

# Fertigung von Festoxidzellen – Laborskala bis zur (Klein)serie

MARCH 12TH, 2026

CHRISTIAN LENSER

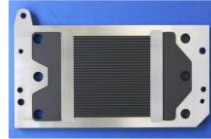
# Motivation

From lab to fab – a progression?

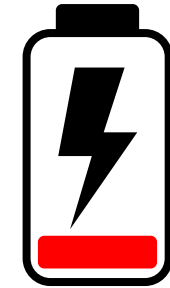
Ceramic materials



Metallic materials & coatings

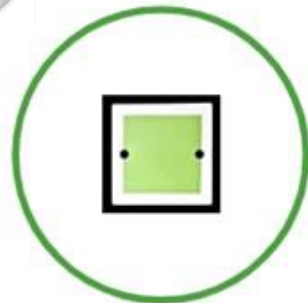


BoP components



Customer & demand

Suspensions



Fuel Cell  
25W



Stack



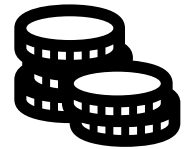
Server Module



Server  
250-300 kW



Power Solution  
250 kW to MWs

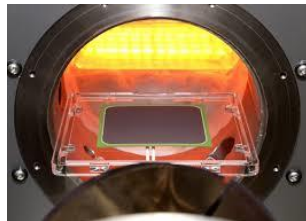


Business case

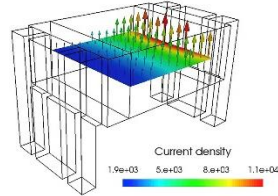
Shaping



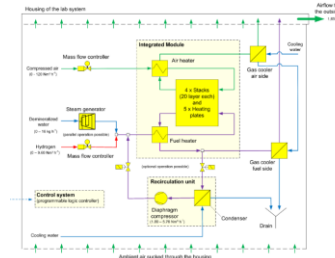
Sintering



Stack design



System layout



Recycling



Regulations



\*<https://www.bloomenergy.com/blog/everything-you-need-to-know-about-solid-oxide-fuel-cells/>

# Motivation

From lab to fab – different requirements with increasing TRL

Science

Engineering

Economics

TRL

Model systems

Material flexibility

Defined conditions

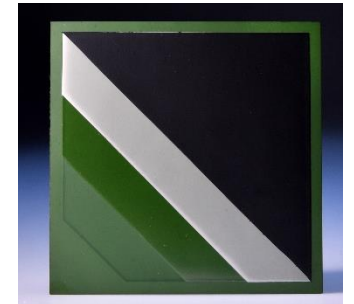
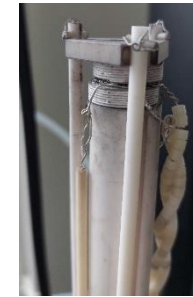
Processing

Optimization

Critical resources

Cost

Supply chain management



# Cell support structures

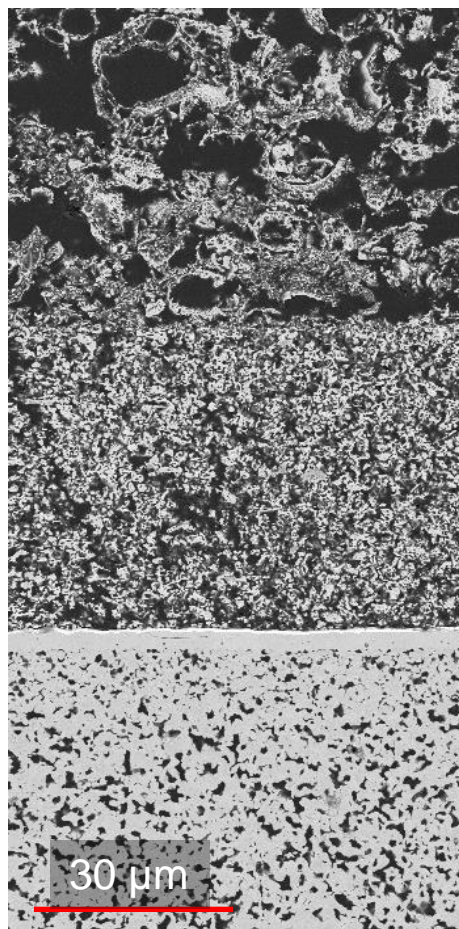
Under Creative Commons 4.0 License from:

\*D. Udomsilp, et al. Cell Reports Physical Science, 1 (2020) 100072.

\*\*N. Thambiraj et al, Energies, 13 (2020) 1624.

\*\*\*F. Wankmüller, et al, Journal of Materials Science, 55 (2020) 11120-11136.

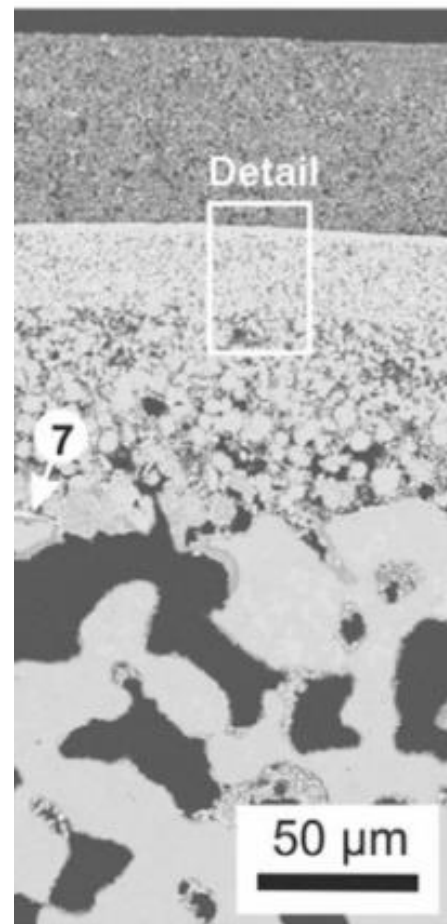
Fuel electrode



$T_{oper}$ : 600 – 800 °C

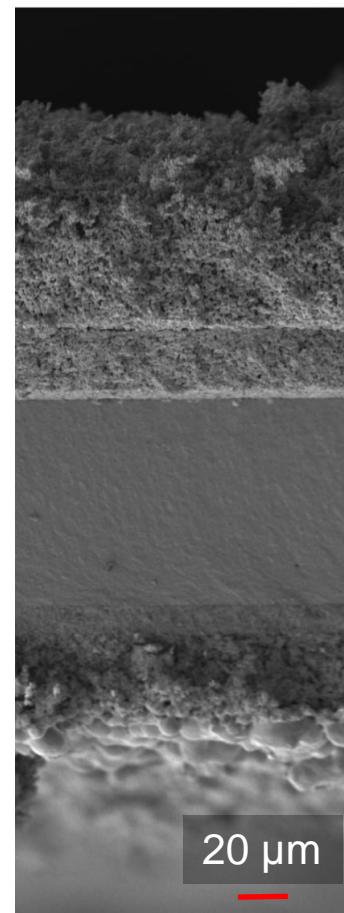
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Metal\*



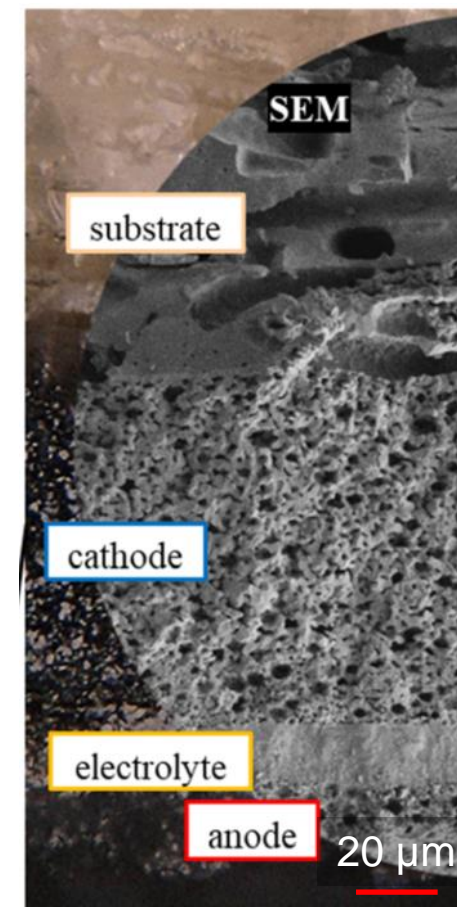
600 – 750 °C

Electrolyte\*\*



750 – 850 °C

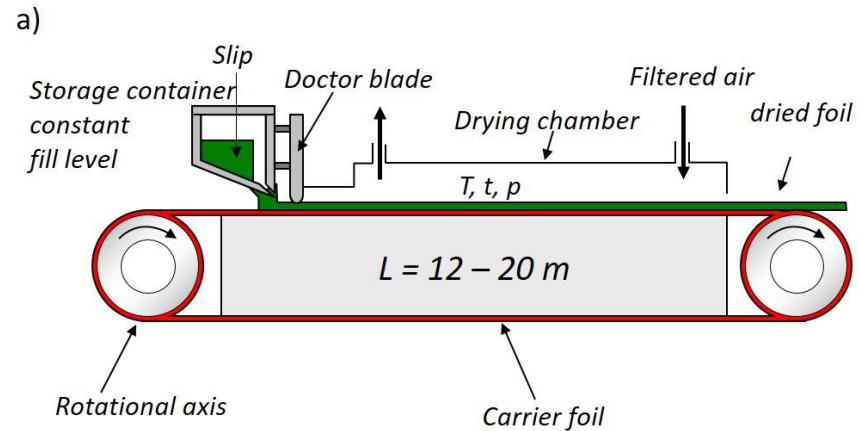
Inert\*\*\*



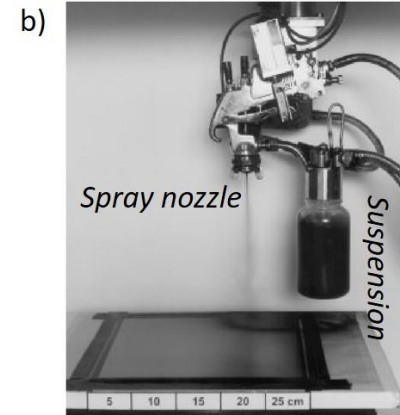
# Production techniques

## Examples

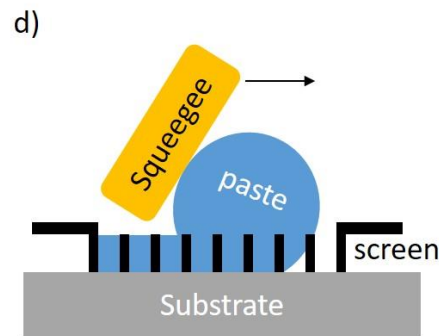
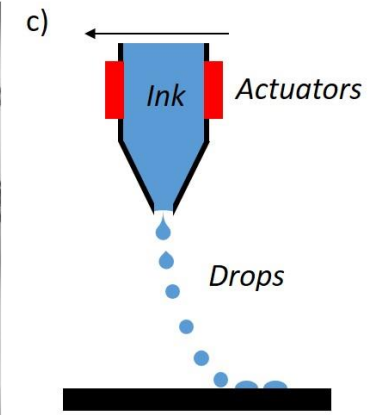
### Tape casting



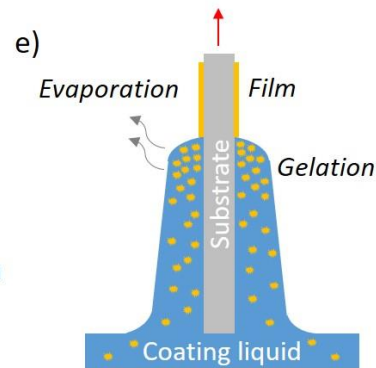
### Wet powder spraying



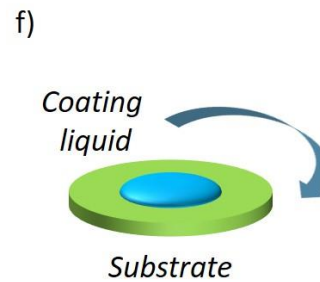
### Inkjet printing



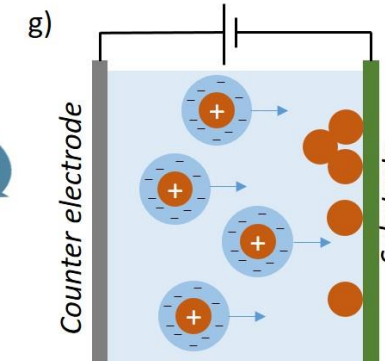
### Screen printing



### Dip coating



### Spin coating

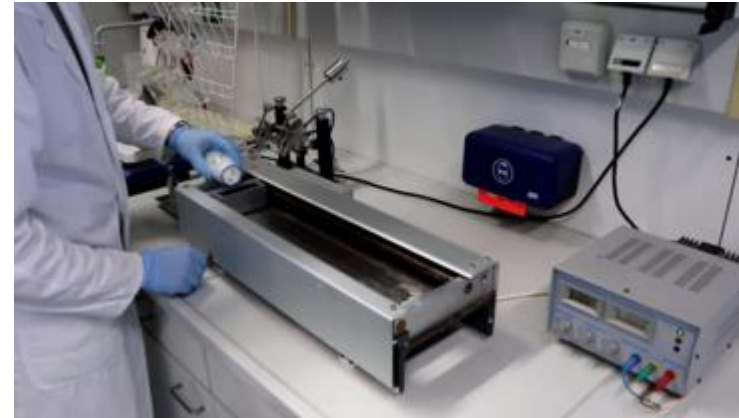
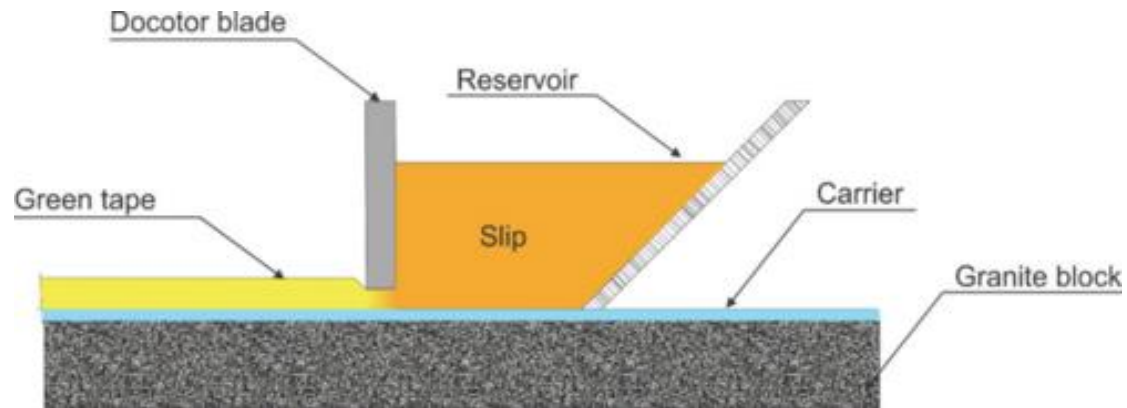


### Electrophoresis

# Production techniques

## Tape casting

- Suspension-based casting on a carrier tape
- Thickness control by doctor blade
- Slip composition is crucial



Laboratory tape caster

Industrial-sized tape caster



[https://apps.fz-juelich.de/ceramics/index.php?title=Tape\\_Casting](https://apps.fz-juelich.de/ceramics/index.php?title=Tape_Casting)  
<https://www.keko-equipment.com/Casting.php>

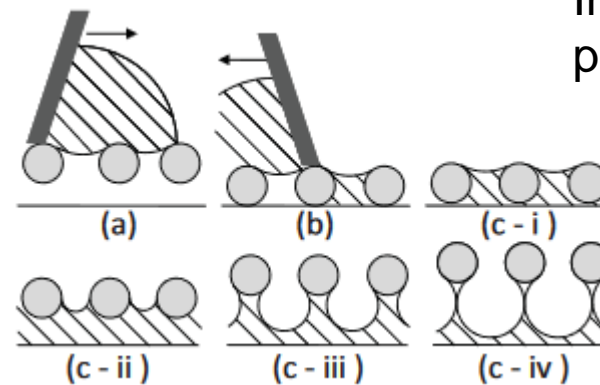
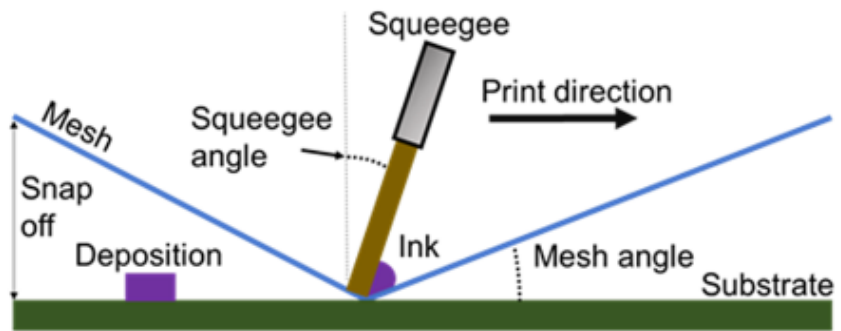
# Production techniques

## Screen printing

- Suspension-based transfer of paste through a mesh
- Thickness control through screen structure (e.g. mesh size)



Laboratory screen printer



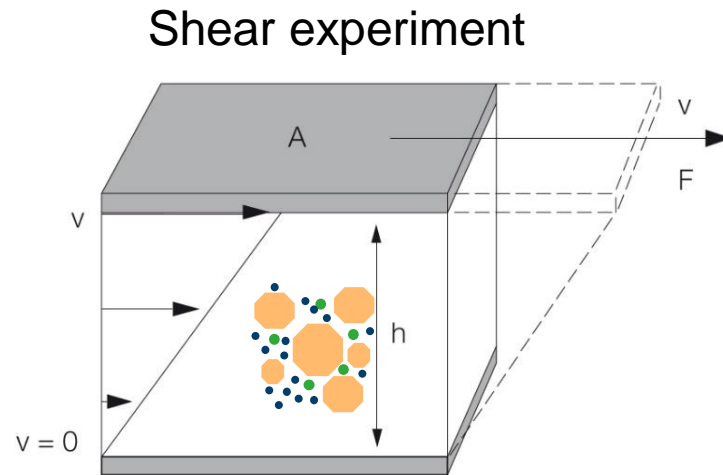
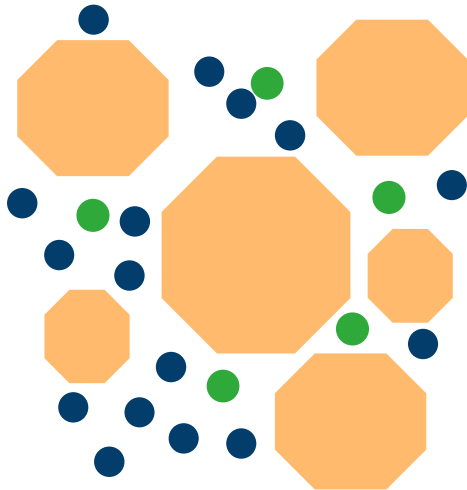
Industrial screen printer



# Rheology

## Particles in suspension

- Suspensions contain a liquid phase, ceramic particles and additives



Viscosity  $\eta$

Shear stress  $\tau = F/A$

Shear rate  $\dot{\gamma} = v/h$

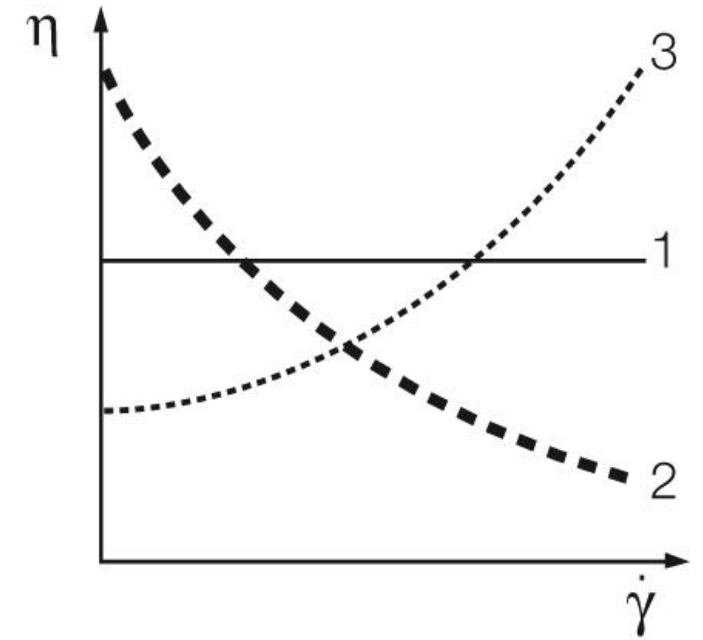
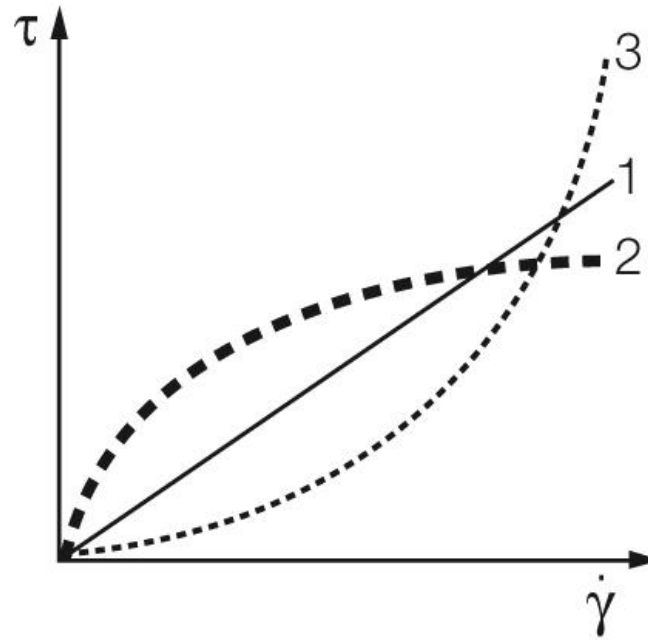
Shear viscosity  $\eta = \tau/\dot{\gamma}$

➤ Viscosity always depends on deformation speed!

# Rheology

## Suspension behavior

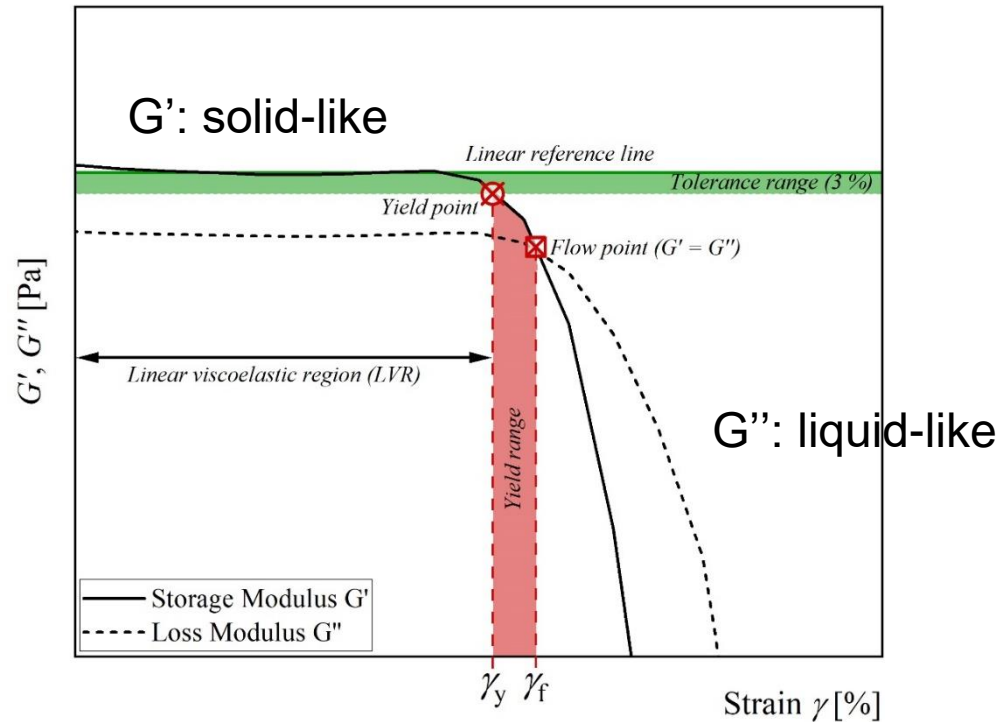
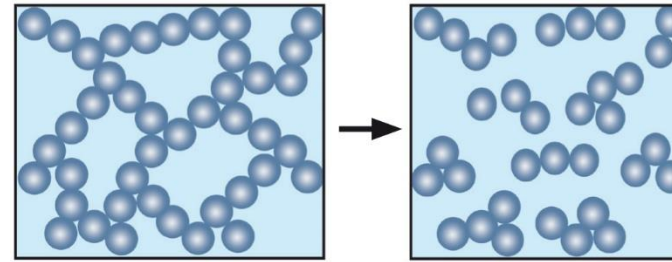
- Suspensions contain a liquid phase, ceramic particles and additives
- Suspension can have different behaviors:
  - Ideal (newtonian)
  - Shear thinning
  - Shear thickening



# Rheology

## Flow curve

$$G = G' + iG''$$



Analysis of rheology by oscillation testing

Shear modulus  $G = G' + iG''$

Damping factor  $\tan \delta = \frac{G''}{G'}$

$\tan \delta < 1 \rightarrow$  elastic

$\tan \delta > 1 \rightarrow$  viscous (liquid-like)

End of linear viscoelastic region  $\rightarrow$  yield point  $\gamma_y$

$G' = G'' \rightarrow$  flow point  $\gamma_f$

D. J. Ramler, R. Mücke, C. Lenser, O. Guillon and N. H. Menzler Journal of the European Ceramic Society 2025

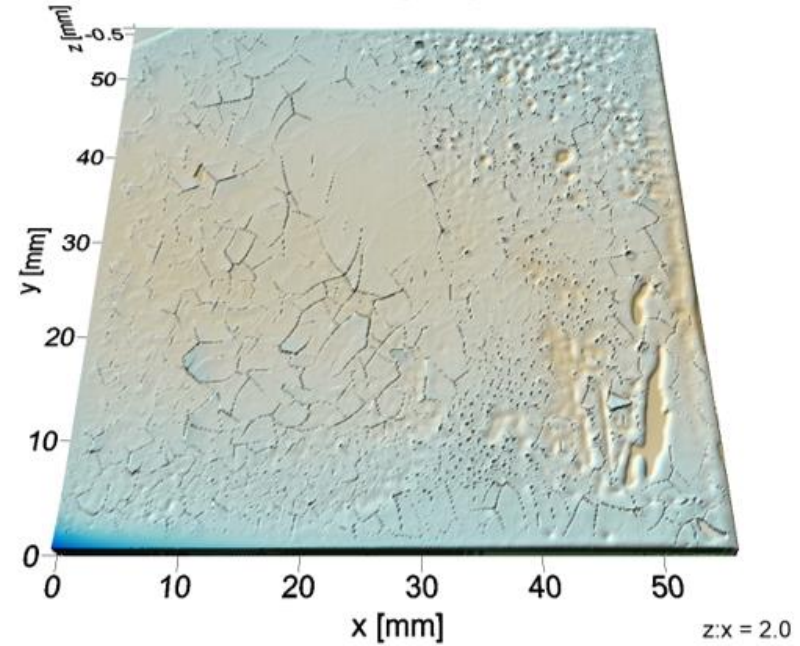
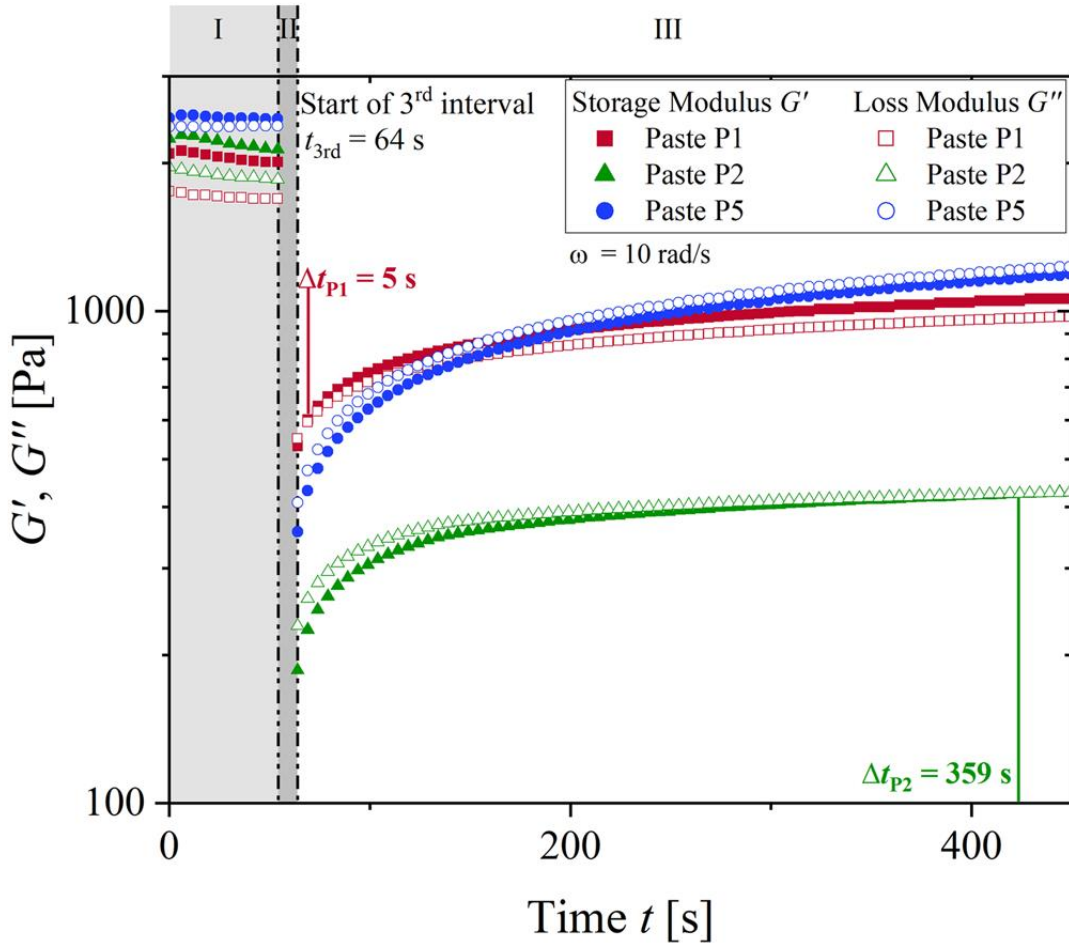
DOI: <https://doi.org/10.1016/j.jeurceramsoc.2025.117570>

<https://wiki.anton-paar.com/en/basics-of-rheology/#basics-of-rheology>

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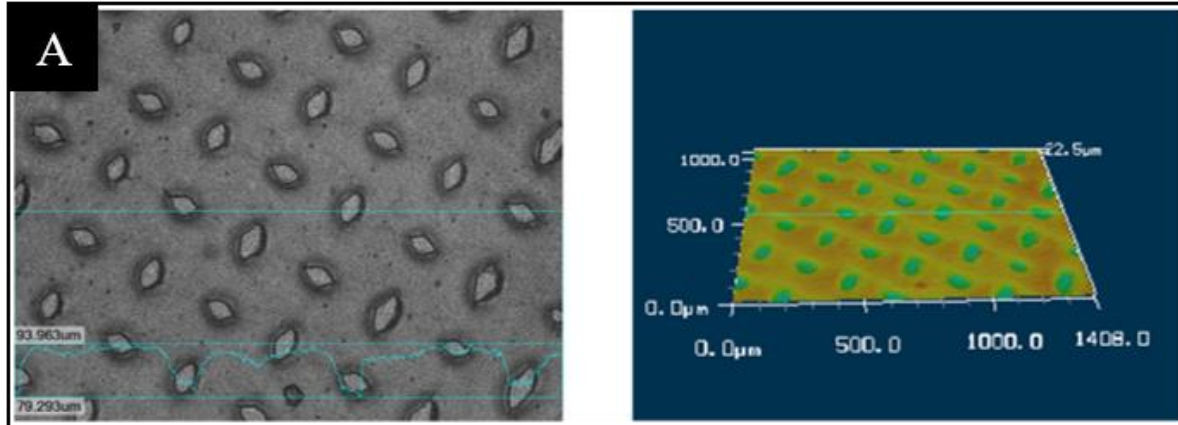
# Thixotropy

## Time-dependent behavior

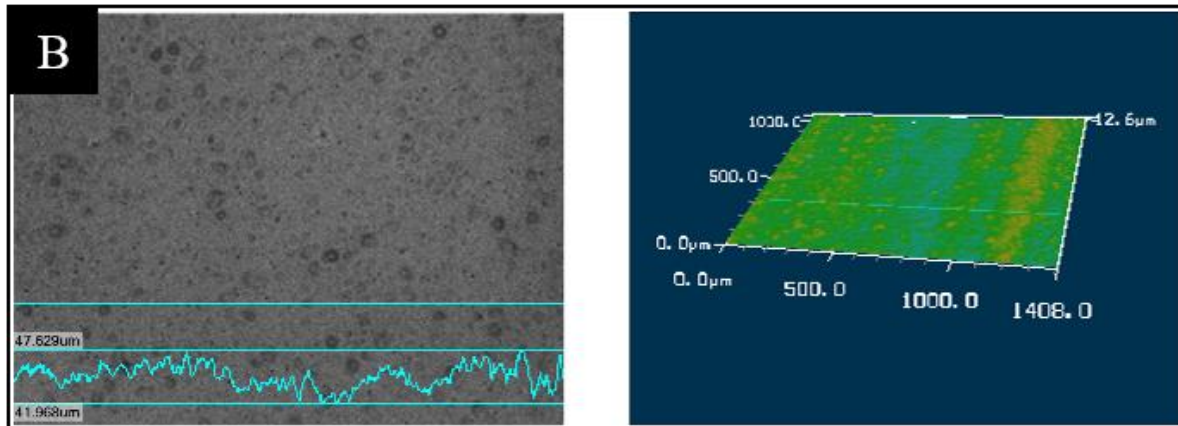


Drying cracks in screen-printed layer, likely due to too-fast drying of the paste

# Relevance of paste rheology – yield point



Paste with yield point at high deformations  
-> screen imprints

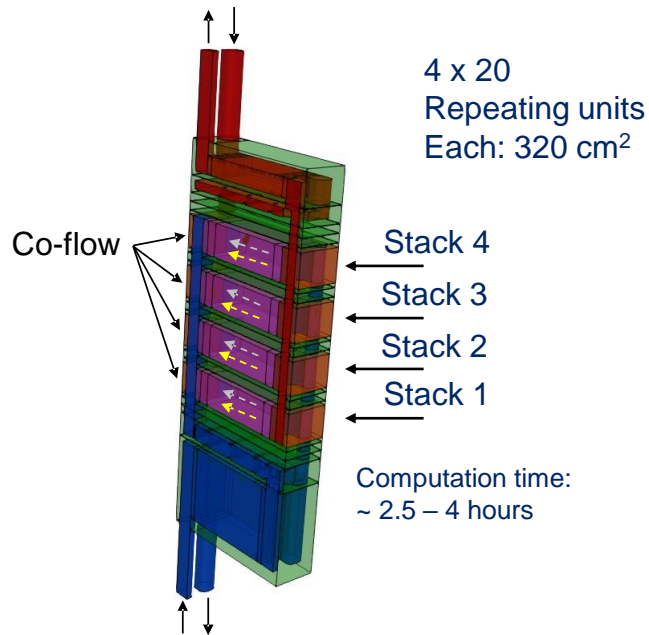


Paste with yield point at low deformations  
-> no screen imprints

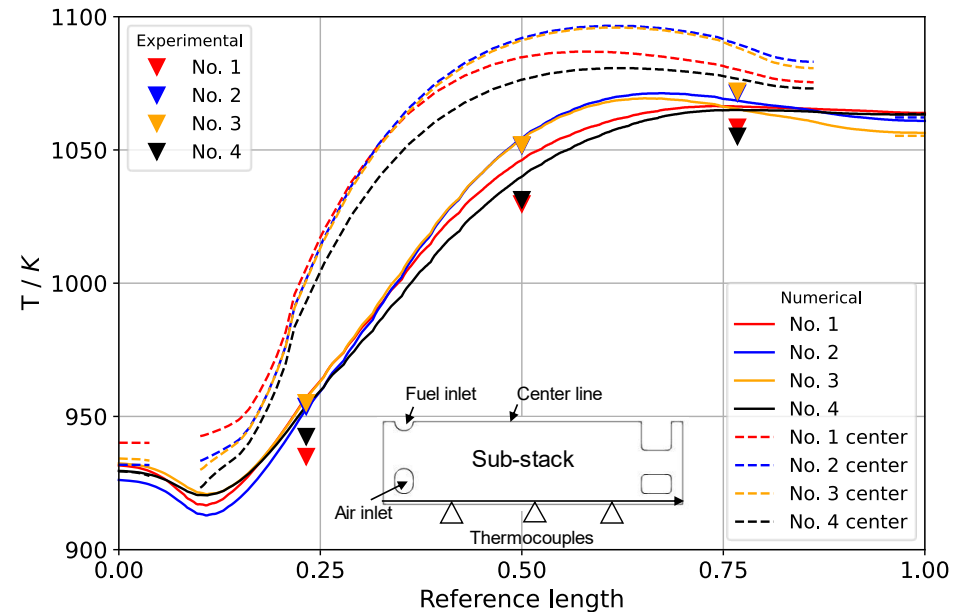
# Button cells

## Why button cells?

Numerical model of Jülich rSOC system



Thermal gradients along flow direction



## Real systems

- Large gradients
- Local conditions hard to access
- System -> averaged behavior

## Button cells

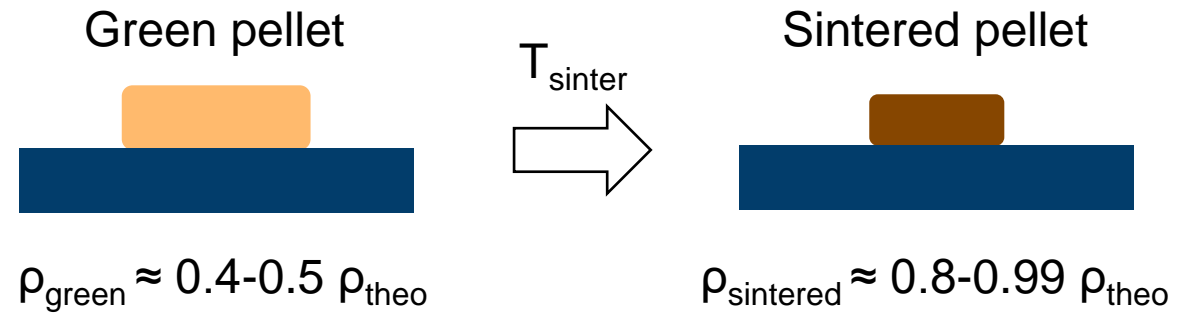
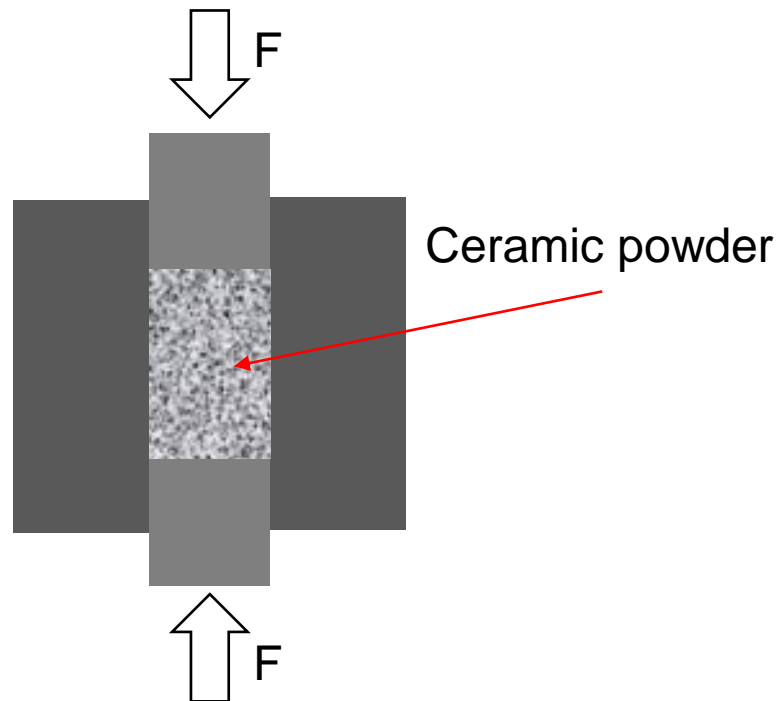
- Small area ~ 1 cm<sup>2</sup>
- Defined conditions
- No gradients over cell area
- Represents local conditions

<https://github.com/openFuelCell2/openFuelCell2>

# Button cells

## Dry pressing

- Simplest (and oldest) way to make a cell

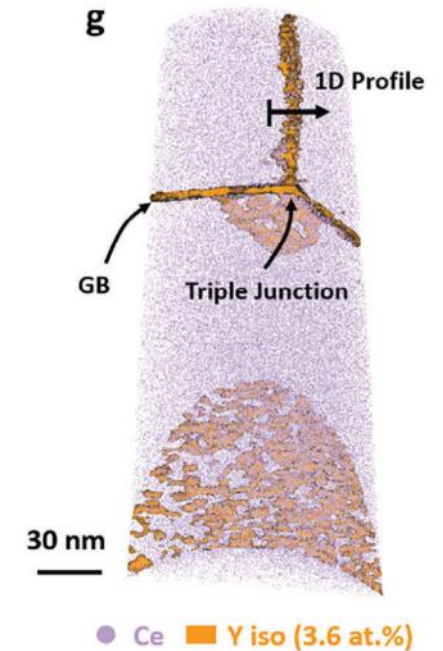
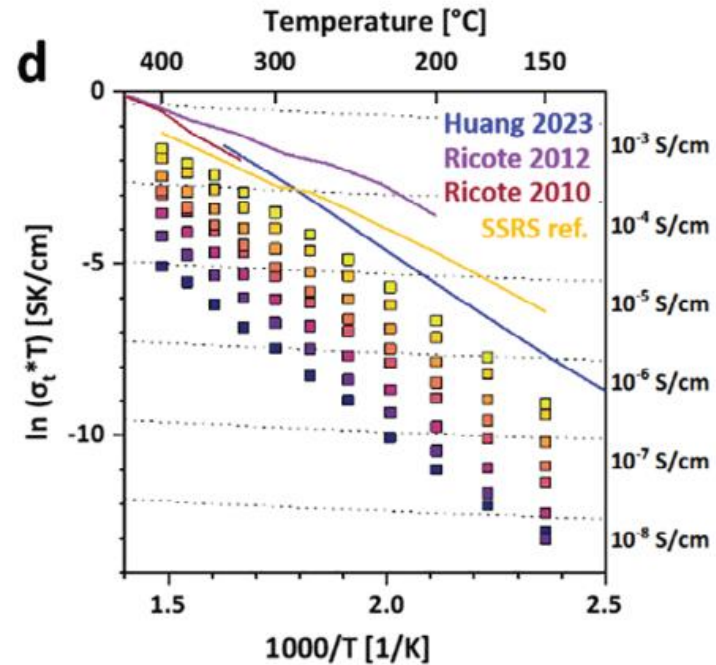
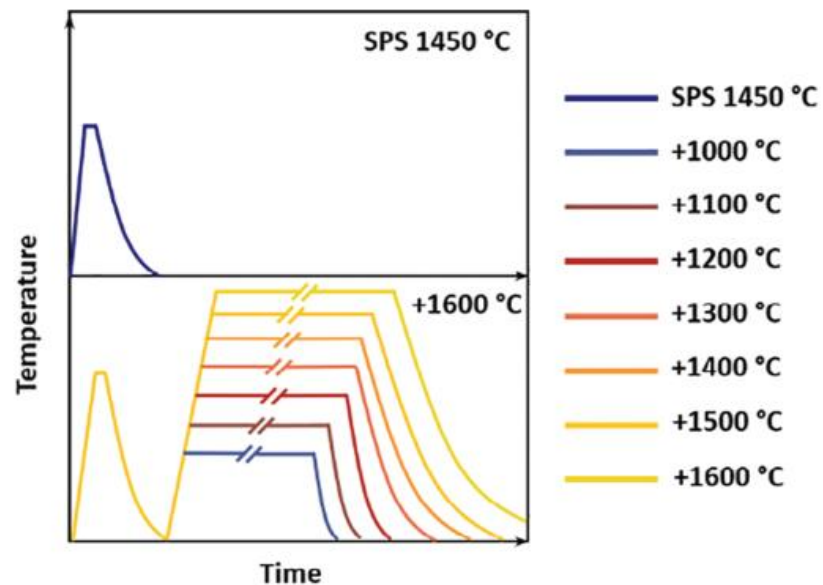


- Minimal effort / invest required
- Ideal for material characterization
  - Conductivity
  - Compatibility / Interdiffusion
- Free sintering
- Fundamental studies – e.g. dilatometry

# Button cells

## Fundamental studies - example

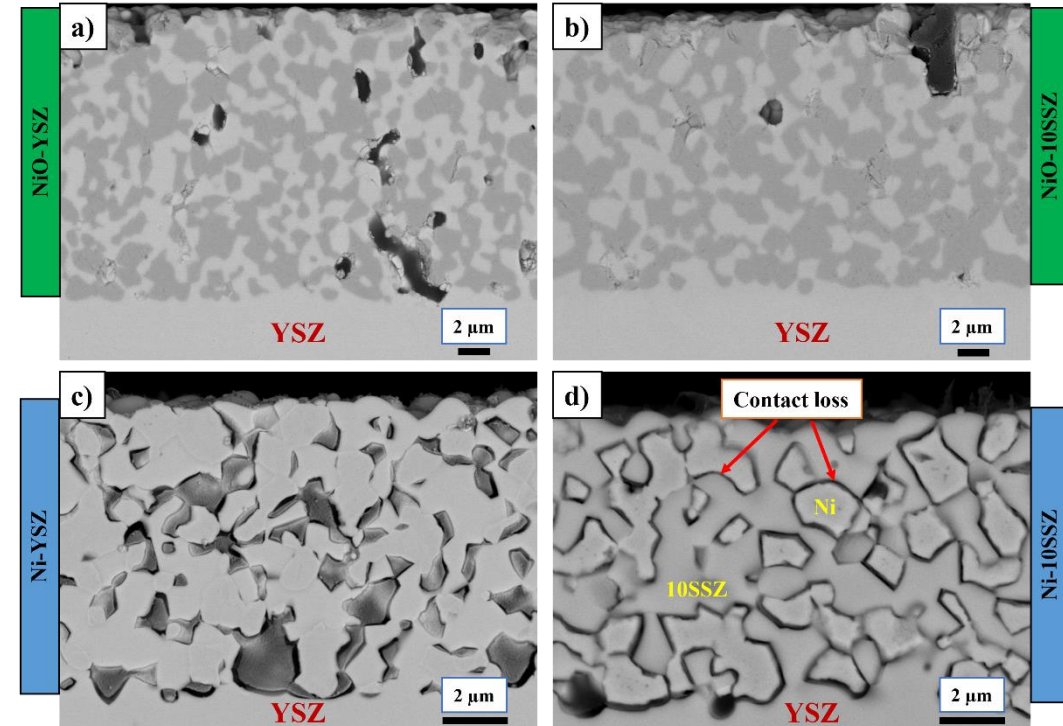
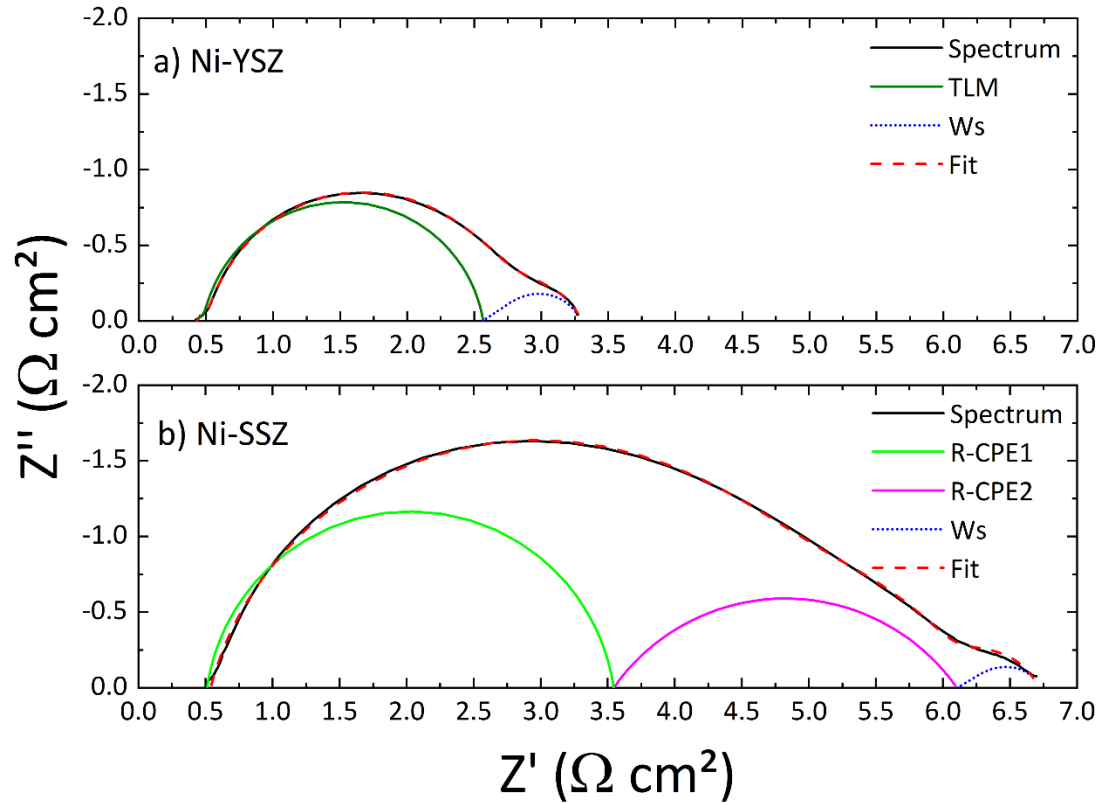
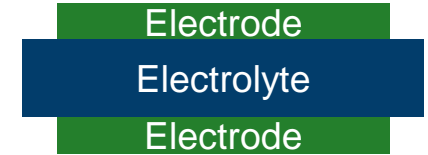
- Sintering of  $\text{BaZr}_{0.7}\text{Ce}_{0.2}\text{Y}_{0.1}\text{O}_{3-\delta}$  pellets by field-assisted sintering (FAST)
- Thermal post-treatment shows conductivity improvement through segregation of Y-dopants to grain boundaries



M. Kindelmann, I. Povstugar, S. Kuffer, D. Jennings, J. N. Ebert, M. L. Weber, et al.; Advanced Energy Materials 2024; DOI: 10.1002/aenm.202404410

# Button cells

## Tape-cast supports (commercial)



M. S. Khan, C. Lenser, C. Dellen, M. Müller, O. Guillon and N. H. Menzler  
 ACS Applied Energy Materials 2025; DOI 10.1021/acsaem.4c02754

Member of the Helmholtz Association

# Single cells

## Scaling to larger size

- Larger cell sizes are necessary for application
- Processing techniques should be scalable / automatable to continuous production
- Larger cell size brings new problems:
  - Mechanical strength
  - Camber during sintering
  - But also:
    - Batch-to-batch variations in raw materials
    - Adapt processing routines



# Camber

- When sintering asymmetric laminates / multilayers, the cell shows warping during sintering
- This camber is a result of mismatching shrinkage rates
- For a bilayer laminate, the rate of curvate  $\dot{\kappa}$  is proportional the rate of the shrinkage mismatch  $\Delta\dot{\epsilon}$ :

$$\dot{\kappa} = \left[ \frac{6(m+1)^2 mn}{m^4 n^2 + 2mn(2m^2 + 3m + 2) + 1} \right] \Delta\dot{\epsilon}$$

$$n = \left( \frac{\eta_1}{1-\nu_1} \right) \left( \frac{1-\nu_2}{\eta_2} \right)$$

Uniaxial viscosity

$$m = \frac{h_1}{h_2}$$

Layer thickness

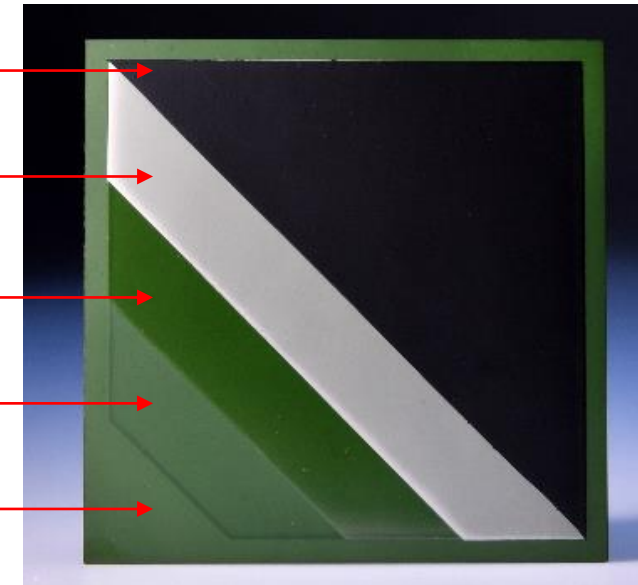
Air electrode

Barrier layer

Electrolyte

Fuel electrode

Support

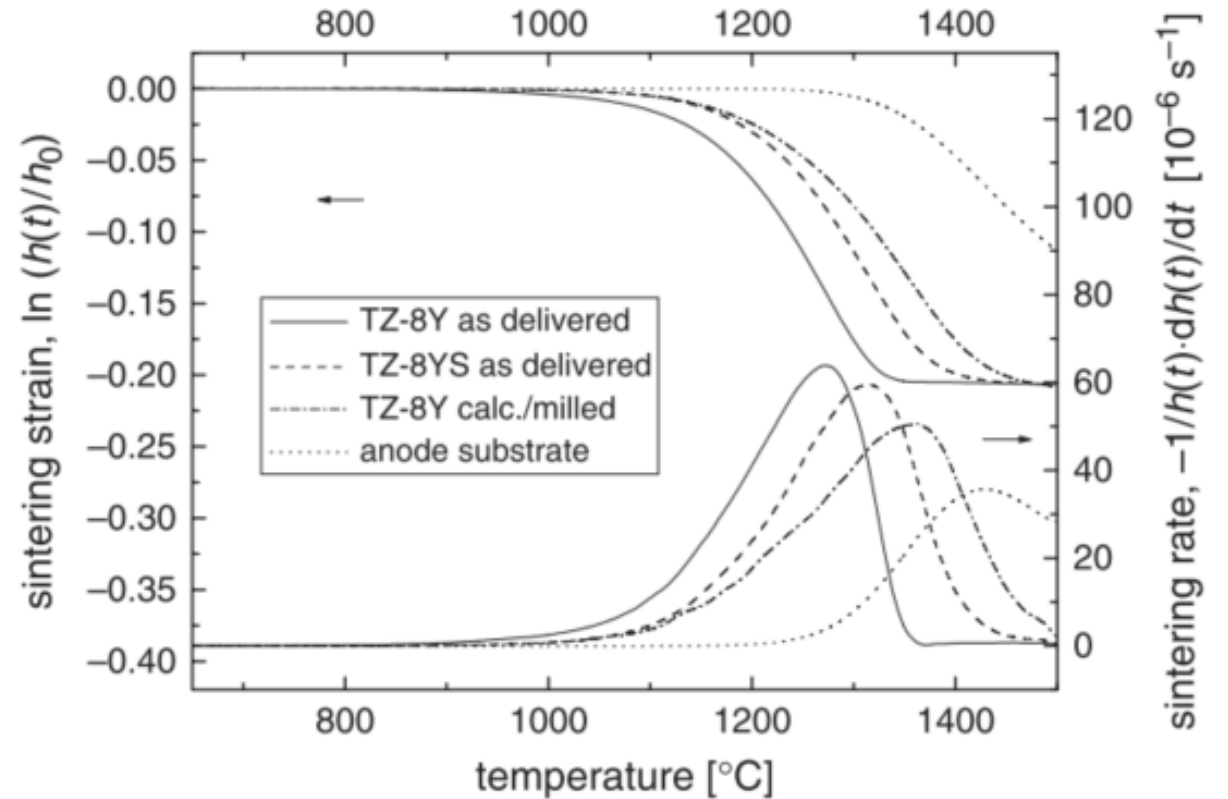


# Camber – shrinkage rates

- Cause for curvature is mismatch in shrinkage rates

$$\dot{\kappa} = \left[ \frac{6(m+1)^2 mn}{m^4 n^2 + 2mn(2m^2 + 3m + 2) + 1} \right] \Delta \dot{\epsilon}$$

- Example Jülich ASC
  - Coarse particles in NiO-YSZ support
  - Fine YSZ powder
  - Powder pre-treatment changes sintering properties

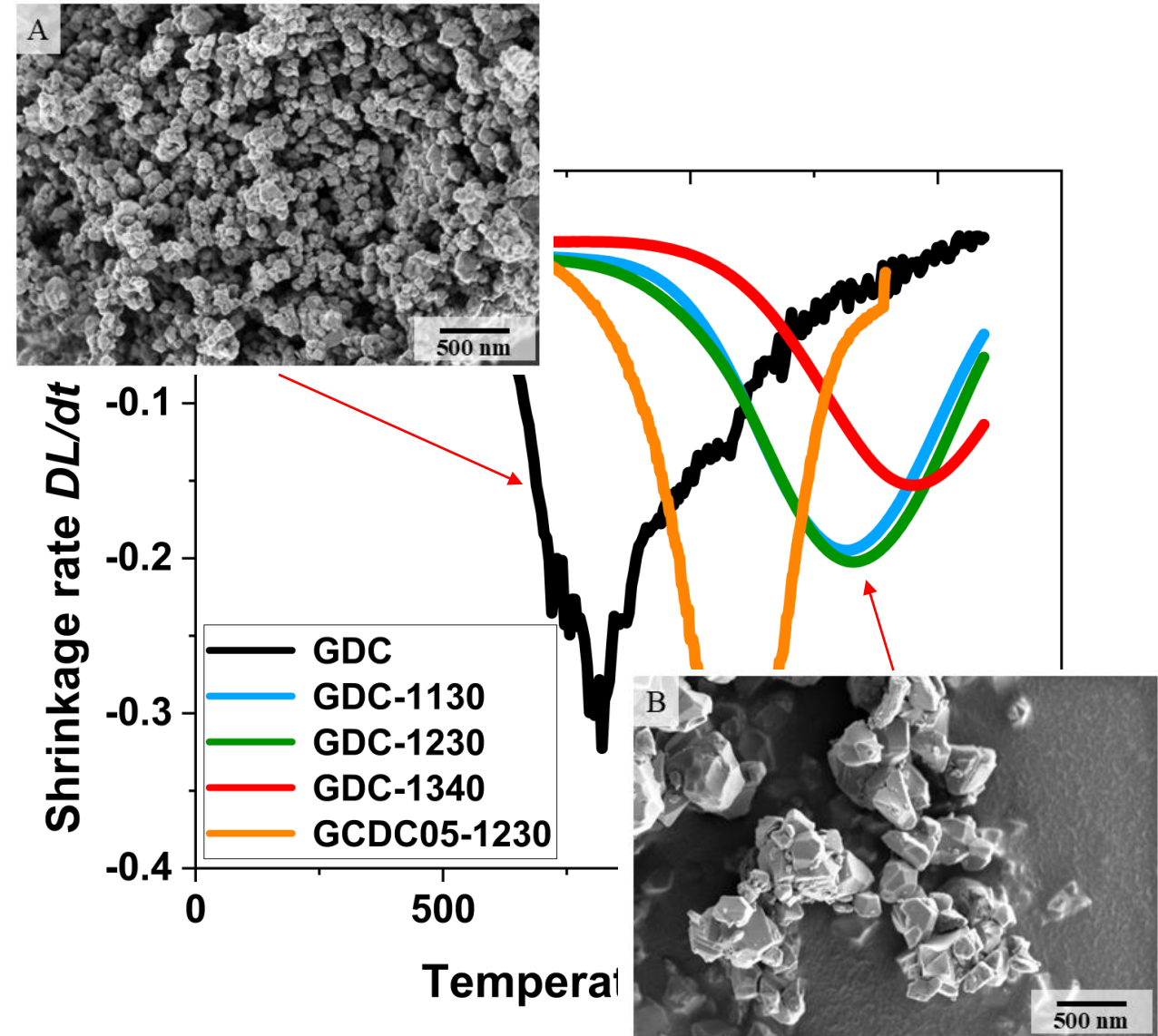


# Camber – shrinkage rates

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$$\dot{\kappa} = \left[ \frac{6(m+1)^2 mn}{m^4 n^2 + 2mn(2m^2 + 3m + 2) + 1} \right] \Delta \dot{\epsilon}$$

- Adjusting shrinkage rates minimizes camber
- Shrinkage rate is controlled by particle size and specific surface area

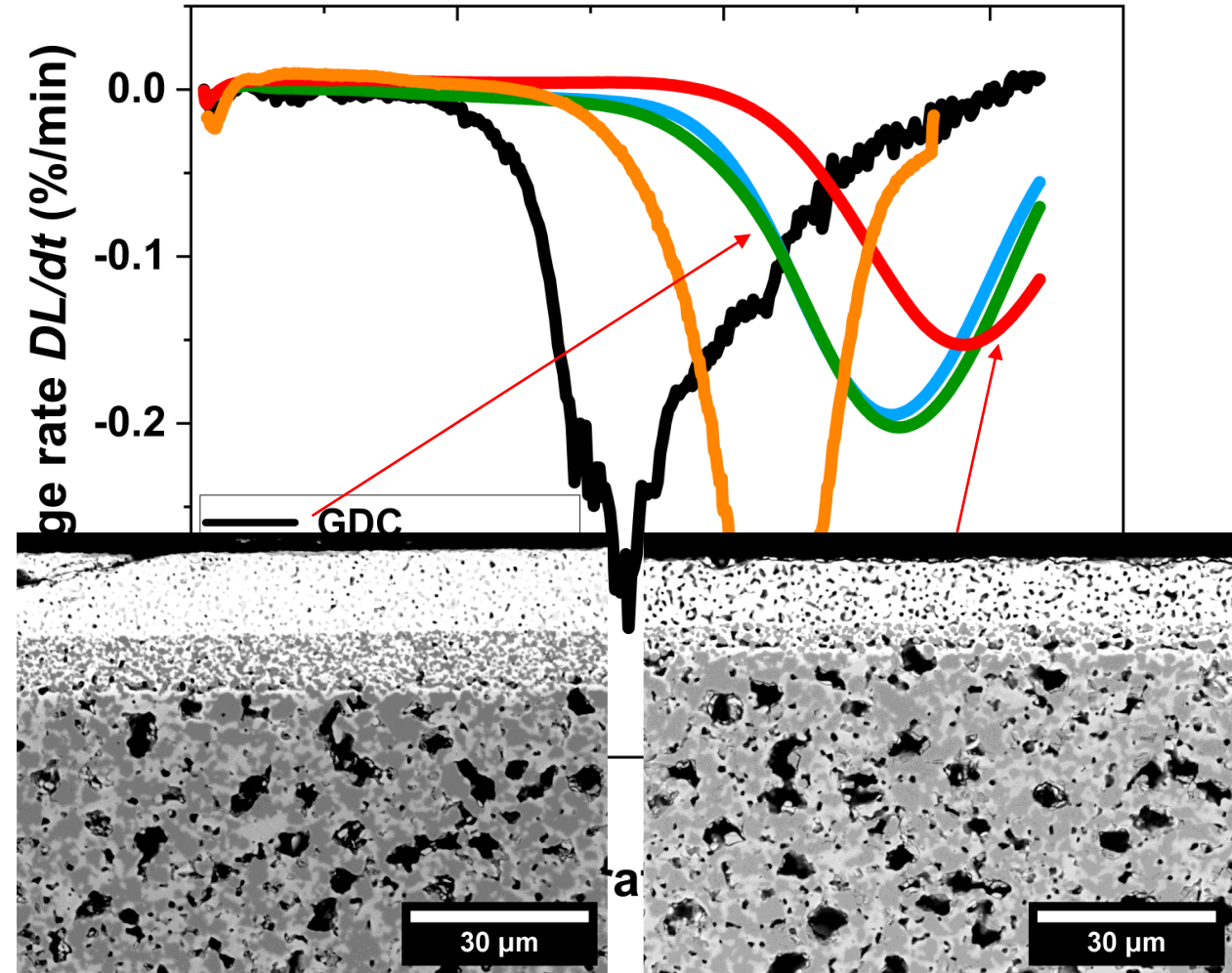


# Camber – shrinkage rates

- Cause for curvature is mismatch in shrinkage rates

$$\dot{\kappa} = \left[ \frac{6(m+1)^2 mn}{m^4 n^2 + 2mn(2m^2 + 3m + 2) + 1} \right] \Delta \dot{\epsilon}$$

- Adjusting shrinkage rates minimizes camber
- Shrinkage rate is controlled by particle size and specific surface area
- Limits in electrolyte densification



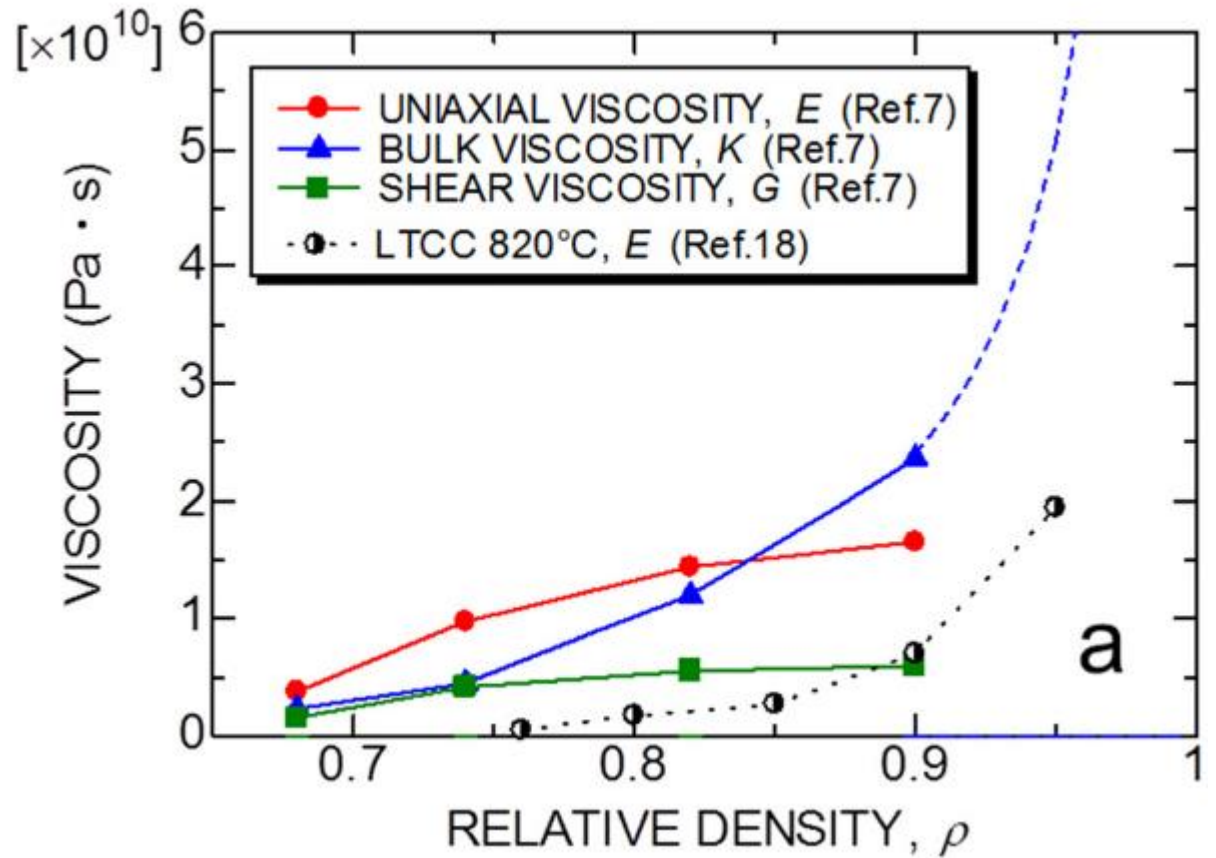
# Camber - viscosity

- Viscosity ratio of layers shows strong influence
- Increasing viscosity with rel. density

$$\dot{\kappa} = \left[ \frac{6(m+1)^2 mn}{m^4 n^2 + 2mn(2m^2 + 3m + 2) + 1} \right] \Delta \dot{\epsilon}$$

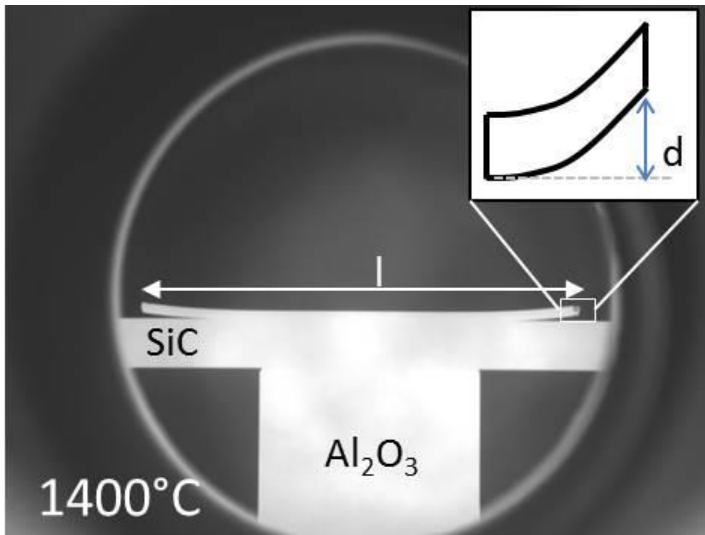
$$n = \left( \frac{\eta_1}{1-\nu_1} \right) \left( \frac{1-\nu_2}{\eta_2} \right)$$

- All parameters change during sintering -> complex & expensive to model precisely



# Camber – optical dilatometry

- Thermo-optical measurement system allows dilatometric measurements during sintering
- Cell is seen along one edge
- Electrolyte is 2  $\mu\text{m}$  of 8YSZ, deposited from a nanosuspension



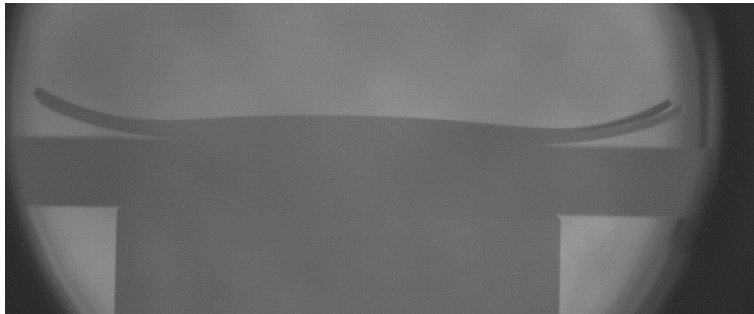
Sample	Composition	Thickness	Manufacturer
STC*	NiO-8YSZ	500 $\mu\text{m}$	FZJ
Type III	NiO-8YSZ	500 $\mu\text{m}$	FZJ
CTJ-e 19	NiO-3YSZ	400 $\mu\text{m}$	Ceramtec

Each cell has a  $\sim 7 \mu\text{m}$  NiO-8YSZ electrode

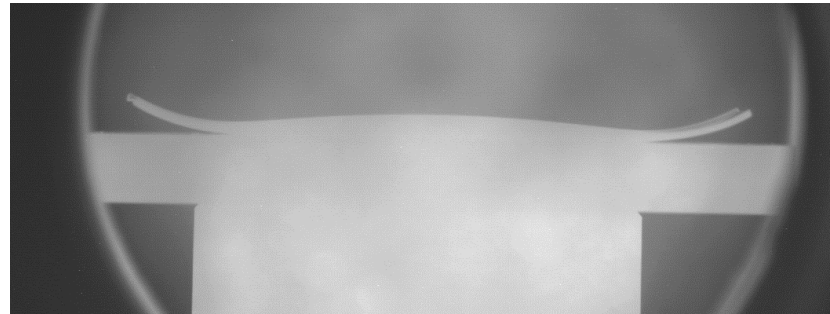
# Camber – optical dilatometry

- Thermo-optical measurement system allows dilatometric measurements during sintering
- Cell is seen along one edge
- Example: CTJ-e 19 (400  $\mu\text{m}$  NiO-3YSZ)

$T = 1300\text{ }^\circ\text{C}$   
 $dT/dt = 3\text{ K/min}$



$T = 1400\text{ }^\circ\text{C}$   
 $dT/dt = 0\text{ K/min}$   
 $t_{\text{hold}} = 0\text{ min}$

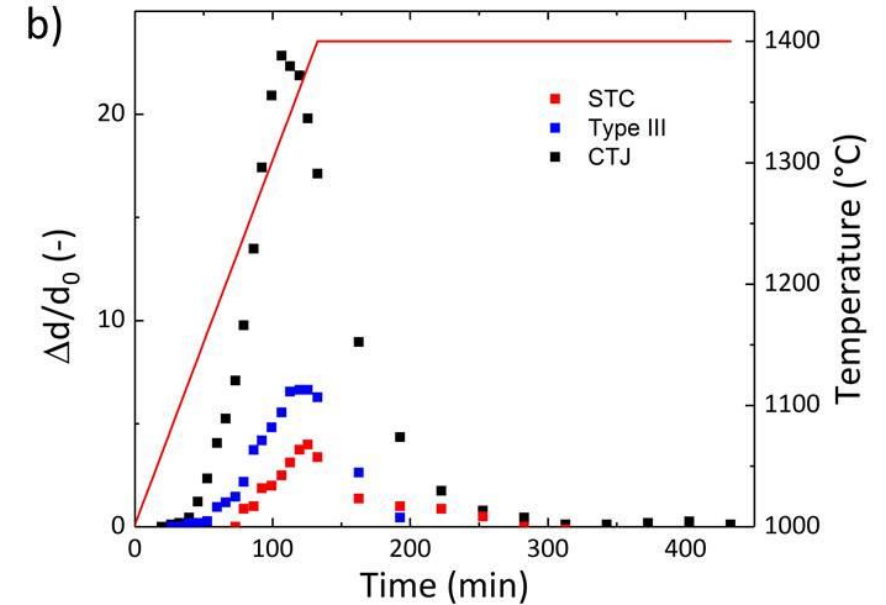
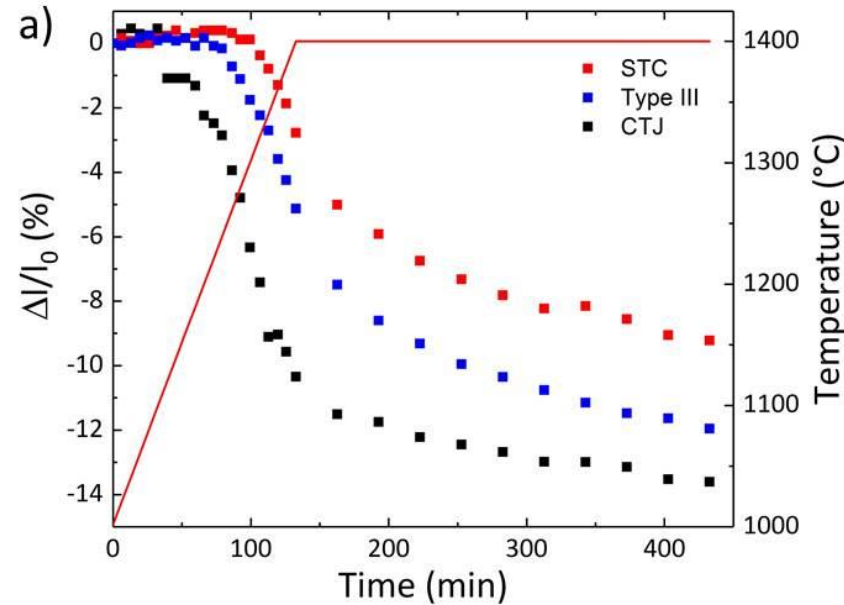
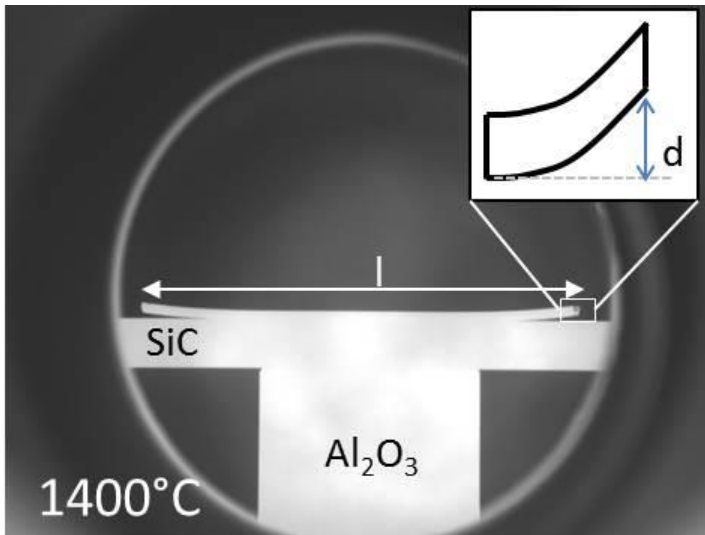


$T = 1400\text{ }^\circ\text{C}$   
 $dT/dt = 0\text{ K/min}$   
 $t_{\text{hold}} = 120\text{ min}$



# Camber – optical dilatometry

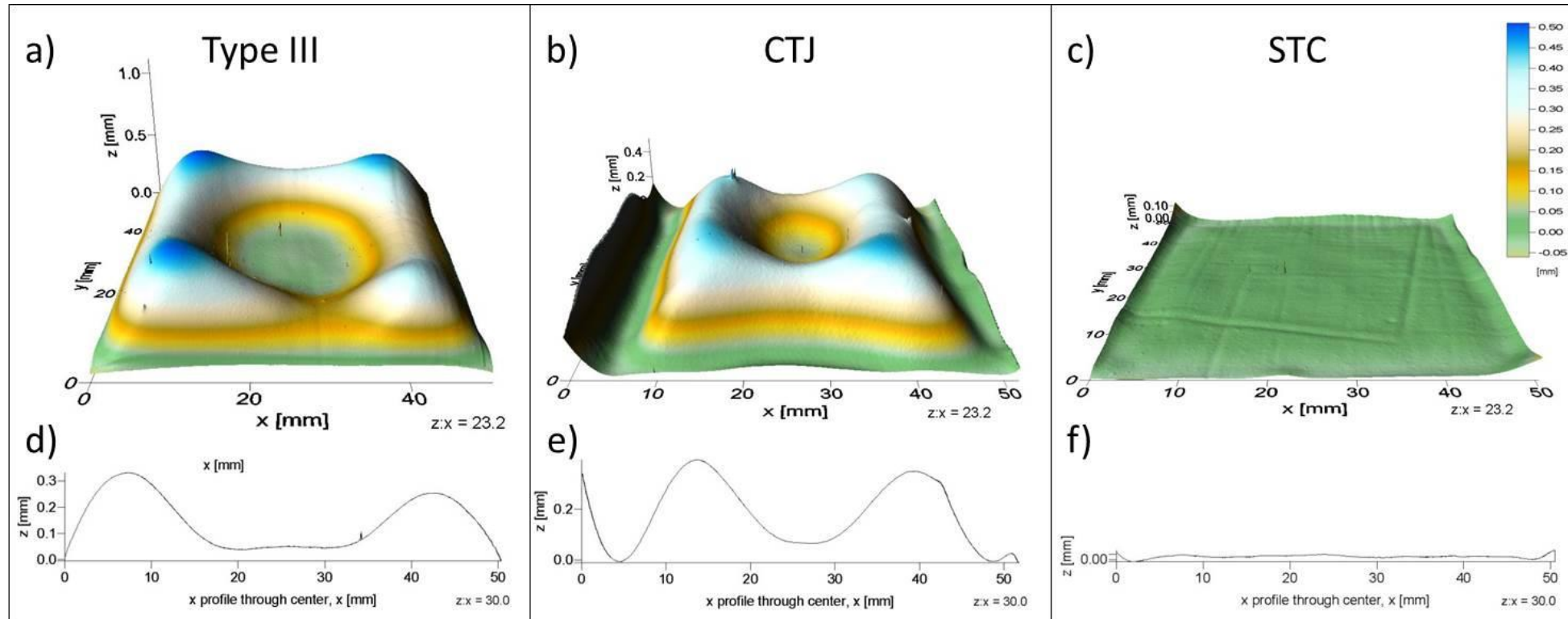
- Thermo-optical measurement system allows dilatometric measurements during sintering
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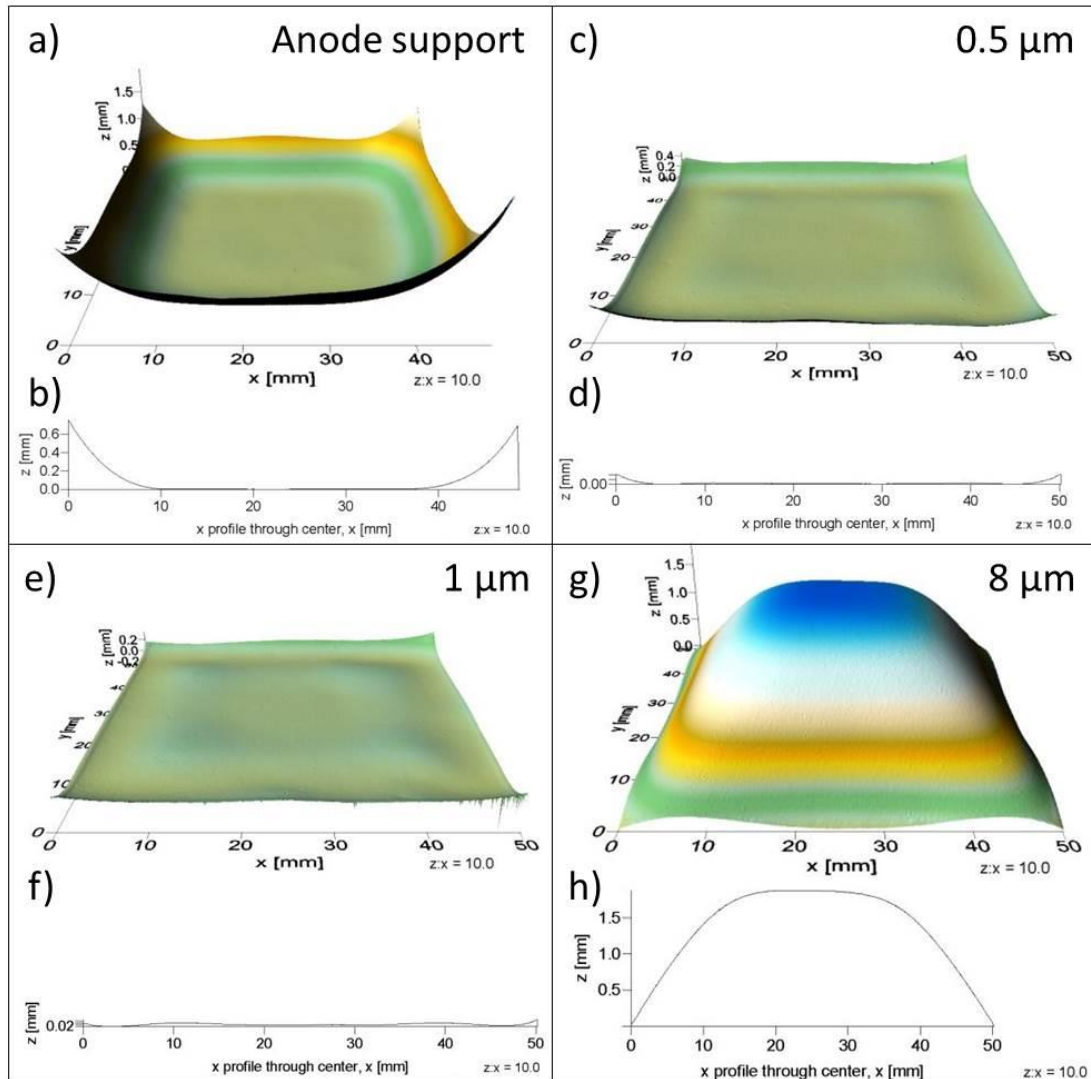
# Camber after sintering

## White-light topography

- Sintered half cells show different camber, depending on support properties
- Least camber for the support with the lowest shrinkage



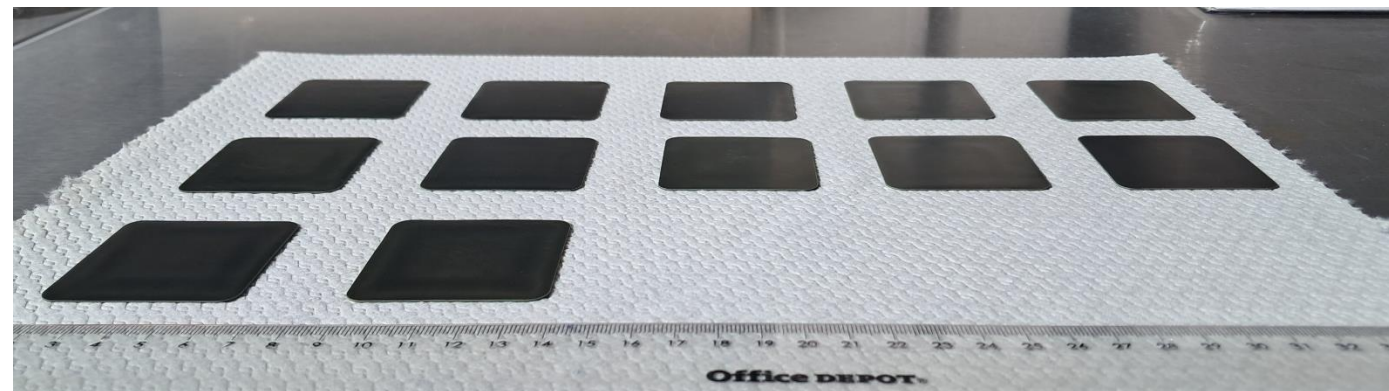
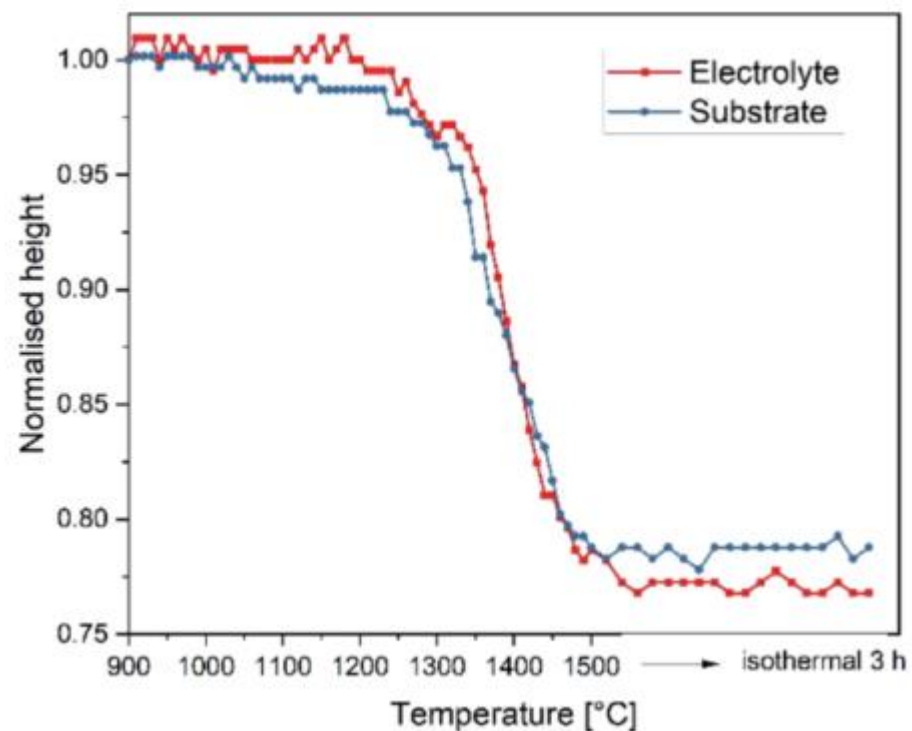
# Camber – electrolyte thickness



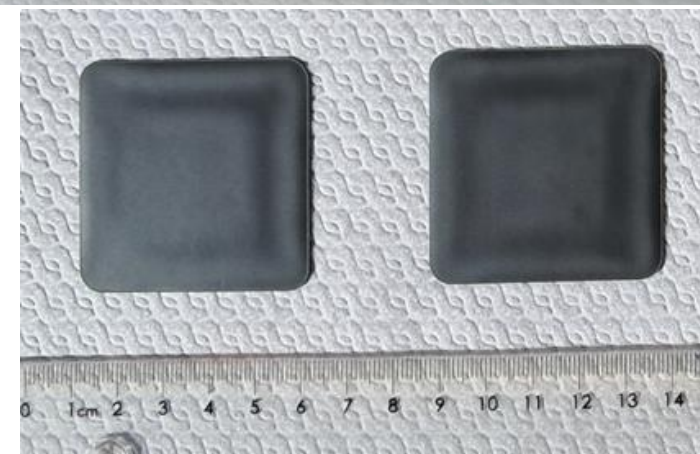
- Support: 500 μm NiO-8YSZ
  - Different electrolyte thickness
  - 0.5 & 1 μm: NP suspension; 8 μm: μm-particles (SP)
- Camber can be influenced by layer thickness
- In practice, one of the most simply accessible parameters

# Camber – matching shrinkage rates

- Adapting layer shrinkage can minimize camber



BZCY // NiO-SZCY // NiO-SCZY  
3-layer half cells after sintering



# Mass production

## Requirements

- Reproducibility
- Cost
- Throughput
- Supply chain management



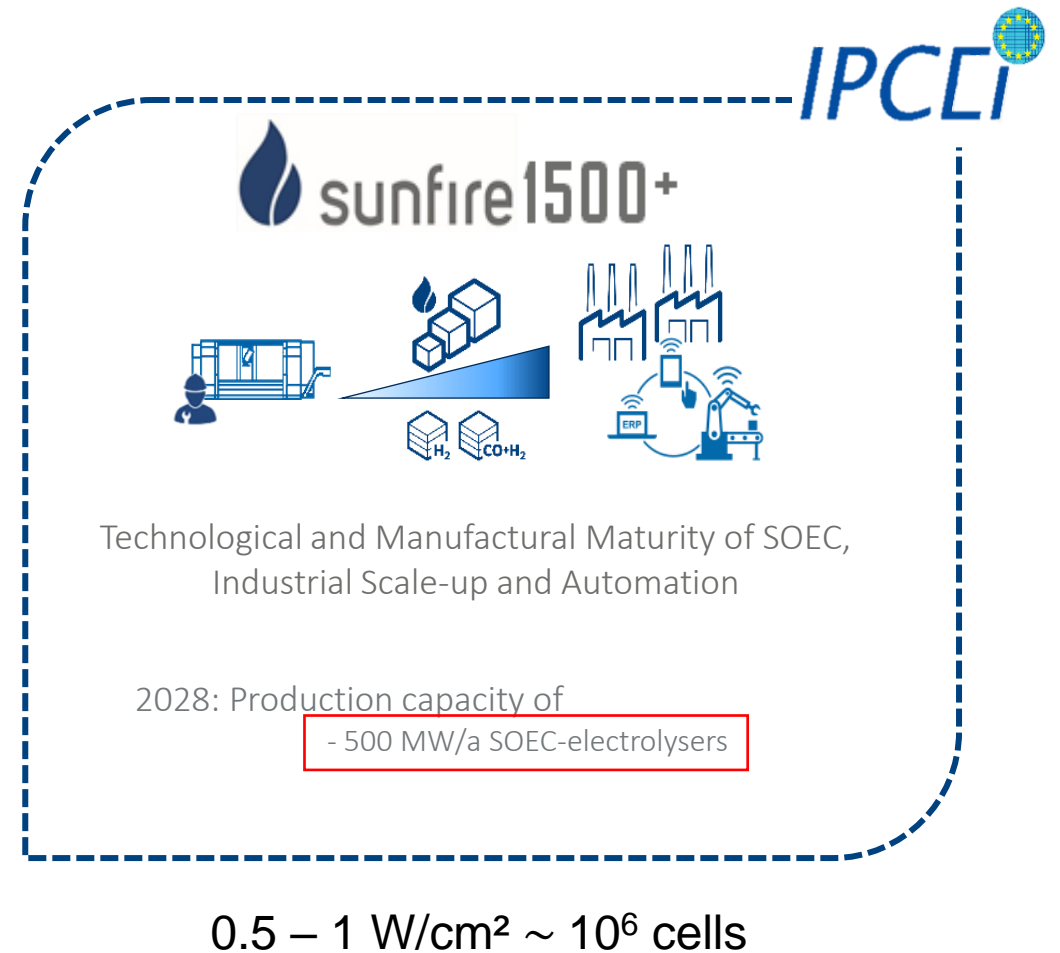
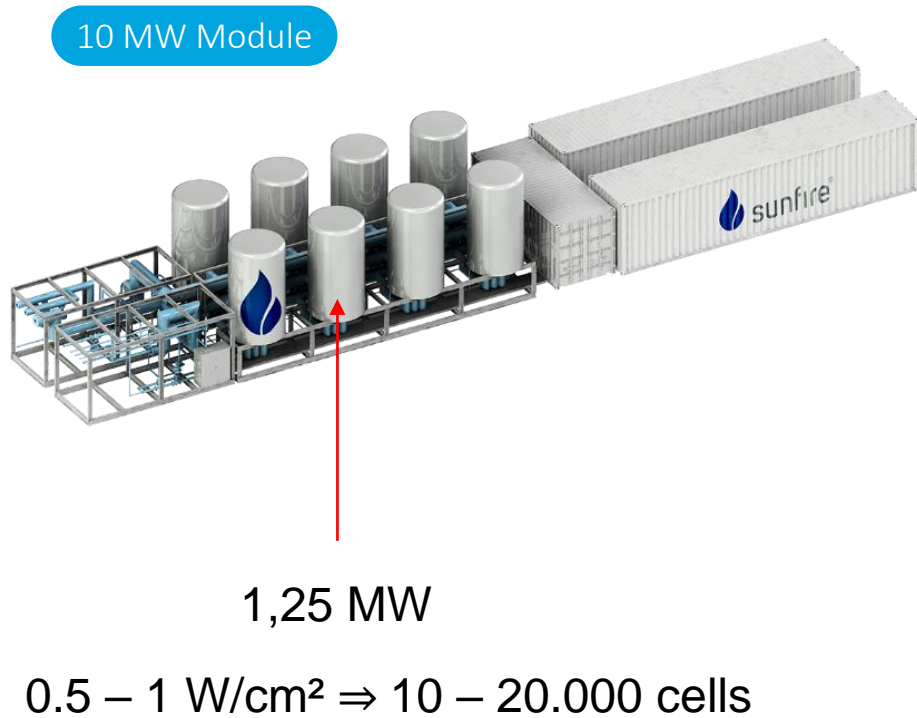
Photo Credit: Bosch-Ceres-Power-Fuel-Cell-Partnership TW|Bosch-Ceres-Power-Fuel-Cell-Partnership



- Money, money, money...
- Public funding
- Private investors
- Market conditions (subsidies, CO<sub>2</sub>-price)

# Mass production

Example: Sunfire (DE)



# Summary

From lab to fab – different requirements with increasing TRL

Science

TRL

Focus on:

- Understanding
- Well defined conditions
- Materials variability

Engineering

Thank you for your attention!

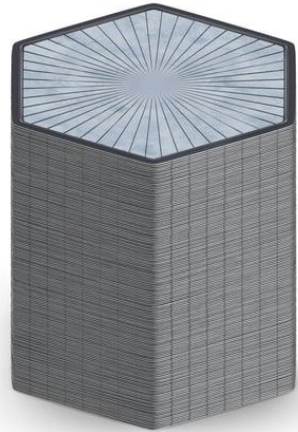
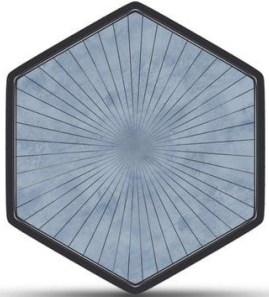
Economics

- Supply chains
- Cost



# Mass production

Example: Topsoe (DK)



100 cells



1200 cells  
350 kW

# Mass production

## Measures to reduce cell numbers

- Increase

# Mass production

