Mechanical Simulation of MQXF Coils

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Workshop on Nb3Sn Rutherford cable characterization for accelerator magnets

Madrid, 17/11/2017

HiLumi LARGE HADRON COLLIDER

U.S. LARP

Outline

- Introduction
- MQXF FE – ‘block coil’ model
- Cable stacks ‘strand’ model
  - Impregnated cable stacks
  - MQXF coil
- Conclusion

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Introduction

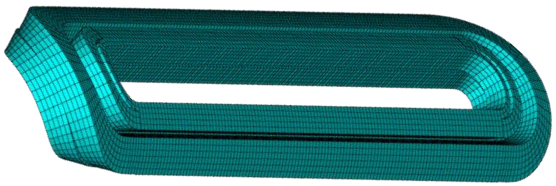
- Magnet **mechanical models** are continuously used for a variety of tasks.
  - E.g.: verify **structural integrity**, increase **understanding** of magnet mechanics, define magnet **prestress, design** in general…

- Model rely somehow heavily on the assumptions made on coil behaviour

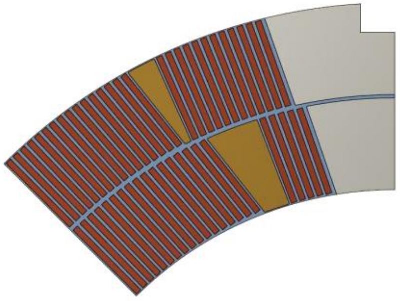
- Direct **strain measurements** on the **conductor** are considered **unreliable**:
  - Strain measured somewhere else → Conductor strain extracted from FE
  - This relies on the correct knowledge of the cable/coil mechanics…

- **Nb_3Sn strands** are prone to critical current **degradation** under the effect of mechanical **strains**
  - Degradation can be produced both with **axial** and **transverse** strains
  - Knowledge of the impregnated cable/coil mechanical properties is then a necessary information to avoid **magnet degradation**

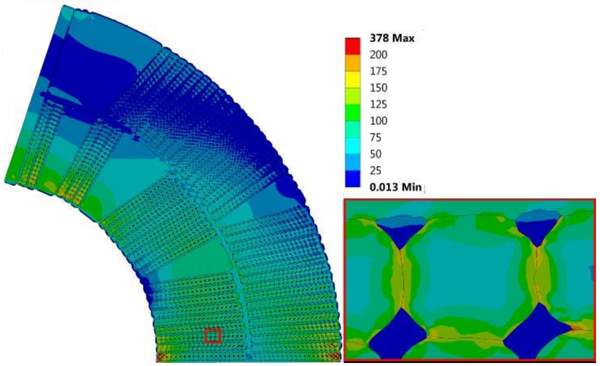
Modelling Strategies



Block Model



Cable Model
C. Löffler et al., EUCAS 2017



Strand Model
M. Daly et al., MT25, 2017

- **Block model** is the current *standard* approach:
  - Coil approximated as an uniform **block** with uniform mechanical properties
  - **Properties** were measured in the past on **impregnated coil stacks**
  - Orthotropic in 2D, isotropic in 3D

- This consistent way of modelling also allowed to define an empirical limit on the **coil equivalent stress** (150:200 MPa - *H. Felice et al., IEEE TAS, 2011*)

- **New** modelling **strategies** are currently under development

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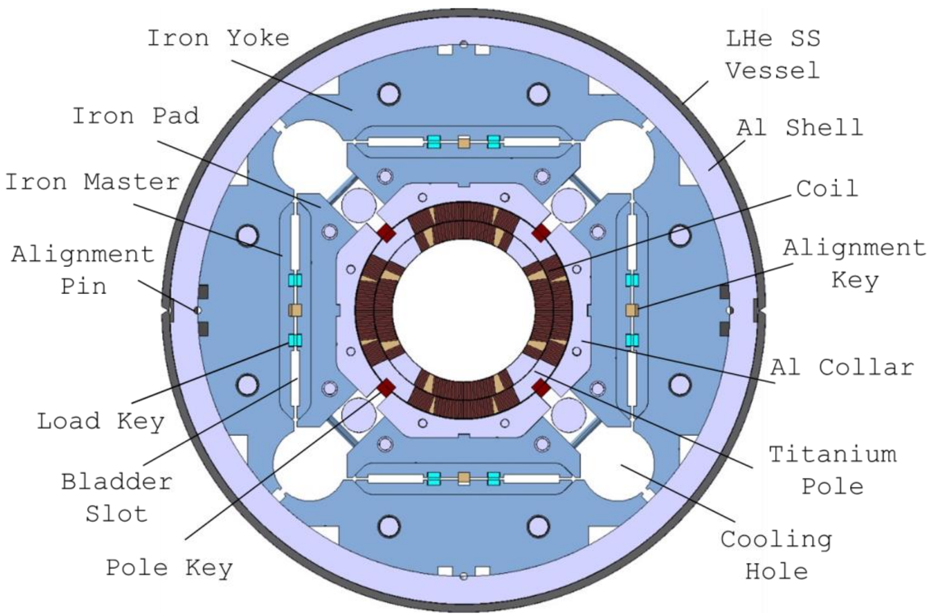
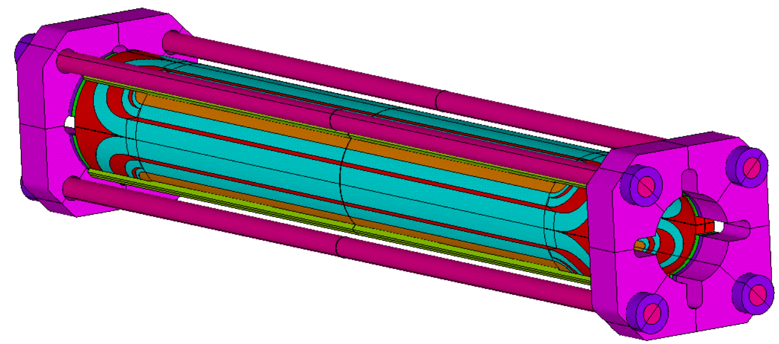
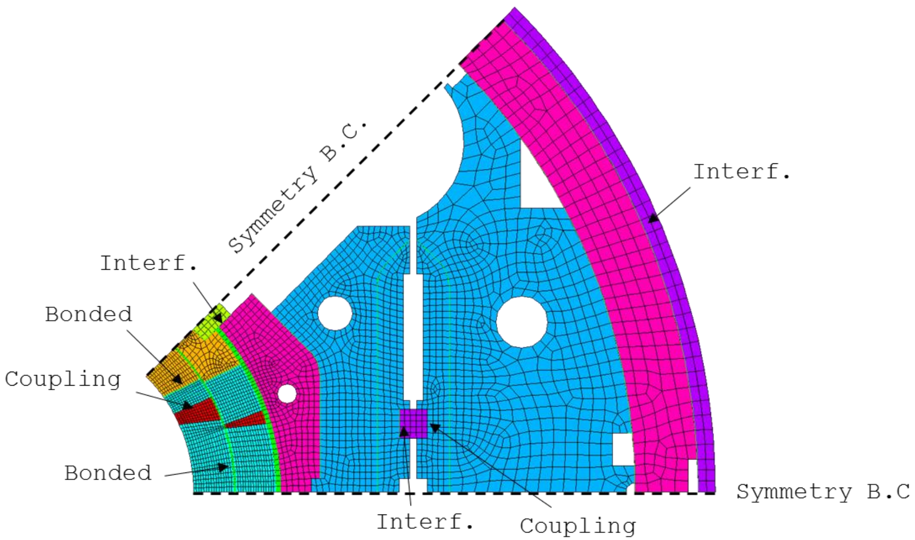
MQXF – Mechanical Structure

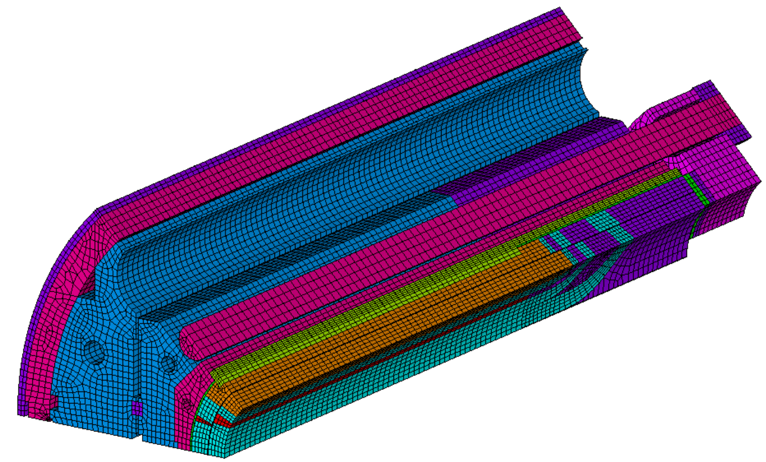




- Azimuthal preload at R.T. applied with **bladders & keys**
  - Al shell compresses the coils. Part of the force is absorbed by the pole key
- Longitudinal preload at r.t. applied pre-tensioning the **rods**
- Both increased by the differential **thermal contraction** during cool-down

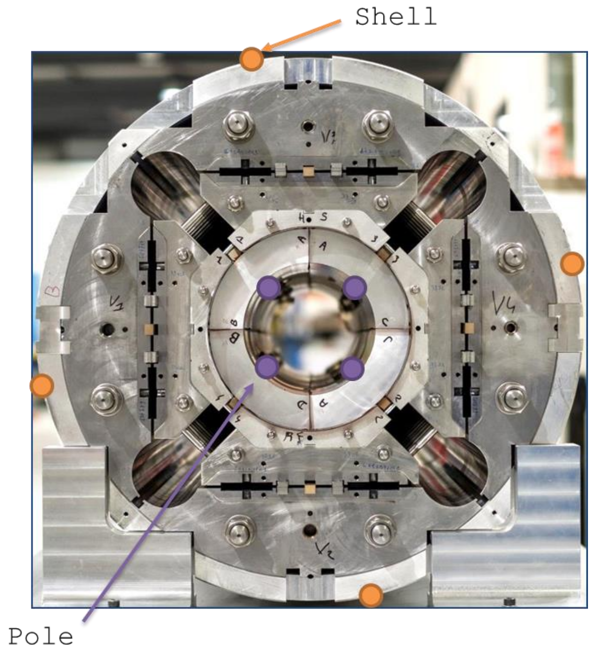
MQXF Mechanical Model

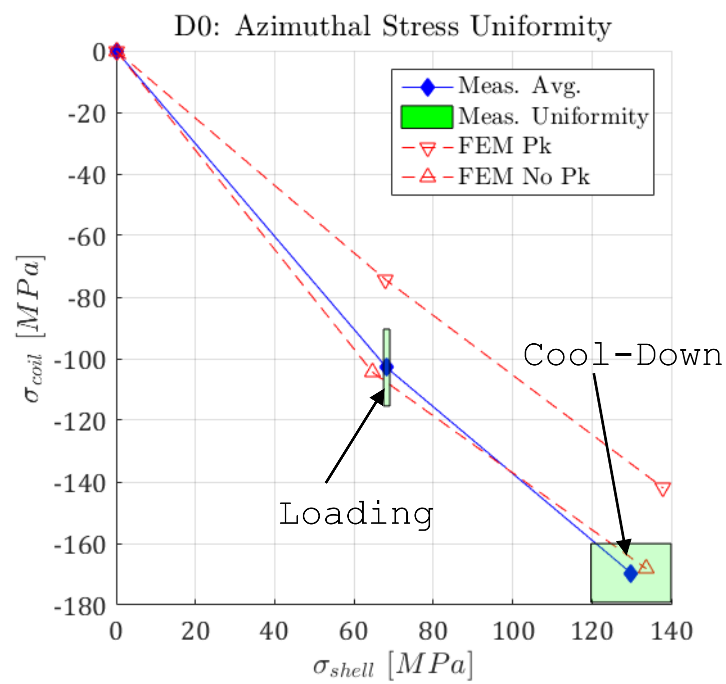




- Coil modelled as a block. Simulations in 2D and 3D.
- Coil properties from LARP experience:
  - Elastic modulus (linear elastic): 44 GPa (azimuthal), 52 GPa (radial)
  - Thermal contraction: 3.35 mm/m

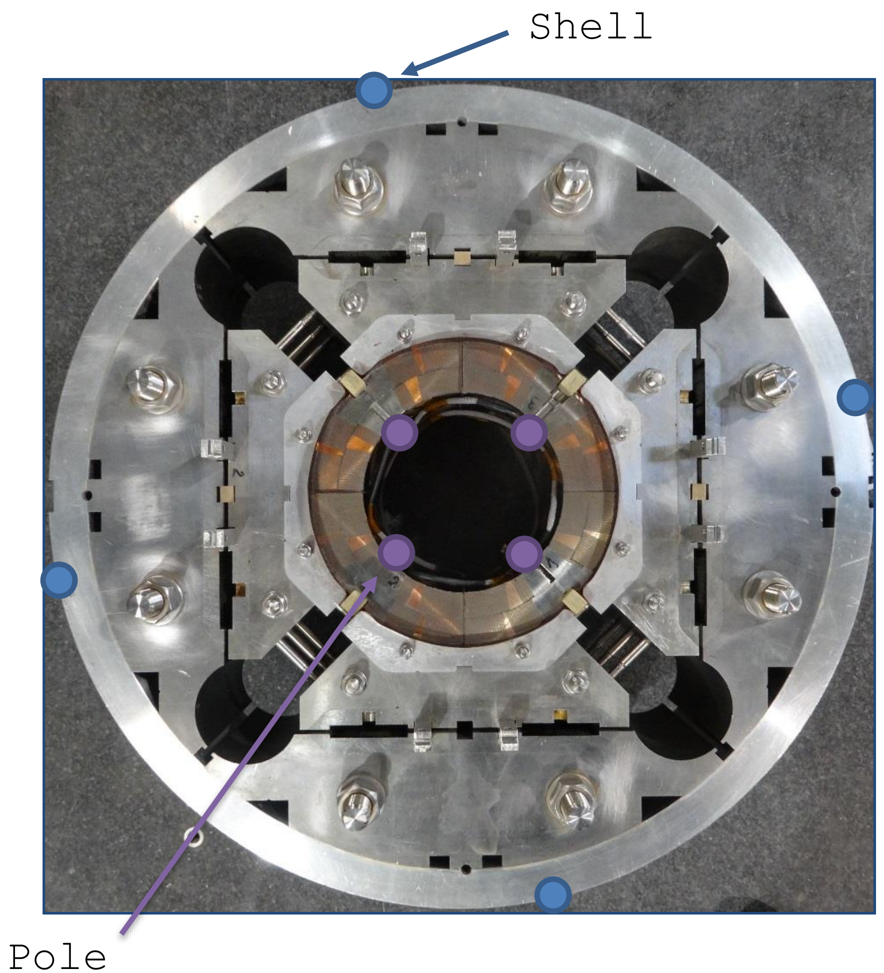
Mechanical Model

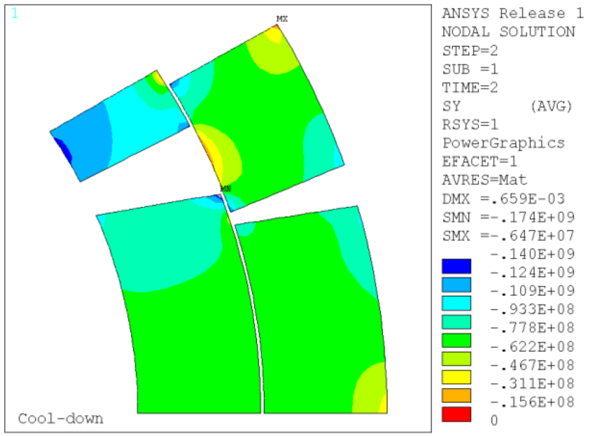


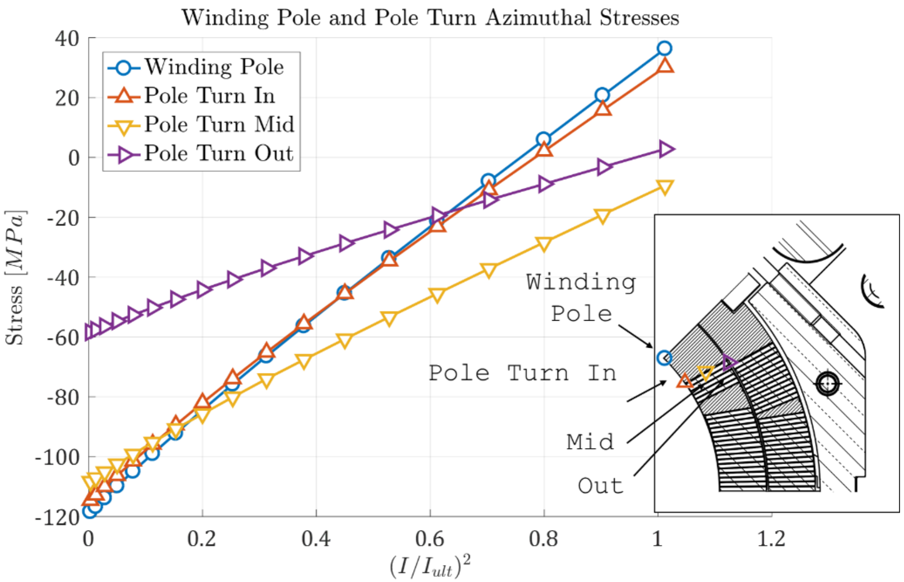


- Mechanical structure was tested with aluminium **dummy** coils
- Transfer Function: force provided by the structure vs coil prestress
  - Very **good agreement** with the numerical model results
  - **No calibration** was performed

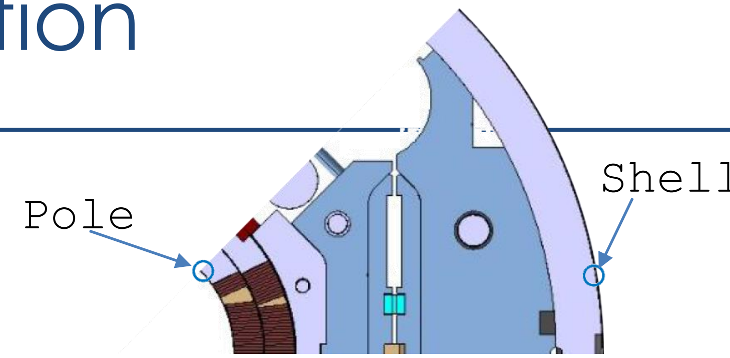
Short Model - Strain Gauge Locations





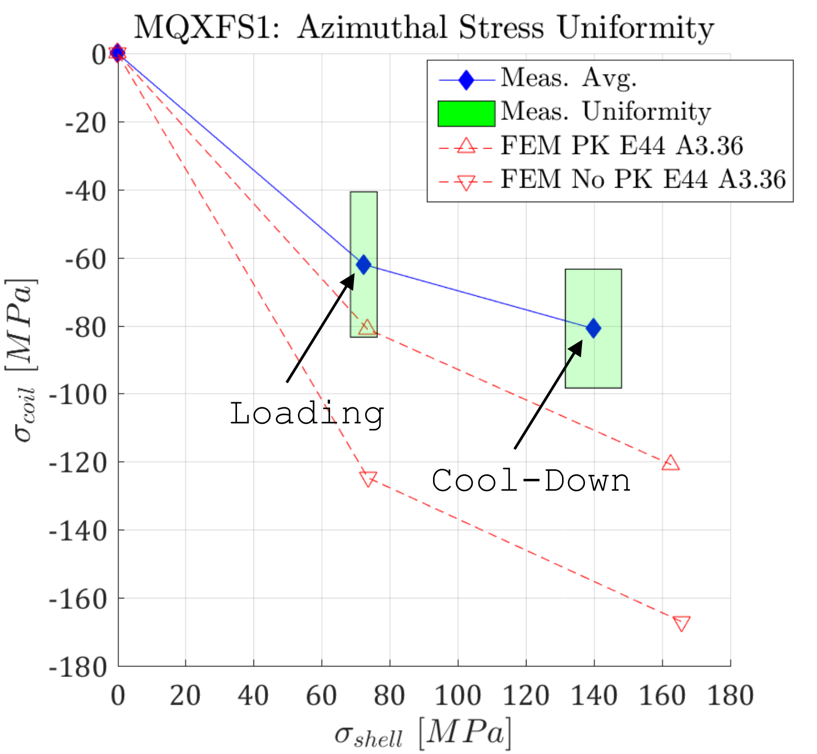


MQXFS1 – Transfer Function

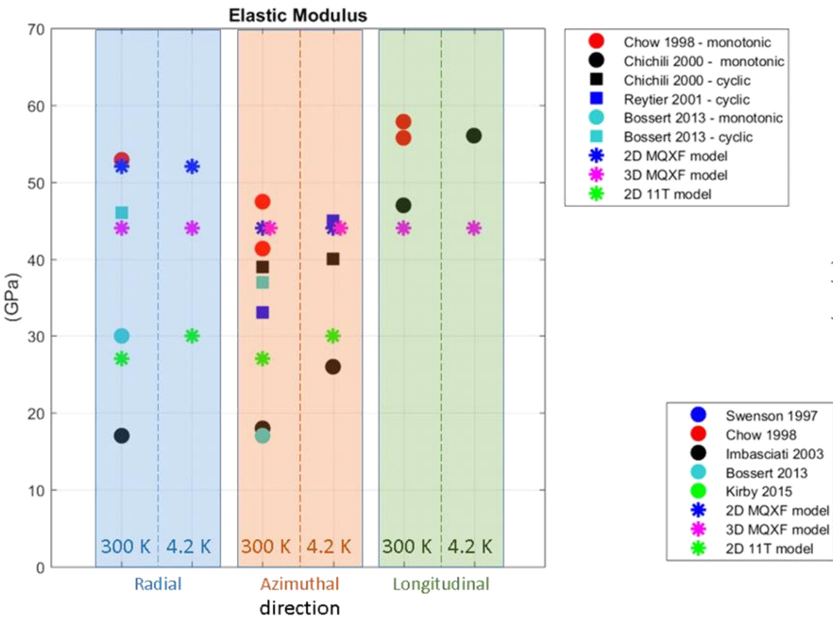


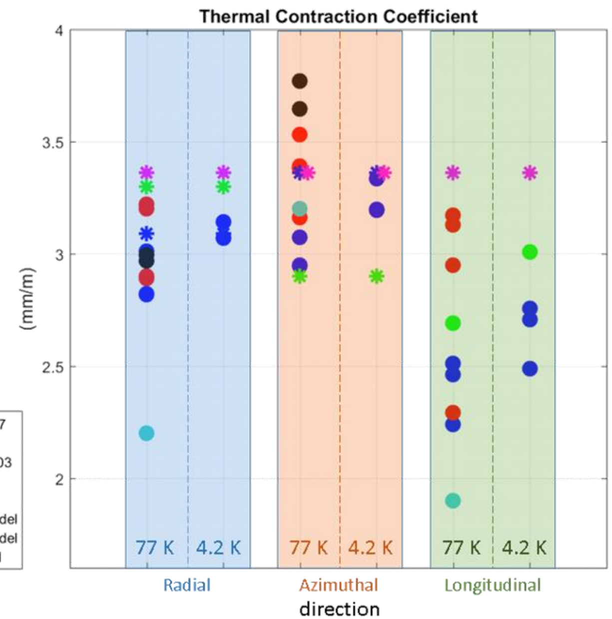
Prestress analysis:

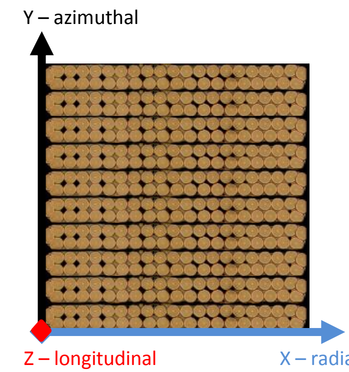
- Prestress variation: $\pm 17\ MPa$
  - Does this set a threshold on expected model precision?
- **Model** result is out of the meas. Uniformity
  - **Pole stress** at warm lower
  - Lower prestress increase during CD
  - Stress after CD **lower** than expected on both shell and coil
- The **mechanical models** experience suggests that the distance between model and measurements is due to the **coil** properties used.



Coil Properties – Available Data

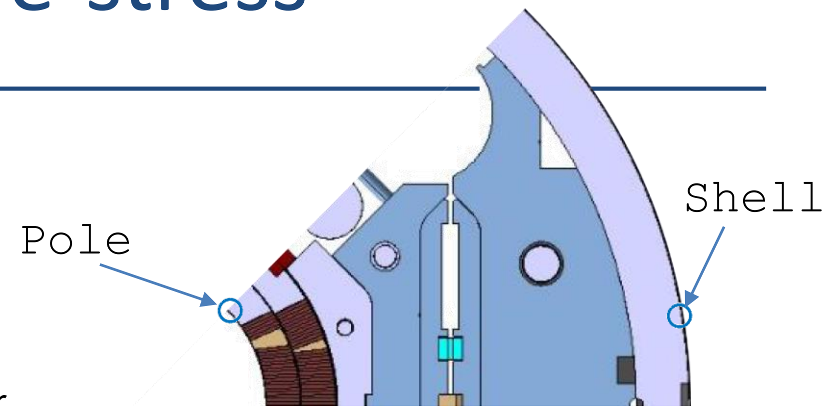




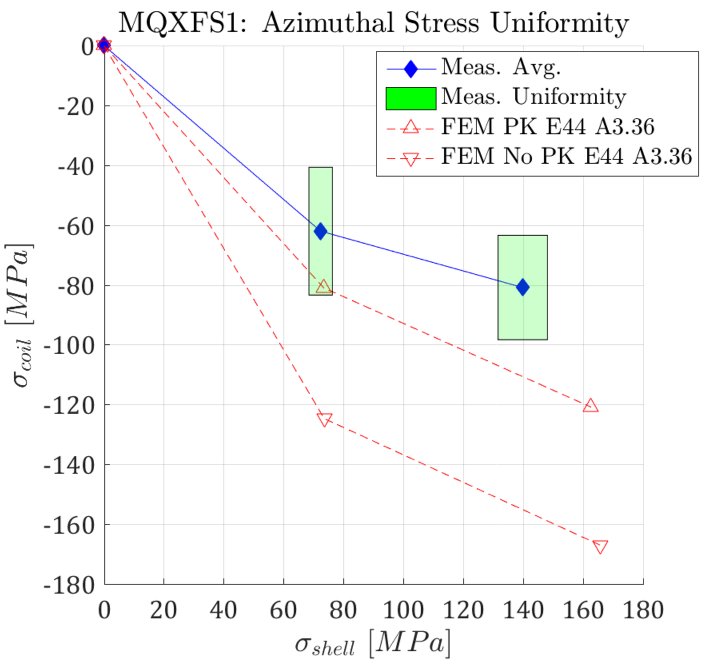


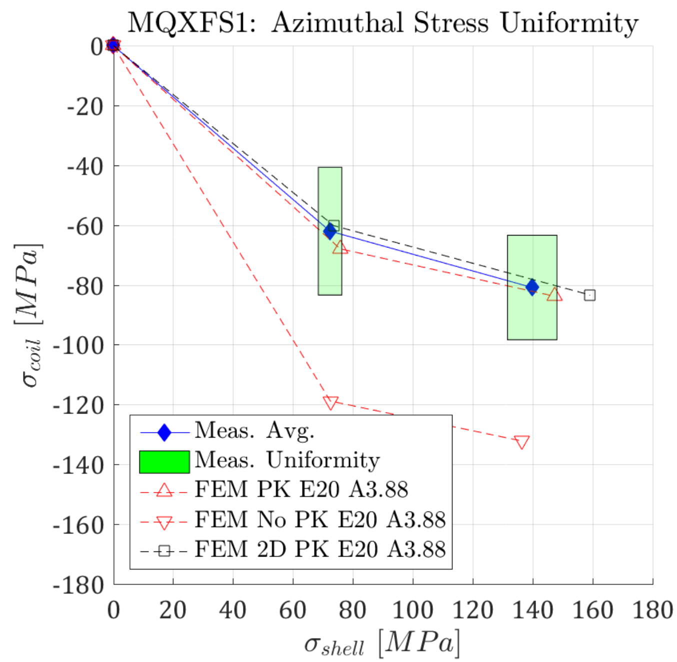
- Available **coil properties** measures highly dispersed
- Measured **Young** modulus: 15-60 GPa. Also depends upon cyclic/monotonic loading phase
- Measured **thermal contraction**: 2-4 mm/m

Azimuthal Pre-stress



- **Parametric** analysis, fixed shell strain at warm:
    - RT → E: 44 GPa → 20 GPa
    - CD → α: 3.36 mm/m → 3.88 mm/m
- One could repeat the same process for other magnets. But not in the design phase!





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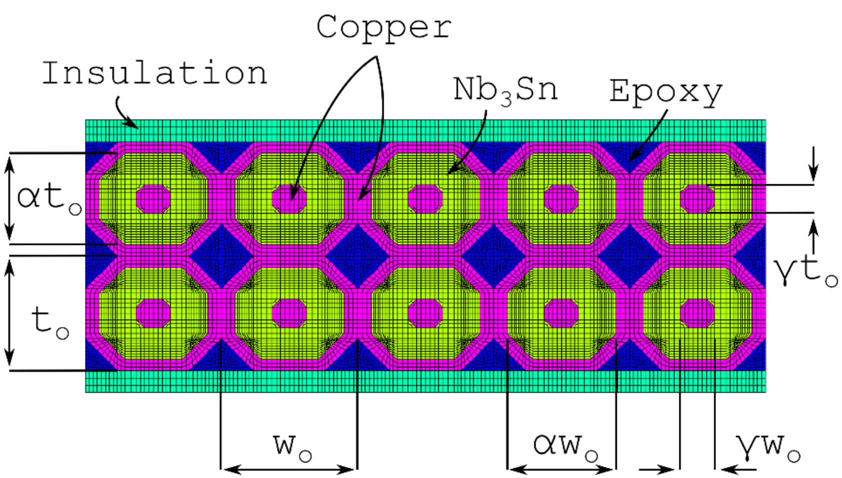
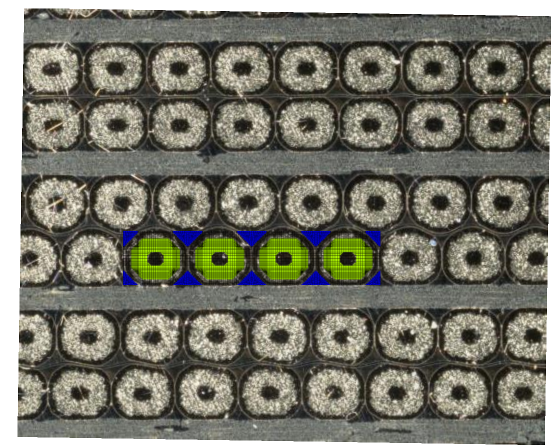
Cable Stacks – FE Model (1)





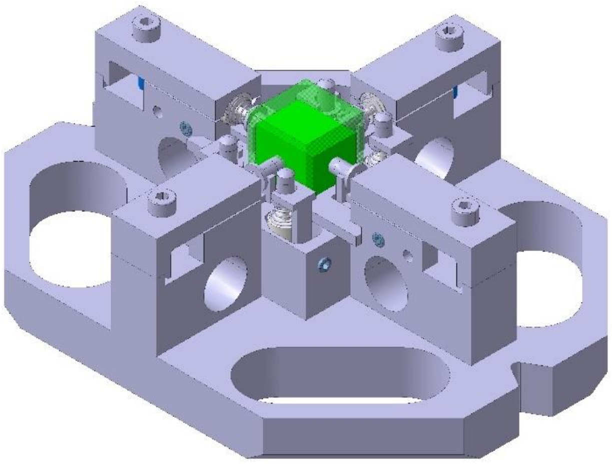
- 2D FE model of the cable stack
- Material properties from literature
- Geometry from a mix of **image analysis** and simple geometric formulas to match the filling factor, copper-non copper etc.

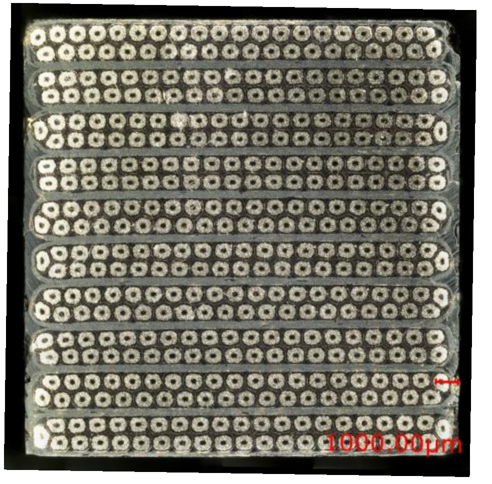
$$e_o = \sqrt{\frac{h_o w_o - A_c \eta_f / N_s}{2}}$$

$$\eta_f = \frac{N_s \pi (d_s/2)^2}{A_c \cos \beta_t}$$

$$\alpha = \sqrt{\frac{1+\gamma^2(1+\eta_{cu})}{1+\eta_{cu}}}$$

Cable Stacks – Transversal Pressure (1)

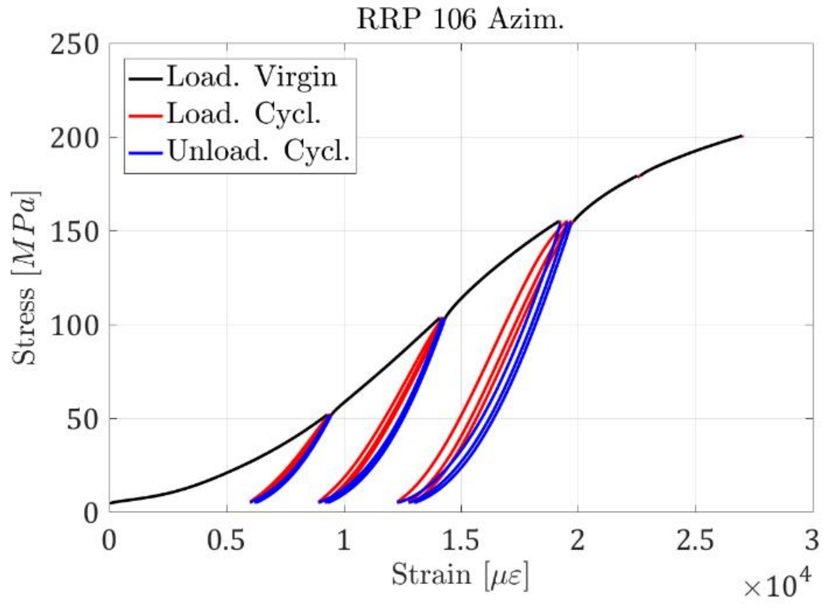




- Measurements on **stacks** of impregnated cables have *always* been used as a reference for coil elastic modulus measurements
- There is a significant **spread** (15-50 GPa, *azimuthal* direction) in the values available in literature
  - The modulus seems sensible to the particular cable tested/testing procedure
- As a consequence, an extensive **campaign** was launched almost 2 years ago

Work to be published by C. Fichera et al.

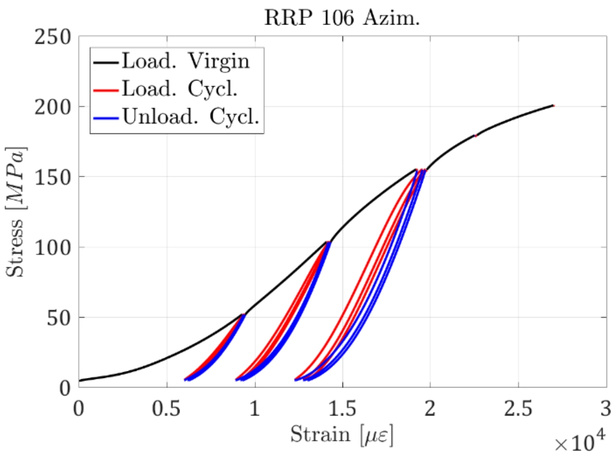
Cable Stacks – Transversal Pressure (2)

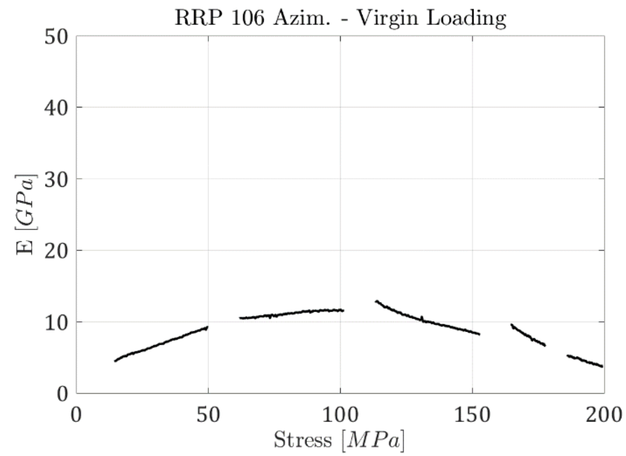


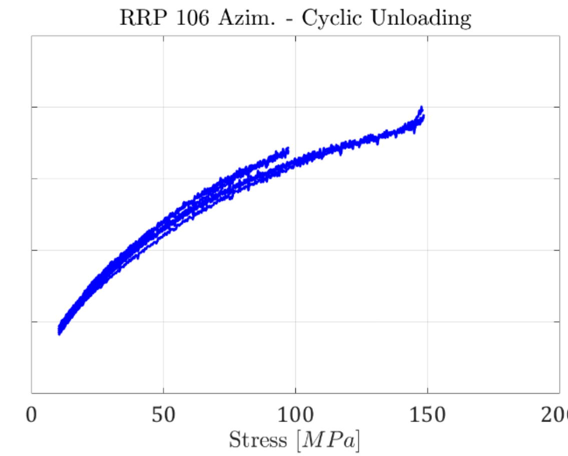
- The specimen (MQXF RRP cable) shows a clear division in **three zones**:
  - *Virgin* loading (black)
  - Unloading (red)
  - *Cyclic* loading (blue)

- **How** to extract a number representative of the **modulus** from such a result?

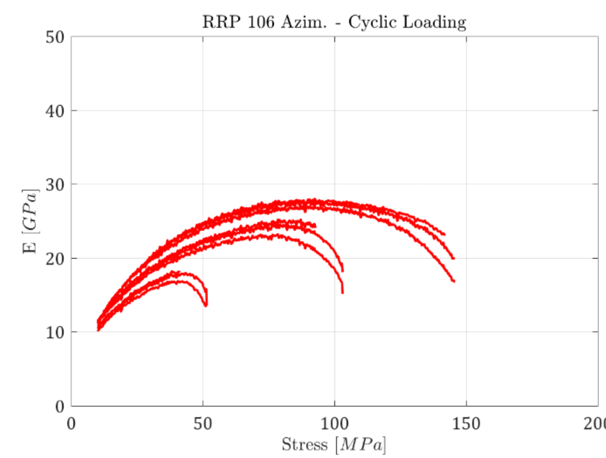
Cable Stacks – Transversal Pressure (3)



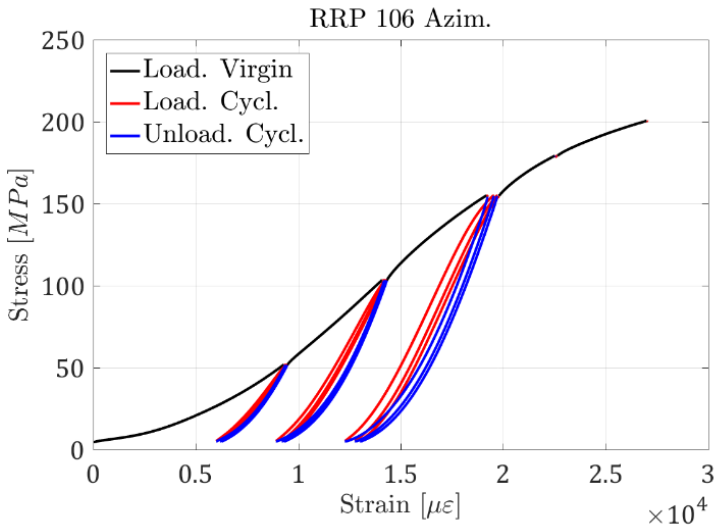


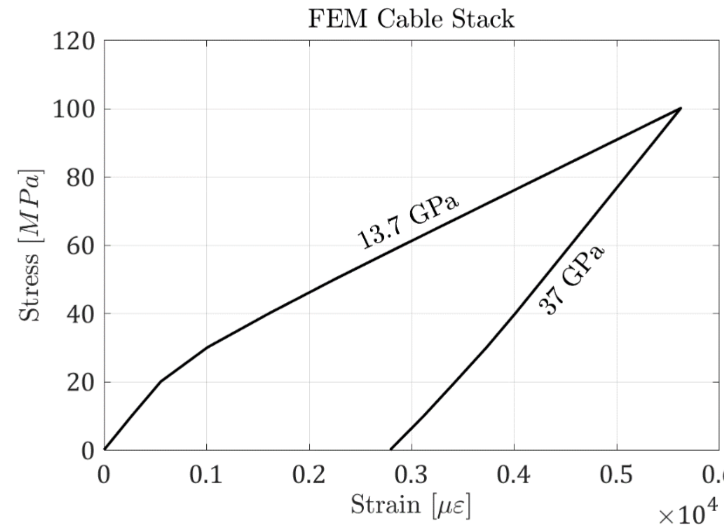


- Very **different** behaviour in the **three phases**
- The *elastic modulus* (slope) varies continuously during the test
- Probably difficult to condensate the coil elastic properties in a **single number** (elastic modulus)



Cable Stacks – FE Model (2)

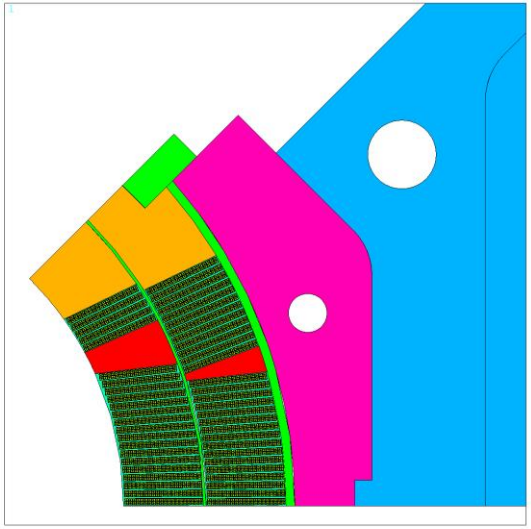


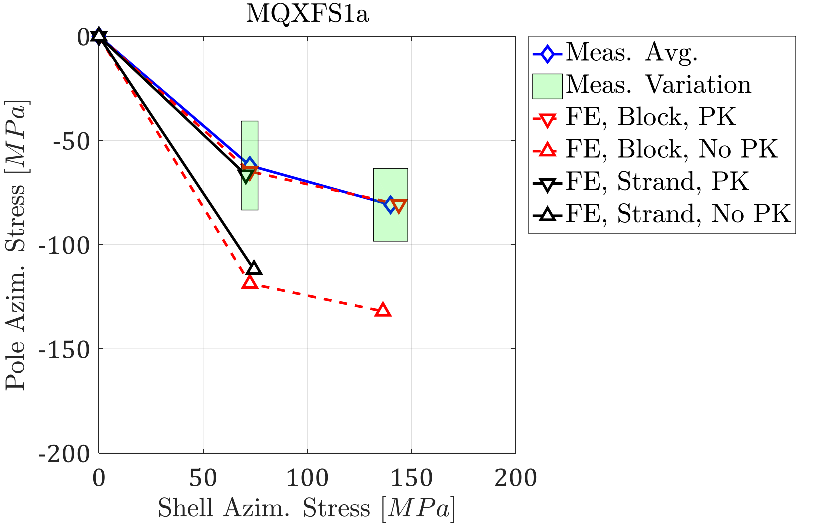


- Virgin/cyclic behaviour explained by **copper plasticization**
- FE slope *reasonably* good especially considering that **no** model **calibration** was necessary
- Initial phase may be due to **compaction**

Parameter	Unit	Value
Copper Elastic Modulus (R.T.)	GPa	110
Copper Elastic Modulus (4.3 K)	GPa	120
Copper Yield Strength	MPa	40
Copper Tangent Modulus	GPa	5
Nb_3Sn Elastic Modulus (R.T.)	GPa	100
Nb_3Sn Elastic Modulus (4.3 K)	GPa	70
Epoxy Resin Elastic Modulus	GPa	5
Impregnated Insulation Elastic Modulus	GPa	13

MQXF – Strand Model





- *Strand* MQXF magnet model. Same approach as before // work in progress!
  - Pros:
    - Useful to verify the strain *inside* the strand
    - We are not relying on properties measured on the stacks
  - Cons:
    - We have extensive experience with **block** models
    - Even a 2D model can become computationally heavy
- Strand model results at R.T. in **agreement** with measurements/block model
- **No calibration** done!

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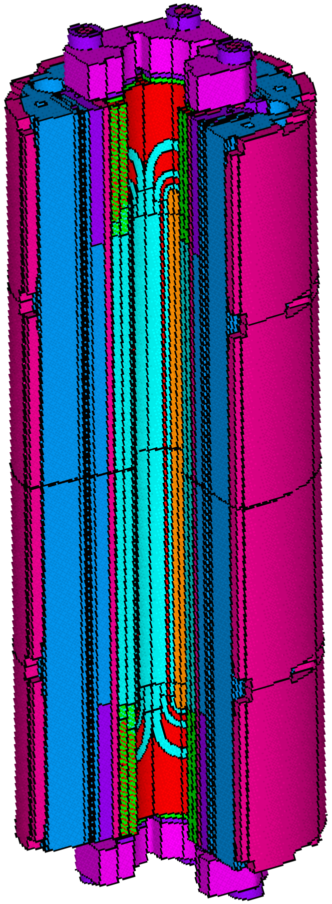
Conclusion (1)

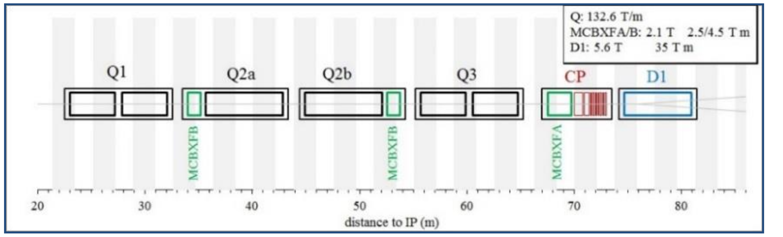
- MQXF FE model **calibration**:
  - Good agreement at the *macroscopic* level
  - The same approach could be used on other magnets (different cable, resin, etc.). Not feasible at the design stage!
- **Impregnated cable stacks**:
  - Strongly **non-linear** behaviour
  - Part of this behaviour can be explained by the **copper plasticization** (and **compaction**)
  - Cable components properties available in literature
  - **Stack strand model** looks reasonably close to reality
- **FE** Model at the **strand** level allows to match the RT transfer function
- Further comments:
  - Available data on cable stacks is quite confusing
  - **Thermal contraction** measurements?
  - What level of **detail** do we really need?
  - Should we use orthotropic non-linear material laws? How do we do this in 3D (ends)?

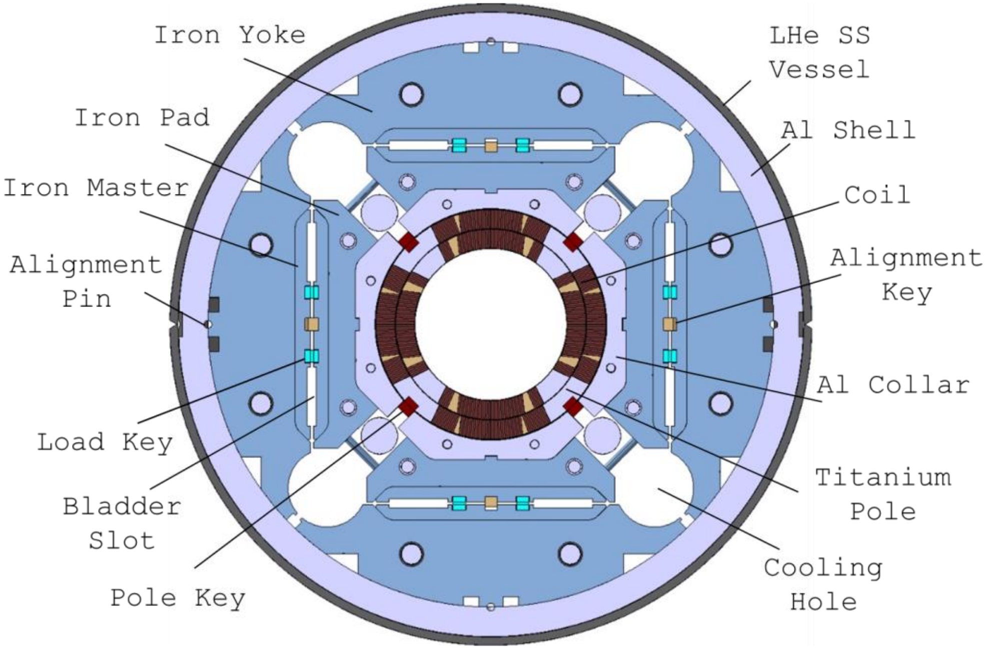


Extra

MQXF Design

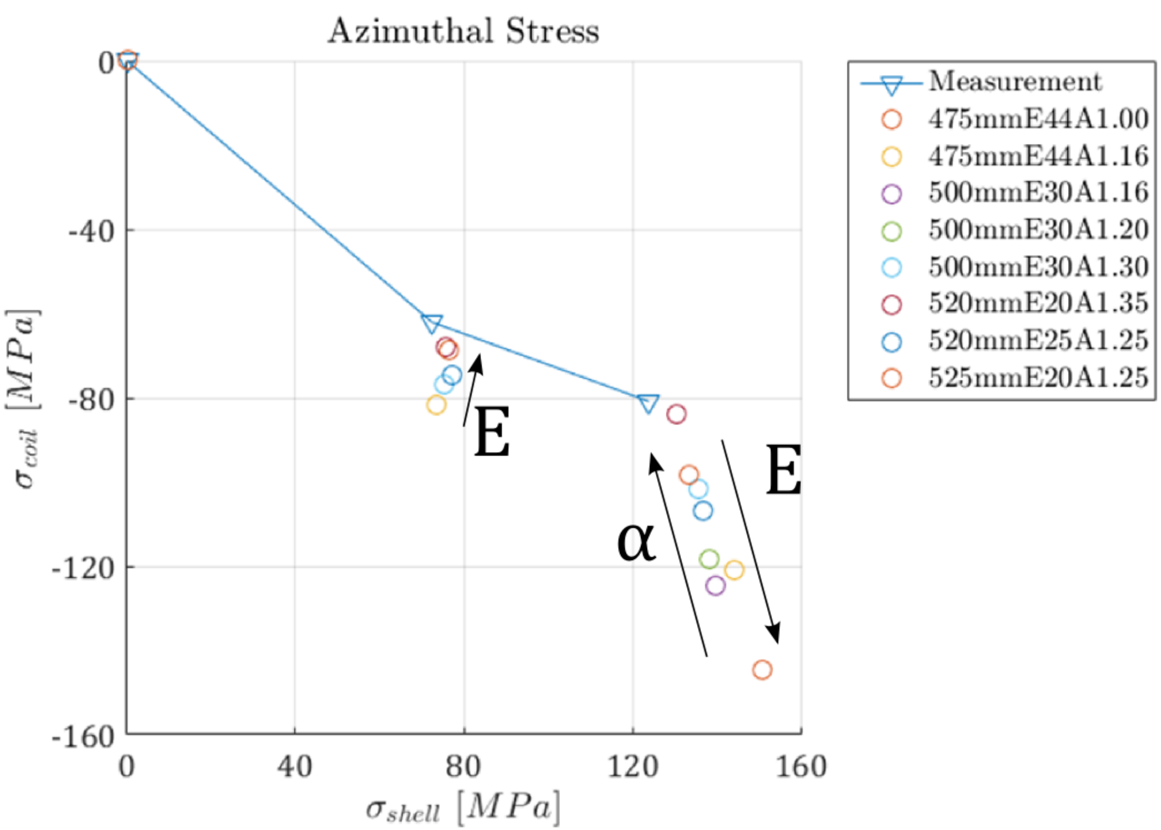
- LHC IR upgraded as a part of HiLumi project
  - Quadrupoles: NbTi → Nb_3Sn
- Target: 132.6 T/m
  - 150 mm coil aperture, 11.4 T B_{peak}
- Q1/Q3 (by US-AUP Project)
  - 2 magnets **MQXFA** with 4.2 m
- Q2a/Q2b (by CERN)
  - 1 magnet **MQXFB** with 7.15 m
- Different lengths, same design
- Short Models (**MQXFS**)
  - 3 models tested up to now
  - Magnetic length 1.2 m





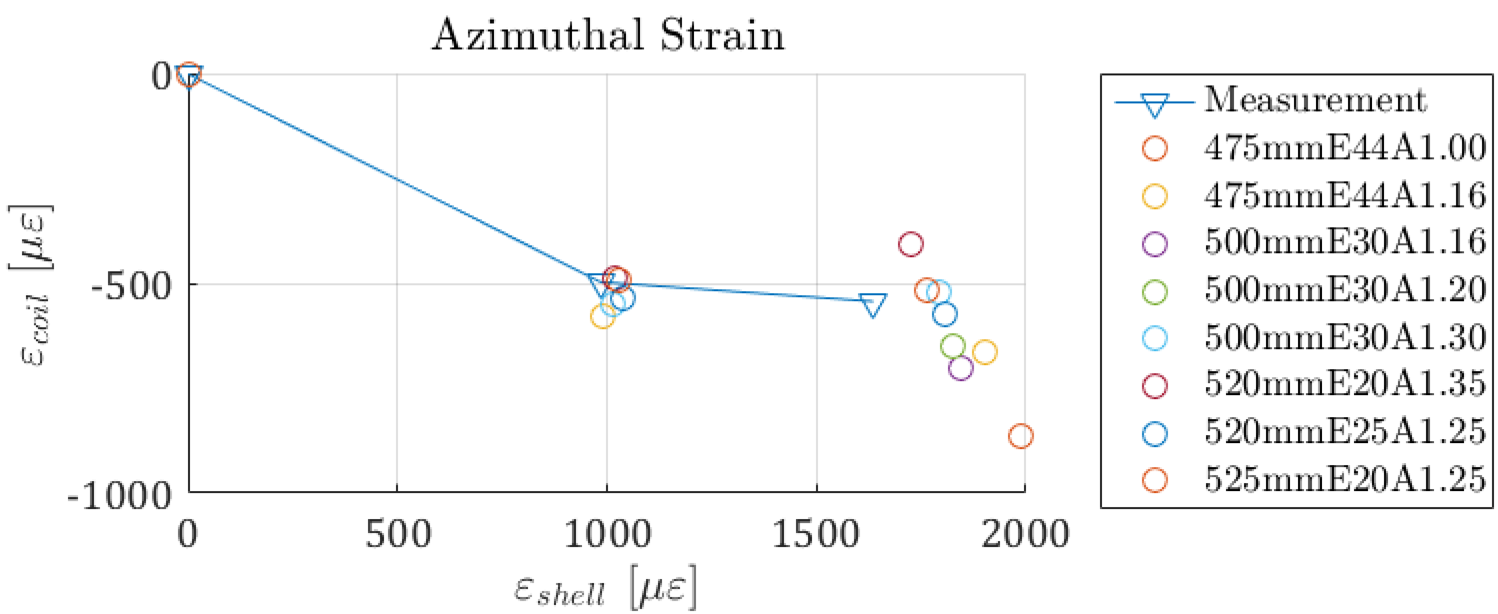
MQXFS1 – Material Calibration

- Parametric analysis:
  - Coil Young Modulus
  - Coil Thermal Expansion
- Current Parameters:
  - $E = 44\ GPa$
  - $\alpha = 1.16 * 10^{-5}\ mm/K$
- The shell strain at warm is imposed
- It is possible to match the overa behaviour. Best parameters:
  - $E = 20\ GPa$
  - $\alpha = 1.35 * 10^{-5}\ mm/K$
  - $3.34\ mm/m \rightarrow 3.88\ mm/m$



AT1 – Material Calibration

- Best stress calibration parameters does not coincide with strain ones.
- Possible improvement:
  - Orthotropic Coil behaviour
  - Friction parametric study



Mechanical Model Validation