PSI

DTU

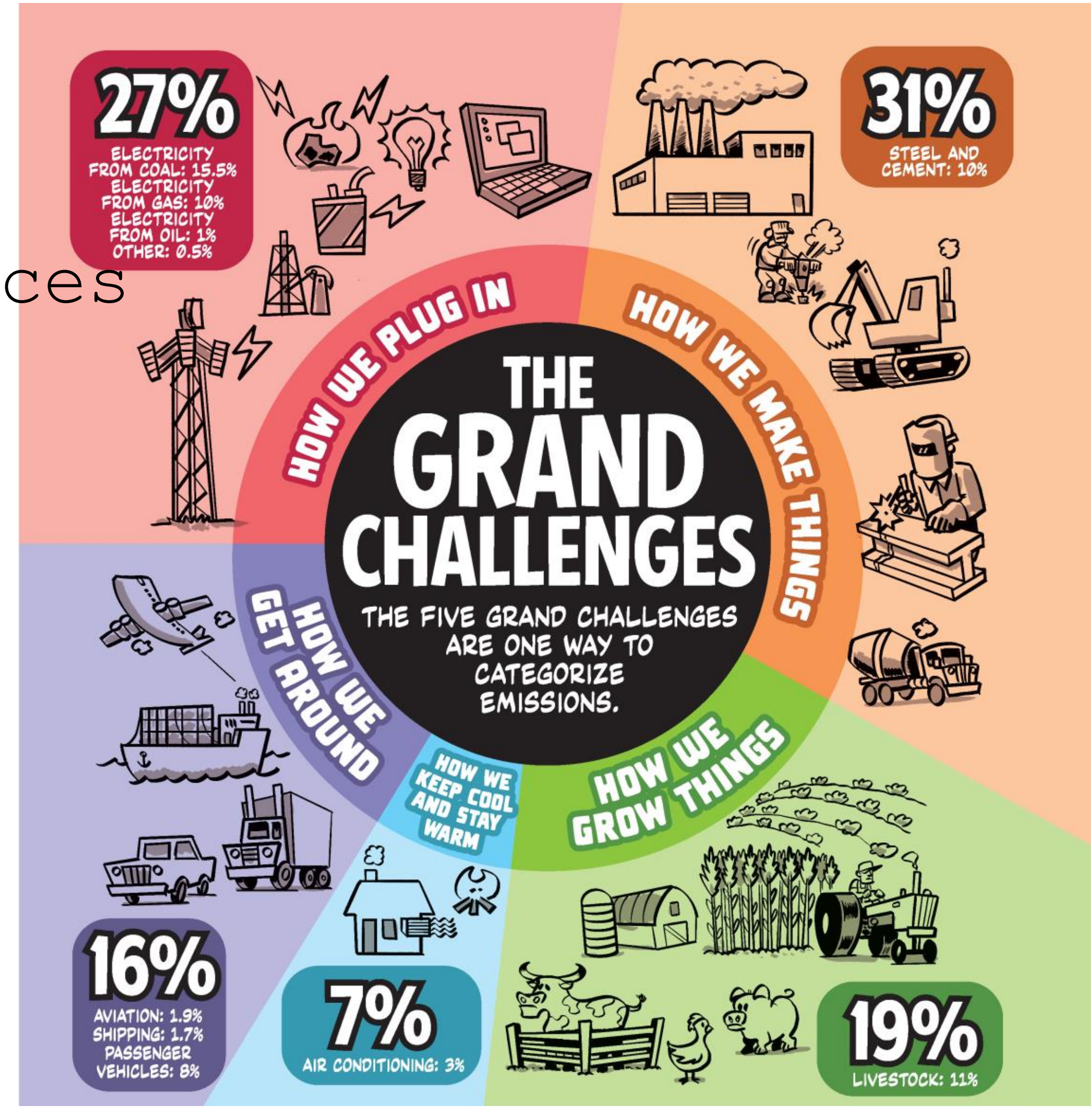
Neutron Imaging for Energy Applications

- M.Strobl, Head of Applied Materials Group
- PSI Center for Neutron and Muon Sciences
- markus.strobl@psi.ch

- FASEM, ILL, Mar. 2026

Societal challenges

- Energy
- Manufacturing
- Natural resources
- Environment
- Food
- Mobility
- Health
- Space
- Defence
- Digitalization
- Quantum techn.
- Governance



Science Drivers

- **Energy**
- Manufacturing
- Natural resources
- Environment
- Food
- Mobility
- Health
- Space
- Defence
- Digitalization
- Quantum techn.
- Governance

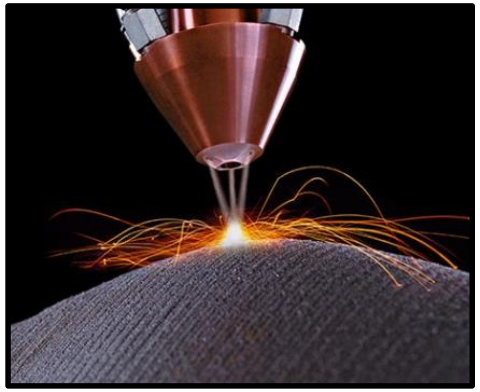
Physical Chemistry

Nuclear Safety

Life/Environmental

Energy

Engineering

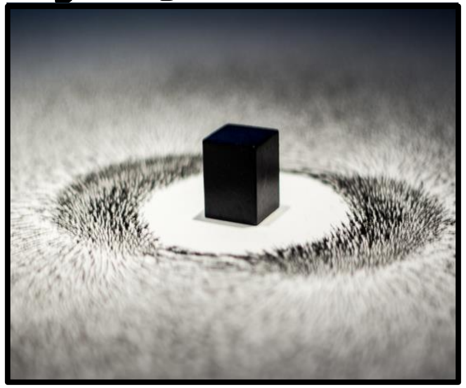


Soft Matter

Structural Materials

Nat./Cult. Heriatge

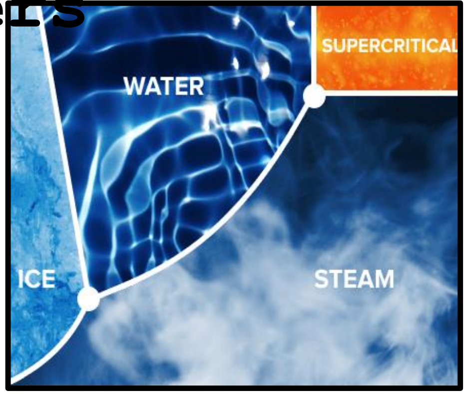
Magnetism



Science Drivers

PSI

Physical Chemistry



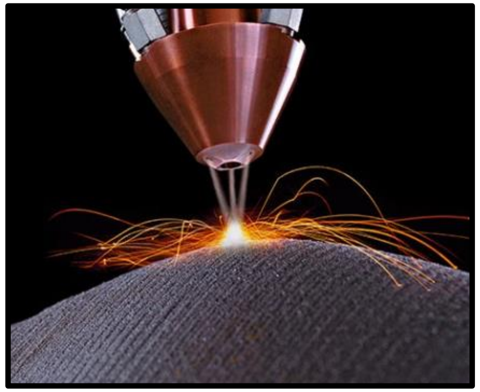
Nuclear Materials

Life/Environmental

Industry

Energy

Engineering/Aerospace

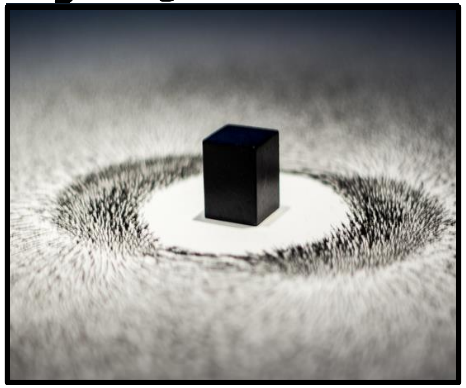


Soft Matter

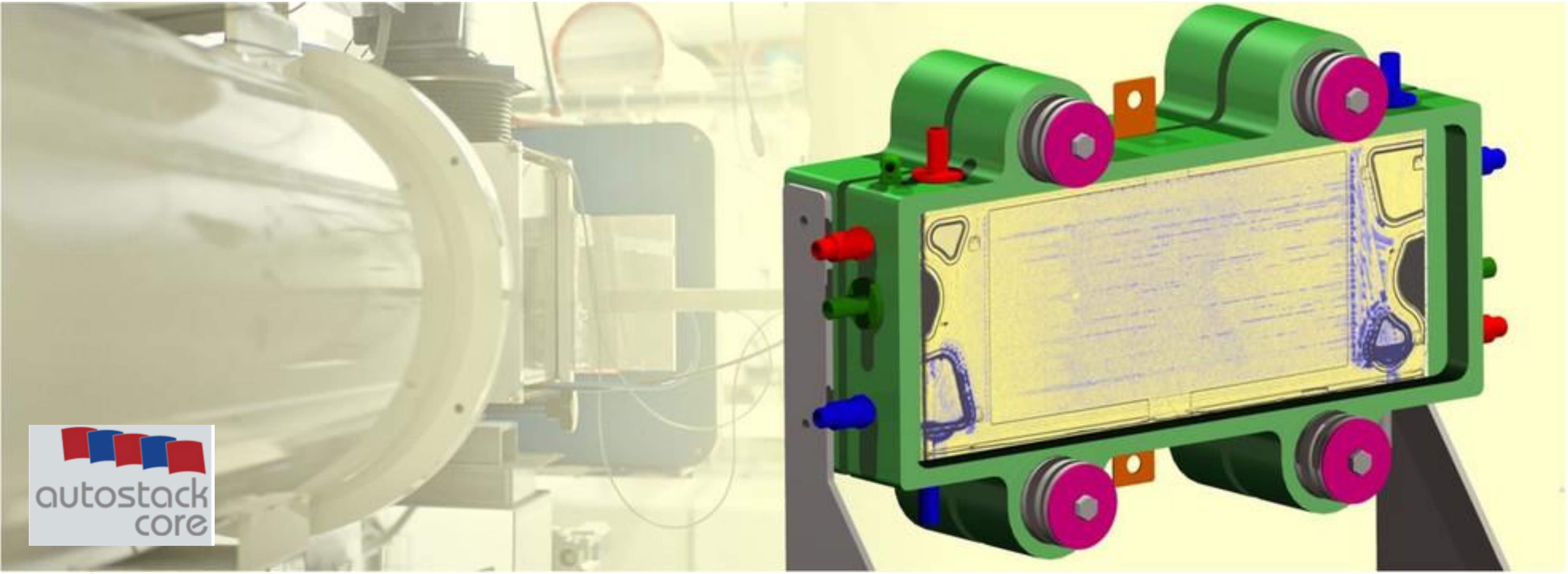
Structural Materials

Nat./Cult. Heriatge

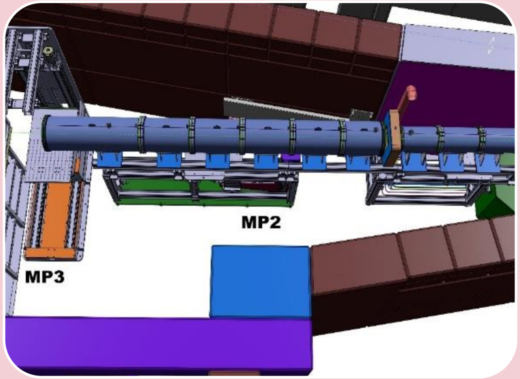
Magnetism

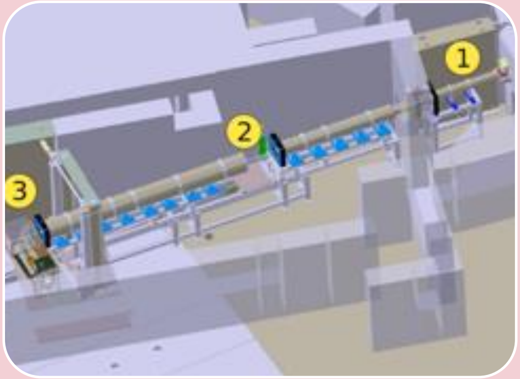


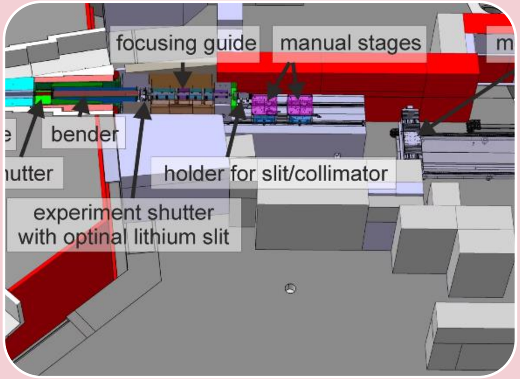
Industrial NDT

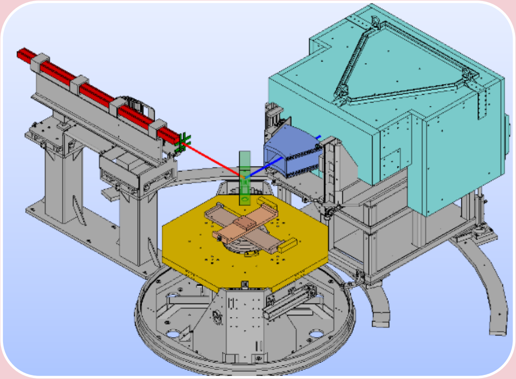


Applied Materials Group, LNS









NEUTRA

Thermal neutrons

-XTRA

-large FoV

-active samples

-industry

-high resolution

-> 20 years

ICON

Cold neutrons

-NGI, ICON-X

-large FoV

-wavelength resolved

-industry

-highest resolution

BOA

Cold neutrons

NGI, PNI

large FoV

wavelength resolved

POLDI

Engineering diffractometer

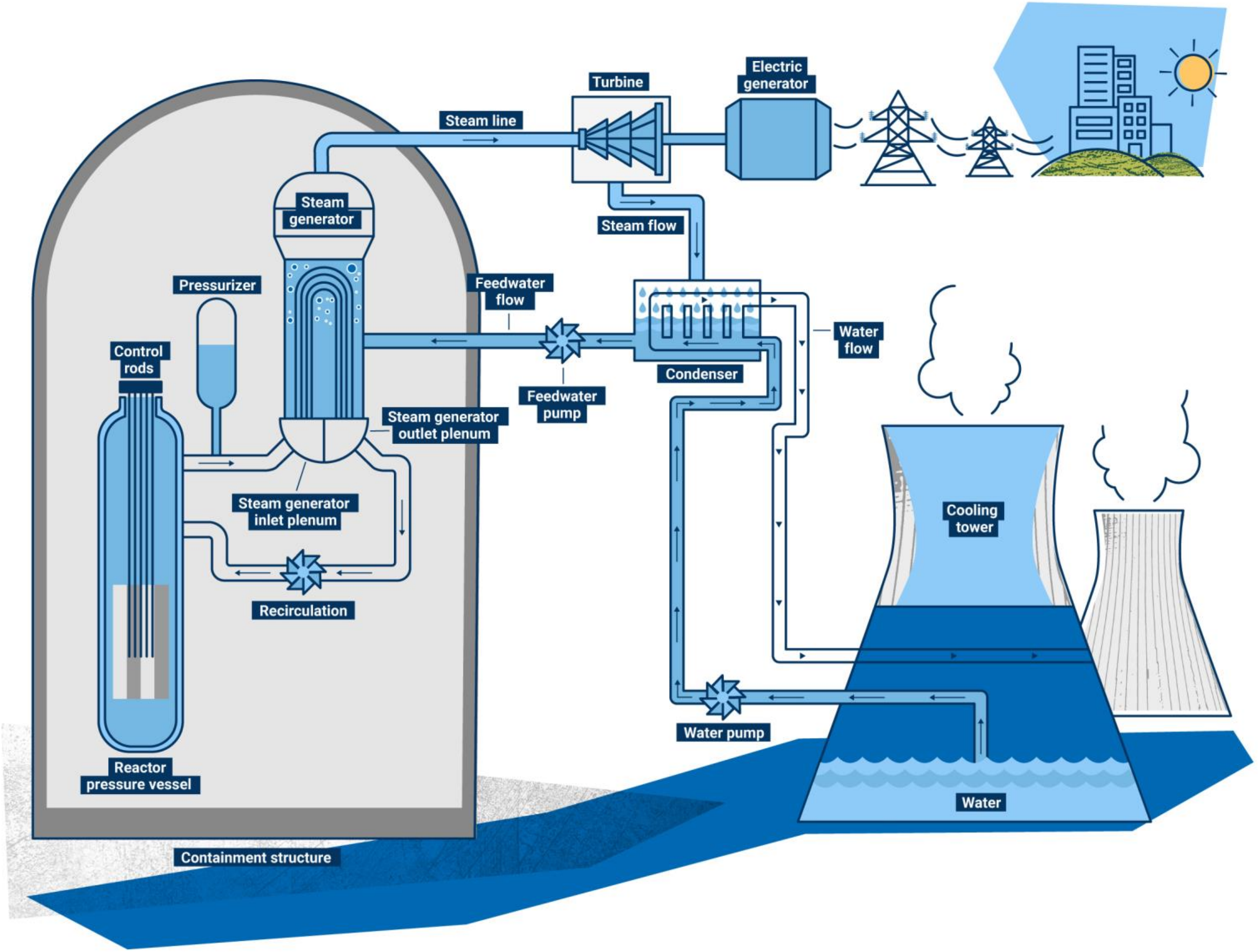
strain mapping

deformation testing

bi-axial loading

DIC, AE, industry

Nuclear Energy

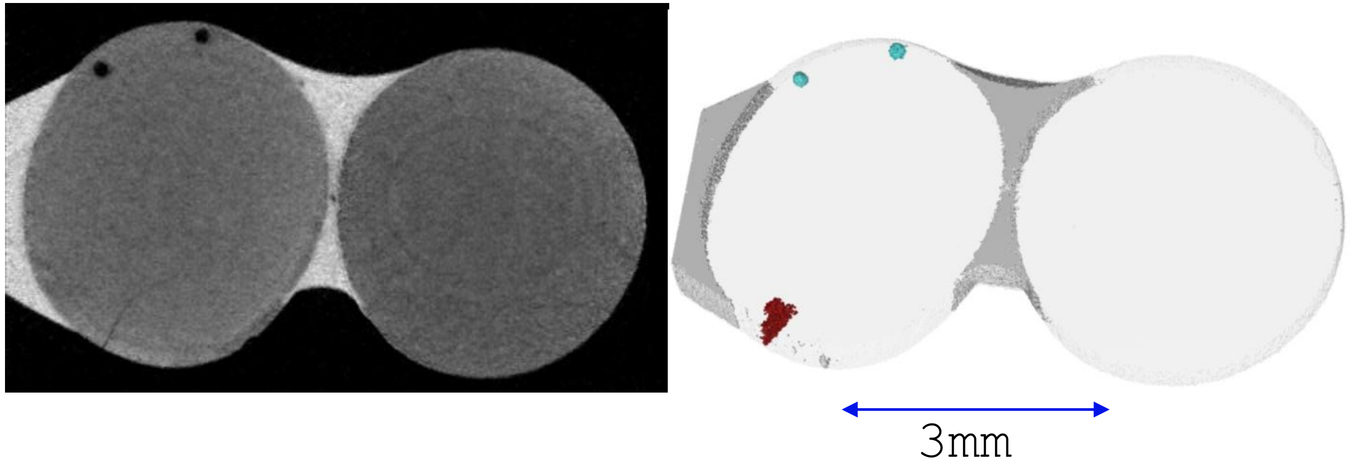


Nuclear Fuel

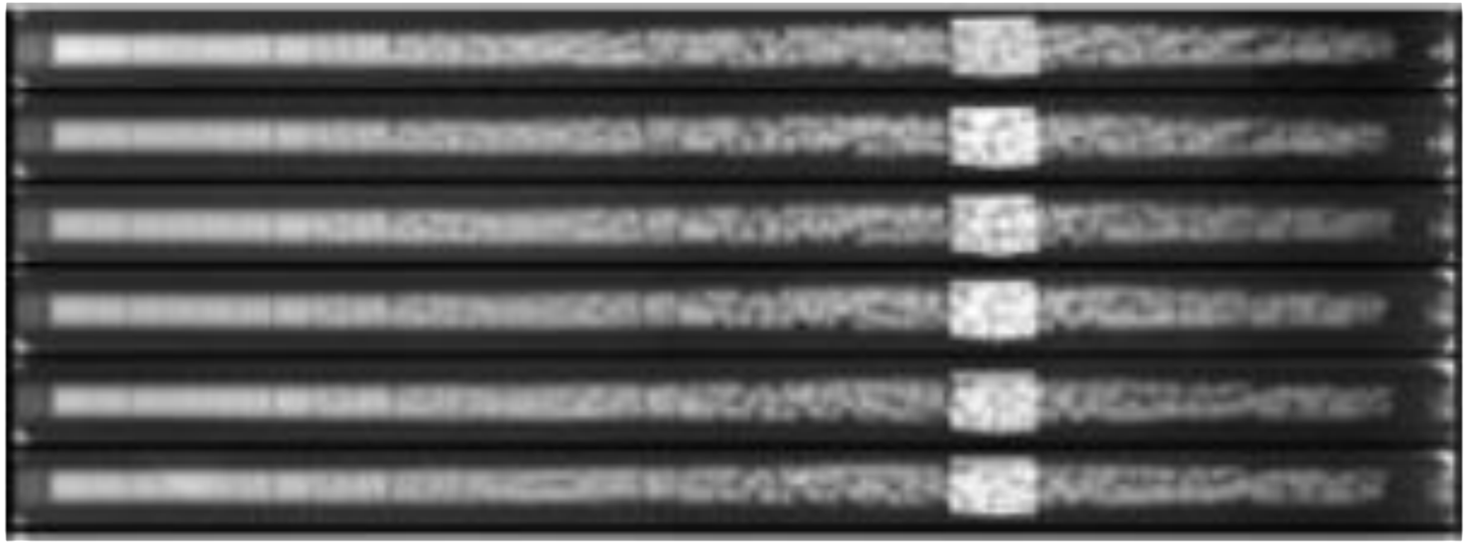
6-cm diameter fuel element from the High Temperature Reactor (HTR) (

Lehmann E H, et al., Nucl. Instrum. Methods Phys. Res. A (2003)

TRISO UO_2 nuclear fuel particles

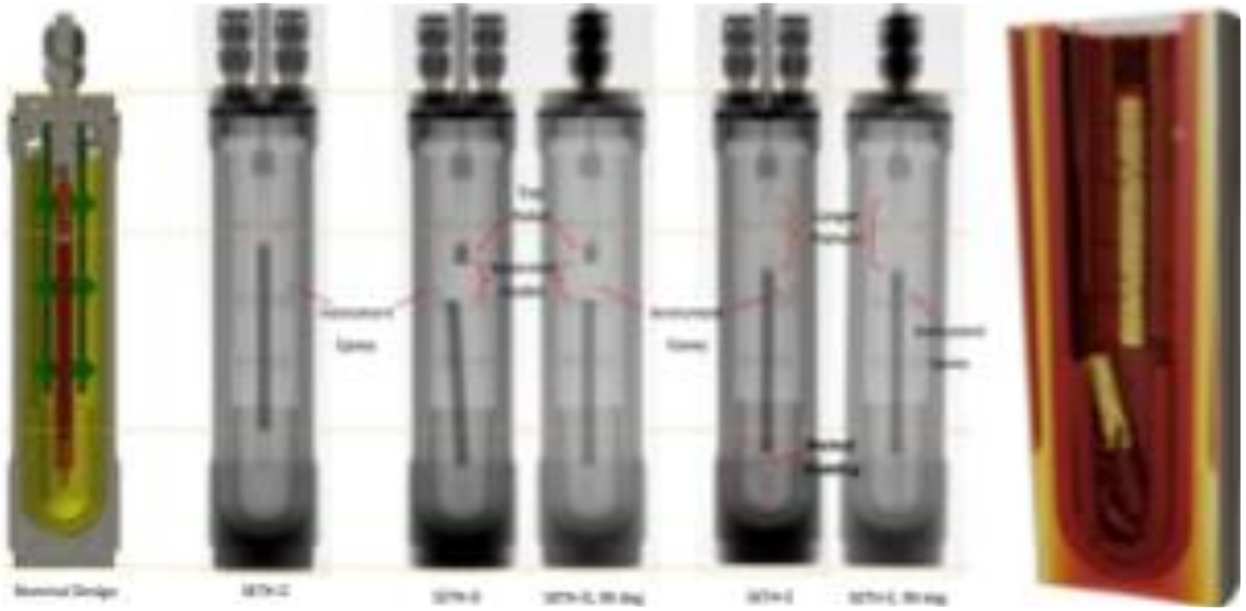


Nuclear Fuel



Fuel rod after loss-of-coolant incident simulation

Jenssen H K, et al., 2014 Prog. Nucl. Energy 72



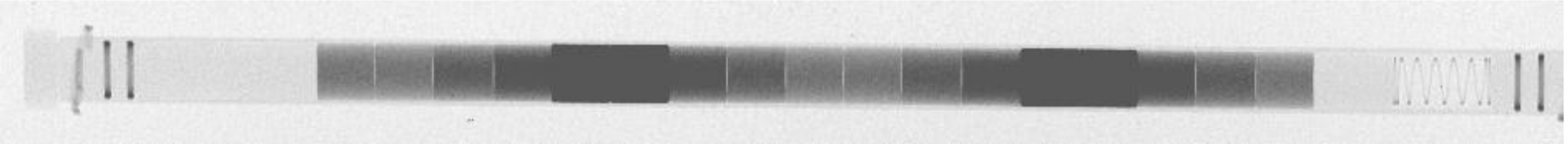
subjected to Gaussian shaped reactivity-initiated accident type transient at 19 GW transient research Reactor TREAT at INL

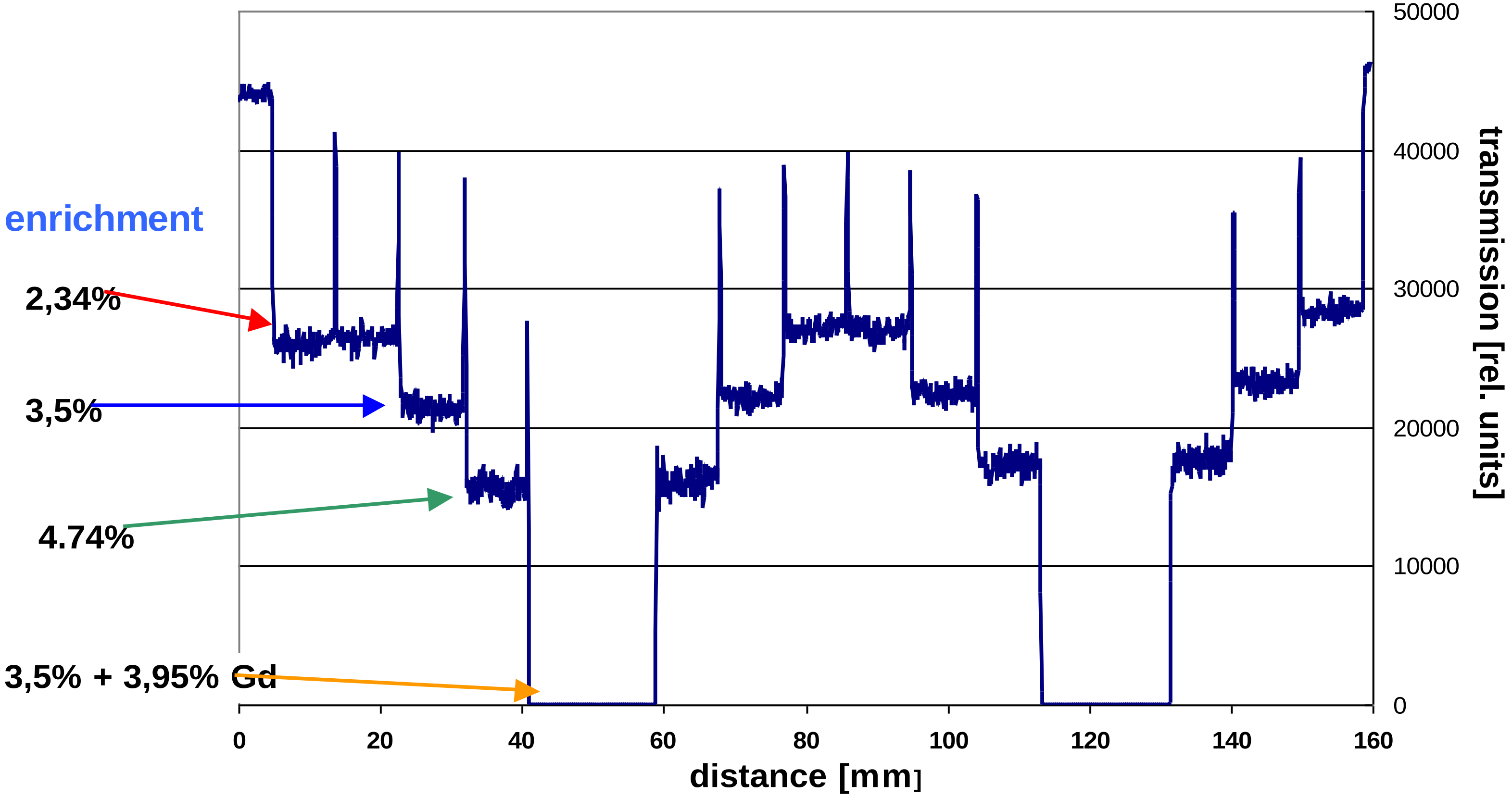
Schulthess J et al 2020 J. Nucl. Mater. 541

Nuclear Fuels

Fission

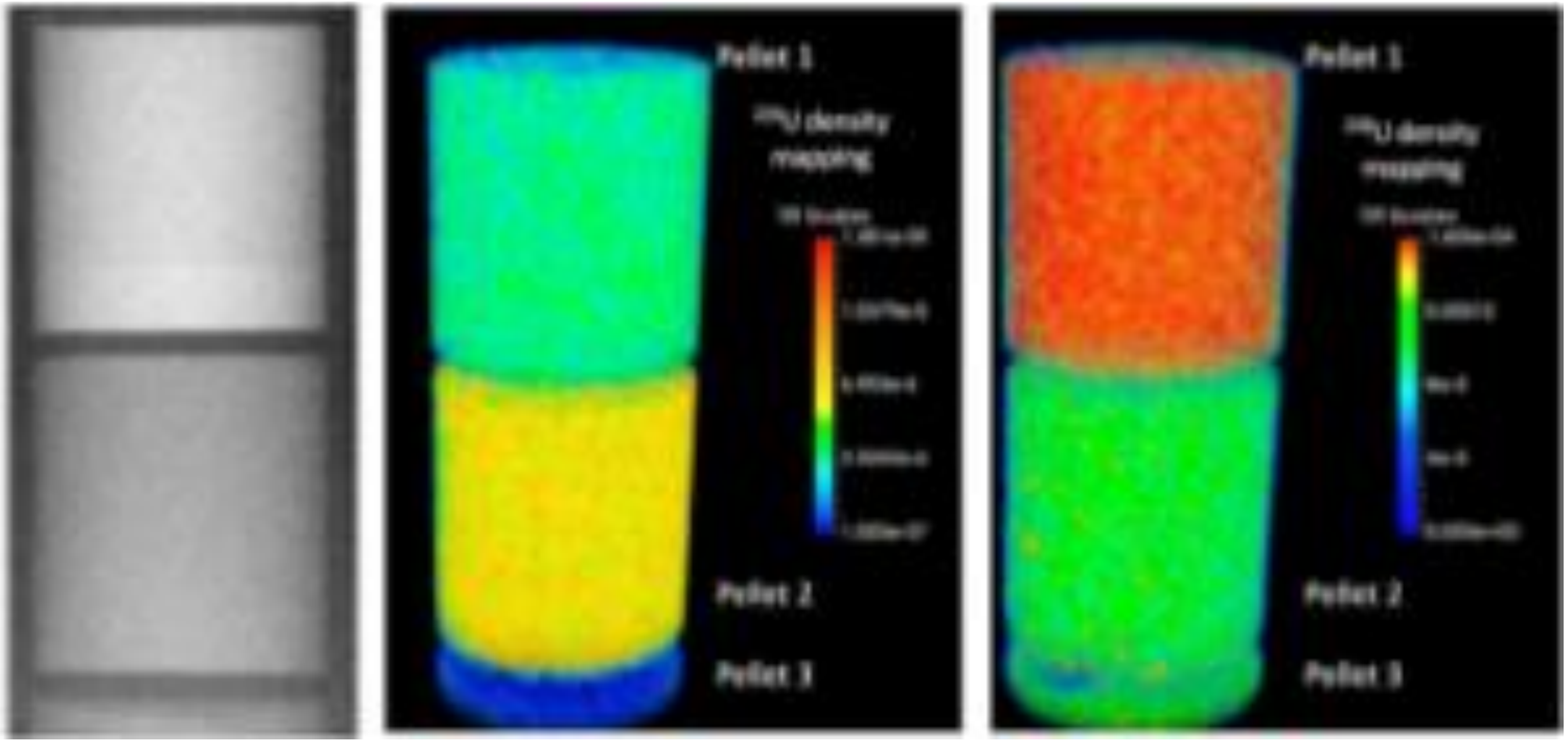
Burn up nuclear fuel





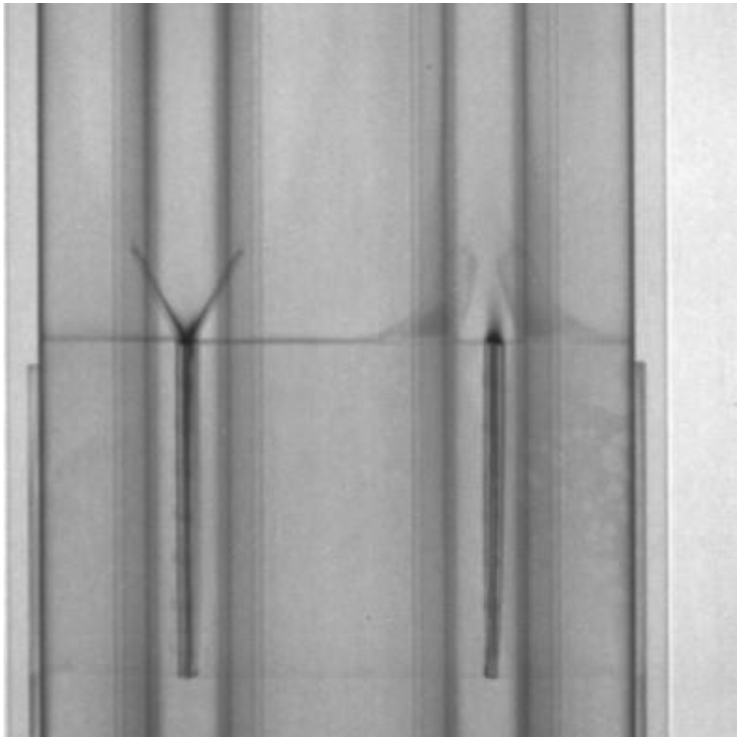
Lehmann E H, et al., Nucl. Instrum. Methods Phys. Res. A (2003)

Nuclear Fuels

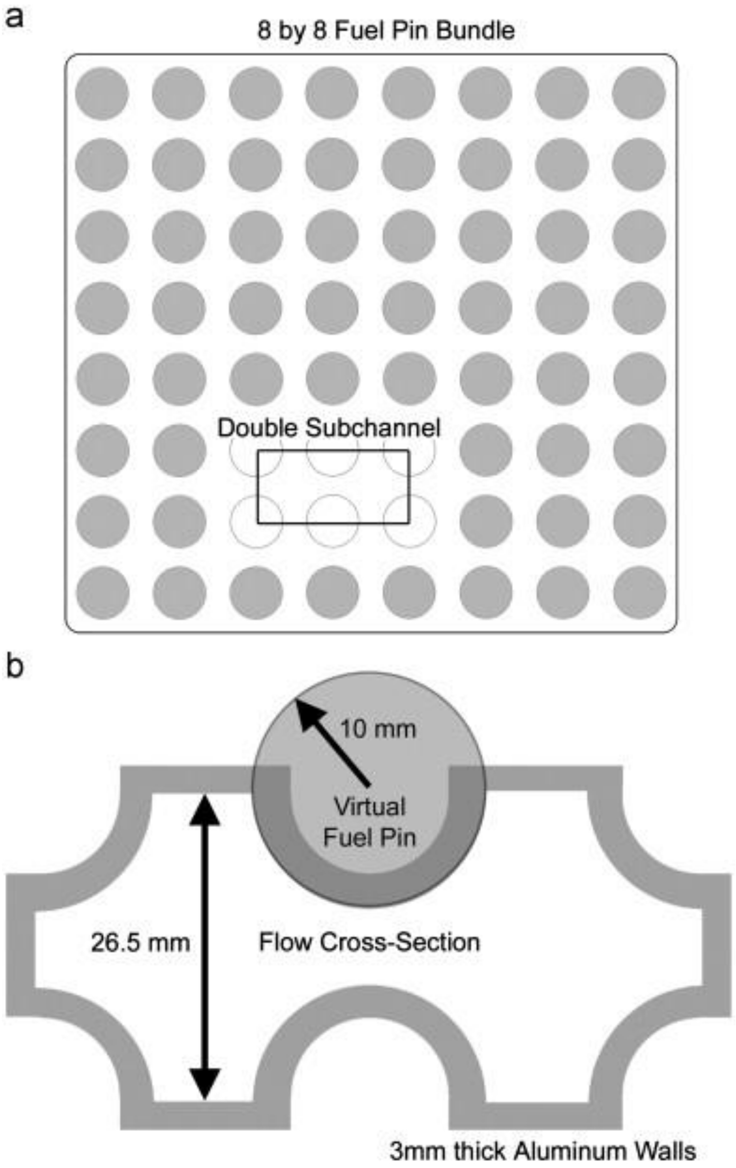


Vogel S C et al 2022 Progress report on mockup irradiation capsule fuel measurements at LANSCE Technical Report LA-UR-22-30854 Los Alamos National Laboratory (LANL)

Application: coolant flow in reactor core

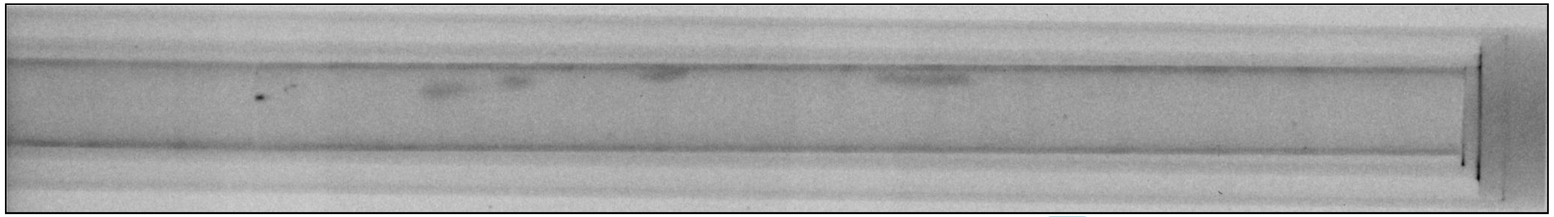


J.L. Kickhofel NIMA 2011



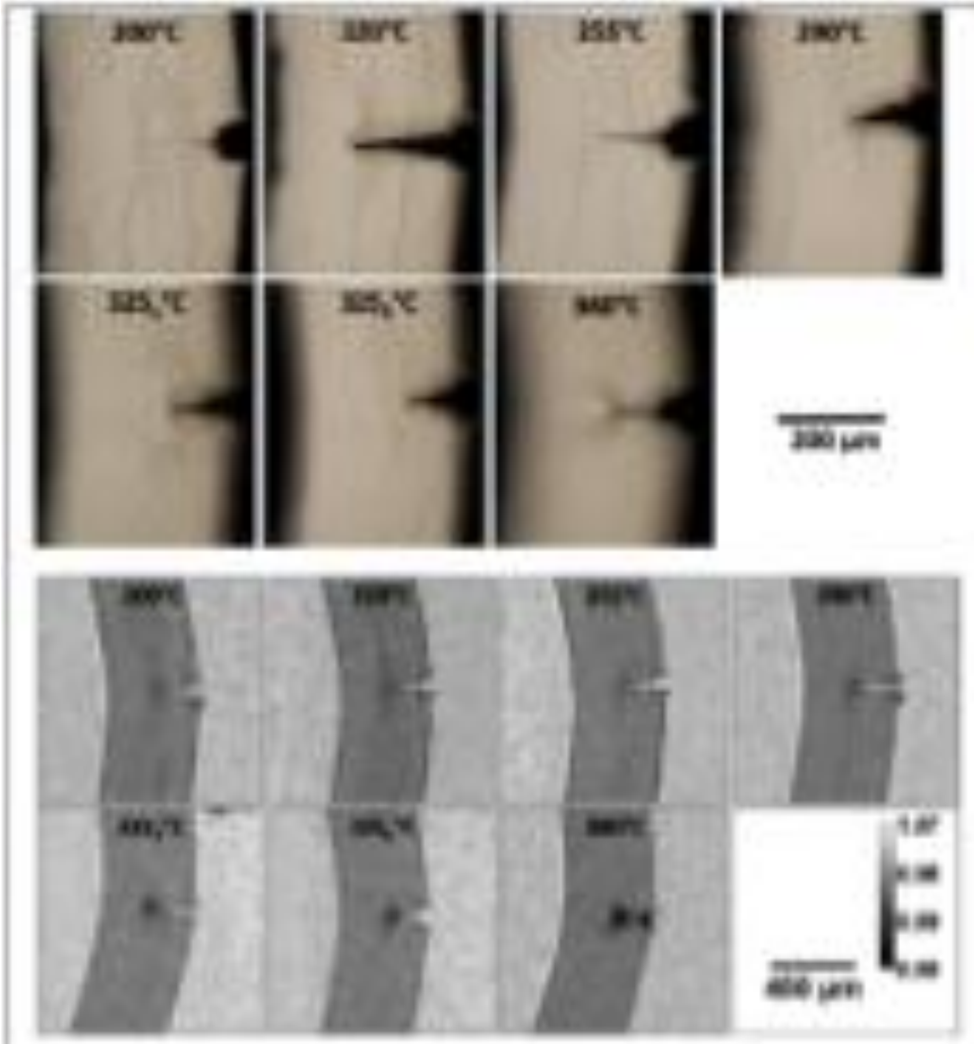
Nuclear Fuel claddings

Zircaloy cladding only: ZrH_2 blisters



Nuclear Fuel claddings and hydrogen cracking

Grosse M 2015 Neutron News 26



Colldeweih A W, et al, 2022 J. Nucl. Mater. 561

Methodical advances for tackling societal challenges/energy

Pushing technological limitations in NI

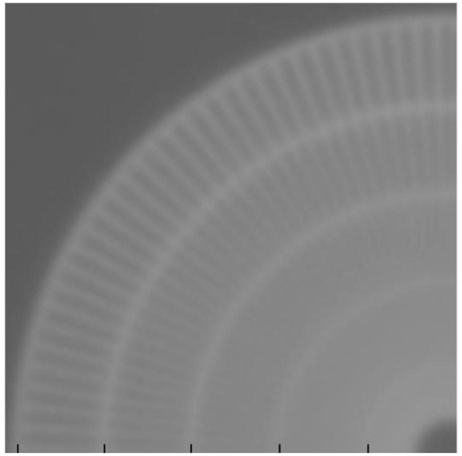
PSI

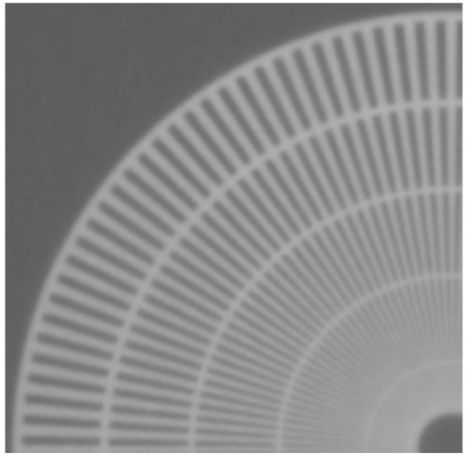
2000 - 2024

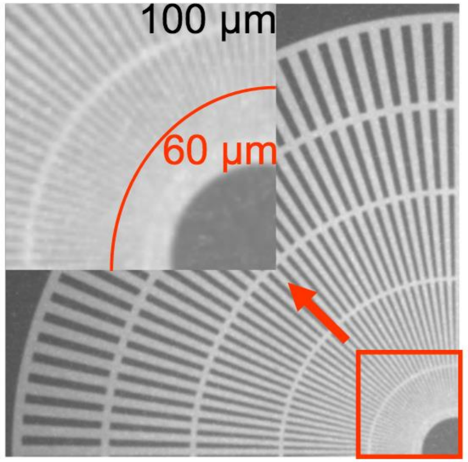
Challenging resolution

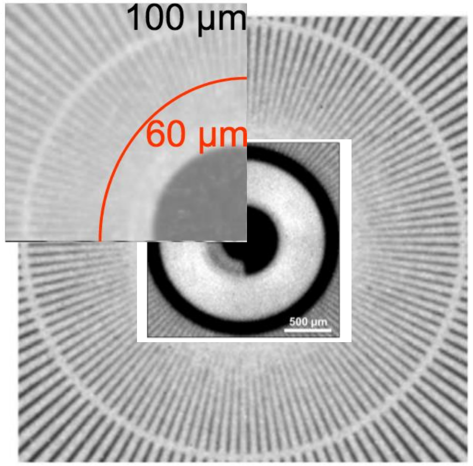
Neutron Microscope Dete
^{157}Gd scintillator

P. Trtik et al., J . Phys 2016



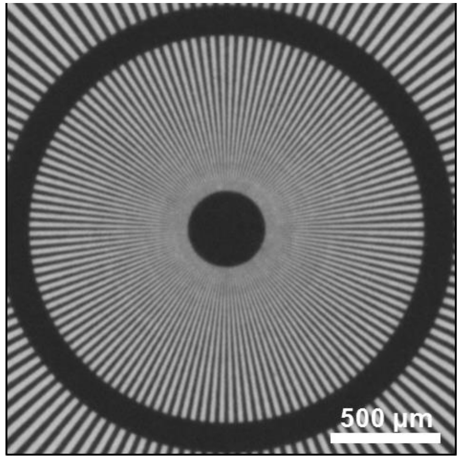






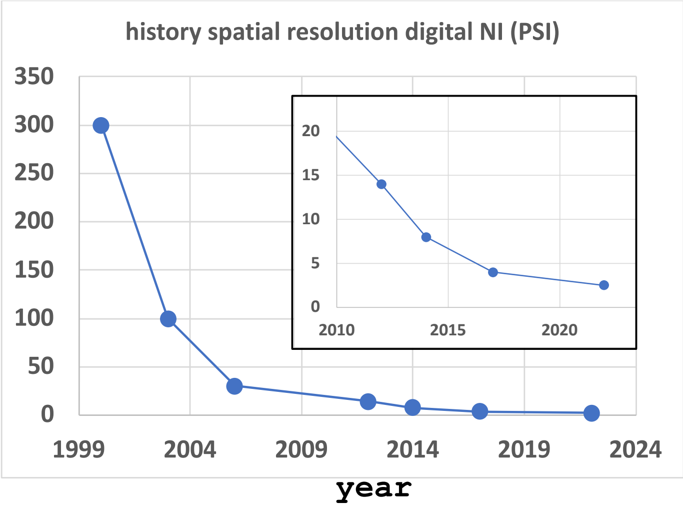
2 mm

13.5 µm pixel size



2 mm

1.3 µm pixel size

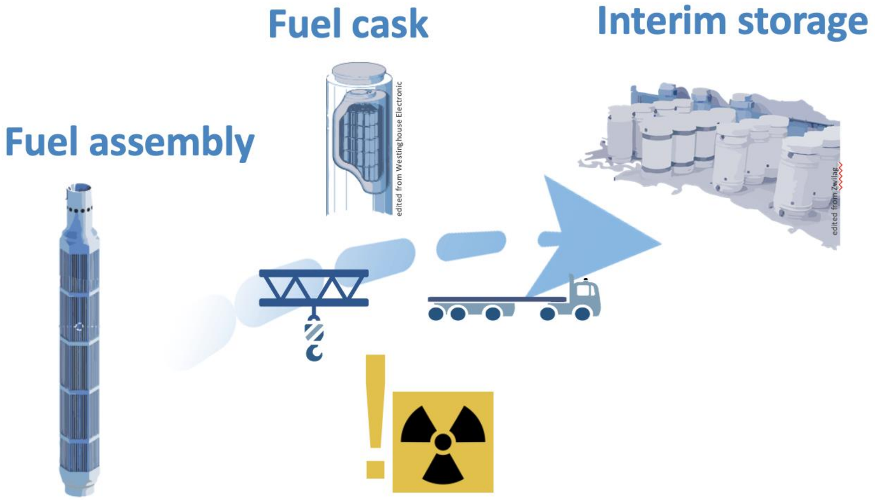


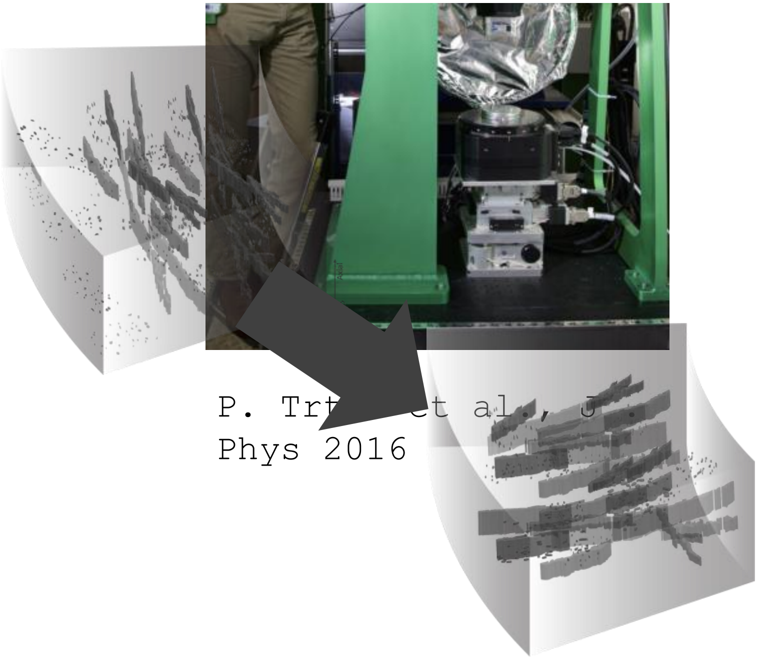
How we plug things: Nuclear

Pushing technological limitations in NI

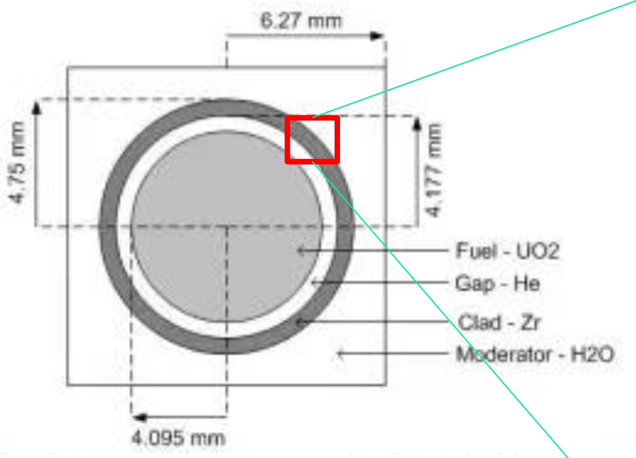
PSI

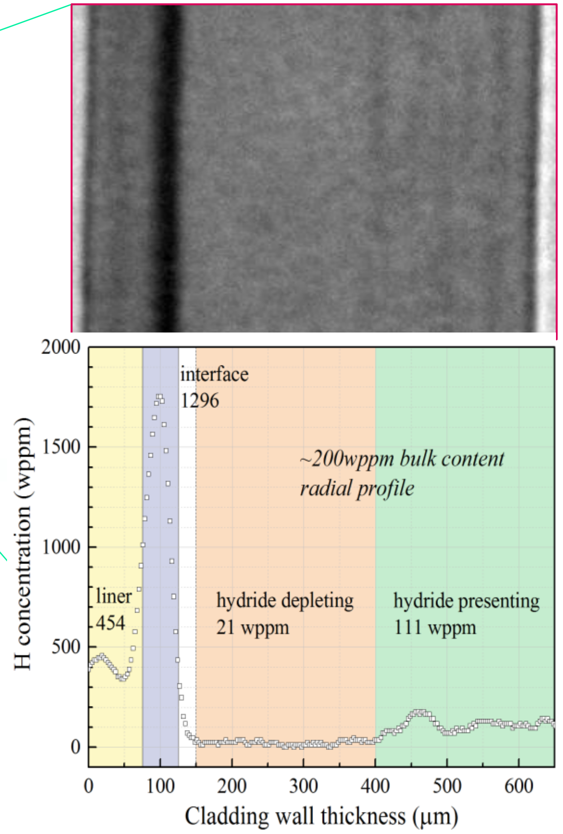
:or





P. Tr… et al., J
Phys 2016





How we plug things: Nuclear

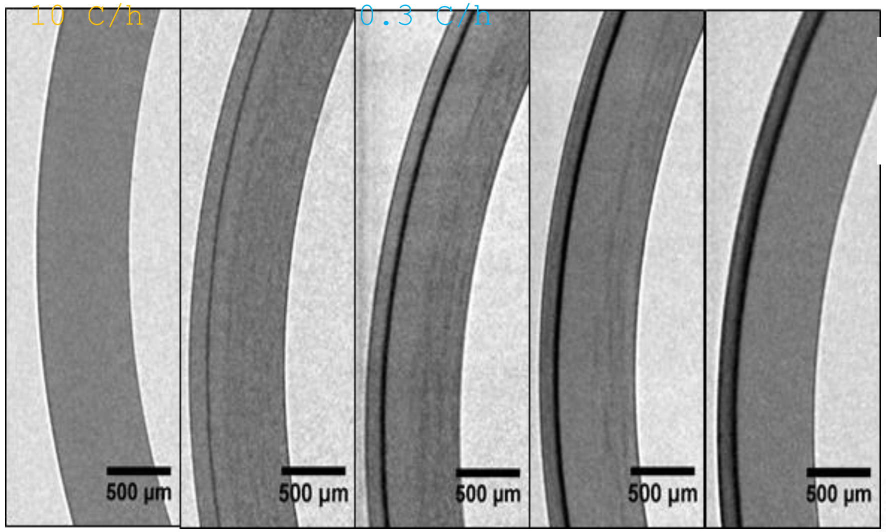
Quench.

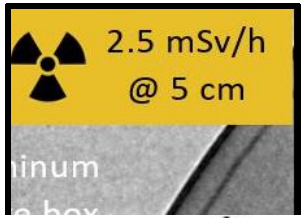
100 C/h

30 C/h

10 C/h

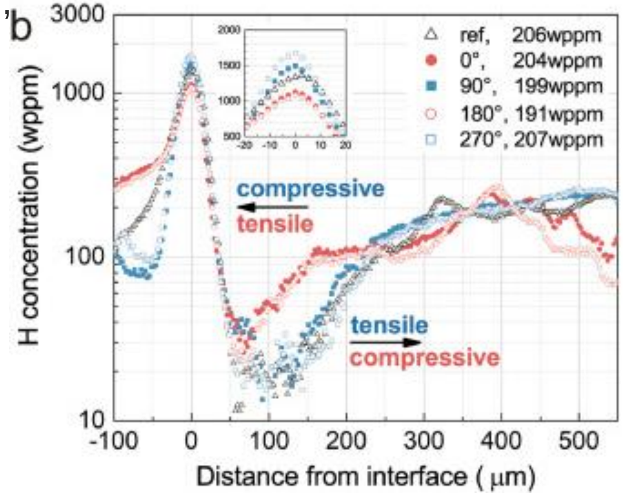
0.3 C/h

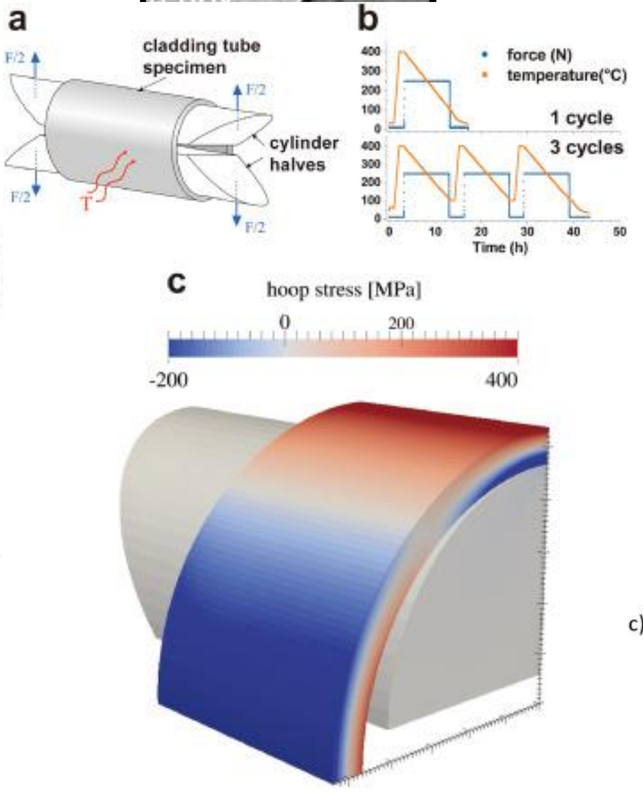


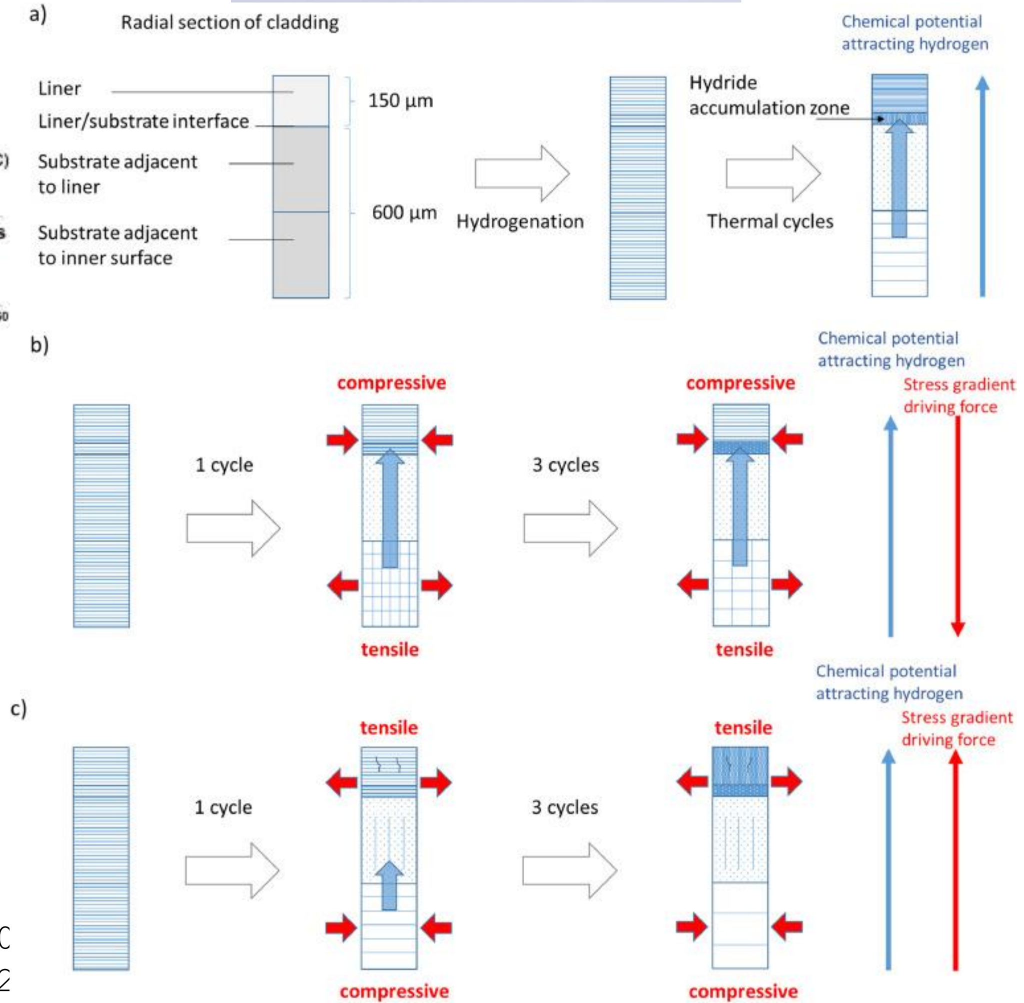


Zircaloy-4 (Zr-4), liner for improved corrosion resistance,

-Sn,





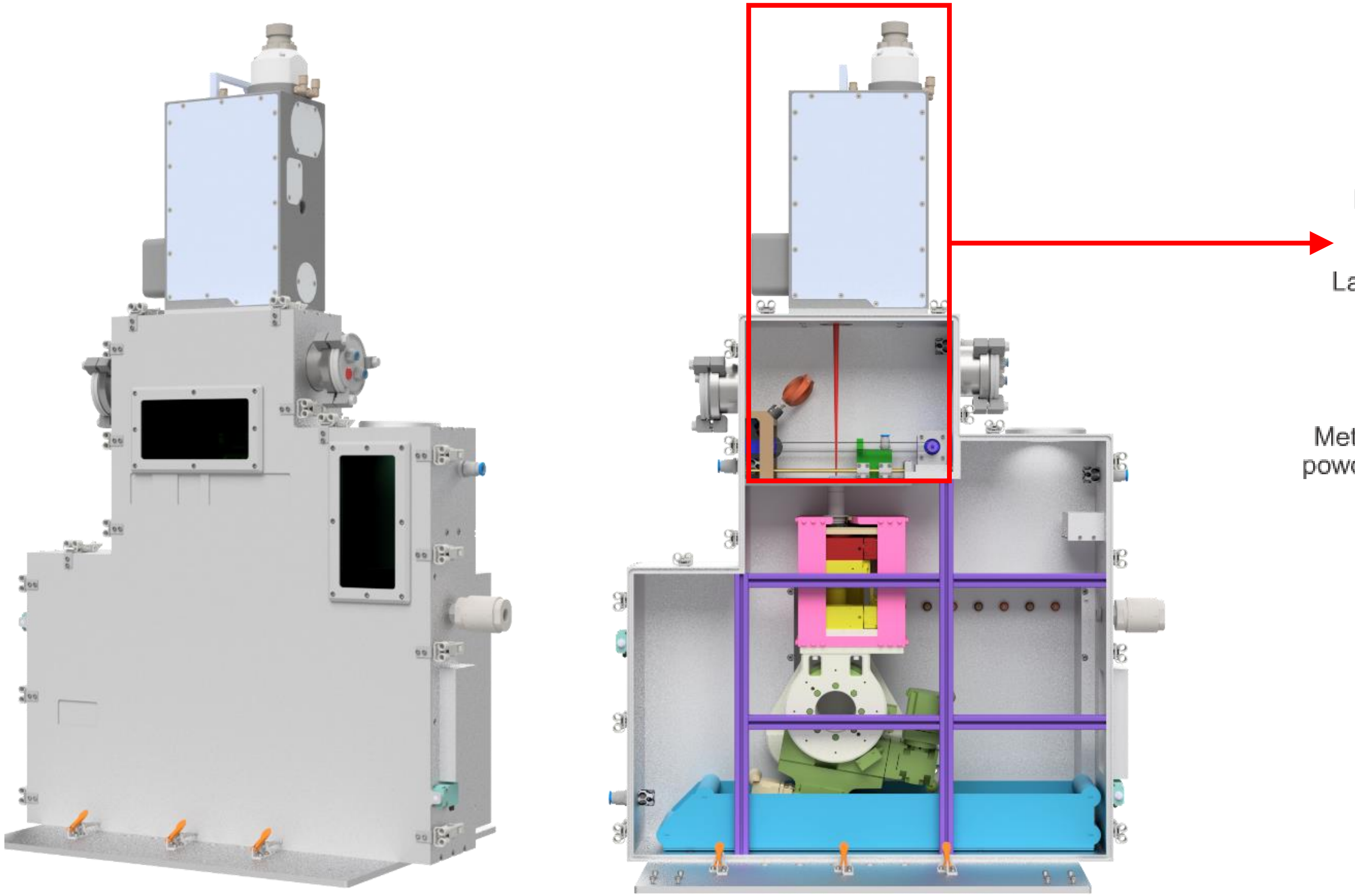


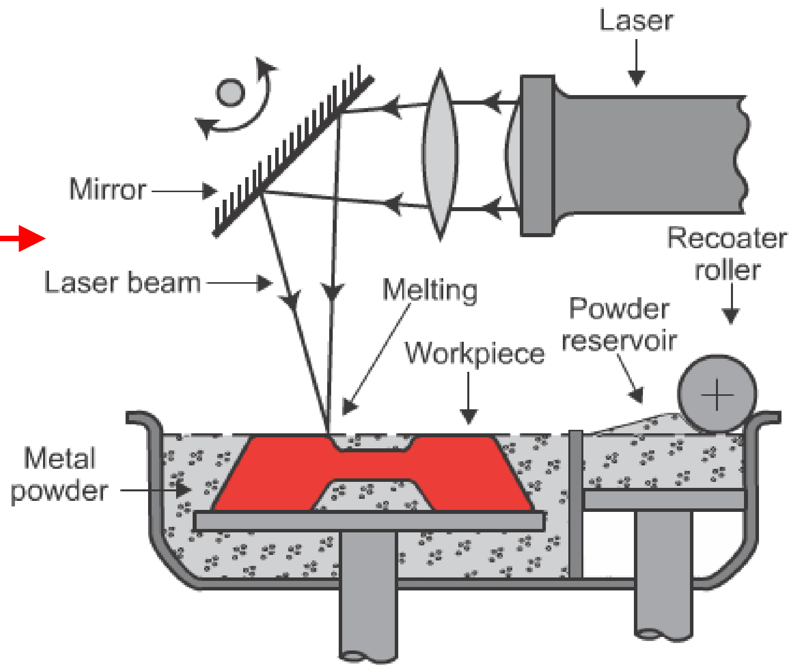
W. Gong et al., J Nucl Mat 20

O. Yetic et al., J Nucl Mat 2

Additive Manufacturing (AM) for Nuclear applications

Operando neutron-SLM machine

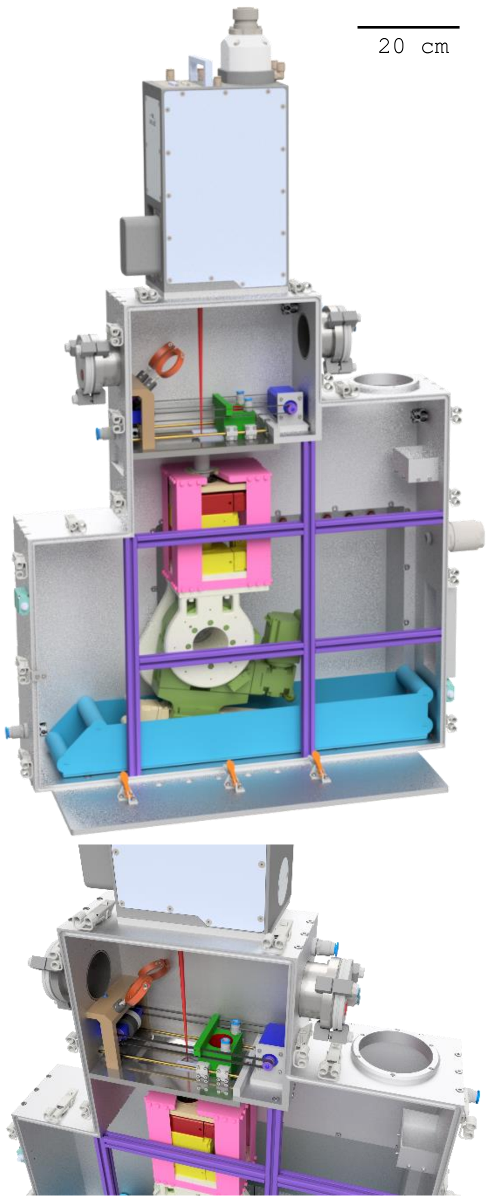


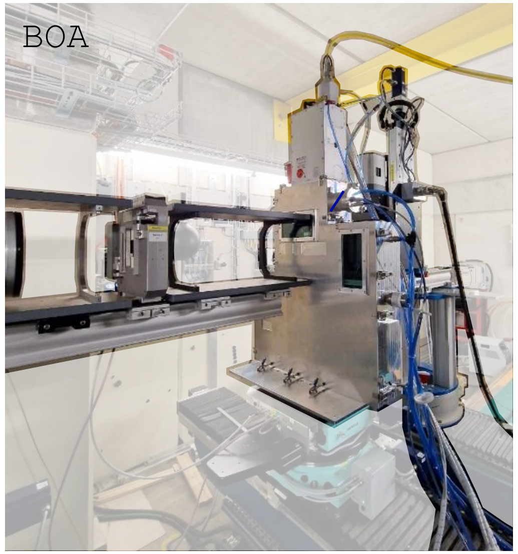


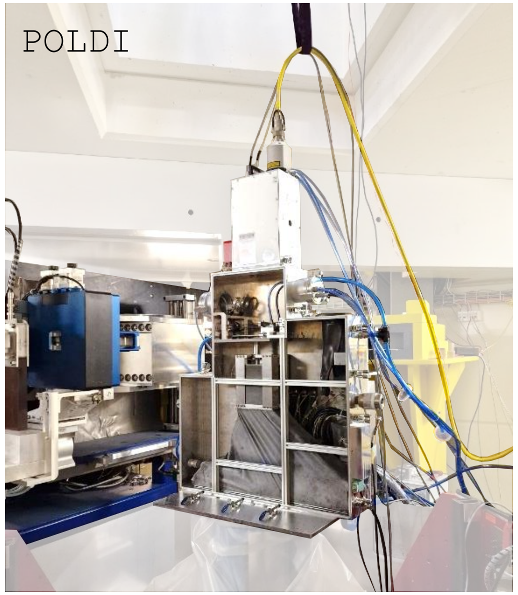
ADDITIVE MANUFACTURING

S. Sumarli et al., ADDMA (2025)

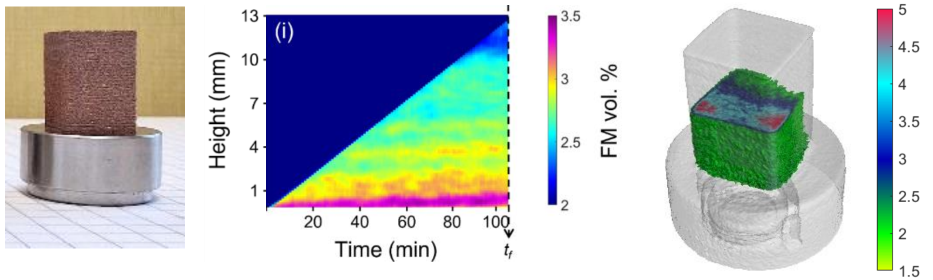
AM: Operando nSLM





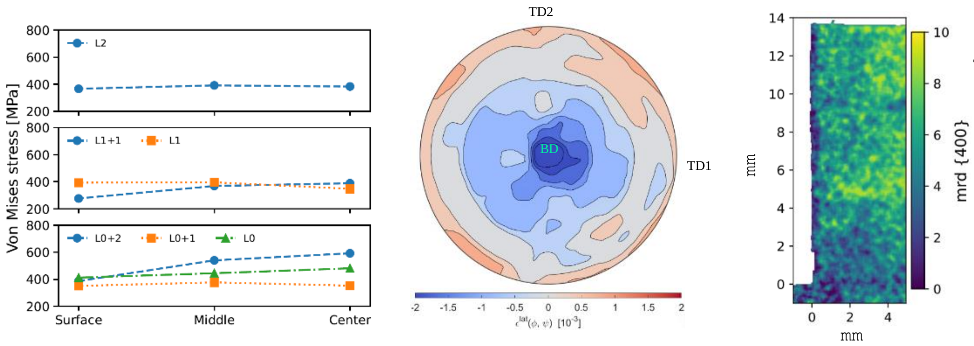


RESULTS



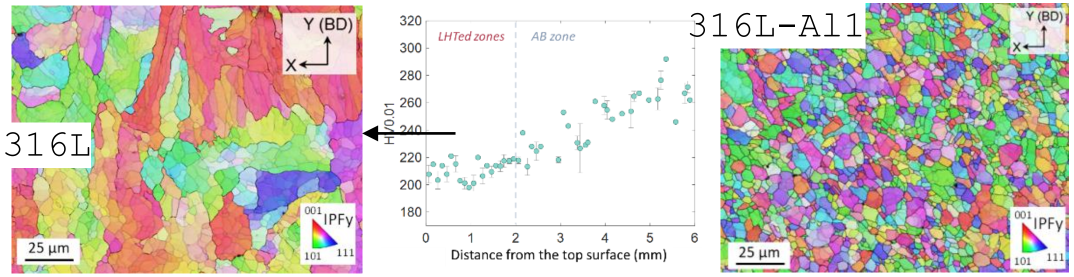
316L + CuCrZr

S. Sumarli et al., Phys.& Virt. Protot. (2024)



DSS 2205

S. Gaudez et al., Mat & Des (2025)



316L

316L-Al1

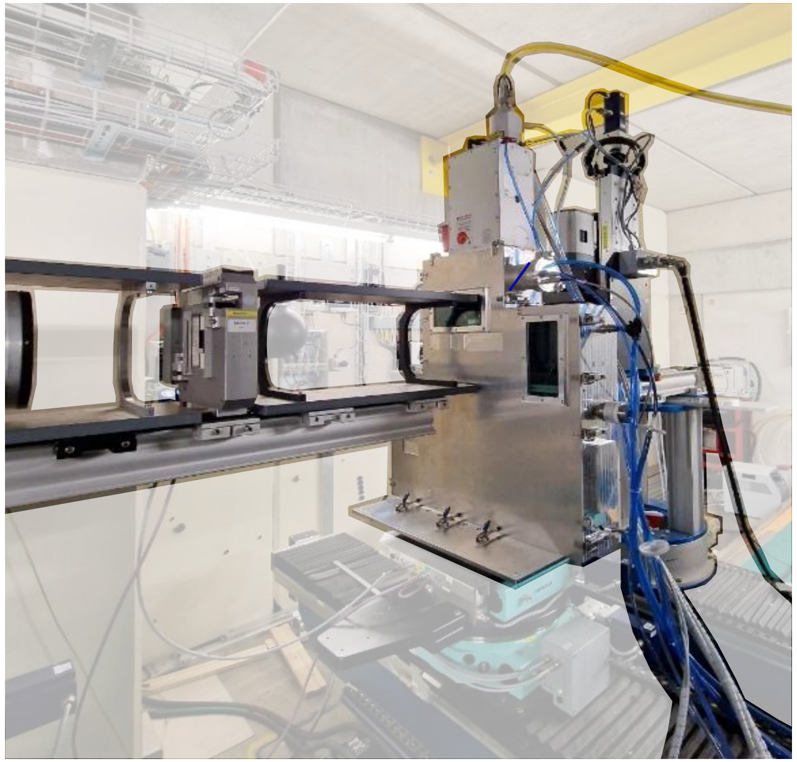
C. Navarre, *Mat & Design* (2025)

materials DESIGN

AM Laboratory @ AMG/PSI

PSI

LPBF

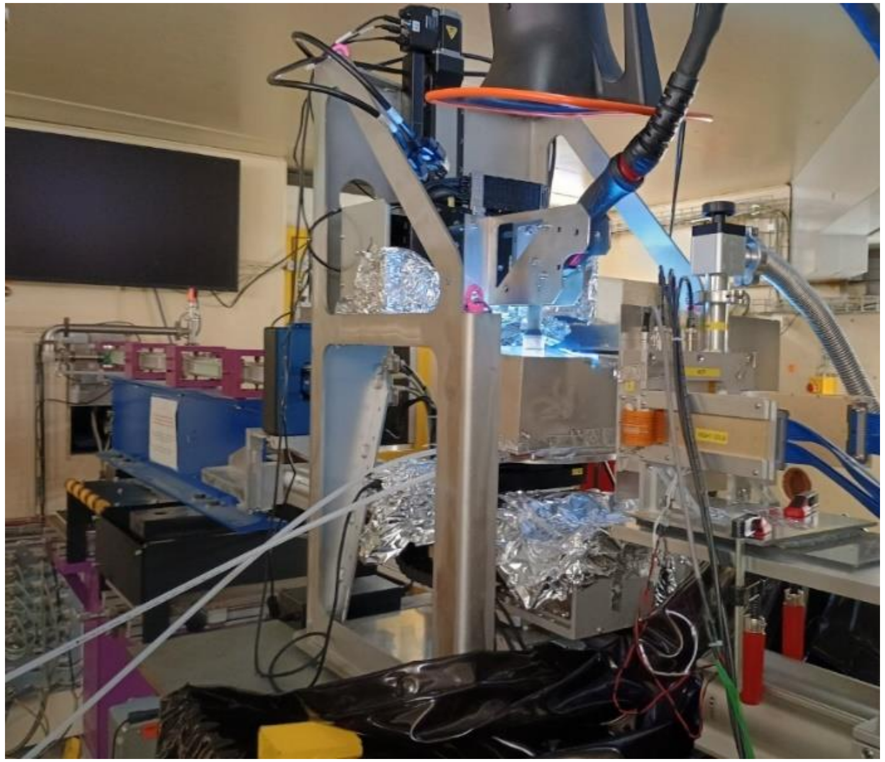


nSLM

WAAM

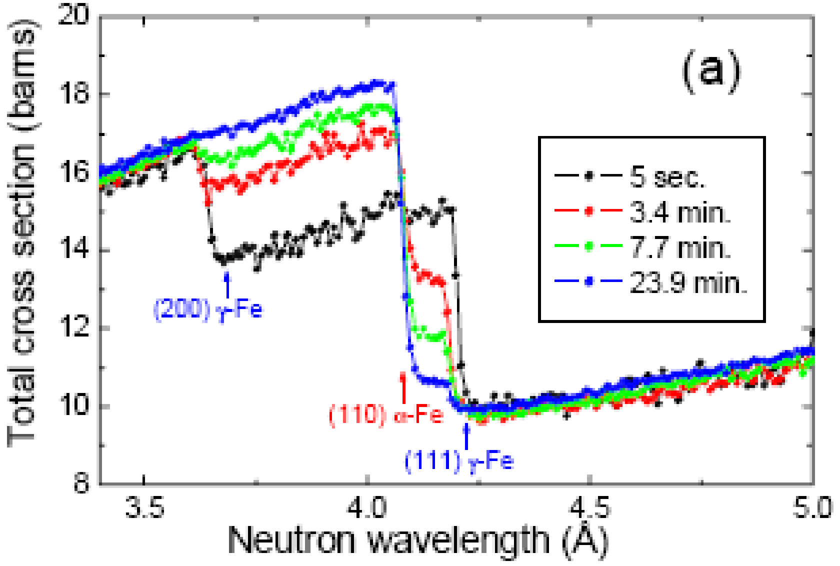
CNC-WAAM

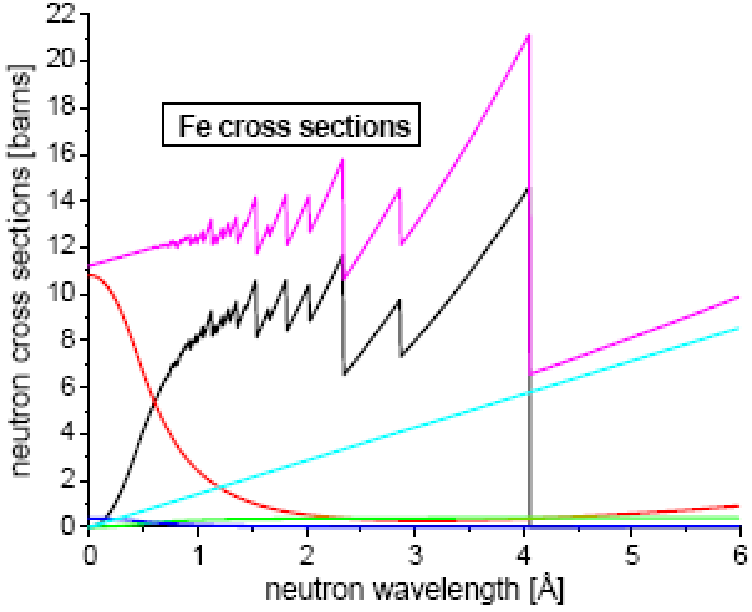
DED

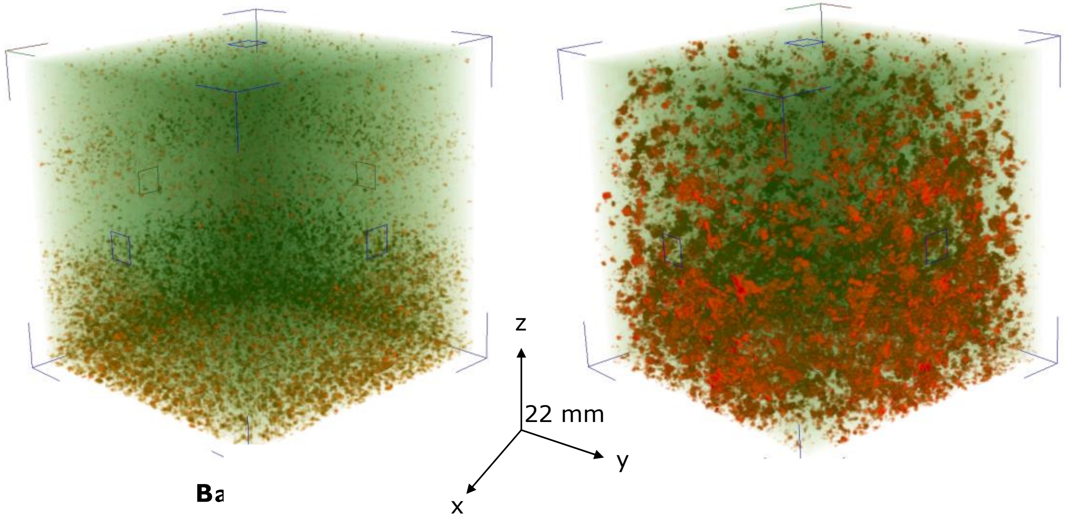


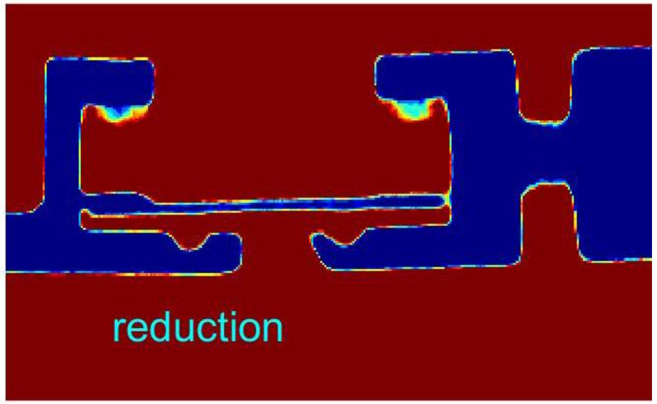
MADISON

Bragg edge





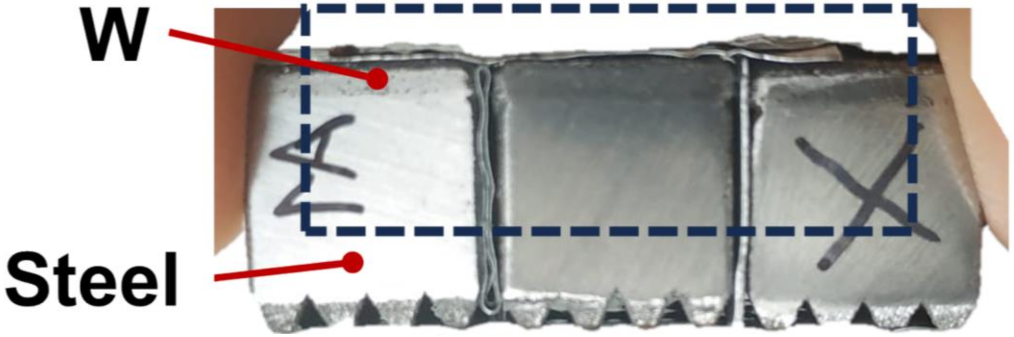


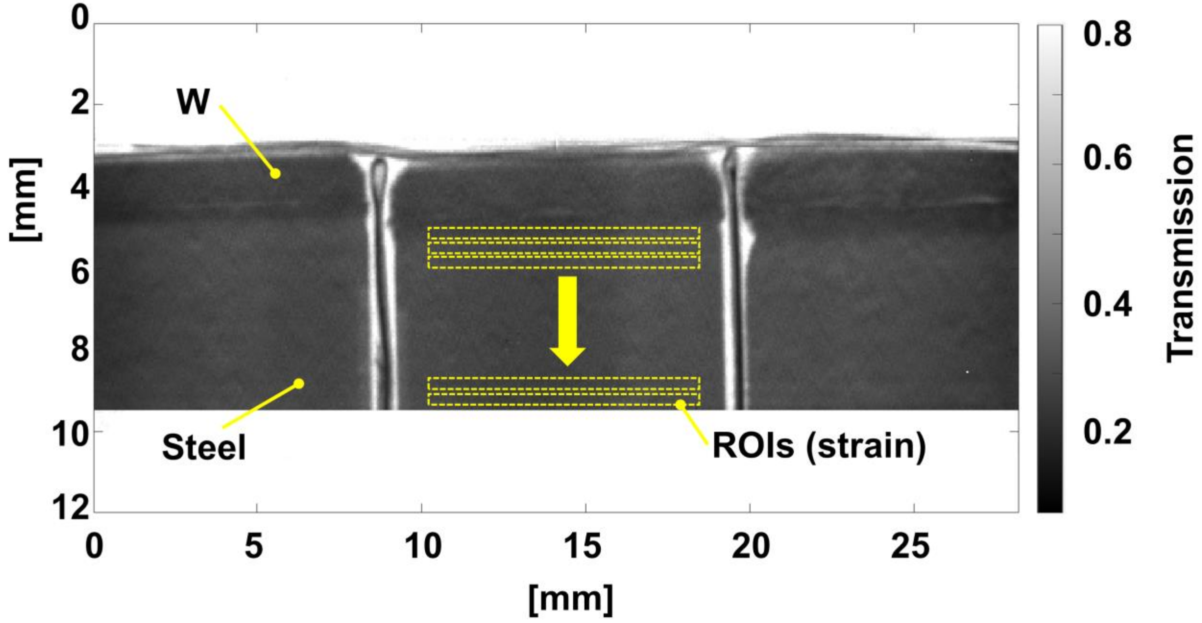


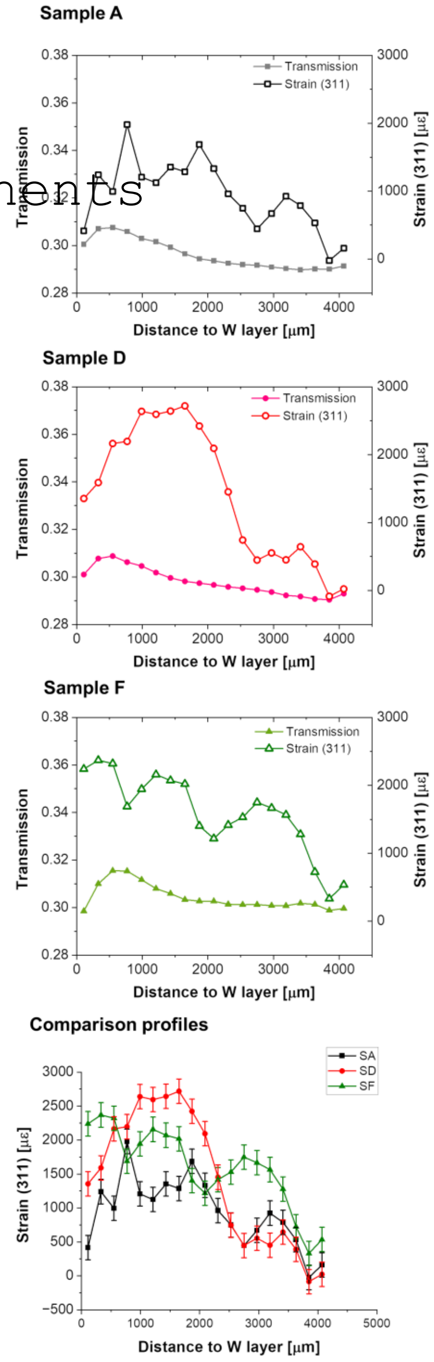
M. Markowska et al.,J. Power Sources 340 (2017)

AM in Nuclear: Eaxmple Fus

breeding blanket, diverter, plasma facing components
→ additive manufacturing



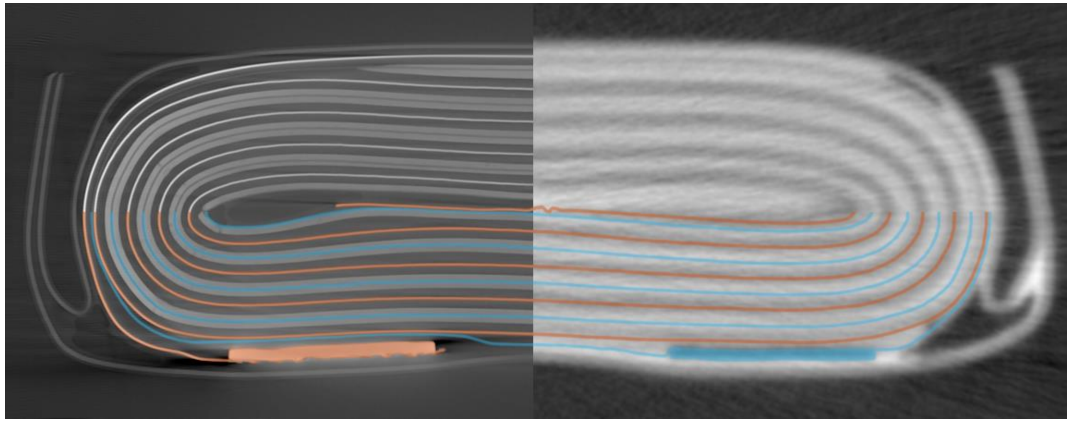




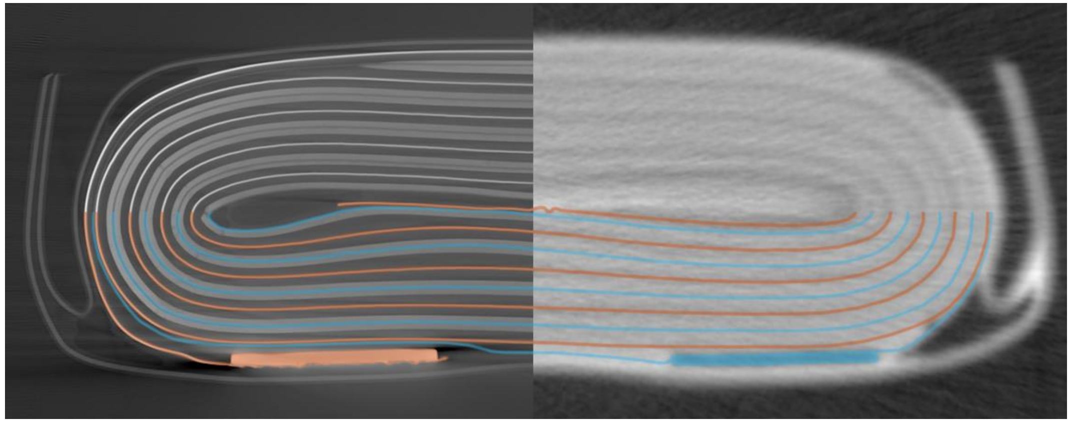
Batteries

Bi-modal n/x tomography

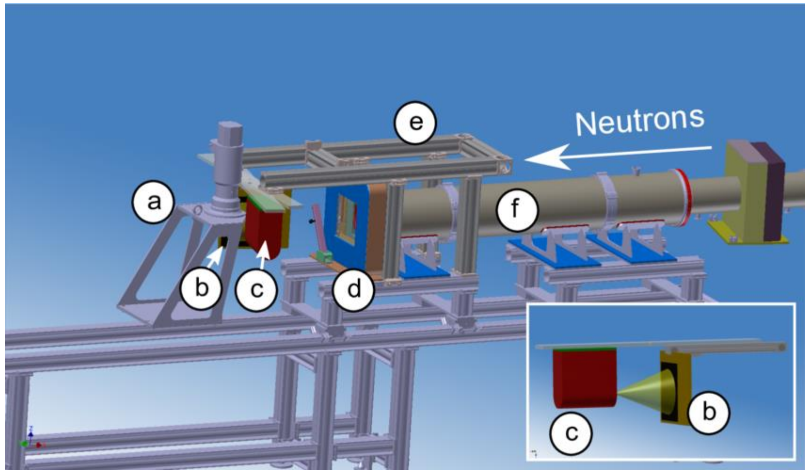
discharged



charged



N/X bimodal tomography

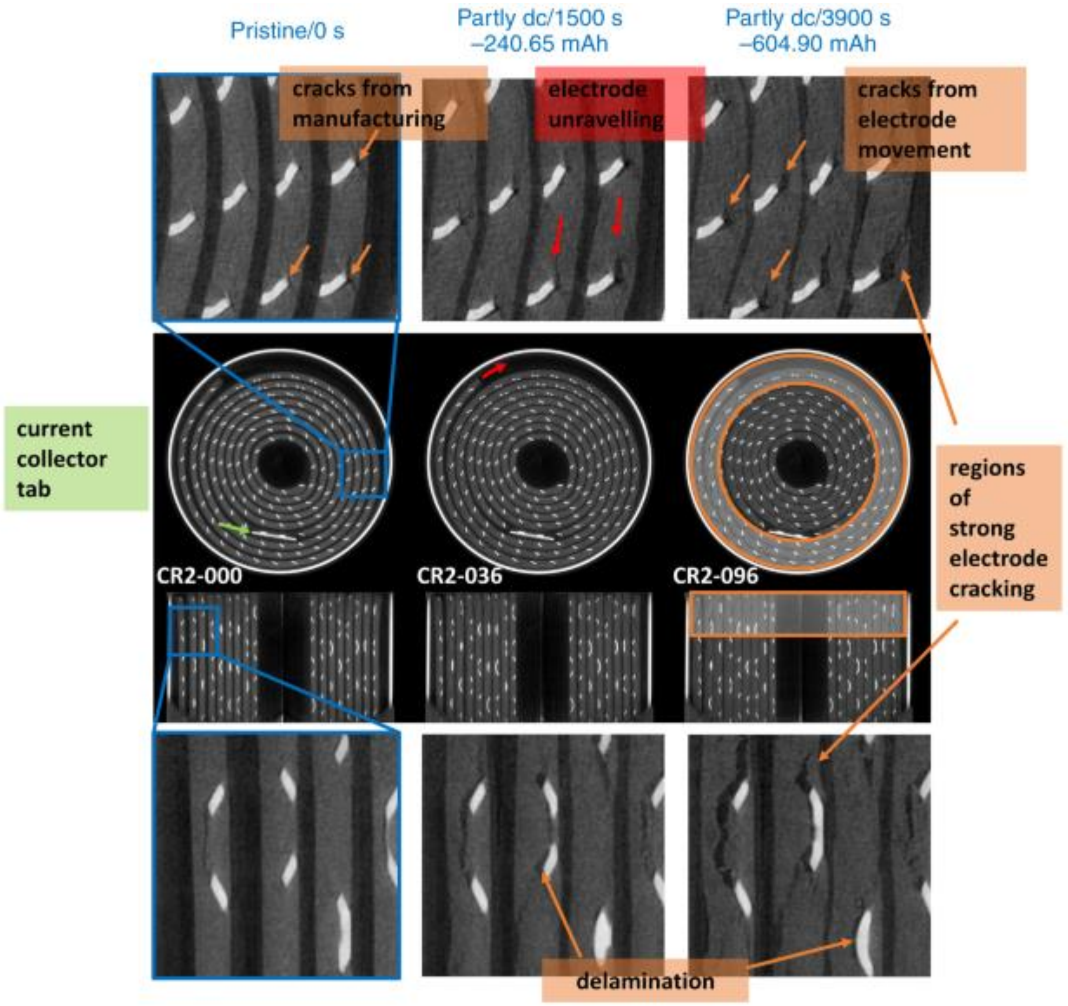


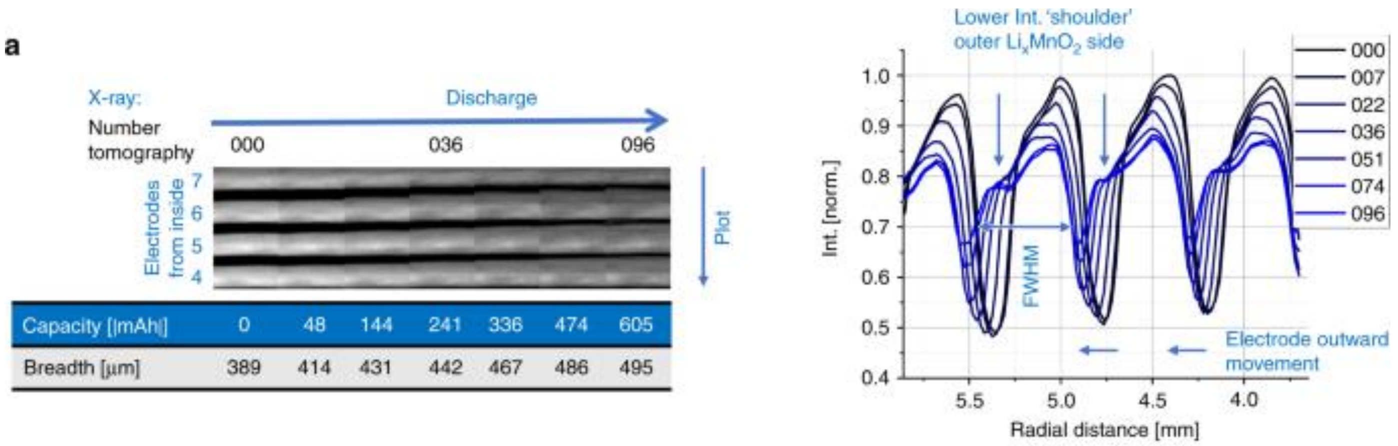
A. Kaestner et al., Physics Procedia 88 (2017)

https://www.ndt.net/events/DIR2015/Paper/58_Kaestner.pdf (2015)

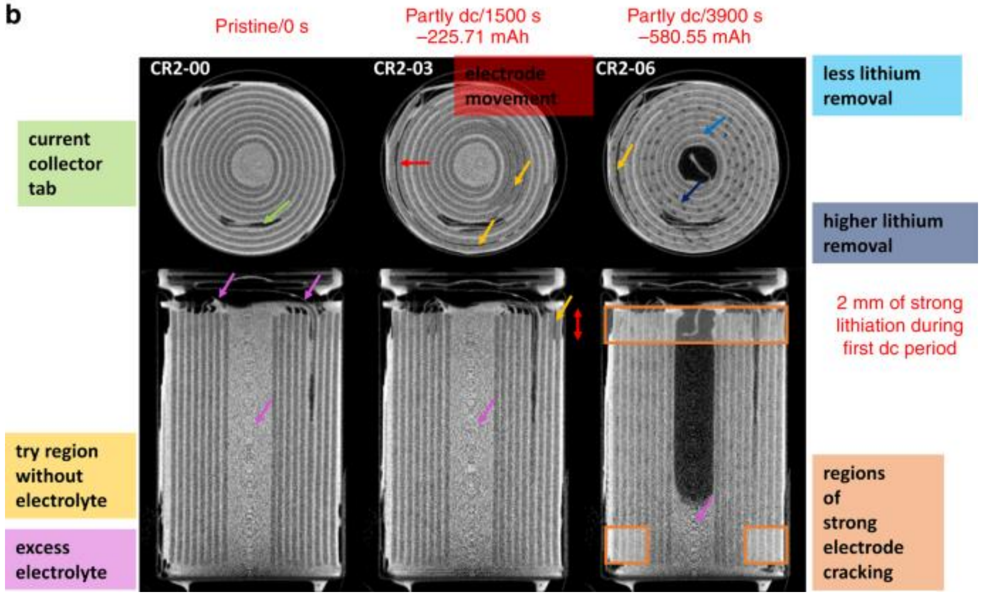
P. Boillat, C. Gruenzweig, D. Mannes et al. PSI 2016

Bi-modal n/x tomography





Ziesche, R.F et al.,*Nat Commun* **11**, 777 (2020)

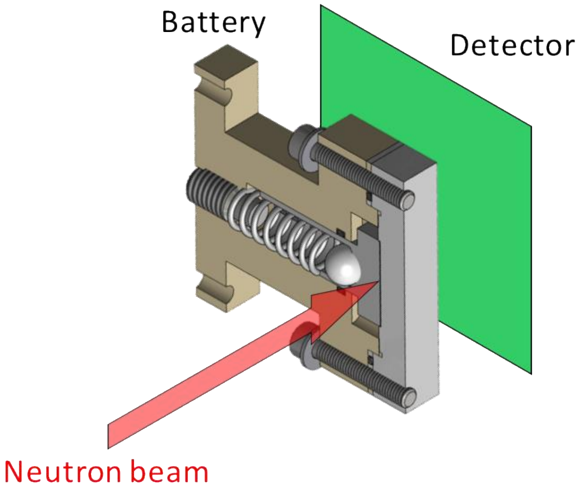


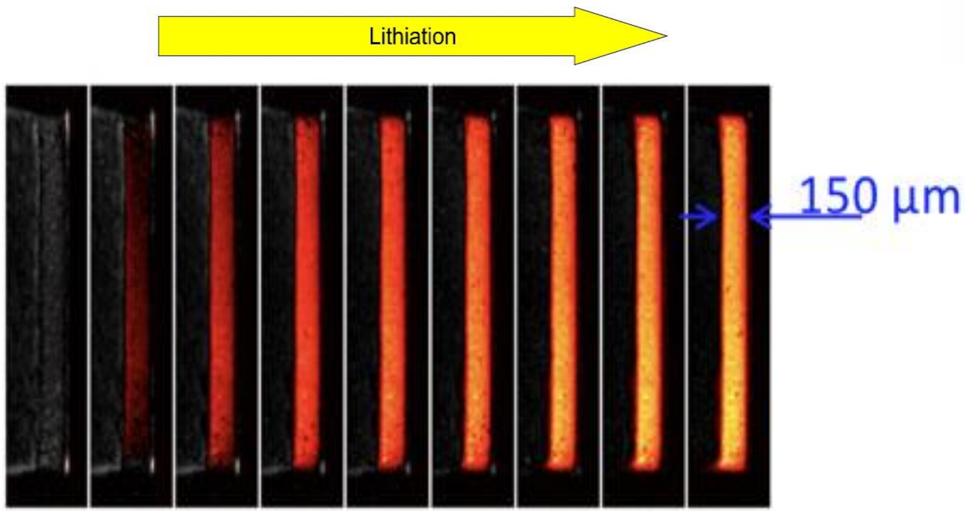
Operando spatially resolved electrode lithiation

PSI

- Contrast enhancement by use of 6Li and deuterated electrolyte

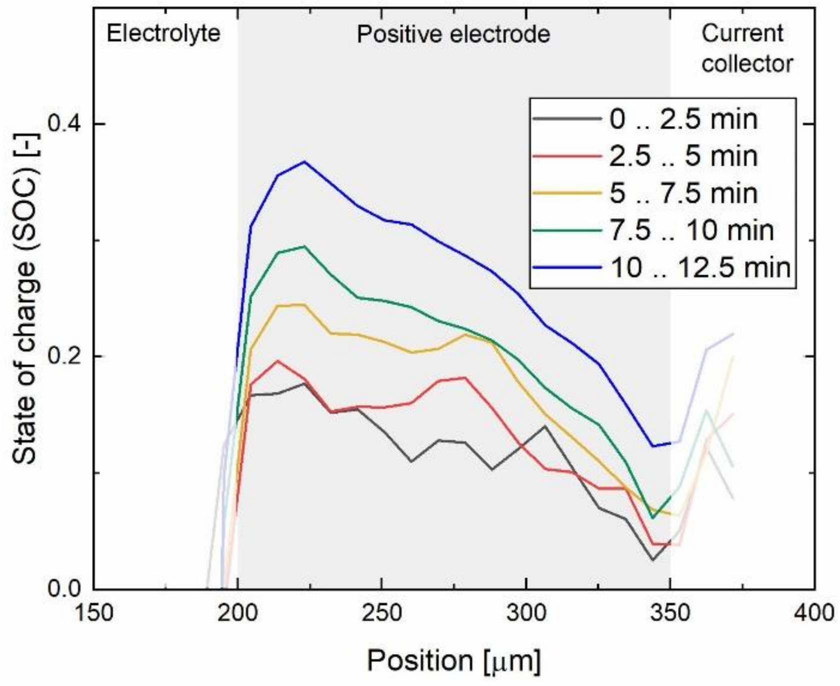
→ image SOC gradients across electrodes (resolut





Li concentration image, C/10 lithiation

Exposure time: 2.5 min



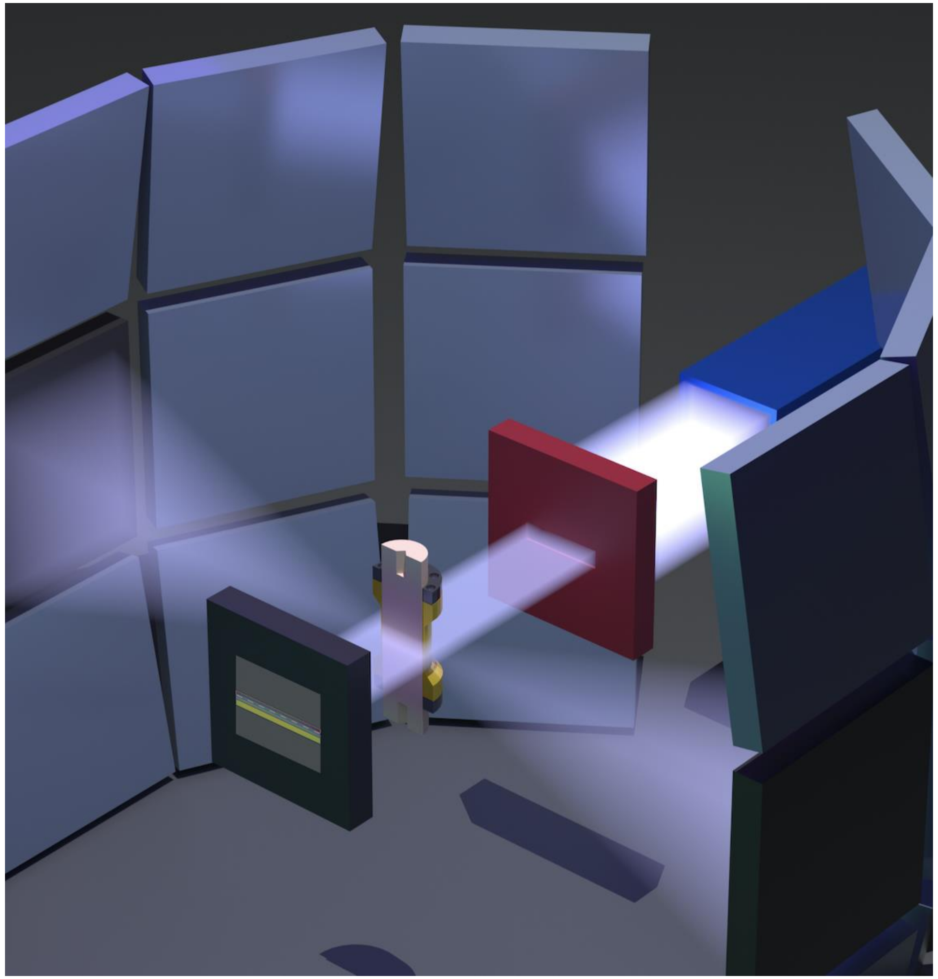
P. Boillat, C. Villevieille et al. PSI 2018

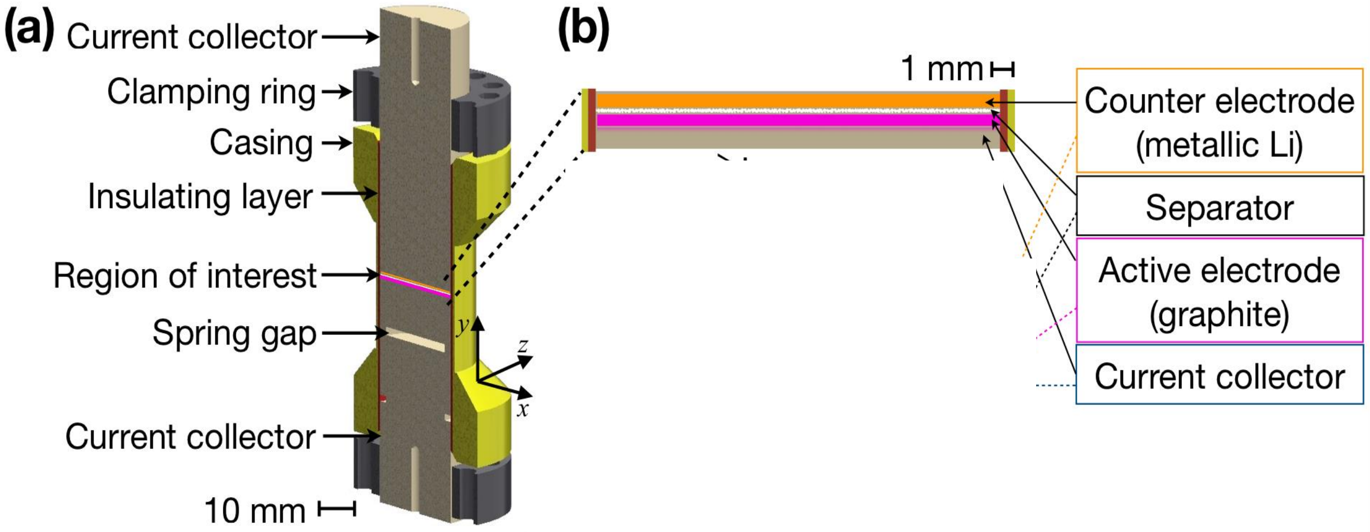
How we plug things: Batteries

Concurrent neutron imaging and diffraction

Wavelength range 2 – 6.4 Å → d-spacing range 1.7–4.4 Å

Operando charge/discharg



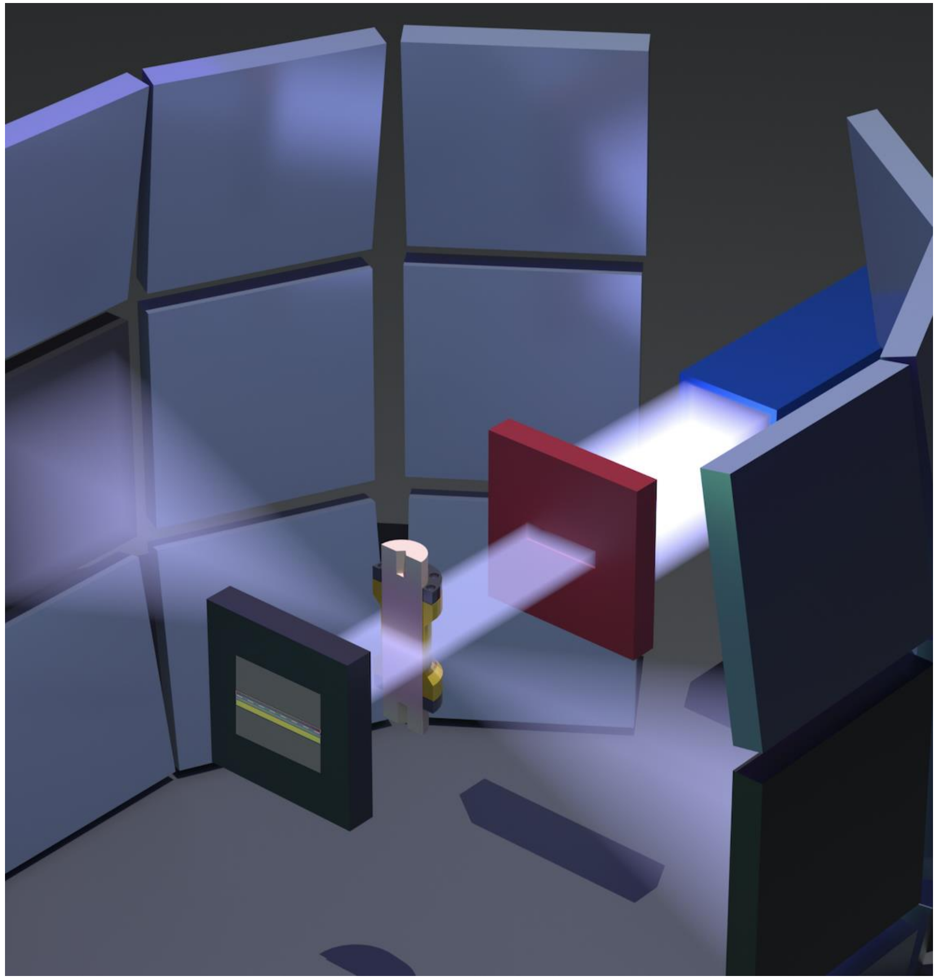


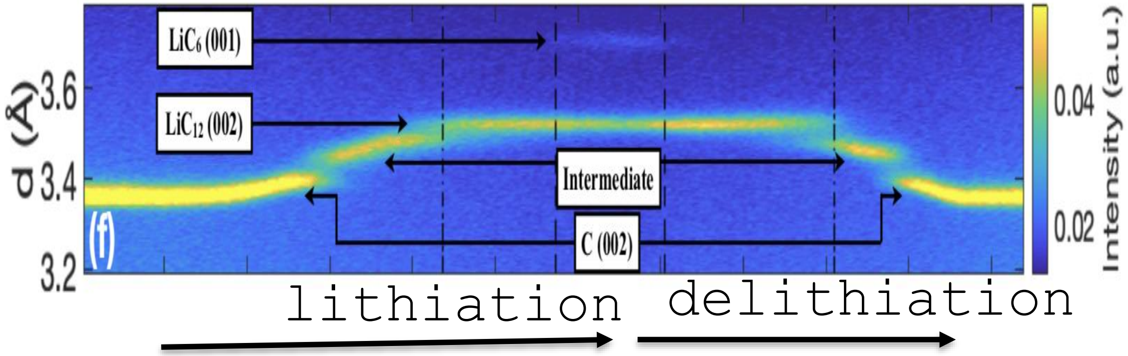
lithiation phases Li_xC_6, i.e. **C(002)**, **LiC_{12}(002)** and **LiC_6(001)** ranging between **3.35 and 3.71 Å**

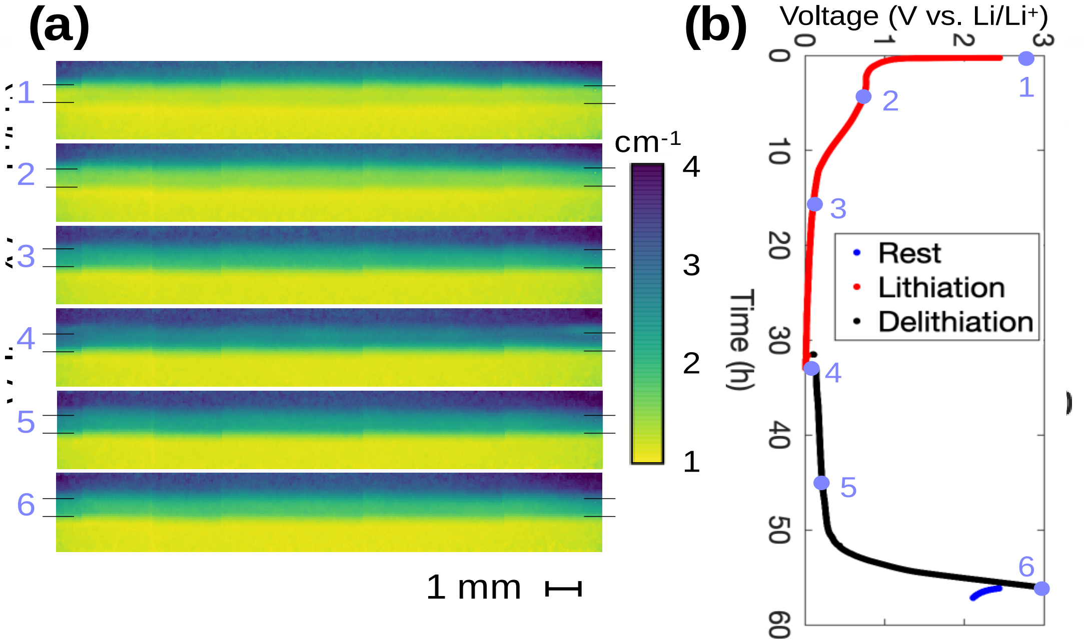
How we plug things: Batteries

Concurrent neutron imaging and diffraction

Operando charge/discharg

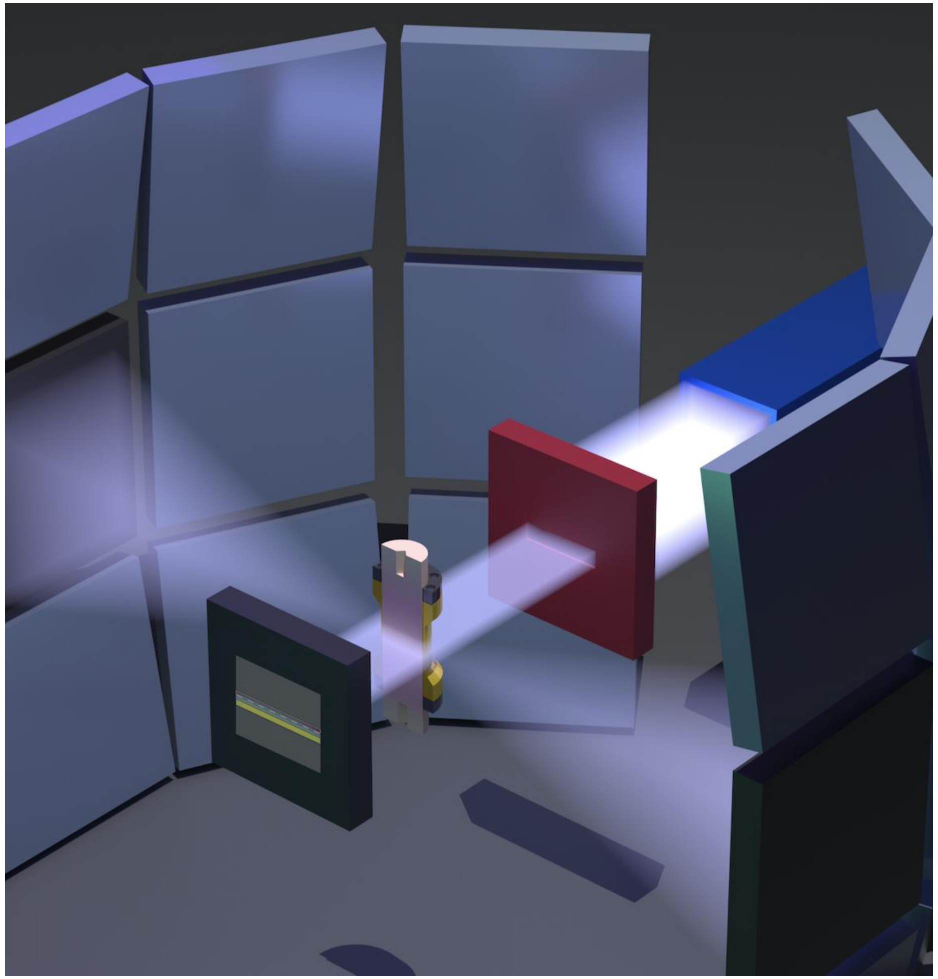


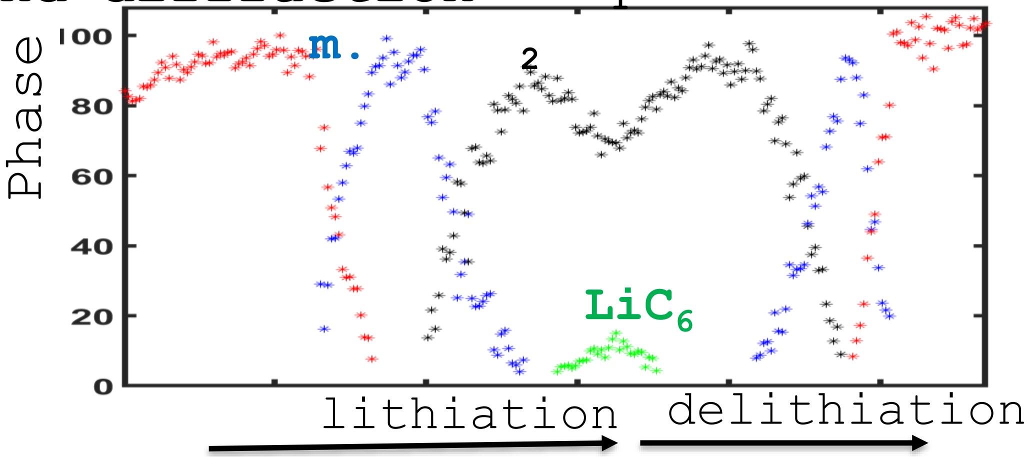


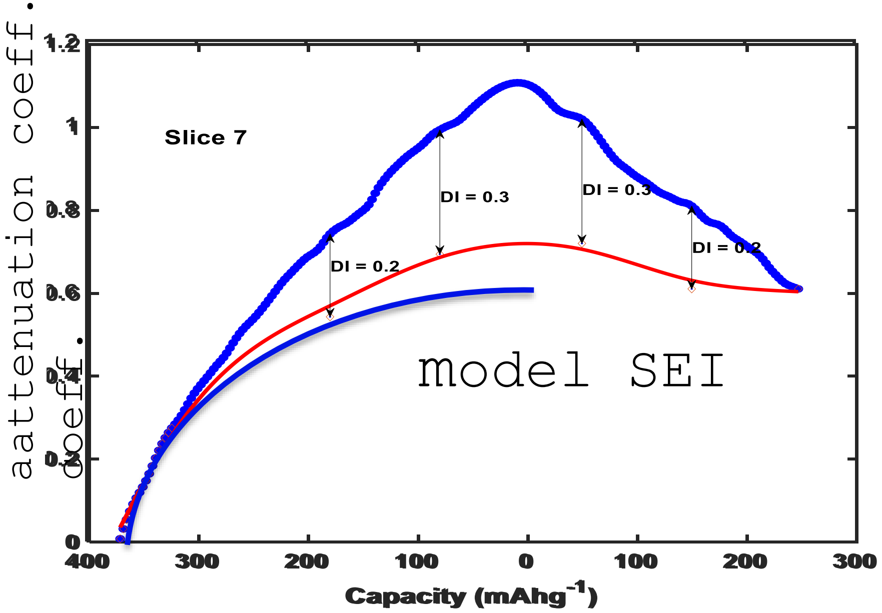


How we plug things: Batteries

Concurrent neutron imaging and diffraction

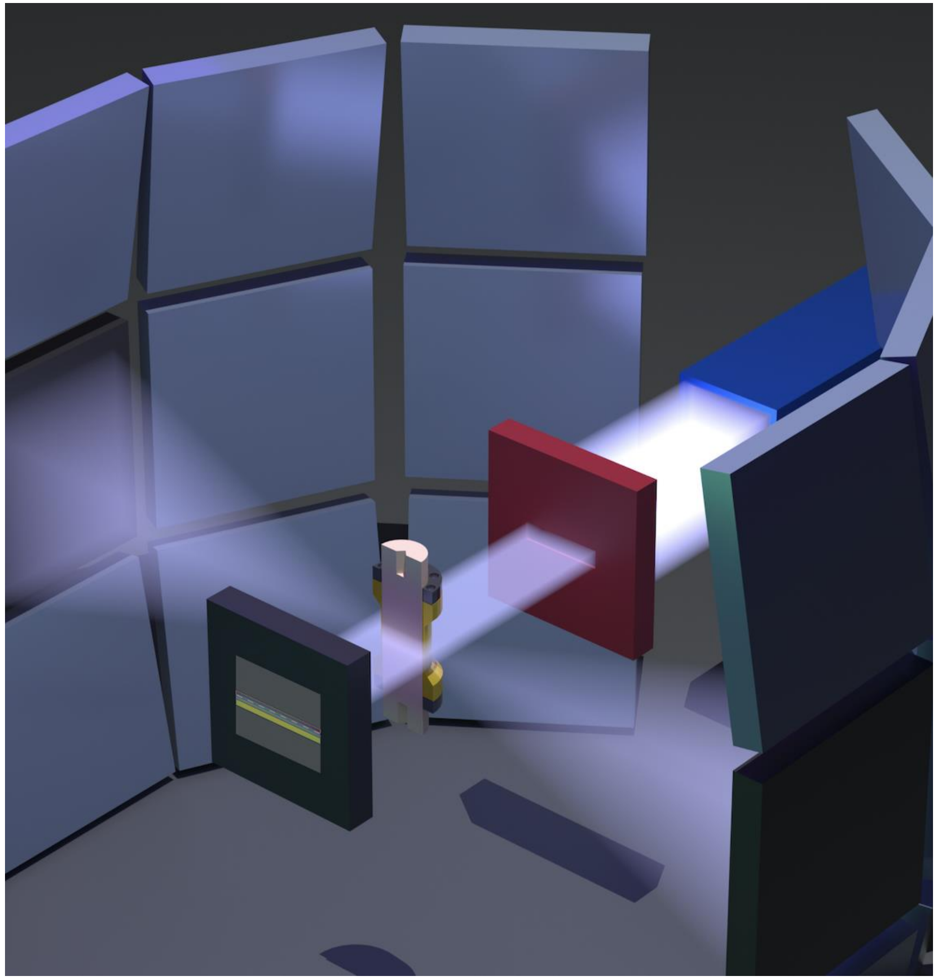


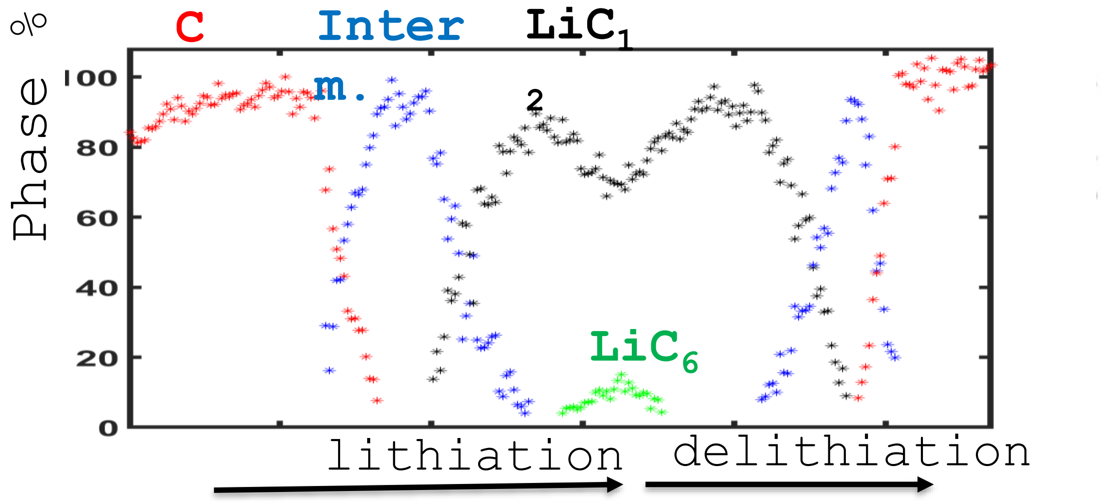


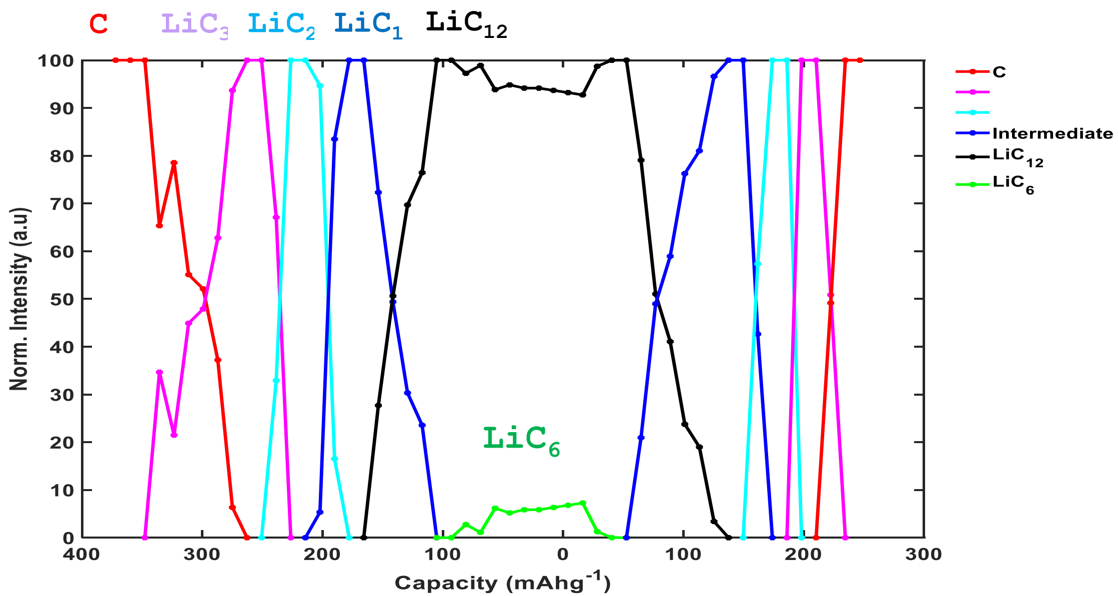


How we plug things: Batteries

Operando charge/discharge

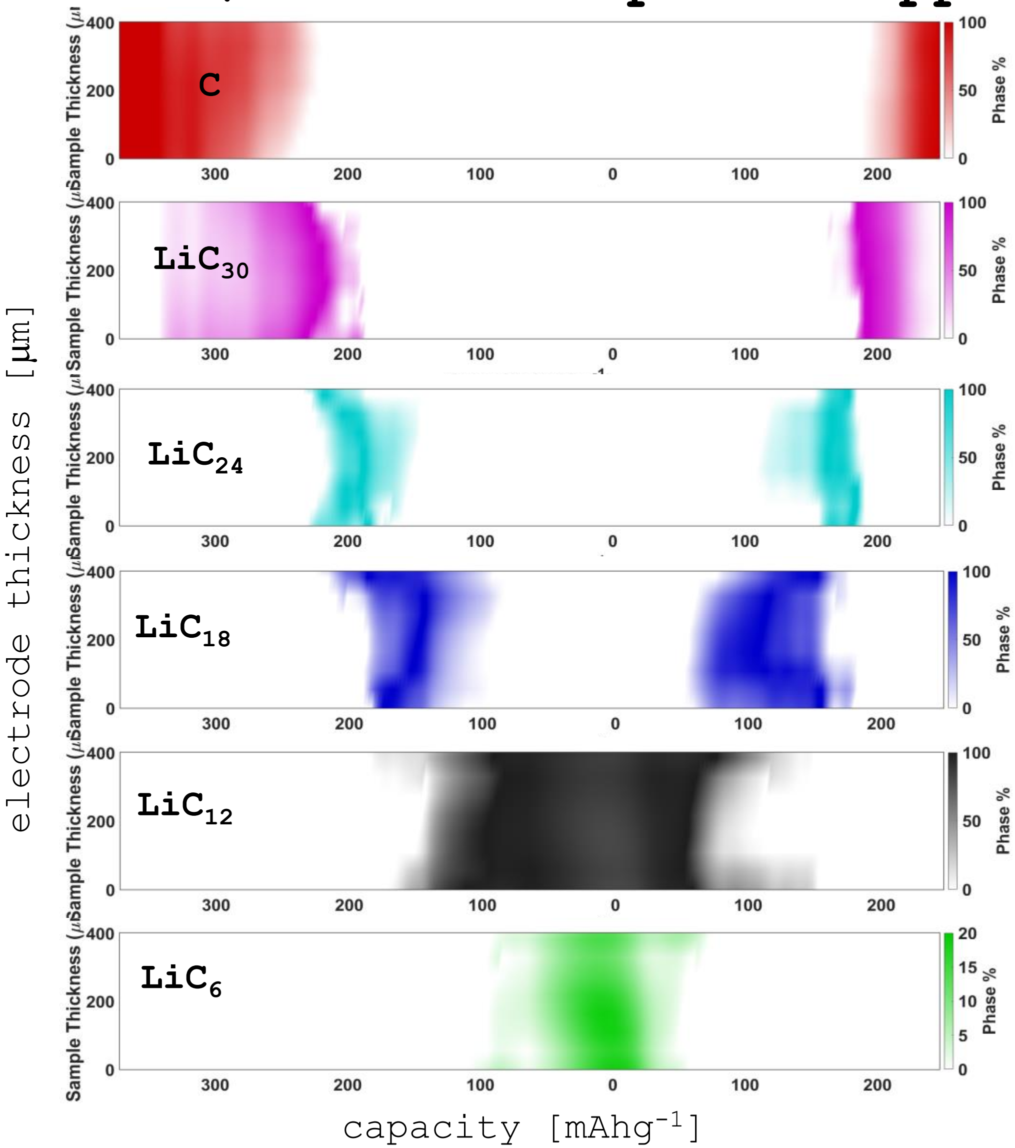


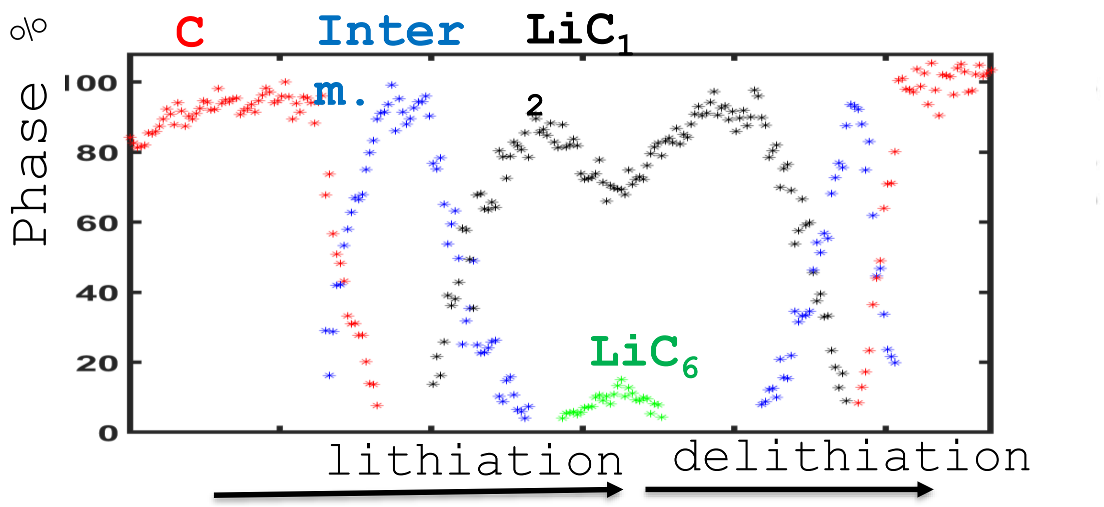


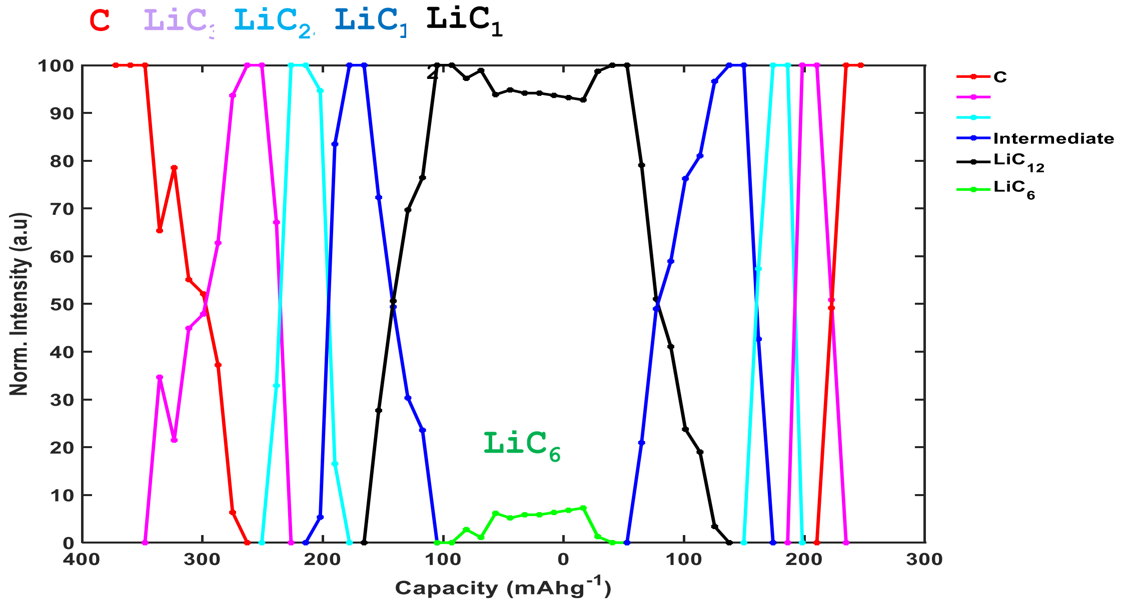


How we plug things: Batteries

De/lithiation phase mapping

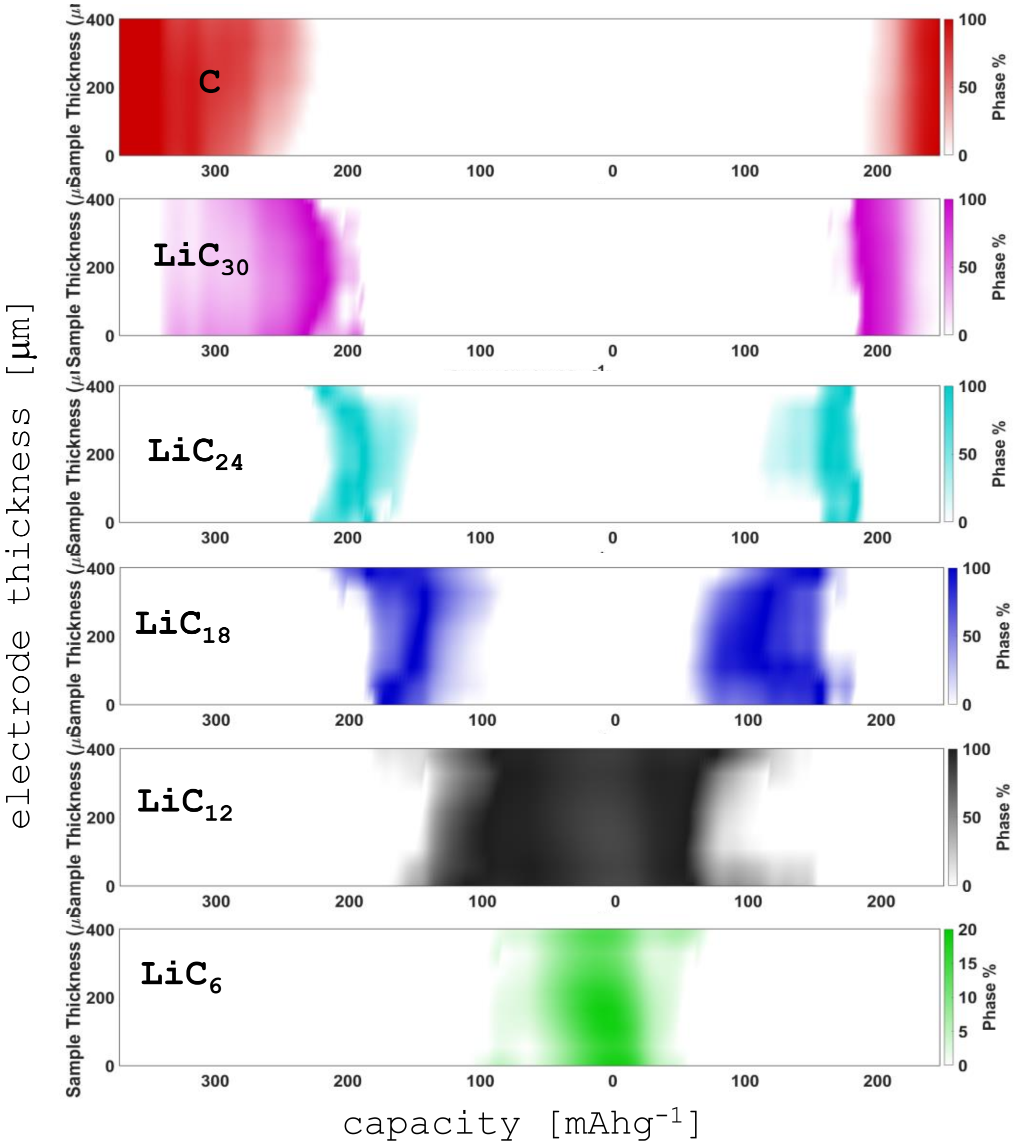




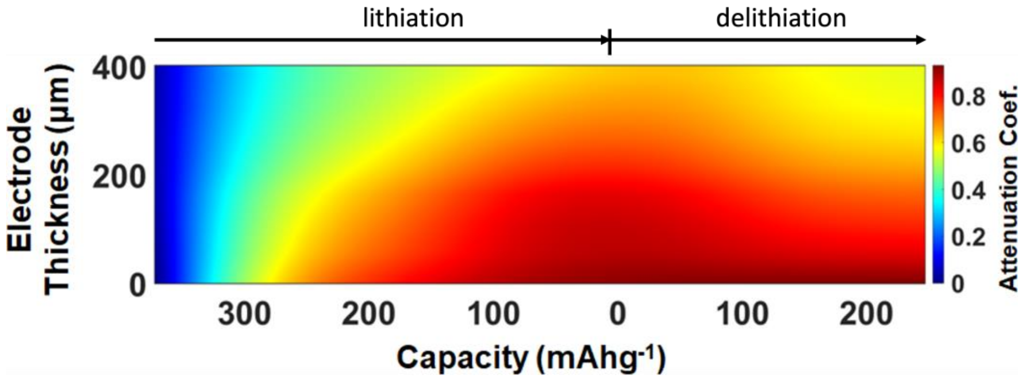


How we plug things: Batteries

De/lithiation phase mapping



SEI formation mapping

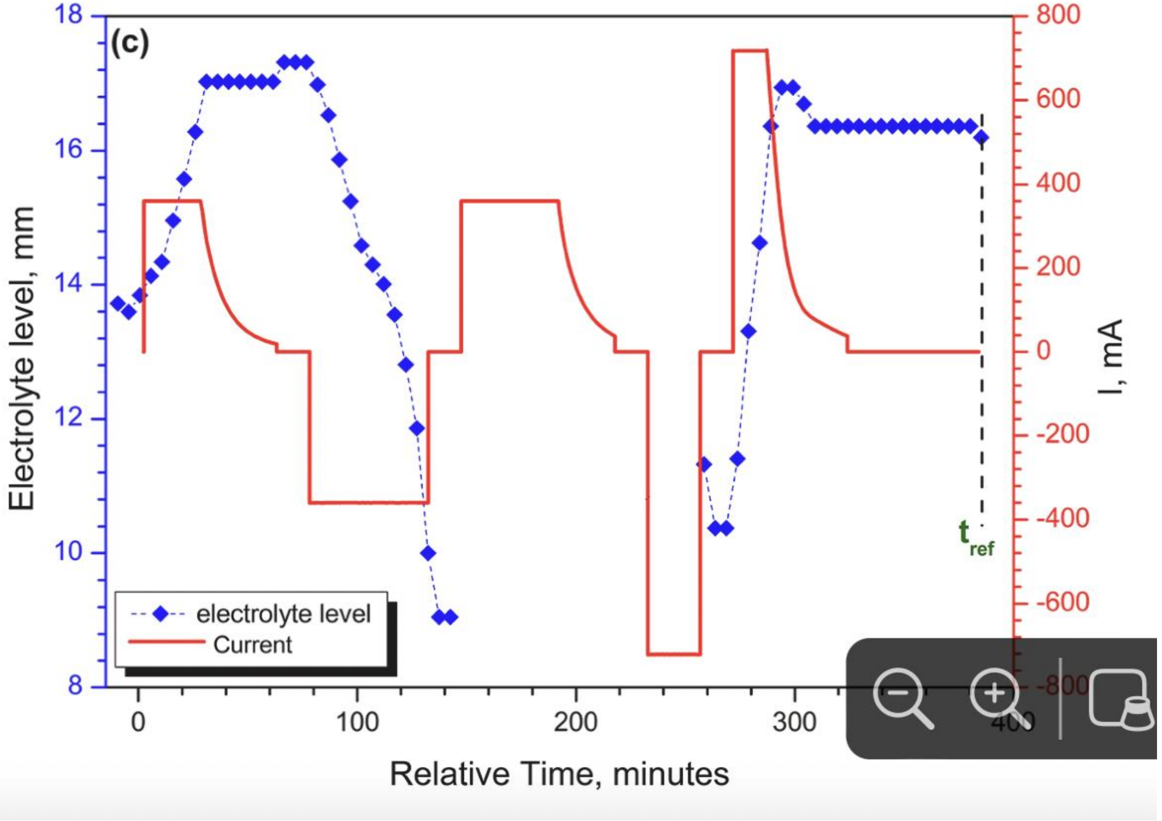


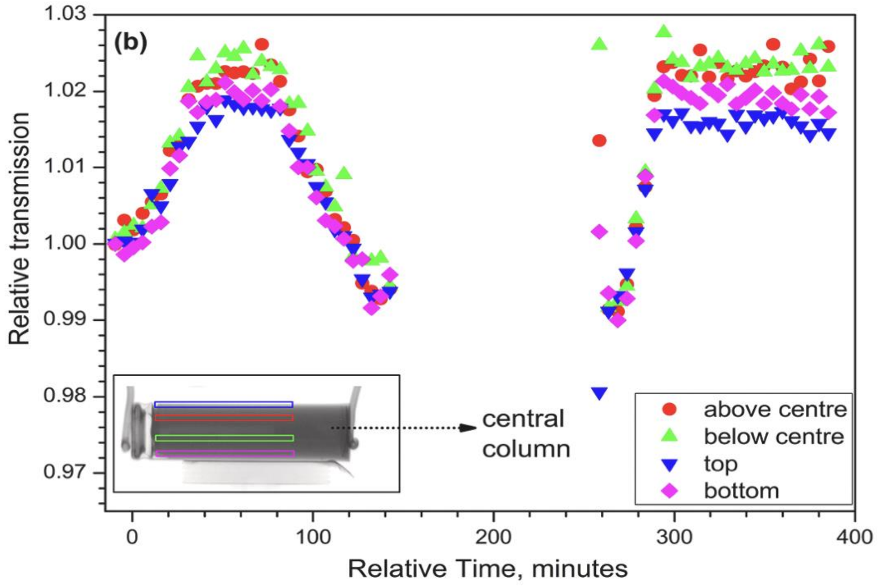
M. Strobl et al., Adv. Energy Ma

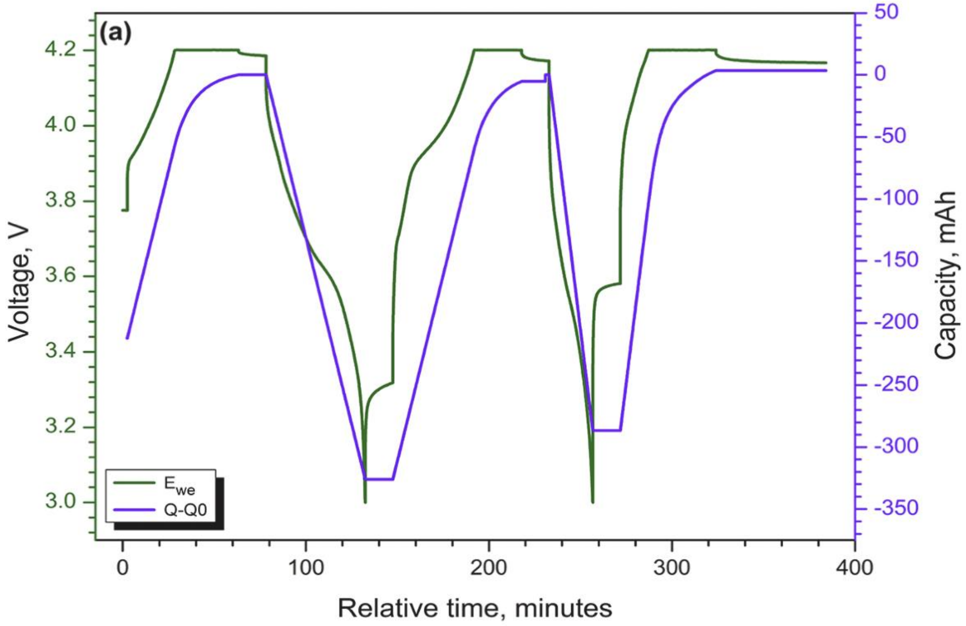
Battery electrolyte

Electrode expansion, electrolyte distribution, gas formation

Commercial cell







N.S.Nazer, M. Strobl, A. Kaestner, P.J.S.Vie, V.A.Yartys, Electrochem. Acta 140793 (2022)

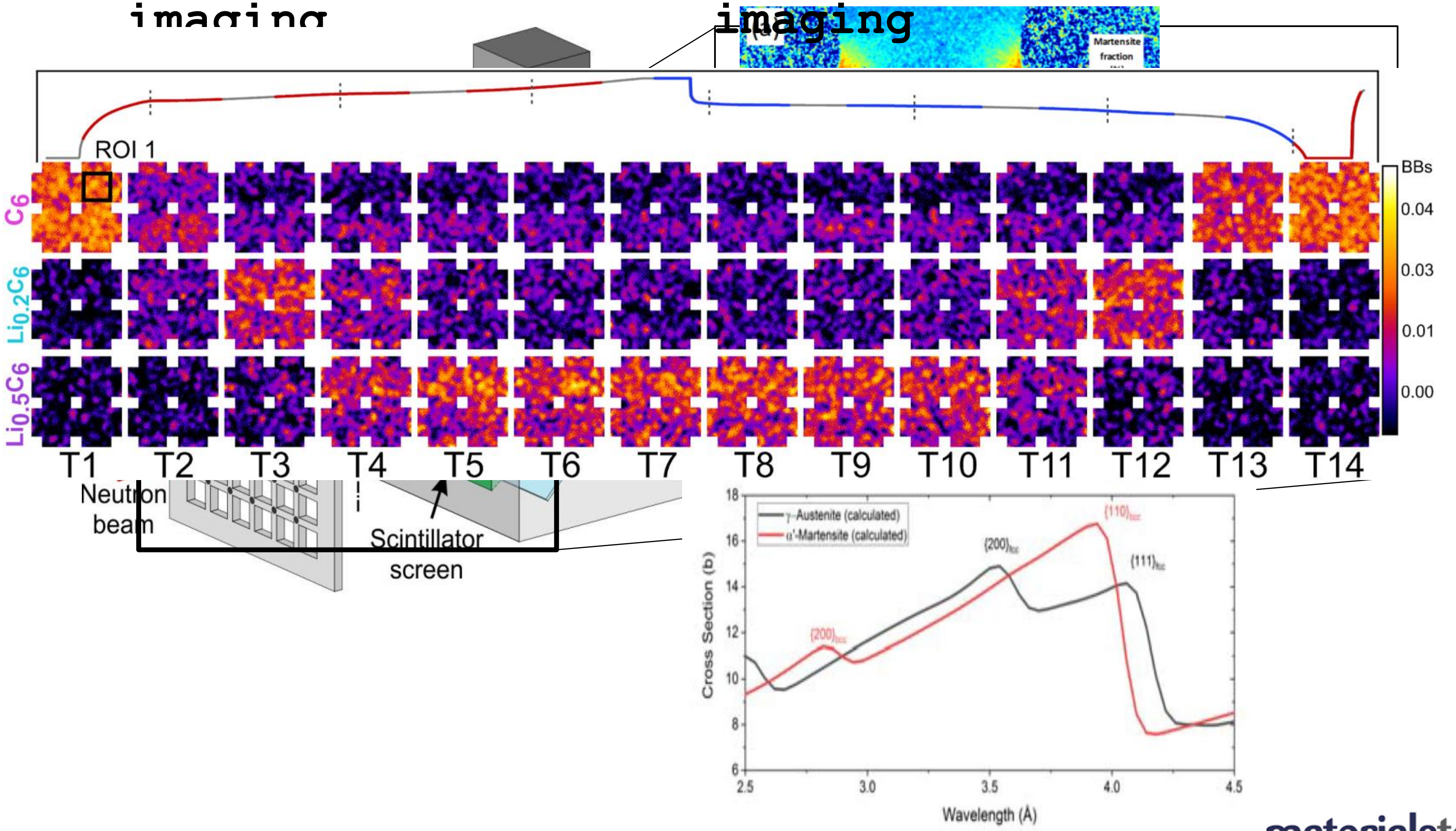
Battery electrolyte

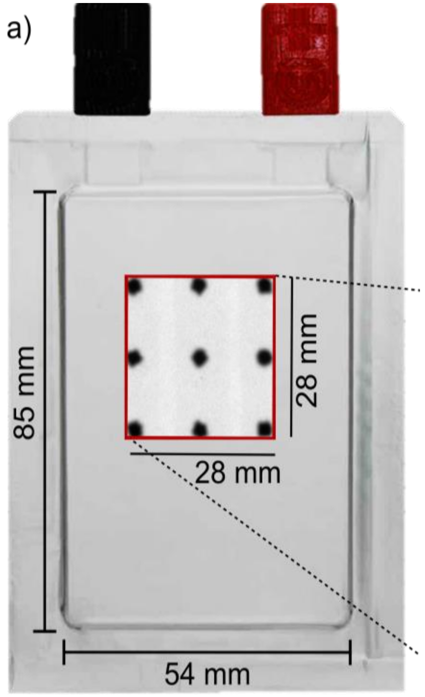
Batteries

PSI

Black Body Corr. → improved quantitative imaging

Diffraction contrast imaging





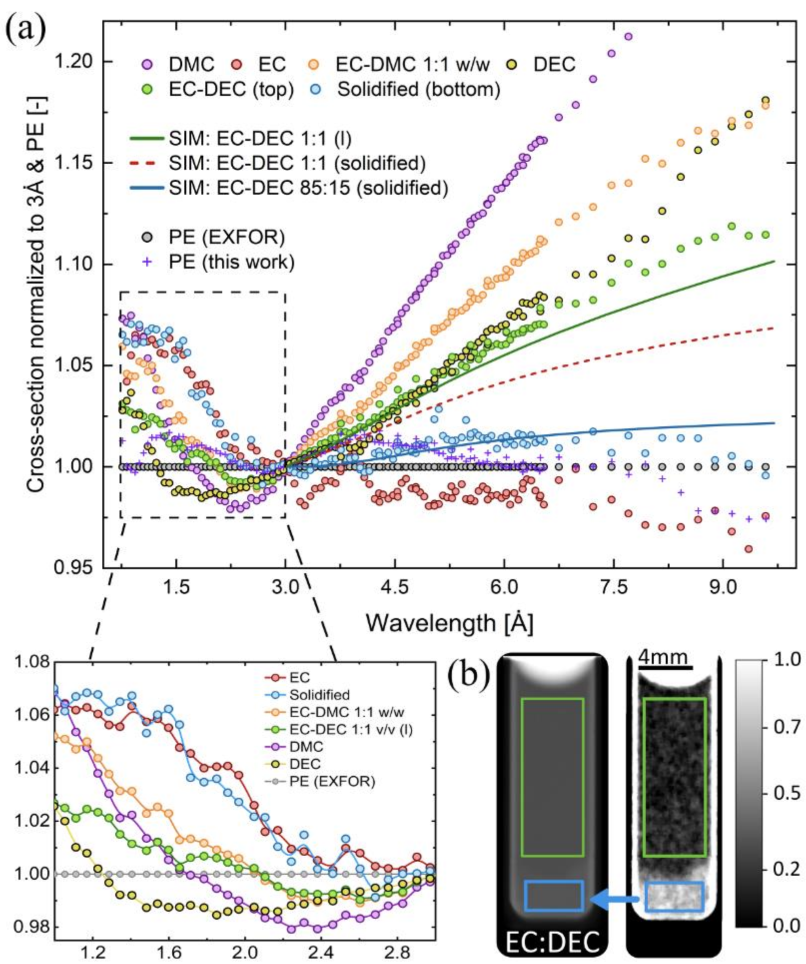
R.E. Carreon Ruiz et al., Materials Today Energy 19 (2024)

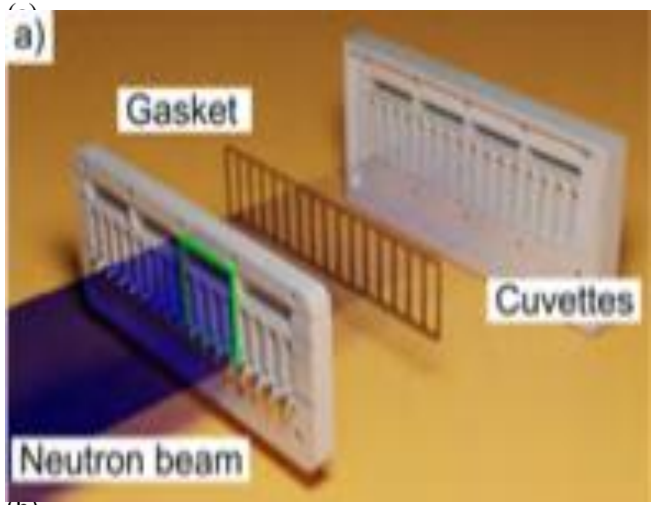
materialstoday ENERGY

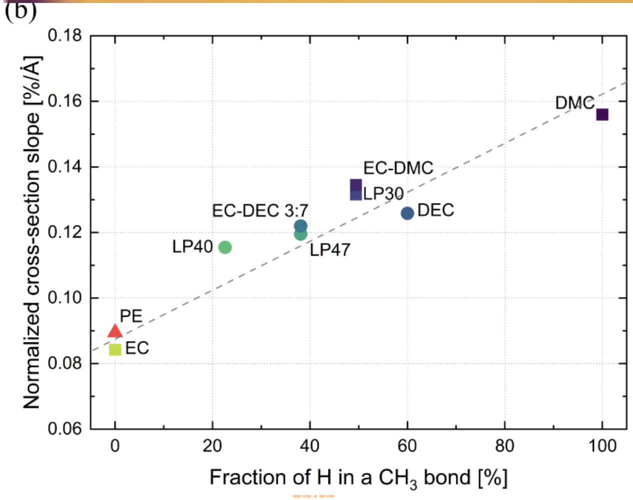
Batteries

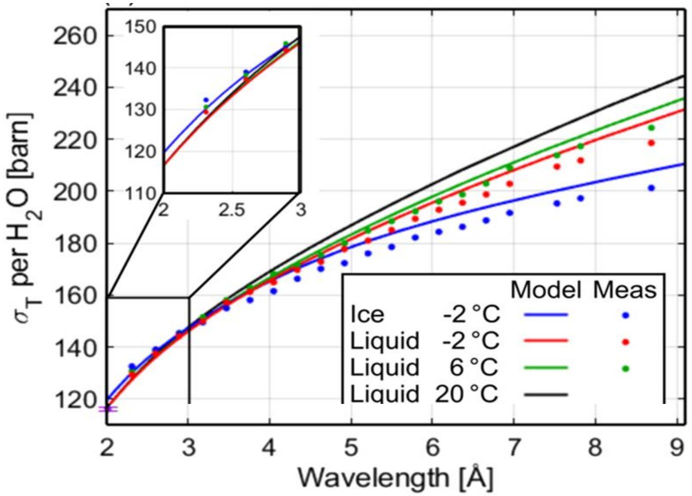
PSI

Inelasic scattering contrast – electrolyte degradation

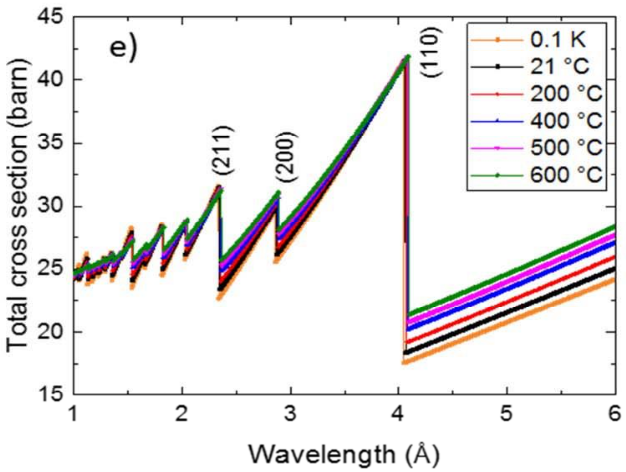








M. Siegwart et al. J. Electrochem. Soc. (2020)
J. Biesdorf et al. PRL (2014)



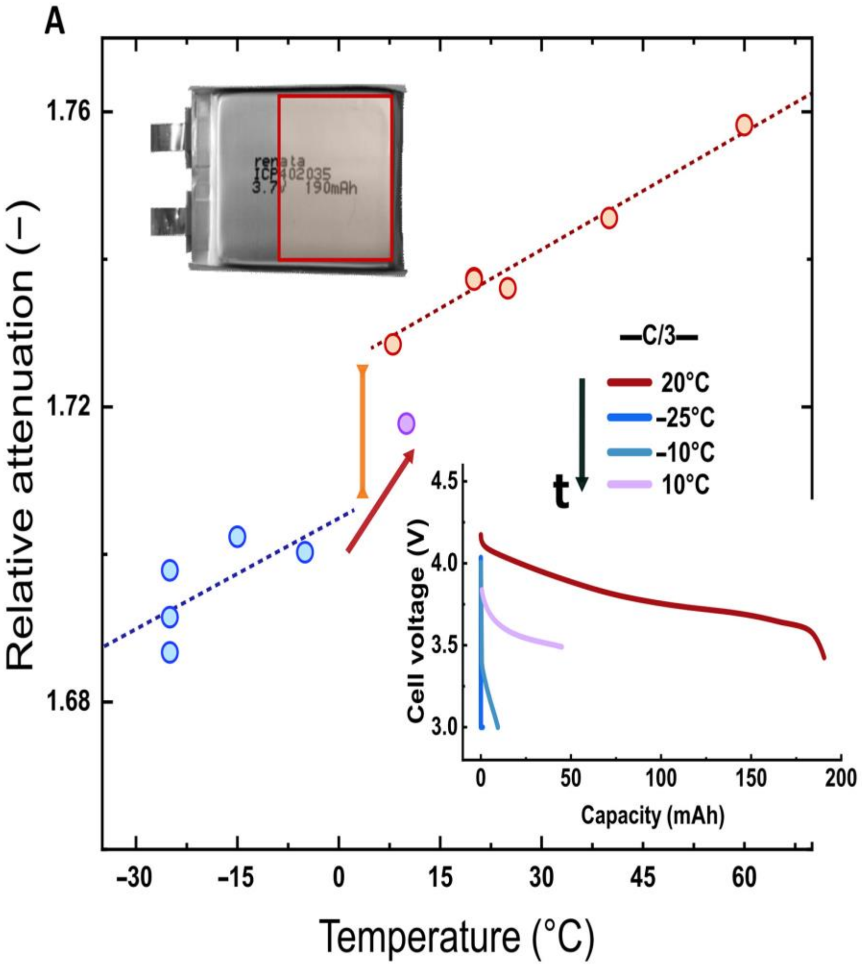
R.E. Carreon Ruiz et al., Materials Today Adva
19 (2023)

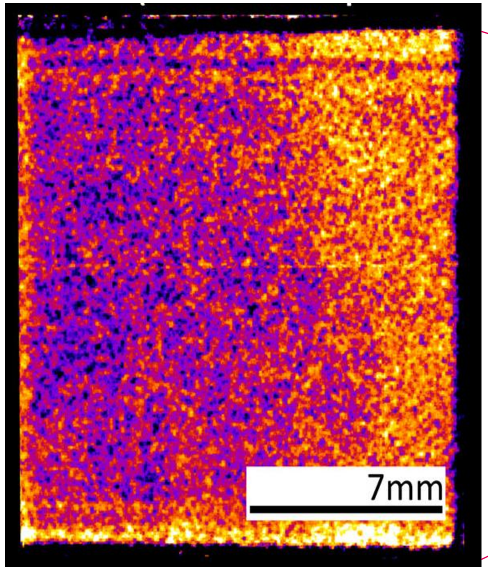
materialstoday ADVANCES

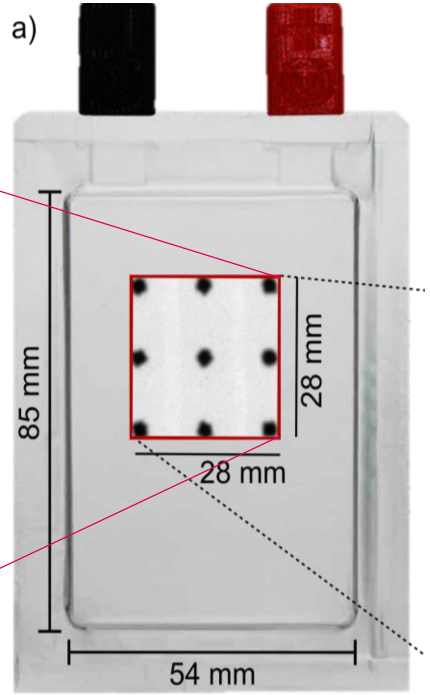
Batteries

Inelasic scattering contrast – electrolyte degradation

Crystallized Electrolyte
of a Leaked Alkaline
Cell (Turelio BY CC 3.0)





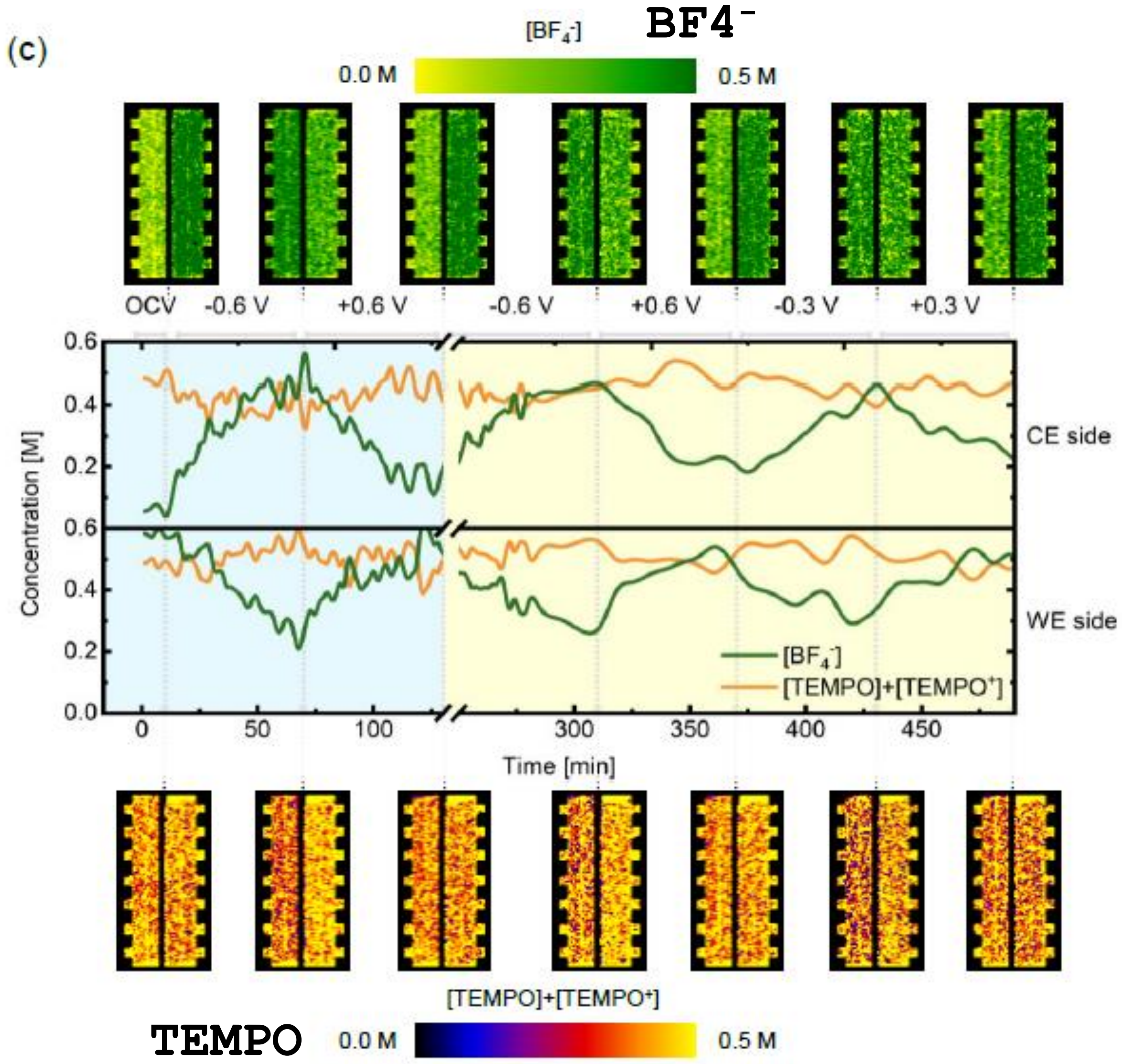


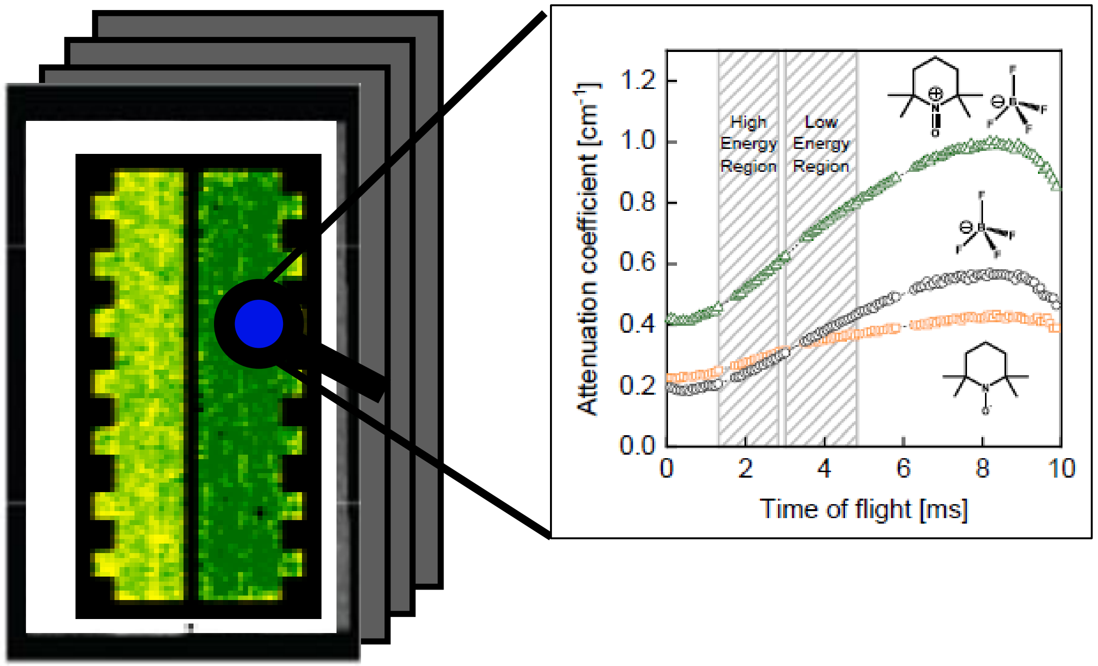
Carreon Ruiz ER et al., *Science Advances*. 2023; 9(39):

Science Advances
AAAS

Batteries

Inelasic scattering contrast – REDOX flow batteries

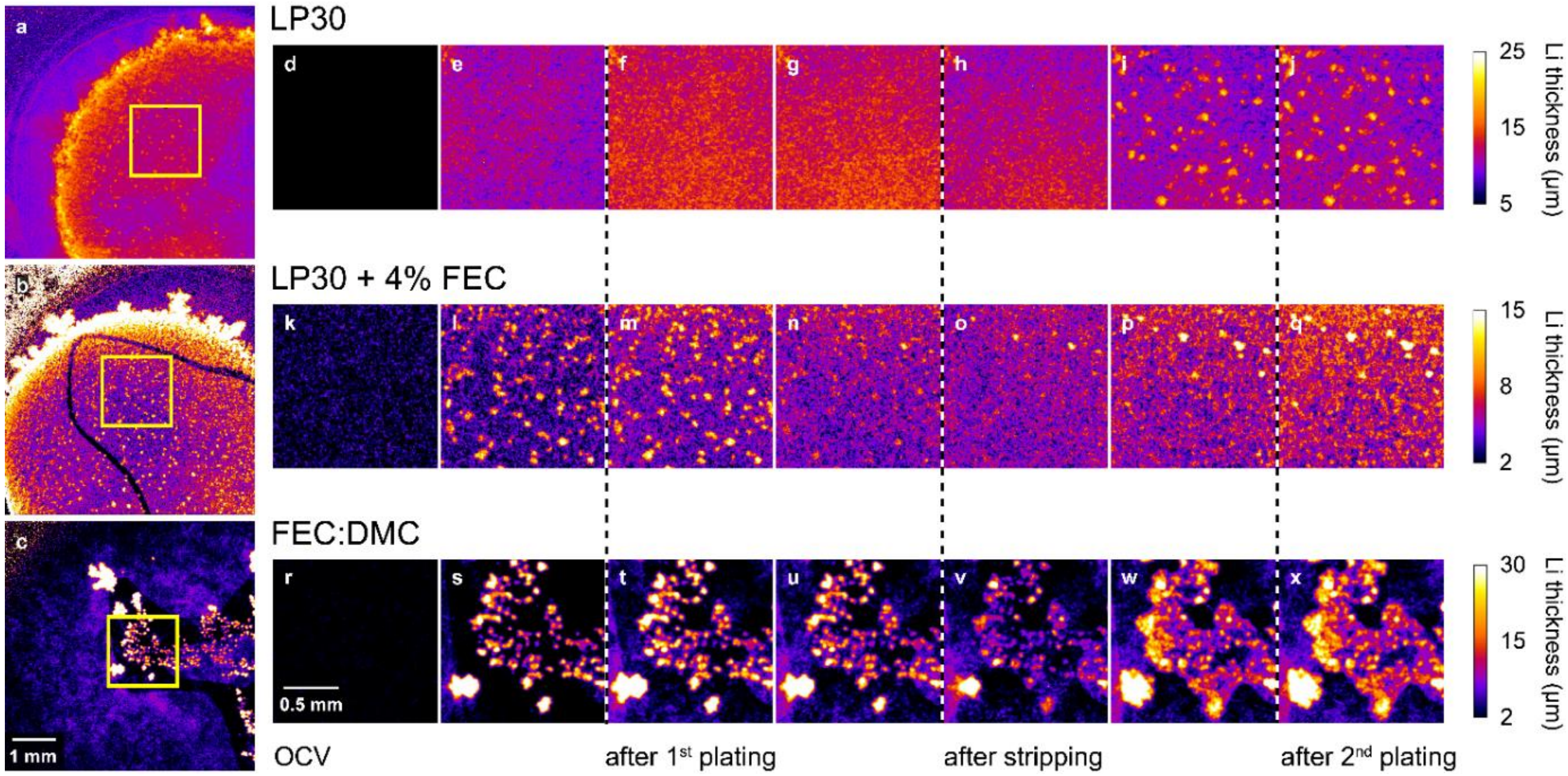




R.R. Jacquemond et al., Nature Comm (2024)

Electroplating Li-metal batteries

include no negative electrode at all in the initial state, the negative electrode being formed by plating on the copper current collector during charge cycle → improved energy density



Visualization of lithium plating morphology on copper with different electrolytes

S. Trabesinger, P. Boillat et al

Thank you!

- Questions?