Mechanical Simulation of Nb_3Sn Coils

G. Vallone, B. Bordini, N. Bourcey, M. Daly, P. Ferracin, C. Fichera, P. Grosclaude, M. Guinchard, S. Izquierdo Bermudez, C. Loffler, J. C. Perez

37th EuroCirCol WP5 Coordination Meeting

CERN, 22/05/2018

Outline

- Introduction
- MQXF – ‘block coil’ model
- Cable stacks ‘strand’ model
- MQXF ‘strand’ model
- 11T ‘block coil’ model
- Conclusion

Outline

- Introduction
- MQXF – ‘block coil’ model
- Cable stacks ‘strand’ model
- MQXF ‘strand’ model
- 11T ‘block coil’ model
- Conclusion

Introduction

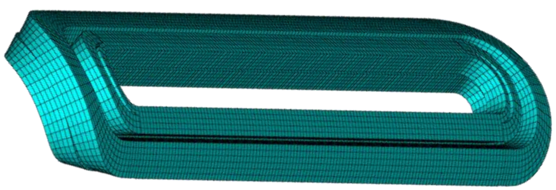
- Magnet **mechanical simulations** rely somehow heavily on the **assumptions** made on **coil behaviour**

- **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

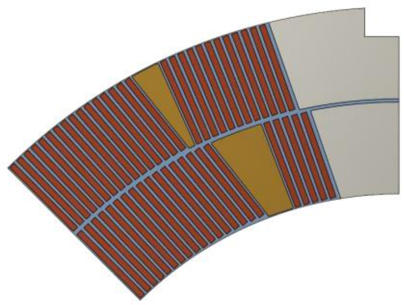
- Direct **strain measurements** on the **conductor** are considered **unreliable**:
  - Strain measured somewhere else → Conductor strain extracted from FE
  - This relies on the correct knowledge of the cable/coil mechanics…

- Knowledge of the impregnated cable/coil mechanical properties is then a necessary information to avoid **magnet degradation**

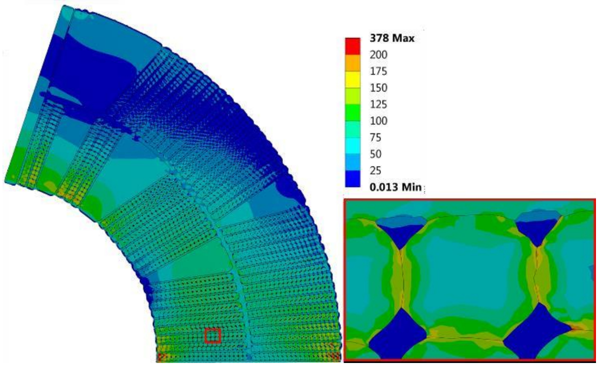
Modelling Strategies



Block Model



Cable Model
C. Löffler et al., EUCAS 2017



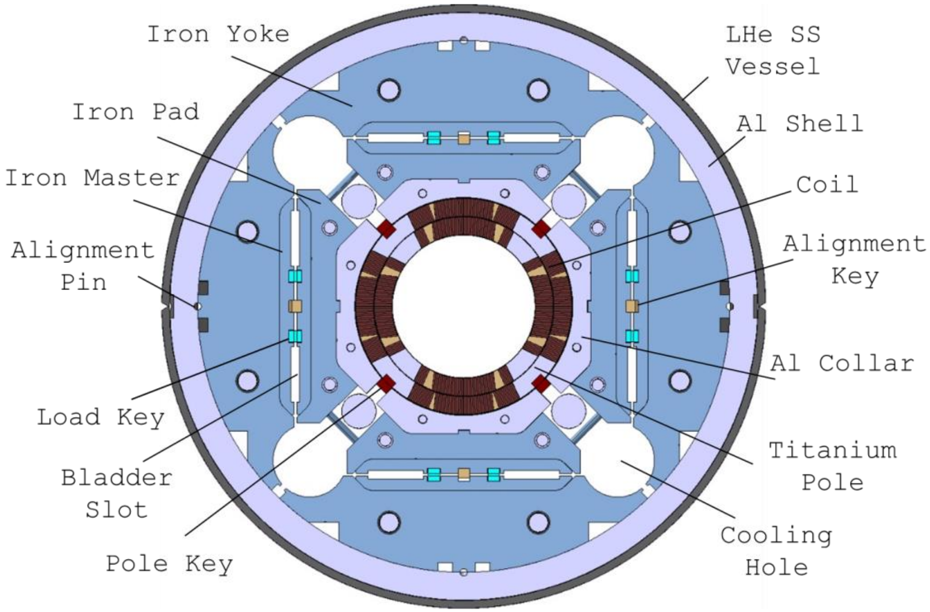
Strand Model
M. Daly et al., MT25, 2017

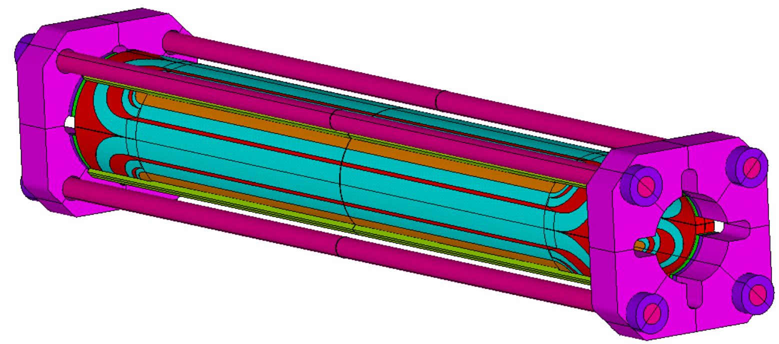
- **Block model** is the current *standard* approach:
  - Coil approximated as an uniform **block** with uniform mechanical properties
  - **Properties** were measured in the past on **impregnated coil stacks**
  - Orthotropic in 2D, isotropic in 3D
- This consistent way of modelling also allowed to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

Outline

- Introduction
- MQXF – ‘block coil’ model
- Cable stacks ‘strand’ model
- MQXF ‘strand’ model
- 11T ‘block coil’ model
- Conclusion

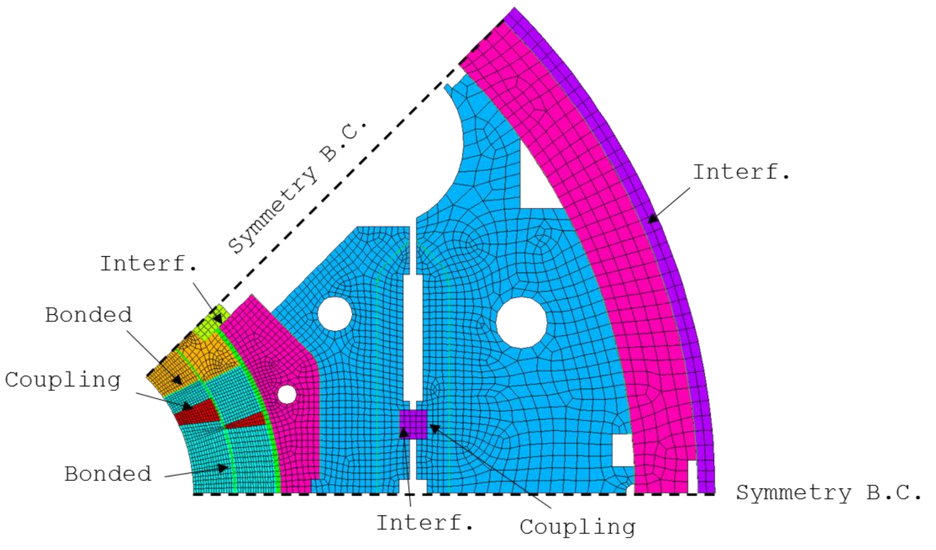
MQXF – Mechanical Structure

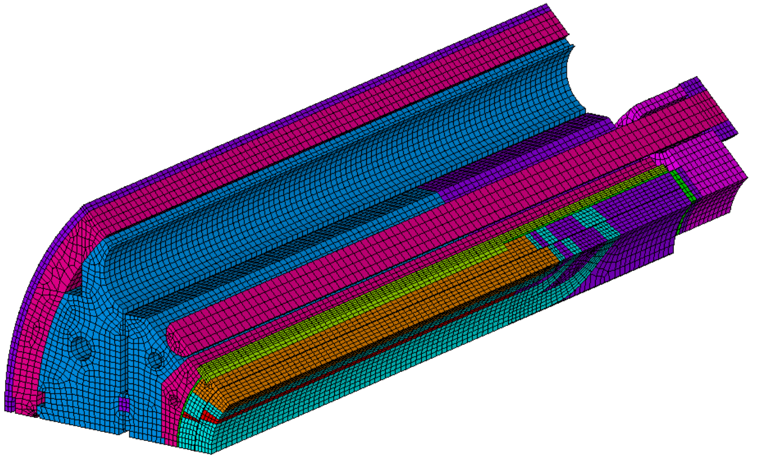




- Azimuthal preload at R.T. applied with **bladders & keys**
  - Al shell compresses the coils. Part of the force is absorbed by the pole key
- Longitudinal preload at r.t. applied pre-tensioning the **rods**
- Both increased by the differential **thermal contraction** during cool-down

MQXF – Block Coil Model



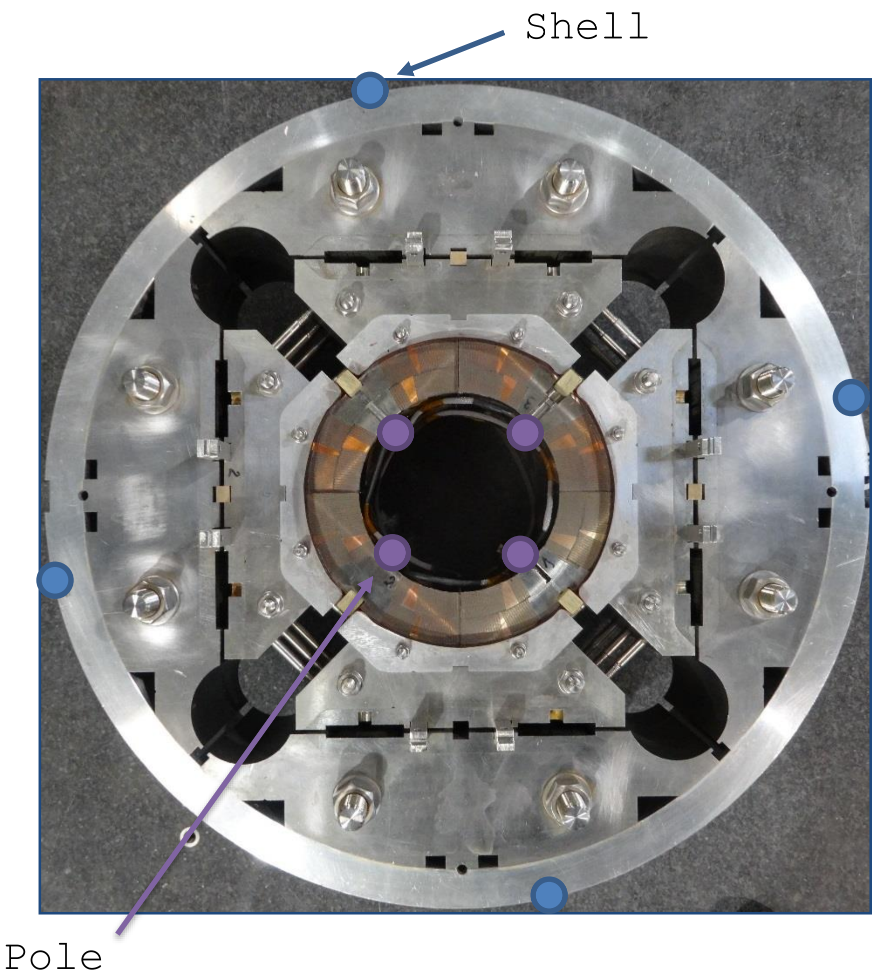


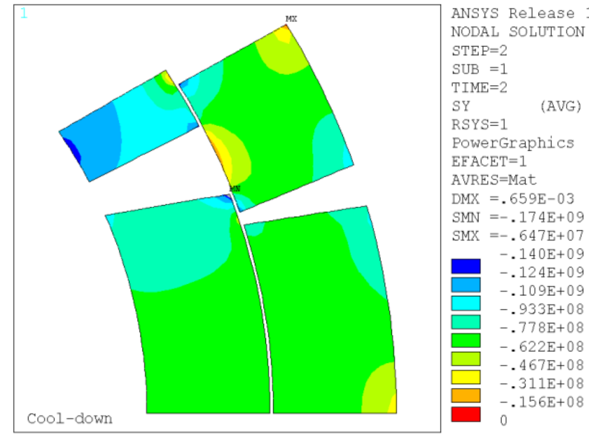
- Coil modelled as a **block**. Simulations in **2D** and **3D**.

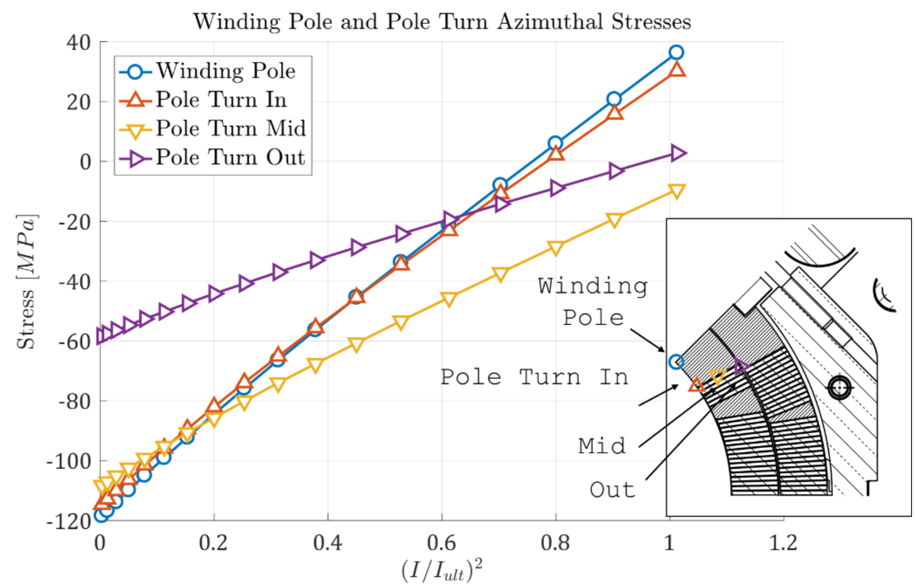
- Coil **properties** from **LARP** experience:

    - Elastic modulus (linear elastic): 44 GPa (azimuthal), 52 GPa (radial)
    - Orthotropic in 2D, isotropic in 3D
    - Thermal contraction: 3.35 mm/m

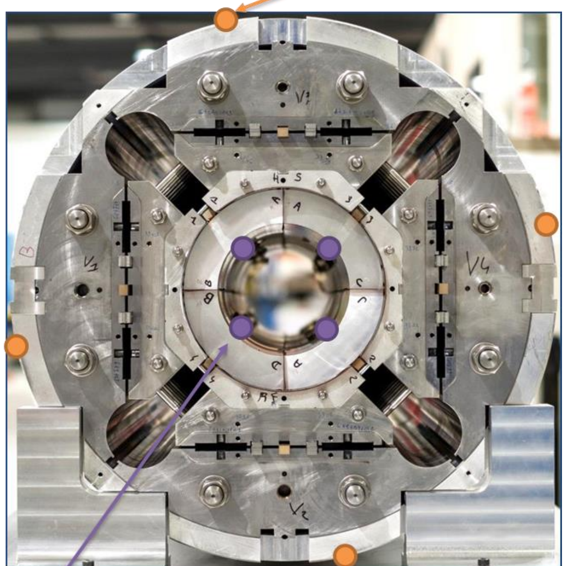
Short Model - Strain Gauge Locations

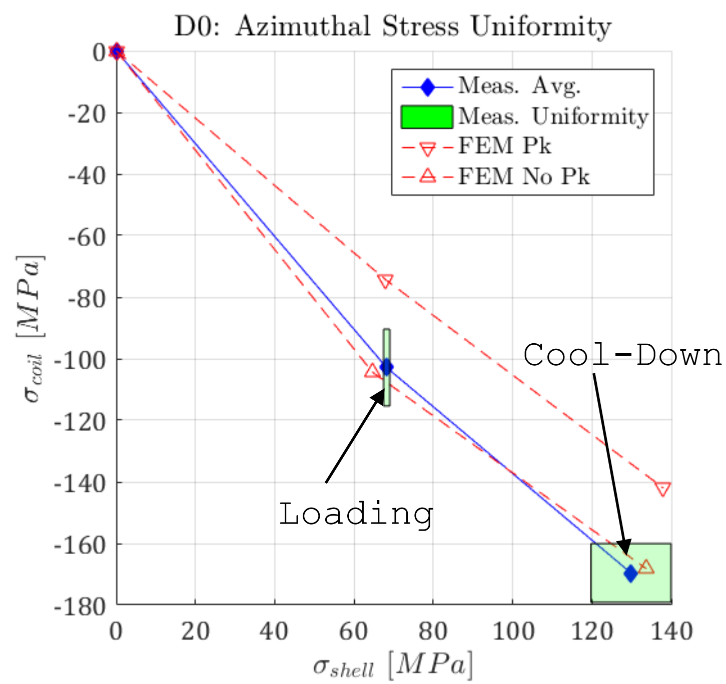






Mechanical Model – MQXFSD0





- 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

MQXFS1 – Transfer Function

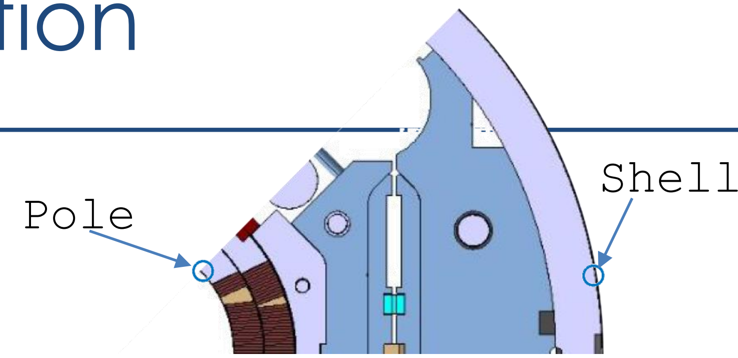
Prestress analysis:

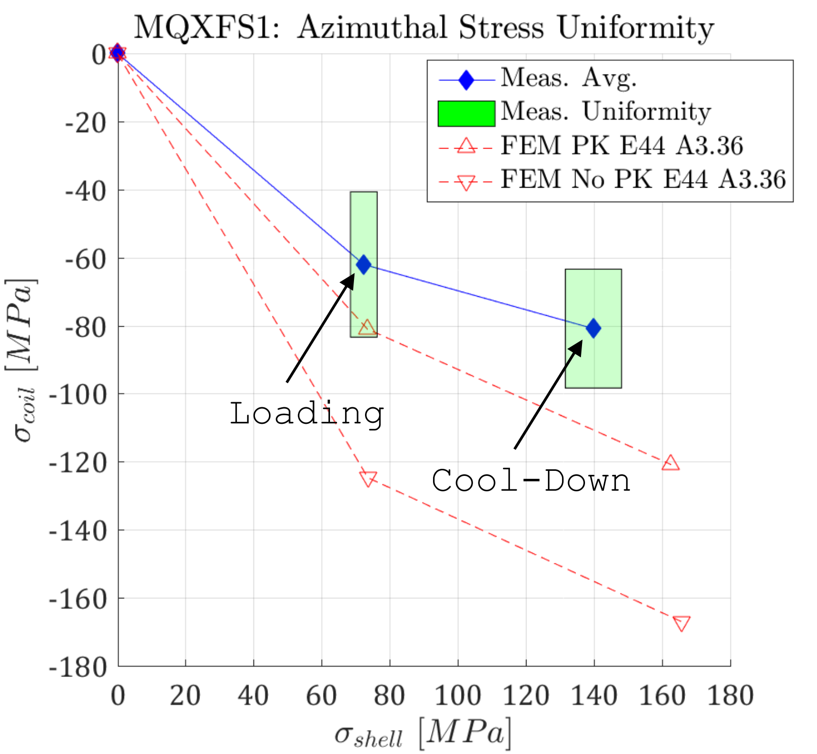
- Prestress variation: $\pm 17\ MPa$
  - Does this set a threshold on expected model precision?

- **Model** result is out of the meas. uniformity

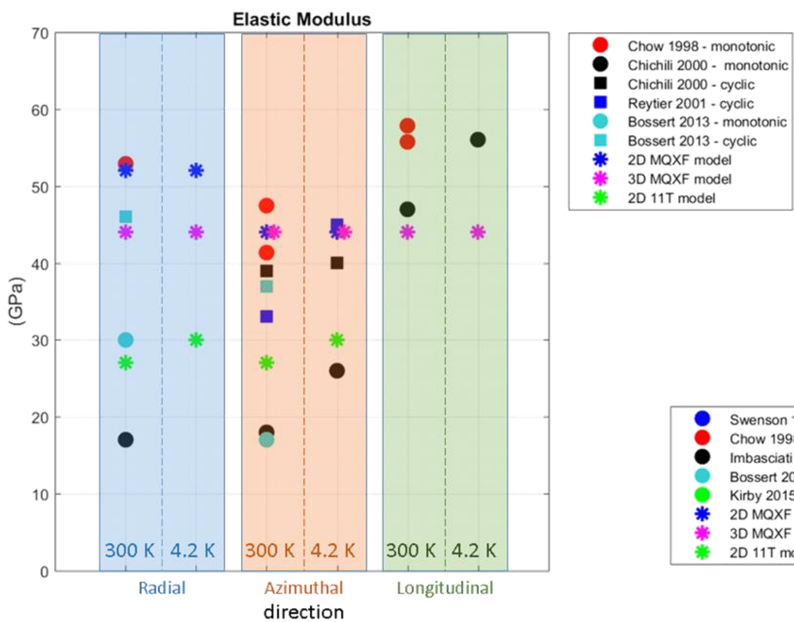
  - **Pole stress** at warm lower
  - Lower prestress increase during CD
  - Stress after CD **lower** than expected on both shell and coil

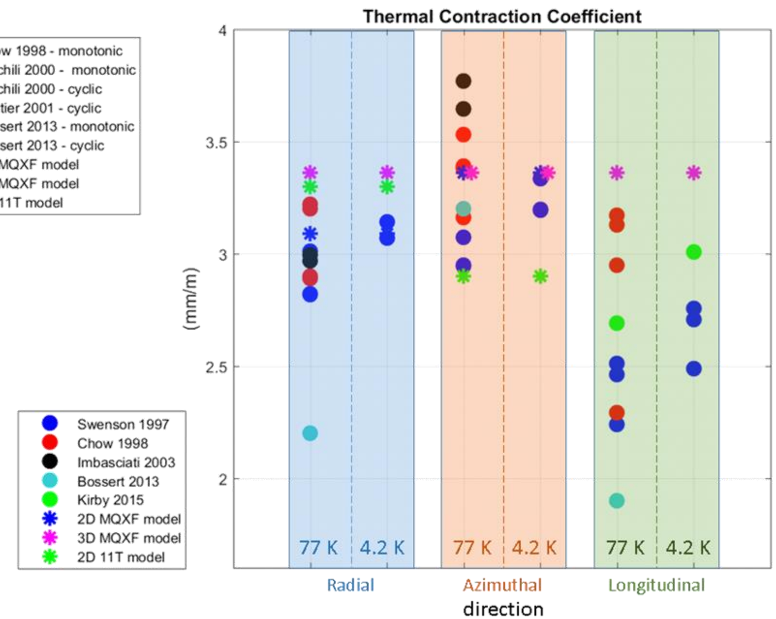
- The **mechanical models** experience suggests that the distance between model and measurements is due to the **coil** properties used.

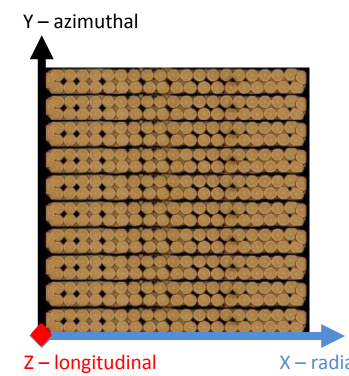




Coil Properties – Available Data



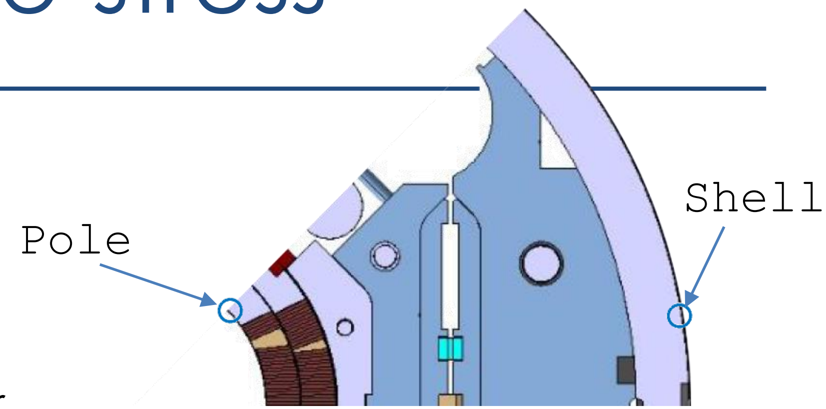


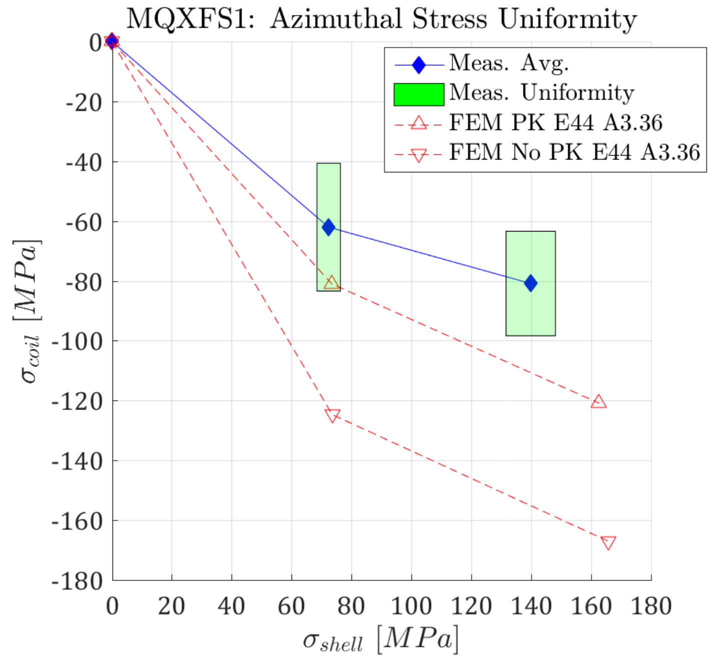


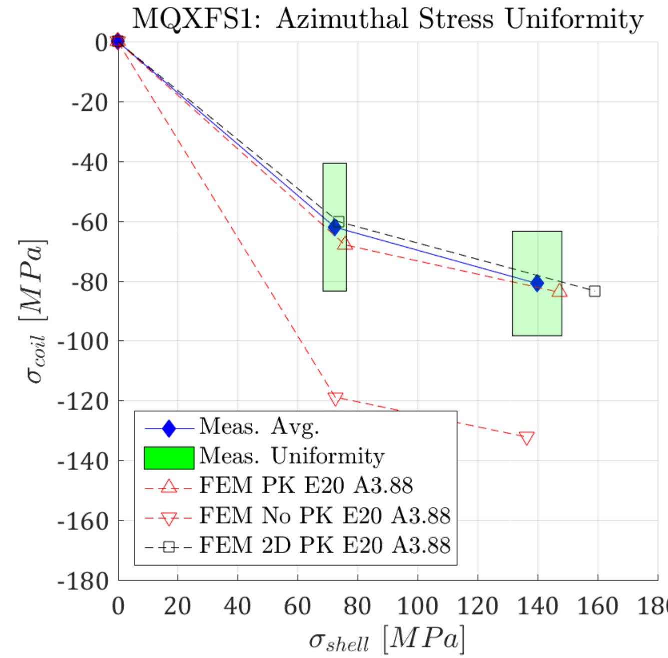
- Available **coil properties** measures highly dispersed
- Measured **Young** modulus: 15-60 GPa. Also depends upon cyclic/monotonic loading phase
- Measured **thermal contraction**: 2-4 mm/m

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!



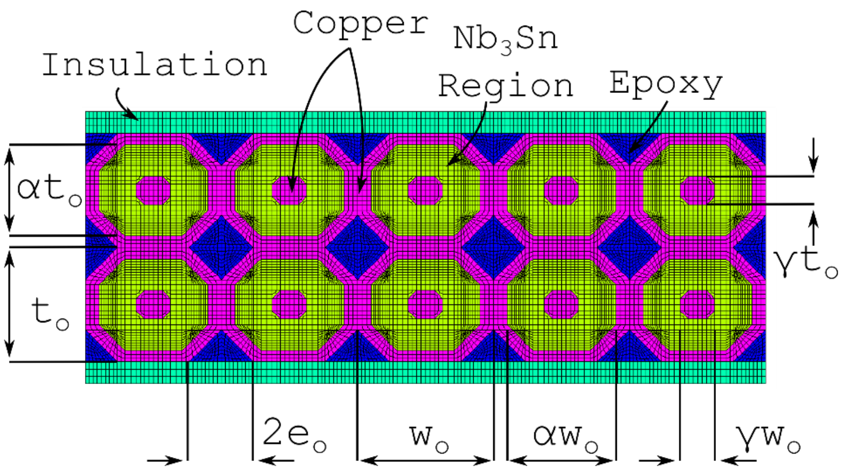


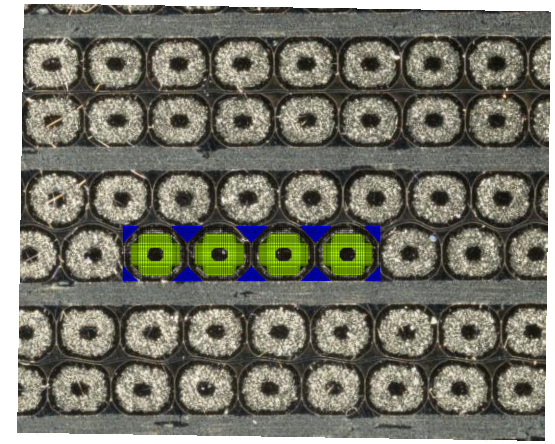


Outline

- Introduction
- MQXF – ‘block coil’ model
- Cable stacks ‘strand’ model
- MQXF ‘strand’ model
- 11T ‘block coil’ model
- Conclusion

Cable Stacks – FE Model (1)





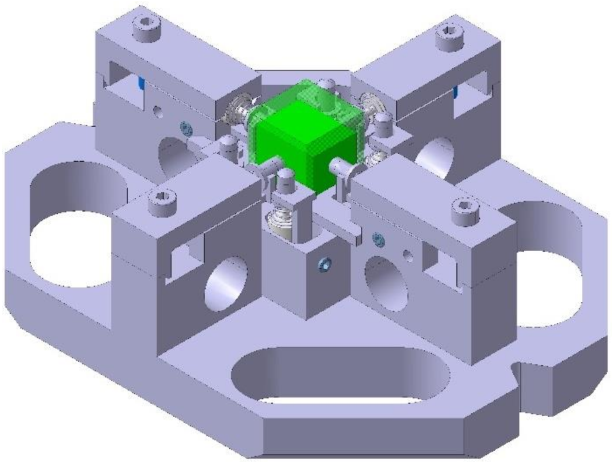
- 2D FE model of the cable stack
- Material properties from literature
- Geometry from a mix of **image analysis** and simple geometric formulas to match the filling factor, copper-non copper etc.

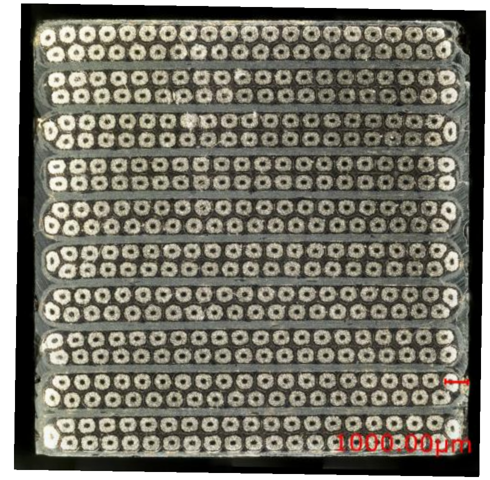
$$e_o = \sqrt{\frac{h_o w_o - A_c \eta_f / N_s}{2}}$$

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

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

Cable Stacks – Transversal Pressure (1)

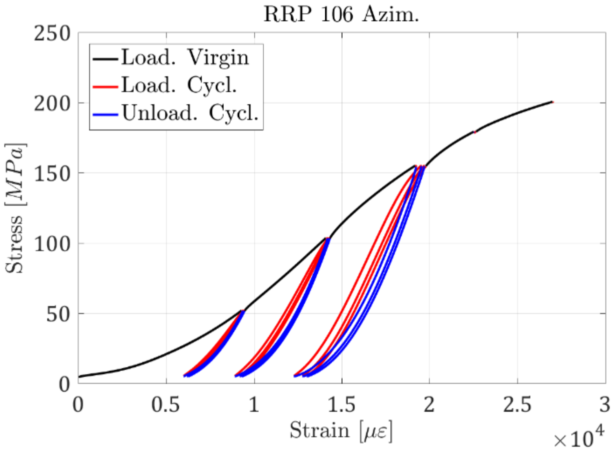


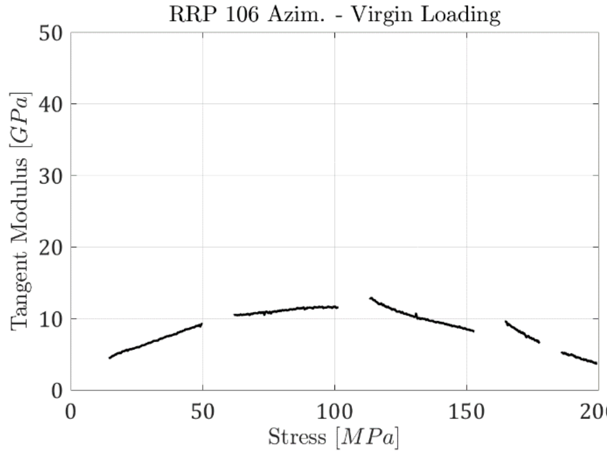


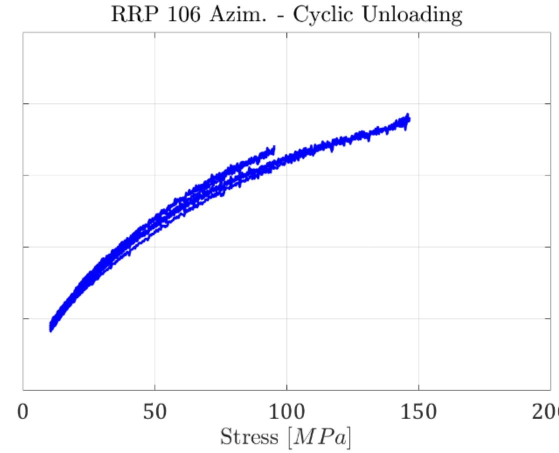
- Measurements on **stacks** of impregnated cables have *always* been used as a reference for coil elastic modulus measurements
- There is a significant **spread** (15-50 GPa, *azimuthal* direction) in the values available in literature
  - The modulus seems sensible to the particular cable tested/testing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

Work to be published by C. Fichera et al.

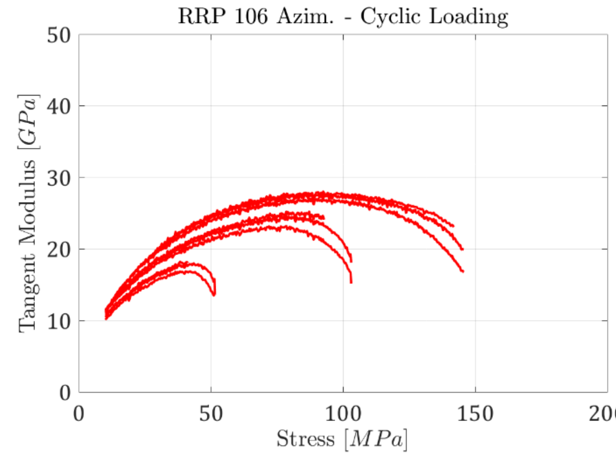
Cable Stacks – Transversal Pressure (2)





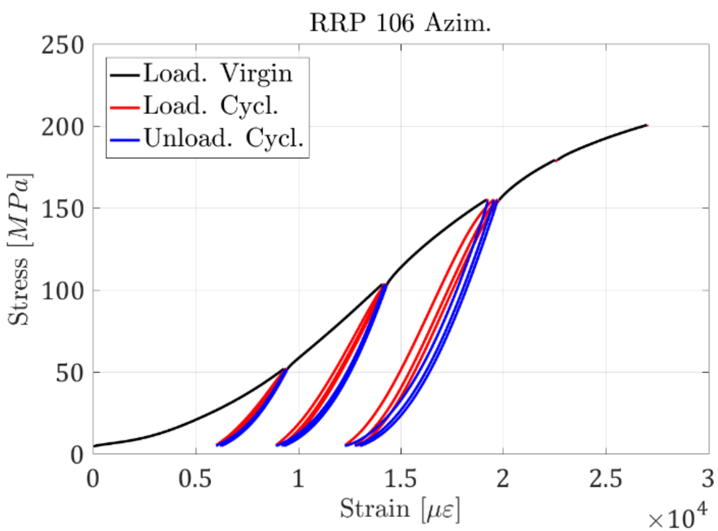


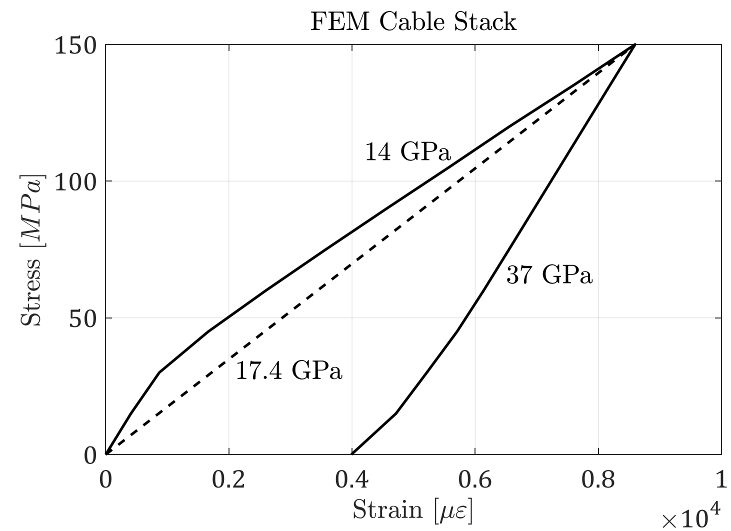
- Very **different** behaviour in the **three phases**
- The *chord and tangent modulus*† vary continuously during the test
- Probably difficult to condensate the coil elastic properties in a **single number** (elastic modulus)



† *ASTM - E111 - 04*

Cable Stacks – FE Model (2)





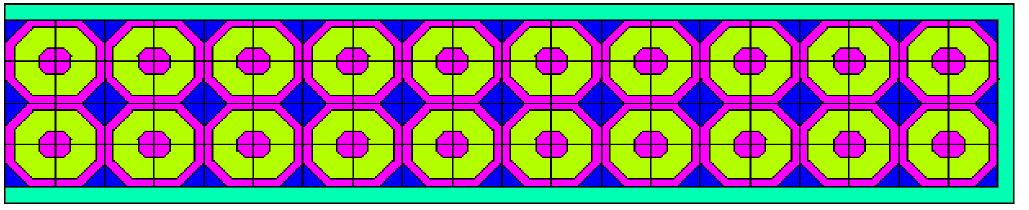
- Virgin/cyclic behaviour explained by **copper plasticization**
- FE slope *reasonably* good especially considering that **no** model **calibration** was necessary
- Initial phase may be due to **compaction**

MATERIAL PROPERTIES

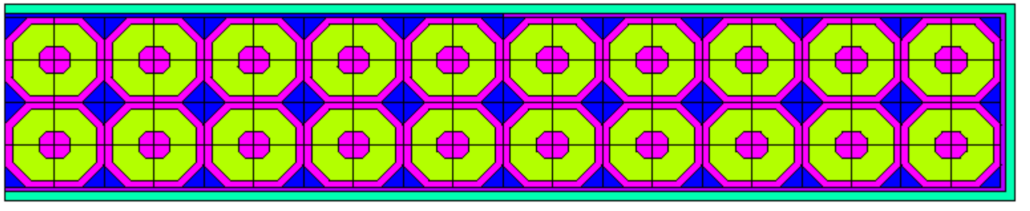
Parameter	Unit	Value
Copper Elastic Modulus (R.T.)	GPa	110
Copper Elastic Modulus (4.3 K)	GPa	120
Copper Yield Strength	MPa	40
Copper Tangent Modulus	GPa	5
Non-Cu Elastic Modulus (R.T.)	GPa	100
Non-Cu Elastic Modulus (4.3 K)	GPa	70
Epoxy Resin Elastic Modulus	GPa	5
Impregnated Insulation Elastic Modulus (R.T.)	GPa	13
Impregnated Insulation Elastic Modulus (4.3 K)	GPa	20

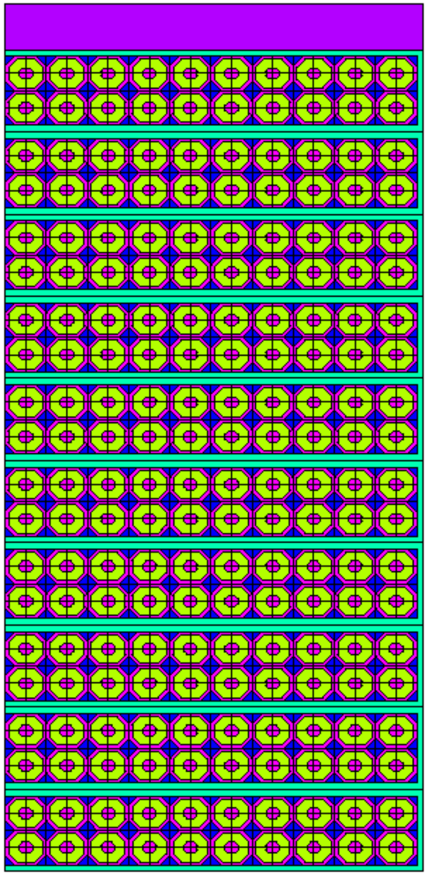
Comparison with 1T Cable

MQXF



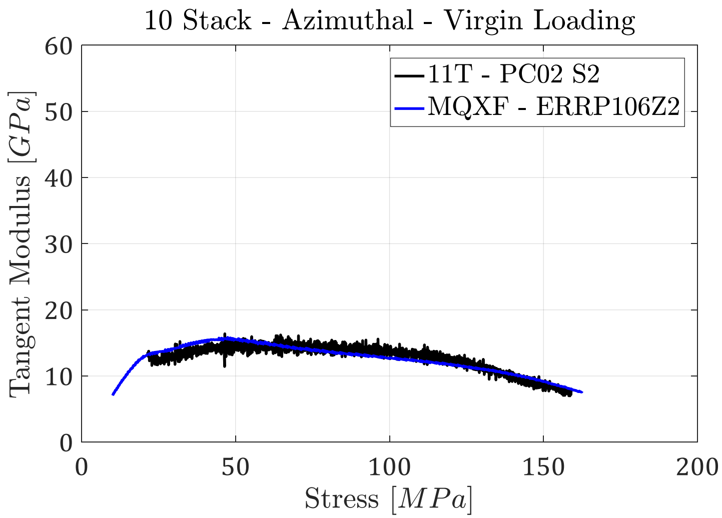
11T

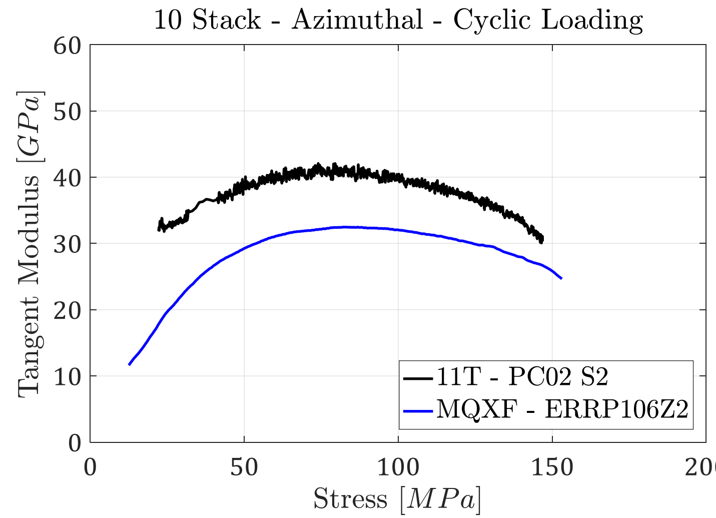




- How the modelling strategy performs on a **different cable**?
- We measured with the same procedure also **11T** cable stacks
- MQXF and 11T Cable comparison
- Mica assumed to be elastic, 170 GPa

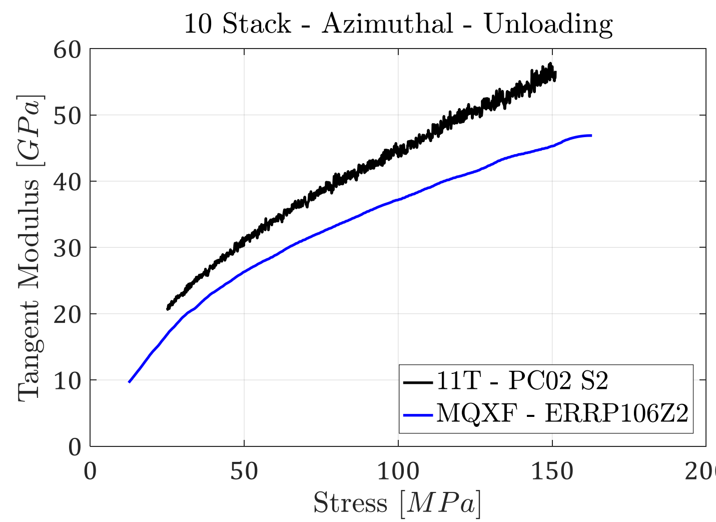
11T/MQXF - Meas. Comparison





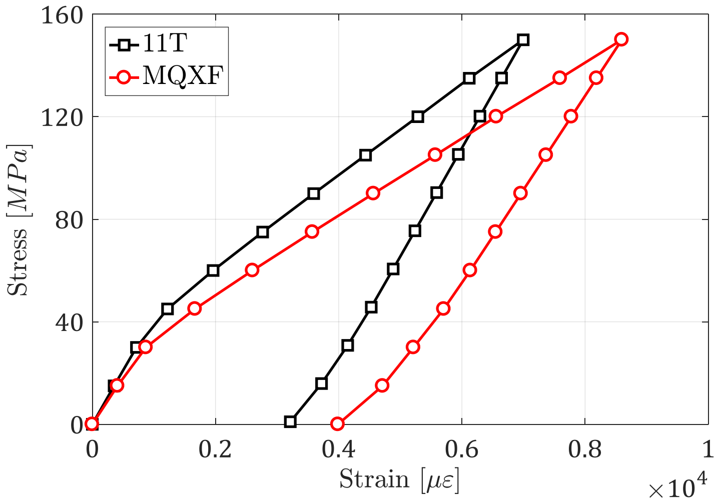
- Very similar results for virgin loading
  - Explained by Cu hardening/compaction?

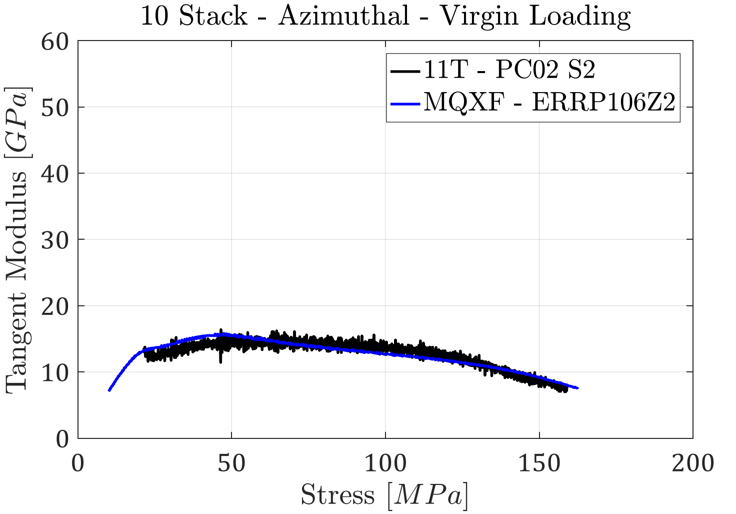
- Cycling behaviour:
  - The 'shape' is very similar
  - The 11T specimen are slightly stiffer ~5-10 GPa

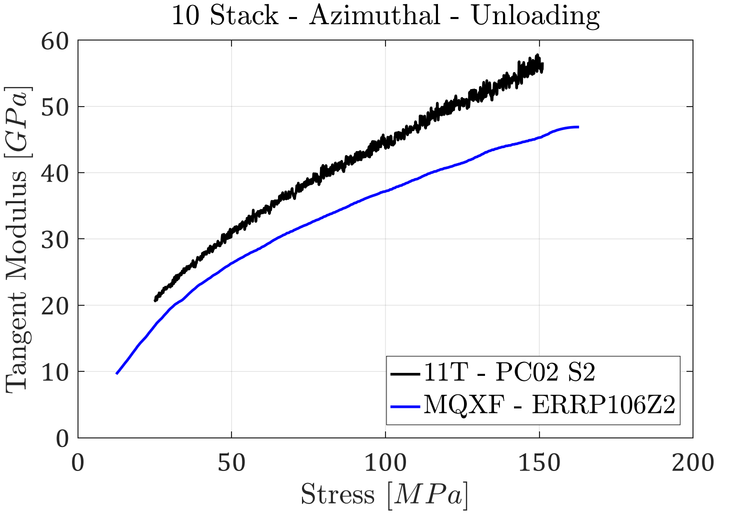


11T Data: M. Daly et al., IEEE TAS, 2017

Mechanical Model – Results (1)







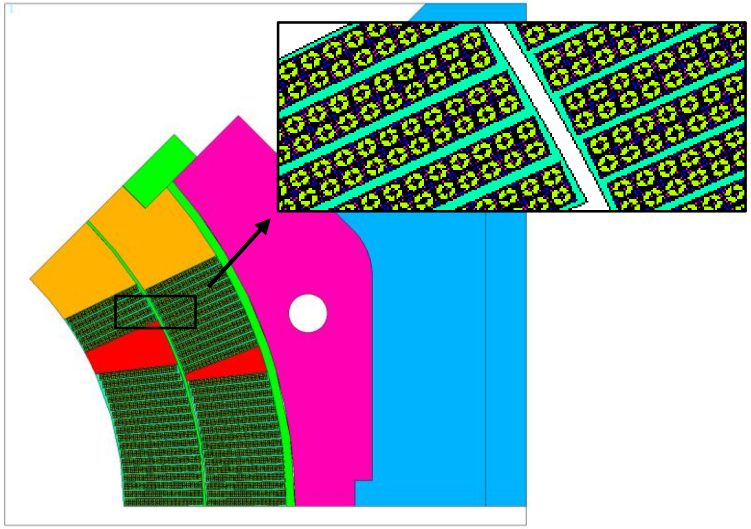
- 11 T Stack Modulus - Model:
  - Virgin Loading – 17 GPa
  - Unloading - 42 GPa

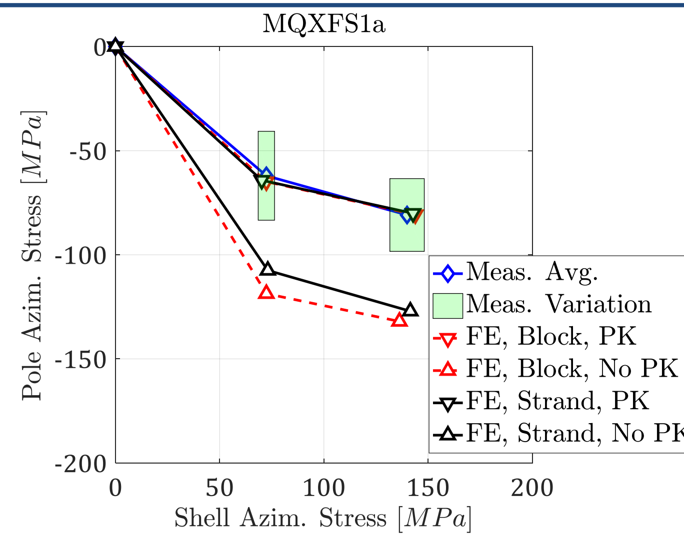
- MQXF Stack Modulus - Model:
  - Virgin Loading – 14 GPa
  - Unloading - 37 GPa

Outline

- Introduction
- MQXF – ‘block coil’ model
- Cable stacks ‘strand’ model
- MQXF ‘strand’ model
- 11T ‘block coil’ model
- Conclusion

MQXF – Strand Model





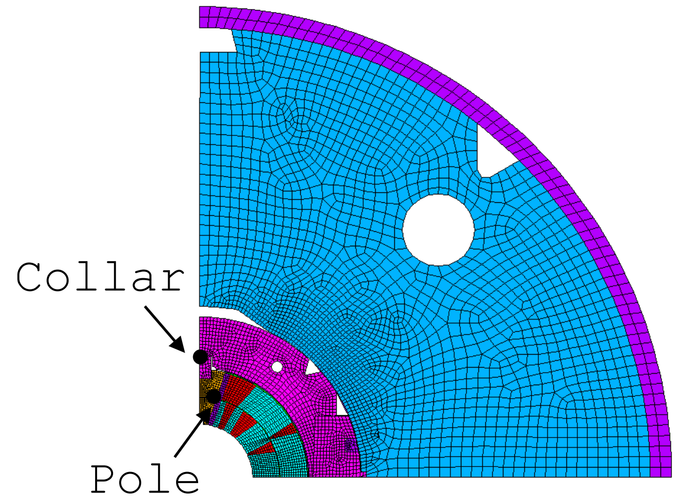
- *Strand* MQXF magnet model. Same approach as before // work in progress!
  - Pros:
    - Useful to verify the strain *inside* the strand
    - We are not relying on properties measured on the stacks
  - Cons:
    - We have extensive experience with **block** models
    - Even a 2D model can become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

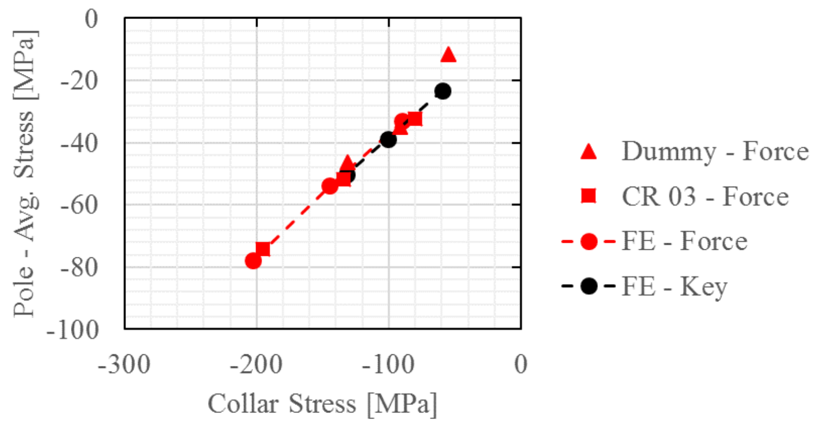
Outline

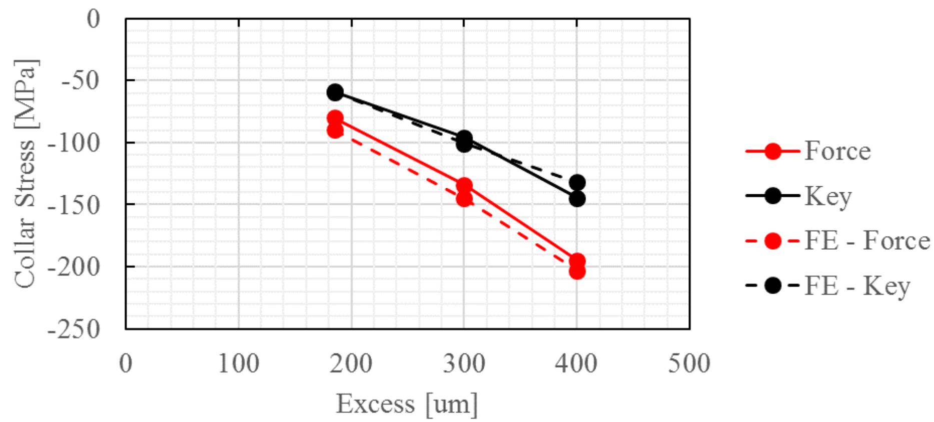
- Introduction
- MQXF – ‘block coil’ model
- Cable stacks ‘strand’ model
- MQXF ‘strand’ model
- 11T ‘block coil’ model
- Conclusion

11T - Block Coil Model

- **Coil block** model
- Most of the prestress applied during **collaring**
- Coil '**plasticity**' (spring-back)accounted for using a bilinear curve
- Material properties currently used:
    - 10/30 GPa (loading, unloading)





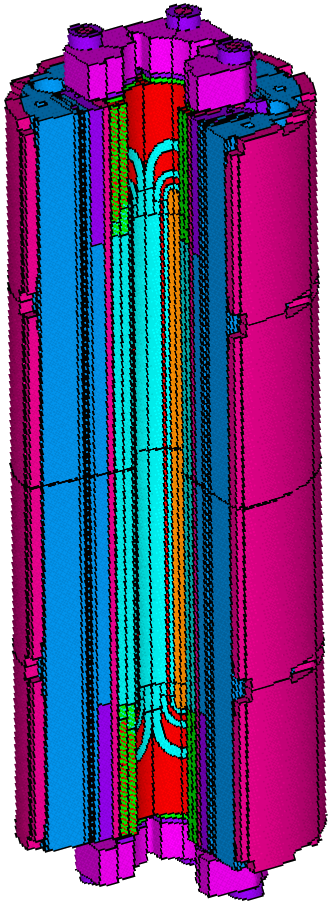


Outline

- Introduction
- MQXF FE – ‘block coil’ model
- Cable stacks ‘strand’ model
- ‘Strand’ model - applications
- Conclusion

Conclusion

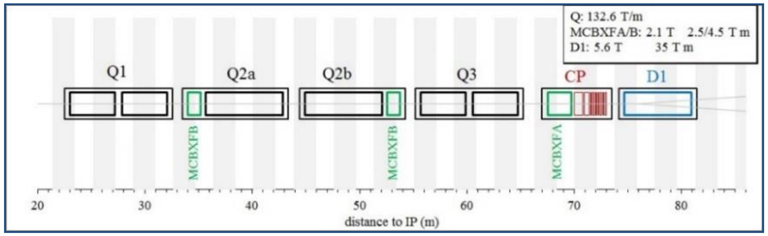
- MQXF FE model **calibration**:
  - Good agreement at the *macroscopic* level
  - The same approach could be used on other magnets (different cable, resin, etc.). Not feasible at the design stage!
- **Impregnated cable stacks**:
  - Strongly **non-linear** behaviour
  - Part of this behaviour can be 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
- The cable stack model seems to be able to predict the **critical current degradation** in the reversible region
- Mat. **properties currently used**:
  - MQXF: 20 GPa, **elastic**
  - 11T: 10/30 GPa, **bilinear**

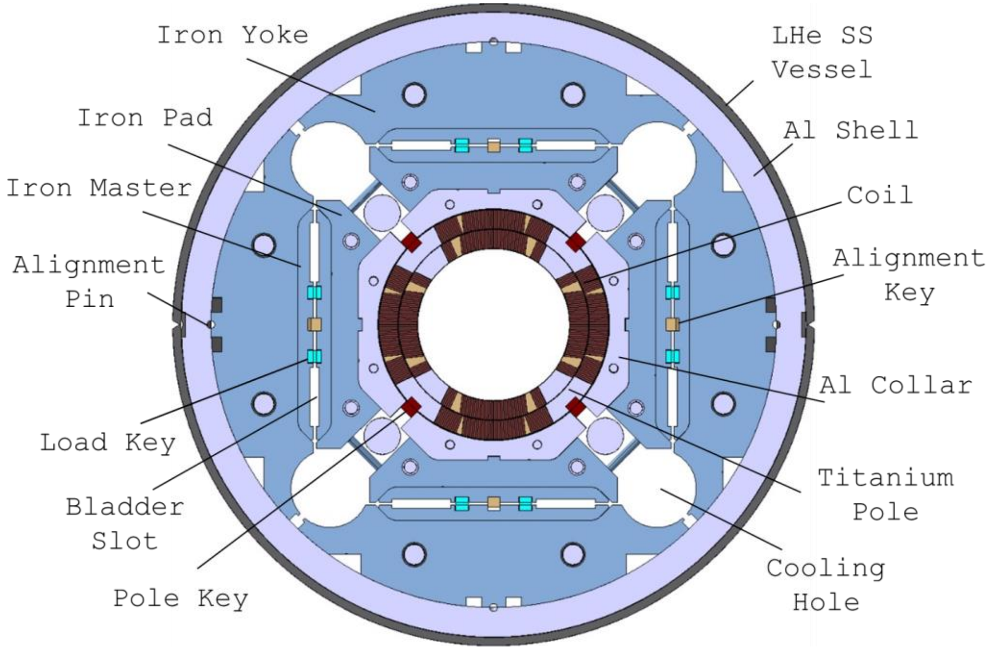


Extra

MQXF Design

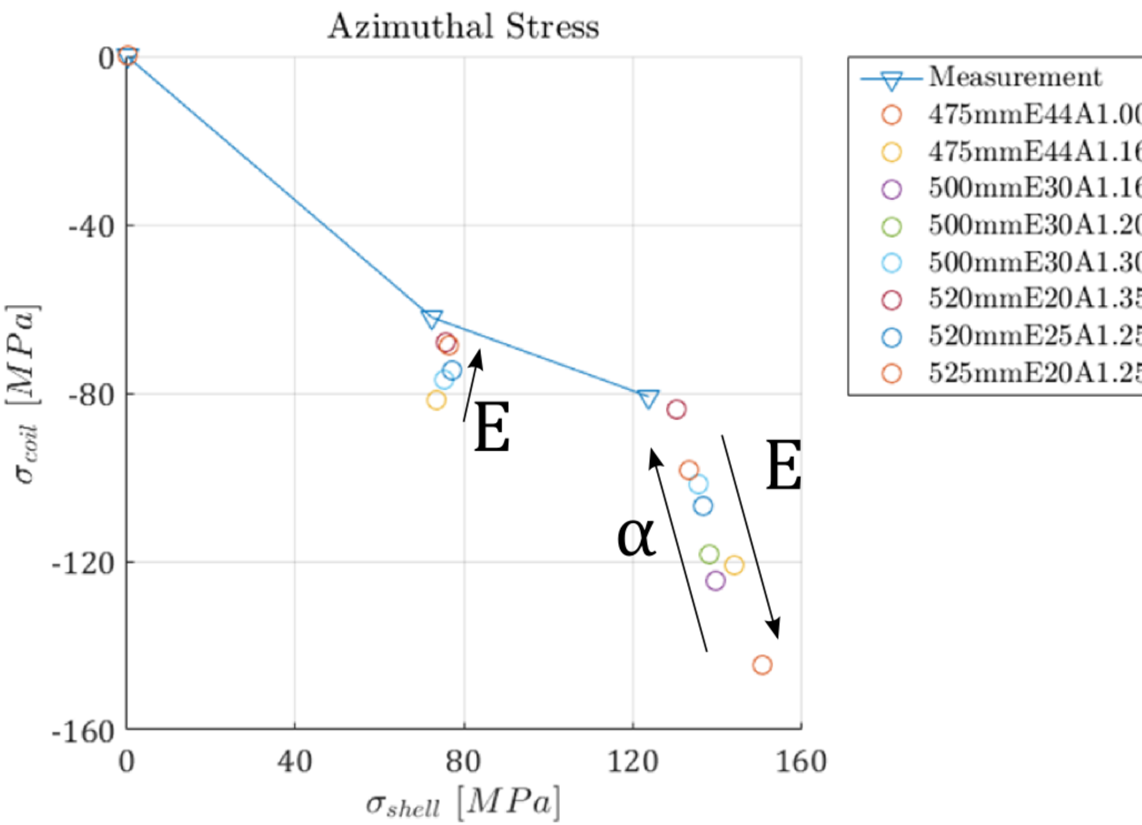
- LHC IR upgraded as a part of HiLumi project
  - Quadrupoles: NbTi → Nb_3Sn
- Target: 132.6 T/m
  - 150 mm coil aperture, 11.4 T B_{peak}
- Q1/Q3 (by US-AUP Project)
  - 2 magnets **MQXFA** with 4.2 m
- Q2a/Q2b (by CERN)
  - 1 magnet **MQXFB** with 7.15 m
- Different lengths, same design
- Short Models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





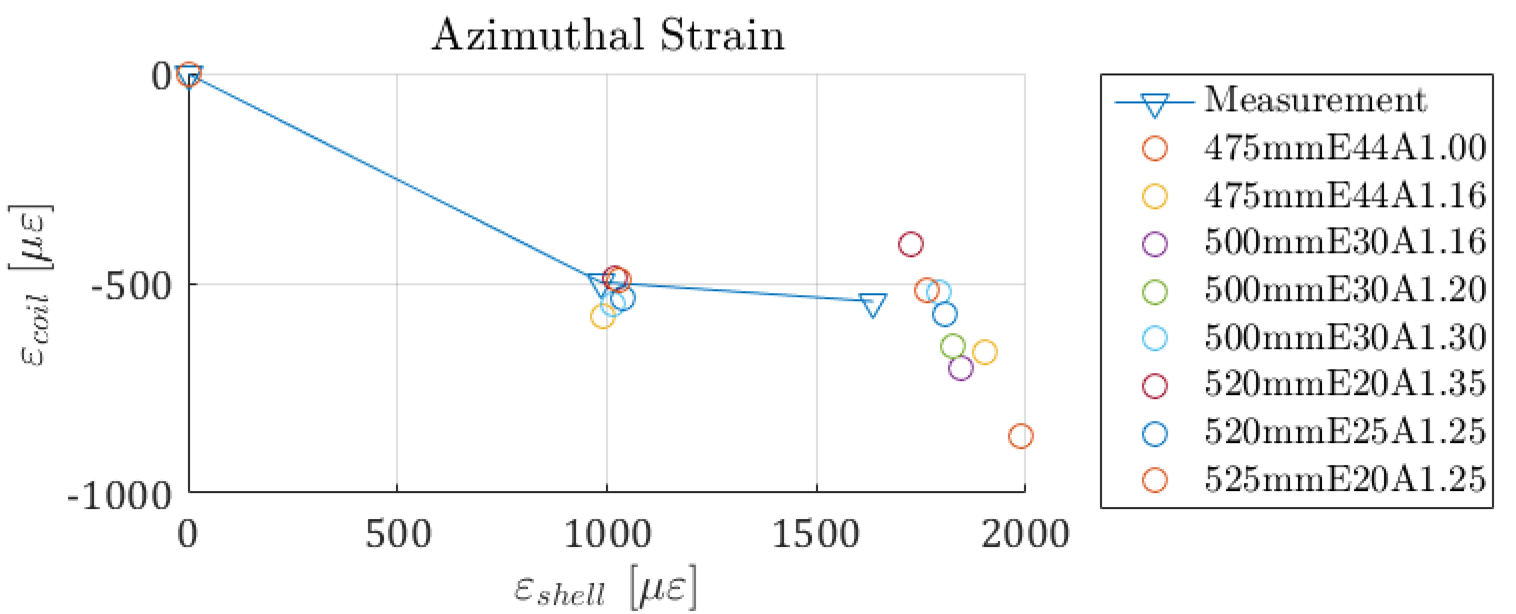
MQXFS1 – Material Calibration

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

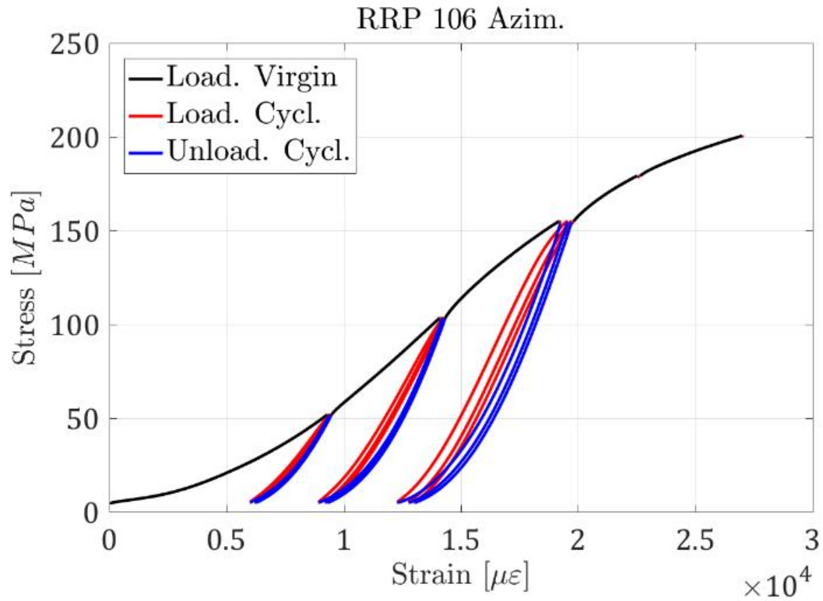


MQXFS1 – Material Calibration

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



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?

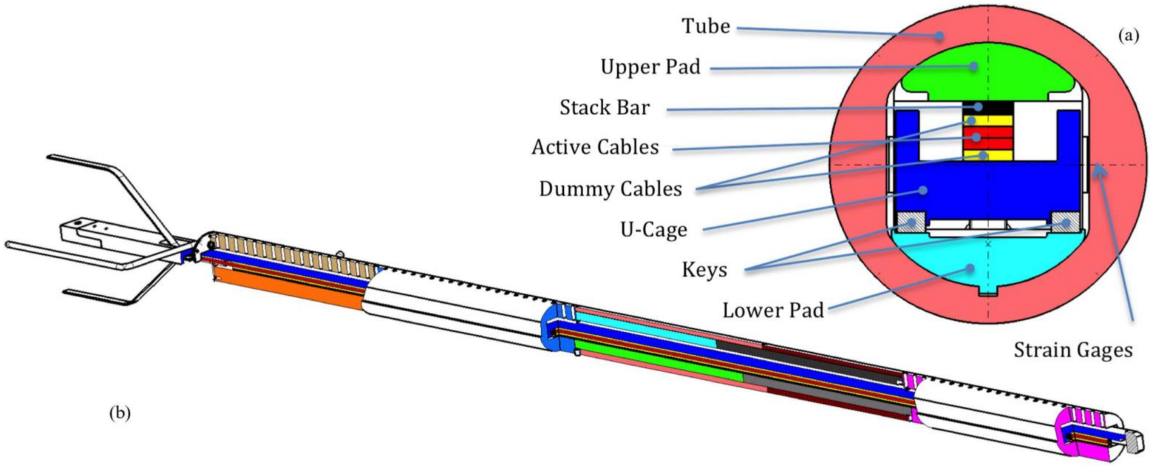
Cable Stacks – Transversal Pressure (3)

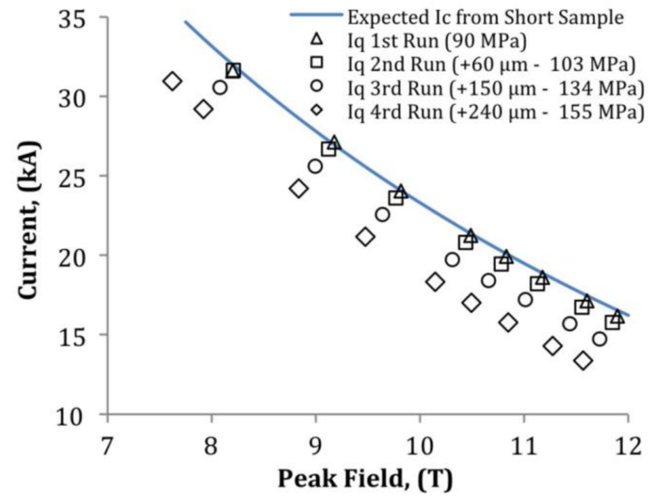
10 Stack - Chord and Tangent Modulus

	Unit	Value		
Stress Range	MPa	[10, 50]	[50, 100]	[100, 150]
Loading A† Chord	GPa	6.9	11.1	10.1
Loading A Tangent	GPa	[4.4, 9.2]	[10.4, 11.6]	[8.1,12.9]
Unloading Chord	GPa	16.8	29.1	34.2
Unloading Tangent	GPa	[9.2, 22.5]	[23.0, 34.2]	[31.7, 38.6]
Loading B‡ Chord	GPa	15.2	22.9	24.7
Loading B Tangent	GPa	[10.4, 17.7]	[15.1, 25.2]	[16.7, 27.6]

† Loading with a new level of maximum stress.
‡ Cyclic loading.

FRESCA Sample Holder (1)

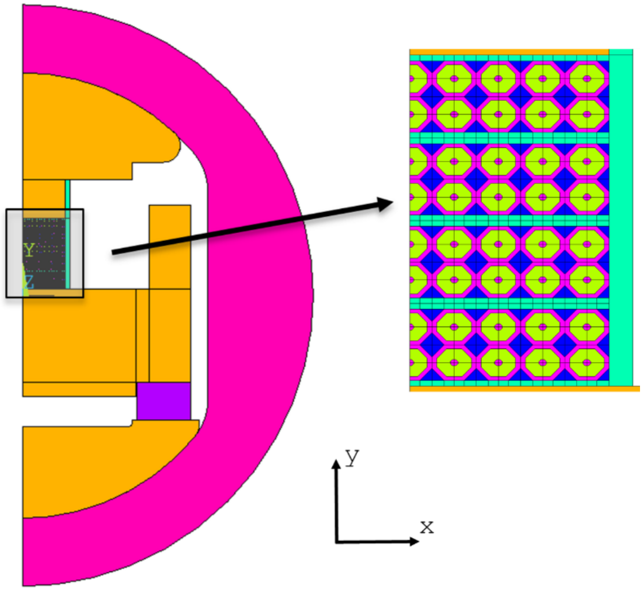




- A novel FRESCA sample holder was built and used at CERN. This tool allows to **measure** the **critical current** of stacks of impregnated cables under **transversal pressure**.
- First results (2014) show how the reversible degradation on a PIT cable can change the critical current between **90 and 155 MPa**

B. Bordini et al., IEEE TAS, 2014

FRESCA Sample Holder (2)

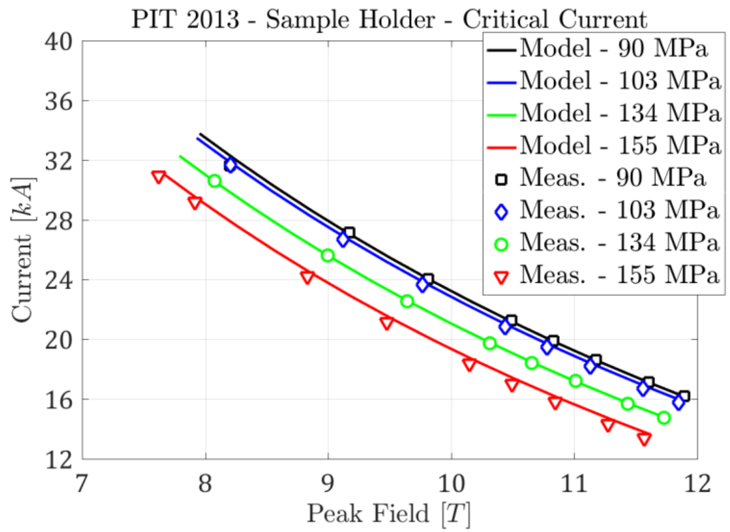


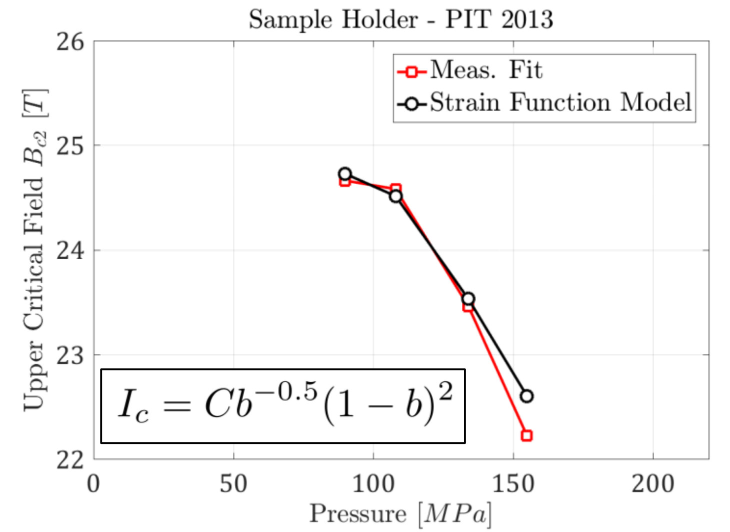
Parameter	Unit	Value - A†	Value - B‡
Strand	/	RRP 108/127	PIT 192
Strand diameter	mm	0.85	1.0
Number of strands in cable	/	40	18
Copper to non-copper	/	1.2	1.22
Twist Pitch	mm	14	63
Cable Bare Width	mm	18.15	10
Mid Thickness	mm	1.525	1.81
Keystone Angle	degrees	0.40	0

† 10-stack cable (MQXF [13]) - *E* measurements.
‡ Sample holder cable [3] - Critical current measurements.

- **2D** mechanical and electro-magnetic model of the **sample holder**
- Cable stack represented with the **mechanical approach** validated from 10-stack measurements
  - Same methodology but different strand/cable parameters

Stack Degradation – Results





- Quench **currents** are matched *reasonably* well. Notice that:
  - On the last loading there was a small **irreversible** degradation
  - The quenches at 90 MPa were at **short sample limit**. The model correctly predicts the same strain function at 0 MPa
  - Only **one fitting** parameter (scaling the strain from the strand to the filament)

- The **upper critical field** as computed fitting the critical currents is also well captured by the model