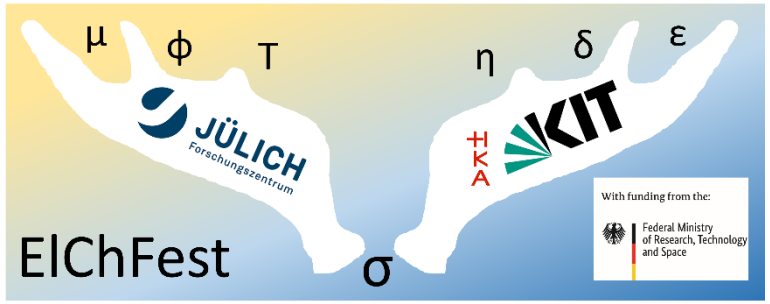

With funding from the:

Federal Ministry of Research, Technology and Space

Processing and durability of fuel electrode-supported cells with Ni-GDC electrode

JULY 3rd, 2026 | C. LENSER (1), D. J. RAMLER (1,2), S. KUCHARSKI (1), L. WEHNER (3), E. WESSEL (3), J. MALZBENDER (3), L. SCHÖLLER (4), D. SCHNEIDER (4,5), B. NESTLER (4,5), I. KOGUT (6), A. WEBER (6), N. H. MENZLER (1,2)

(1) Institute of Energy Materials and Devices (IMD), Materials Synthesis and Processing (IMD-2), Forschungszentrum Jülich GmbH 52425 Jülich/Germany
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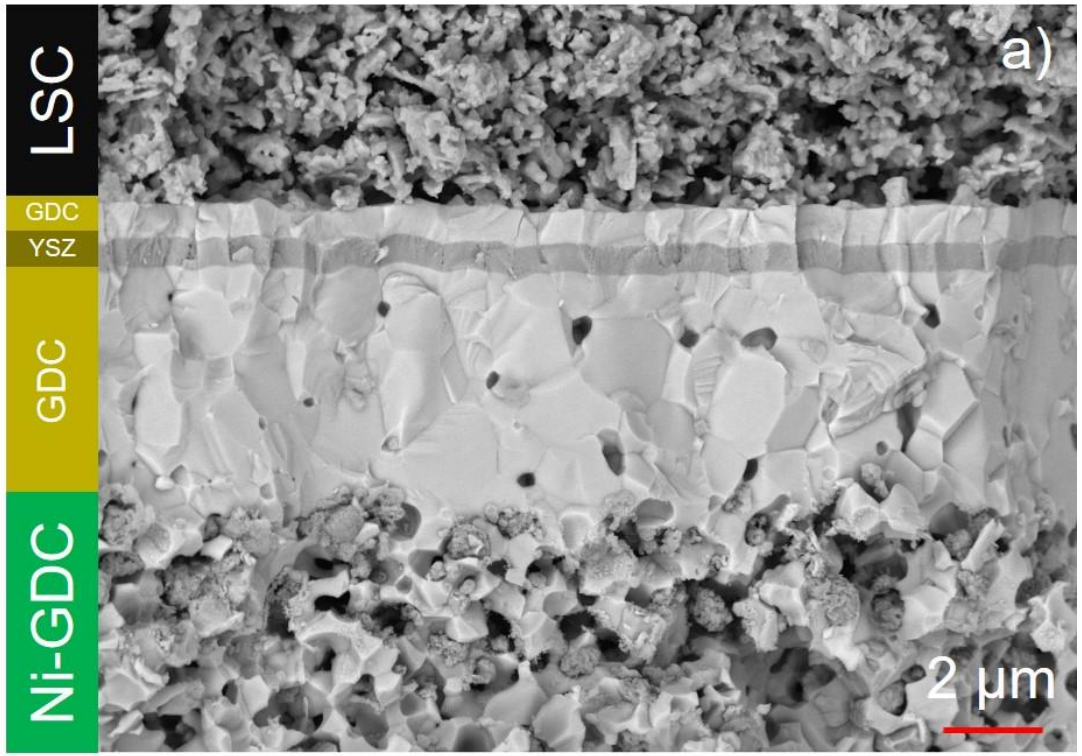
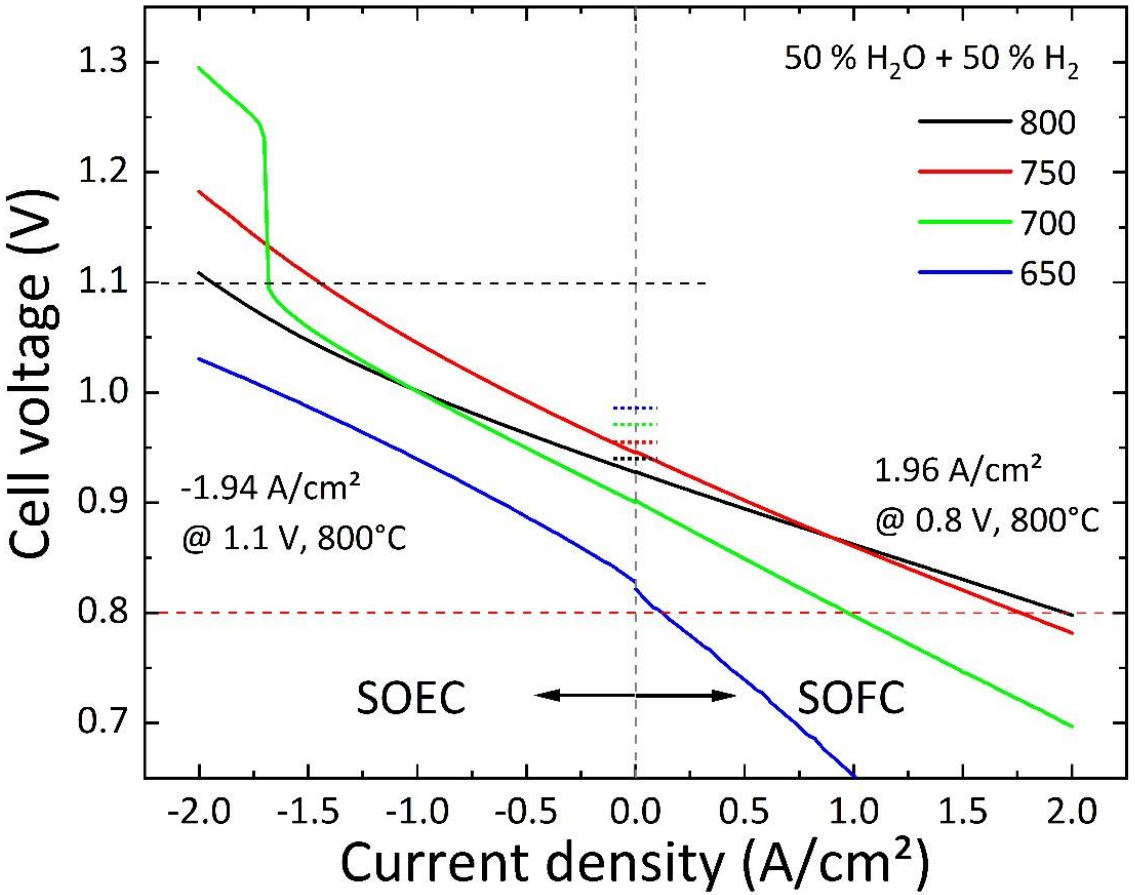
(3) Institute of Energy Materials and Devices (IMD), Structure and Function of Materials (IMD-1), Forschungszentrum Jülich GmbH, 52425 Jülich/Germany
(4) Institute for Applied Materials (IAM-MMS), Karlsruhe Institute of Technology (KIT), Strasse am Forum 7, 76131 Karlsruhe, Germany
(5) Institute of Digital Materials Science (IDM), Karlsruhe University of Applied Sciences, Moltkestrasse 30, 76133 Karlsruhe, Germany
(6) Institute for Applied Materials (IAM-ET), Karlsruhe Institute of Technology (KIT), Adenauerring 20b, 76131 Karlsruhe, Germany

Starting point

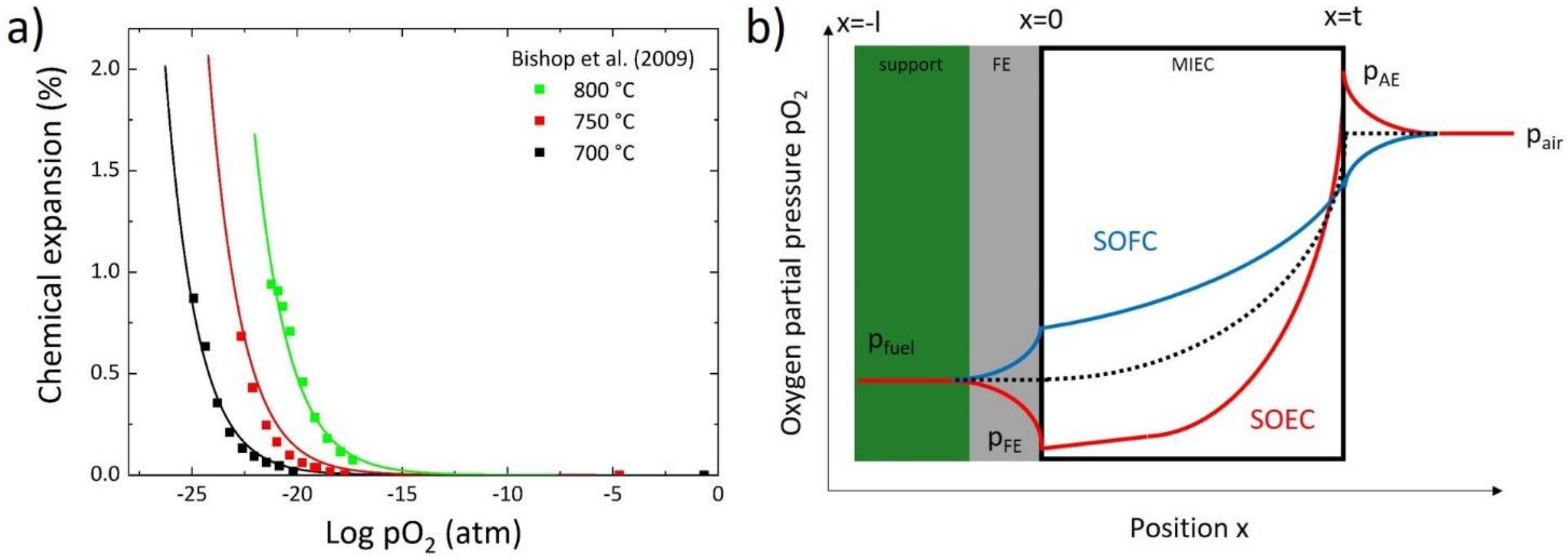




- Electrode-supported cell with Ni-GDC electrode and GDC-YSZ-GDC electrolyte

[1] J. Zhang, C. Lenser, N. Russner, A. Weber, N.H. Menzler, O. Guillon, Journal of the American Ceramic Society, 106 (2022) 93-99.
[2] C. Lenser, J. Zhang, N. Russner, A. Weber, O. Guillon, N.H. Menzler, Journal of Power Sources, 541 (2022) 231505.

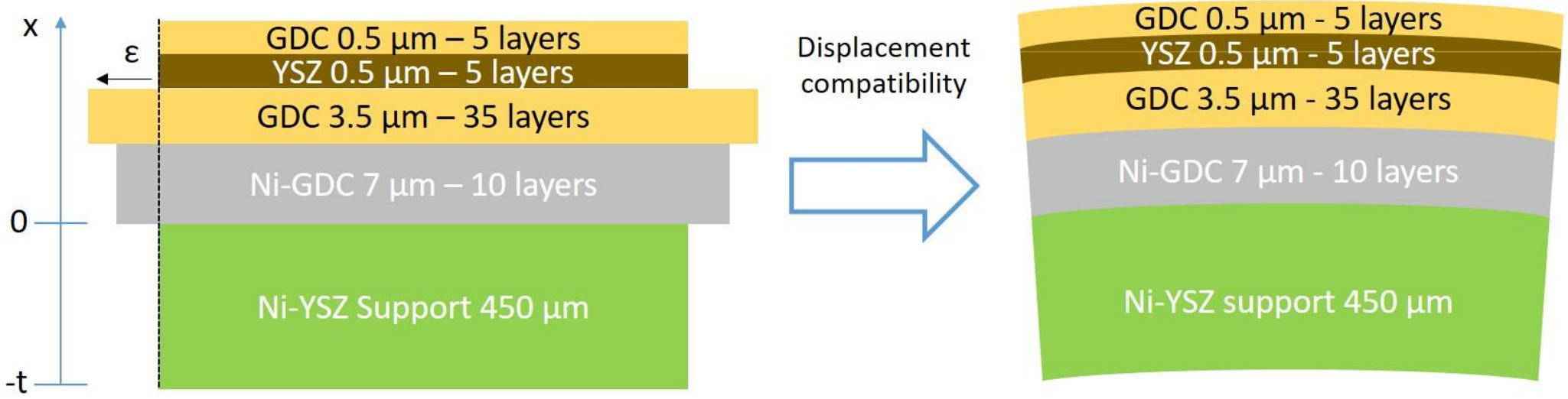
Electro-chemical expansion



- Ceria shows chemical expansion at low oxygen activity
- Cathodic overpotential can induce stronger degradation than pure hydrogen

[1] C. Lenser, J. Zhang, N. Russner, A. Weber, O. Guillon, N.H. Menzler, Journal of Power Sources, 541 (2022) 231505.

Electro-chemo-mechanical stress in a multilayer system



Local strain

$$\varepsilon = c + \frac{x - t_b}{r}$$

support layers

$$c = \frac{\left(E_s t_s \varepsilon_{c,s} + \sum_{i=1}^{n} E_i t_i \varepsilon_{c,i}\right)}{\sum_{i=1}^{n} E_i t_i}$$

$$t_b = \frac{-E_s t_s^2 + \sum_{i=1}^{n} E_i t_i (2h_{i-1} + t_i)}{2\left(E_s t_s + \sum_{i=1}^{n} E_i t_i\right)}$$

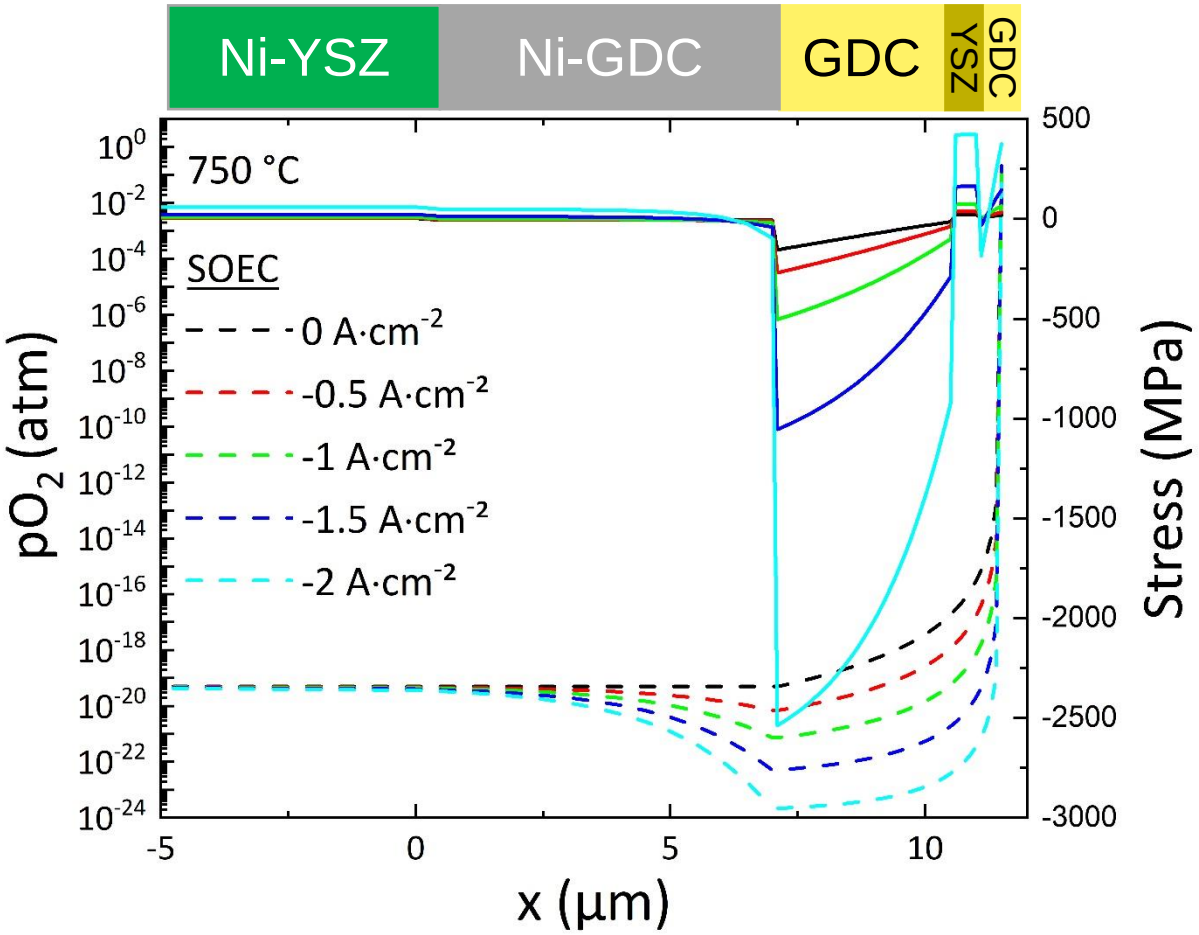
Biaxial modulus: E‘ = E/(1-v)

➡ Need ε_c (x)

$$\frac{1}{r} = \frac{3\left[E_s\left(c - \varepsilon_{c,s}\right)t_s^2 - \sum_{i=1}^{n} E_i t_i (c - \varepsilon_{c,i})(2h_{i-1} + t_i)\right]}{E_s t_s^2 (2t_s + 3t_b) + \sum_{i=1}^{n} E_i t_i [6h_{i-1}^2 + 6h_{i-1} t_i + 2t_i^2 - 3t_b(2h_{i-1} + t_i)]}$$

C.H. Hsueh, Thin Solid Films, 418 (2002) 182-188.
C. Lenser et al., Journal of Power Sources, 541 (2022) 231505.

Electro-chemo-mechanical stress



- One-dimensional model predicts very high compressive stresses in GDC layer
- Tensile stresses in YSZ depend on cell constraints

➢ Can we do this better?

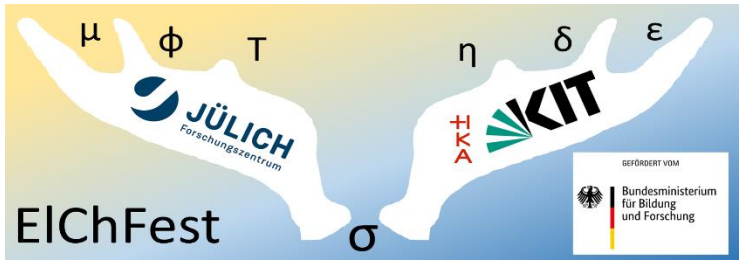
➢ Model in 3 Dimensions

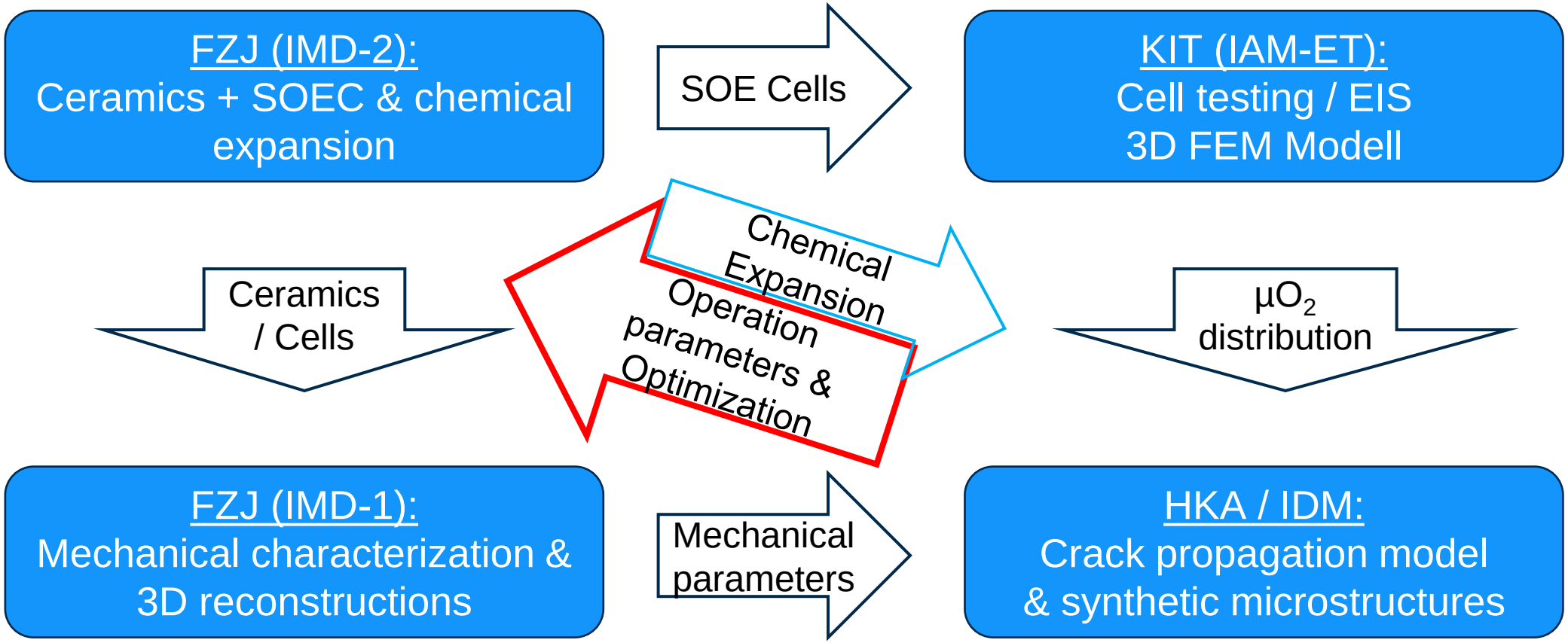
➢ Use synthetic microstructures to accelerate microstructure optimization

[1] J. Zhang, C. Lenser, N. Russner, A. Weber, N.H. Menzler, O. Guillon, Journal of the American Ceramic Society, 106 (2022) 93-99.
[2] C. Lenser, J. Zhang, N. Russner, A. Weber, O. Guillon, N.H. Menzler, Journal of Power Sources, 541 (2022) 231505.

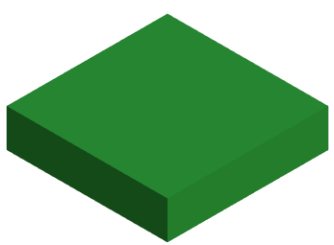
The ElChFest project

Understand and mitigate ECM-failure



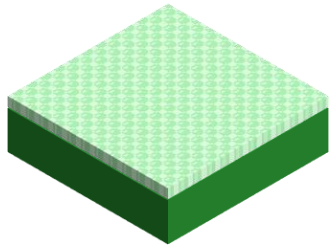


Cell manufacturing – PVD cells



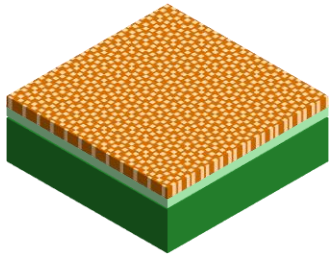
NiO-YSZ support
Tape casting

1230 °C



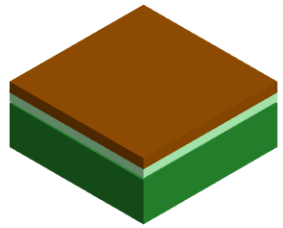
NiO-**GDC** fuel electrode
Screen printing

1000 °C

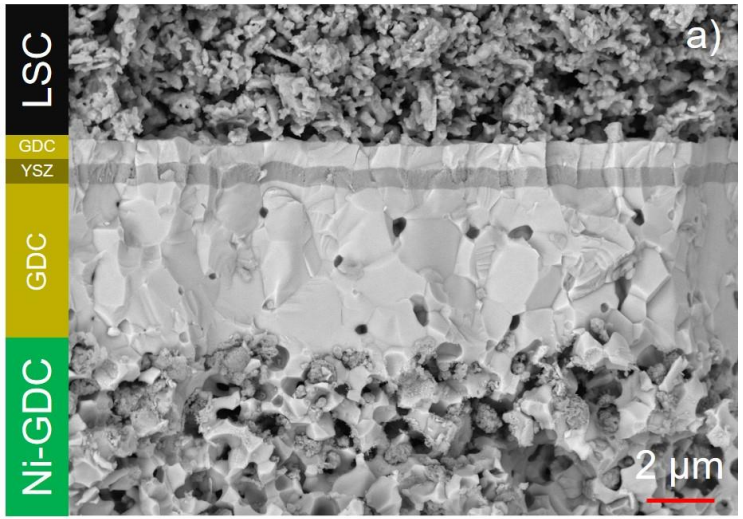


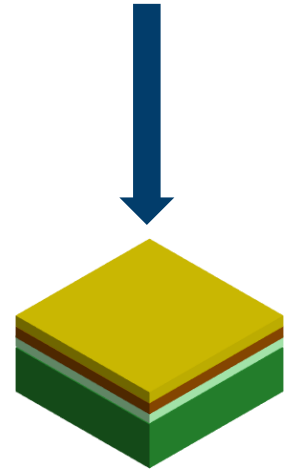
GDC electrolyte
Screen printing

1400 °C

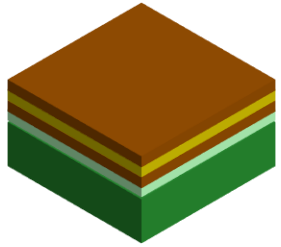


Sintered half cell



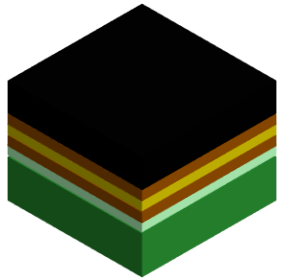


8YSZ layer (PVD)



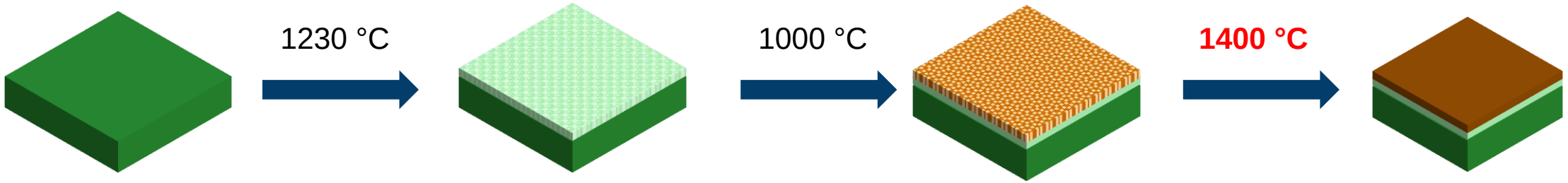
GDC layer (PVD)

850 °C



LSC air electrode
Screen printing

Cell manufacturing – SP cells

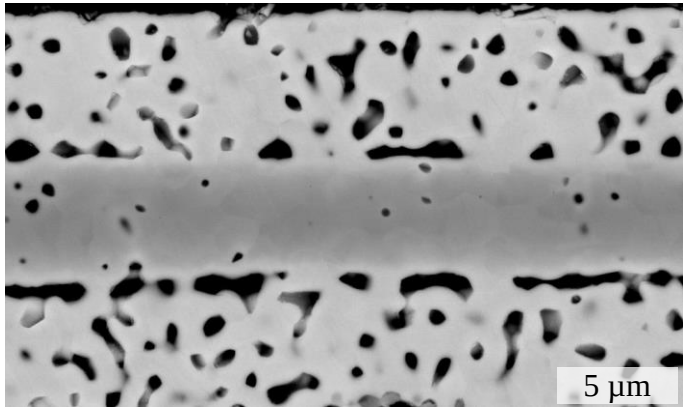


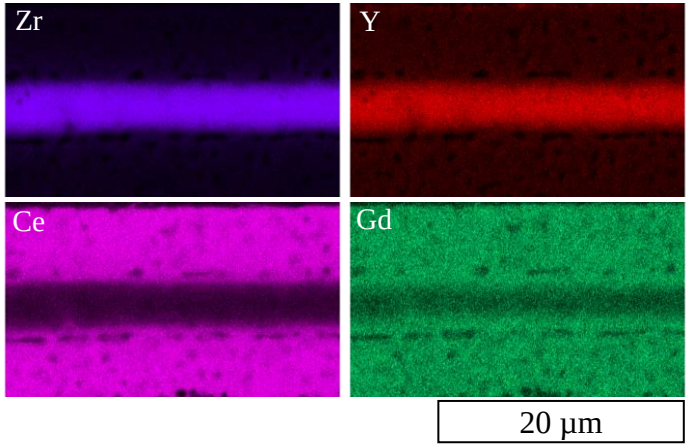
NiO-YSZ support
Tape casting

NiO-**GDC** fuel electrode
Screen printing

GDC / YSZ / GDC electrolyte
Screen printing

Sintered half cell

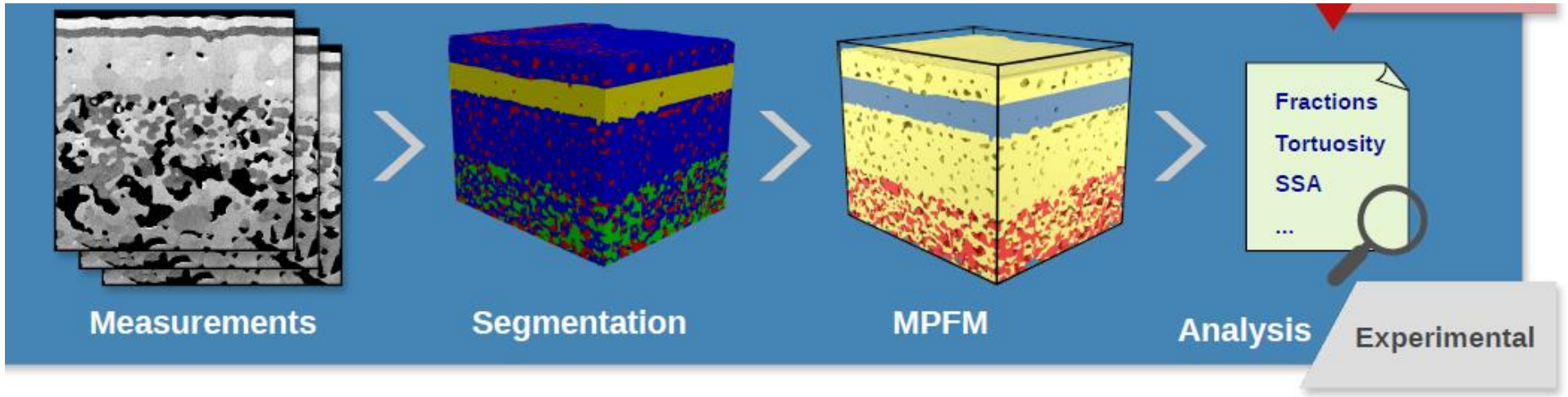




- Strong interdiffusion during sintering
- ID-length ~ 6 µm
- 10% Ce in middle of YSZ
- → OCV 0.6 – 0.7 V

- Learn more: A1606

3D microstructure analysis

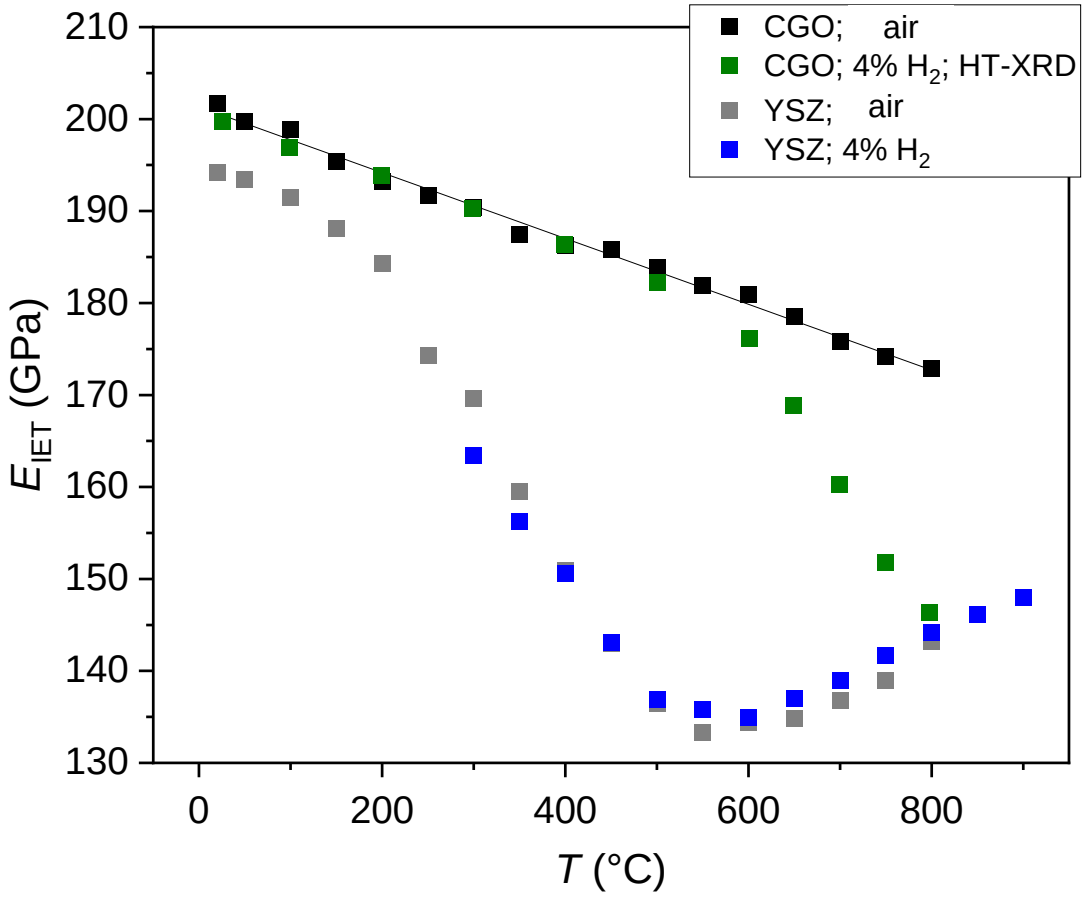


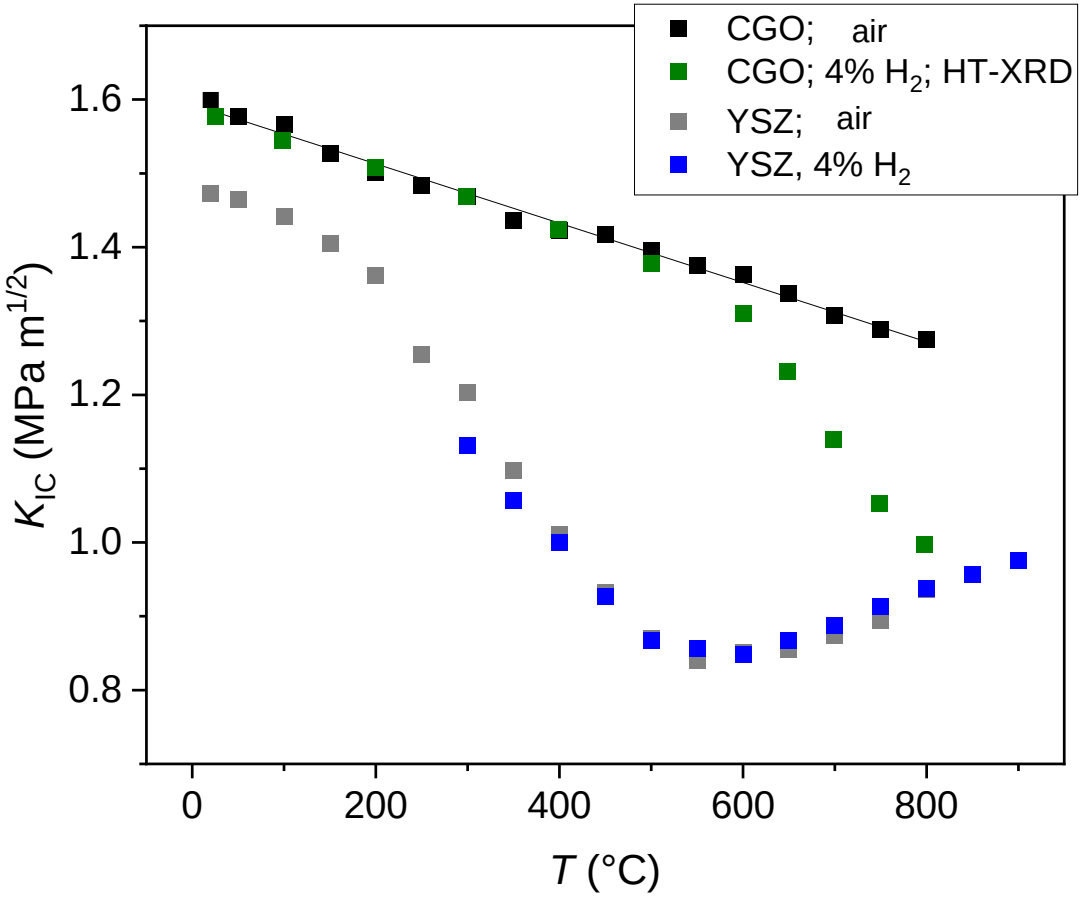
- FIB-SEM tomography to produce the microstructural parameters required for the model:
  - Phase fractions
  - Tortuosity
  - Grain size
  - Porosity etc

Virtual design of multilayered SOFC microstructures based on particle packing and spherical harmonics
L. Schöller, L. Wehner, D. Schneider, R. Schwaiger and B. Nestler
Modelling and Simulation in Materials Science and Engineering 2026
http://iopscience.iop.org/article/10.1088/1361-651X/ae7138

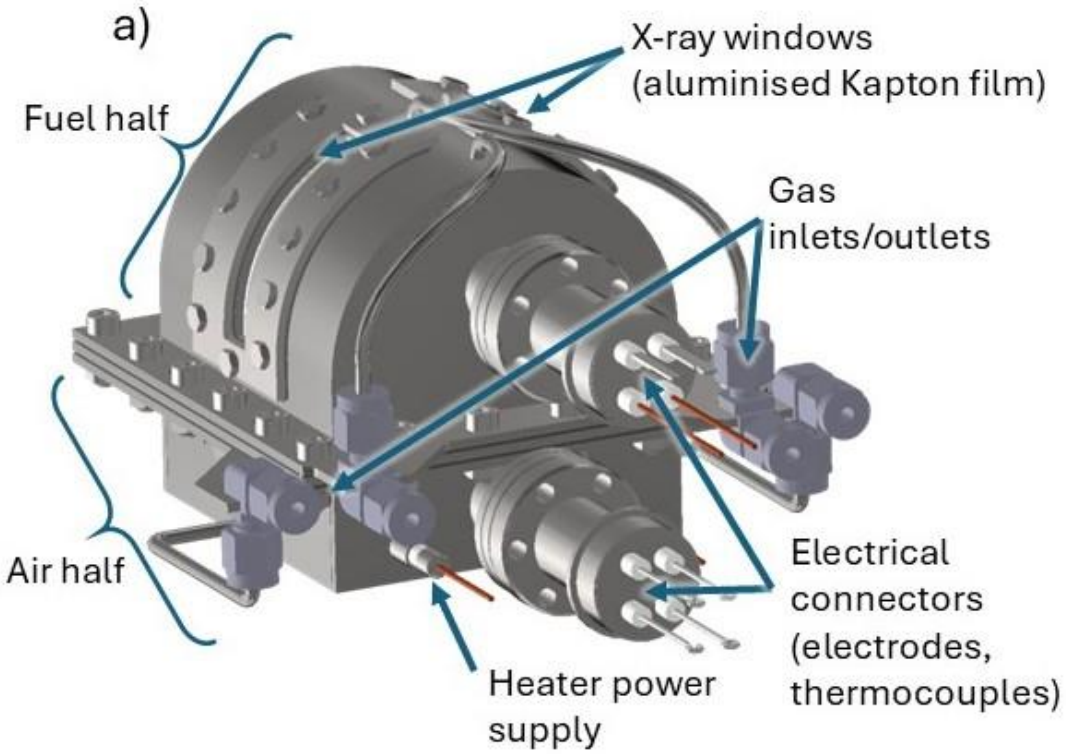
Mechanical testing

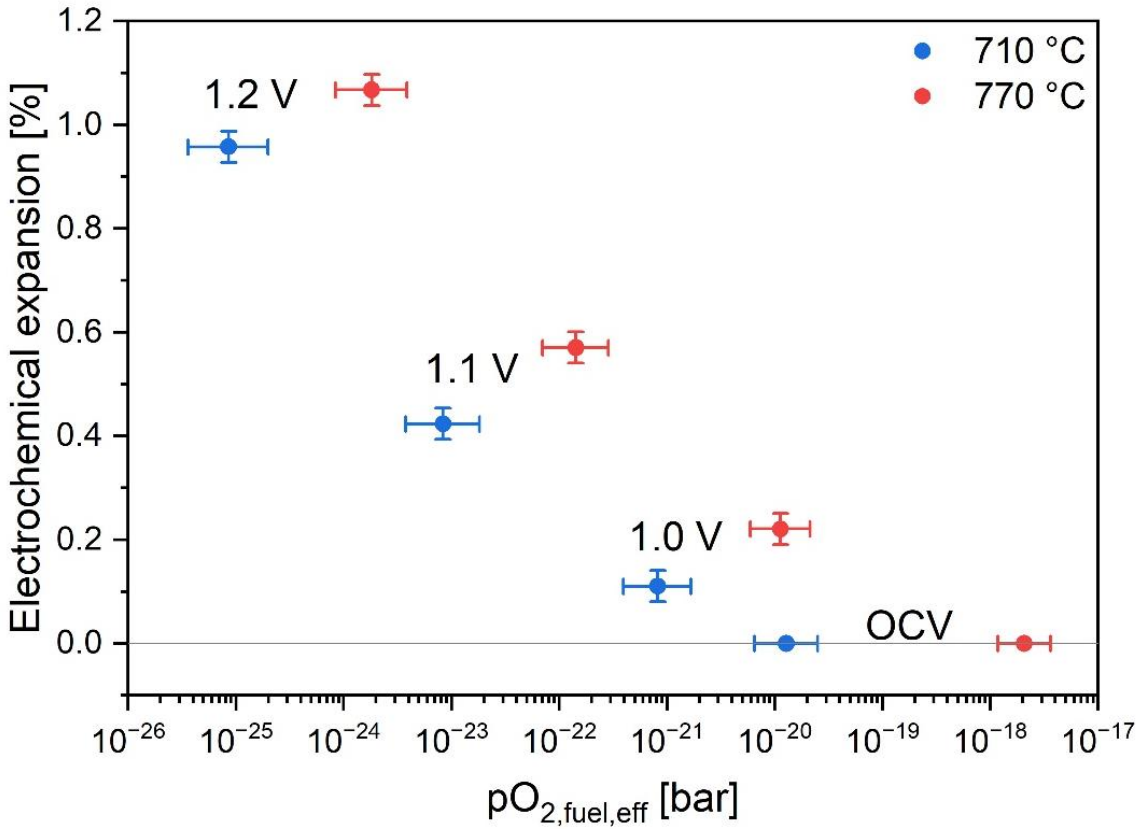
Impulse Excitation Technique





Chemical expansion of ceria

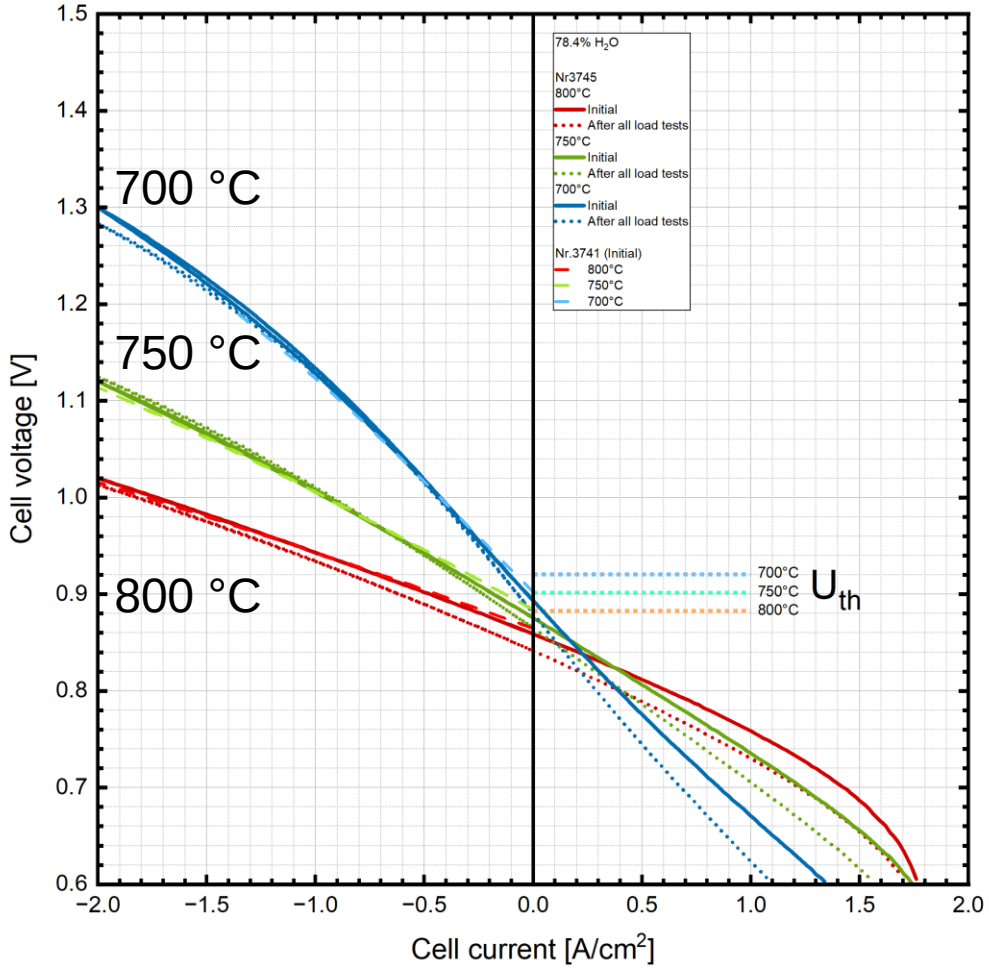


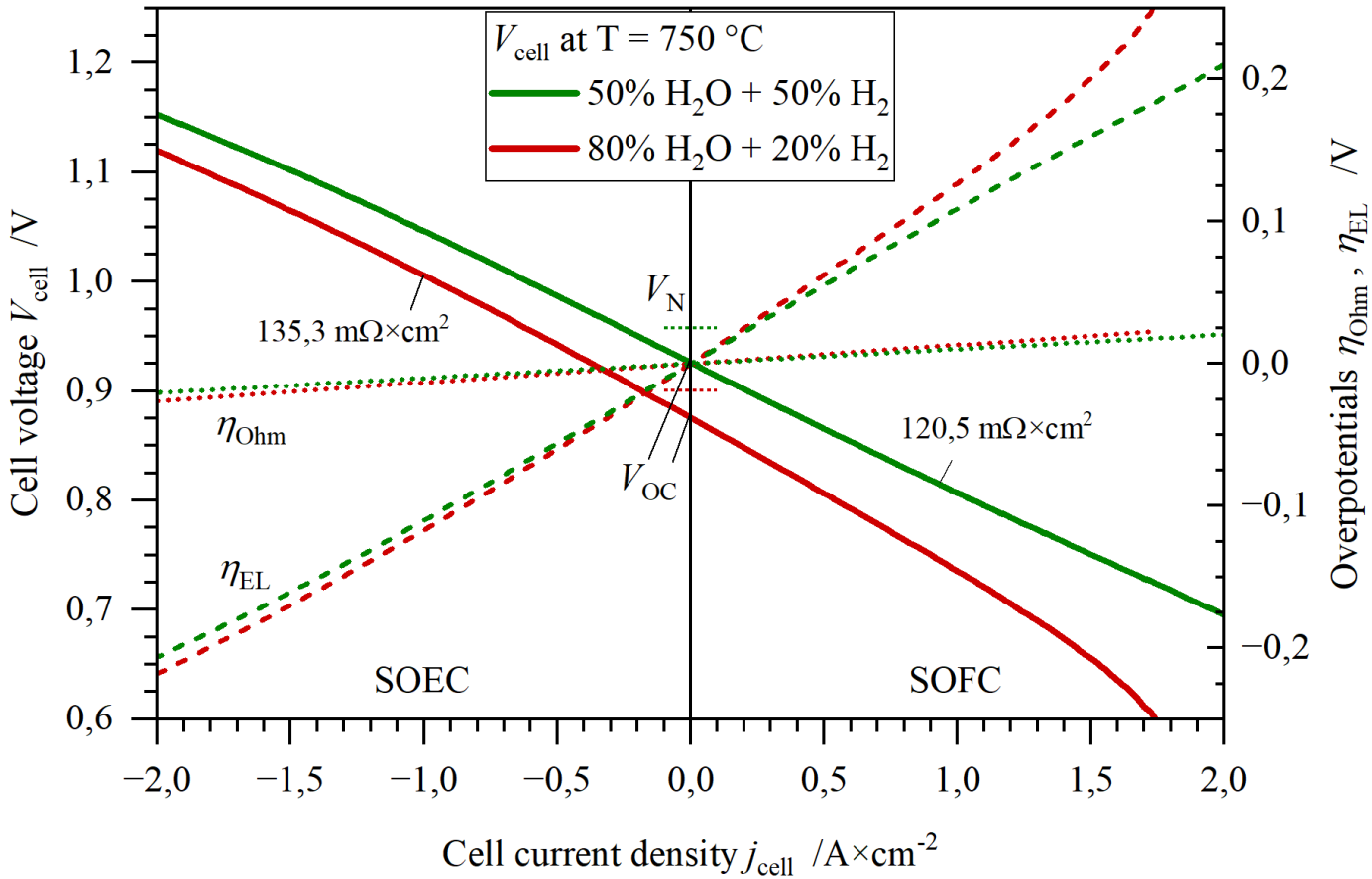


https://chemrxiv.org/doi/full/10.26434/chemrxiv.15004327/v1

https://zenodo.org/records/17816329

Electrochemical testing

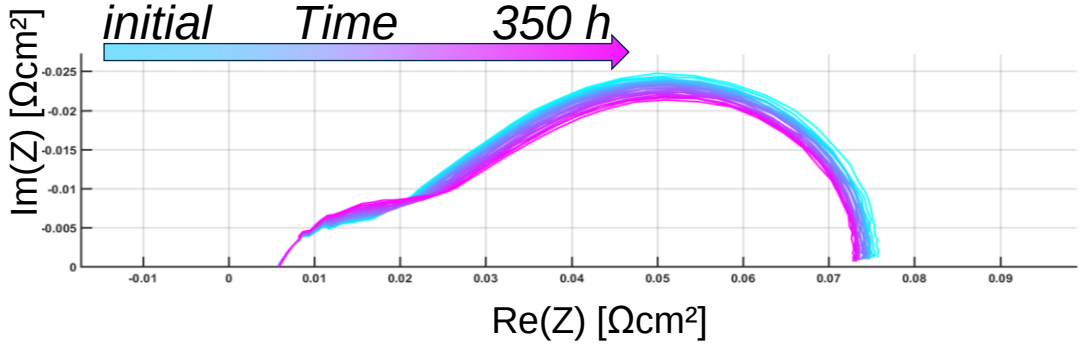


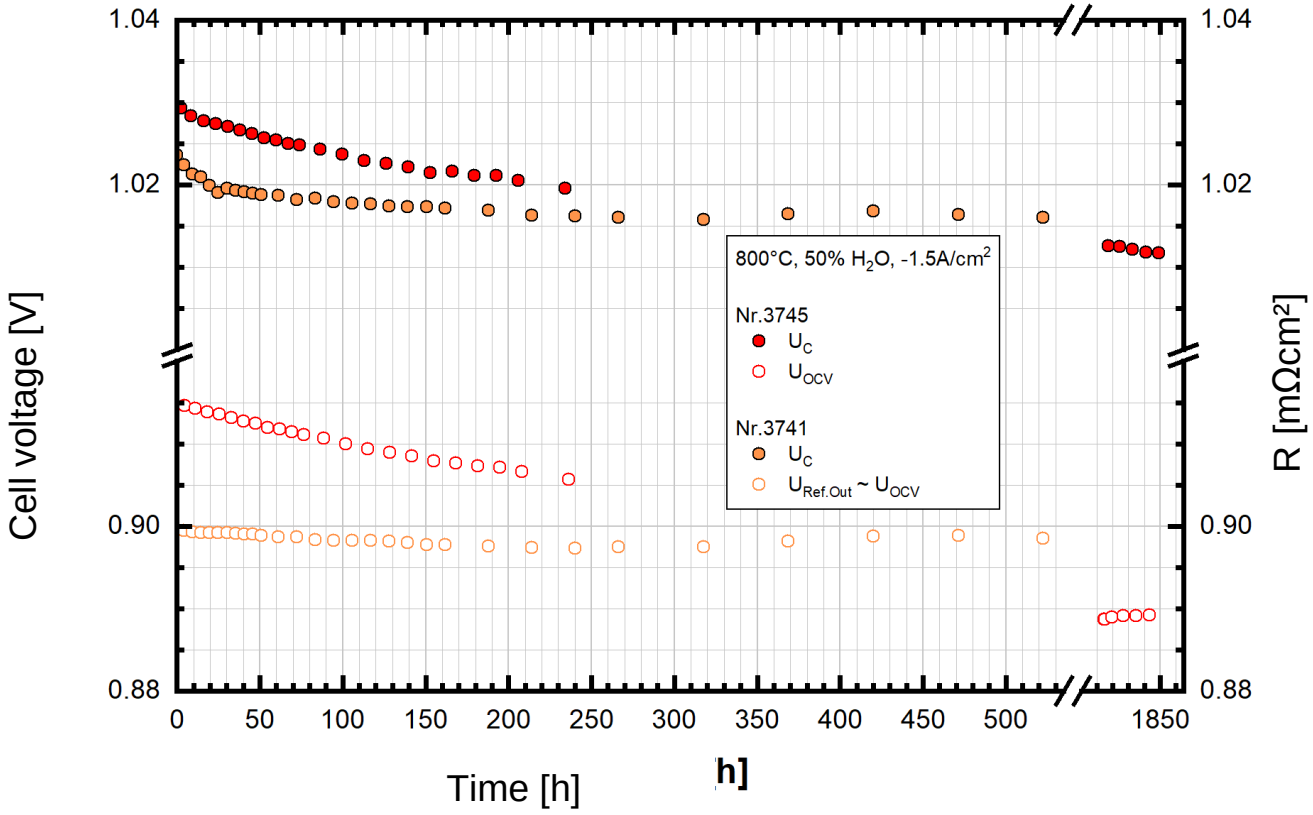


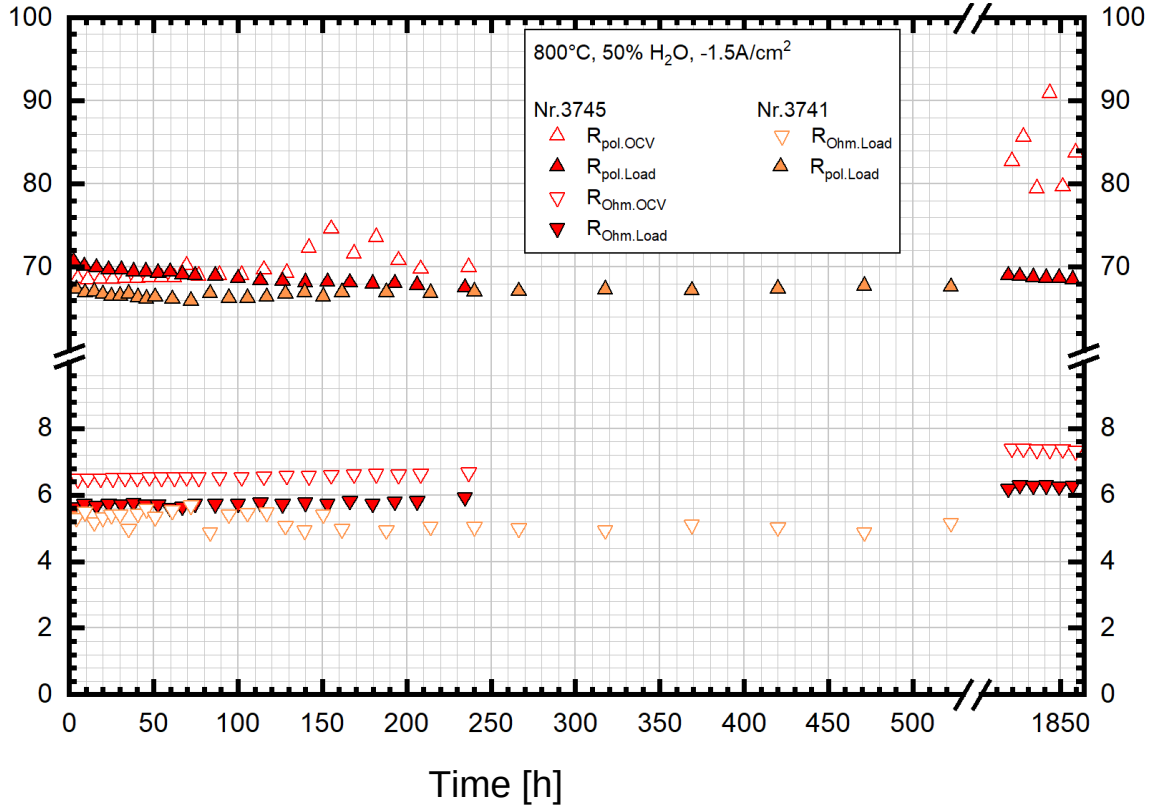
JÜLICH Forschungszentrum

Degradation test

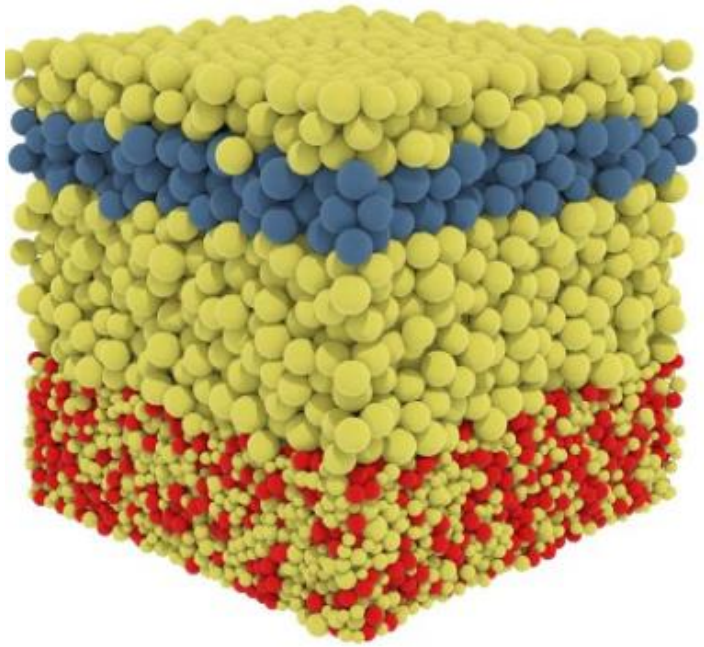
800 °C, 50:50 H_2:H_2O, -1.5 Acm^{-2}



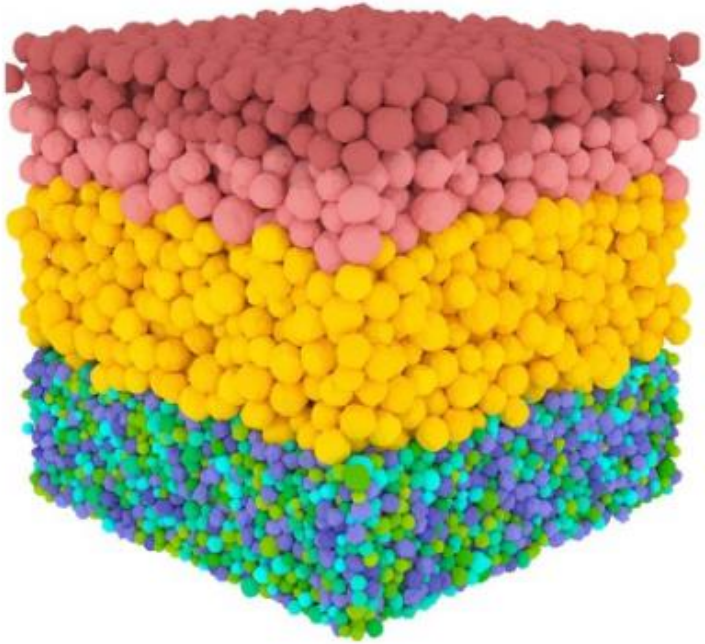




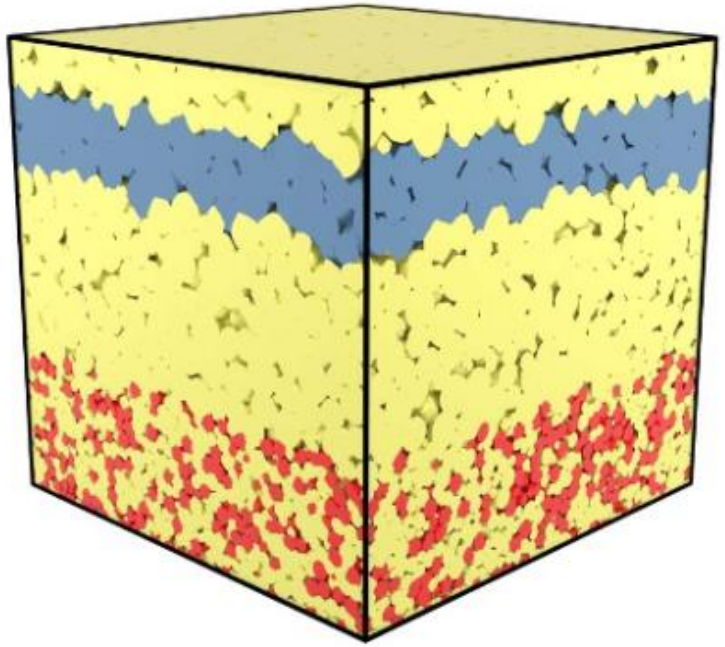
Microstructure generator



Packing of spheres



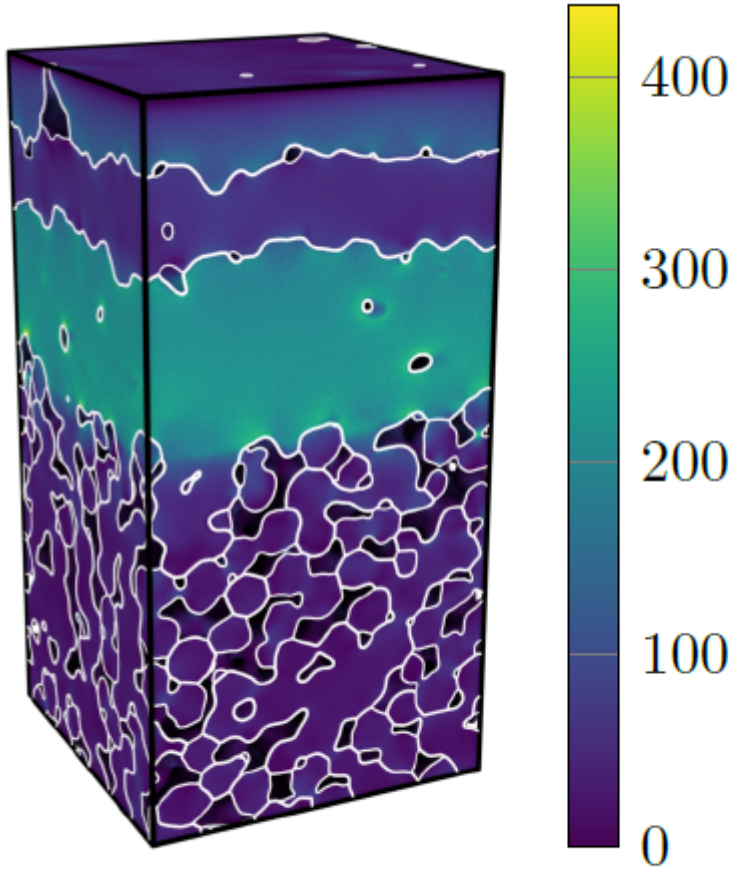
Generating particle shapes



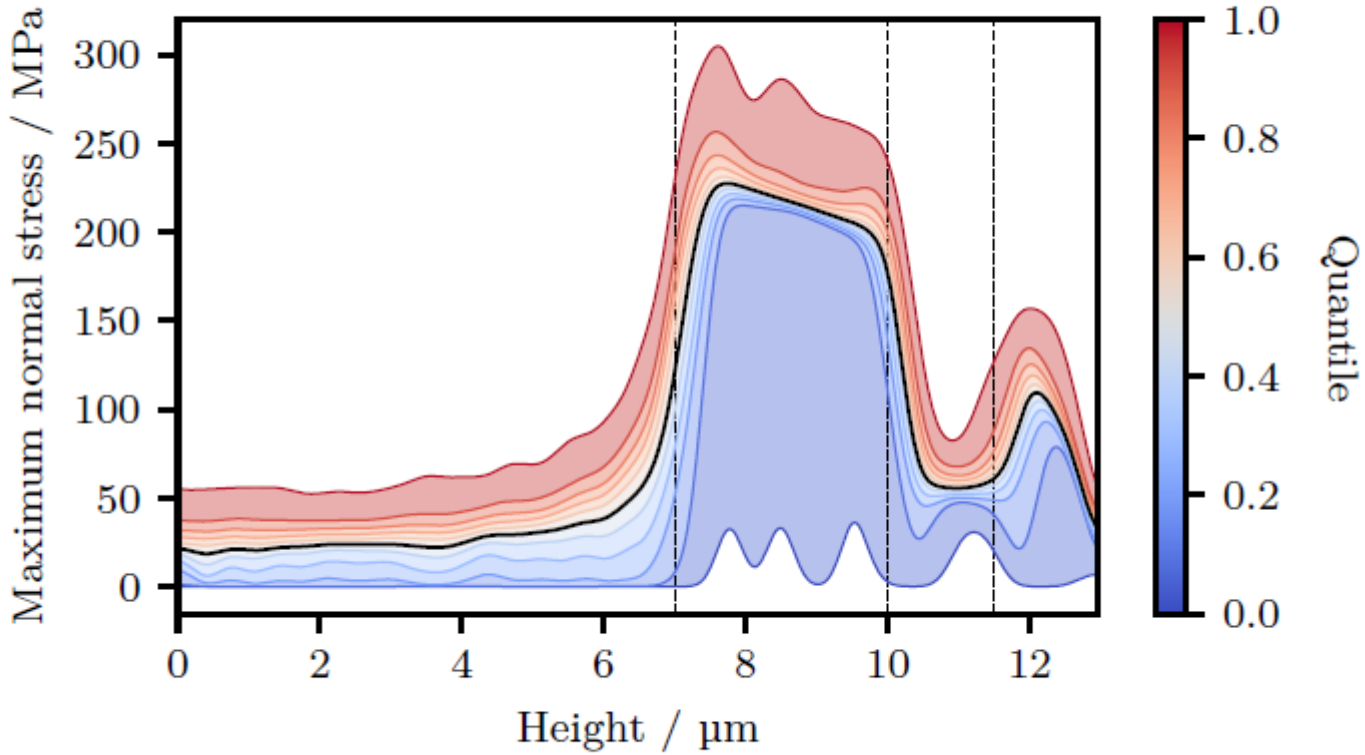
Phase-field representation

Virtual design of multilayered SOFC microstructures based on particle packing and spherical harmonics
L. Schöller, L. Wehner, D. Schneider, R. Schwaiger and B. Nestler
Modelling and Simulation in Materials Science and Engineering 2026
http://iopscience.iop.org/article/10.1088/1361-651X/ae7138

3D stress distribution



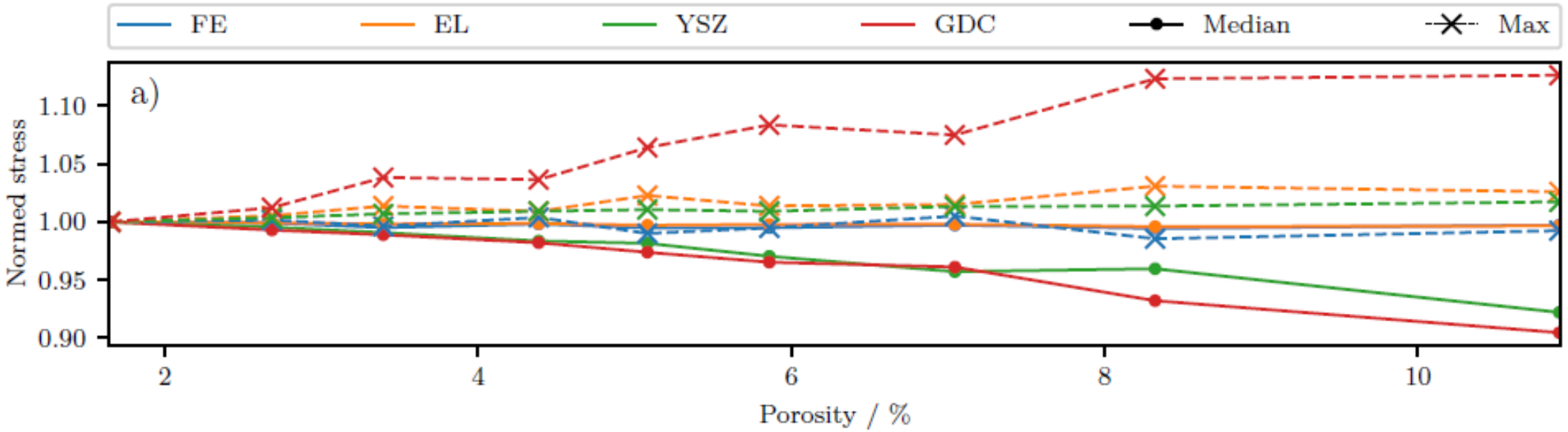
(a) Full field distribution



(b) Statistical distribution over height

Microstructure variation

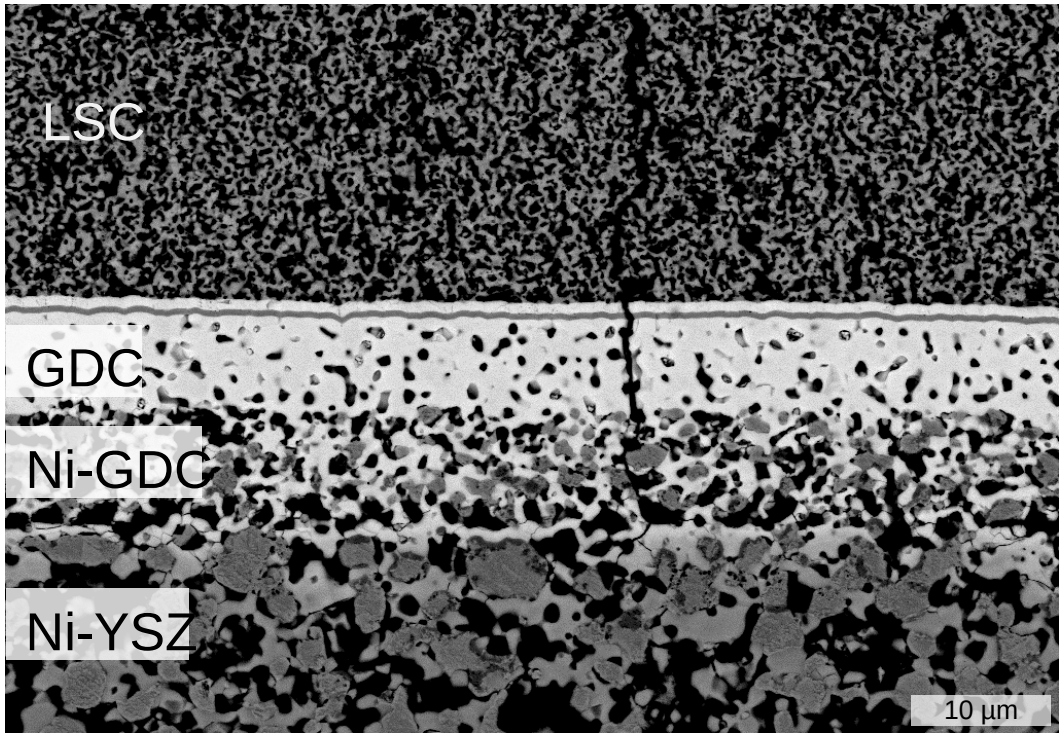
Porosity



Increased porosity leads to lower average stresses in GDC barrier and YSZ layer
→ More compliant layers
But maximum stress increases slightly
→ Stress concentration around pores

Conclusions

- 3D model to predict distribution of electro-chemo-mechanical stress in microstructure
- Requires detailed information of material parameters
- Boundary conditions limit accuracy and reliability
- Great performance for SOE cells, but questions remain



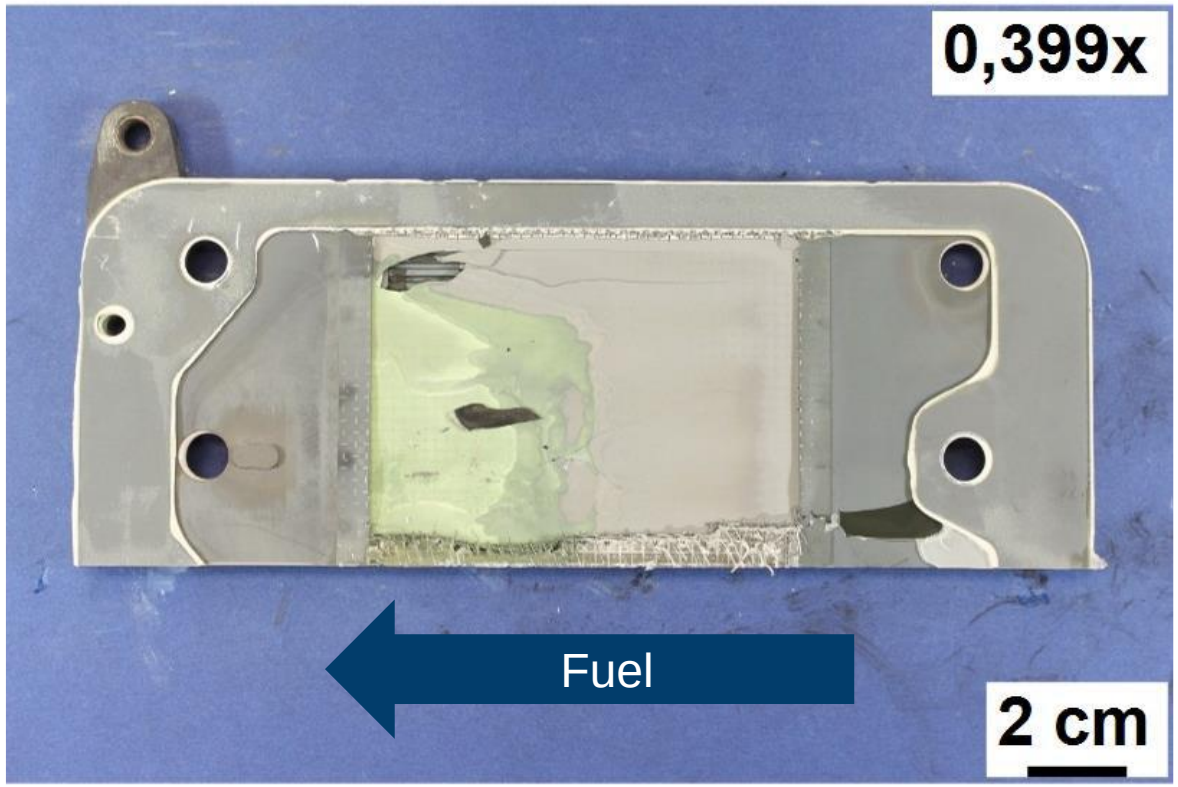
With funding from the:

Federal Ministry of Research, Technology and Space

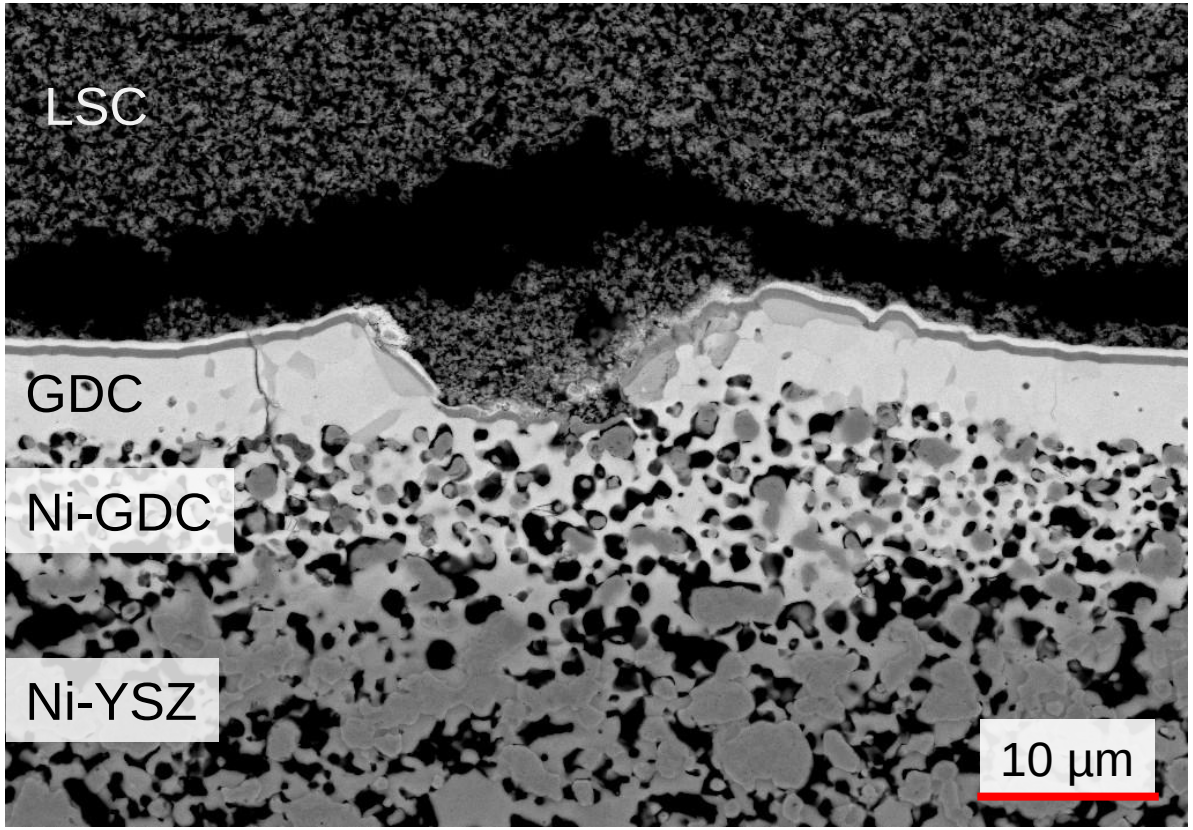
Funding from the German Ministry of Research, Technology and Space (FK: 03SF0641A) is greatly appreciated.

2-layer shortstack with PVD electrolyte

Image from stack opening – massive reoxidation

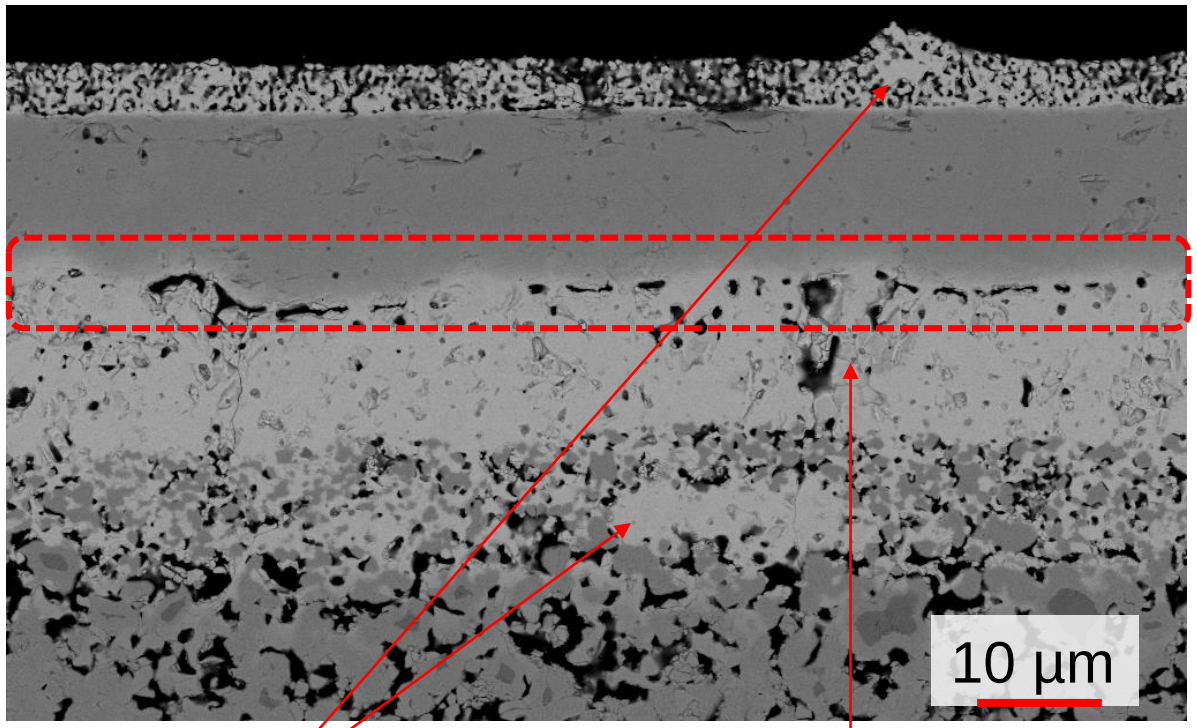


Air electrode touches GDC



SP- cell: Microstructure

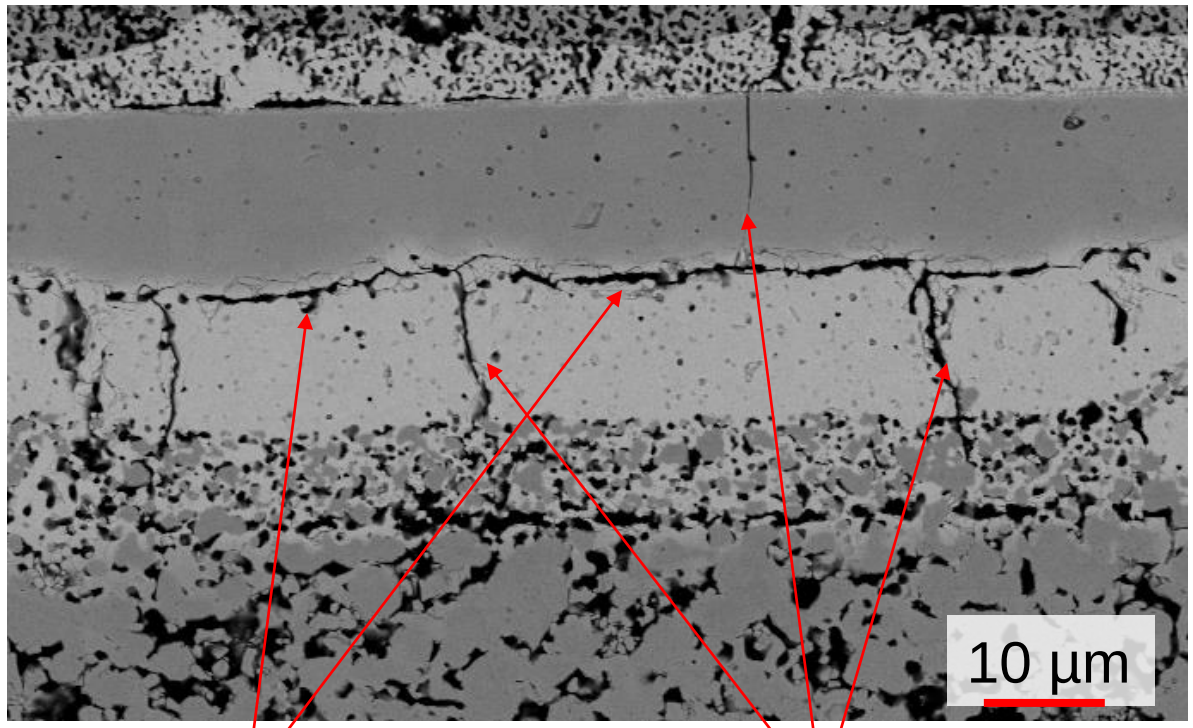
Reduction only



Agglomerates

Interface porosity

After testing

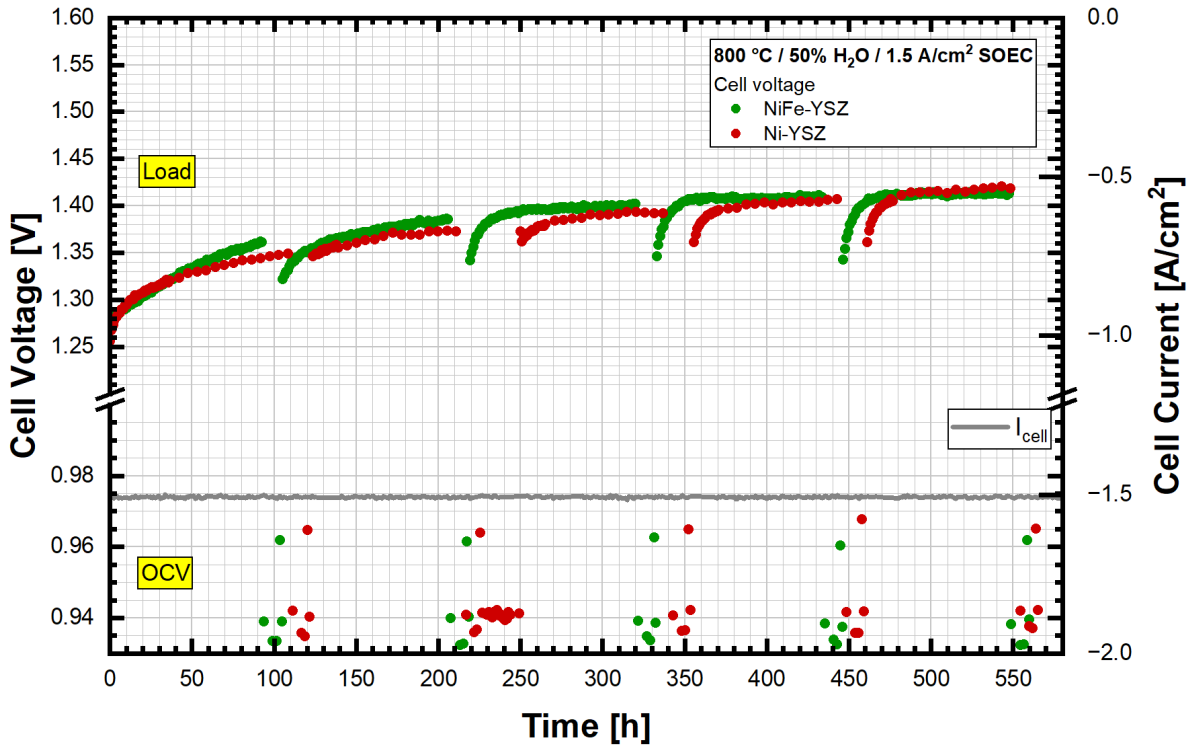


Delamination

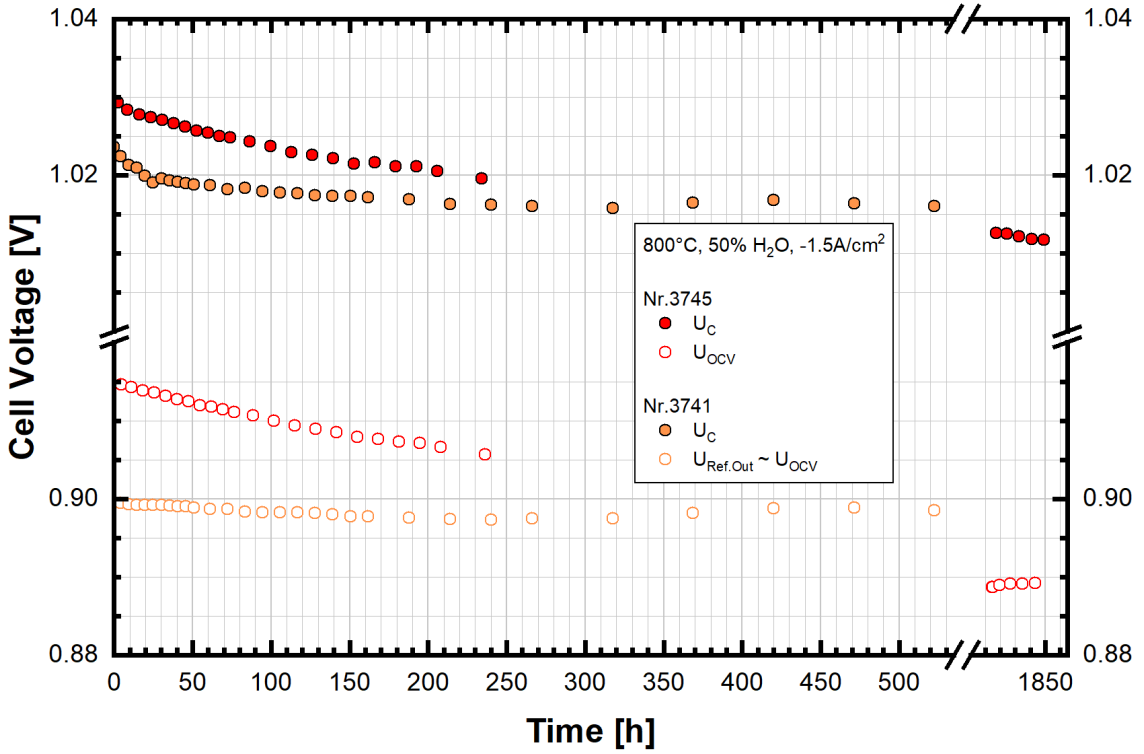
Cracks

Durability test – PVD cells

Baseline: Ni-YSZ & NiFe-YSZ

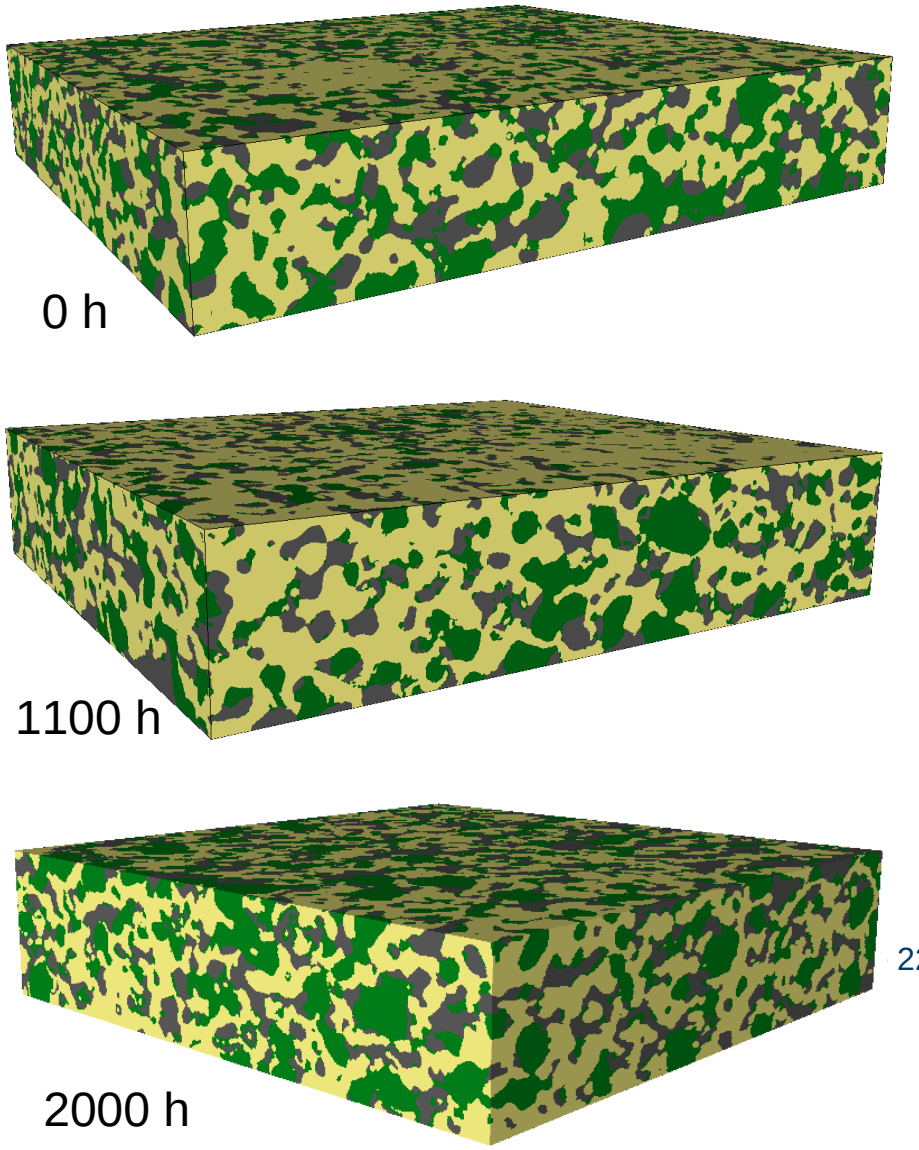


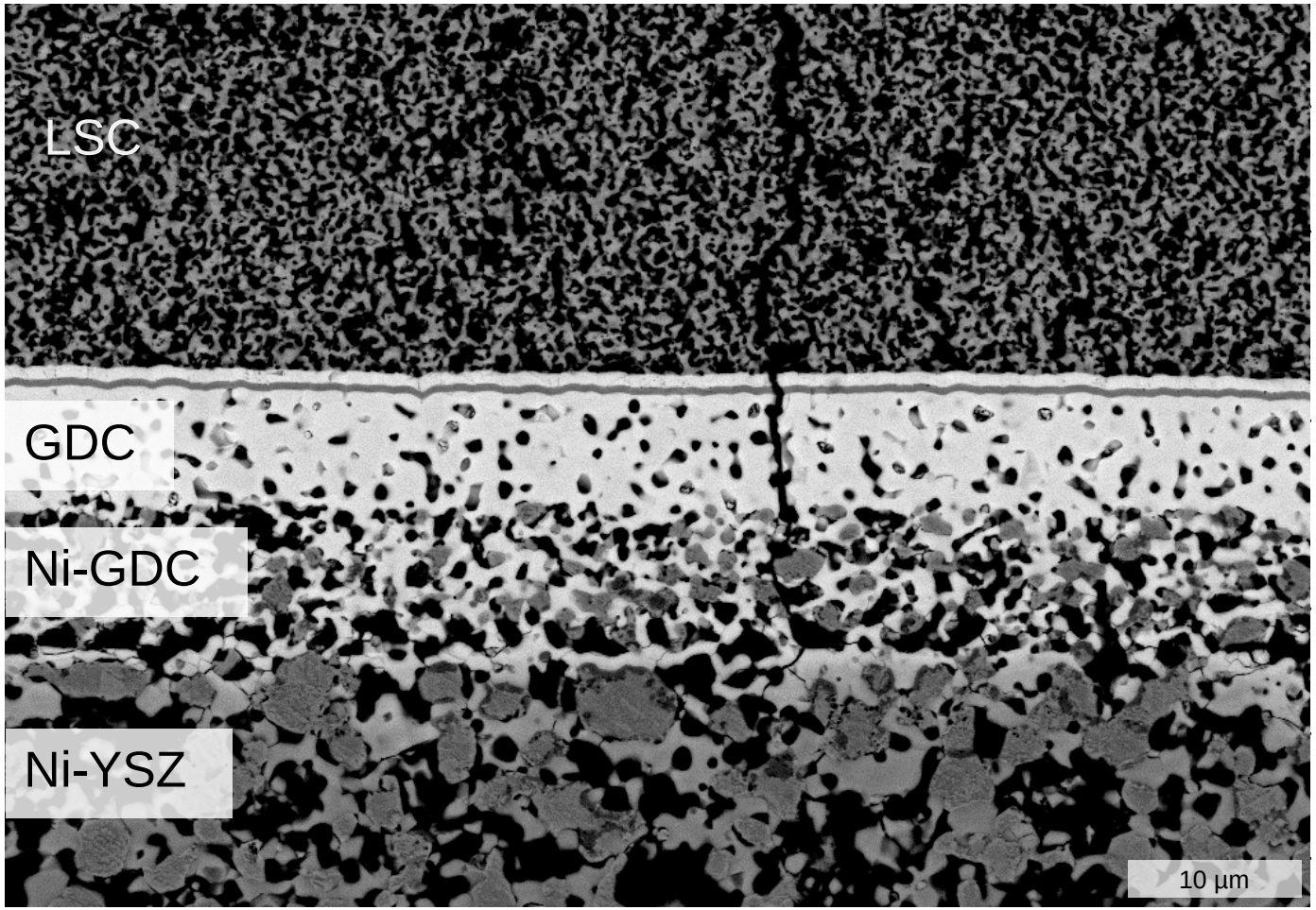
Ni-GDC with PVD electrolyte



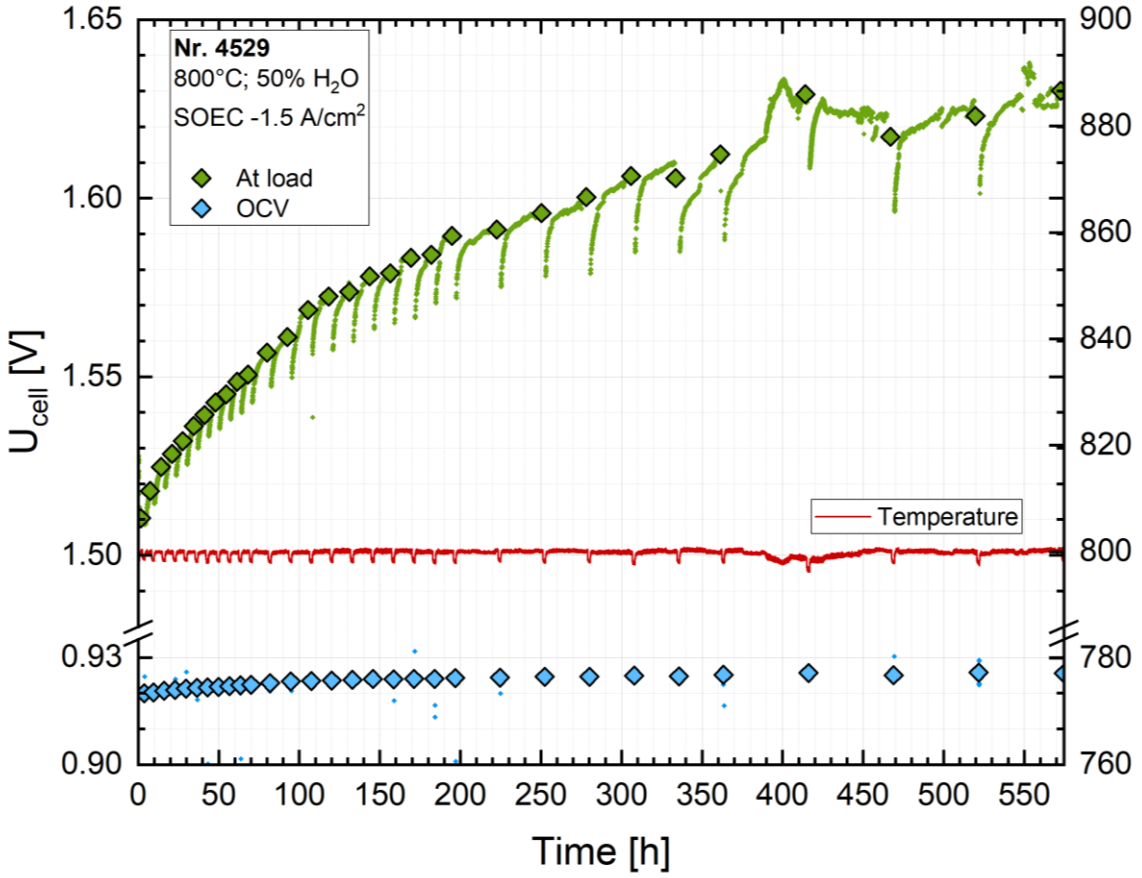
- 800 °C, 50:50 H_2/H_2O, 1.5 Acm^{-2}: Ni(Fe)-YSZ shows strong degradation
- Ni-GDC very stable over 2000 h, slight decreasing in (open circuit) voltage
- But: Faradaic efficiency unknown!

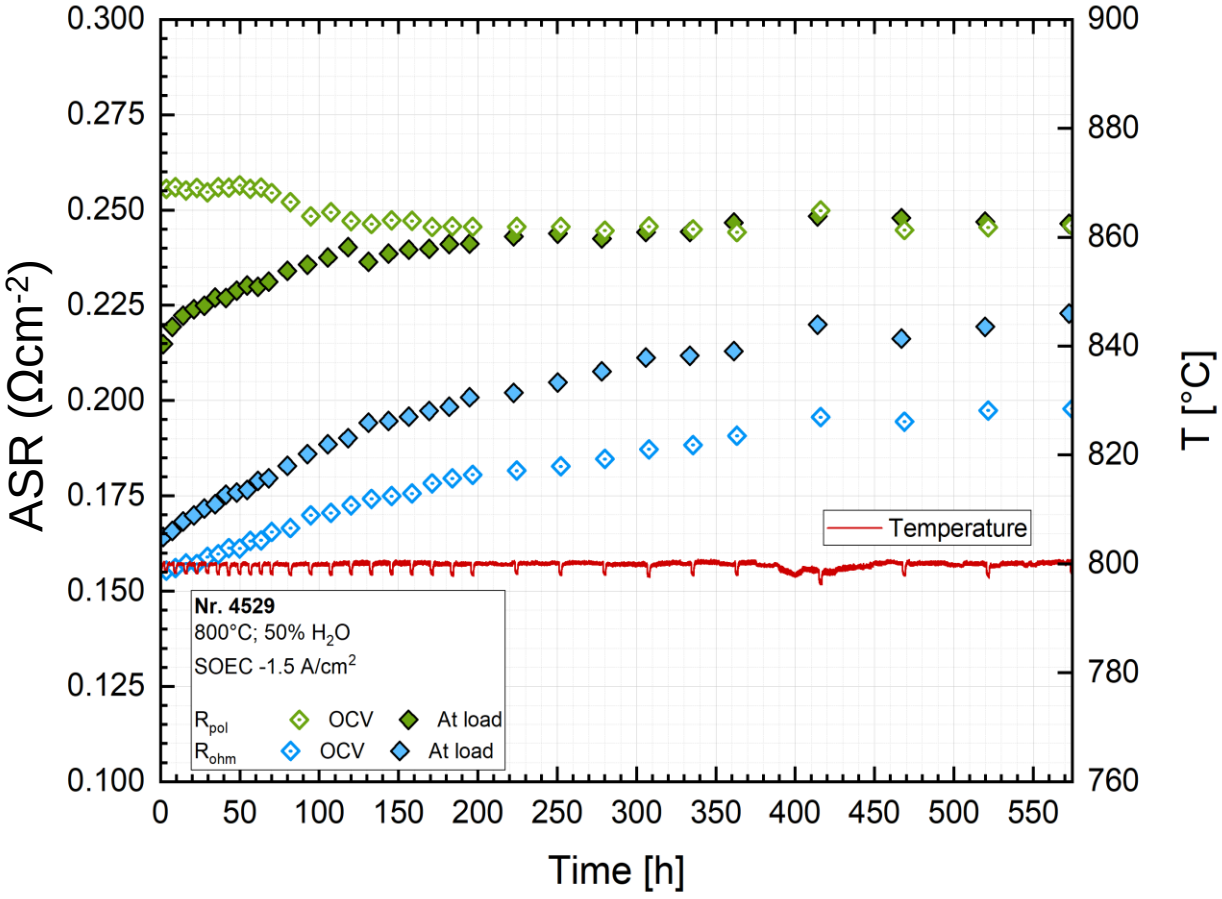
Post-test PVD cells: FIB-SEM reconstructions





Durability test – SP cell





- 800 °C, 50:50 H_2/H_2O, 1.5 Acm^{-2}: Substantial degradation; mostly ohmic ASR