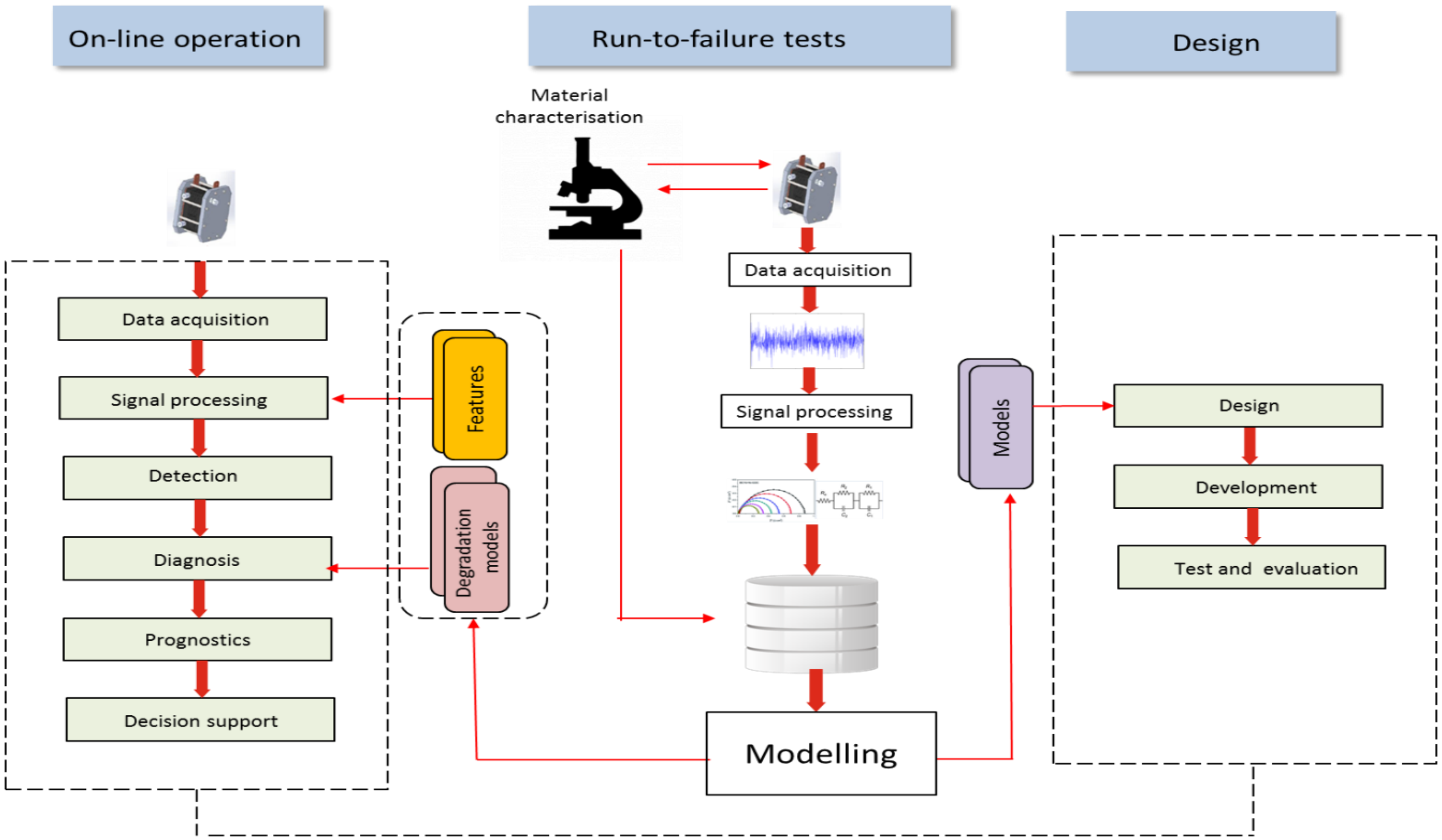
Project **RUBY**

Robust and reliable general management tool for performance and durability improvement of fuel cell stationary units

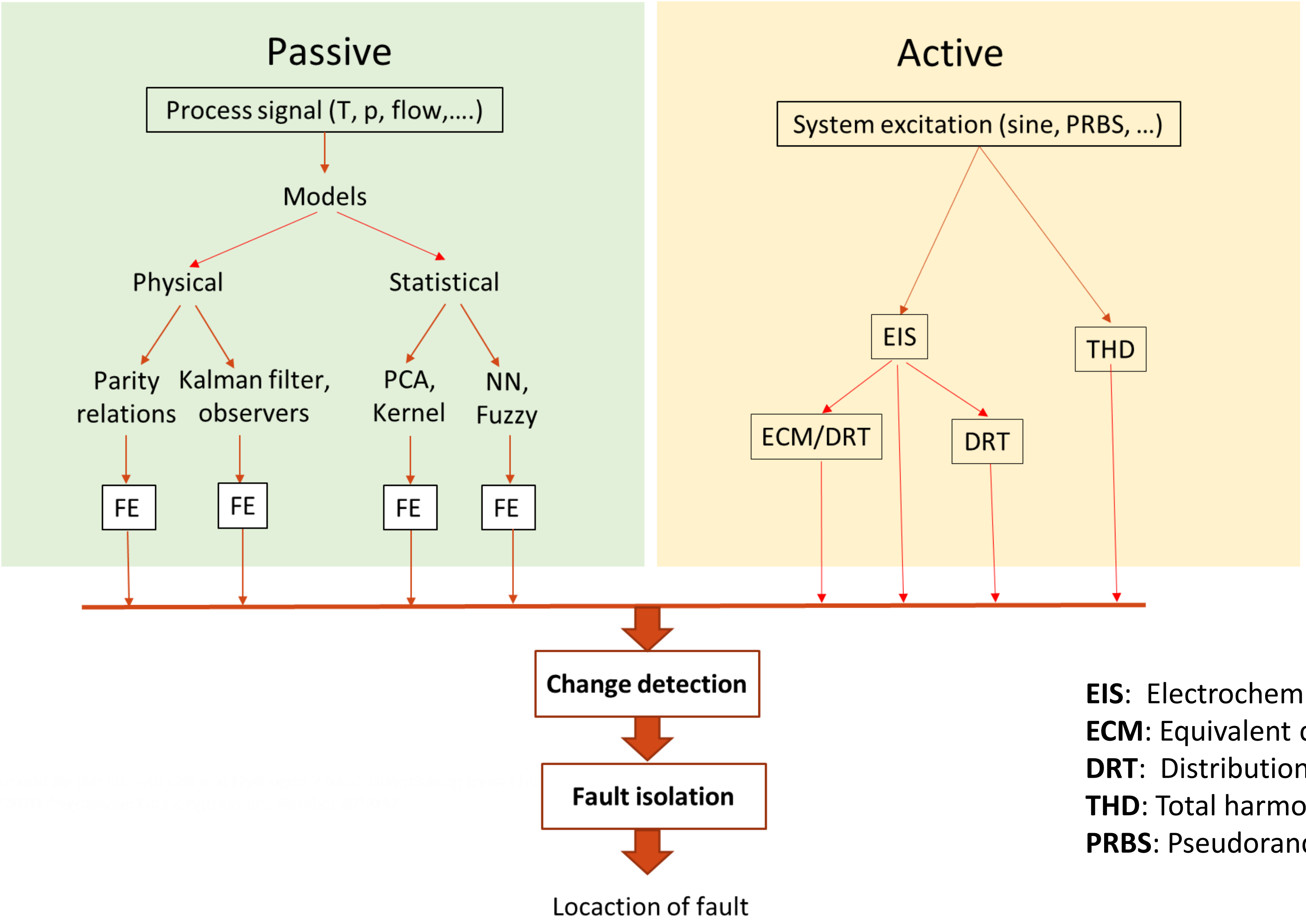
ACTIVE AND PASSIVE DIAGNOSIS OF SOFC CELLS AND STACKS

Framework



Funded by the EU Fuel Cell and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) –
H2020 Programme Grant Agreement Number 875047

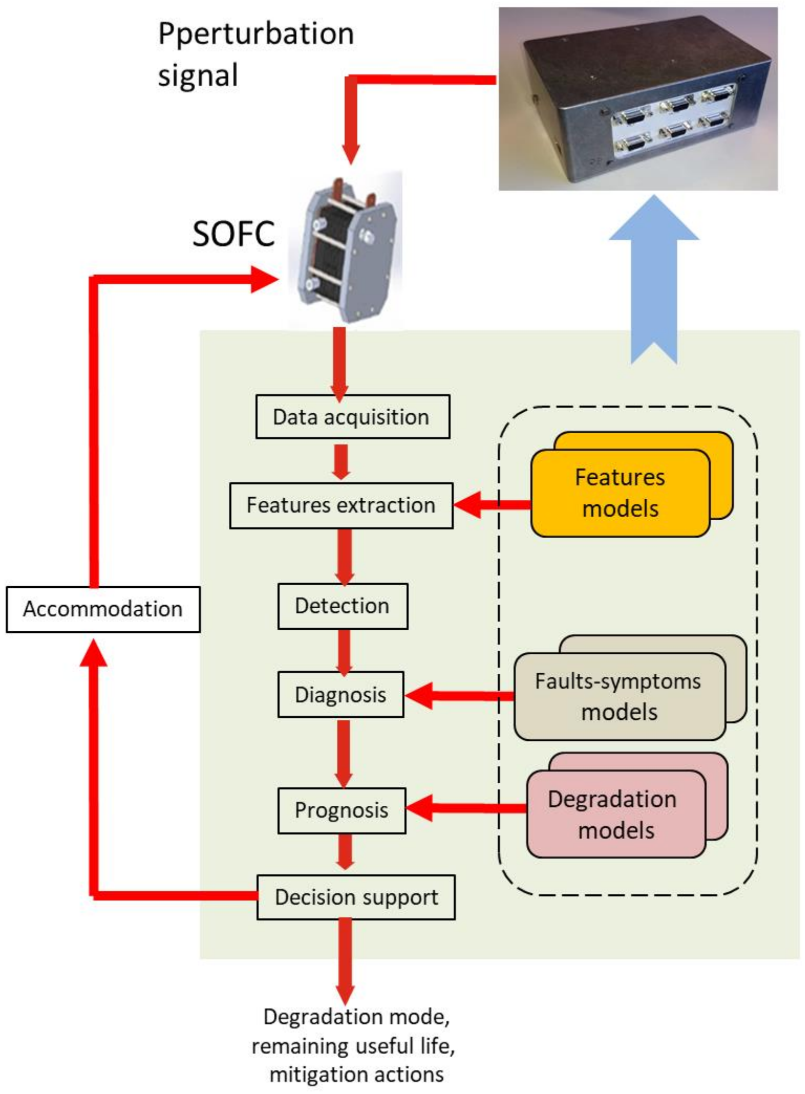
Passive and active diagnosis



EIS: Electrochemical impedance spectrum
ECM: Equivalent circuit model
DRT: Distribution of relaxation times
THD: Total harmonic distortion
PRBS: Pseudorandom binary signal

Funded by the EU Fuel Cell and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) –
H2020 Programme Grant Agreement Number 875047

Active diagnosis: objectives



- Develop fault detection and isolation (FDI) algorithms for stack diagnostics, to be embedded in the HW;
- Exploit EIS, THD and dynamic stack perturbation together with model- and signal-based approaches for features (metrics) extraction ;
- Use knowledge-based approach to derive Fault-Signature Matrix as the link between metrics and faults ;
- Identify features for fault/degradation mitigation for future implementation.
- Provide unified diagnostic framework for active and passive diagnosis

Funded by the EU Fuel Cell and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) –
H2020 Programme Grant Agreement Number 875047

Fast EIS: perturbation by means of DRBS

Rationale:

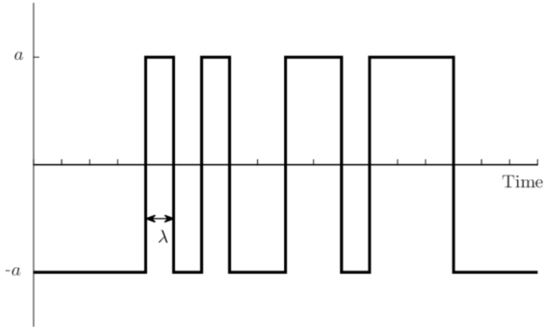
- EIS at low frequencies takes prohibitively long times!
- how to assure stable conditions?

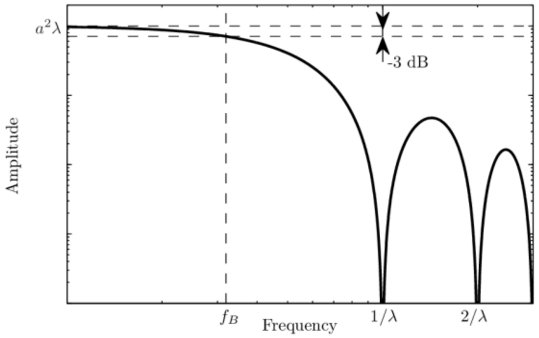
For example …..

- measurement time for **one point** on EIS curve at f=10 μHztakes ≈ 10.000s ≈ **2h47min**
- scan from **1mHz to 1kHz**, 61 frequencies, ecquidistant on log scale is ≈ **2h47min**
- scan **1Hz to 1MHz**, 61 frequencies, equidistant on log scale is ≈ **7min**

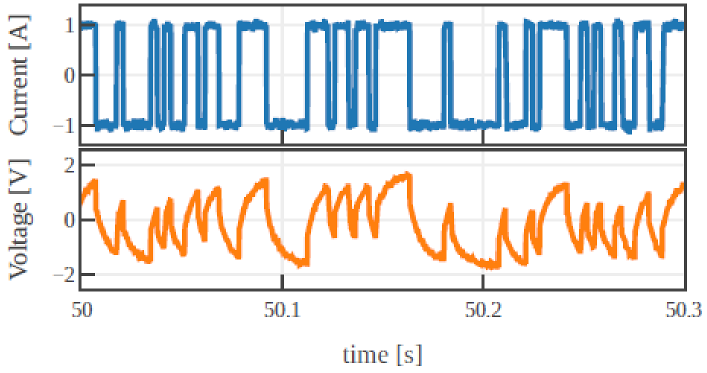
System perturbation with PRBS:

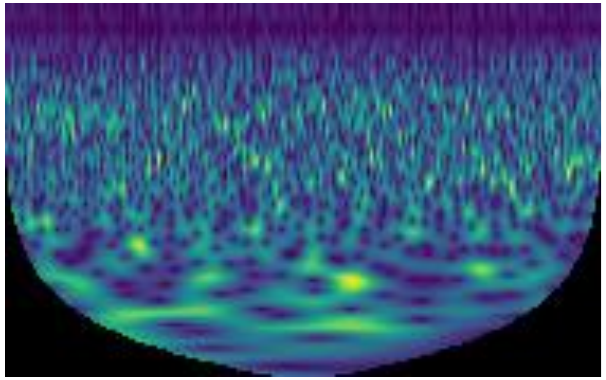
- Limited signal amplitude ⇒ guaranteed excitation of linear mode of SOFC operation;
- Almost flat power spectrum;
- EIS characteristic is evaluated on a continuous frequency interval, while with (multi/mono) sine approach the impedance is checked only at a limited number of frequency points!

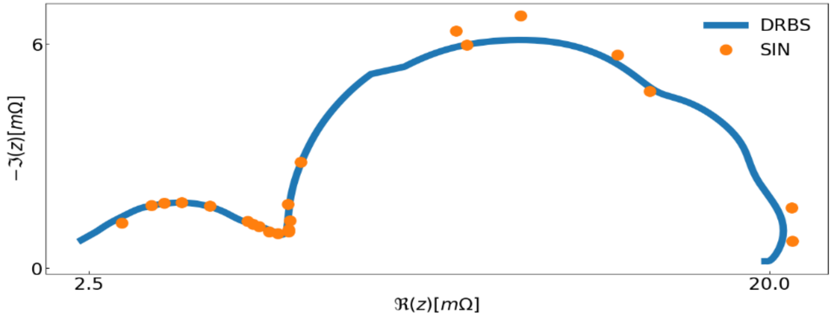




$$\Delta f_{res} \sim \frac{1}{T_s}$$





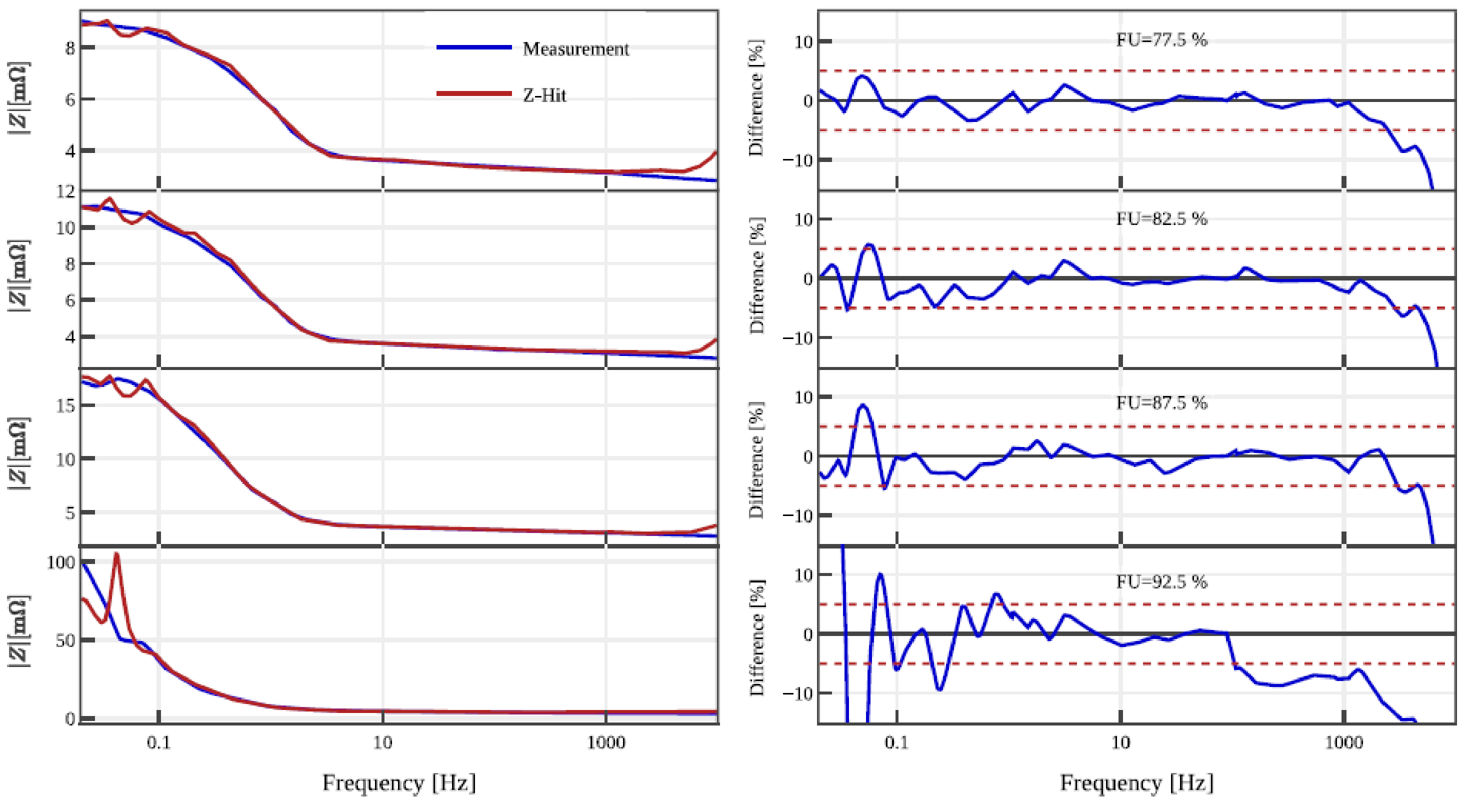


Funded by the EU Fuel Cell and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) –
H2020 Programme Grant Agreement Number 875047

Impedance Hilbert Transform (Z-HIT)

- **linearity**: small amplitudes of perturbations
- **stability:** the overall state of the system should not change during DAQ $\Rightarrow$ minimize **mesurement time**
- **causality**: mind the artefacts, nonlinearities $\Rightarrow$ **Z-HIT test**
- eliminate **parasitic** phenomena (e.g. inductivity of cables) not detectable by KK test

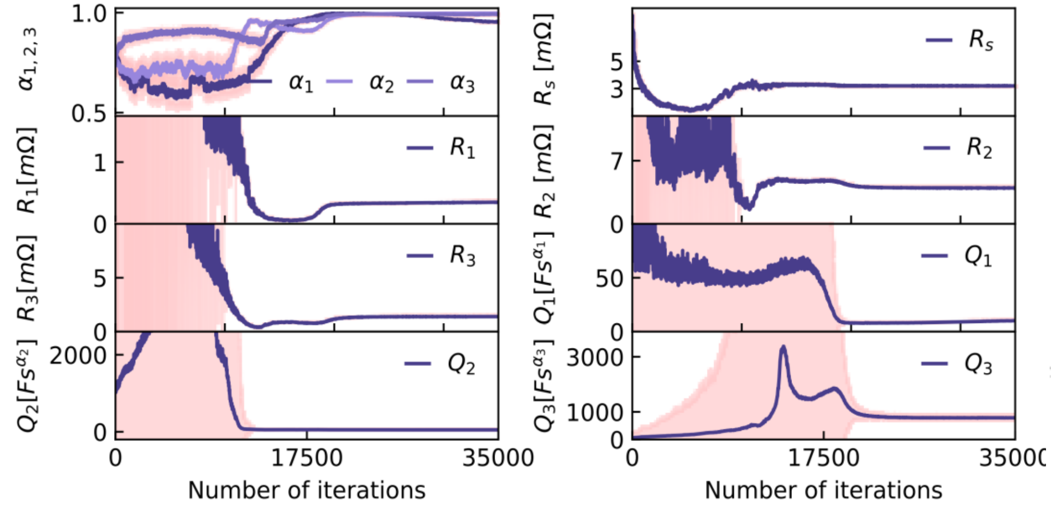
Problem with multiplexing in DAQ: detection with Z-HIT test

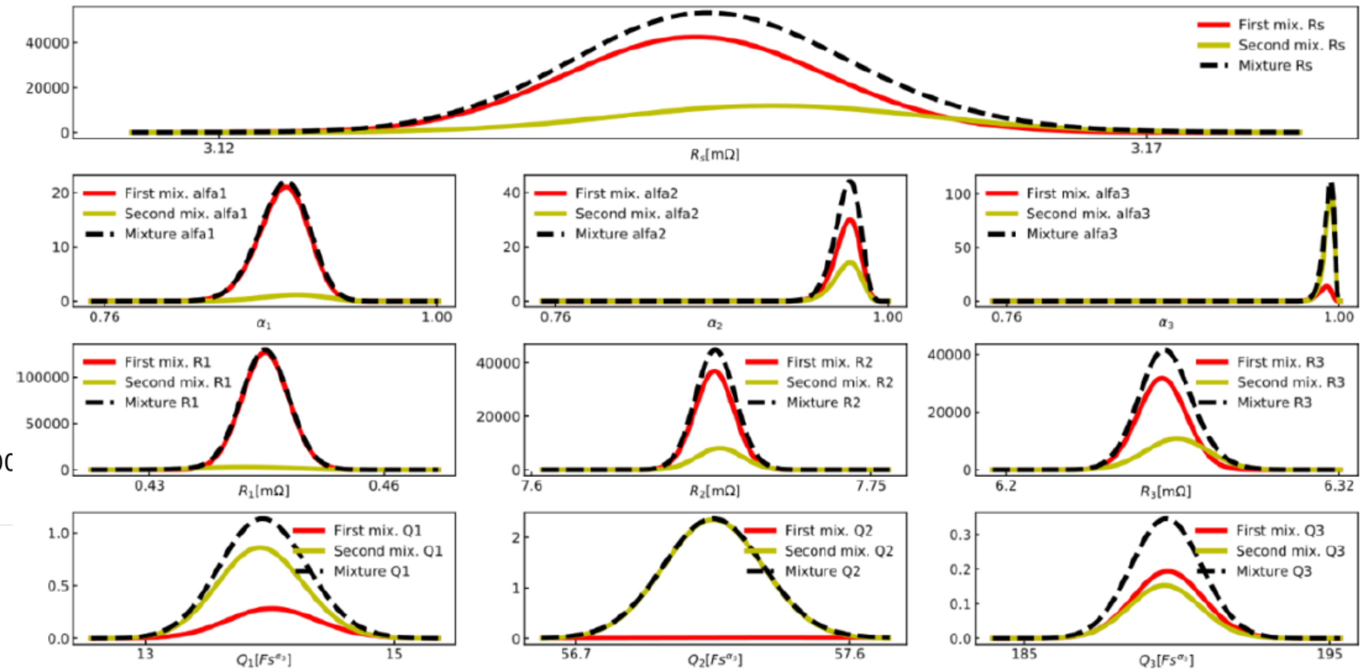


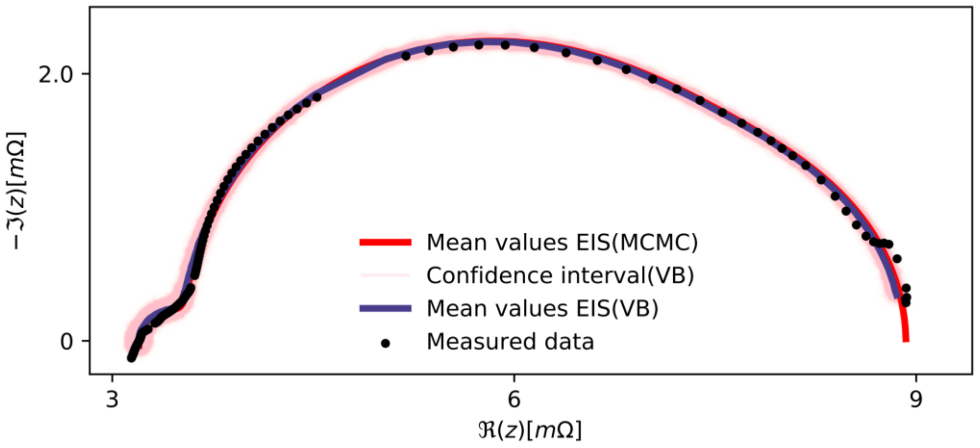
Funded by the EU Fuel Cell and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) –
H2020 Programme Grant Agreement Number 875047

EIS deconvolution via ECM

Learning ECM parameters vith Variational Bayes







Surprisingly low uncertainty in ECM parameters under correct experiment

Funded by the EU Fuel Cell and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) –
H2020 Programme Grant Agreement Number 875047

Characterising the low-frequency part of the EIS curve

Fault-symptom matrix

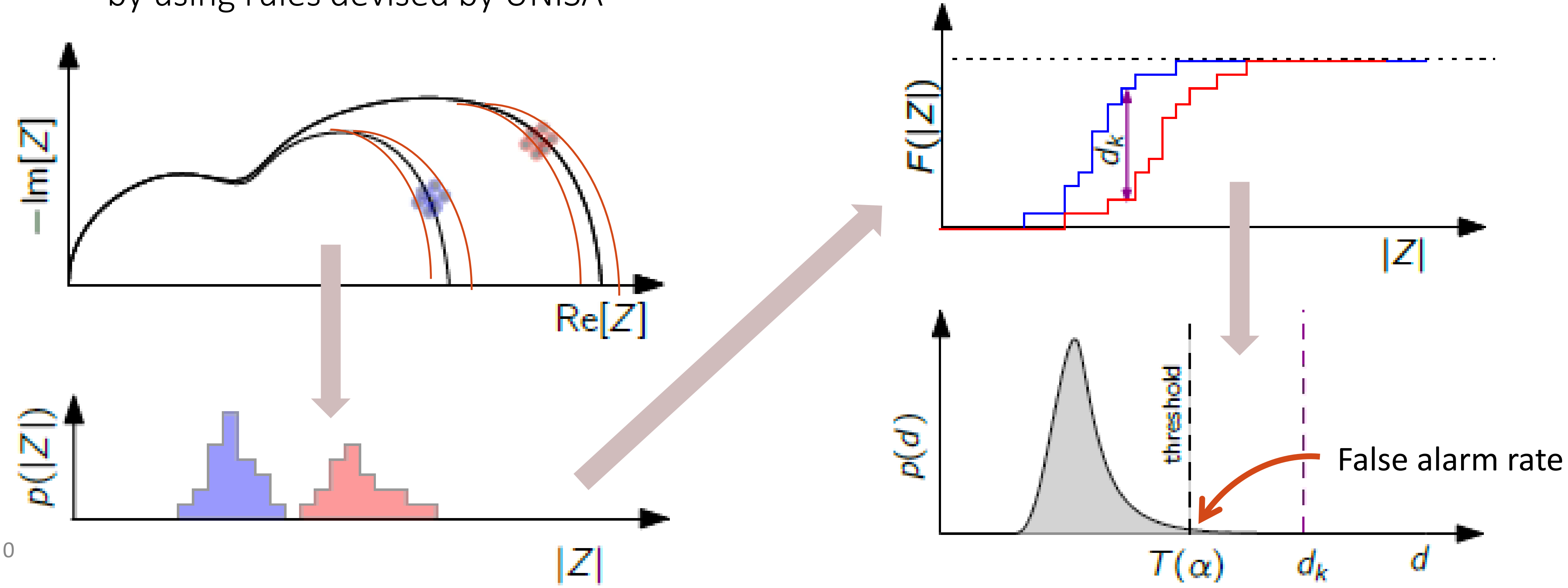
	Low frequency	Mid frequency	High frequency	Rs
Fuel utilisation	x			
Delamination	x	x	x	x
Carbon deposition	x		x	
Leakage	x			x
Ni agglomeration			x	
Cr poissoning		x		x
S poissoning			x	x

Issue:
- efficient characterization of the low-frequency part of the EIS curve by sinusoidal perturbation takes notoriously long perturbations for yet low EIS resolution
- DRBS is better, but going down to the mHz region takes also longer perturbation session

Funded by the EU Fuel Cell and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) –
H2020 Programme Grant Agreement Number 875047

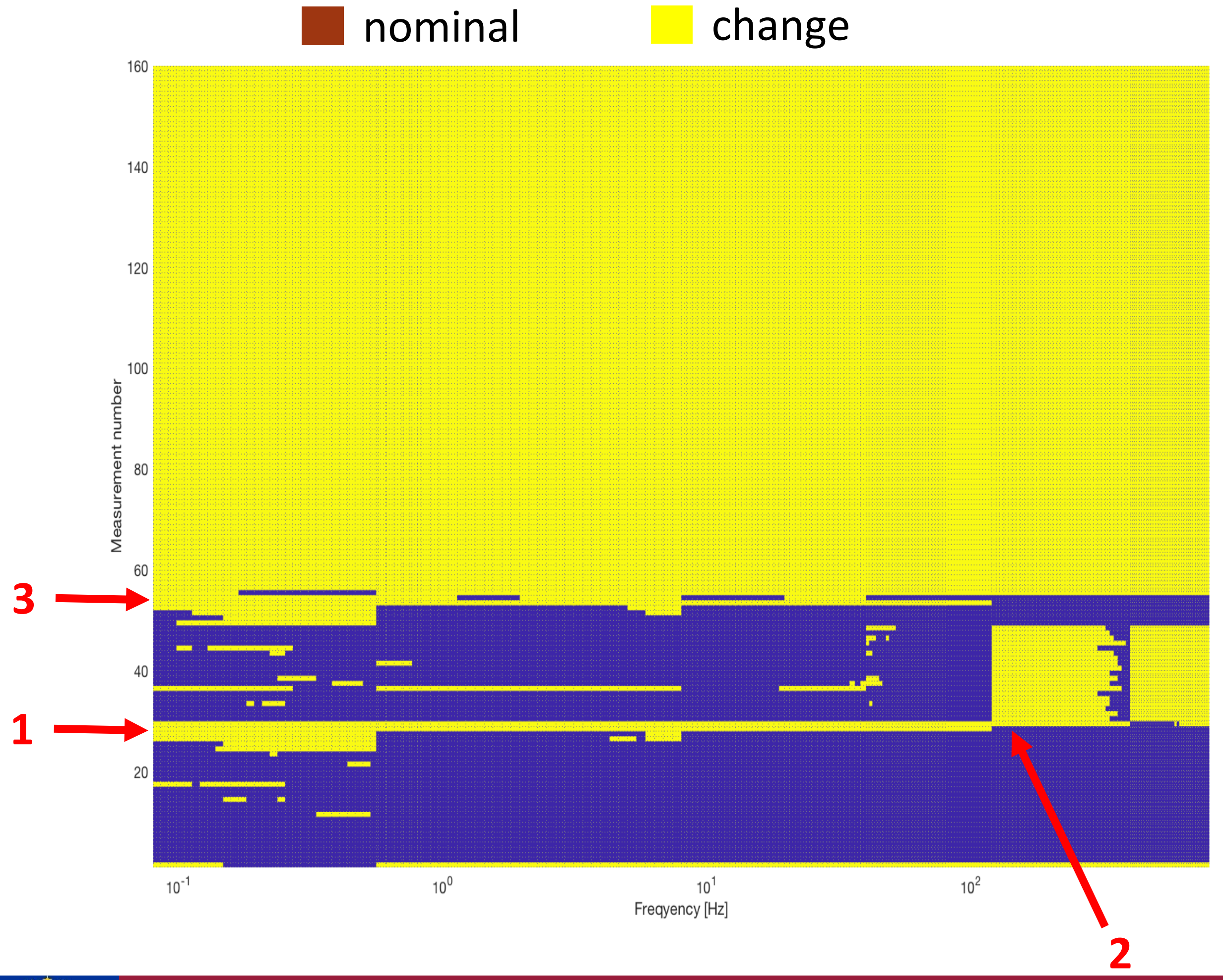
Feature extraction directly from EIS

- Change detection based on Kolmogorov-Smirnov (KS) test (data-driven approach)
- **Motivation**: alleviate laborious threshold selection for symptoms with respect to faults
- **Main idea**: judge upon changes relative to the reference data
- **Main achievement**: tolerated missed alarm rate is the only design parameter
- **Isolation**: after detection is completed, changes in the particular frequency bands are checked by using rules devised by UNISA



Feature extraction directly from EIS – cont'd

Response of the KS detection algorithm applied to cell 3, short stack CEA:

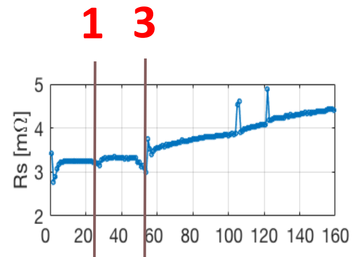


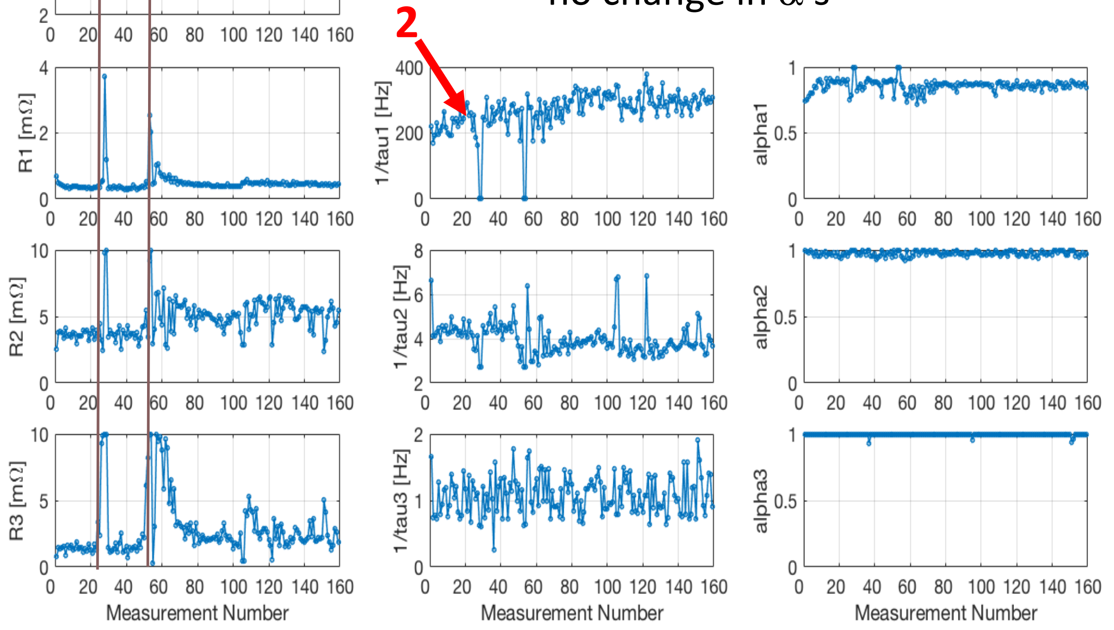
1 – first high FU

2 – change range f>200Hz ($\downarrow\tau_1$)

3 – massive change across the entire spectrum ($\uparrow R_s \downarrow\tau_3 \uparrow\tau_2$)

- no change in α's

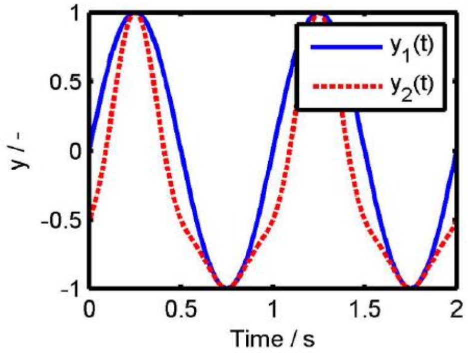


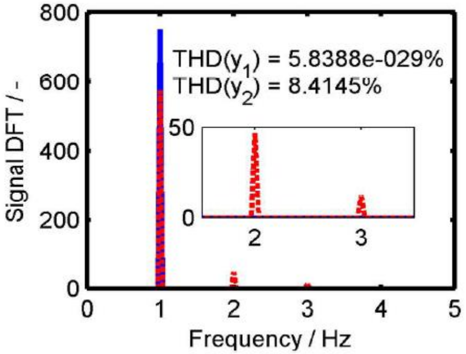


DRT parameters resulting from the **fractional order model** of the cell

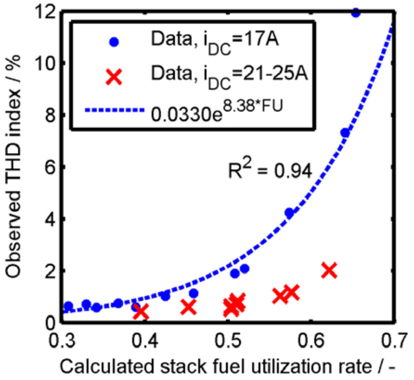
Detection of high FU, various features

Total Harmonic Distortion (THD)



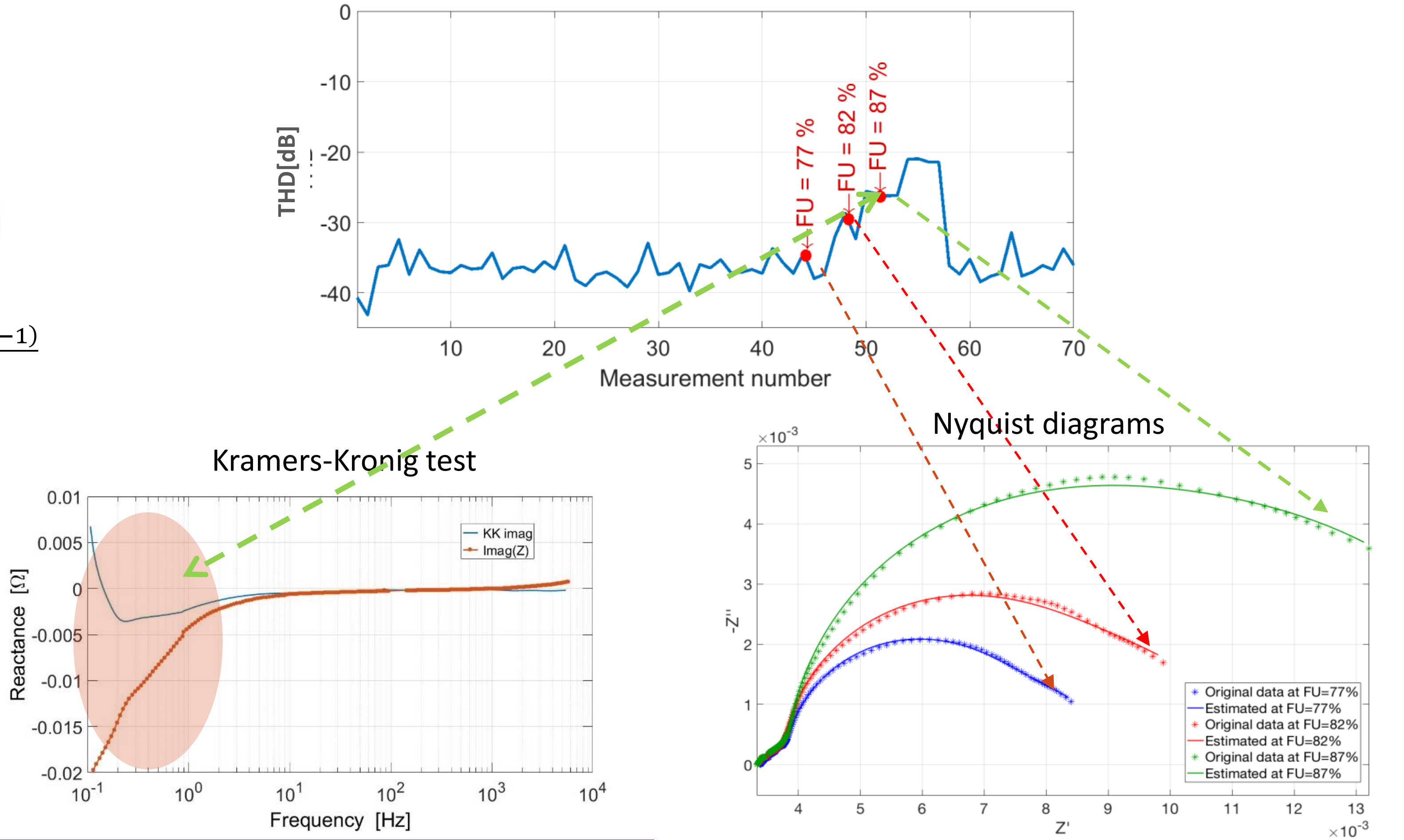


$$DFT(y)_k = \sum_{n=1}^{L_B} y_n e^{\frac{-2\pi j(k-1)(n-1)}{L_B}}$$

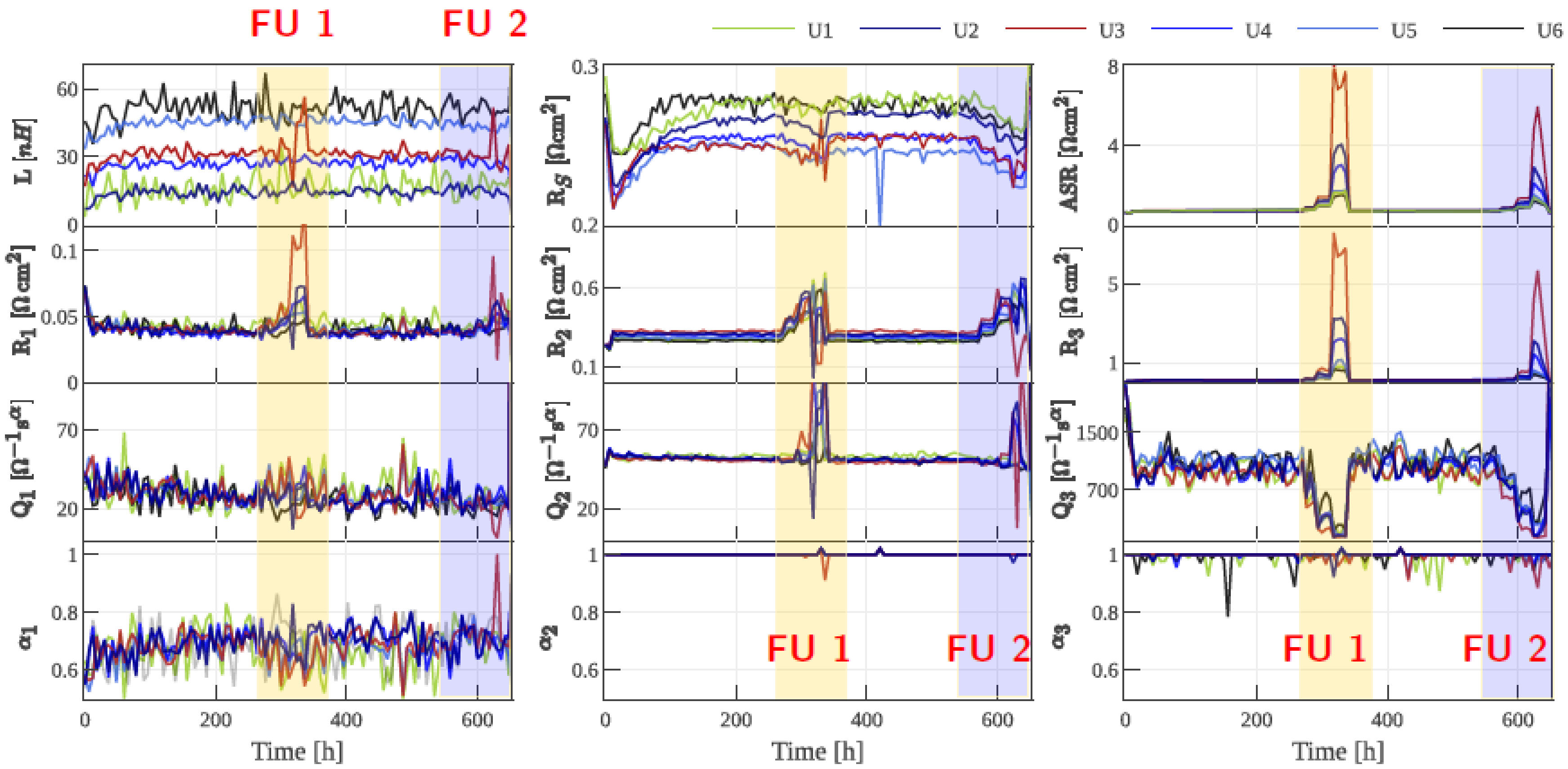


$$THD_{index} = \frac{\sqrt{\sum_{i=2}^{n_H} Y_i^2}}{Y_1} 100$$

THD index, CEA short stack, cell #3



Impact of high FU on ECM parameters



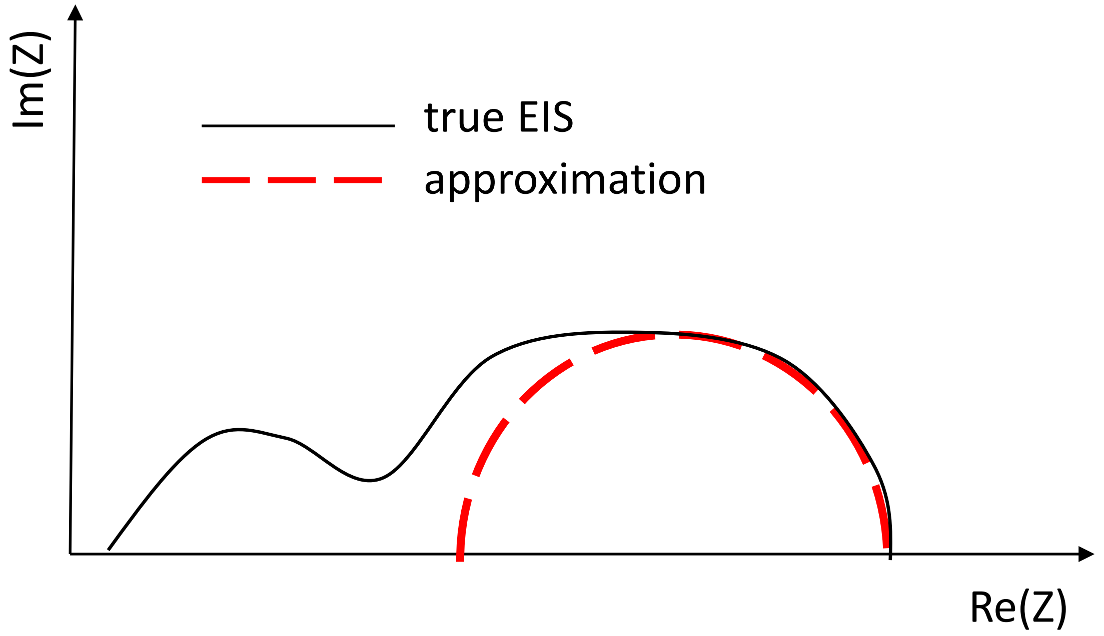
Funded by the EU Fuel Cell and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) –
H2020 Programme Grant Agreement Number 875047

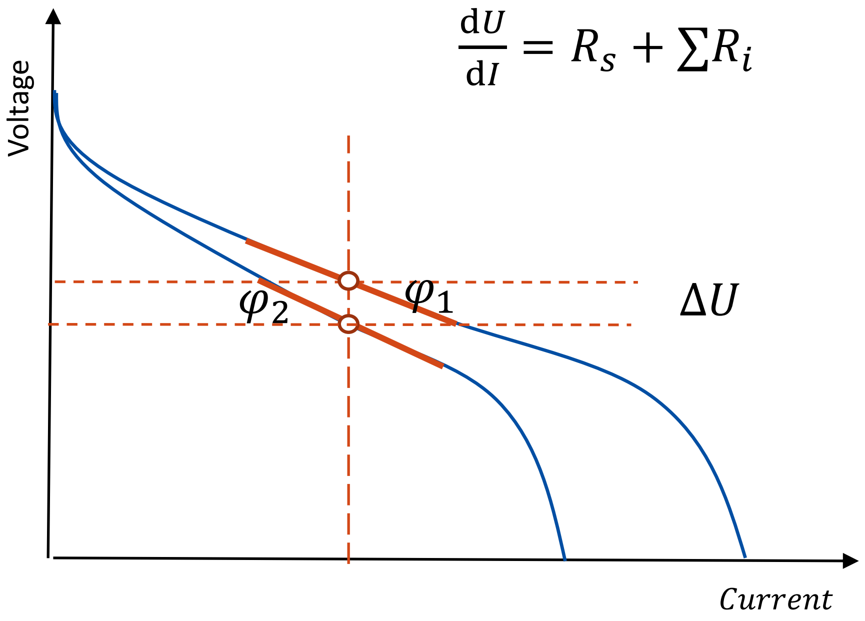
Characterising the low-frequency part of the EIS curve

Issue:
- efficient characterization of the low-frequency part of the EIS curve by sinusoidal perturbation takes notoriously long perturbations for yet low EIS resolution
- DRBS is better, but going down to the mHz region takes also longer perturbation session

Idea: approximate the low-frequency part with a continuous low-order model ⇒ high resolution EIS of order of 1/fs

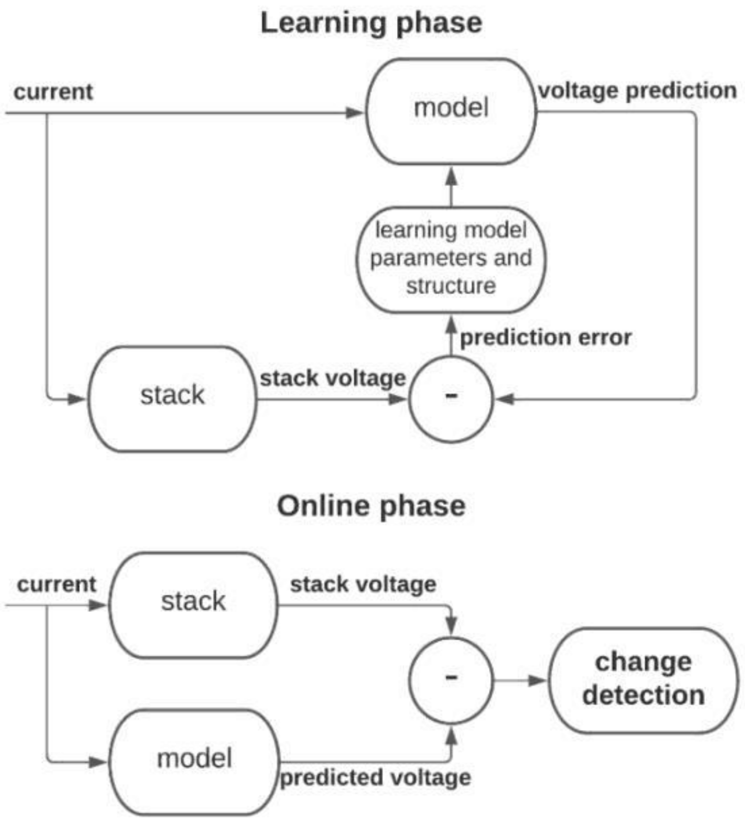
Approach: system identification

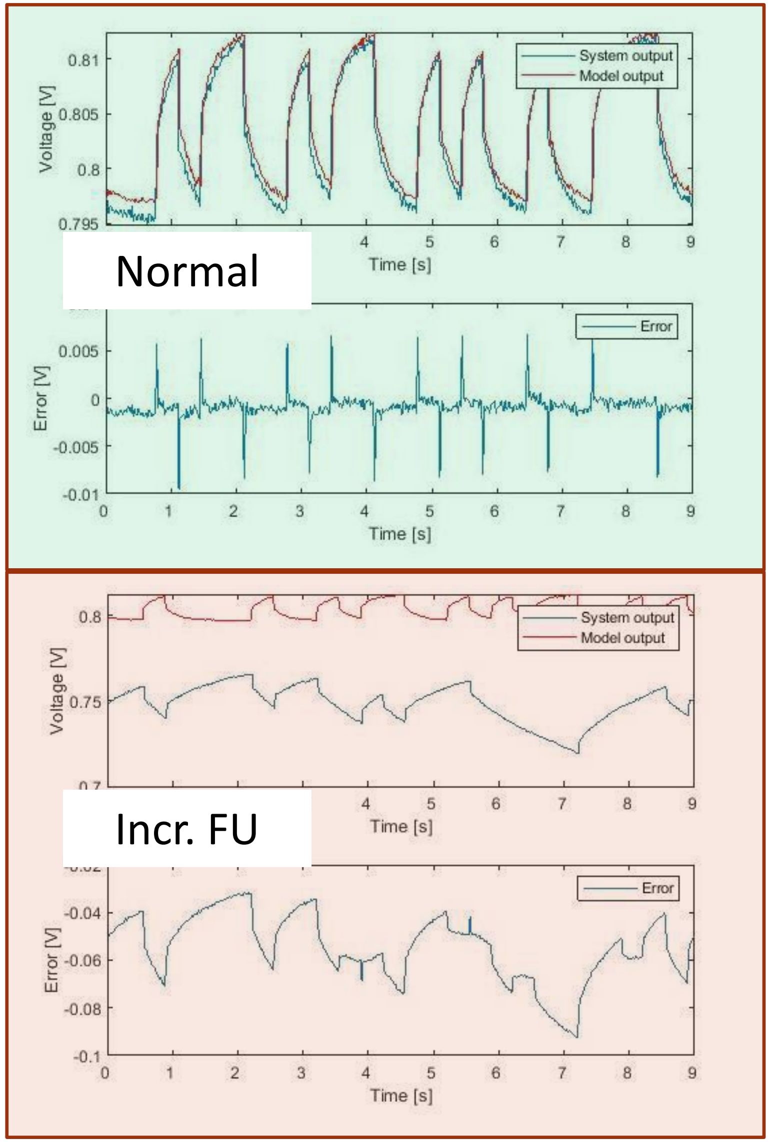


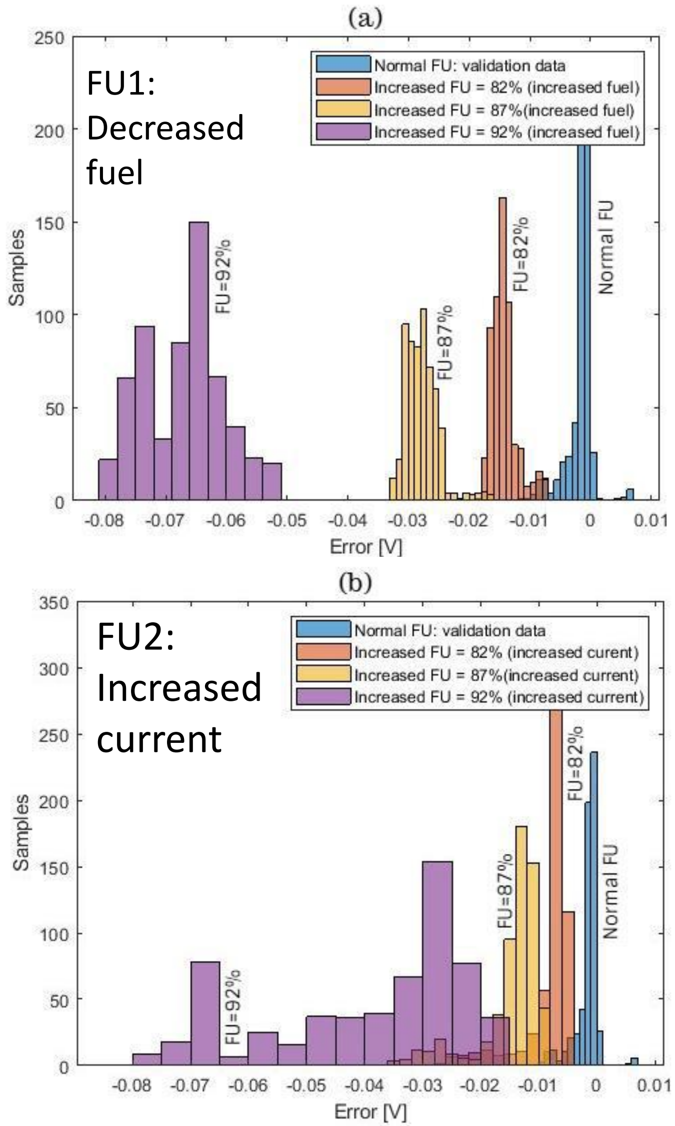


Funded by the EU Fuel Cell and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) –
H2020 Programme Grant Agreement Number 875047

Characterising the low-frequency part of the EIS curve (cont’d)

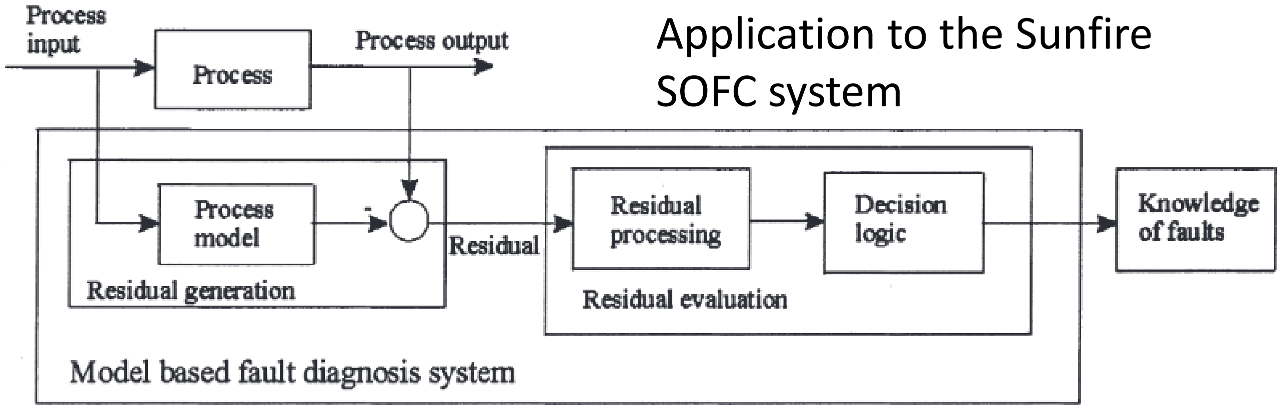






Funded by the EU Fuel Cell and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) –
H2020 Programme Grant Agreement Number 875047

Passive approach: model-based residual generation



Application to the Sunfire SOFC system

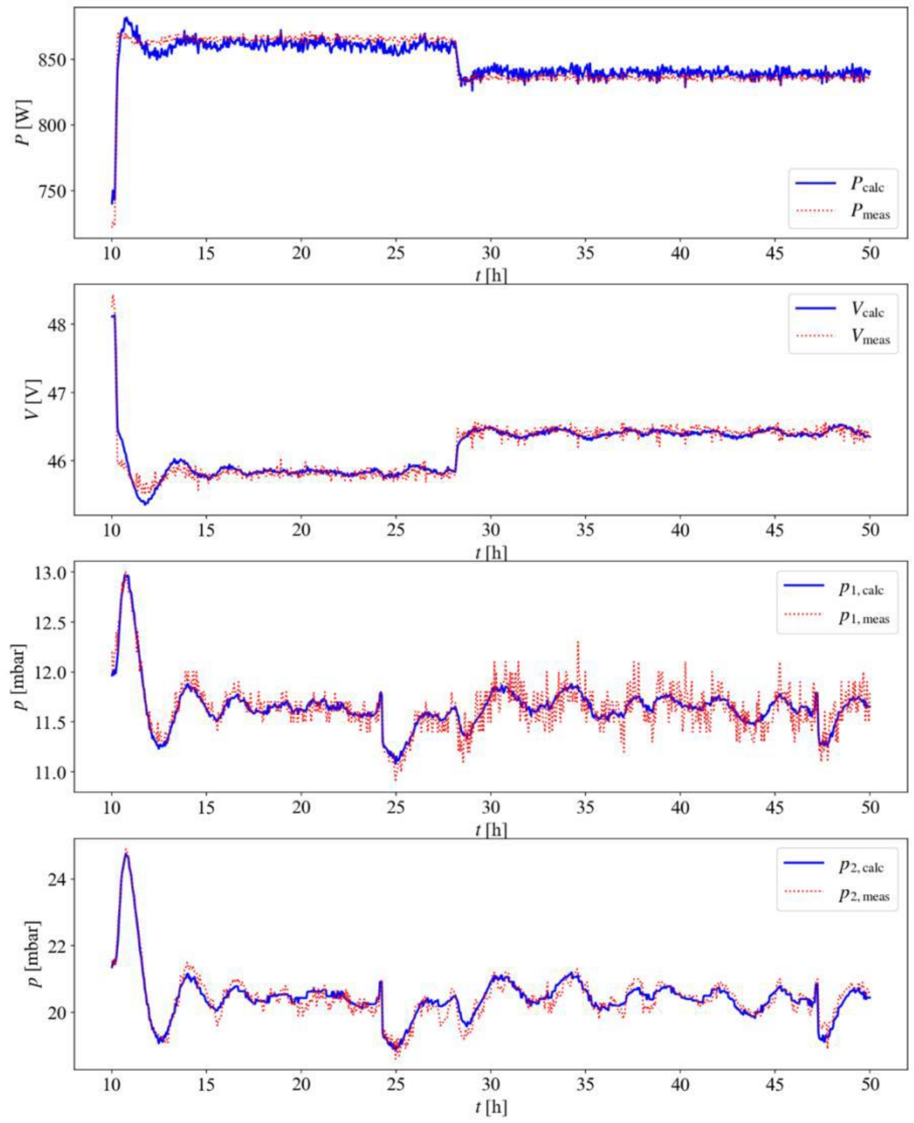
$$k_1 \cdot \frac{\Delta T_{stack}}{\Delta t} + k_2 \cdot p_{2,air} \cdot (T_{air,\,out} - T_{air,\,in}) + \frac{k_3 \cdot T_{stack} \cdot n_{cell} \cdot I_{stack}}{2 \cdot F} = \left(\frac{LHV_{H_2} \cdot n_{cell}}{2 \cdot F} - U_{stack}\right) \cdot I_{stack} \quad (1)$$

$$\frac{LHV_{H_2}}{2 \cdot F} - \frac{k_4 \cdot T_{stack} \cdot I_{stack}}{p_{2,air}} - \frac{k_5 \cdot R \cdot T_{stack} \cdot \operatorname{arcsin}h\left(\frac{I_{stack}}{I_0}\right)}{2 \cdot F} - k_6 \cdot I_{stack} \cdot \exp\left(\frac{10300K}{T_{stack}}\right) = \frac{U_{stack}}{n_{cell}} \quad (2)$$

$$k_7 \cdot PWM_1 = p_{1,air} \quad (3)$$

$$k_8 \cdot PWM_2 = p_{2,air} \quad (4)$$

	Sensor Fault						
Residual #	T_{stack}	$T_{air,in}$	$T_{air,out}$	U_{stack}	I_{stack}	$p_{1,air}$	$p_{2,air}$
1	1	1	1	1	1	0	1
2	1	0	0	1	1	0	1
3	0	0	0	0	0	1	0
4	0	0	0	0	0	0	1



Funded by the EU Fuel Cell and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) –
H2020 Programme Grant Agreement Number 875047

Properties of the residuals

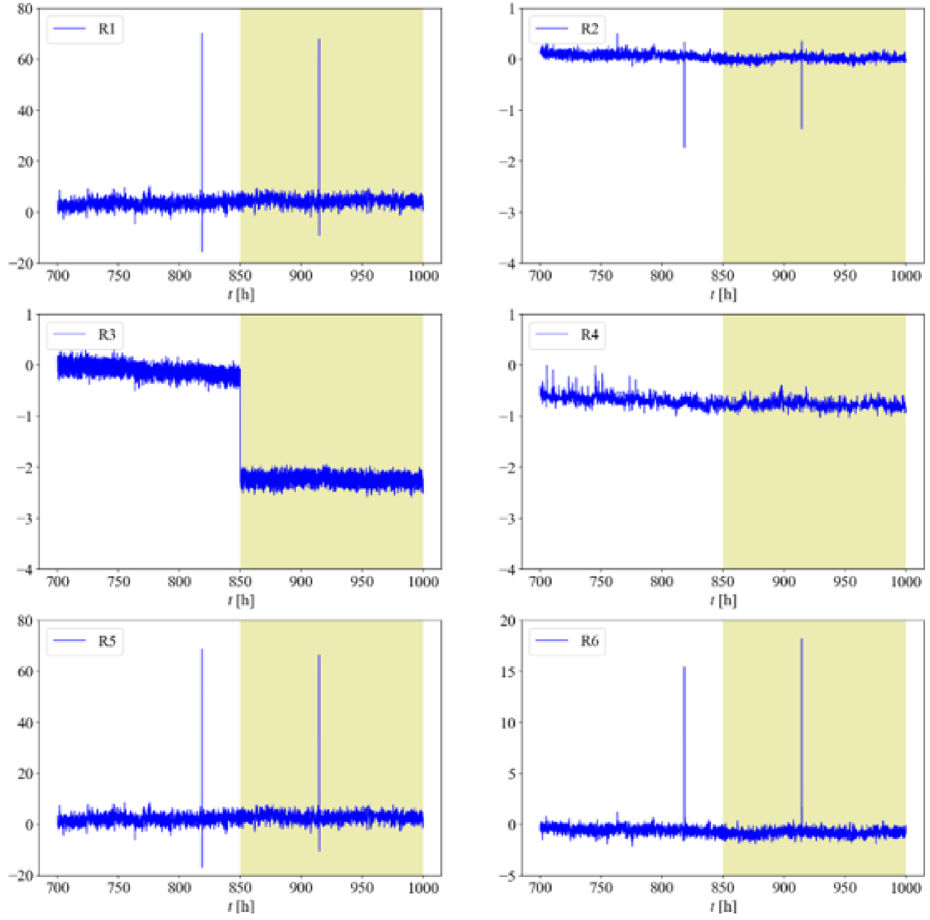
- 2 groups of non-isolable sensor faults ($T_{air,in}$ and $T_{air,out}$) and (T_{stack} and U_{stack})
- other faults are weakly isolable
- for better isolability more senors are needed

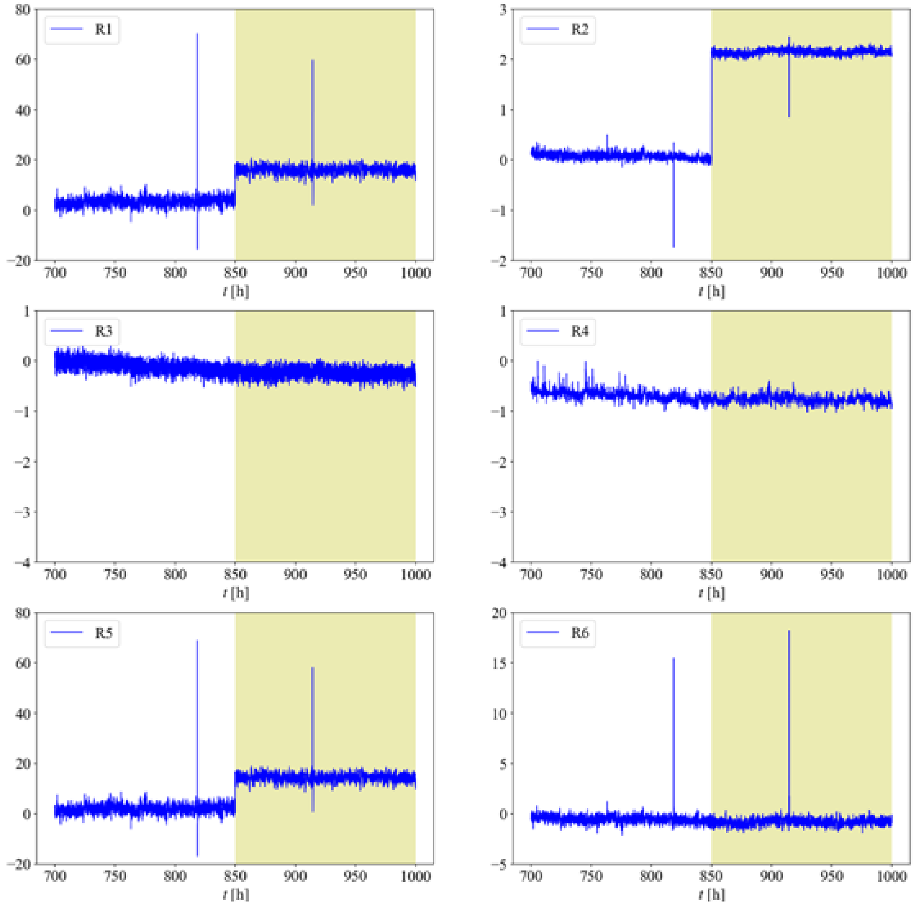
		Sensor Fault						
	Residual #	T_{stack}	$T_{air,in}$	$T_{air,out}$	U_{stack}	I_{stack}	$p_{1,air}$	$p_{2,air}$
Primary esiduals	1	1	1	1	1	1	0	1
	2	1	0	0	1	1	0	1
	3	0	0	0	0	0	1	0
	4	0	0	0	0	0	0	1
Secondary residuals	5	1	1	1	1	1	0	0
	6	1	1	1	1	0	0	1

Funded by the EU Fuel Cell and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) –
H2020 Programme Grant Agreement Number 875047

- emulated air pressure offset $\Delta p_{1,air}$ = 2 mbar
- change only in residual R3 ⇒ pressure sensor fault

- emulated air pressure offset $\Delta p_{1,air}$ = 2 mbar
- change only in residual R3 ⇒ pressure sensor fault





Funded by the EU Fuel Cell and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) –
H2020 Programme Grant Agreement Number 875047

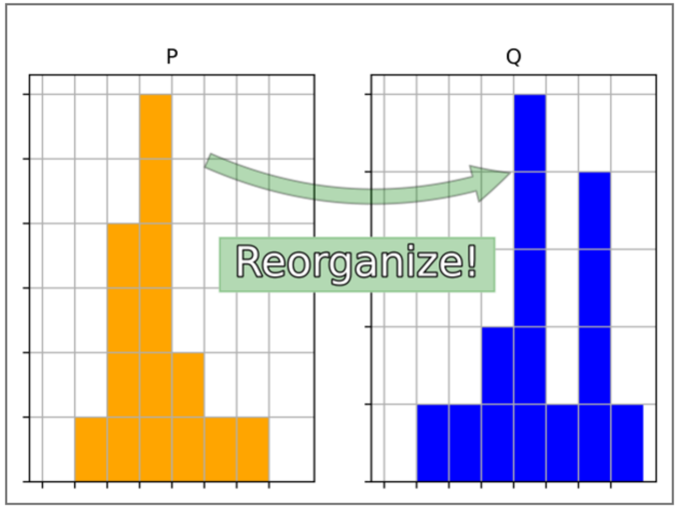
Fault detection

Issues:

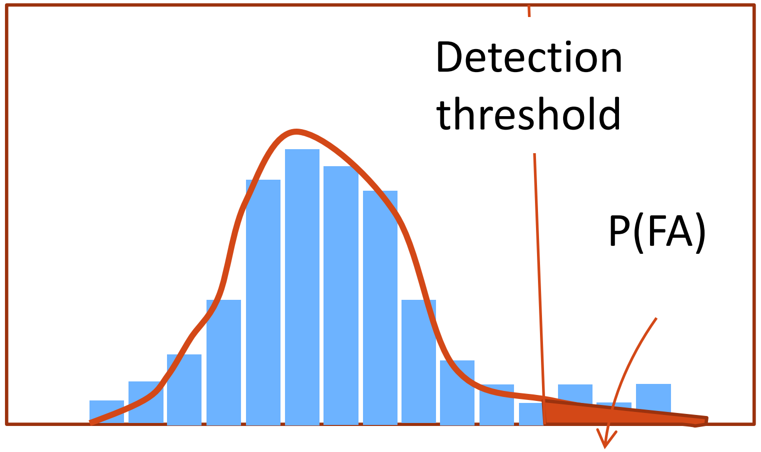
- detection threshold?
- tolerated false alarm rate?
- missed alarm rate?
- minimal detection delay (strongly tied with diagnostic sensitivity)?

Concept of features evaluation:

- Features (continuous or discrete) are considered as the realisation of stochastic processes
- change in the features statistic in is assessed through the "**distance**" between their histograms P and Q
- "distance" can be expressed by non-negative divergence measures (Kullback-Leibler, f-divergence etc.)
- "distances" can improve the **diagnostic sensitivity**
- detection threshold can be evaluated from (i) the reference distribution of the distances and the (ii) tolerated false alarm rate

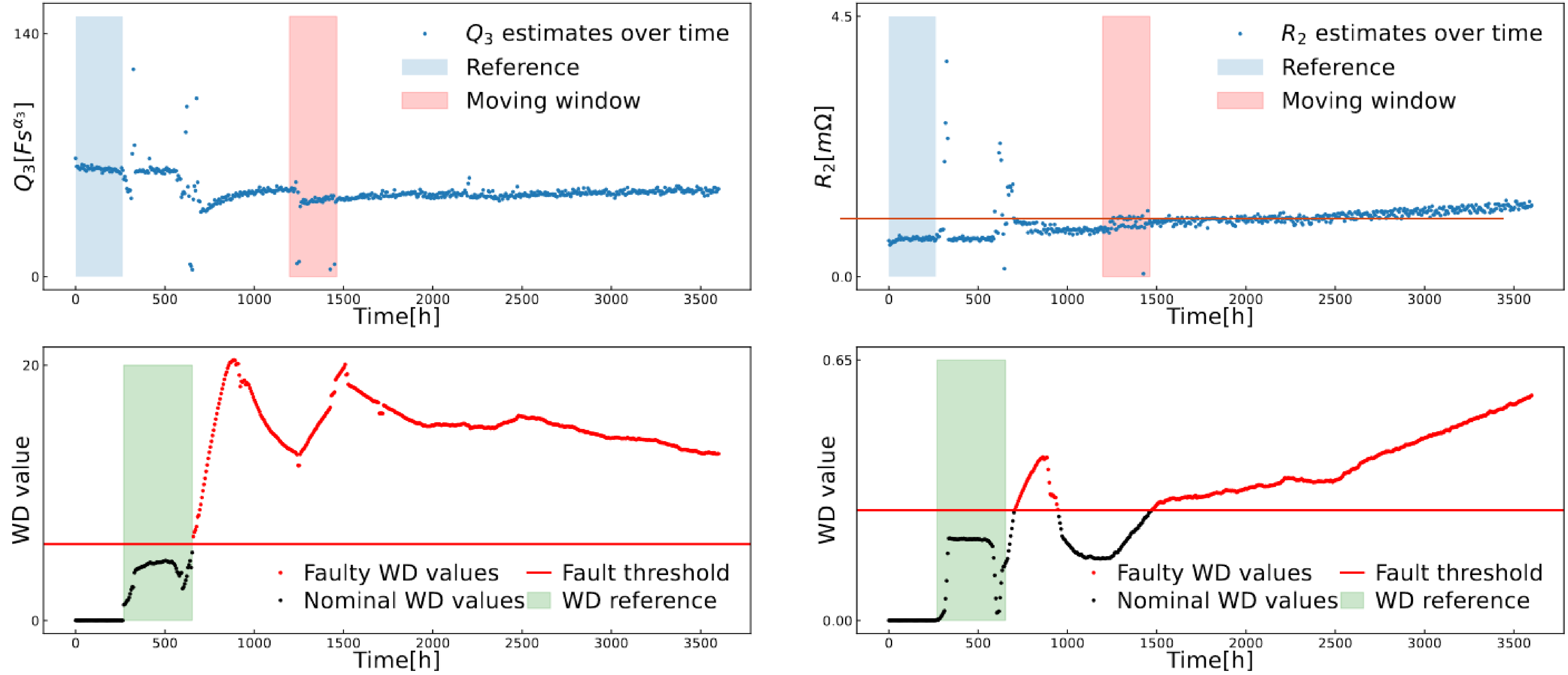


The distribution of distances



Funded by the EU Fuel Cell and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) – H2020 Programme Grant Agreement Number 875047

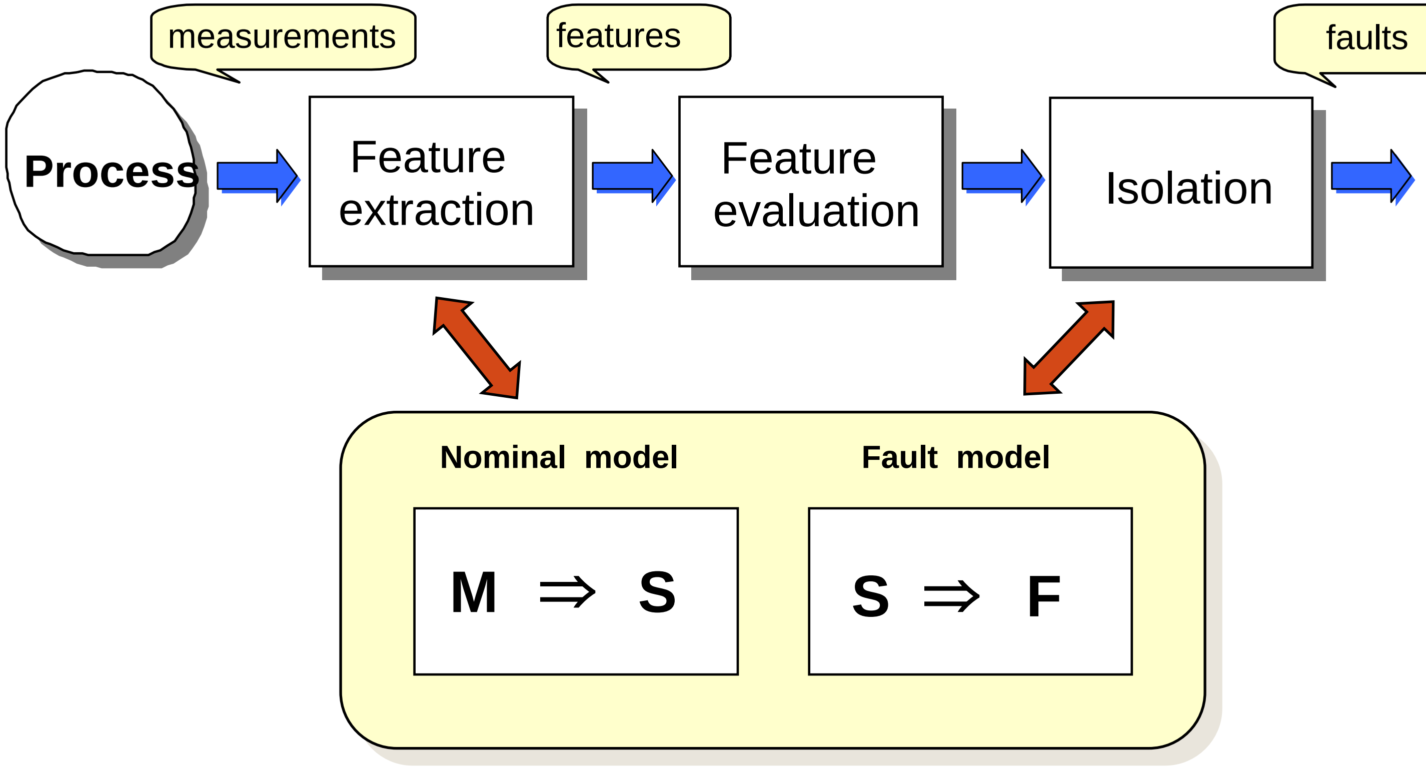
Example: detecting changes in ECM parameters

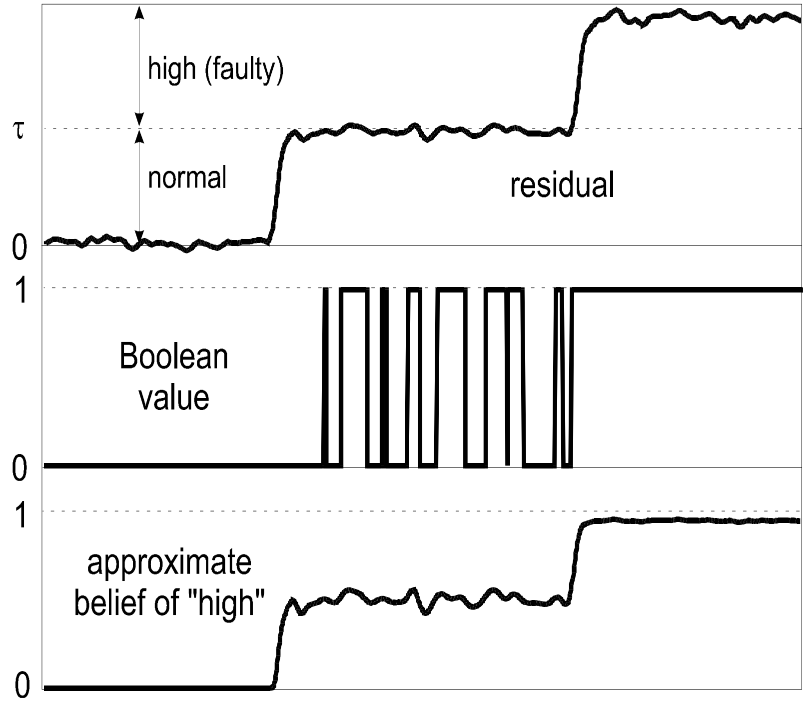


Funded by the EU Fuel Cell and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) –
H2020 Programme Grant Agreement Number 875047

Fault isolation

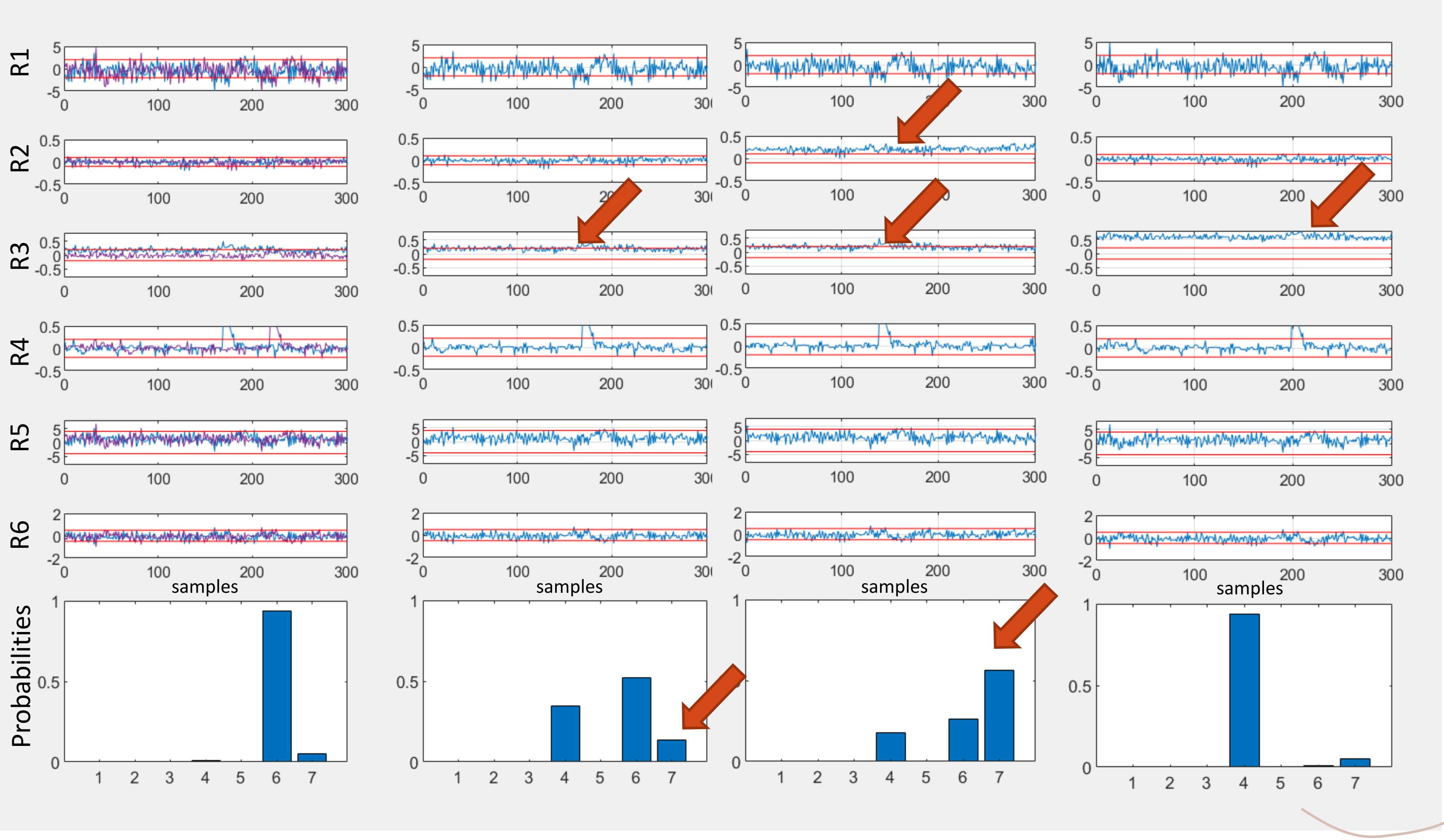
- fault isolation is **inverse problem**: from fault-symptom matrix and evaluated symptoms from fault symptom matrix





Funded by the EU Fuel Cell and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) –
H2020 Programme Grant Agreement Number 875047

Application of the Transferable Belief Model



Demonstration on the Sunfire data

	Description
1	(Sensor T_{stack}) OR (Sensor $T_{air,out}$)
2	(Sensor T_{stack}) OR (Sensor U_{stack})
3	Sensor I_{stack}
4	Sensor $p_{1,air}$
5	Sensor $p_{2,air}$
6	Norma operation
7	Strength of conflict

Funded by the EU Fuel Cell and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) –
H2020 Programme Grant Agreement Number 875047

Conclusions

- Some feature extraction techniques based on active and passive approach have been reviewed;
- passive approach complements active with pointing on problems with BoP
- probabilistic approach to EIS analysis and deconvolution is presented
- A unified framework for fault isolation based on fault-symptoms table by means of the approximate reasoning circumvents the issues related to the disturbances, imprecision in the process model
- Questions:
  - Fault isolation has to be further assessed (with incoming lifelong data);
  - Can we unambiguously distinguish between different faults/degradation modes?

Funded by the EU Fuel Cell and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) –
H2020 Programme Grant Agreement Number 875047

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No 875047. This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation programme, Hydrogen Europe and Hydrogen Europe Research.