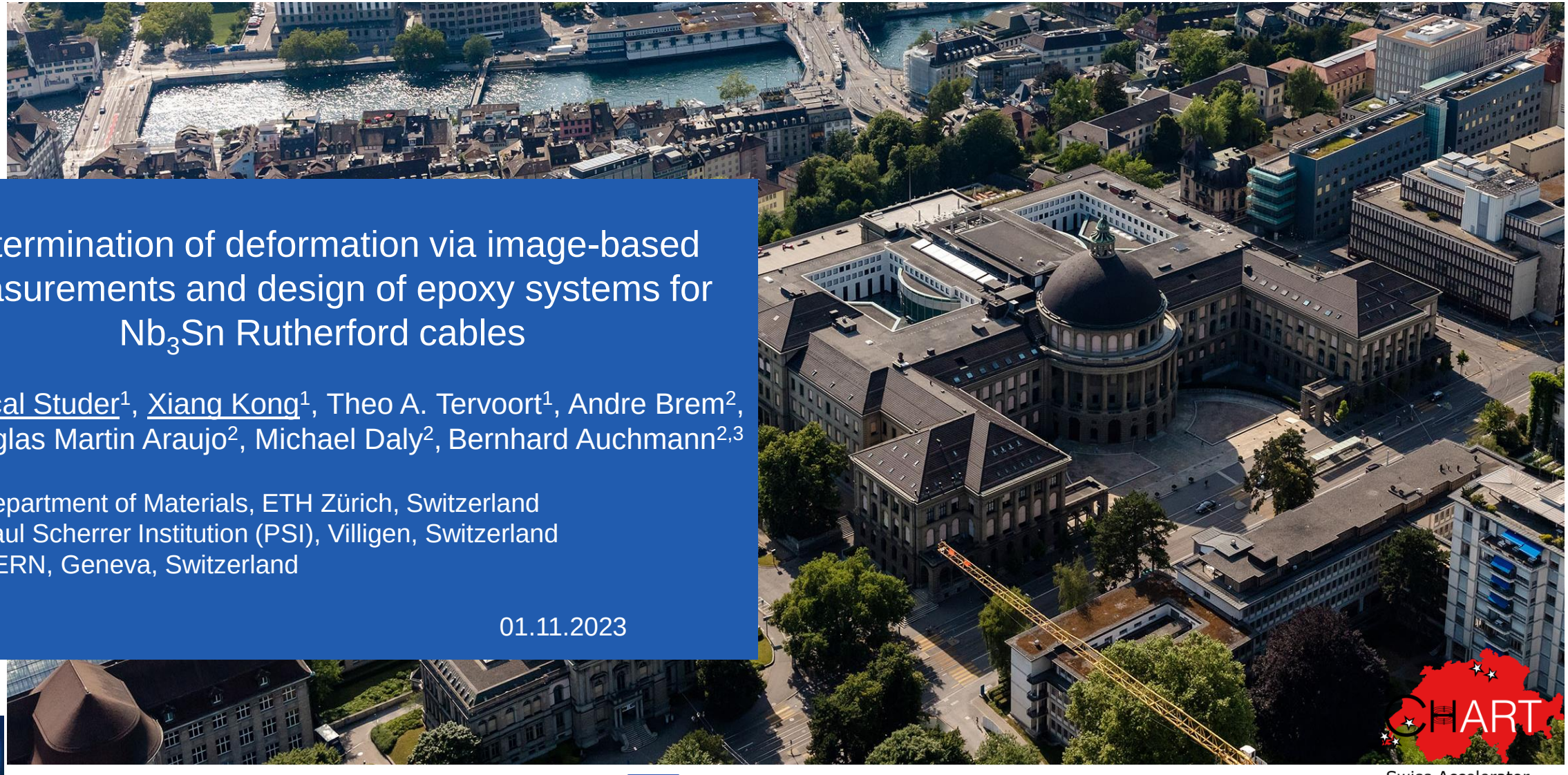
ETH zürich D MATL. SOFTMAT



Determination of deformation via image-based measurements and design of epoxy systems for Nb_3Sn Rutherford cables

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1. Department of Materials, ETH Zürich, Switzerland
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3. CERN, Geneva, Switzerland

01.11.2023

HFM annual meeting 2023 (30 Oct – 2 Nov)

HFM High Field Magnets

CERN

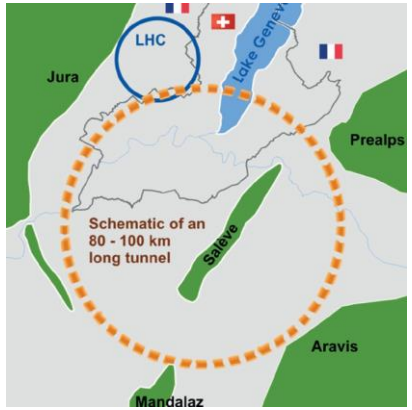
PAUL SCHERRER INSTITUT PSI

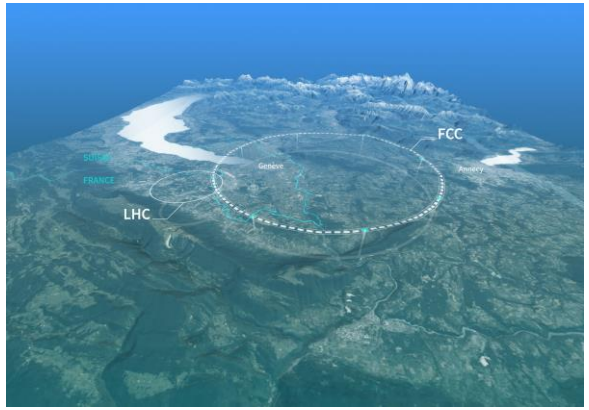
Swiss Accelerator Research and Technology

CHART

Introduction

Future Circular Collider (FCC)





Ferracin et al. 2015

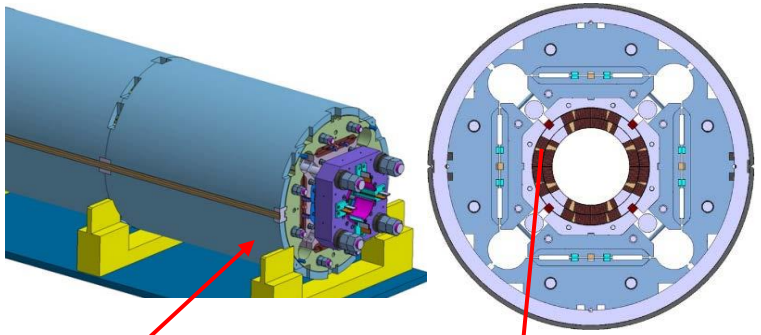
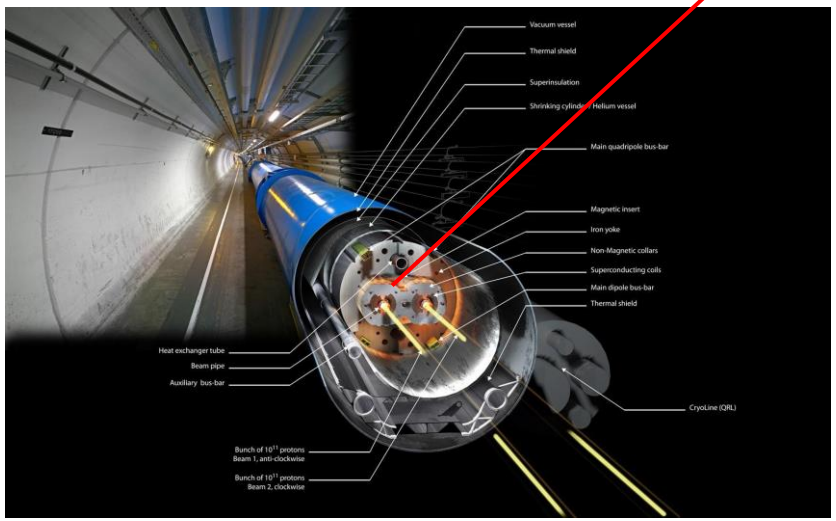
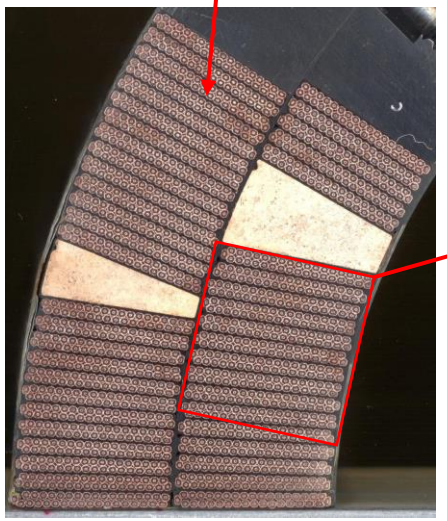


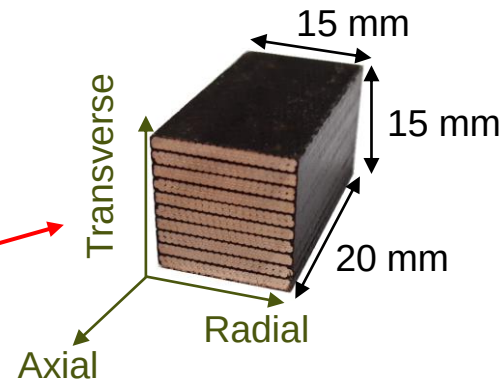
CHART project

Swiss Accelerator Research and Technology



CERN website

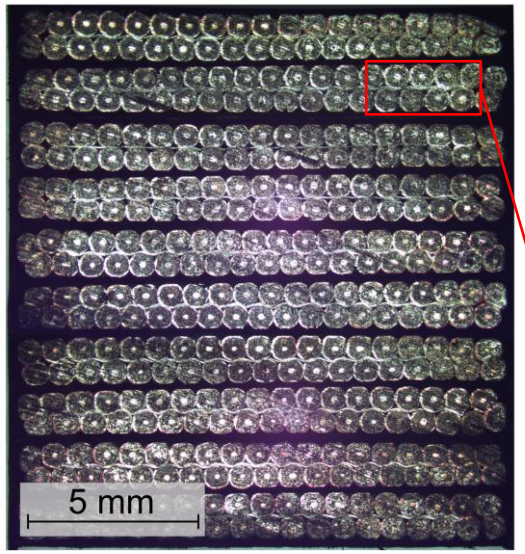




Daly et al. 2018

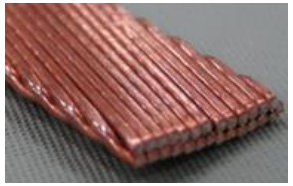
Ferracin et al. 2015 Transactions on Applied Superconductivity (Volume: 26, Issue: 4, June 2016)
Daly et al. 2018 Transactions on Applied Superconductivity (Volume: 28, Issue: 3, April 2018)

Multiscale structure → heterogeneous

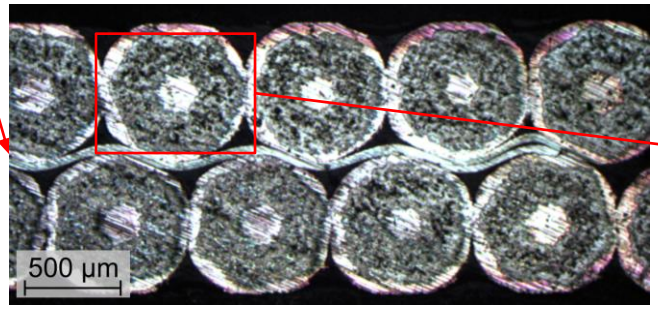


~15 mm

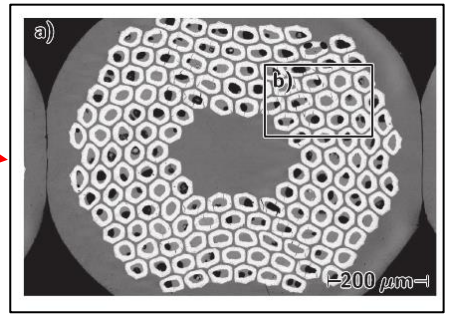
Rutherford cable stack



Vallone, MDP Meeting 2022

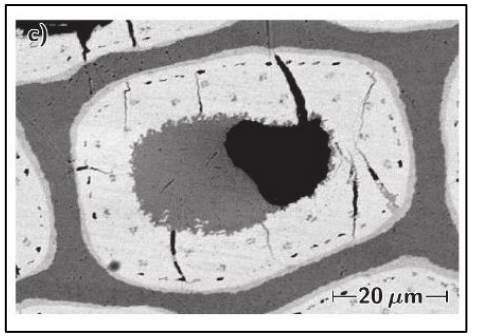


~ 1 mm



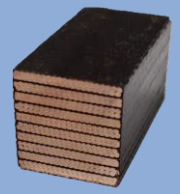
~750 µm

Ebermann et al. 2018



~50 µm

Cubic level



10-stack cable

Stack level

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

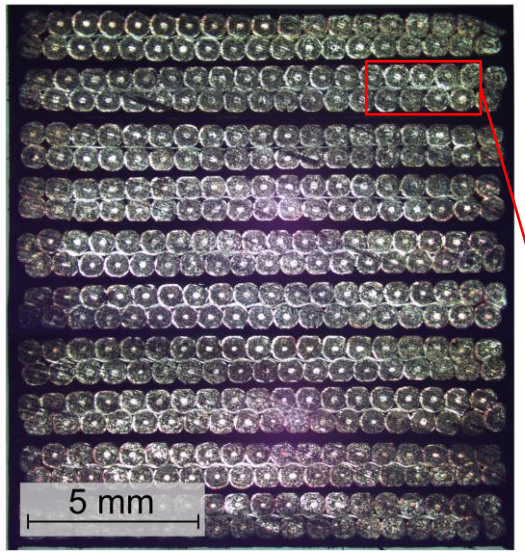
Strand level

- ○ Copper matrix
- ○ Nb_3Sn micro filaments

Filament level

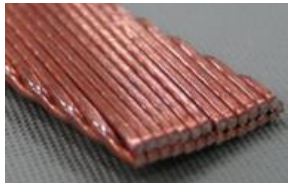
- • Nb_3Sn filament
- • Copper matrix
- • Void

MagRes: Development of optimized resin system for SC magnet coil production

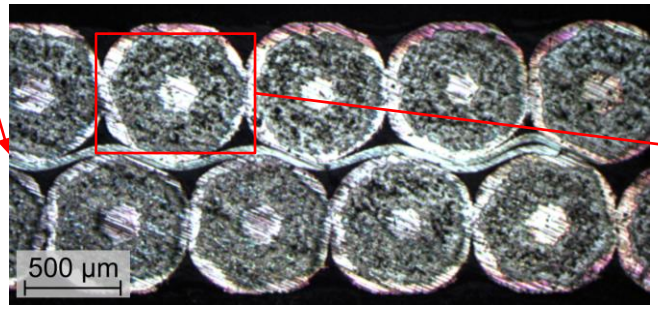


~15 mm

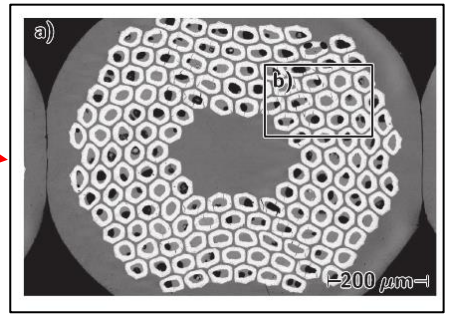
Rutherford cable stack



Vallone, MDP Meeting 2022

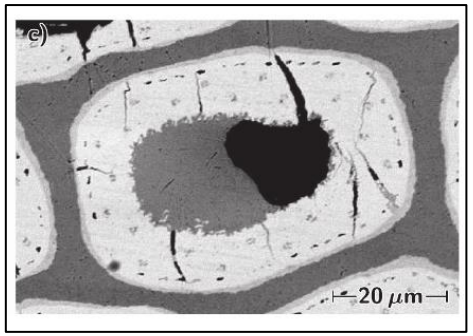


~ 1 mm



~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

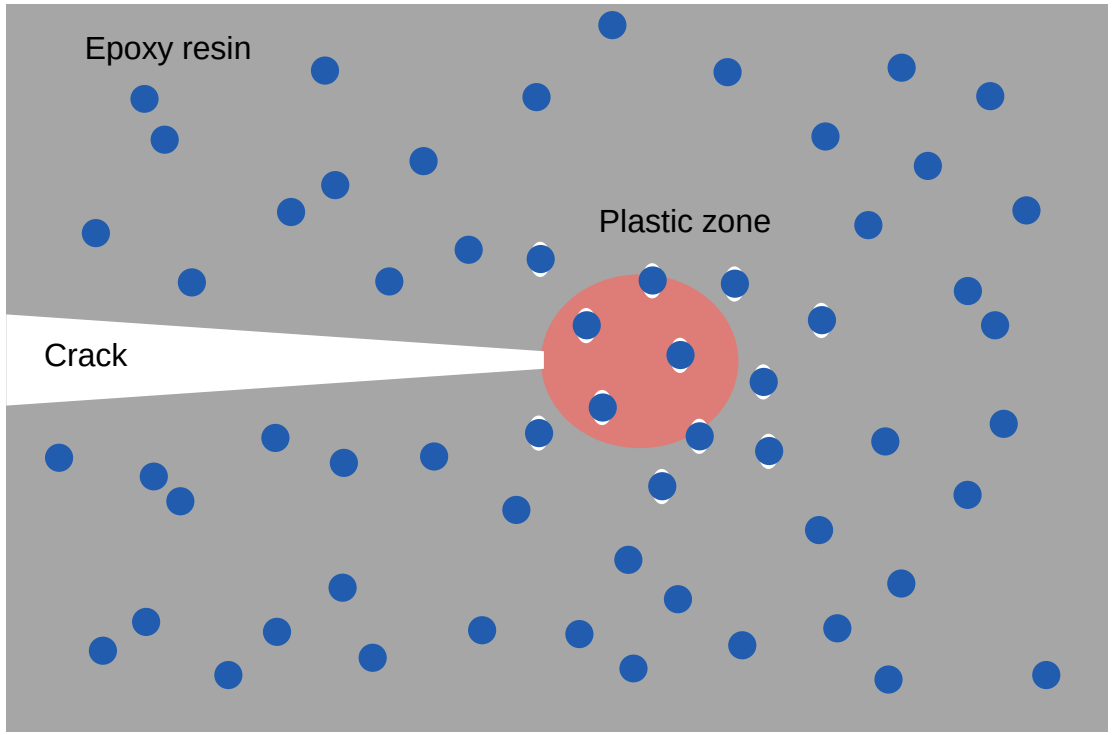
Introduction

The toughness paradox:

→ For non-stress managed magnets, strength & toughness are needed

→ However, high toughness means more heat dissipation at the crack tip and thus might *also promote quenching, even in the absence of macroscopic cracks*

→ Particles can improve toughness even further by localized yielding



Ultimate goal:

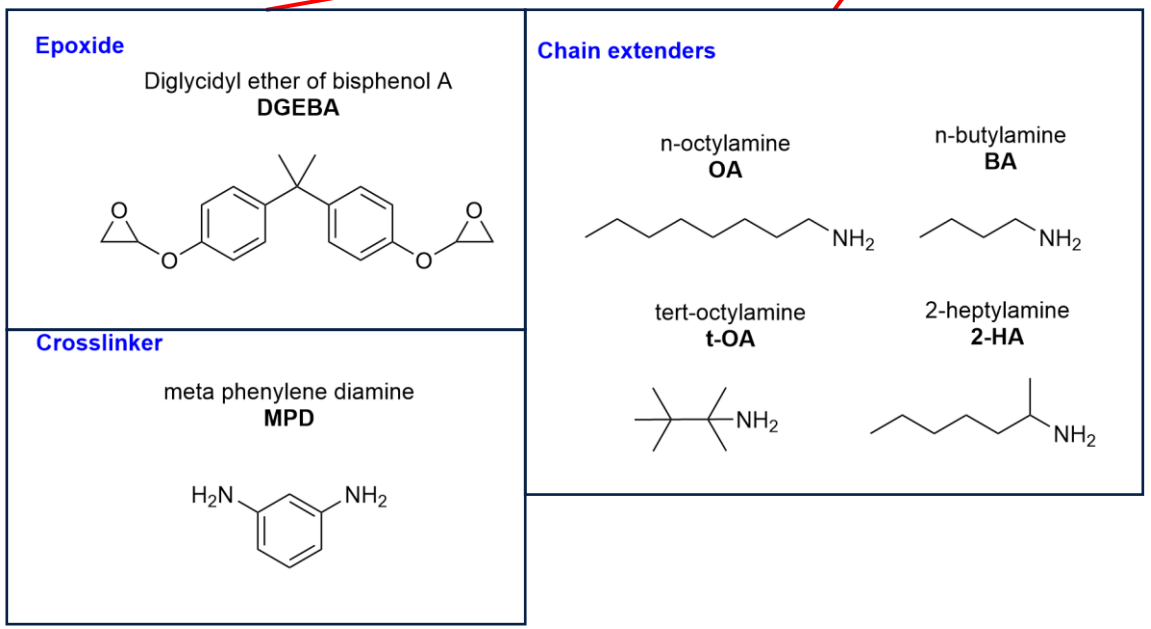
- Gadolinium nanoparticles with anomalous high c_p at 4 K

- these particles initiate yielding, increasing the fracture toughness, while at the same time absorbing the heat that develops due to the plastic deformation.

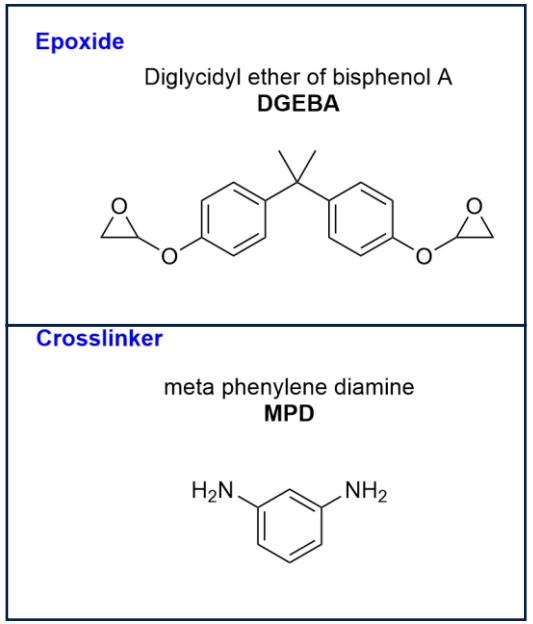
Plain epoxy resin systems

- We use our in-house developed system and compare it to a standard epoxy resin

BA-3-8/9
BA Butylamine
3 Functionality of crosslinker
8/9 Molar ratio of Epoxide to chain extender

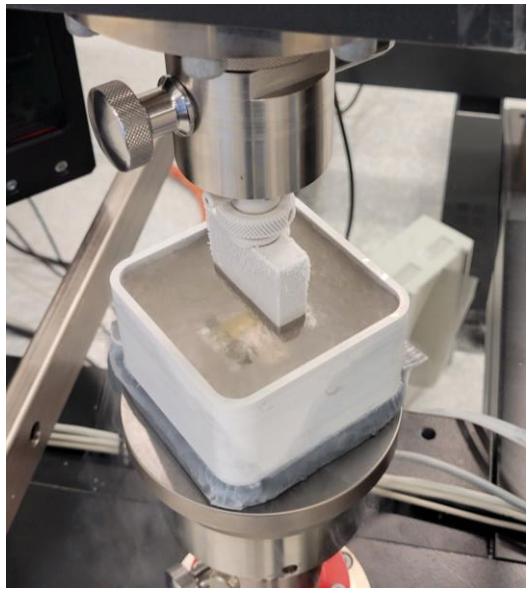


Base resin
Just DGEBA+MPD



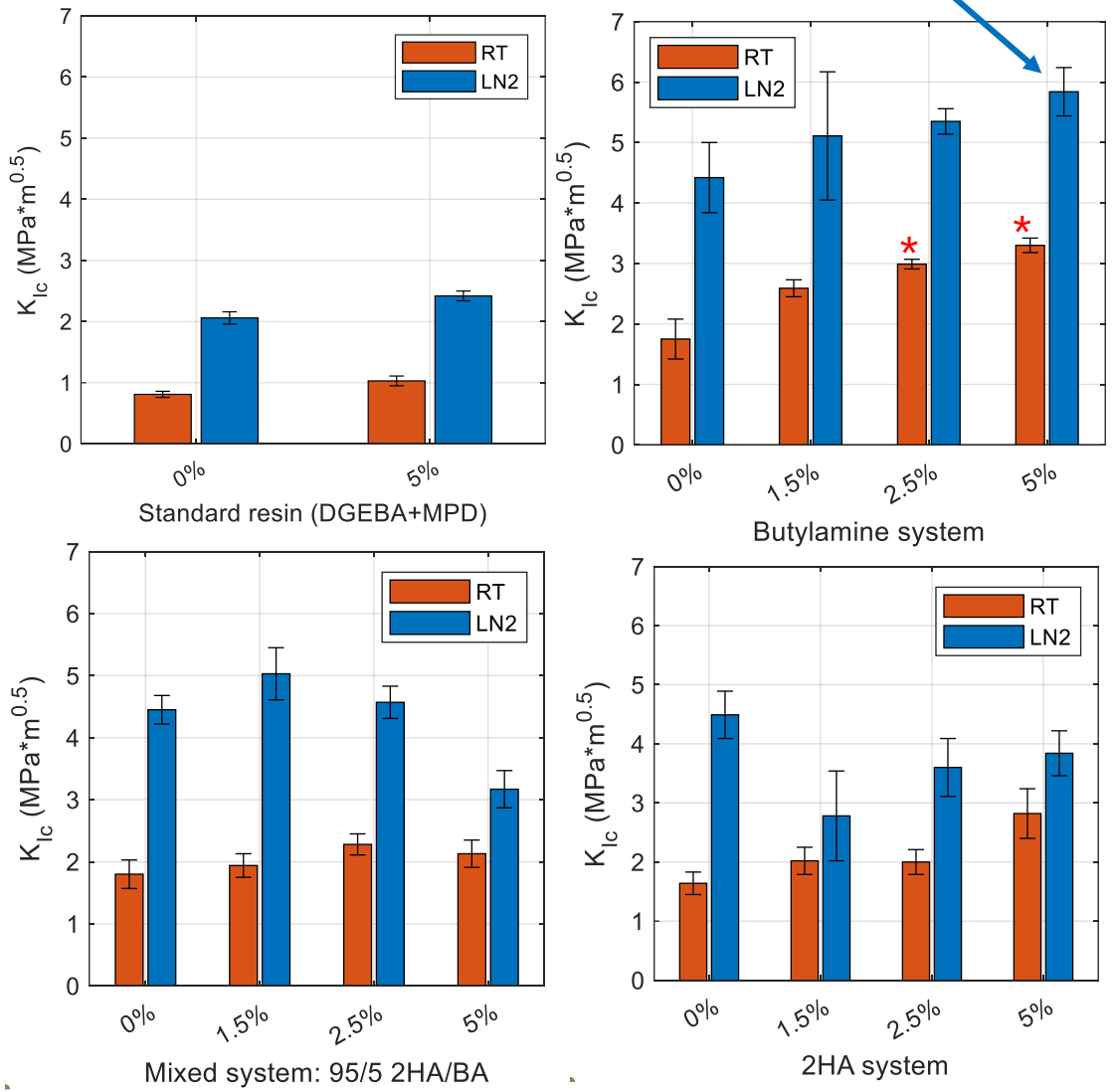
Results

- SENB Testing

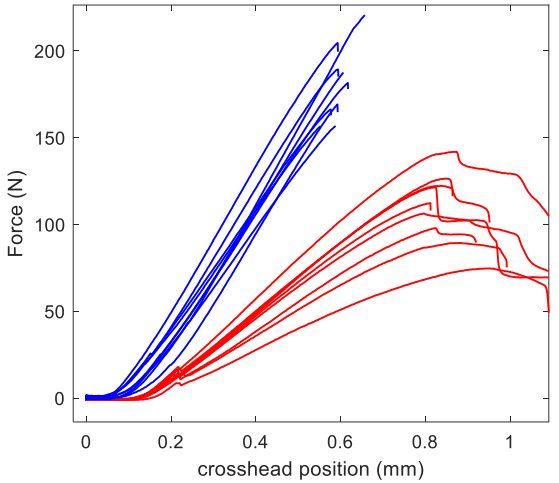


Add nano-SiO2

30% increase!



Butylamine, 5% system



*: Size of plastic zone gets very large with respect to sample size.

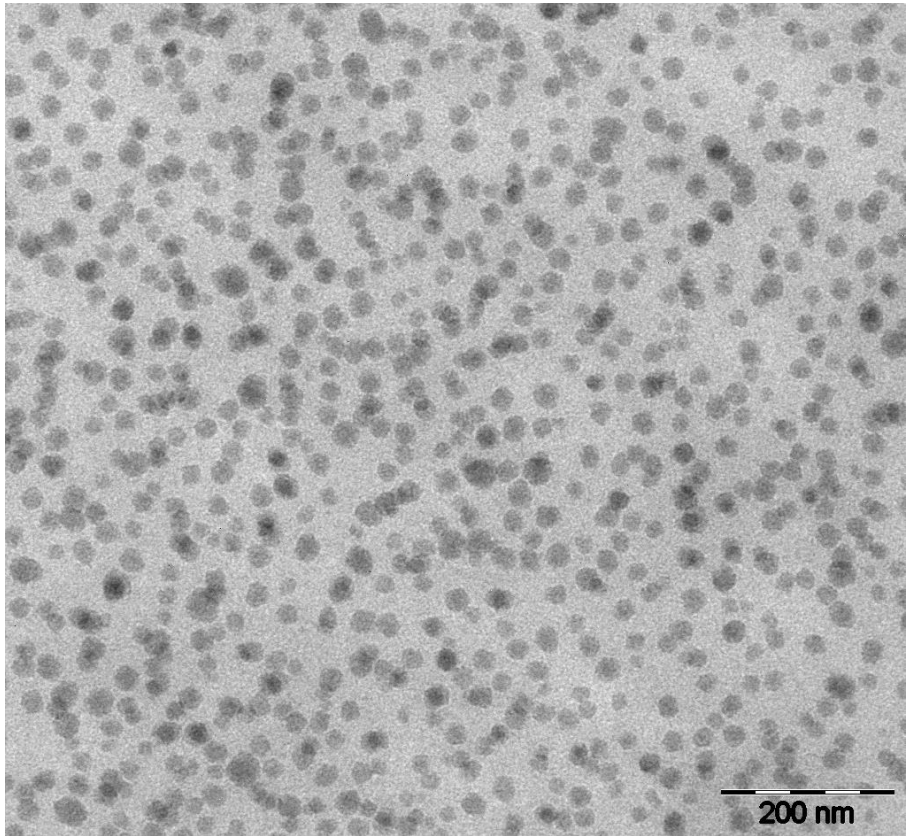
Criterion for valid K_{Ic}

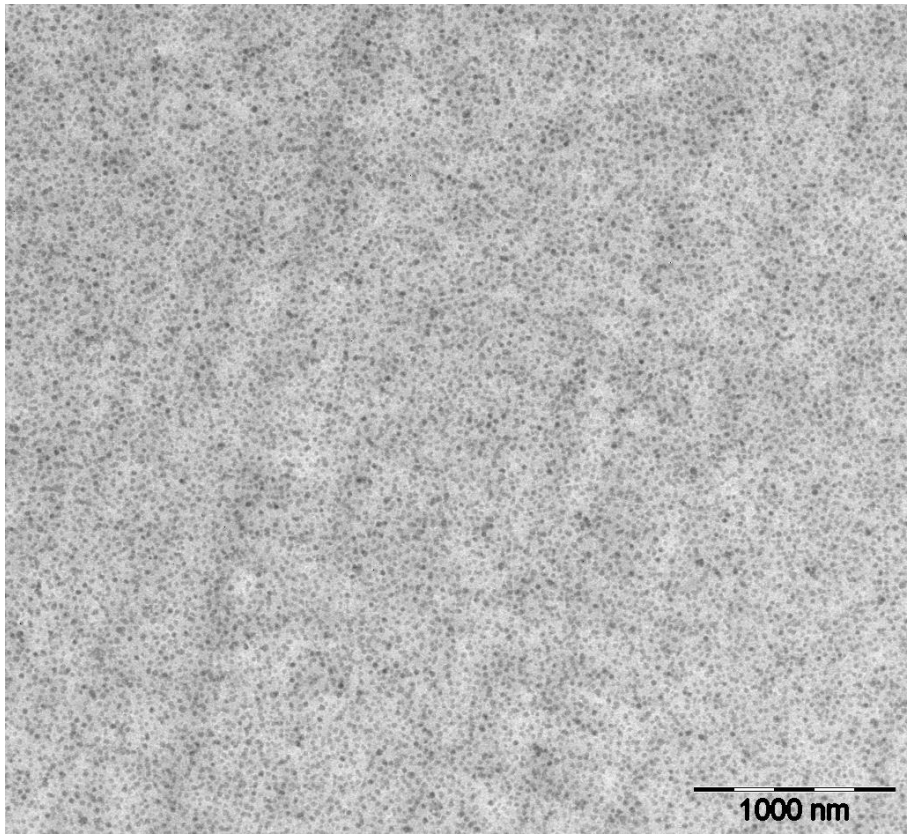
$$b, a, h - a \geq 2.5 \left(\frac{K_I}{\sigma_y} \right)^2$$

Results

- Transmission electron microscopy

7.5 vol. % SiO_2, Butylamine sample (excluded from study due to bubbles) 60 nm section



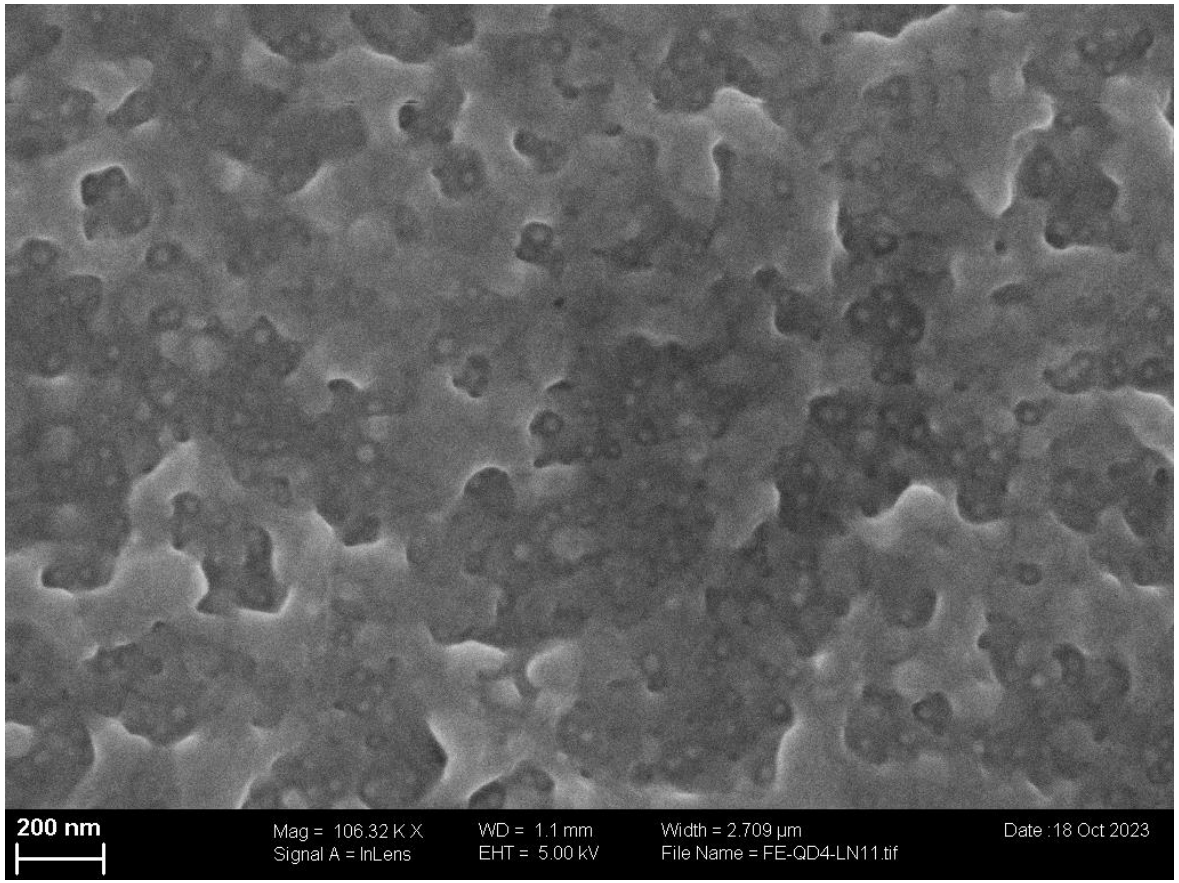


Particles are not agglomerated and **well dispersed**

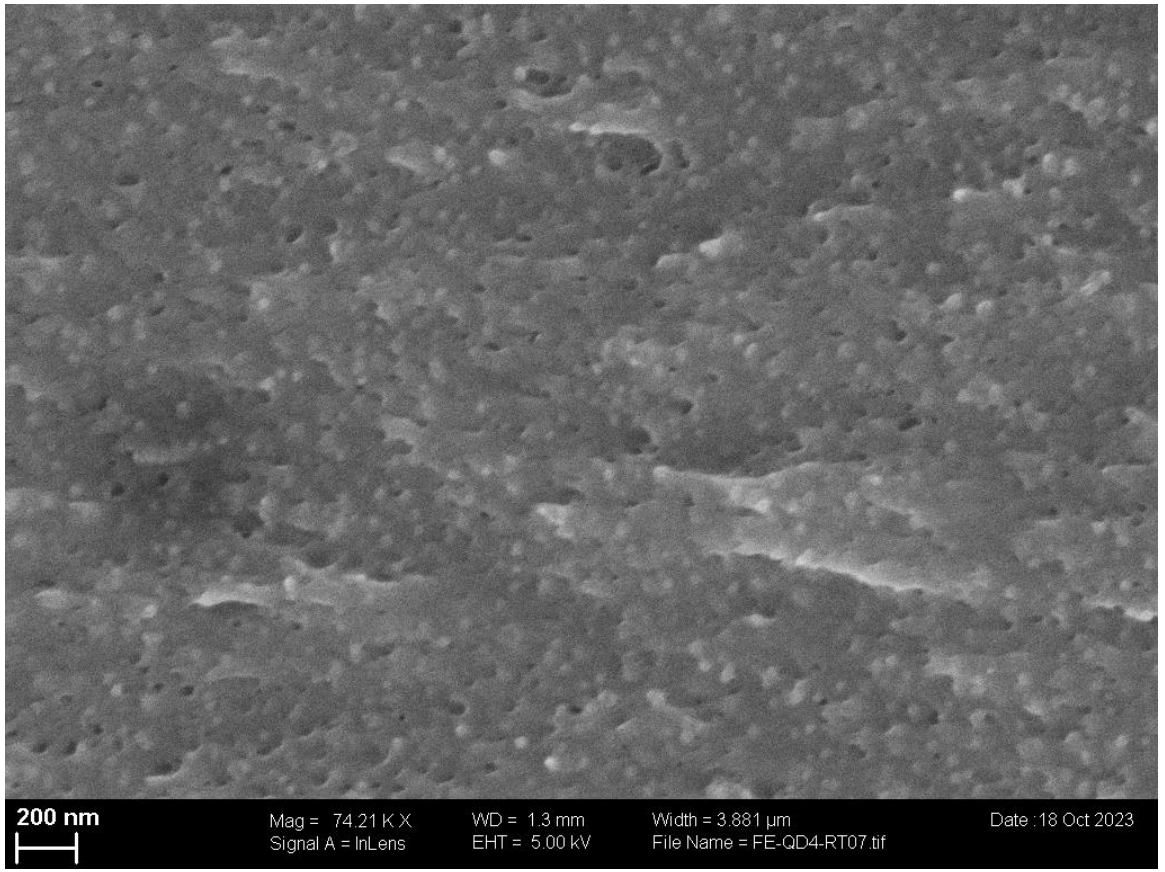
Good dispersion is also observed on samples with decreased toughness

SEM of crack surfaces

- Localized yielding!



RT

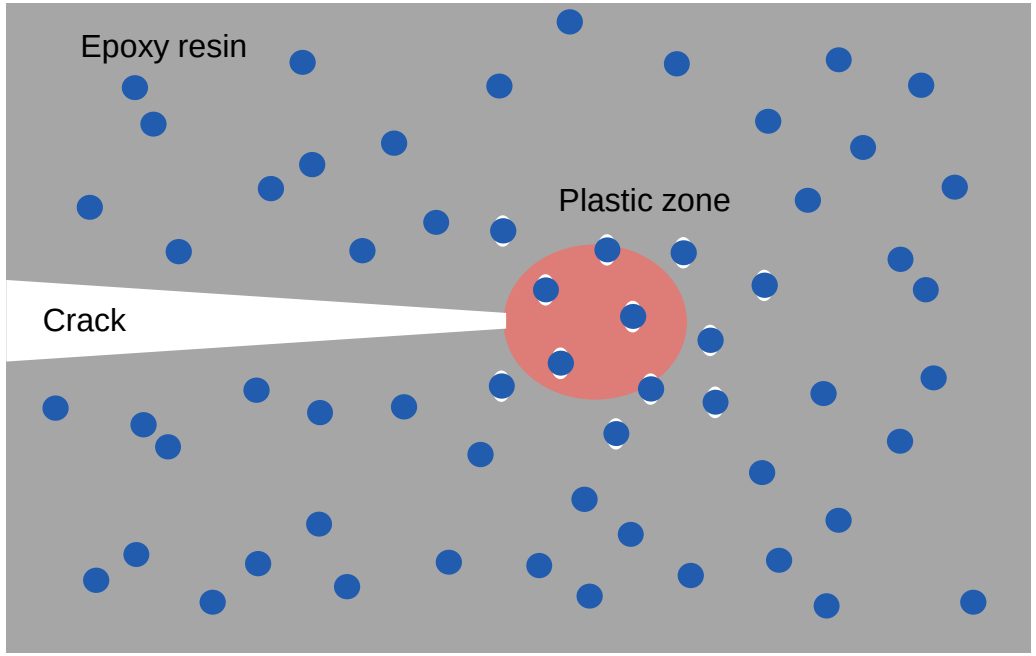


LN

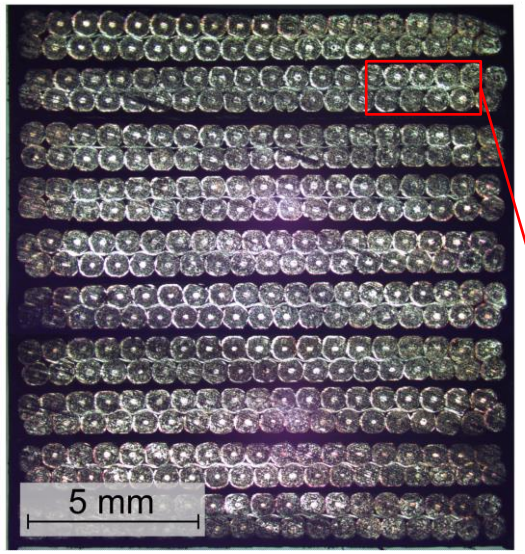
5 vol.% particles, Butylamine/DGEBA/MPD matrix

Conclusion

- We engineered epoxy systems with tuned Tg and very high toughness
- Particles improved toughness for our systems, evidenced by localized yielding
- The reason for this huge improvement might be lower particle-matrix adhesion

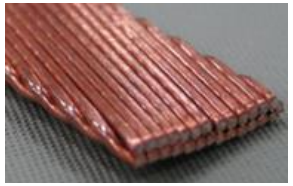


MagComp: Mechanical Modelling and failure identification of impregnated Nb_3Sn Rutherford cable stacks

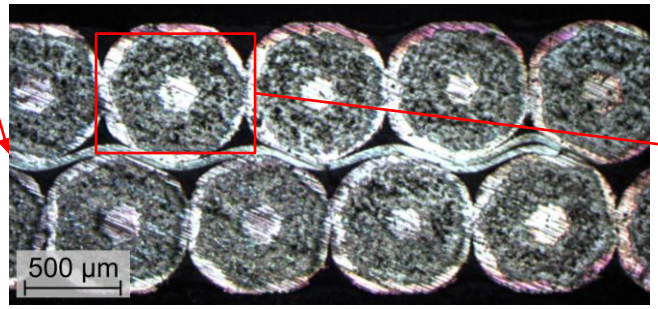


~15 mm

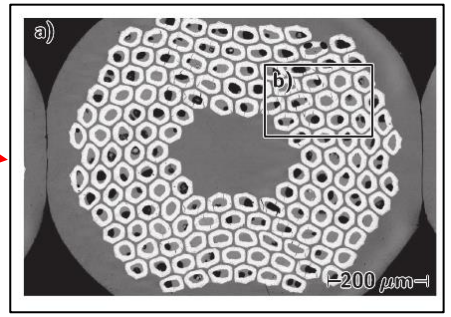
Rutherford cable stack



Vallone, MDP Meeting 2022

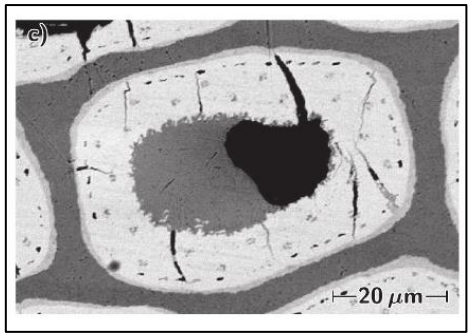


~ 1 mm



~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

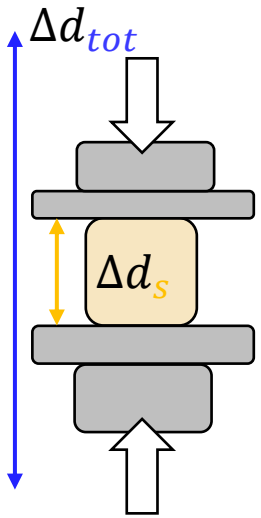
Filament level

- • Nb_3Sn filament
- • Copper matrix
- • Void

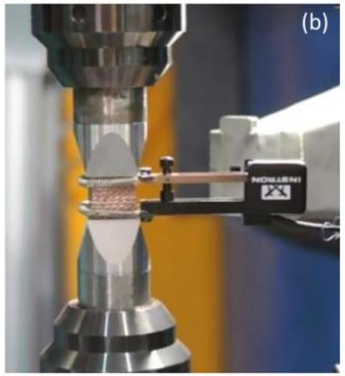
Ebermann et al. 2018, Supercond. Sci. Technol. 31 (2018) 065009

Bibliography

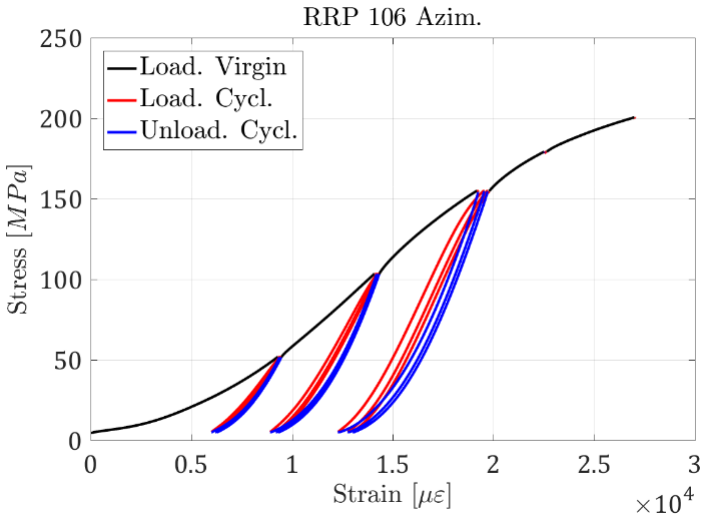
‘Strain – stress’ identification

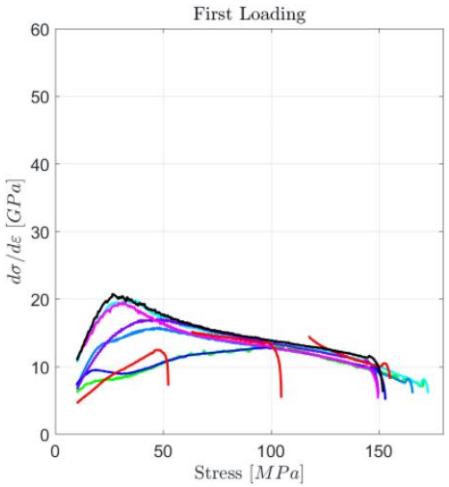


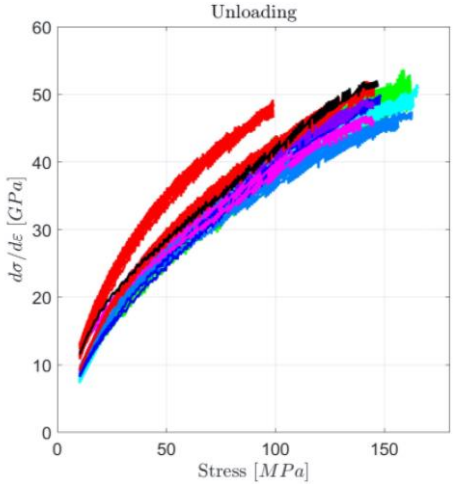
Clip-on extensometer



Scheuerlein et al. 2019



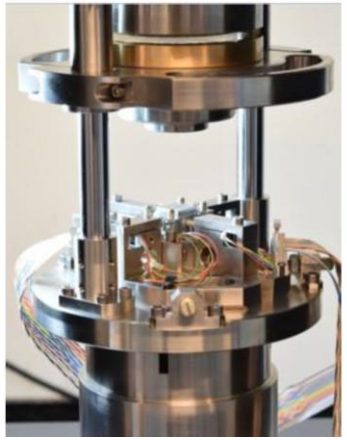


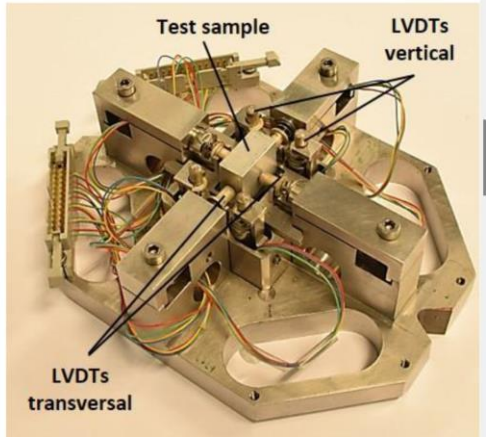


Vallone et al. 2018

Nonlinear → unloading → modulus

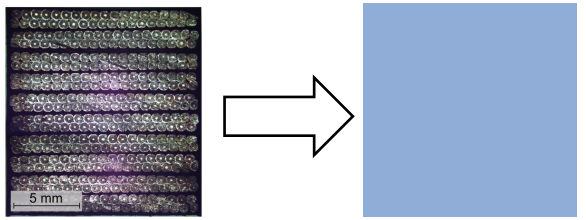
LVDT: Linear Variable Differential Transformer





Fichera et al. 2019

Homogenization



Limitation:

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

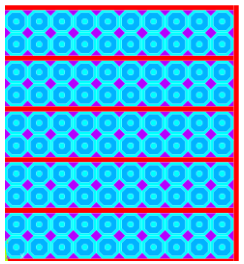
Scheuerlein et al. 2019 Supercond. Sci. Technol. 32 (2019) 045011
Vallone et al. 2018 Transactions on Applied Superconductivity (Volume: 28, Issue: 4, June 2018)
Fichera et al. 2019 Transactions on Applied Superconductivity (Volume: 29, Issue: 7, October 2019)

Structure

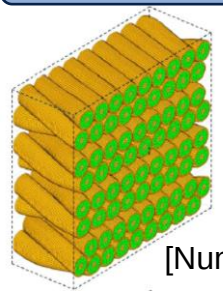
FEM modeling

Ansys

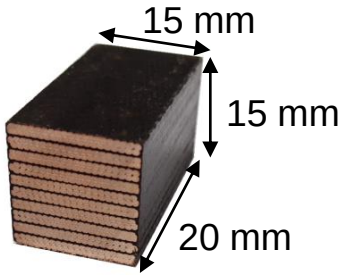
2D octagon



3D mesh



[Nunio 2019]



Experiment

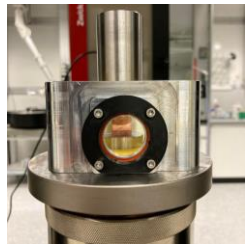
Component characterization

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

10-stack

- Transverse
- Axial/radial/other loads

Set-ups at LN_2

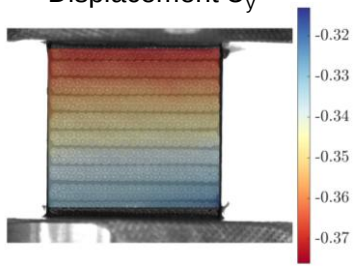


Digital Image Correlation (DIC)
- Displacement field
- Strain field

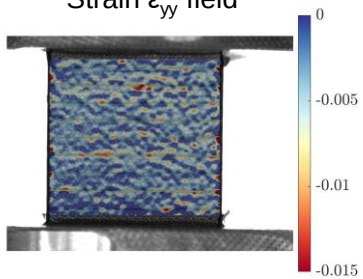
Image analysis

Local measurement

Displacement U_y



Strain ε_{yy} field



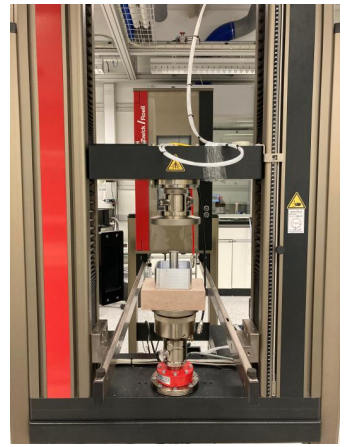
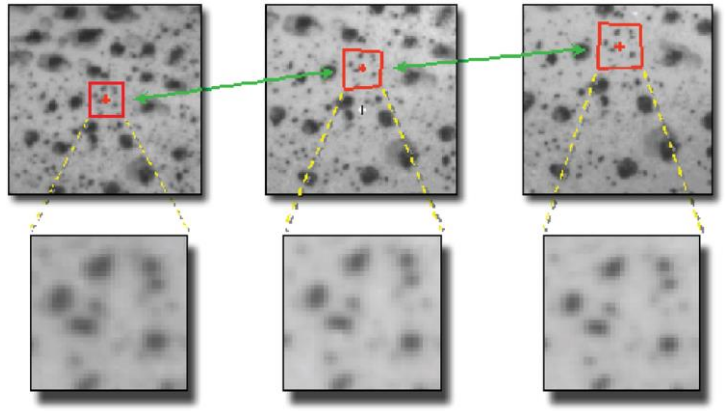
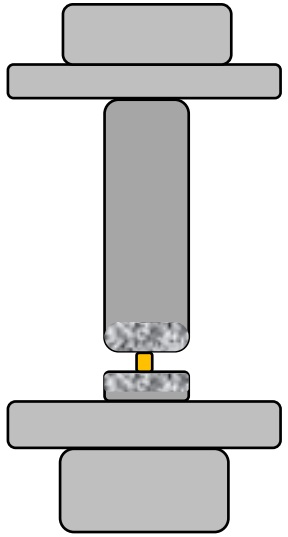


Image analysis: optical extensometer

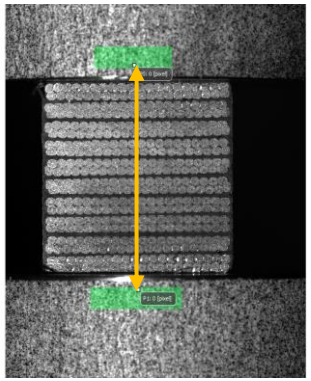
Digital image correlation (DIC)

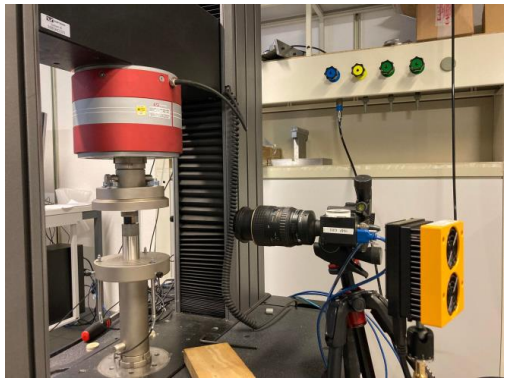


VIC2d

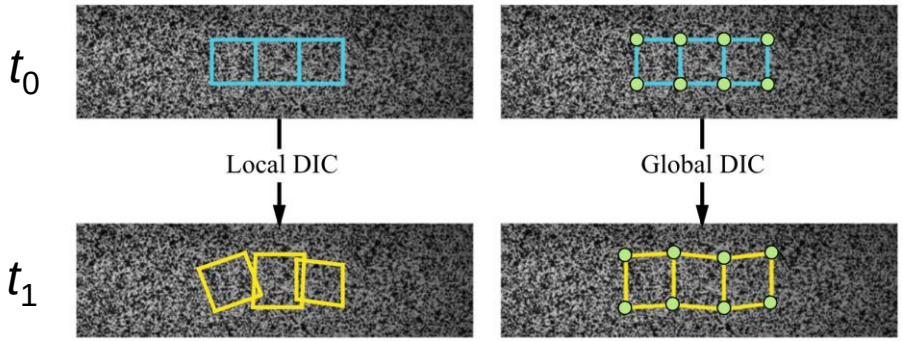


Measure local displacement by *undeformed markers* at cubic level (15 mm)





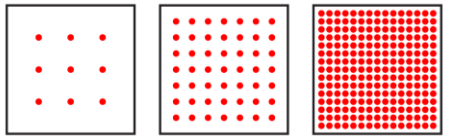
Courtesy of Tancogne-Dejean @MAVT-Mohr's lab

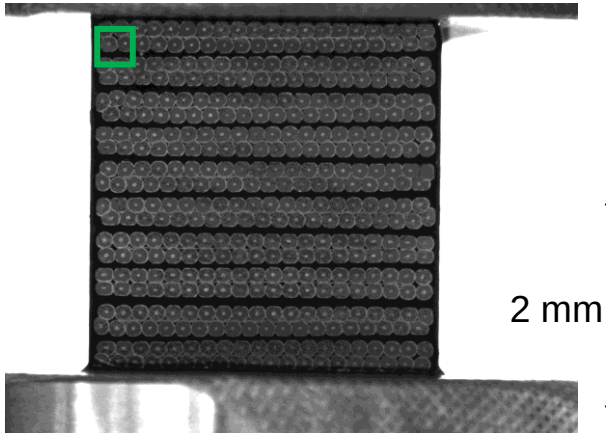


Yang, Bhattacharya, Exp Mech (2019)

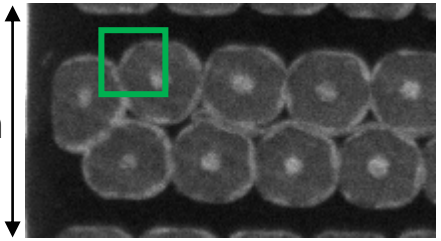
$$f(\boldsymbol{x}, t_0) \approx g(\boldsymbol{x} + \boldsymbol{u}(\boldsymbol{x}), t_1)$$

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





1440x1080 px^2, 17.1 µm/px



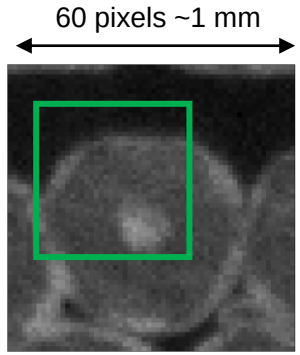
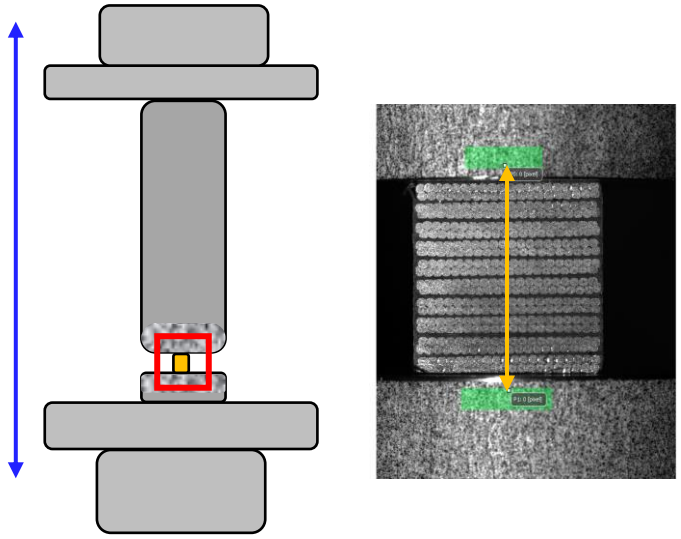
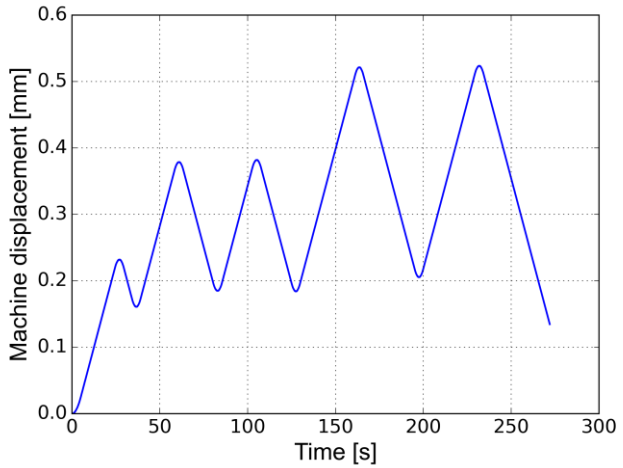


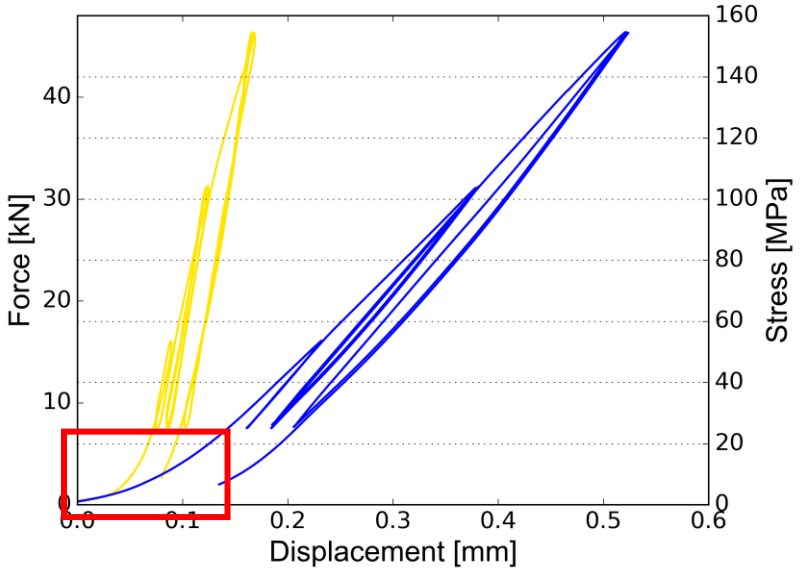
Image analysis: optical extensometer



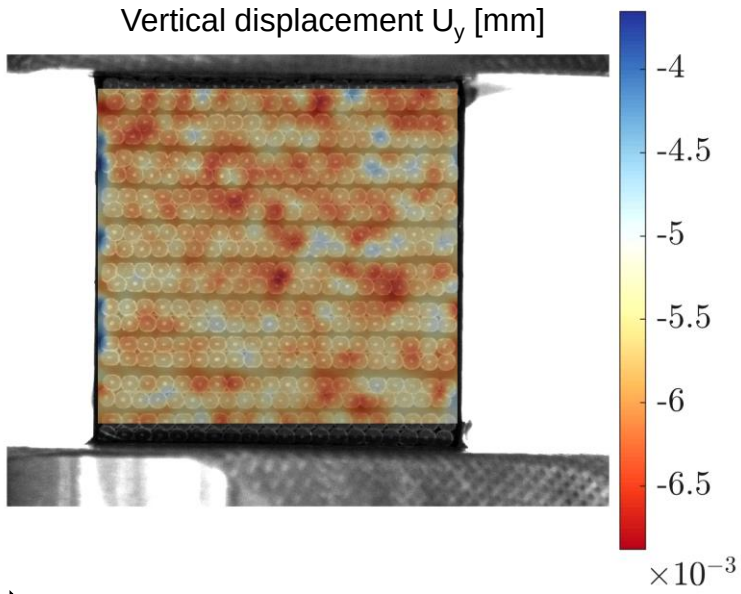
Displacement-controlled: 10 µm/s ~ 1 kN/s
Image capture rate: 1 s^{-1} (273 images)



Cubic level



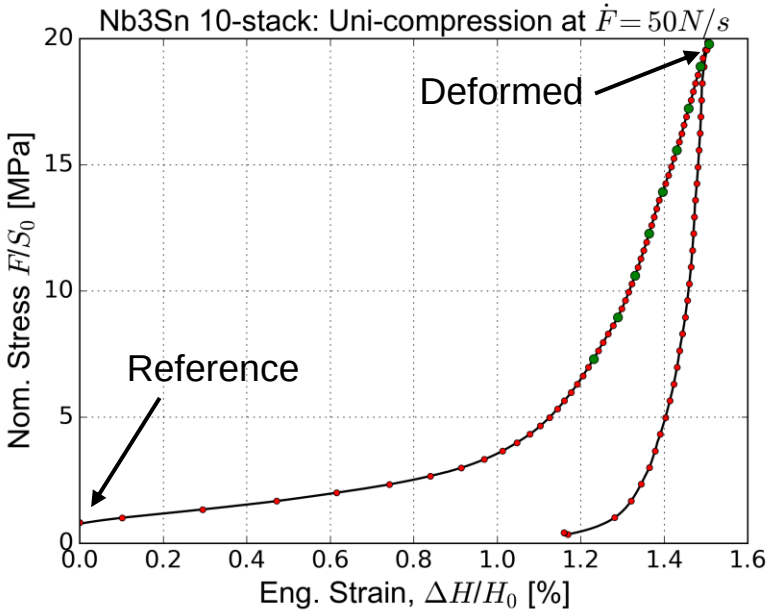
Stack level



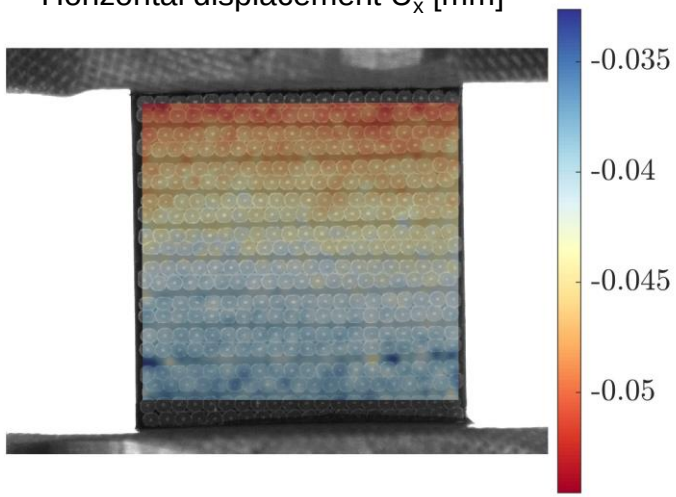
1D information

2D information

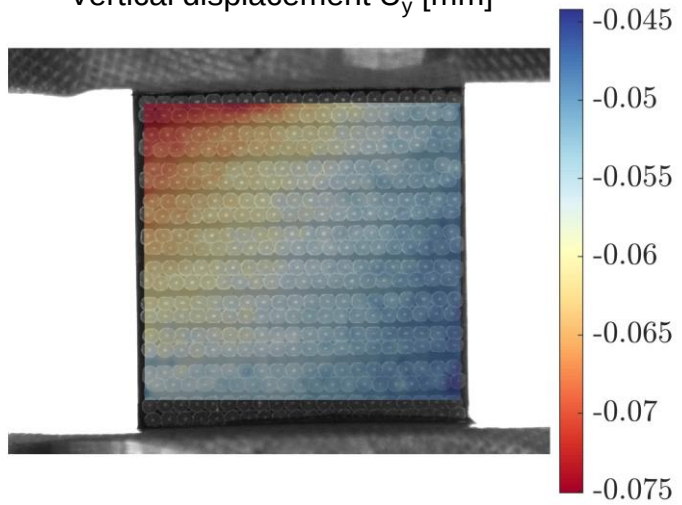
Displacement fields at low force (20 MPa)

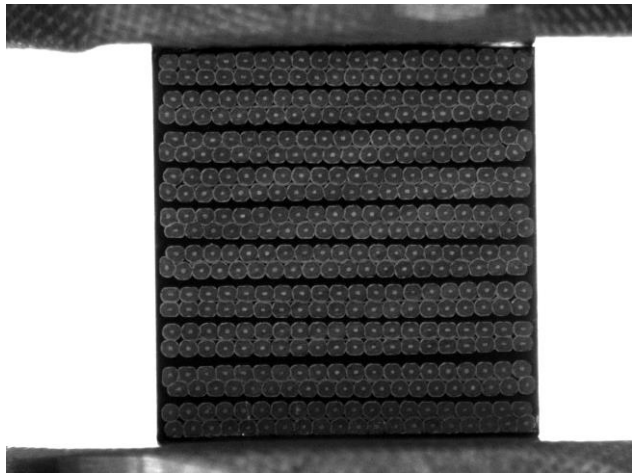


Horizontal displacement U_x [mm]

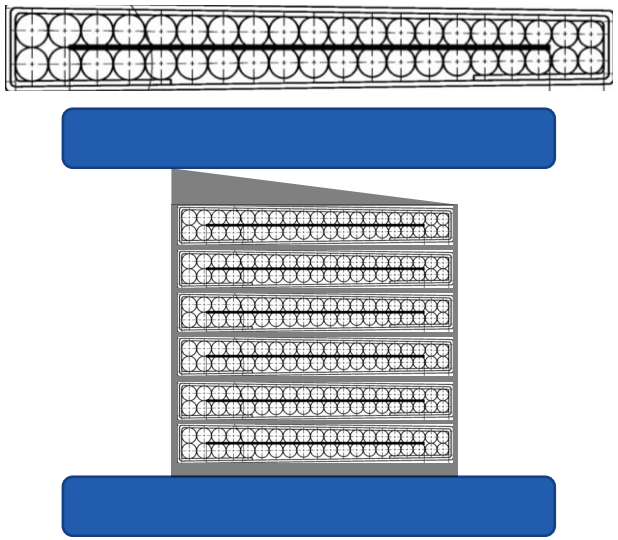


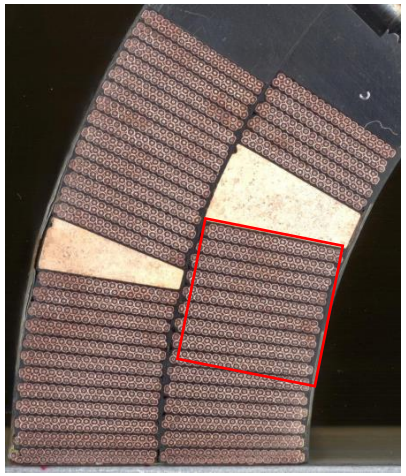
Vertical displacement U_y [mm]





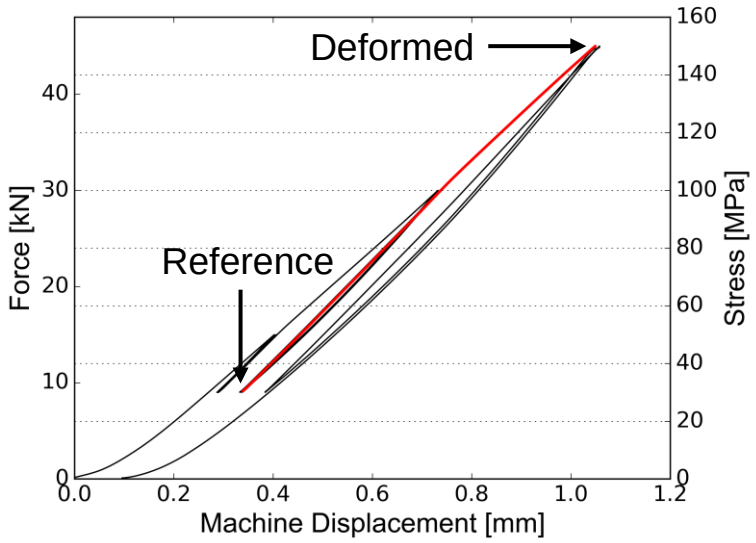
CERN, 11T dipole magnet (2013)



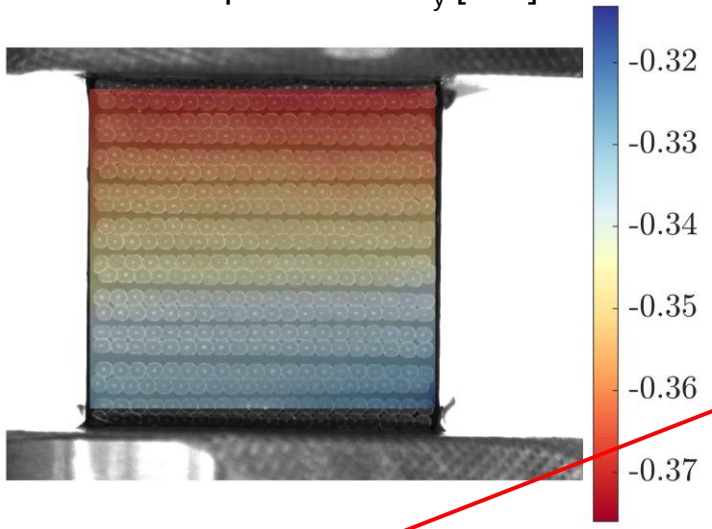


→ start from 20MPa as pre-loading

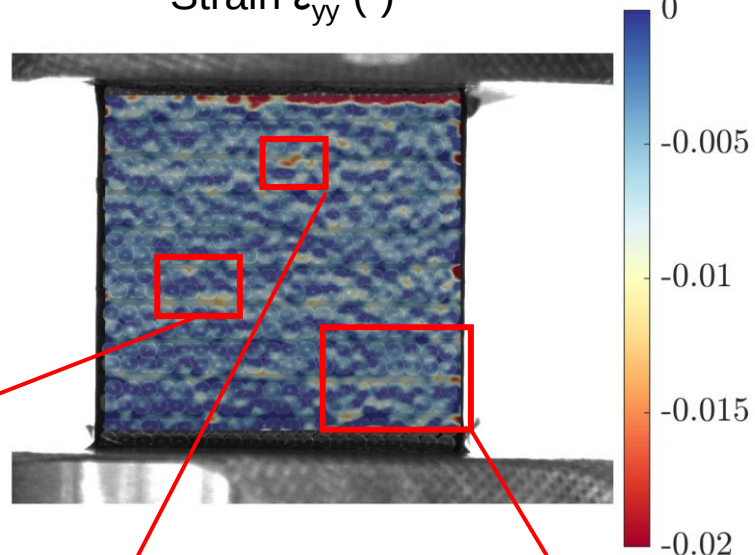
DIC results up to 150MPa



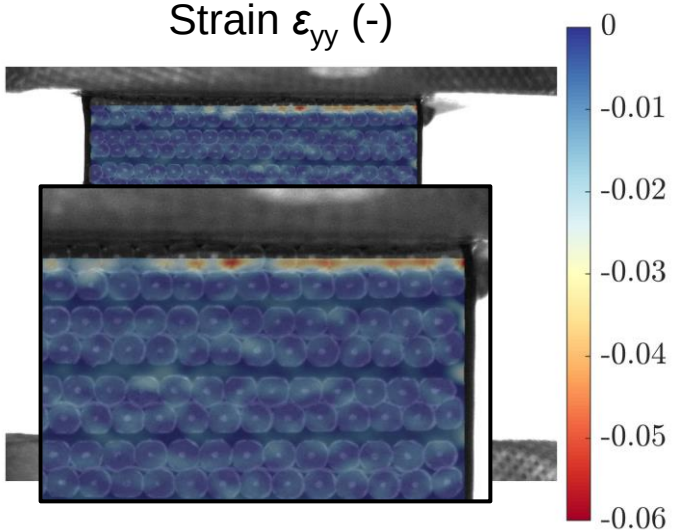
Vertical displacement U_y [mm]

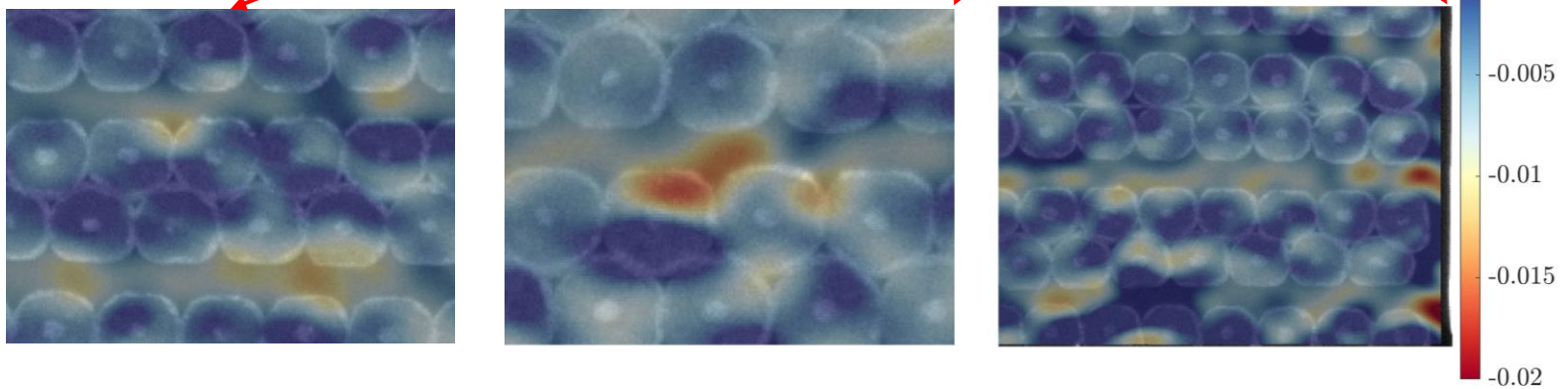


Strain ε_{yy} (-)



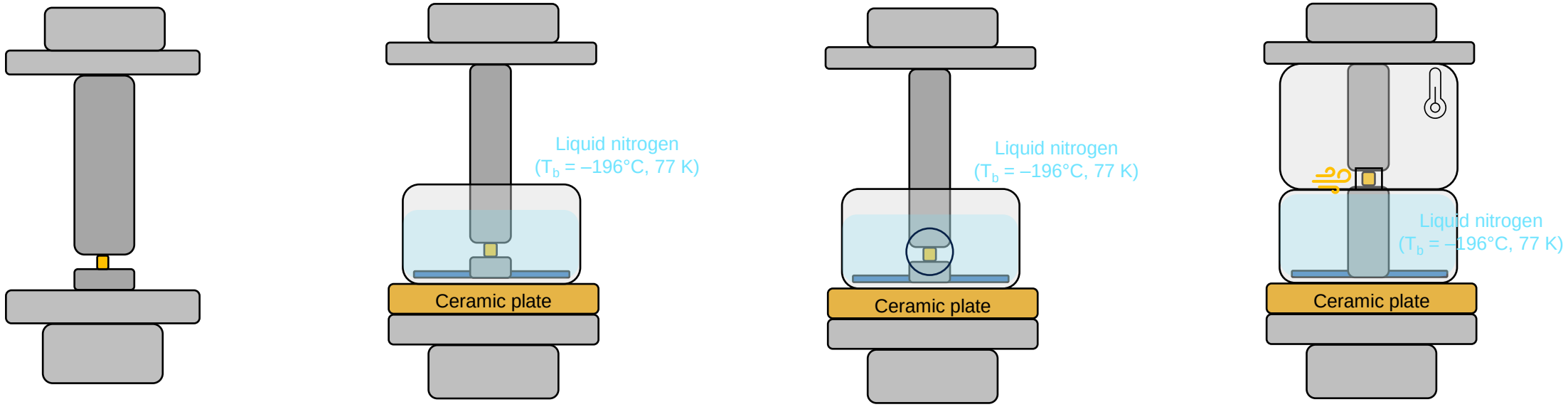
Strain ε_{yy} (-)

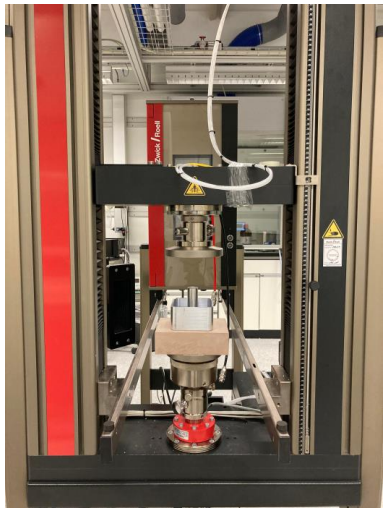


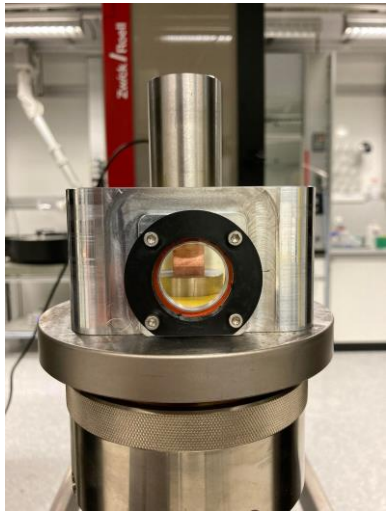


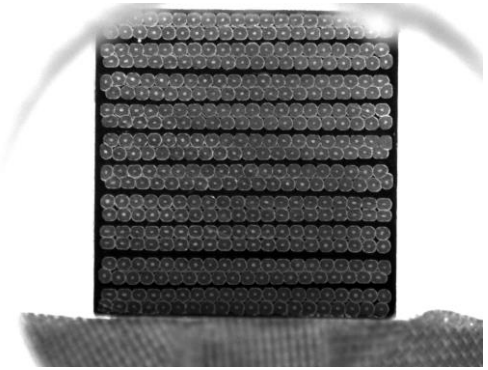
- Sample edges (top/bottom) are the most deformed region (6%)
- Some insulation layers are 1-2% strain level
- The strain values depend on ‘mesh-equivalent’ parameters (subset, step)

From RT to LN_2









Still developing:

- Liquid boiling affects image capture

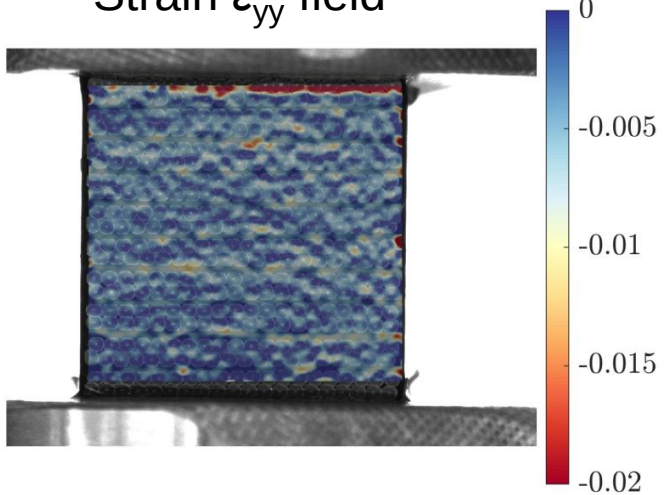
Conclusion & Outlook

- An *in situ* full-field deformation measurement is performed at the level of cable stacks via image-based analyses
- Compressive strain localization can be experimentally measured at insulation layer

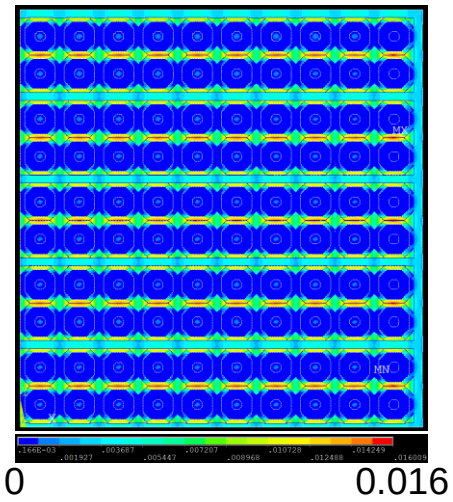
❖The approach will be applied at cryogenic temperature

❖The deformation measurement can be compared with the numerical results at multiscale

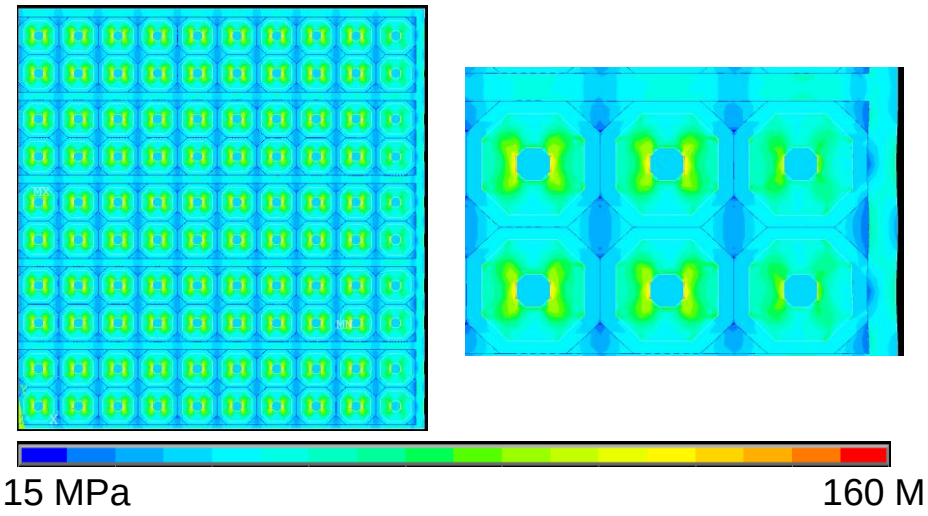
Strain ε_{yy} field



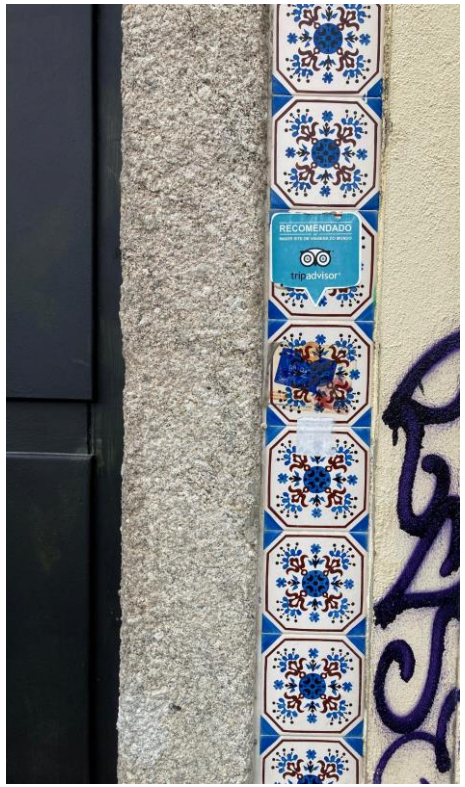
Strain field

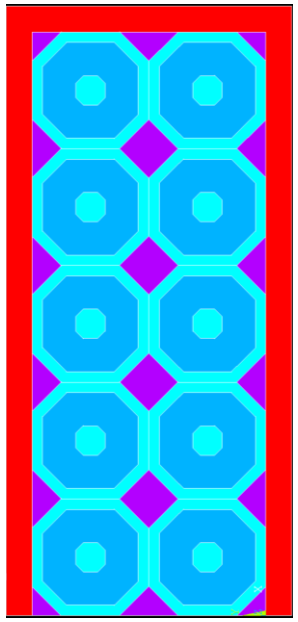


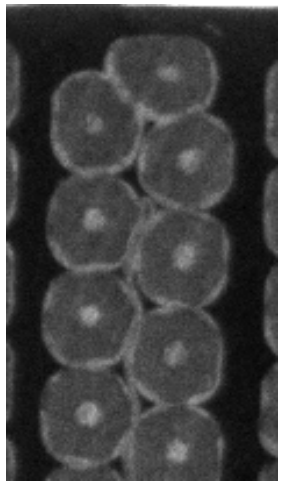
VM. stress field



Strand-like Azulejo (ceramic tilework) in Porto







Any questions?

Thanks to our collaborators

ETH Zurich

- Prof. Theo A. Tervoort, Prof. Jan Vermant
- Soft Matter group

PSI Villigen, CHART

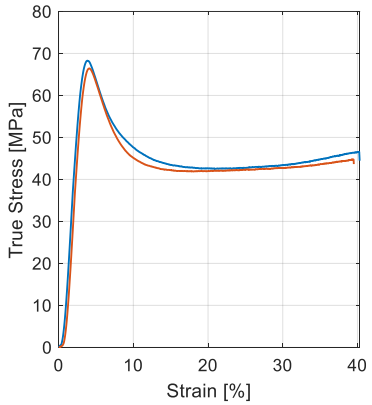
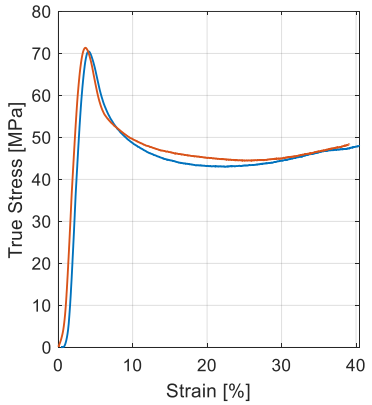
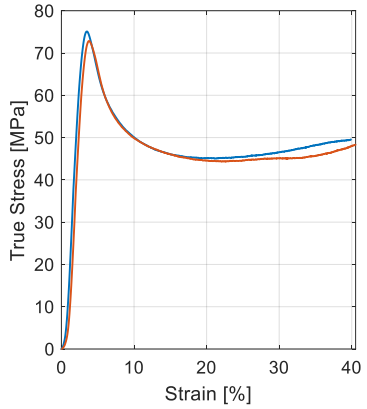
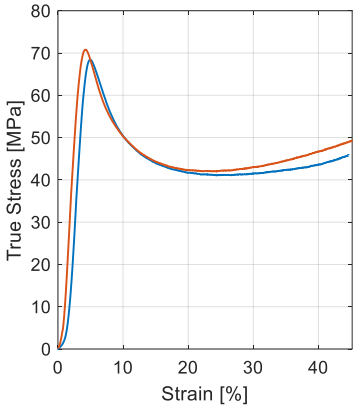
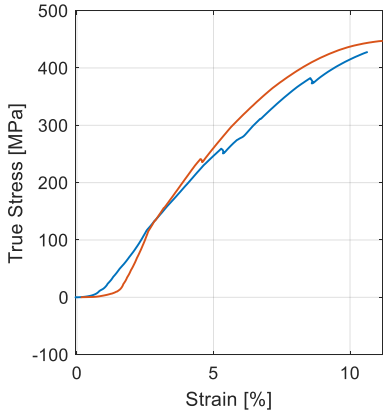
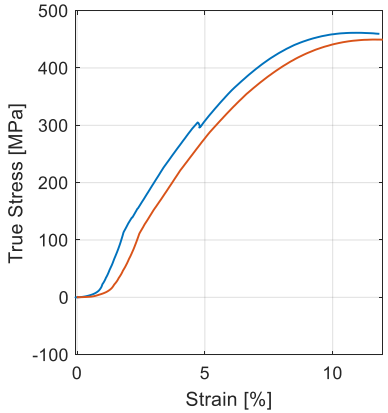
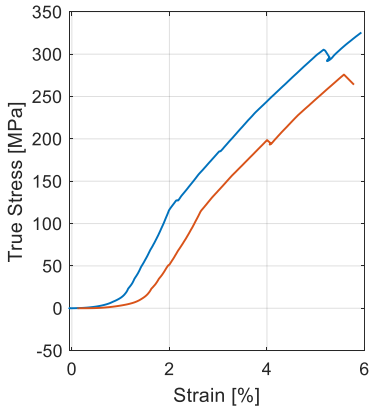
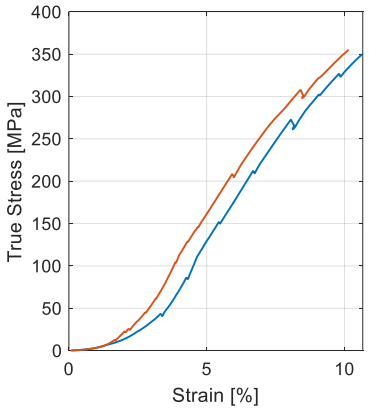
- Bernhard Auchmann, André Brém, Douglas Martin Araujo, Micheal Daly

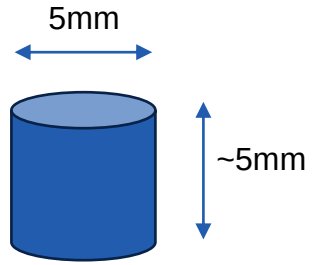
CERN Meyrin, Polymer Lab

- Roland Piccin, Christian Scheuerlein, Bharti Verma, Mauro Taborelli, Stefano Sgobba, Daria Ternova, Sebastian Clément

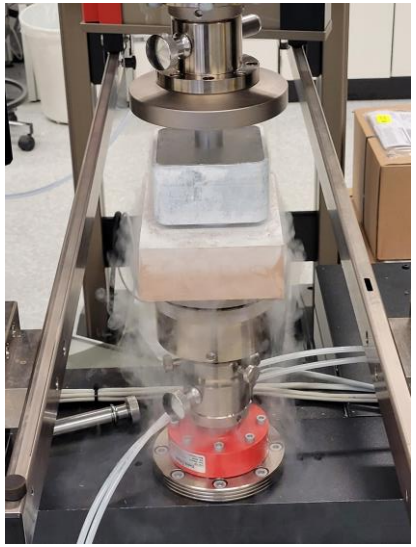
Results

- Compressive Yield behaviour

	Butylamine system		Mix system	
RT				
	0%	5%		
LN				

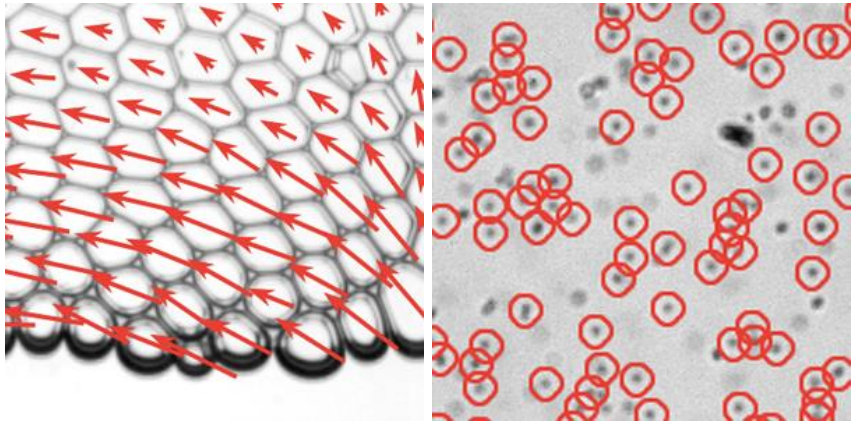


- Compliance corrected
- True stress (assuming constant volume)



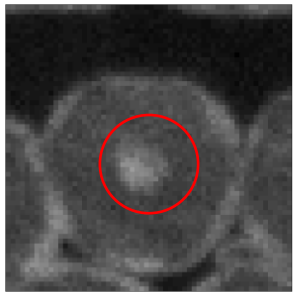
Particle tracking

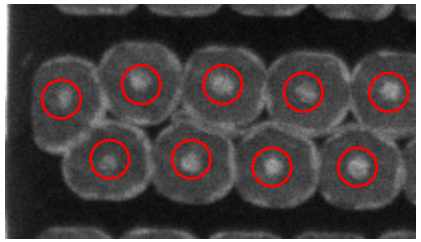
Trackpy: python package for particle tracking

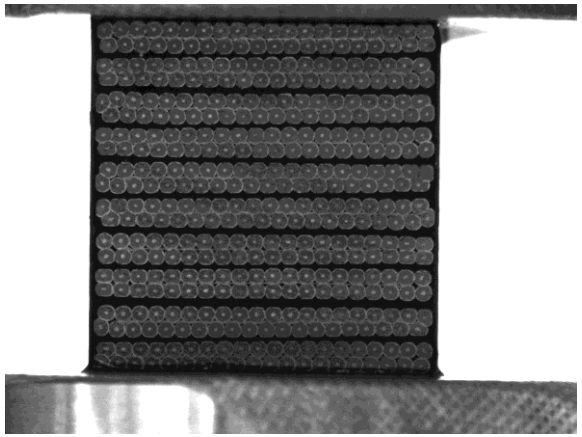


Trackpy

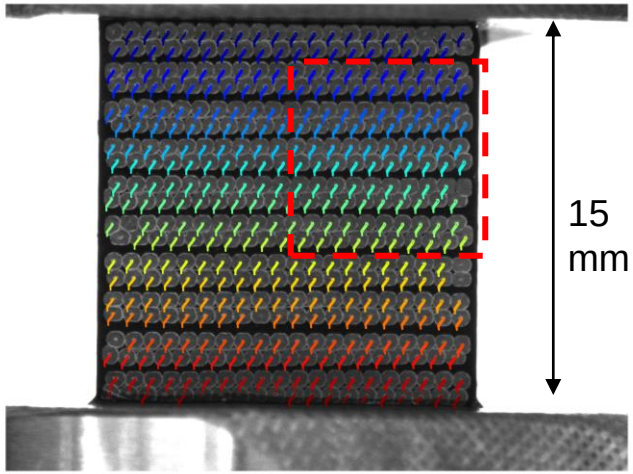
Strand core as natural mark (d~10 pixels)

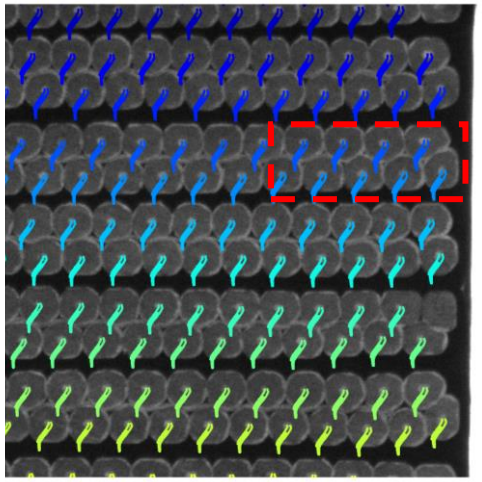


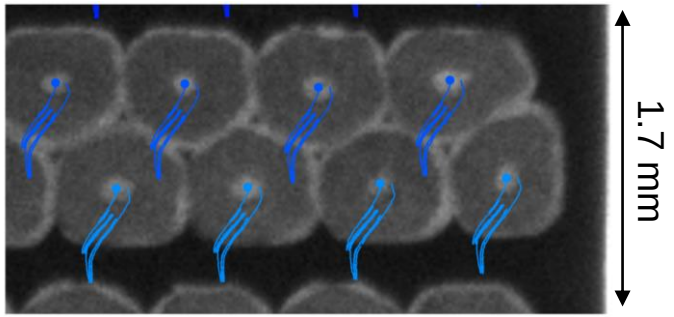


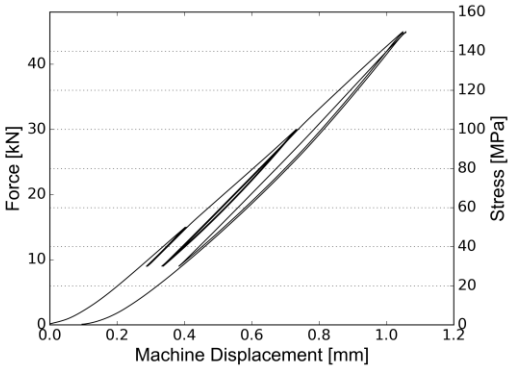


Trajectory of each strand-core



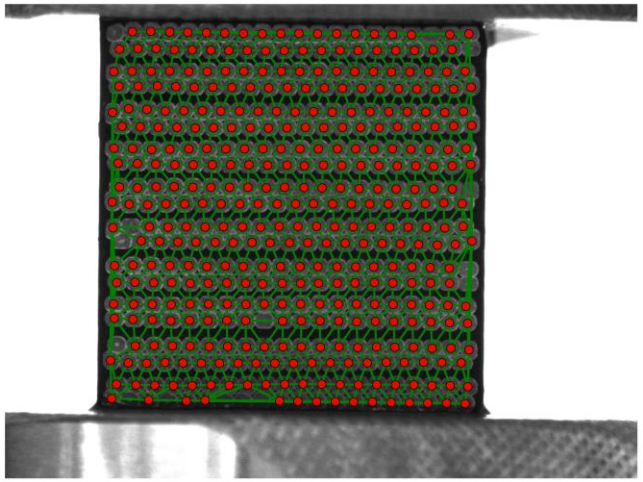




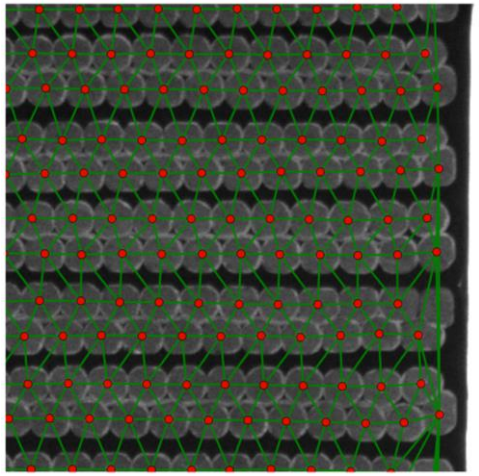


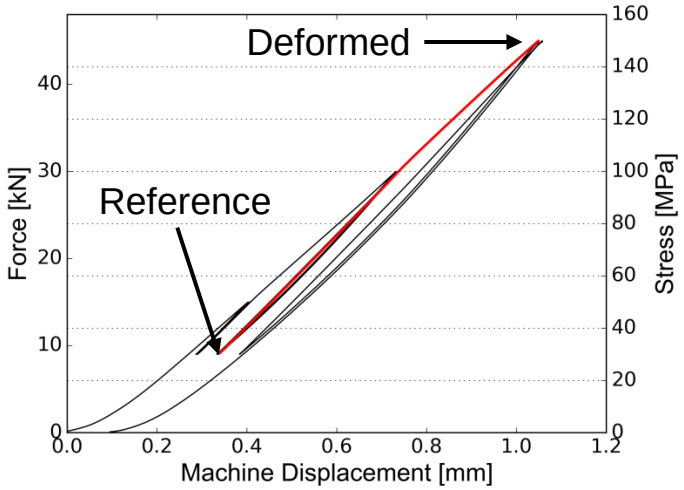
- Most (380/400) strands are tracked during the loading
- There is a horizontal rigid body motion

Fields comparison



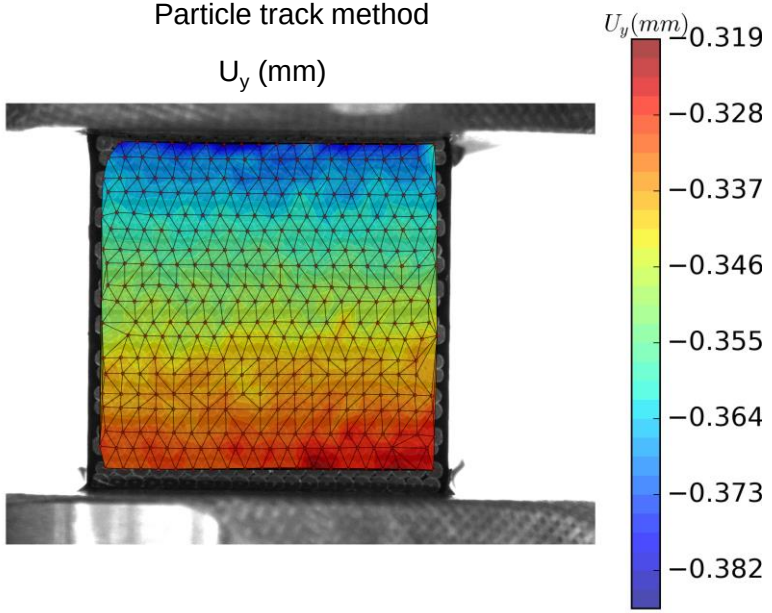
Strand-based mesh





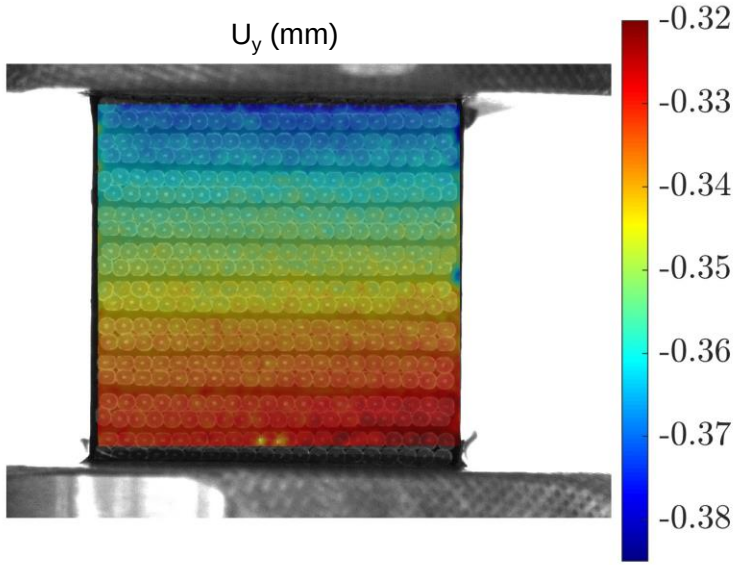
Particle track method

U_y (mm)



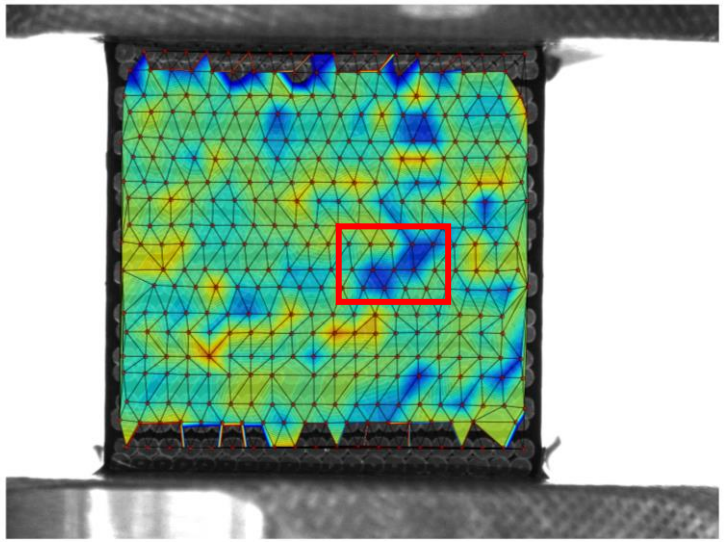
AL-DIC: 1440x1080 px^2, subset:20 px, step:5 px

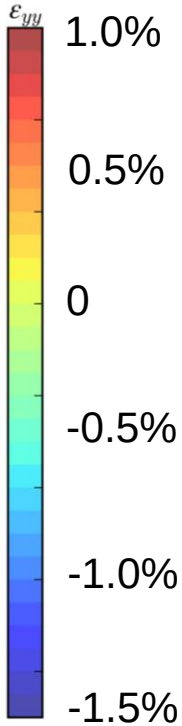
U_y (mm)

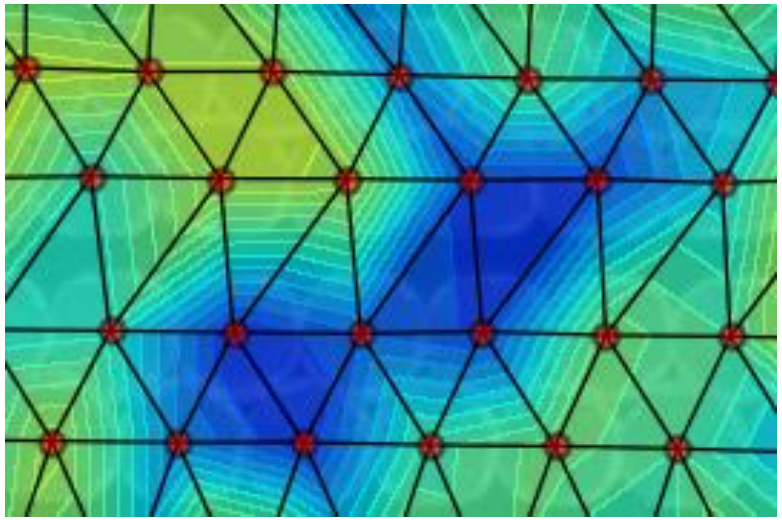


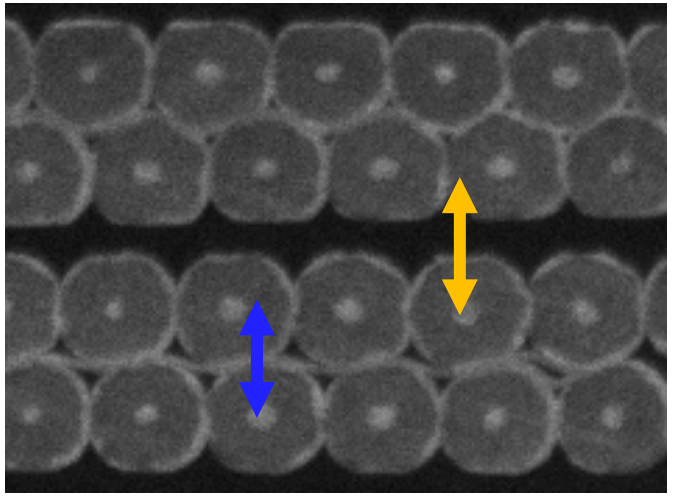
- There is a good agreement of displacement fields between two approaches.

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**

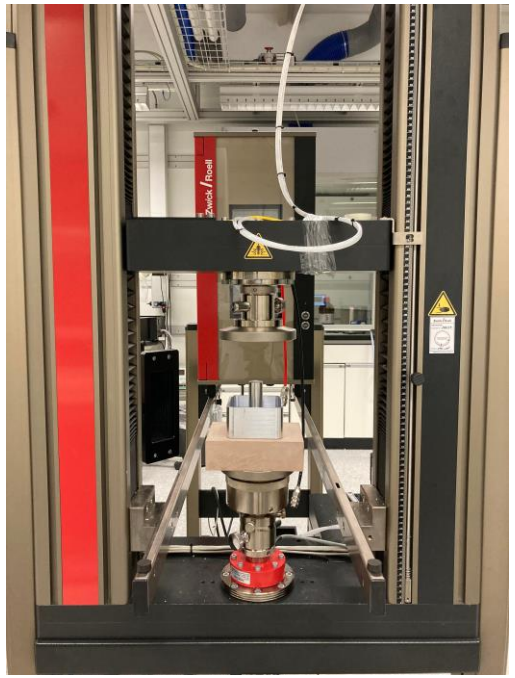
$$\mathbf{E} = \frac{1}{2}(\mathbf{F}^{\mathrm{T}}\mathbf{F} - \mathbf{I})$$

Conclusion

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

Machines with different measurements

Zwick050@D496

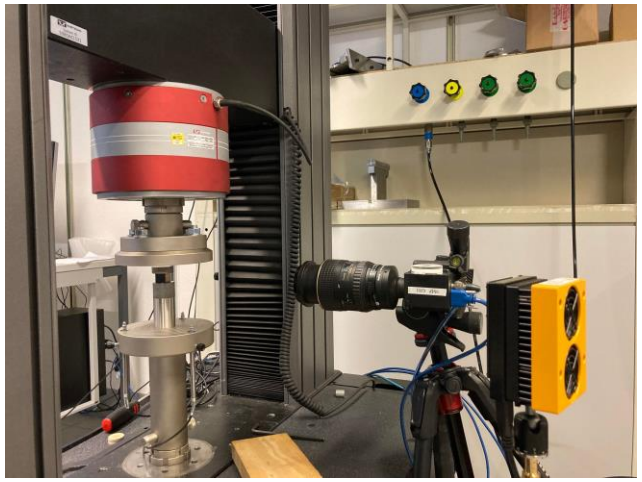


- Global correction
- DIC

Zwick100@D467

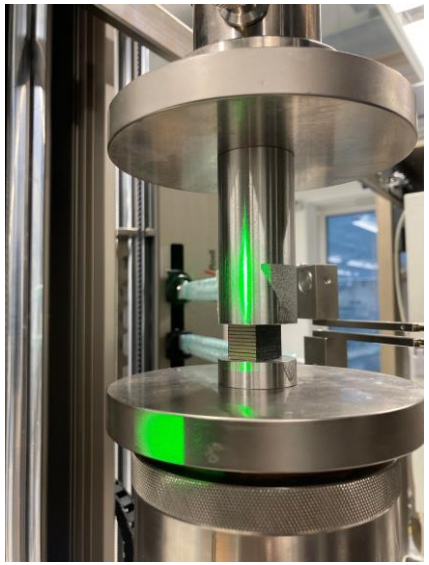
- Global correction
- MacroExtenso
- LaserExtenso
- DIC
- laser

Instron250@MAVT-Mohr

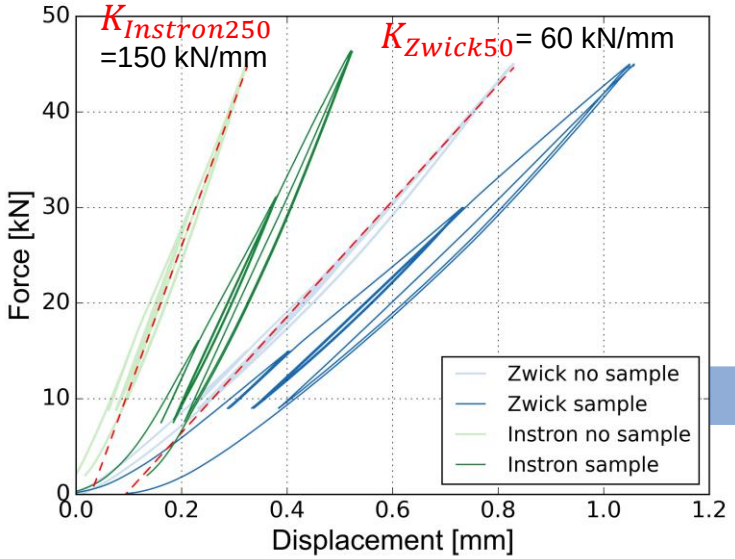


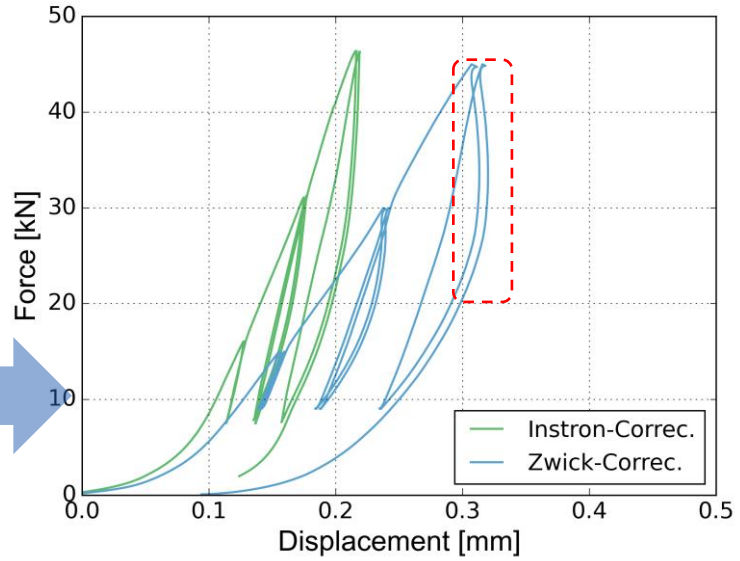
- Global correction
- DIC

Ongoing work @Z100-D467



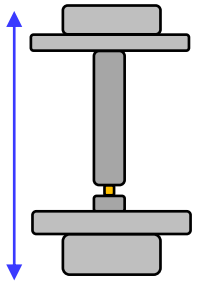
Correction

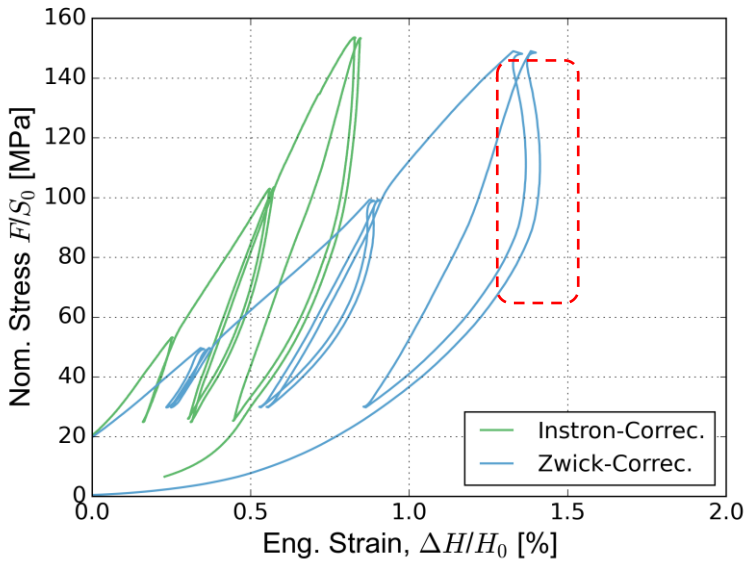




$$\Delta d_{s-corr.} = \Delta d_{tot} - \Delta d_{machine}$$

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





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

Zwick100