Modelisation of impregnated Nb3Sn cable composite at CERN -11T-

RD Line 4 fourth Forum meeting - Modelling Tools, Materials Protection and Cryogenics:

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Outline

- **Context: aim of the 3D model for 11 T**
- **Geometrical simplifications**
- **Contacts and coordinate systems**
- **Submodelling**
- **Modelisation of impregnated Nb3Sn cable**
  - Prestress during collaring phase
  - Thermal contraction of a 2m long coil
- **Conclusions**

Aim of the model

- Understand the overall behaviour of the 11 T series magnet, in particular in the connection side during the thermal and powering cycles;
- Validation of the loading phases via available measurements;
- Assess the transfer of the longitudinal force within the structure;
- Identify critical areas in the coil during thermal and powering cycles.

Not aiming at

- Precise study of the complex collaring phase;
- Local stress distribution in the cable.

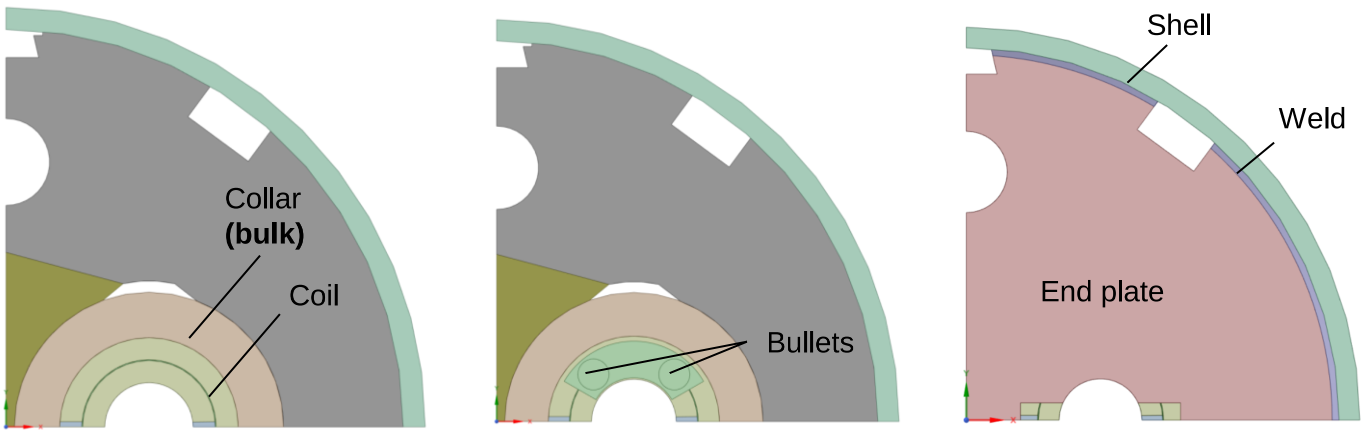
Geometrical simplifications

Symmetries adopted to lower the computational load of the FEM model, resulting in:

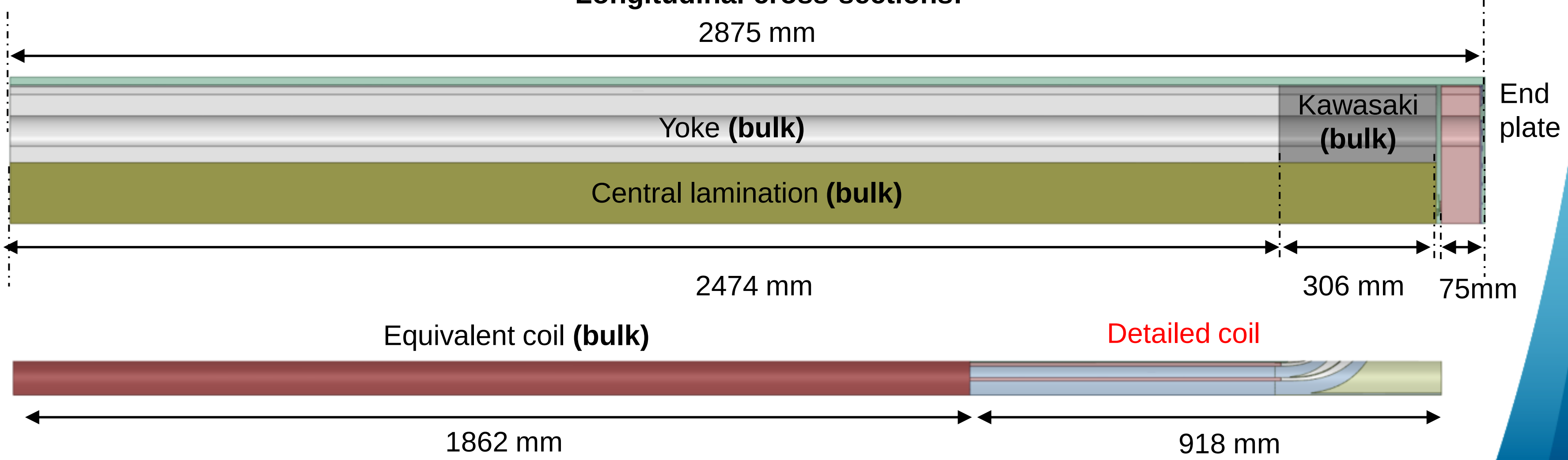
- ¼ of the transversal cross section;
- ½ of the longitudinal cross section.

Yoke, collars and cable were considered as bulky components. Their mechanical stiffnesses were modified accordingly.

Transversal cross-sections:



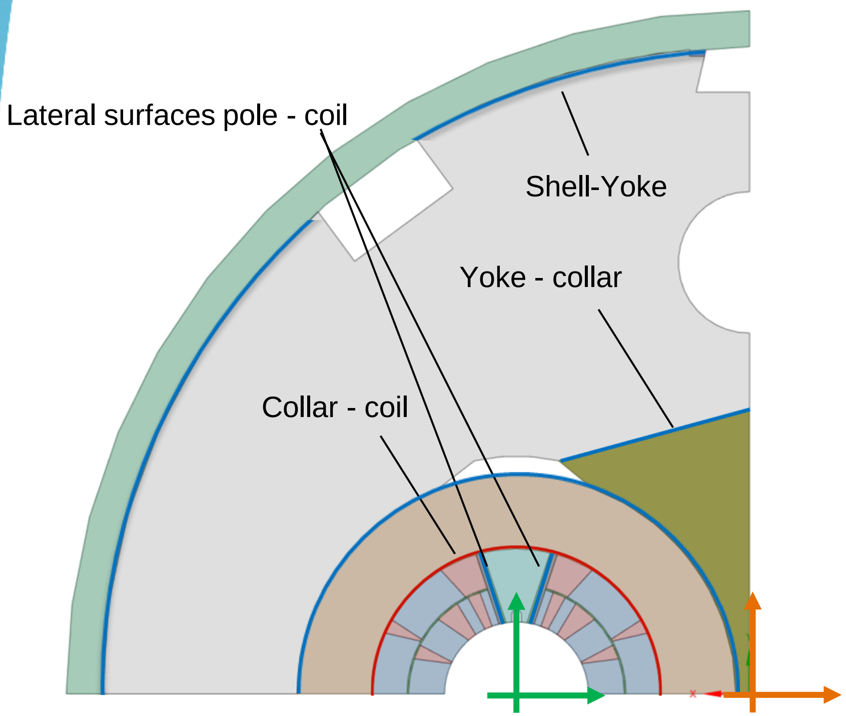
Longitudinal cross-sections:

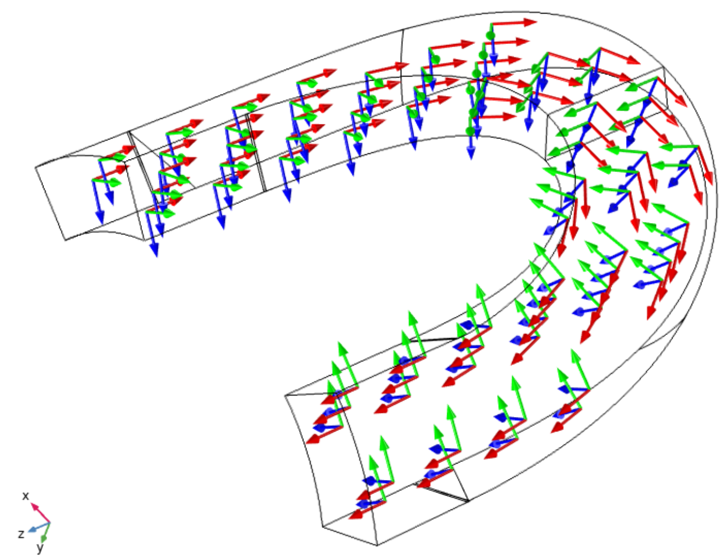


Contacts & coordinate systems

Frictionless contact

Frictional contact (μ=0.2)





Two cylindrical coordinate systems are used to assign the material properties. One centred in the coil (green) and the other at the centre of the magnet (orange).

A curvilinear system is adopted to better distribute the Lorentz force and to account for the curvature of the cable in the material properties.

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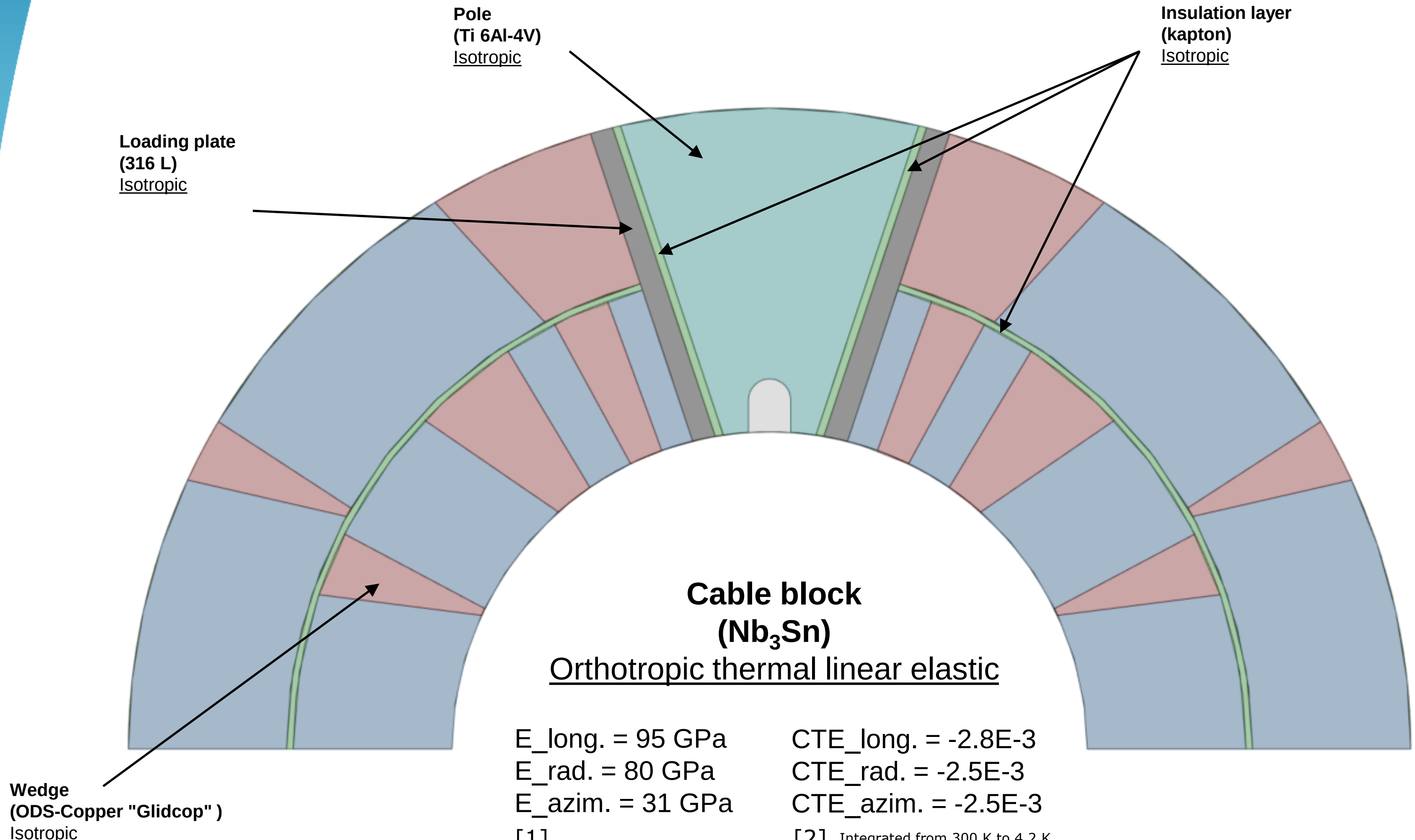
Geometrical simplifications

Cross section of the detailed coil



E_long. = 95 GPa
E_rad. = 80 GPa
E_azim. = 31 GPa
[1]

CTE_long. = -2.8E-3
CTE_rad. = -2.5E-3
CTE_azim. = -2.5E-3
[2] Integrated from 300 K to 4.2 K.

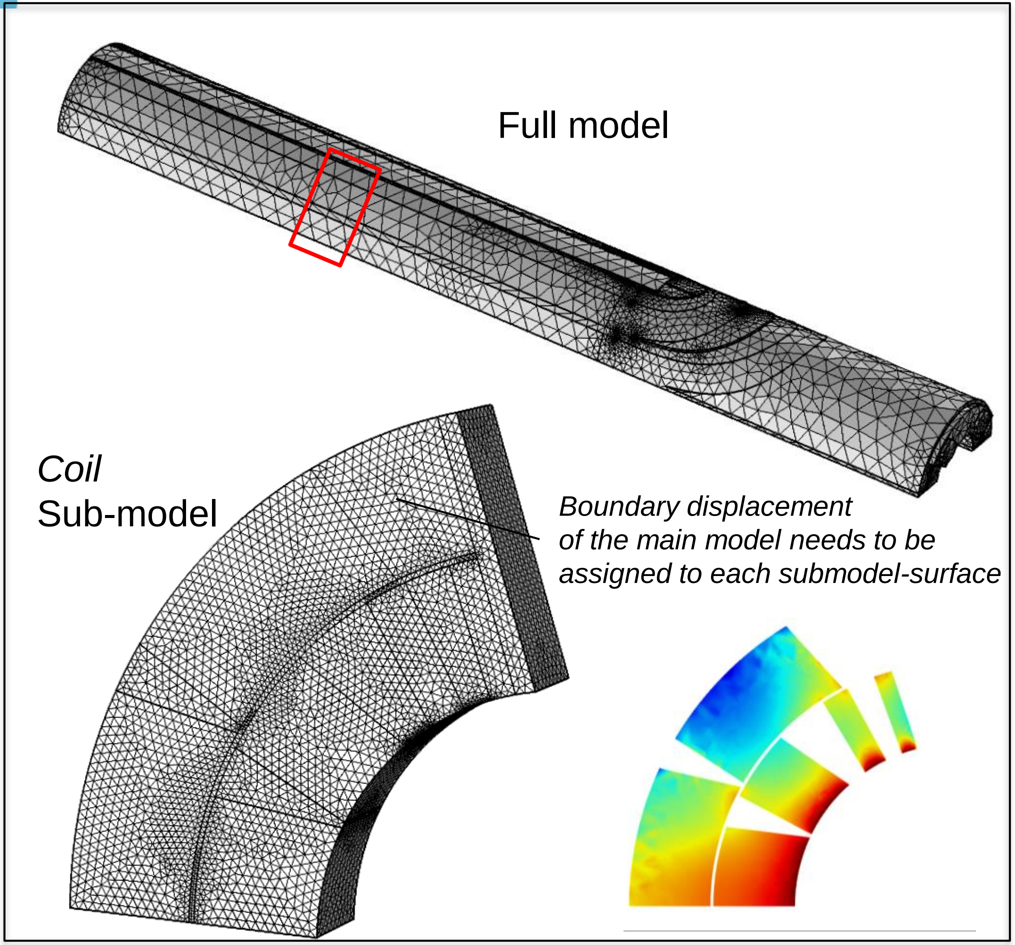
[1] Wolf, F., Lackner, F., Hofmann, M., Scheuerlein, C., Schoerling, D., & Tommasini, D. (2019). Effect of epoxy volume fraction on the stiffness of Nb 3 Sn Rutherford cable stacks. IEEE Transactions on Applied Superconductivity, 29(5), 1-6.

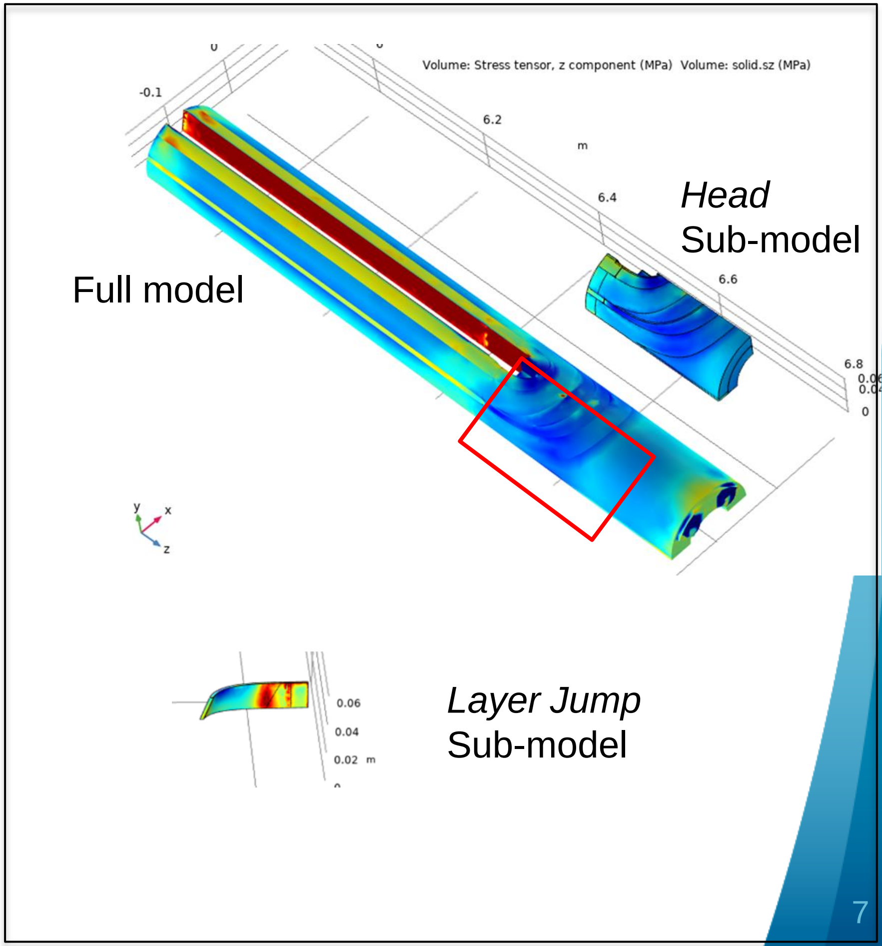
[2] Kriboo et al., Dilatation of impregnated coil samples, Nov. 2019, CRG report.

Sub-modelling

The submodelling technique was implemented in the model to have a better mesh and then higher stress/strain resolution in critical areas. However there are some underlying assumptions when using submodels:

- The global model is accurate enough to give <u>correct displacements on the boundary to the submodel</u>.
- The improvements introduced in the submodel are so small that they do not introduce significant changes in stiffness on the global level. Given this, it could still be possible to introduce a nonlinear material locally in the submodel.



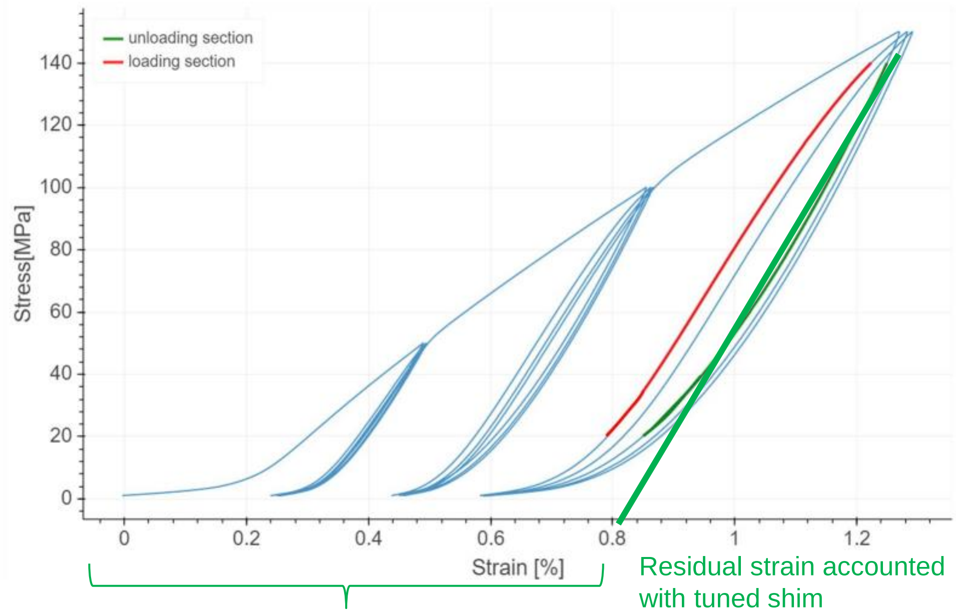


Modelisation of impregnated Nb_3Sn cable

10-stack campaigns consistently show a characteristic nonlinear mechanical behavior with 3 distinct phases: primary loading, unloading, reloading;

Post-processing was define as the best fit (linear regression) from 20 to 140 MPa (when possible) calculated on the three loading and unloading phases up to 150 MPa;

Measurements performed in the 3 directions



Courtesy O. Sacristan, M. Guinchard
EDMS 2572505

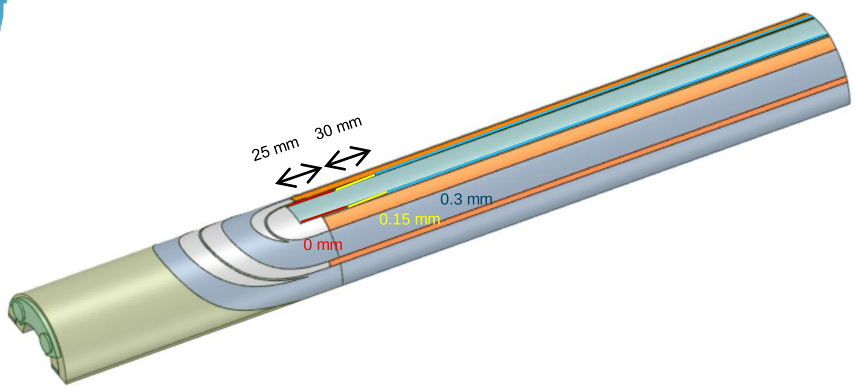
To understand the global longitudinal behaviour of the 11 T magnet, the approach used to model the Nb_3Sn cable neglects its loading history characterised by a highly non-linear behaviour.

The prestress in the coil during collaring is applied by tuning an equivalent shimming where only the unloading stiffness (green slope) is considered and that corresponds to the residual strain. This results in the measured azimuthal stress.

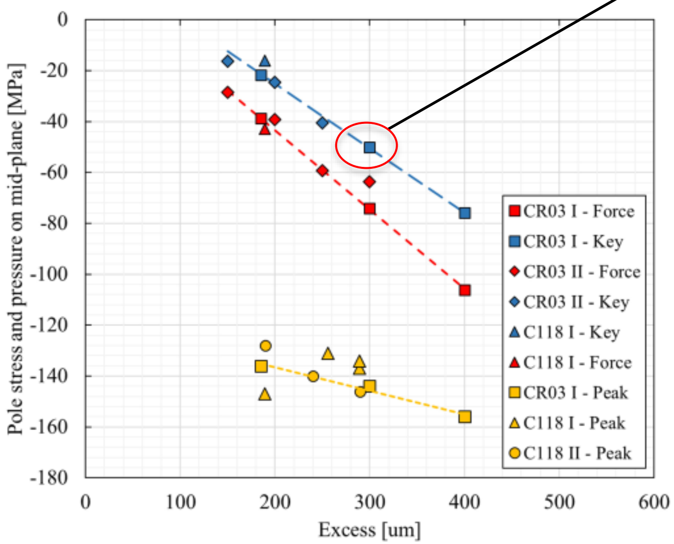
Modelisation of impregnated Nb_3Sn cable

-Prestress during collaring phase-

benchmark #1

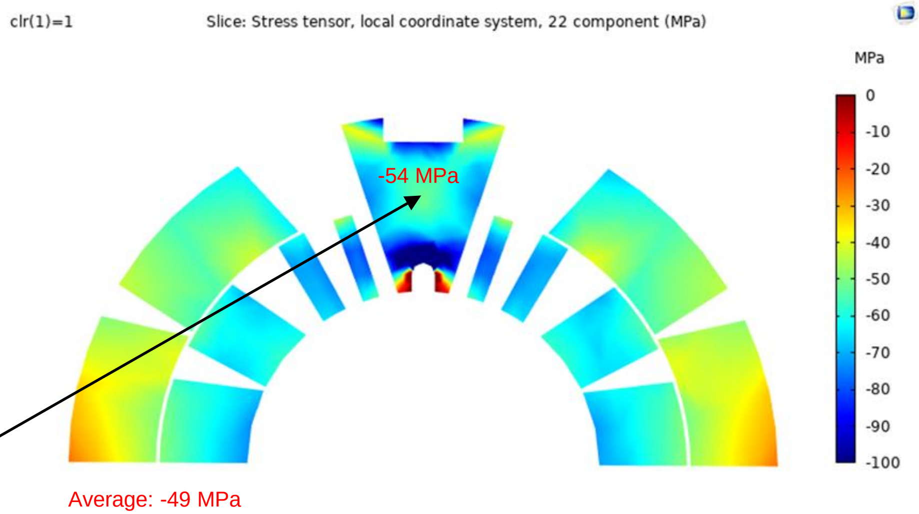


The nominal operational shimming is **300 um** in the central part of the pole.

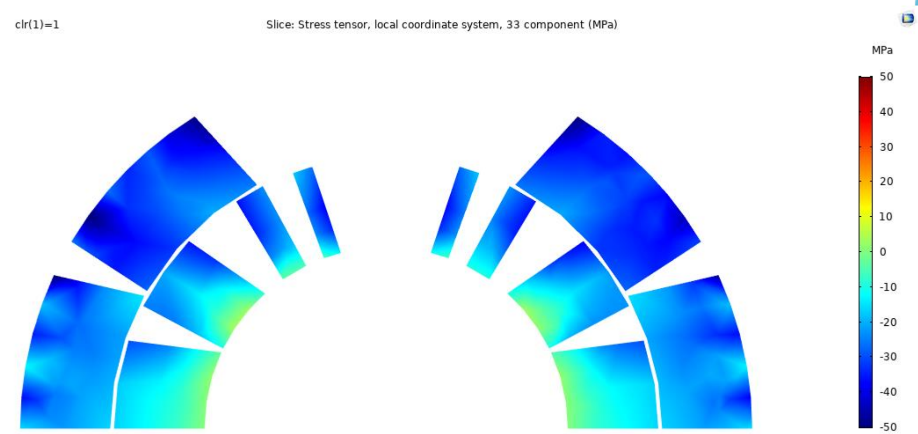


Measurement of the prestress in the pole on a dedicated setup

Azimuthal stress [MPa]



Radial stress [MPa]



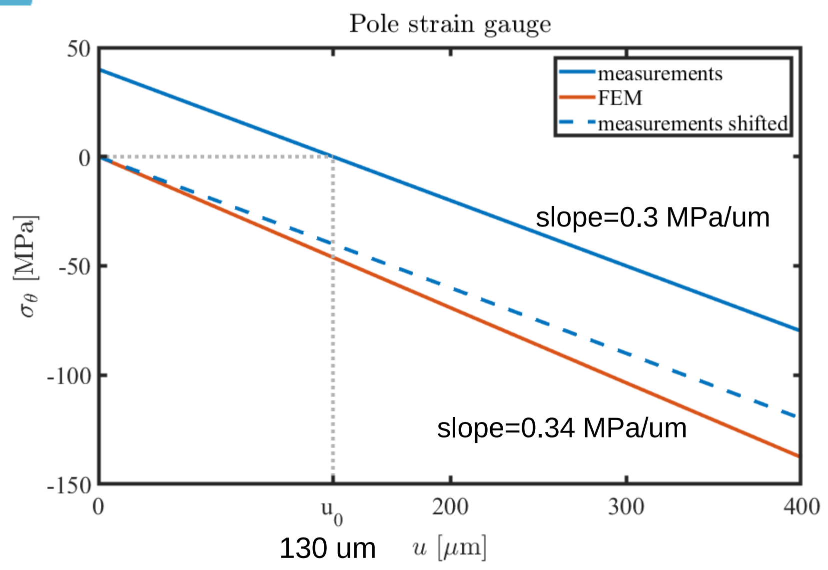
Estimated azimuthal and radial stresses by means of an equivalent shimming of **170 um**

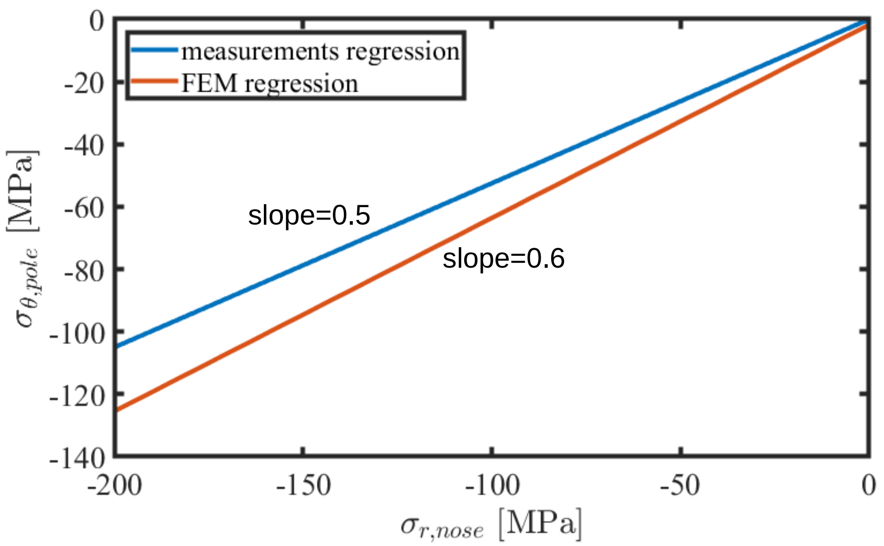
Modelisation of impregnated Nb_3Sn cable

-Prestress during collaring phase-

benchmark #1

Measurements vs simulations





The azimuthal stress in the centre of the pole is compared with the measured one for different excess values. The slope of the measurement (linear fit) is 0.3 MPa/um, the slope of the FEM analysis is 0.34 MPa/um.

The ratio between the stress measured in the pole (azimuthal stress) and the collar nose (radial stress) is around 0.5. The equivalent ratio in the FEM model is 0.6.

The applied equivalent shimming is then 170 um
and is set as a **contact offset** between the pole and the loading plate.

Measurement reference:
https://ieeexplore.ieee.org/document/8642408

FEM reference:
Edms 2643402

Modelisation of impregnated Nb_3Sn cable

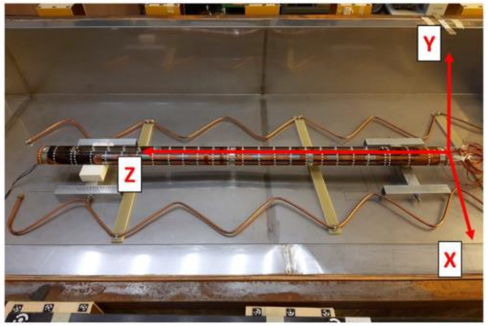
-Thermal contraction of a 2m long 11T coil-

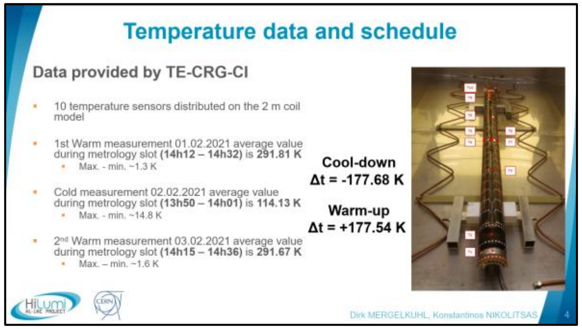
benchmark #2

Measurement

The deformation of a coil has been assessed after a cooldown/warm up cycle.

The lowest temperature reached during the test is **114 K** (-/+7.5 K)





Temperature data and schedule

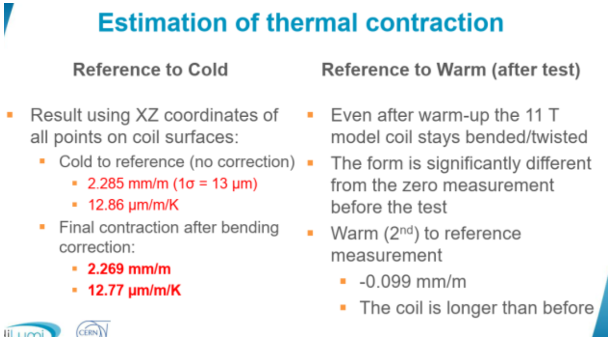
Data provided by TE-CRG-CI

- 10 temperature sensors distributed on the 2 m coil model
- 1st Warm measurement 01.02.2021 average value during metrology slot **(14h12 – 14h32)** is **291.81 K**
  - Max. - min. ~1.3 K
- Cold measurement 02.02.2021 average value during metrology slot **(13h50 – 14h01)** is **114.13 K**
  - Max. - min. ~14.8 K
- 2nd Warm measurement 03.02.2021 average value during metrology slot **(14h15 – 14h36)** is **291.67 K**
  - Max. – min. ~1.6 K

Cool-down
Δt = -177.68 K

Warm-up
Δt = +177.54 K

Dirk MERGELKUHL, Konstantinos NIKOLITSAS 4



Estimation of thermal contraction

Reference to Cold	Reference to Warm (after test)

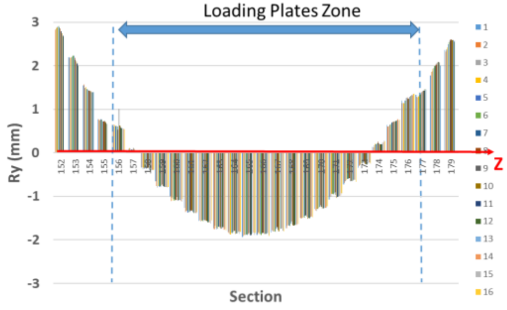
Reference to Cold

- Result using XZ coordinates of all points on coil surfaces:
  - Cold to reference (no correction)
    - 2.285 mm/m (1σ = 13 µm)
    - 12.86 µm/m/K
  - Final contraction after bending correction:
    - **2.269 mm/m**
    - **12.77 µm/m/K**

Reference to Warm (after test)

- Even after warm-up the 11 T model coil stays bended/twisted
- The form is significantly different from the zero measurement before the test
- Warm (2nd) to reference measurement
  - -0.099 mm/m
  - The coil is longer than before

The coil is bended by +2.9/-1.9 mm



Main outcomes:

- A longitudinal CTE of around 2.27E-3 has been measured.
- A significant bending has been observed at cold (4.8 mm).
- A significant residual bending has been observed after warmup (3 mm).

https://edms.cern.ch/ui/file/2479210/2/2021.02.11_11T_Coil_Thermal_Contraction.pdf

Modelisation of impregnated Nb_3Sn cable

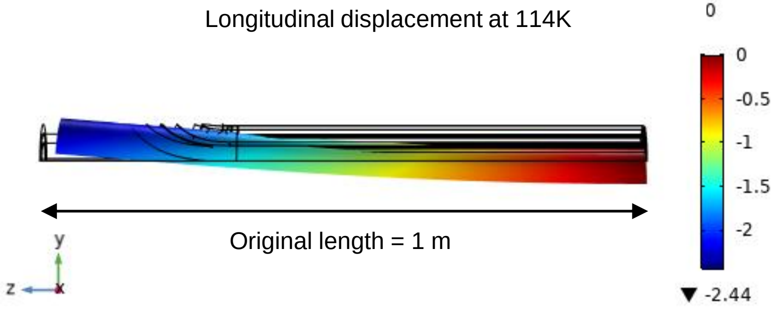
-Thermal contraction of a 2m long 11T coil-

benchmark #2

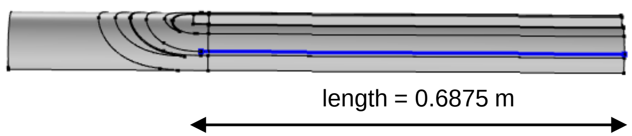
Model estimation

CTE

Longitudinal displacement at 114K



→ **CTE= -2.44 e-3**

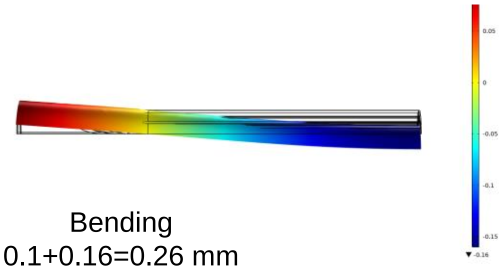


The thermal contraction of the straight part of the coil (saddle and head not considered) is about 1.58 mm.

→ **CTE=-2.3e-3** (compared to -2.32e-3 measured between sections 156 and 175).

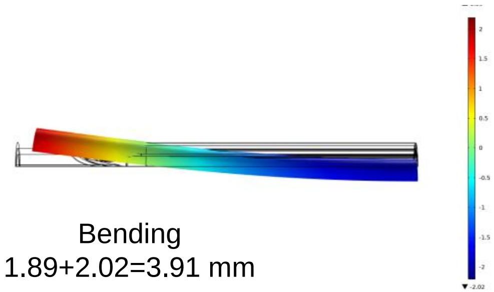
Bending

Vertical displacement under gravity at room temperature



Bending
0.1+0.16=0.26 mm

Vertical displacement under gravity at 114K

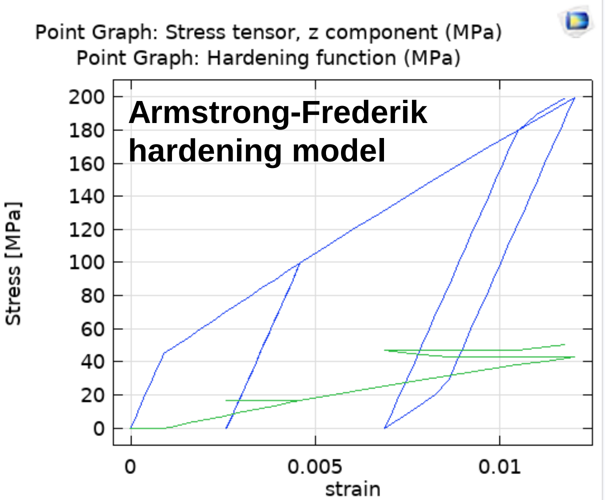


Bending
1.89+2.02=3.91 mm

→ Bending due to cooldown: 3.65 mm

Conclusions

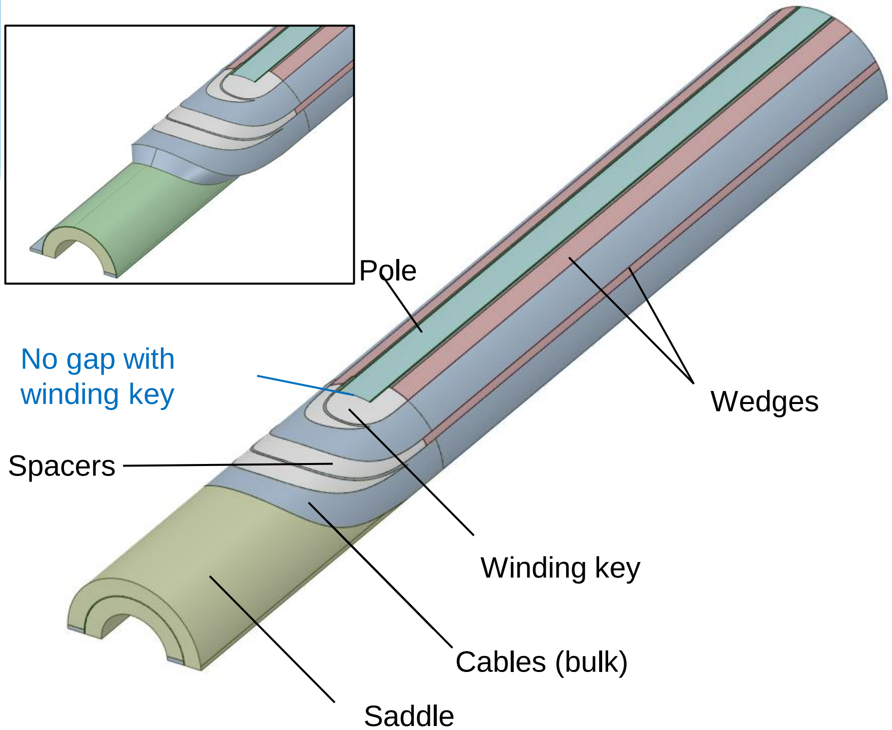
- A 3D CFD-thermal-mechanical model of the 11T was developed.
- The impregnated Nb3Sn cable blocks were considered as bulk components to lower the computational load of the analysis.
- They have been modelled with an orthotropic linear thermal-elastic model
- The loading history of the Nb_3Sn cable, characterised by a highly non-linear behaviour, was omitted as the focus of the model was to characterise the behaviour of the magnet mainly during thermal cycles and powering.
- The prestress in the coil during collaring was applied by tuning an equivalent shimming to account for the cable non-linearity aimed at obtaining the measured azimuthal stress.
- Armstrong-Frederik hardening model was foreseen to refine the conductor's behaviour but it will require an extra effort for parameter identification and validation.

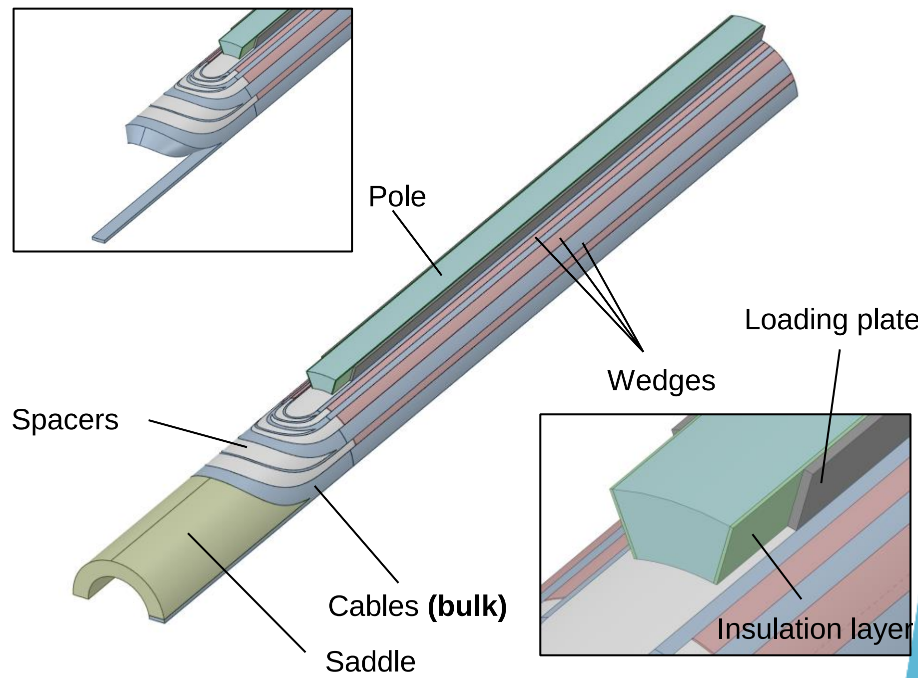


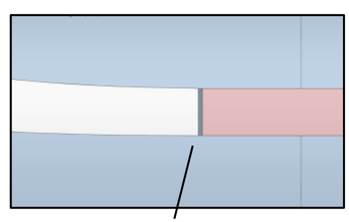
Extra

Geometrical simplifications

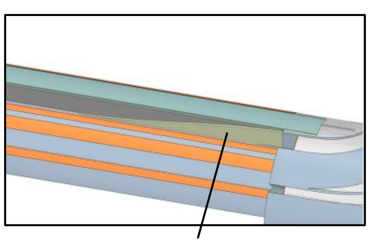
Detailed coil







0.5 mm gap between wedge and spacers



Layer jump **(bulk)**