Computation of the Reversible Critical Current Degradation in Nb_3Sn Rutherford Cables

G. Vallone, B. Bordini, P. Ferracin

Workshop on Nb_3Sn Technology for Accelerator Magnets

Paris, 12/10/2018

HiLumi LARGE HADRON COLLIDER

U.S. LARP

Outline

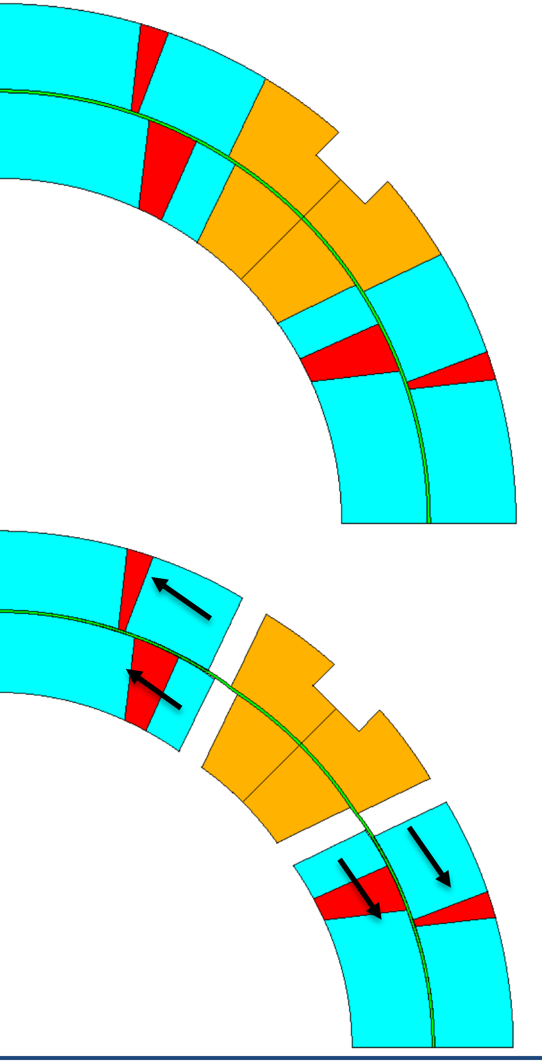
- Introduction
- Reversible Degradation in Strands
- Cable Stacks Under Transversal Pressure
- Critical Current Reversible Degradation
- Application to Superconducting Magnets
- Conclusion

Outline

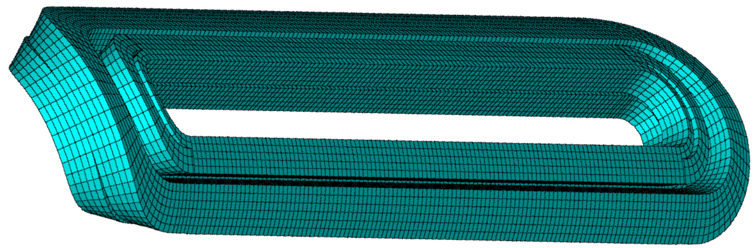
- Introduction
- Reversible Degradation in Strands
- Cable Stacks Under Transversal Pressure
- Critical Current Reversible Degradation
- Application to Superconducting Magnets
- Conclusion

Introduction

- A typical strategy to reduce the number of training quenches is to **prevent coil motions** applying a **prestress**:
  - The prestress **compresses** the coil against the winding pole
  - E.m. forces **pull** the winding from the pole
  - The **coil motion** drastically **increases** as soon as the available **prestress** is **exhausted**
- However, Nb_3Sn is **strain sensitive**
- Increasing the prestress above a certain limit could **degrade** the magnet performance
- We need a **methodology** to evaluate the **magnet performances** under high stresses



Nb_3Sn Magnets – State of Art



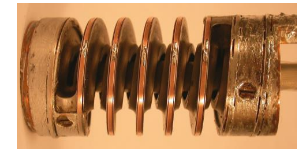
- Currently, we use an **empiric limit** of 150-200 MPa on the coil **equivalent stress**
- We *cannot* **measure** directly the **strain** on the **coil**
  - This limit is verified against **numerical model** results (eventually validated with indirect measurements)
  - In these models the coil is considered a **block** with **uniform elastic properties**, measured on **cable stacks**

H. Felice et al., IEEE TAS, 2011

Outline

- Introduction
- Reversible Degradation in Strands
- Cable Stacks Under Transversal Pressure
- Critical Current Reversible Degradation
- Application to Superconducting Magnets
- Conclusion

Strand Degradation



- Significant amount of **experimental data** exists about the performance of Nb_3Sn wires under **axial strain**. This allowed to define clear laws.
- The main parameter governing the degradation in the reversible region is the **strain function** $s(\varepsilon)$:

$$s(\varepsilon) = \frac{B_{c2}(0,\varepsilon)}{B_{c2}(0,0)}$$

- The strain dependence of the superconducting properties can be written as a function of $s(\varepsilon)$:

$$T_c(\varepsilon) = T_c(0)s(\varepsilon)^{\frac{1}{w}} \qquad t = T/T_c(\varepsilon)$$

$$B_{c2}(T,\varepsilon) = B_{c2}(0,0)s(\varepsilon)(1-t^{\nu}) \qquad b = B/B_{c2}(T,\varepsilon)$$

$$F_p = J_c(B,T,\varepsilon) \times B = Cg(s(\varepsilon))h(t)b^p(1-b)^q$$

The Exponential Strain Function (1)

- Recently (2013), a new law was proposed to describe the evolution of the strain function:

$$s(\boldsymbol{\varepsilon}) = \frac{e^{-C_1 \frac{J_2+3}{J_2+1} J_2} + e^{-C_1 \frac{I_1^2+3}{I_1^2+1} I_1^2}}{2}$$

- With I_1 being the first invariant of the strain tensor and J_2 the second invariant of its deviatoric part:

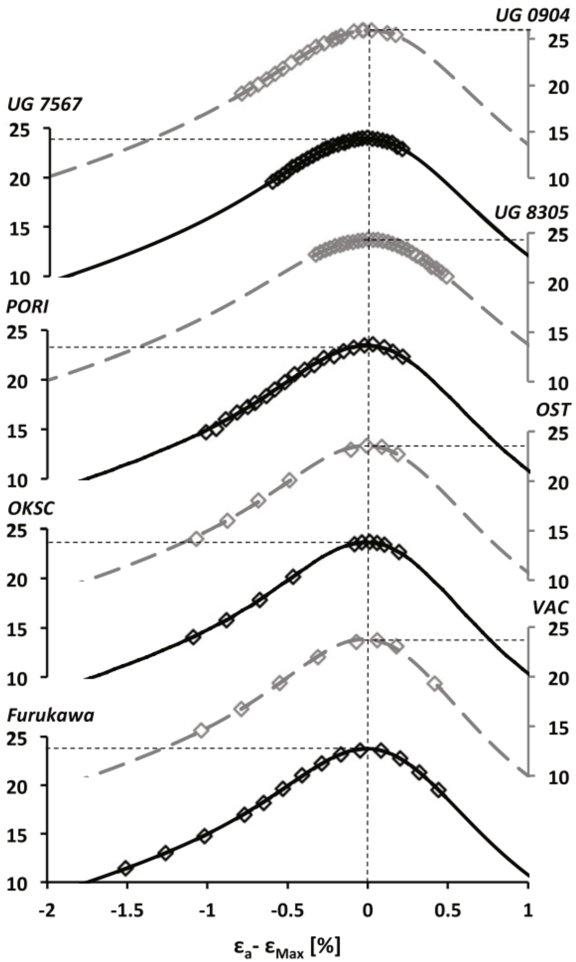
$$I_1 = \sum(\varepsilon_1 + \varepsilon_2 + \varepsilon_3)$$

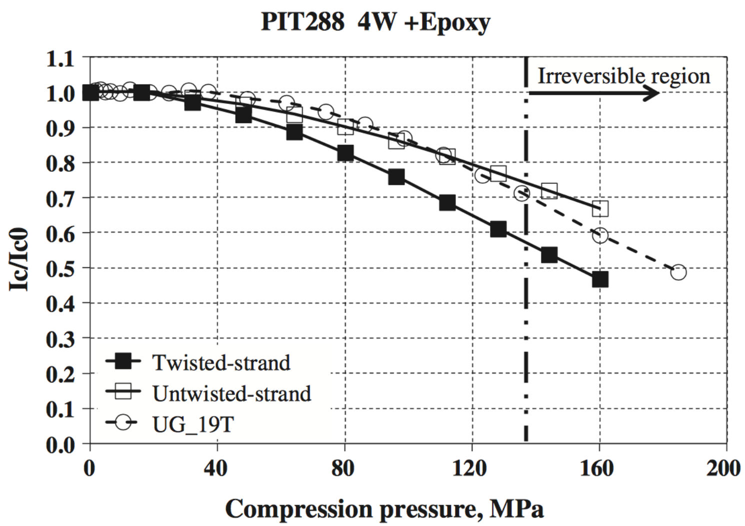
$$J_2 = \frac{1}{6}\left[\sum(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2\right]$$

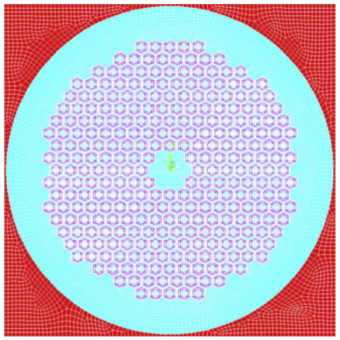
- The strain tensor has to consider the applied load + the pre-compression strain

B. Bordini et al., SuST, 2013

The Exponential Strain Function (2)







- In 2014, the scaling law was implemented in a 2D FE model of a **strand**, surprisingly matching the critical current degradation as a function of the **applied pressure (transversal)**

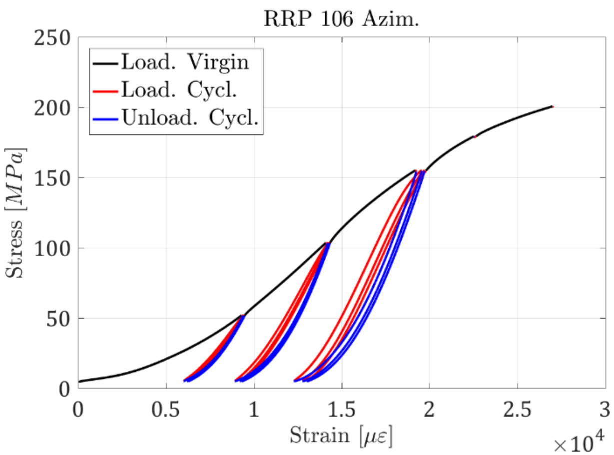
- Does this law **apply** also **to** our **coils**?
- **How** can we **implement** it?

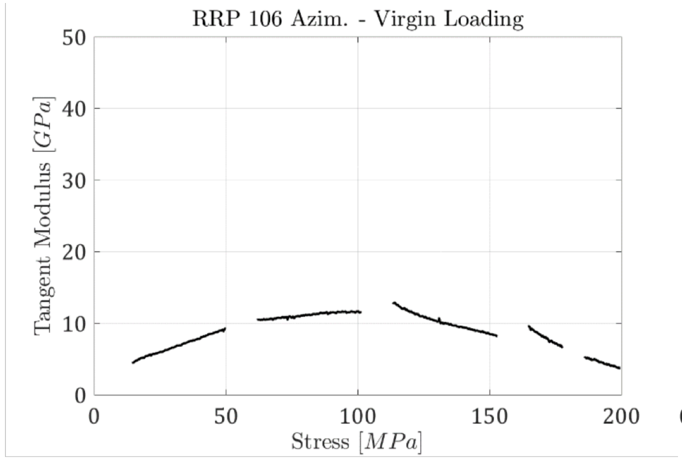
T. Wang et al., Cryogenics, 2014

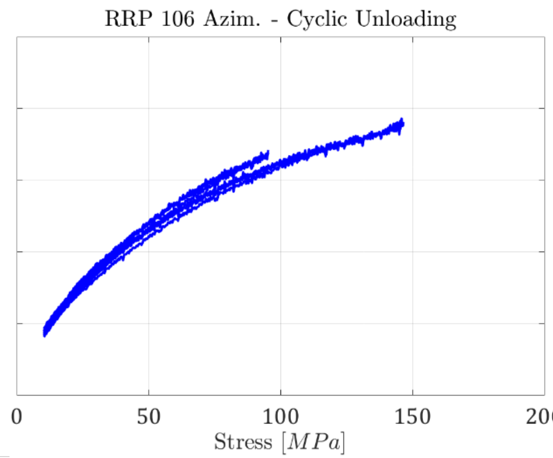
Outline

- Introduction
- Reversible Degradation in Strands
- Cable Stacks Under Transversal Pressure
- Critical Current Reversible Degradation
- Application to Superconducting Magnets
- Conclusion

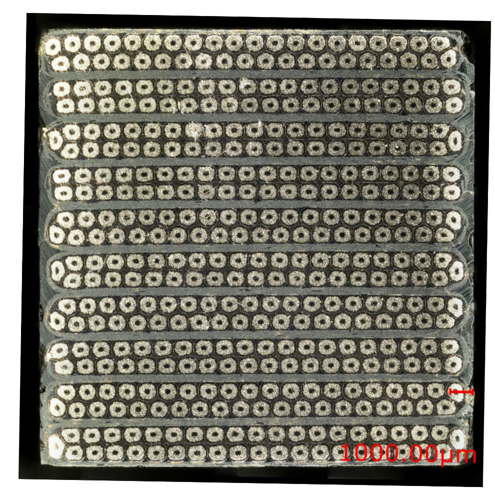
Cable Stacks – Transversal Pressure





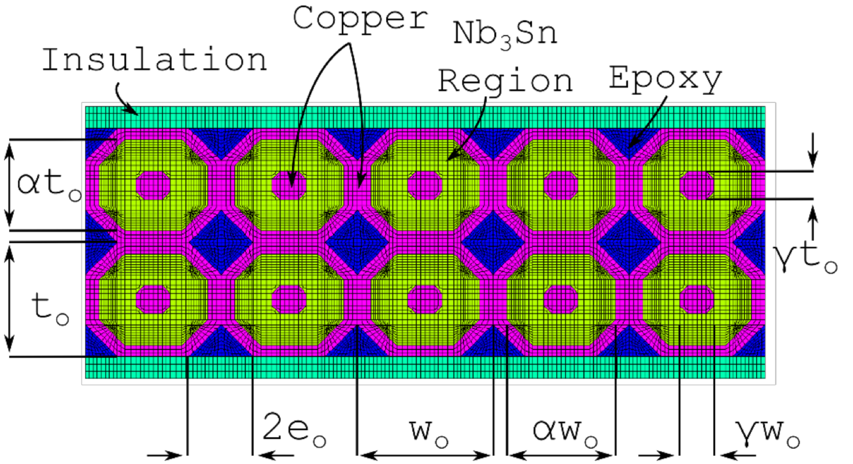


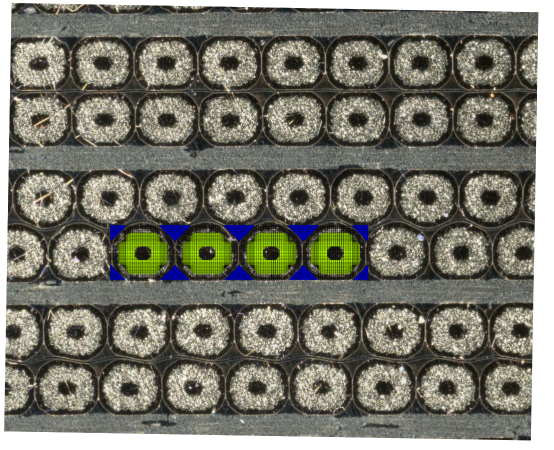
- Measurements on **stacks** of impregnated cables:
  - Very **different** behaviour in the **three phases**
  - The *chord and tangent modulus*† vary continuously during the test
- Probably difficult to condensate the coil elastic properties in a **single number** (elastic modulus)



† *ASTM - E111 - 04*

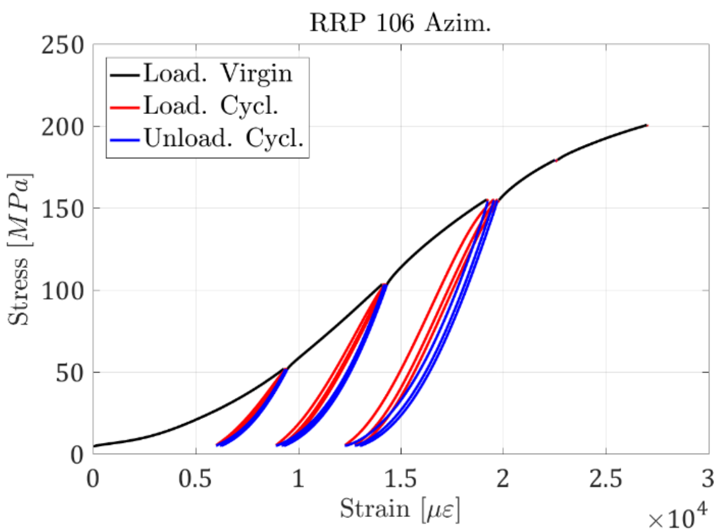
Cable Stacks – FE Model (1)

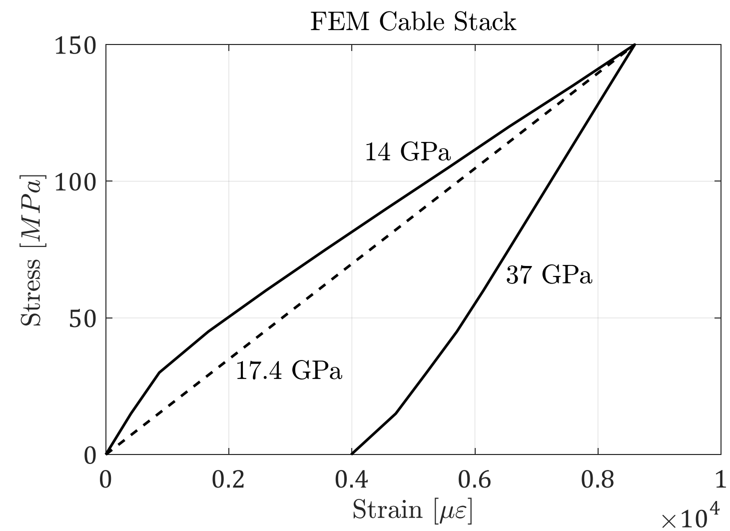




- 2D FE model of a Rutherford cable **stack**
- Material properties from literature
- Geometry from a mix of **image analysis** and simple geometric formulas to match the filling factor, copper-non copper etc.
- Stiffness validated against **measurements** on impregnated 10 stacks

Cable Stacks – FE Model (2)



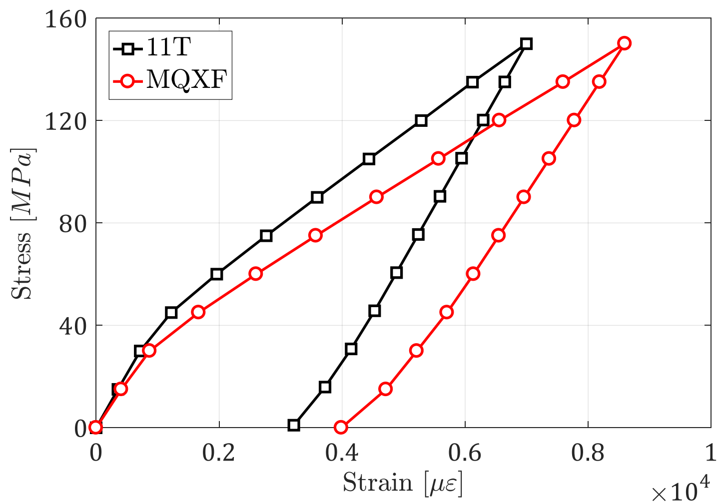


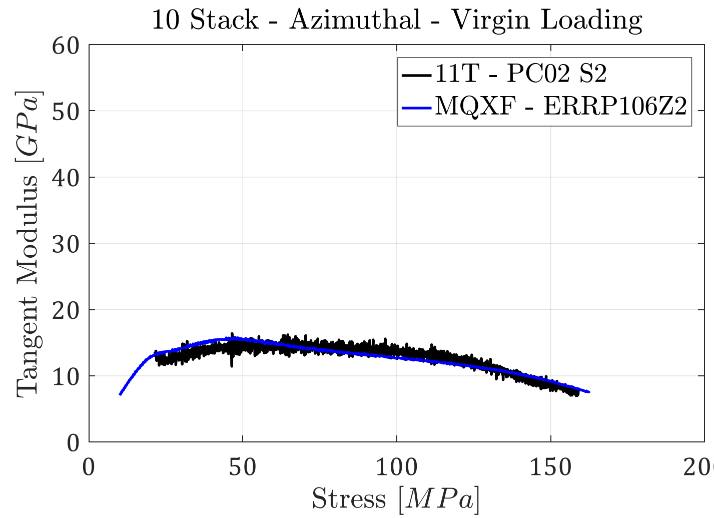
- Virgin/cyclic behaviour explained by **copper plasticization**
- FE slope *reasonably* good especially considering that **no** model **calibration** was necessary
- Initial phase may be due to **compaction**

MATERIAL PROPERTIES

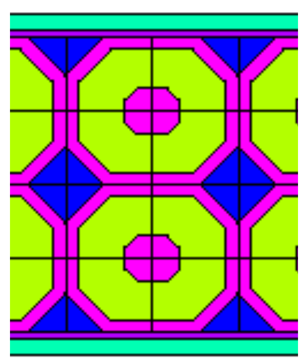
Parameter	Unit	Value
Copper Elastic Modulus (R.T.)	GPa	110
Copper Elastic Modulus (4.3 K)	GPa	120
Copper Yield Strength	MPa	40
Copper Tangent Modulus	GPa	5
Non-Cu Elastic Modulus (R.T.)	GPa	100
Non-Cu Elastic Modulus (4.3 K)	GPa	70
Epoxy Resin Elastic Modulus	GPa	5
Impregnated Insulation Elastic Modulus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

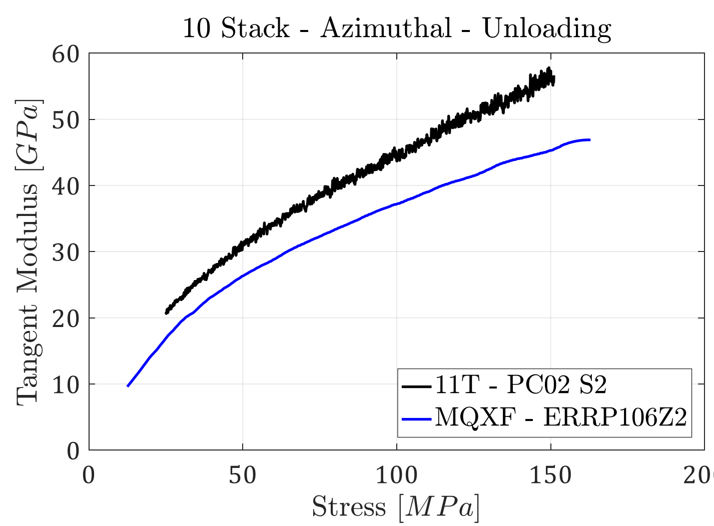
Comparison with 11T Cable





- 11 T Stack Modulus - Model:
  - Virgin Loading – 17 GPa
  - Unloading - 42 GPa
- MQXF Stack Results - Model:
  - Virgin Loading – 14 GPa
  - Unloading - 37 GPa



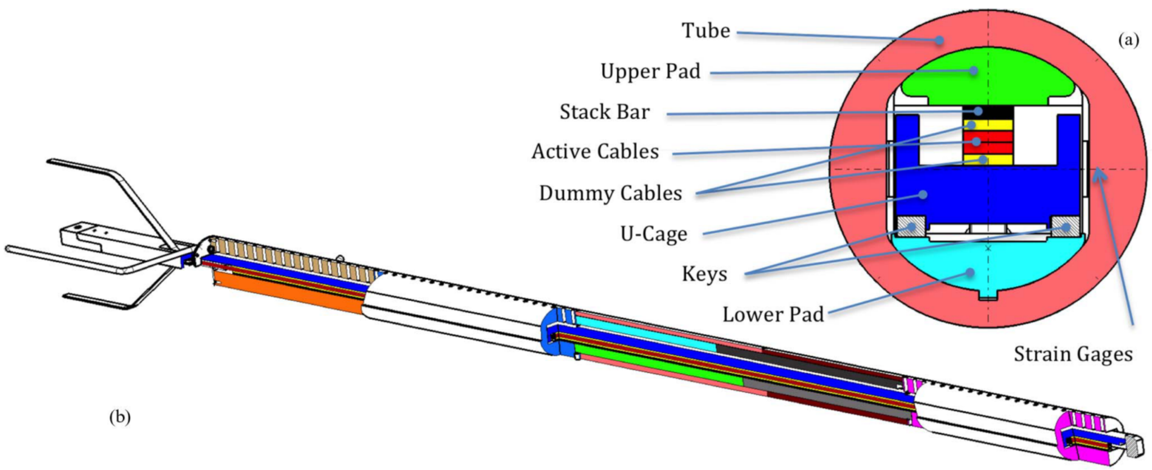


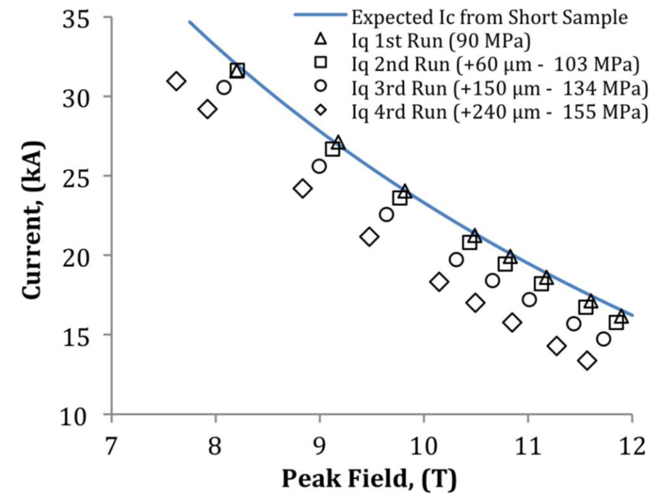
11T Data: M. Daly et al., IEEE TAS, 2017

Outline

- Introduction
- Reversible Degradation in Strands
- Cable Stacks Under Transversal Pressure
- Critical Current Reversible Degradation
- Application to Superconducting Magnets
- Conclusion

FRESCA Sample Holder (1)



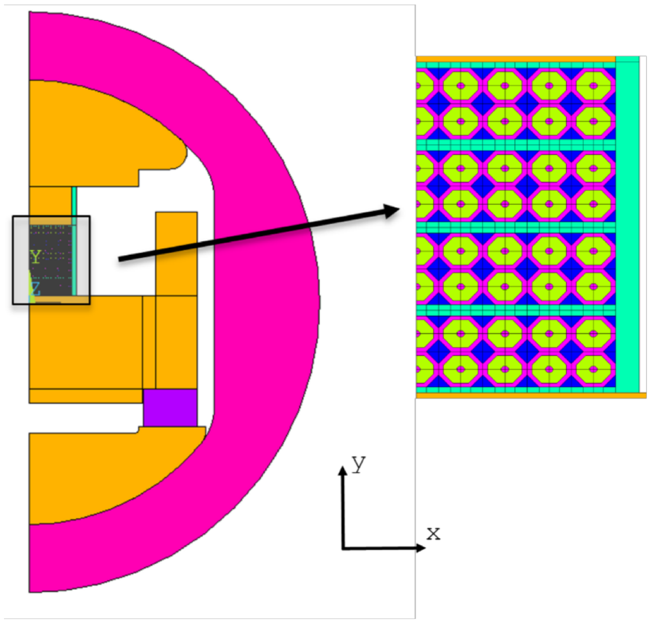


- A novel FRESCA sample holder was built and used at CERN. This tool allows to **measure** the **critical current** of stacks of impregnated cables under **transversal pressure**.

- 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)

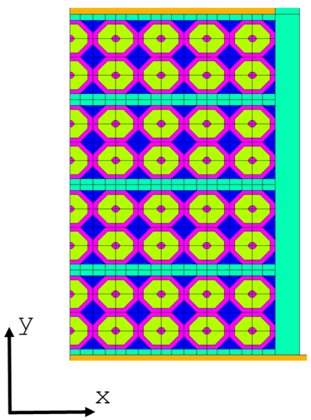


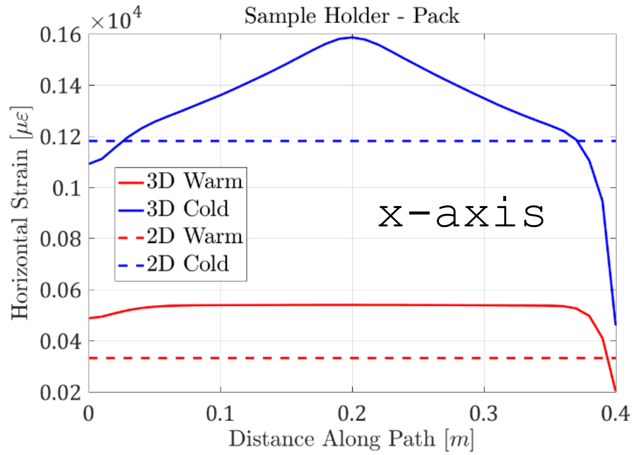
Parameter	Unit	Value - A†	Value - B‡
Strand	/	RRP 108/127	PIT 192
Strand diameter	mm	0.85	1.0
Number of strands in cable	/	40	18
Copper to non-copper	/	1.2	1.22
Twist Pitch	mm	14	63
Cable Bare Width	mm	18.15	10
Mid Thickness	mm	1.525	1.81
Keystone Angle	degrees	0.40	0

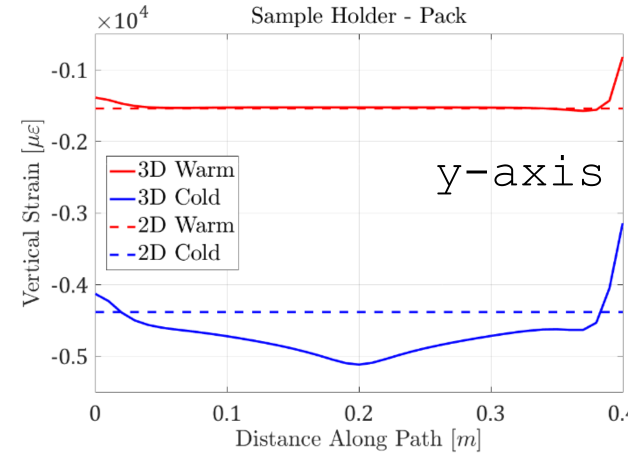
† 10-stack cable (MQXF [13]) - E measurements.
‡ Sample holder cable [3] - Critical current measurements.

- **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

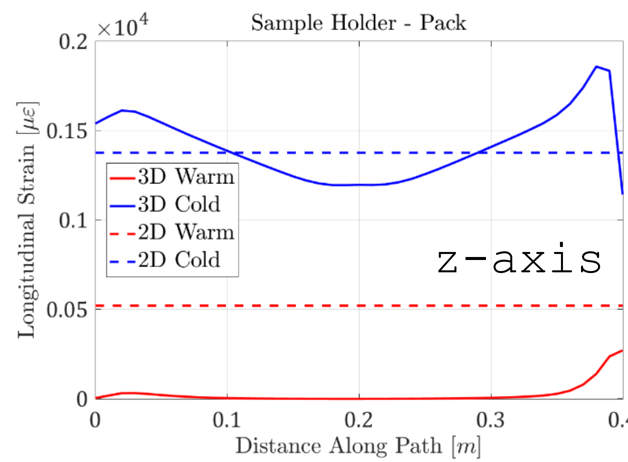
FRESCA Sample Holder (3)







- The **strain function** requires the 3D strain **tensor**…
- **2D vs 3D** FE **block** model (stack strain):
  - Similar **average**
  - 20% **more vertical** strain in the center
  - z-axis strain only due to **Poisson** effect

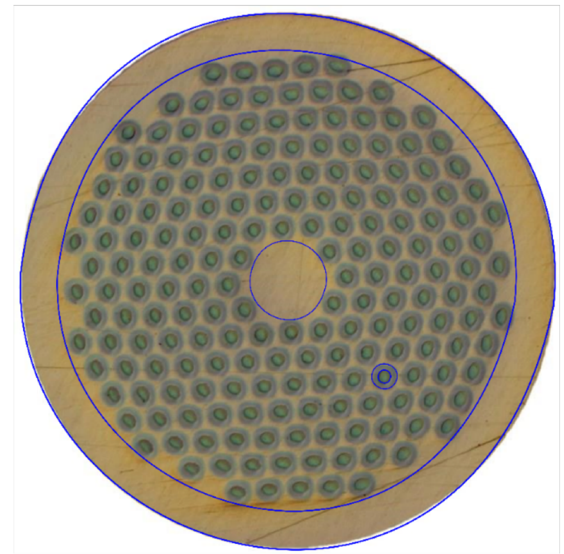


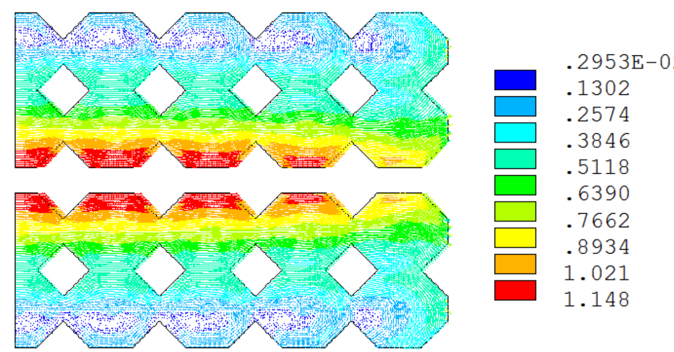
Stack Degradation - Effective Strain

- The horizontal and vertical strain in the Nb_3Sn area were **amplified** with a **constant factor** α_f: **stress amplification** factor to *scale* the model to the **filament** level (*strand-to-filament amplification factor*)

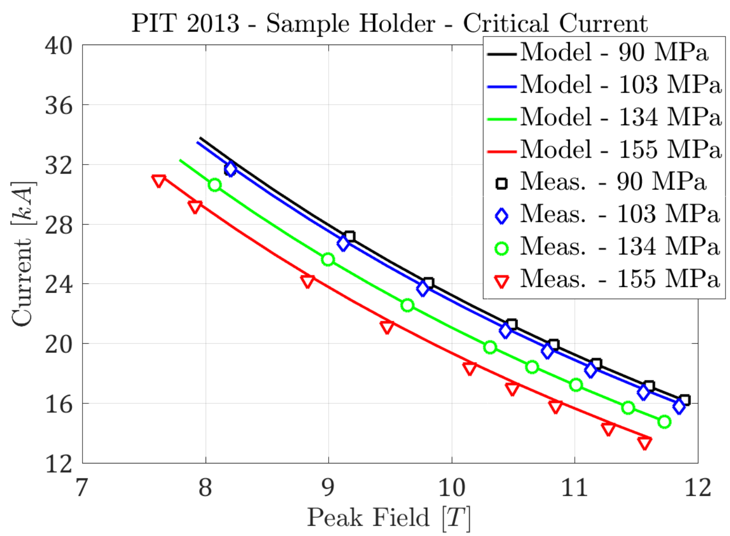
- The parameter was **calibrated against measurements** and found equal to **1.7**:
  - 2D → 3D: 20% local increase
  - The remaining 50% is very close to the amount of non-superconducting material in the superconducting region (~55% of the superconducting area)

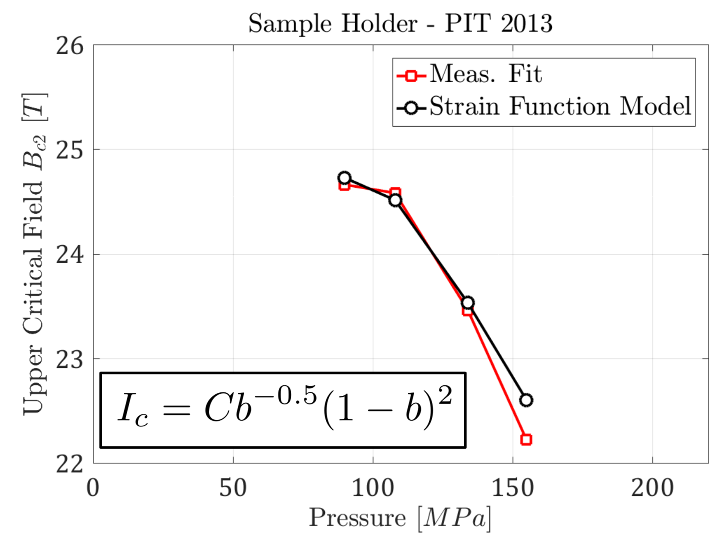
- Magnetic field: **background field + self-field**





Stack Degradation – Results





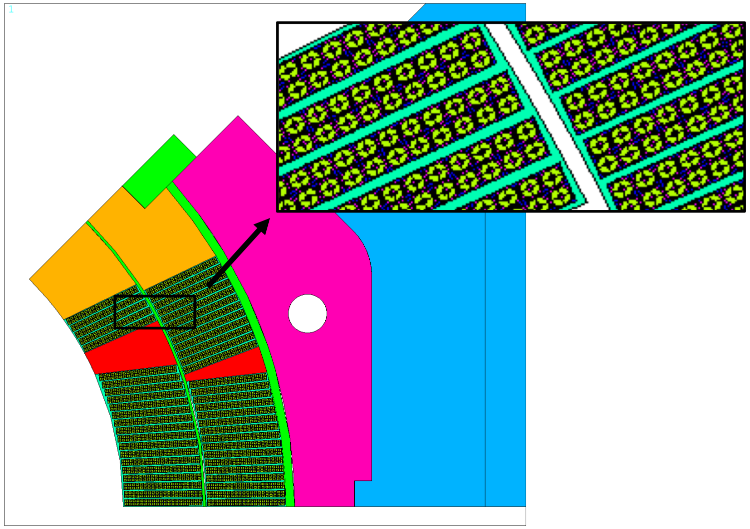
- Quench **currents** are matched *reasonably* well. Notice that:
  - On the last loading there was a small **irreversible** degradation
  - The quenches at 90 MPa were at **short sample limit**. The model correctly predicts the same strain function at 0 MPa

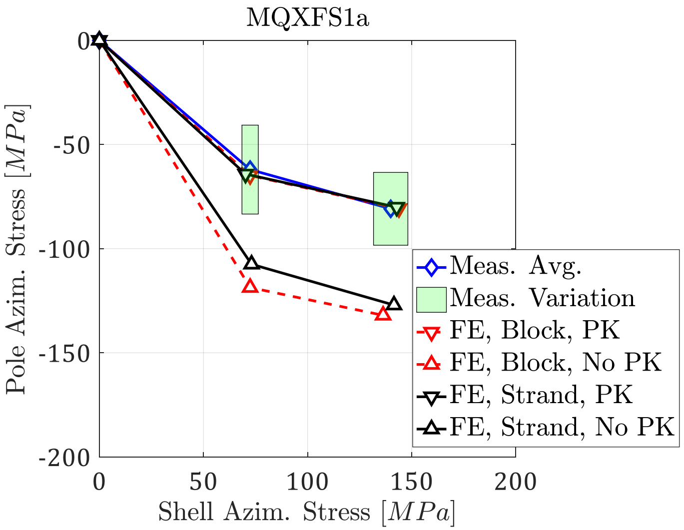
- The **upper critical field** as computed fitting the critical currents is also well captured by the model

Outline

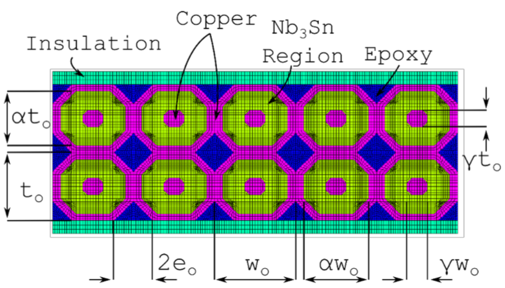
- Introduction
- Reversible Degradation in Strands
- Cable Stacks Under Transversal Pressure
- Critical Current Reversible Degradation
- Application to Superconducting Magnets
- Conclusion

MQXF – Strand Model





- **MQXF magnet** *strand* model
  - Same **approach** as for the Cable Holder / 10 stack model
  - **Preload** and **cool-down** simulation
  - Results match the 'Shell-Pole **Transfer Function**'



- **Thermal contraction** in the green area computed as:

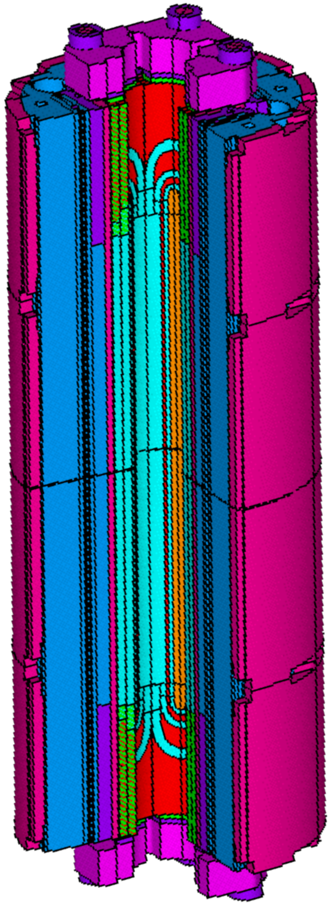
$$\alpha_g = \rho_{Nb_3Sn}\alpha_{Nb_3Sn} + \rho_{Cu}\alpha_{Cu}$$

Outline

- Introduction
- Reversible Degradation in Strands
- Cable Stacks Under Transversal Pressure
- Critical Current Reversible Degradation
- Application to Superconducting Magnets
- Conclusion

Conclusion

- Impregnated **cable stacks** under **transversal pressure**:
  - **Stiffness** is continuously varying
  - Comparison with **FE** model shows that the **copper plasticization** may explain part of this behaviour
- Cable stack **degradation model** results suggest that:
  - The stack degradation may be reproduced using a **law** developed on **axial tests**
  - We do not need to model the **filaments**
- Application to magnets:
  - Cable model allows to **fit** well the **measurements**
  - We still have to compute the **degradation** for this case



Thanks for your attention!

More info available in:

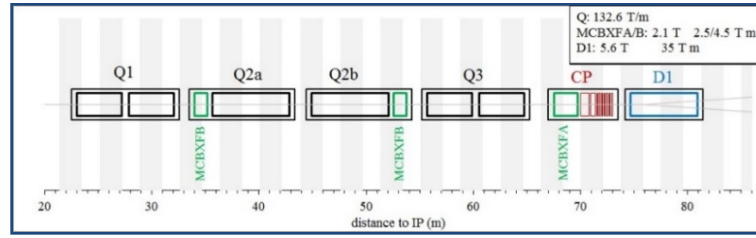
[1] G. Vallone, B. Bordini, and P. Ferracin, "Computation of the reversible critical current degradation in Nb_3Sn Rutherford cables for particle accelerator magnets", *IEEE Transactions on Applied Superconductivity*, vol. 28, no. 4, 2018.

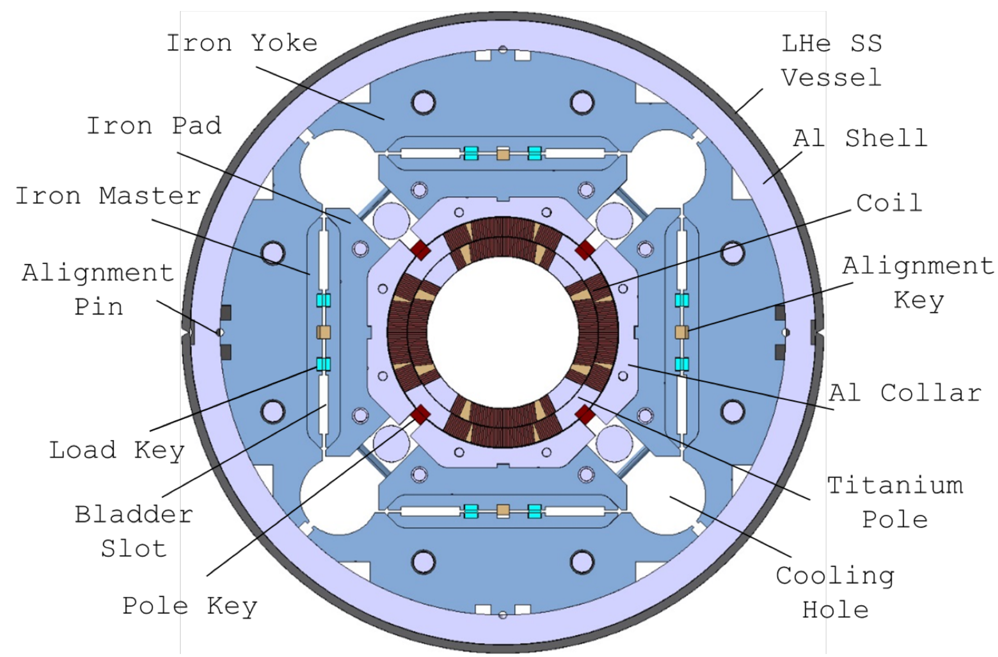
[2] G. Vallone *et al.*, "Mechanical analysis of the short model magnets for the Nb_3Sn low-β quadrupole MQXF", *IEEE Transactions on Applied Superconductivity*, vol. 28, no. 3, 2018.

Extra

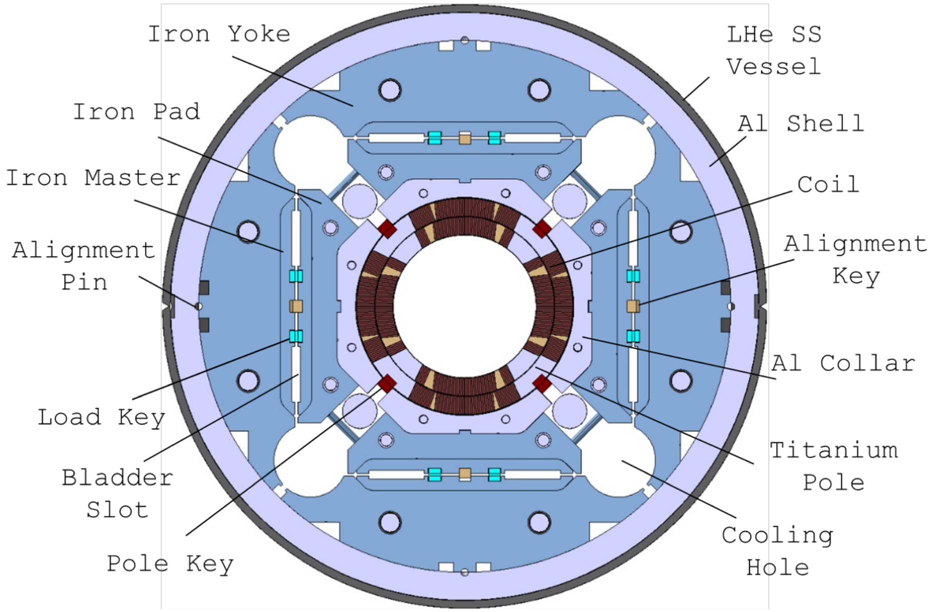
MQXF Design

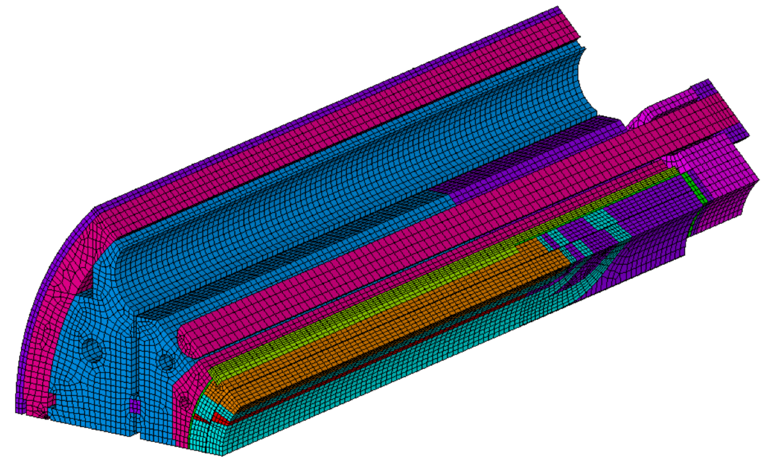
- LHC IR upgraded as a part of HiLumi project
  - Quadrupoles: NbTi → Nb_3Sn
- Target: 132.6 T/m
  - 150 mm coil aperture, 11.4 T B_{peak}
- Q1/Q3 (by US-AUP Project)
  - 2 magnets **MQXFA** with 4.2 m
- Q2a/Q2b (by CERN)
  - 1 magnet **MQXFB** with 7.15 m
- Different lengths, same design
- Short Models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

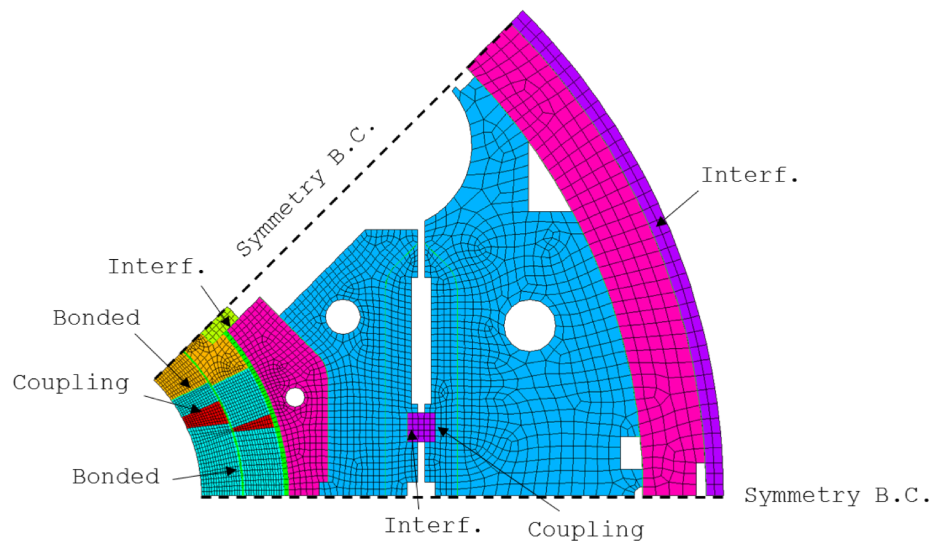




MQXF Prestress

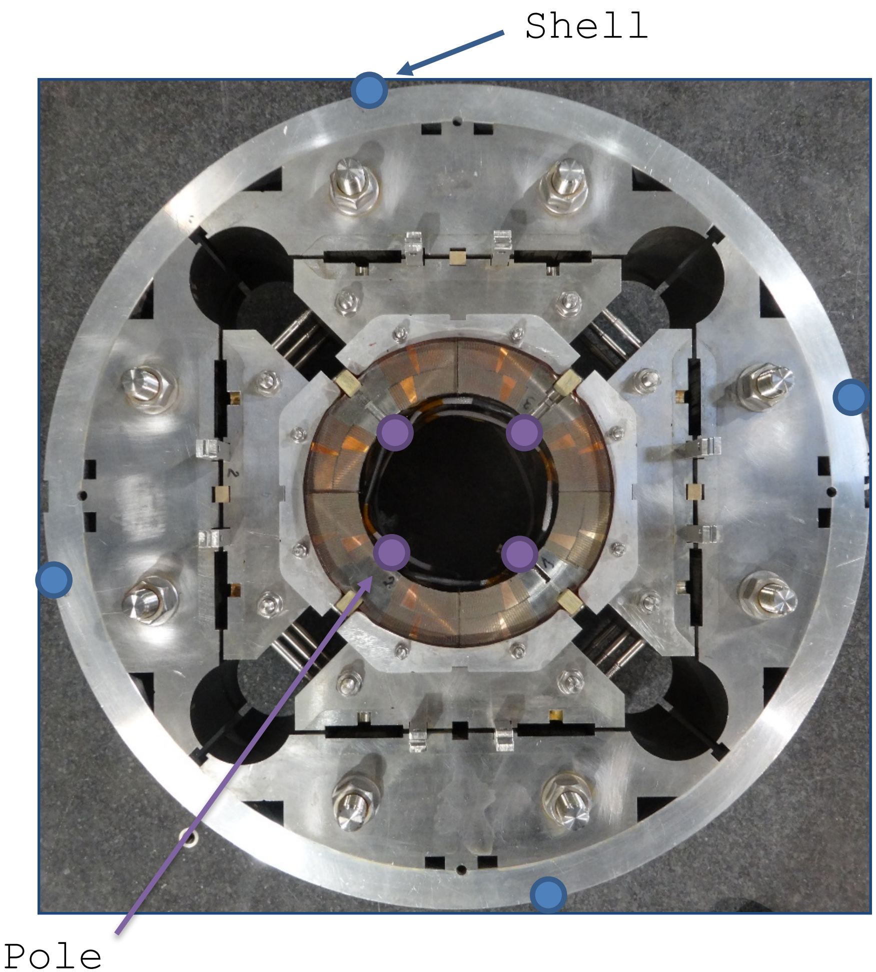


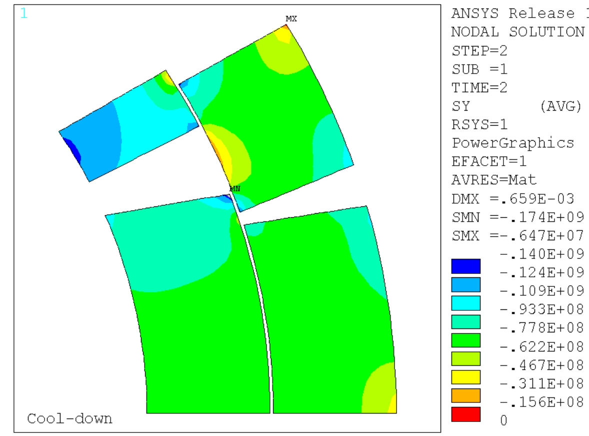


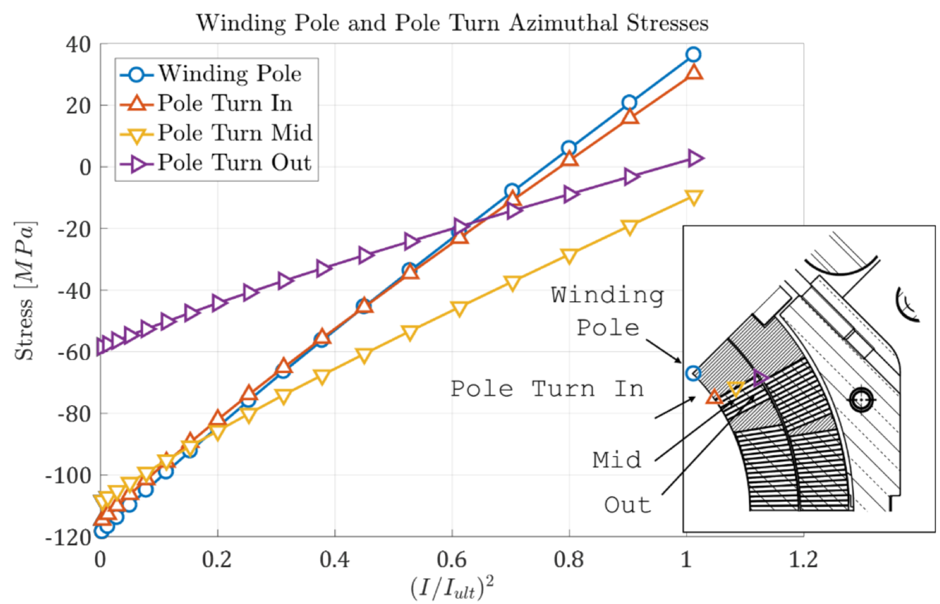


- Azimuthal preload at R.T. applied with **bladders & keys**
- Increased by the differential **thermal contraction** during cool-down

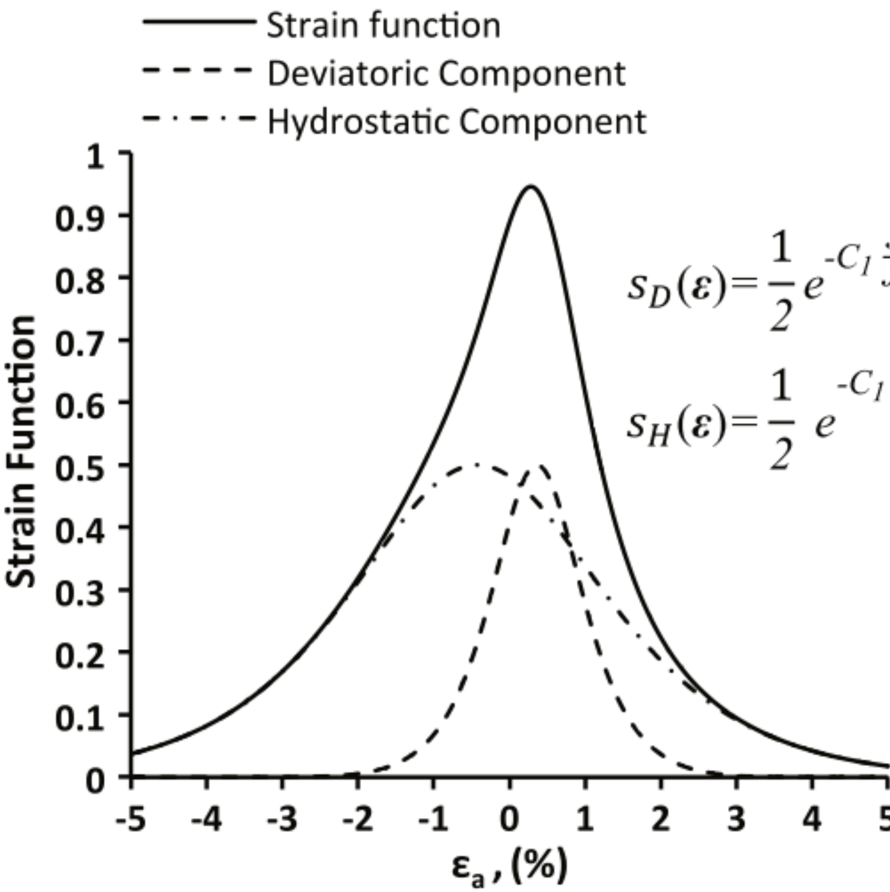
Strain Gauge Locations







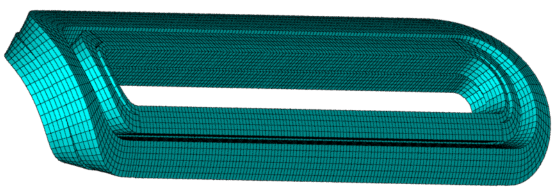
The Exponential Strain Function (x)



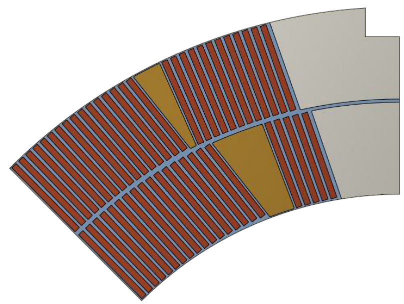
$$s_D(\varepsilon)=\frac{1}{2}e^{-C_1\frac{J_2+3}{J_2+1}J_2}$$

$$s_H(\varepsilon)=\frac{1}{2}e^{-C_1\frac{I_1^2+3}{I_1^2+1}I_1^2}$$

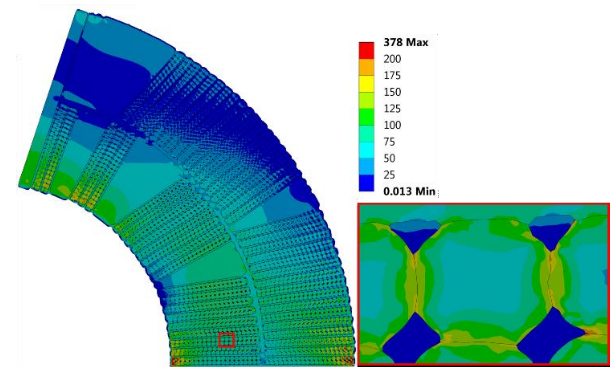
Modelling Strategies



Block Model



Cable Model
C. Löffler et al., EUCAS 2017



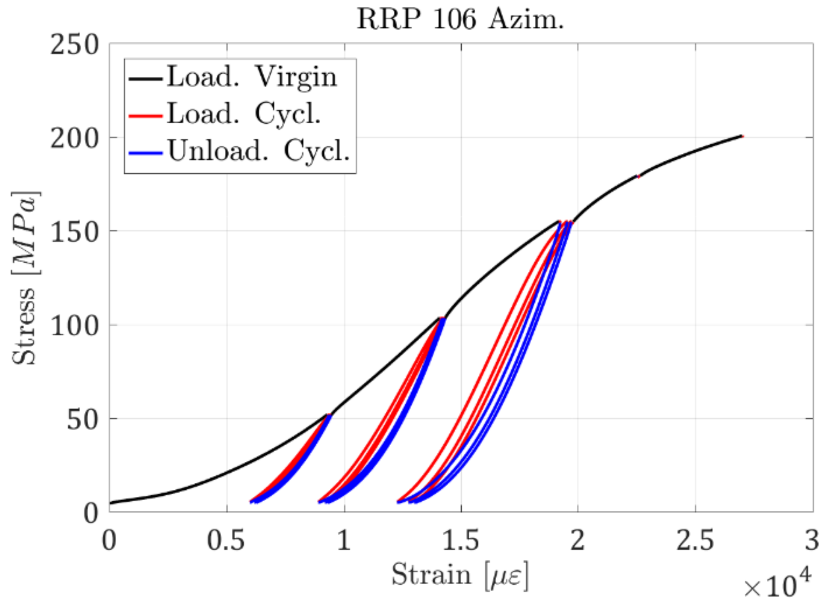
Strand Model
M. Daly et al., MT25, 2017

- **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

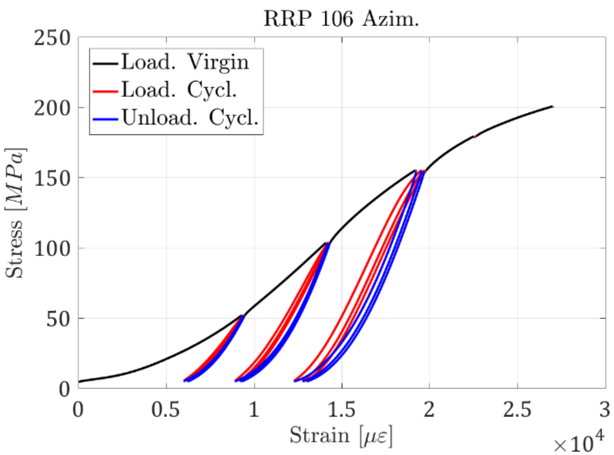
Cable Stacks – Transversal Pressure (2)

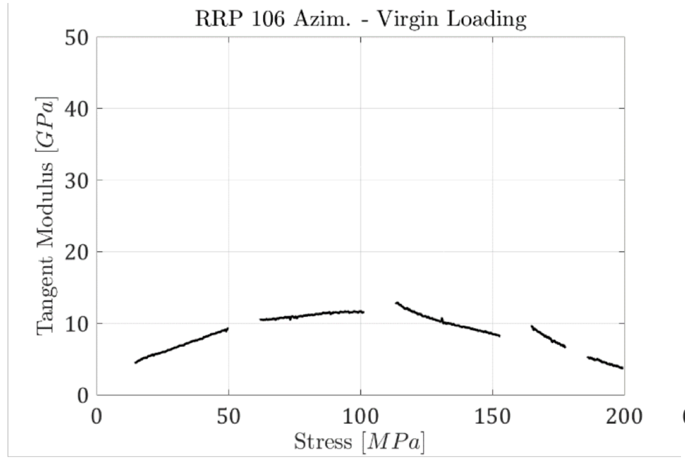


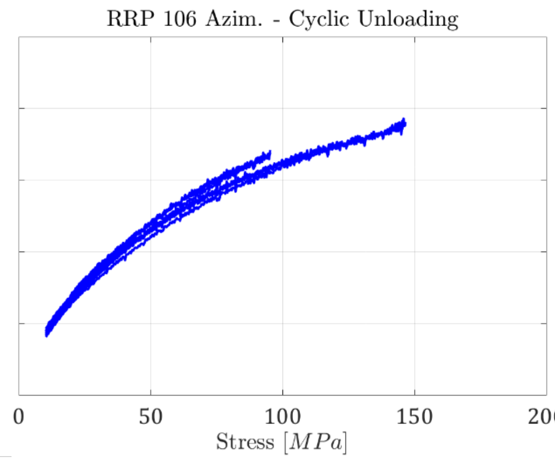
- The specimen (MQXF RRP cable) shows a clear division in **three zones**:
  - *Virgin* loading (black)
  - Unloading (red)
  - *Cyclic* loading (blue)

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

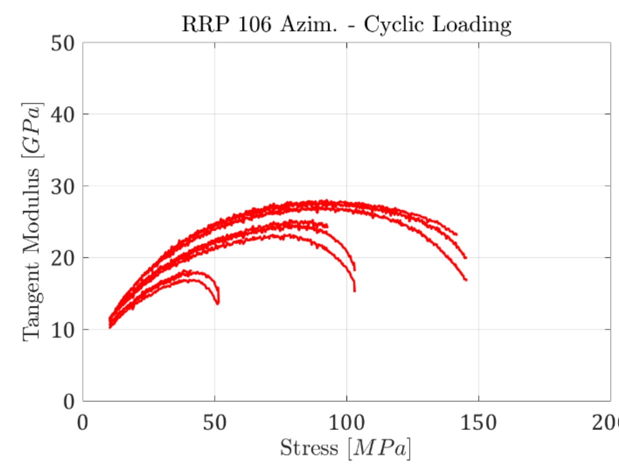
Cable Stacks – Transversal Pressure (2)







- 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 – Transversal Pressure (3)

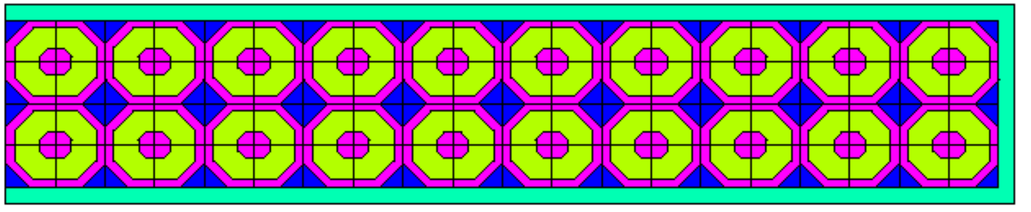
10 Stack - Chord and Tangent Modulus

	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]

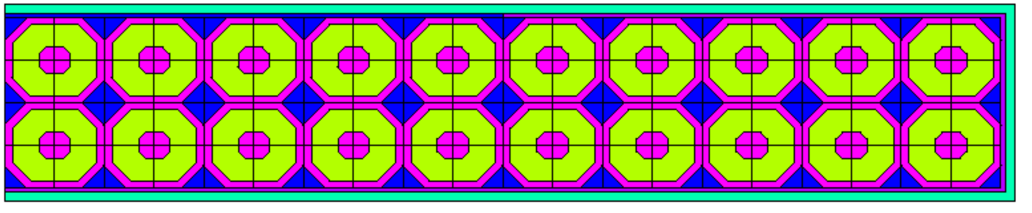
† Loading with a new level of maximum stress.
‡ Cyclic loading.

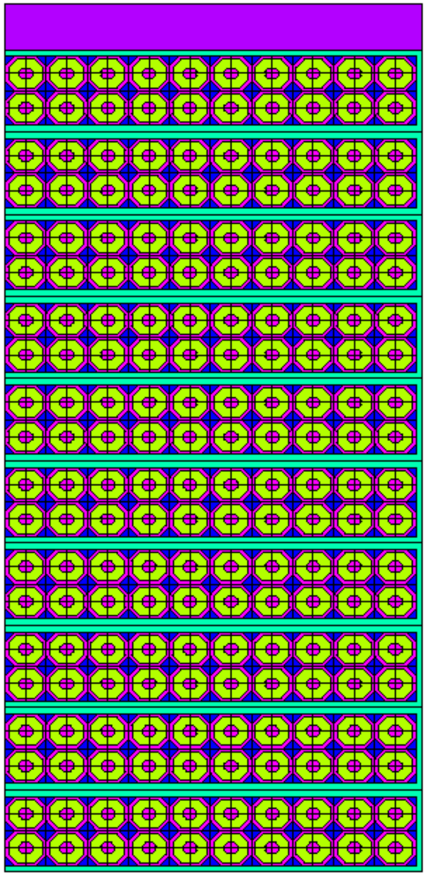
Comparison with 11T Cable

MQXF



11T



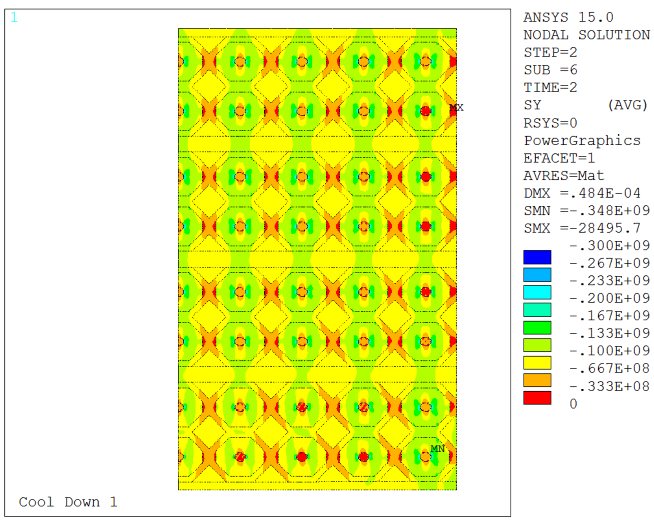


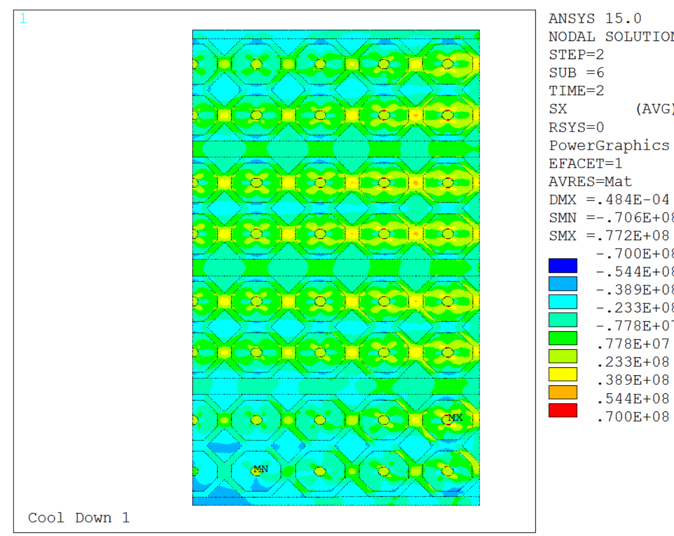
- How the modelling strategy performs on a **different cable**?
- We measured with the same procedure also **11T** cable stacks
- MQXF and 11T Cable comparison
- Mica assumed to be elastic, 170 GPa.

Stack Degradation - Effective Strain

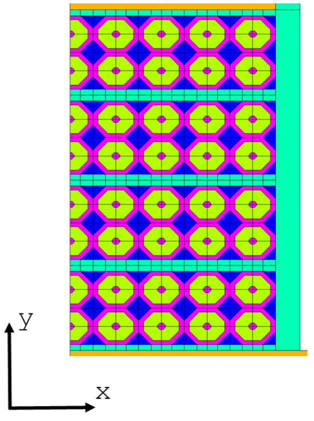
- Experiments show that strands have a longitudinal and transversal **pre-compression**
- This pre-compression **strain tensor** was **added** to the one computed by the **mechanical** model

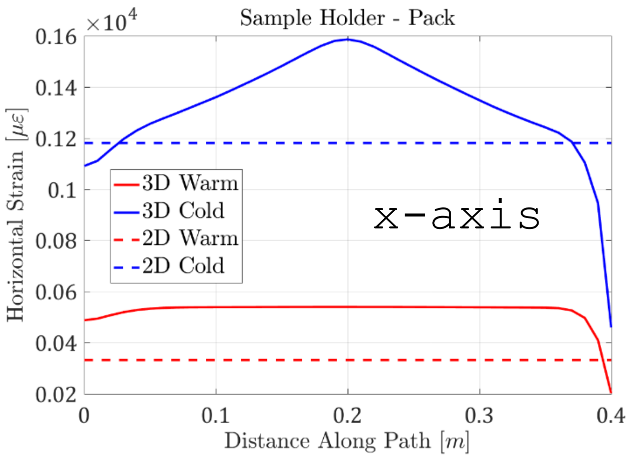
$$\varepsilon_{t0} = -\nu\varepsilon_{l0} + 0.1$$

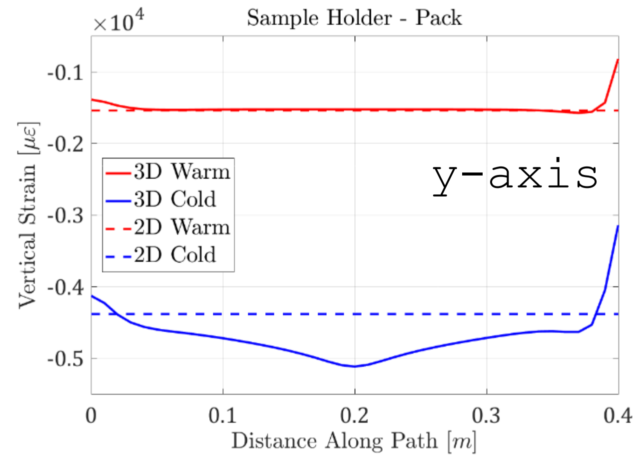




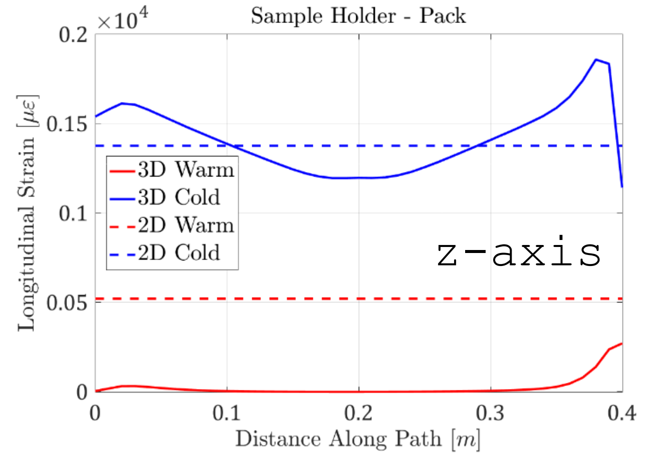
FRESCA Sample Holder (3)





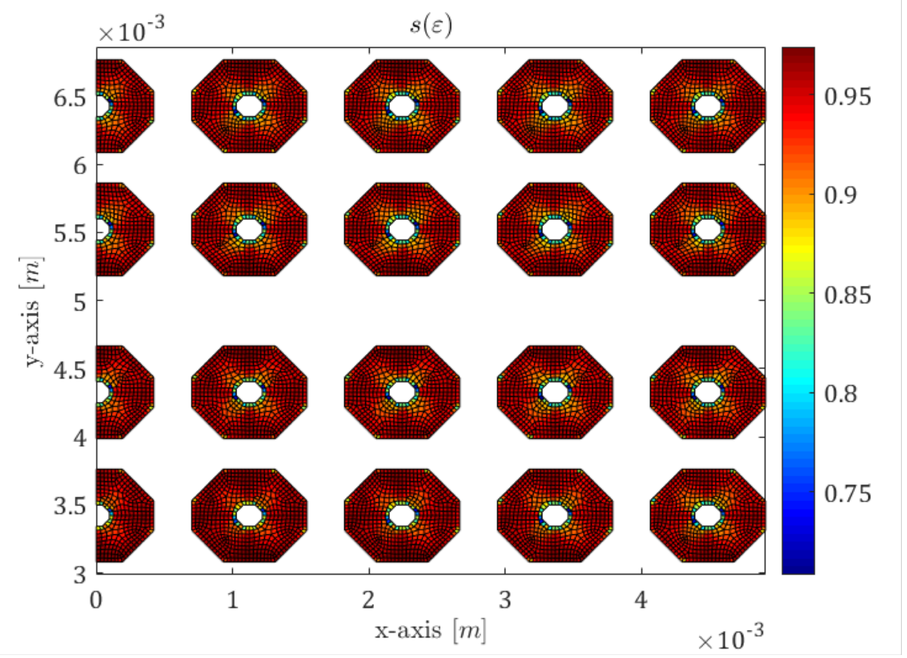


- The **strain function** requires the 3D strain **tensor**…
- **2D vs 3D** FE **block** model (stack strain):
  - Similar **average**
  - 20% **more vertical** strain in the center
  - z-axis strain only due to **Poisson** effect

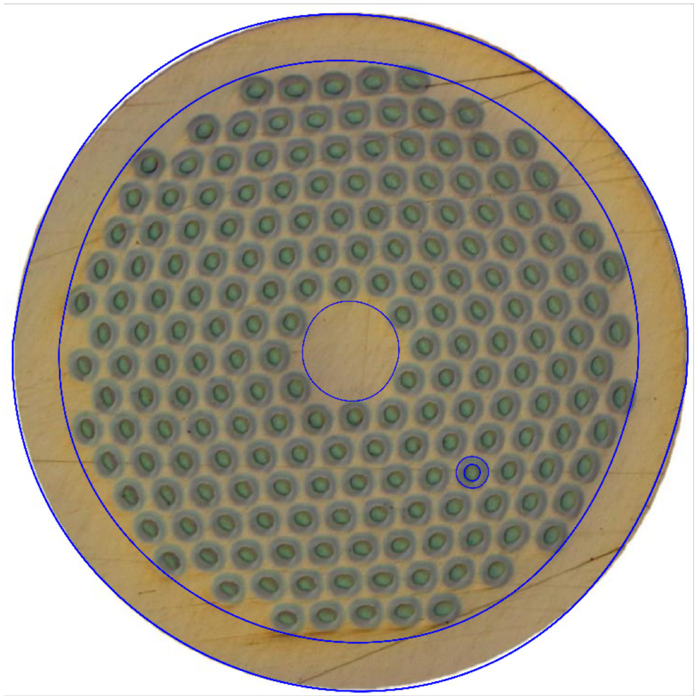


Stack Degradation – Strain Function

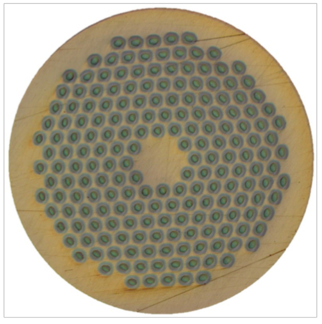
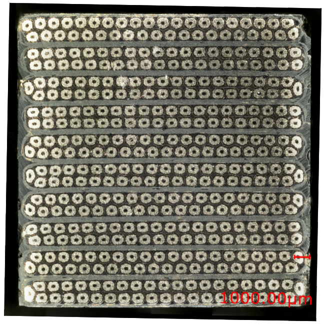
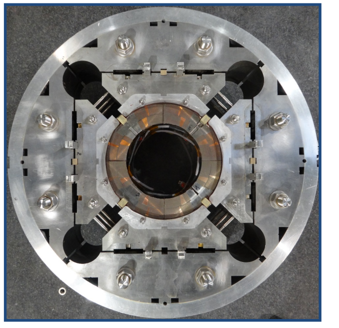
- Strands and filaments are twisted. We assume that the **same strain/field** along the sample will be experienced by:
  - **Strands**
  - **Filaments** at the same distance from the strand center
- We also assume that within the strand the current can redistribute between different filaments
- Therefore, we **average** the strain function **along** the strand **radius**

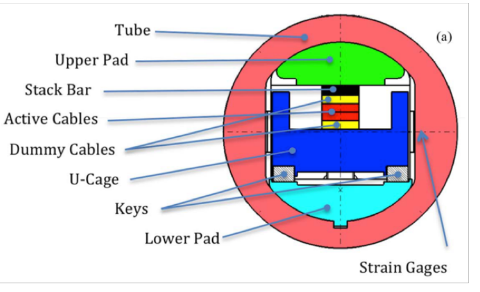


$$s_\mu(\theta) = \frac{1}{\Delta R} \int_{R_i}^{R_o} s(\boldsymbol{\varepsilon}(r,\theta))dr$$



Area inside the blue lines: 100%, 73.74%, 2.11%, 0.22%, 0.058%.



1000.00μm



Tube
Upper Pad
Stack Bar
Active Cables
Dummy Cables
U-Cage
Keys
Lower Pad
Strain Gages
(a)