Analysis and development of polymer electrolyte membrane fuel cell power generation systems

PhD candidate: Ing. **Robert RADU**

Tutor: Prof. **Diego MICHELI**, Università degli Studi di Trieste

Coordinator: Prof. **Piero PINAMONTI**, Università degli Studi di Udine

Motivation and objectives

Power generation systems based on **fuel cells** represent a **promising technology** for the future. The main reasons are related to the **efficiency** of the energy conversion which is higher than that of other technologies and to the **lower emissions** level.

automotive

PEMFC

stationary power

mobile devices

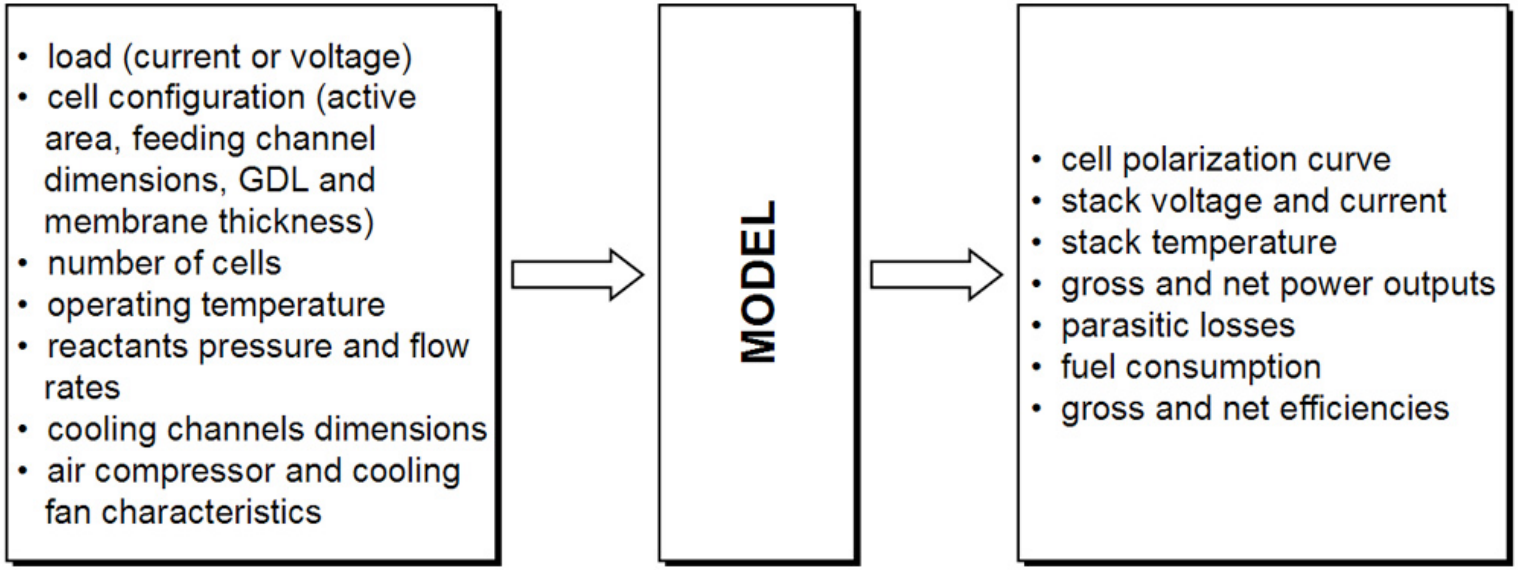
Motivation and objectives

This study aims to identify, through experiments and simulations, the main aspects concerning the PEMFC systems operation and to put into practice the acquired know-how during the design and development phase of a PEMFC stack.

Fuel cell model → **Experimental tests** → **Stack design & testing**

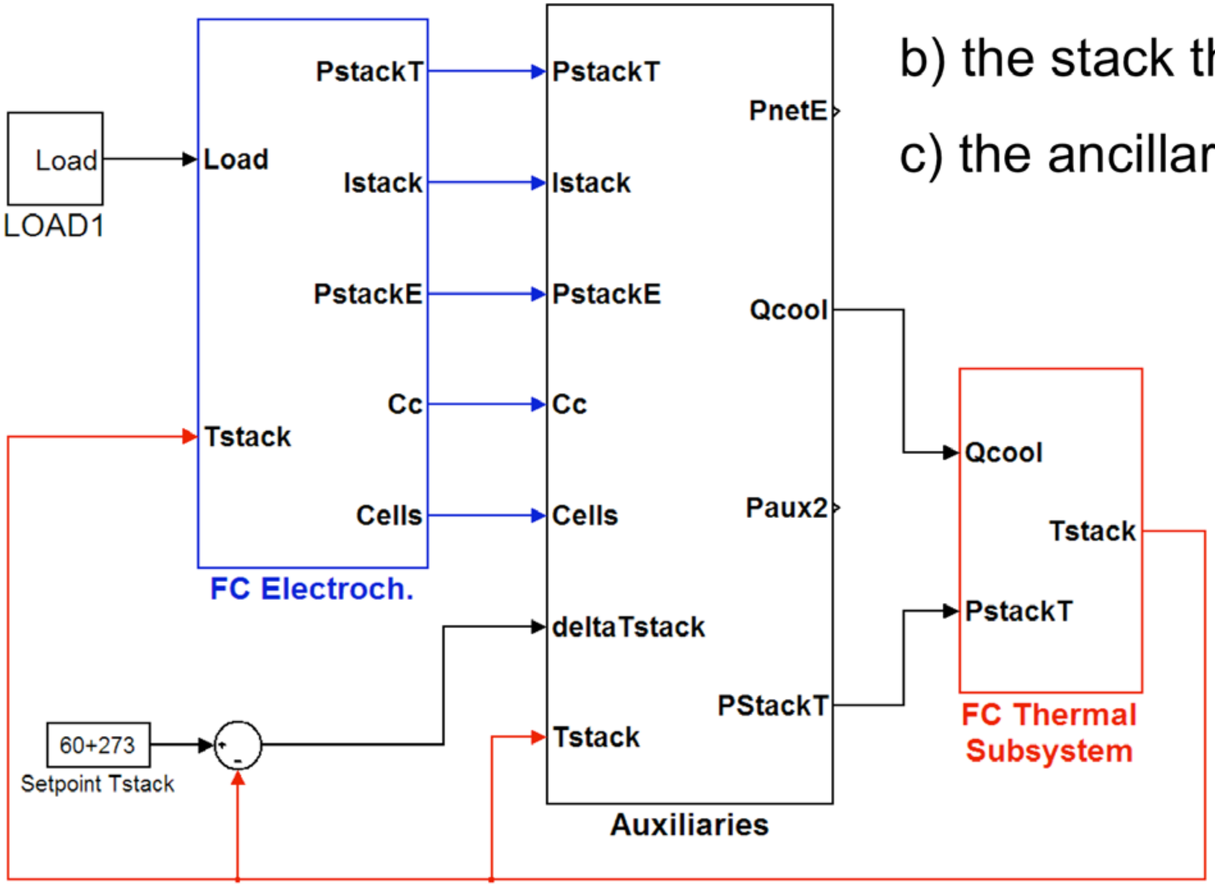
Fuel cell stack model

The present work proposes a model which integrates the finite element method in a dynamic simulation, in order to achieve a higher accuracy and the possibility to investigate the influence of various parameters on the fuel cell system dynamics.



Fuel cell stack model

The model is implemented using Matlab/Simulink and consists of three interacting main subsystems that simulate: a) the stack electrochemistry; b) the stack thermal behavior; c) the ancillaries.



Electrochemical model

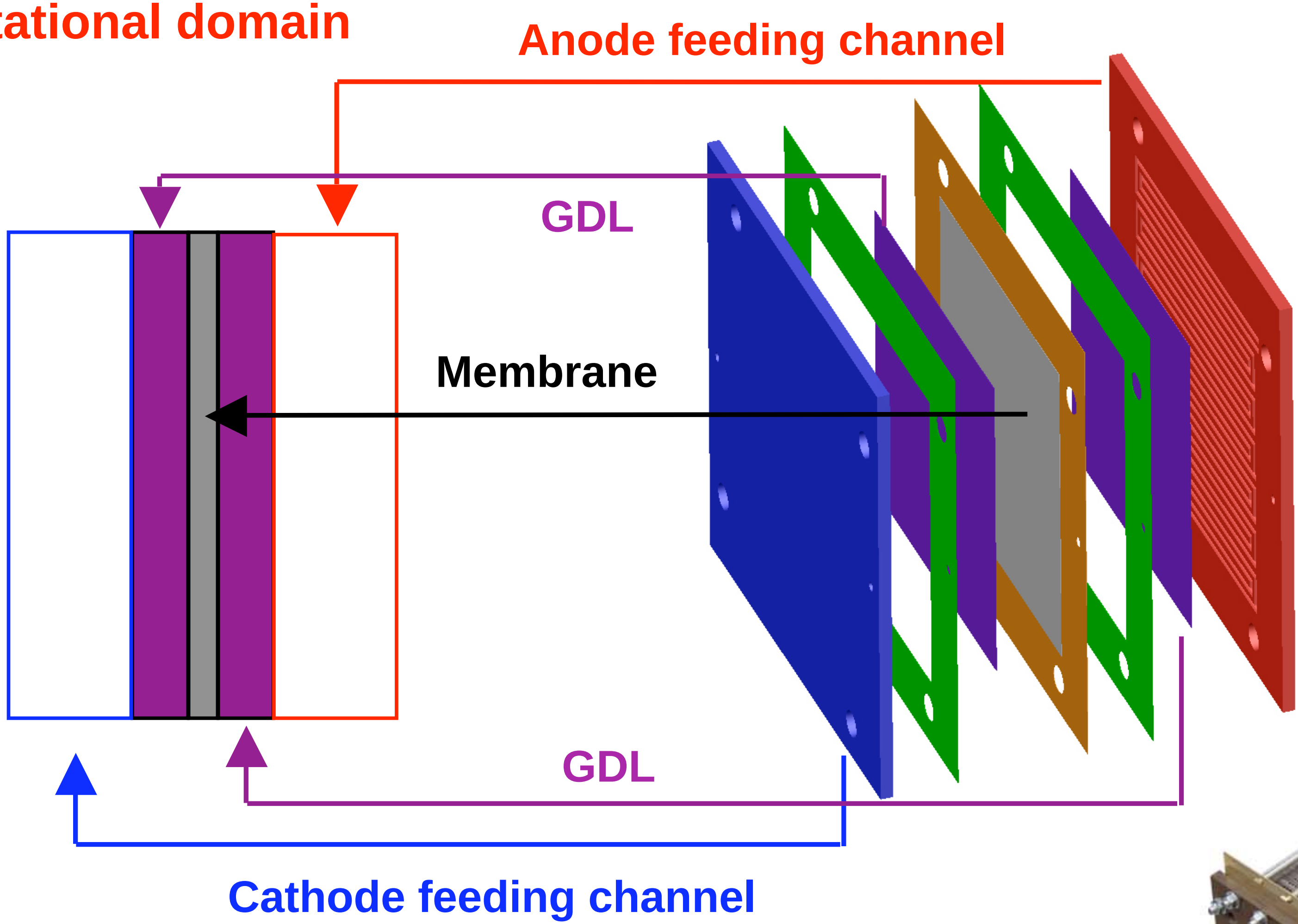
The electrochemical model was realized in **Femlab**, the mass transport and electrochemical phenomena being simulated with the differential equations implemented in various *application modes*.

Assumptions →

- ✓ ideal gas mixtures;
- ✓ isothermal;
- ✓ incompressible and laminar flow;
- ✓ homogeneous electrodes;
- ✓ impermeable membrane;
- ✓ zero-thickness active layers.

Electrochemical model

Computational domain



Electrochemical model

Equations

[redacted]

$$\eta \nabla^2 \mathbf{u} = \frac{\nabla p}{\rho} + \mathbf{u} \cdot \nabla \mathbf{u}$$

Navier Stokes Eq.

Electrochemical model

Equations

[redacted]

$$-\nabla p = \mathbf{u} \cdot \frac{\eta}{k} - \eta \nabla^2 \mathbf{u}$$ **Brinkman Eq.**

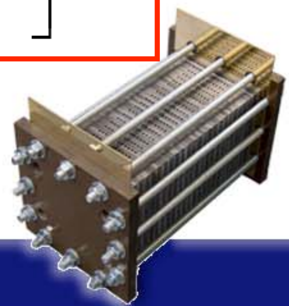
Electrochemical model

Equations

[redacted]

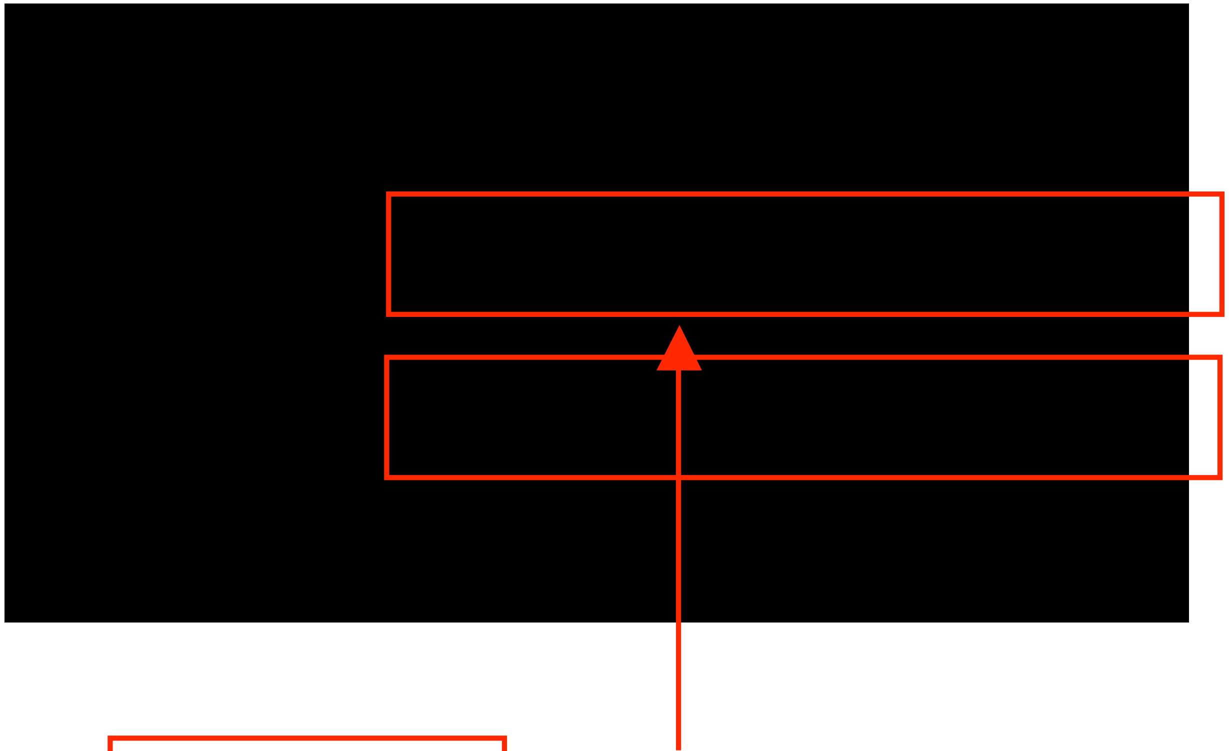
$$\nabla \cdot \left[-\rho w_i \sum_j D_{ij}^{eff} \left\{ \frac{M}{M_j} \left(\nabla w_j + w_j \frac{\nabla M}{M} \right) + \left(x_j - w_j \right) \frac{\nabla p}{p} \right\} + w_i \rho \, \mathbf{u} \right] = 0$$

Maxwell – Stefan Eq.



Electrochemical model

Equations



$$\nabla \cdot \left(-\sigma \nabla \phi \right) = 0$$

Conductive Media DC Eq.

Thermal model

The thermal dynamic behaviour of the FC system can be described by the following equation:

$f(P_{el}, \eta)$

$$\frac{dT}{dt} = \frac{1}{m \cdot C}\left(Q_{stack} - Q_w\right)$$

Femlab model

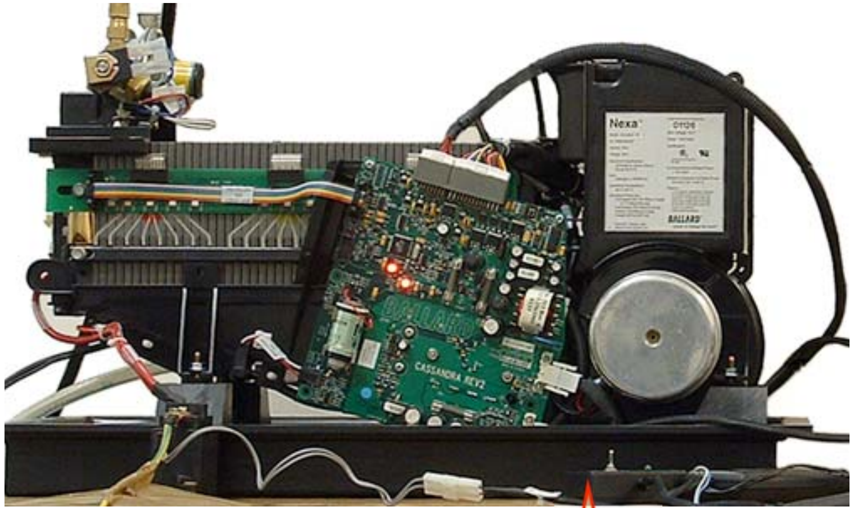
Q_{stack} = generated heat flux

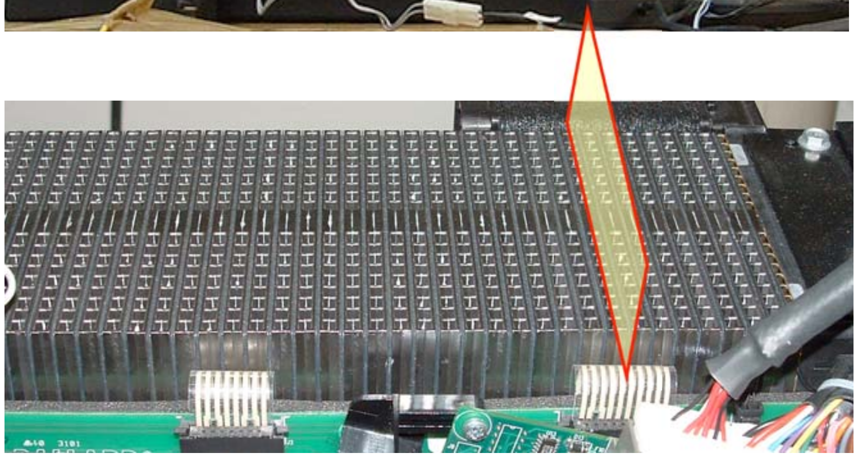
Q_W = extracted heat flux

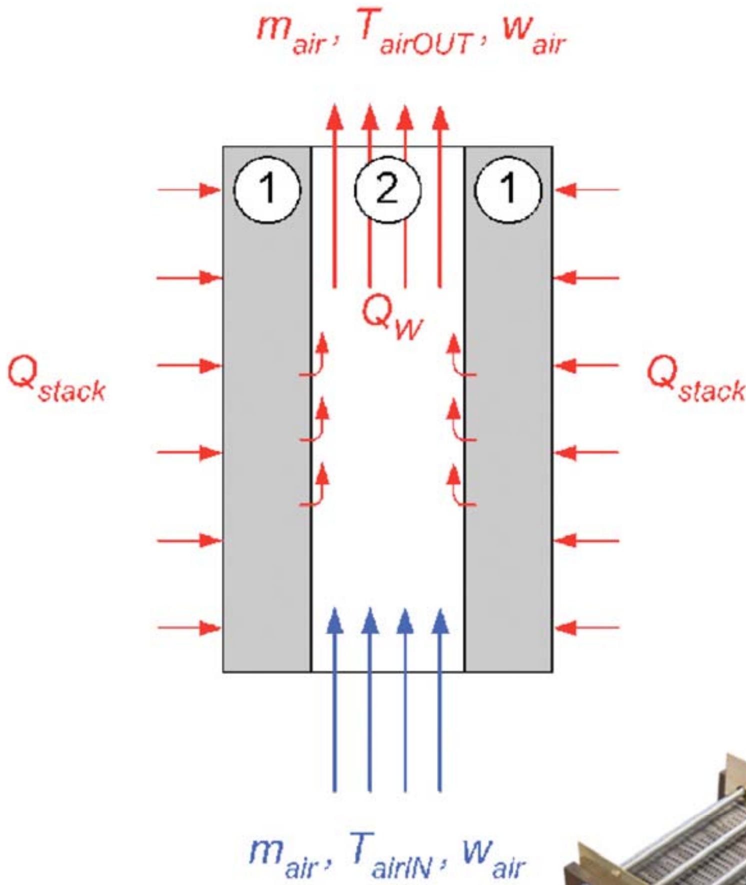
Computational domain

The overall model was validated using the experimental data acquired on a **Ballard Nexa** 1.5 kWe PEM system

Thermal model - Computational domain



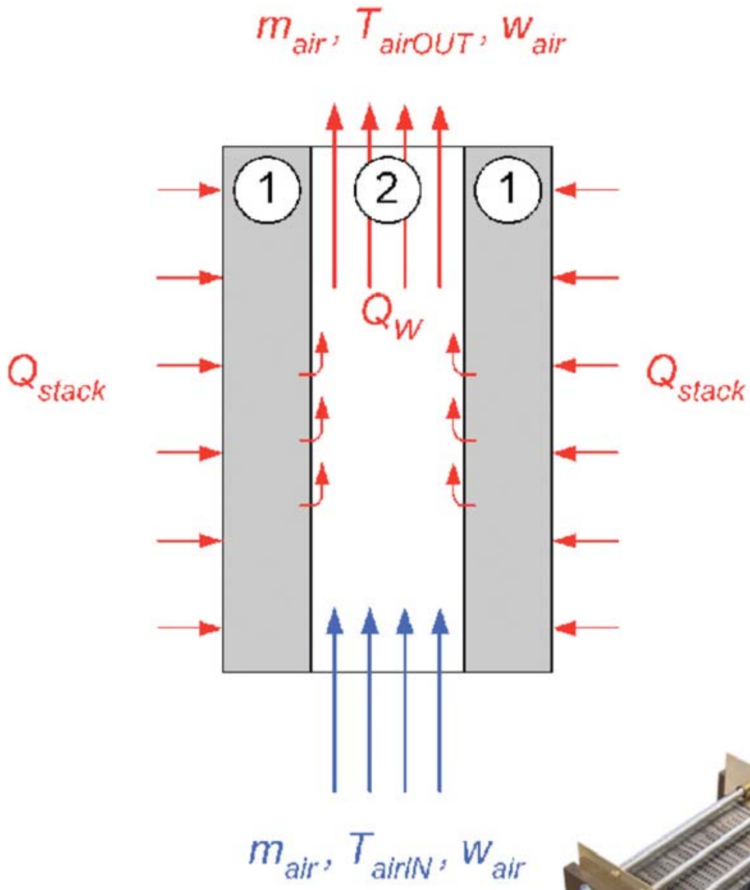




Thermal model - Equations

The thermal model is based on the Femlab *Convection and Conduction application mode.*

$$\nabla \cdot \left(-\alpha \nabla T + \rho C T \mathbf{u}\right) = Q$$



Auxiliaries model

Using simple models, it simulates the behavior of two main stack components: cathode air compressor and cooling fan.

$$P_{compr} = \frac{\dot{Q}_{air} \cdot \Delta p}{\eta_{compr}}$$

$\dot{Q}_{air}$ → Control, I_{stack}

Δp → Exp.data

$$P_{fan} = \frac{\dot{Q}_{cool} \cdot \Delta p_{cool}}{\eta_{fan}}$$

Δp_{cool} → $F(w_{air}, A_{ch})$

Objectives

Fuel cell model → **Experimental tests** → **Stack design & testing**

The preliminary experimentation phase was carried out using commercial hardware (Electrochem single cells and Ballard Nexa stack system) in order to set-up the experimental equipment, to understand the main issues regarding fuel cell operation and to validate the simulation model.

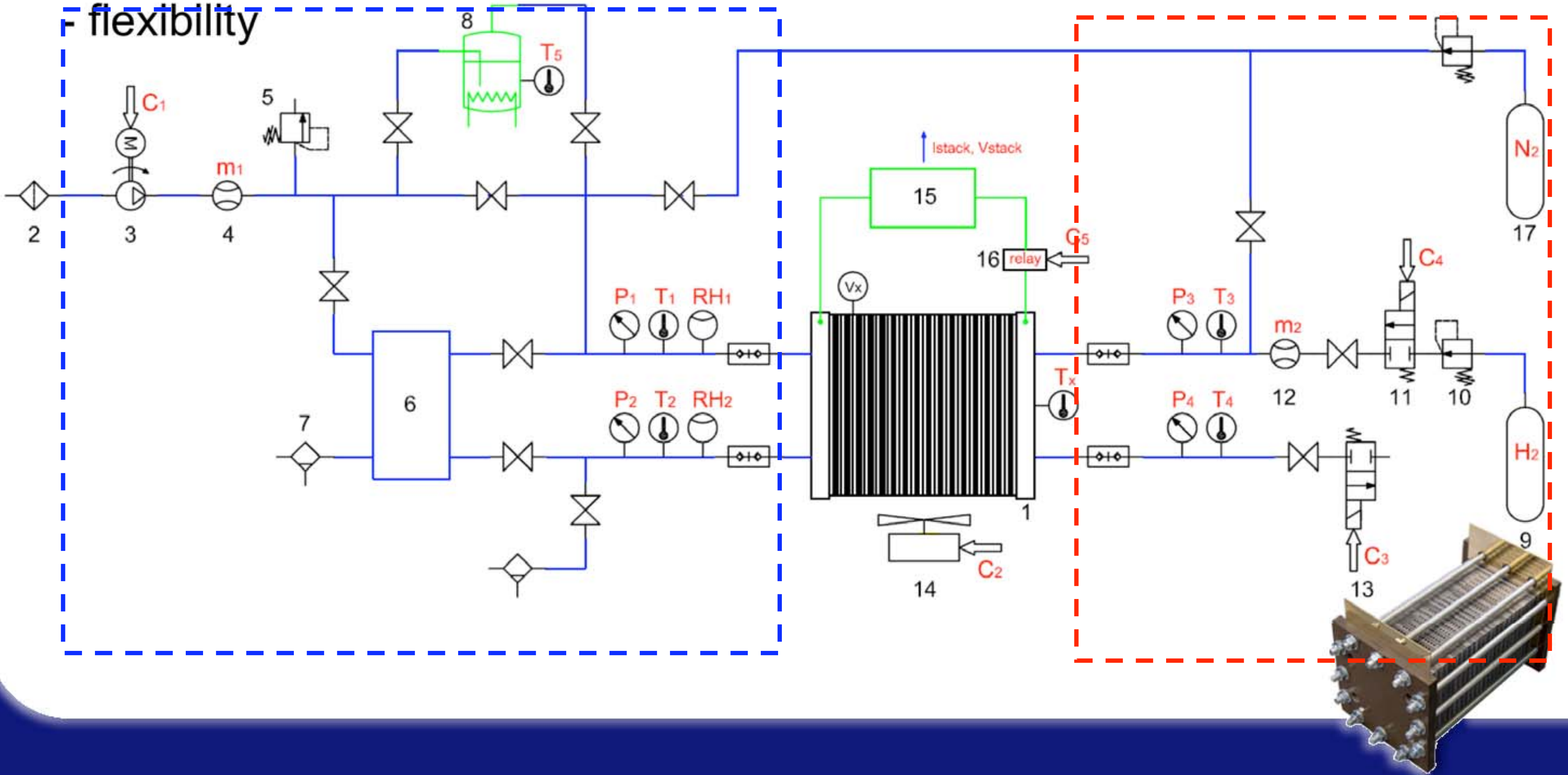
Test bed configuration

Requirements:

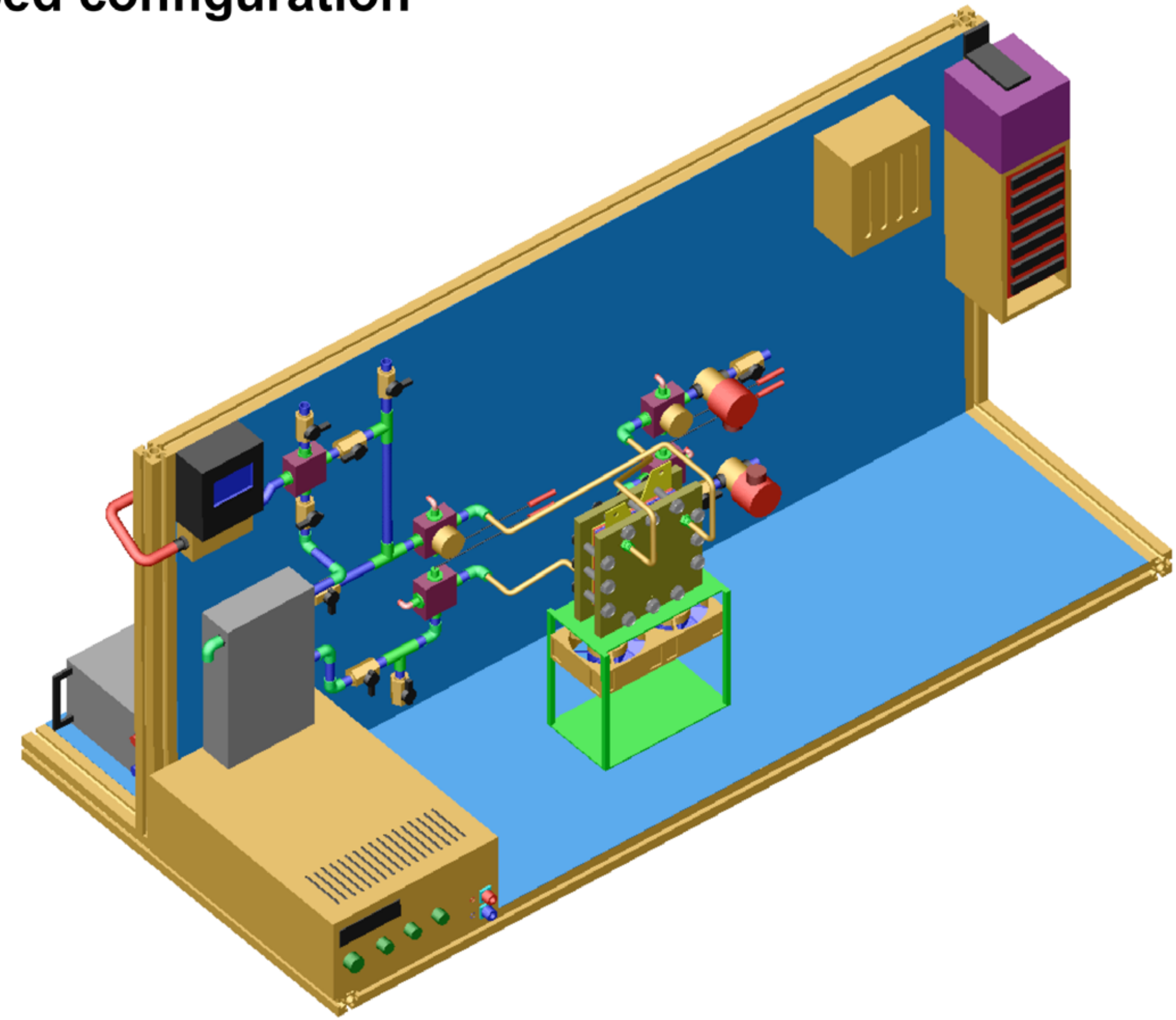
- DAQ of the fuel cell (stack) parameters

- control the fuel cell (stack) main functions

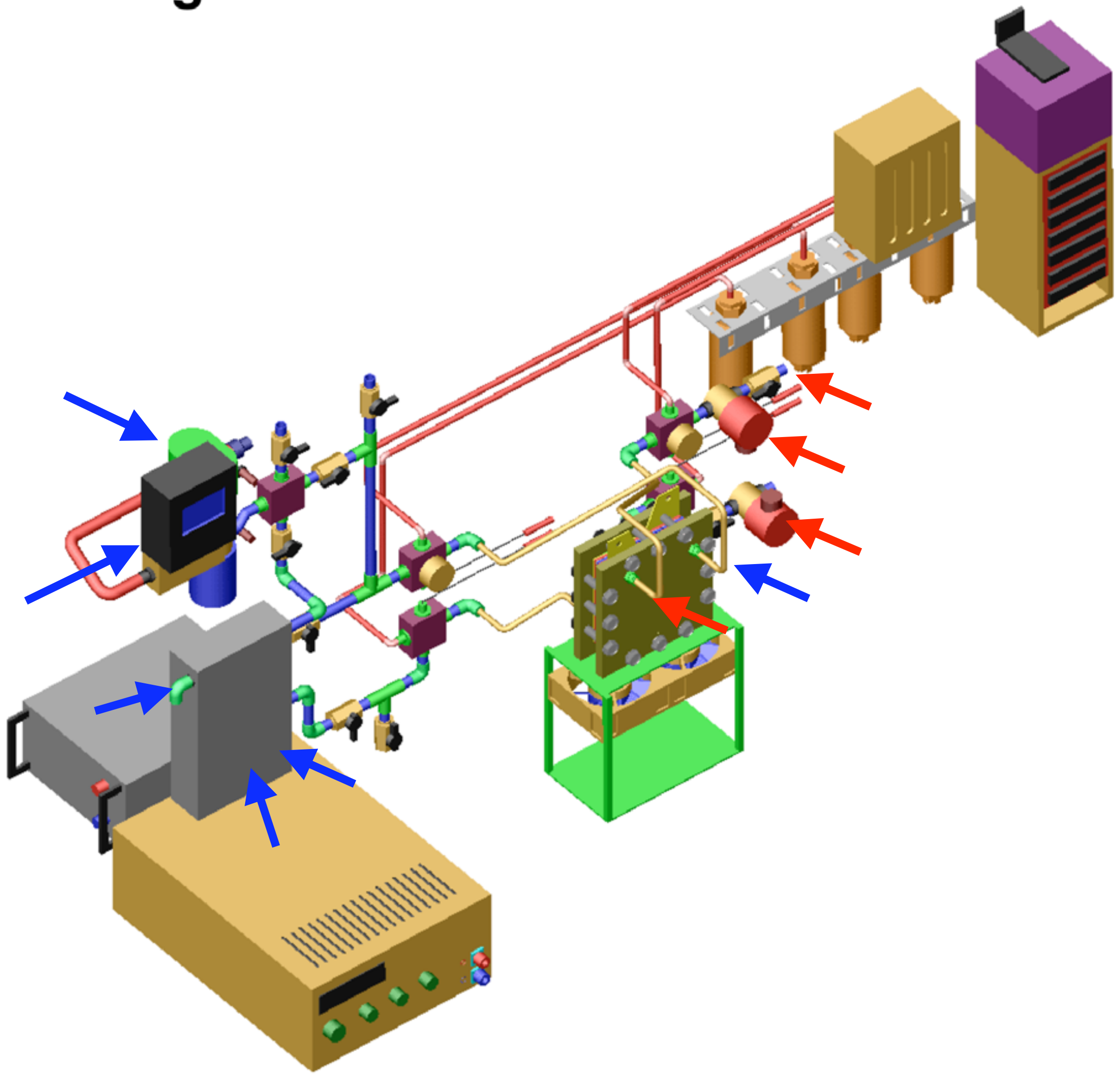
- flexibility



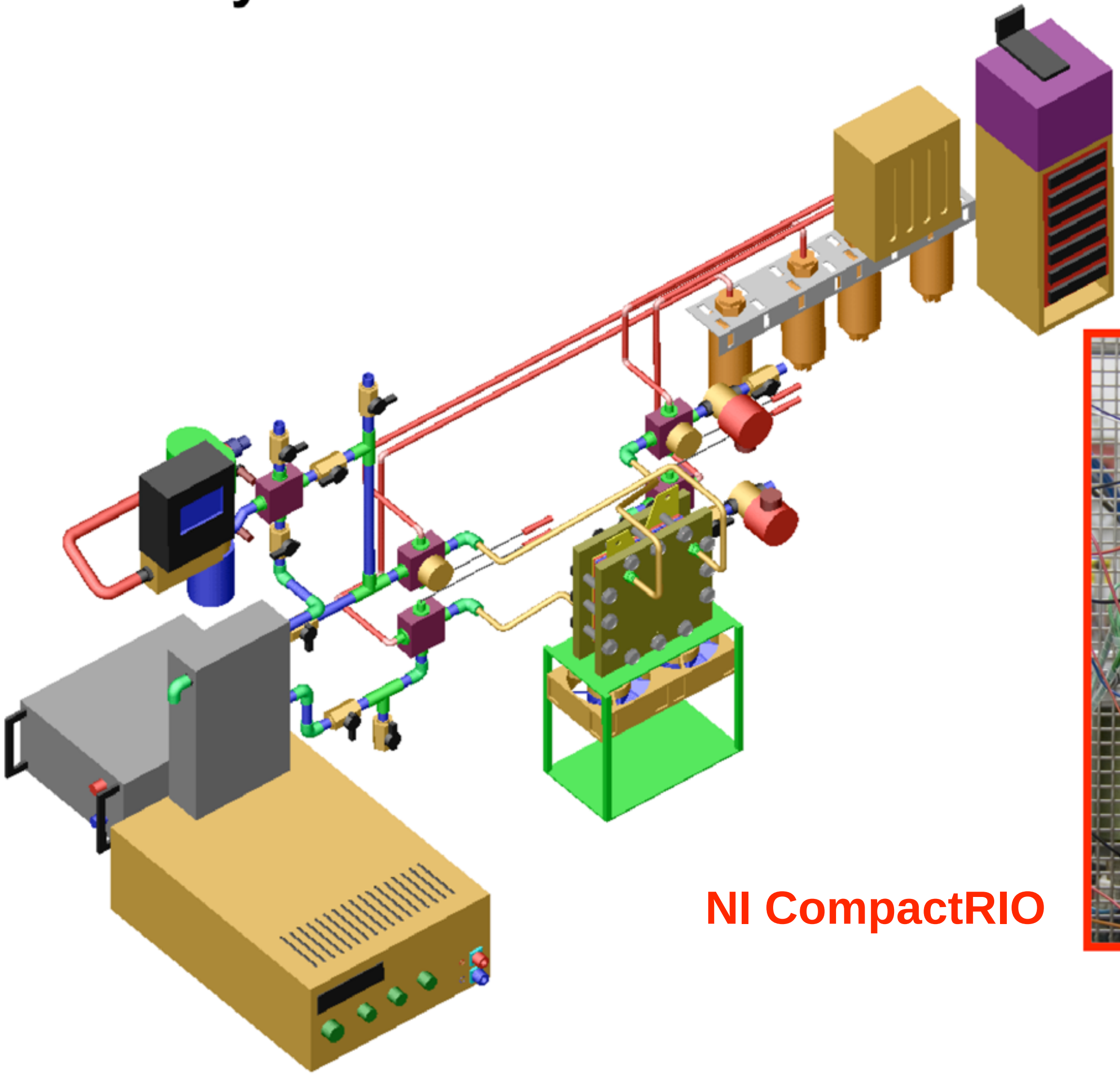
Test bed configuration

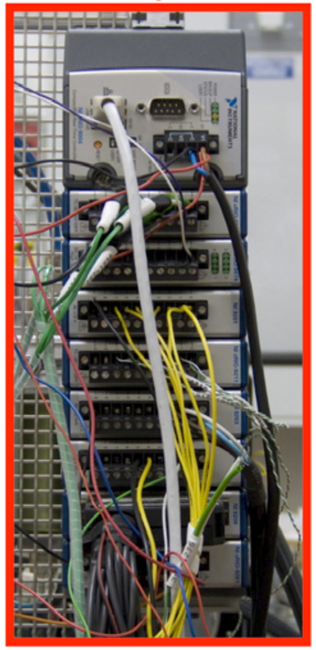


Test bed configuration

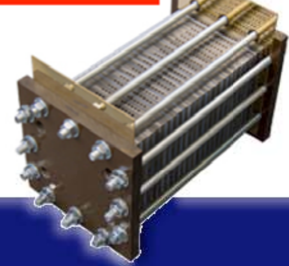


DAQ & Control system

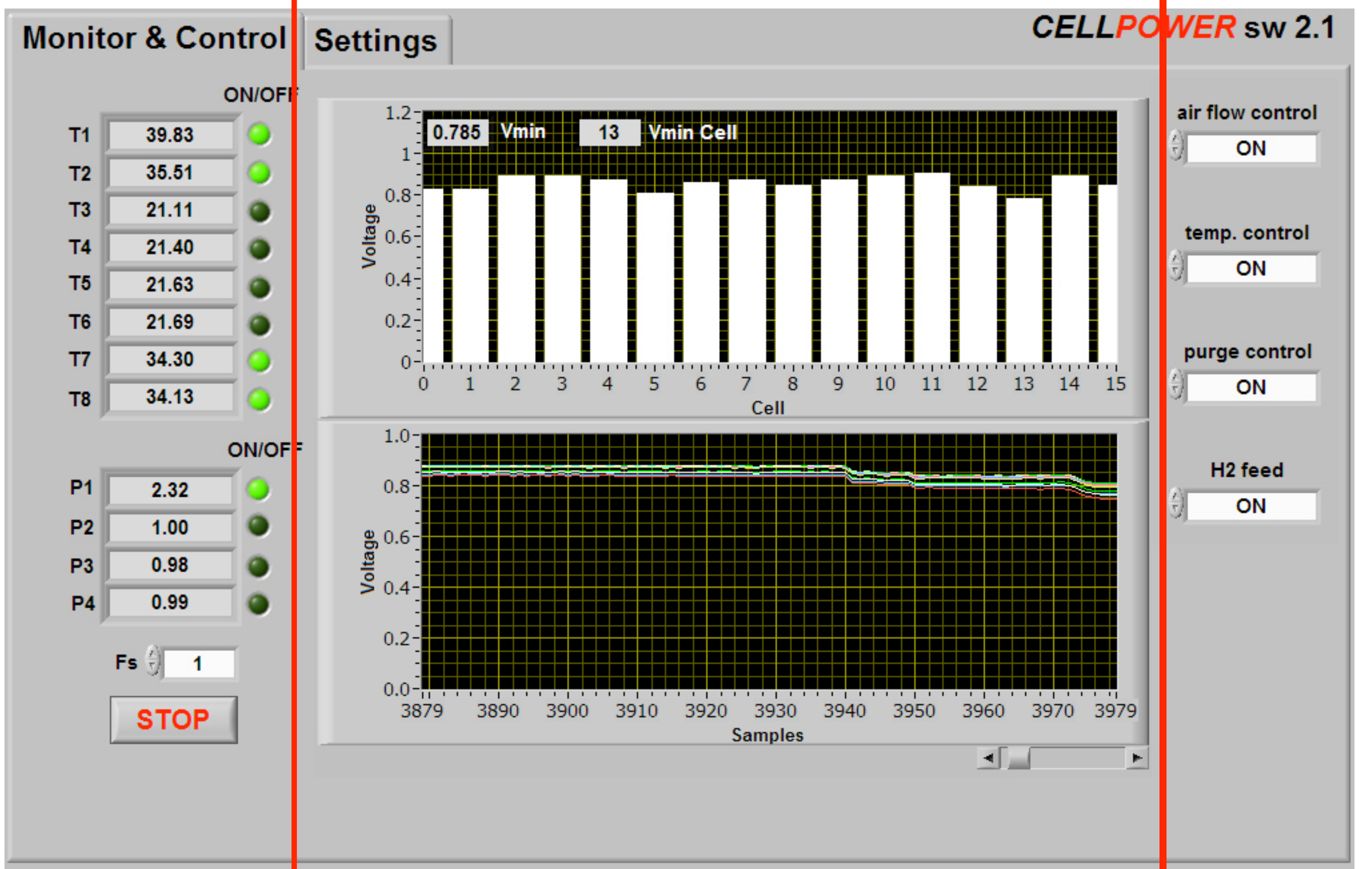




NI CompactRIO



DAQ & Control software



Single cell tests

- hardware: Electrochem;
- experimental procedure: European project FCTESTNET, US Fuel Cell Council.

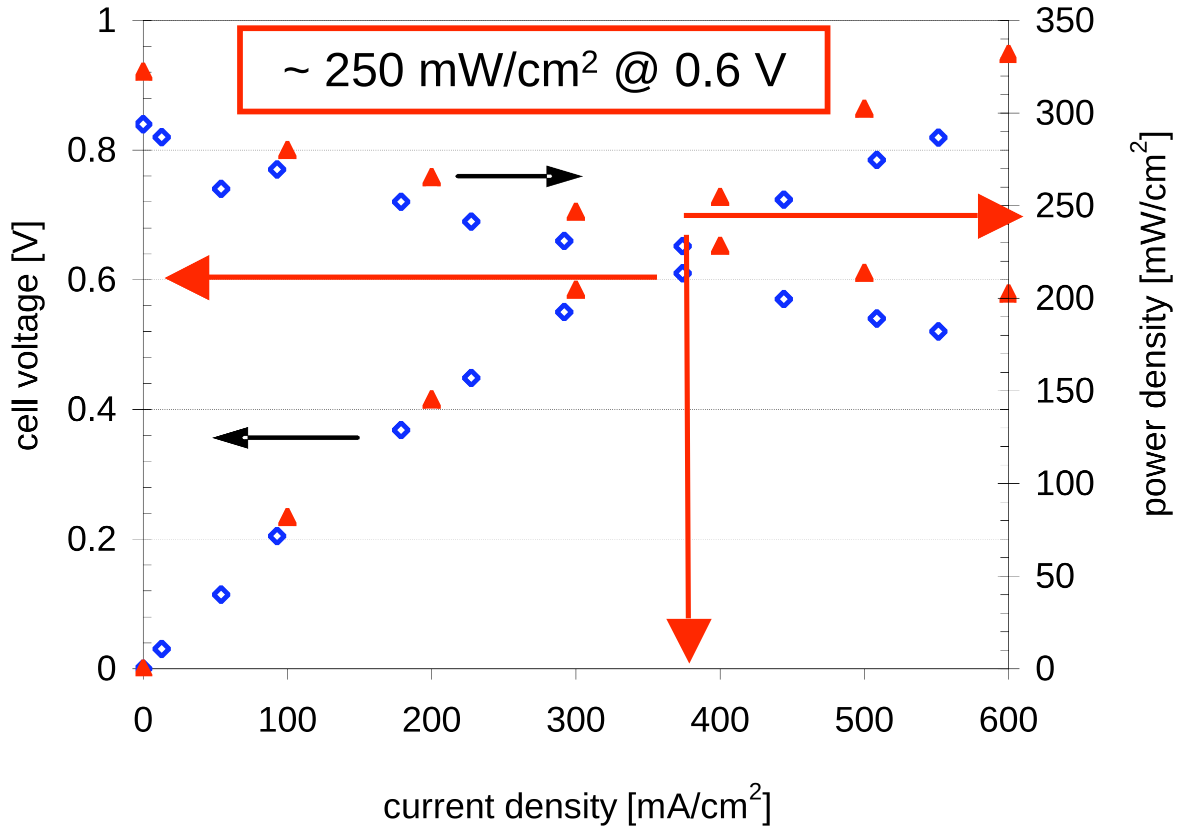
	Configuration #1	Configuration #2
Membrane	Nafion 113	Nafion 113
GDLs	Toray	SEAL tissue[8]
Anode catalyst load	1 mg/cm^2	0.6 mg/cm^2
Cathode catalyst load	1 mg/cm^2	0.3 mg/cm^2

CCM
25 cm^2

CCM results

Polarization curve – Configuration #2

(air flow = 2.0 slpm, reactant gas pressure = 1.8 bar, cell temperature 45 °C, tightening torque 2.5 Nm). Red triangle marker – manufacturer data, blue rhomb marker – in house measured data.



Ballard Nexa tests

Targets:

• understand the main issues regarding the stack operation

• test the monitoring and control system, implemented with the National Instruments platform

• 47 cells

• 1.5 kWe gross power

• 1.2 kWe nett power

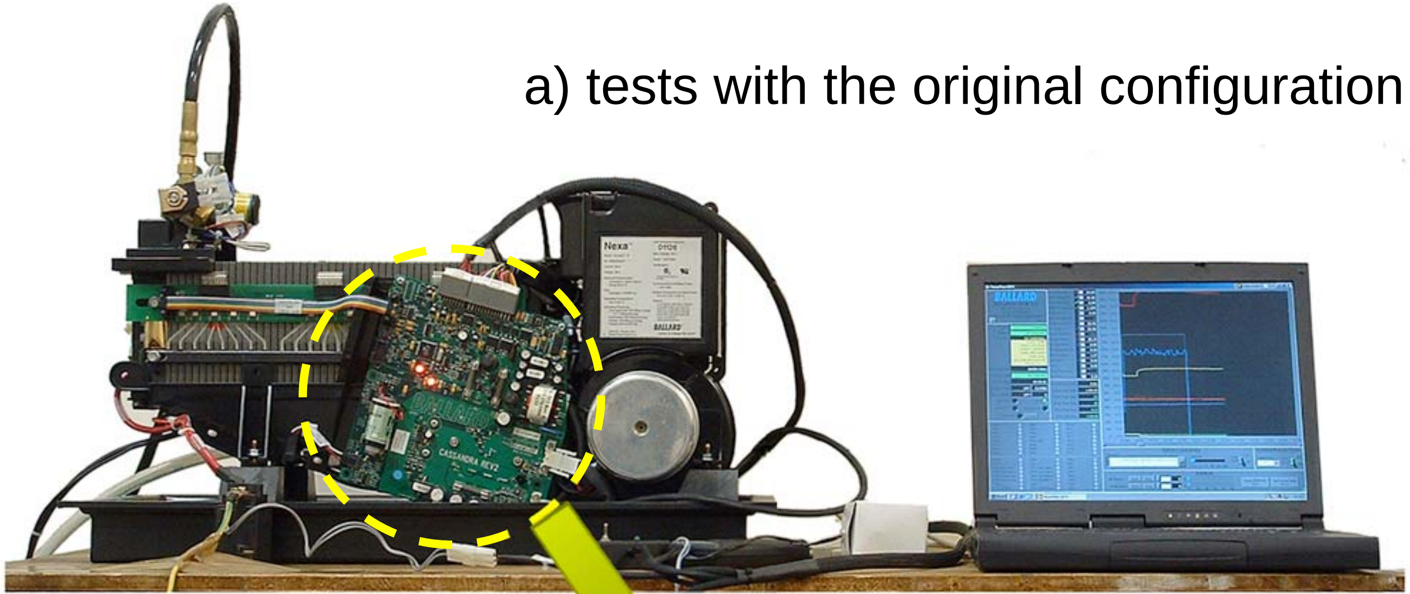
• voltage = 43 V @ idle ÷ 26 V @ FL

• operates with pure hydrogen

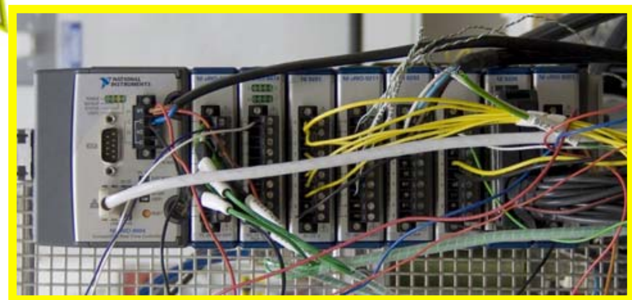
• air cooled

Ballard Nexa tests

a) tests with the original configuration

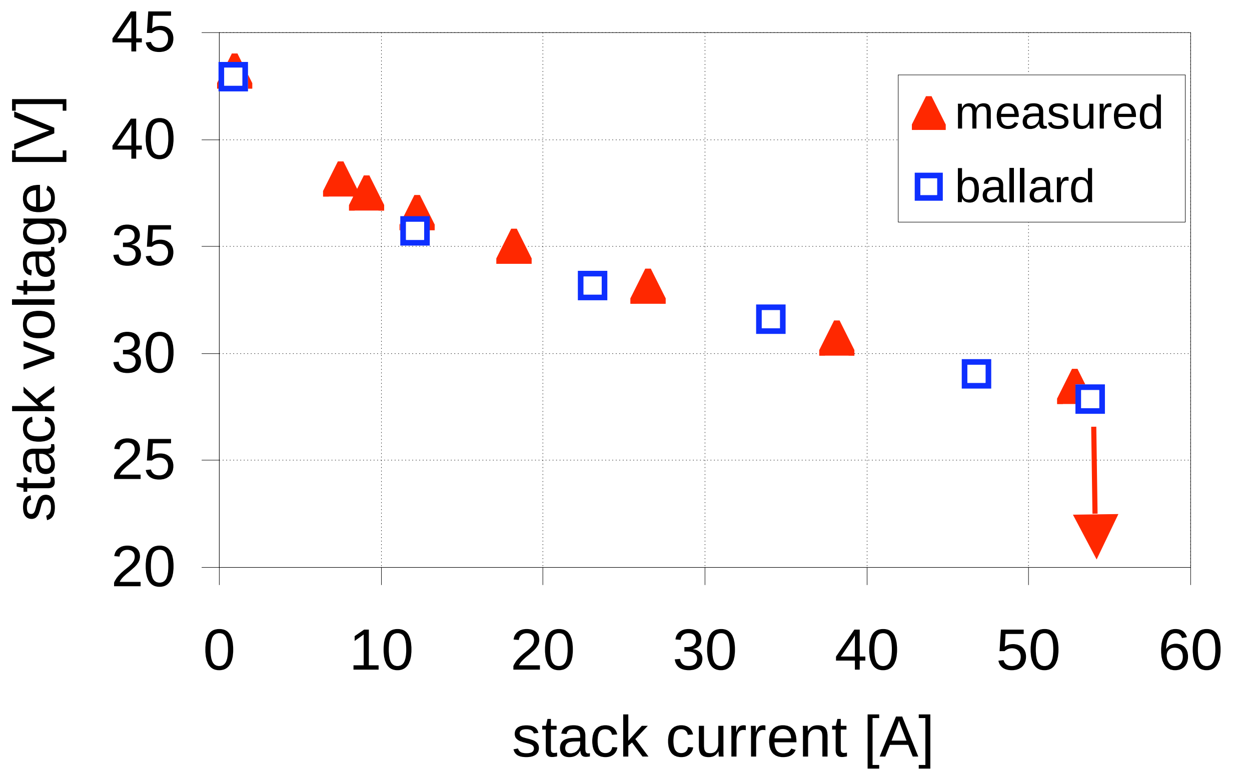


b) tests with the alternative controller



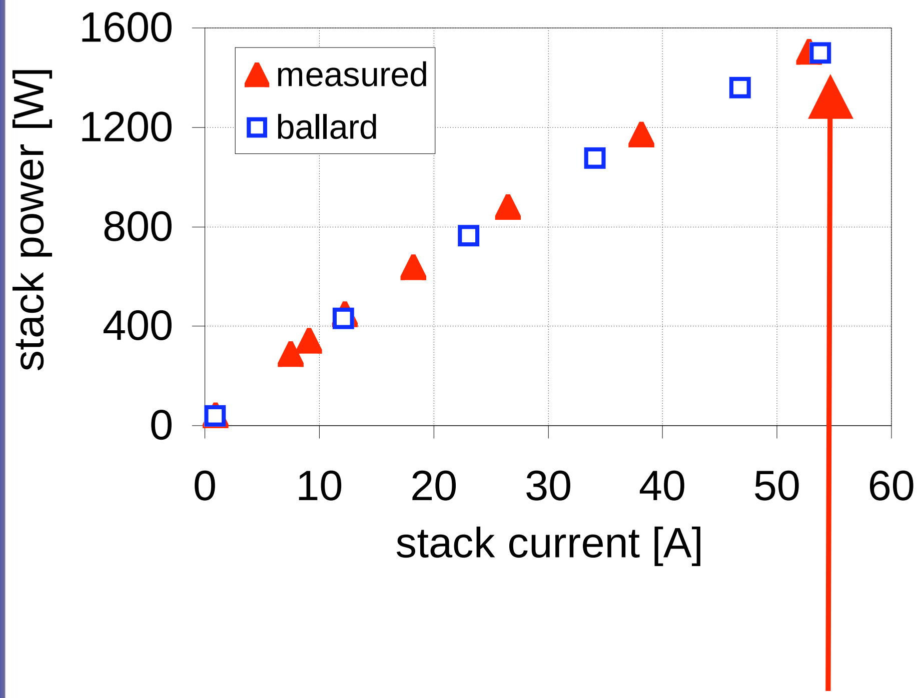
Ballard Nexa results – tests with the original configuration

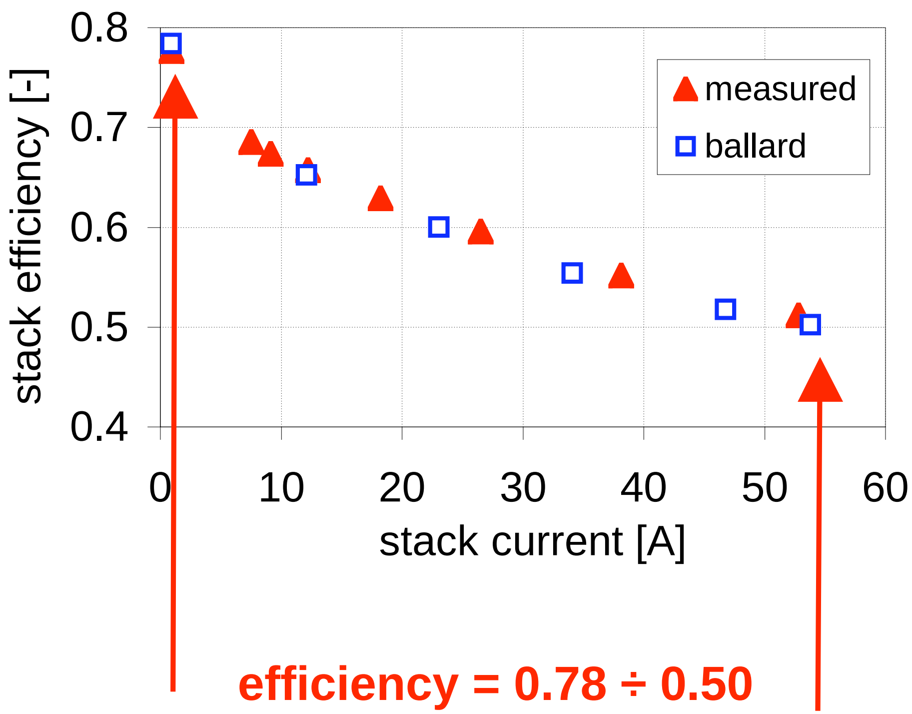
Comparison between measurements and manufacturer data



Ballard Nexa results – tests with the original configuration

Comparison between measurements and manufacturer data



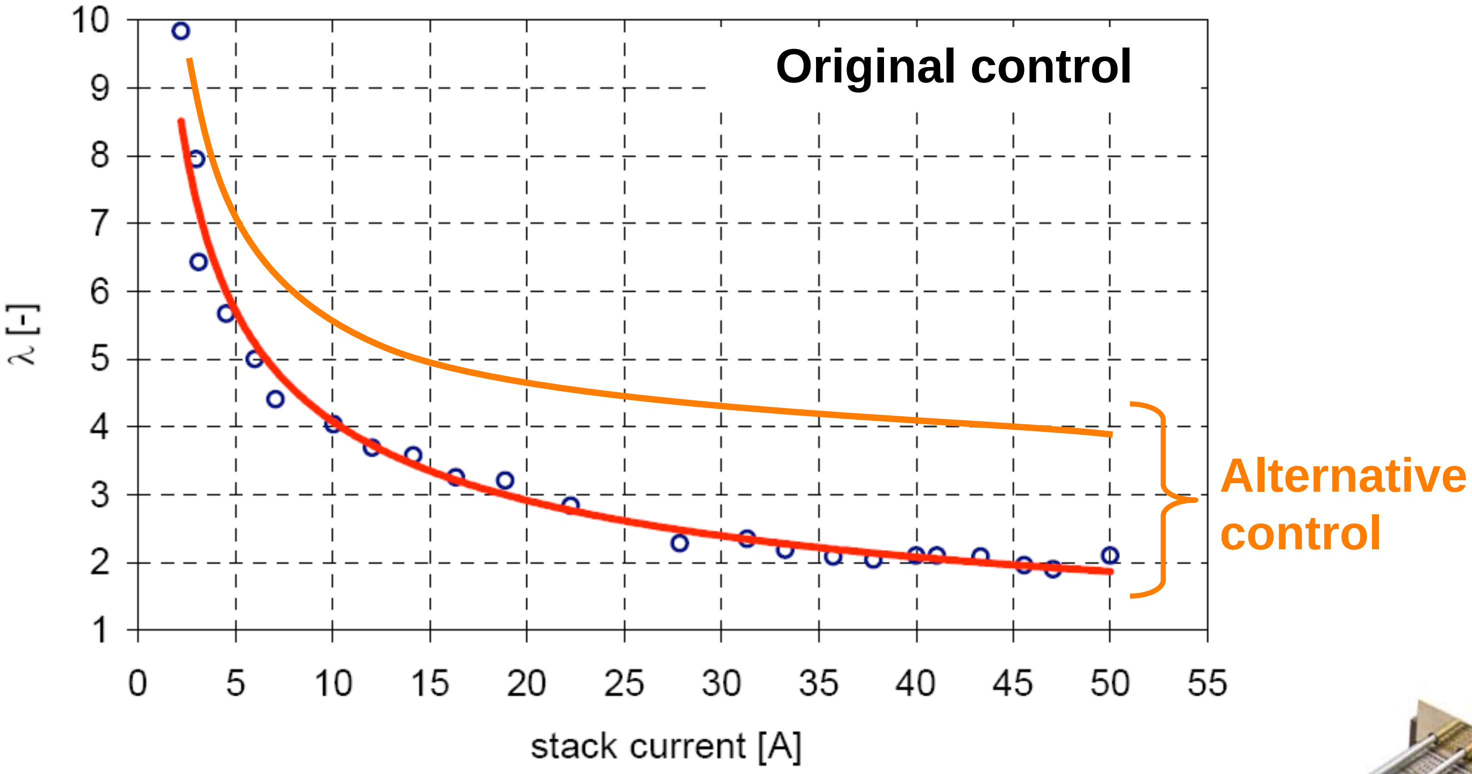


efficiency = 0.78 ÷ 0.50

~ 1500 W

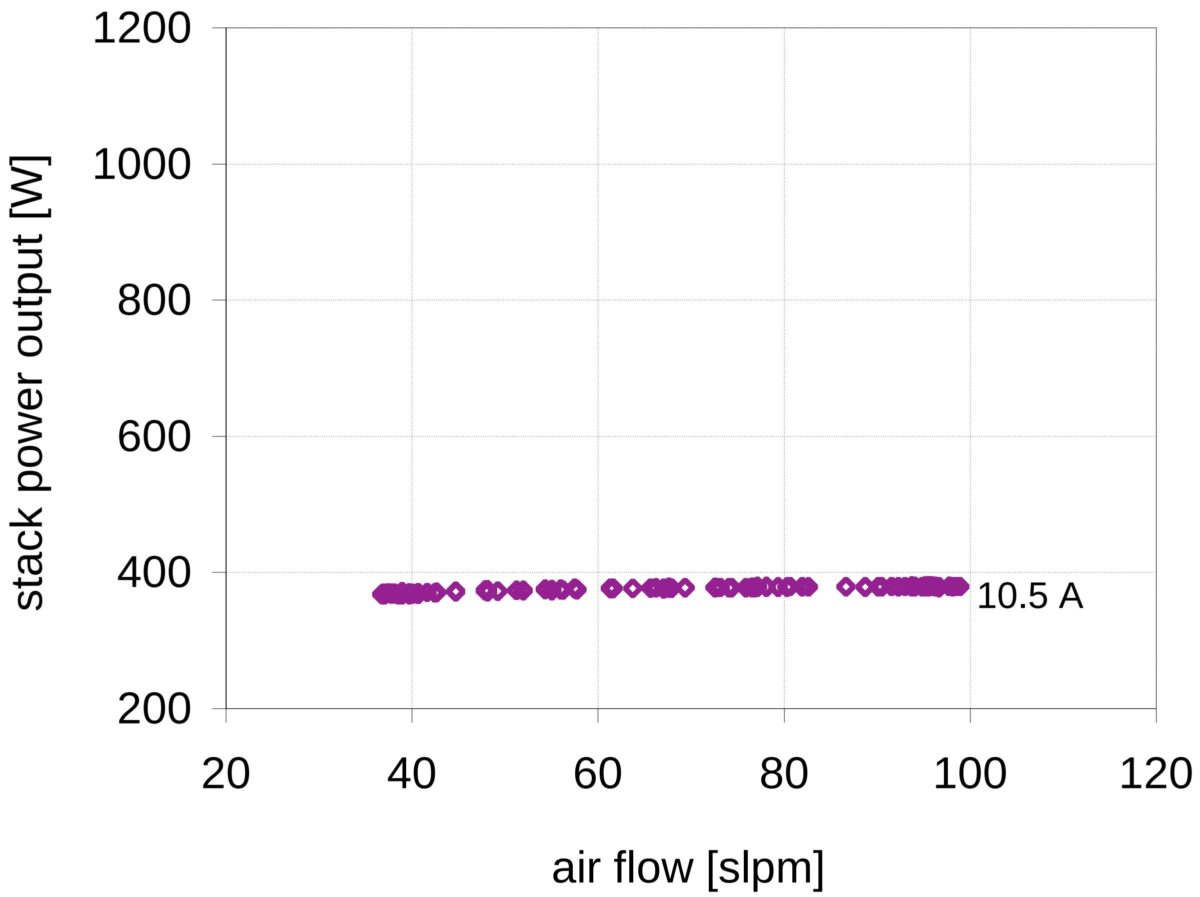
Ballard Nexa results – tests with the alternative controller

Air flow control



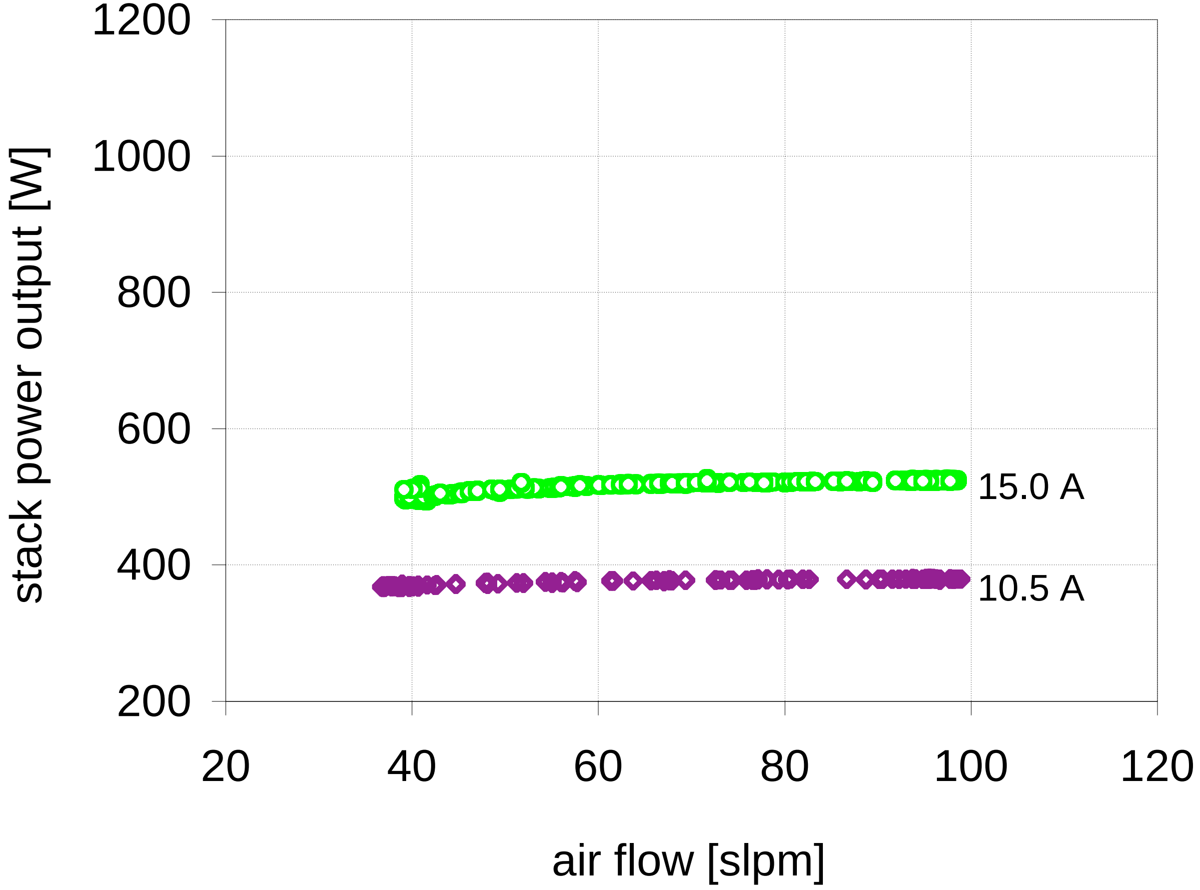
Ballard Nexa results – tests with the alternative controller

Air flow control



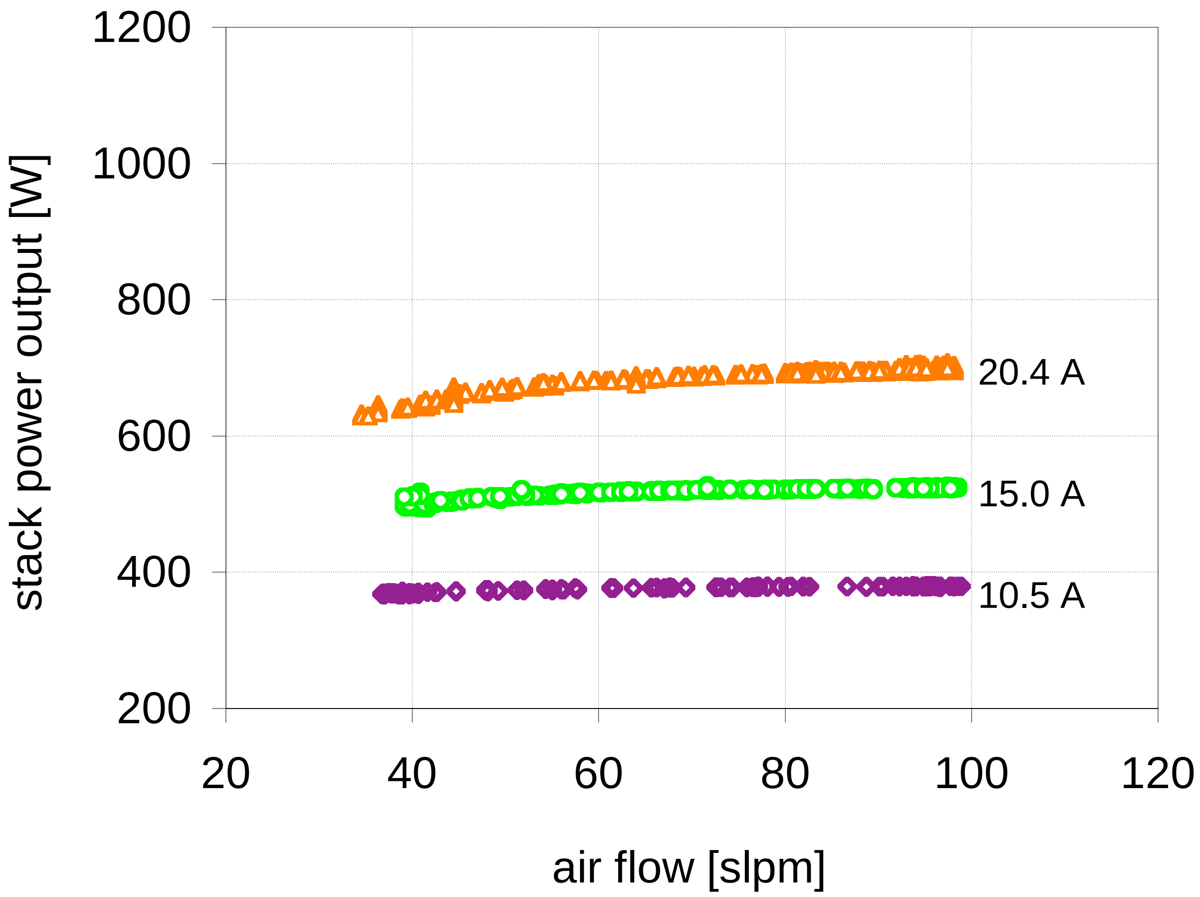
Ballard Nexa results – tests with the alternative controller

Air flow control



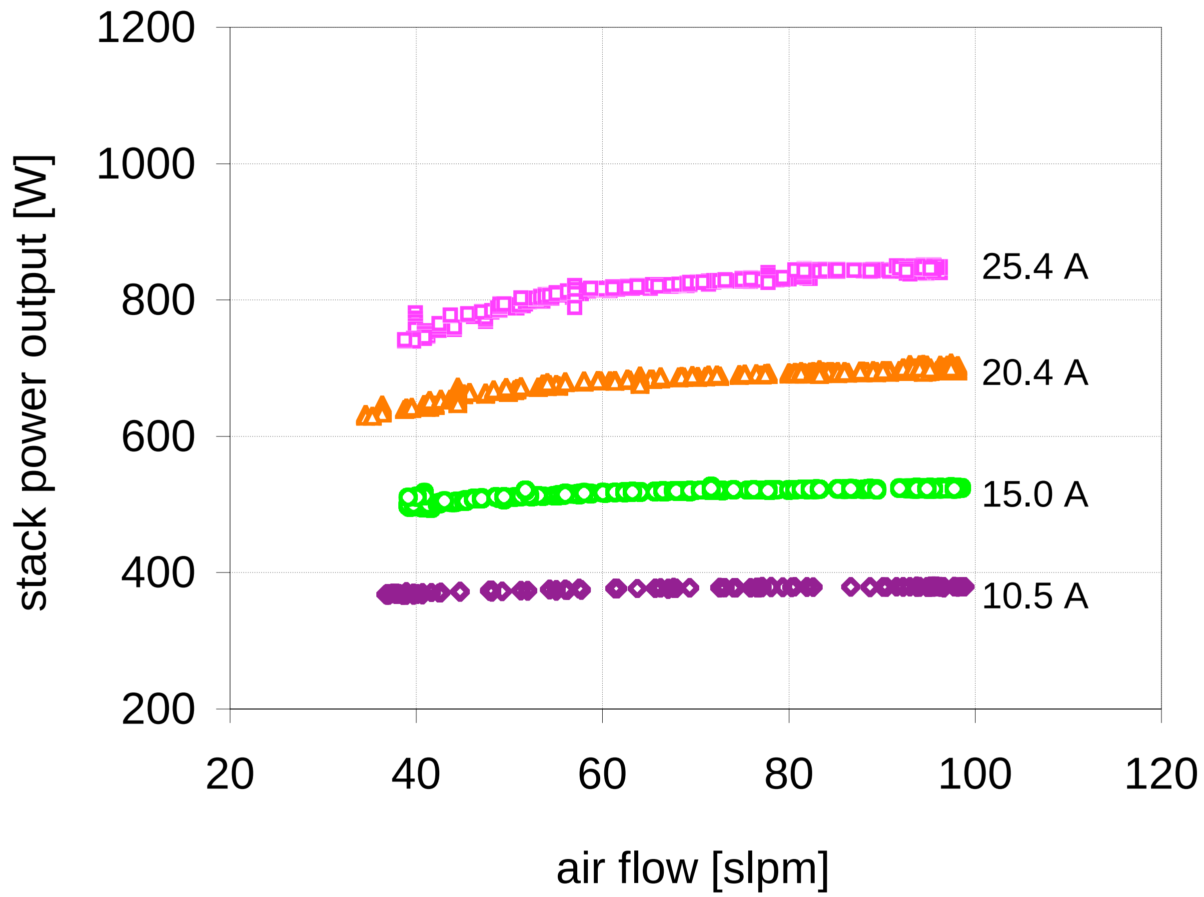
Ballard Nexa results – tests with the alternative controller

Air flow control



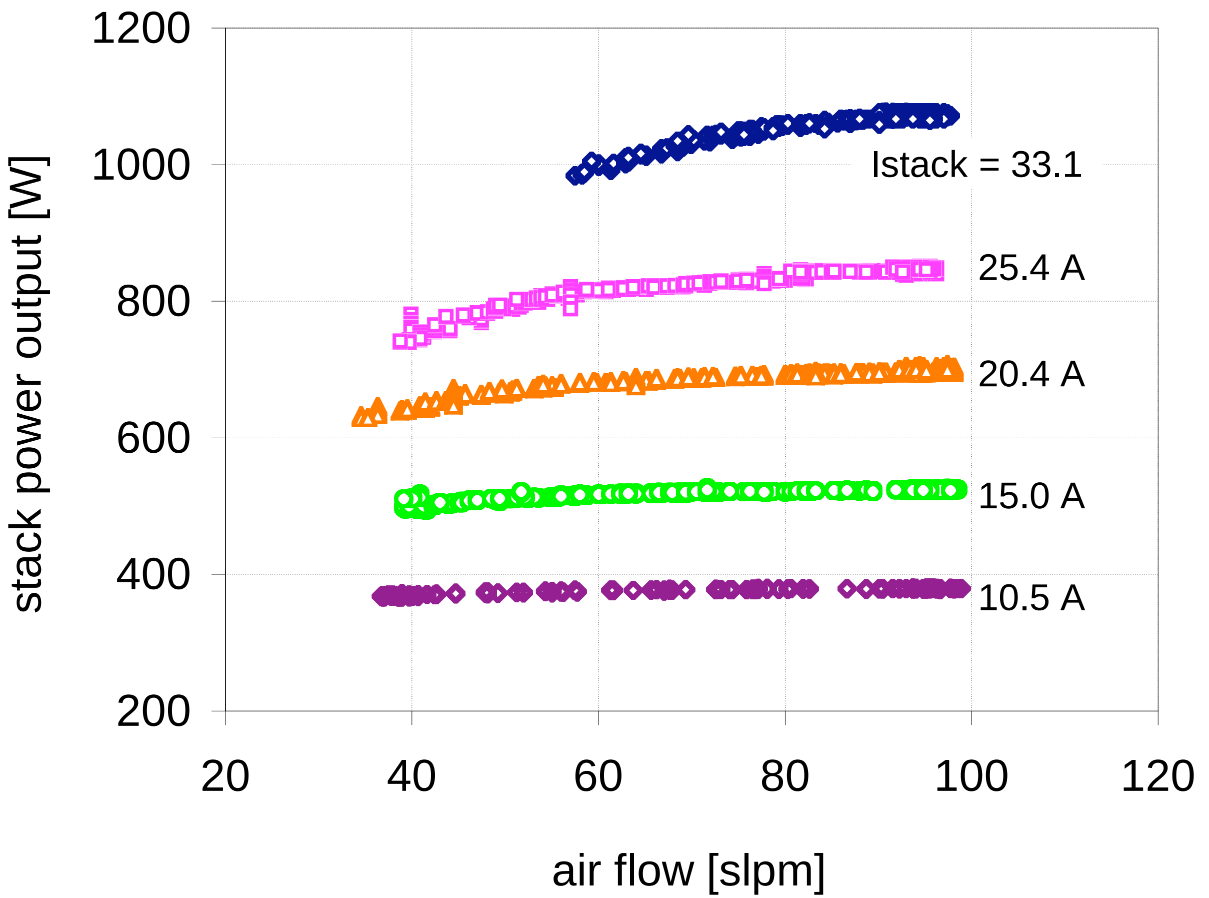
Ballard Nexa results – tests with the alternative controller

Air flow control



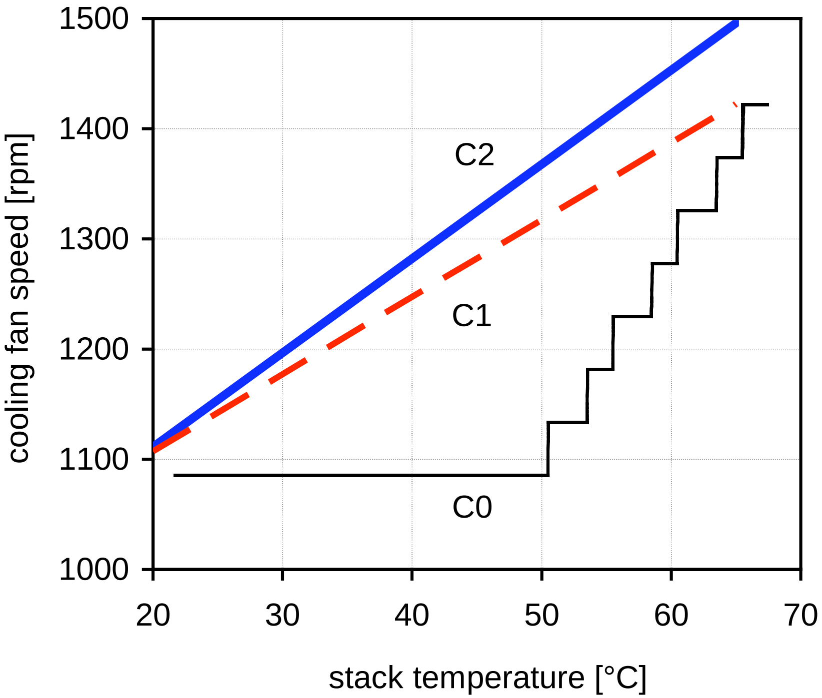
Ballard Nexa results – tests with the alternative controller

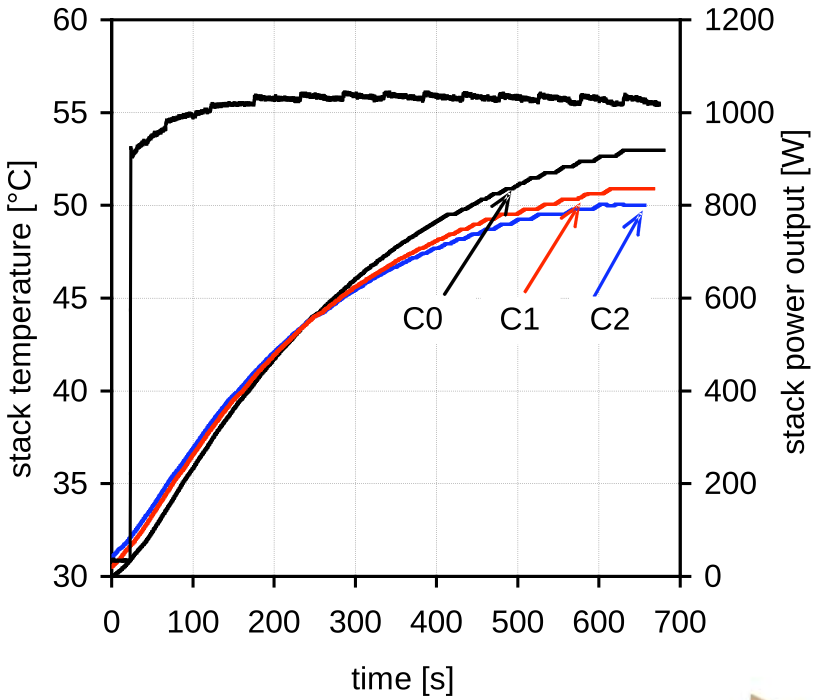
Air flow control



Ballard Nexa results – tests with the alternative controller

Temperature control

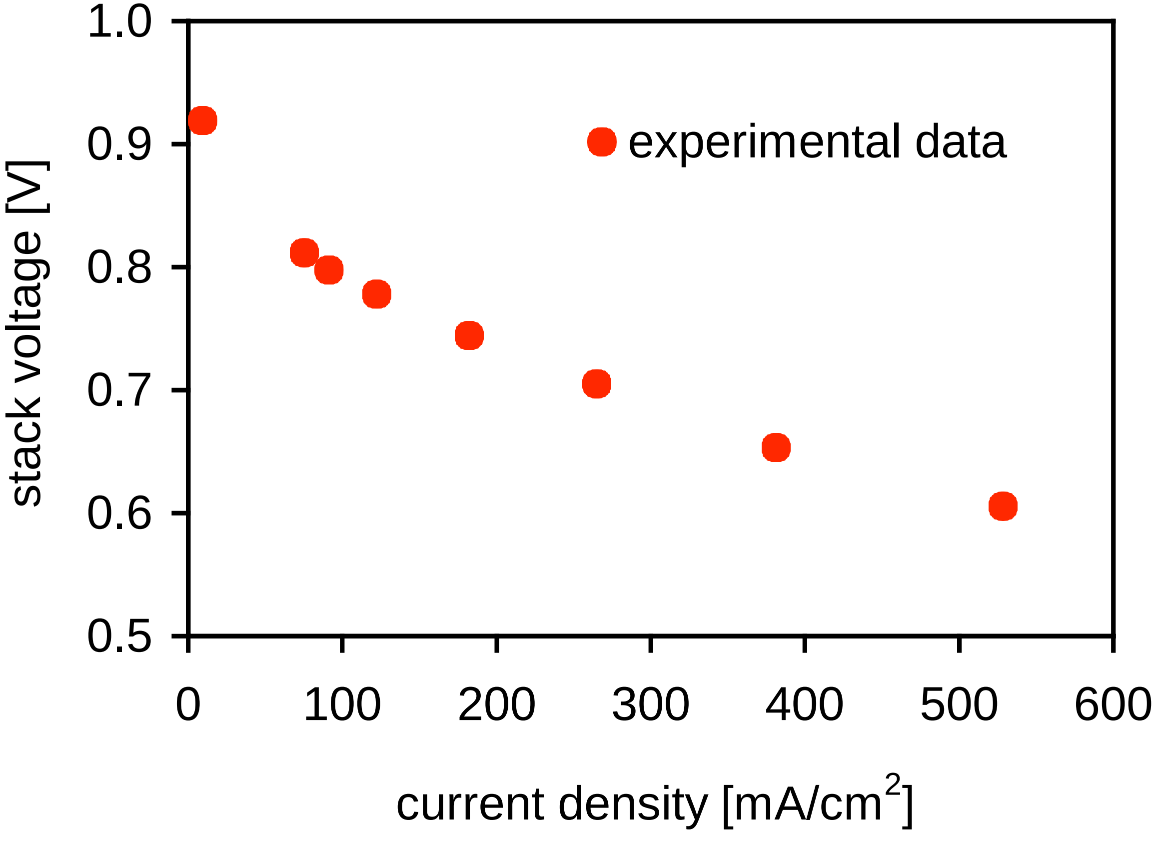




C0 = Nexa control, C1 and C2 = alternative controls implemented with the CompactRIO system

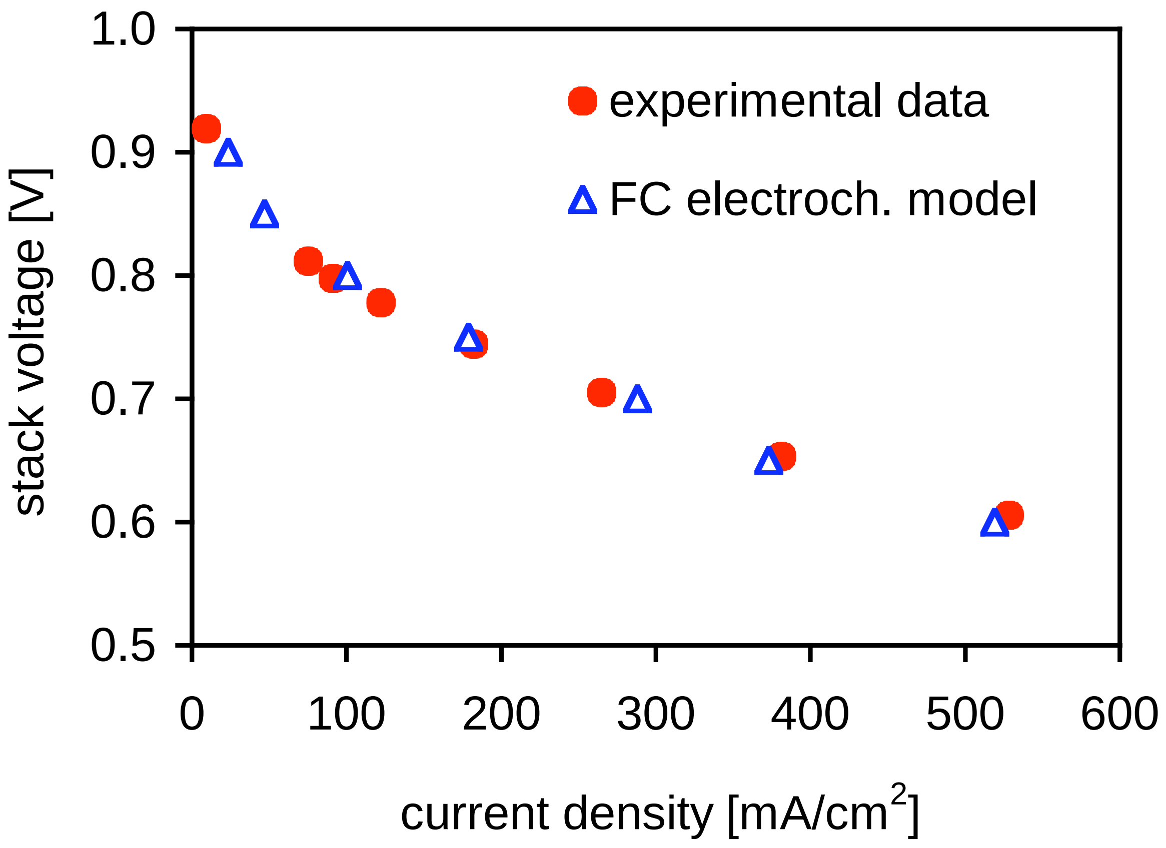
Ballard Nexa results – FC model validation

Electrochemical model



Ballard Nexa results – FC model validation

Electrochemical model

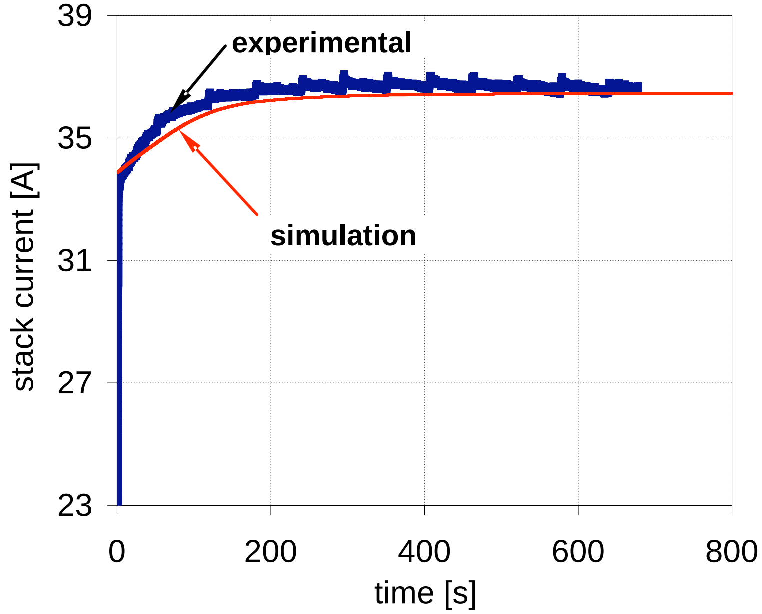


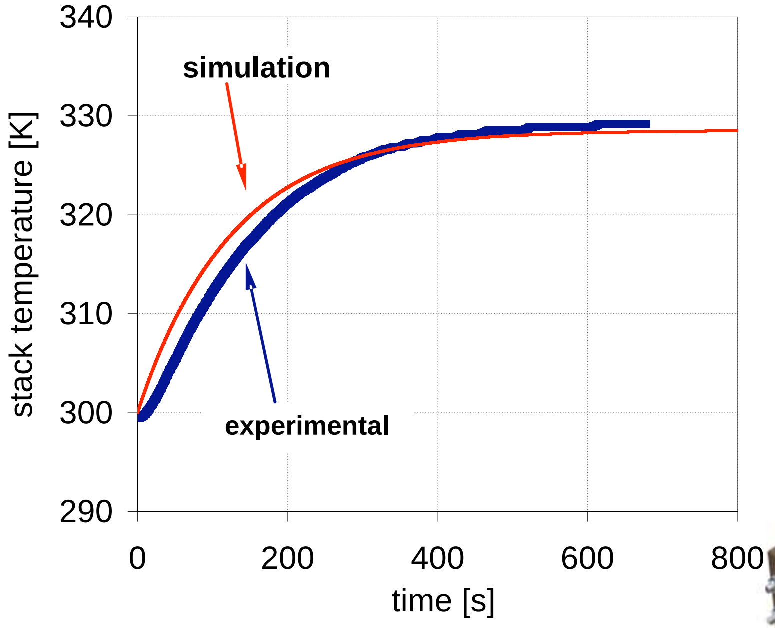
Ballard Nexa results – FC model validation

Thermal model

Stack power [W]	Measured Tstack [°C]	Calculated Tstack [°C]	Error [°C]	Error [%]
215	26.5	27.4	- 0.9	+ 3.3
1130	56.2	55.6	+ 0.6	- 1.1
1500	67.4	66.0	+ 1.4	- 2.1

Overall model





Objectives

Fuel cell model → **Experimental tests** → **Stack design & testing**

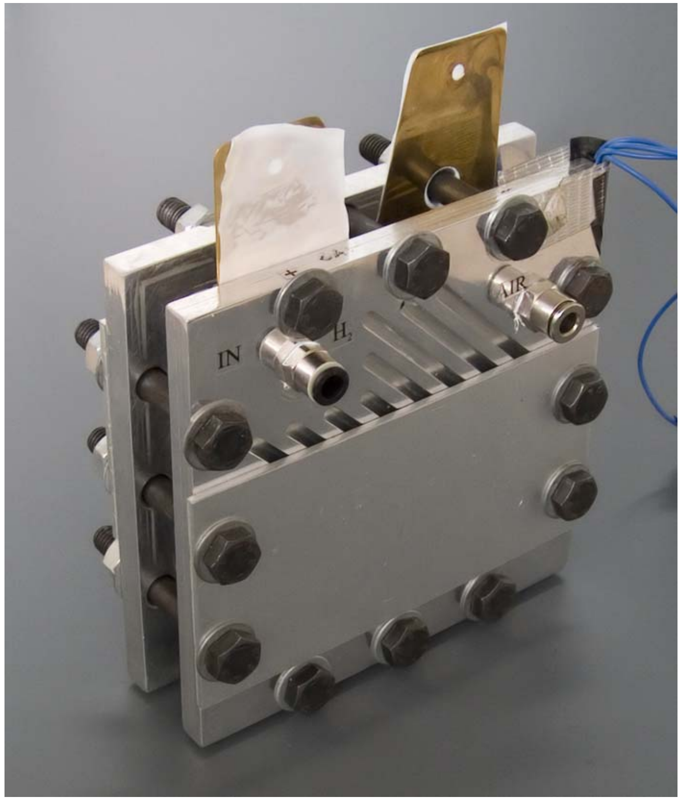
Stack design and testing

The development of the new system → a two step approach:

• Stack#1 used to check if the chosen CCM offers the same performance on a stack system like on the single cell and to test the control system, especially on the temperature and purge controls.

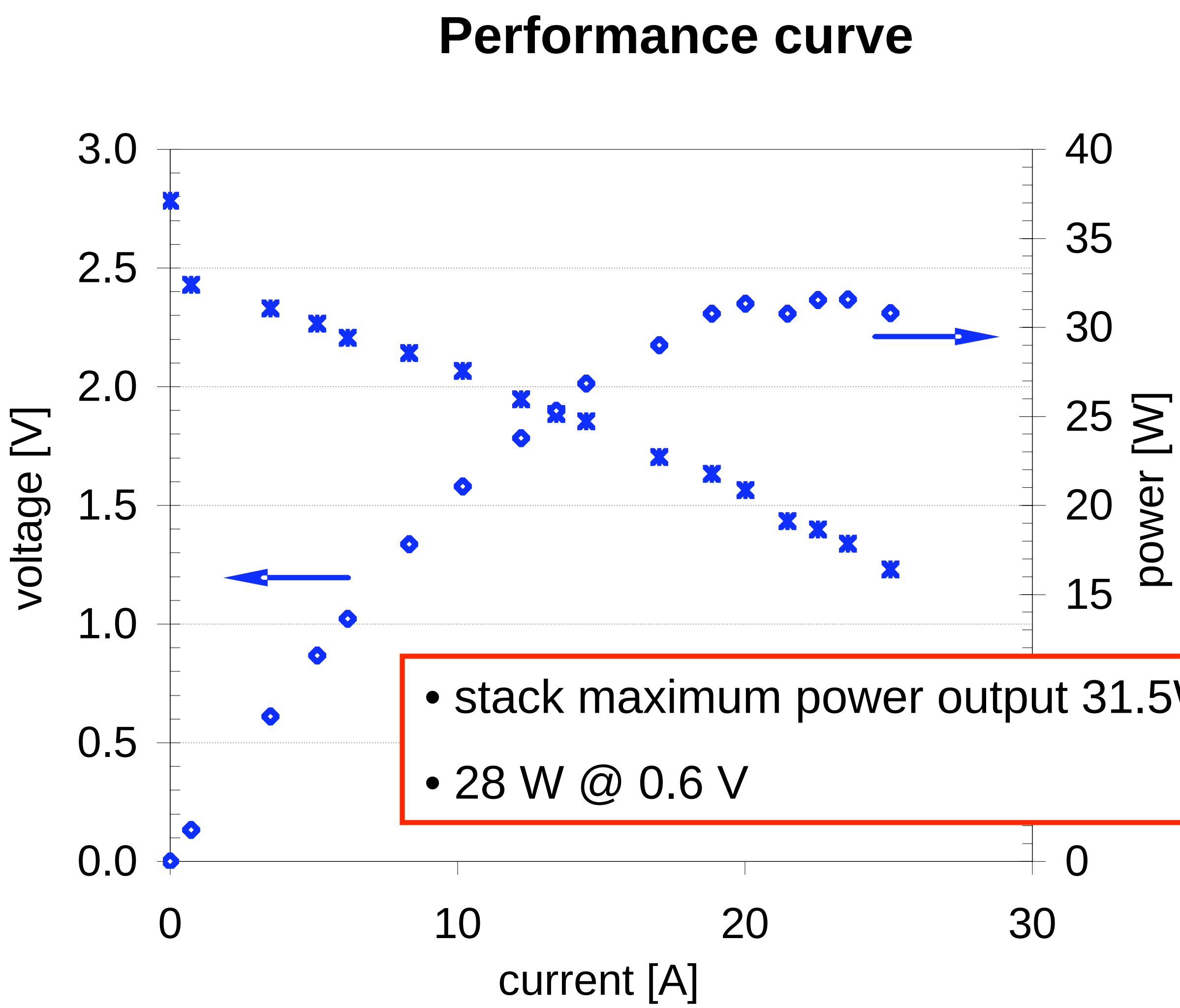
• Many issues that came up during the experimental activity on Stack#1 were useful for the designing of the final system, which will be called further Stack#2.

Stack#1



- three cell system
- 50 cm^2 CCM
- multiple serpentine BP
- serial feeding circuit
- dead end hydrogen circuit
- air cooling

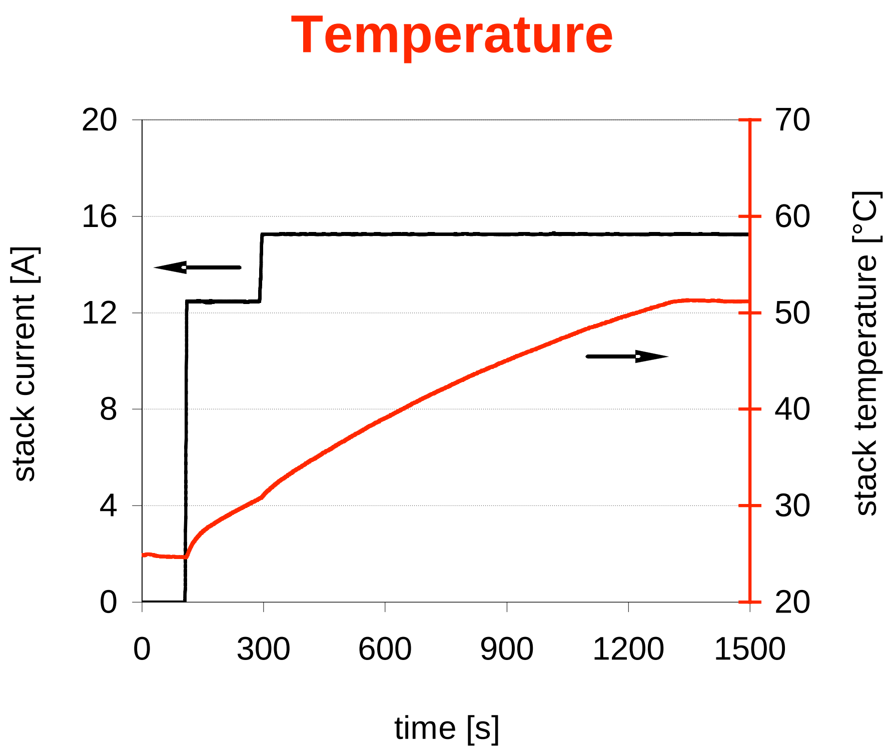
Stack#1

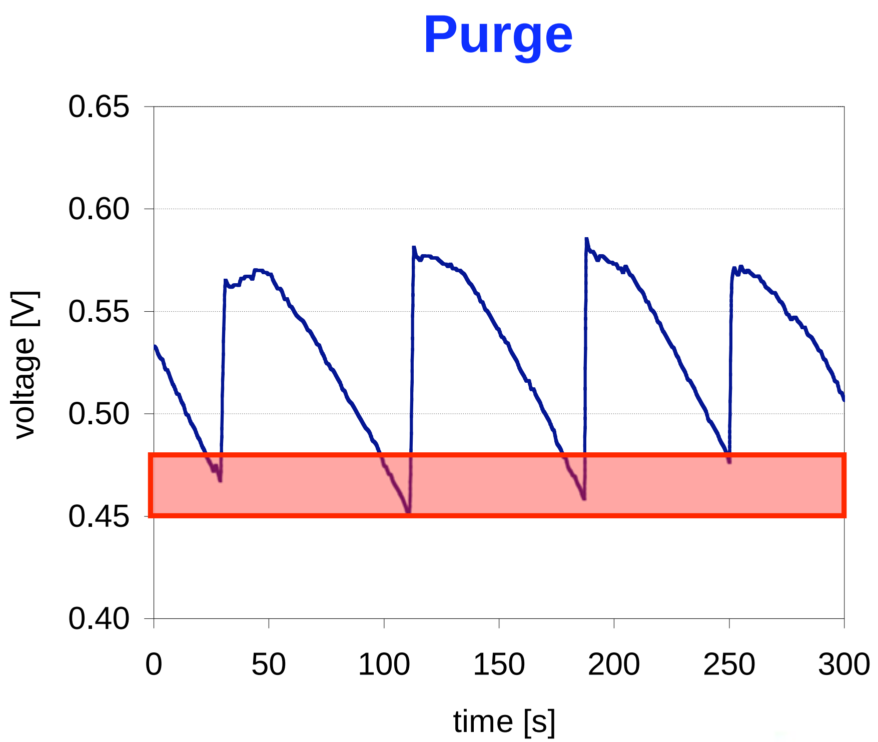


- stack maximum power output 31.5W @ 1.35 V
- 28 W @ 0.6 V

Stack#1

Control tests





Stack#2 design and dimensioning

Number of cells $$n_{cells} = \frac{P_{stack}}{A \cdot i \cdot V} = \mathbf{23}\ cells$$ → ***25 cells***

200 W

300 mA @ 0.6 V

Stack voltage $$V_{stack} = n_{cells} \cdot V = \mathbf{15}\,V$$

Stack current $$I_{stack} = i \cdot A = \mathbf{15\ A}$$

Fuel cons. $$\dot{m}_{fuel} = \frac{I_{stack} \cdot n_{cells}}{2 \cdot F} \cdot \frac{8.314 \cdot T_0}{p_0} \cdot 60 \cdot 10^3 = \mathbf{2.9}\ slpm$$

Stoich. air. cons. $$\dot{m}_{airST} = \frac{I_{stack} \cdot n_{cells}}{4 \cdot F} \cdot \frac{8.314 \cdot T_0}{p_0} \cdot 60 \cdot 10^3 = \mathbf{6.9}\ slpm$$

Air. cons. $$\dot{m}_{air} = \lambda \cdot \dot{m}_{airST} = \mathbf{17.3}\ slpm$$

2.5

Stack#2 performance simulation

simple dimensioning method

- 25 cells
- 200 W @ 0.6 V
- air cooled
- dead end anode
- parallel feeding circuit

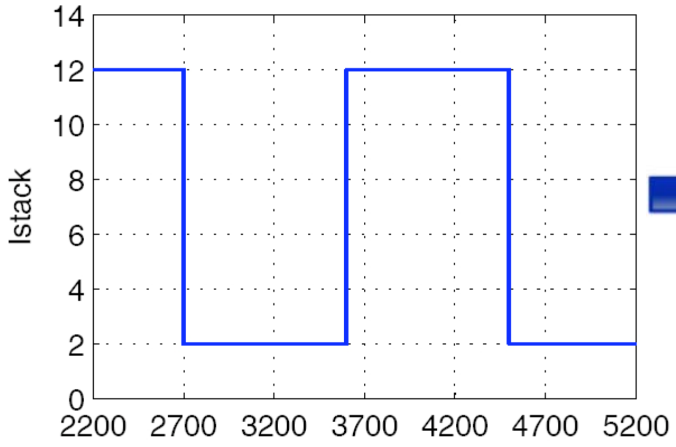
Electroch. model = recalibrated with Stack #1 data

Simulation model

Thermal model = recalibrated with Stack #1 data

Auxiliaries

Stack#2 performance simulation

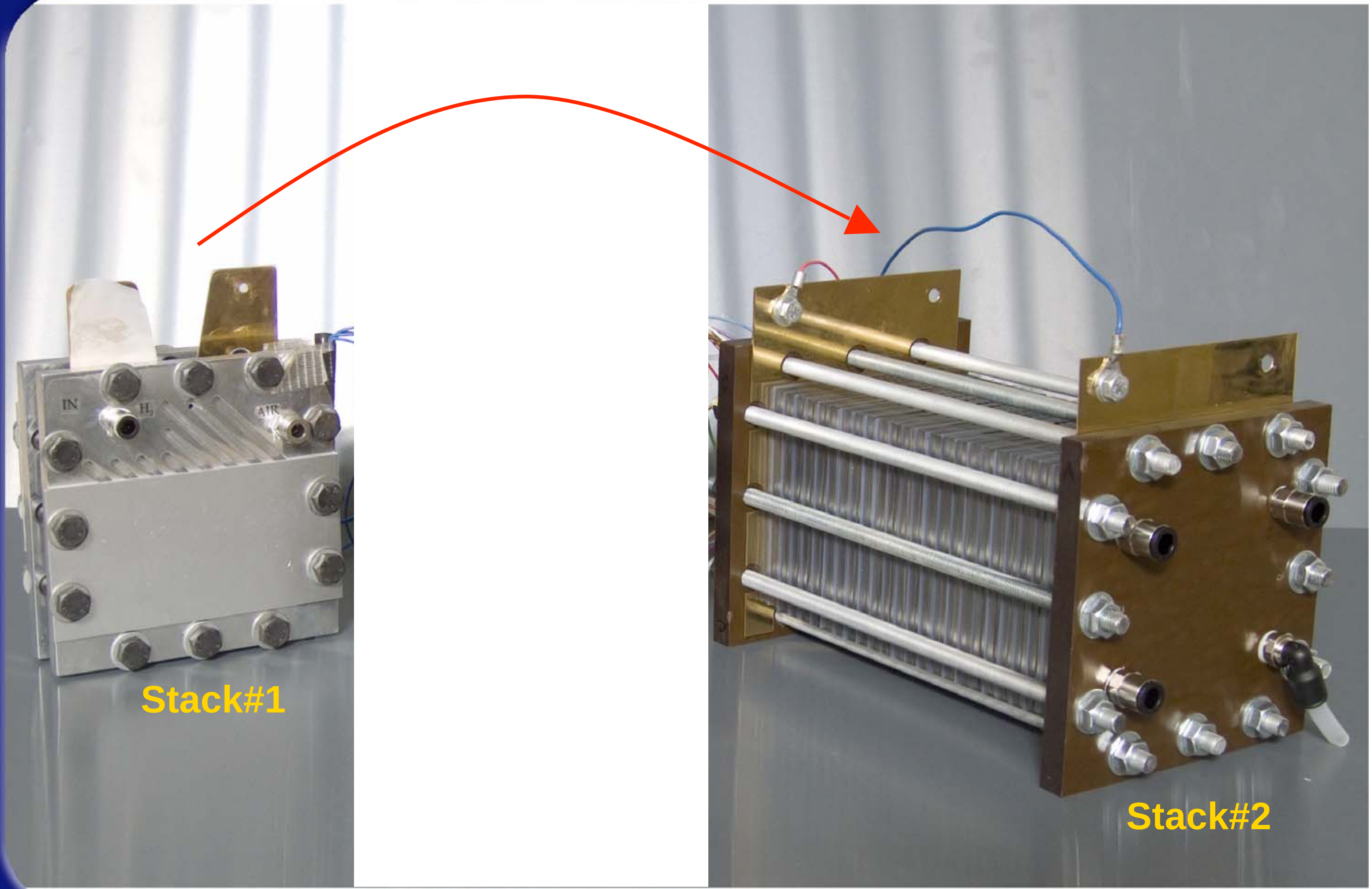


Simulation model

T_{set} = 60°C

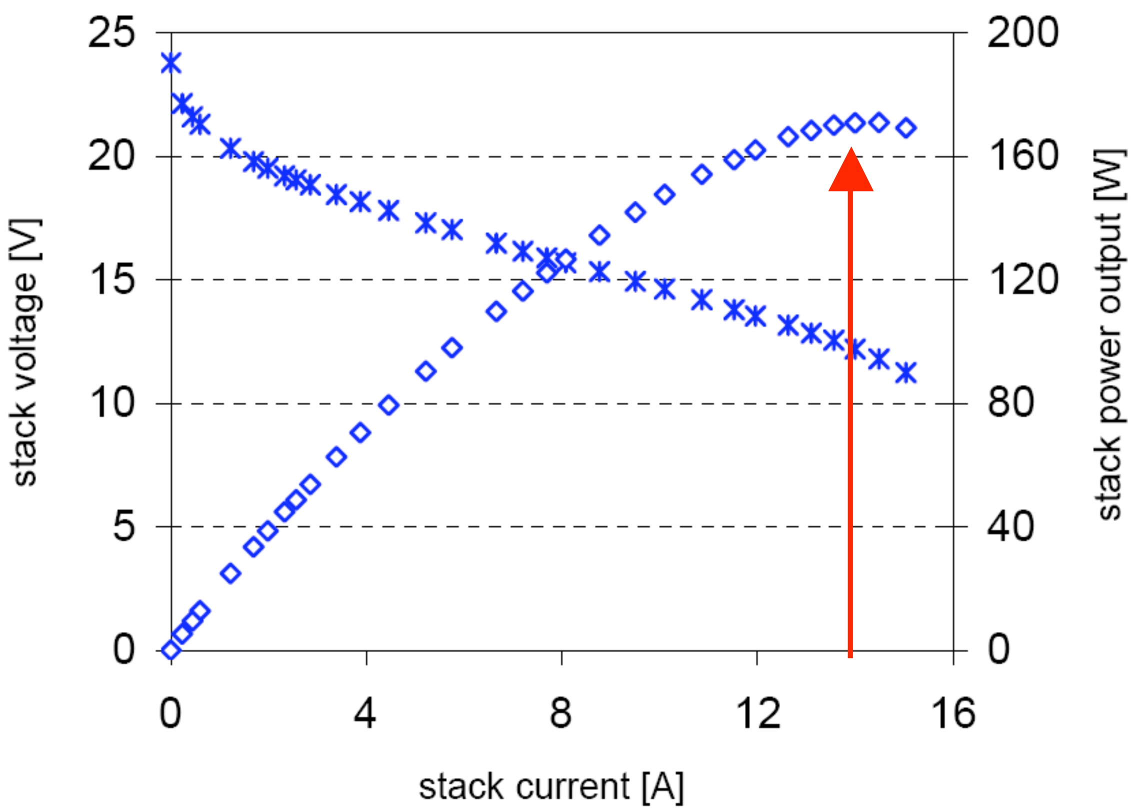
$\lambda = f(I_{stack})$,
λ_{min} = 2.5

- stack power ≈ 200 W @ 12 V
- stack efficiency = 0.48 ÷ 0.61
- system efficiency = 0.43 ÷ 0.55
- max cooling flow = 230 slpm


Stack#1
Stack#2

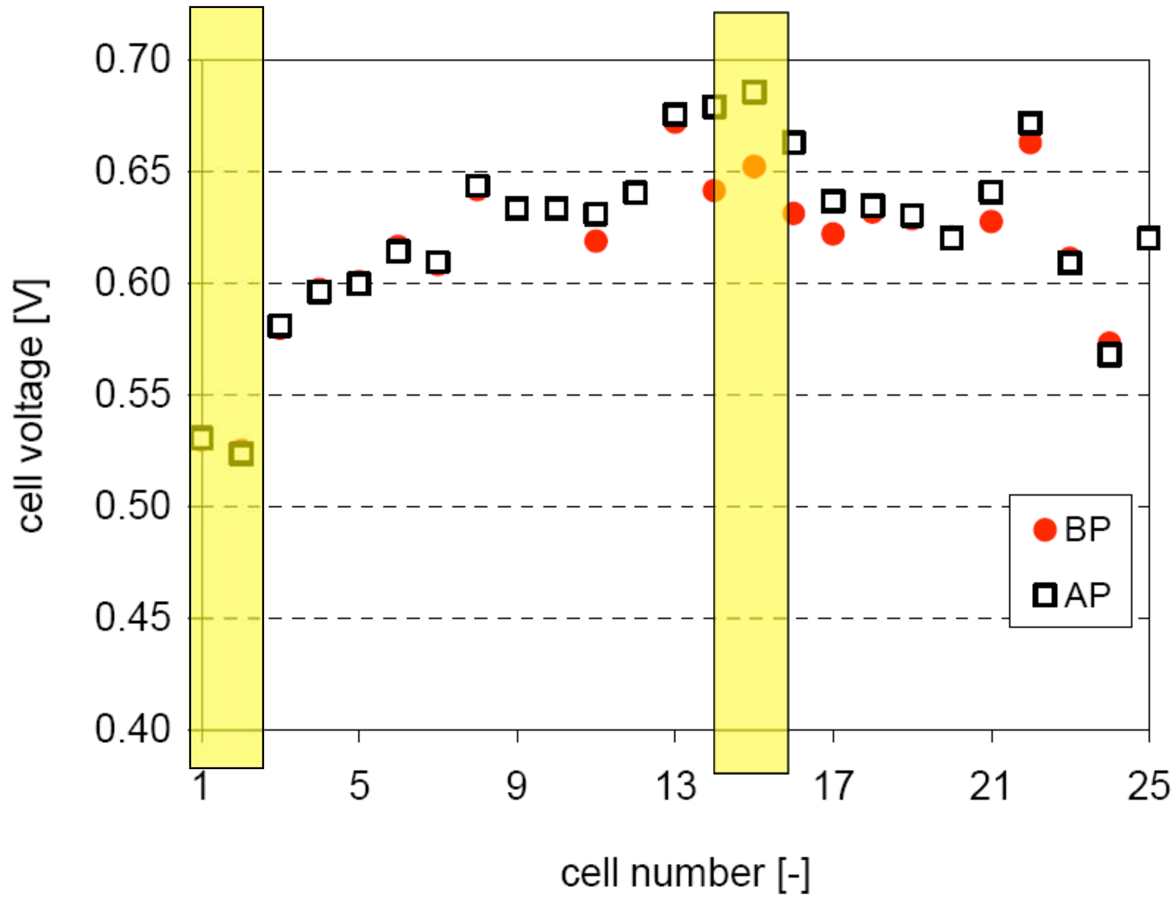
Stack#2 preliminary results

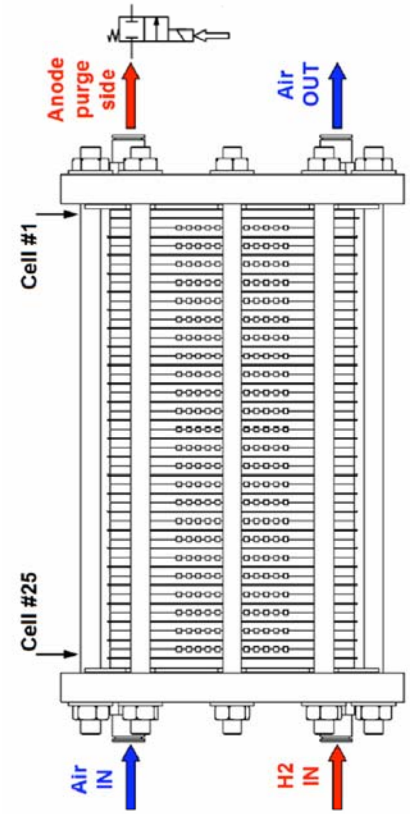
Stack#2 preliminary performance curves (after 21h conditioning, reactant gases pressure = 1.05 bar, stack temperature 60 °C)



Stack#2 preliminary results

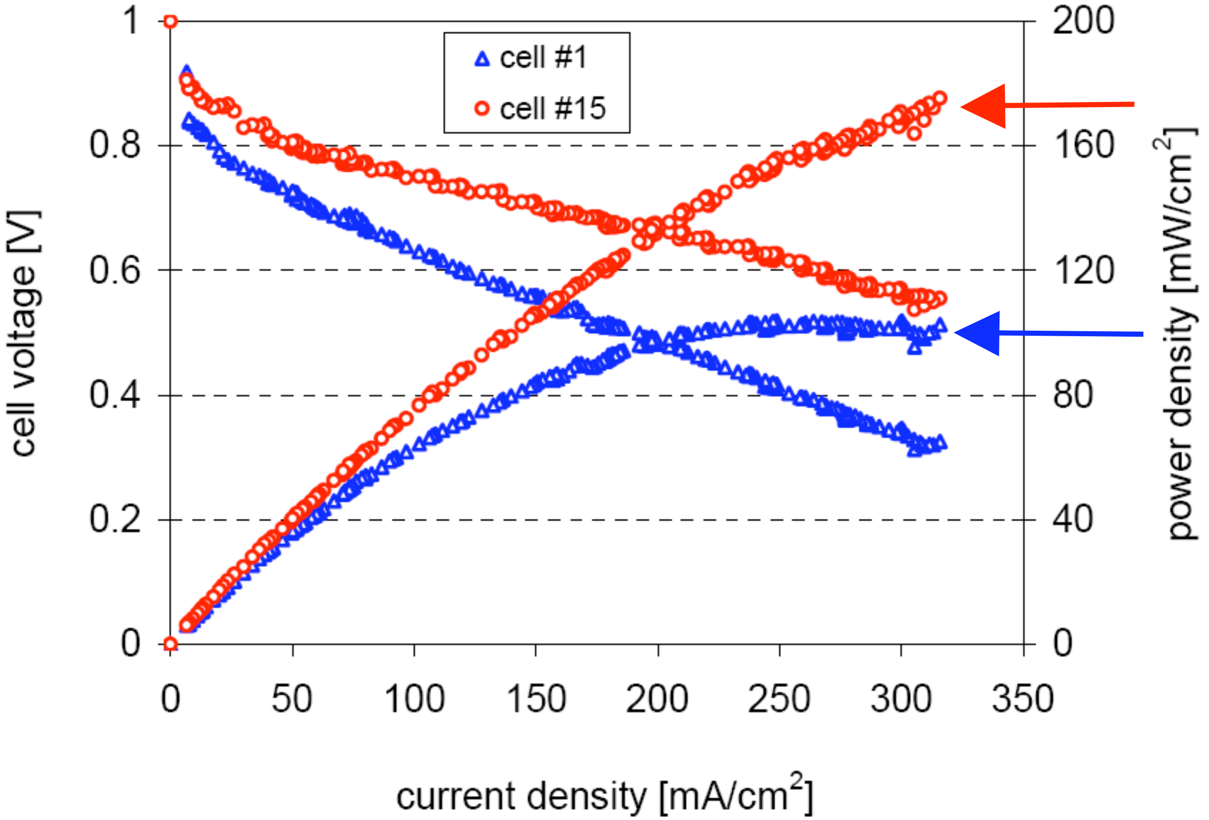
Voltage distribution before (BP) and after (AP) the anode purge
(stack current 6A, lambda 2.6, stack temperature 65 °C)





Stack#2 preliminary results

Comparison between the best and worst performing cells



Final conclusions and future developments

- ✓ the simulation model proved its ability to simulate accurately the fuel cell
- ✓ the potential of the data acquisition and control system was confirmed the
- ✓ accurate experimental procedure
- ✓ Stack#1 is able to reach a fair performance (31.5W @ 1.35 V)
- ✓ even if Stack#2 performance did not reach the expectations, it demonstrates that during the last three years, **we succeed to build strong theoretical and experimental skills which will be applied on the development of further fuel cell based systems**
- ✓ enhancement of the Stack#2 performance and to its integration in a self sustaining system
- ✓ exploring other alternatives