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CONTROL, PROGNOSTICS AND DIAGNOSTICS OF PEM FUEL CELLS

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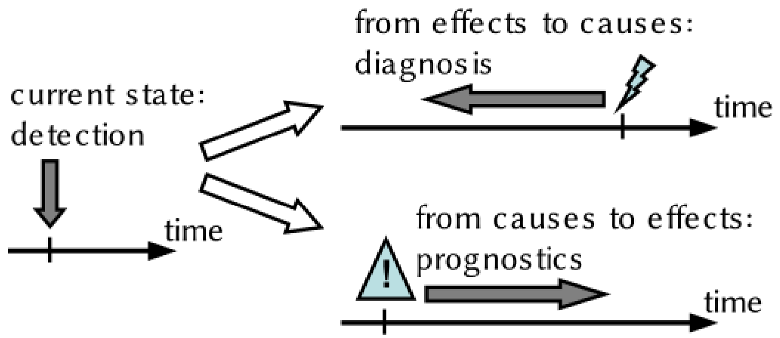
Outline

- Diagnostics and Prognostics
- Degradation Pathways and how to Detect them
- Prognostic Variables
- Diagnostic and counteraction
  - CO contamination
  - Humidity
  - Starvation
- Stack Rejuvenation

Diagnostics and Prognostics

- Entered the area with EU project SAPPHIRE, µCHP fuel-cell systems
  - Cooperation with FCLAB in Eastern France
  - Other partners: FESB, ZSW, EIFER
  - System by Dantherm Power (now Ballard Europe)
- Definitions:
  - *Diagnostics*: evaluate the State of Health (SoH) based on sensors
  - *Prognostics*: evaluate the Residual Useful Life (RUL) based on SoH



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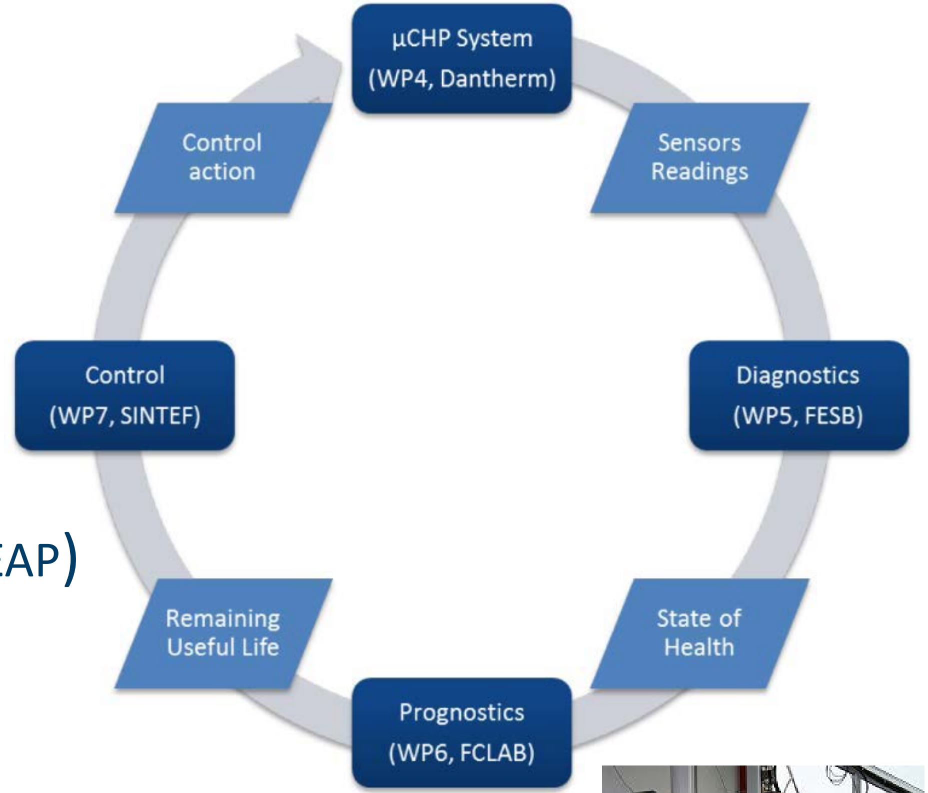
The Role of Control

- Idea: integrate control into the loop
  - SAPPHIRE successful, but not in the way we had planned!
- Continued topic in automotive for buses (GIANTLEAP)
  - High degree of hybridisation with large battery
  - Fuel cell as range extender
  - Small-ish fuel cell (60-80 kW)
  - Also focus on Balance-of-Plant (BoP) components



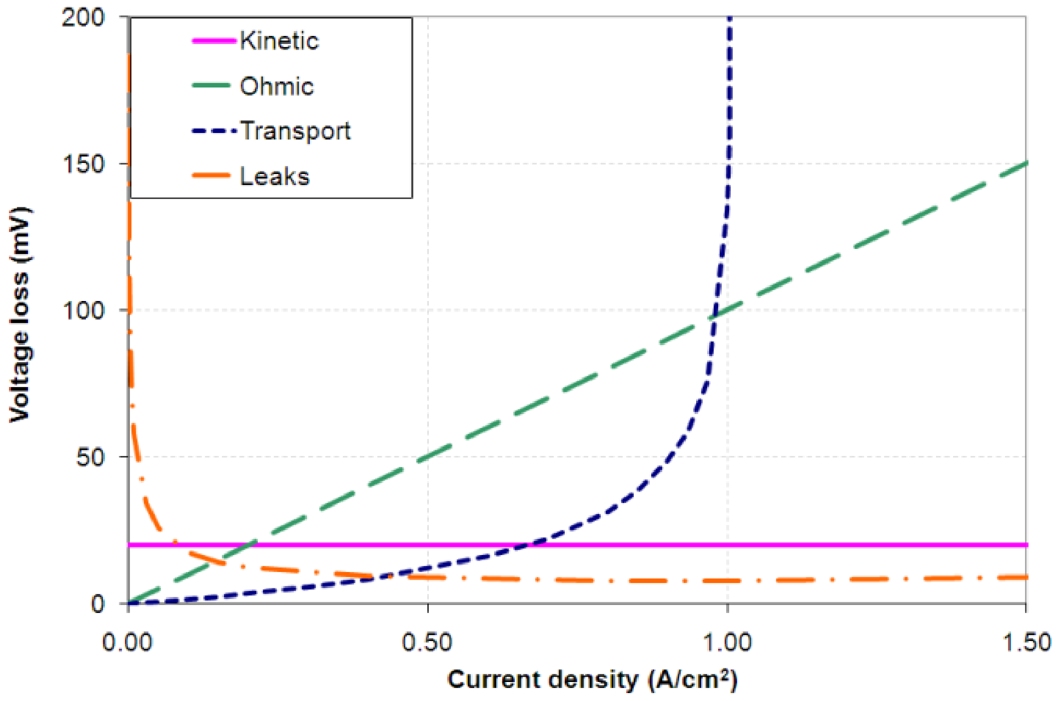
GIANTLEAP

Degradation Pathways (in LT-PEMFCs)

- Most degradation pathways reduce the voltage
- Need closer look to verify what is happening
  - Cathodic catalytic layer: oxidation, high voltages
  - Anodic catalytic layer: impurities, e.g. CO
  - Cathodic mass-transport layer: flooding
  - Membrane ohmic loss: drying
- Some degradation gives short or no warning
  - Anodic catalyst support: starvation
  - Membrane failure: humidity and temperature cycling

Laboratory and Field Methods

- Laboratories' favourite tool: Electrochemical Impedance Spectroscopy (EIS)
  - Not the industry's favourite: cumbersome and expensive (Yet: miniaturisation ongoing in D-CODE, HEALTH-CODE)
- Devise simpler techniques with available sensors whenever possible
- See SAPPHIRE deliverable D5.1, available from www.sapphire-project.eu



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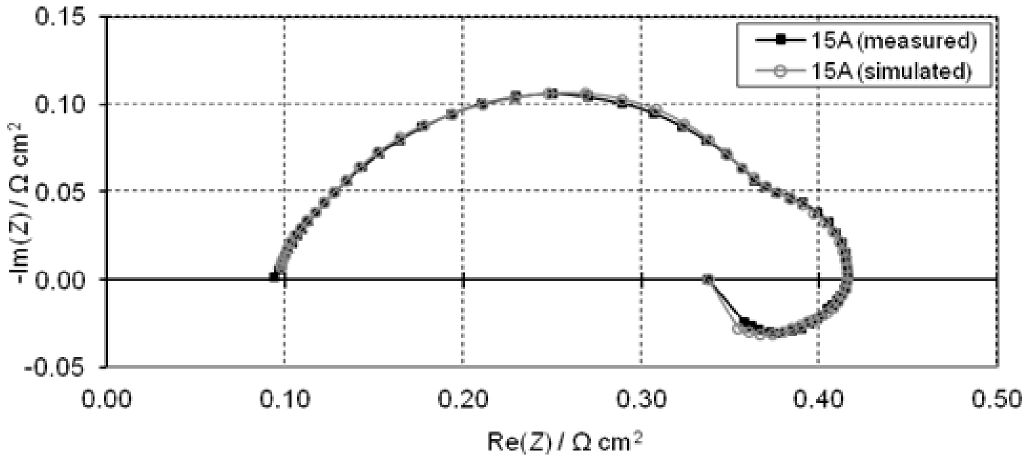
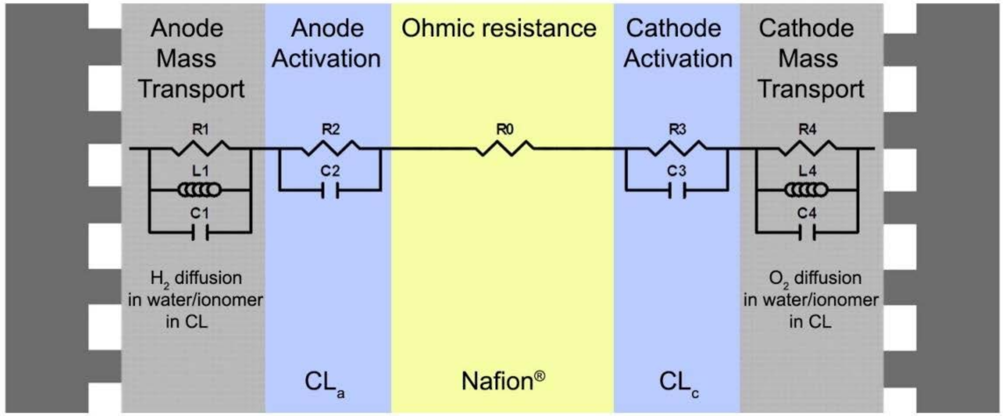
Prognostic Variables

- EIS: measure impedance from kHz to mHz
- Modelled with a *resonant element*
  - Short circuit at *both* steady state and fast dynamics
  - Resistance R_4 is a prognostic variable!
  - As degradation advances, R_4 increases
- SINTEF algorithm for R_4 estimate by relay
  - Simulation: converges in about 7 seconds
  - Requires no EIS equipment
  - To be presented at EFC in December 2017





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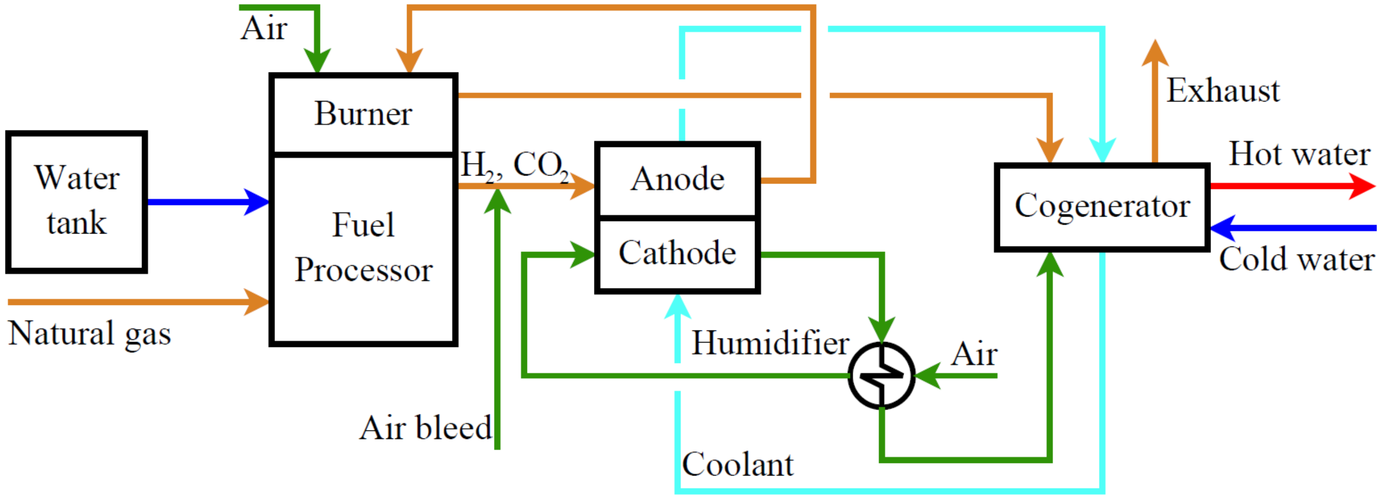
CO Contamination



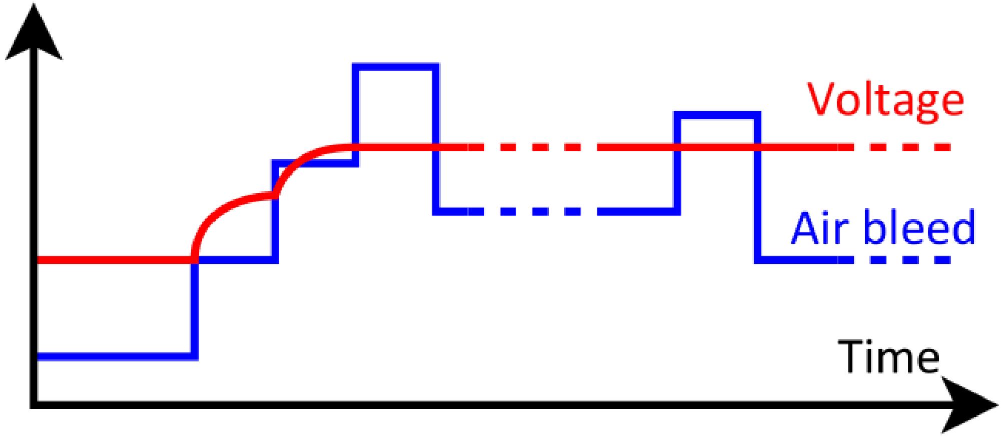
- Reformate-fed fuel cells can be poisoned by CO
- CO takes over 99% of reaction sites on anode
  - CO maximum under reformer transients
- A fixed **air bleed** is added to hydrogen: O_2 removes CO continuously
  - Air bleed is heavily overdimensioned
  - Loss of efficiency, faster degradation (hot spots)

CO Contamination: air bleed control

- Practical feedback:
  - CO measurement is expensive/cumbersome
  - Slow poisoning dynamics (hours)
  - Fast cleaning dynamics (minutes)
- Use voltage as poisoning measurement:

1. Increase bleed
2. If voltage increases, back to 1.
3. If not, step back 150% and wait several hours, then back to 1.

(Klages et al., Dual control of low concentration CO poisoning…, J. Pow. Sour. 336 (2016) 212-223)



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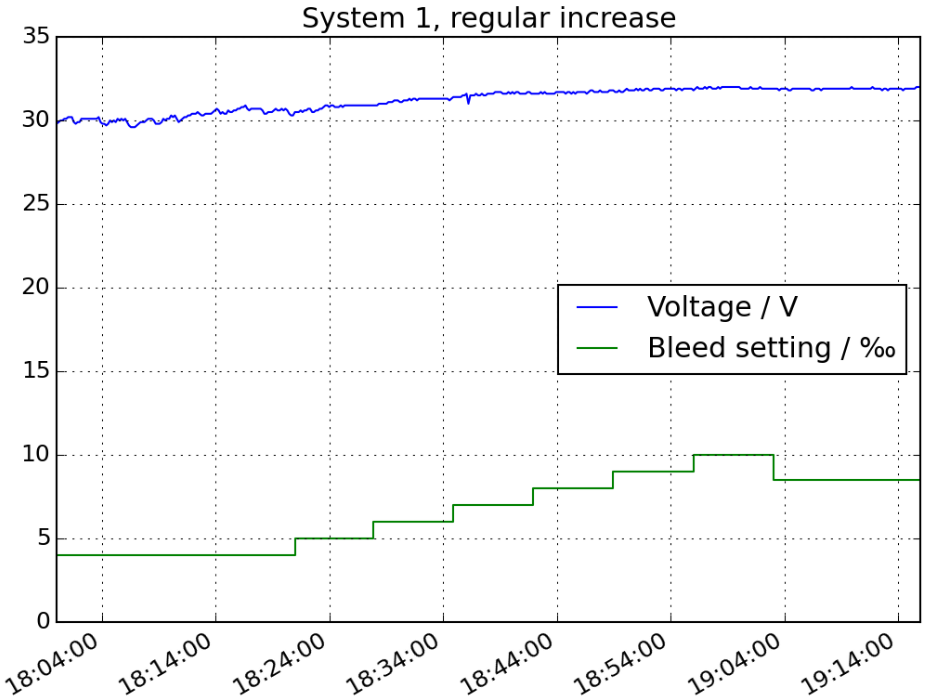
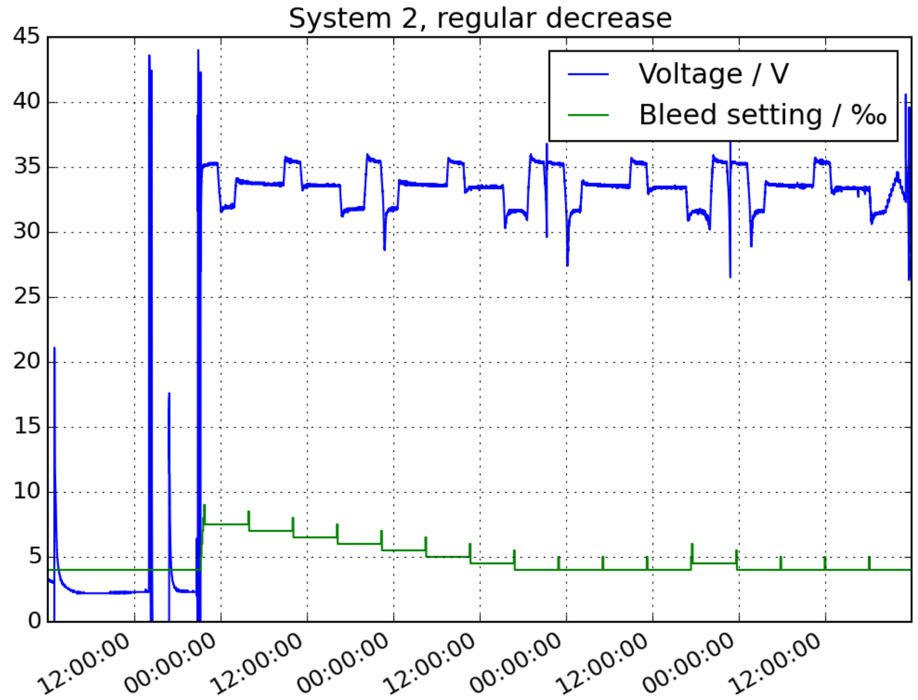
CO Contamination: Demonstration





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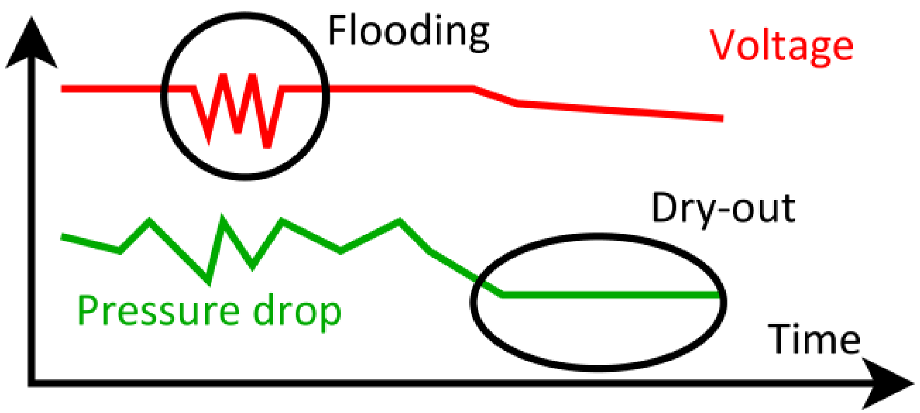
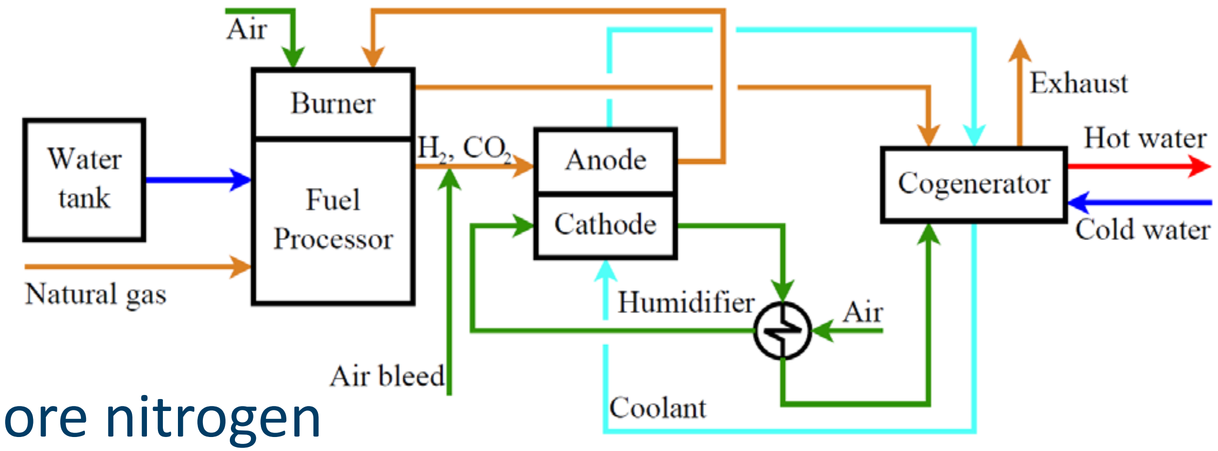
Humidity

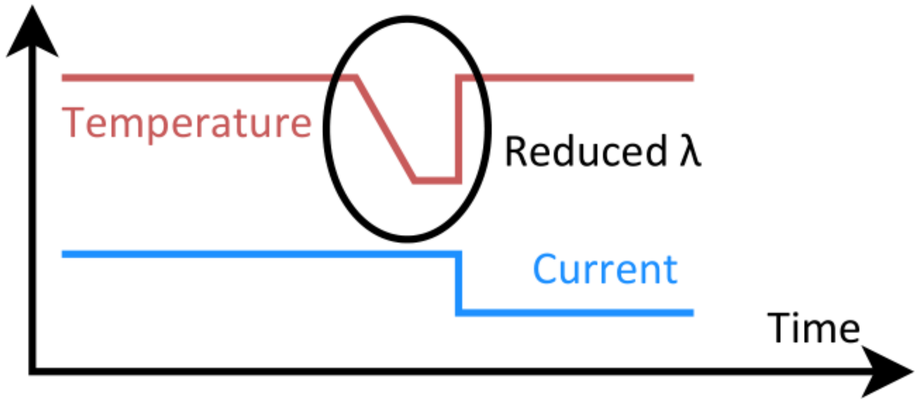
- Low-T PEM FCs must have right humidity, slightly above 100%
  - Low humidity: drying cycling, ohmic resistance increase
  - High humidity: flooding, reduced maximum current
- Main disturbance is *temperature*
- Practical feedback *for stacks*:
  - Flooding: Droplets cover reaction sites → Voltage noise
  - Drying: Droplets disappear → Reduced pressure drop on cathode
- Increase/decrease cooling to adjust humidification



Fuel Composition



- NG composition changes in winter, more nitrogen
  - No composition measurement to warn us
- Anode side runs at low λ for maximum efficiency
  - Risk of anode starvation if not enough CH_4
  - Reverse electrolysis within seconds, irreversible stack failure
- Anode outlet is burnt for reformer heating
- Practical feedback: reformer flame temperature
  - Highly magnified effect of λ variations
  - When flame temperature falls, cut current



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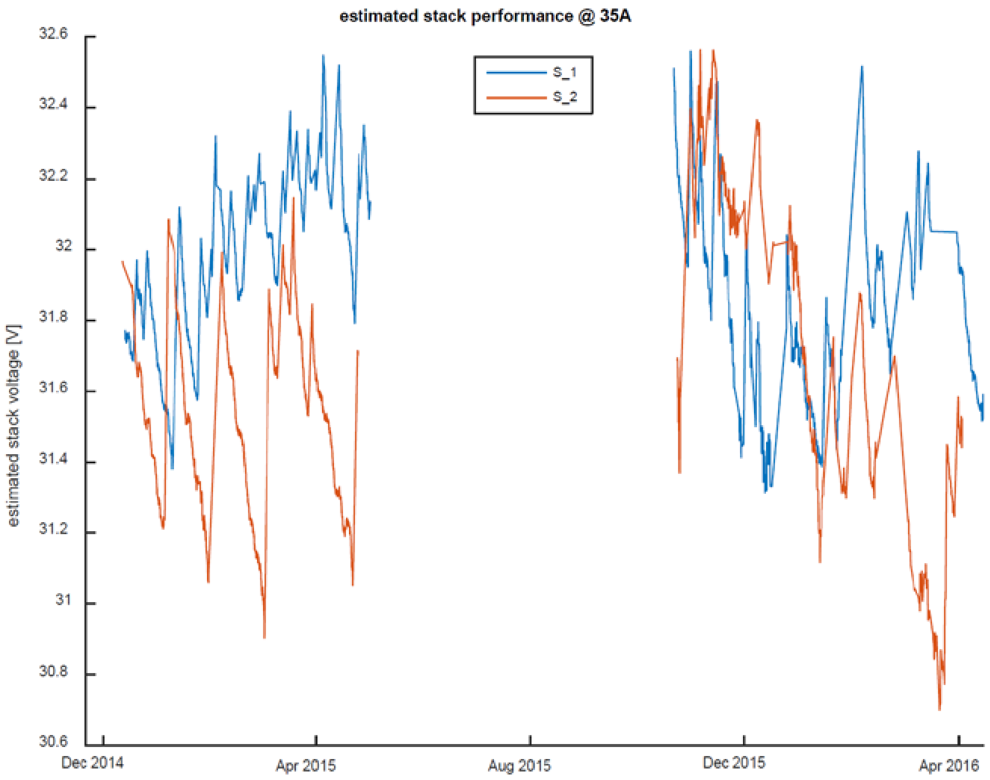
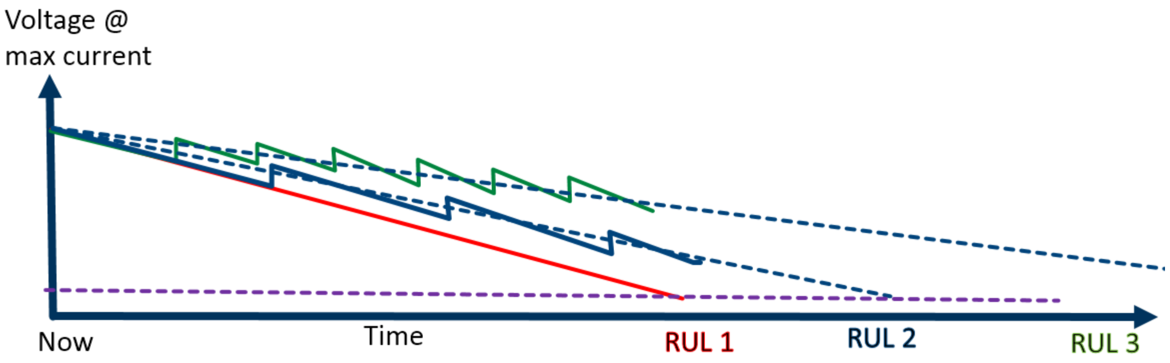
Rejuvenation

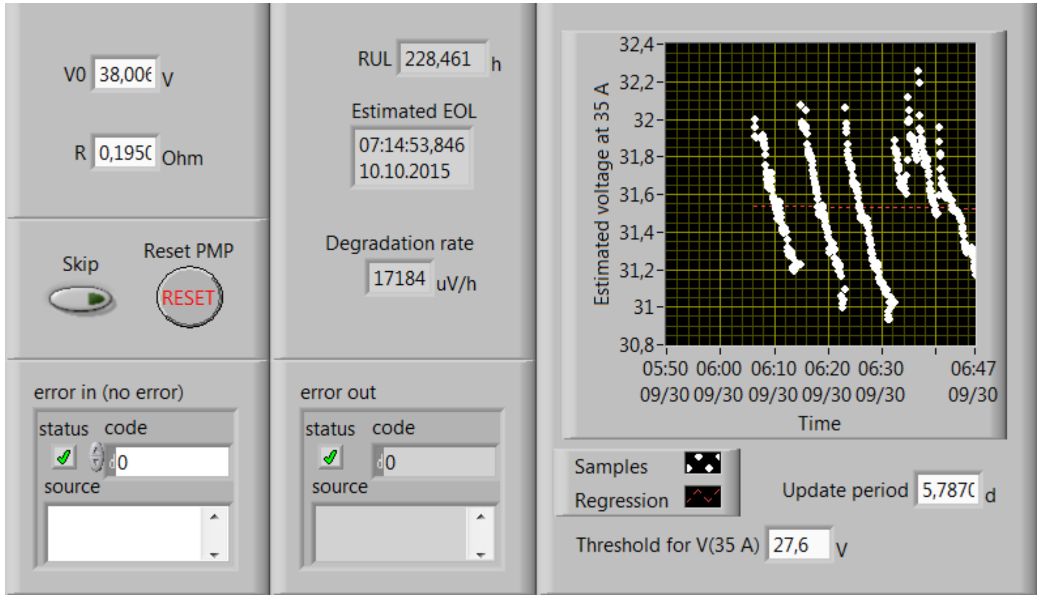
- Tests in SAPPHIRE on industrial PC for logging
- Not enough bandwidth, computer crashes
- At every restart, voltage was a bit higher…
  - Over 3000 hours: –0.2 µV/h and +4 µV/h per cell
  - **Two simultaneous world records!**
- Something went *right* in the crashes, but we are not sure *what*
  - Likely improvement in cathodic catalyst
- Phenomenon verified in second campaign (3000 hours)



Rejuvenation



- Difficult to prognosticate RUL before understanding mechanism
- Follow-up in GIANTLEAP with FESB & NTNU
- It is possible to develop a *Poor Man's prognostics*
  - Model voltage as $V = V_0 + I \times R$
  - Track V_0 and R for at least 1000 hours
  - Make a linear regression
  - Fairly robust in predictable conditions



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Conclusions

- Diagnostics of fuel cells
  - Methods for humidity, CO poisoning, anode starvation
  - Laboratory methods (EIS) are not the best in applications
- Prognostics
  - Still little known about rejuvenation
  - There are advanced methods, but not applicable
- What about Balance of Plant? No data available
  - Compressors are the first thing to break in an FCS!

Attracting attention
at the highest levels!

Acknowledgements

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