245th ECS Meeting, San Francisco CA

I01-1893 - Enhancing Efficiency and Durability of PEM Water Electrolysis with Low Iridium Loading through Nanofiber-Modified Porous Transport Electrodes

Xin Wen, Bastien Penninckx, Sankar Sasidharan, Ellinor Ehrnberg, Fabian Wenger

Smoltek Hydrogen AB, Gothenburg, Sweden

2024-05-30

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Smoltek Hydrogen – Our Purpose (1/2)

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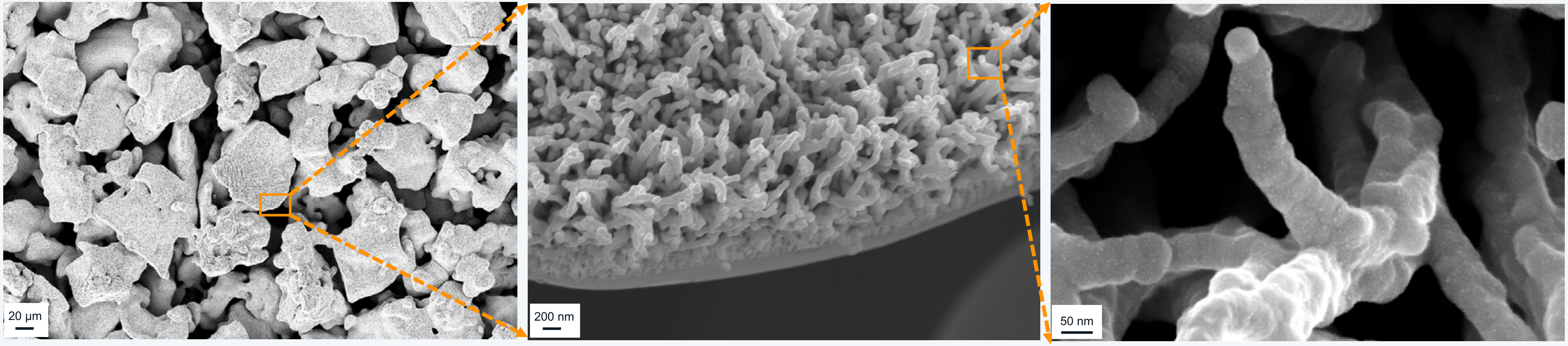
- Unlock 10 GW-manufacturing scale-up for PEM water electrolyzers
- Durable performance at iridium loading below 0.2 mg/cm^2
- Porous transport electrode (PTE) with enhanced surface area
- Cost-efficient supply chain for all volume processing steps for PTE



Porous transport electrode | Enhanced surface area | Coated nanostructure

Fabian Wenger, Head of R&D at Smoltek Hydrogen AB, fabian.wenger@smoltek.com

Smoltek Hydrogen – Our Purpose (2/2)

- Unlock 10 GW-manufacturing scale-up for PEM water electrolyzers
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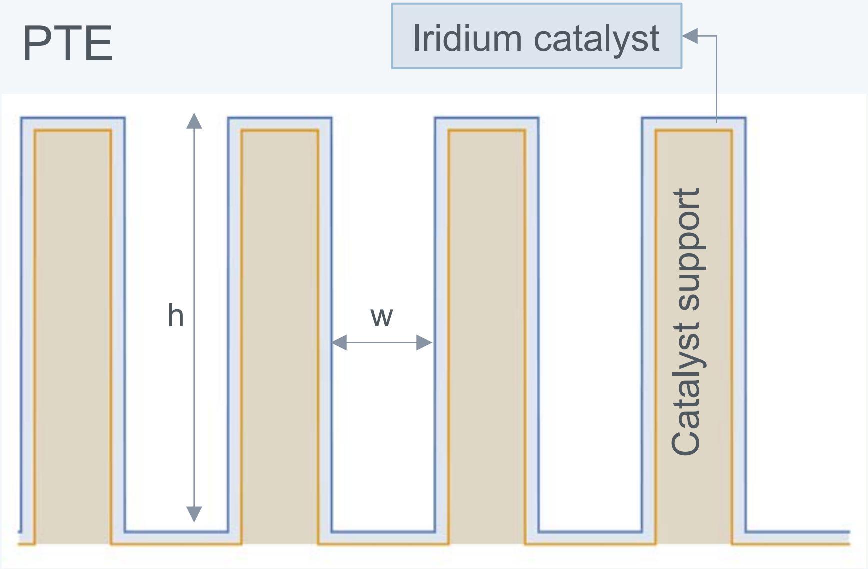

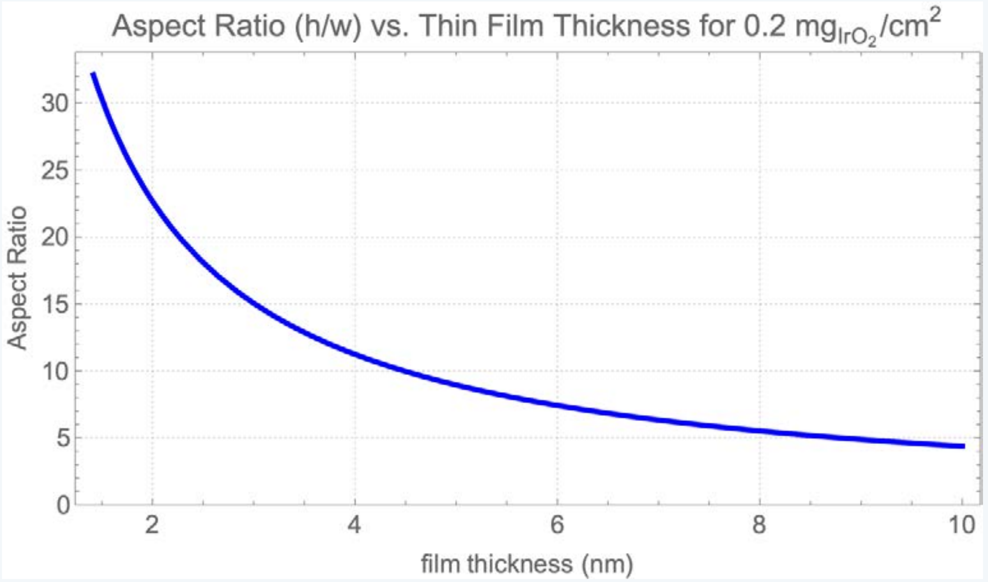

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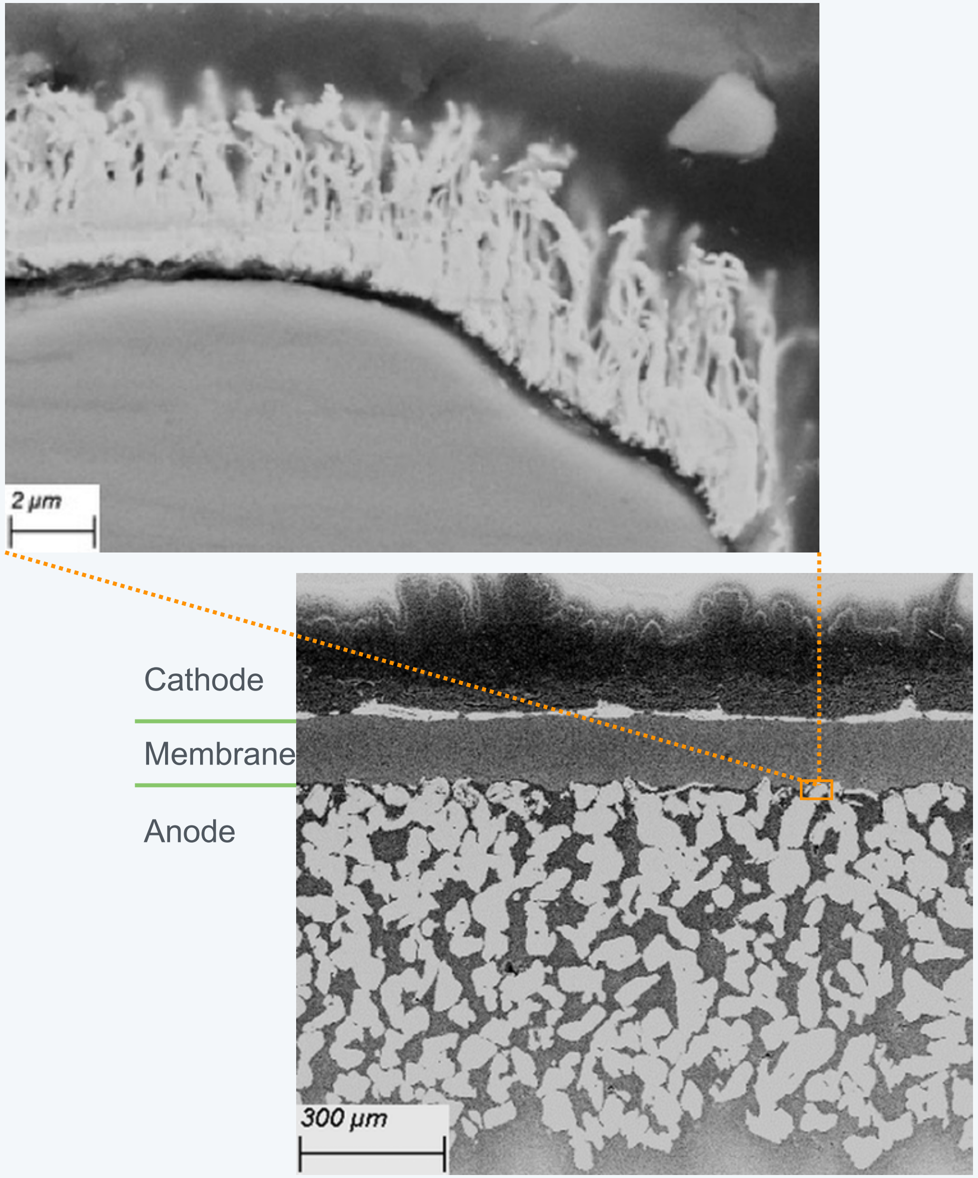
Nanostructured PEMWE Anode Characteristics



- **Tolerates up to 2.6 V @ 2A/cm^2 for 1000 hours**
- PTE Anode:
  - **3**…10 µm vertical nanofiber, **100**…150 nm thick, 20…**50**% porosity
  - Graphitic core, ALD Pt coating 12…**25**…50 nm without pin holes
  - electrodeposited 6…20 nm porous Iridium nanoparticle layer
  - Iridium loading 0.1…**0.2**…0.7 mg/cm^2,
    Platinum loading 0.5…**1.1**…1.3 mg/cm^2
- Ionomer drop coating and hot-pressing with Nafion 115
- Cathode: Generic (Fuel Cell Store)
- **Lab and A4 size prototypes**

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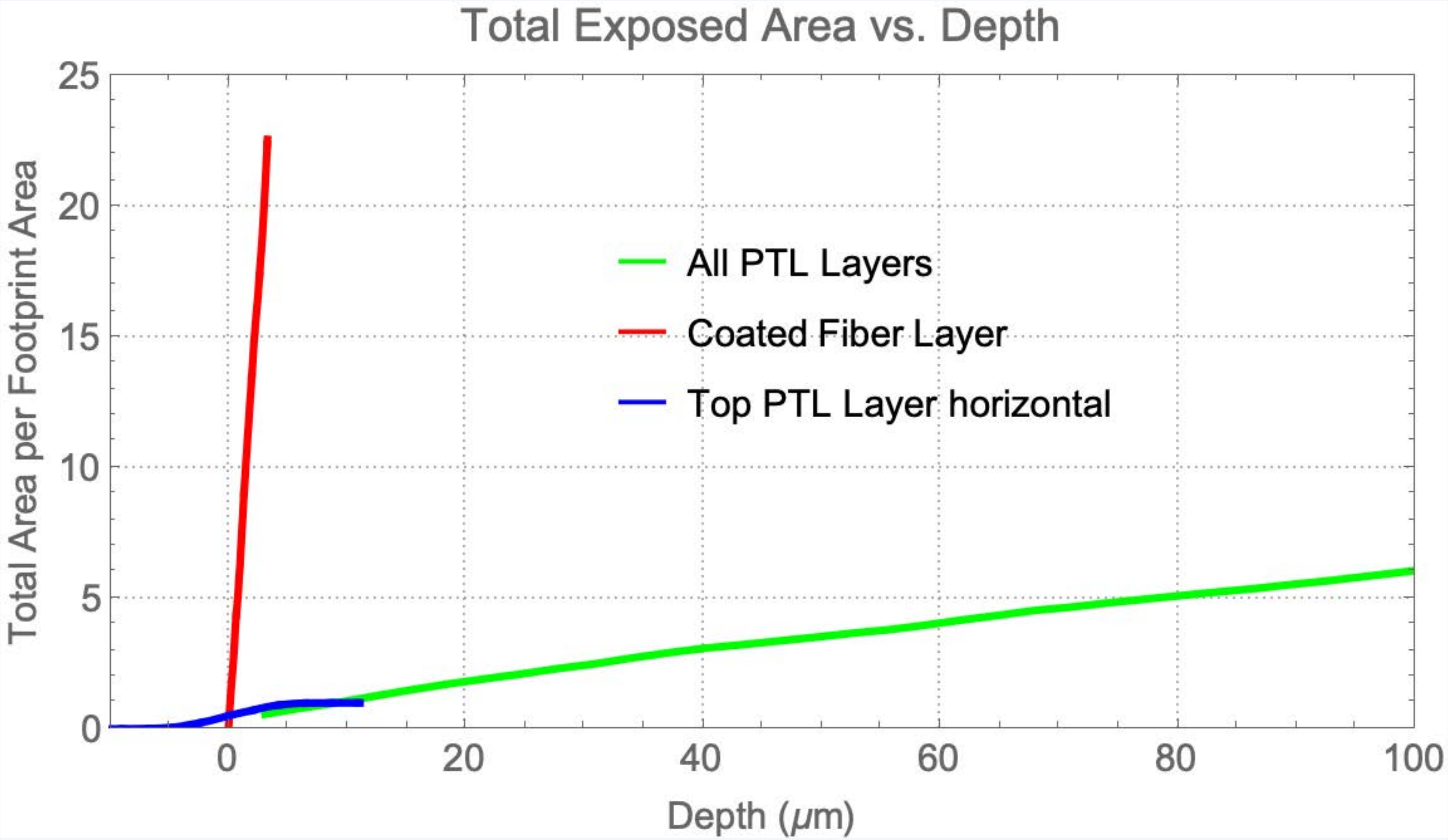
Get The Active Area Close to the Ionomer!



- **Nanofiber catalyst layer preserves proximity to membrane and metallic contact**
- A standard PTL will not expose enough area in close proximity even at low loadings

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OER Half-Cell LSV: 1000 h Durability Test Anode Post-Mortem Activity Comparison (1/2)

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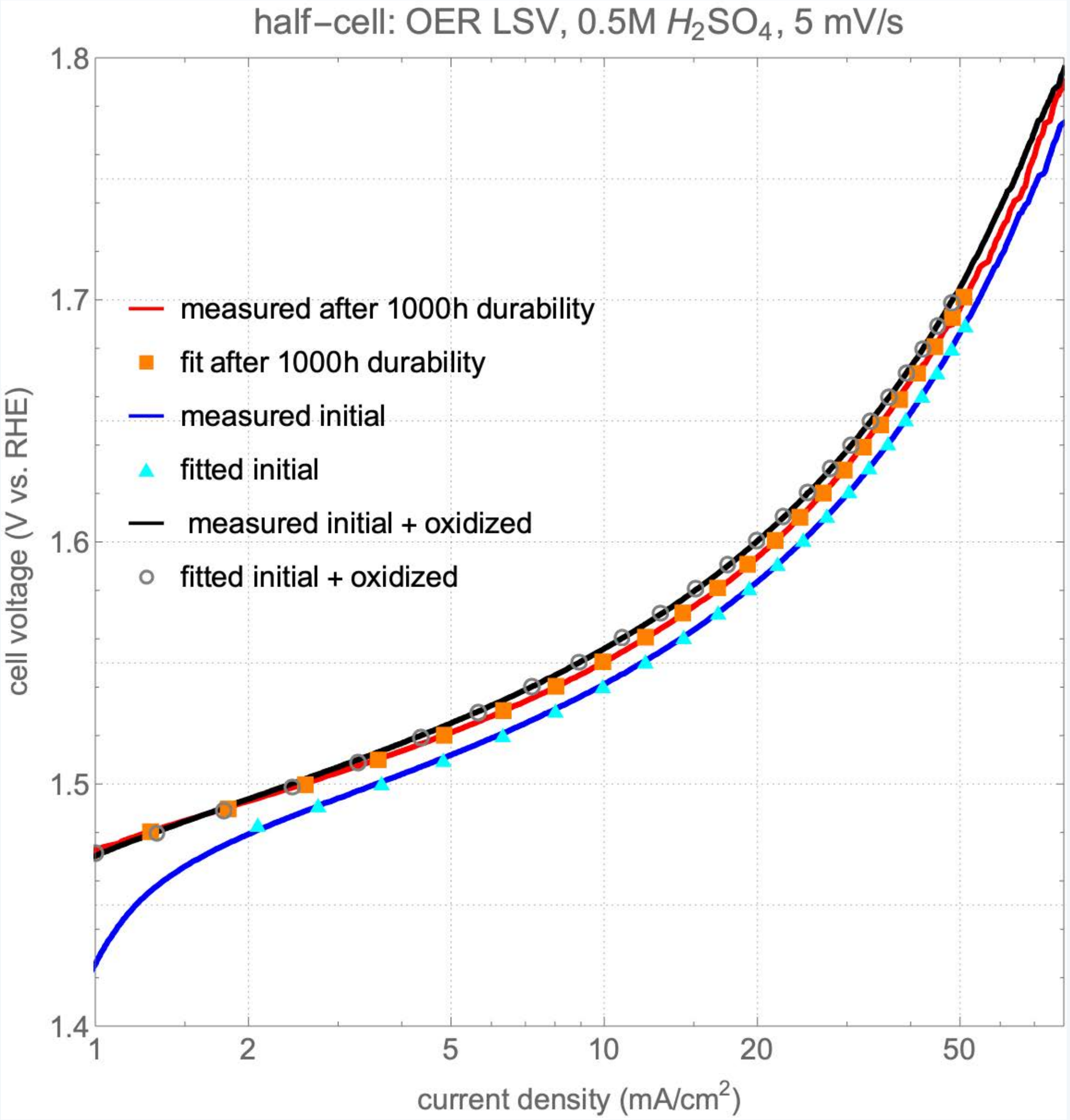

- **Most of the apparent irreversible loss of the full cell performance is recovered by subjecting the anode to half-cell OER environment again!**
- PTE: all is well in half-cell
- $E = A + B \text{ Log}_{10}\, j/j_0 + R\, j$

Parameter Fit	A (V)	B (mV/dec)	j_0 (mA/cm^2)	R (Ω cm^2)
1000h	1.47	52	1.12	2.8
initial	1.45	53	0.88	2.7
initial+ox	1.47	60	1.05	2.7

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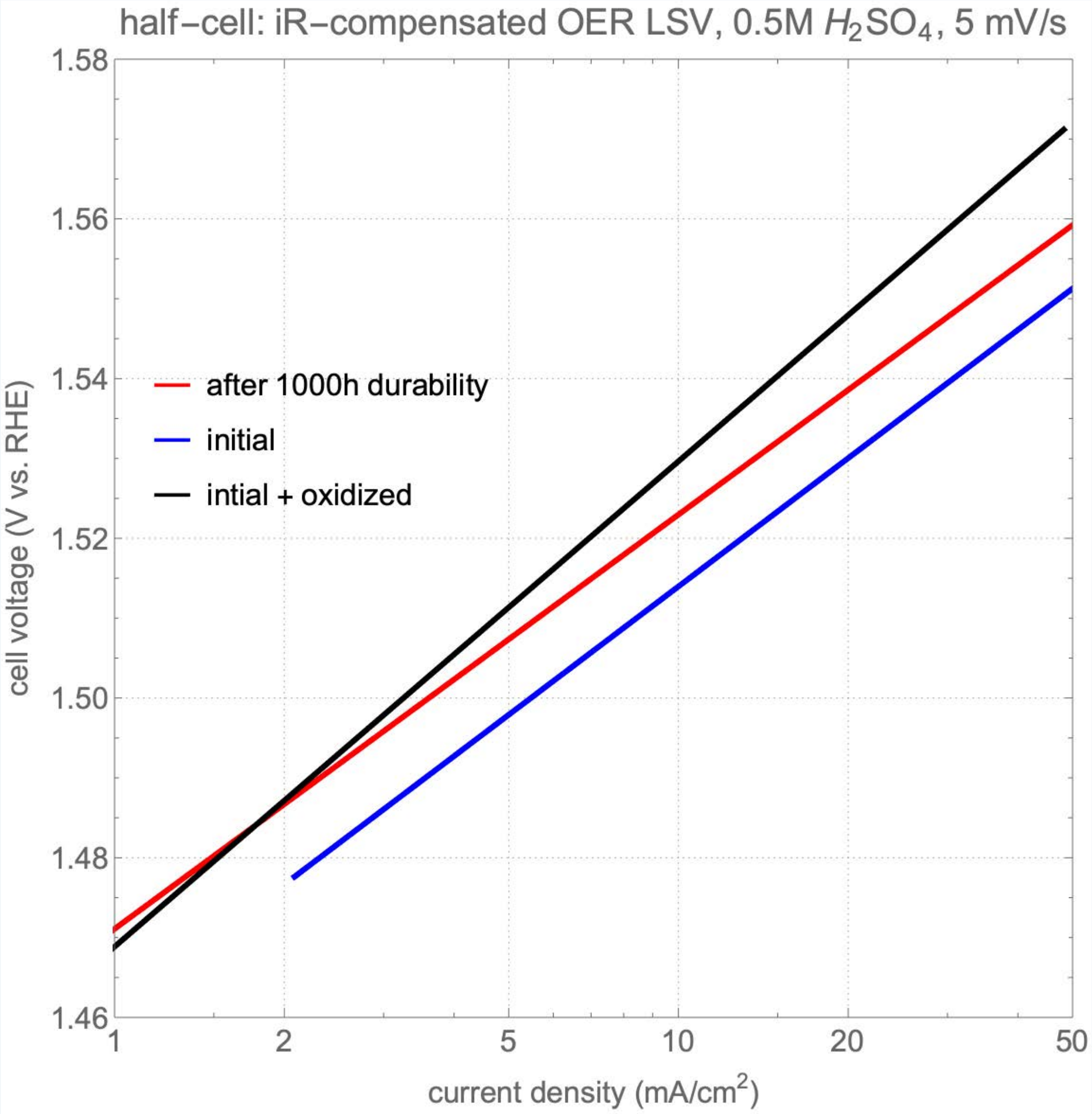
OER Half-Cell LSV: 1000 h Durability Test Anode Post-Mortem Activity Comparison (2/2)



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0.2 mg_{Ir}/cm^2: 1000 Hours Durability Test at $2A/cm^2$, 60°C, 1 bar

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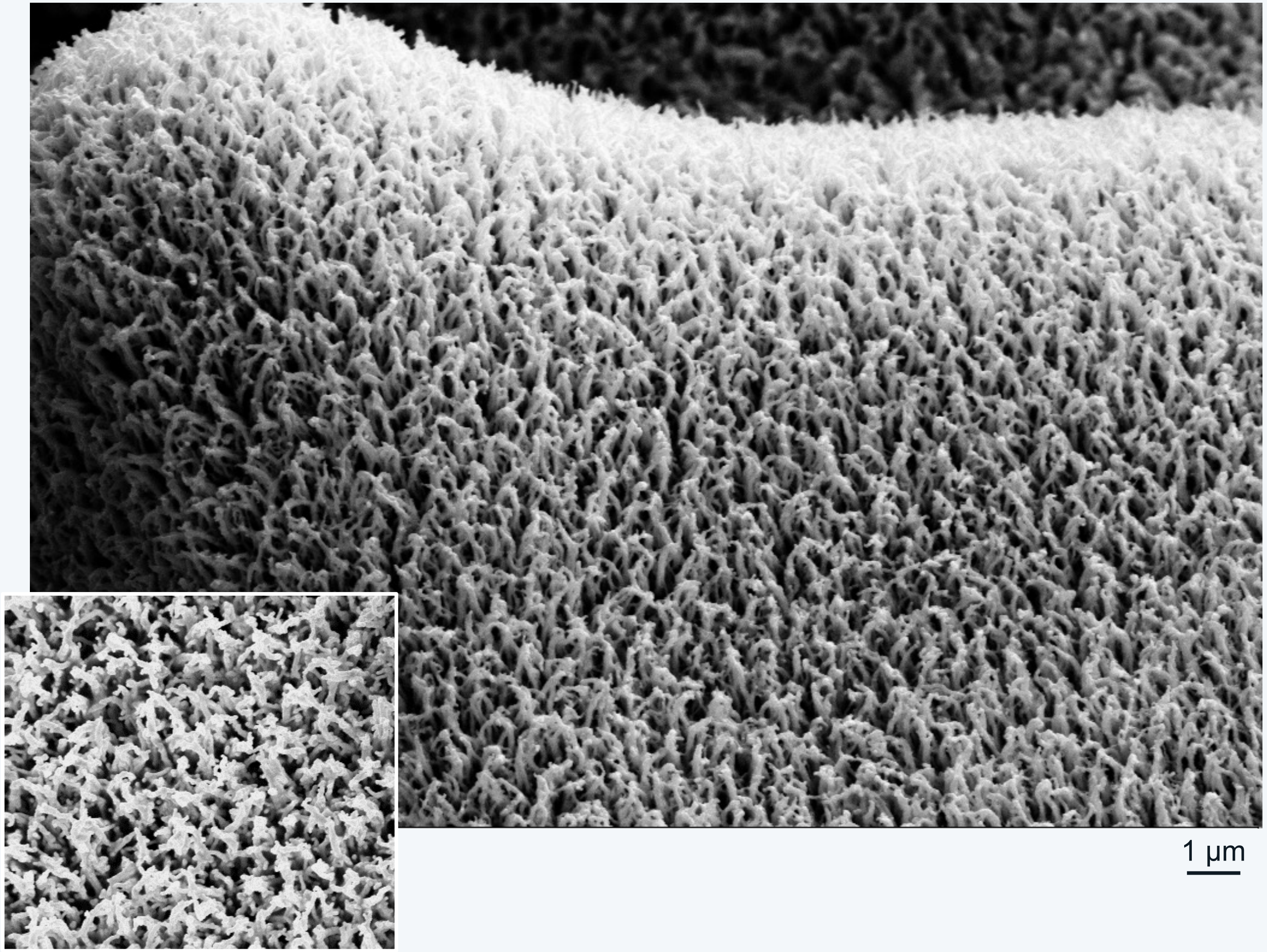
After



Before

- No degradation of fiber morphology
- Rapid increase of voltage the first 10h from 2 to 2.5V, then stable
- After cell disassembly the anode displays the activity of an initially electrochemically oxidized sample at same loading (see previous slides)
- All EIS and polarization data taken at 80**°C** , but test system limited to 60**°C** for long-term stability tests

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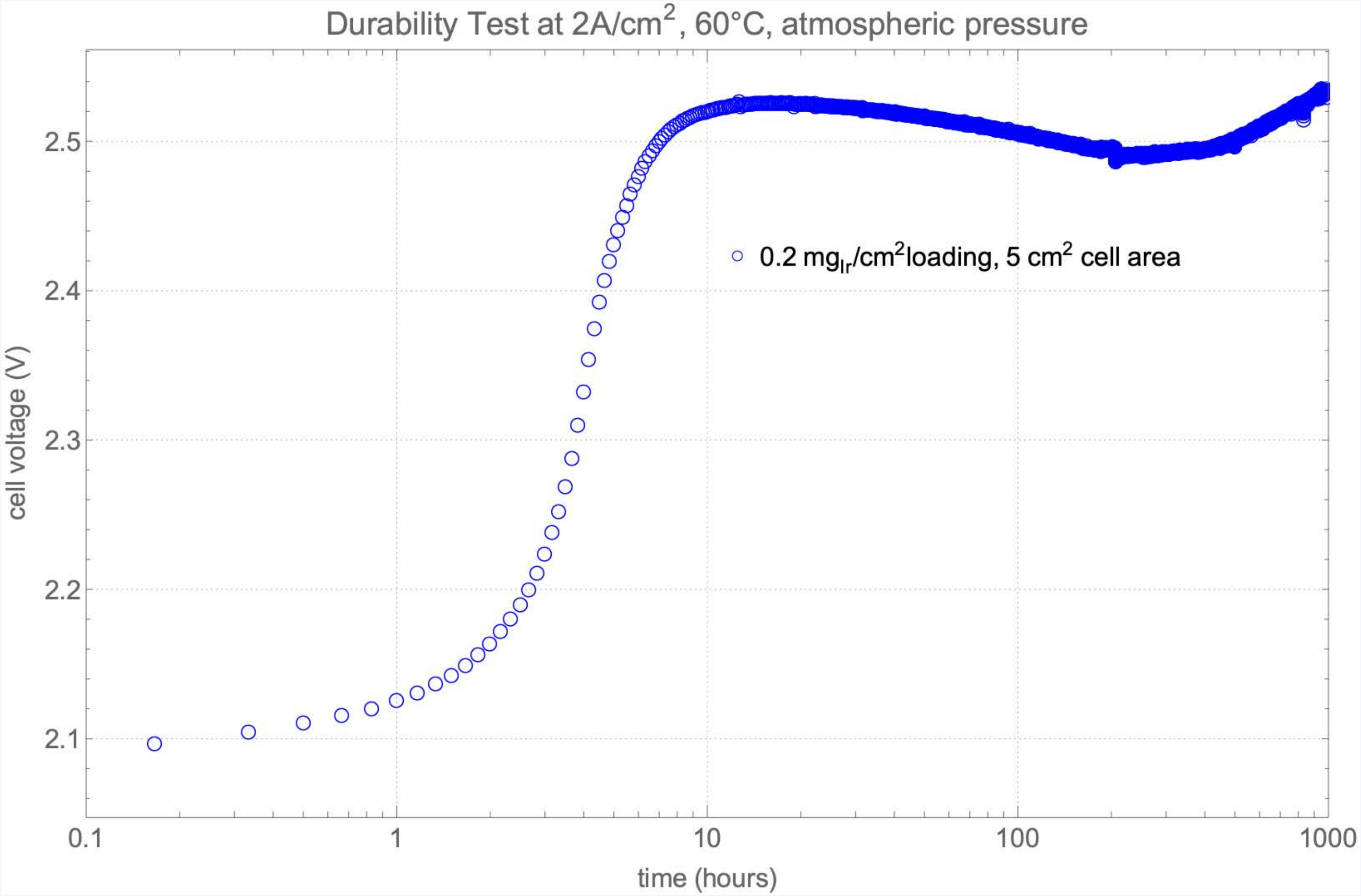

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1000 Hours Durability Test at 2A/cm²: Polarization (1/2)

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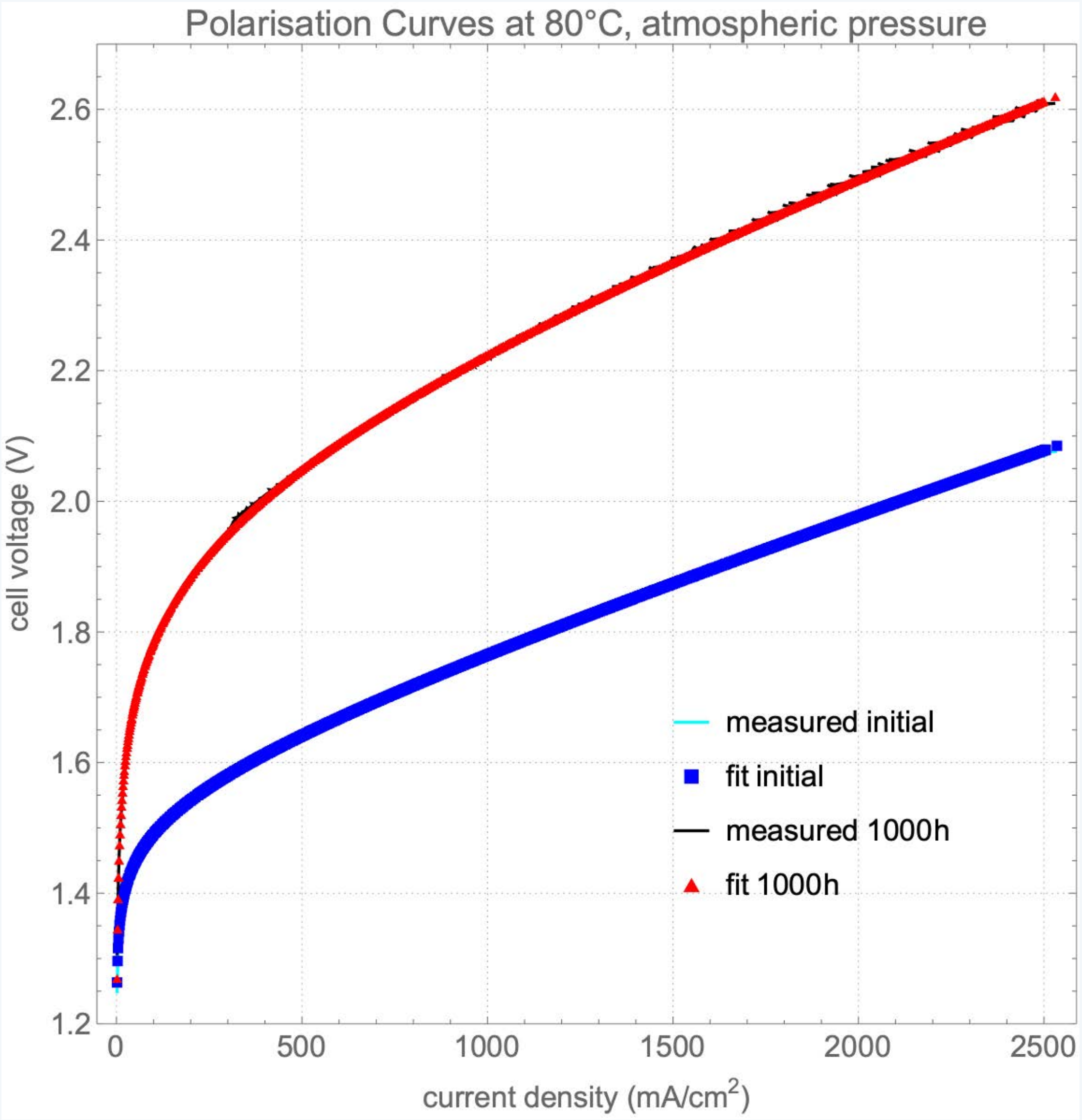

- High Tafel slopes
- $E = E_0 + B \, Log_{10} \, j/j_0 + R \, j$

Parameter Fit	E_0 (V)	B (mV/dec)	j_0 (mA/cm²)	R (mΩ cm²)
0h	1.25	**113**	1.17	179
1000h	1.23	**271**	1.14	187

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1000 Hours Durability Test at 2A/cm²: Polarization (2/2)

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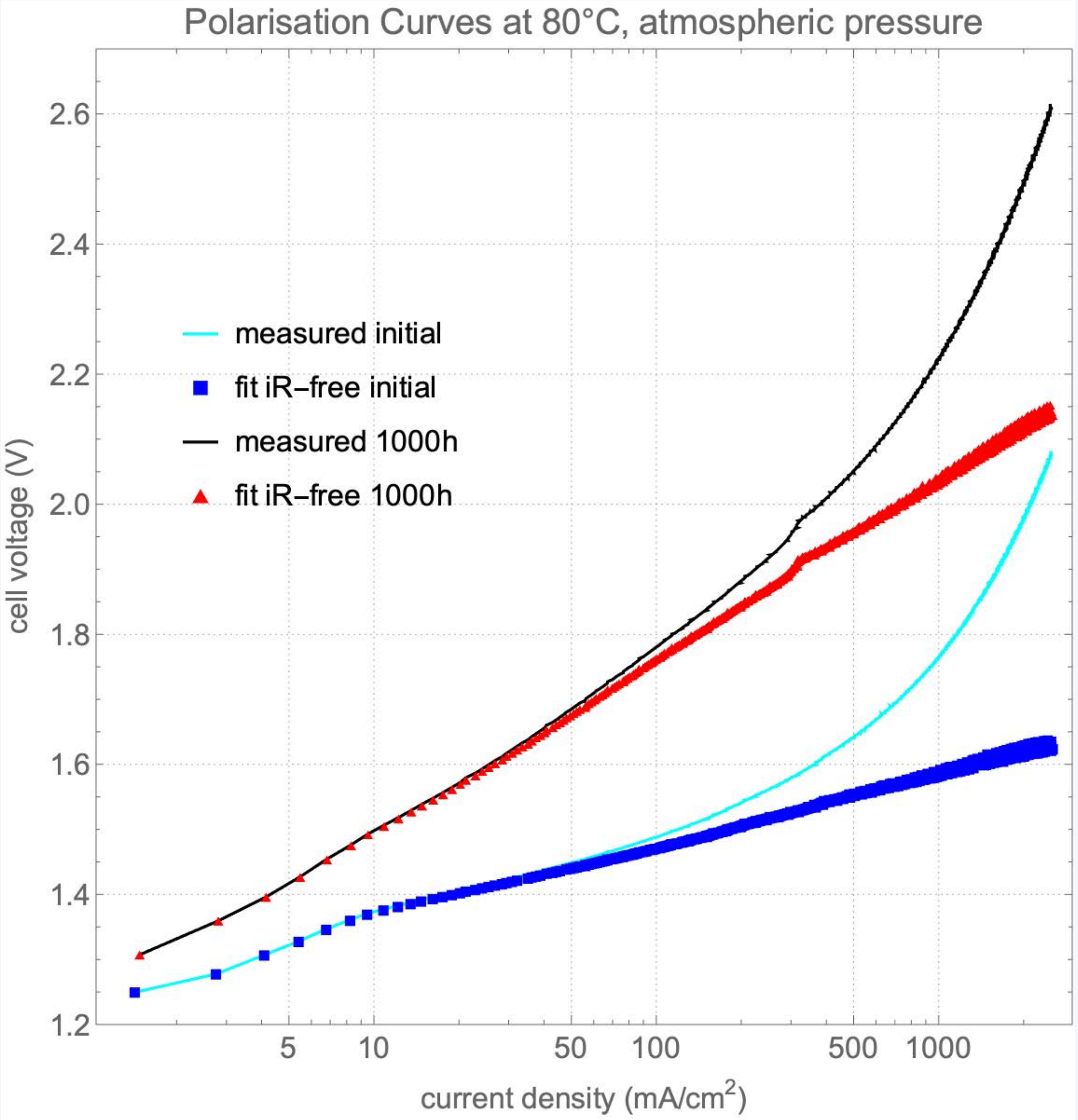

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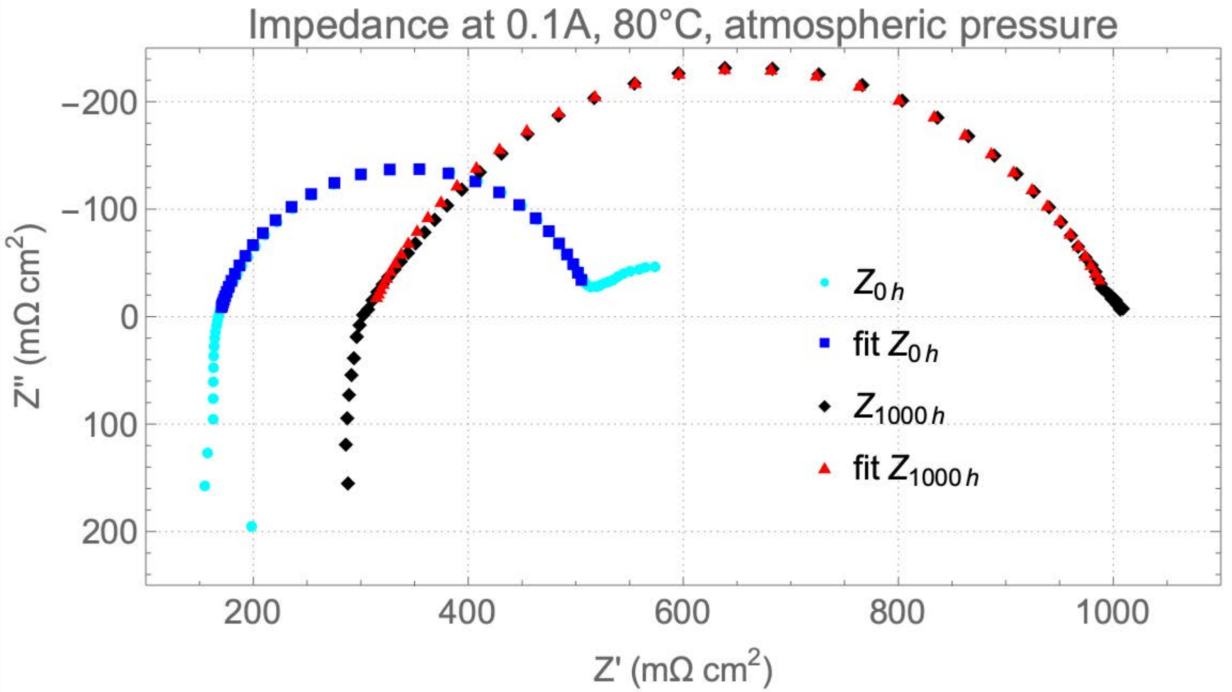
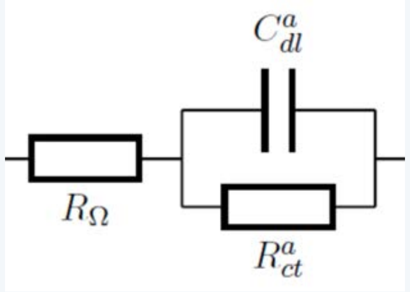
1000 Hours Durability Test at 2A/cm^2 – EIS at 0.1A/cm^2 (1/2)



- EIS model simplified Randles circuit with CPE and non-linear fit of exponent in selected frequency interval



EIS @ 0.1A	HFR (mΩ cm^2)	R_{CT} (mΩ cm^2)	a	C_{CPE} (s^{a-1} mF/cm^2)
0h	168	349	0.85	20
1000h	306	698	0.74	10

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1000 Hours Durability Test at 2A/cm^2 – Ir catalyst

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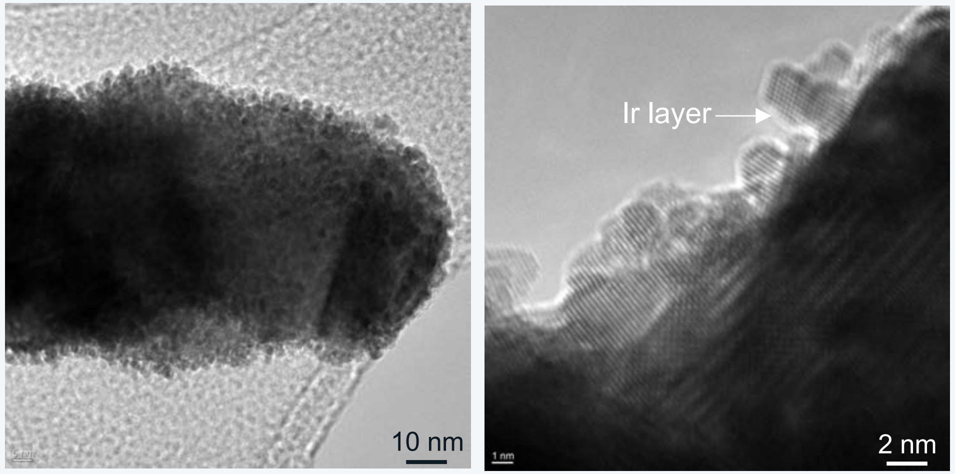
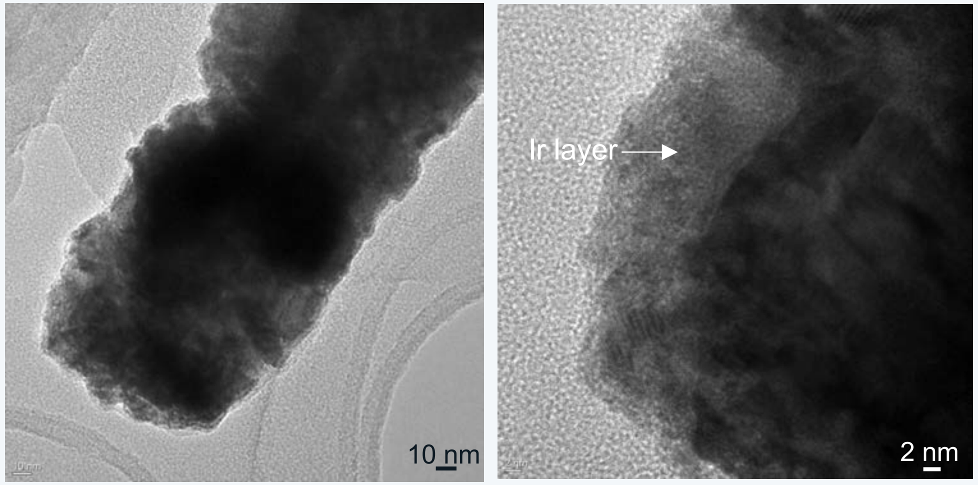
- Ir catalyst remained on the PTE after 1000h durability test but became less crystallized.

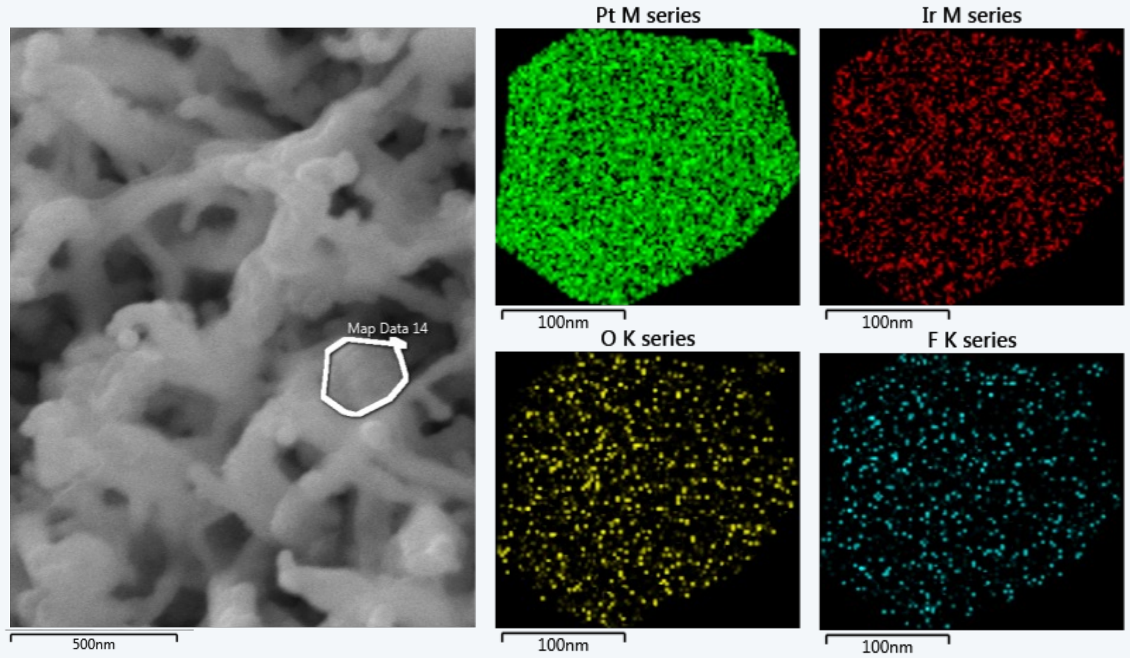
Before 1000h



After 1000h



EDS mapping after 1000h



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Evolve Towards Robust Distribution of Ionomer

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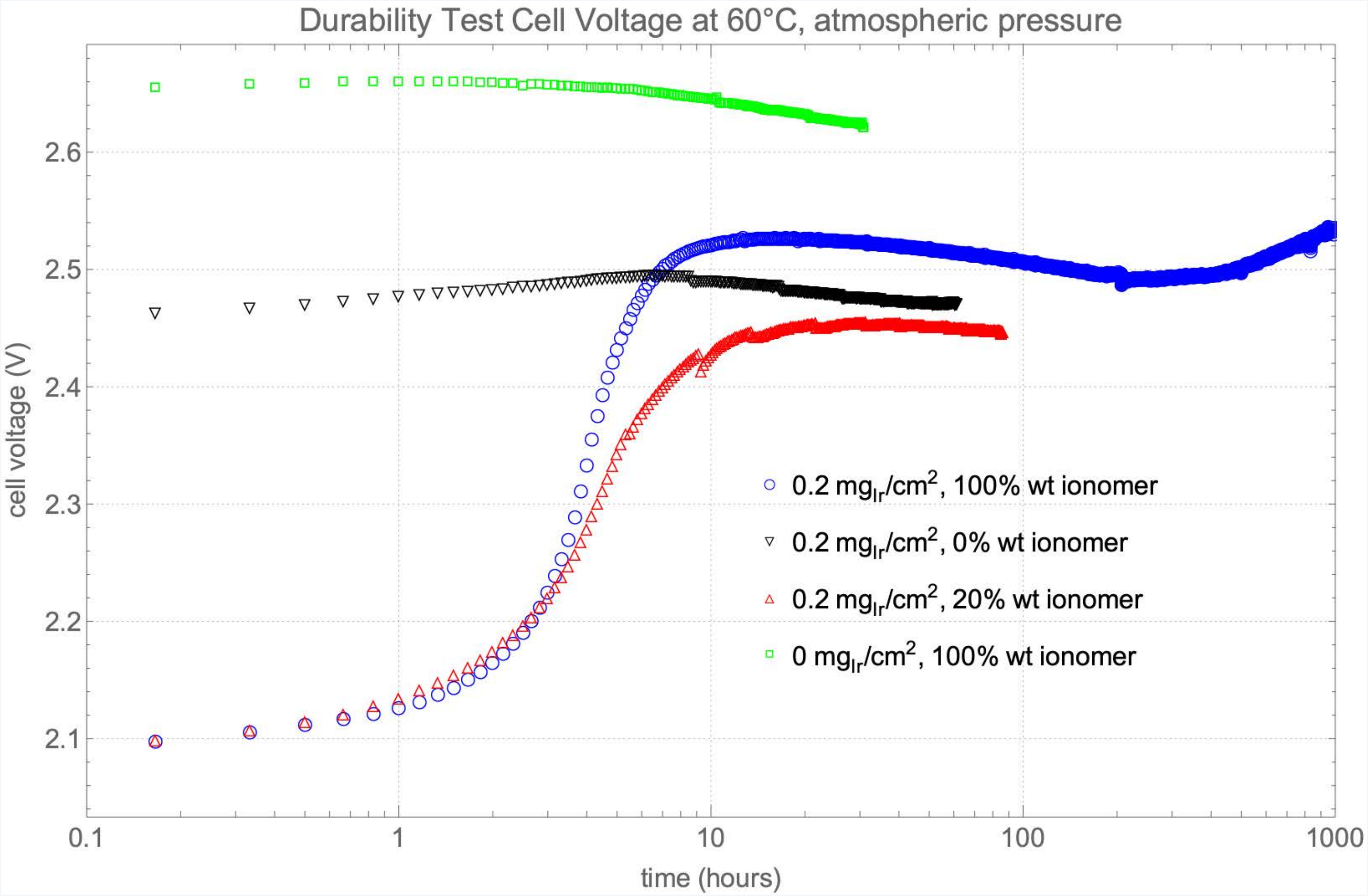
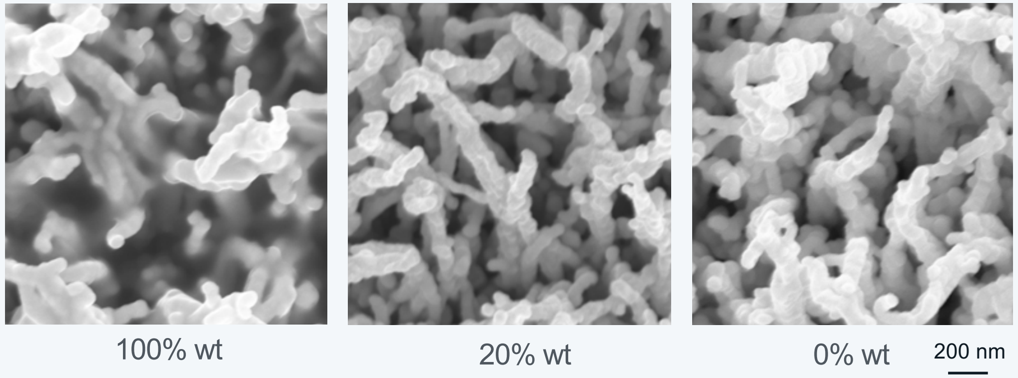
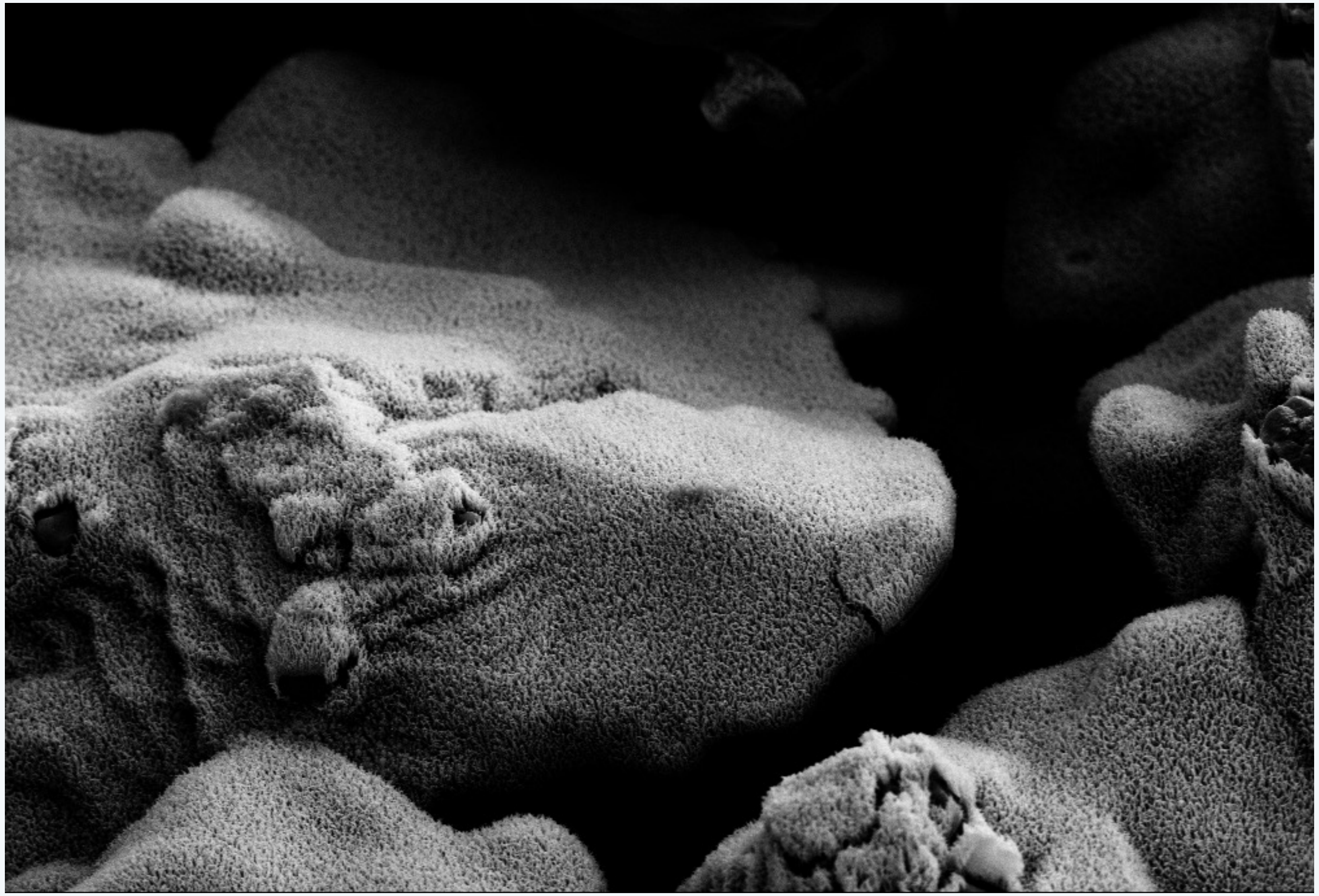


- Optimize the coverage and adhesion of ionomer towards PTE
- Initial catalyst activation protocol
- Match porosity parameters PTE – membrane e.g. extruded Nafion nanostructure
- **Modified PTL surface to work with thinner membranes**



Summary and Outlook



- Now at 0.2 mg_{Ir}/cm^2 :
  - Catalytic nanofiber substrate: 1000h at $2A/cm^2$ and up to 2.5V
- Targets:
  - 2 A/cm^2 below 2V for 2000 hours
  - Prototype cells up to size A4
  - **Seeking Scale-Up Partners!**

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Partner With Us – Raising Capital

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https://www.smoltek.com/hydrogen/

Backup Slides

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High Volume Production Roadmap

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Head of Volume Processes

PhD in Microtechnology and Nanoscience, 2005

Réka Simon-Bálint
Head of Quality and Project Management

MSc in Physics & Materials, 2012

2023	2024	2025	2026	2027	2028	2029	2030

Develop industrial concept for large scale production.

Validation of industrial concepts.
Small-scale manufacturing with industrial technologies in pilot plant.
Design first high-volume production unit.

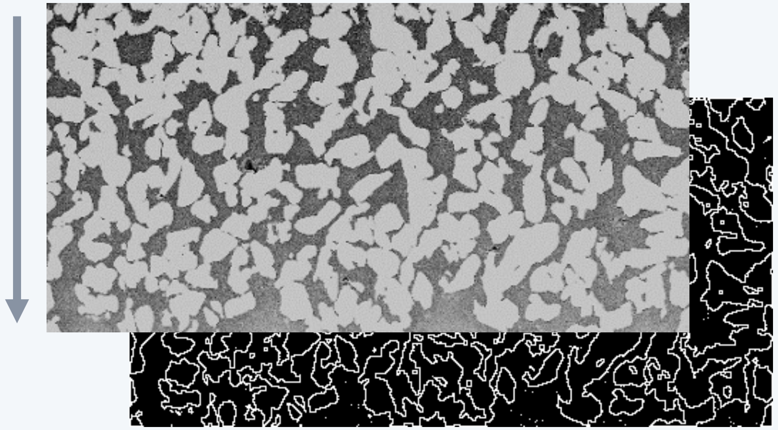
Additional high volume production units to be planned and build.

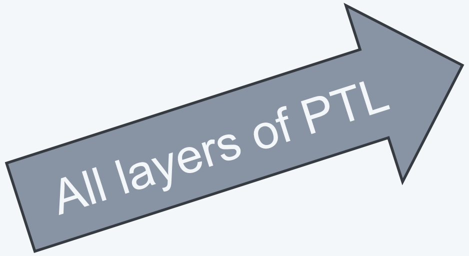
DEVELOPMENT → INDUSTRIALIZATION & COMMERCIALIZATION → SCALE UP

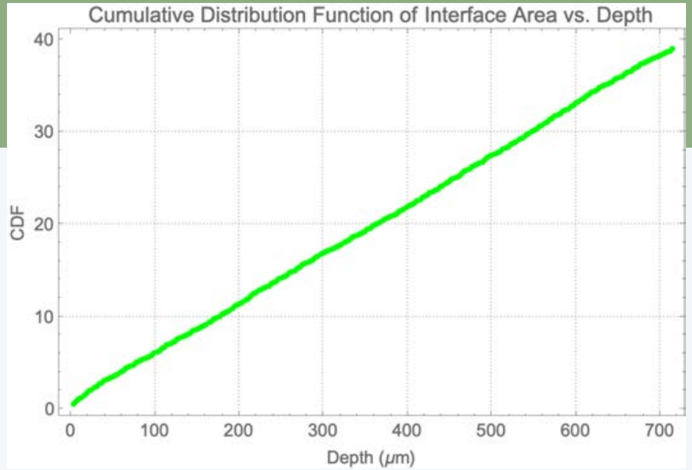
Test samples manufactured with lab technology

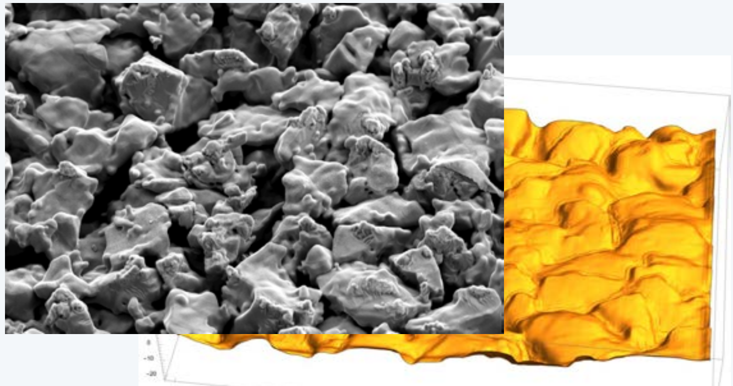
Scaling up manufacturing with industrial technology

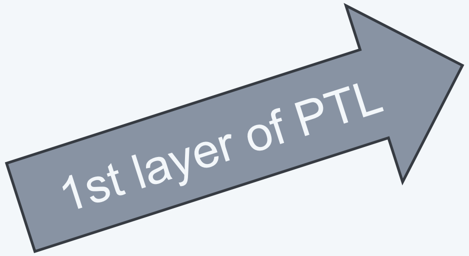
Active Area In Proximity To Ionomer

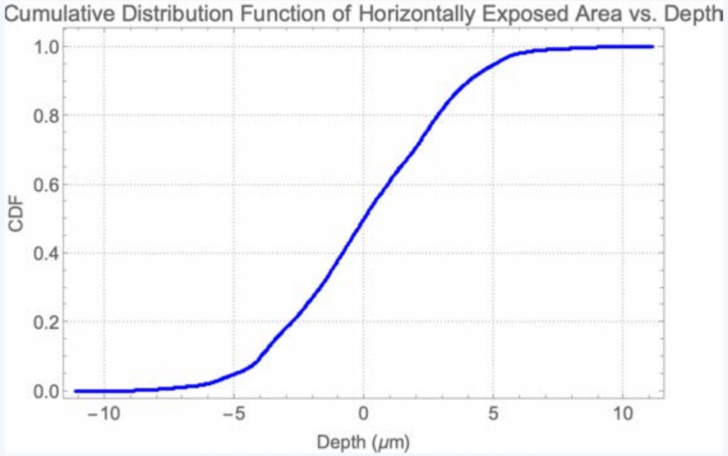


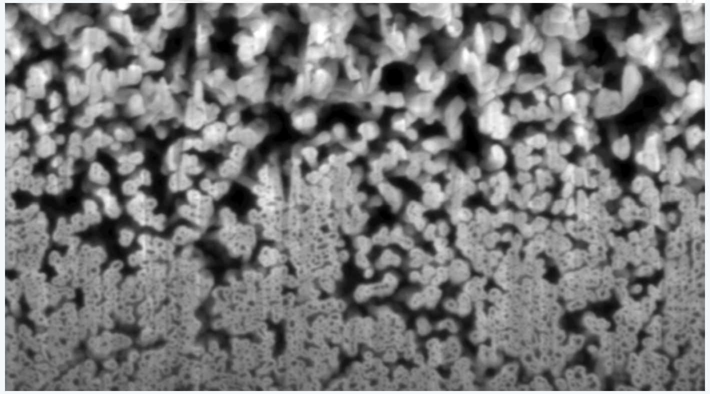


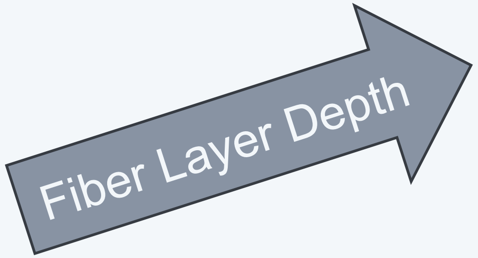


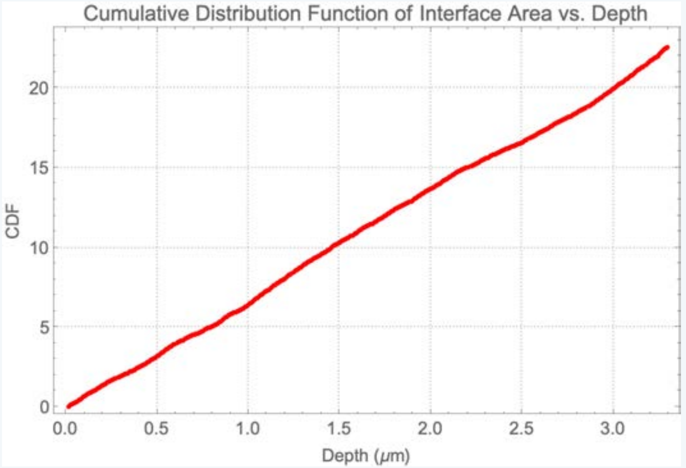












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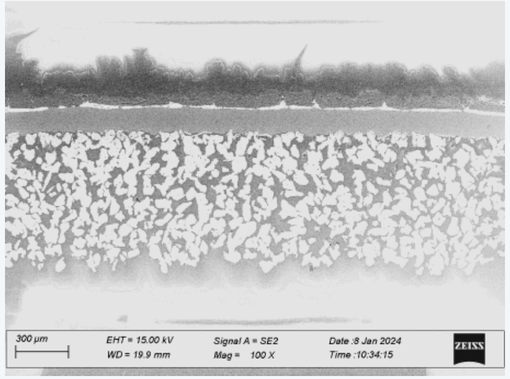
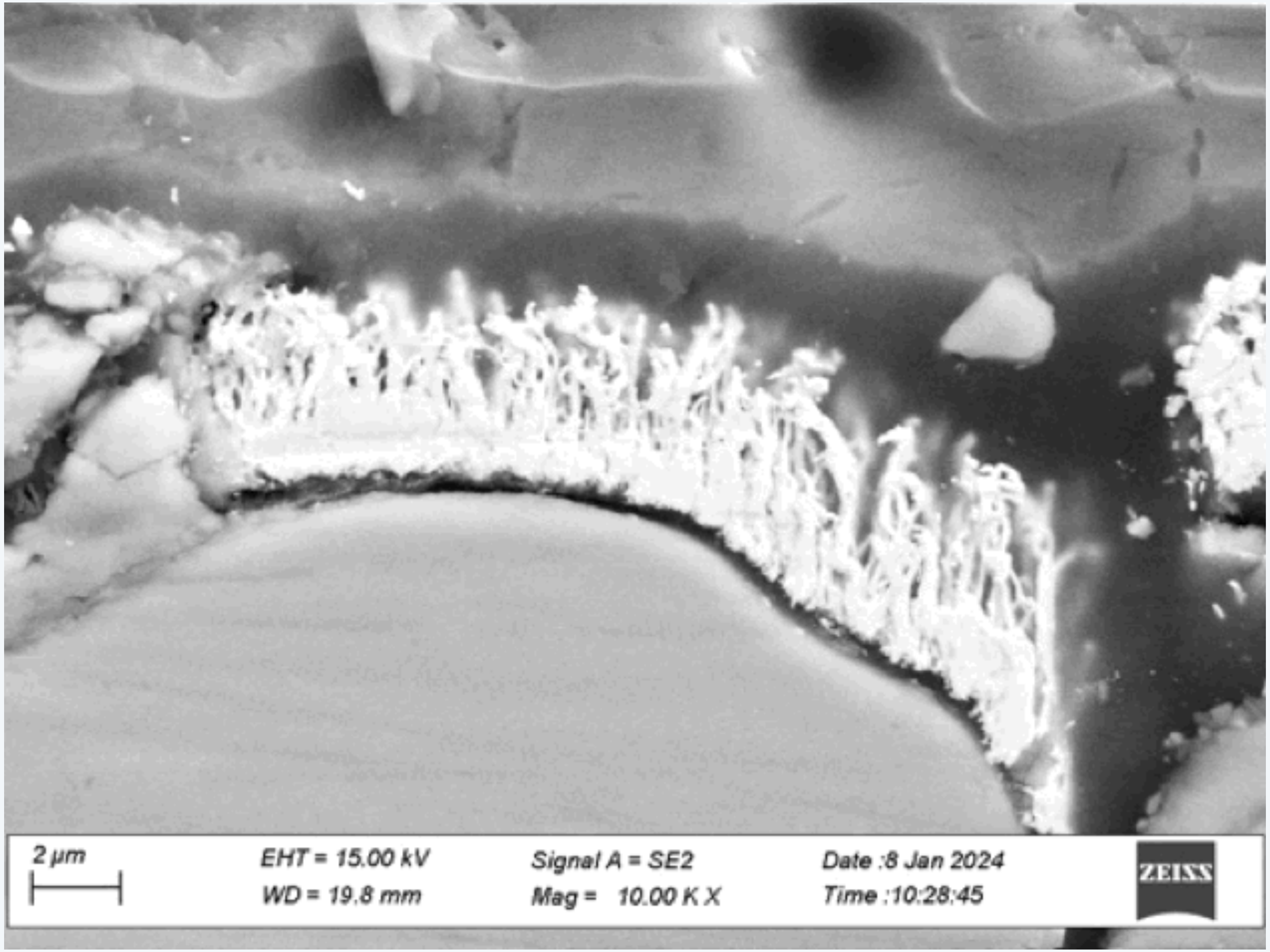
Swedish Electricity Storage and Balancing Centre

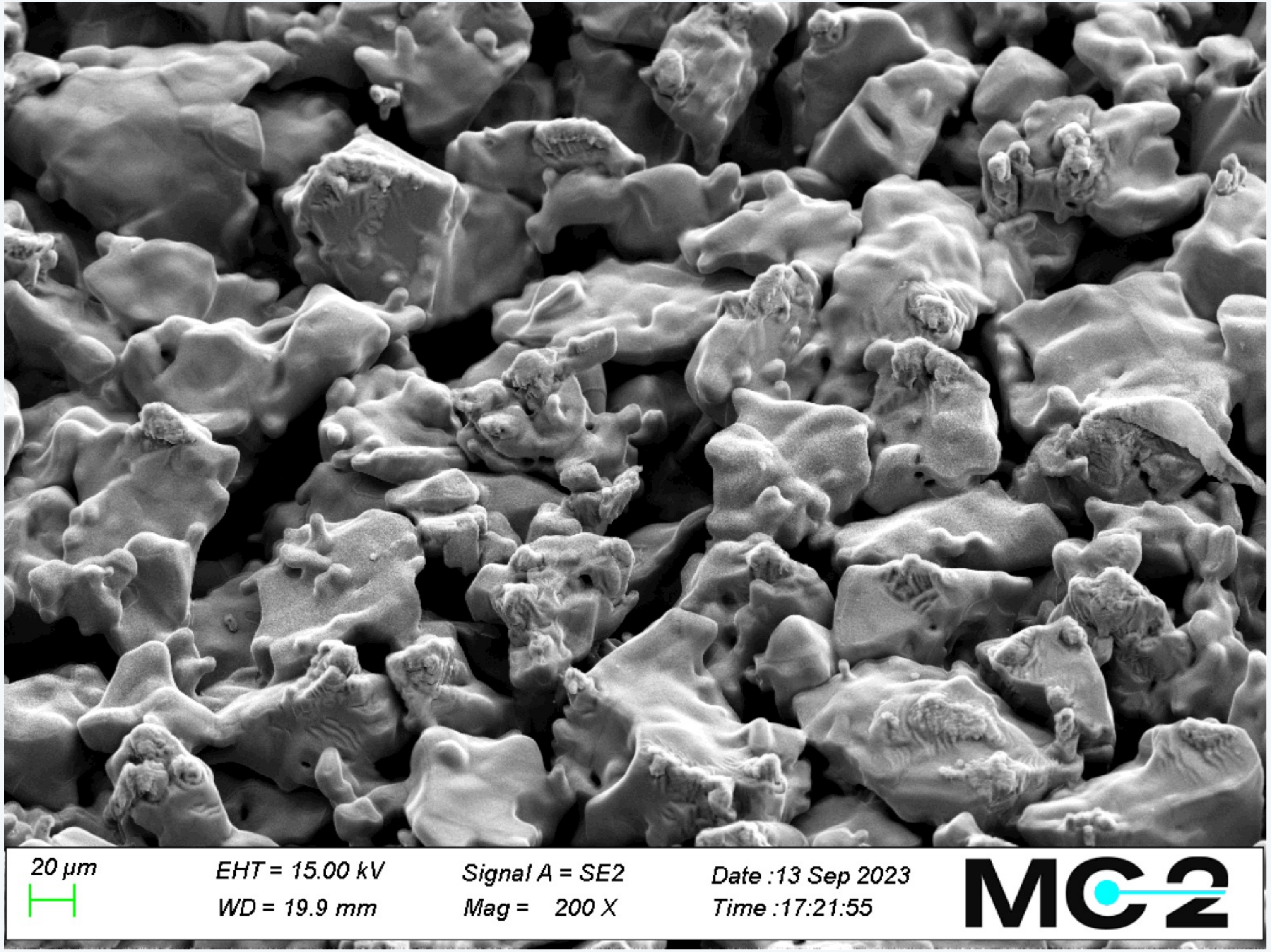
Collaborators:
Dylan Schulz,
Anna Martinelli

Cross-Section Images





Fiber-Coated Top Layer PTL - Full-size image



Inclined FIB-SEM Cut of Fibers – Full-size image

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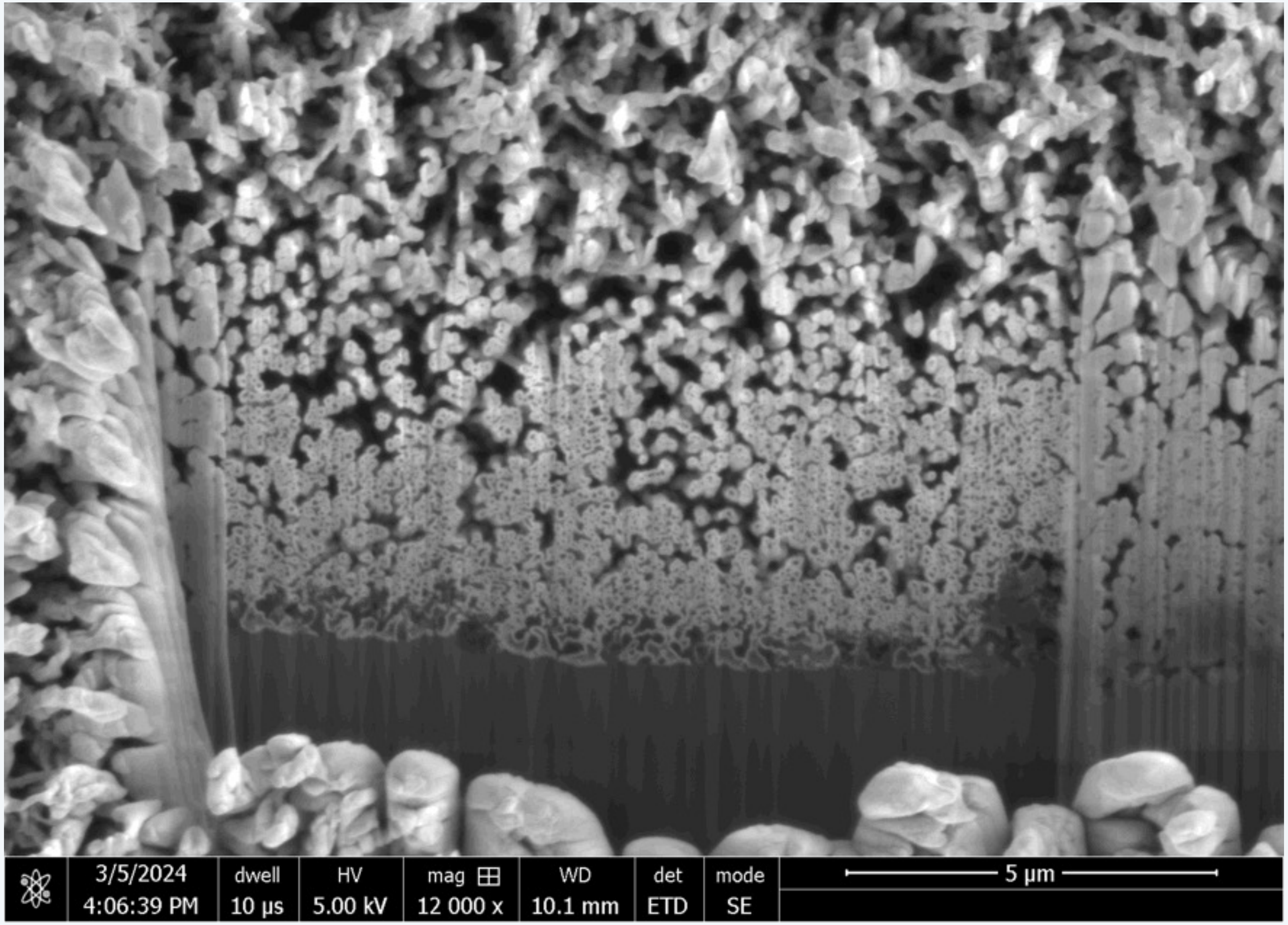

Inclined FIB-SEM Cut of Fibers – Porosity vs. Depth

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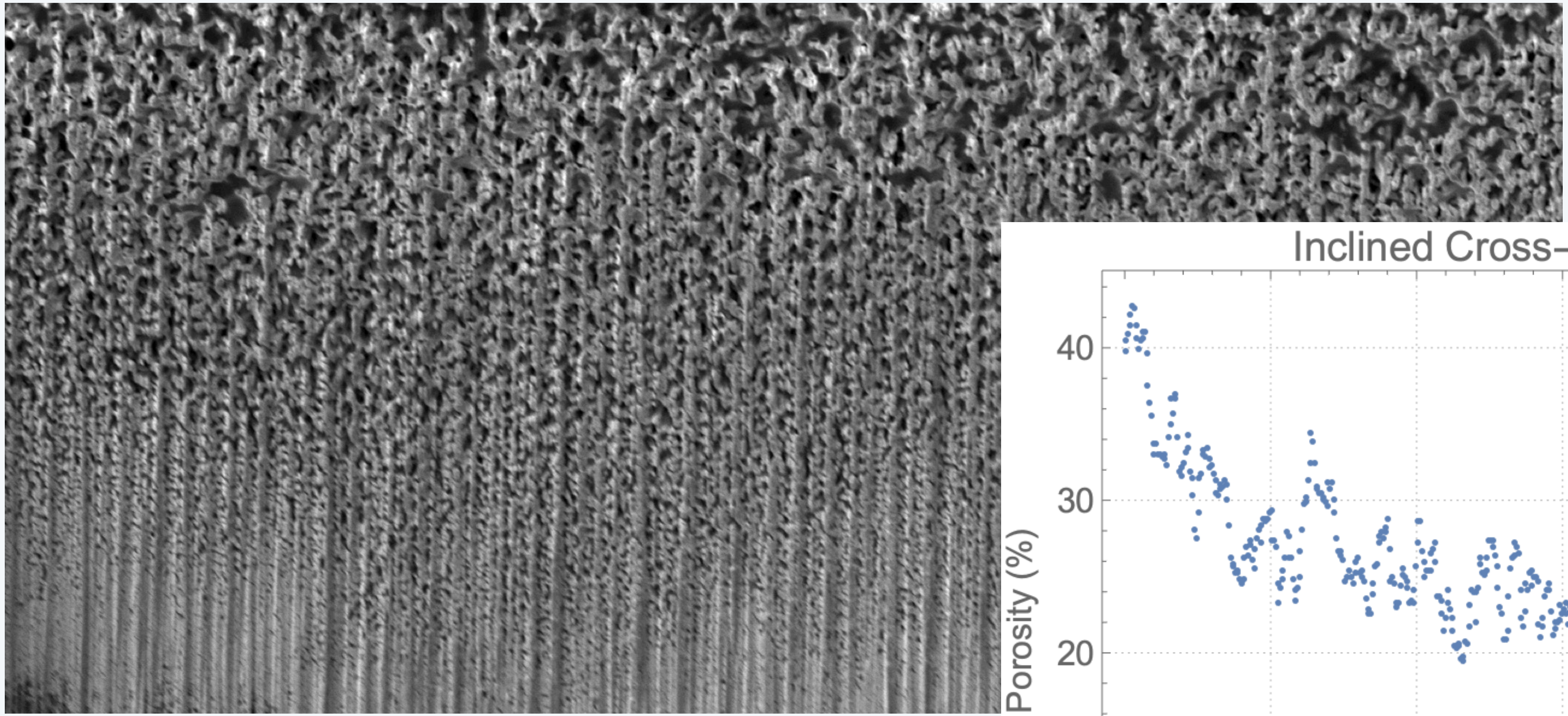

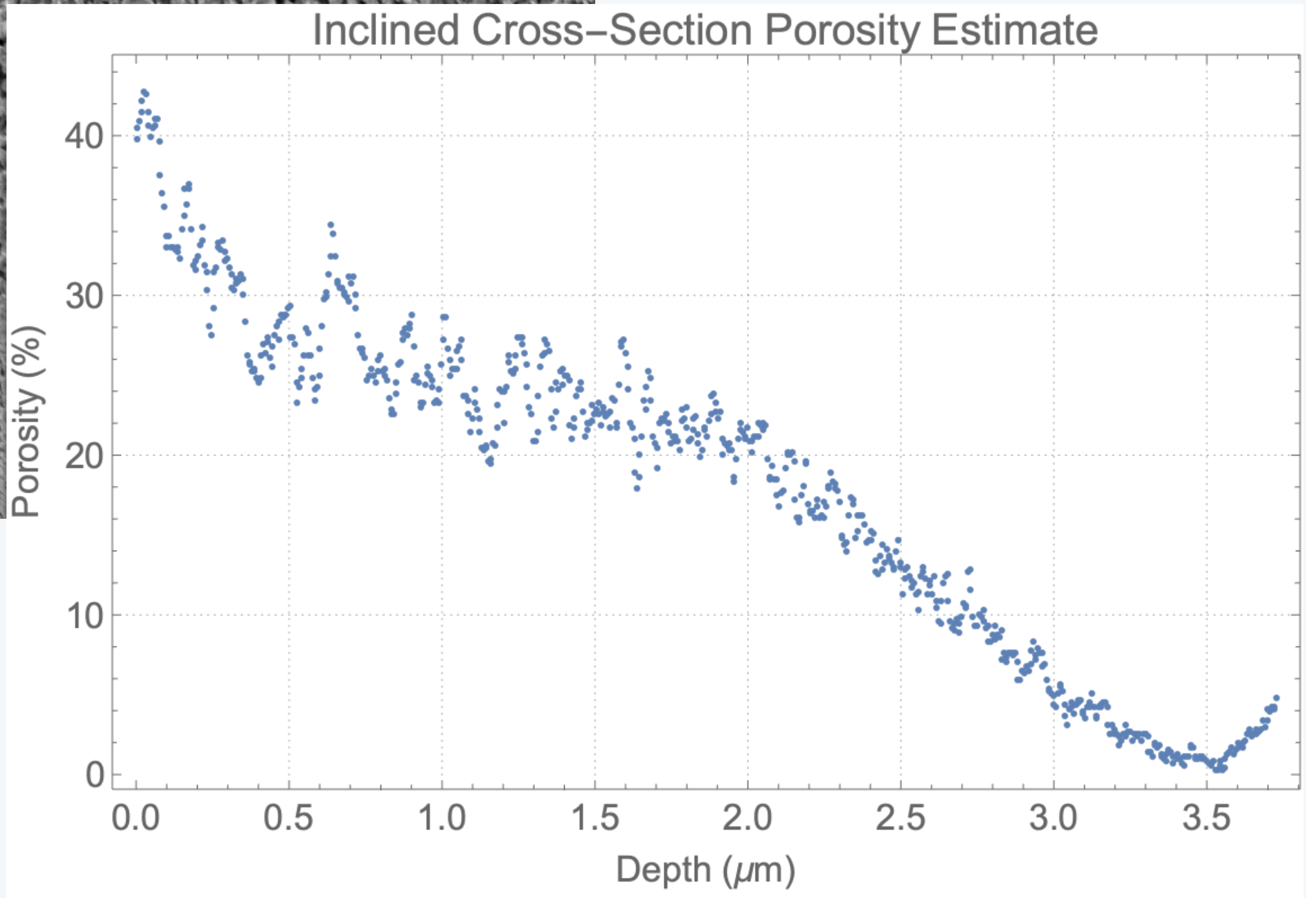

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Platinum High Tafel Slope Indications vs. Ir Ionomer Contact

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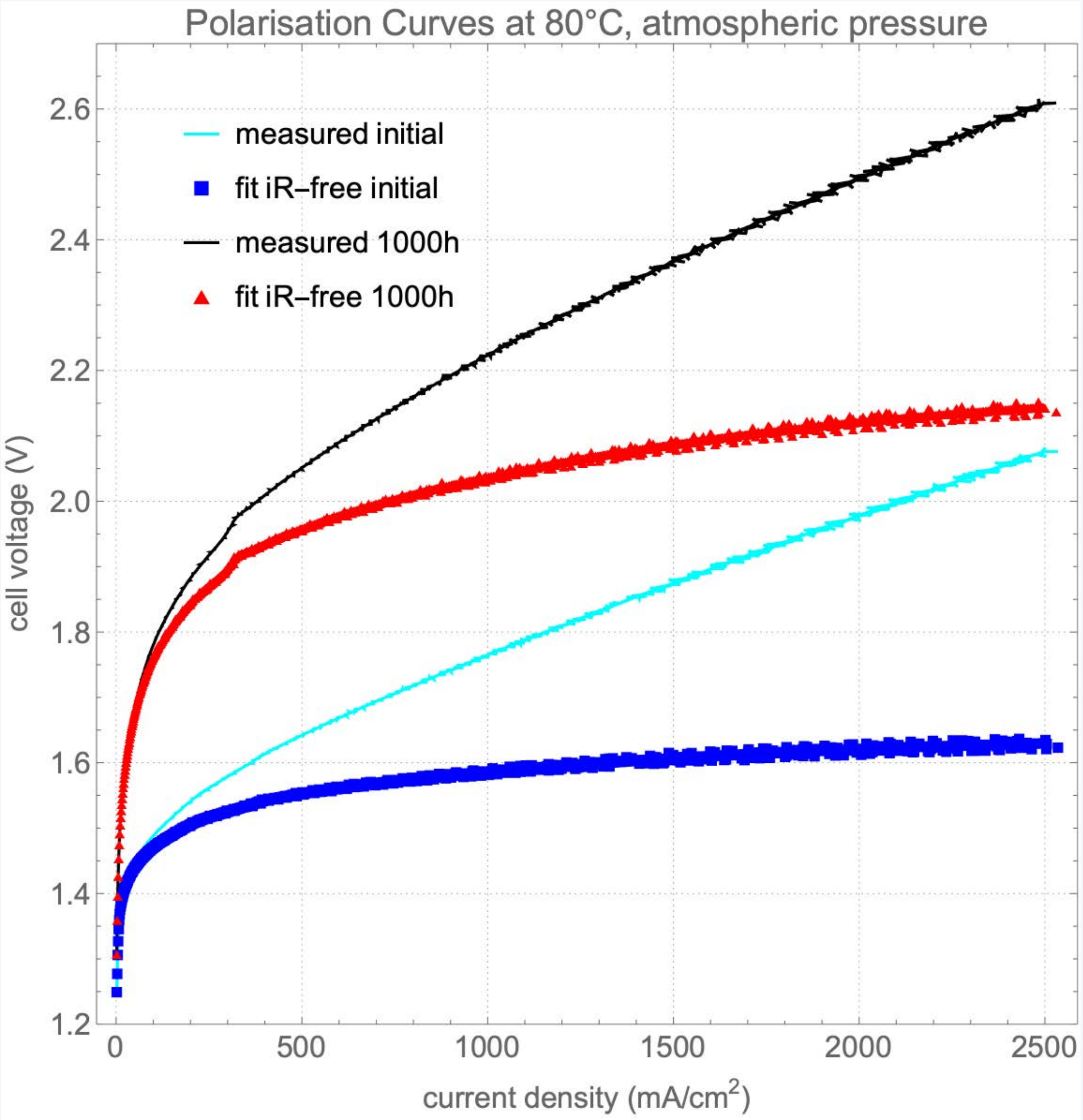

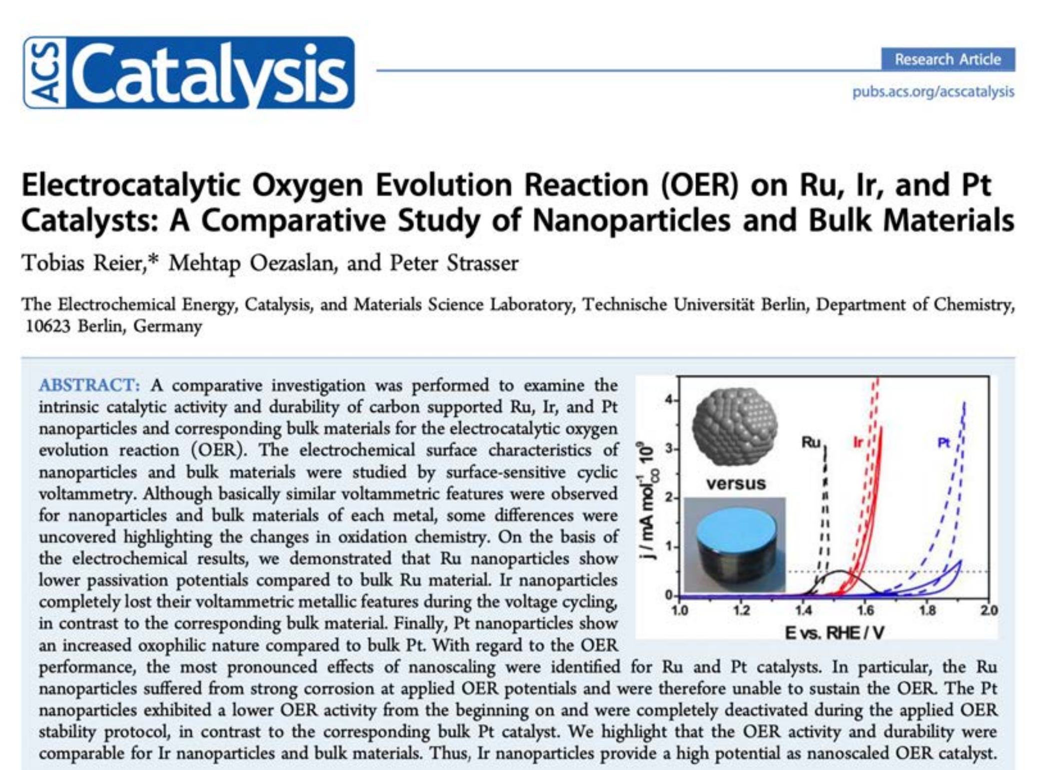

ACS Catalysis
Research Article
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Electrocatalytic Oxygen Evolution Reaction (OER) on Ru, Ir, and Pt Catalysts: A Comparative Study of Nanoparticles and Bulk Materials

Tobias Reier,* Mehtap Oezaslan, and Peter Strasser

The Electrochemical Energy, Catalysis, and Materials Science Laboratory, Technische Universität Berlin, Department of Chemistry, 10623 Berlin, Germany

ABSTRACT: A comparative investigation was performed to examine the intrinsic catalytic activity and durability of carbon supported Ru, Ir, and Pt nanoparticles and corresponding bulk materials for the electrocatalytic oxygen evolution reaction (OER). The electrochemical surface characteristics of nanoparticles and bulk materials were studied by surface-sensitive cyclic voltammetry. Although basically similar voltammetric features were observed for nanoparticles and bulk materials of each metal, some differences were uncovered highlighting the changes in oxidation chemistry. On the basis of the electrochemical results, we demonstrated that Ru nanoparticles show lower passivation potentials compared to bulk Ru material. Ir nanoparticles completely lost their voltammetric metallic features during the voltage cycling, in contrast to the corresponding bulk material. Finally, Pt nanoparticles show an increased oxophilic nature compared to bulk Pt. With regard to the OER performance, the most pronounced effects of nanoscaling were identified for Ru and Pt catalysts. In particular, the Ru nanoparticles suffered from strong corrosion at applied OER potentials and were therefore unable to sustain the OER. The Pt nanoparticles exhibited a lower OER activity from the beginning on and were completely deactivated during the applied OER stability protocol, in contrast to the corresponding bulk Pt catalyst. We highlight that the OER activity and durability were comparable for Ir nanoparticles and bulk materials. Thus, Ir nanoparticles provide a high potential as nanoscaled OER catalyst.

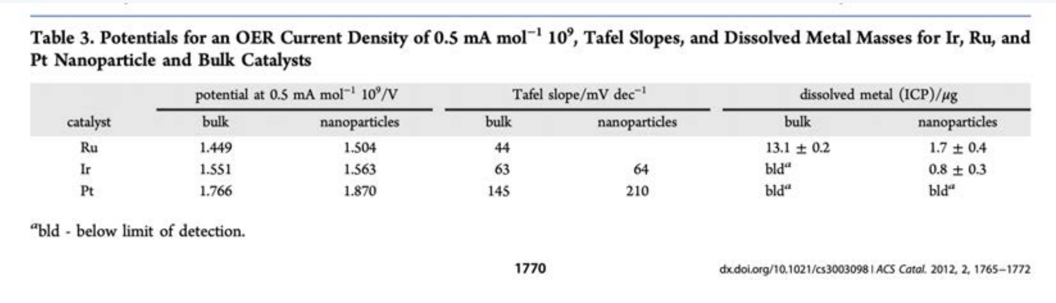

Table 3. Potentials for an OER Current Density of 0.5 mA mol^{-1} 10^9, Tafel Slopes, and Dissolved Metal Masses for Ir, Ru, and Pt Nanoparticle and Bulk Catalysts

catalyst	potential at 0.5 mA mol^{-1} 10^9/V		Tafel slope/mV dec^{-1}		dissolved metal (ICP)/μg	
	bulk	nanoparticles	bulk	nanoparticles	bulk	nanoparticles
Ru	1.449	1.504	44		13.1 ± 0.2	1.7 ± 0.4
Ir	1.551	1.563	63	64	bld[a]	0.8 ± 0.3
Pt	1.766	1.870	145	210	bld[a]	bld[a]

[a]bld - below limit of detection.

1770

dx.doi.org/10.1021/cs3003098 | ACS Catal. 2012, 2, 1765−1772

1000 Hours Durability Test at 2A/cm² – EIS at 1A/cm² (2/2)

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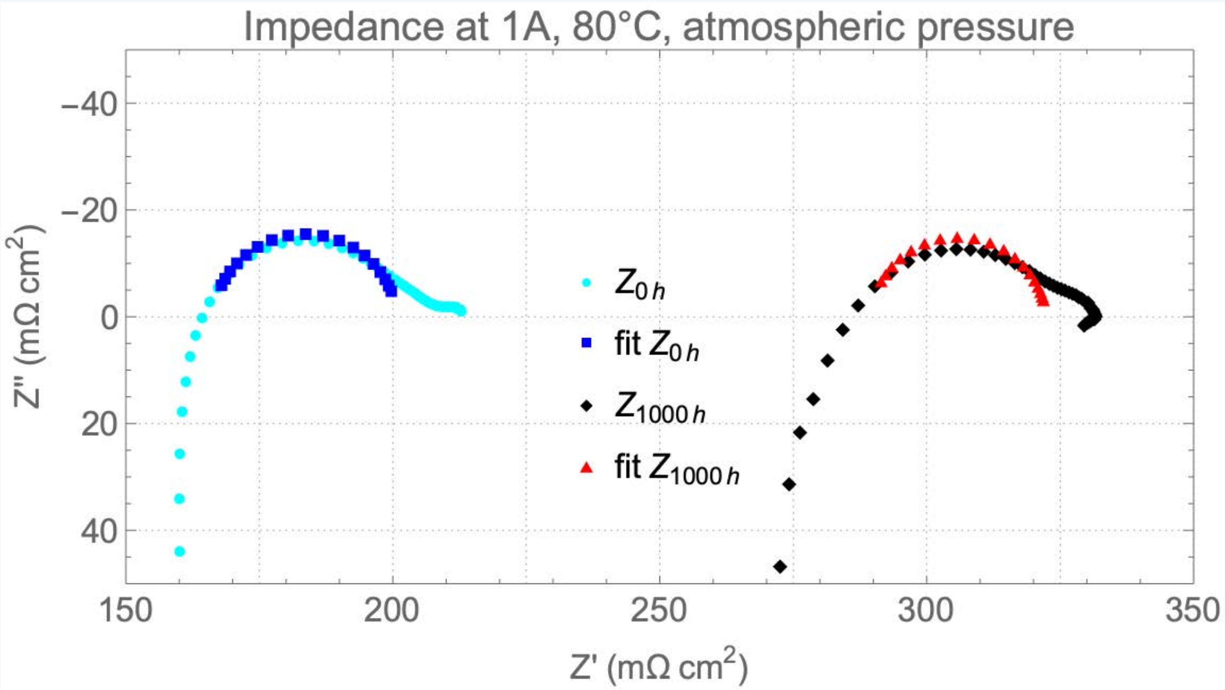
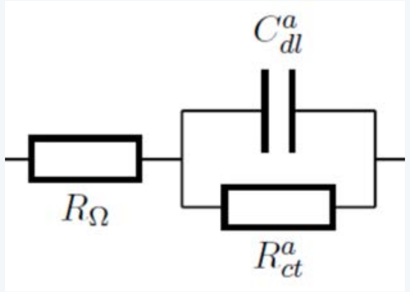
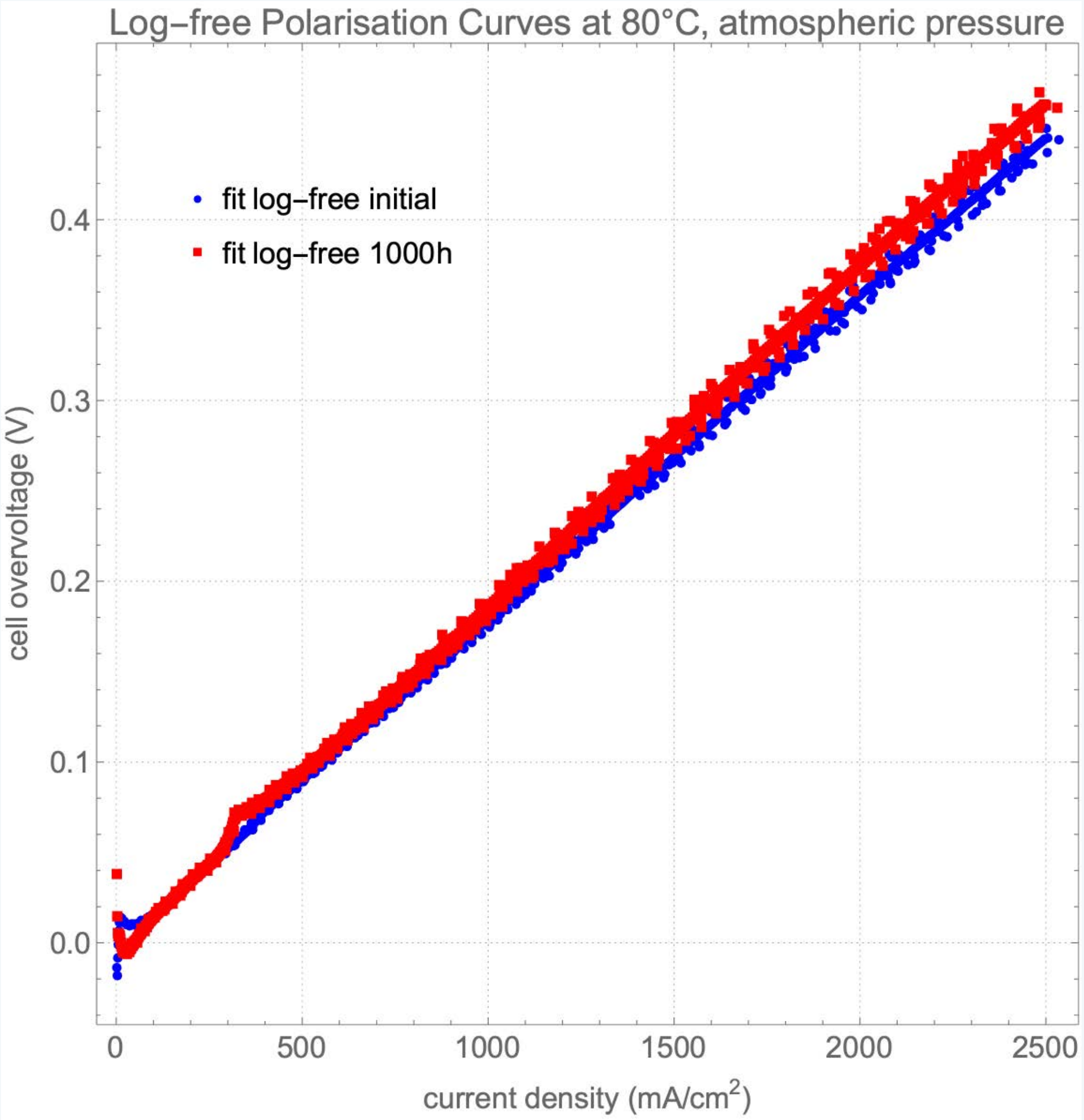


- EIS model simplified Randles circuit with CPE and non-linear fit of exponent in selected frequency interval

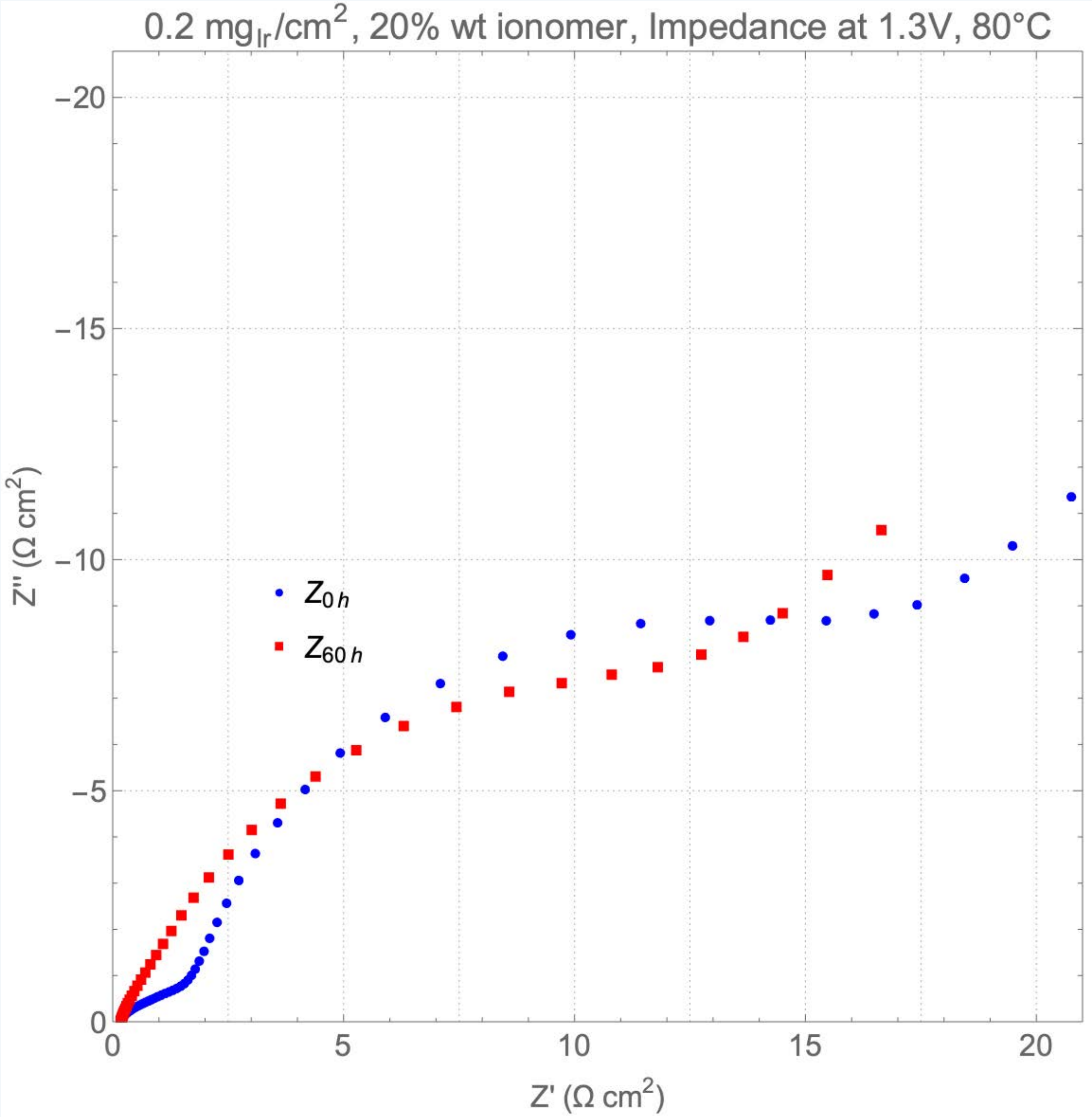


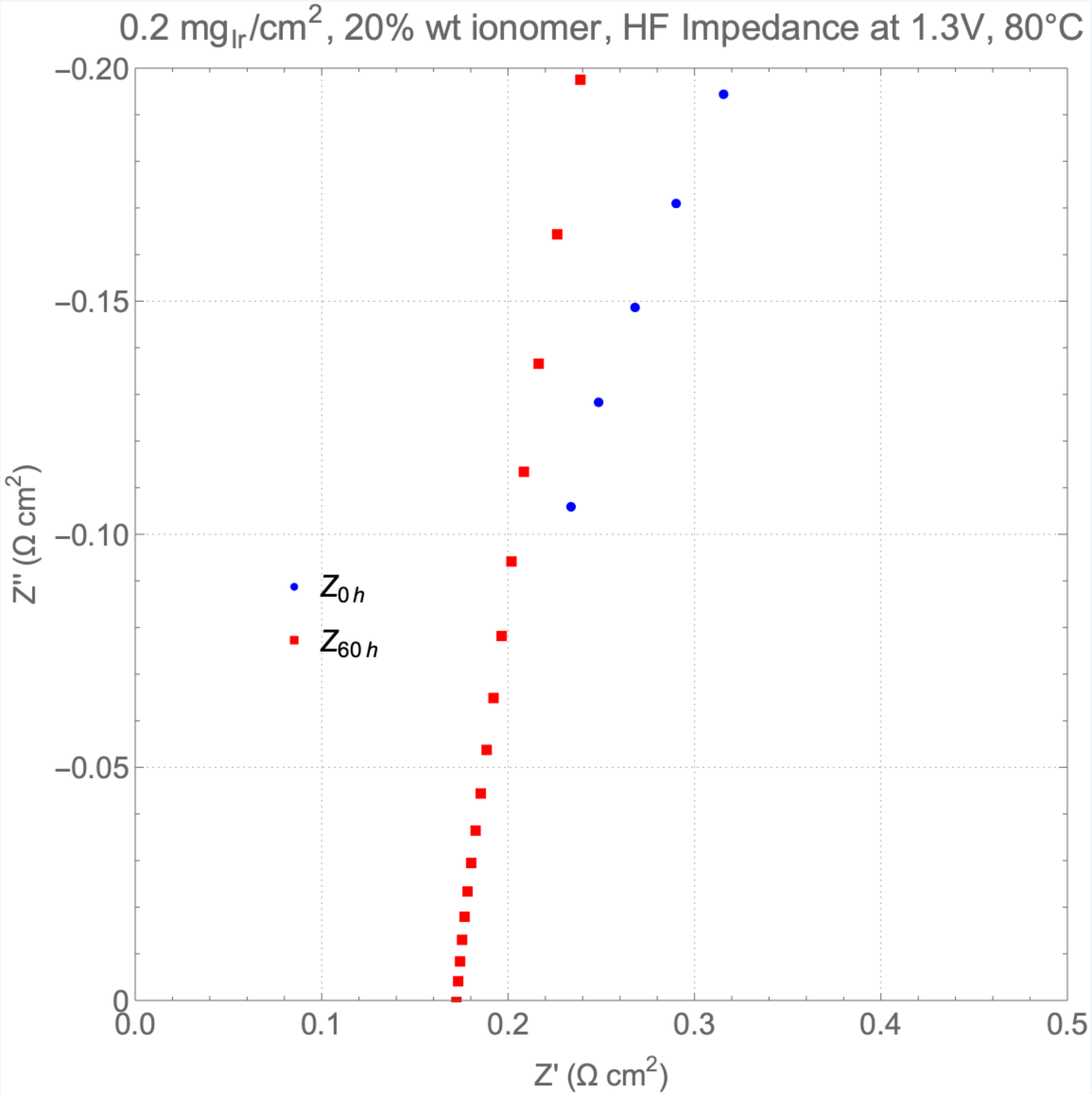
EIS @ 1A	HFR (mΩ cm²)	R_{CT} (mΩ cm²)	a	C_{CPE} (s^{a-1} mF/cm²)
0h	166	34	0.92	13
1000h	289	33	0.93	6

E0 And Tafel Fit Subtracted From Polarization Data



EIS @ 1.3 V – Non-Faradaic Currents, Membrane Resistance

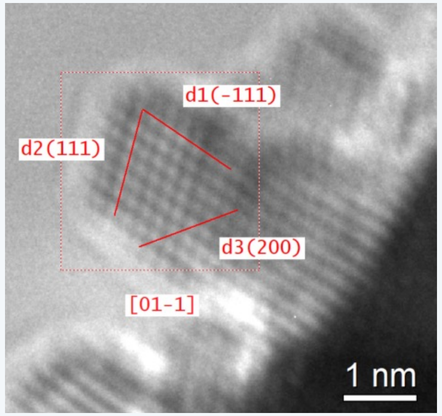




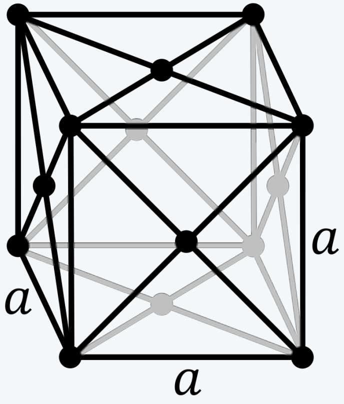
TEM analysis of Iridium nanoparticles

Before 1000h durability test

Metallic Ir



High Resolution (HR) image



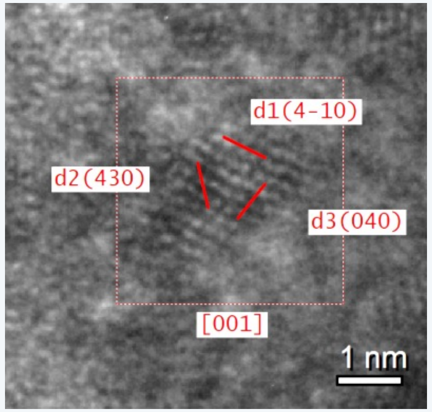
Cubic crystal system
a = 0.3840 nm

d1 = 0.21637 nm
d2 = 0.21654 nm
d3 = 0.18940 nm
∠d1d2 = 69.86˚
∠d2d3 = 53.31˚

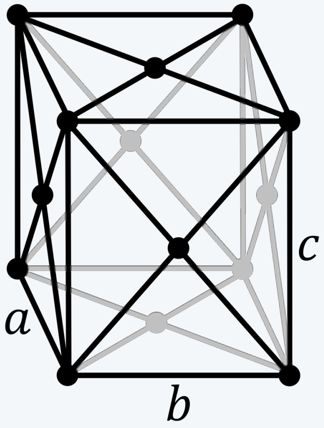
d(-111) = 0.2217 nm
d(111) = 0.2217 nm
d(200) = 0.192 nm
∠d1d2 = 70.53˚
∠d2d3 = 54.74˚

After 1000h durability test

IrF_4



High Resolution (HR) image



Orthorhombic crystal system
a = 0.9640 nm
b = 0.9250 nm
c = 0.5670 nm

d1 = 0.2296 nm
d2 = 0.1817 nm
d3 = 0.2271 nm
∠d1d2 = 52.79˚
∠d2d3 = 51.67˚

d(4-10) = 0.2332 nm
d(430) = 0.1899 nm
d(040) = 0.2313 nm
∠d1d2 = 52.62˚
∠d2d3 = 51.99˚

Next-Gen PTL: ECS246