HFM

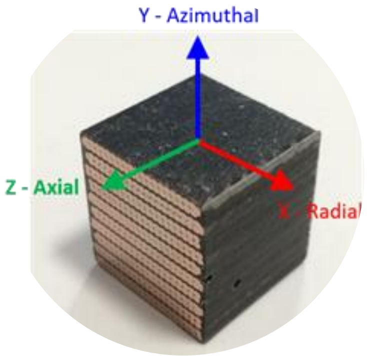
High Field Magnets

Modelization of impregnated Nb_3Sn cable composite

Marco Masci

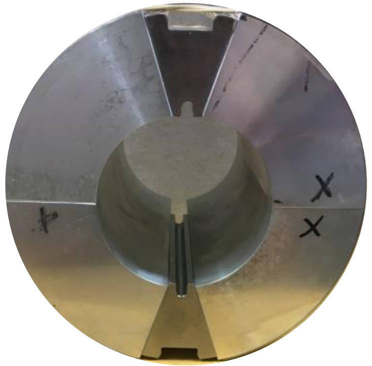
TE-MSC-SMT

Context of the material model & modelization technique development and what they have been benchmarked against



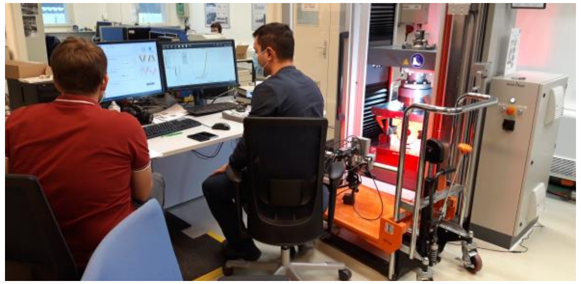
Preliminary Phase:

- **Review of key 11T design features** and assembly procedures.
- **Harmonization of experimental data** on Nb_3Sn cable stacks.
- **Development of a nonlinear constitutive model** for impregnated cable



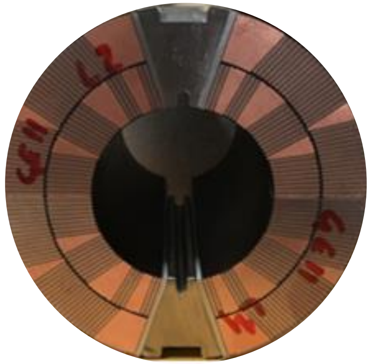
Phase 1:

- Given the large range of unknowns, study first an “**all-metal” mockup configuration** (**Mk1**) to remove uncertainties from materials nonlinearities and **focus on system mechanism and the role of interfaces**
- **QC**, **manufacturing,** and **instrumentation** of components
- Concurrent experimental **measurements** and **simulation**



Phase 2:

- Test and simulate **hybrid mockup** (**Mk2**) introducing 2 Nb_3Sn segments and maintaining 2 Al segments to allow correlating mid-plane strain measurements with well-known Al response



Phase 3:

- Test and simulate **all - Nb_3Sn mockup** (**Mk3**). Final report and publications. Further studies (e.g., capacitive gauges, see seminar F. Wolf *https://indico.cern.ch/event/1070409/*)

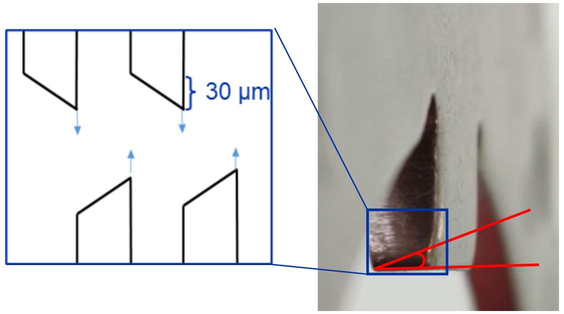
The Team

Project responsible Friedrich Lackner (TE-MSC - until 12.2021) Alessandro Bertarelli (EN-MME)	**FEM simulations** Marco Masci (EN-MME) Michal Holko (EN-MME & TE-MSC)
Documentation / Follow up Friedrich Lackner (TE-MSC) Felix Wolf (TE-MSC) Stefan Höll (EN-MME)	**Consulting (EN-MME)** Alessandro Dallocchio (Components and FEA) Federico Carra (FEA) Thomas Sahner (CAD)
Metrology (EN-MME) Ahmed Cherif Bartosz Bulat Dominique Pugnat Maciej Burkowski	**CAD (EN-MME)** Benoit Riffaud
Experimental measurements and instrumentation Michael Guinchard (EN-MME) Oscar Sacristan De Frutos (EN-MME) Felix Wolf (TE-MSC) Friedrich Lackner (TE-MSC)	**Collaborations** Internal discussions (Jose Luis Rudeiros Fernandez, Emma Gautheron, Arnaud Foussat, …) ETH Zürich (Prof. Tervoort,) EPFL – PSI (B. Auchmann, M. Daly, André Brem)

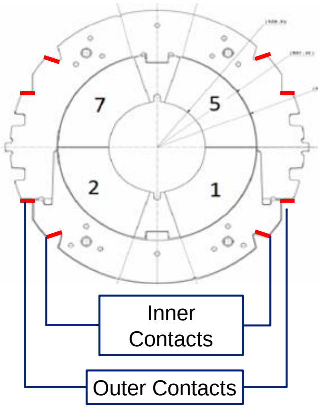
Sources of non linearities in a collared coil

Geometrical Imperfections

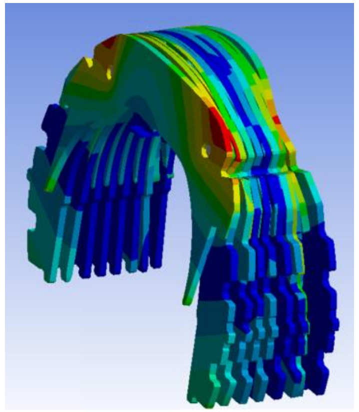
Fine blanking

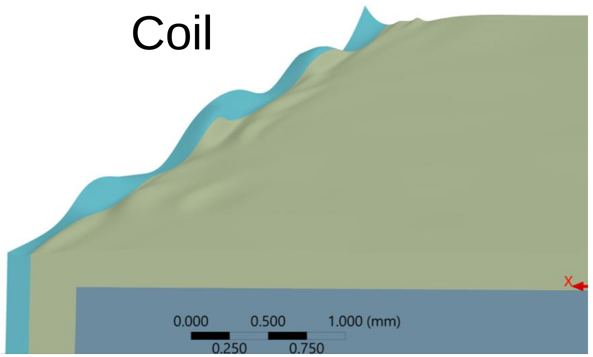


Hyperstaticity

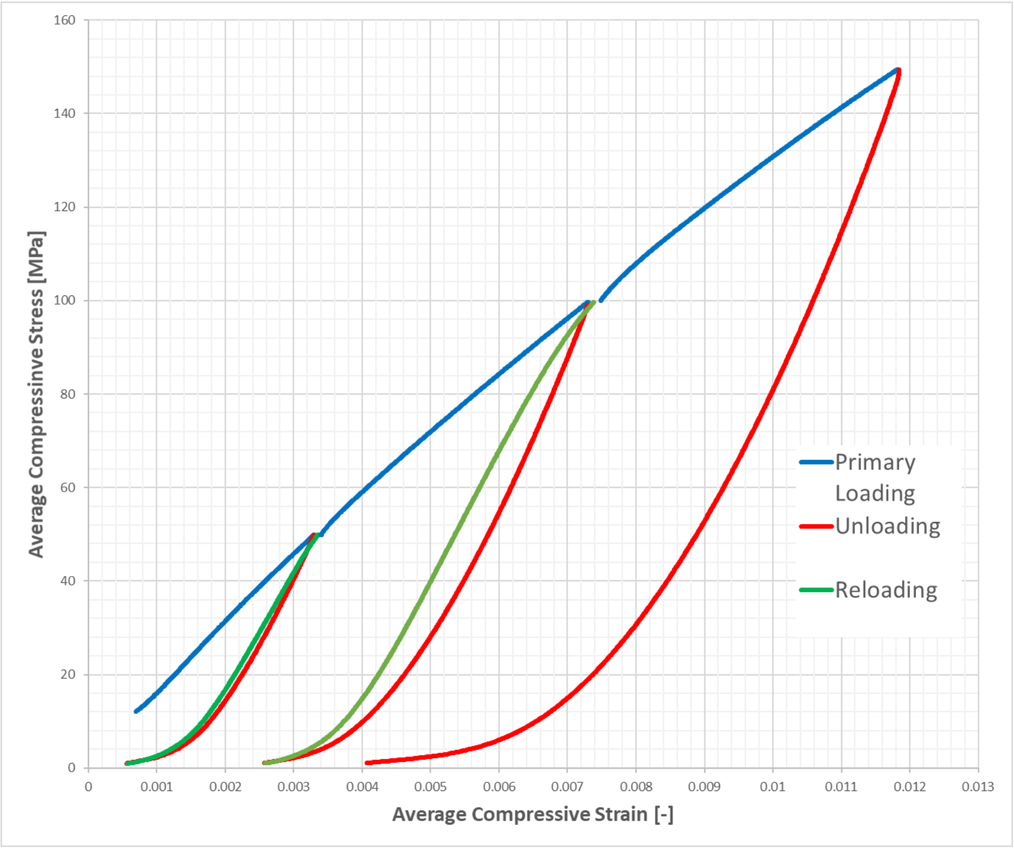


Collar Pack flaring

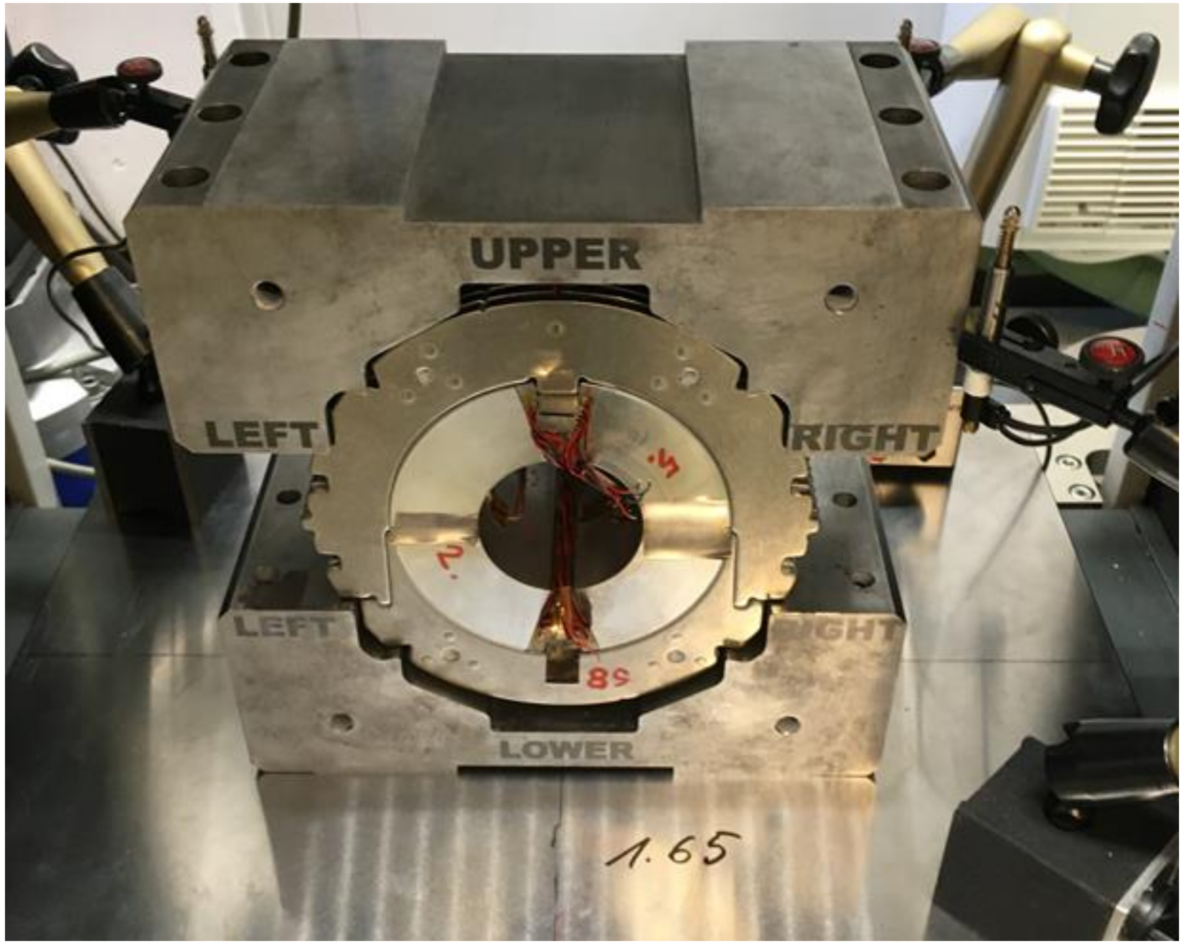


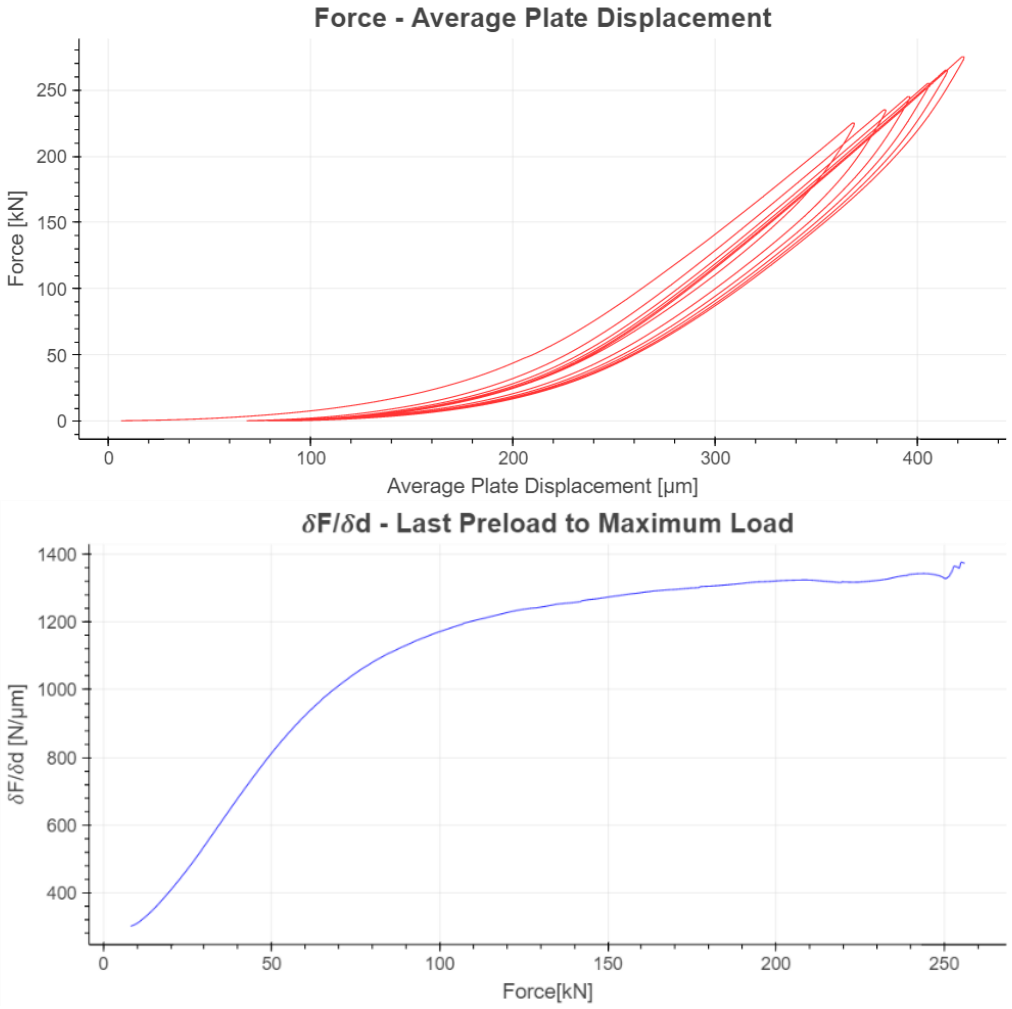


Coil material properties

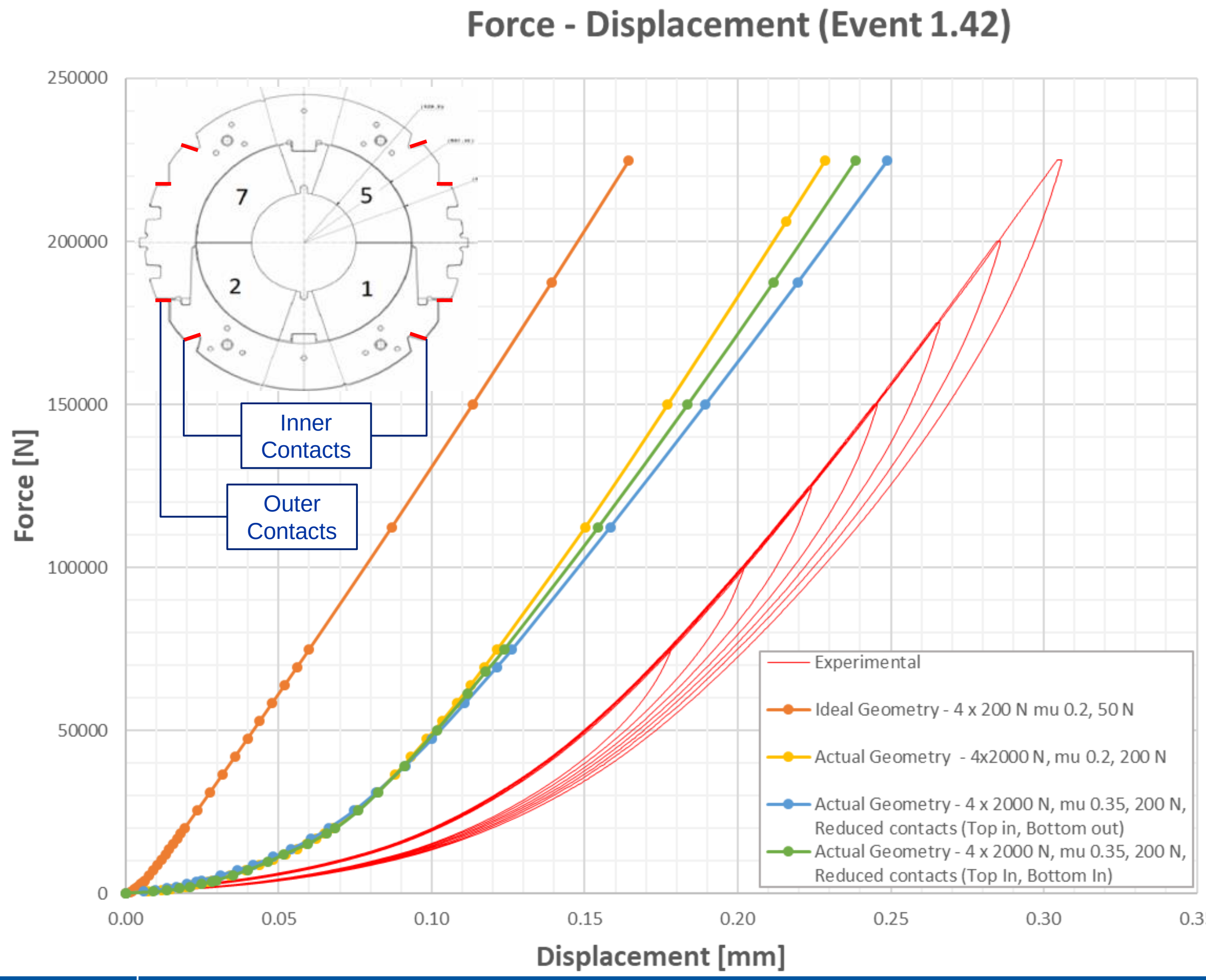


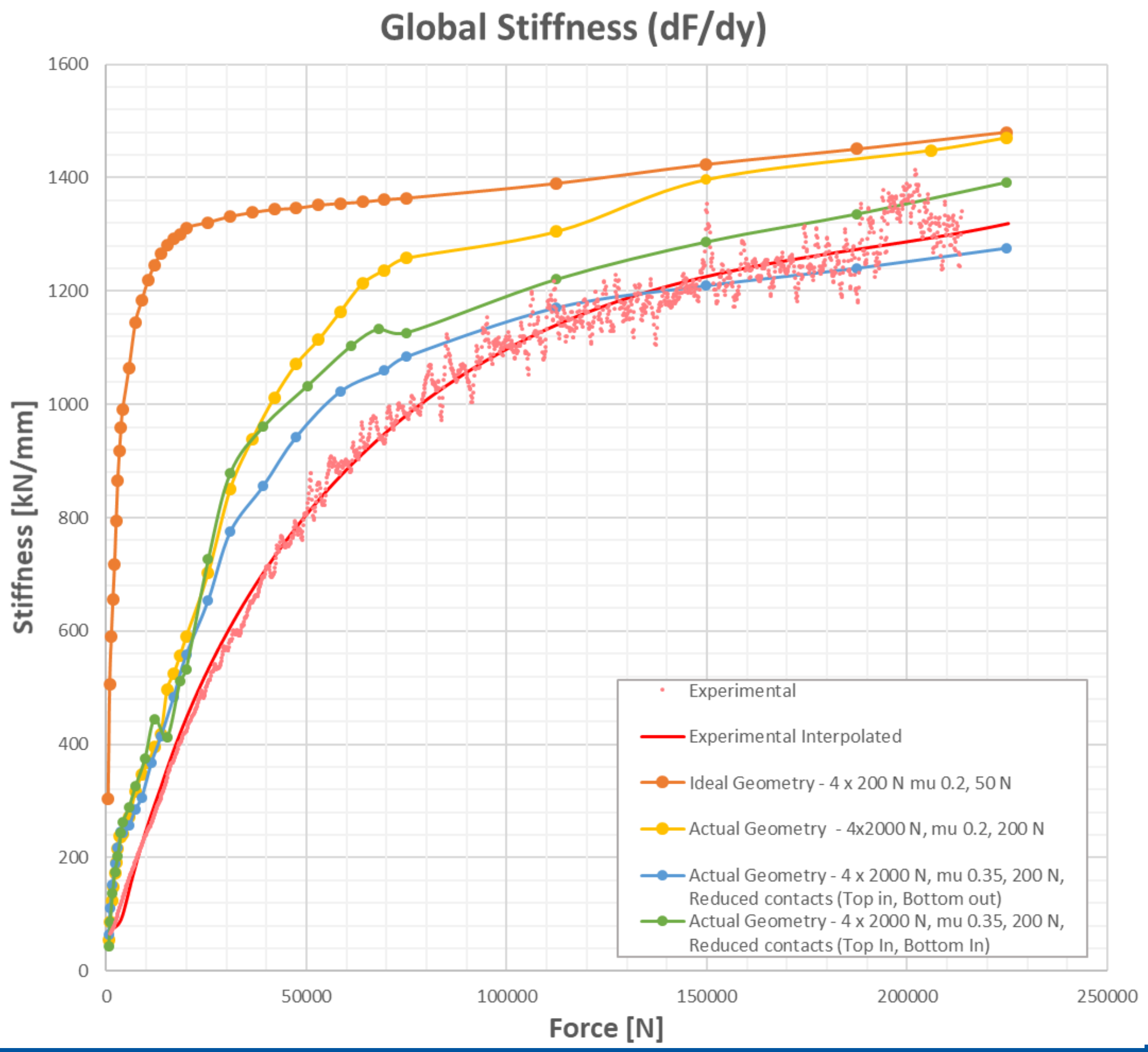
Hysteresis in full metal collared coil





Effect of imperfections on fully metallic collared mk





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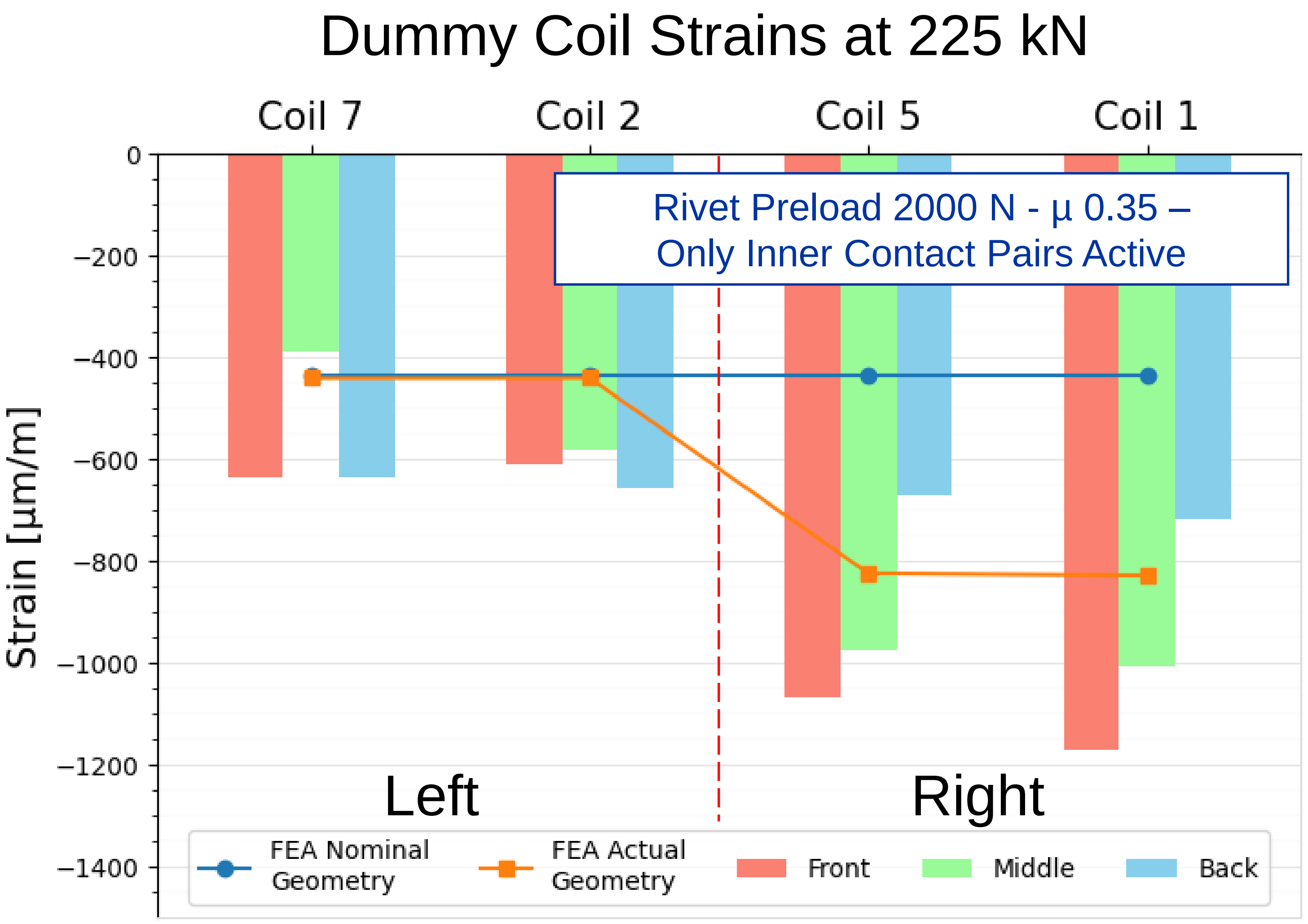
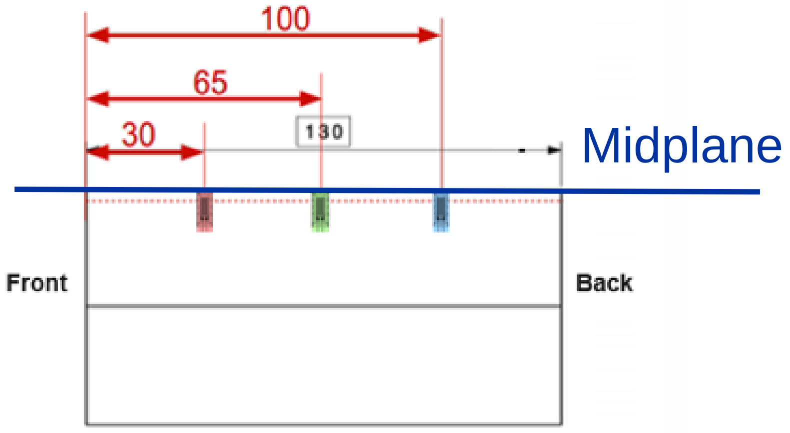
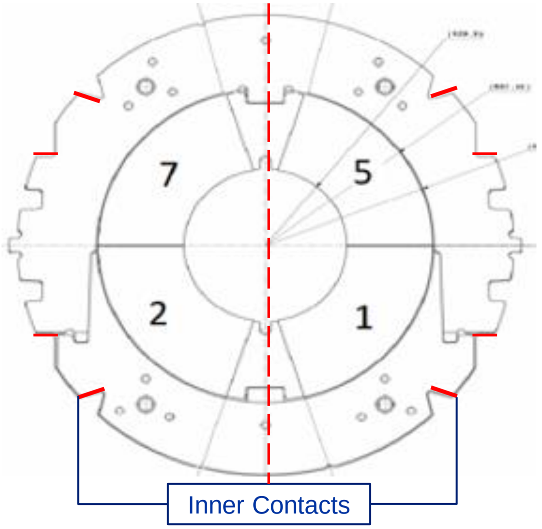
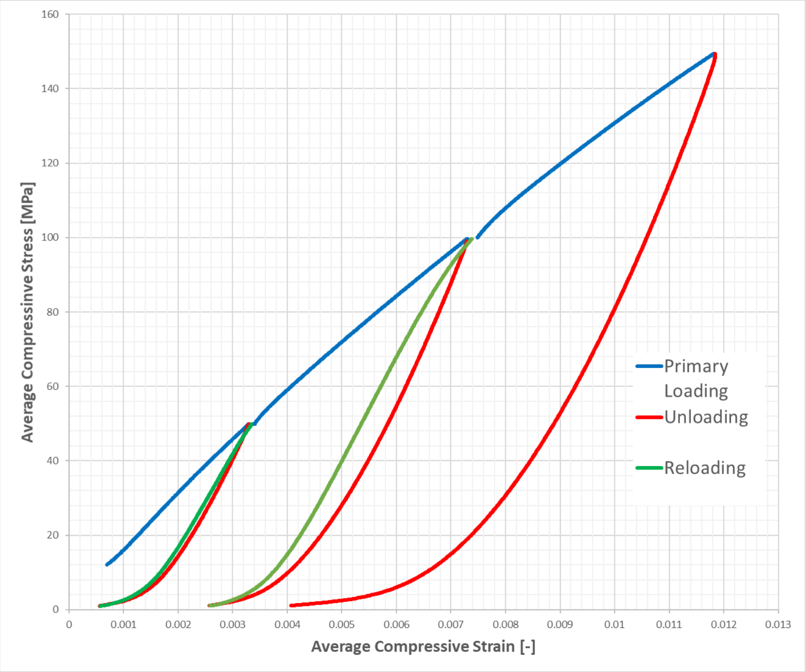




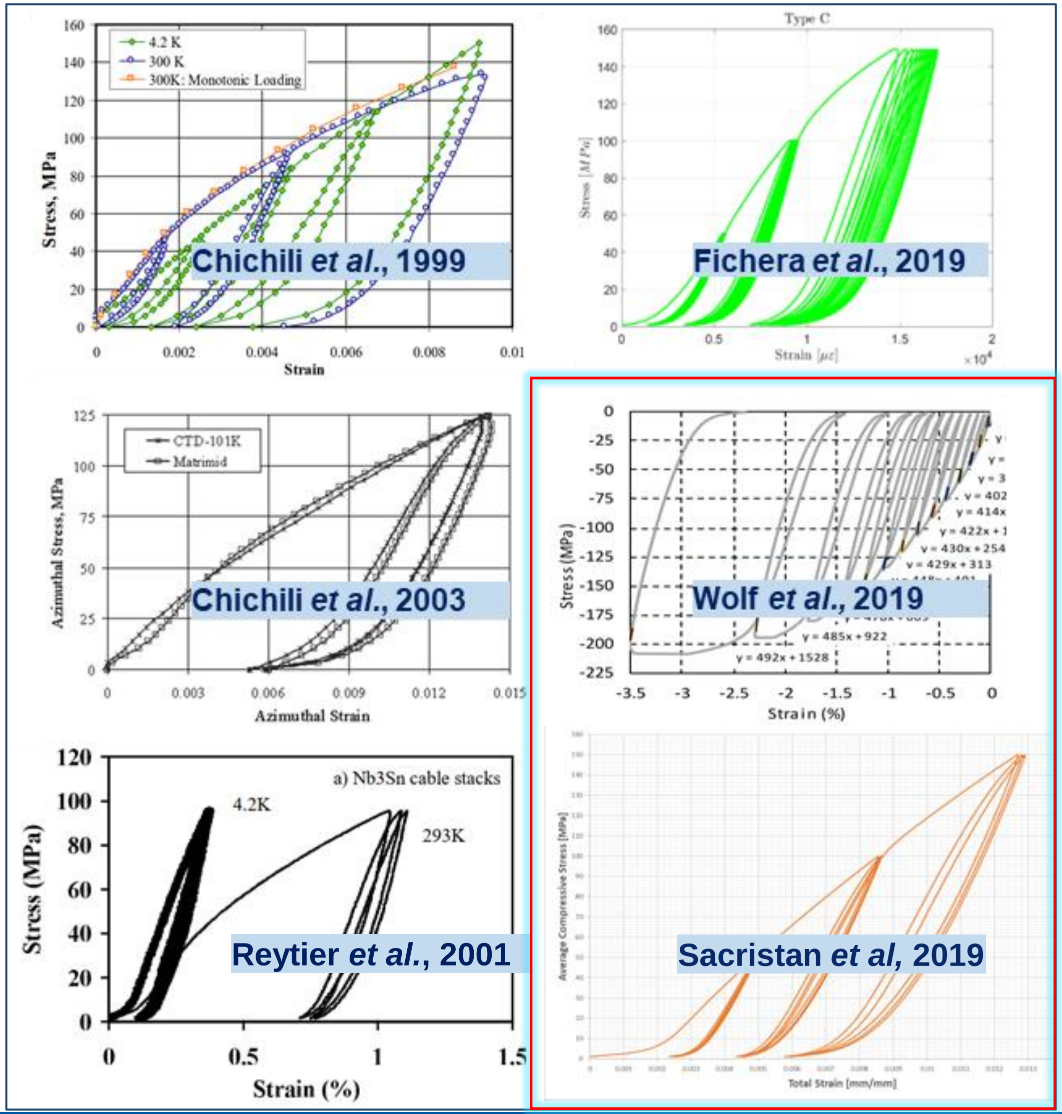


Nb_3Sn 10-Stack Measurements Harmonization

- Analysis of **multiple experimental campaigns** of Nb_3Sn 10-cable stacks since late 1990's consistently show a characteristic **nonlinear mechanical behavior** with **3 distinct phases**:

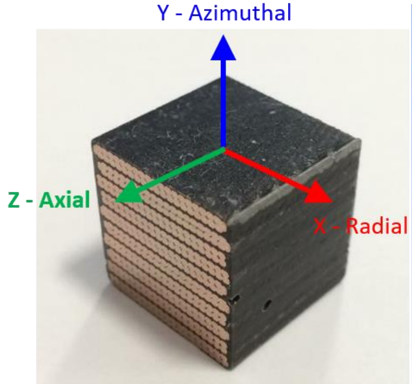


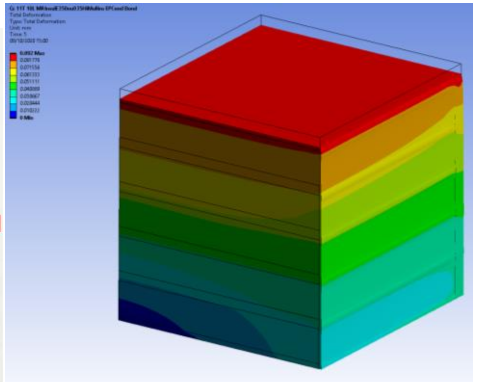
  - Excluding the **initial toe**, the **primary (first) loading** follows a **monotonic**, mildly **softening path** …
  - **Unloading** follows a drastically different path, with an initial (quasi) linear part followed by a softening which is more evident for higher peak stresses and in global measurements;
  - **Reloading** closely retraces unloading path (with **some hysteresis**) until previous peak stress is reached; if **further loading** is applied the path becomes a **continuation** of the **primary loading**.

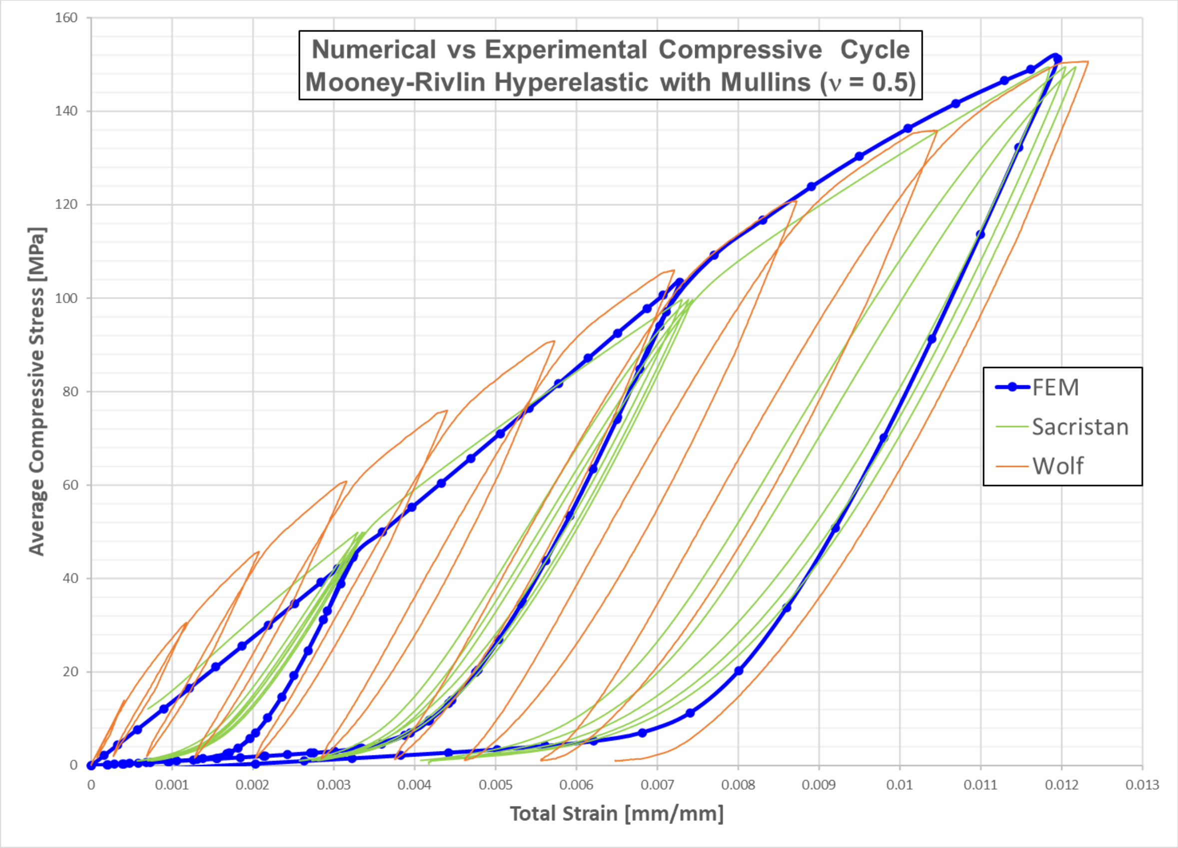


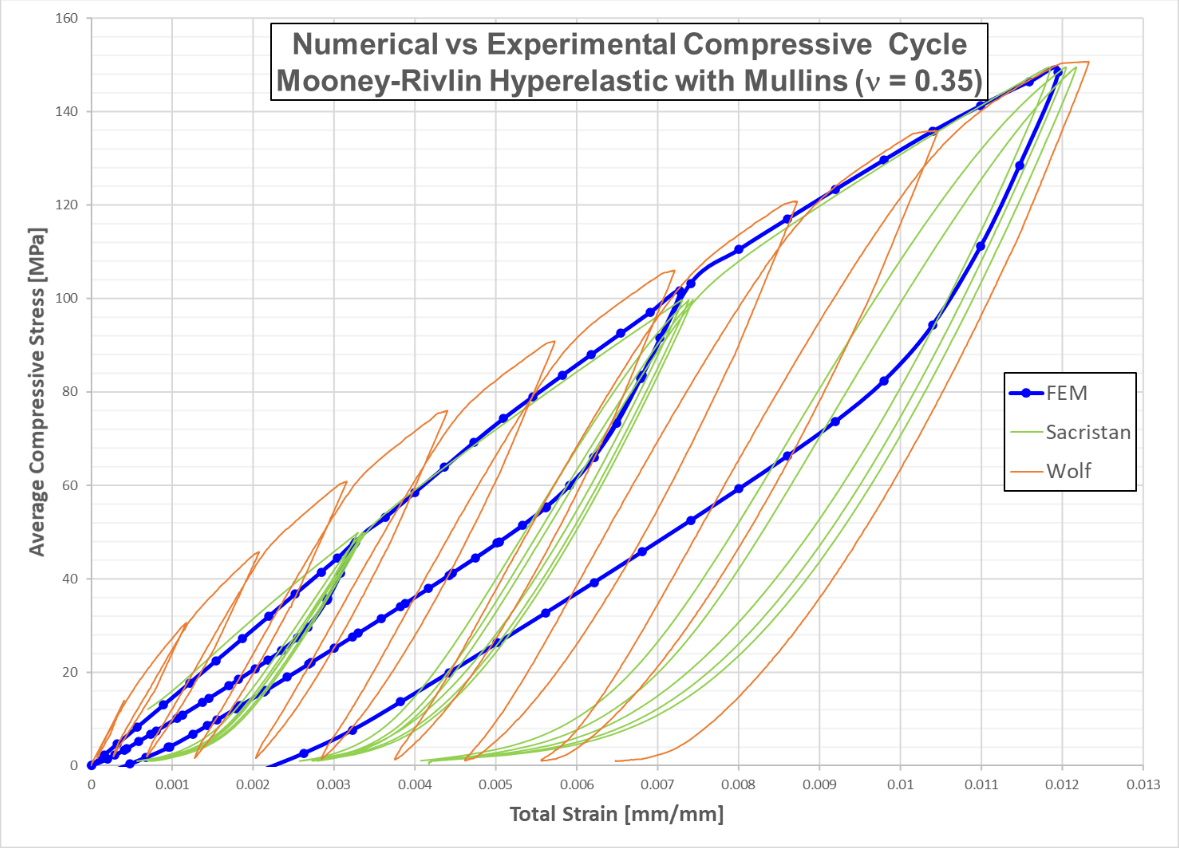
10-Stack: FEM vs Experimental

Comparison between material models:
average stress vs **total** strain curves for 10-stack specimens









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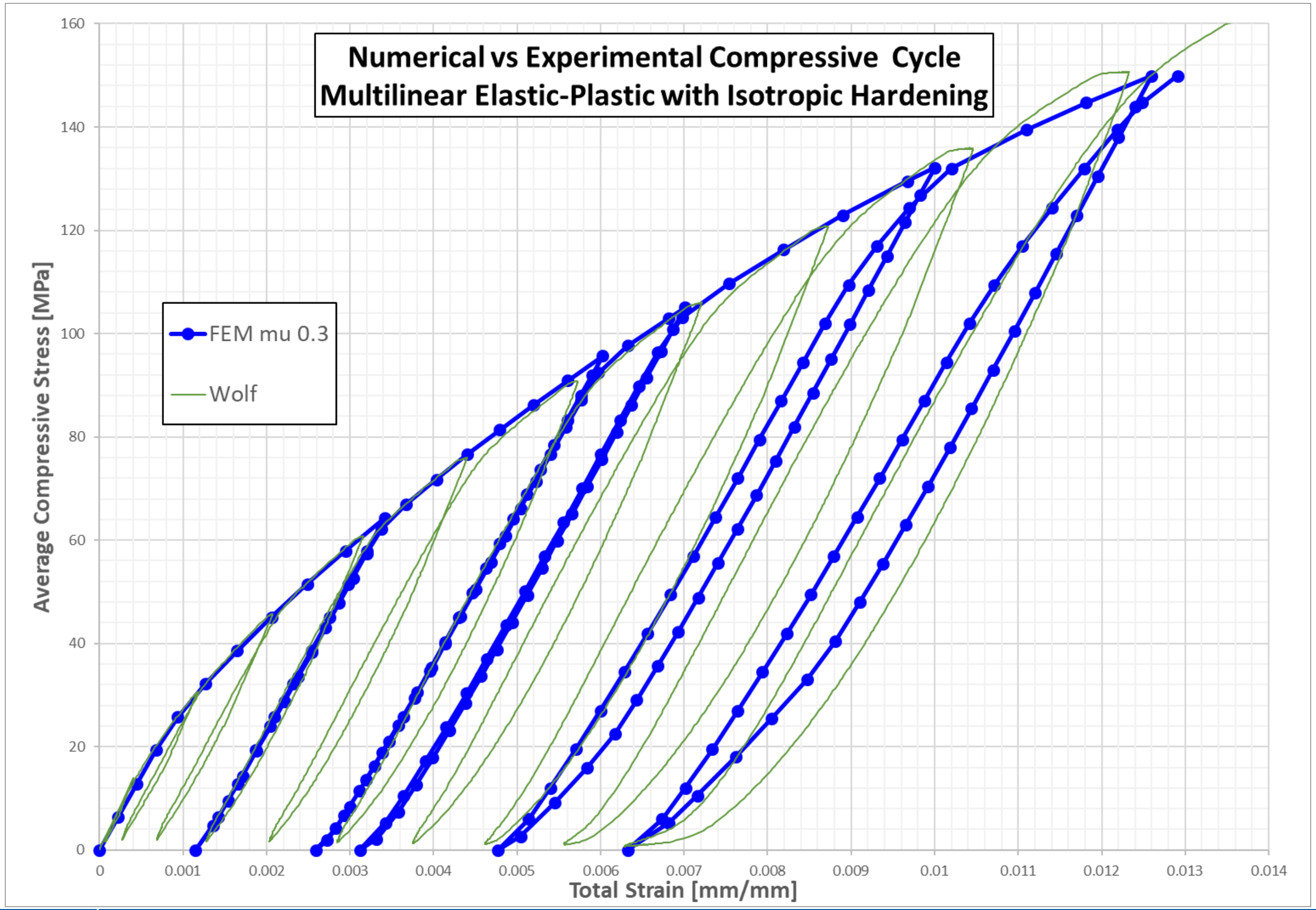
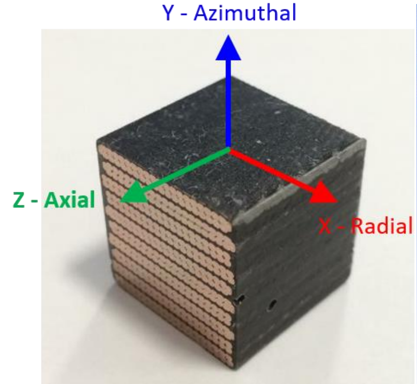
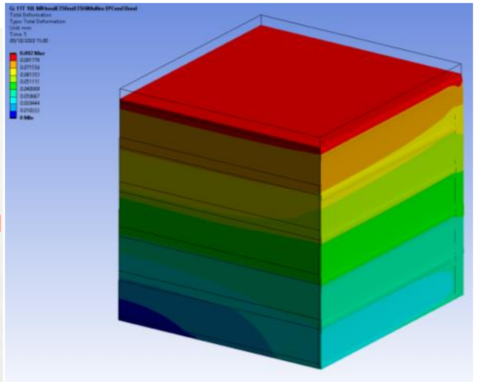
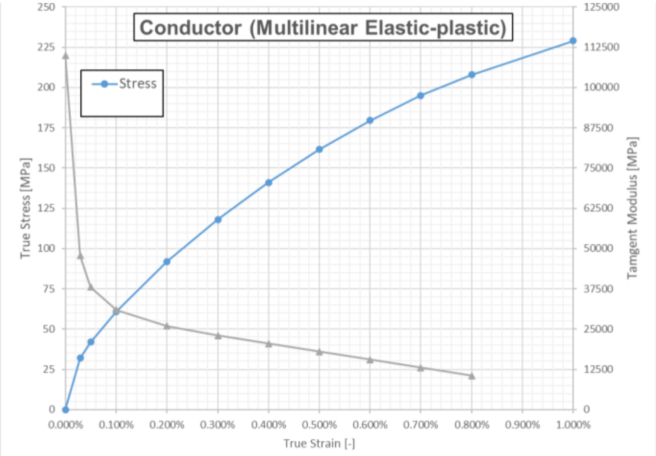
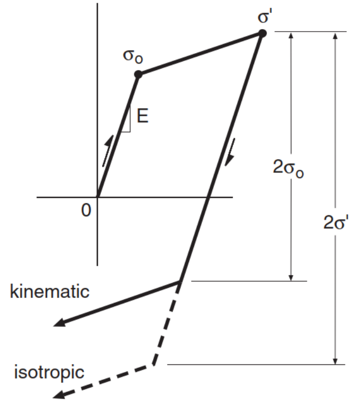
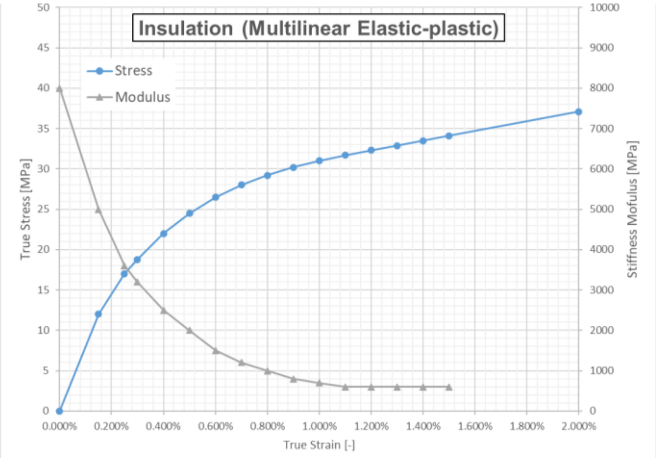












Conductor:

- MISO
- E 110 GPa; ν 0.3
- σ_0 32 MPa

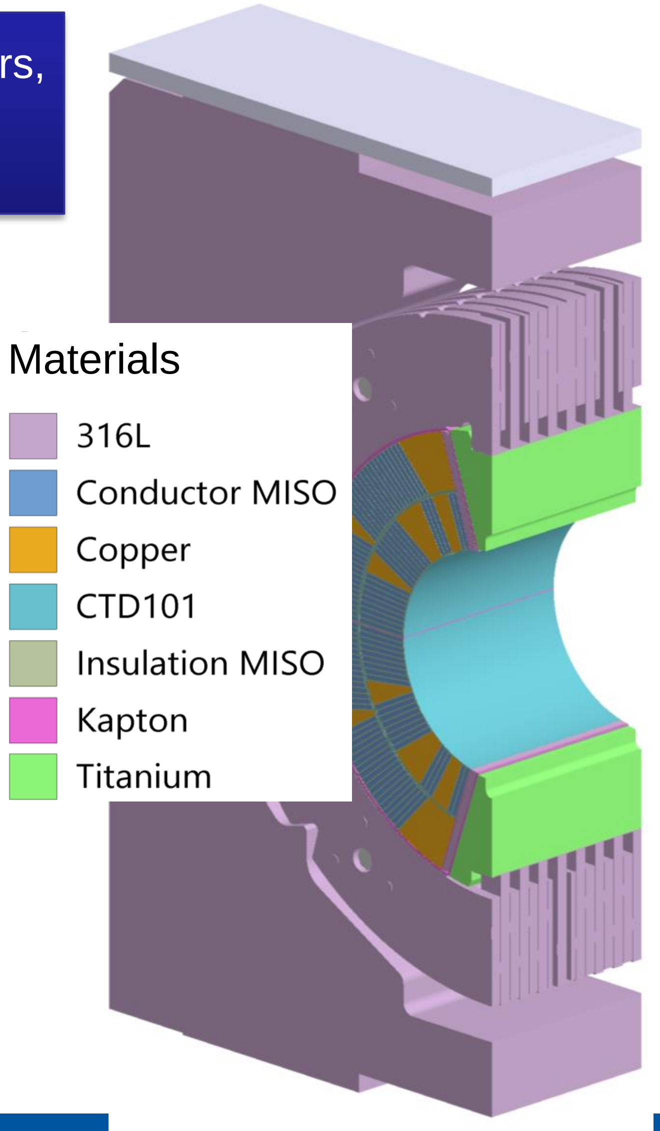
Insulation:

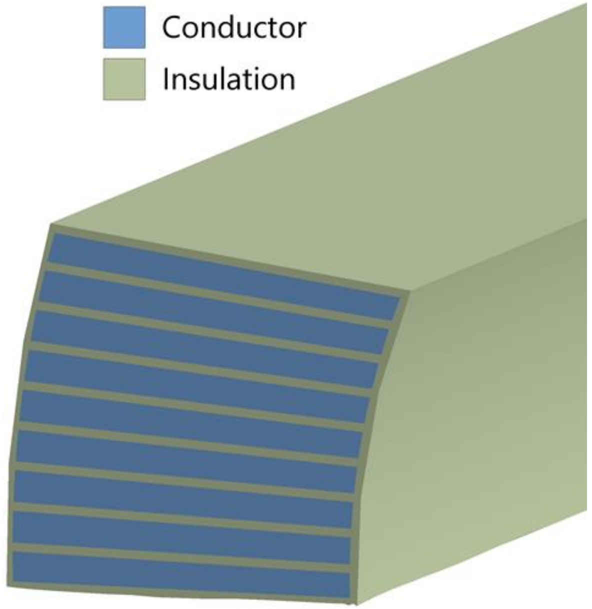
- MISO
- E 8 GPa; ν 0.3
- σ_0 12 MPa

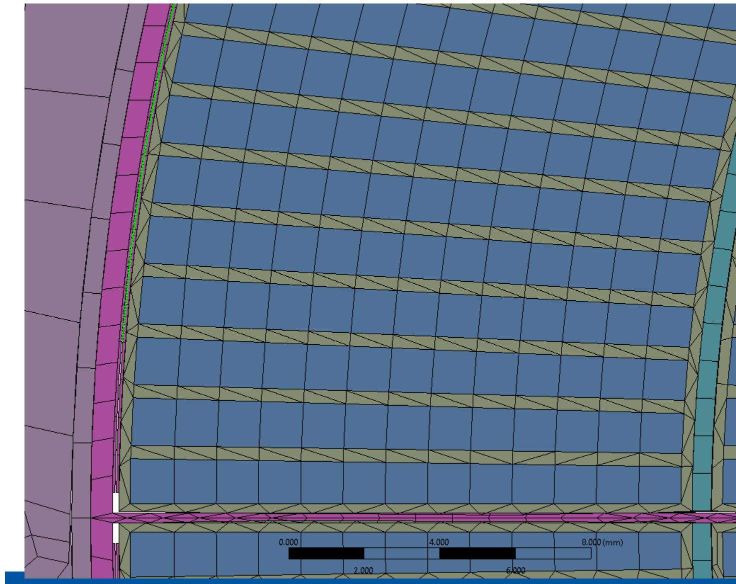
Mk Finite Element Model

Complex 3D FEM including all key system parts (coils, collars, insulation layers, quench heaters, shoes, poles, shims, cradles, crosshead ...)

- **51 mm** thick, i.e., one **large collar pack** (16 collar pairs, 3 **instrumented** collars)
- Coil **cable** modelled as **bi-material solid**, with **inner core** lumping **conductor** elements and **outer layer** condensing all **insulation** (**ratio 70/30** respected)
- All other materials **Linear Elastic**
- **2 Geometrical configurations**: **ideal** (symmetric) and **imperfect coils** (all other parts having ideal geometry)
- **Collar nose draft angle** included (30 µm slope)
- **Several shimming configurations**: **0** (nominal cylinder) to **300 µm** (11 T prescribed shimming)
- **Rivet preload** 2000 N (educated guess)
- **Frictional** contacts (µ 0.2)
- Typical **element size ~1 mm** (less for thinner parts), a trade-off between the level of detail and computational issues







Mk - Finite Element Model

Method to implement geometrical imperfections improved compared to Phase 1

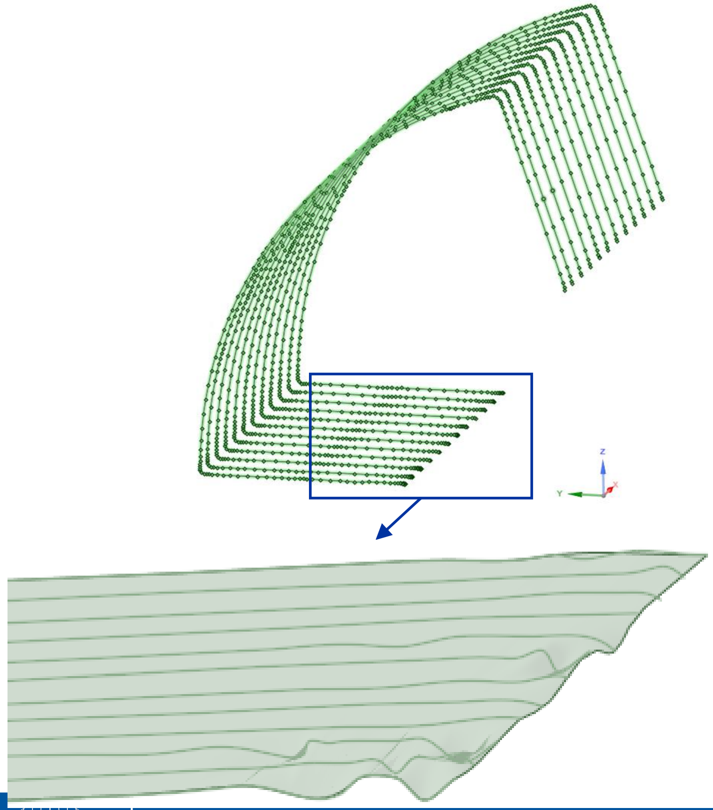
Coil CMM measurements
(5 mm steps)

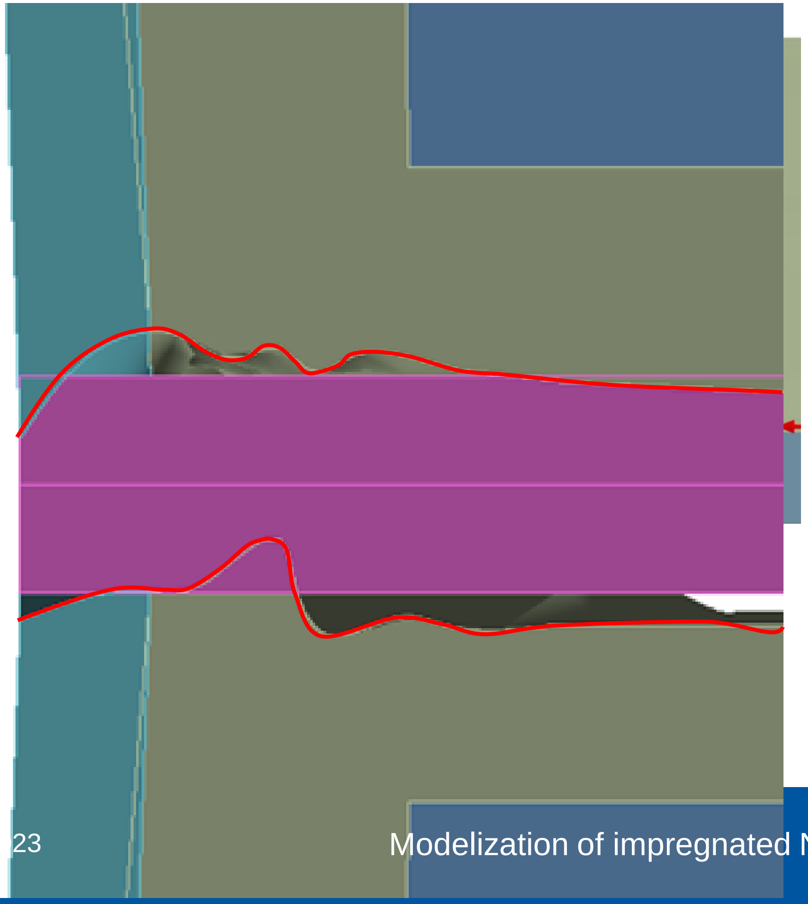
⇒

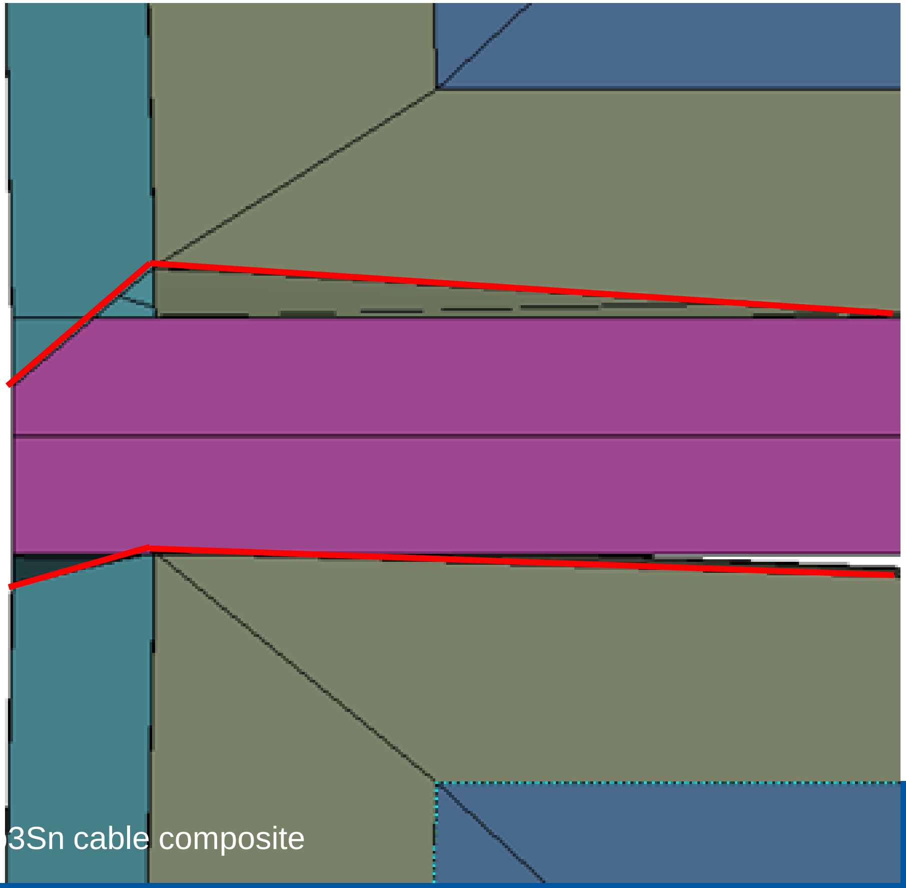
Measured wireframe imported in Ansys and coil surfaces generated

⇒

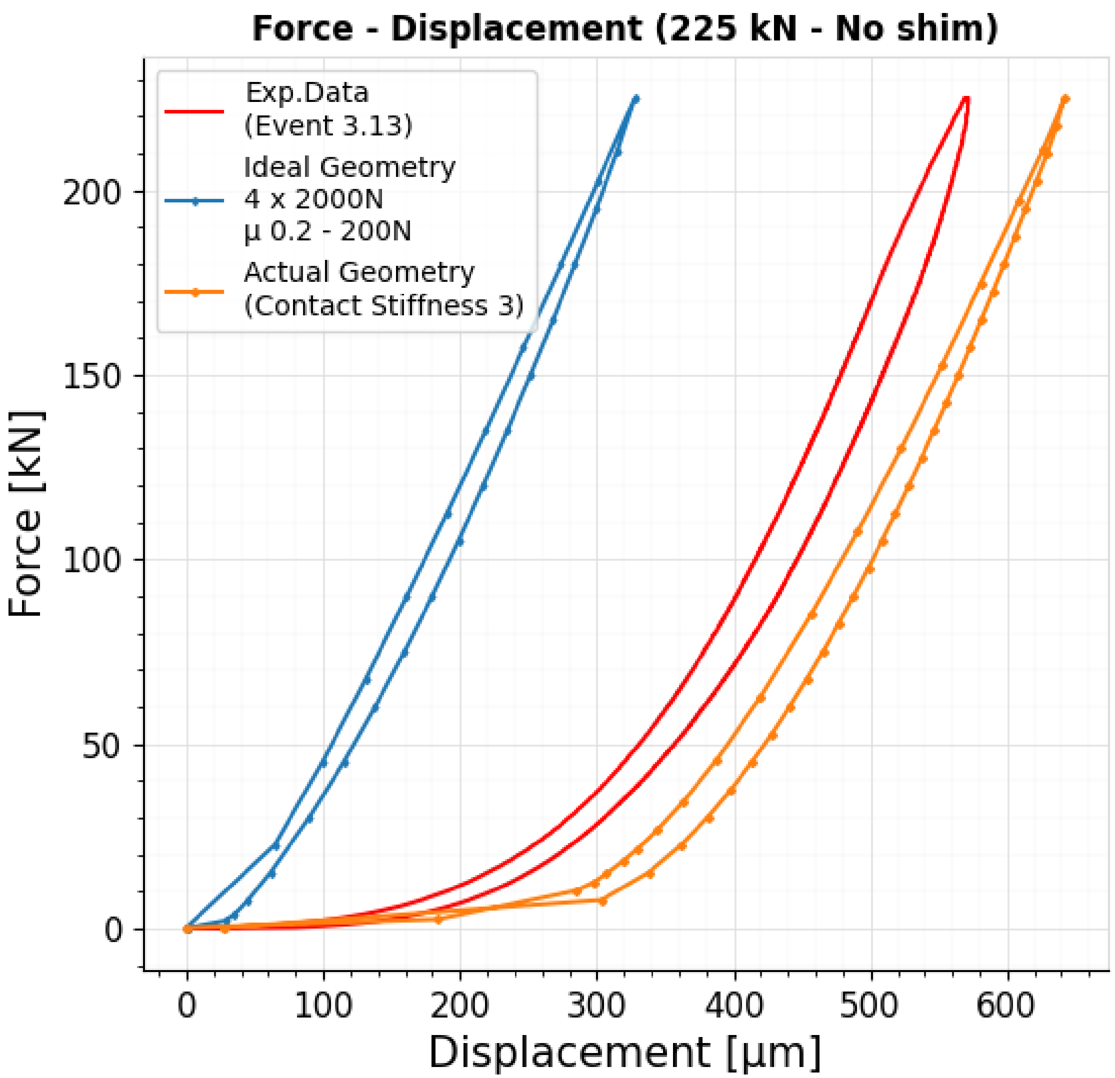
Generated mesh interpolating geometry. Fitting accuracy depends on element size

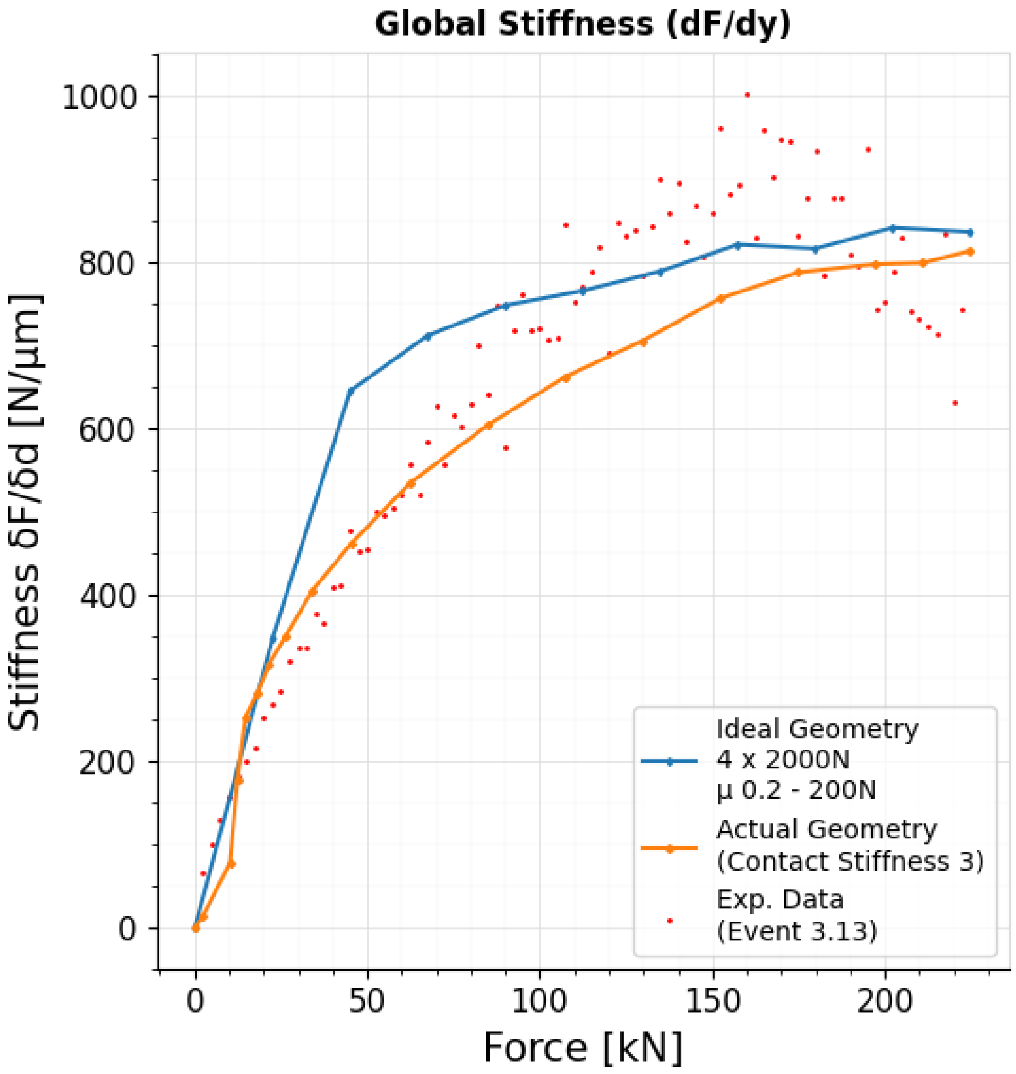




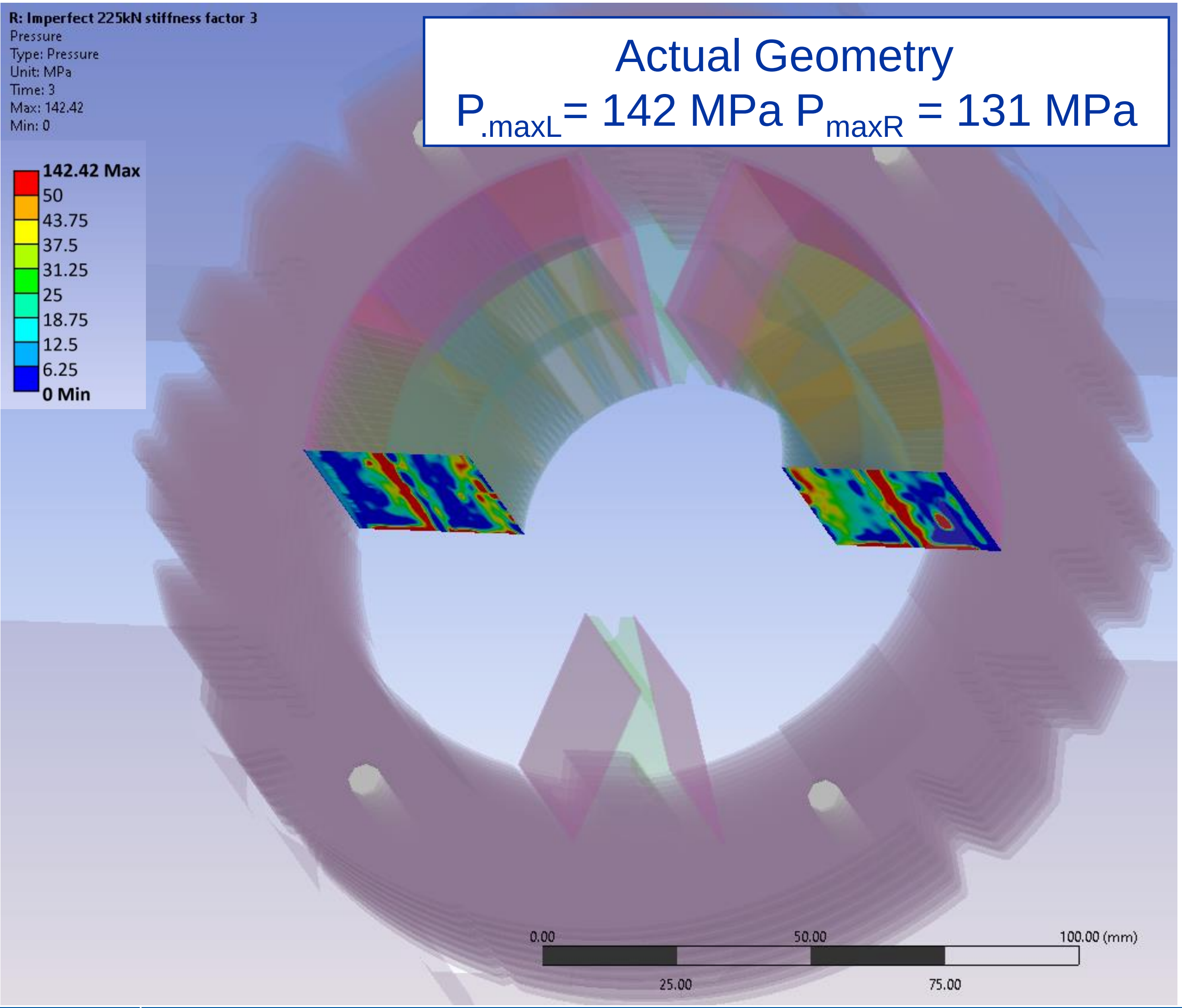


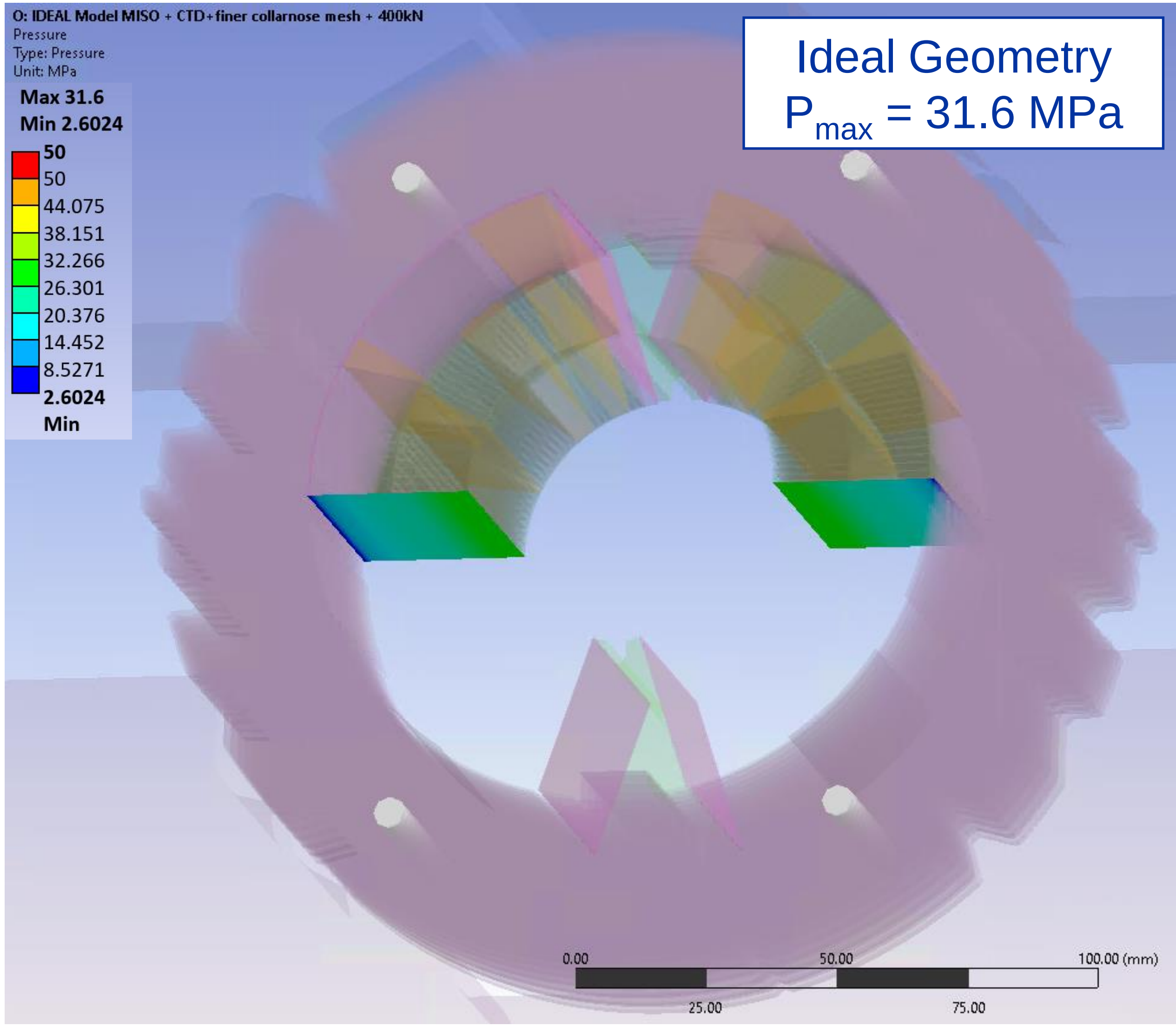
225 kN (27 MPa) No Shim: Deformation and Stiffness





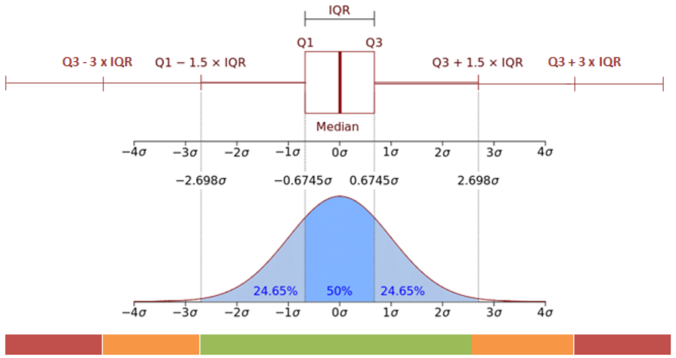
225 kN (27 MPa) - Mid-plane Pressure



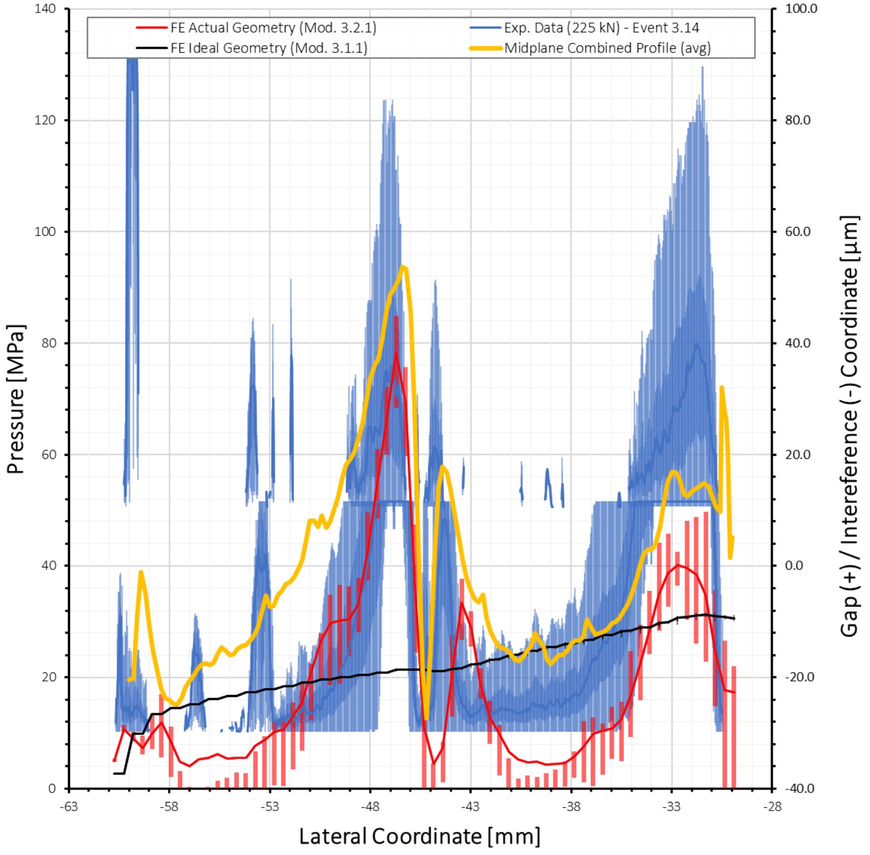


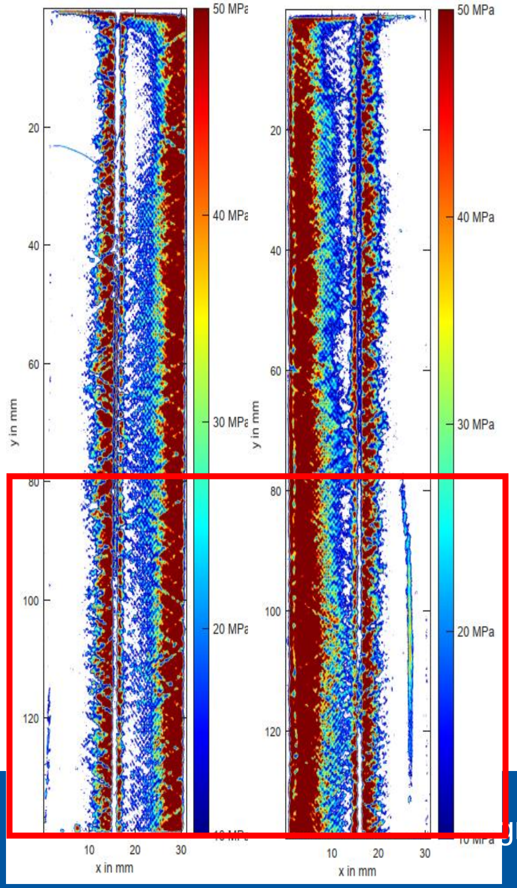
225 kN (27 MPa) No Shim – Fuji Film vs FEM Midplane

- Fuji Film data from MS (10÷50 MPa range) and HS (50÷130 MPa range) films (Event 3.14)
- FEM with contact stiffness factor 3 between pole wedges and cable blocks
- Box and whiskers plots condensing all data for the first collar pack (51 mm)
- Reasonable consistency between simulations and measurements, in particular at the transition between inner and outer layers (systematic geometrical imperfection)

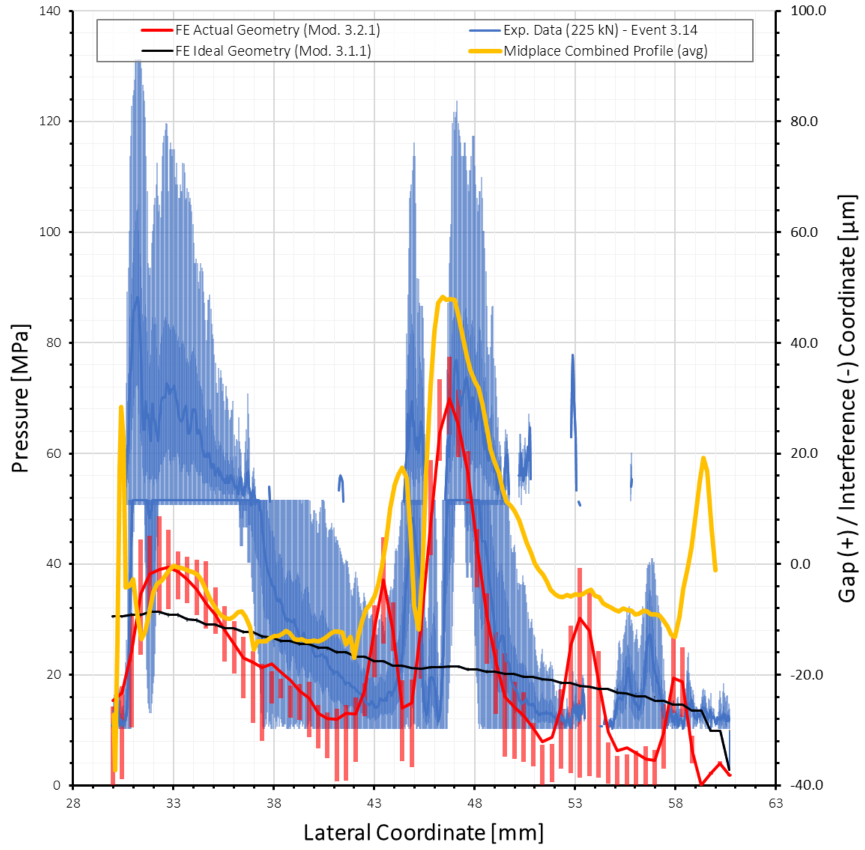


Force 225kN (27 MPa) – No Shim – Left Side





Force 225kN (27 MPa) – No Shim – Right Side



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