DOLPHIN

Disruptive pemfc stack with nOvel materiaLs, Processes, arcHitecture and optimized INterfaces

DOLPHIN Workshop, Ulm June 16th 2023

Technological highlights: components, production technology, performance results

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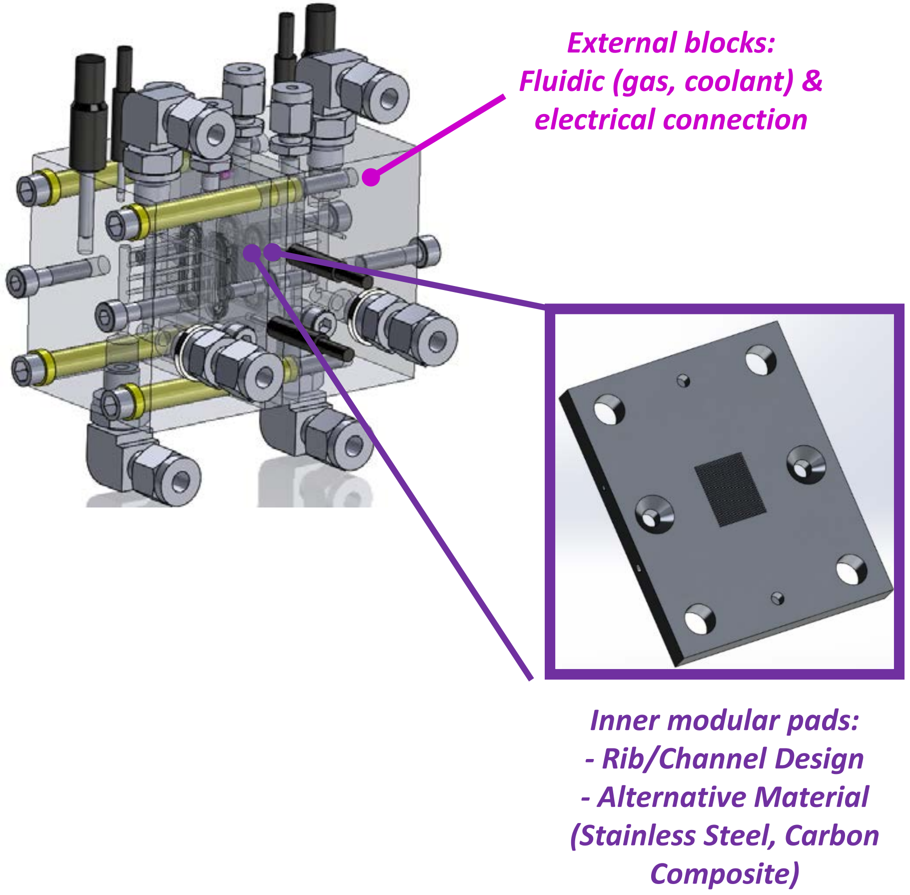
ZSW Team : Benjamin WIEDEMANN, Michael SCHMID, Sepehr SAADAT, Florian WILHELM

First evaluation of the different concepts EC and EFC at small scale

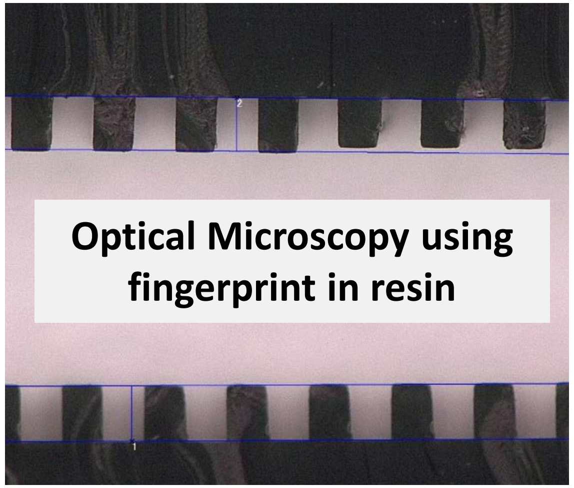
- **Use of differential cell « zero gradient »**
  - Homogeneous fluidic conditions
  - Homogeneous T°, RH and concentrations
  - Reproduction of local stack operation

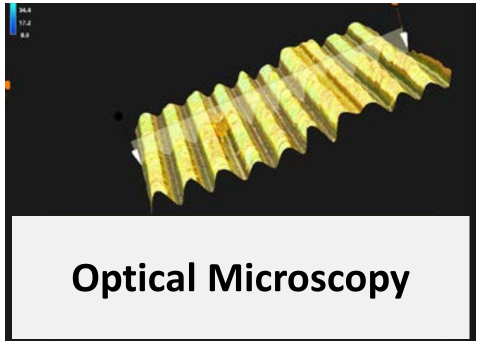
- **Many designs and configurations to be evaluated**
  - Model Rib/channel designs **(EFC)**
    - ✓ **3D printing (CEA) and additive manufacturing (DMG Mori)**
    - ✓ **Channels formed into GDM**
  - EC|EFC Interface
    - ✓ **Optimisation of MPL layer (ZSW)**
    - ✓ **Removal of GDM/GDL**
  - CCM material (membrane and electrode composition) **(EC)**
  - Impact of Single Layer Graphene onto the PFSA membrane **(EC)**
    - ✓ **Presentation of SLG by University of Manchester**



Experimental methodology

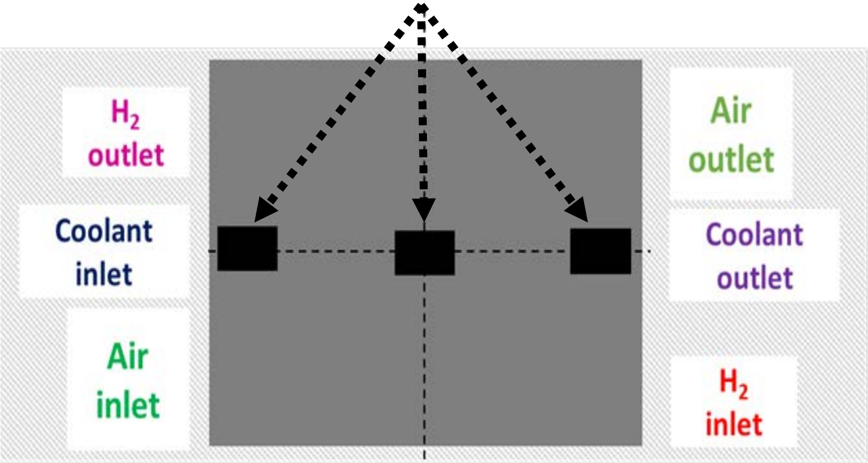
- **Approach based on system and stack specifications**
- **Further definition of local operating conditions based on modeling at cell level**
- **Reference and commercial materials used as EC and EFC**
  - Commercial Gore CCM (0.1 / 0.4 mg_{Pt}/cm^2) & Commercial GDL materials
  - Model flowfield designs by machining





Metrology control for reference milled designs

3 local areas considered



3 sets of operating conditions tested Low/Max Power and Flooded

Performances evaluation from local operating conditions

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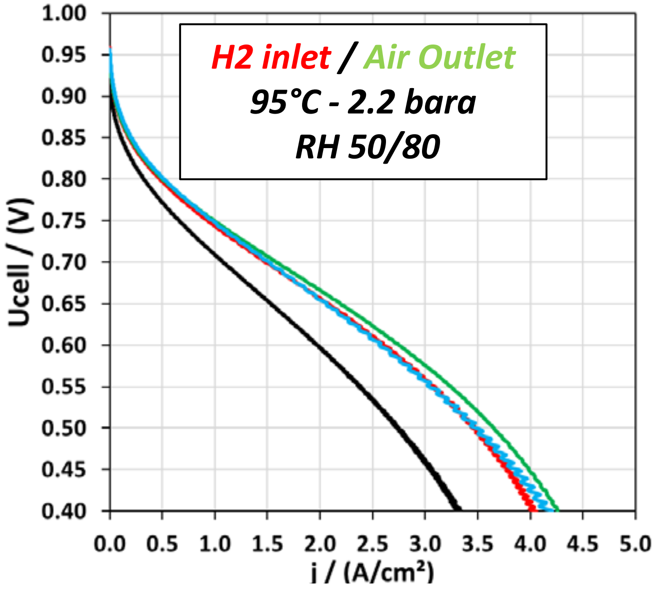
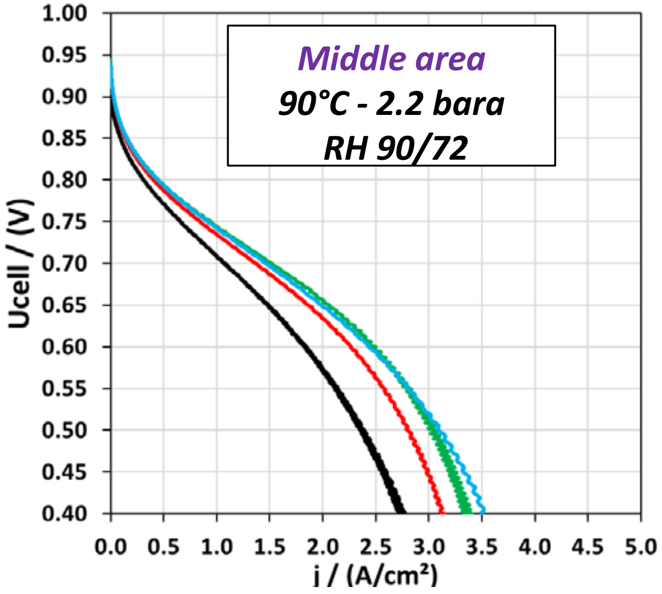
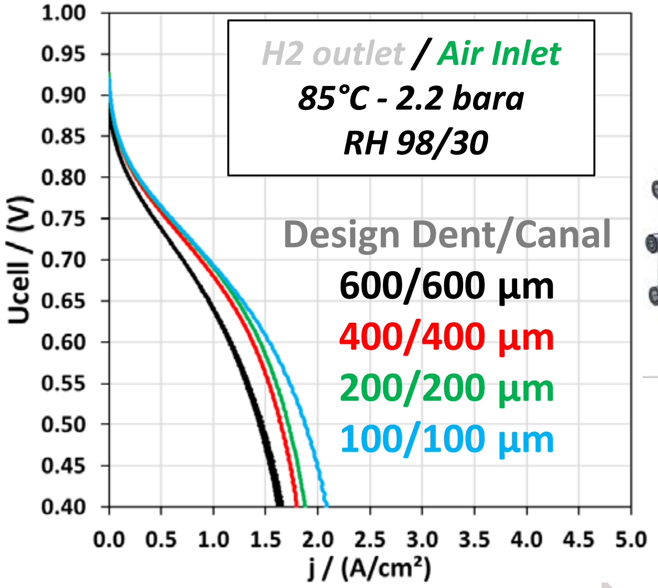
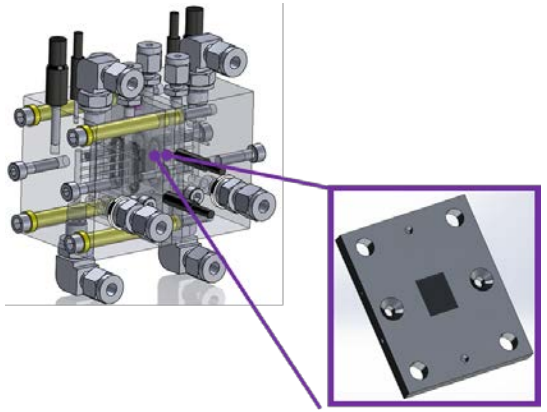
- **Characterization of local performances at maximum power conditions**

Cathode Air Flow









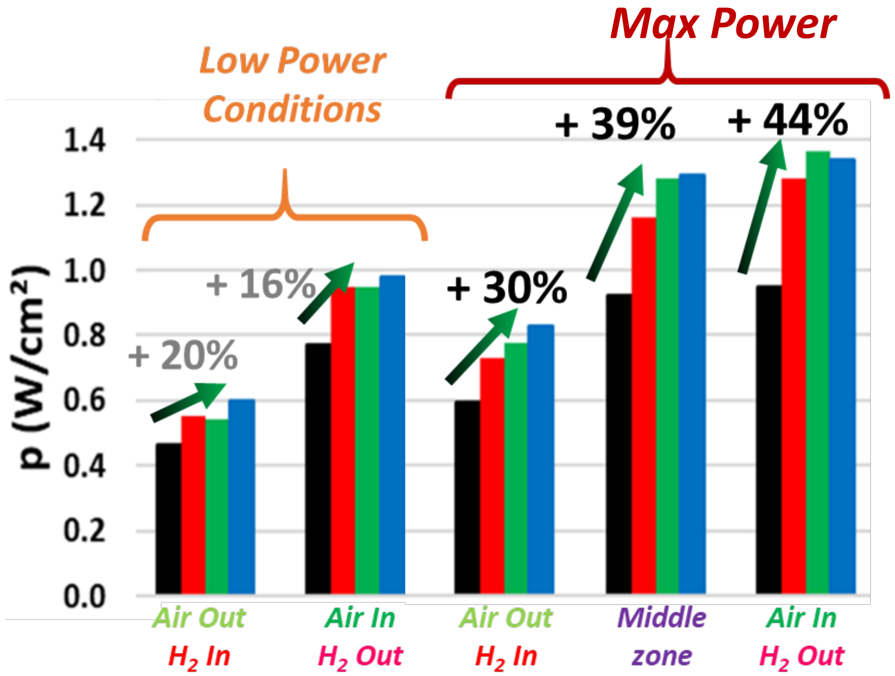
Anode H2 Flow

Performances greatly improved by reducing the rib/channel size in every local area and under every operating condition

→ Even in differential/zero gradient cell with high stoichiometries : flow-field design strongly impacts the raw performances

→ High interest to decrease rib/channel size down to at least 400 µm – Minor improvement below 200 µm

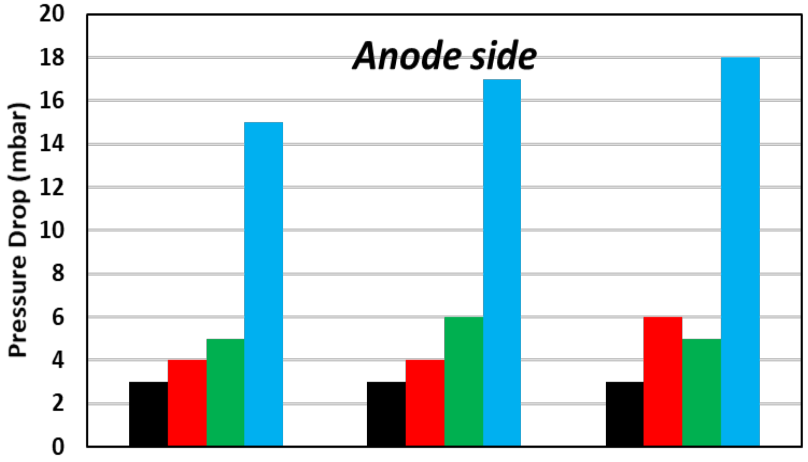
Performances evaluation from local operating conditions

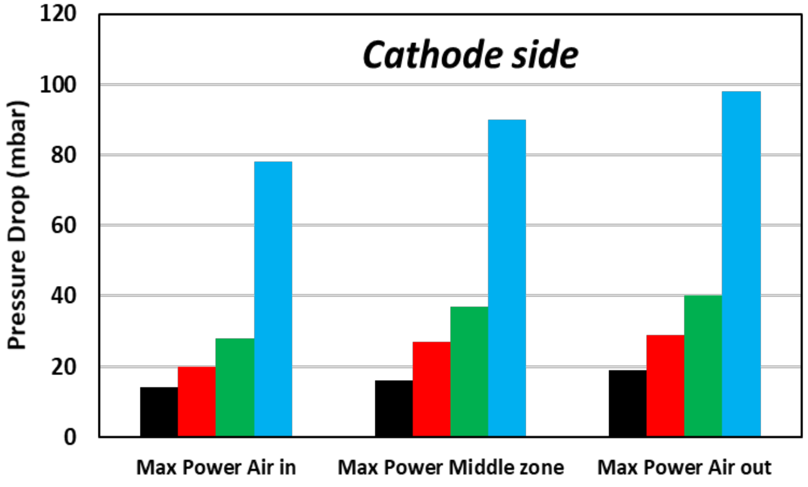


Rib/Channel Design

600/600 µm 200/200 µm

400/400 µm 100/100 µm





- Performance increased in every condition with refined flow field
- Power density enhancement : +30%/+44 % @ 0.66 V at max power
- No significant difference between 100/100 & 200/200 µm designs

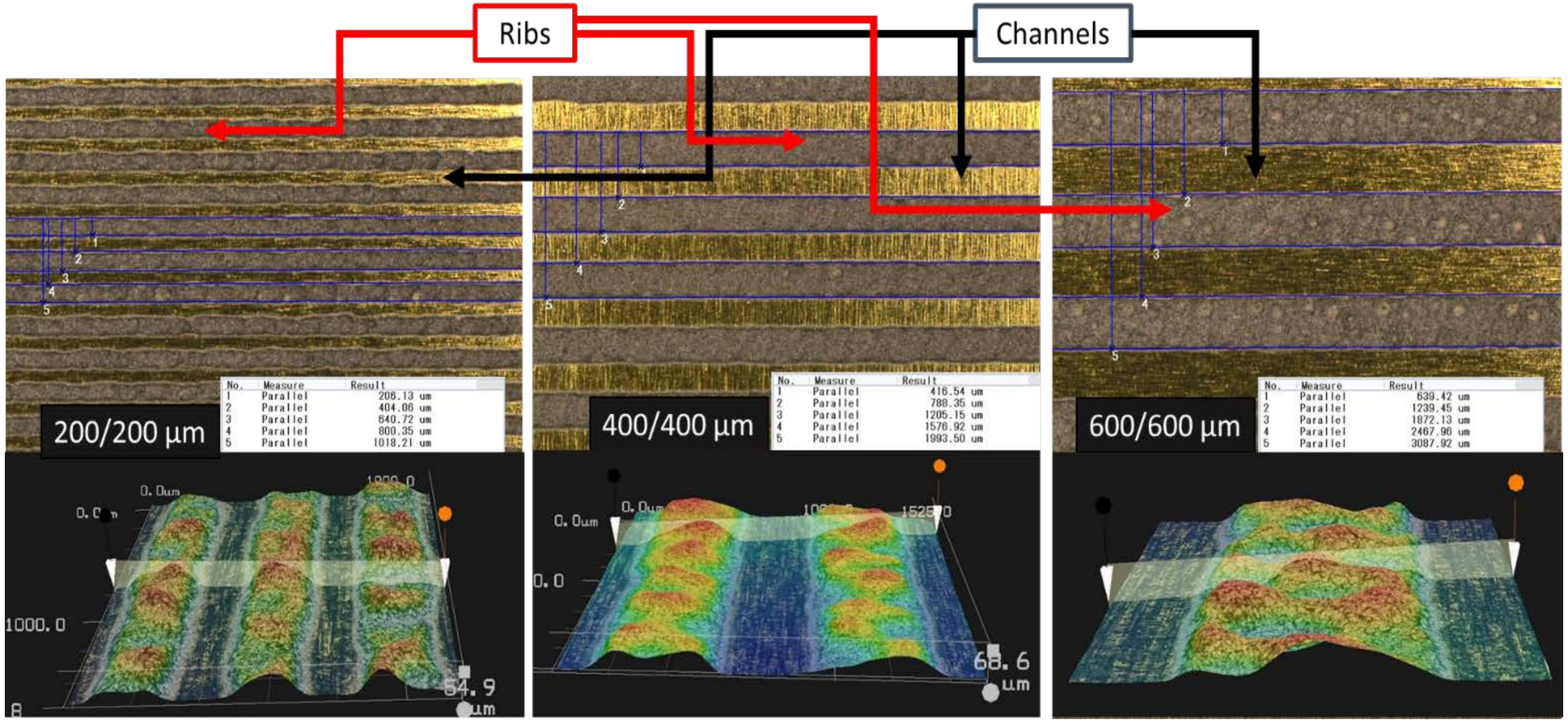
- High pressure drop below 200/200/200 µm design
- « 100 µm size » not realistic for cathode side on large active surface area

Investigations for innovative flow-field & manufacturing processes

- **Refined flow-field not achievable by SoA metallic sheet stamping**
- **New manufacturing methods have to be found**
  - Carbon ribs printing onto flat substrate
  - Channel integration into GDM layer
  - Additive manufacturing plates / Laser milling

(Carbon ribs printing; Channel integration) → Preliminary developed/tested at small scale (2 cm²)

(Additive manufacturing plates / Laser milling) → **Prototypes directly tested at 100 cm²**



-Very thin designs can be obtained by printing carbon ribs

- Very flexible manufacturing process by screen printing

Investigations for innovative flow-field manufacturing processes

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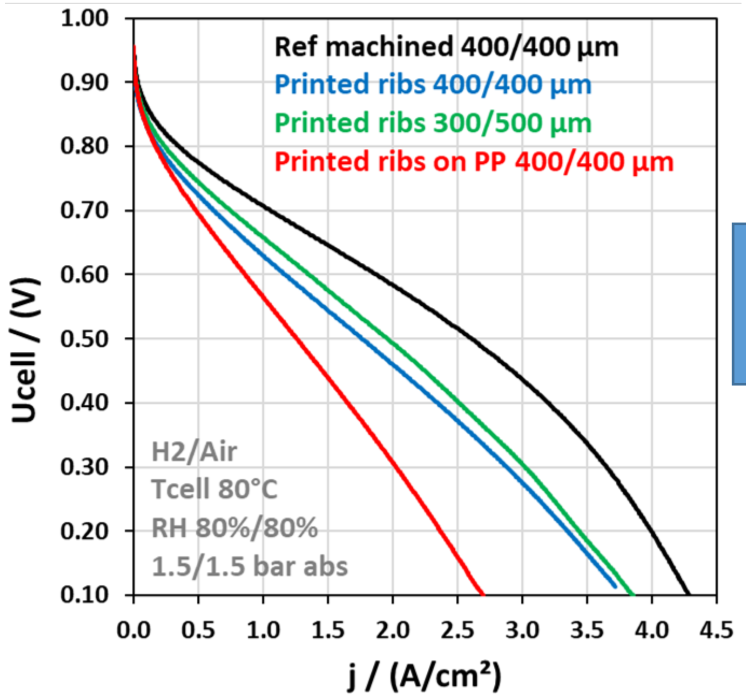
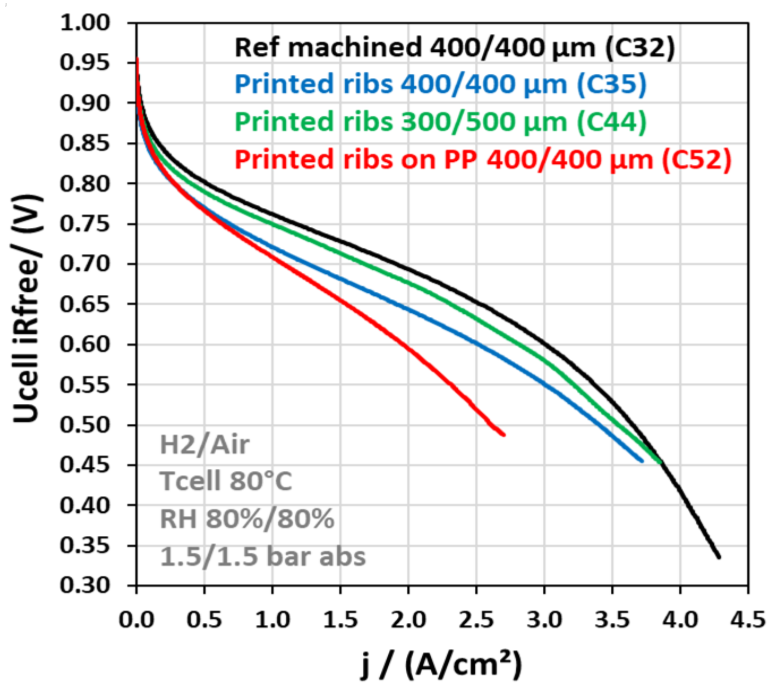


Ohmic drop correction



- **Lower electrochemical performances**
- **Gap mainly due to intrinsic electronic resistance within the ribs**
- **Further optimization of the ink composition still in progress**
- **Prepreg materials : not suitable so far to be integrated as substrate**

Investigations for innovative flow-field manufacturing processes

- **Refined flow-field not achievable by SoA metallic sheet stamping**
- **New manufacturing methods have to be developed**
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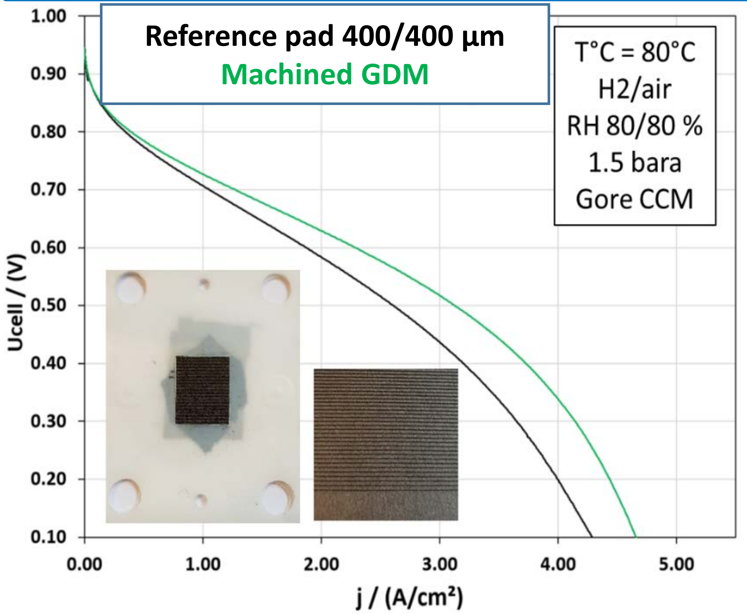

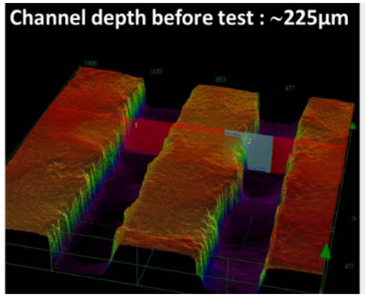

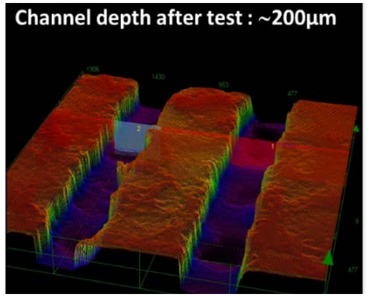

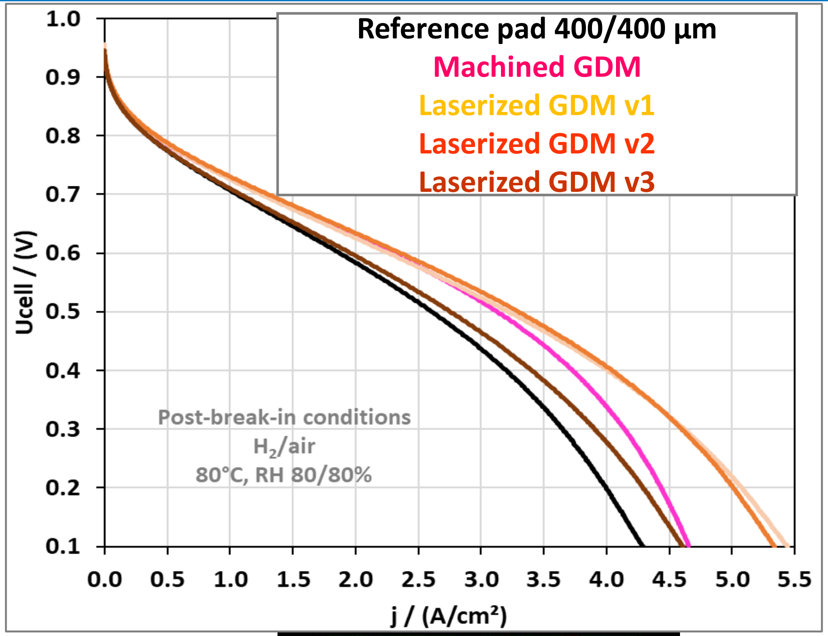

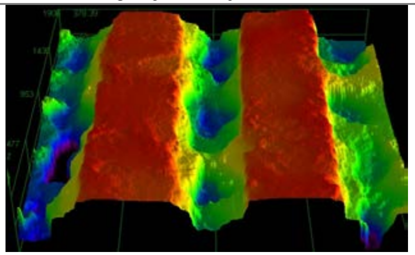

- Require thicker GDM/GDL to create channels (but overall cell thickness decreased) and specific GDL structure

- Alternative process tested by laser milling : Possible at small scale but further development needed at large scale (GDL deformation/twist caused during the process)

Investigations into innovative cell architectures

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Disruptive pemfc stack with nOvel materiaLs, Processes, arcHitecture and optimized INterfaces

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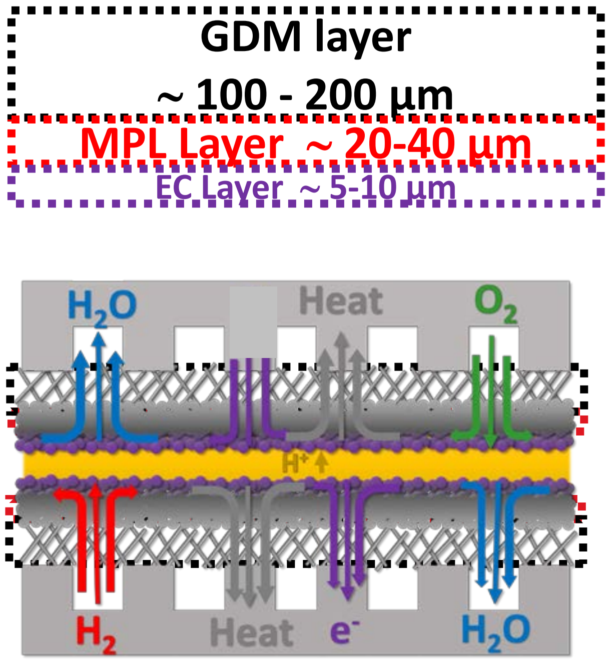
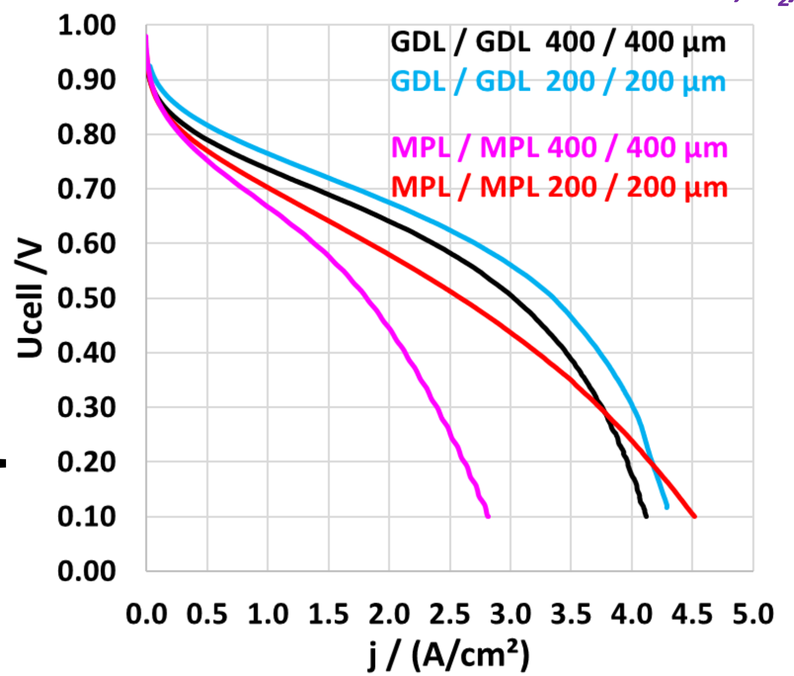
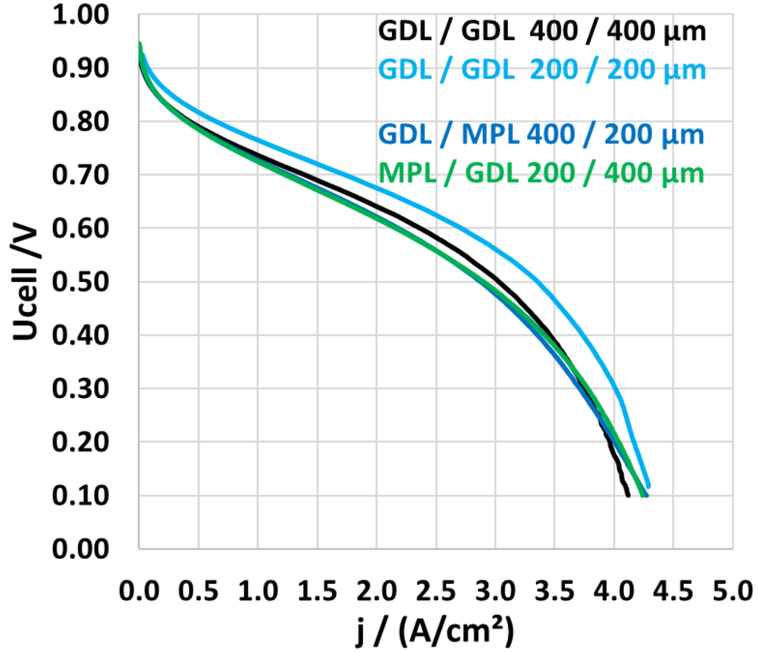
- Association of refined flow-field designs with single or dual GDM removal

Operating conditions (post break-in)
80°C, H_2/Air , 1.5/1.5 bar abs , RH 80%/80%

State-Of-Art Cell Architecture « GDL / GDL »







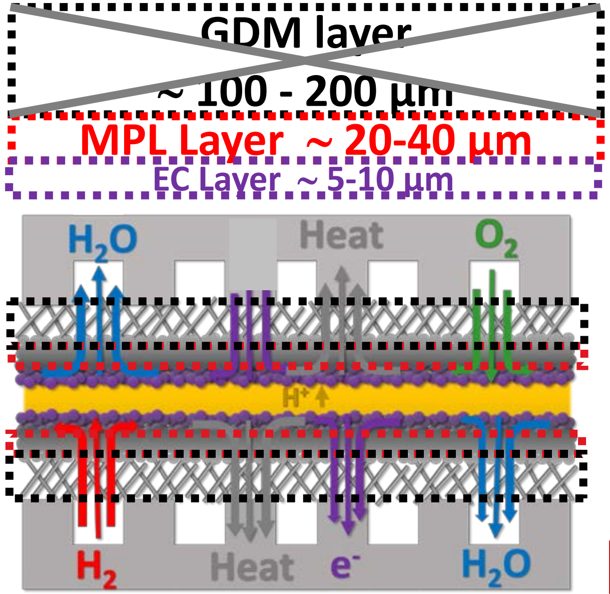
- Very poor performance without GDM with 400/400 µm design
- Higher performances with 200/200 µm but still lower than reference GDL/GDL configurations

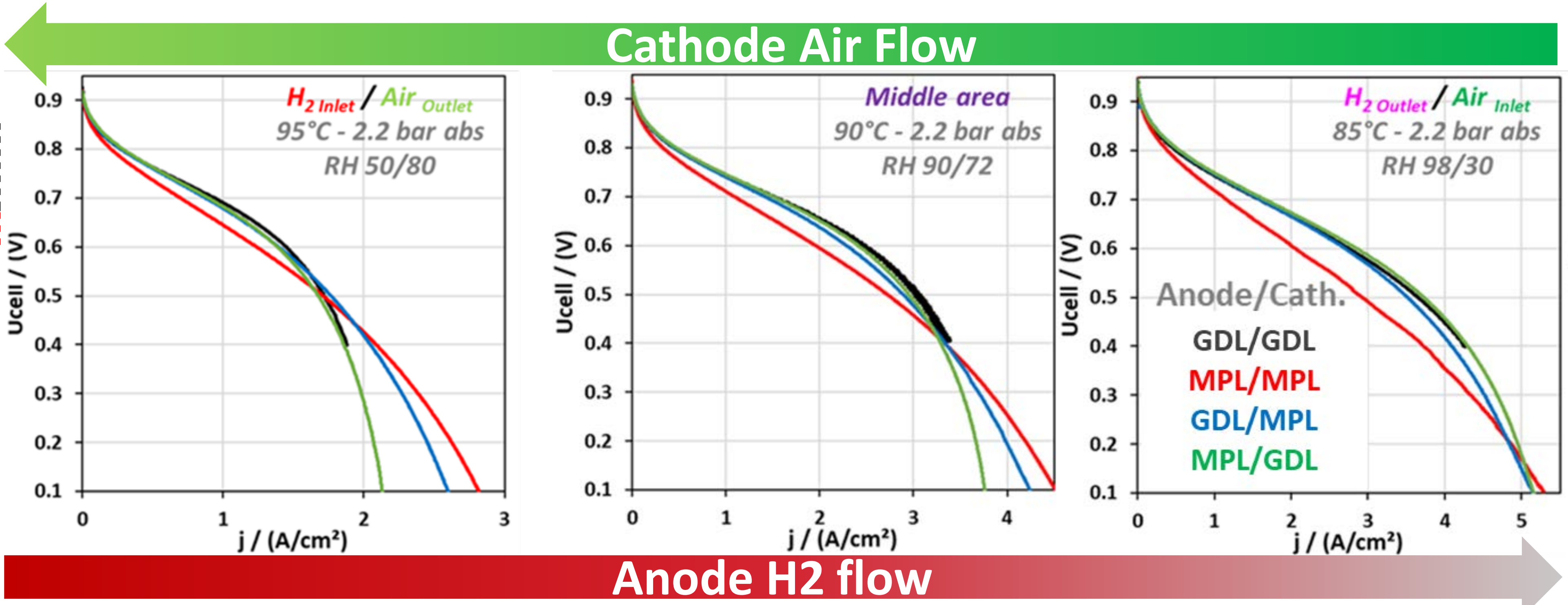
- **Suppressing one GDM enable to reach satisfying performances post break-in under model operating conditions**
- **Preliminary validation of these innovative types of cell configuration**

Investigations into innovative cell architectures

- R&D on new architectures coupling « Refined designs » and « single sided-GDL MEA »

New Cell Architecture
« MPL / GDL »





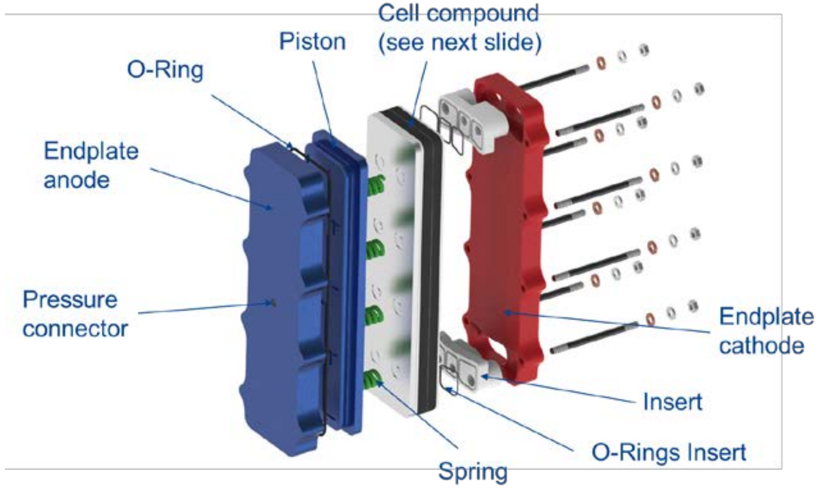
- **Both GDM suppression → Decrease of performances linked to ionomer drying at inlets/outlets and to insufficient in-plane electronic conduction within MPL**
- **Performances maintained or even slightly better by removing only one GDM**

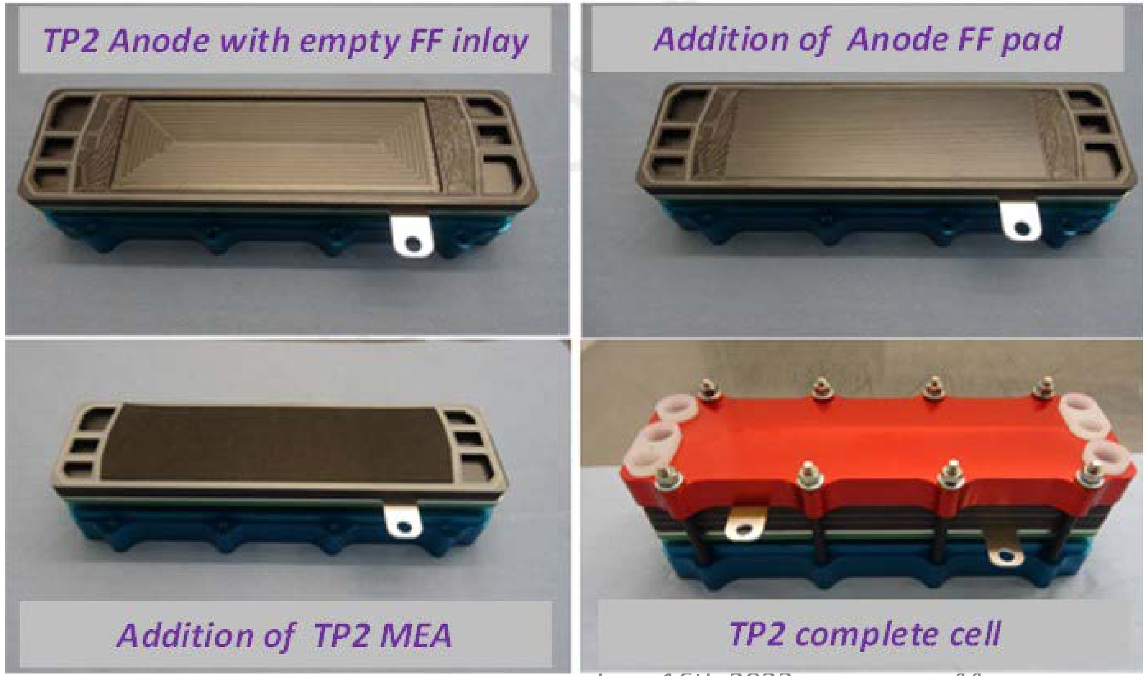
→ **Decrease of cell pitch, materials and cost saving**

- **Best configuration : GDL Anode + MPL on cathode active layer**→ Planned at 100 cm² scale

Performances at representative scale

- **Interest of Test Platform 2 « TP2 »**
  - **Scaling up for EC/EFC** to representative active area size (100 cm²)
  - **Validation** of cell electrochemical **performances under several EU conditions from previous projects** (EU Harmonized from JRC recommandations, AutoStackCore, GAIA…)
  - Characterizations of **fluidics and thermal behavior** to support stack design
  - Validation of EC core formulation and **further insights for local texturing**
  - **Performances/Durability characterizations** in representative and heterogeneous operating condition
  - **Hardware can be reused for TP3 short-stack**





Innovative EFC: Additive manufacturing process

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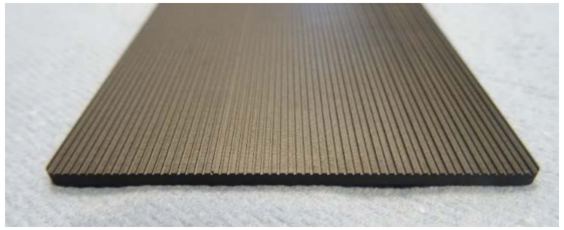
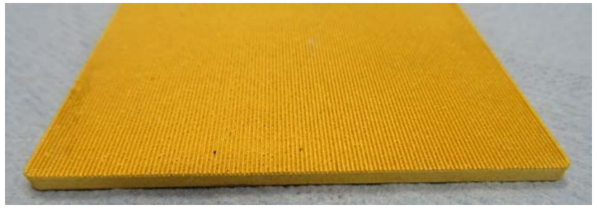
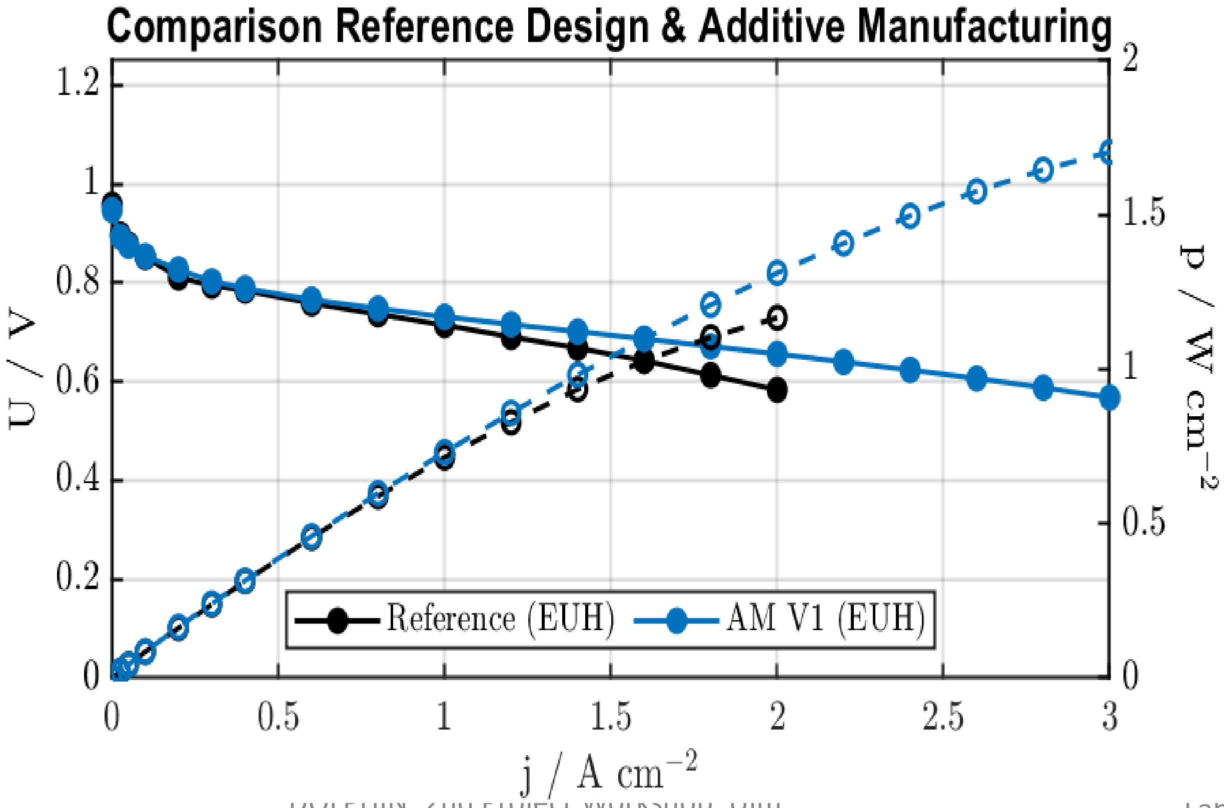
Reference Flowfield
Carbon composite



AM V1 Flowfield
Stainless steel + gold coating





Parameter	Unit	EUH
T Cl	°C	80
T A/C	°C	82
DPT A/C	°C	64.0/53.0
RH A/C	%	50.5/30.2
Stoic A/C	1	1.4/1.6
p A/C	barg	1.5/1.3
p in/out	-	out
Mingas A/C	A/cm²	0.3
N_2 A	%	0

- **Reference EFC**
  - **Channel/rib/depth**
  - **Ref Anode: 400 / 400 / 200**
  - **Reference Cathode: 500 / 500 / 300**
- **Tests of 2 versions of AM TP2 EFC**
  - **Channel/rib : Anode & Cathode**
  - **AM v1 : ~ 330 / 260 µm**
  - **AM v2 : ~ 300 / 200 µm**
- **Use of EU-Harmonized conditions (pressure regulated at cell outlet)**
- **Performances AM v1**
  - **3 A/cm² @ 0.58 V : 1.75 W/cm²**
- **AM v1 pressure drops**
  - **~ 50 / 260 mbar @ 0.66 V (*ca.* 2 A cm⁻²)**

Innovative EFC: Additive manufacturing and laser milling

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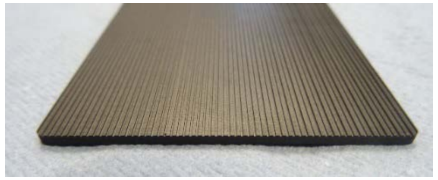
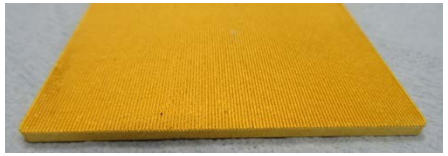
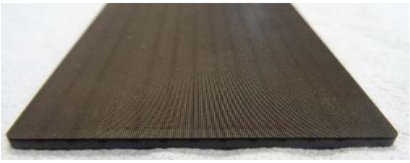
Reference Flowfield
Carbon-based

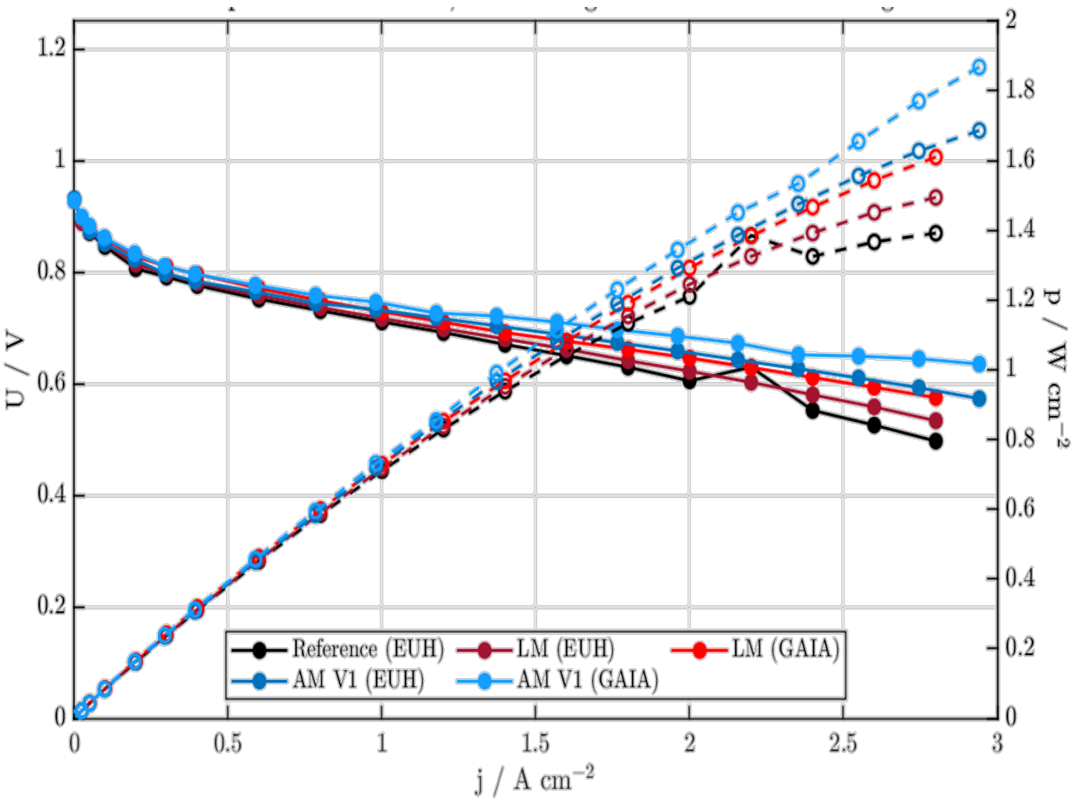


AM V1 Flowfield
Stainless steel + gold coating



Laser-Milled Flowfield
Carbon-based pad





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RH A/C	%	50.5/30.2
Stoic A/C	1	1.4/1.6
p A/C	barg	1.5/1.3
p in/out	-	out
Mingas A/C	A/cm²	0.3
N_2 A	%	0

GAIA conditions not disclosed

- **Alternative Laser Milled EFC**
  - **Channel/rib/depth dimensions**
  - **Anode : ~ 200 / 100 µm**
  - **Cathode : ~ 200 / 100 µm**
  - **Very thing pattern & smaller sizes obtained for LM vs. AM v1**
- **Comparison between EU-Harmonized and GAIA conditions (pressure regulated at cell outlet)**
- **Performances AM v1 > LM**
- **GAIA conditions leads to higher performances than EUH**

Innovative EFC: Carbon –printed ribs

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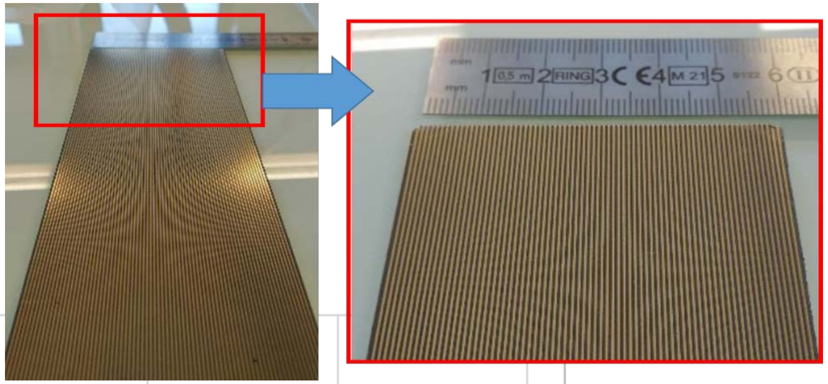
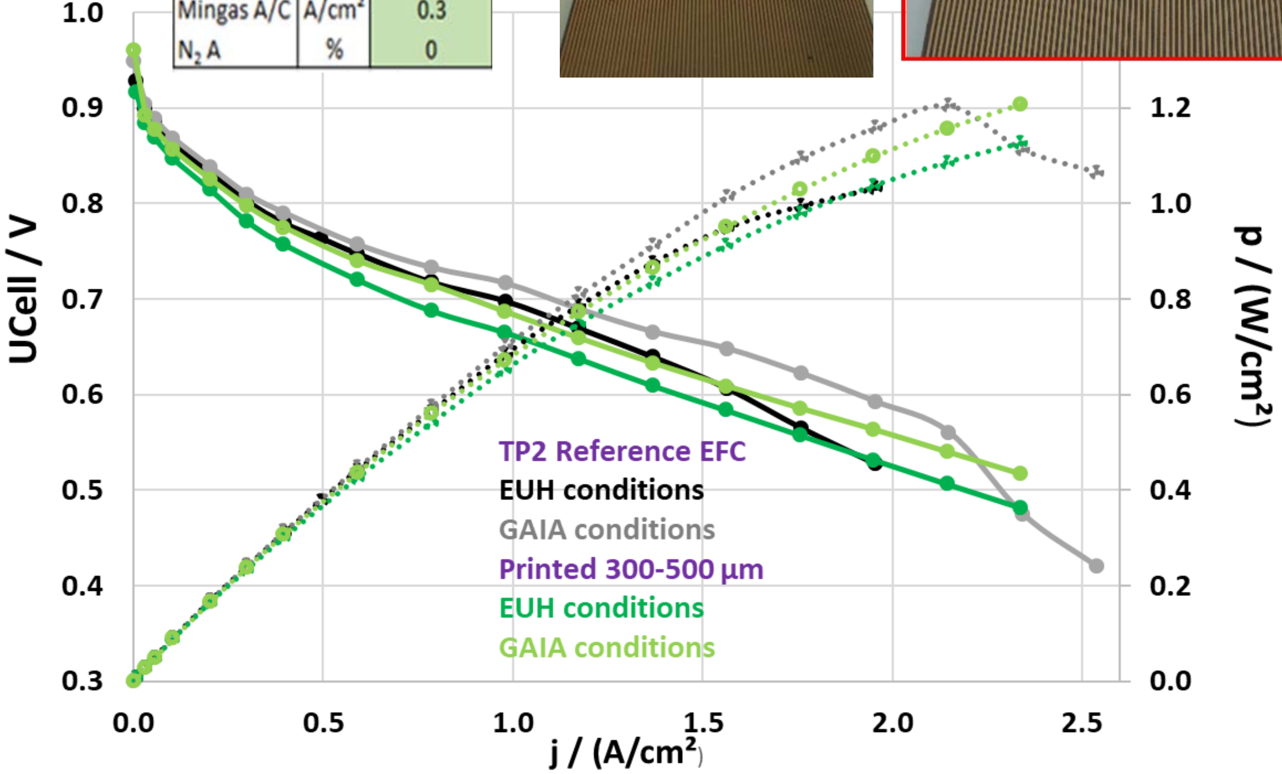
TP2 pad with printed ribs

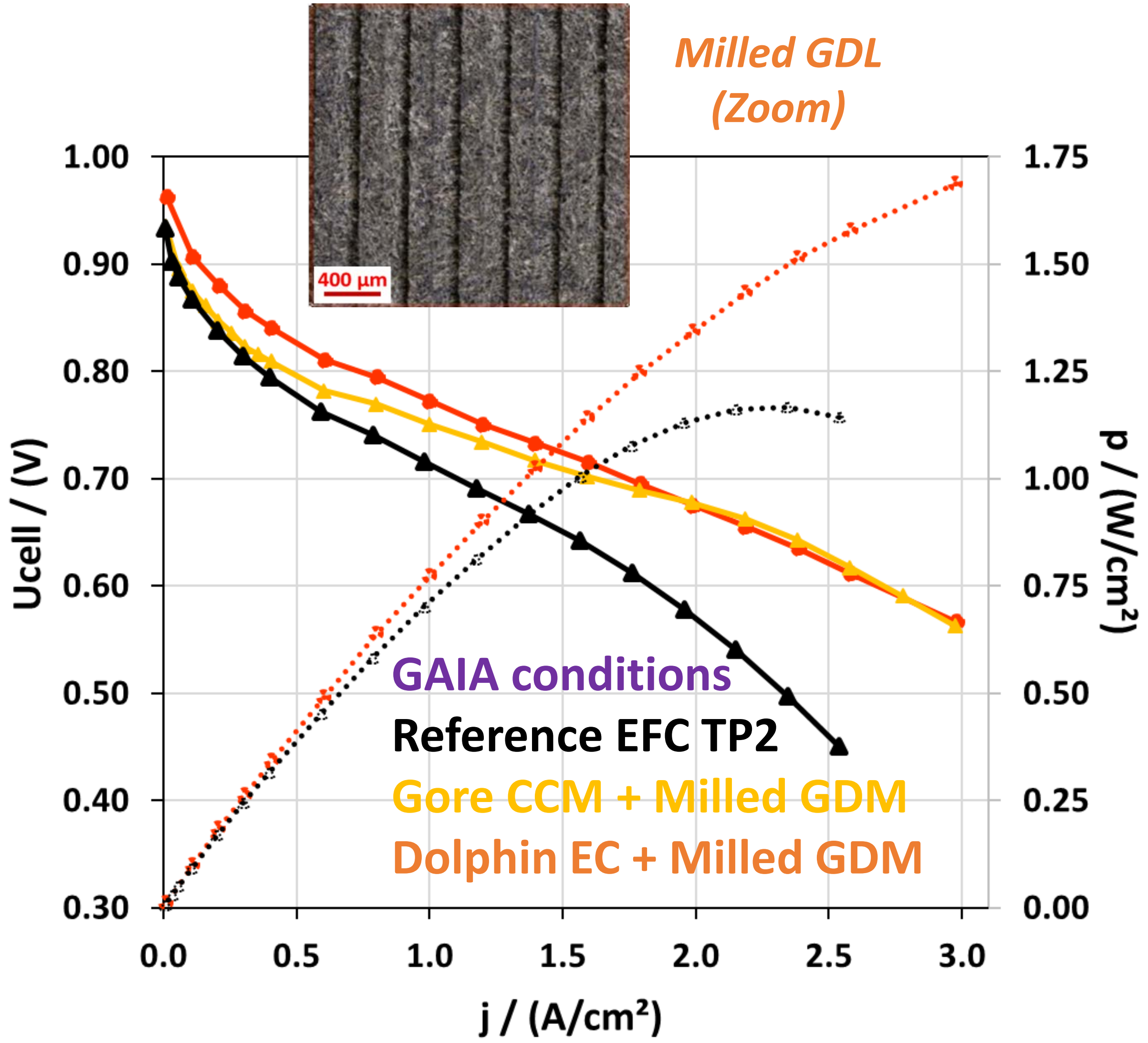
Parameter	Unit	EUH
T Cl	°C	80
T A/C	°C	82
DPT A/C	°C	64.0/53.0
RH A/C	%	50.5/30.2
Stoic A/C	1	1.4/1.6
p A/C	barg	1.5/1.3
p in/out	-	out
Mingas A/C	A/cm²	0.3
N_2 A	%	0





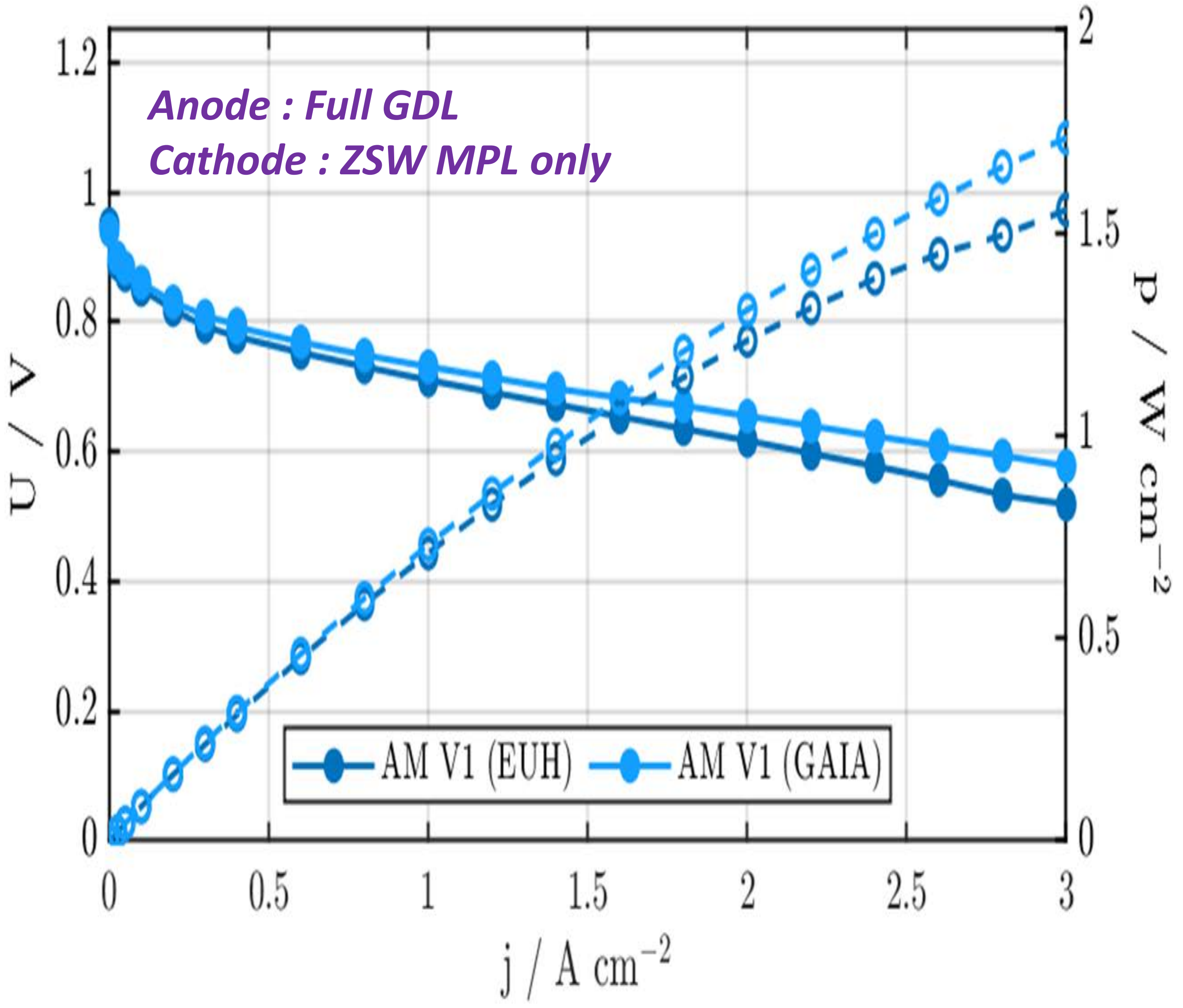
- **Raw electrochemical performances slightly lower for printed ribs than reference design (Ohmic drop / compression effect)**
- **Positive effect from refined pattern for rib/channel is balanced with higher electronic resistivity within ribs.**
- **Technology still interesting at complete stack level in terms power density**

Innovative EFC: Channels integrated into GDM



- **Deposition of ZSW MPL onto machined GDM**
- **Cell assembly with Gore EC and advanced DOLPHIN EC**
  - **2.2 A/cm² @ 0.66 V : 1.4 W/cm²** (~ 1 W/cm²)
  - **3.0 A/cm² @ 0.57 V : 1.7 W/cm²**
- **Cell assembly and EFC concept validated at representative scale but milling not suitable with all GDM (GDL) materials in terms of thickness and mechanical properties.**

Innovative EFC |EC interfaces: Suppression of one GDM layer



- **Tests of 2 configurations using AM v1 EFC**
  - *Single MPL Anode & GDL Cathode (not shown)*
  - **Anode GDL and MPL Cathode**
- **Single MPL at the cathode gives the best performances in 100 cm² single cell** (as expected from 2 cm² single cell results)
- **Performances obtained :**
  - **1.8 A/cm² @ 0.66 V : 1.2 W/cm²**
  - **3 A/cm² @ 0.58 V : 1.75 W/cm²**
- **Interesting Architecture regarding materials & cost saving**

TP2 : Comparison between reference EFC and EC and the best DOLPHIN concept

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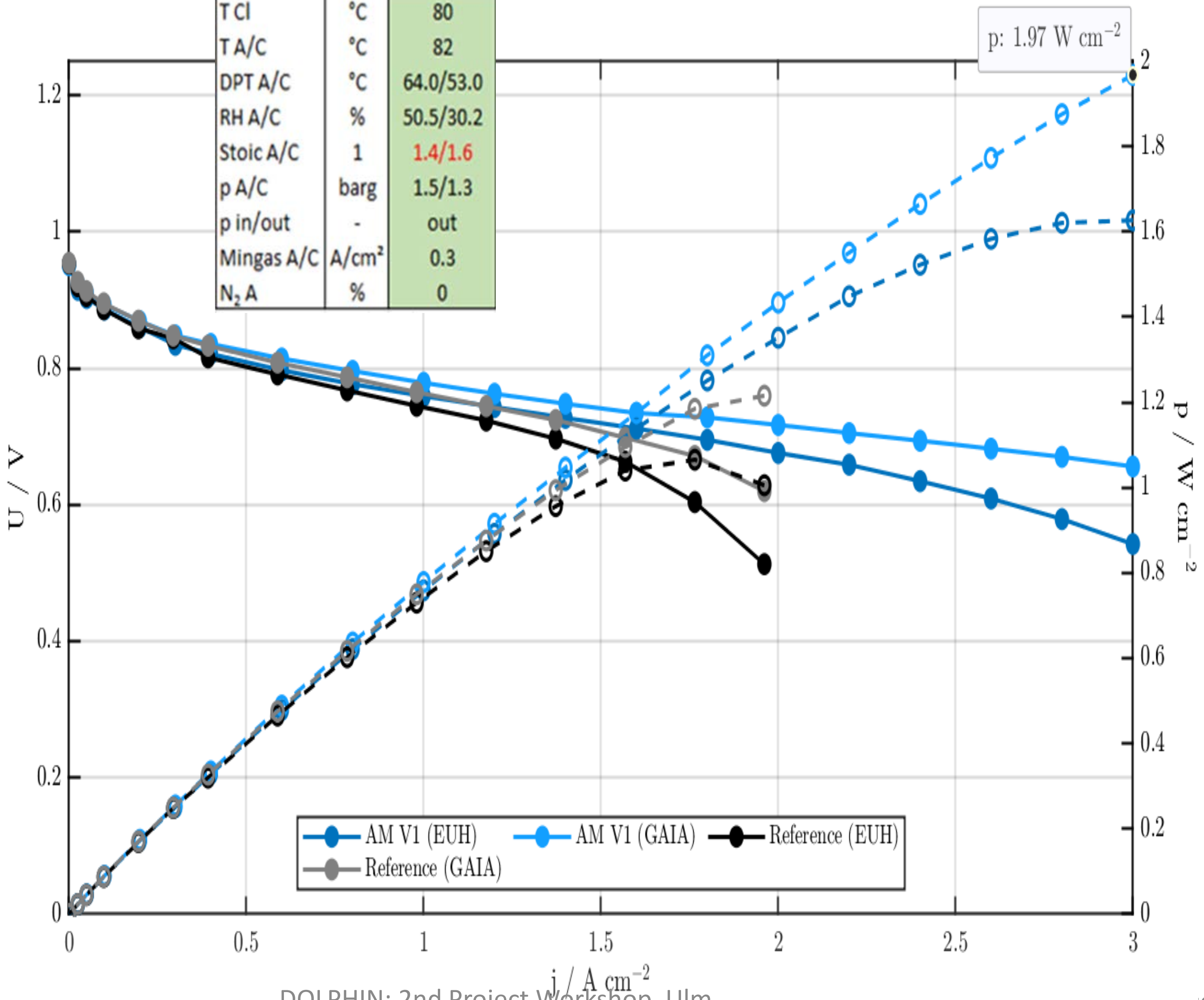
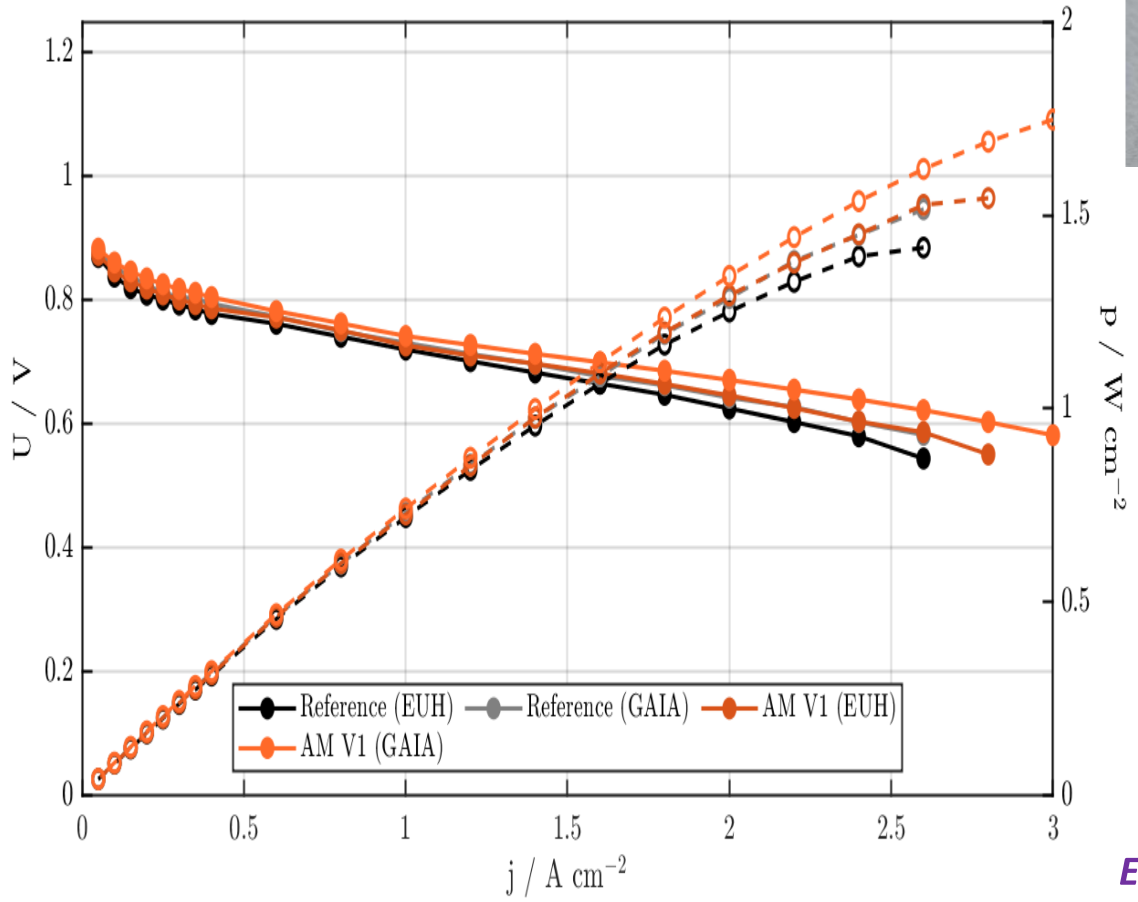


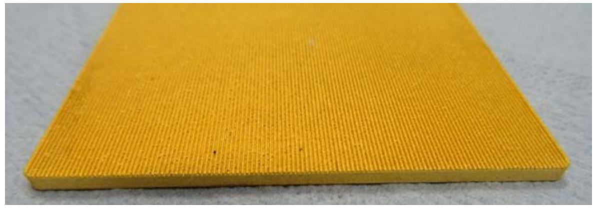
- **Comparison from the reference case (SoA) and the best DOLPHIN configuration tested so far**
- **Reference EFC and reference EC (Gore CCM)**
- **AM v1 and latest DOLPHIN EC**
  - **RP4 DOLPHIN active layers**
  - **Advanced CHEMOURS membrane NDP 8011**
  - **Thin GDL**
- **Performances obtained under GAIA conditions**
  - **3 A/cm² @ 0.657 V : 1.97 W/cm² !**

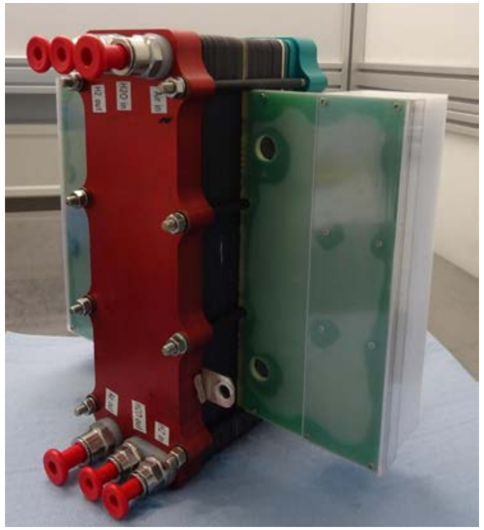
TP3: Validation of additive manufacturing EFC and DOLPHIN EC into short stacks

Polarization curves obtained in TP3 short-stack



AM V1 Flowfield
Stainless steel + gold coating





TP3 short-stack

EFC : AM v1
EC : Gore CCM and commercial GDL

- **Assembly of short-stack using AM V1 EFC and Reference Gore EC**
- **1.6 W/cm² obtained under EUH conditions**
- **1.8 W/cm² under GAIA conditions**
- **Evaluation of durability in progress at ZSW using FC-DLC cycles under EUH conditions**
- **Performances and durability to be compared with full-stacks (Q3/Q4 2023)**

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Estimation of KPIs

J.-P. Poirot-Crouvezier, all

cea liten

SYMBIO A FAURECIA MICHELIN HYDROGEN COMPANY

ZSW

HEXCEL

MANCHESTER 1824 The University of Manchester

Chemours™

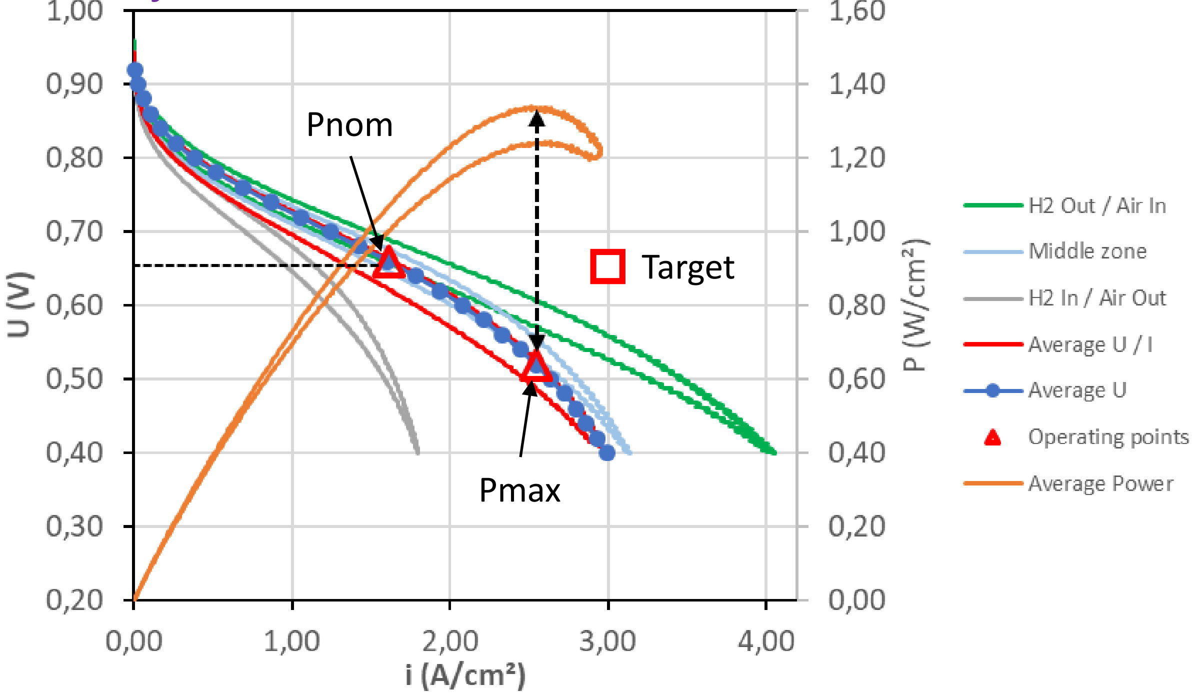
DMG MORI ADDITIVE

Estimation of KPIs

- **Objective**
  - Estimate the gravimetric and volumetric power density for a stack with the different EFCs studied
- **Results**
  - Gravimetric and volumetric power density for a stack
    - Ideal (at 2 W/cm²)
      - ☐ Target = 3 A/cm² @ 0,66 V
    - Expected considering experimental results
      - △ Pnom = performance @ 0,66 V
      - △ Pmax = performance at maximum cell power
- **TP1 (2 cm²)**
  - 3 local operating conditions corresponding to cell inlet/middle/outlet for DOLPHIN « Max power » condition
  - ➢ Extrapolated cell polarization curve → Pnom/Pmax
- **TP2 (100 cm²)**
  - European Harmonized conditions (EUH)
  - GAIA conditions
  - ➢ Pnom/Pmax for each operating condition

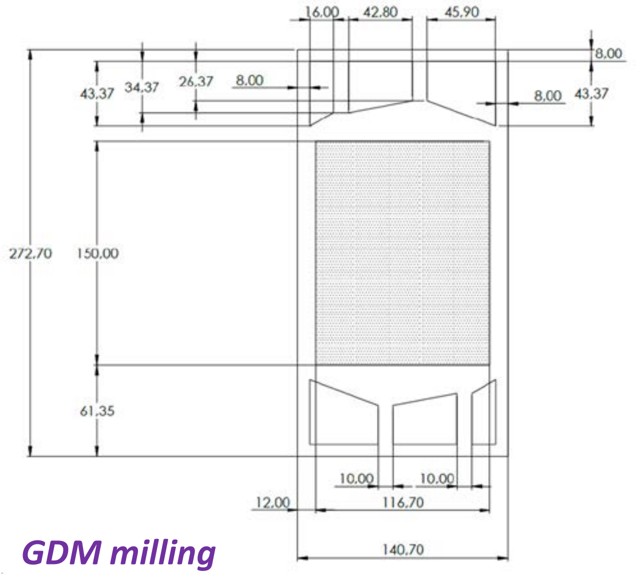
Local conditions	T / °C	P A/C bar abs	RH A/C (%)	% O2 in dry gas	H2 Flow rate Nl/h	Air Flow rate Nl/h	N2 Flowrate Nl/h
Based on max power							
H2 outlet /Air Inlet	85	2.2 / 2.2	98 / 30	21	38	95	--
Middle zone	90	2.2 / 2.2	90 / 72	14,5	38	65.6	29.4
H2 Inlet / Air Outlet	95	2.2 / 2.2	50 / 80	7,8	38	35.3	59.7

Example of polarization curve obtained from TP1 results in DOLPHIN conditions

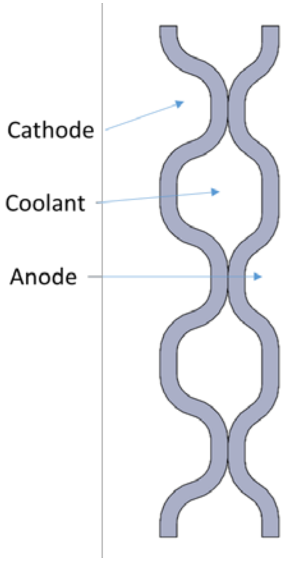


Sizing of 100 kW stacks

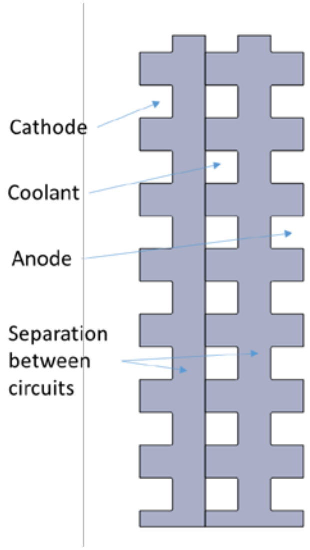
- **Input data for each EFC**
  - General dimensions of TP4 cells
    - 175 cm² active area
    - 380 cm² active area
  - Specific geometrical data (material density, thickness of the different layers...)
- **Stack hardware**
  - Additional weight = 5 kg
  - Additional volume = 2,5 liters
- **Adjusted parameter**
  - Number of cells in the stack



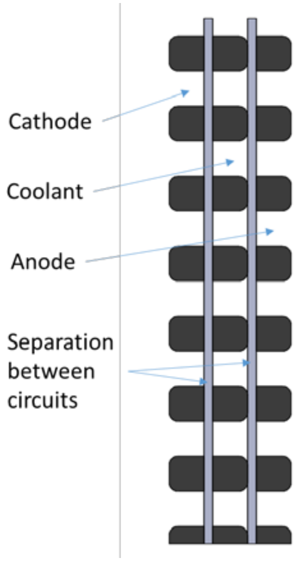
Stamping (reference)



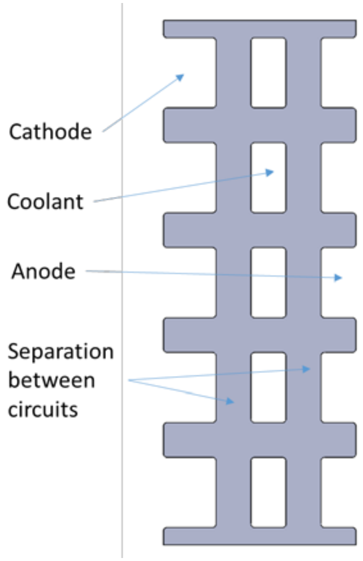
Laser Milling of carbon plates



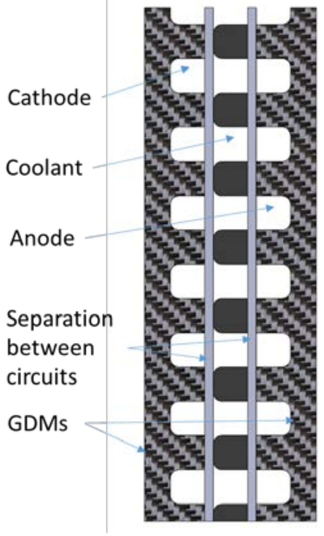
Printing on stainless steel sheets



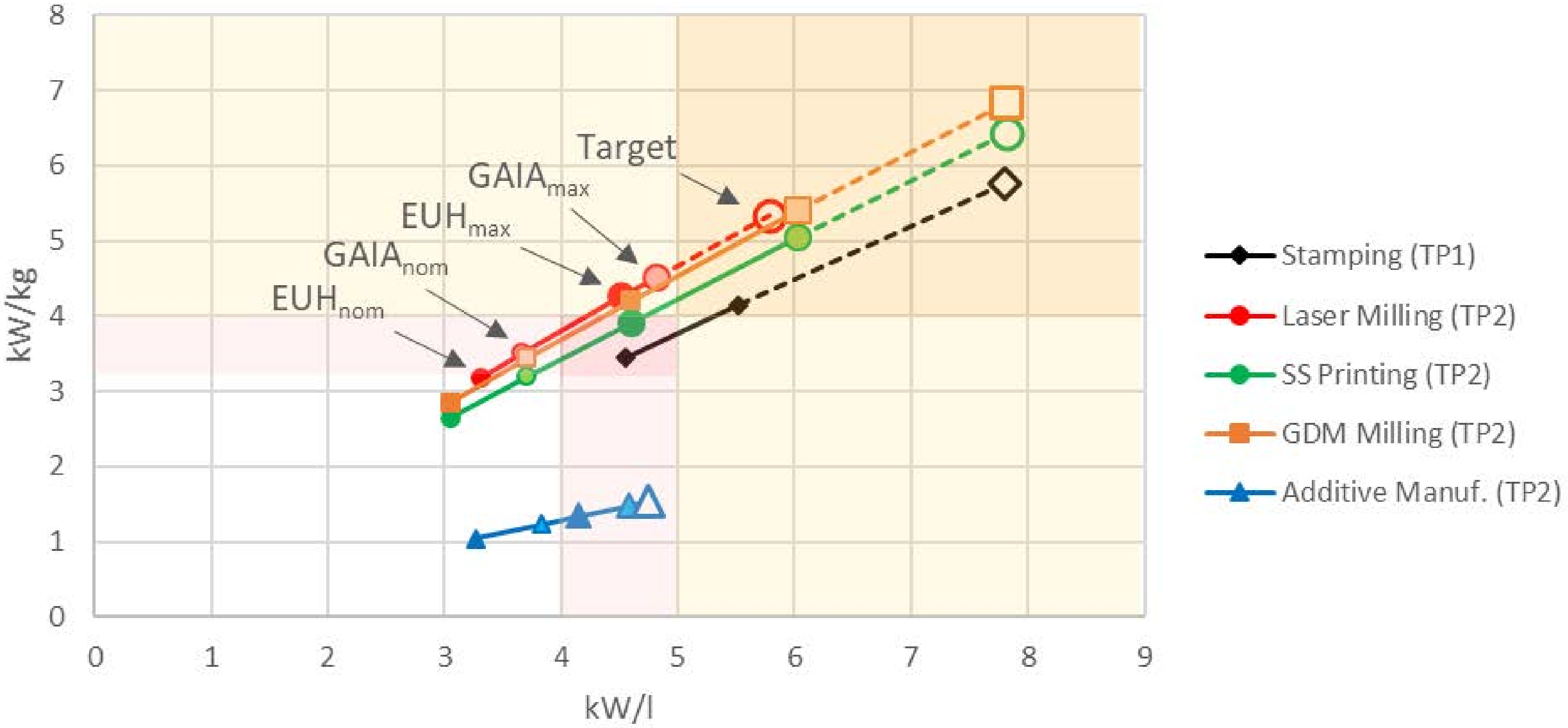
Stainless steel additive manufacturing



GDM milling



KPI values for several EFCs



- **AM is very close to target for GAIA$_{max}$**
  - Gravimetric power density remains low due to the density of stainless steel
- **GDM Milling and Printing don't reach 2W/cm² but power densities are high thanks to thin metal sheets**

DOLPHIN

Disruptive pemfc stack with n**O**vel materia**L**s, **P**rocesses, arc**H**itecture and optimized **IN**terfaces

Clean Hydrogen Partnership
Co-funded by the European Union

DOLPHIN Workshop, Ulm June 16th 2023

Back-up

cea liten
SYMBIO A FAURECIA MICHELIN HYDROGEN COMPANY
ZSW
HEXCEL
MANCHESTER 1824 The University of Manchester
Chemours
DMG MORI ADDITIVE

Presentation outline

- **Experimental strategy** for the validation of innovative concepts for Electrochemical and Electric and Fluidic Cores

- **Main aspects first studied at small scale**
  - **Electric and Fluidics Core**

  → Impact of the rib/channel design on the performances

  → Innovative fabrication processes

  - **Optimization of the EC|EFC interface**

  → Development of self-standing MPL materials

  → Towards the suppression of GDM support materials to reduce cell thickness

  - **Optimization of the EC**

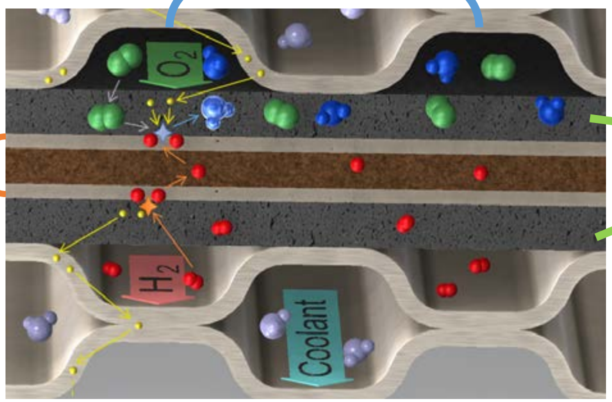
  →Integration of new materials (membrane, catalysts)

  →Optimization of electrode composition

- **Validation of performance at representative scale**

Reduction of the rib/channel size design

Electrochemical Core



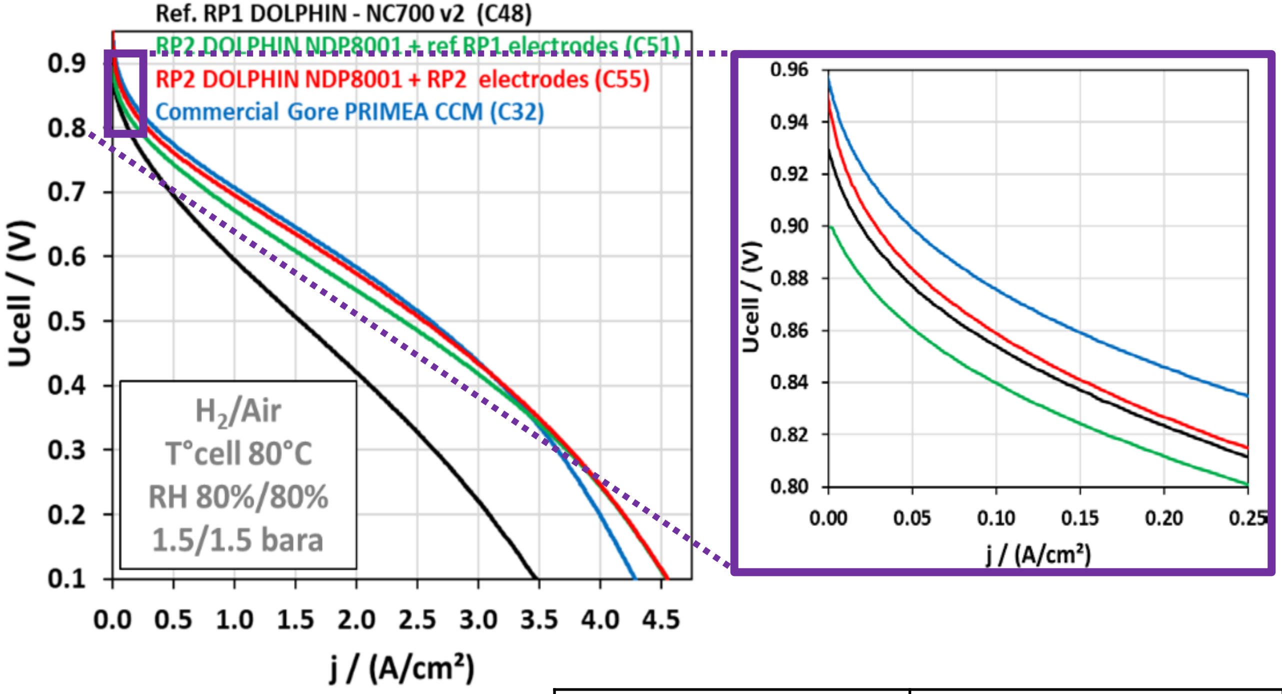
Improving interfaces & Increasing mass transport with thinner layers

Development of new EC components

- **Characterizations of reference EC and developement in RP1 and RP2**
  - **Commercial Gore CCM (0.1/0.4 mgPt/cm²)**
  - **DOLPHIN RP1: Ref. membrane CHEMOURS + RP1 electrodes (0.1/0.4 mgPt/cm²)**
  - **DOLPHIN RP2 : NDP8001 + RP1 electrodes (~ 0.1/0.4 mgPt/cm²)**
  - **DOLPHIN RP2 : NDP 8001 + RP2 electrodes (~ 0.05/0.3 mgPt/cm²)**

- **Integration of new membranes from CHEMOURS**
  - **Thinner membrane:** 10 µm vs 18 µm
  - **Higher performances / increased proton conductivity**
  - **NDP8011 version available for the project since 2022**

- **Modification/Improvement of electrodes manufacturing**
  Softer manufacturing conditions
  - **Less mechanical stress** for the membrane (+ 50 mV @ OCP)
  - **Better electrochemical activity** at low overpotential…



EC type	An/Cath. Pt Loading (mg/cm²)	@ 0.66 V j / (A/cm²)	@ 0.66 V p / (W/cm²)	@ 0.50 V j / (A/cm²)	@ 0.50 V p / (W/cm²)
Ref DOLPHIN from RP1	0.1/0.4	0.66	0.44	1.54	0.72
NDP 8001 + RP1 electrodes	0.16/0.4	1.09	0.72	2.39	1.20
NDP 8001 + RP2 electrodes	0.023/0.26	1.30	0.86	2.56	1.25
Gore PRIMEA CCM	0.1/0.4	1.39	0.92	2.61	1.30