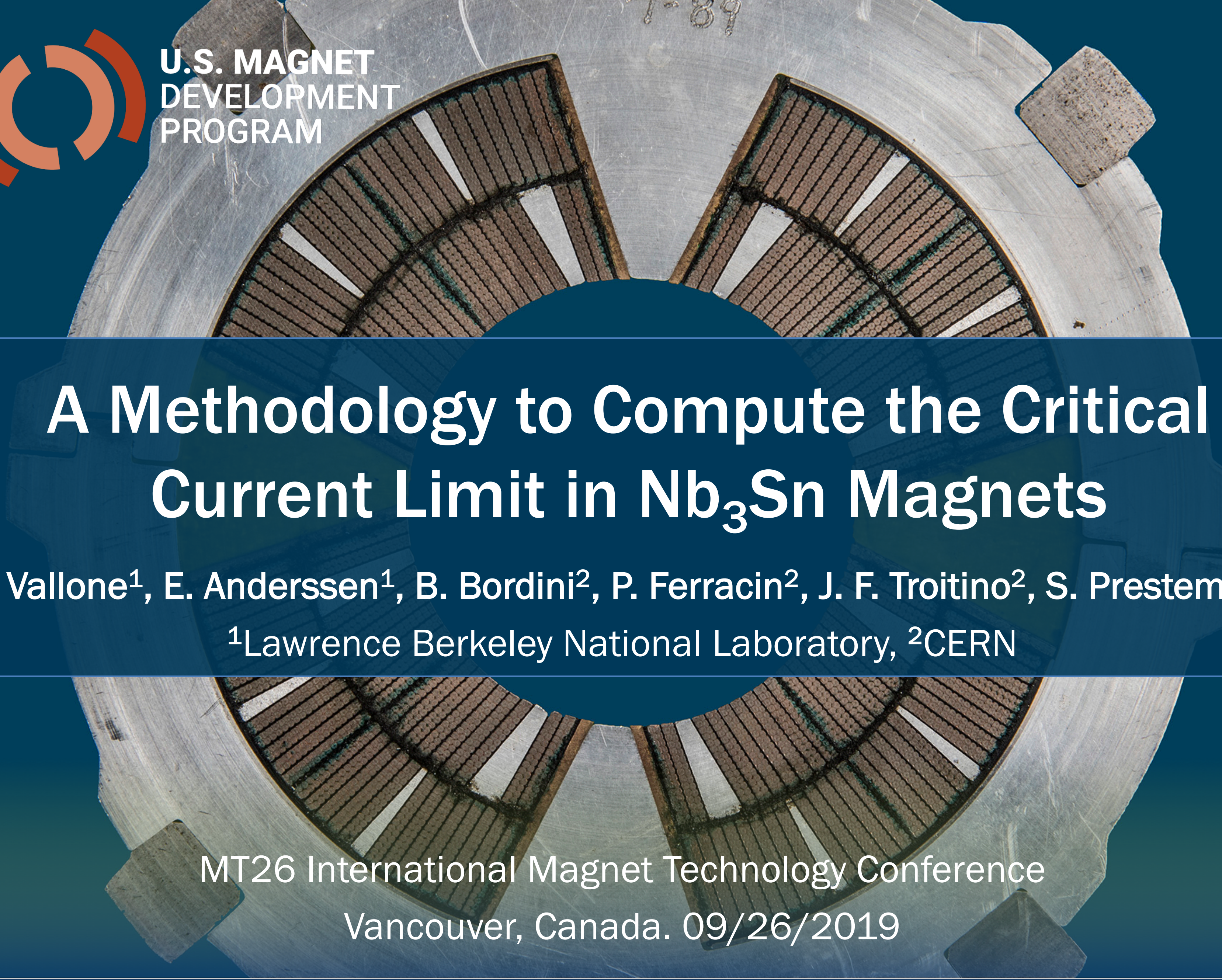

U.S. MAGNET DEVELOPMENT PROGRAM

A Methodology to Compute the Critical Current Limit in Nb_3Sn Magnets

G. Vallone[1], E. Anderssen[1], B. Bordini[2], P. Ferracin[2], J. F. Troitino[2], S. Prestemon[1]

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MT26 International Magnet Technology Conference

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U.S. DEPARTMENT OF ENERGY | Office of Science

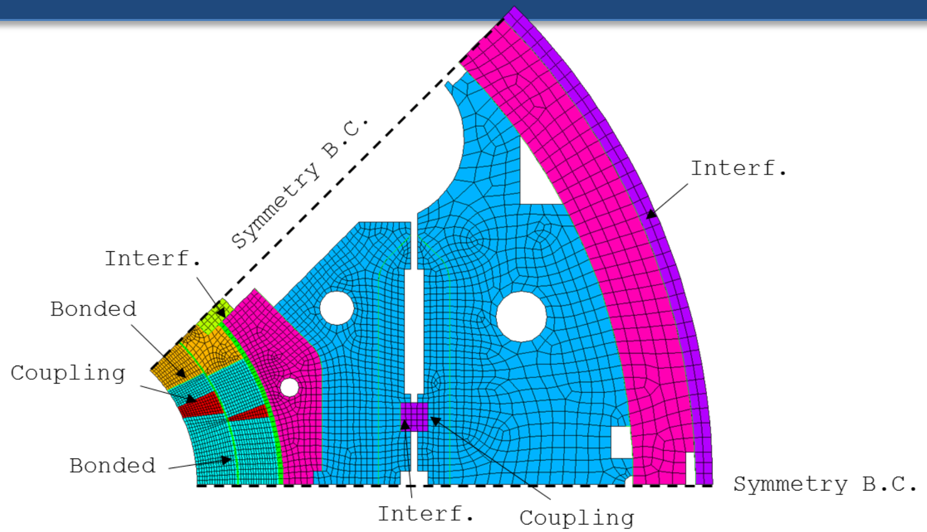
Outline

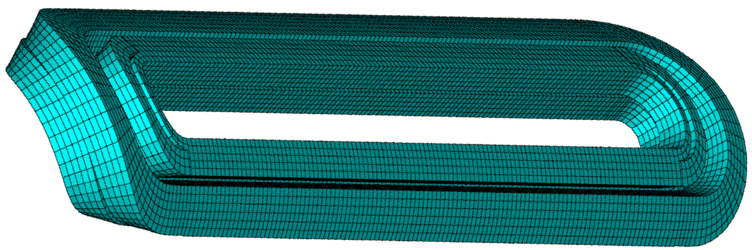
- Introduction
- Cable Stacks Under Transversal Pressure
- Application to Superconducting Magnets
- Conclusion

Introduction

- **Nb_3Sn strands** are prone to critical current **reduction** under the effect of mechanical **strains**
  - This strain dependence can be caused both by **axial** and **transverse** strains
  - For *high* strains the reduction can become permanent (**degradation**)
  - Similar effects were measured also for **Rutherford cable** stacks
- The **fields** required by particle accelerators are continuously **growing**
  - Stronger e.m. forces → higher stresses/strains → possible current reduction/degradation → lower performances
- We need a **methodology** to evaluate the **magnet performances** under high stresses

Coils Mechanical Limits





- 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

Strands Critical Current - Axial Strain

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

- The main parameter governing the strain dependence in the **reversible** region is the **strain function** $s(\varepsilon)$:

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

- In 2013, an **exponential scaling law** was proposed to describe the evolution of the strain function†:

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

- Can we use this law in our magnets? **How**?

†*B. Bordini et al., SuST, 2013*

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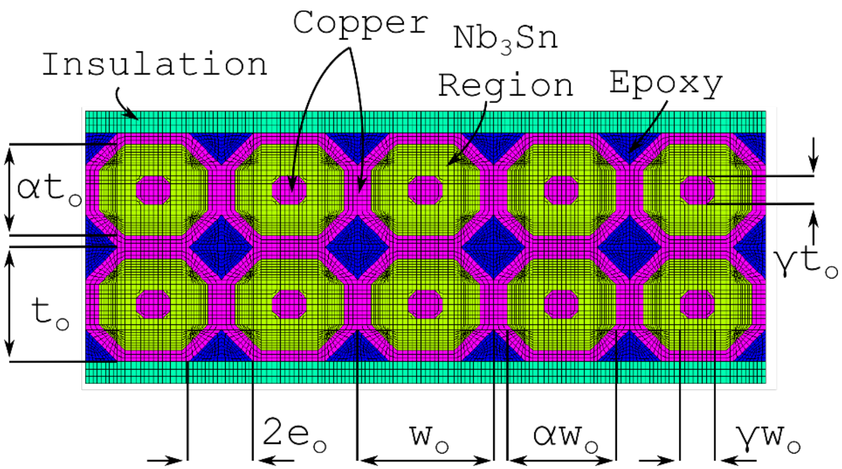
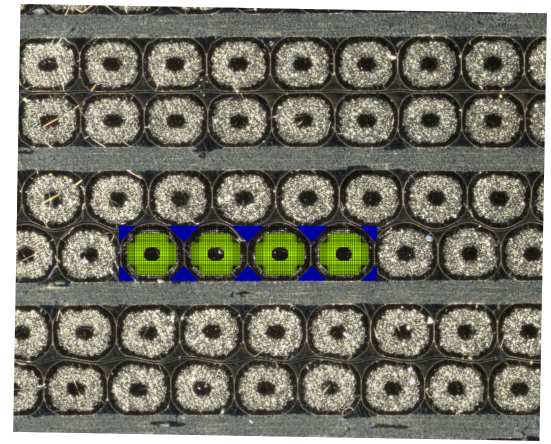
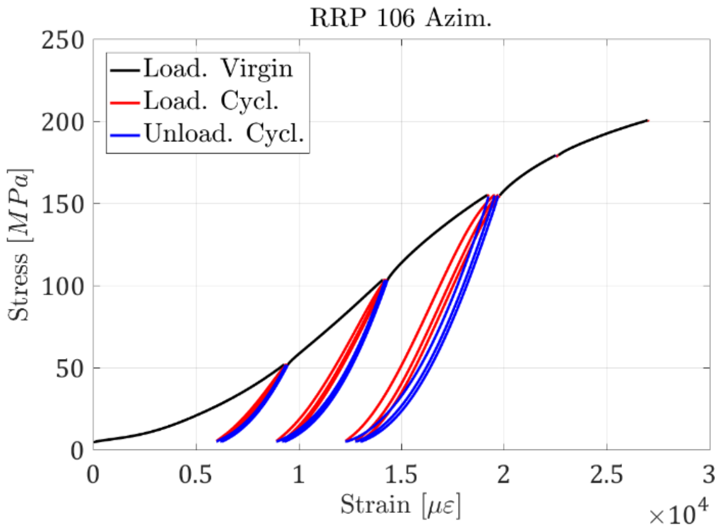
Cable Stacks – FE Model (1)

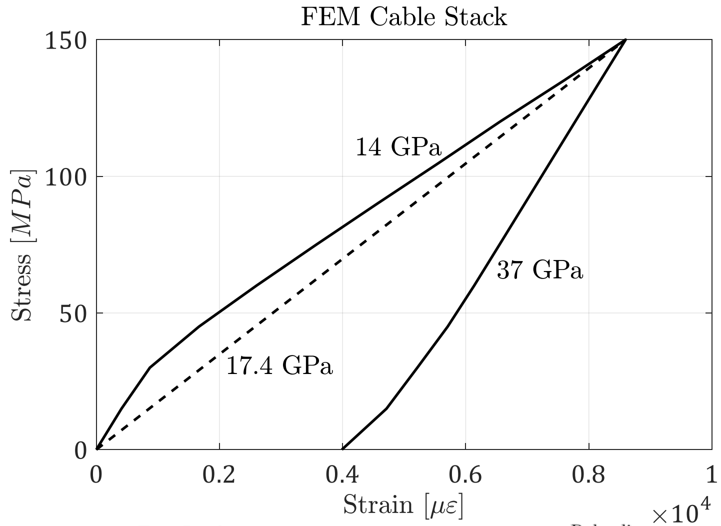




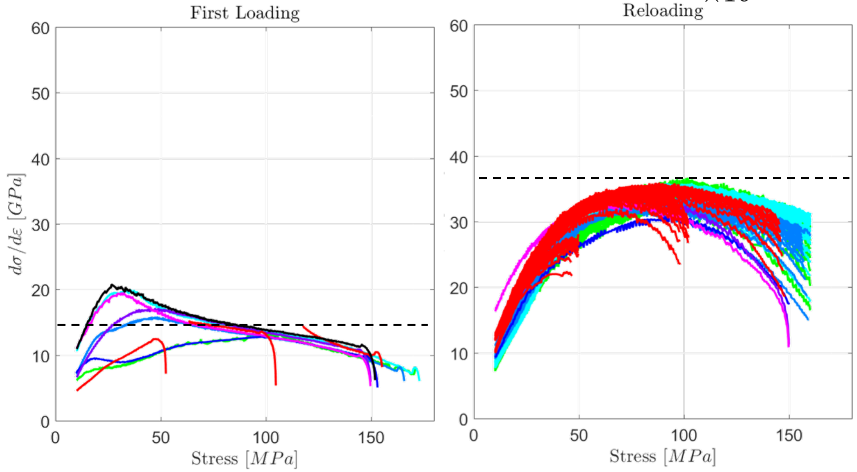
- 2D FE model of a Rutherford cable **stack**
- Material properties from literature
- Geometry from a mix of **image analysis** and simple geometric formulas to match the filling factor, copper-non copper etc.
- Stiffness validated against **measurements** on impregnated 10 stacks

Cable Stacks – FE Model (2)



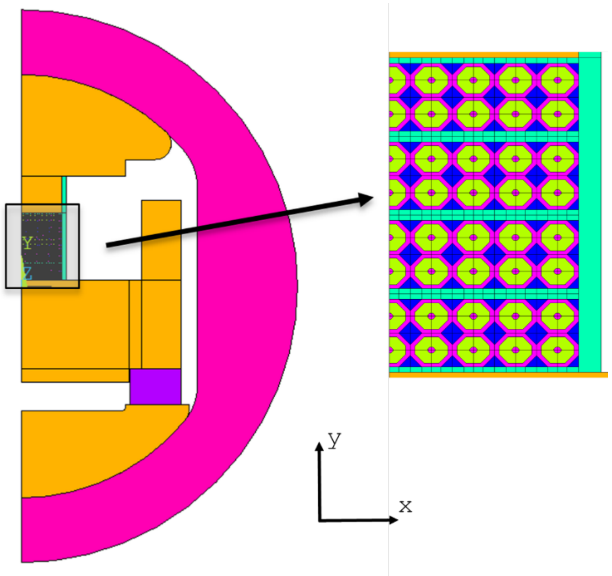


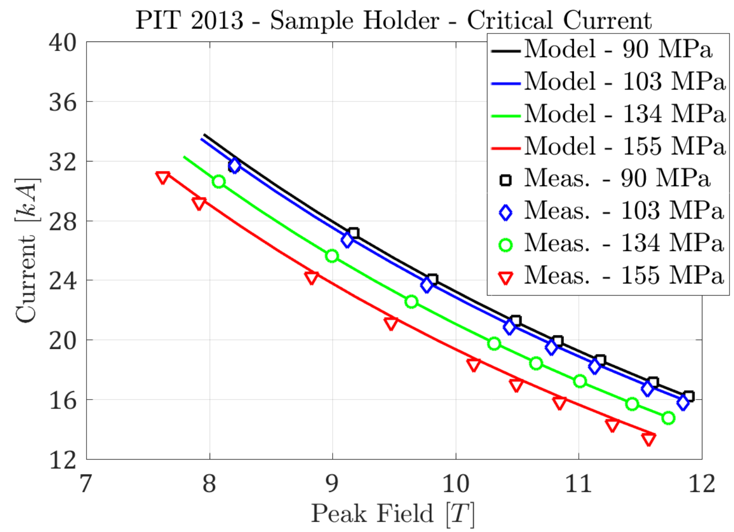
- Difficult to condensate the coil elastic properties in a **single number** (modulus)
- Virgin/cyclic behaviour explained by **copper plasticization**
- FE slope *reasonably* good - **no** model **calibration** was performed…
- **Model** successfully predicted the higher stiffness (20%) of 11T cables



Meas. data from C. Fichera et. et al., IEEE TAS, 2019

Cable Stacks - Critical Current





- **2D** mechanical and electro-magnetic model of the **sample holder**
- Cable stack modelled with the **mechanical approach** validated from 10-stack measurements
- 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

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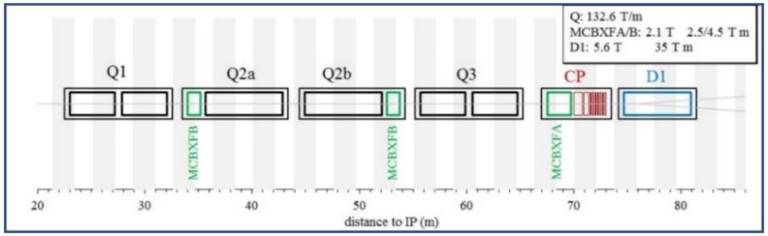
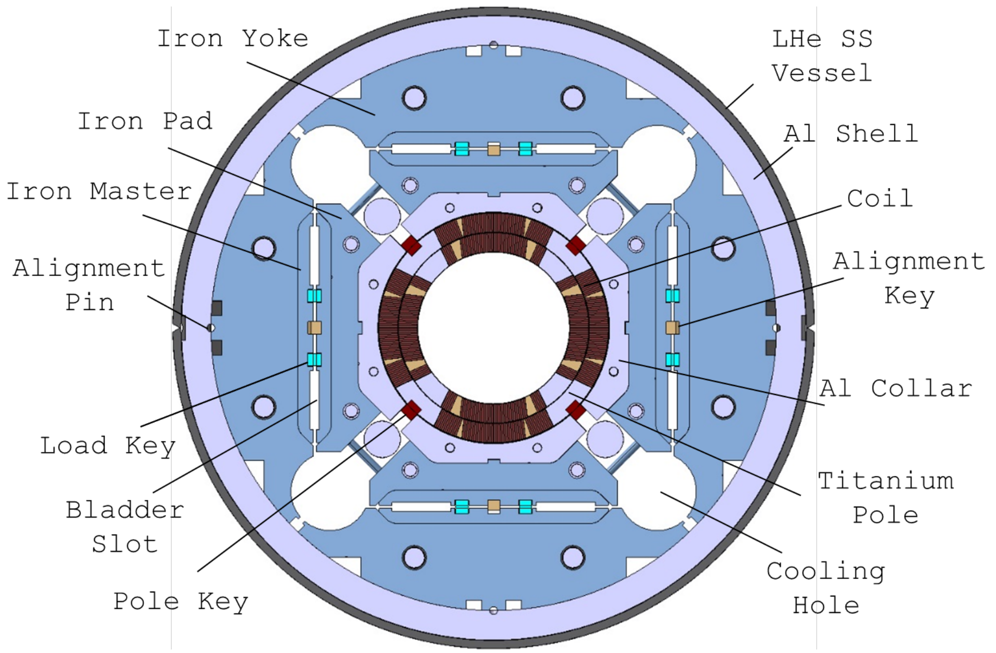
MQXF Design

- LHC IR upgraded as a part of **High-Luminosity** project
  - Quadrupoles: NbTi → Nb_3Sn
  - 150 mm coil aperture



- Target **gradient** and peak **field**:
  - Nominal: 132.6 T/m, 11.4 T
  - Ultimate: 143.2 T/m, 12.3 T

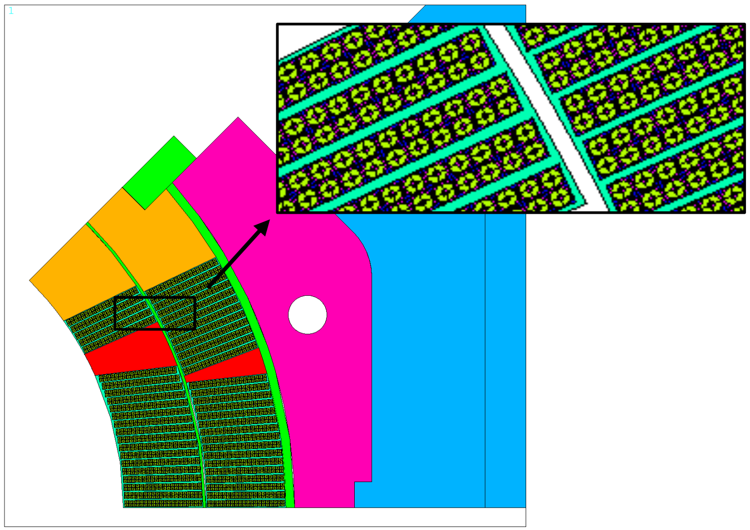


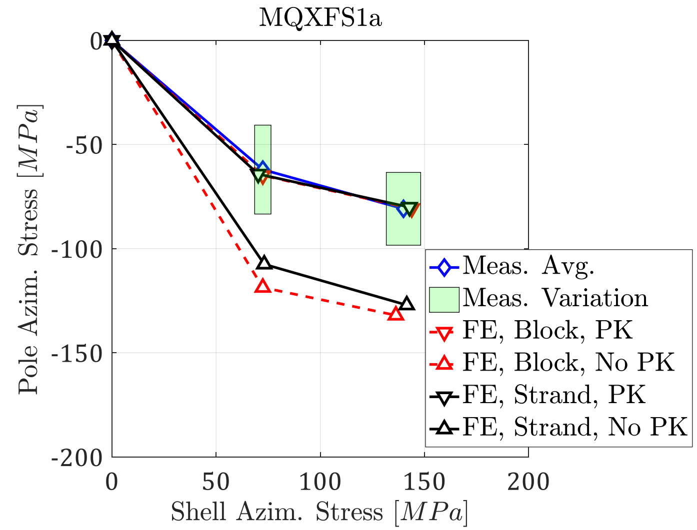
- Azimuthal preload at R.T. applied with **bladders & keys**

- Longitudinal preload at r.t. applied pre-tensioning the **rods**

- Both increased by the differential **thermal contraction** during cool-down

MQXF - Mechanical Model (1)

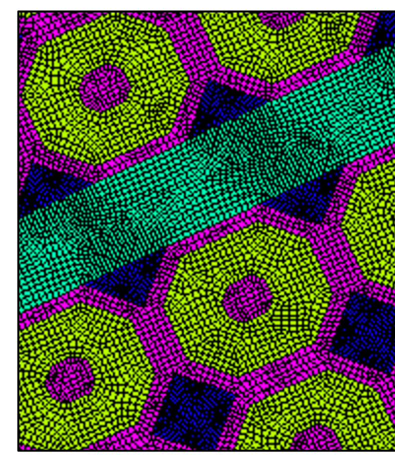




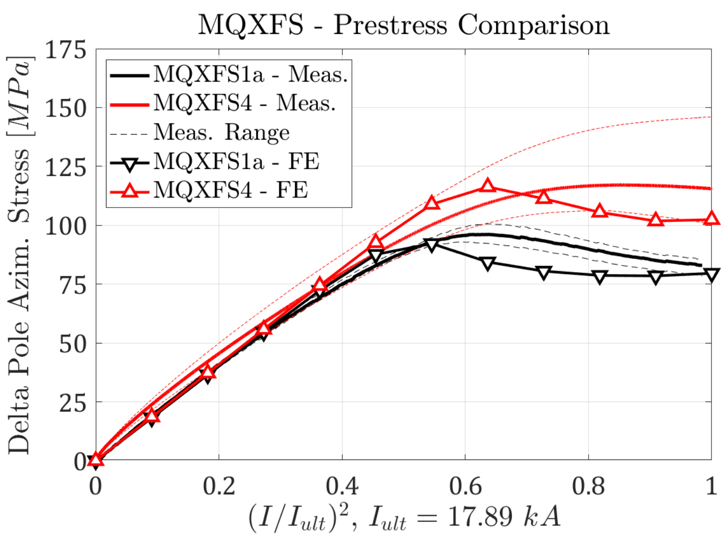
- **MQXF magnet** *strand* model
  - Same **approach** as for the Cable Holder / 10 stack model
  - **Preload** and **cool-down** simulation
  - Results match the 'Shell-Pole **Transfer Function**'

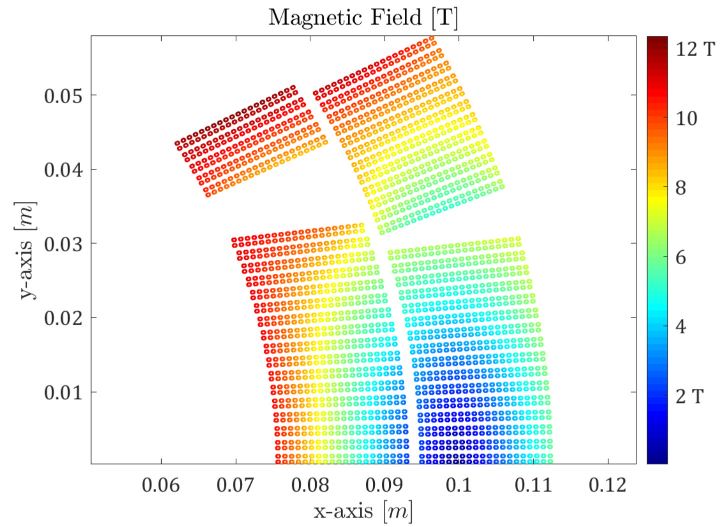
- **Thermal contraction** in the green area computed as:

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

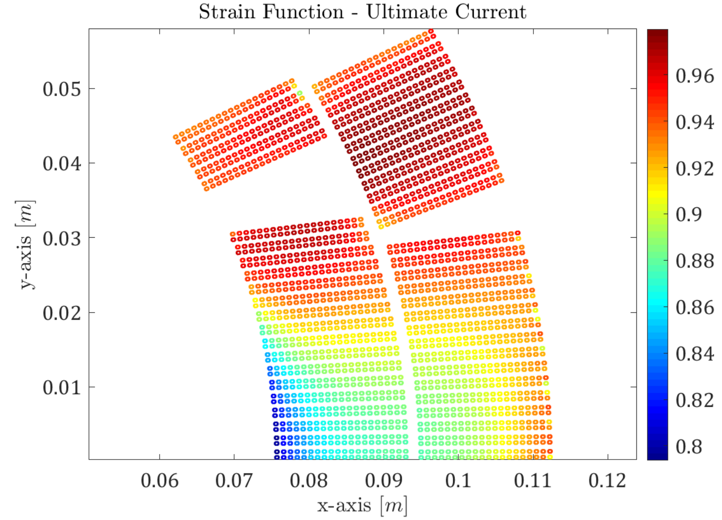


MQXF - Mechanical Model (2)



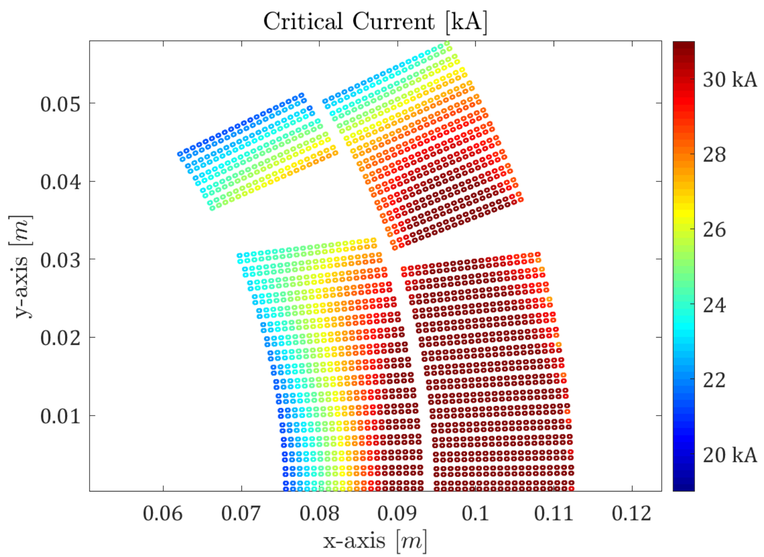


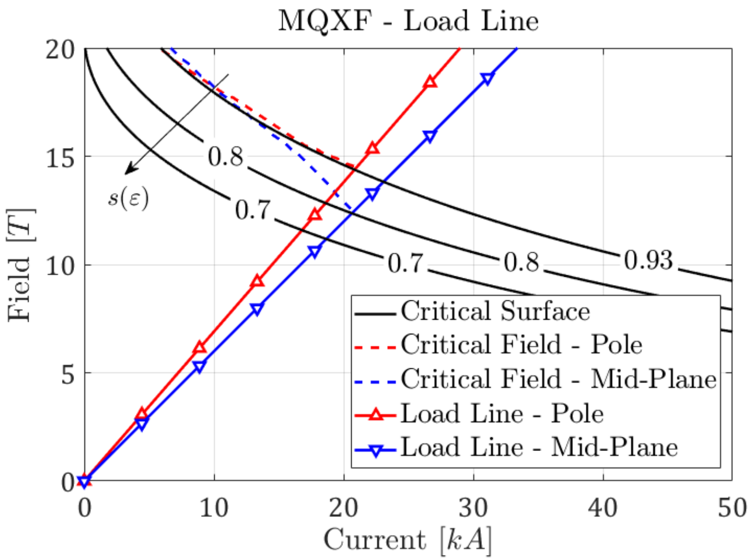
- **Powering** simulation:
  - Mechanics simulation during powering refined in the past †
  - The strand model during **unloading** is slightly stiffer than expected from the measurements
- Strain Function at **ultimate** current > 0.8



† *G. Vallone and P. Ferracin, IEEE TAS, 2017*

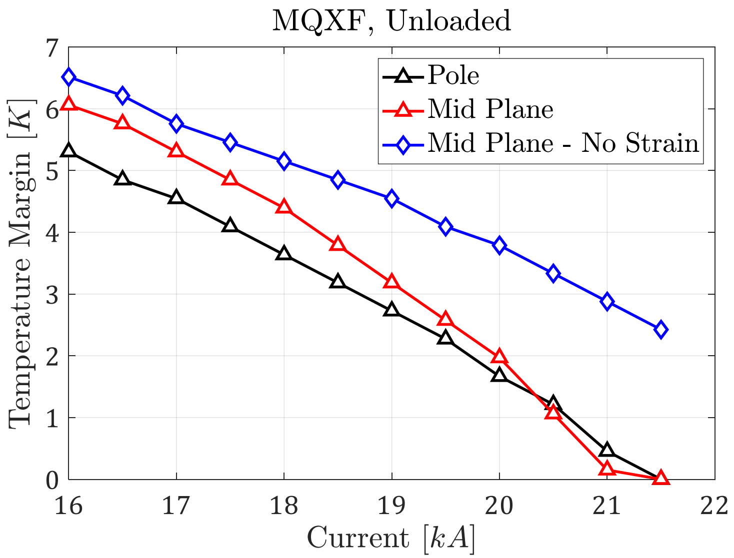
MQXF – Critical Current

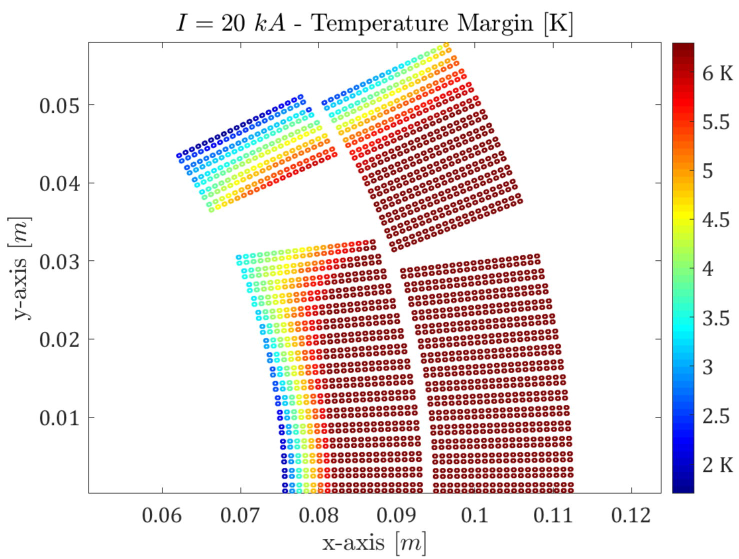




- **Powering** results:
  - Critical strands near the **mid-plane**, 20.7 kA (SSL, pole, 21 kA)
  - Inner layer, 2nd turn: the e.m. forces and the outer layer pole corner create a **stress concentration**, reducing the available margin
    - The impact of **local strain spikes** is difficult to evaluate in block models
  - **Critical current** is almost the same on the mid-plane and on the pole
    - This is probably due to the empirical approach from past results

MQXF – Temperature Margin





- **Temperature margin:**
  - The **critical surface** movement caused by the **strain** can reduce the available **margin** against sudden energy depositions, potentially decreasing the magnet performances
  - The **temperature margin** reduction is:
    - 0.7 K at ultimate current
    - 2.5 K at the limit current

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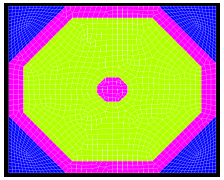
Conclusion

- **Cable stacks** under transversal pressure:
  - Results suggest that we could use this modelling approach to estimate the stiffness of **future cable** designs
  - The critical current reduction can be reproduced using a **law** developed on **axial tests**
  - It seems that we do not need to model the **filaments**
- Accelerator **magnets**:
  - Reasonable **agreement** between the **measurements** and computations
  - The methodology can provide:
    - A more accurate **critical current** and load-line margin computation
    - Location of potential **critical regions** in the magnet (e.g. pole corners)
    - Updated **temperature margin**



- Questions?

The Exponential Strain Function (1)

- In 2013, an **exponential scaling law** was proposed to describe the evolution of the strain function:

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

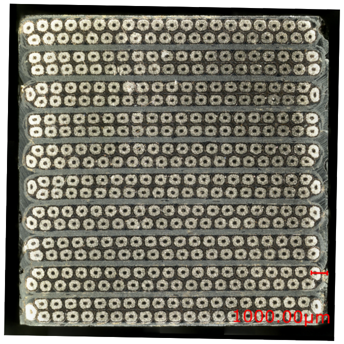
- With I_1 being the first invariant of the strain tensor and J_2 the second invariant of its deviatoric part:

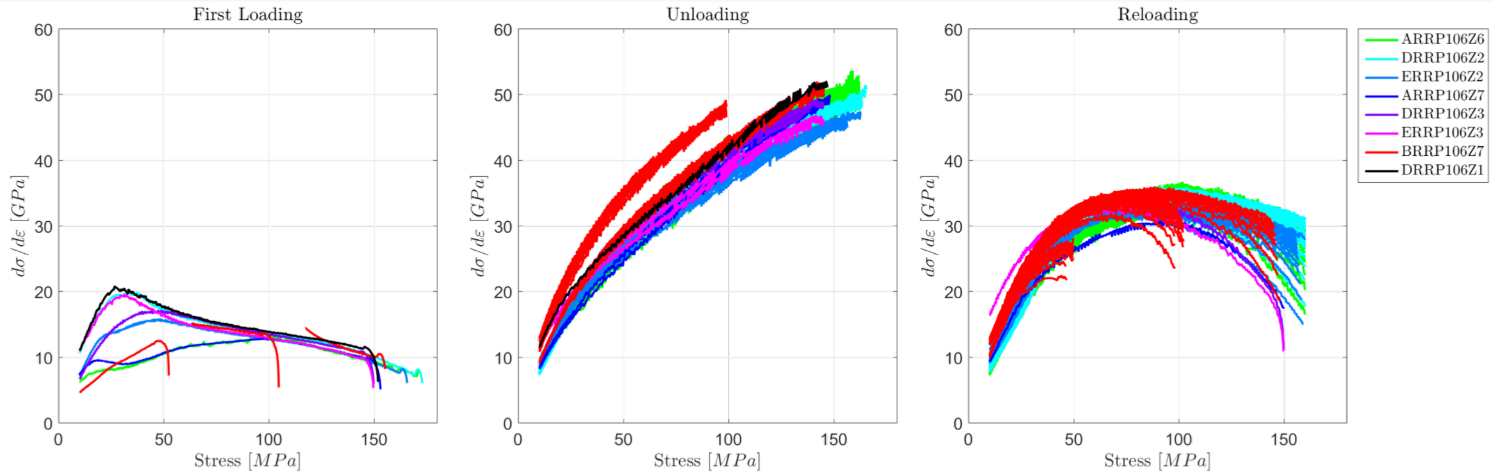
$$I_1 = \sum(\varepsilon_1 + \varepsilon_2 + \varepsilon_3)$$
$$J_2 = \frac{1}{6}\left[\sum(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2\right]$$

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

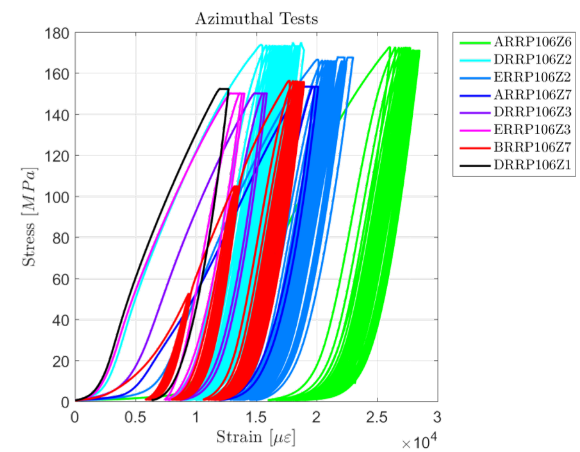
B. Bordini et al., SuST, 2013

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

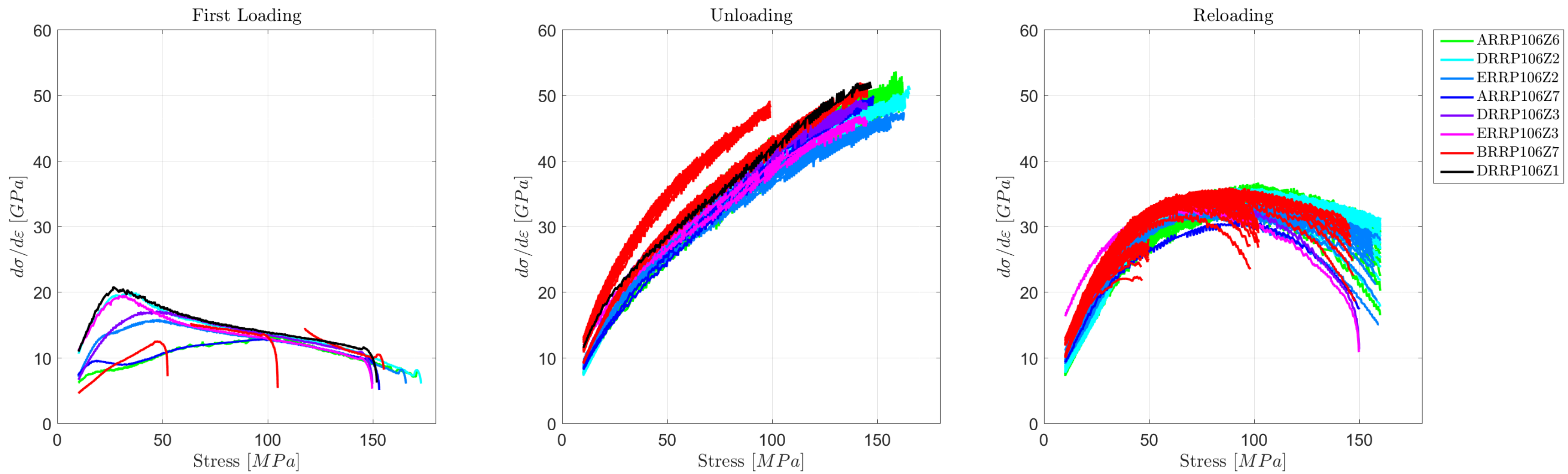


- Probably difficult to condensate the coil elastic properties in a **single number** (elastic modulus)

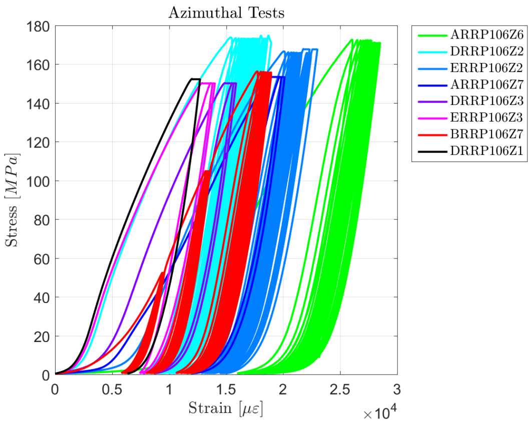
- **Non-linear** stress-strain relationship
  - Unreliable stress from strain measurements on coil

†*C. Fichera et. et al., IEEE TAS, 2019*
‡*ASTM - E111 - 04*

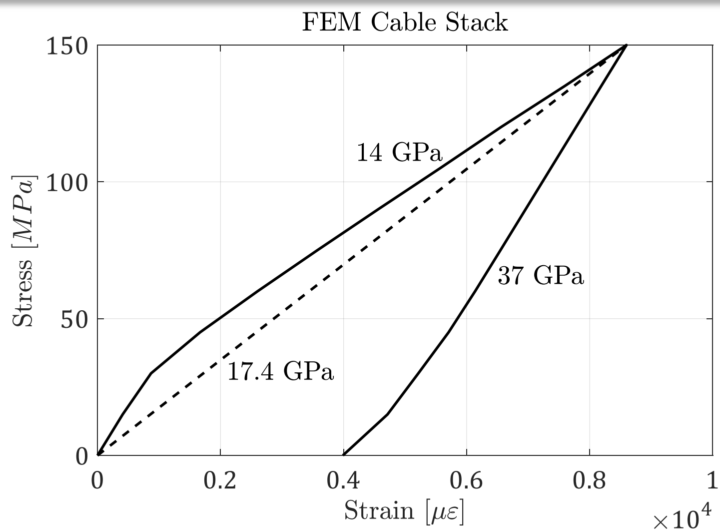
Cable Stacks – Transversal Pressure

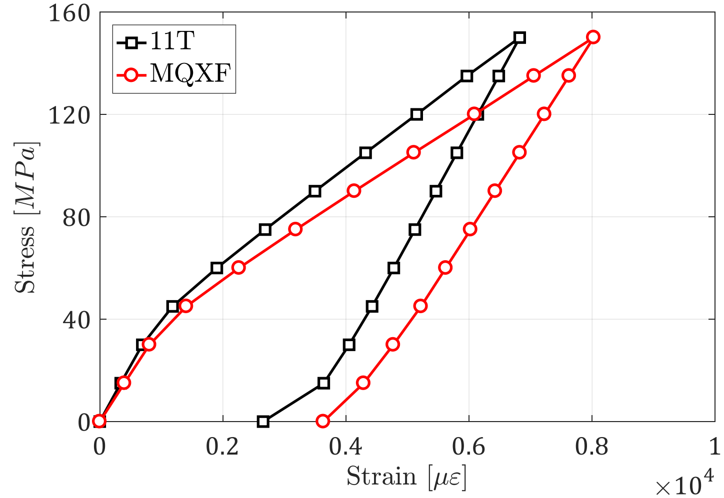


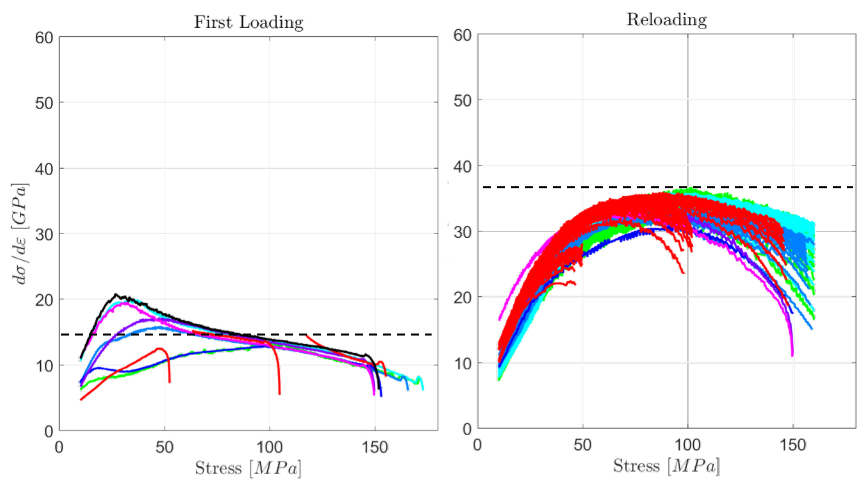
- **MQXF** cable, 10 stack campaign
- Virgin loading: peak at ~25-30 MPa (Cu plasticization?), then ~15 GPa
- Unloading: non-linear, max at 50 GPa
- Reloading: non linear, max at 35 GPa



Cable Stacks – FE Model (2)

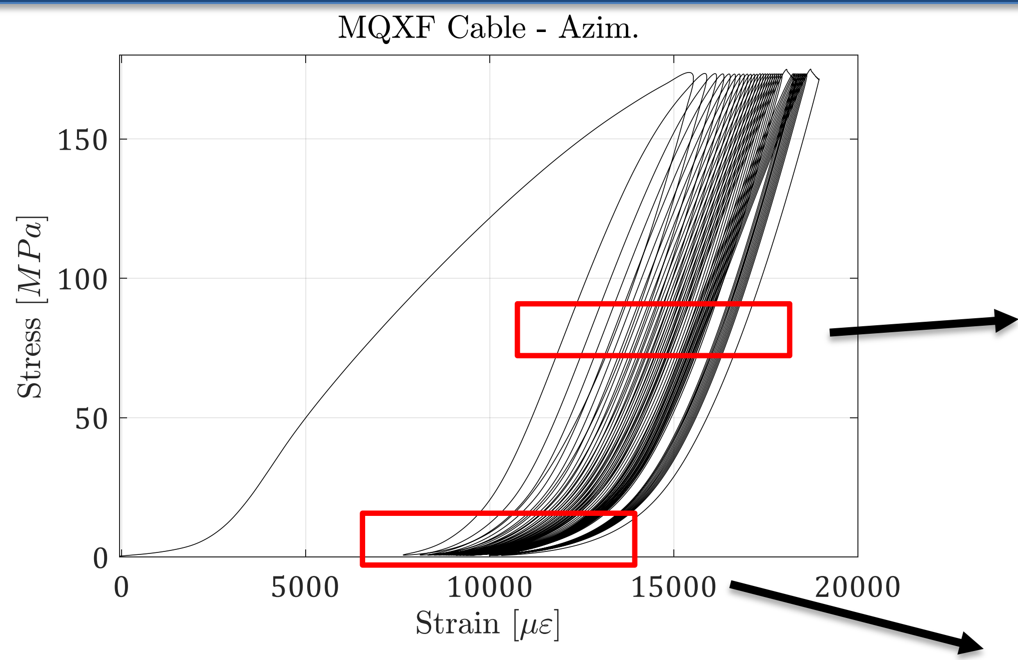


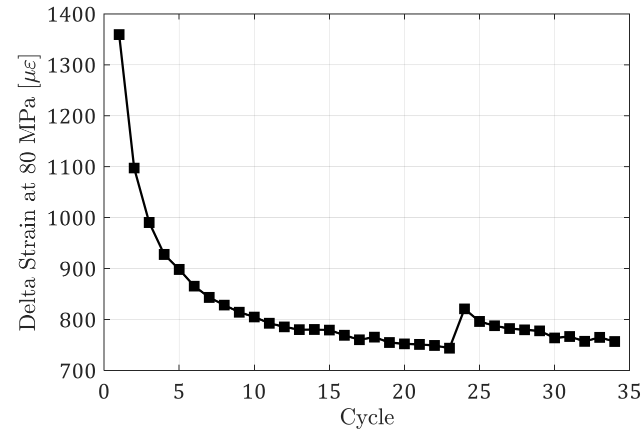


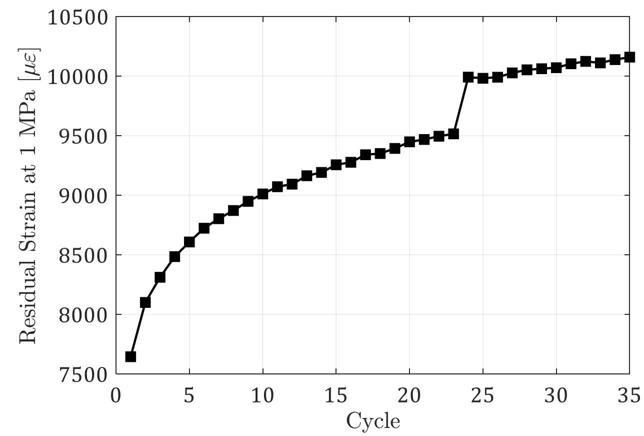


- Virgin/cyclic behaviour explained by **copper plasticization**
- FE slope *reasonably* good especially considering that **no** model **calibration** was performed
- Initial phase may be due to **compaction**
- **Model** successfully predicts the higher stiffness (20%) of 11T cables

Cable Stacks – Hysteresis

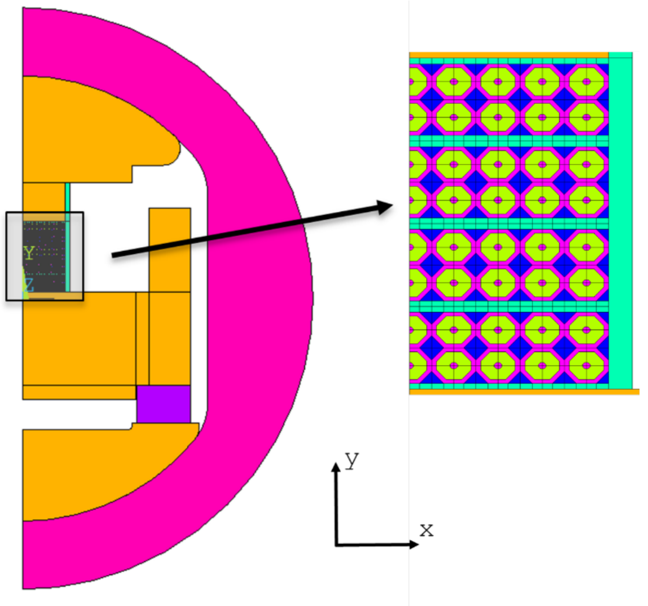






- **Hysteresis** behaviour test:
  - ~35 **cycles**, sample used also to study **creep**
  - Need to repeat also at lower **load levels**
- The width of the curve (~energy **dissipation**) converges
- The **residual strain** keeps increasing
- Energy dissipation ~ 100/150 mJ/cm^3

FRESCA Sample Holder

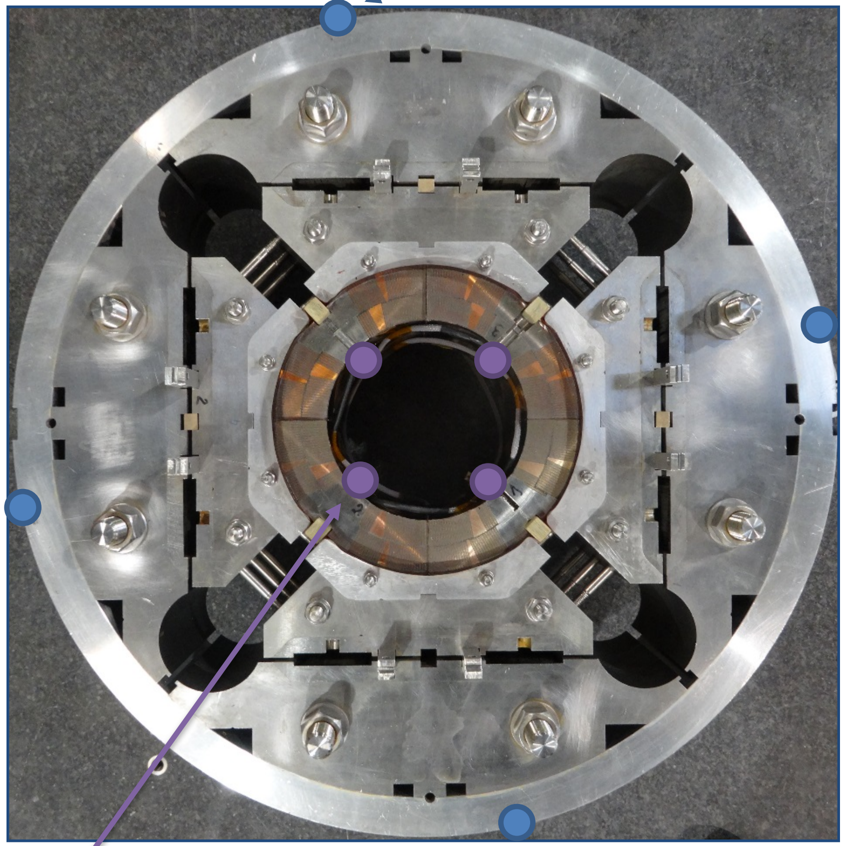


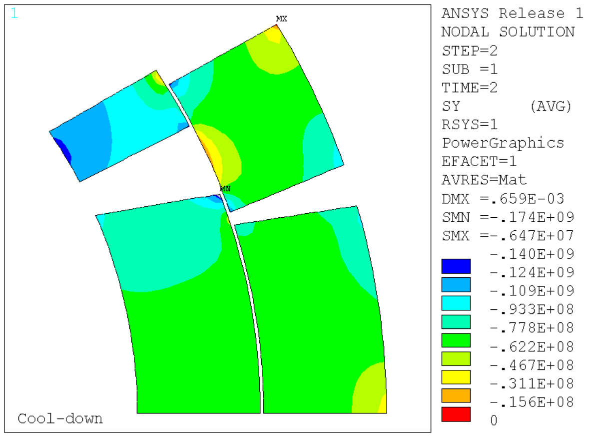
Parameter	Unit	Value - A†	Value - B‡
Strand	/	RRP 108/127	PIT 192
Strand diameter	mm	0.85	1.0
Number of strands in cable	/	40	18
Copper to non-copper	/	1.2	1.22
Twist Pitch	mm	14	63
Cable Bare Width	mm	18.15	10
Mid Thickness	mm	1.525	1.81
Keystone Angle	degrees	0.40	0

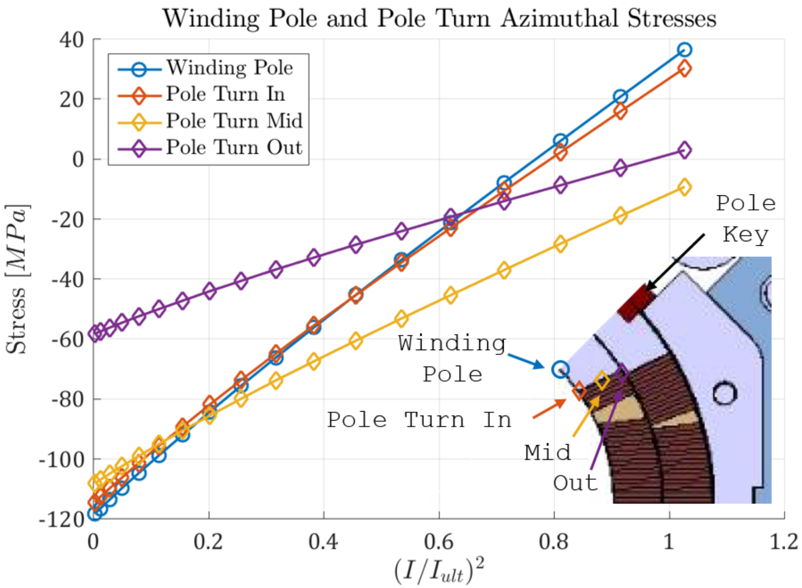
† 10-stack cable (MQXF [13]) - E measurements.
‡ Sample holder cable [3] - Critical current measurements.

- **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

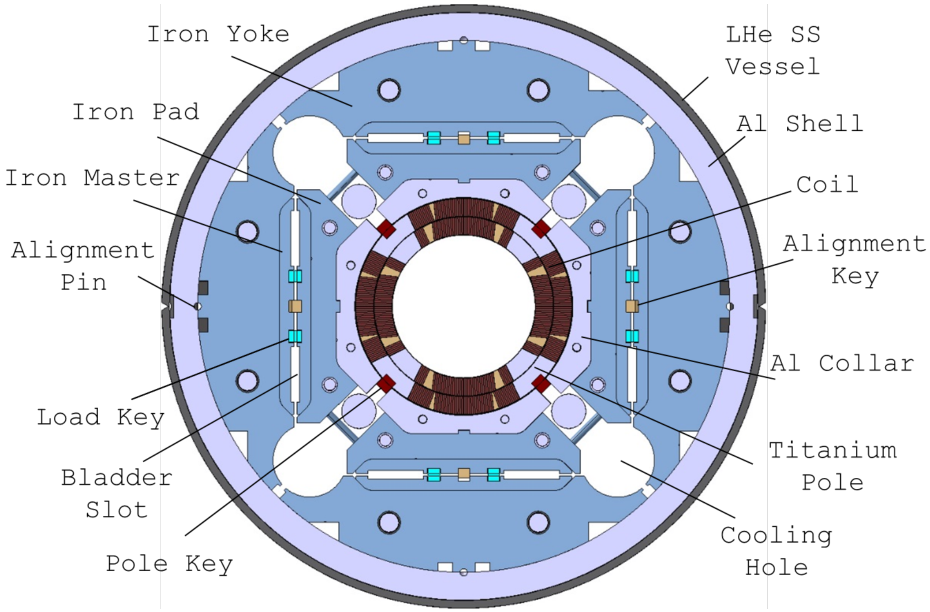
Strain Gauge Locations

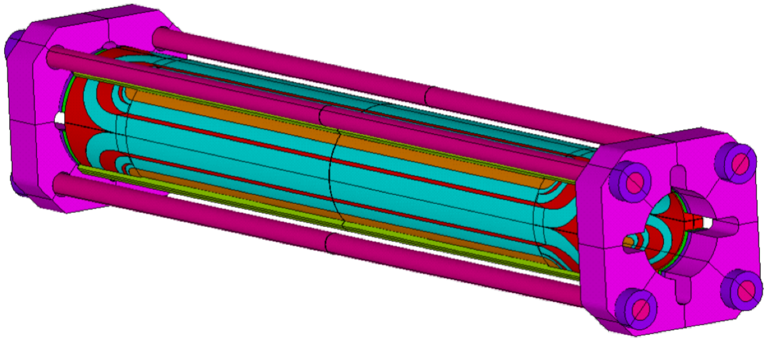






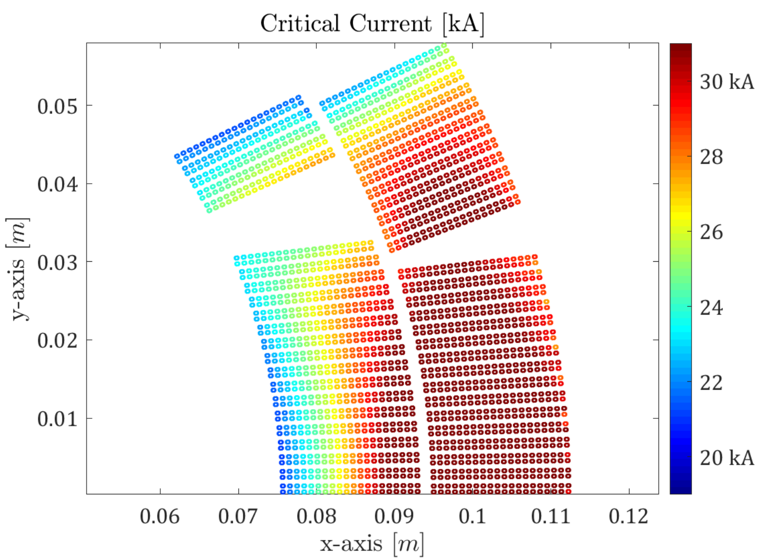
MQXF Prestress

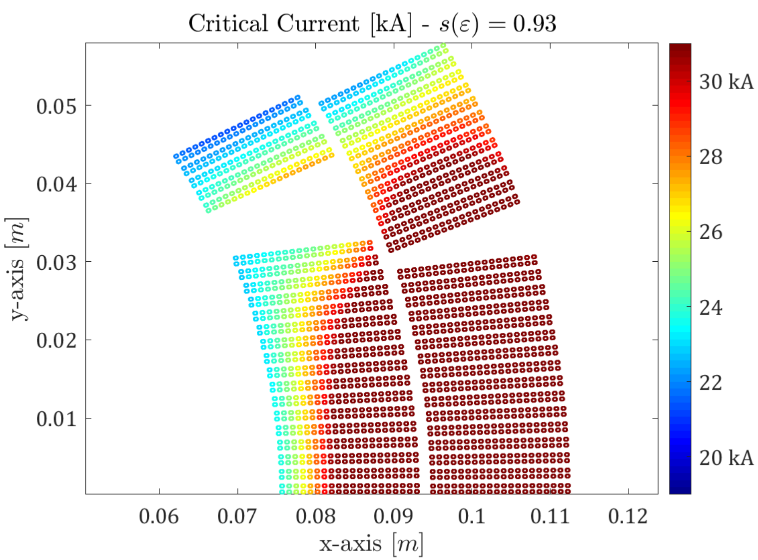




- Azimuthal preload at R.T. applied with **bladders & keys**
  - Al shell compresses the coils. Part of the force is absorbed by the pole key
- Longitudinal preload at r.t. applied pre-tensioning the **rods**
- Both increased by the differential **thermal contraction** during cool-down

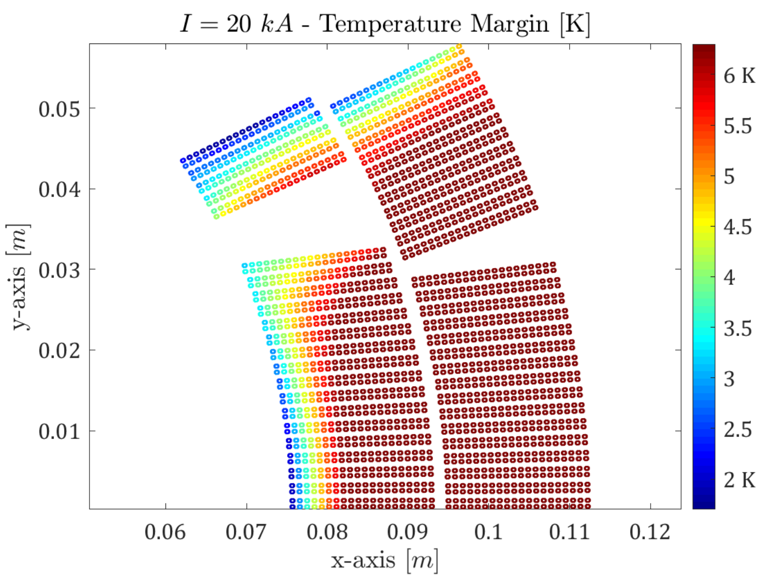
Critical Current – Strain/No Strain

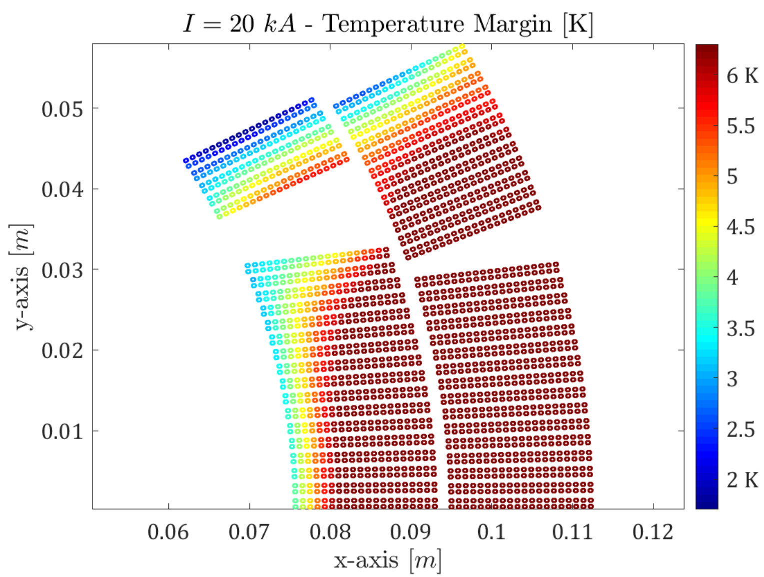




- Strain → left
- No strain (strain function = 0.93) → right

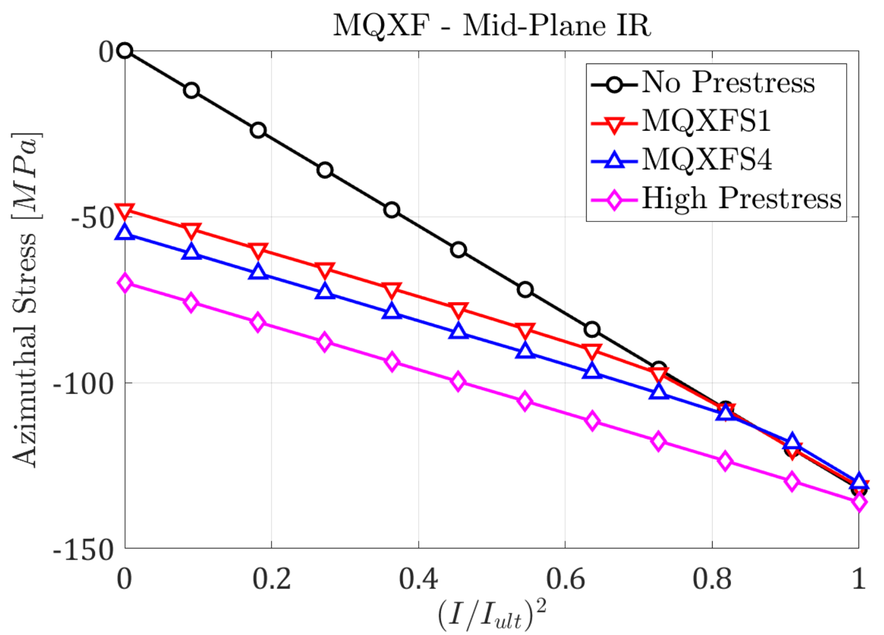
Temperature Margin





- Strain → left
- No strain (strain function = 0.93) → right

Mid-Plane Stress



- Mid-plane stress (inner radius), not a function of applied prestress if the magnet is unloaded