A new load cycle and durability test procedure based on vehicle fleet data

Bernd Müller, Thomas Mittermeier, Thomas Hofmann (BMW Group)

Florian Wilhelm, Michael Schmid, Jürgen Hunger, Jürgen Kaczerowski (ZSW)

ID-FAST Final Workshop

16th December 2021
Online in the Framework of the EFC21

Realistic PEM Fuel Cell Drive Cycle Development

Outline

- Boundaries for drive cycle development
- BMW requirements
- Development of „ID FAST DLC“
- Summary and conclusions of part I

Drive Cycle Development. Boundaries.

Degradation caused by

Unavoidable stressors:

Load cycle
- Operation at various (load) conditions
- Transitions between (load) conditions
- Idle times (involve operation strategy)

Modular stress tests
- Controlled on/off "short shut downs" (H_2 still present)
- Cold/freeze starts (involve operation strategy)
- Mechanical stress (shock, vibration, etc.)
- Climatic stress

Not considered here

Drive cycle

Avoidable stressors:

Modular stress tests
- H_2/air fronts "long shut downs" – anode under air
- Fuel starvation (local and gross)
- Flooding

Drive Cycle Development. Boundaries.

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For load cycle development: focus on load-triggered stress

Other stressors: modular ex-situ ASTs

Modular Specific Stress Tests.

In-Spec stressors:

- Controlled on/off
  "short shut downs" (H_2 still present)
- Cold/freeze starts
  (involve operation strategy)

Off-Spec stressors:

- H_2/air fronts
  "long shut downs" – anode under air
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- Flooding

Per h operation	Short shut-down	Cold/freeze start	H_2/air front	Cell reversal
Frequency:	1x / 0.5 h	1x / 5 h	1x / 250 h	1x / 1000 h
Data source:	BMW internal requirement	BMW internal requirement	From customer data, stop time >7 d	From BMW Demo fleet
Conditions / details:	H_2 in Anode, shut cathode, apply current	<100 mV_{cell} @ load TMC's rapid warm-up	Room temp., <0.5 s residence time	Always U_{min} > -0.2 V

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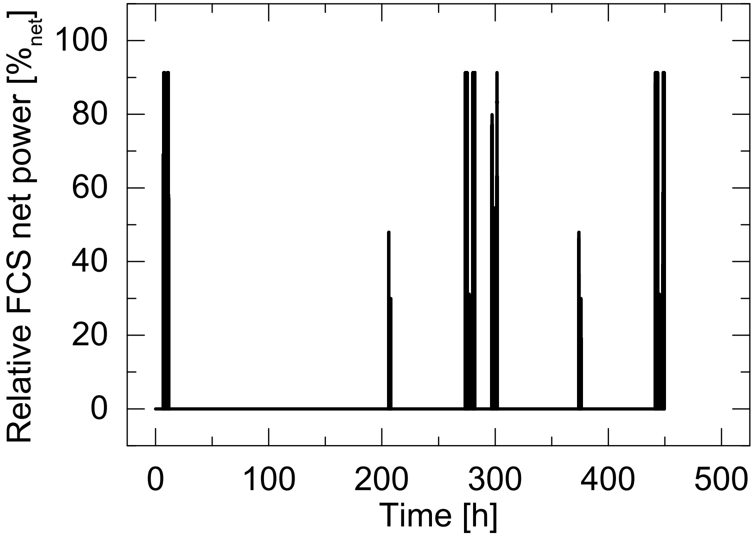
<-25°C	1x / 1200 h
-25 – -20°C	1x / 600 h
-20 – -15°C	1x / 120 h
-15 – -10°C	1x / 60 h
-10 – -5°C	1x / 15 h
-5 – 0°C	1x / 10 h

Total: 1x / 5 h

Operation States.

Proprietary 99% customer profile:



- From analysis of 1000’s h real drive data
- Relevant car-class (ICE) utilized
- Implicitly includes FCEV hybridization

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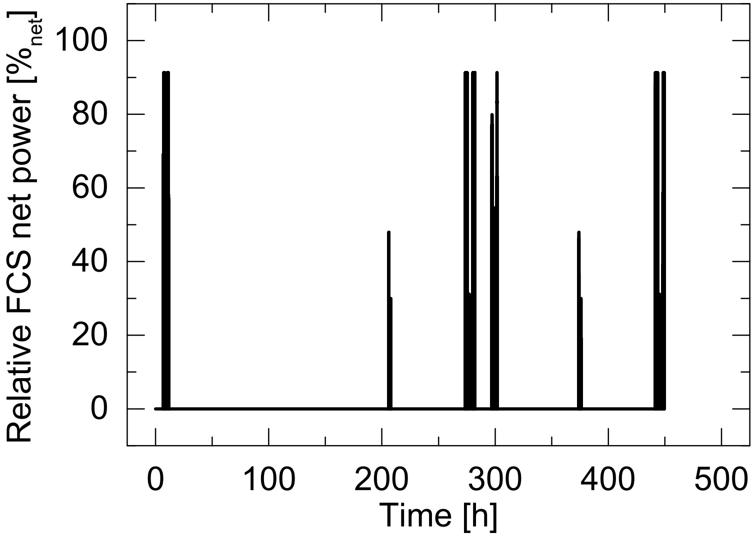
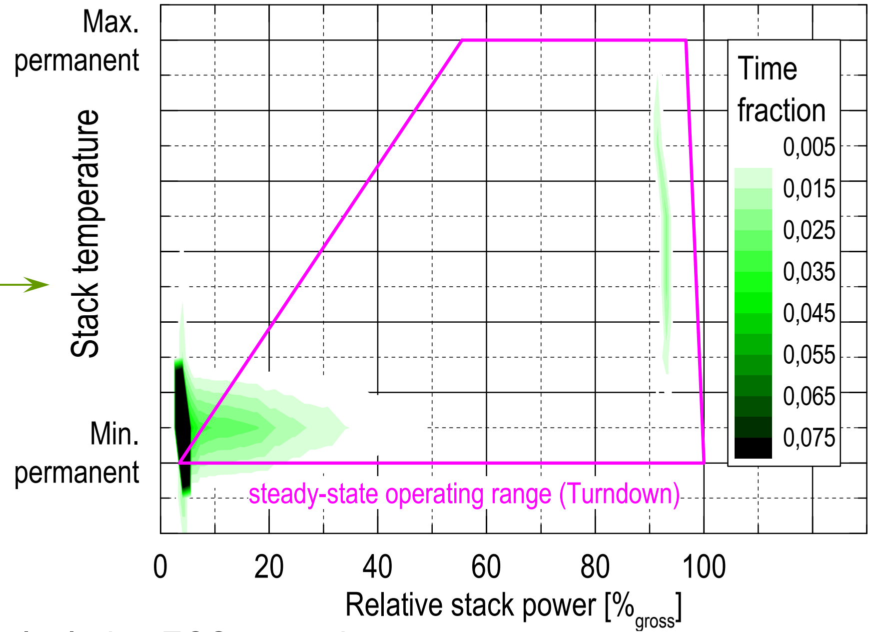


Evaluate time fractions

Operating map (Turndown):



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- Includes FCS operation strategy (each point is fully defined with operation parameters)

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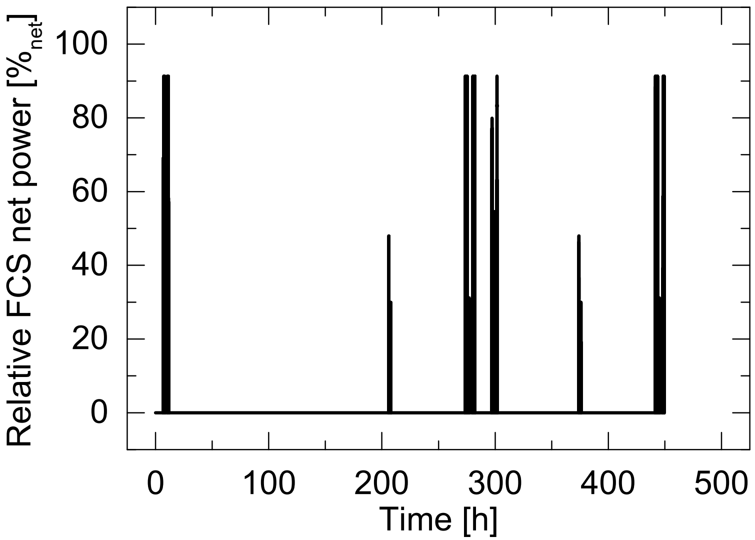

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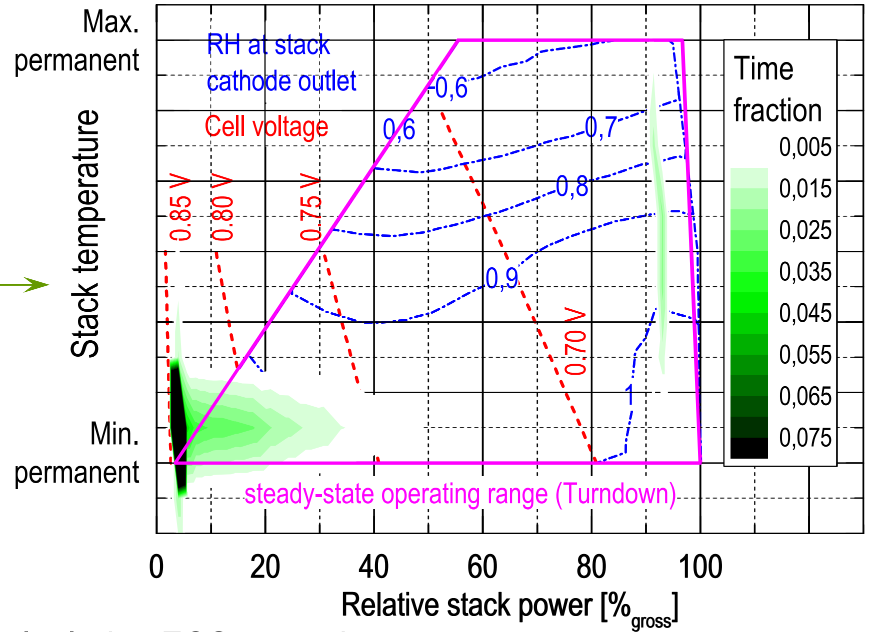


- From analysis of 1000's h real drive data
- Relevant car-class (ICE) utilized
- Implicitly includes FCEV hybridization

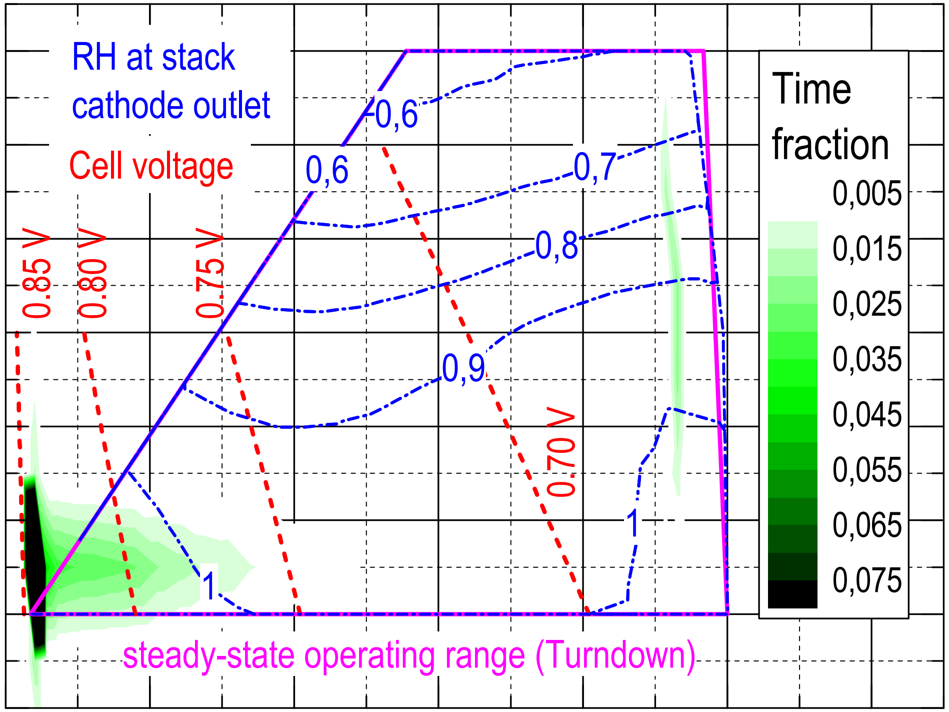
- Includes FCS operation strategy (each point is fully defined with operation parameters)
- Classify operation states according to
  - Cell voltage
  - Cathode outlet relative humidity (RH)

Next: Evaluate time fractions and transitions on cell voltage base

Load Cycle from Customer Data. Load Classification.

Voltage domains:

- Simplify equi-voltage lines by vertical lines
- Divide in load classes of ~50 mV equivalent



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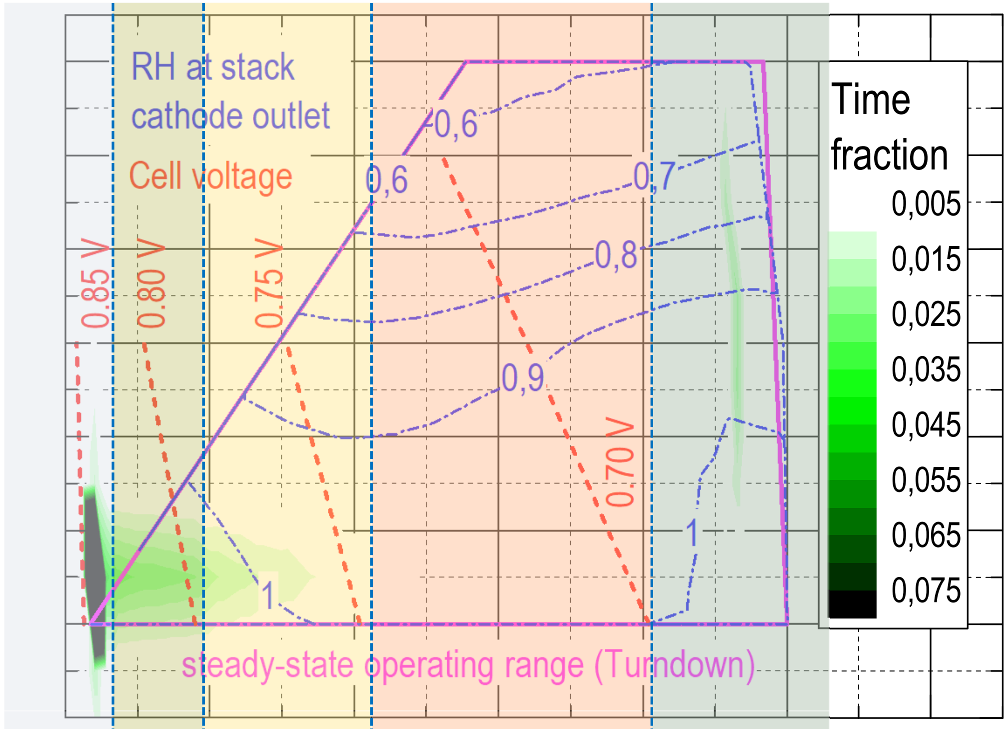


Power class:	<6.5	<19	<42	<81	≥81	$\%_{gross}$
Weighted center:	5.0	13	31	67	92	$\%_{gross}$
Time share:	50	18	11	8	13	%

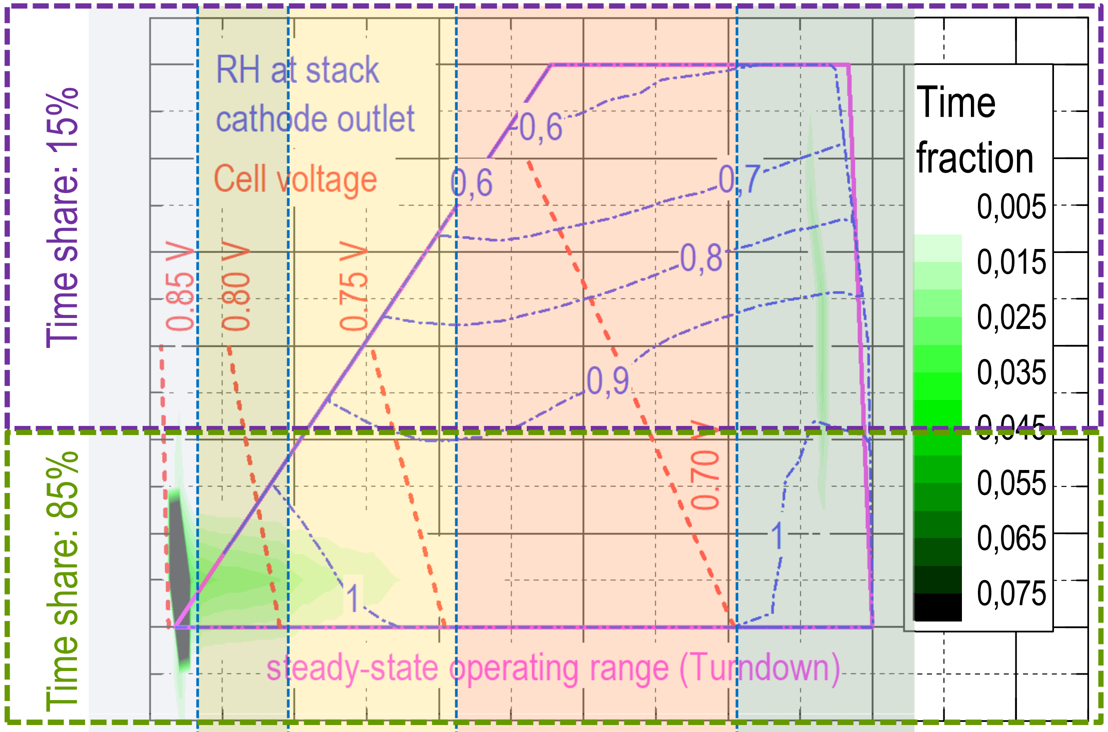
Load Cycle from Customer Data.
Load Classification.

Voltage domains:

- Simplify equi-voltage lines by vertical lines
- Divide in load classes of ~50 mV equivalent

Temperature / RH domains:

- Simplify equi-RH lines by horizontal lines
- Divide in two temperature domains
  → corresponds to wet / dry region



Transitions between load classes?

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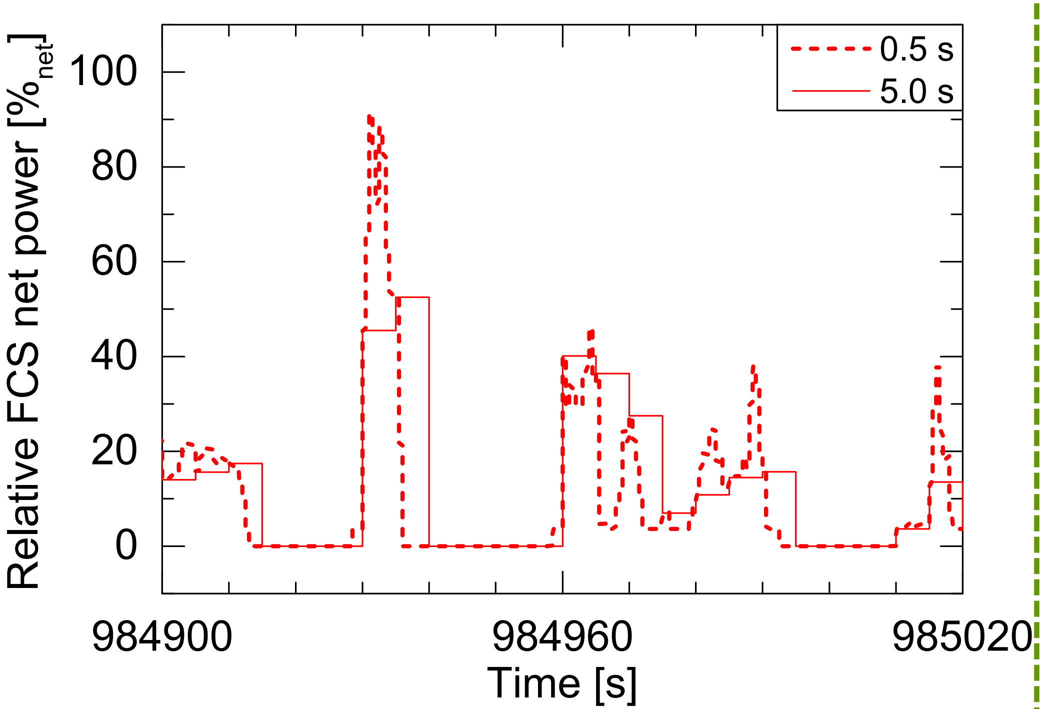
Load Cycle from Customer Data.
Load Class Transitions.

Excerpt of raw customer drive dataset:



- Time resolution determines accountable transitions between load classes
- At smaller time resolution: more transitions

Load Cycle from Customer Data. Load Class Transitions.

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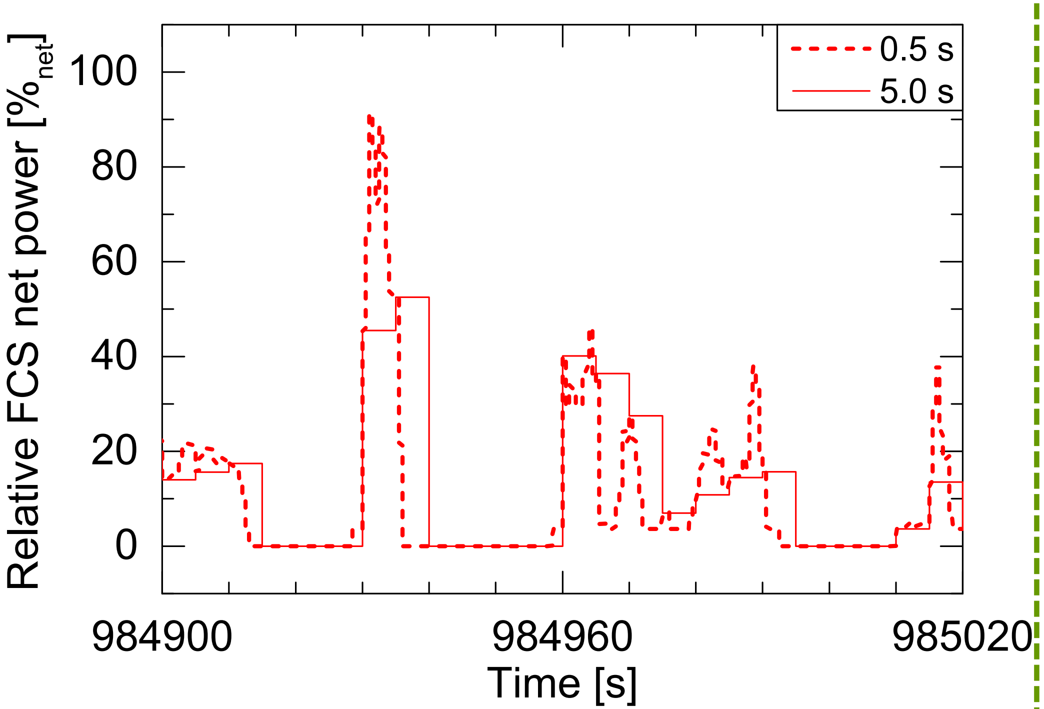

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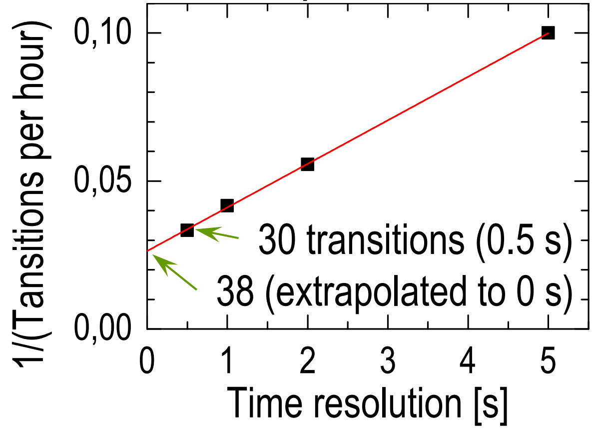
Sum over all transitions per hour:



- Extrapolation to 0: ~25% more transitions than for 0.5 s resolution
- Unclear: distribution – from where to where?
- ➢ Best guess: 0.5 s resolution x 38/30

Load Cycle from Customer Data. Load Class Transitions.

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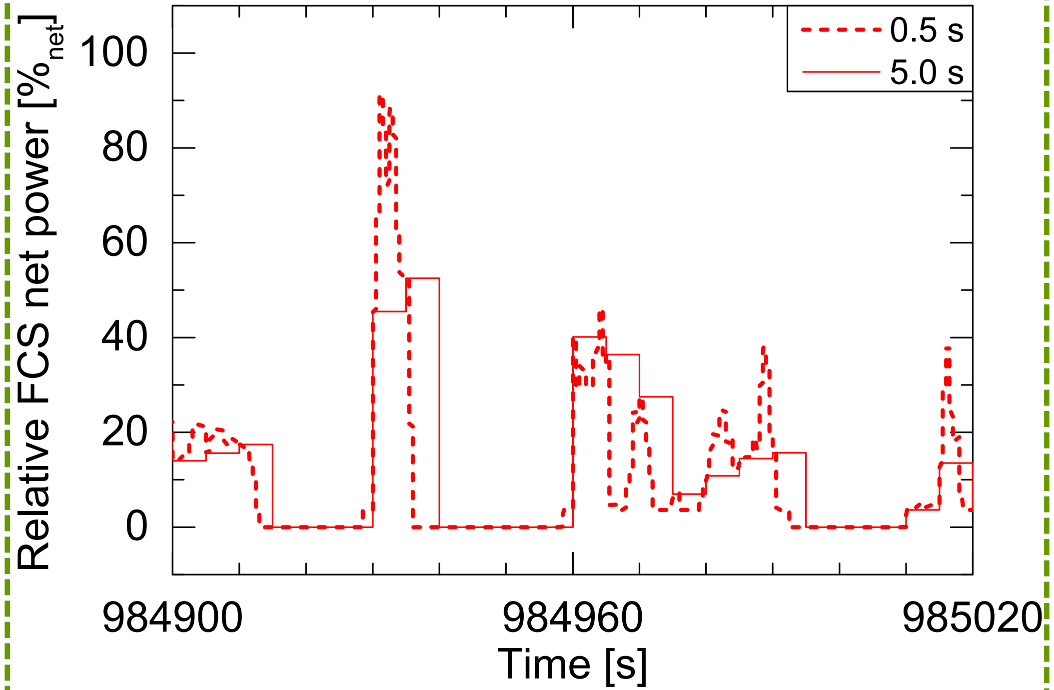

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Timefractions & transitions known.
Next: load cycle

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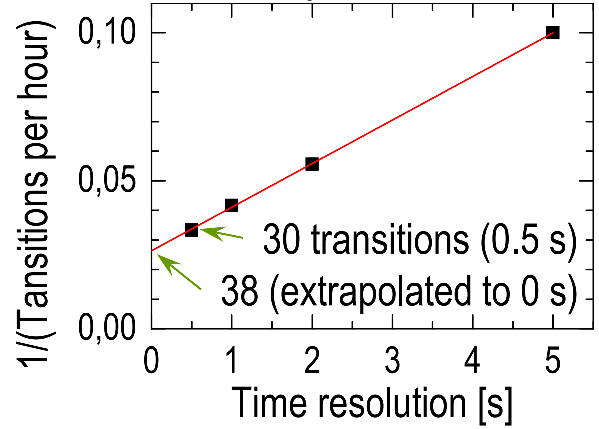

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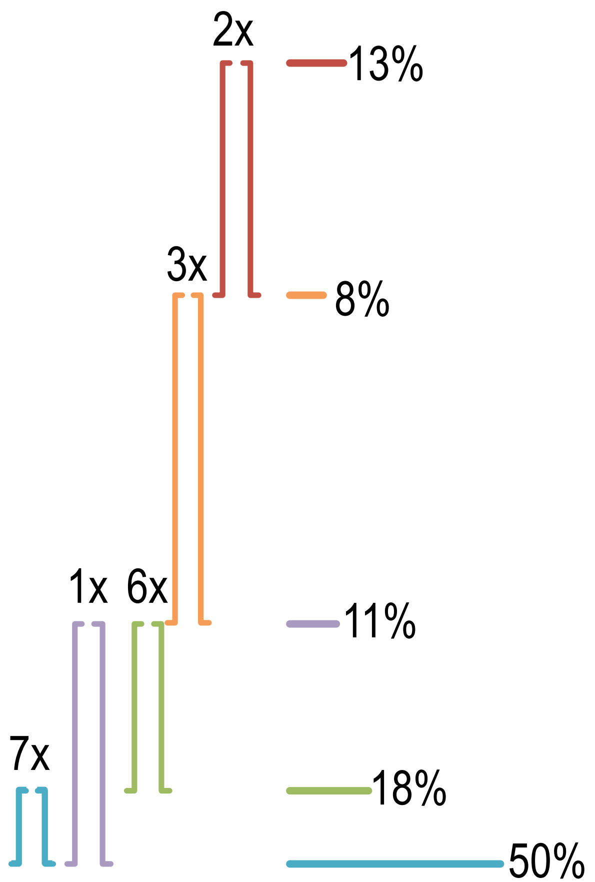
Stack power transitions per hour (0.5 s resolution) x 38/30:

from [%gross] \ to [%gross]	<6.5	<19	<42	<81	≥81
<6.5		7	1	0	0
<19	7		6	0	0
<42	1	6		3	0
<81	0	0	3		2
≥81	0	0	0	2	

Load Cycle from Customer Data.

Transitions & steady-state distribution:



- Not unique:
  - Order of transitions
  - Distribution of steady-state phases

Source: Thomas Mittermeier, Bernd Müller et al. (BMW); text available as part of the public ID-FAST deliverable report “D4.3–Analysis of coupling between mechanisms and definition of combined ASTs” (http://www.id-fast.eu).

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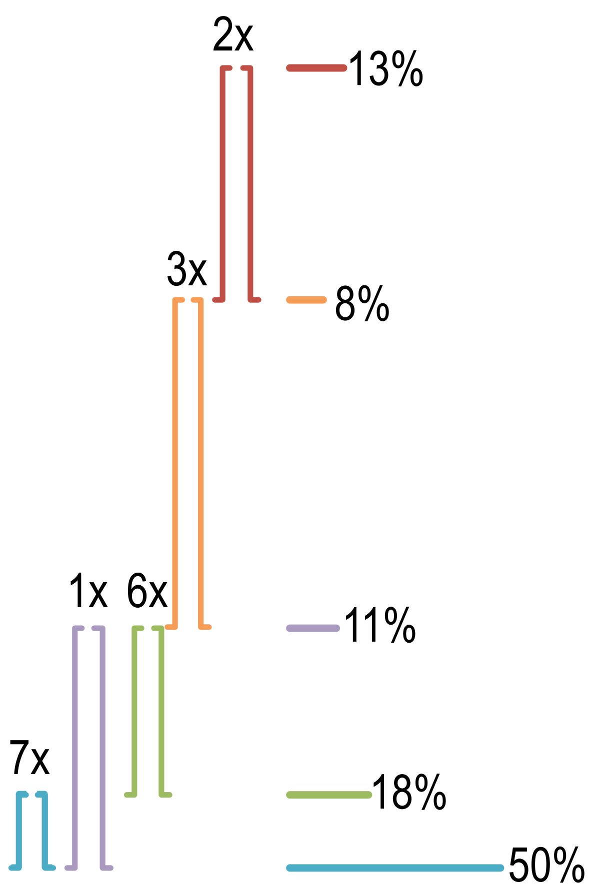
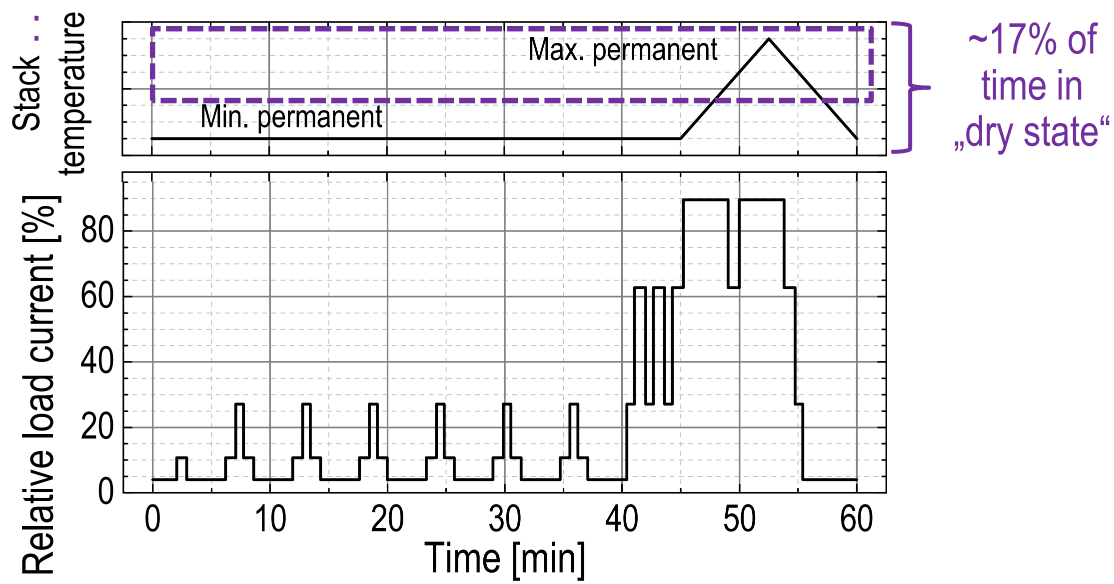


- Not unique:
  - Order of transitions
  - Distribution of steady-state phases
- Temperature/RH domains: considered via thermal cycle at high load
- Best guess:
  - Even distribution of steady-state periods
  - One thermal cycle

Proposed load cycle „ID-FAST DLC“



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Summary (I)

- ❑ Load cycle (“ID FAST DLC”) defined*
  - Load case distribution
  - Load transitions
  - Temperature / RH variation
- ❑ “short shut-down” defined
- ❑ Cold/freeze start requirements
- ❑ “long shut-down” requirements
- ❑ Cell reversal requirements

=> Complete ID FAST durability test program is defined

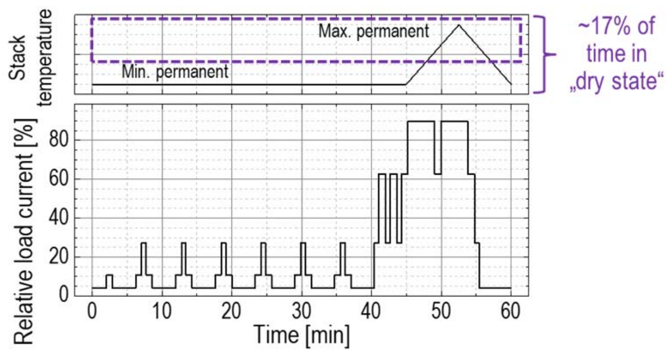
* Actual implementation may be not straightforward, depending on testbench and stack hardware

Implementation and practical application

Motivation

- How to implement the ID-FAST DLC (dynamic load cycle) into a realistic durability test program
  - **Auxiliary modules**
  - **Incorporation of in-spec and selected off-spec stressors**
  - **Addition of in-situ analysis modules**
- Practical application (example PowerCell S3 short stack)
  - **Consideration of applicable definition of operating conditions**
  - **Adjustment of gas pressure values**
  - **Temperature & RH control**
  - **Modifications to obtain stable & reproducible performance data**

Appropriate implementation *is* **depending on stack hardware!**



Auxiliary modules, stressor modules

Required definitions:

- **Start-up**
- **Shut-down**
- **Break-in**
- **Short stop**
- **Cold soak**
- **Long stop including air/air start (“anode reactivation”)**
- **Conditioning**
- **Polarization curve**
- **…**

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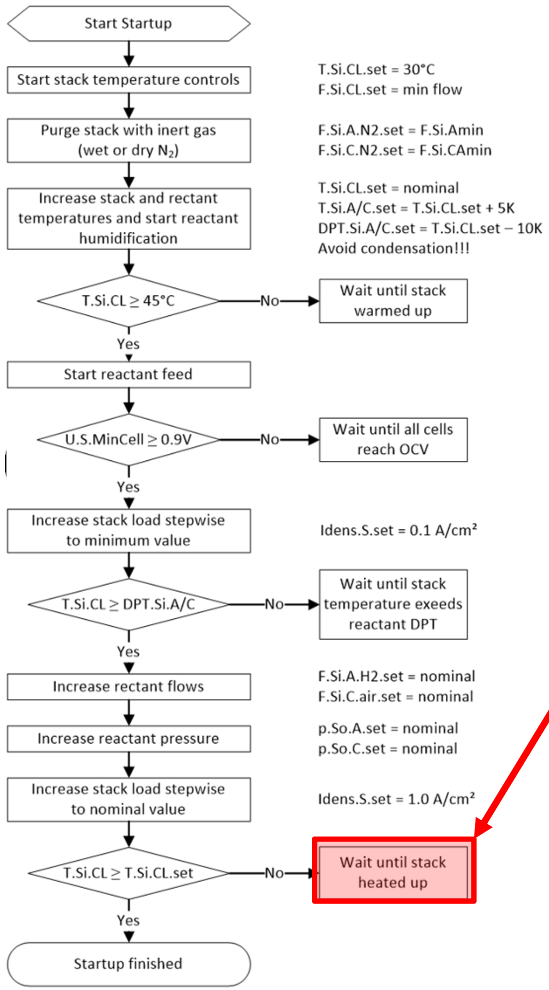

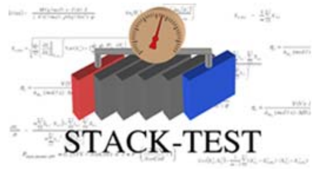

Active or passive heating?

Auxiliary modules, stressor modules

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- **Conditioning**
- **Polarization curve**
- **…**

Appropriate implementation *is* **depending on stack hardware and even cell count!**

Generic templates for these modules resulting from the STACK-TEST project (FCH-JU) can be found at http://stacktest.zsw-bw.de/

Incorporation of in-spec and selected off-spec stressors

- In-Spec stressors
  - **Short stops**

- Reduce electric load & gas flows to minimum values (voltage clipping)
- Reduce gas pressures to ambient
- Turn off the oxidant flow, keeping the minimum fuel flow until the mean cell voltage drops below 0.2 V.
- Turn off the electric load
- Remain in this state for 5 minutes, no cooling down

- Off-Spec stressors
  - **Air/air start (“anode reactivation”, “H_2/air front”)**
    - Implementation not trivial, safety aspects!
    - Deviating implementations will possibly give significantly different results

Air/air start (induced by diffusion):
mimics the situation that a car is left in shutdown state without being started for a long time (several days/weeks), so diffusion will lead to a **significant concentration of oxygen on the anode side**

- In **cold** state (25°C)!
- Anode under N_2, without gas flow
- Purge cathode with air
- Stop air flow, wait for *N* minutes.
- Perform startup procedure

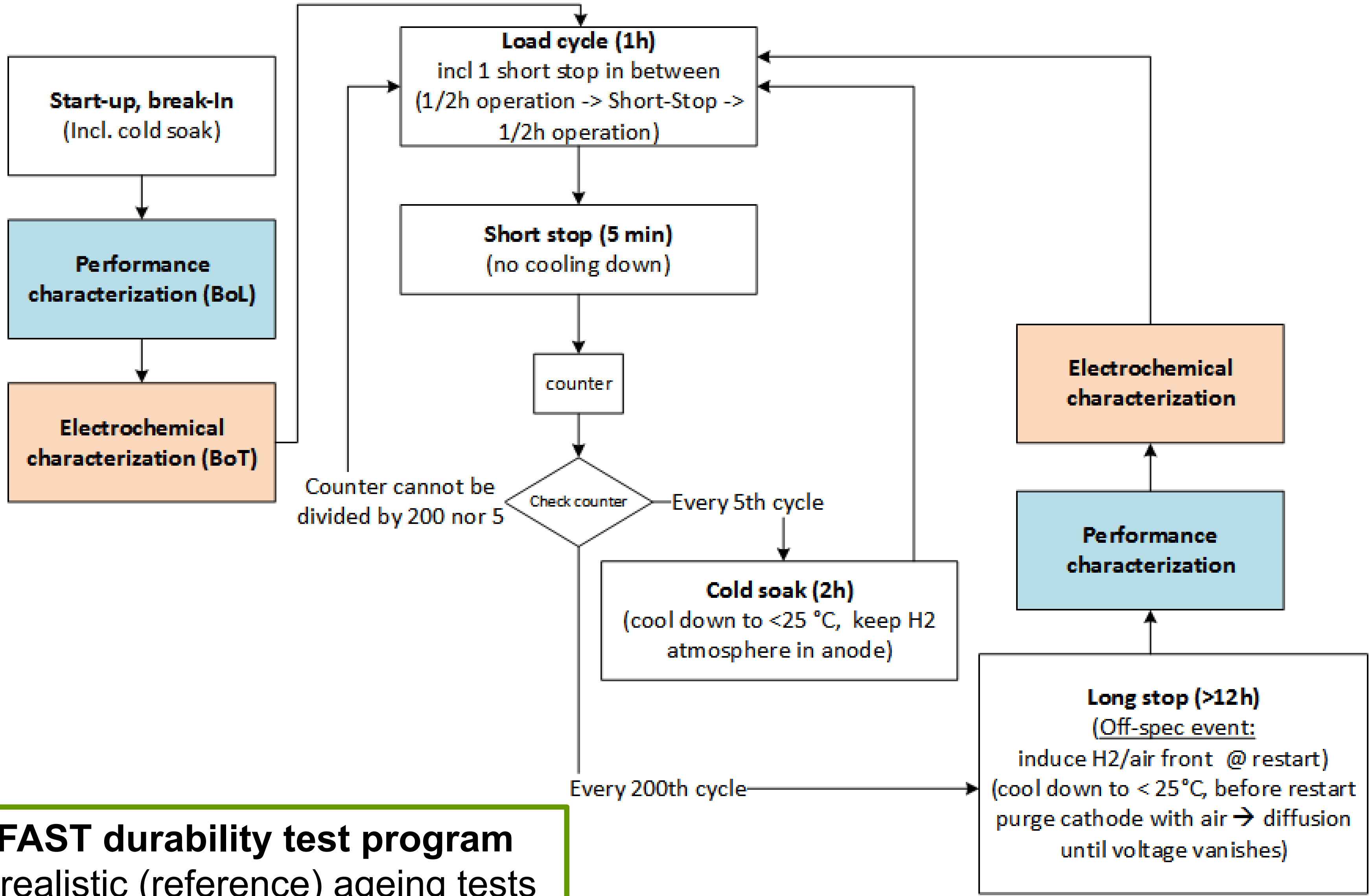
Analysis modules

- Performance characterization
  - **Polarization curves under 4 reference conditions:**
    - AUTOSTACK Core
    - EU Harmonized
    - INSPIRE
    - ID-FAST

Parameter	EU Harmonized	ID-FAST
Temp. coolant in	80°C	68°C
Gas inlet dewpoint A/C	64 / 53°C	58 / 43°C
Stoichiometry A/C*	1.3 / 1.5	1.4 / 1.6
Gas outlet pressure A/C	250 / 230 kPaabs	300 / 280 kPaabs
	inlet pressure	outlet pressure (const.)
Minimum current density for stoichiometry	0.2 A/cm²	0.2 A/cm²
Gas composition A	Pure H2 5.0 quality	90% H2 / 10% N2

  - **4 FC-DLC cycles (harmonized fuel cell dynamic load cycle) for each set of conditions**
- Electrochemical characterization
  - **CV** (Electrochemically Active Surface Area)
  - **EIS** (high frequency, mass transport and charge transfer resistances)
  - …

Combining them all …



ID-FAST durability test program
for realistic (reference) ageing tests

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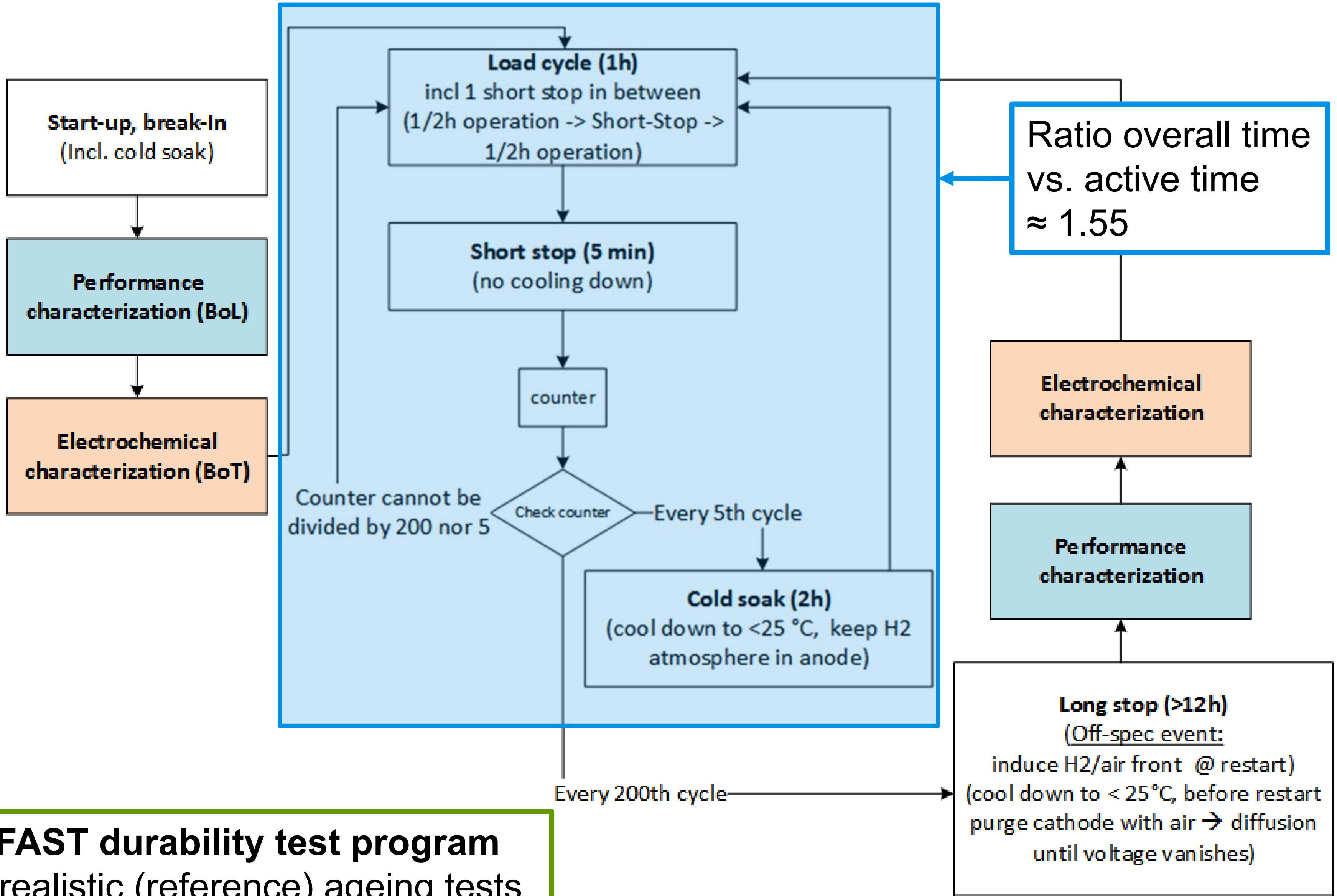


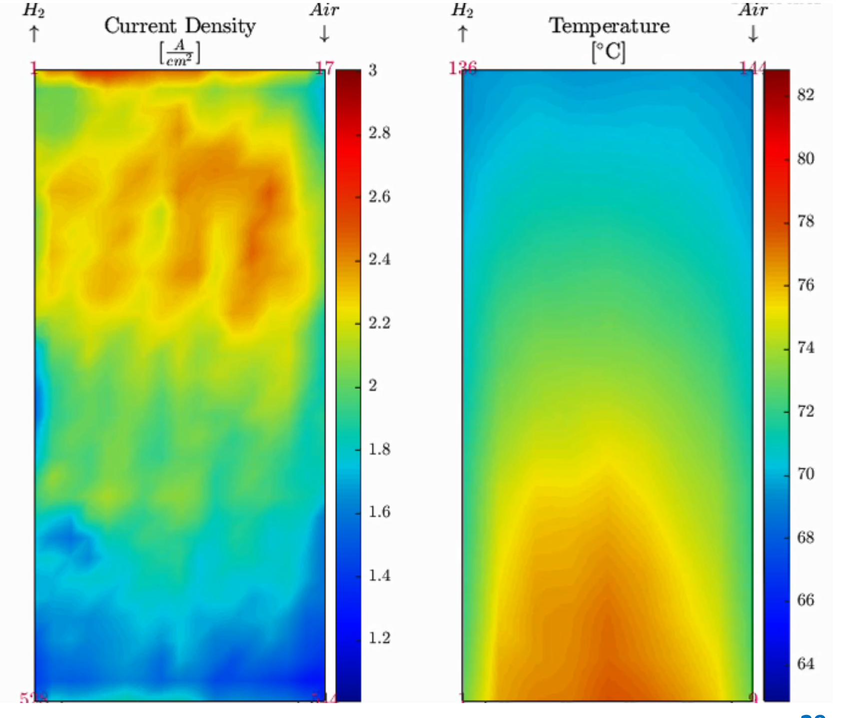
ID-FAST durability test program
for realistic (reference) ageing tests

Practical application (example PowerCell S3 short stack)

- ❑ Determine 100% load point depending on stack hardware
  - **For S3 stack under ID-FAST conditions 1.9 A/cm²**
- ❑ Determine maximum allowable temperature at coolant outlet for “hot” operating conditions / max. load, not to exceed maximum temperature @membrane, maximum ΔT

Example current scan shunt data for S3 stack, appropriate modelling may be required in addition to assess temperature difference active area → bipolar plate

Pressurized coolant sub-system may be necessary for testbench to avoid formation of steam bubbles!



Practical application (example PowerCell S3 short stack)

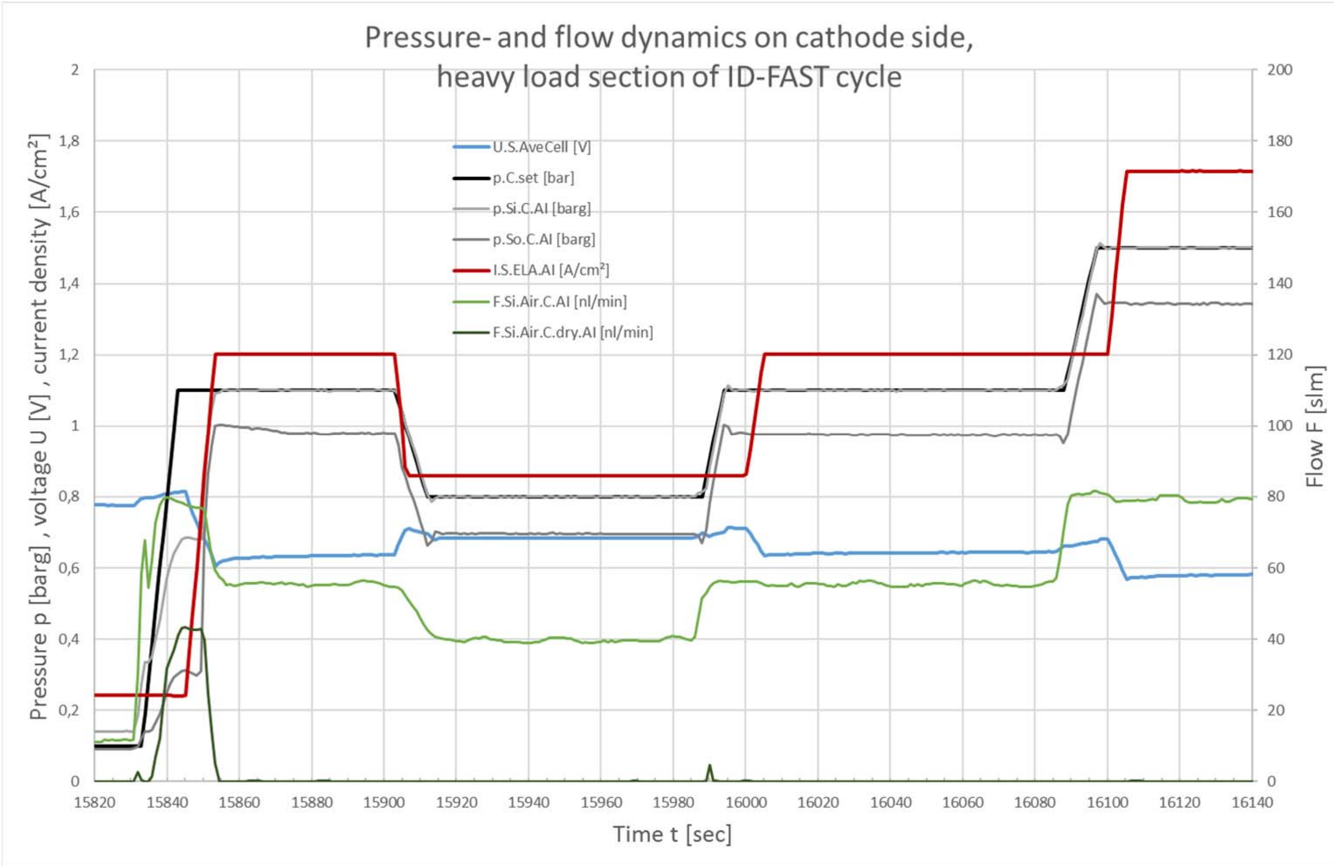
- Mimic system behaviour: define adapted pressure / dew point / temperature as a function of load level

Conditions for load cycle:								
	unit			**cold**			**hot**	
Performance								
Current Fraction	**%**	**5**	**13**	**31**	**67**	**92**	**92**	**67**
Current density	A/cm2	0,095	0,247	0,589	1,273	1,748	1,748	1,273
Coolant								
Temp. coolant out	°C	74	74	74	74	74	93	93
Anode								
Pressure stack out anode	bara	1,90	1,90	2,00	2,75	3,00	3,00	2,75
Dew point anode	°C	58	58	58	58	58	72	72
Cathode								
Pressure stack cathode out	bara	1,40	1,40	1,52	2,48	2,80	2,80	2,48
Dew point cathode	°C	43	43	43	43	43	57	57

* Minimum gas flow corresponding to 0.2 A/cm^2
Remark: Delta T coolant outlet 19K (cold-hot), coolant inlet at cathode inlet, anode in counterflow configuration
100% load = 1,9 A/cm^2

Practical application (example PowerCell S3 short stack)

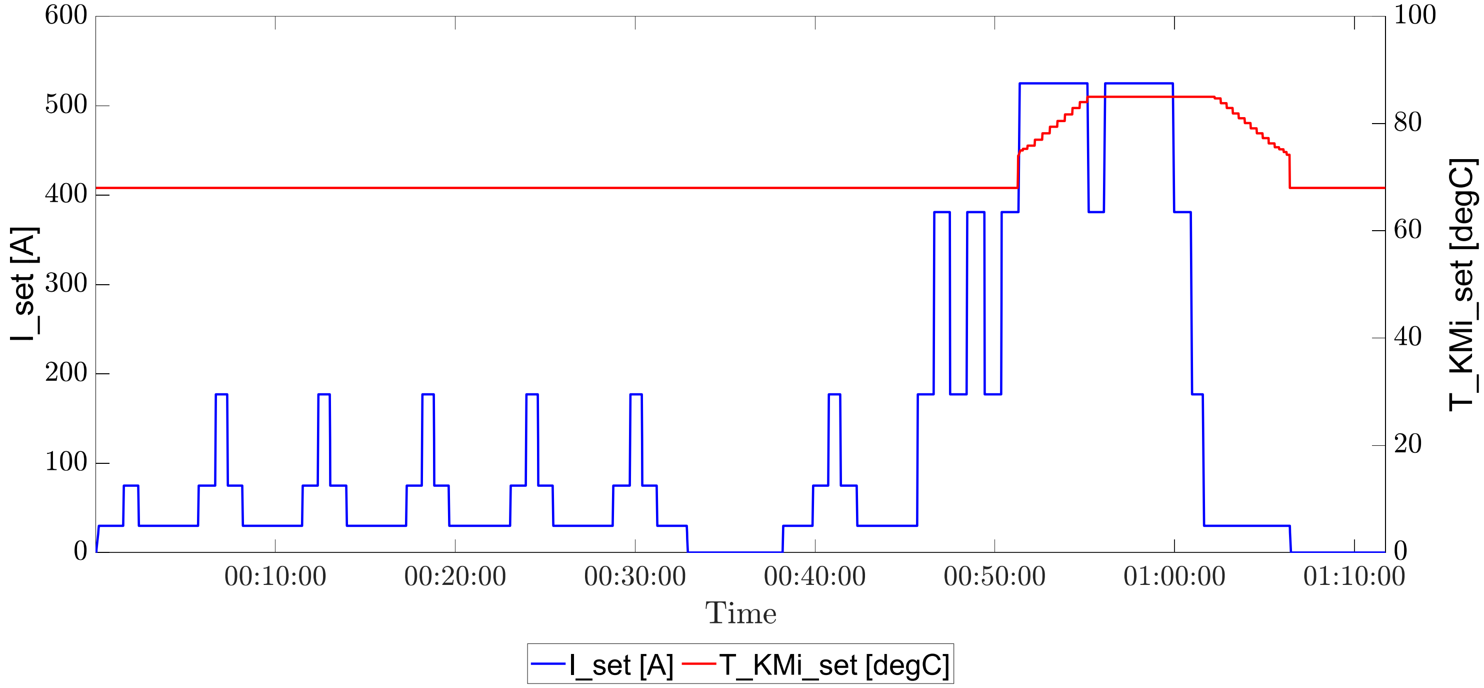
- ❑ Challenge: appropriate dynamic adaption of pressure levels during load cycle



- Fast adaption of pressure levels, pilot time of ~15 sec needed
- Specific control algorithm to avoid overshooting *and* ensure fast adaption

Practical application (example PowerCell S3 short stack)

- ❑ Challenge: appropriate dynamic adaption of temperature & RH during load cycle
- ❑ First implementation of temperature ramps featuring steps instead of a smooth transition
  - **Related to restrictions of test bench controls**



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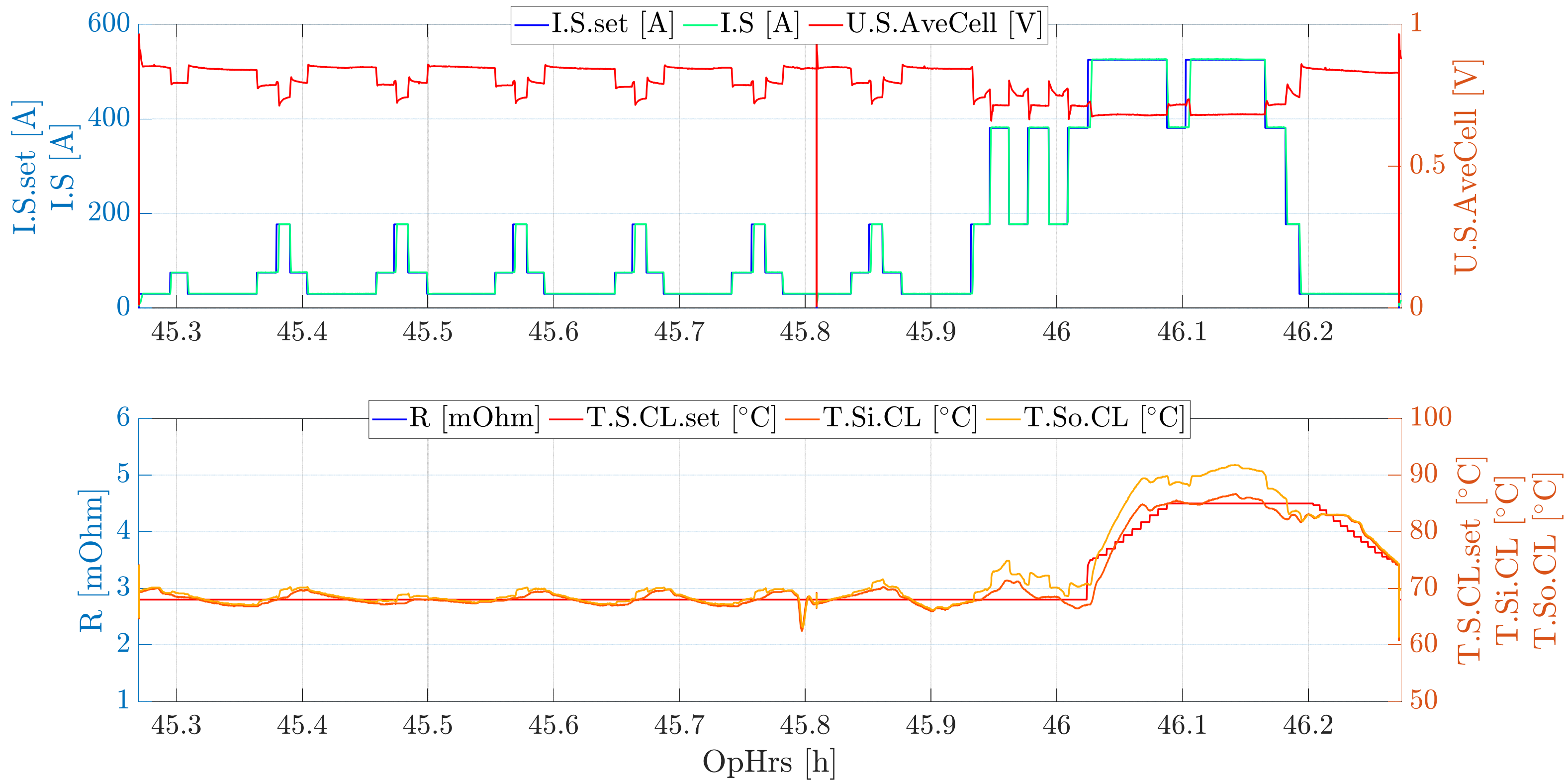

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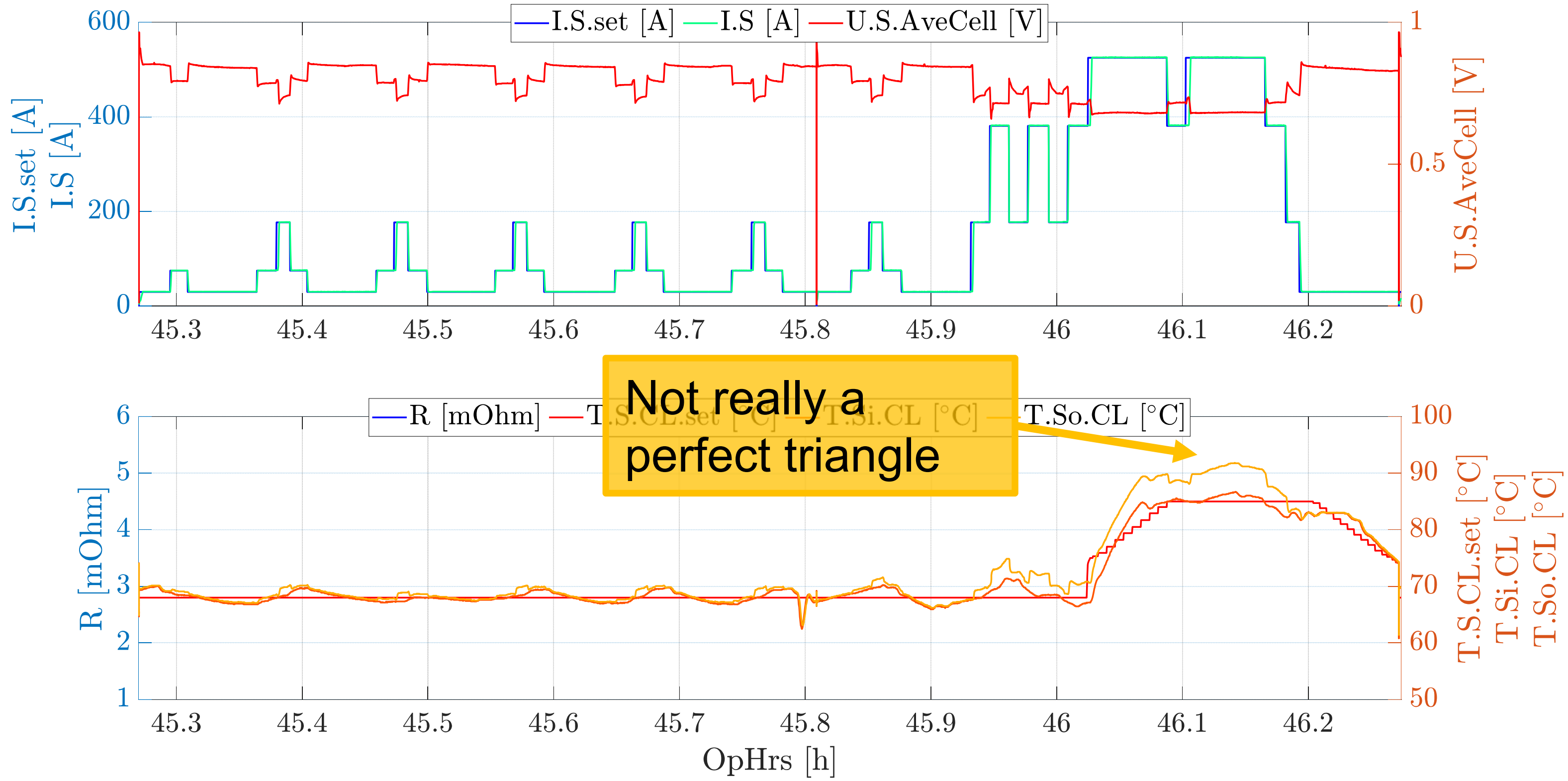
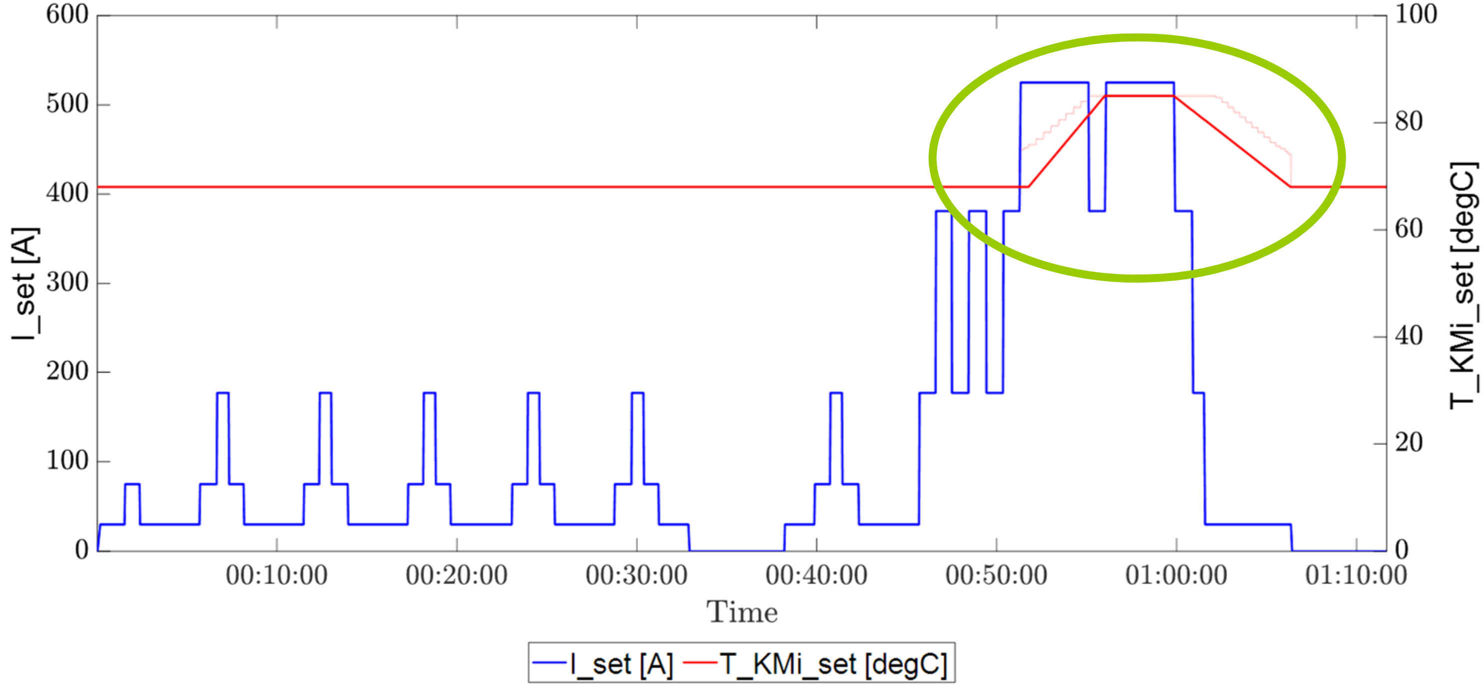


Practical application (example PowerCell S3 short stack)

- Second implementation of load cycle featuring a smooth temperature ramp and adapted dwell times (improved controls)



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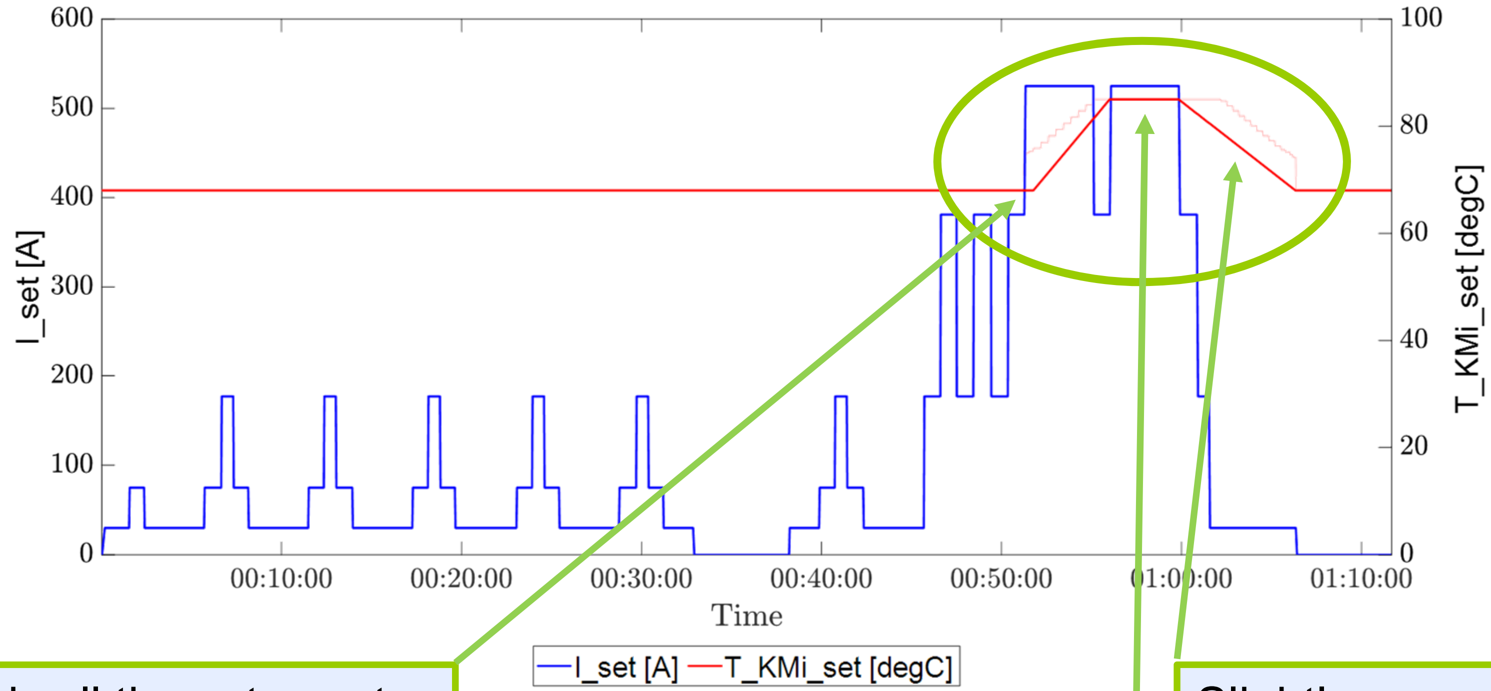

Short dwell time at const. T nominal → stabilized voltage@highest load for analysis

Dwell time at const. T max → stabilized voltage@highest load for analysis

Slightly asymmetric to maintain same duration

Practical application (example PowerCell S3 short stack)

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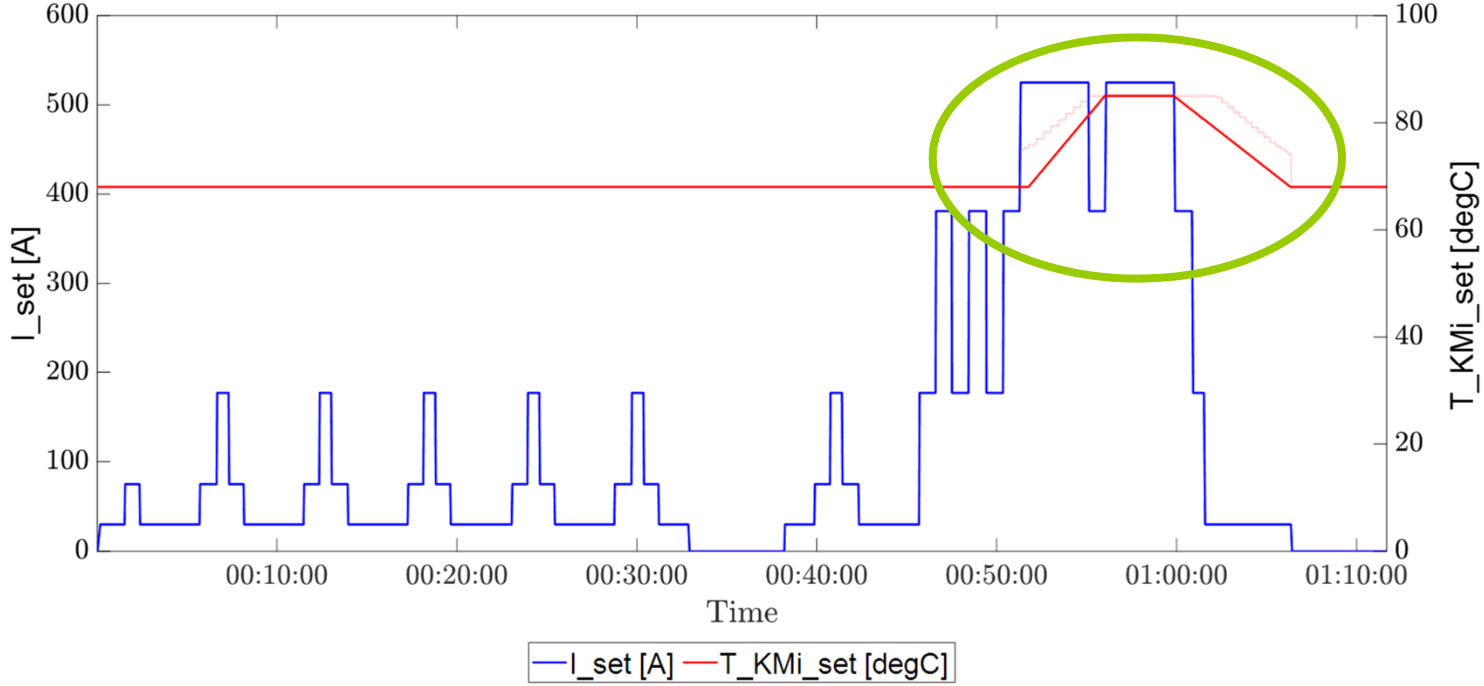

- Similar challenge for RH/dewpoint controls

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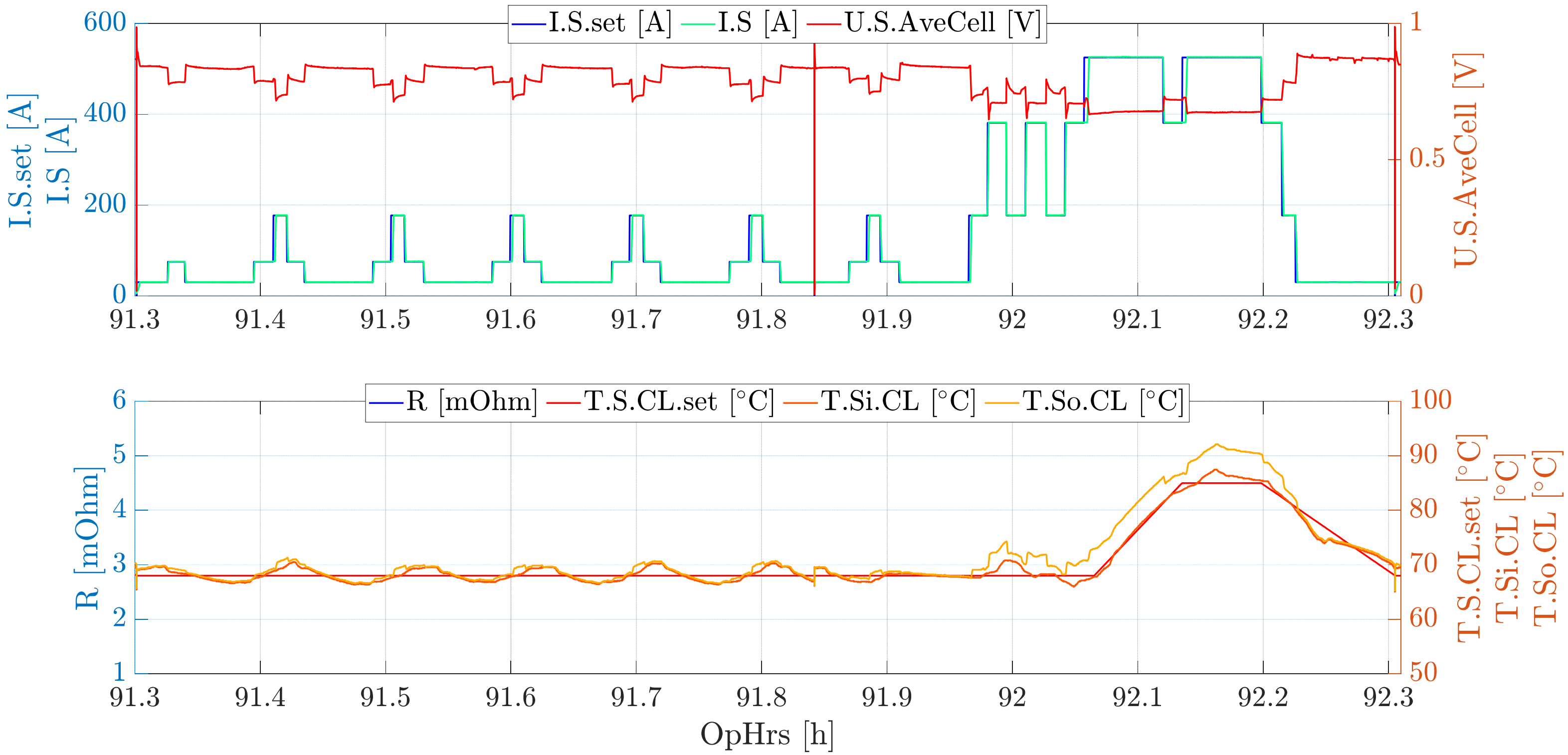

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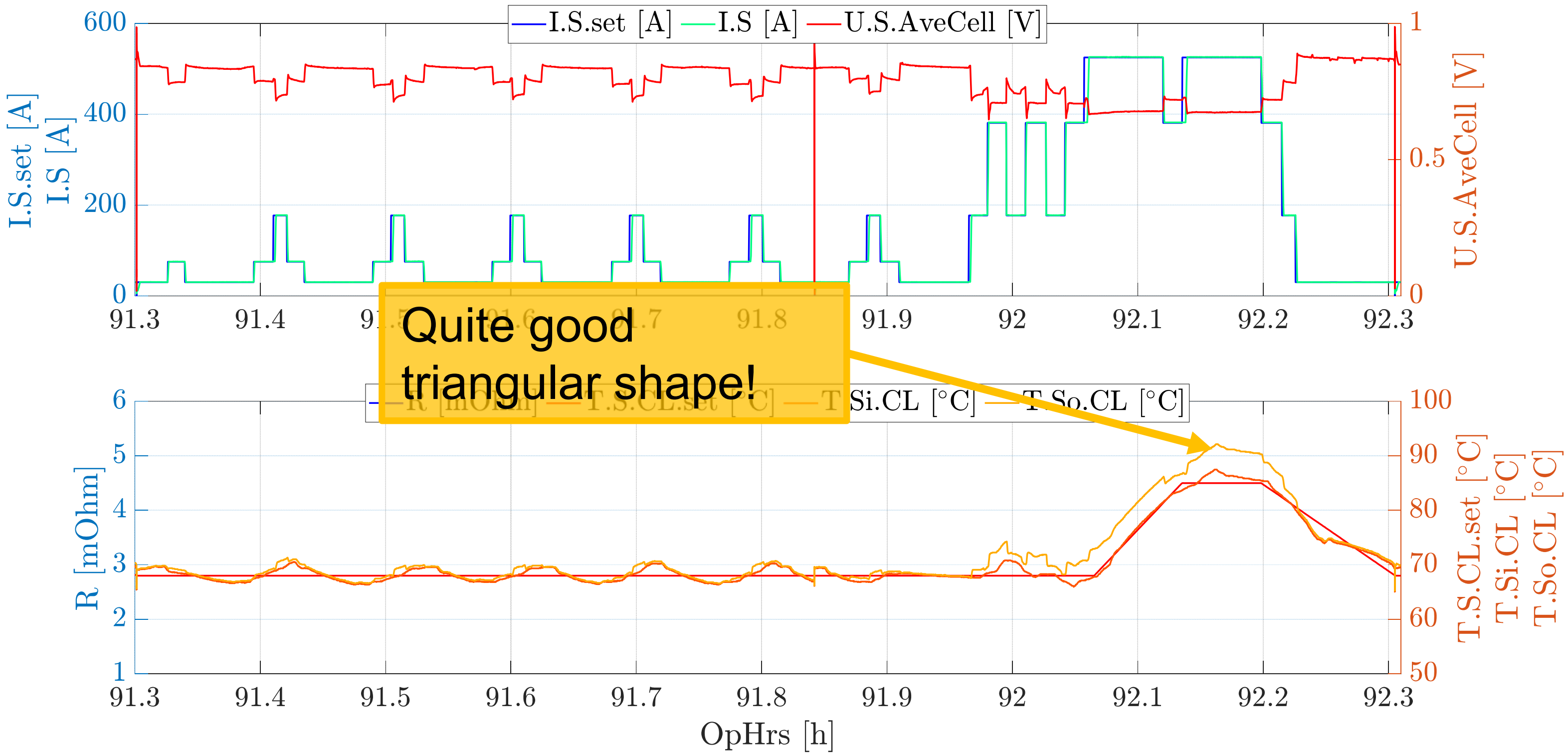

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ID-FAST

Summary (II)

- Methodology applied is general and can be transferred to other cases / applications
- Adaption to the stack hardware employed is necessary
- It may be a long way between finalizing the definitions (DLC, additional stressor modules) and the actual application in a feasible & realistic durability test program
- Definitions and application done for the
  - **ID-FAST durability test program**
  - **For two sets of stack hardware (PowerCell S3 & CEA F design), cf. presentation later this afternoon for results**
  - **For single cells (segmented POLIMI cell and 25 cm^2 CEA cell for stoichiometric operation, zero-gradient cells), cf. presentation later this afternoon for results**
- Realistic basis for AST development
  - **Intention: AST implementation should be as straightforward as possible (SC & stack)**

Acknowledgements

ID-FAST

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under the European Union's Horizon 2020 research and innovation program under grant agreement No. 779565.

THANK YOU FOR YOUR ATTENTION