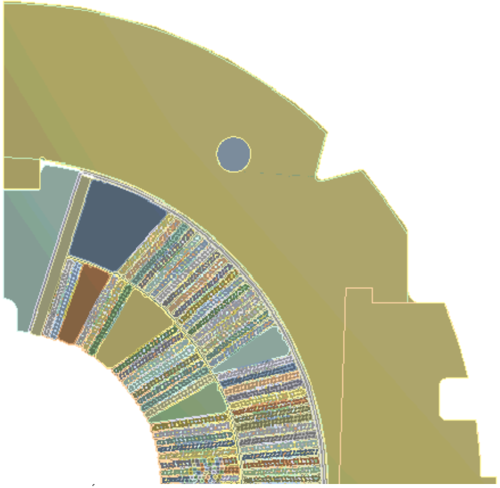
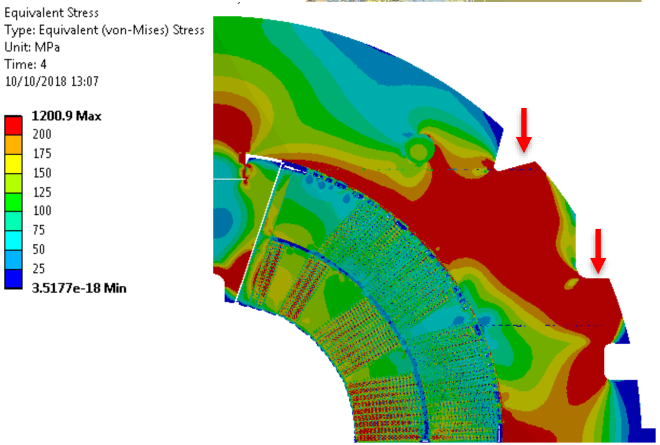
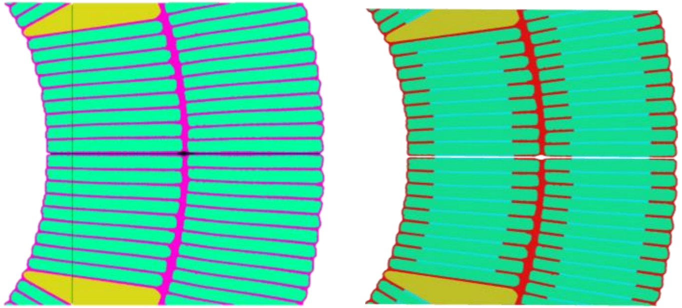


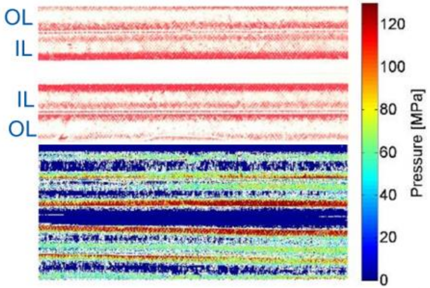


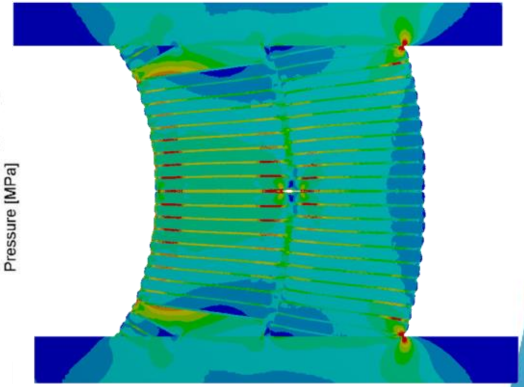
Mid-plane High Stresses

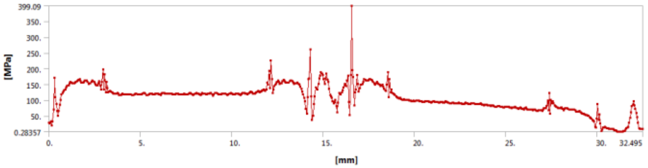
MICA effects on mid-plane

- In order to investigate the effects of the C-shape MICA on the mid-plane stresses observed using Fuji paper, the stresses were computed using the geometry of Coil 107.
- Stresses on the mid-plane were seen to vary along the cable width. This is a result of the keystone (geometry) and increased stiffness as a result of the C-shape MICA.





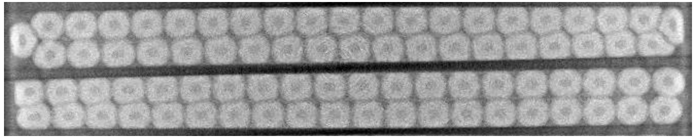


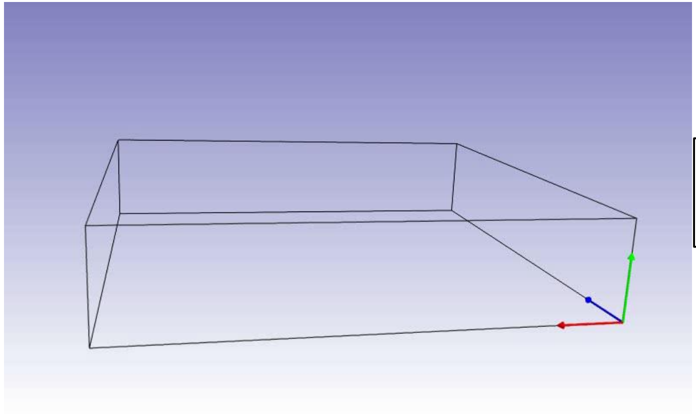


Fuji analysis courtesy of F.Wolf & S.Izquierdo Bermudez

3D 2-Stack

- Impregnated Nb_3Sn 10-stack imaged in 3D using lab-based X-ray Tomography imaging.
- Two central cables were chosen for 3D segmentation.
- Geometry representative of the 2-stack cables used for characterising Ic degradation during transverse loading.
- 3 materials segmented:
  - Conductor
  - Pure Resin
  - Composite: Resin/fibre glass/Mica
- Can be used to analyse the effects of the Rutherford cable geometry in 2D or 3D:
  - Estimate stresses/strains in the straight and twisted sections.





VIDEO

3D X-ray Imaging done at BAM, Courtesy of C.Scheuerlein.

3D reconstruction achieved using ScanIP..

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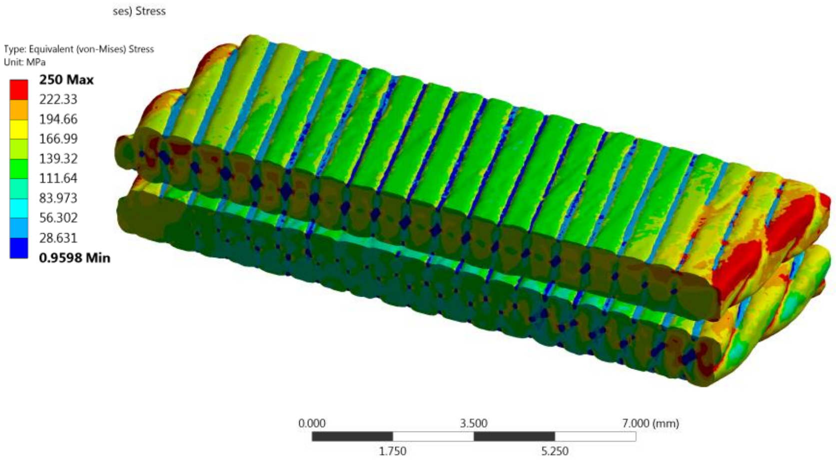
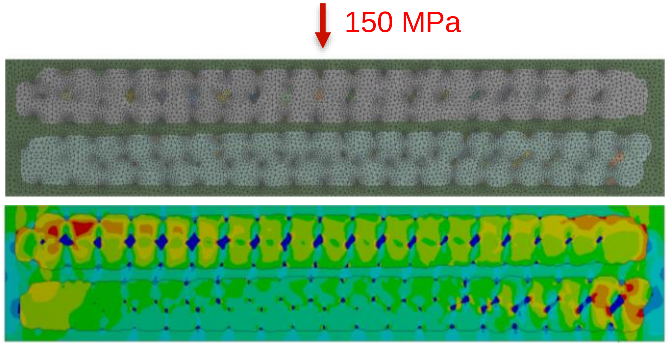
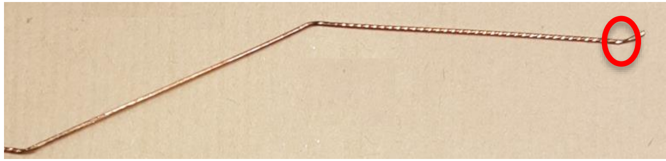
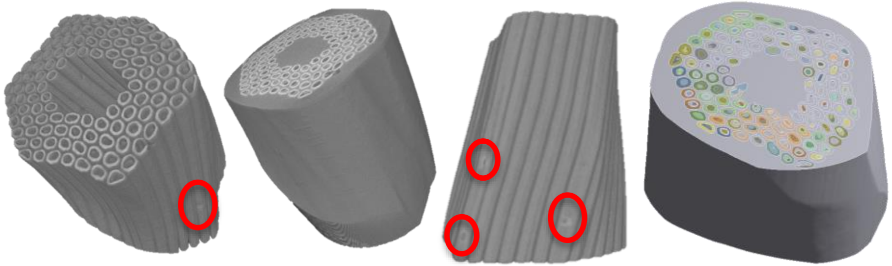




3D Strand

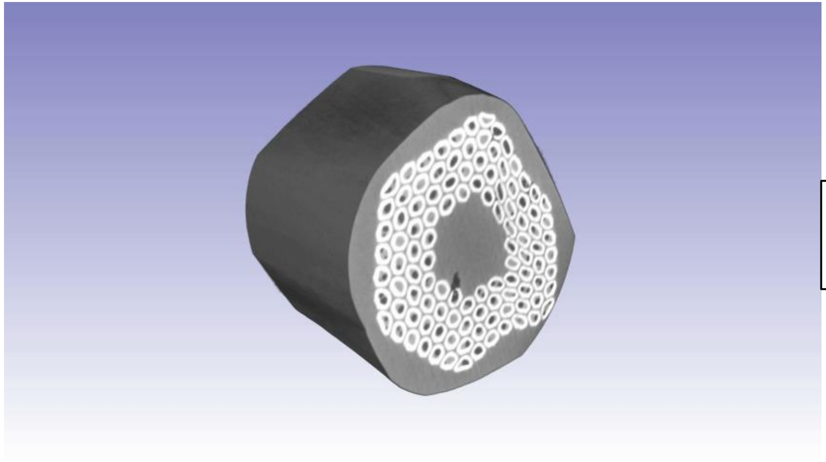
- 3D X-ray tomography of the bent region of the RRP Rutherford Cable.
- Regions were segmented into thee materials in ScanIP:
  - SC Conductor
  - Copper Matrix
  - 2nd Phase/Void
- 3D X-ray tomography images of the bent strand showed regions of leakage and puncture holes in the filaments.
- Deformation due to cabling can be rendered in 3D.
- Simulations can be performed on the 3D volume using ScanIP volumes exported to Ansys using the most recent material properties.





3D X-ray Tomography data

Ansys Model exported from ScanIP

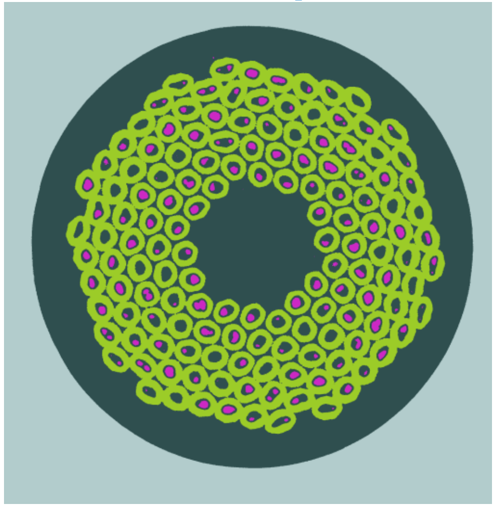


VIDEO

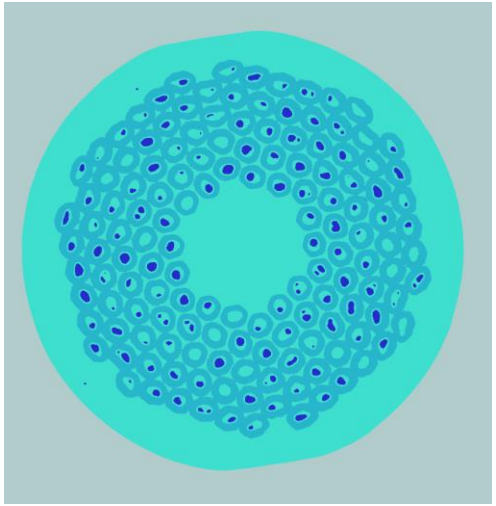
3D data obtained from the University of Manchester MXIF

Comparative Study of Nb3Sn Reacted Strands

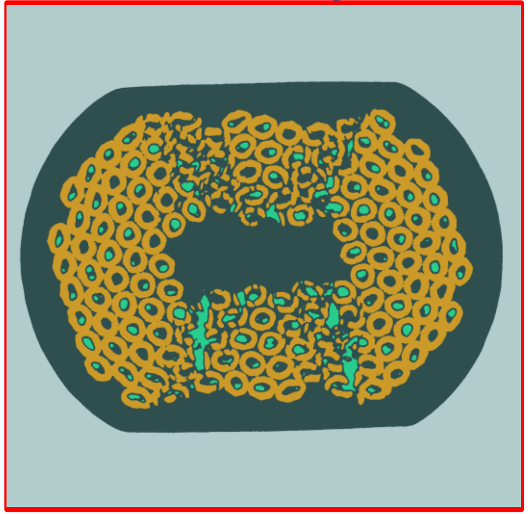
0 MPa Compression



100 MPa Compression / **Segmented Parts**



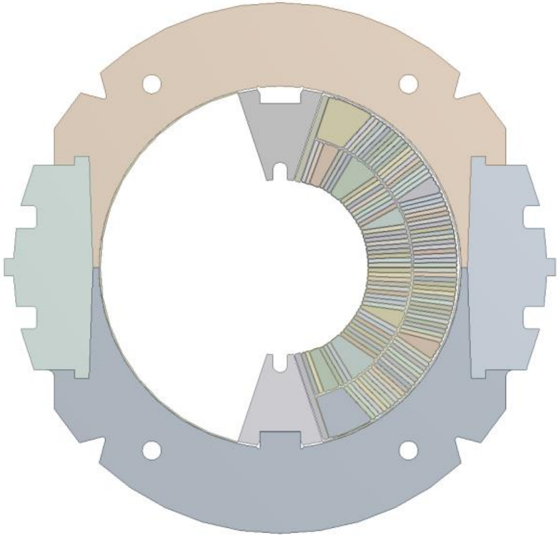
200 MPa Compression / **Subelement Mesh**

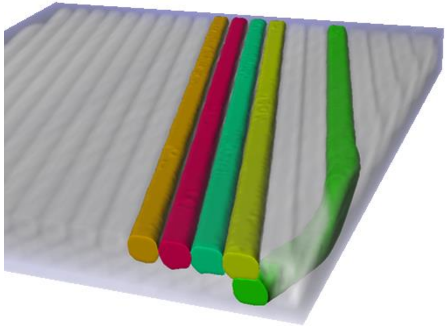


3D X-ray Imaging done at the Manchester X-ray Imaging Facility (MXIF),
Work done in close collaboration with Patrick Ebermann (CERN).

Concluding Remarks

- A successful attempt at characterising the material properties of the 11T dipole magnet using 10-stack and equivalent geometries. But this requires a more standard and repetitive approach.
- Developed a sub-modelling method for obtaining the global and local stress-strain states of coils down to filaments.
- Feasibility of introducing complex geometries to current CAD models used for designing and optimising the 11T dipole.
- The added detail has helped understand and verify some observed phenomena from the 11T prototype.
- Aiming to continue to use the validated material models to assess the degradation of superconducting properties as a result of transversal loads at the strand and filament level.





HiLumi
HL-LHC PROJECT

Thank you for listening

Further acknowledgements: N.Bourcey, C. Fichera, F. Lackner, J. Mazet, T. Mikkola, J C. Perez, C. Scheuerlein, J.Behnsen (MXIF), J. Carr (MXIF).

CERN

Additional Slides

Experimental

- 10-stack sample preparation
  - Reproduces as best as possible the fabrication of the 11T dipole.
  - Cavity size equivalent to 10 cables in coil cross-section.
- Specific mould design
  - Ease of use/unmoulding
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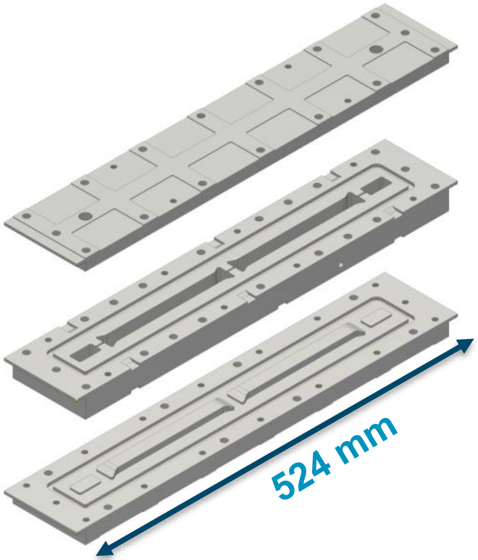

Coil Cross section simulations