FUEL CELLS AND HYDROGEN JOINT UNDERTAKING

HEALTH CODE

Real operation pem fuel cell **HEALTH**-state monitoring and diagnosis based on DC/DC **CO**nverter embedde**D** **E**is

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Programme Review Days 2018

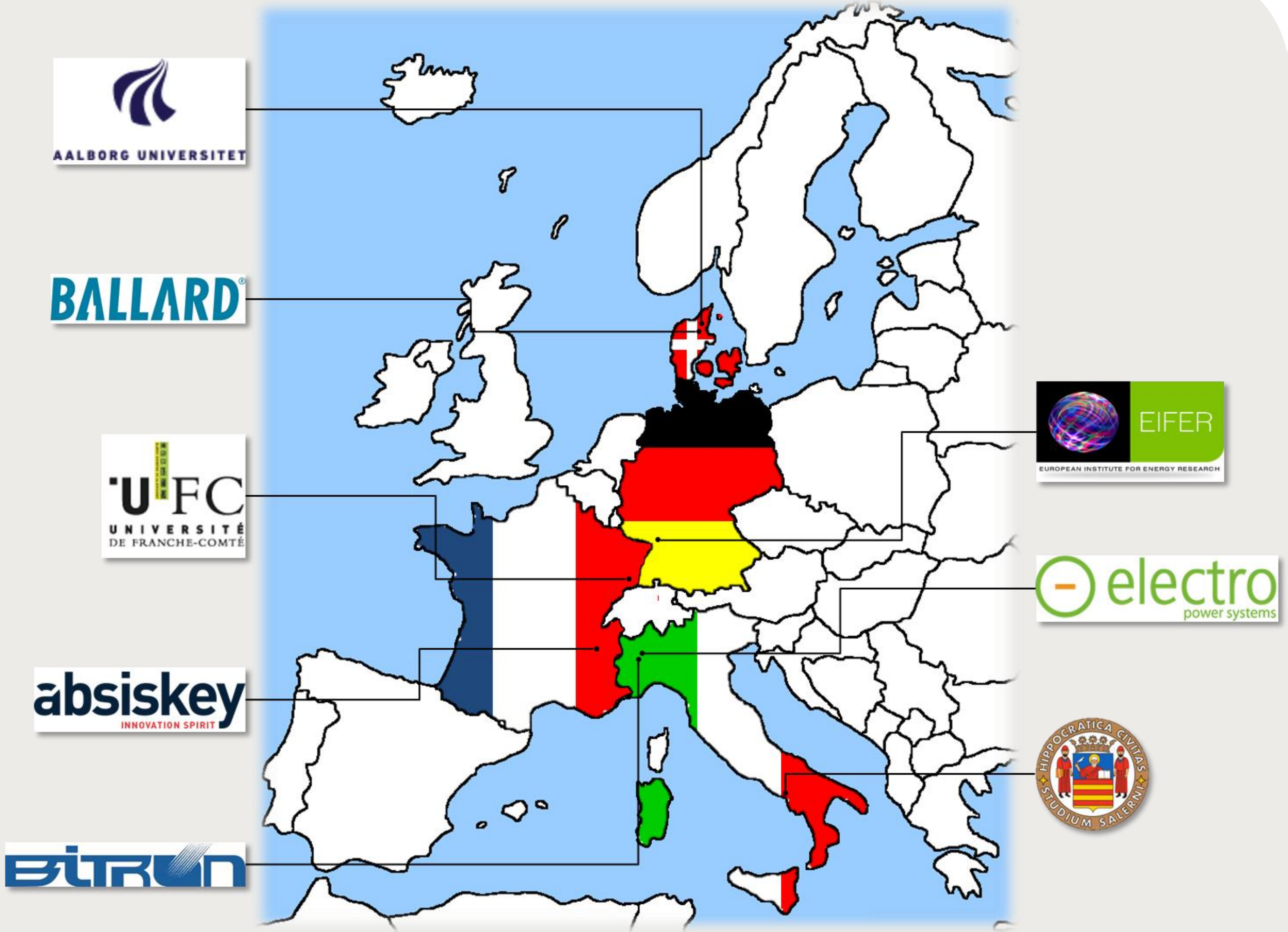
Brussels, 14-15 November 2018

PROJECT OVERVIEW

- **Call year: 2014**
- **Call topic: FCH-02-3-2014**

  Stationary fuel cell system diagnostics: development of online monitoring and diagnostics systems for reliable and durable fuel cell system operation

- **Project dates: 01/09/15 – 31/12/18**
- **Stage of implementation 01/11/2018: 95%**
- **Total project budget: 2,358,736€**
- **FCH JU max. contribution: 100%**

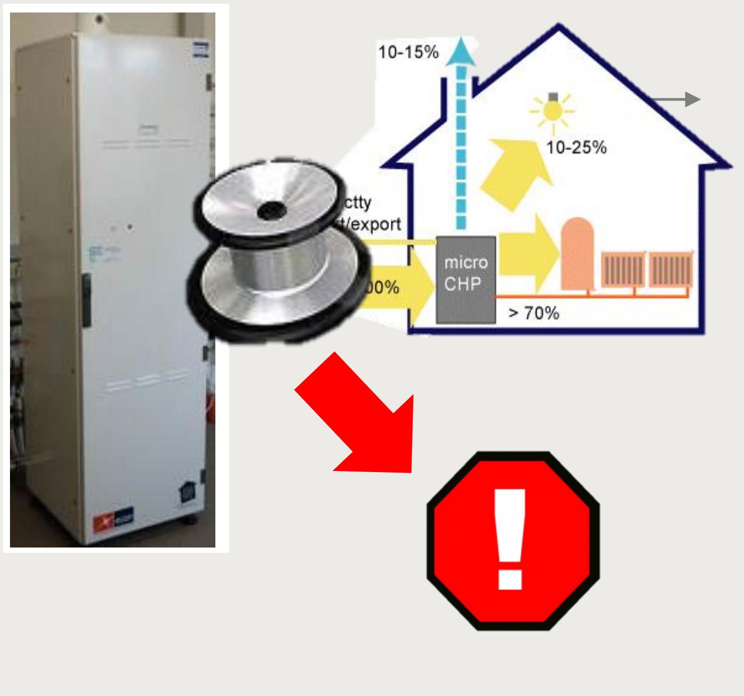


*Former Dantherm Power A/S.

PROJECT OBJECTIVES

1. Enhancement of **EIS-based diagnosis for embedded on-line applications**;
2. Development of a monitoring and diagnostic tool for **state-of-health assessment, fault detection and isolation** as well as degradation level analysis for **lifetime inference**;
3. EIS-oriented experimental analysis for **5 failure modes**: i) fuel composition, ii) air starvation, iii) fuel starvation, iv) sulphur poisoning, v) flooding & dehydration;
4. **EIS scaling-up** algorithm to reduce **time and costs of new stack characterization.**

Performance, Durability, Availability



Reduce OPEX

PROJECT ACHIEVEMENTS

Embed the tool for Electrochemical Impedance Spectroscopy (EIS) for advanced Fuel Cells Monitoring & Diagnosis.

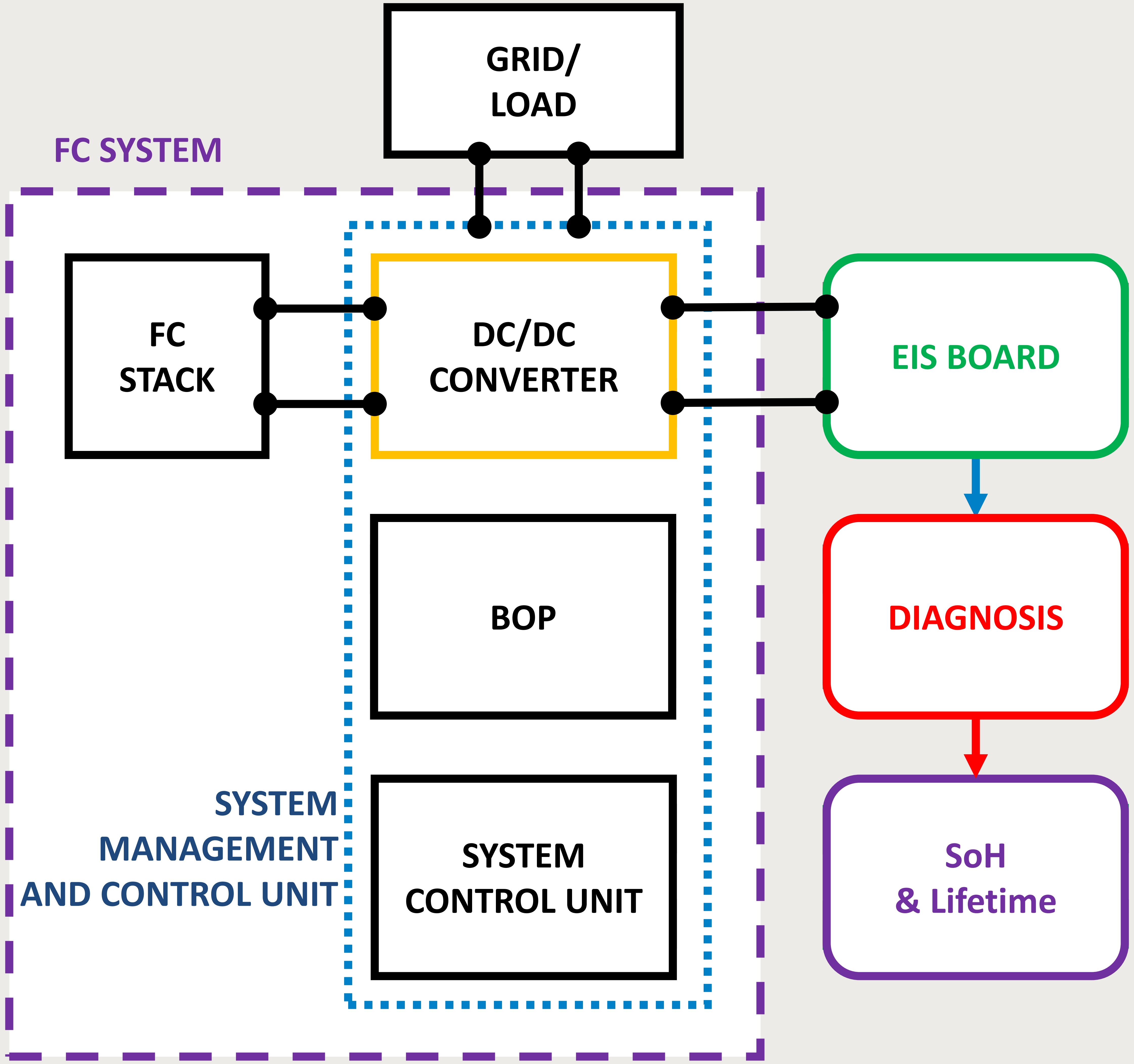
The tool performs **EIS-based** condition monitoring of FC stacks and **isolates 5 stack faults**.

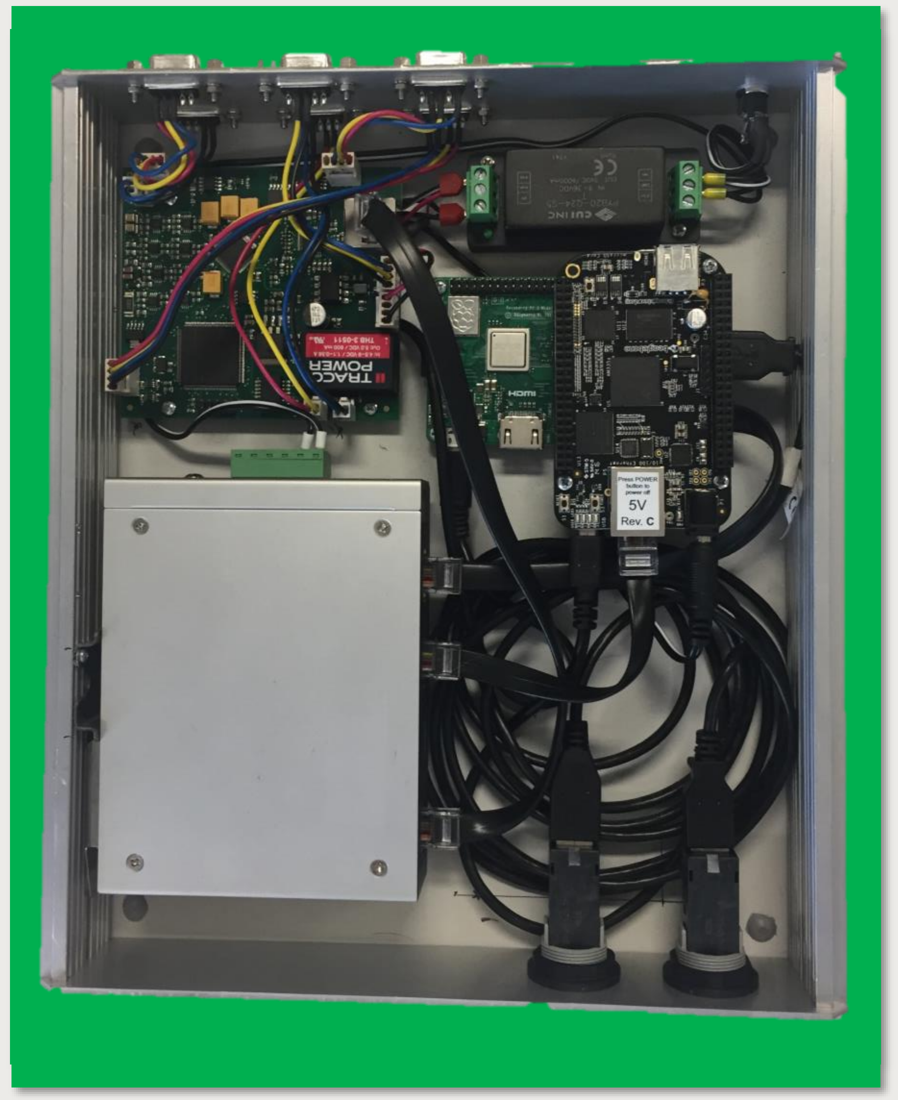
Advanced knowledge **(Air+Ref./O_2+H_2 -fed stacks) 2200+ EIS spectra**; New device **(EIS Board)**; HW enhancement and interfacing **(Converters)**, Monitoring & Diagnostics **(Algorithms)**.

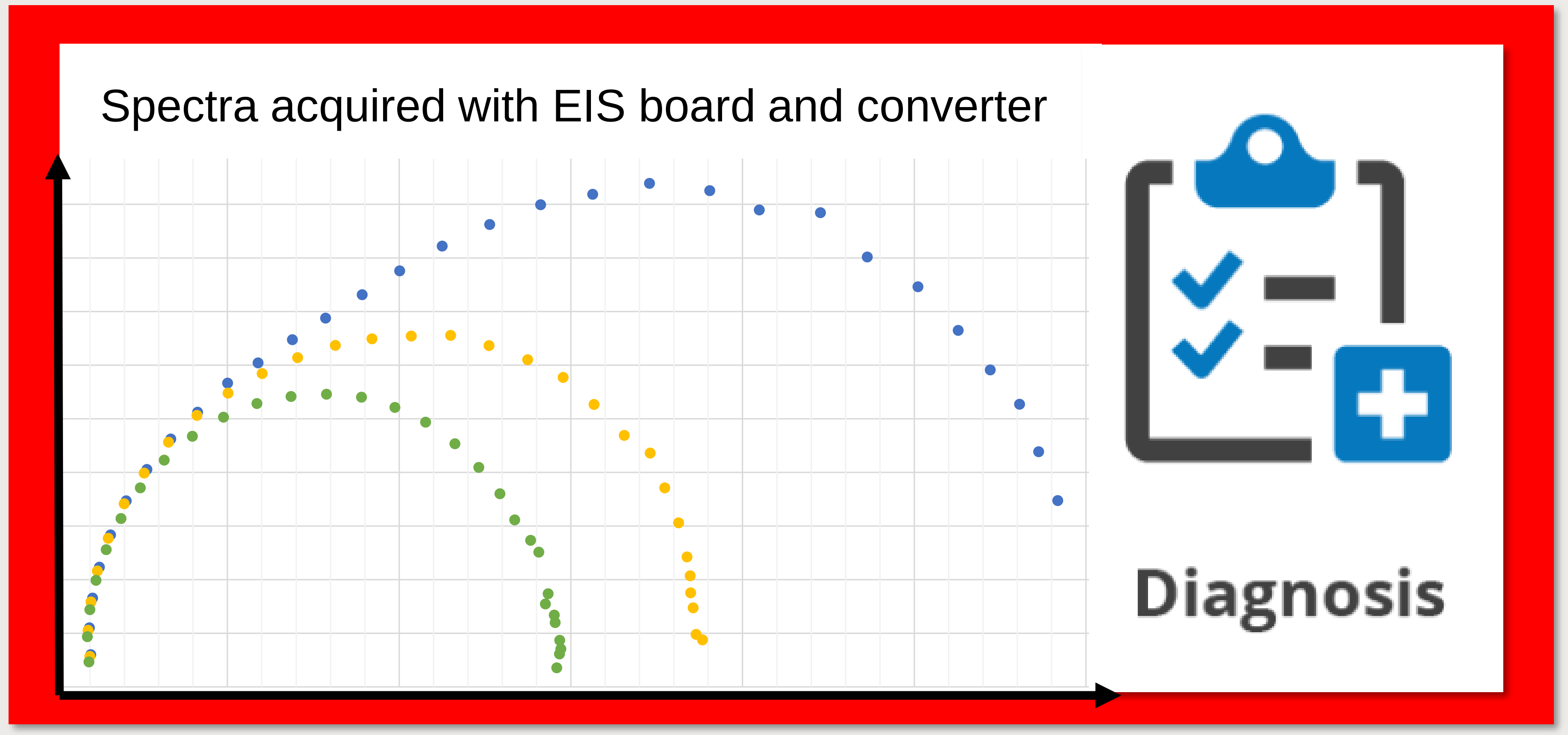
EIS board (TRL 6)	Converter (TRL 6)	Algorithms (TRL 5)
EIS board has been prototyped (proto 2) ready to be engineered for system embedding.	Conventional HW is modified/re-engineered to allow flexibility and multiple market choice for manufacturer strategies.	Detection and Isolation of 5 faults in stacks fed with Air+Reformate / O_2+H_2.

EIS board cost < 500€ (3% of Total Cost of Ownership)

PROJECT CONCEPT







PROJECT PROGRESS & ACTIVITIES

Activities completion

Activities

- Experiments
- EIS Board
- DC/DC converters
- Diagnostic algorithms
- System integration

Experiments: Air-fed (μ-CHP) and O2-fed (backup) stacks fully tested in both nominal and faulty conditions (fuel starvation, air/O2 starvation, flooding, drying, CO contamination and Sulphur poisoning); final system testing under completion.

EIS board: final version of EIS board completed and verified in relevant environment (EIS measurements performed with DC/DC converter connected).

DC/DC converters: modified EPS converter and BPSE new converter completed and tested.

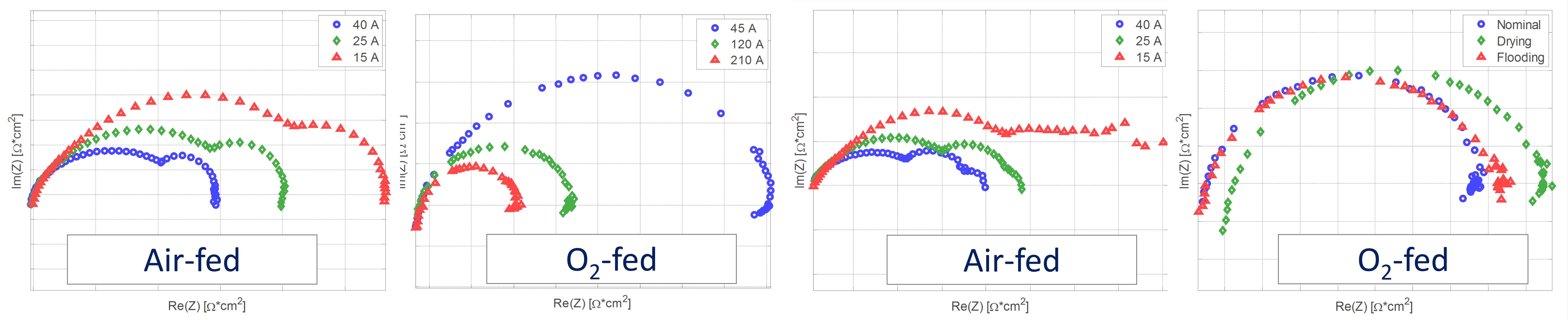
Diagnostic algorithms: all algorithms trained and tested on all the performed EIS measurements (algorithms benchmarking); characterization on FC system to be finally assessed.

System integration: FC systems (BPSE μ-CHP and EPS backup) integrated with DC/DC converters and BITRON final EIS board; algorithm on-board implementation done for final algorithm verification (ongoing).

EIS SPECTRA MEASURED ON SHORT AND FULL STACKS

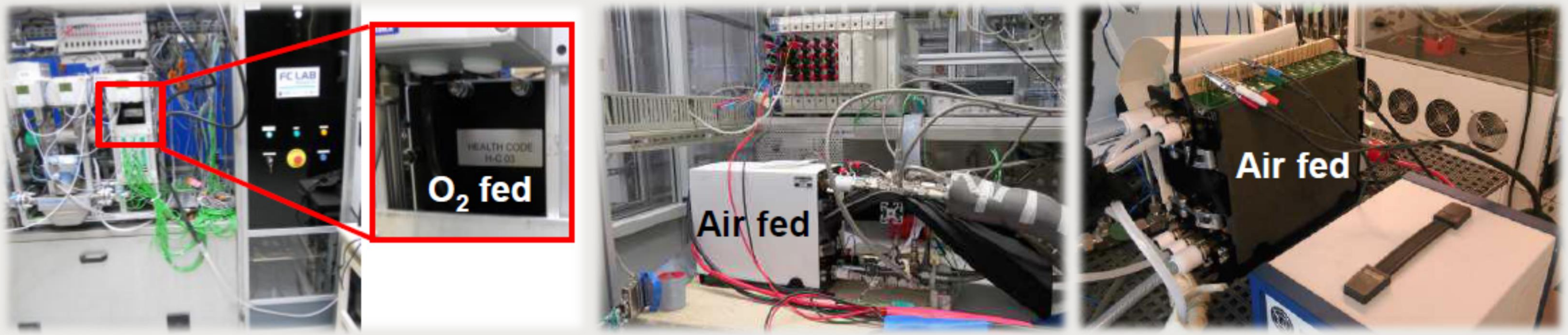
2200+ EIS spectra for stacks (10%) and cells, **25% in nominal** and **75% in faulty operations**

- Nominal spectra set the monitoring reference
- Faulty ones drive the setting of faults isolation algorithm



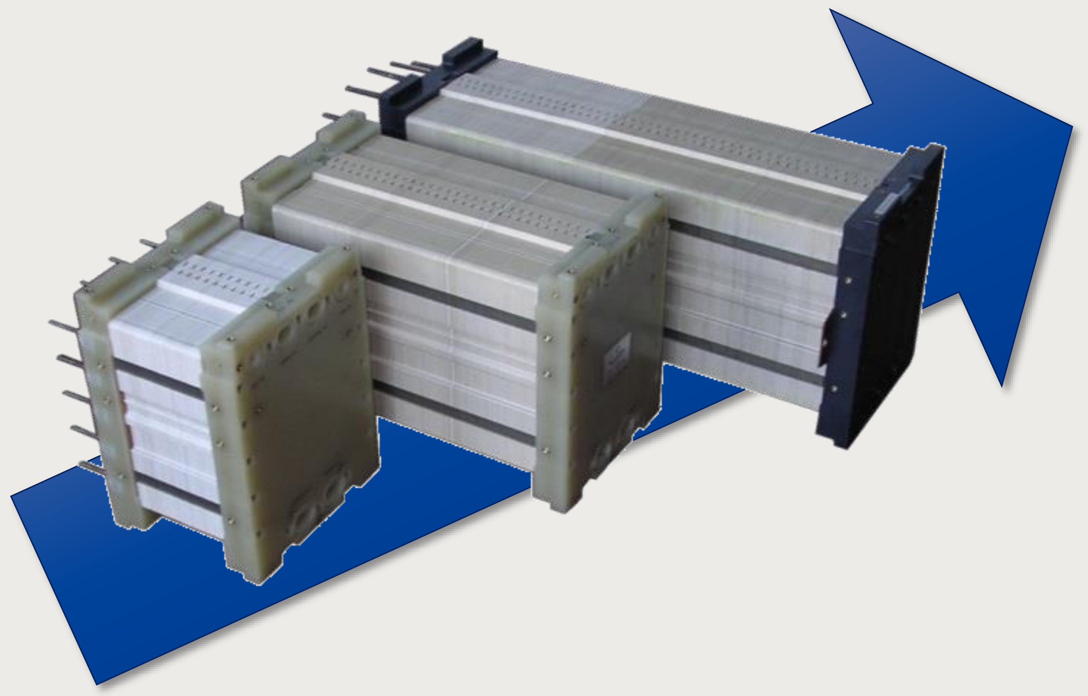
Faults

- **fuel starvation,**
- **air/O2 starvation,**
- **flooding/drying,**
- **CO contamination**
- **sulphur poisoning**

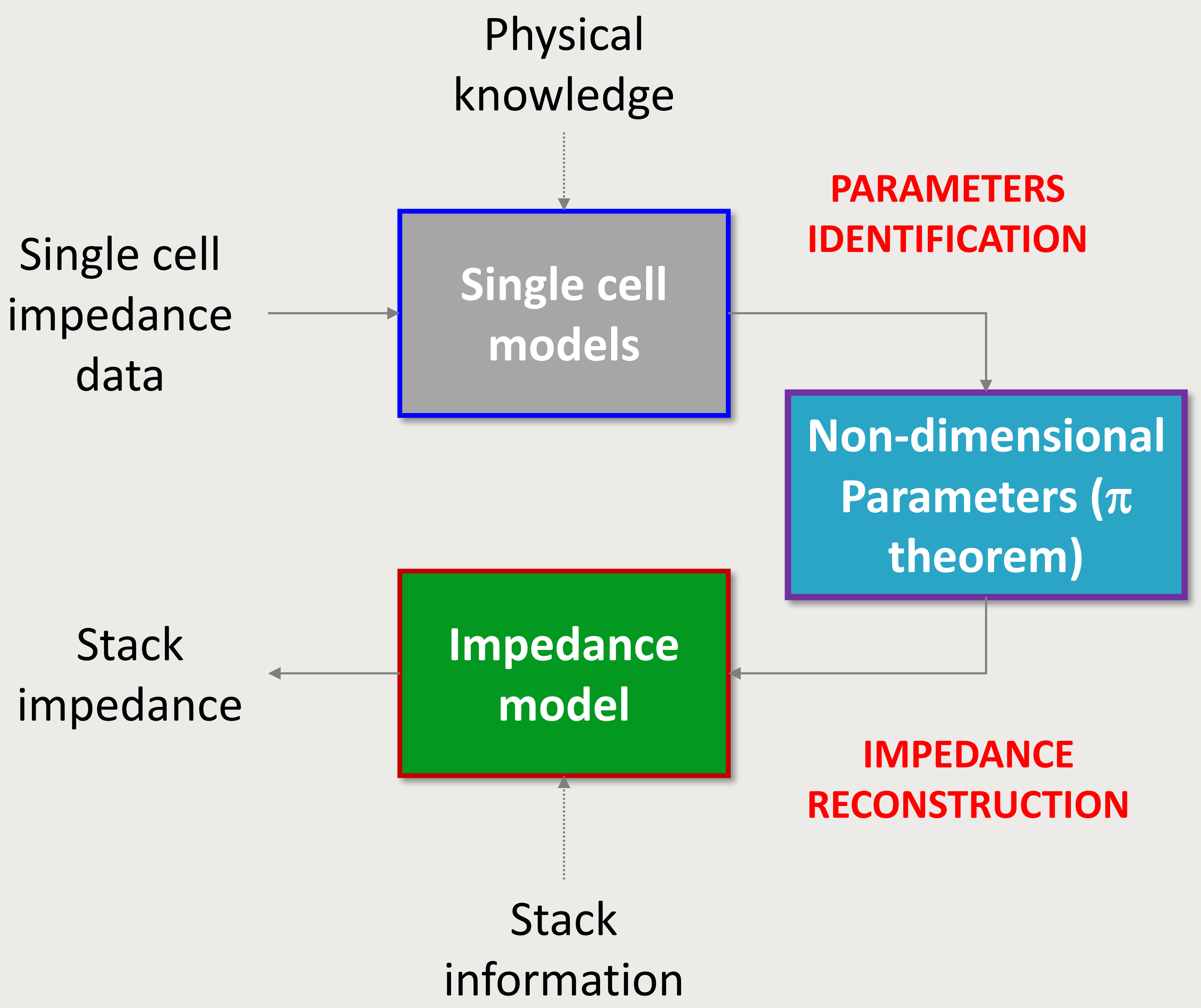


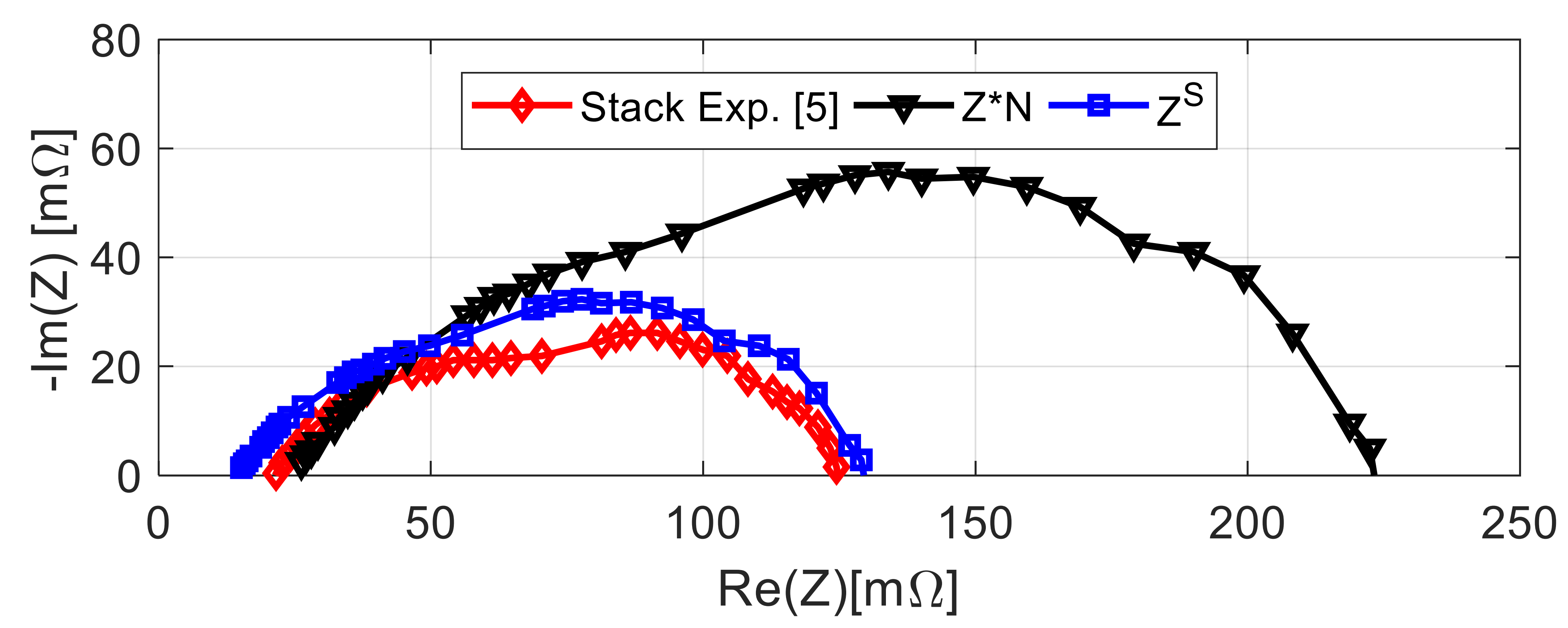
SCALING-UP

- **Reduce fuel cells (FCs) testing costs** providing a **scaling-up algorithm** able to extrapolate full stack performance and impedance behaviour from single cell and/or short stack (i.e. single repeated unit – SRU) data;
- Derive **stack faulty behaviour** from single cell tests performed under faulty conditions to **improve FC systems lifetime**.



Cell → Short stack→ Full Stack



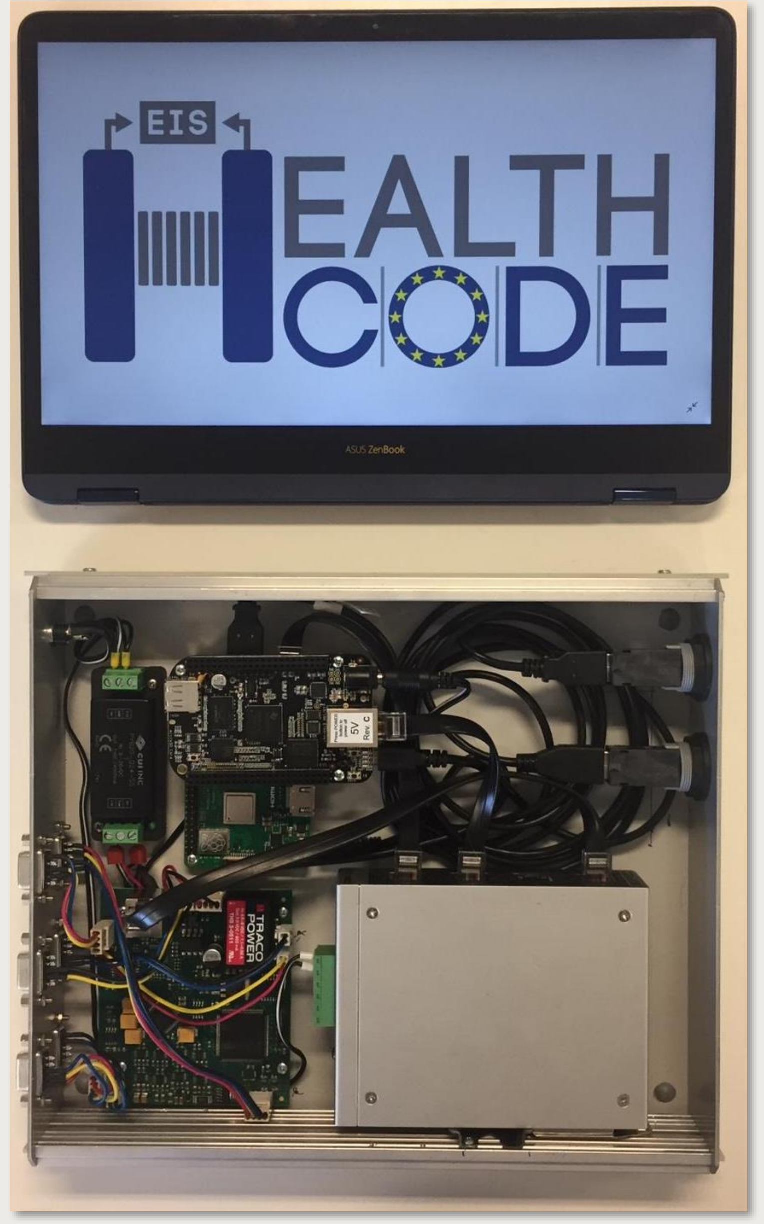


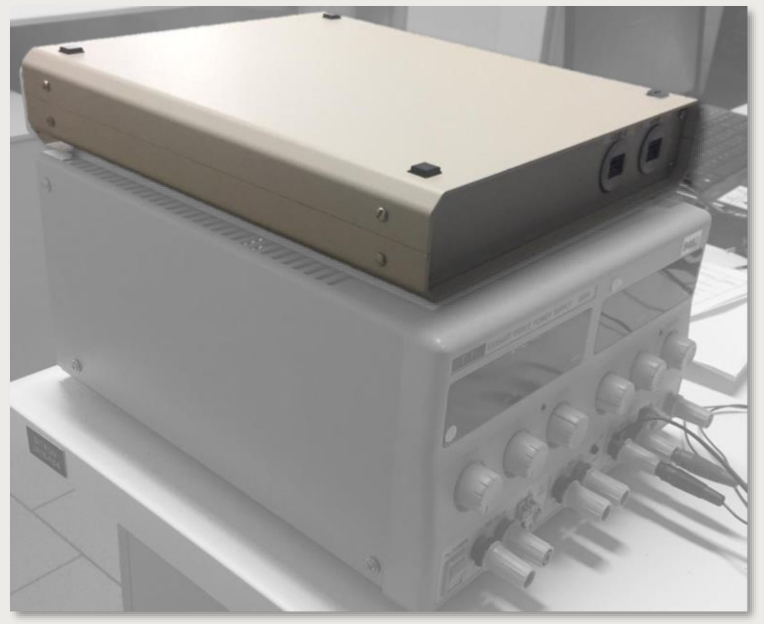
Russo et al. (2016) - Application of Buckingham theorem for scaling-up oriented fast modelling of Proton Exchange Membrane Fuel Cell impedance, Journal of Power Sources 353, 277-286.

Polverino et al. (2018) - Generalized scaling-up approach based on Buckingham theorem for Polymer Electrolyte Membrane Fuel Cells impedance simulation10th International Conference on Applied Energy (ICAE2018), Aug 22-25, Hong Kong, China. (to be published on Energy Procedia – Selected for Applied Energy Special Issue submission)

EIS-BOARD & CONVERTER

2nd Generation PROTO 2

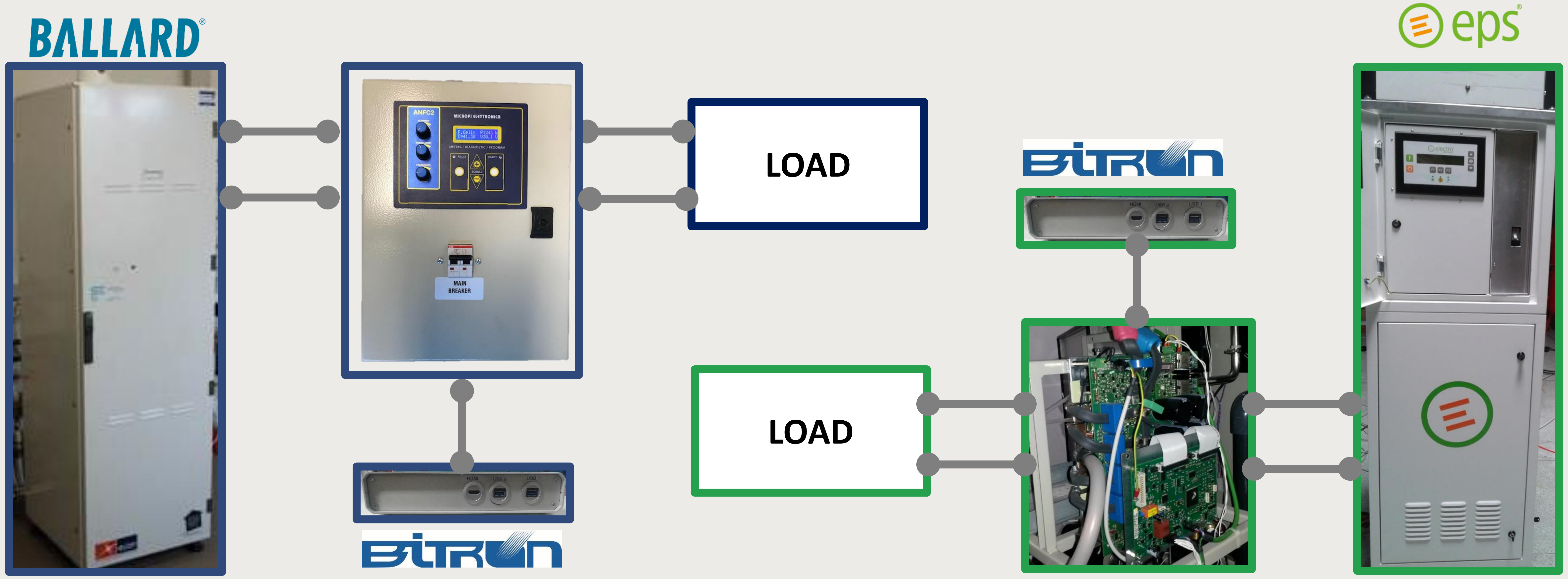




USEFUL GUIDELINES for companies

to implement the EIS board on industrial FC systems:

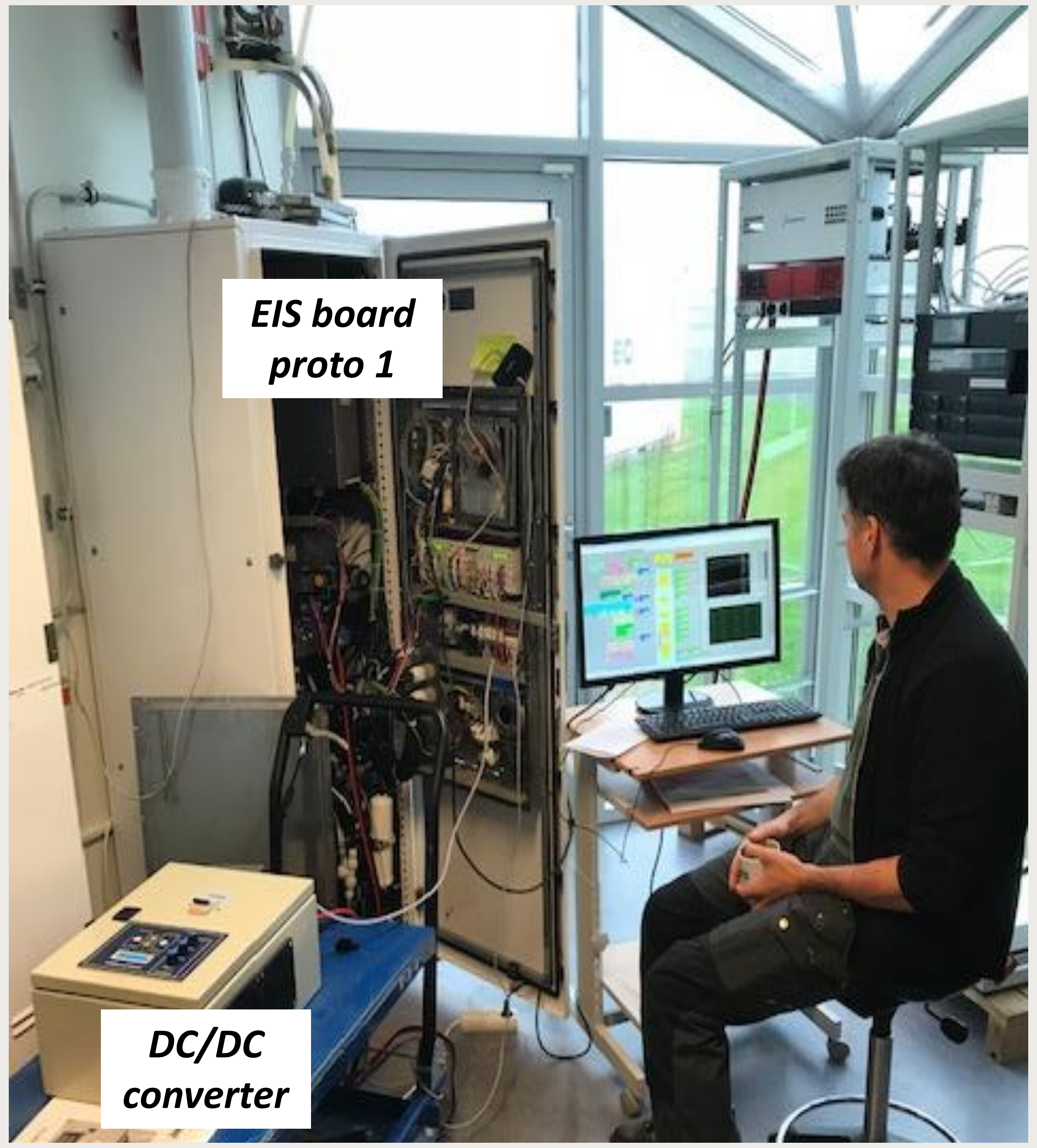
- **NEW DC/DC converter** (designed to interact with the EIS board)
- **ADAPT AVAILABLE converter** to allow the communication with the EIS board.



Sampling Frequency of EIS board up to about **18 kHz** to measure **up to 3 samples** per sinusoid **@6kHz** of injected disturbance.

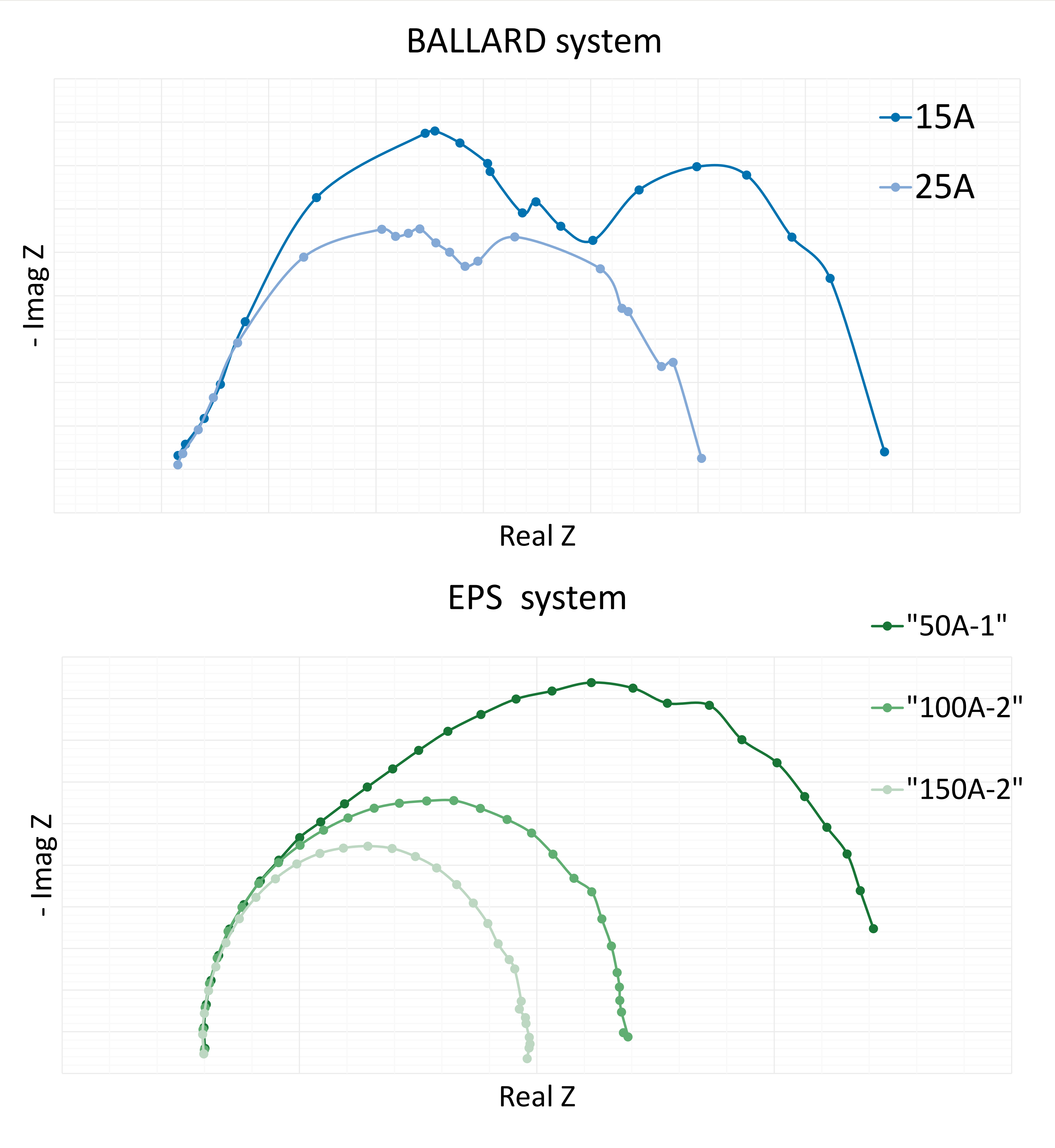
TESTED SYSTEMS

Ballard Europe µ-CHP system

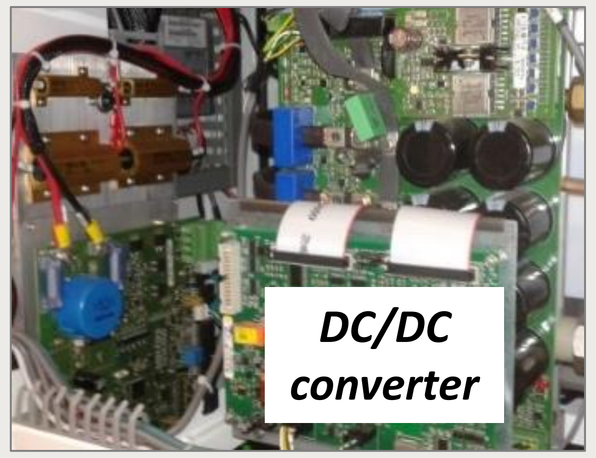


Power:	1.3 kW;
Cooling :	Water cooled;
Reactants:	**Air** & **Reformate**;
Applications:	Residential µ-CHP

ACQUIRED SPECTRA



EPS backup/energy system

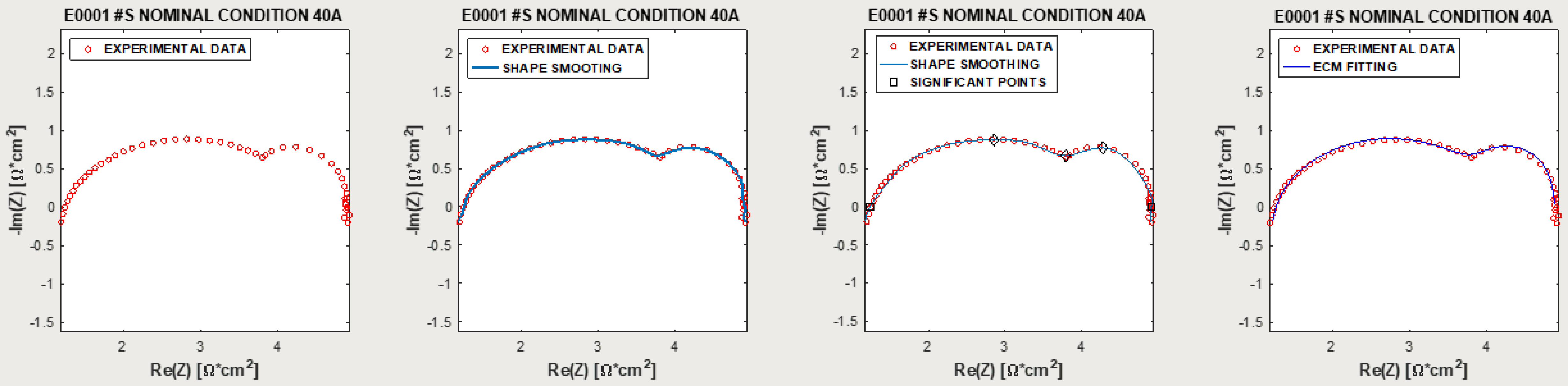


Power:	3 kW;
Cooling:	Water cooled;
Reactants:	**Oxygen** & **Hydrogen**;
Applications:	Backup electric power H_2 as energy buffer.

SW – ALGORITHMS AND TOOLS 1/2

Equivalent Circuit Modelling

EIS SPECTRA → SHAPE SMOOTHING → SIGNIFICANT EIS POINTS → ECM FITTING

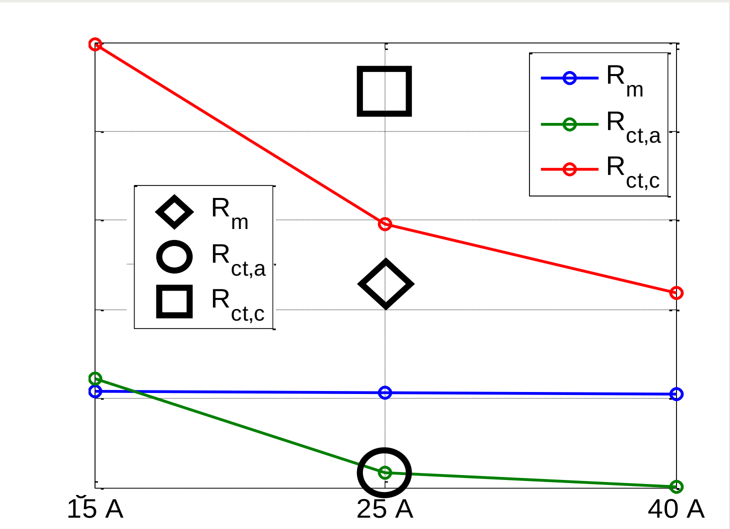


Change detection with nominal behaviour

EIS spectrum in **faulty condition**

↓

Parameters extraction ⇒



⇒ Fault Pattern

1
0
1

CHECK

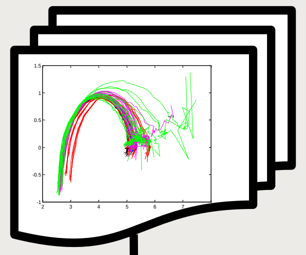
FSM		ECM PARAMETERS							
		R_m	$R_{ct,a}$	$R_{ct,c}$	C_a	Q	φ	R_d	τ
FAULTS	Flooding	0	0	1	-	-	-	-	-
	Drying	1	0	1	-	-	-	-	-
	Others	-	-	-	-	-	-	-	-

FAULT ISOLATION: DRYING

Patent implemented WO/2016/071801 (2016) – Method and apparatus for monitoring and diagnosing electrochemical devices based on automatic EIS.

Fuzzy Clustering approach

Algorithm Learning : Off-line



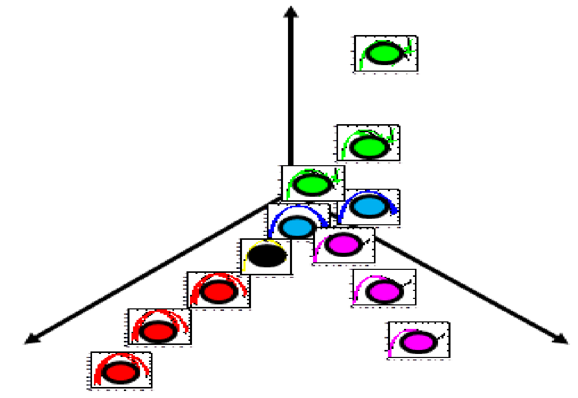
EIS learning data set

I] Automated features-selection

- I1: Normalization
- I2: Variance-Correlative Coef. analysis
- I3: Space dimension selection

II] Fuzzy clustering

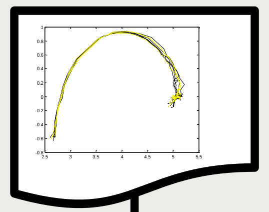
Clusters' definition



Save *data file*

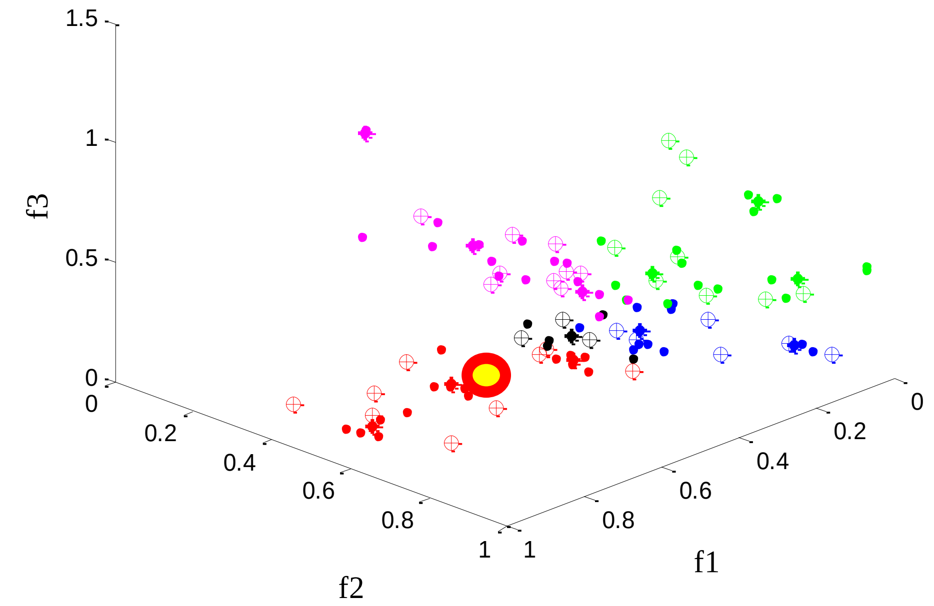
FDI : Off-line validation & On-board application

New EIS measurement



Data file → **Features' Normalization**

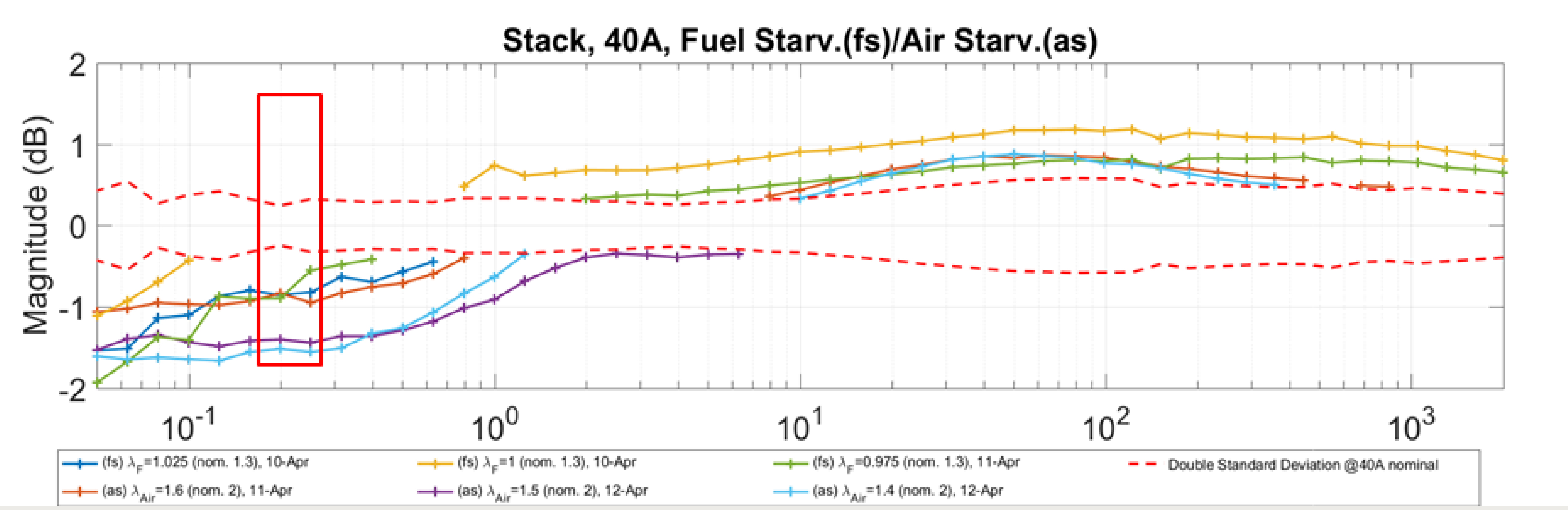
III] Classification & Decision making

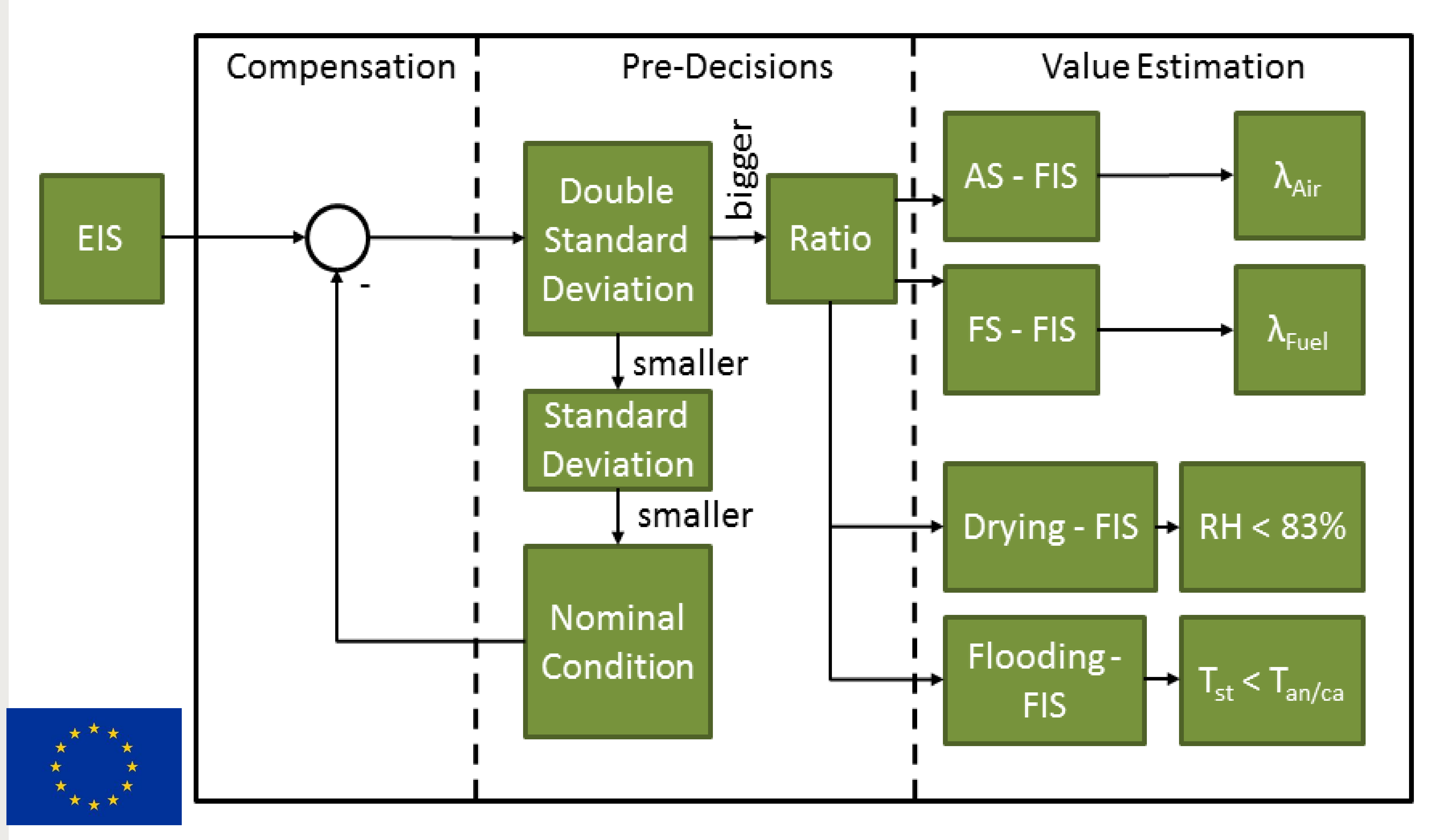


SOH Assessment

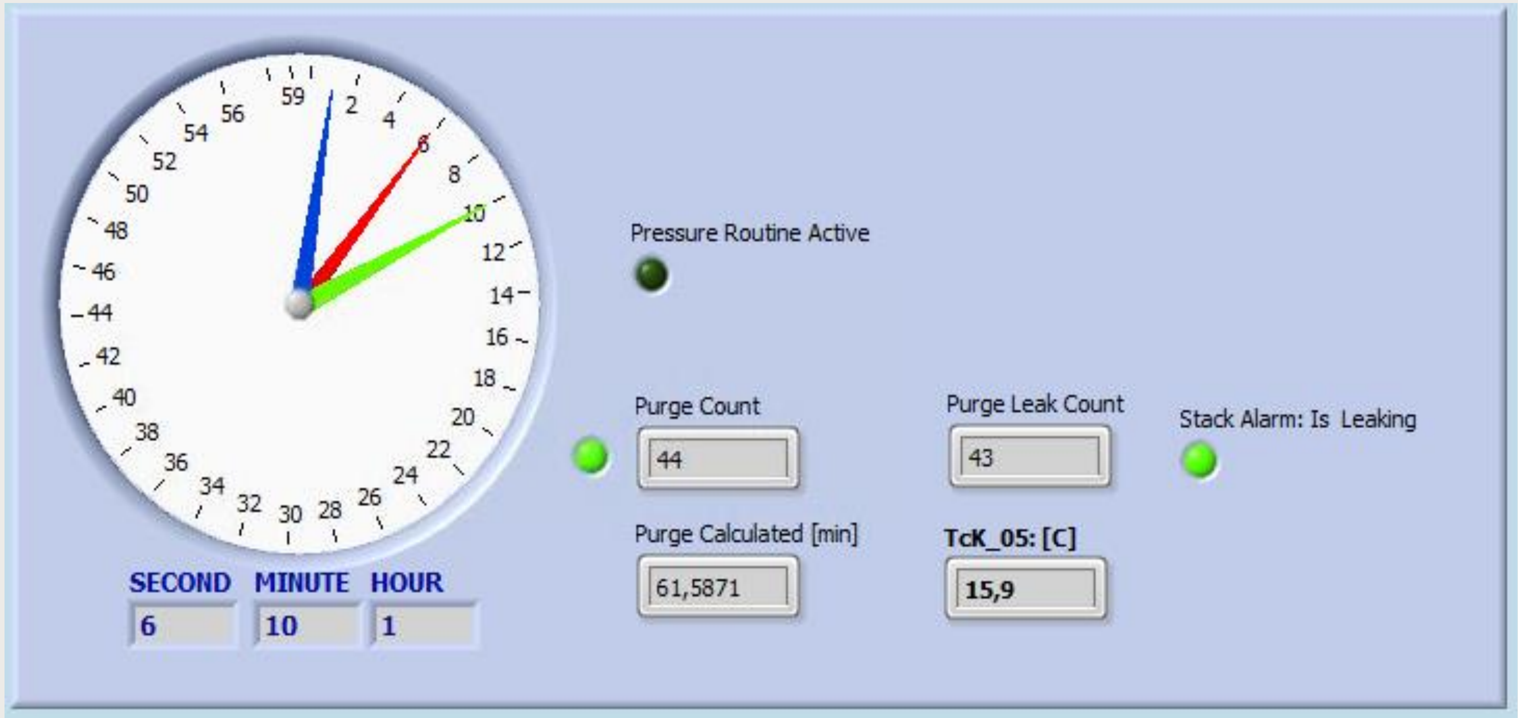
SW – ALGORITHMS AND TOOLS 2/2

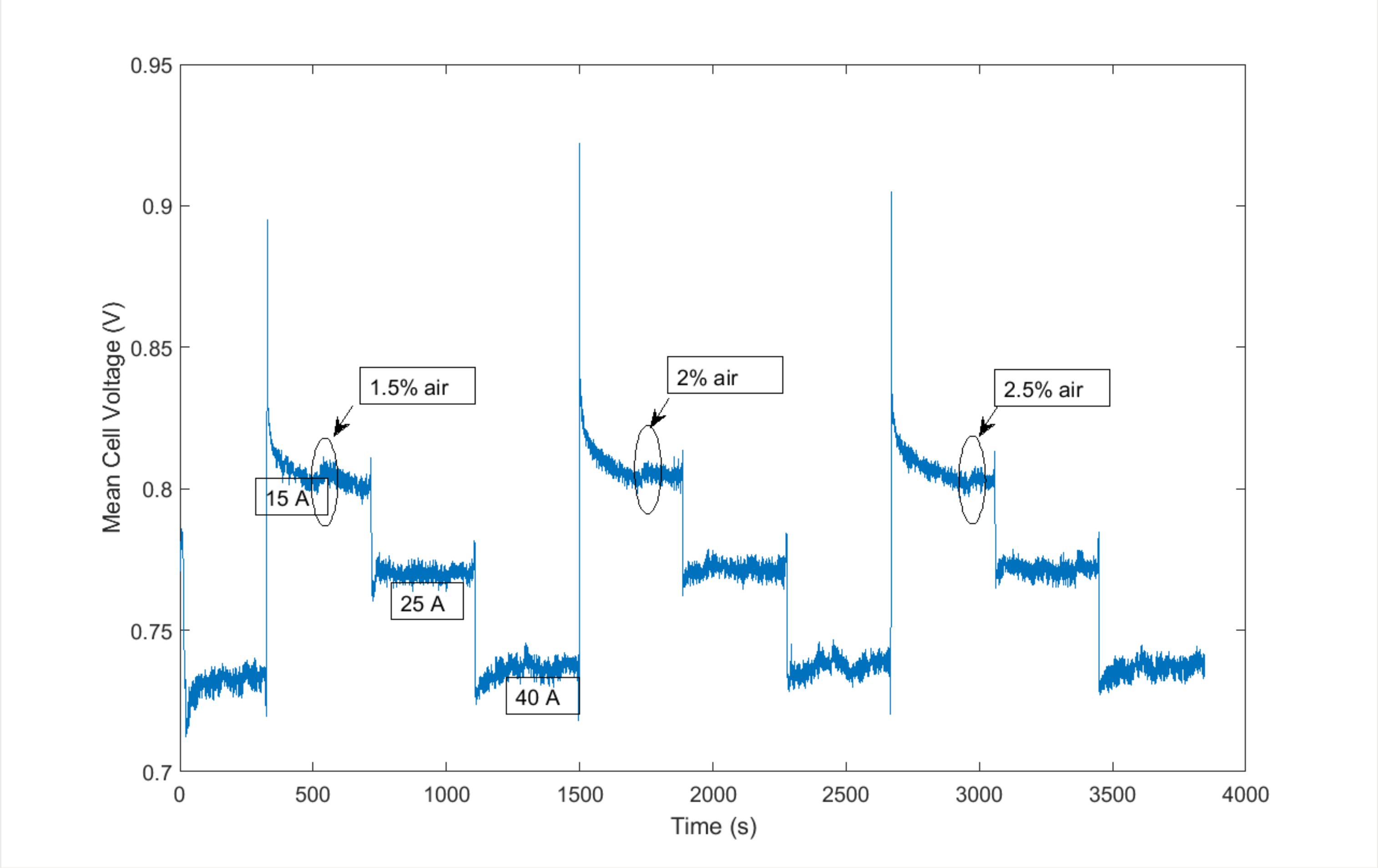
Adaptive Neuro Fuzzy Inference System

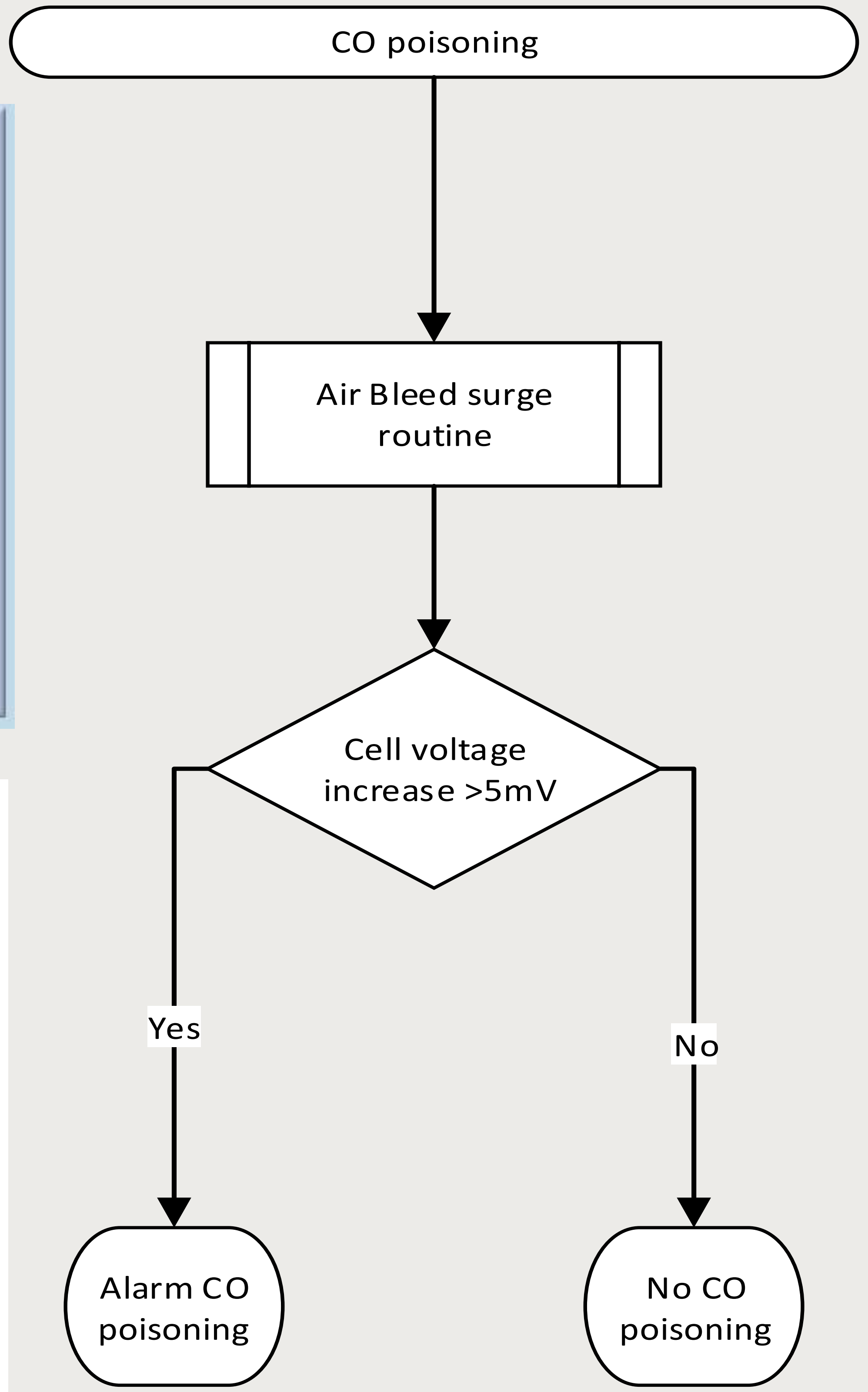




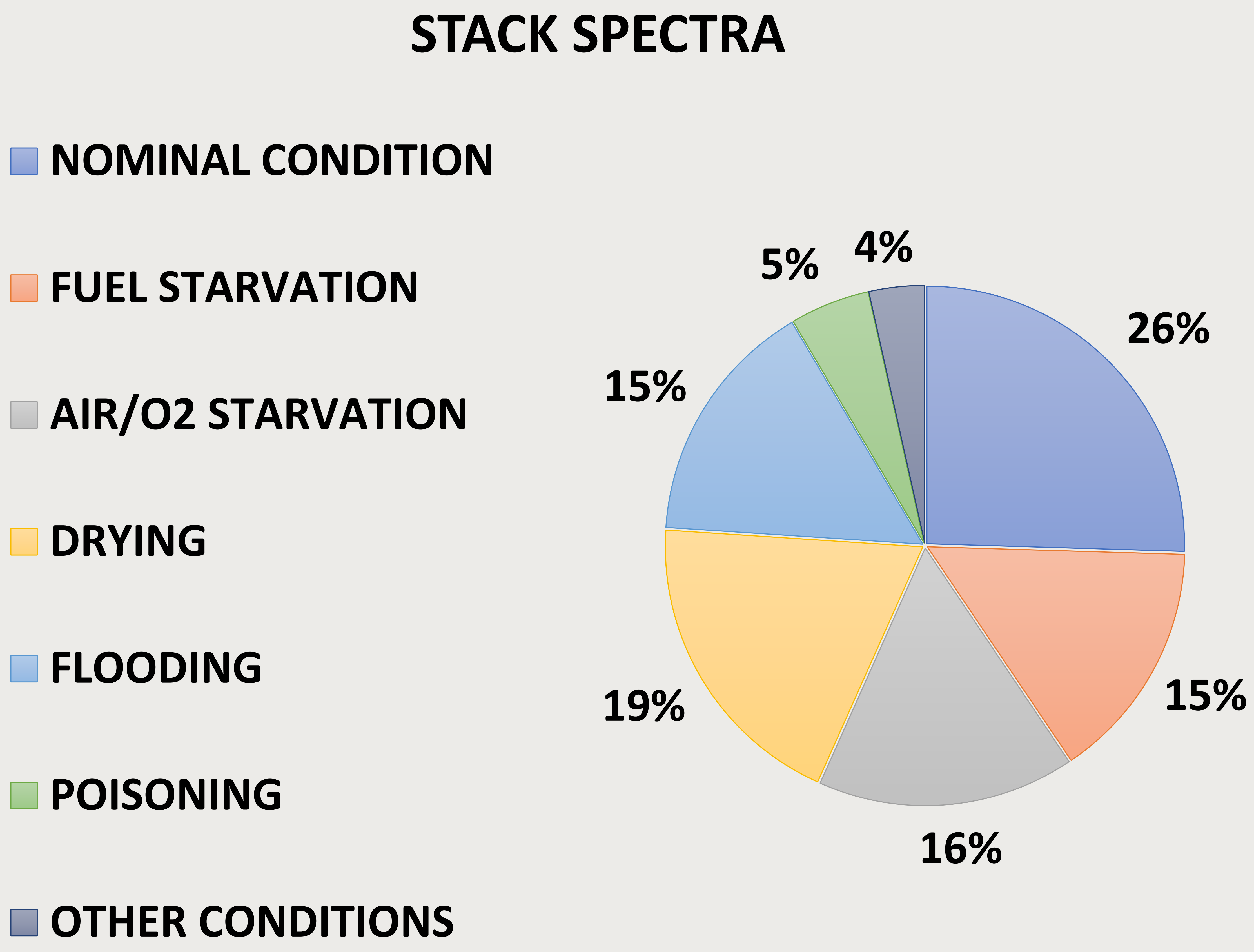
Active diagnosis







PRELIMINARY ANALYSIS ON DIAGNOSIS RESULTS



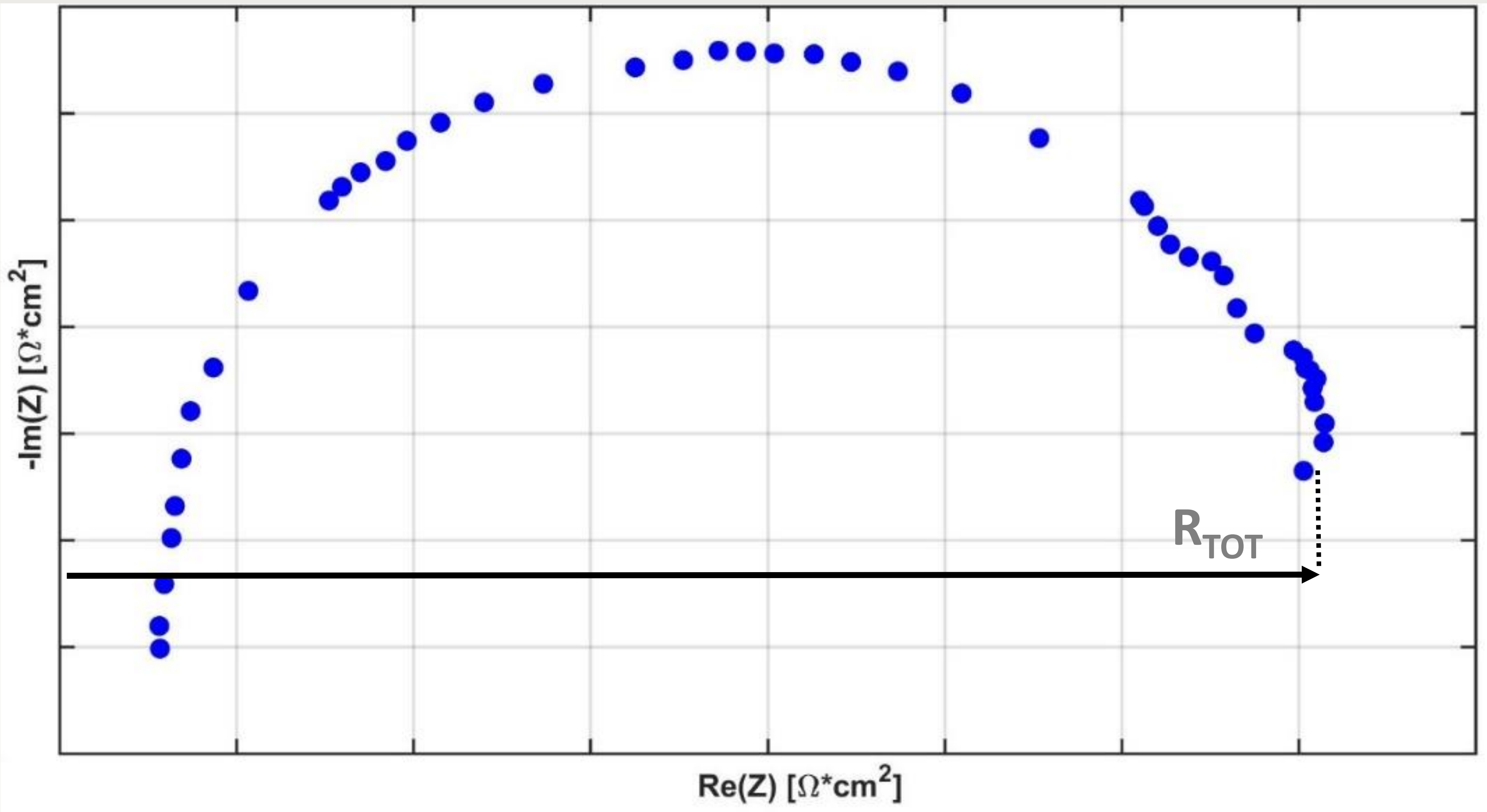
Diagnostic tools ver1	Ballard	EPS
Precision	87%	90%
Error	20%	20%

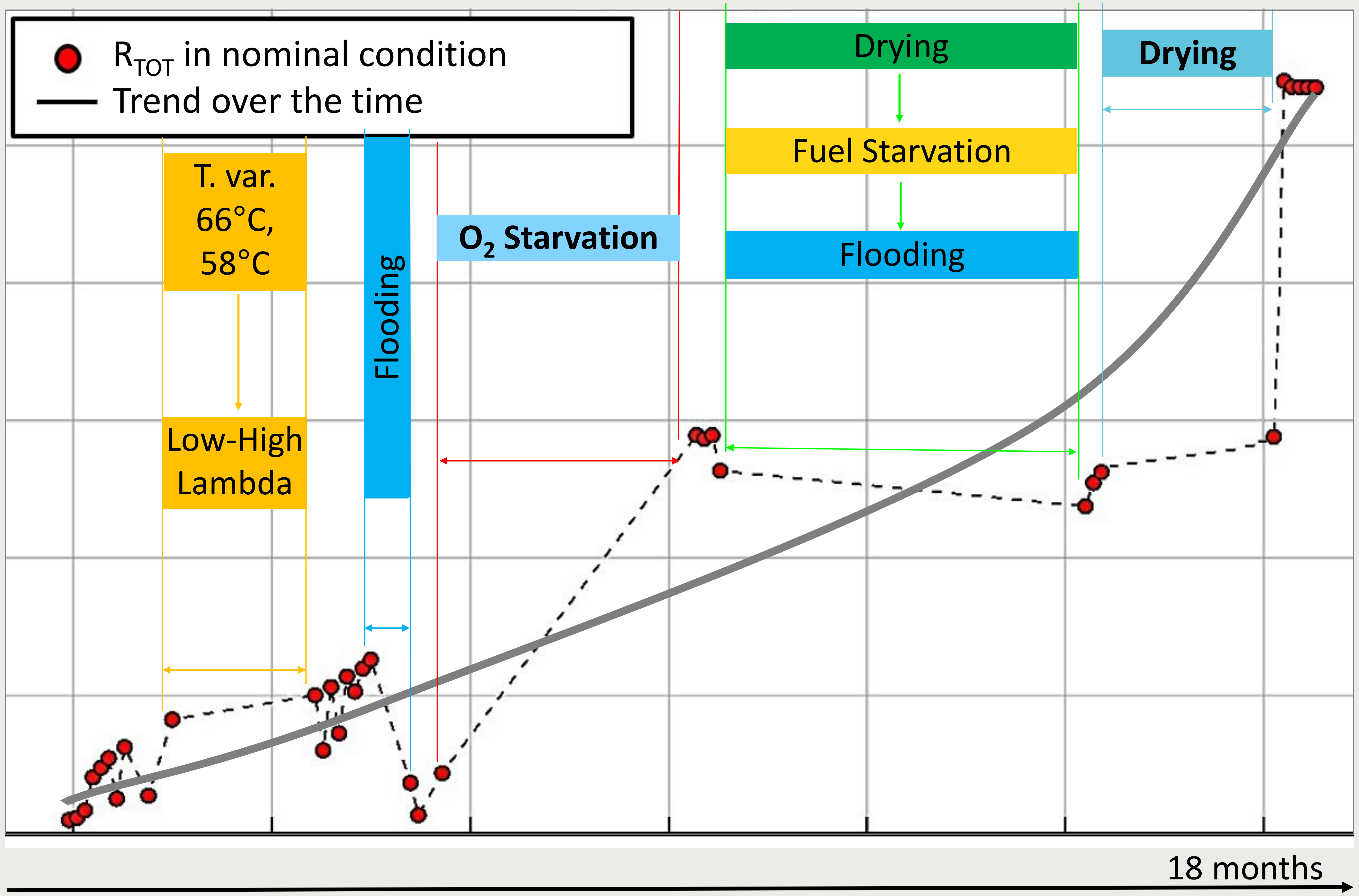
Version 1 of Diagnostic Tools
Version 2 is under assessment (better detection and threshold evaluation)

LIFETIME INFERENCE

ECM PARAMETERS							
L	R_m	R_{cpe1}	n_{cpe1}	F_{cpe1}	R_{cpe2}	n_{cpe2}	F_{cpe2}

R_{TOT}





IMPACT

The implementation of HEALTH-CODE **outcomes** will:

- help in increasing **electrical efficiency** and **durability** of the different fuel cells used for power production
- contribute to **reduce degradation** by implementing the monitoring and diagnostic tool
- lead to a reduction of total cost ownership (**TCO**) by increasing the FC system efficiency
- contribute to improve **grid stability** (with advanced monitoring) in the future by applying stationary fuel cells together with **energy storage**; the EPS backup system has grid interface for H_2 & O_2 production and can support grid balancing

Improvements **envisaged** by industrial partners BPSE and EPS are:

- **Lifetime** from B10-5 to B10-10 (BX-Y: X% of running systems will experience a fault in Y years)
- **Efficiency** from 32 to 36%
- **Availability** from 99.6% to 99.9%
- **Durability increase 30%**
- **Warranty condition** from 15000 h/1000 cycles to 20000 h/1500 cycles

DISSEMINATION ACTIVITIES

Papers (3 Published - 2 Under Submission)

DOI: 10.1002/fuce.201700112 — Fuel Cells — ORIGINAL RESEARCH PAPER

Characterization of an H_2/O_2 PEMFC Short-Stack Performance Aimed to Health-State Monitoring and Diagnosis▲

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[3] UNISA, DIIN, University of Salerno, Salerno, Italy

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Abstract

Proton exchange membrane fuel cell (PEMFC) is one of the most promising technologies in energy conversion. Nevertheless, improper operating conditions can severely affect the fuel cell (FC) lifespan. It is a matter of fact, that several degradation mechanisms could take place inside the cell in case of abnormal operating conditions. Among these, improper water managements, fuel quality and starvation conditions can show critical effects on PEMFC performance. Furthermore, if the exposure time to these faulty conditions resulted quite long, irreversible degradations and system ageing would occur. This work aims to investigate the impact of both improper water managements and reactants starvation conditions on H_2/O_2 PEMFC short-stacks performance. To this purpose, the experimental activity performed to characterize the stack health-state both in normal and abnormal conditions is presented. Particular attention is dedicated to the effects caused by improper conditions on stack electrochemical impedance spectroscopy (EIS) measurements' variations. Depending on the faulty conditions, the experimental results are then analyzed for health-state monitoring and diagnosis purposes.

Keywords: Diagnosis, EIS Spectra, Hydrogen/Oxygen PEM Fuel Cells, State-of-Health

Journal of Power Sources 353 (2017) 277–286

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

ELSEVIER

POWER SOURCES

Application of Buckingham π theorem for scaling-up oriented fast modelling of Proton Exchange Membrane Fuel Cell impedance

CrossMark

Luigi Russo, Marco Sorrentino*, Pierpaolo Polverino, Cesare Pianese

Department of Industrial Engineering, University of Salerno, Via Giovanni Paolo II, 132, 84084 Fisciano, SA, Italy

H I G H L I G H T S

- A methodology to reproduce PEMFC impedance is proposed.
- Non-dimensional parameters are defined by exploiting the Buckingham's π theorem.
- Good accuracy in PEMFC impedance prediction is proved.
- The possibility to use this methodology with scaling-up purposes is demonstrated.

A R T I C L E   I N F O

Article history:
Received 17 November 2016
Received in revised form
23 March 2017
Accepted 24 March 2017
Available online 10 April 2017

Keywords:
Electrochemical impedance spectroscopy
Proton exchange membrane fuel cell
Impedance modelling
Dimensional analysis
Scaling-up

A B S T R A C T

This work focuses on the development of a fast PEMFC impedance model, built starting from both physical and geometrical variables. Buckingham's π theorem is proposed to define non-dimensional parameters that allow suitably describing the relationships linking the physical variables involved in the process under-study to the fundamental dimensions. This approach is a useful solution for those problems, whose first principles-based models are not known, difficult to build or computationally unfeasible. The key contributions of the proposed similarity theory-based modelling approach are presented and discussed. The major advantage resides in its straightforward online applicability, thanks to very low computational burden, while preserving good level of accuracy. This makes the model suitable for several purposes, such as design, control, diagnostics, state of health monitoring and prognostics. Experimental data, collected in different operating conditions, have been analysed to demonstrate the capability of the model to reproduce PEMFC impedance at different loads and temperatures. This results in a reduction of the experimental effort for the FCS lab characterization. Moreover, it is highlighted the possibility to use the model with scaling-up purposes to reproduce the full stack impedance from single-cell one, thus supporting FC design and development from lab-to commercial system-scale.

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- **Generalized scaling-up approach based on Buckingham theorem for Polymer Electrolyte Membrane Fuel Cells impedance simulation**. Polverino, P.; Bove, G.; Sorrentino, M.; Pianese, C - ICAE2018, published on Energy Procedia – Selected for Applied Energy Special Issue submission.

Under submission: 2 journal papers on the state of the art of diagnostics techniques and PEMFC faults.

Conferences and events

- 6th Int. European PEFC & Electrolyser Forum 2017
- Electrochemical Science and Technology Conference and Annual Meeting of The Danish Electrochemical Society 2017
- IEEE, Vehicle Power and Propulsion Conference, 2017
- Fundamentals & Development of Fuel Cells, 2017
- 7th EFC "Piero Lunghi" Conference, 2017
- FCH2JU Review Days 2016 – 2017 – 2018

Students involvement

- 2 PhD students
- 1 master + 6 bachelor students

COMMUNICATIONS ACTIVITIES

www.pemfc.health-code.eu

Joint workshop HEALTH-CODE-DIAMOND Luzern (July 2017) - 6th EFCF

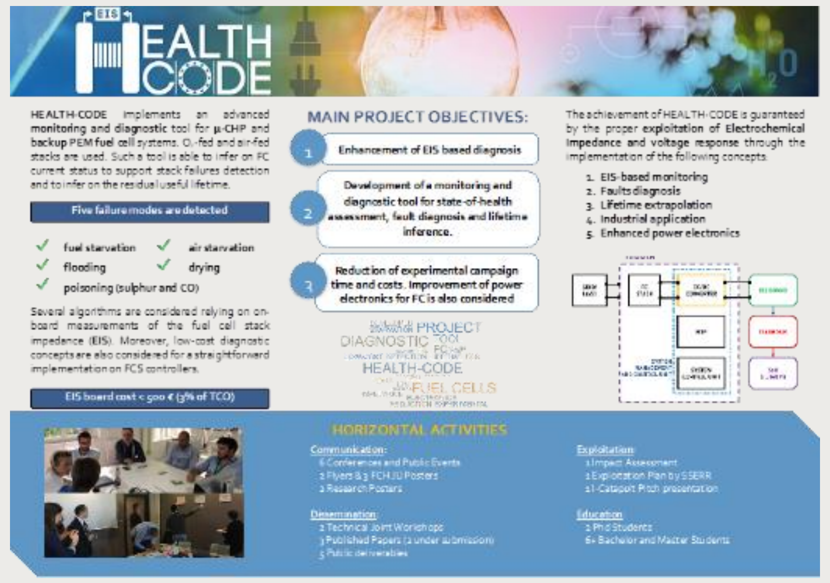
- 45+ Participants
- 16 presentations
  1 speech from industry
  1 special contribution
- 100+ Flyers distributed

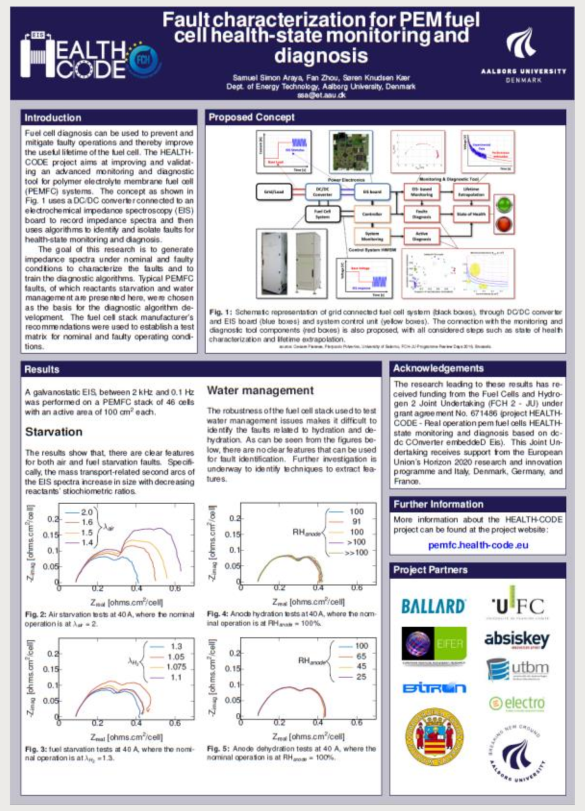
Joint workshop HEALTH-CODE-INSIGHT Brussels (November 2018) – PRD2018

- 70+ Participants
- 12 presentations (4 speeches from industry)
- Future exploitation focus

Communication materials

- 2 flyers & 3 FCH JU posters
- 3 posters
- 1 video (on-board EIS diagnosis) on the **website**





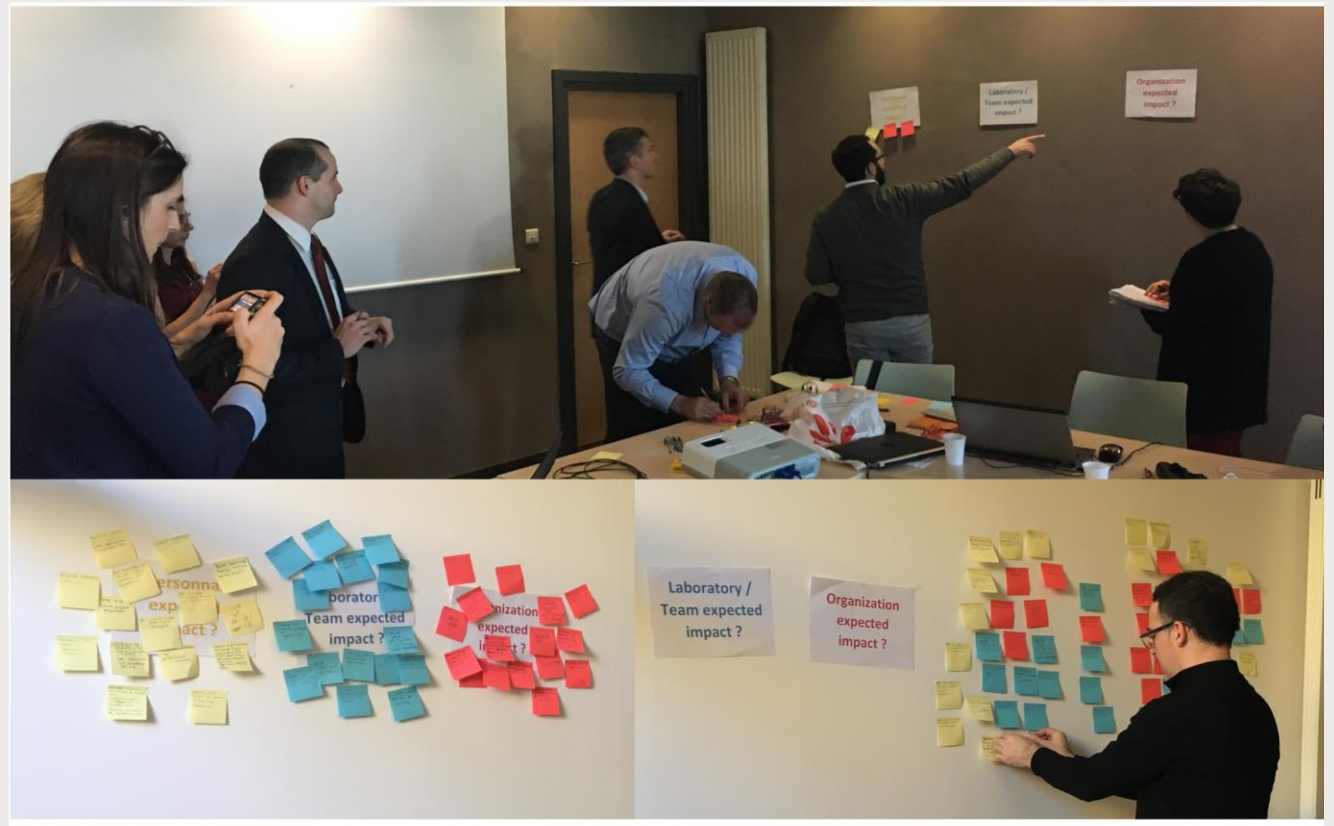
EXPLOITATION PLAN supported by

2+ potential industrial follow-up

SSERR
Support Services for Exploitation of Research Results

FCH – Fuel Cells and Hydrogen Joint Undertaking

Inputs for Business Plan



M18 Impact assessment Belfort (FR)

I-CATAPULT 2018 EIFER innovation challenge

I-Catapult 2018
Catapult your ideas!

M37 SSERR exploitation Turin (IT)

"How to turn concept into Business"

The Lean Canvas | Health-Code project | 21-sep-2018 | Iteration #1 LABS

Problem
Top 3 problems
- Expensive, large and complex equipments
- Quality of measurments
- To many device

AlternativeSolutions
- Impedance device manufacturers

Solution
Top 3 features
- Algorithm (SW)
- B. board (HW)
- Converter (HW)

Key Metrics
Key activities you measure
- Time of processing
- Number of fails
- Accuracy index

Unique Value Proposition
- Providing data analysis autonomously and custom made for the FC sector

Unfair Advantage
Can't be easily copied or bought
- Patent

Channels
- Direct contacts (IT, FR, DK, DE)
- Fairs
- Papers
- Expo. Within conferences
- Academic connections

Customer Segments
Target customers
- University labs
- Company labs
- End of Line (EoL) test rigs

Early adopters
- Fuel Cell technicians
- Spin off

Cost Structure
- people
- distribution
- administration
- patents
- facilities
- IT
- HW
- Support

Revenue Streams
- Sell the device (HW)
- License the algorithm (SW)

PRODUCT | MARKET

FUEL CELLS AND HYDROGEN
JOINT UNDERTAKING

EIS HEALTH CODE

Real operation pem fuel cell HEALTH-state monitoring and diagnosis based on DC/DC COnverter embeddeD Eis

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Thank You!