Mechanical modelling and failure identification of impregnated Nb_3Sn Rutherford cable stacks

Xiang Kong[1], Theo A. Tervoort[1], Andre Brem[2], Douglas Martin Araujo[2], Michael Daly[2], Bernhard Auchmann[2,3]

1. Department of Materials, ETH Zürich, Switzerland
2. Paul Scherrer Institution (PSI), Villigen, Switzerland
3. CERN, Geneva, Switzerland

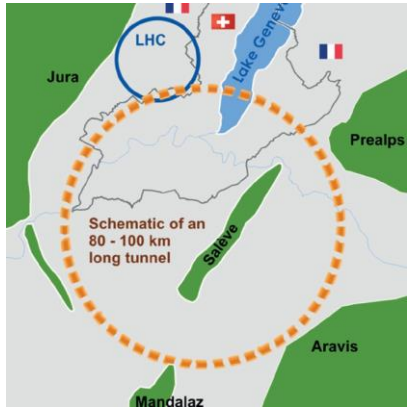
11.10.2023

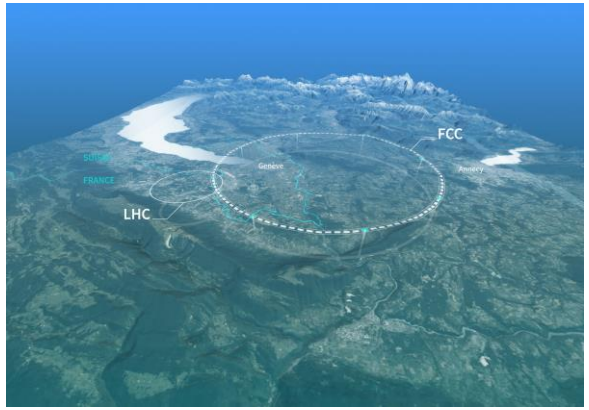
CHART Workshop 2023

Swiss Accelerator Research and Technology

Introduction

Future Circular Collider (FCC)





Ferracin et al. 2015

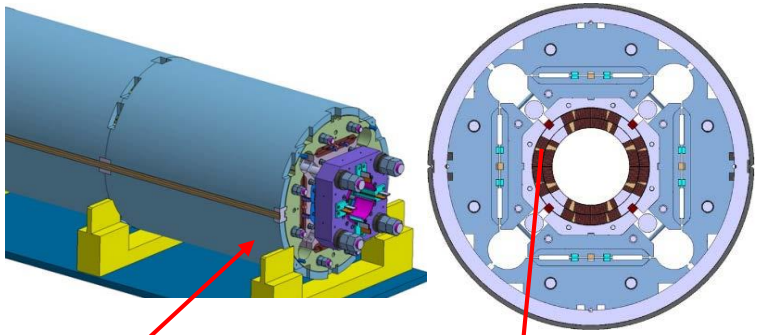
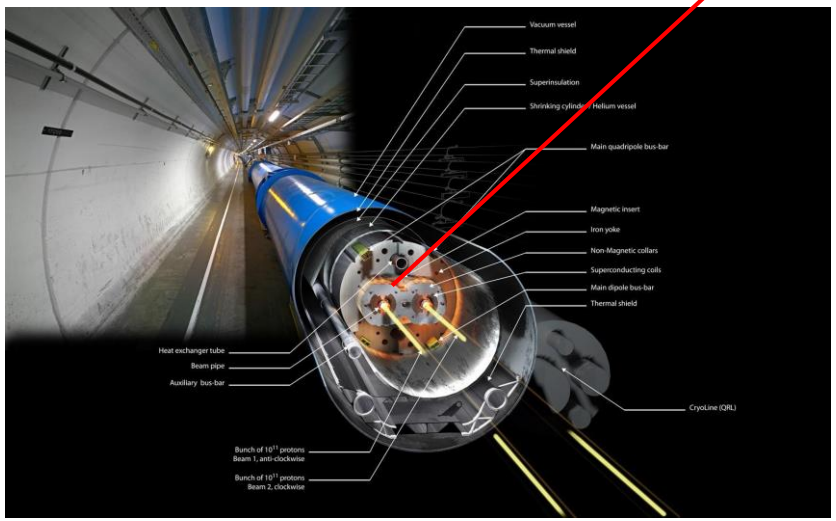
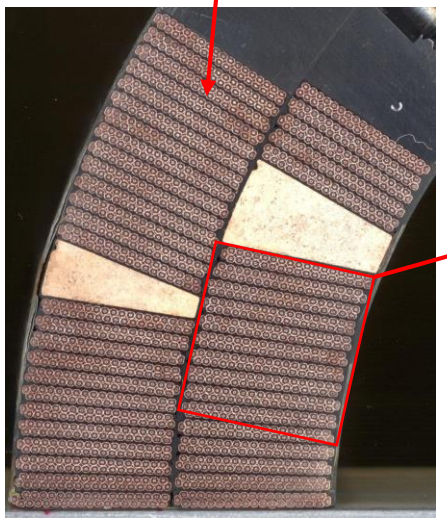


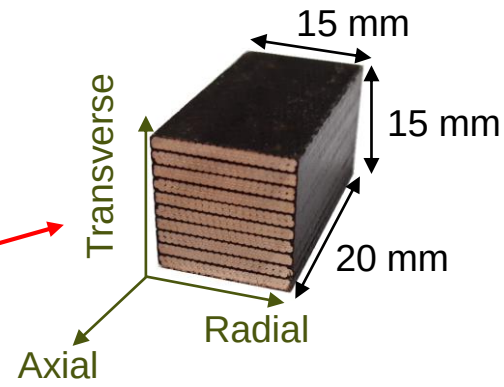
CHART project

Swiss Accelerator Research and Technology



CERN website

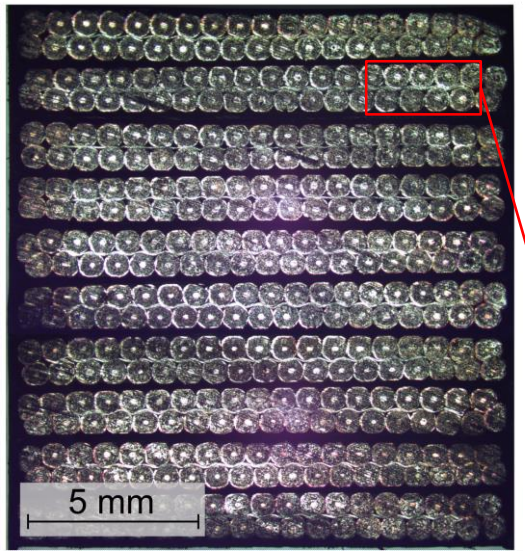




Daly et al. 2018

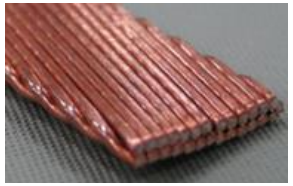
Ferracin et al. 2015 Transactions on Applied Superconductivity (Volume: 26, Issue: 4, June 2016)
Daly et al. 2018 Transactions on Applied Superconductivity (Volume: 28, Issue: 3, April 2018)

Multiscale structure → heterogeneous

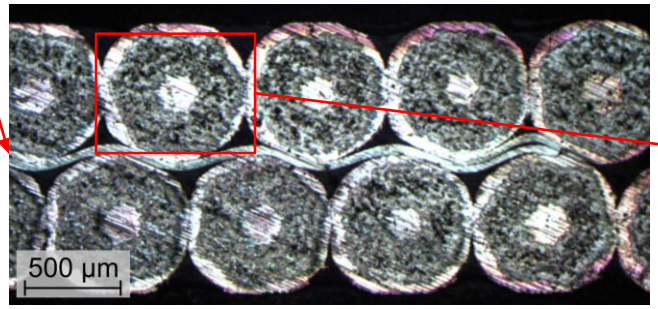


~15 mm

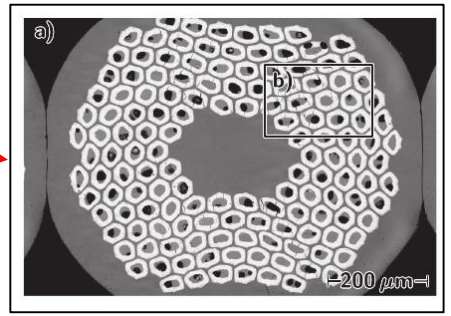
Rutherford cable stack



Vallone, MDP Meeting 2022

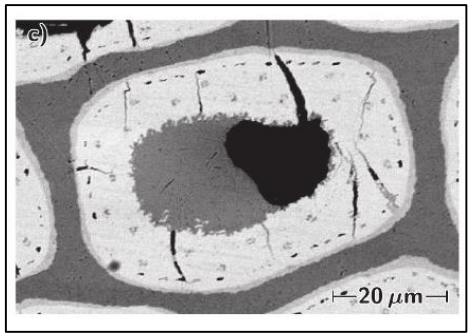


~ 1 mm



~750 µm

Ebermann et al. 2018



~50 µm

Cubic level

10-stack cable

Stack level

- ❑ Epoxy
- ❑ Strand
- ❑ Insulation
- ❑ Stainless-steel core

Strand level

- ○ Copper matrix
- ○ Nb_3Sn micro filaments

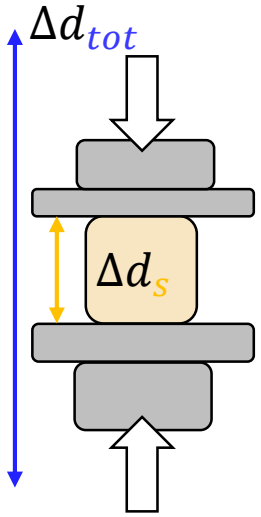
Filament level

- • Nb_3Sn filament
- • Copper matrix
- • Void

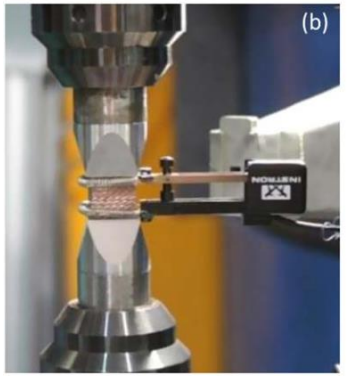
Ebermann et al. 2018, Supercond. Sci. Technol. 31 (2018) 065009

Bibliography

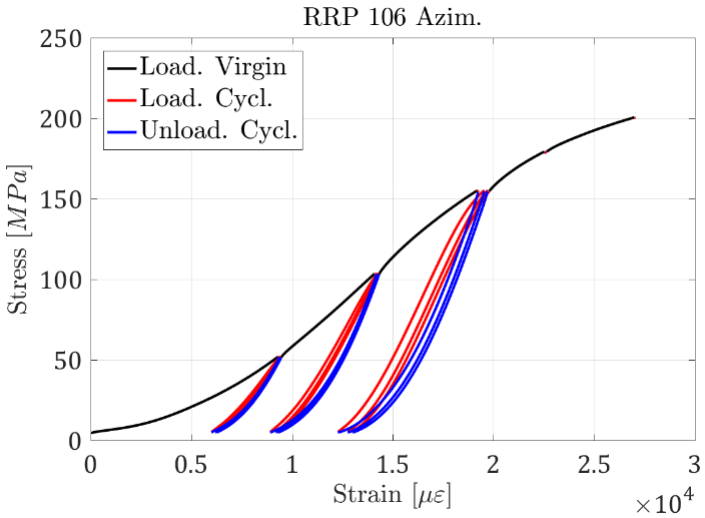
‘Strain – stress’ identification

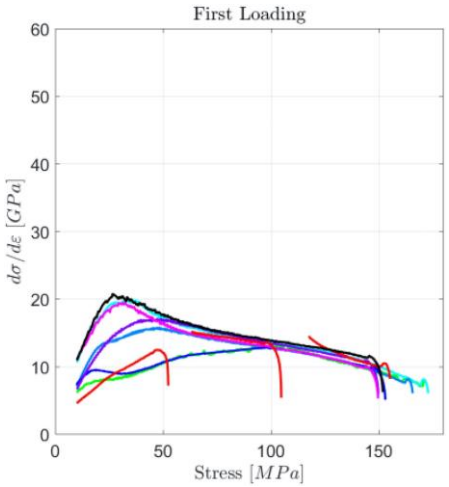


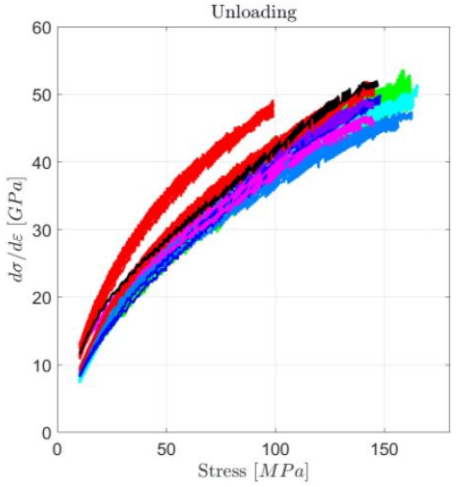
Clip-on extensometer



Scheuerlein et al. 2019



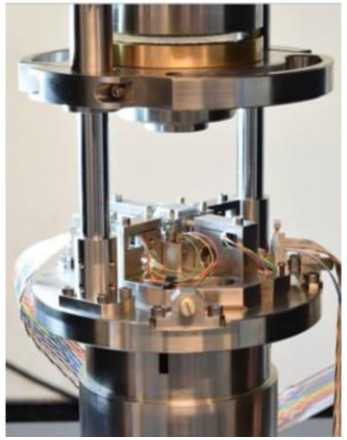


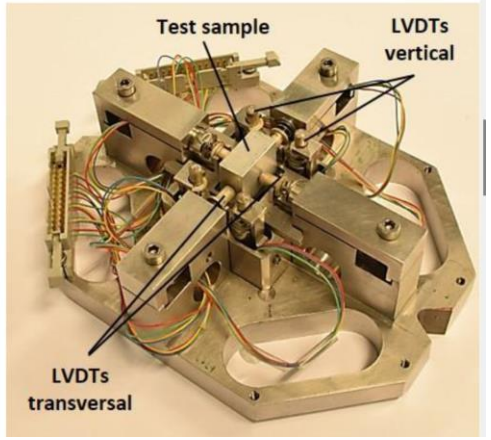


Vallone et al. 2018

Nonlinear → unloading → modulus

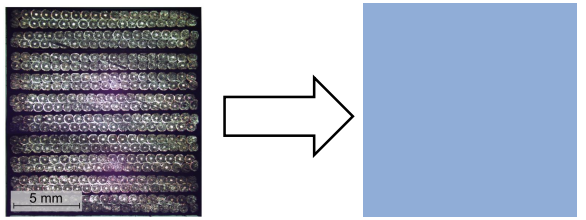
LVDT: Linear Variable Differential Transformer





Fichera et al. 2019

Homogenization



Limitation:

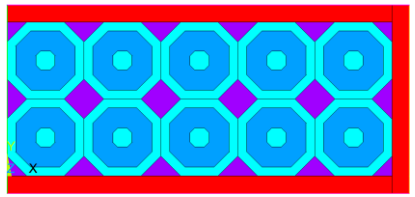
- ❑ Homogenization: 1D information
- ❑ Hardly measure at cryogenics (e.g., LN_2)

Scheuerlein et al. 2019 Supercond. Sci. Technol. 32 (2019) 045011
Vallone et al. 2018 Transactions on Applied Superconductivity (Volume: 28, Issue: 4, June 2018)
Fichera et al. 2019 Transactions on Applied Superconductivity (Volume: 29, Issue: 7, October 2019)

Structure

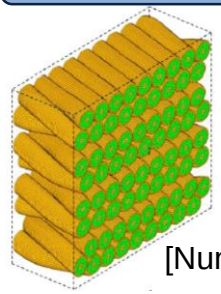
FEM modeling

2D octagon

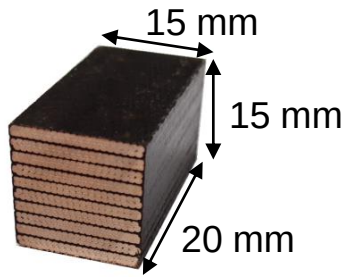


Ansys

3D mesh



[Nunio 2019]



Experiment

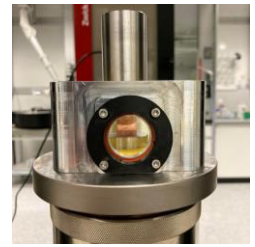
Component characterization

- Epoxy (CTD101K)
- Annealed Copper
- Fiber glass etc.

10-stack

- Transverse
- Axial/radial/other loads

Set-ups at LN_2



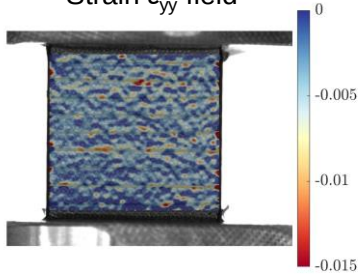
Local measurement

Image analysis

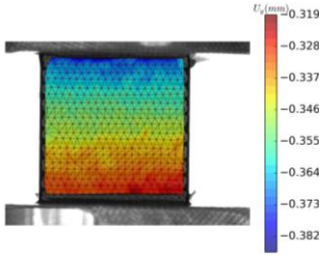
Digital Image Correlation (DIC)
- Displacement field
- Strain field

'Strand' tracking
- Measure by marker
- Postprocess strain

Strain ε_{yy} field



Displacement U_y



Strain ε_{yy} field

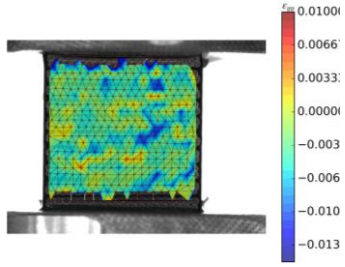
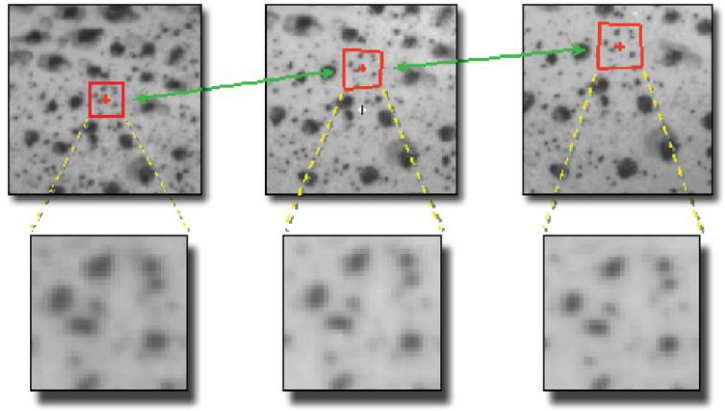
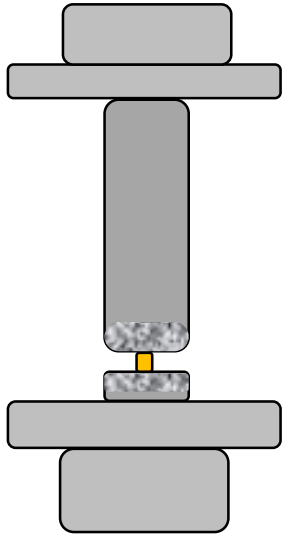


Image analysis: optical extensometer

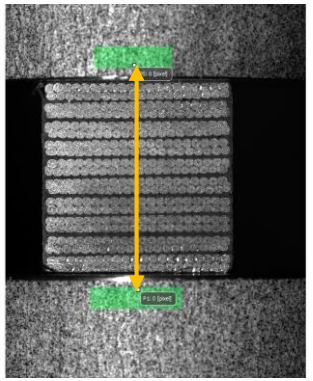
Digital image correlation (DIC)

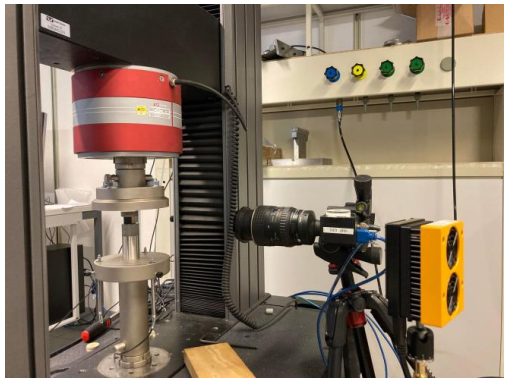


VIC2d

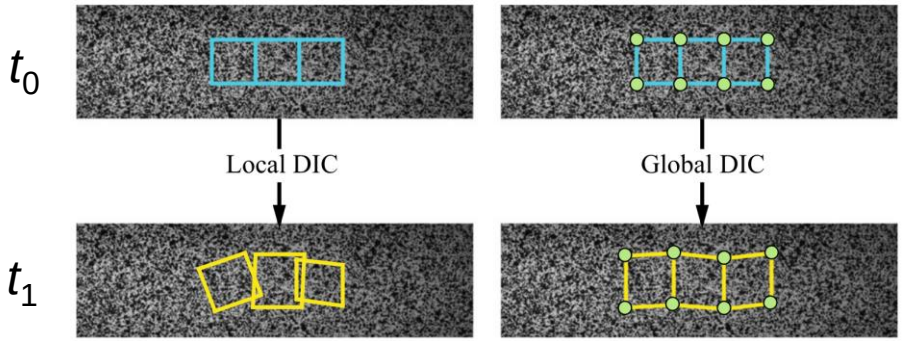


Measure local displacement by *undeformed markers* at cubic level (15 mm)





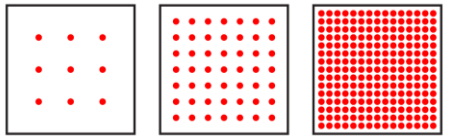
Courtesy of Tancogne-Dejean @MAVT-Mohr's lab

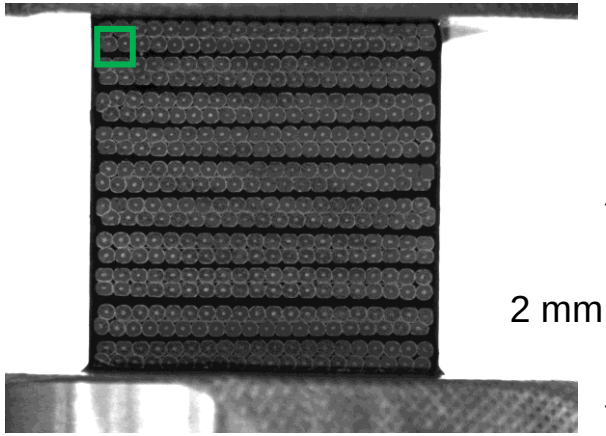


Yang, Bhattacharya, Exp Mech (2019)

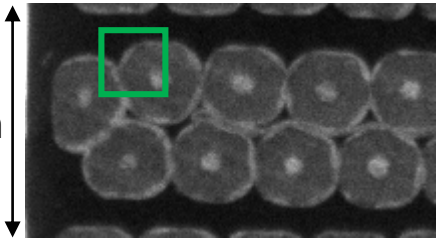
$$f(\boldsymbol{x}, t_0) \approx g(\boldsymbol{x} + \boldsymbol{u}(\boldsymbol{x}), t_1)$$

Subset size → measure at stack level
Step size → control *nodal* points within one subset





1440x1080 px^2, 17.1 μm/px



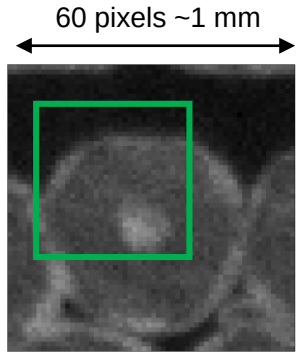
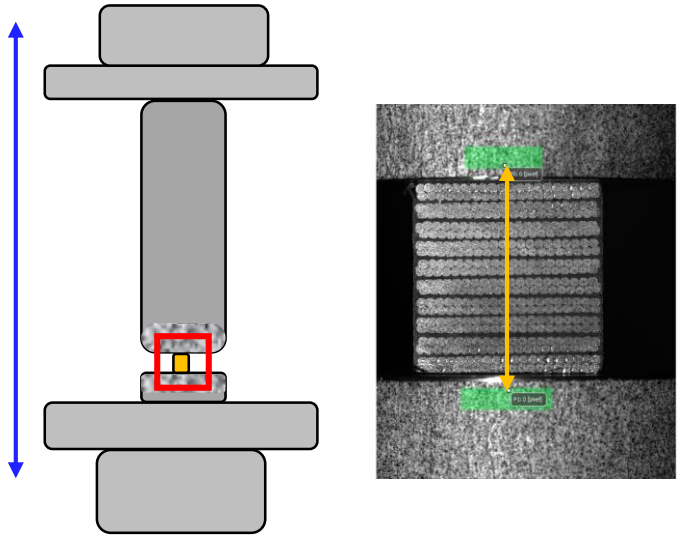
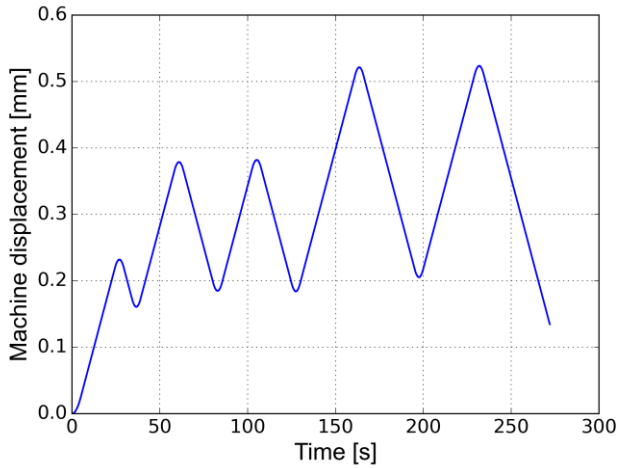


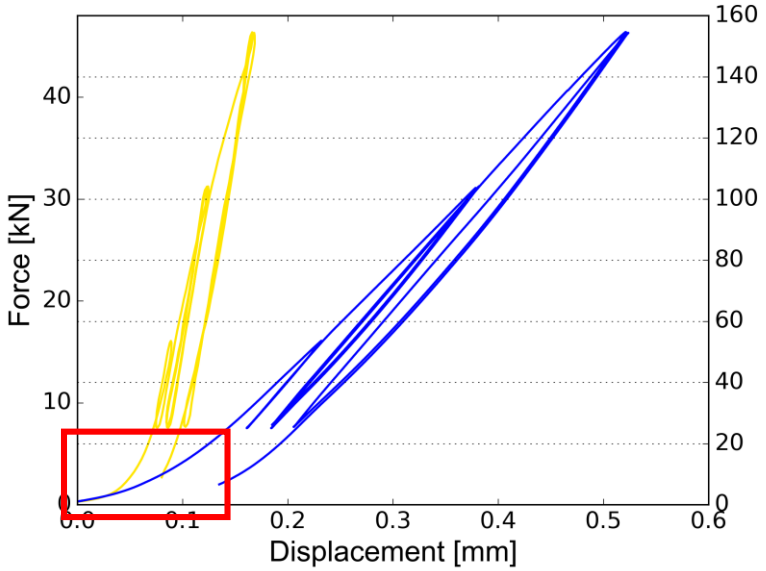
Image analysis: optical extensometer



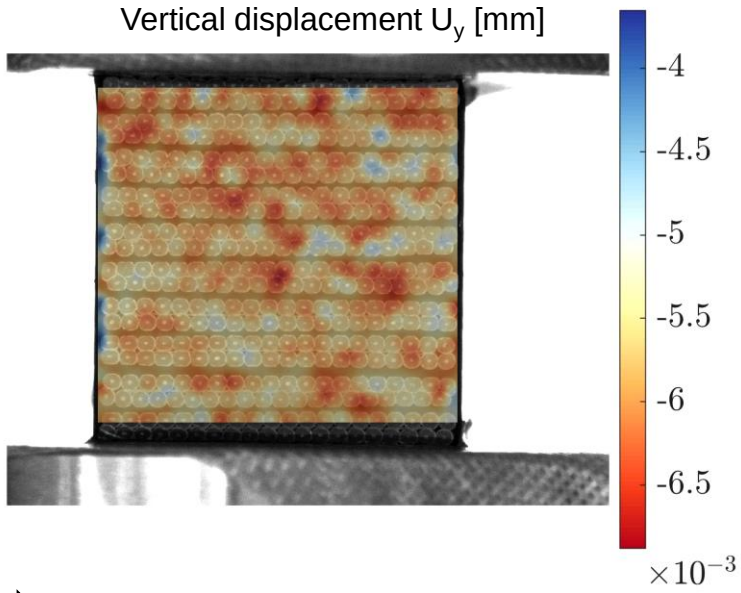
Displacement-controlled: 10 µm/s ~ 1 kN/s
Image capture rate: 1 s^{-1} (273 images)



Cubic level



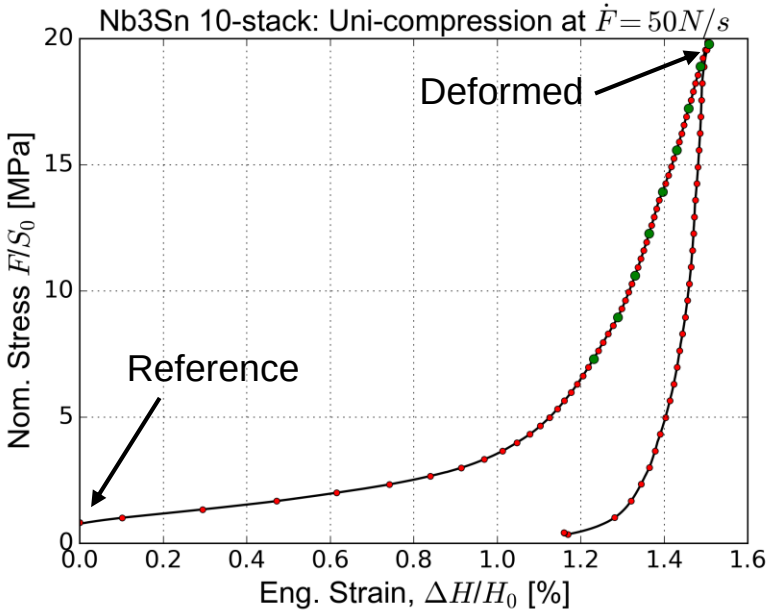
Stack level



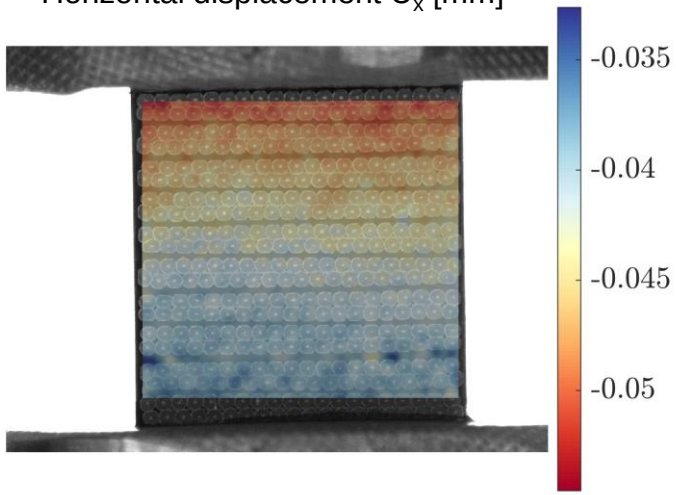
1D information

2D information

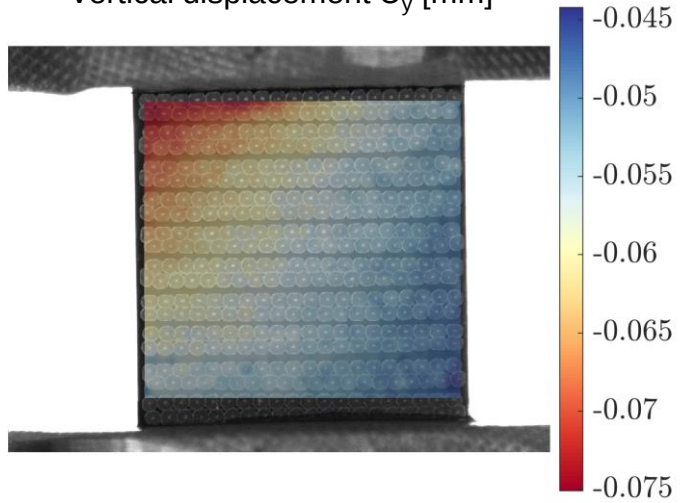
Displacement fields at low force (20 MPa)

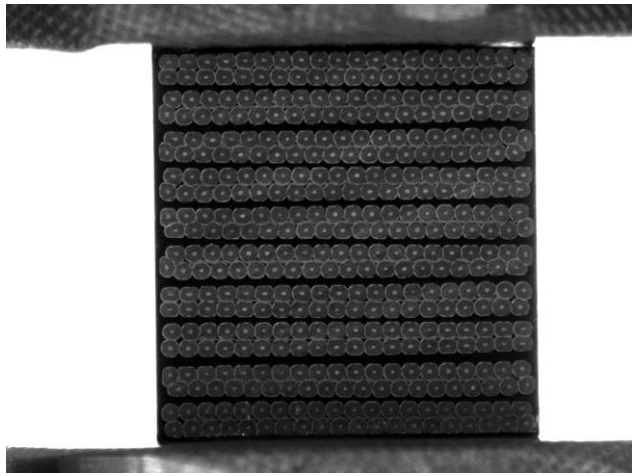


Horizontal displacement U_x [mm]

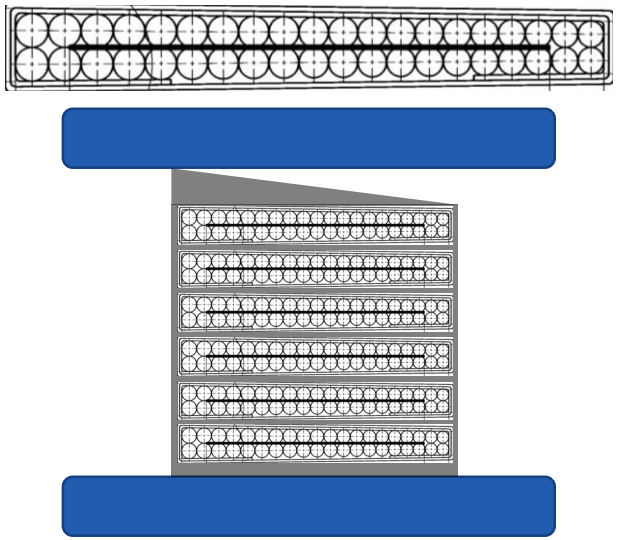


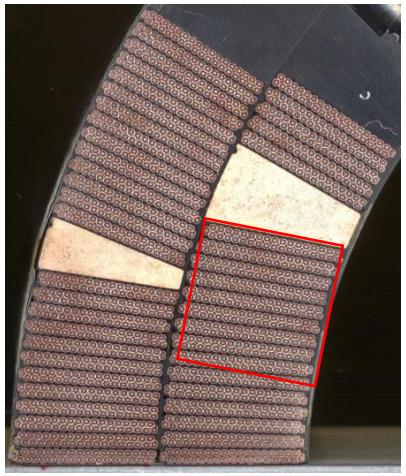
Vertical displacement U_y [mm]





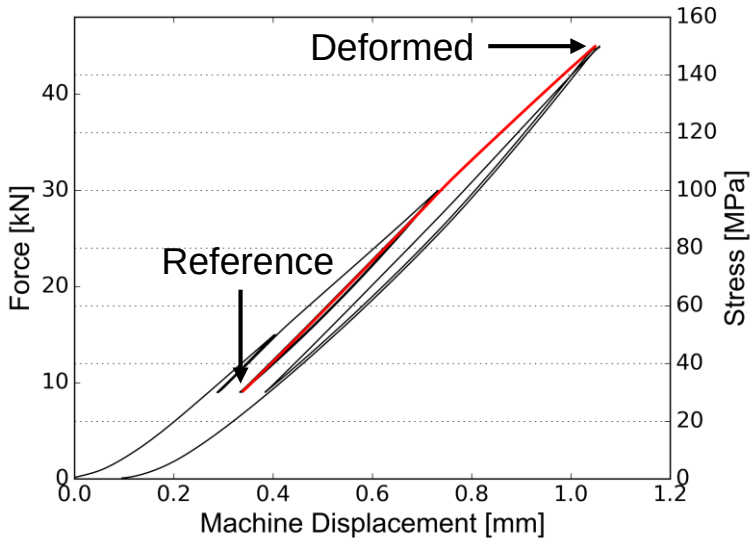
CERN, 11T dipole magnet (2013)



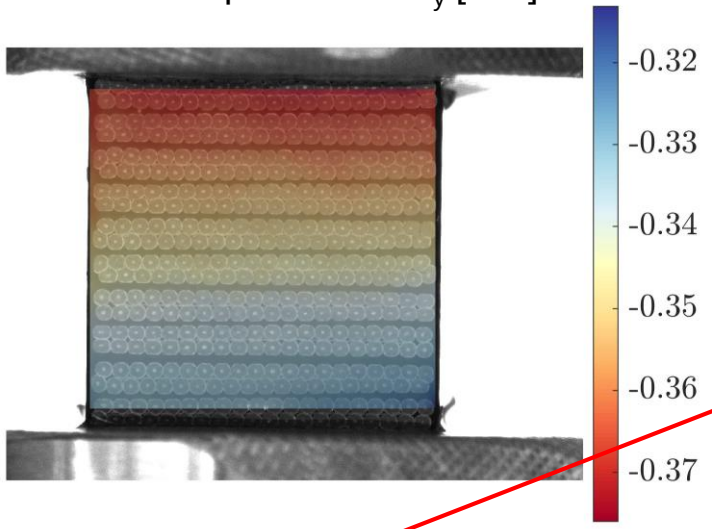


→ start from 20MPa as pre-loading

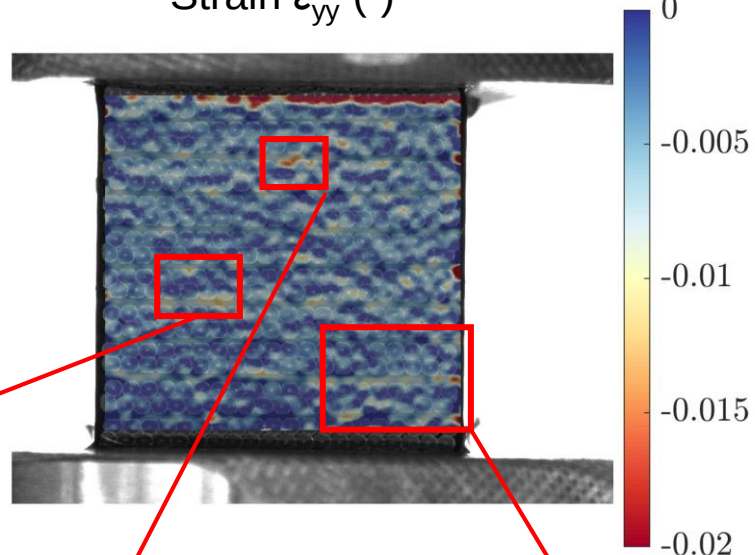
DIC results up to 150MPa



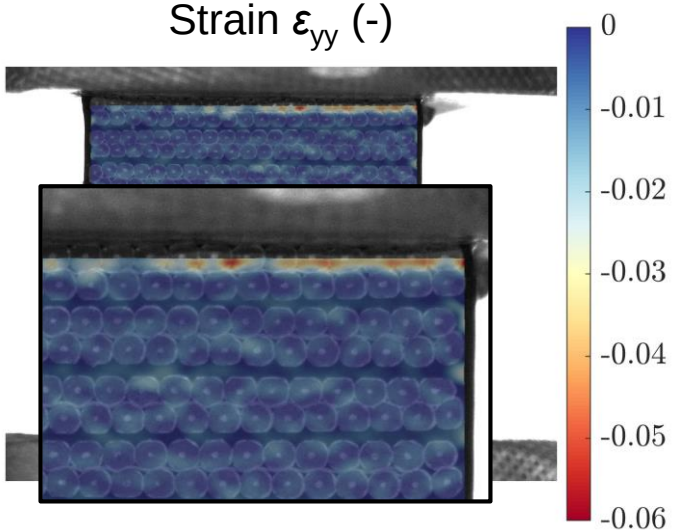
Vertical displacement U_y [mm]

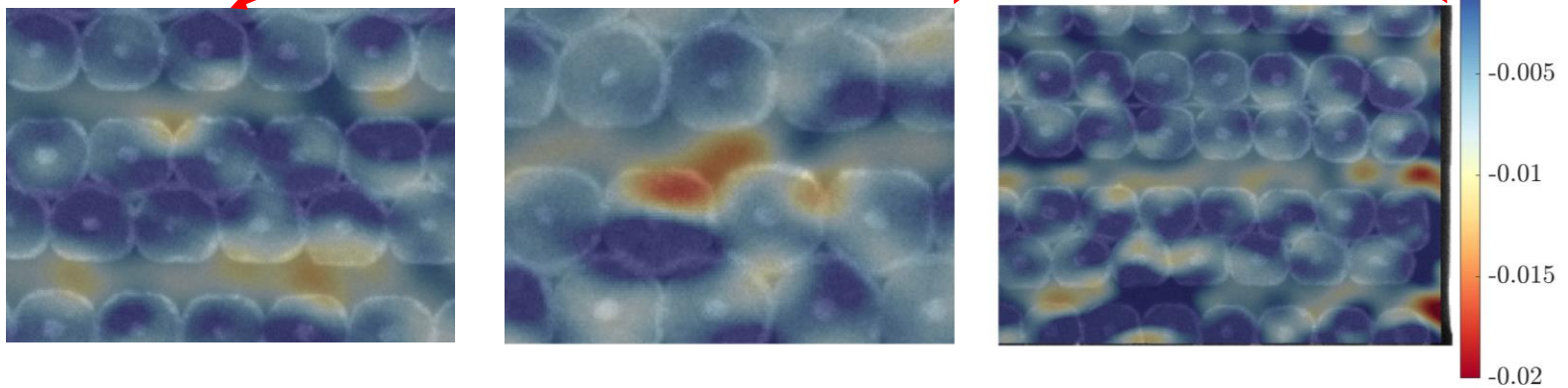


Strain ε_{yy} (-)



Strain ε_{yy} (-)

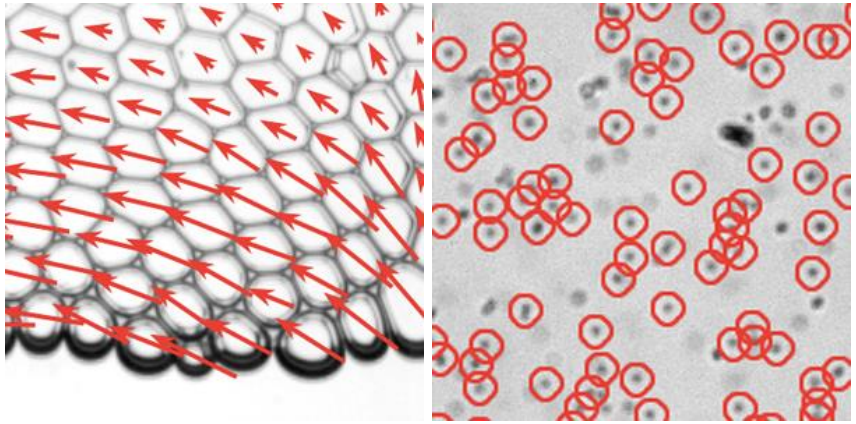




- Sample edges (top/bottom) are the most deformed region (6%)
- Some insulation layers are 1-2% strain level
- The strain values depend on ‘mesh-equivalent’ parameters (subset, step)

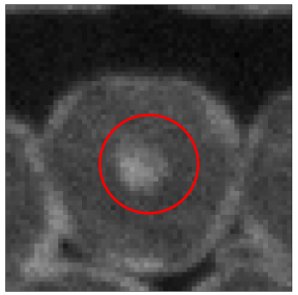
Particle tracking

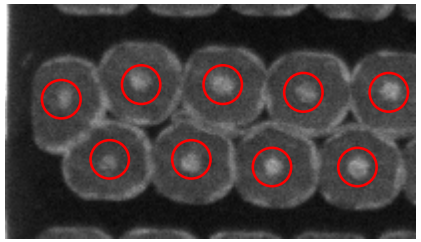
Trackpy: python package for particle tracking

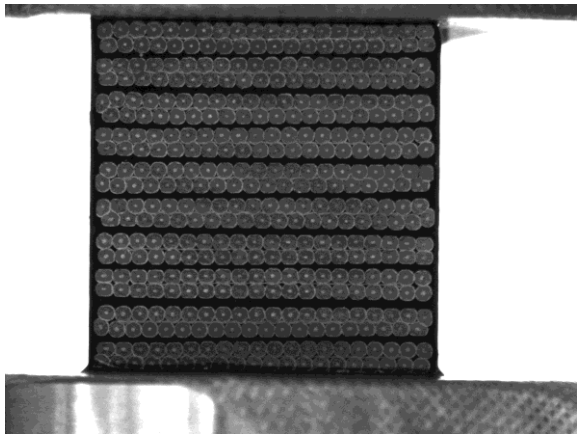


Trackpy

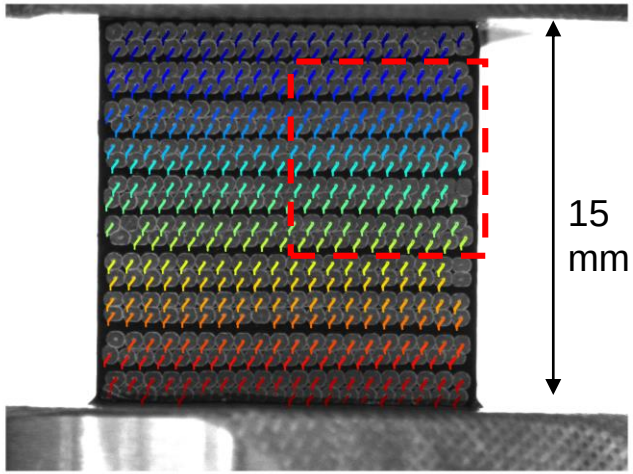
Strand core as natural mark (d~10 pixels)

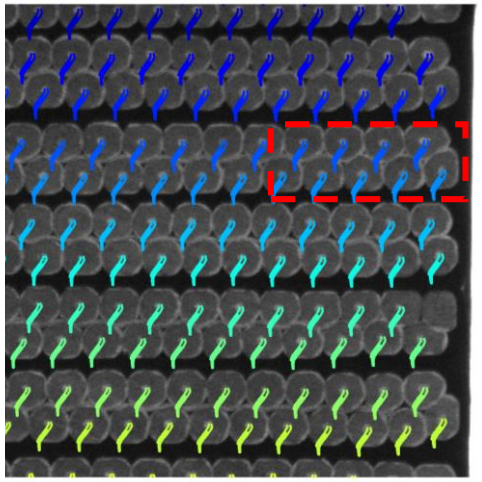


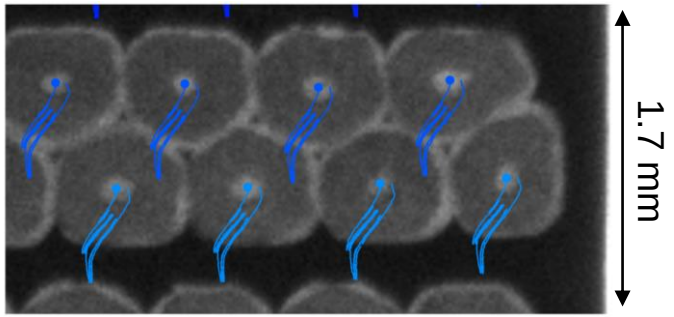


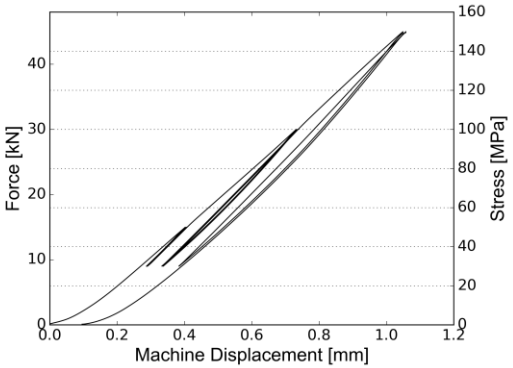


Trajectory of each strand-core



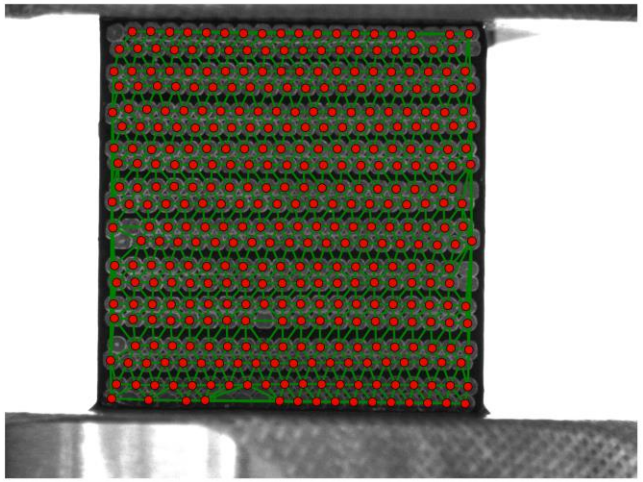




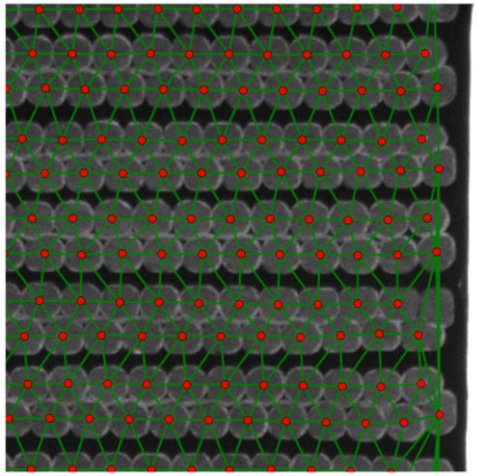


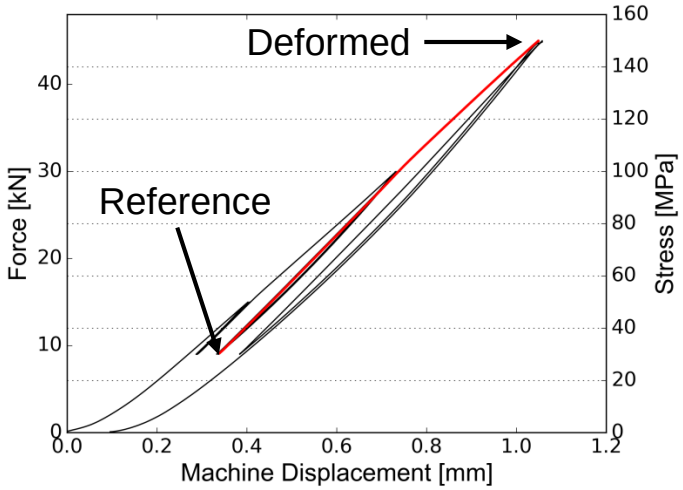
- Most (380/400) strands are tracked during the loading
- There is a horizontal rigid body motion

Fields comparison



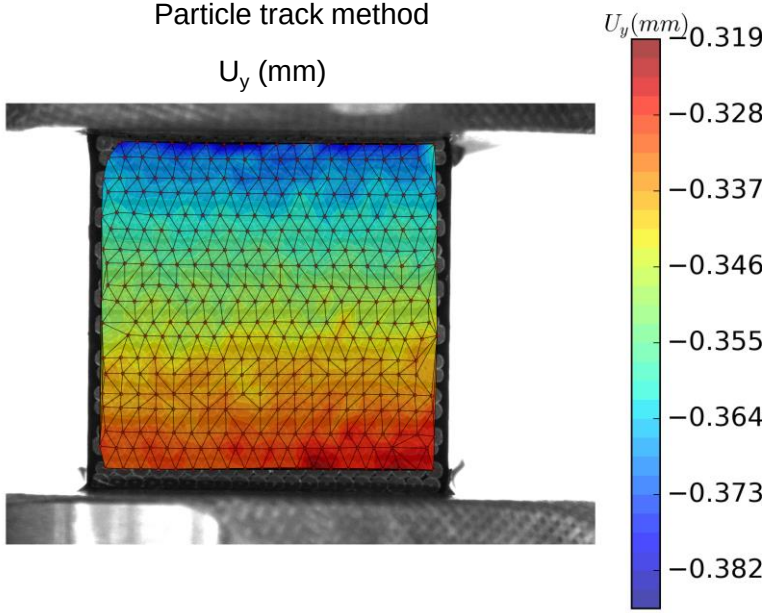
Strand-based mesh





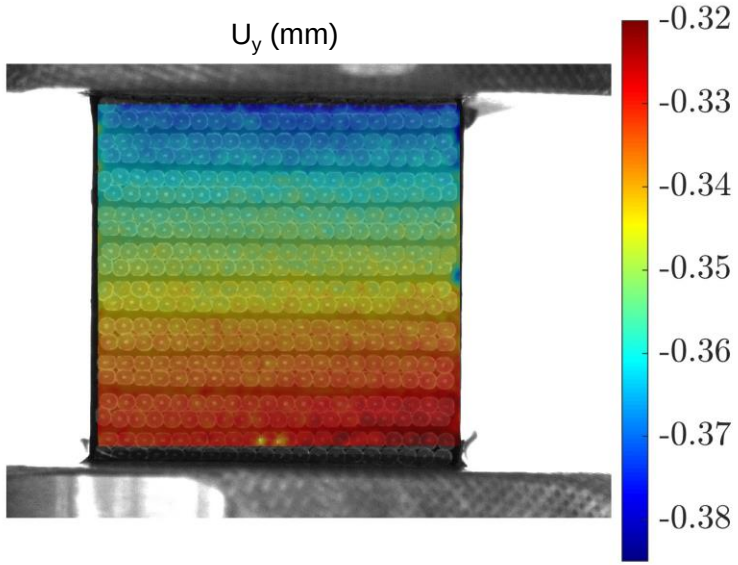
Particle track method

U_y (mm)



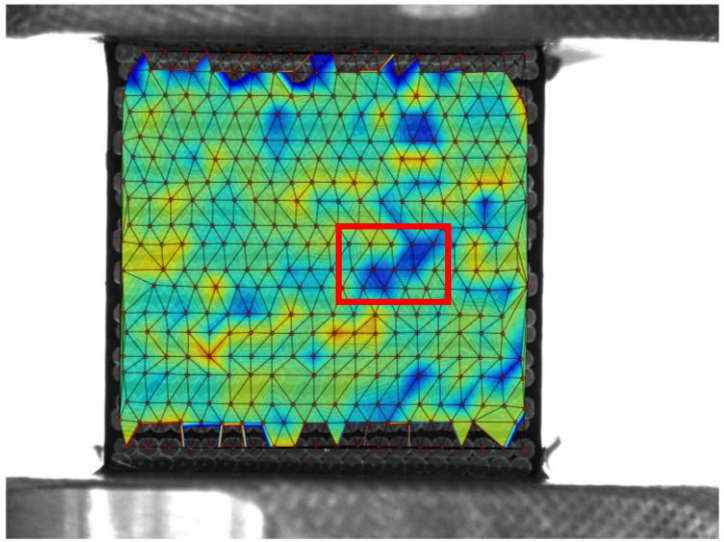
AL-DIC: 1440x1080 px^2, subset:20 px, step:5 px

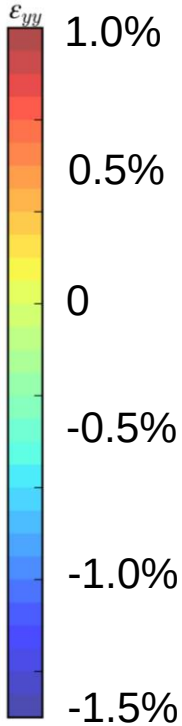
U_y (mm)

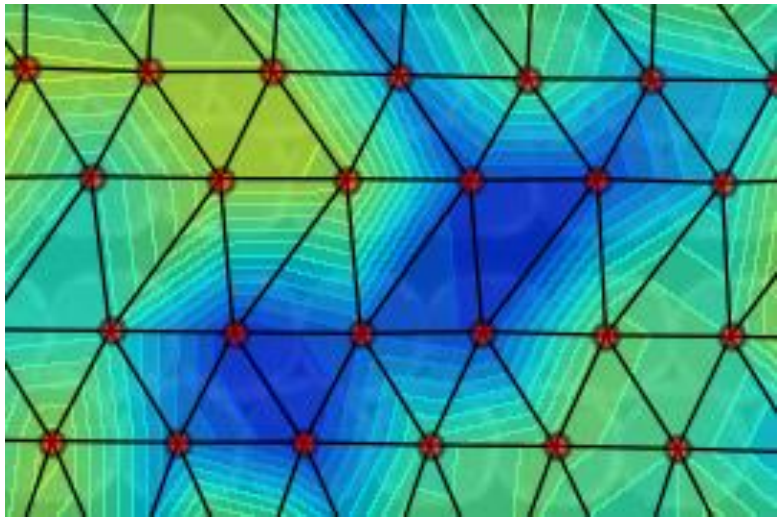


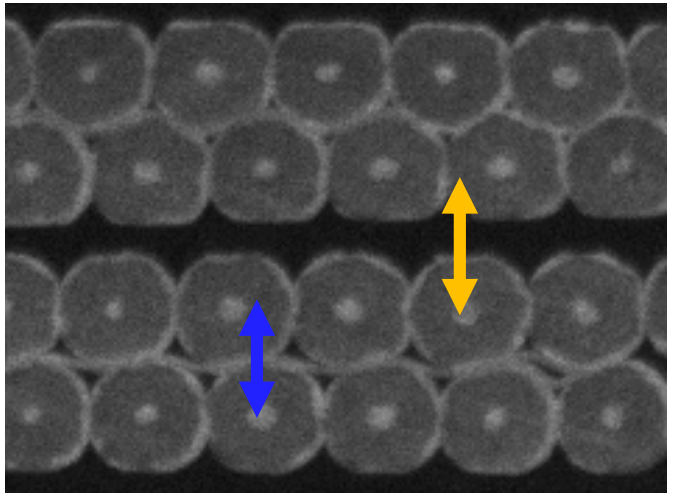
- There is a good agreement of displacement fields between two approaches.

Strain field









Deformation gradient **F**

$$\mathbf{F} = {}^{\mathrm{d}\mathbf{U}}/_{\mathrm{d}\mathbf{X}} + \mathbf{I} = \left[{}^{\mathrm{dU_x}}/_{\mathrm{dx}} + 1, {}^{\mathrm{dU_x}}/_{\mathrm{dy}}; {}^{\mathrm{dU_y}}/_{\mathrm{dx}}, {}^{\mathrm{dU_y}}/_{\mathrm{dy}} + 1\right]$$

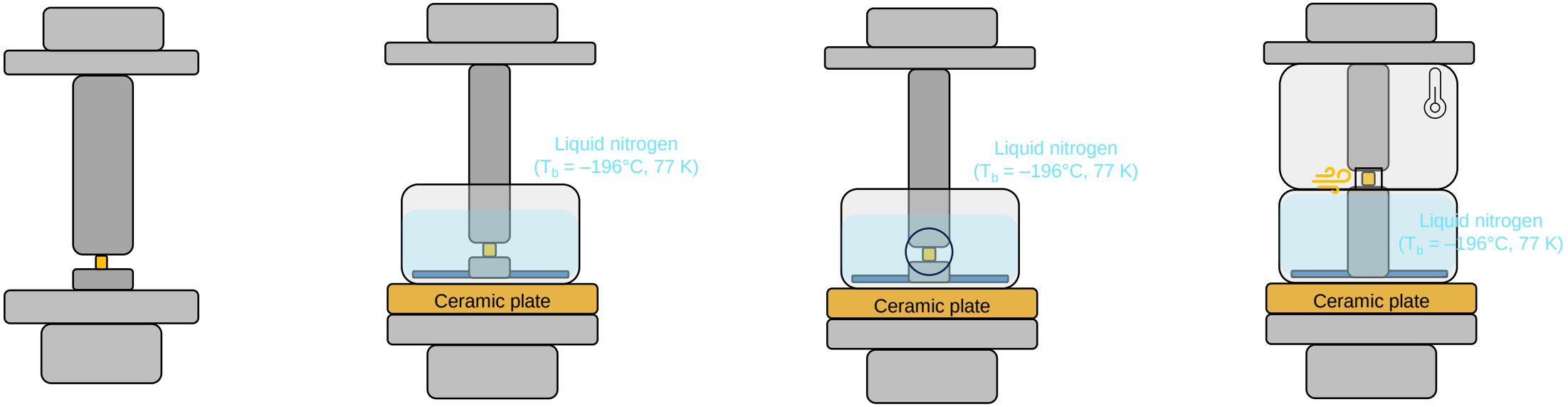
Green-Lagrangian strain **E**

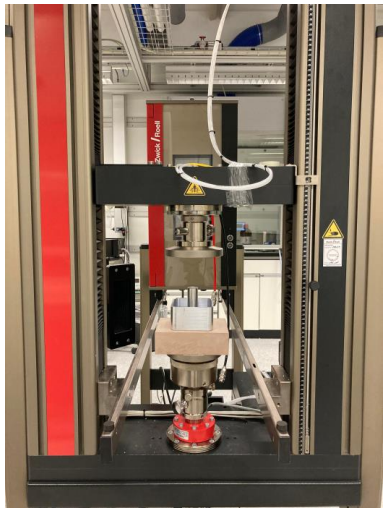
$$\mathbf{E} = \frac{1}{2}(\mathbf{F}^{\mathrm{T}}\mathbf{F} - \mathbf{I})$$

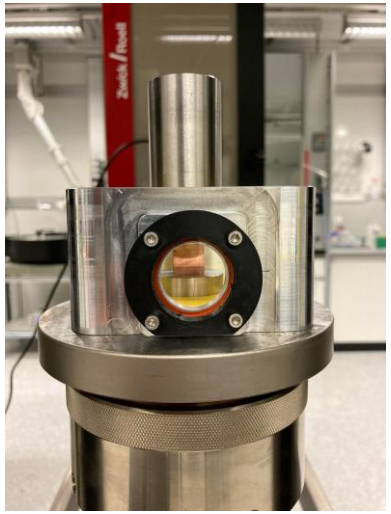
Conclusion

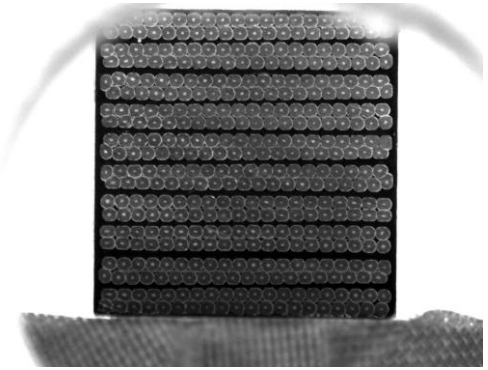
- ❑ Strain localization at **inter-stack** and **intra-stack**
- ❑ Local tensile state (red) exists

From RT to LN_2









Still developing:

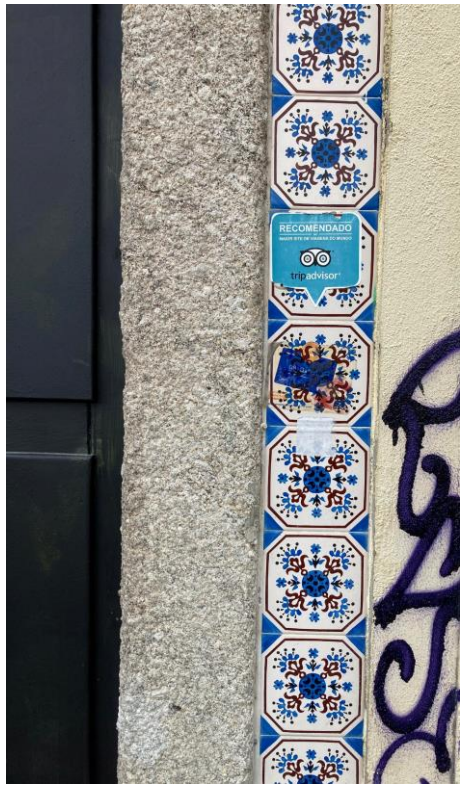
- Liquid boiling affects image capture

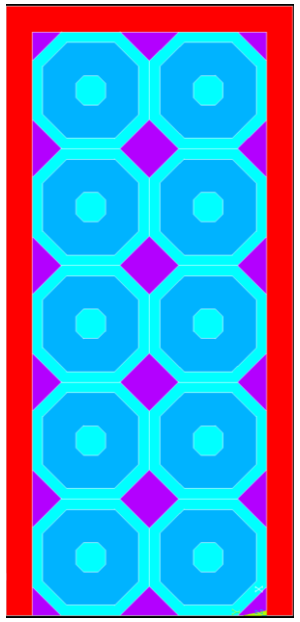
Conclusion & Outlook

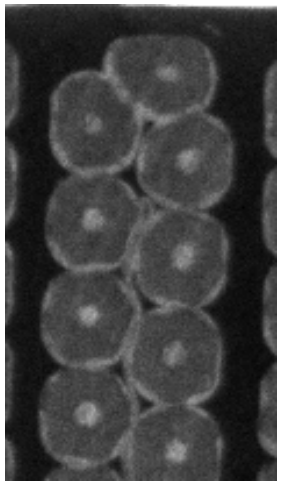
- An *in situ* full-field deformation measurement is performed at the level of cable stacks via two different image-based analyses
- Compressive strain localization can be measured both at inter-stack and intra-stack, even tensile state at few positions

- The approach will be applied at cryogenic temperature
- The deformation measurement can be compared with the numerical results at multiscale

Strand-like Azulejo (ceramic tilework) in Porto

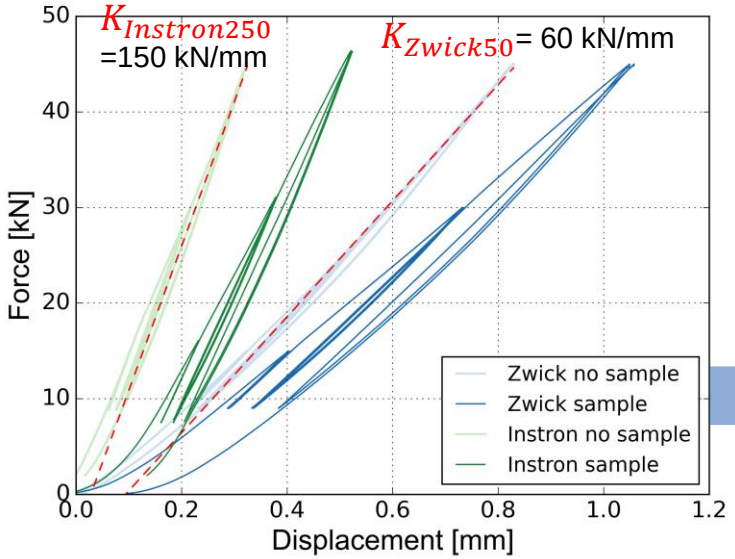


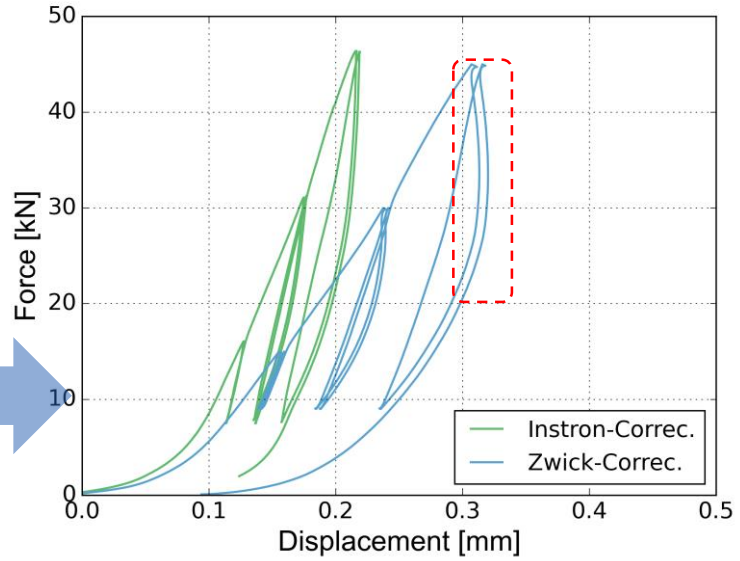




Any questions?

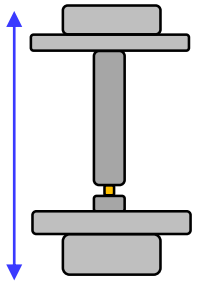
Correction

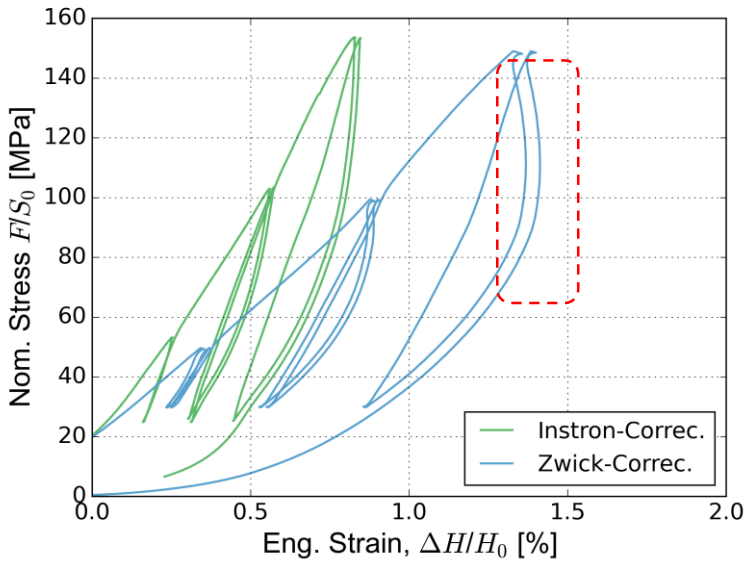




$$\Delta d_{s-corr.} = \Delta d_{tot} - \Delta d_{machine}$$

$$\Delta d_{s-corr.} = \Delta d_{tot} - \Delta F / K_{machine}$$



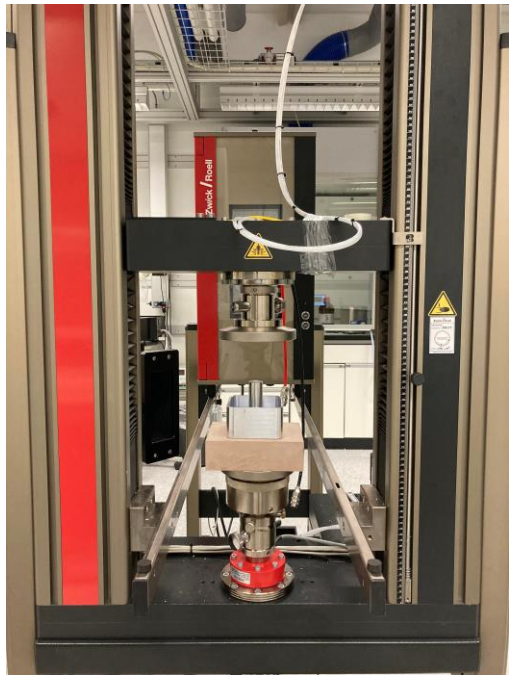


- Due to less stiff of Zwick-50 machine, the unload-displacement (hysteresis loop?) is not corrected properly.

Zwick100

Machines with different measurements

Zwick050@D496

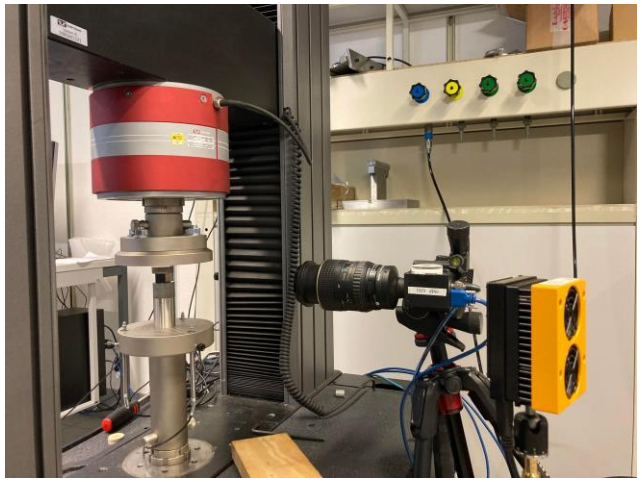


- Global correction
- DIC

Zwick100@D467

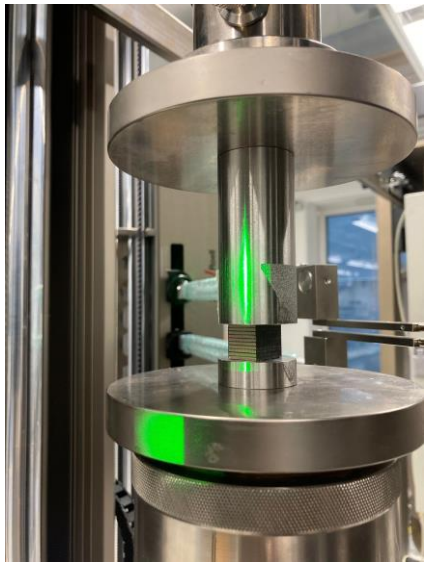
- Global correction
- MacroExtenso
- LaserExtenso
- DIC
- laser

Instron250@MAVT-Mohr



- Global correction
- DIC

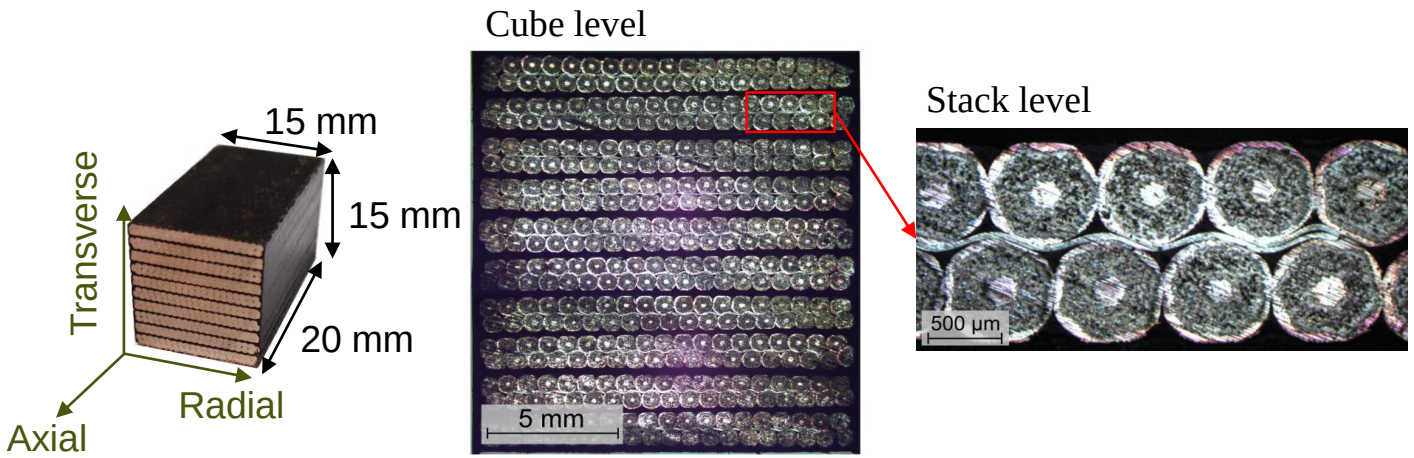
Ongoing work @Z100-D467



Aims

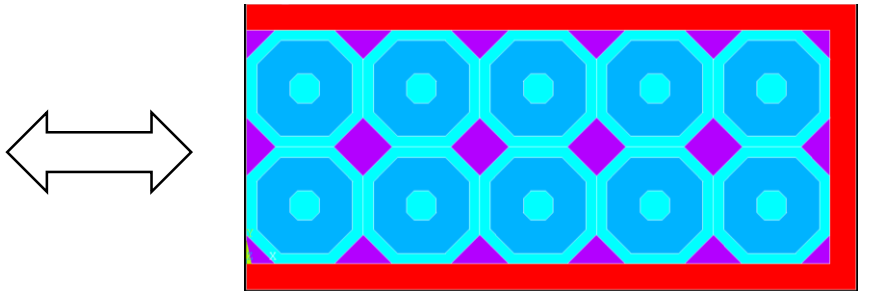
MagComp: *Mechanical modelling and failure identification of impregnated Nb3Sn Rutherford cable stacks*

Experiment



Numerical simulation

Ansys



Working with D. M. Araujo, M. Daly (PSI)

- ❑ Characterize mechanical properties of each components at **ambient** and **cryogenics** temperature
- ❑ Perform compressive tests on 10-stack sample

- ❑ Implement the constitutive model in finite element software