Computation of the Reversible Critical Current Degradation in Superconducting Nb_3Sn Coils

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HiLumi LARGE HADRON COLLIDER
U.S. LARP

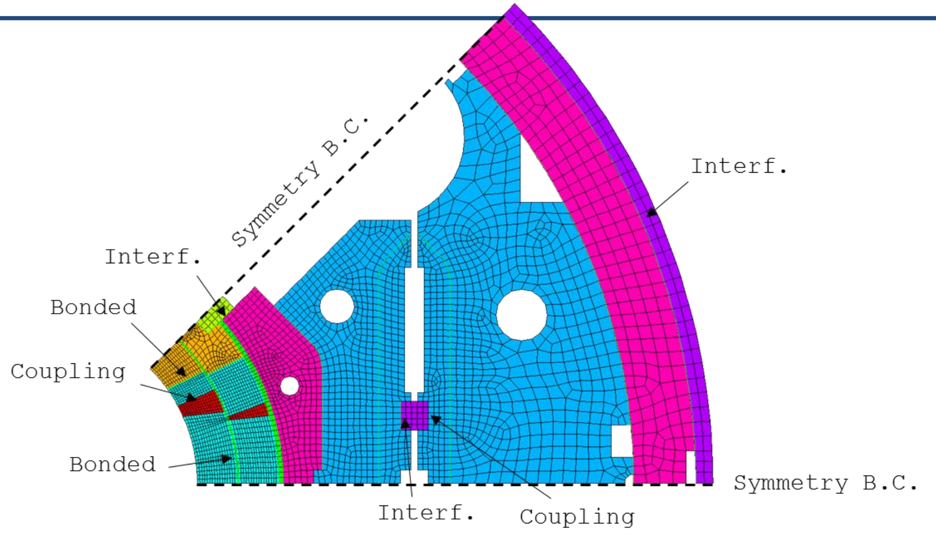
Outline

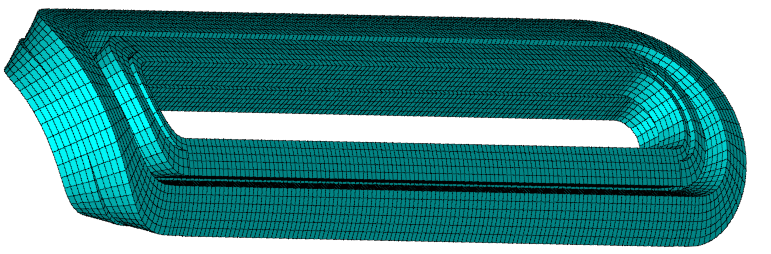
- Introduction
- Cable Stacks Under Transversal Pressure
  - Measurements
  - FE Model
- FRESCA Sample Holder Experiment
- Cable Stack Degradation
- Application to Superconducting Magnets
- Conclusion

Introduction

- **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
  - A similar effect was also measured on **Rutherford cable** stacks
- The **fields** required by particle accelerators are continuously **growing**
  - Stronger e.m. forces → higher stresses/strains → possible degradation compromising performances
- We need a **methodology** to evaluate the **magnet performances** under high stresses

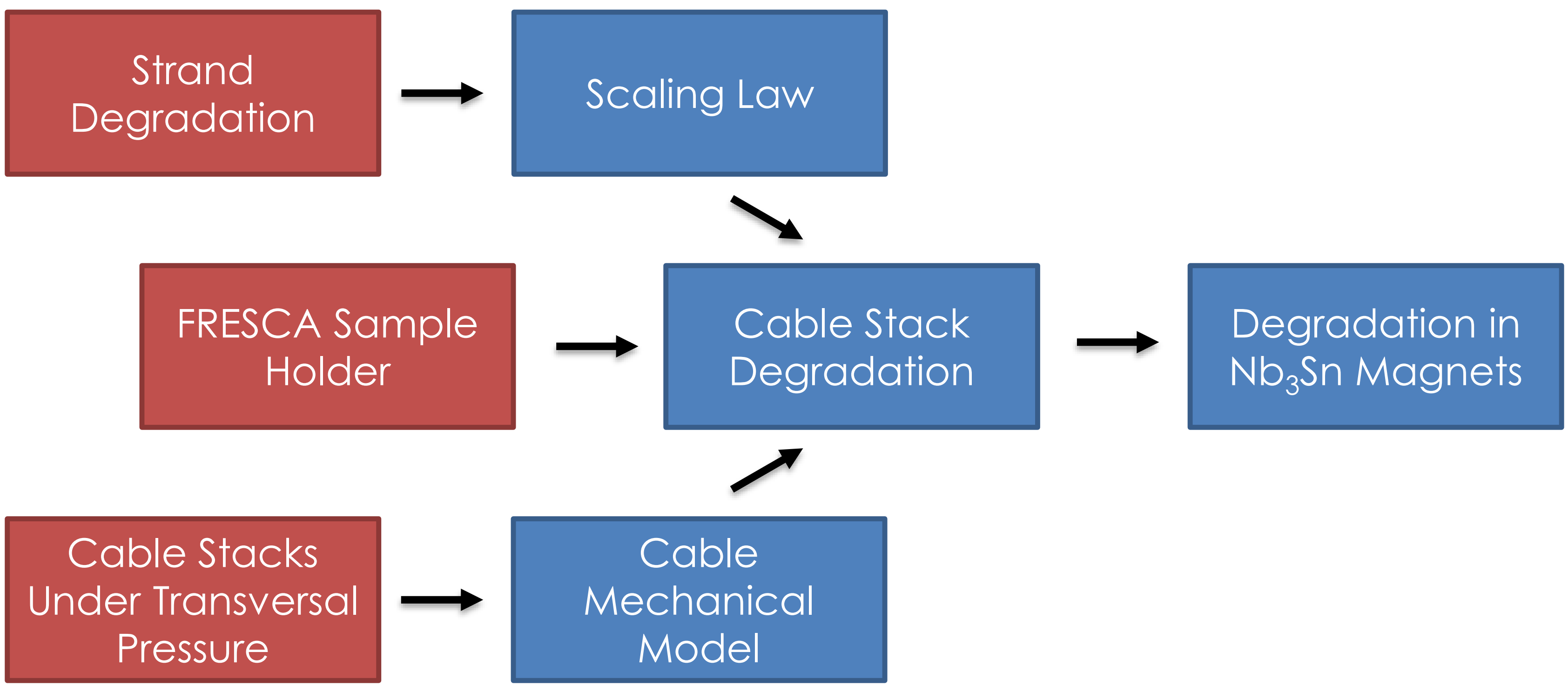
Coils Degradation

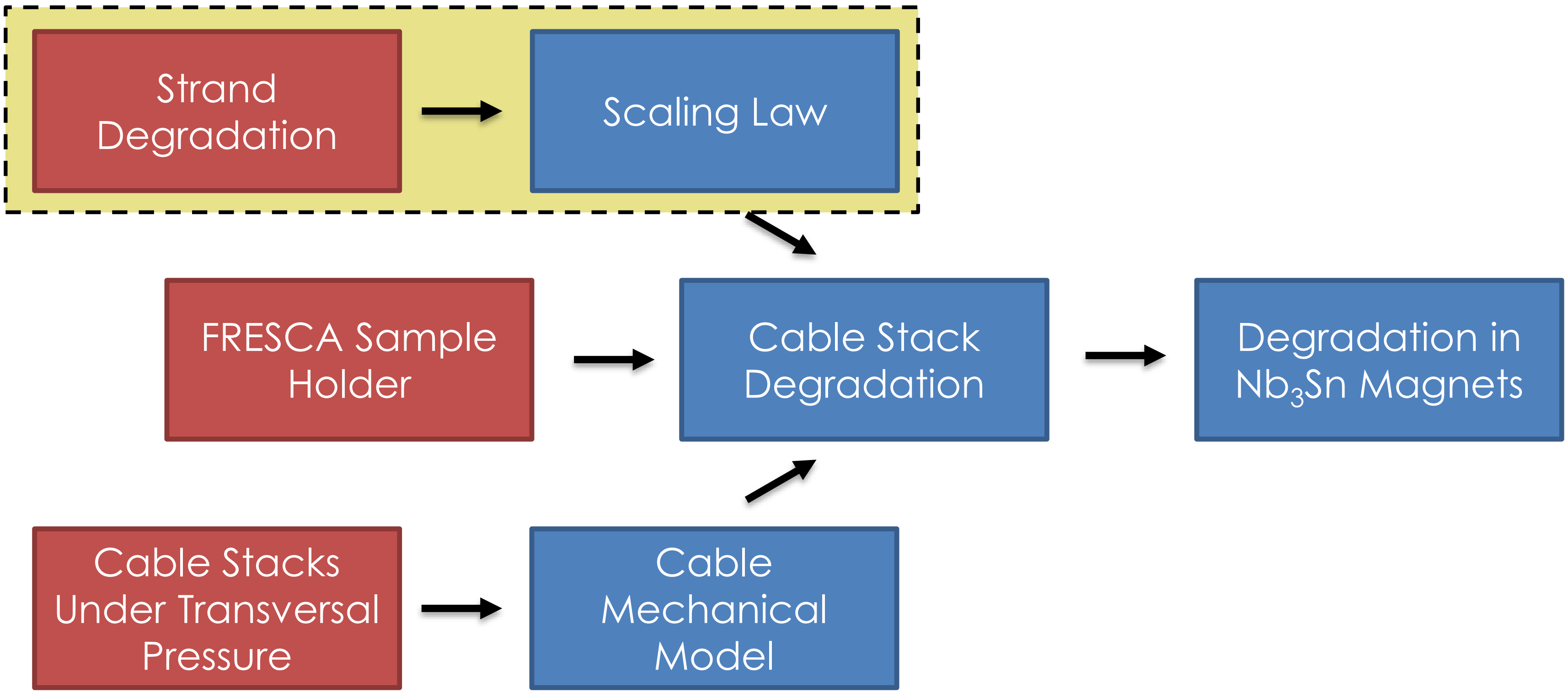




- Currently, we use an **empiric limit** of 150-200 MPa on the coil **equivalent stress**
- We *cannot* **measure** directly the **strain** on the **coil**
  - This limit is verified against **numerical model** results (eventually validated with indirect measurements)
  - In these models the coil is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

H. Felice et al., IEEE TAS, 2011


Strand Degradation
Scaling Law
FRESCA Sample Holder
Cable Stack Degradation
Degradation in Nb_3Sn Magnets
Cable Stacks Under Transversal Pressure
Cable Mechanical Model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Strand Degradation

- Significant amount of **experimental data** exists about the performance of Nb_3Sn wires under **axial strain**.

- 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:

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

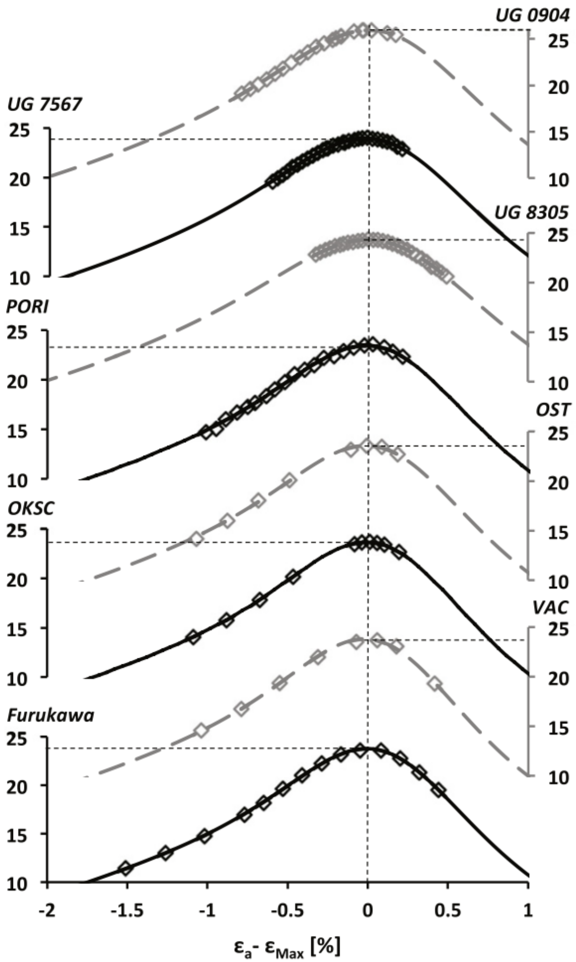
- With I_1 being the first invariant of the strain tensor and J_2 the second invariant of its deviatoric part:

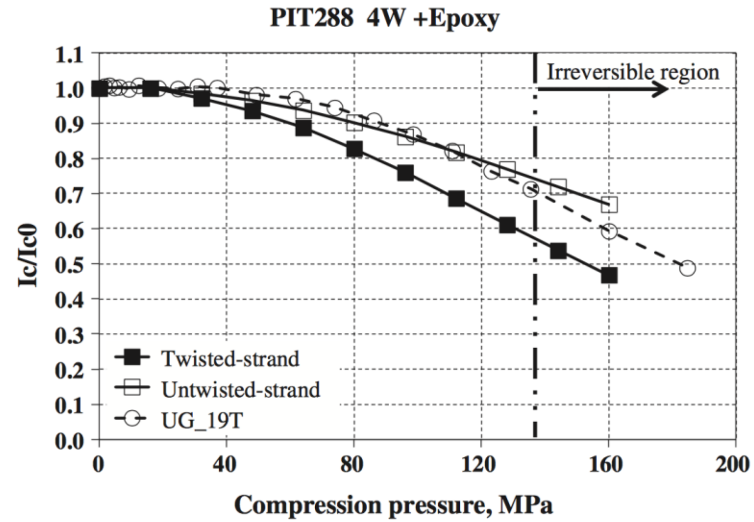
$$I_1 = \sum(\varepsilon_1 + \varepsilon_2 + \varepsilon_3)$$
$$J_2 = \frac{1}{6}\left[\sum(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2\right]$$

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

B. Bordini et al., SuST, 2013

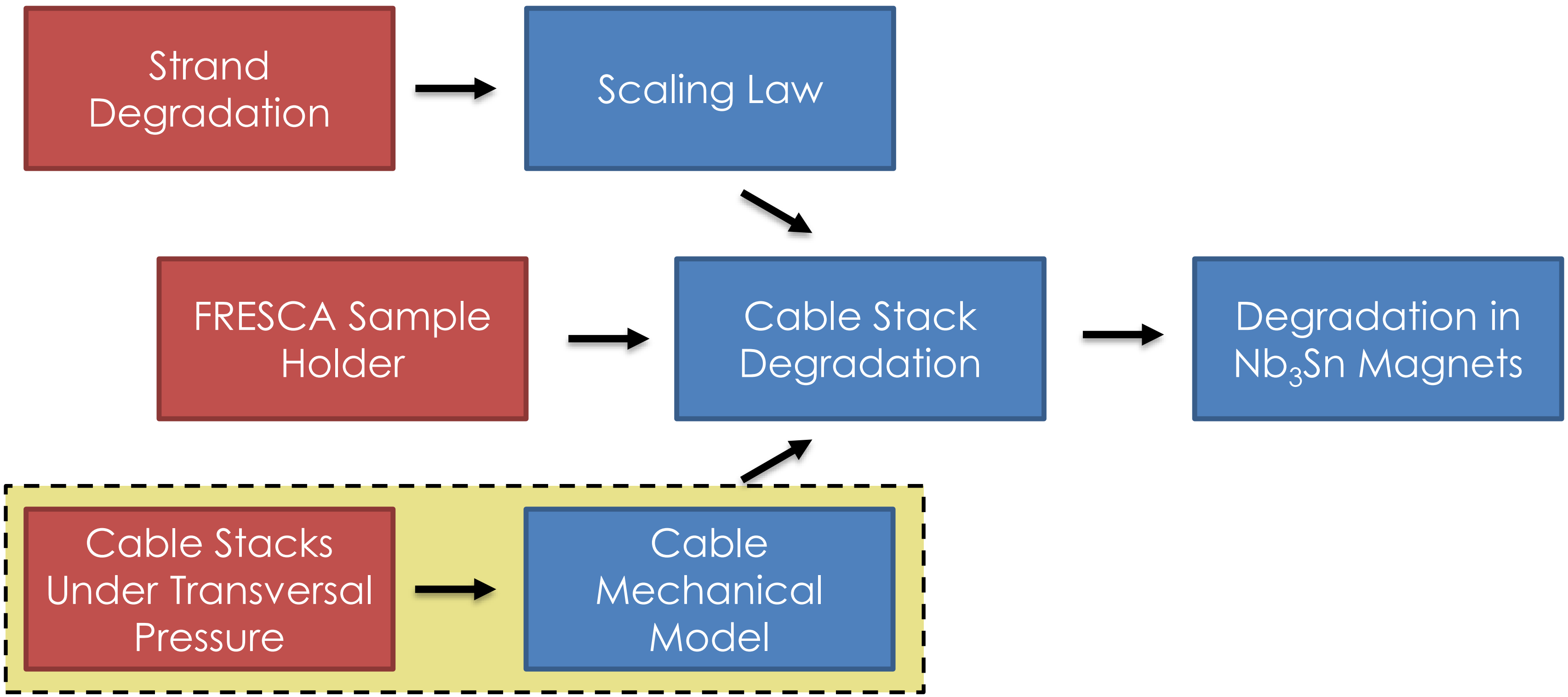
The Exponential Strain Function (2)





- 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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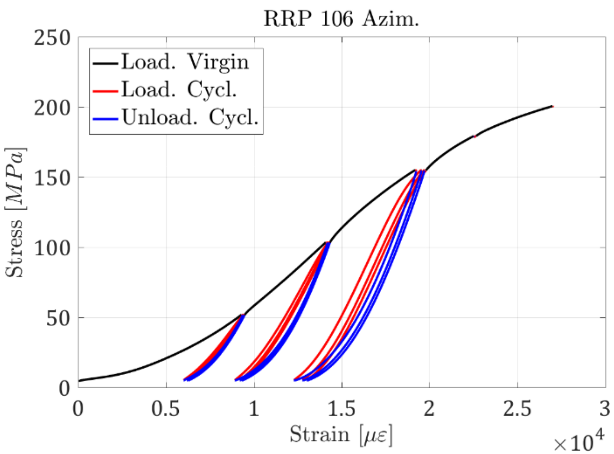
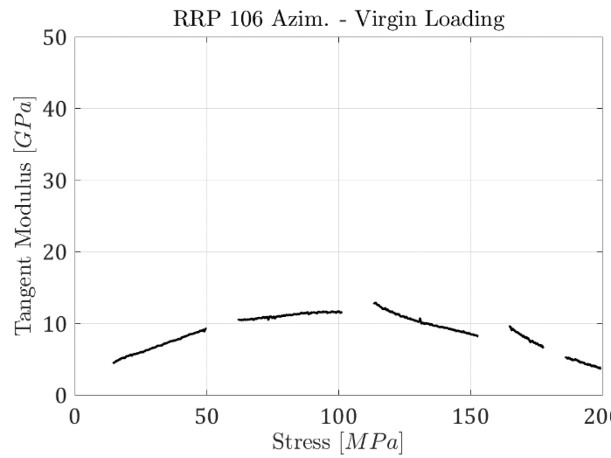
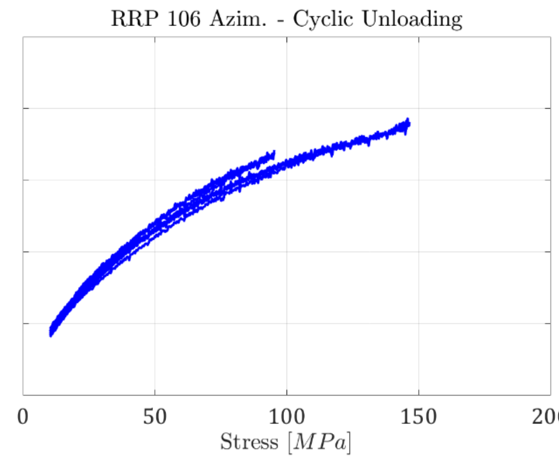
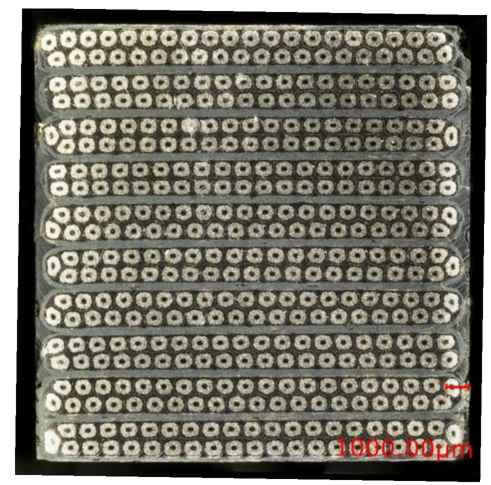
Cable Stacks – Transversal Pressure







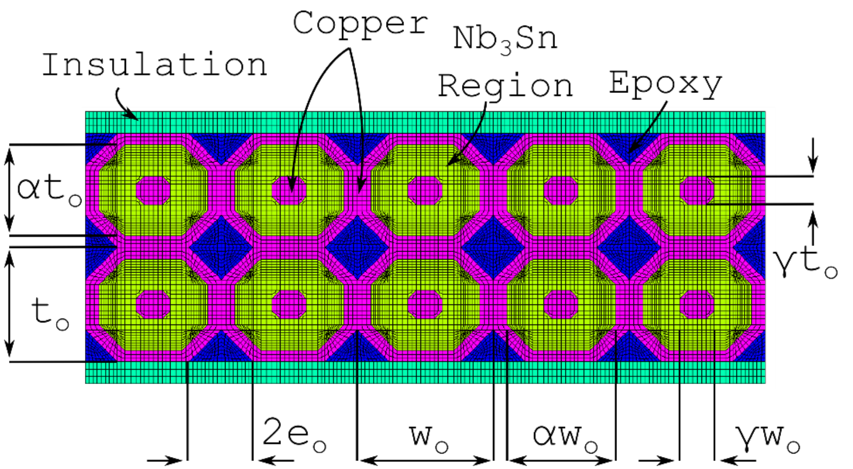
- Measurements on **stacks** of impregnated cables:
  - Very **different** behaviour in the **three phases**
  - The *chord and tangent modulus*† vary continuously during the test

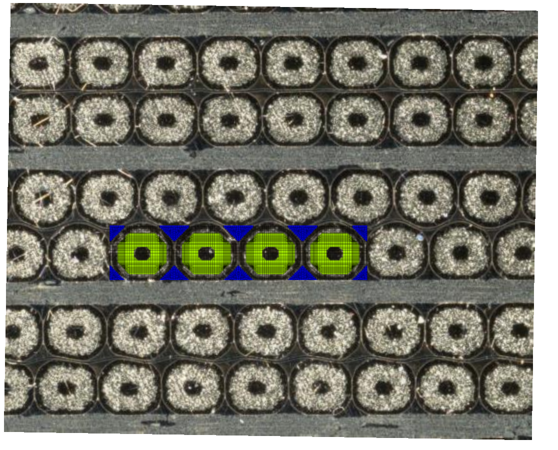


- Probably difficult to condensate the coil elastic properties in a **single number** (elastic modulus)
- **Non-linear** stress-strain relationship

† *ASTM - E111 - 04*

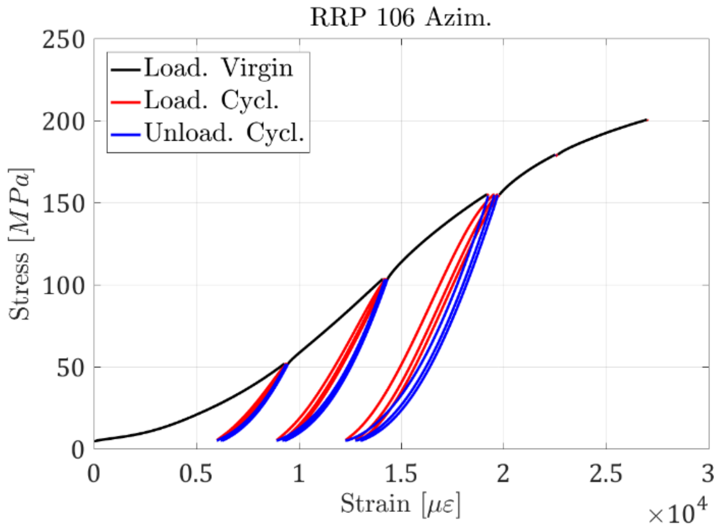
Cable Stacks – FE Model (1)

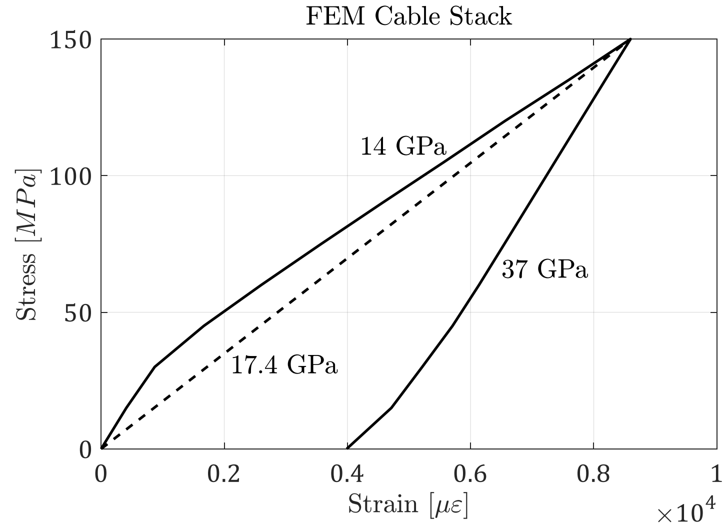




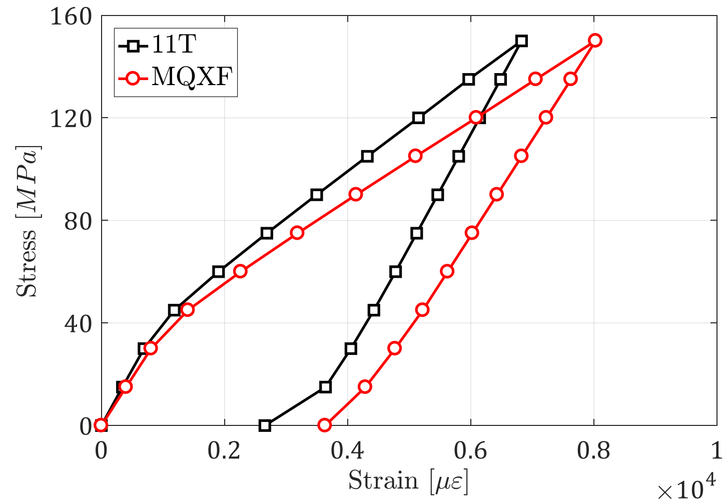
- 2D FE model of a Rutherford cable **stack**
- Material properties from literature
- Geometry from a mix of **image analysis** and simple geometric formulas to match the filling factor, copper-non copper etc.
- Stiffness validated against **measurements** on impregnated 10 stacks

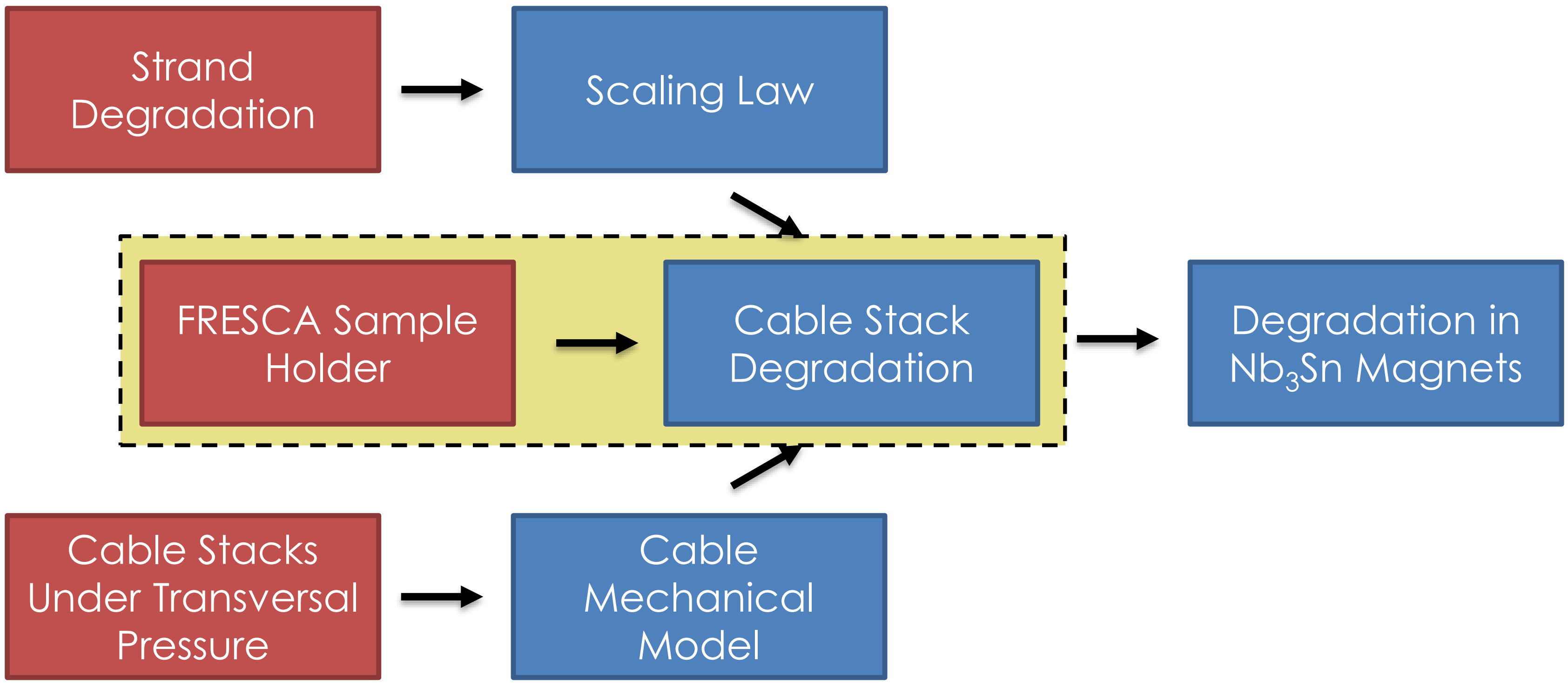
Cable Stacks – FE Model (2)





- Virgin/cyclic behaviour explained by **copper plasticization**
- FE slope *reasonably* good especially considering that **no** model **calibration** was performed
- Initial phase may be due to **compaction**
- **Model** predicts the higher stiffness (20%) of 11T cables

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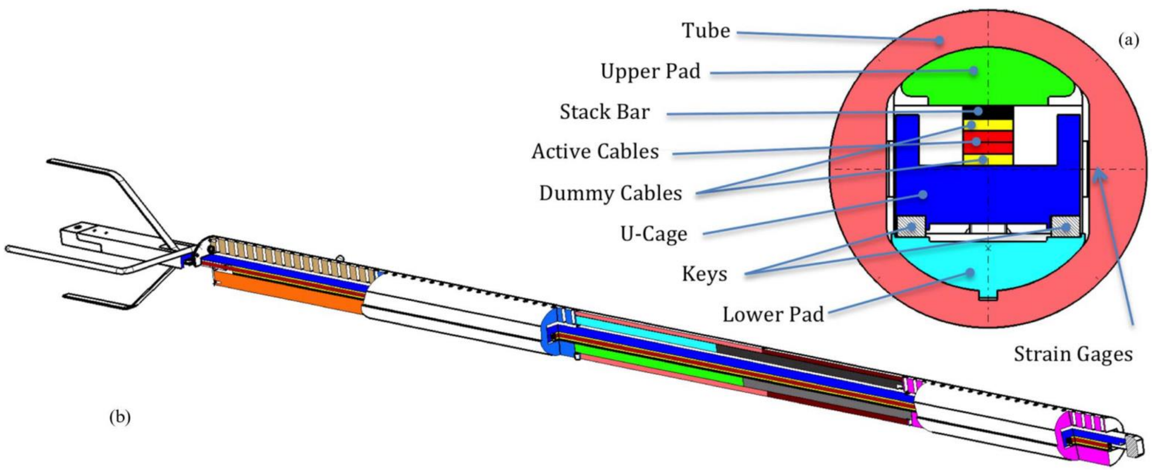
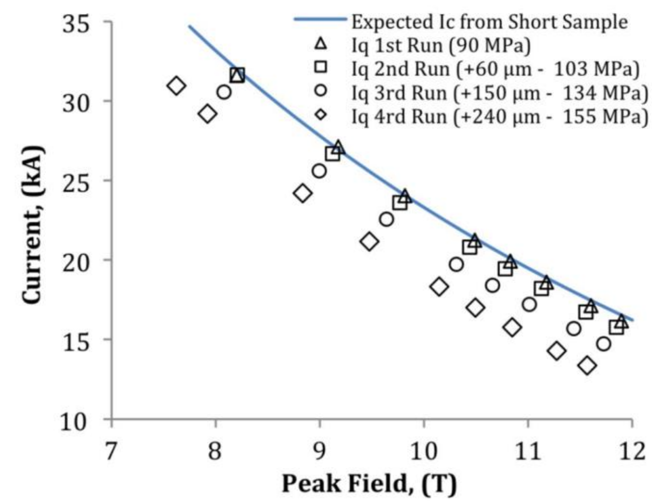
FRESCA Sample Holder (1)



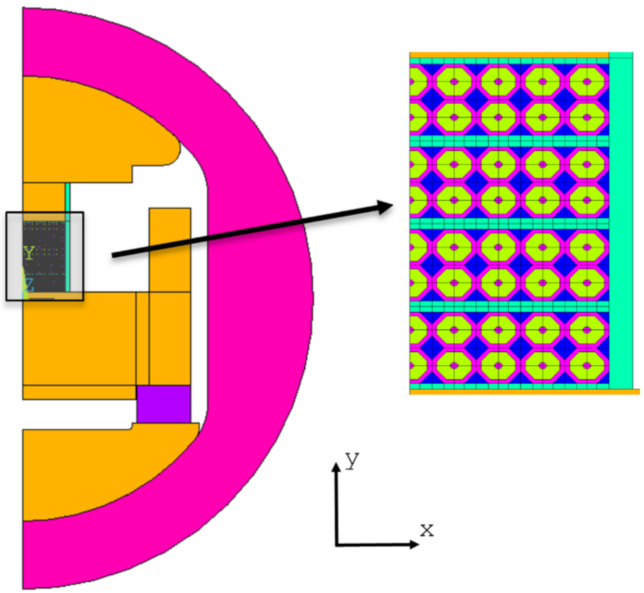


- A novel FRESCA sample holder was built and used at CERN. This tool allows to **measure** the **critical current** of stacks of impregnated cables under **transversal pressure**.

- 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)

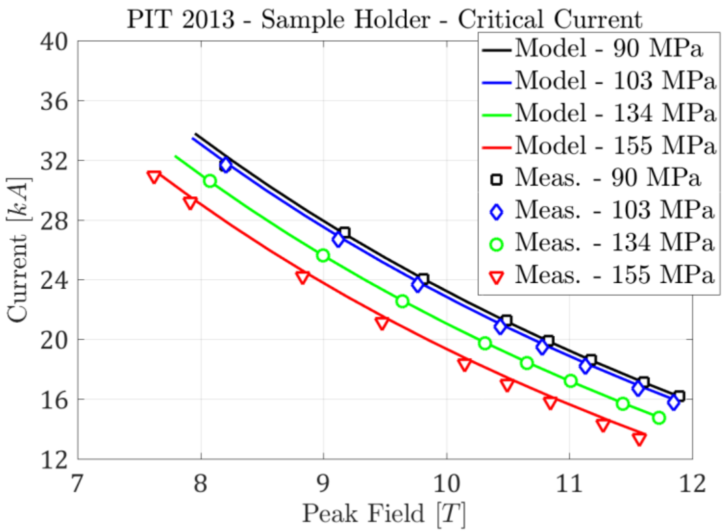


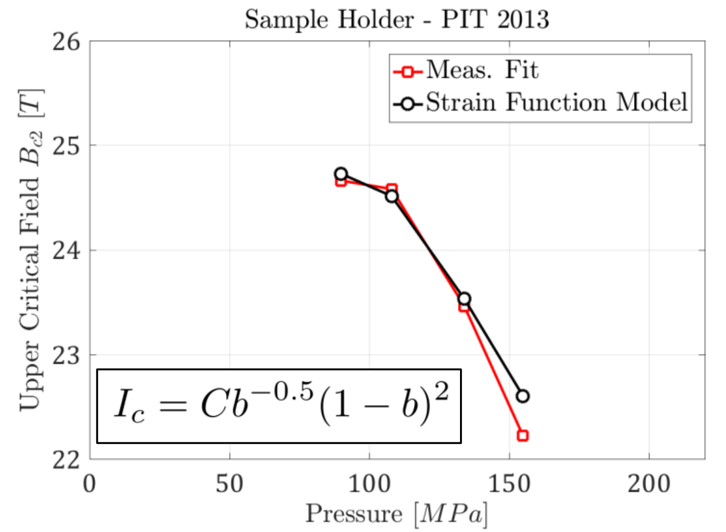
Parameter	Unit	Value - A†	Value - B‡
Strand	/	RRP 108/127	PIT 192
Strand diameter	mm	0.85	1.0
Number of strands in cable	/	40	18
Copper to non-copper	/	1.2	1.22
Twist Pitch	mm	14	63
Cable Bare Width	mm	18.15	10
Mid Thickness	mm	1.525	1.81
Keystone Angle	degrees	0.40	0

† 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

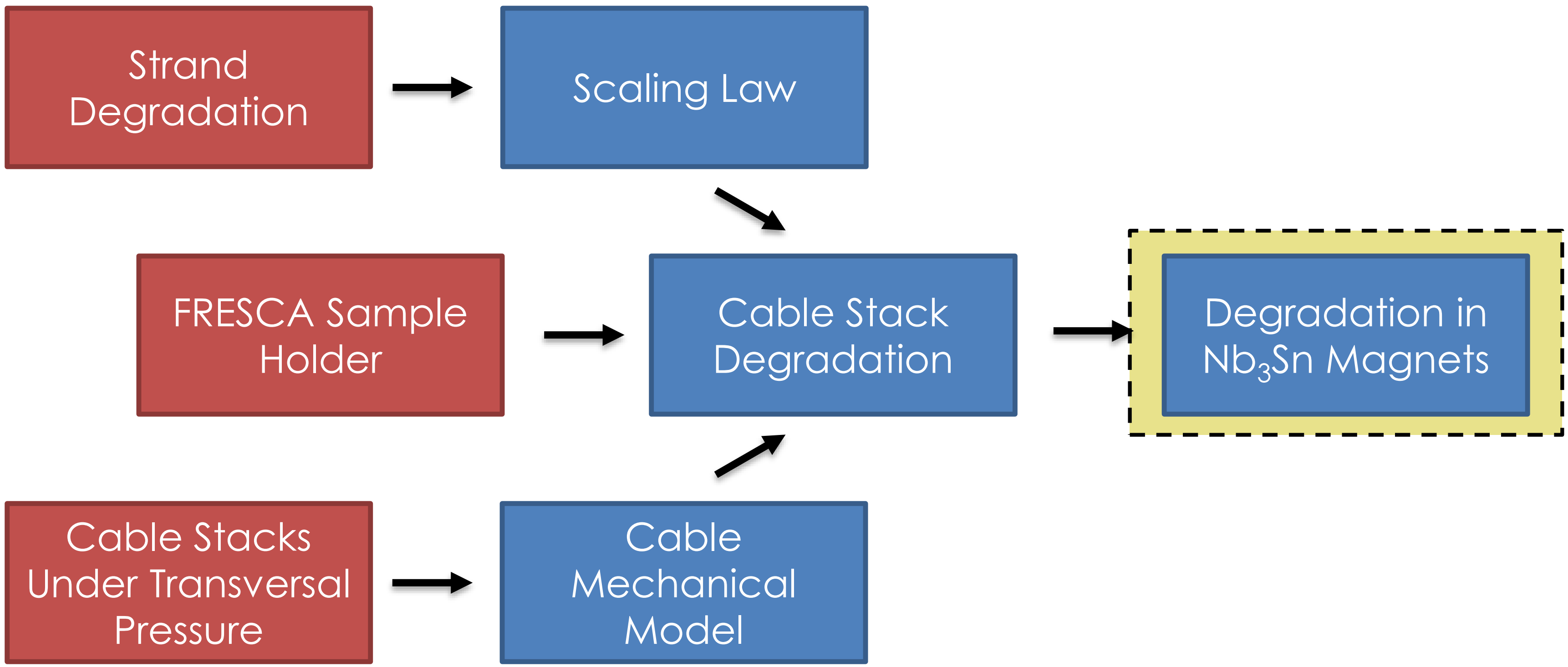
Stack Degradation – Results





- 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

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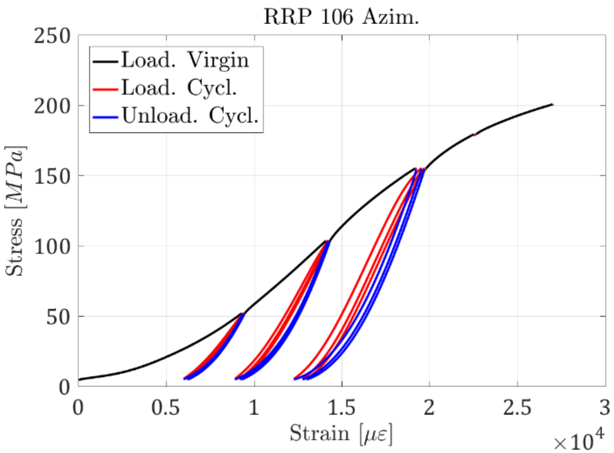
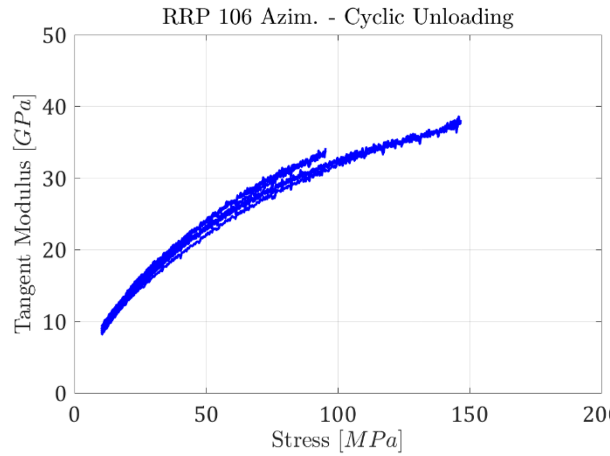
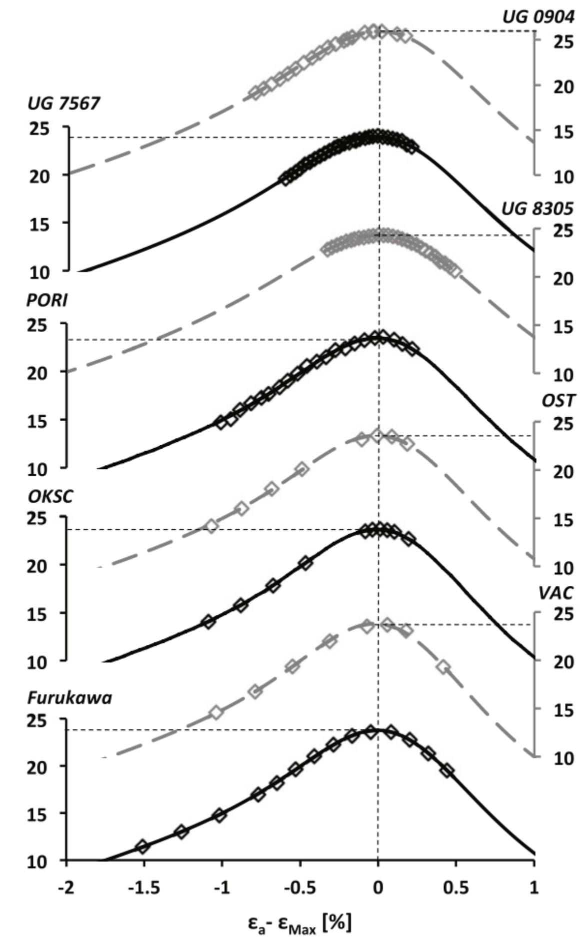
Reversible Degradation in Magnets

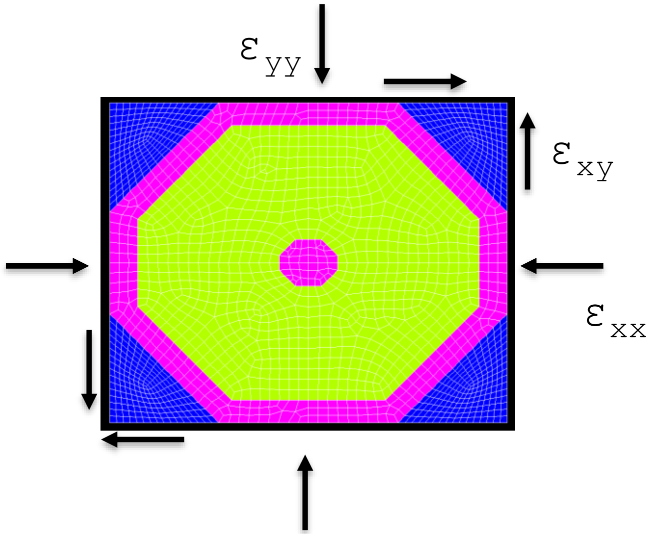


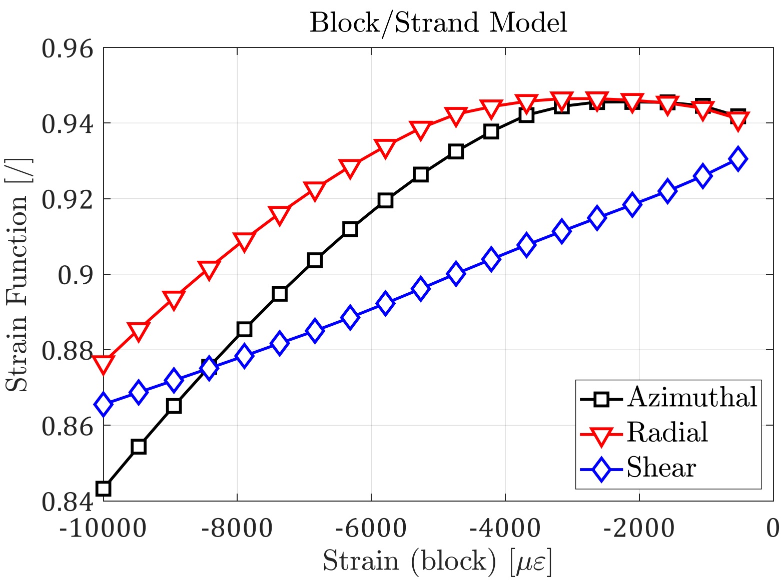




- **Considerations:**
  - Strand experiments suggest that the **reversible** degradation is a function of the full **strain tensor**
  - Stress/strain relationship is **not linear**
  - **Strand model** seems **too complicated** to be quickly applied during the magnet design process
  - No cable degradation data for complex strain/stress states

Reversible Degradation in Magnets





- We can use the strain law and the validated cable/strand model to check the behavior under complex loading conditions
- **Model assumptions:**
  - Single **strand**, modelling strategy is the same used for the cable holder model
  - Three cases: vertical/horizontal/shear displacements applied on the boundary

Reversible Degradation in Magnets

- **Block Model Strain Function:**

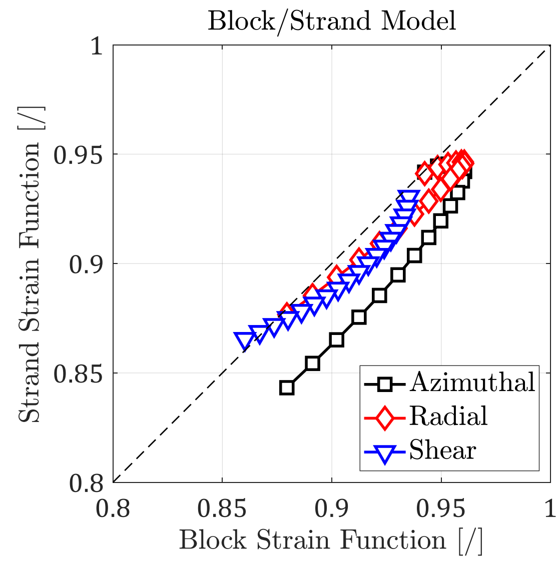
- We can **compare** the results with the strain function *computed* from an hypothetical **block** model (e.g. vertical strain)

$$[\varepsilon] = \begin{bmatrix} \nu\varepsilon_{yy} & 0 & 0 \\ 0 & \varepsilon_{yy} & 0 \\ 0 & 0 & \nu\varepsilon_{yy} \end{bmatrix}$$

  – The strains, however, are not distributed uniformly in the strand

    - Strain tensor used to compute the 'Block Strain Function': $[\varepsilon_s] = [\varepsilon] * 30/100$

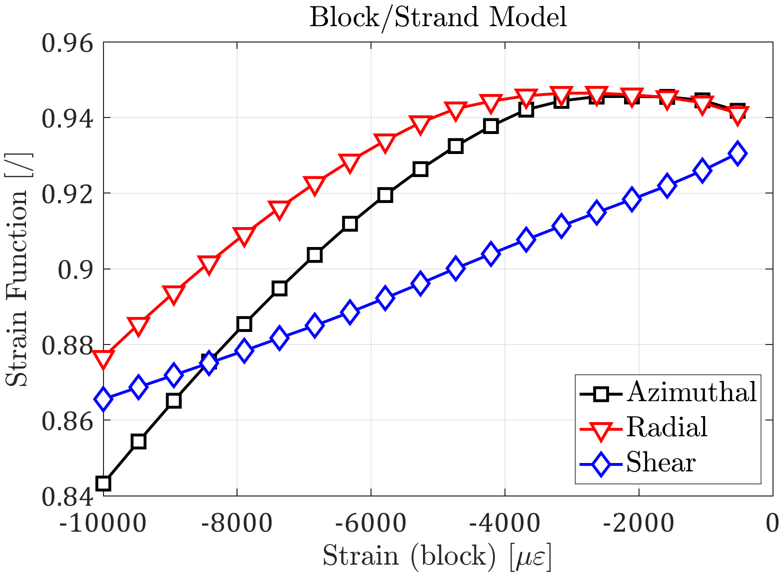
    - The coefficient is roughly the ratio between the avg. **strand modulus** (~30 GPa), and the **Nb_3Sn** one (100 GPa)



Error seems reasonably **small** in the region of interest (irreversible degradation for higher strains)

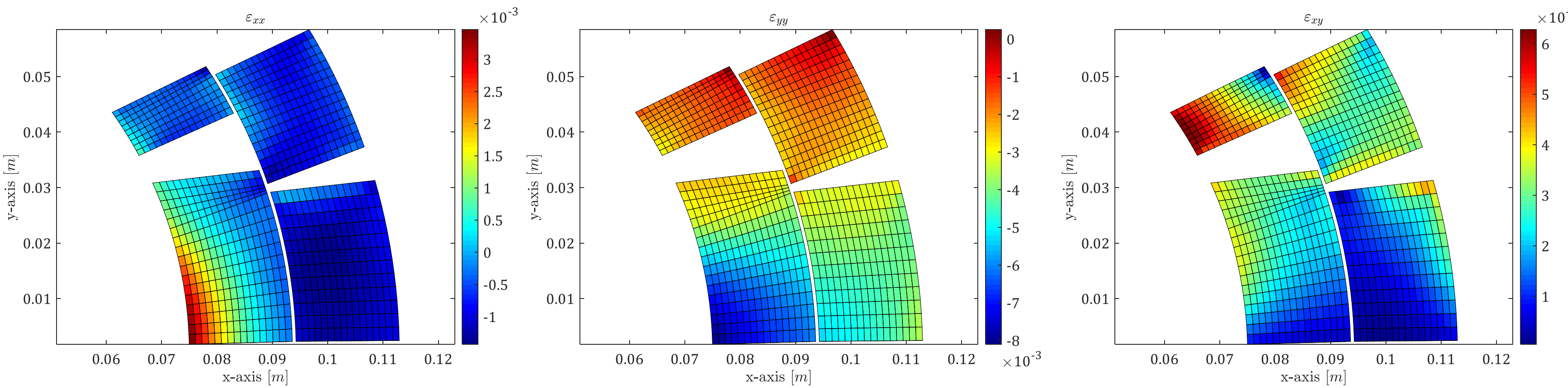
Application to Magnets

1. Compute the coil strains with a *block* model
2. If one strain is prevalent an estimate of the strain function can be obtained from the plot on the right
3. Extract the full strain tensor
4. Scale the strain values against a strand model (results may change with different strand geometries!)
5. Compute the strain function with the exponential scaling law
6. Compute the pinning force / critical current

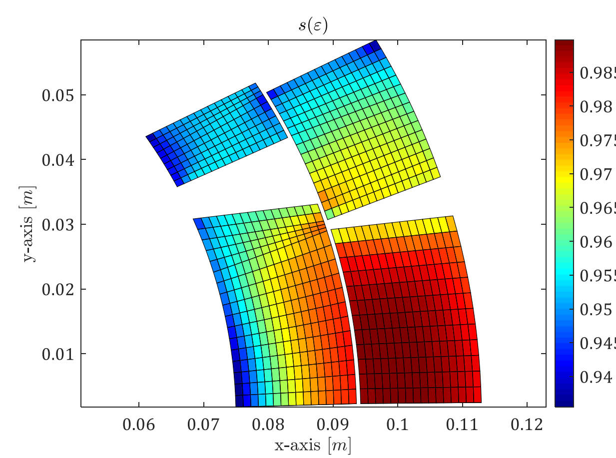


Note: results are only relevant if the mesh is not smaller than a single strand

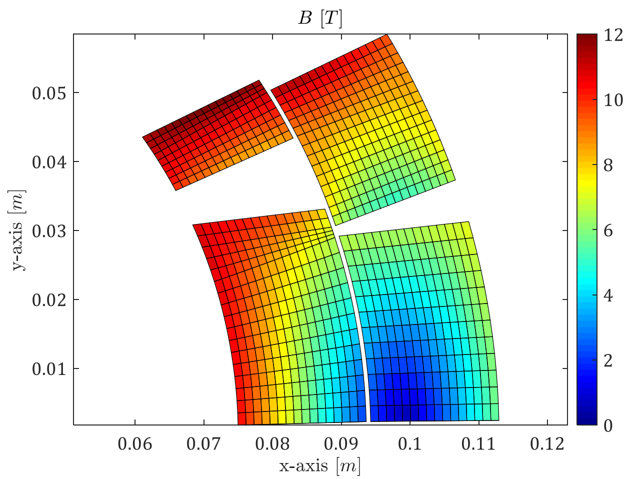
Application to MQXF (1)

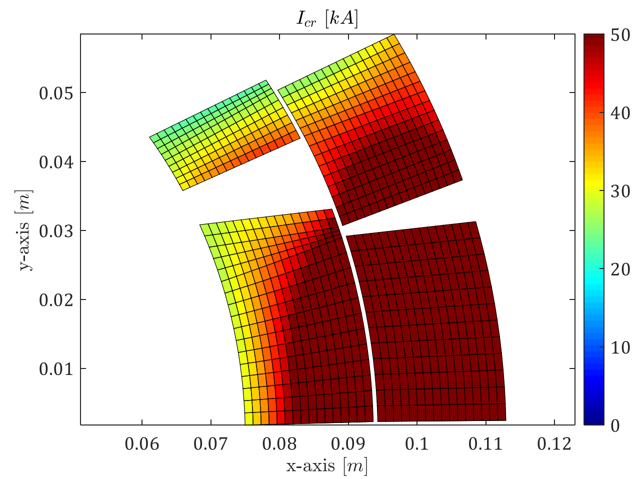


- Case 1 – medium preload (MQXFS4 magnet)
- **Strain function** (ultimate) always higher than 0.94
- Interestingly, the minimum of the strain function is at the pole turn, even if the magnet is completely unloaded



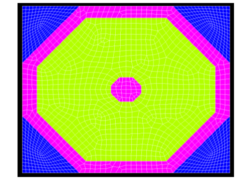
Application to MQXF (2)





- Critical current (ultimate)
- Minimum: 23 kA, at the pole turn

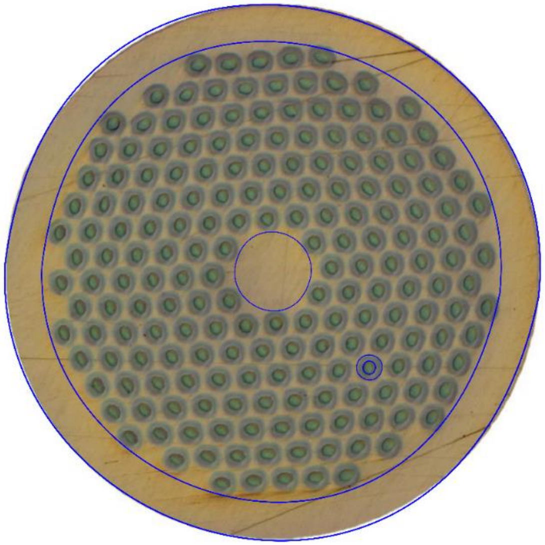
Conclusion



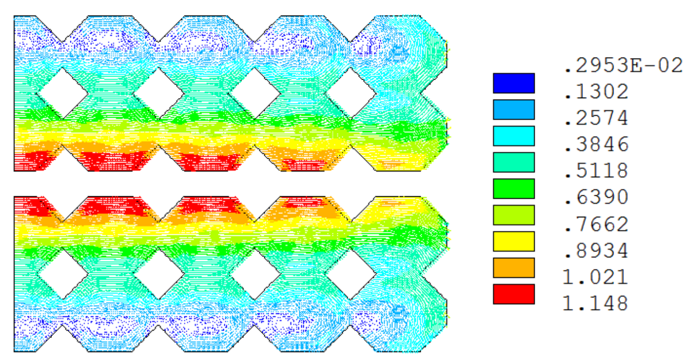
- Impregnated **cable stacks** under **transversal pressure**:
  - **Stiffness** is continuously varying
  - Comparison with **FE** model shows that the **copper plasticization** may explain part of this behaviour
- Cable stack **degradation model** results suggest that:
  - The stack degradation may be surprisingly reproduced using a **law** developed on **axial tests**
  - We do not need to model the **filaments**
- A **simplified** methodology for magnet design purposes was proposed
  - The approach was *tested* against the more refined one
  - An application example was performed on a real magnet design

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**:
  - About 0.2 may be explained by the 2D approximation
  - The remaining 0.5 is very close to the amount of non-superconducting material in the superconducting region (~55% of the superconducting area)



- Magnetic field in the strand was computed as **sum** of the **background field** and the **self-field** contribution