VTS for On-board charger

Hexagon case study

NEWTWEN

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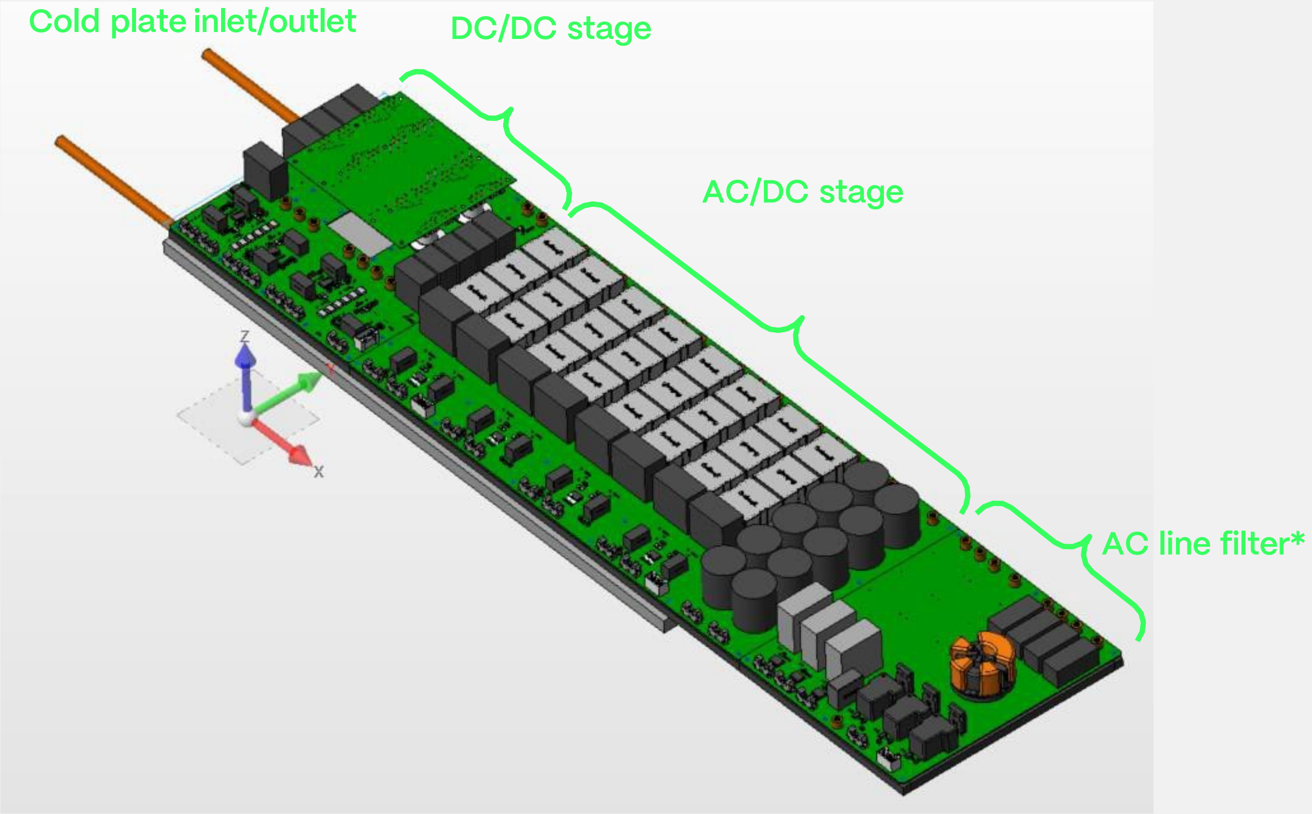
Description of the case study

Case Study

Hexagon Applied Solutions On-Board-Charger (OBC)



*For the first prototype, 3 separate PCBs were designed and manufactured for the 3 OBC stages.

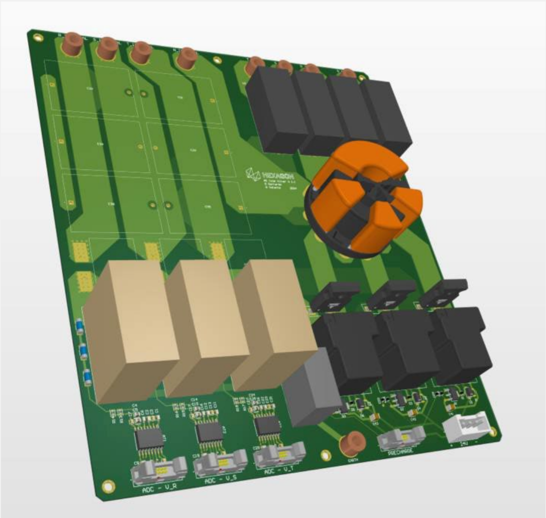
Parameter	Value/description
Power	11 kW
Voltage AC side	230 Vac (ph – N)
Voltage DC side	400 / 800 Vdc
Number of phases	1ph / 3ph
Power flow	Bi-directional power flow
Cooling	Water cooling
Power devices technology	Discrete SiC MOSFETs

Description of the case study

Case Study

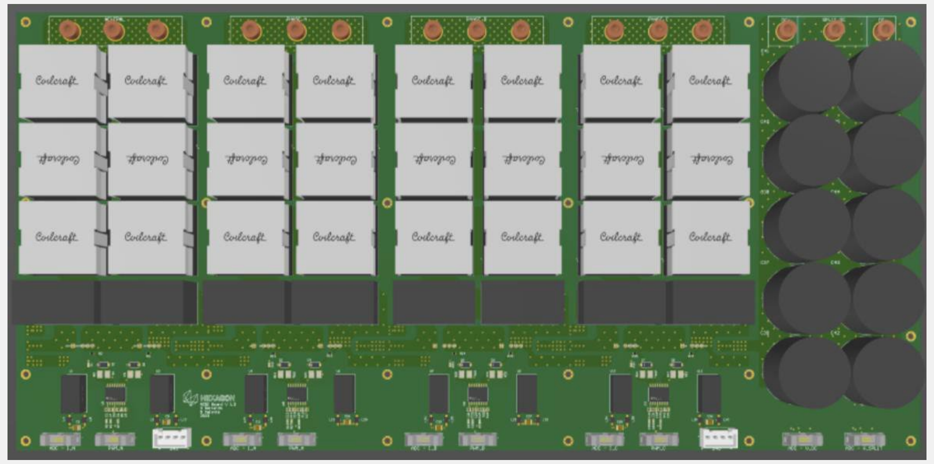
Hexagon Applied Solutions On-Board-Charger (OBC)

AC line filter



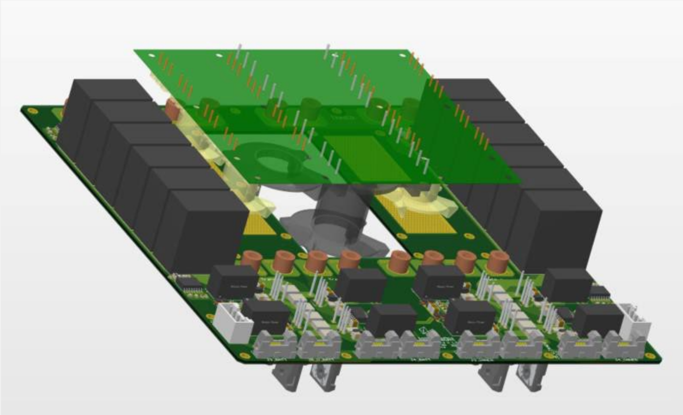
- LCL filter
- Common mode choke
- Pre-charge circuit
- Protection fuses

AC/DC stage



- 3ph full bridge with neutral
- SiC MOSFET technology

DC/DC stage



- Full bridge CLLLC topology
- Bi-directional power flow
- Reconfigurable transformer for 400 and 800V batteries

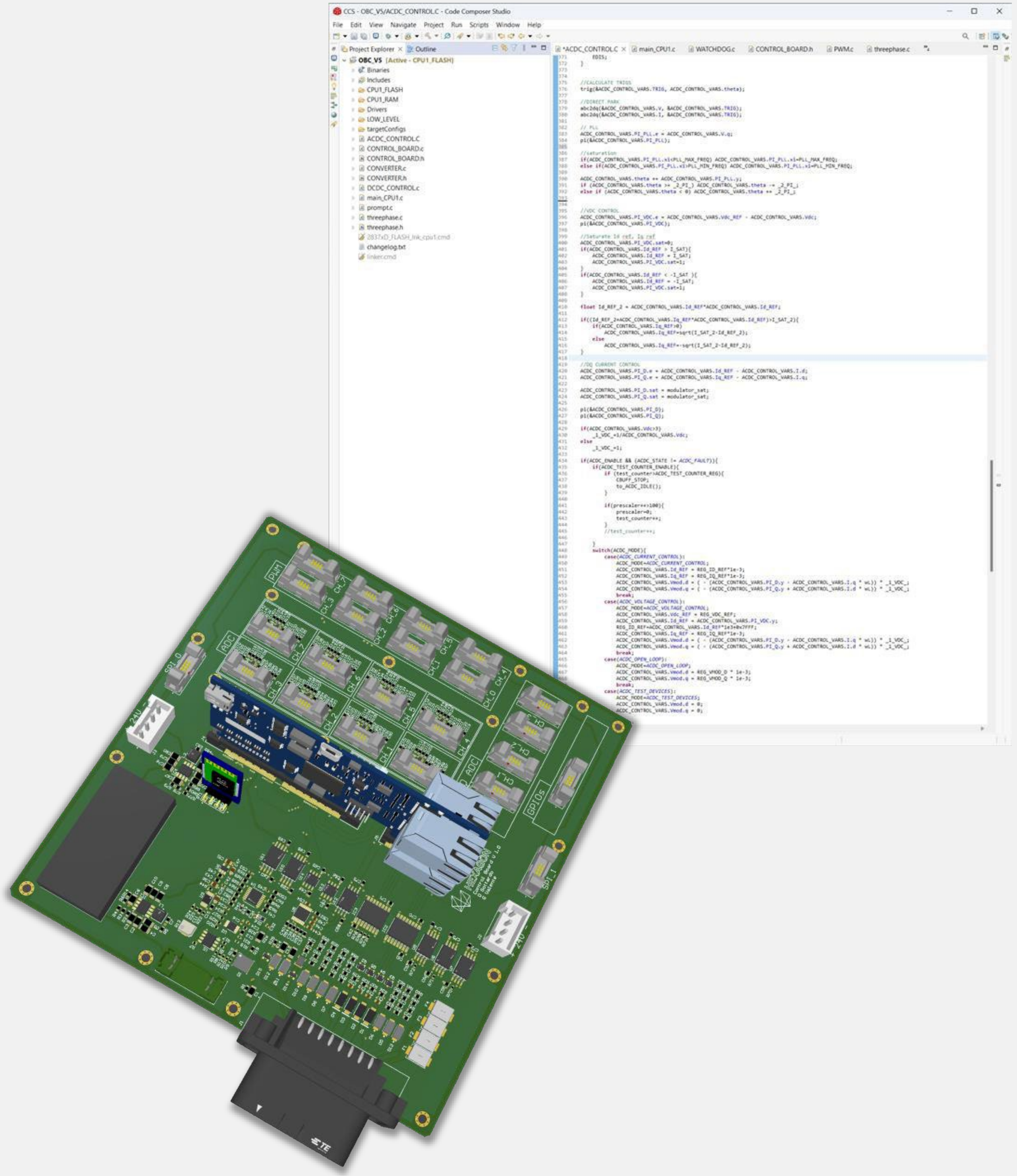
Description of the case study

Case Study

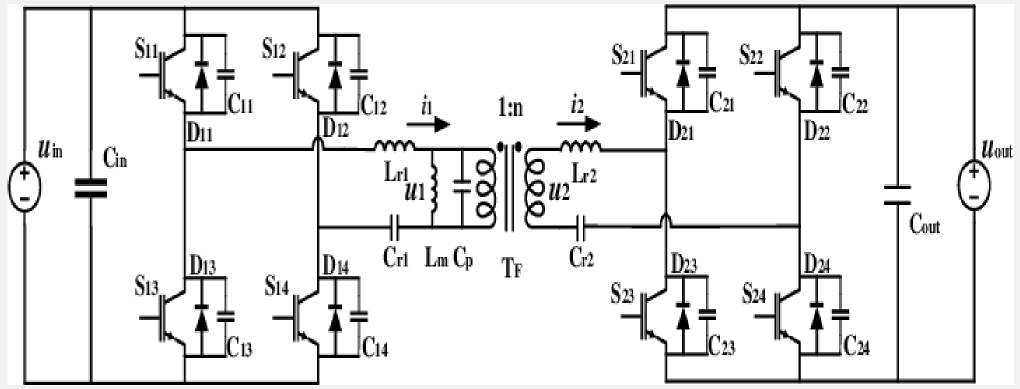
Hexagon Applied Solutions On-Board-Charger (OBC)

Control board and software development

- Based on Texas Instrument C2000 DSP.
- Fully flexible design (8x ADC inputs, 4x Sigma delta ADC digital inputs, 8x PWM outputs).
- 14-pins automotive connector (with additional analog&digital inputs and outputs), CAN bus connectivity, interlock circuit.
- In-house software development including base software layer and application layer.



Description of the case study

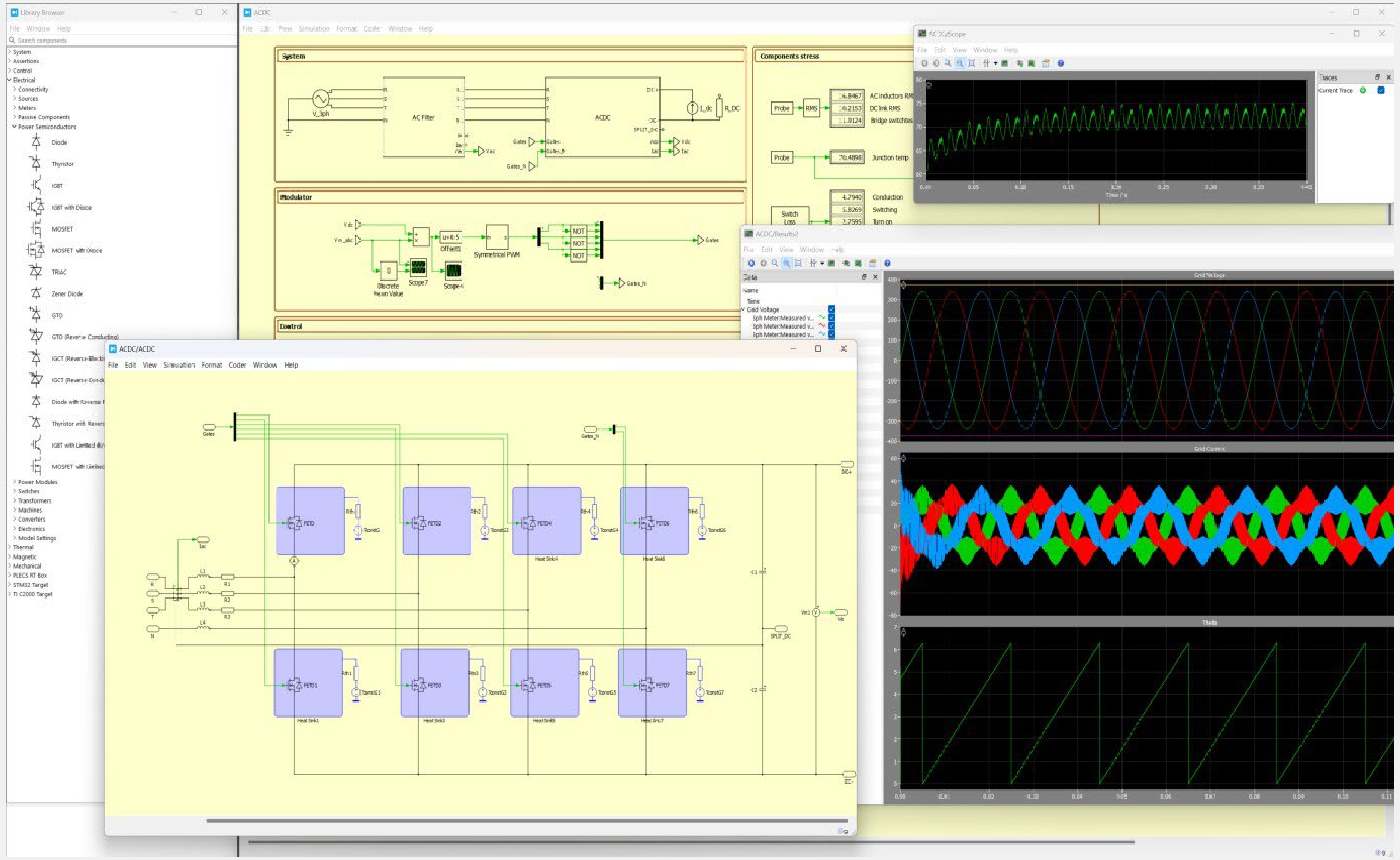


Case Study

Hexagon Applied Solutions On-Board-Charger (OBC)

Preliminary design and controller tuning

- Topology selection.
- Script-based optimization of the AC/DC and DC/DC passives with PLECS.
- Control design and behavioral model using PLECS.
- Validation of DSP control code via c-script block.



Thermal analysis

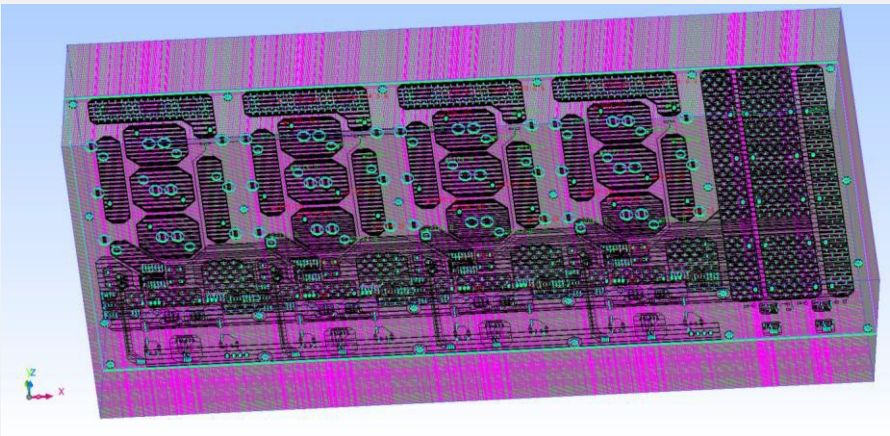
Thermal analysis

PCB Thermal analysis

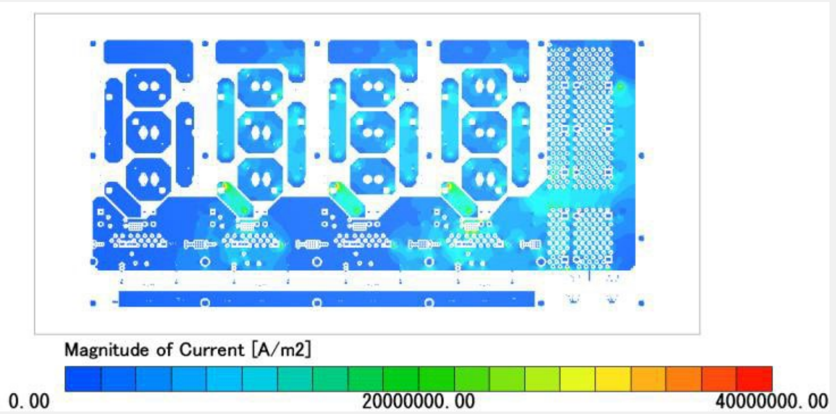
Preliminary design and controller tuning

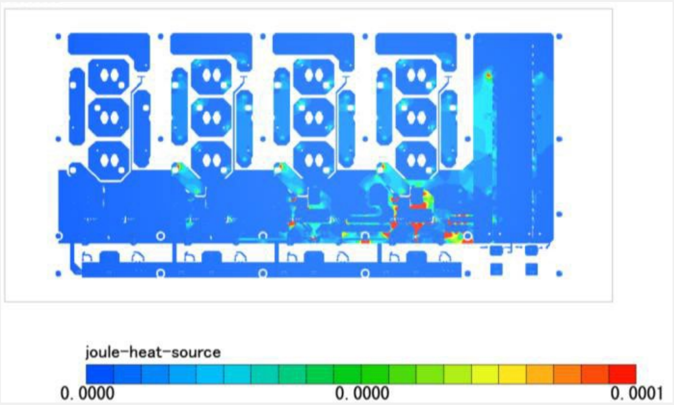
- The PCB routing was imported as gerber files which were generated from the Altium project.
- The PCB has 6 layers, so a total of 6 gerber files were imported.
- The current analysis was executed within scStream in order to calculate the Joule losses to be used in the thermal analysis.

Gerber file import in scStream



Current density and Joule losses calculated by scStream



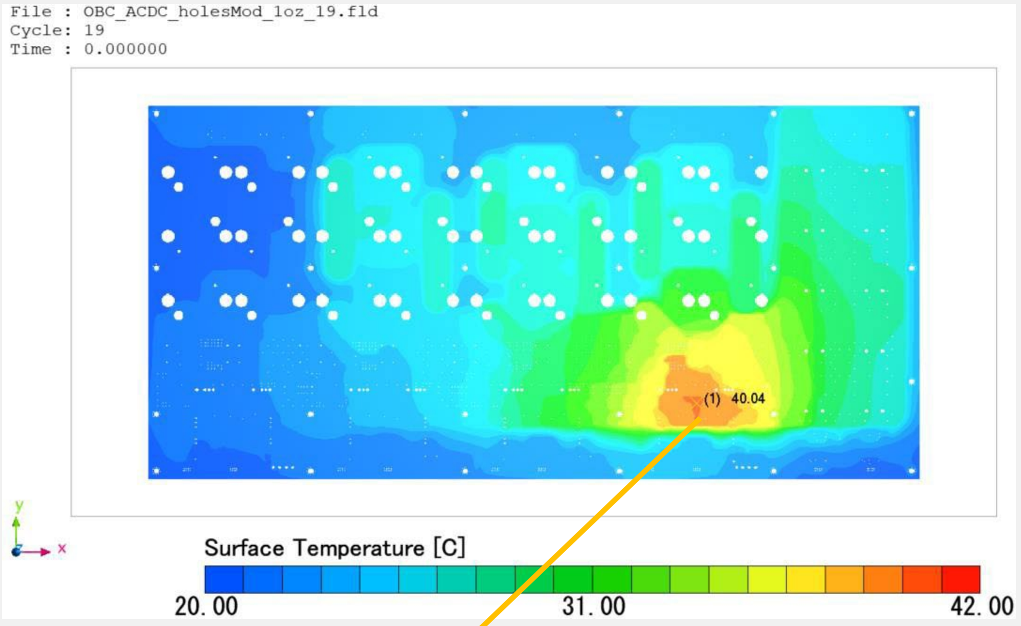


Thermal analysis

Thermal analysis

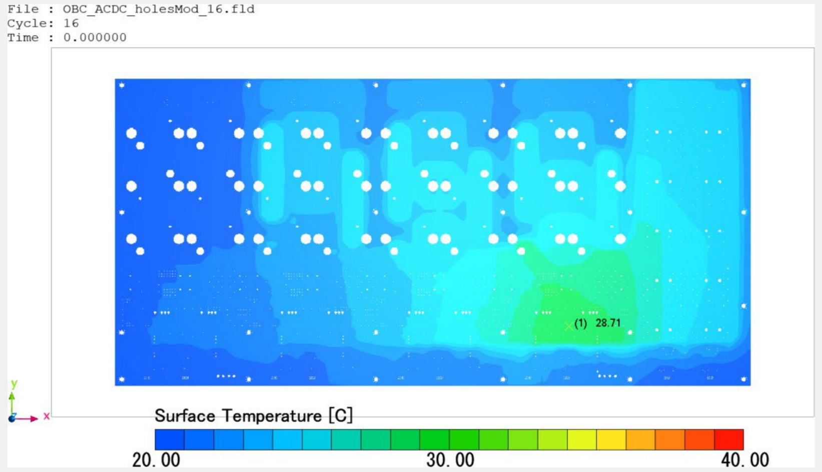
PCB Thermal analysis

Initial design with 6 layers, all with the same thickness (35um)



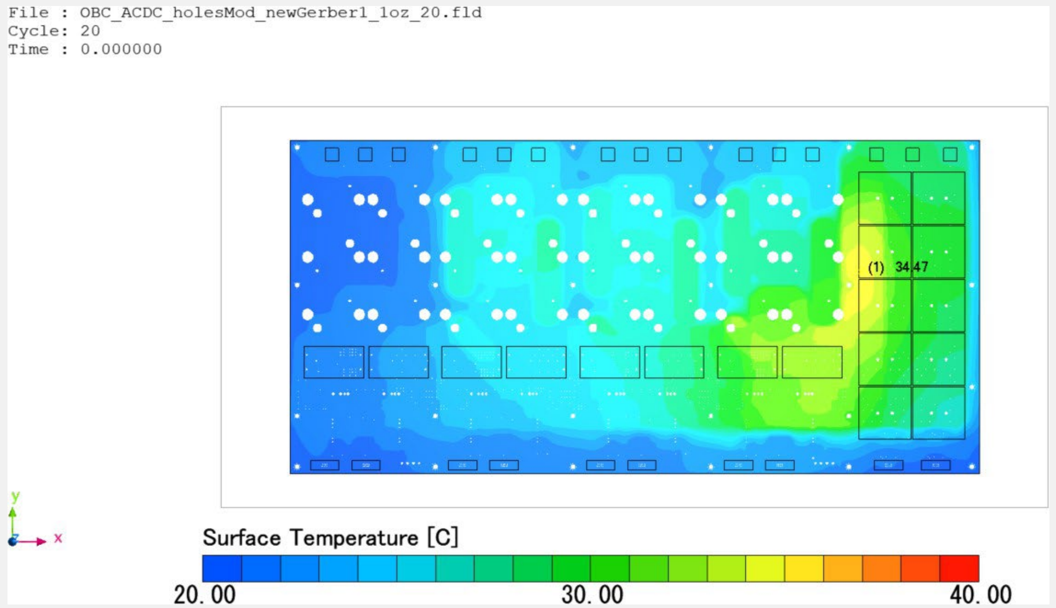
High delta temperature (around 20degC)

Option 1: keep the same PCB routing and increase the thickness to 70um



Less copper = cost saving

Option 2: keep the same PCB thickness (35um) and optimize the routing to remove current choke points

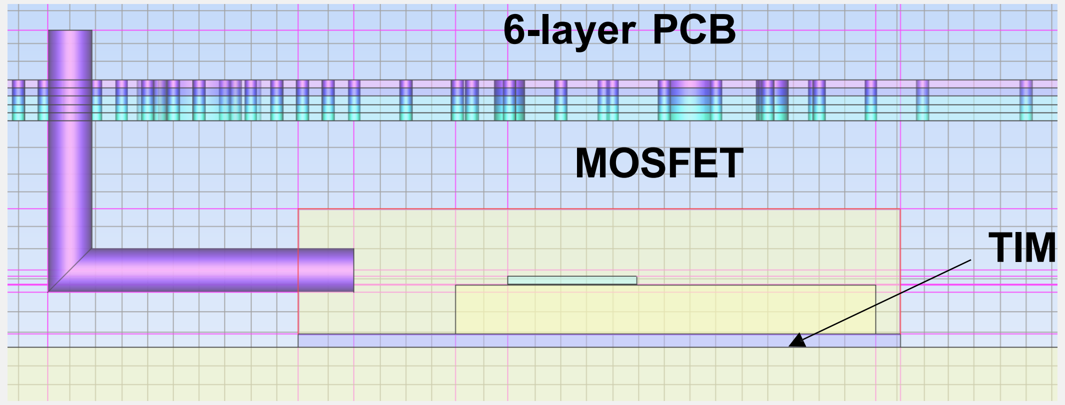


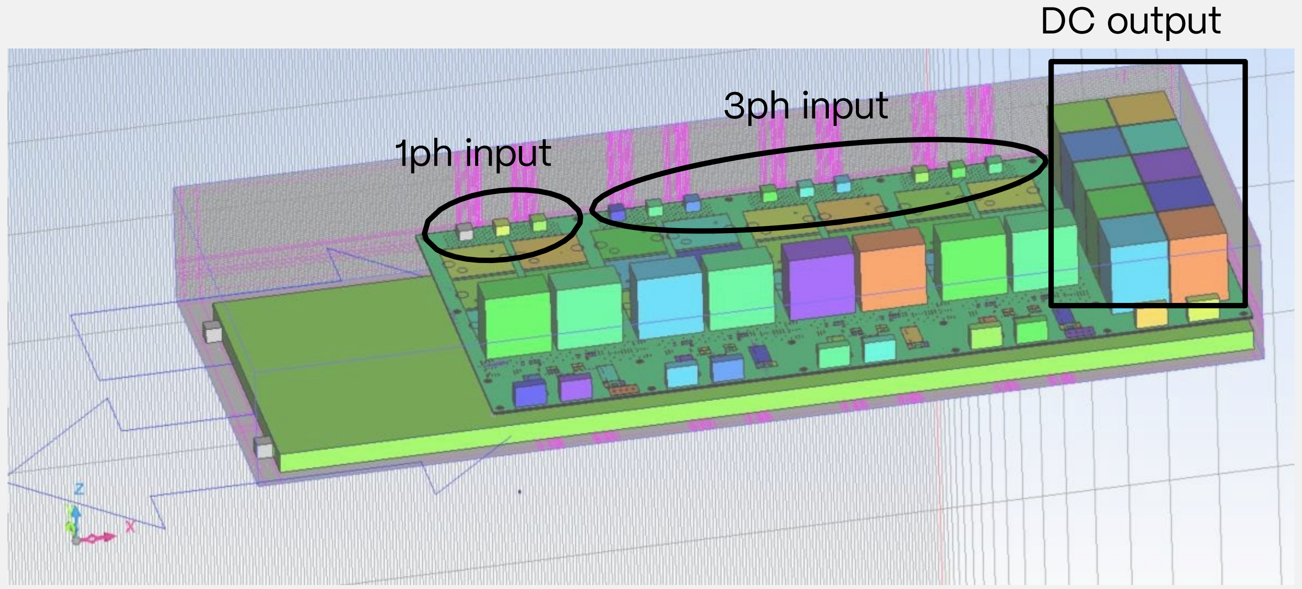
Thermal analysis

Thermal analysis

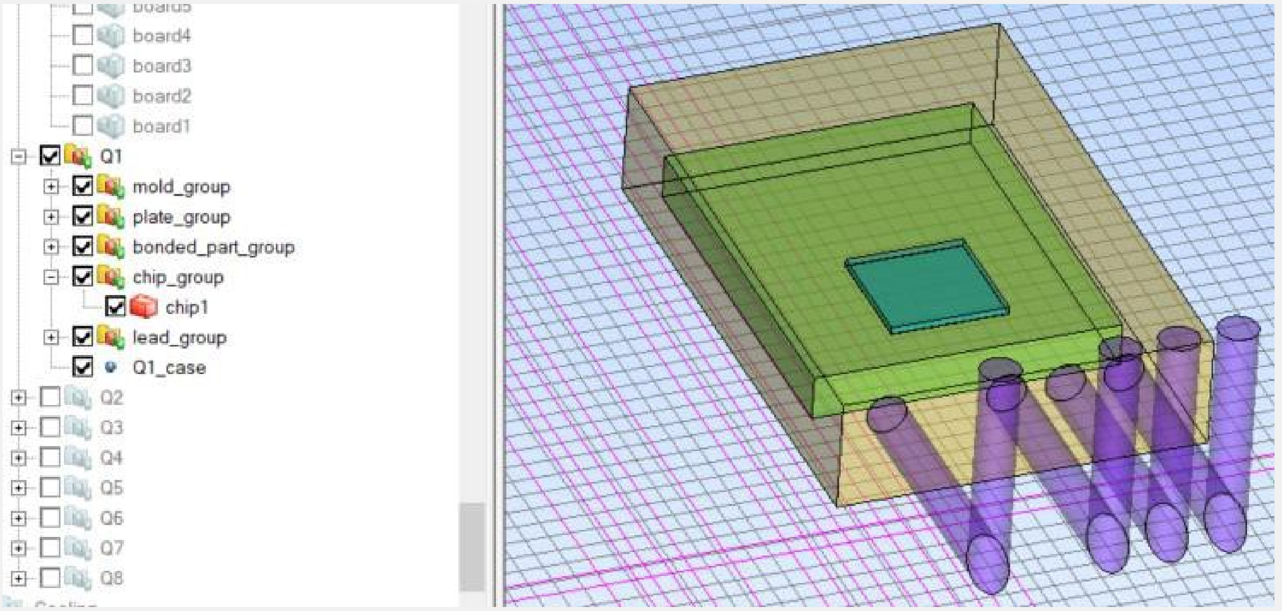
Thermal analysis on the full converter

- The AC/DC stage of the OBC was imported as an IDF file which was generated from the Altium design project .
- The internal parts of the MOSFETs are modelled within scStream.
- The MOSFET components are: the mold, the plate, the leads, the chip (where the losses are applied) and the bonding between chip and the plate
- A 0.5mm layer of TIM was placed between each MOSFET and the cold plate.





MOSFET (TO-247-4) model

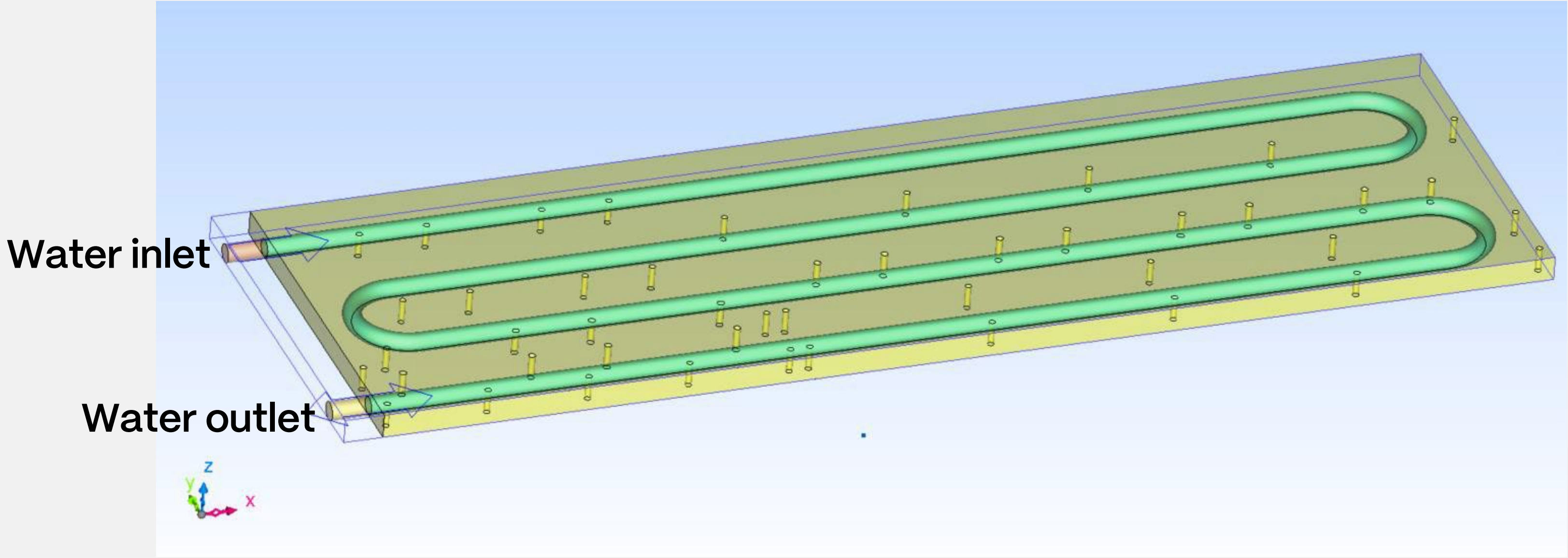


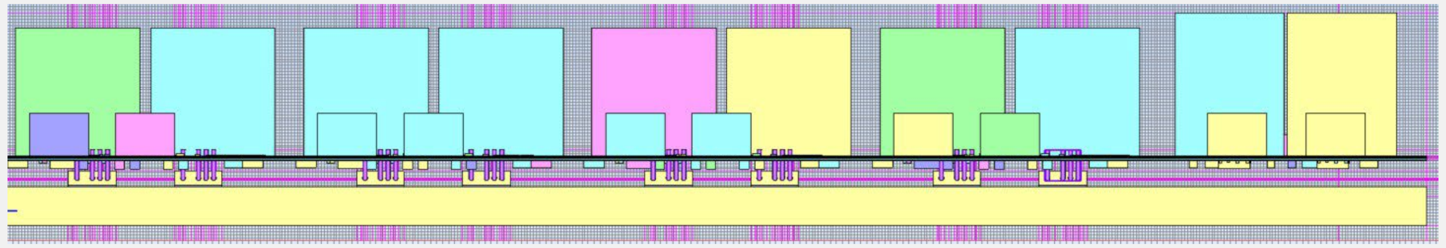
Thermal analysis

Thermal analysis

Thermal analysis on the full converter

- A water-cooled cold plate with 4 passes was built in scStream.
- The water flowrate and inlet temperatures are:
- Flowrate = 5 lpm
- Inlet temperature = 60degC
- The MOSFETs were mounted on top of the coldplate.



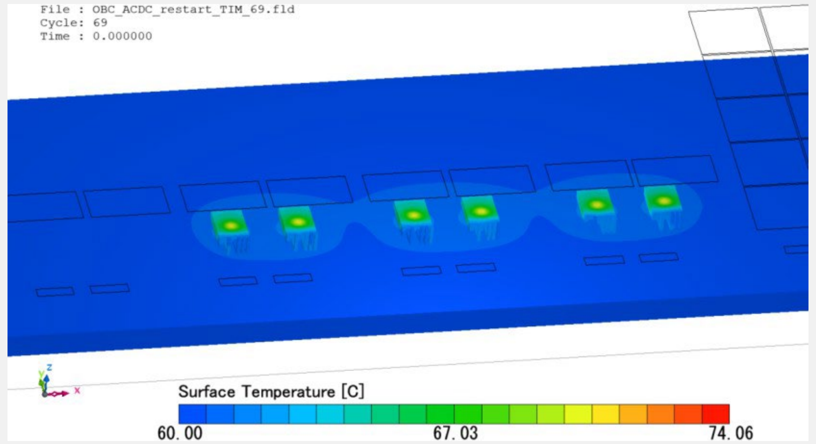


Thermal analysis

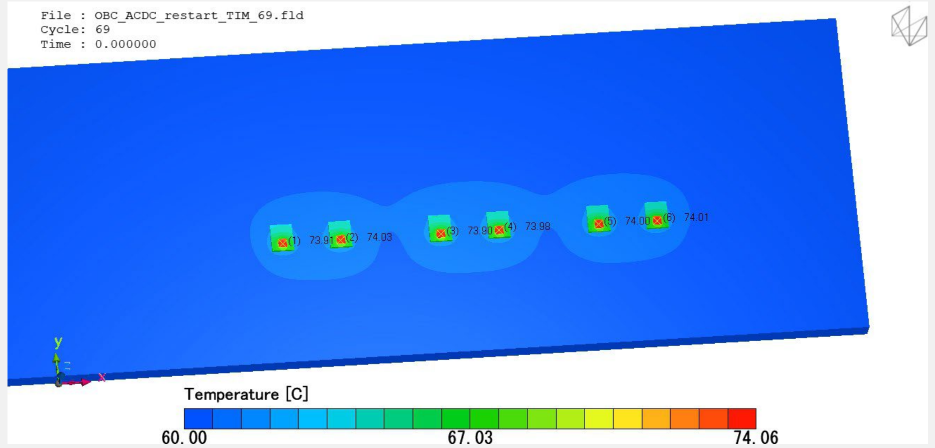
Thermal analysis

Thermal analysis on the full converter

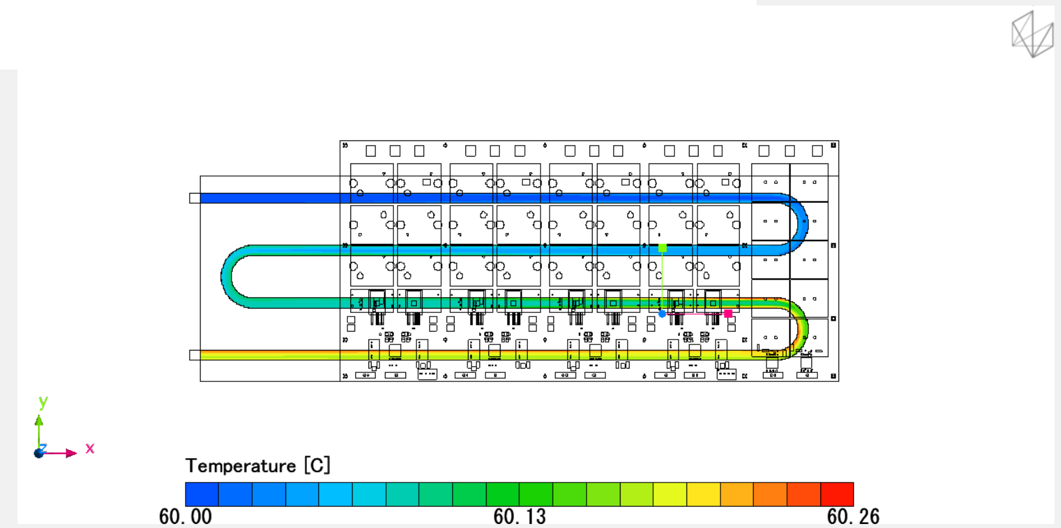
Temperature on the case of the MOSFETs



Temperature on the chip area of the MOSFETs



Temperature of the cooling water

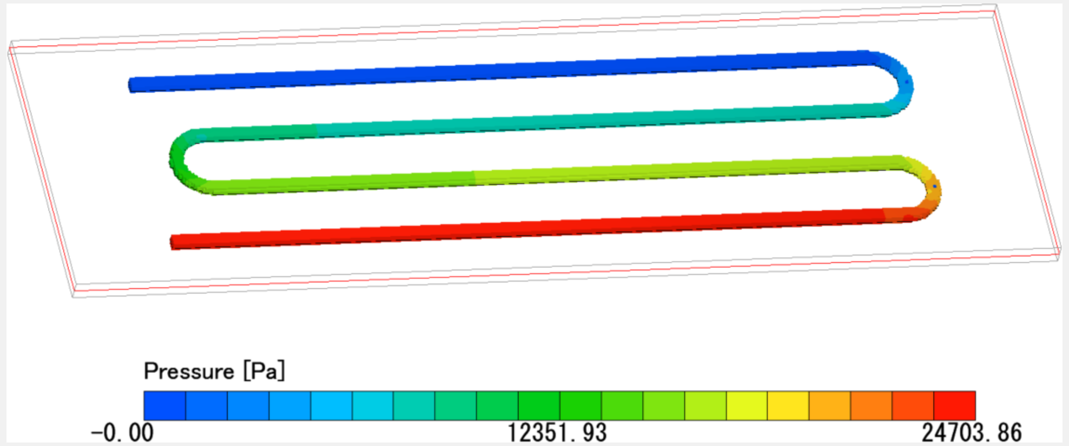


Thermal analysis

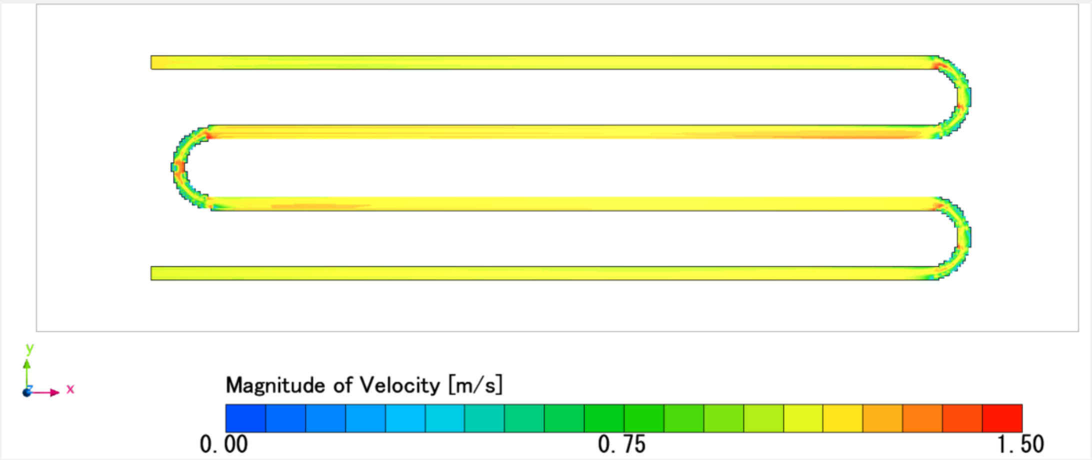
Thermal analysis

Thermal analysis on the full converter

Pressure distribution in the cooling pipe

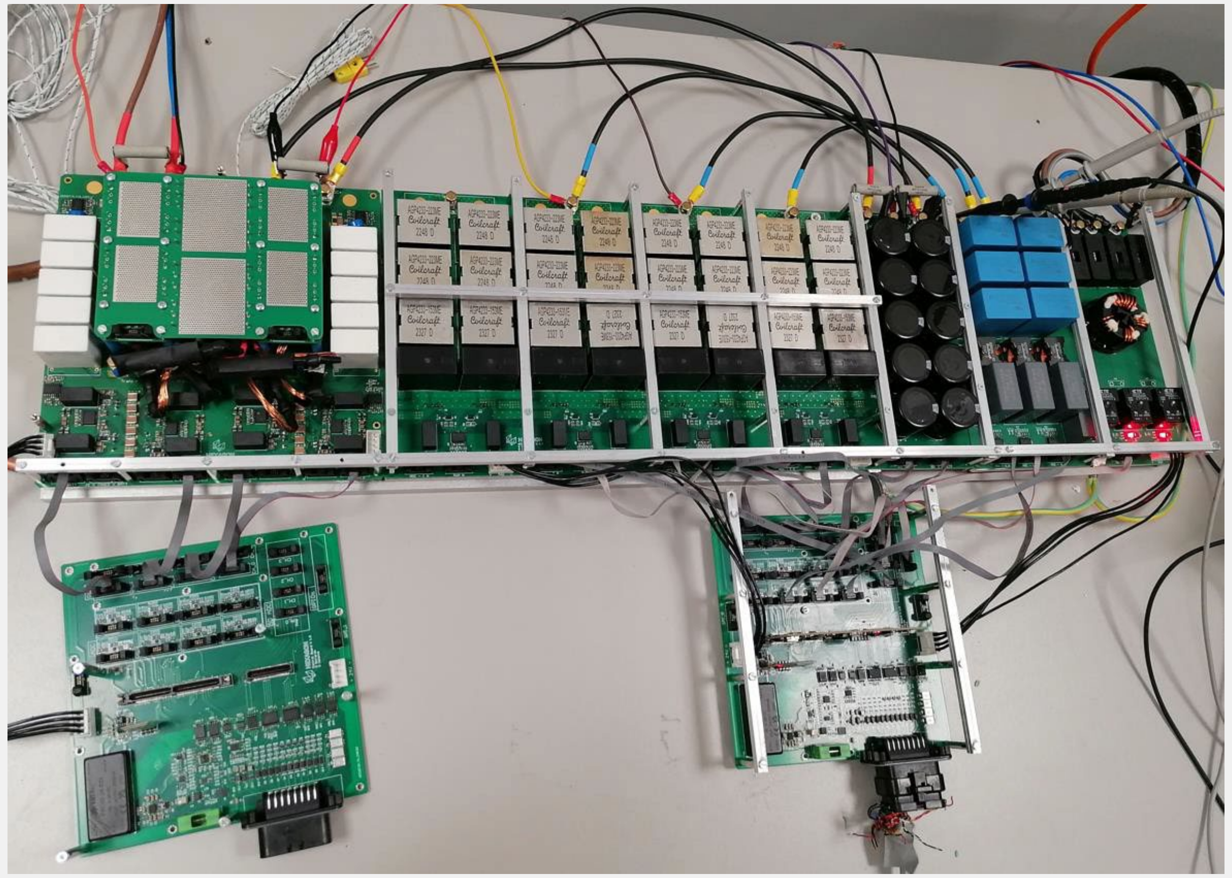


Velocity field in the cooling pipe



Experimental tests

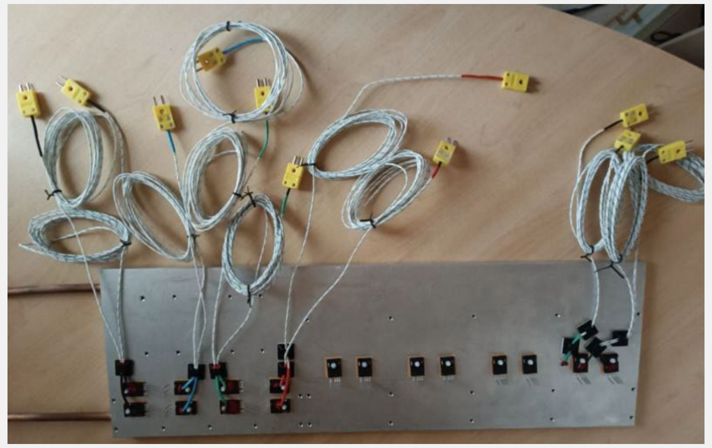
The prototype was tested within the University of Sheffield laboratories

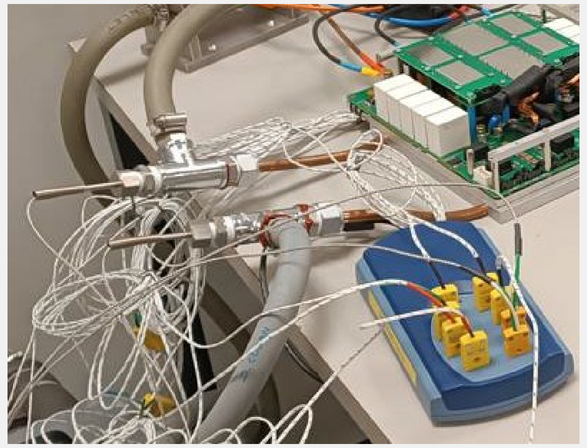


University of Sheffield

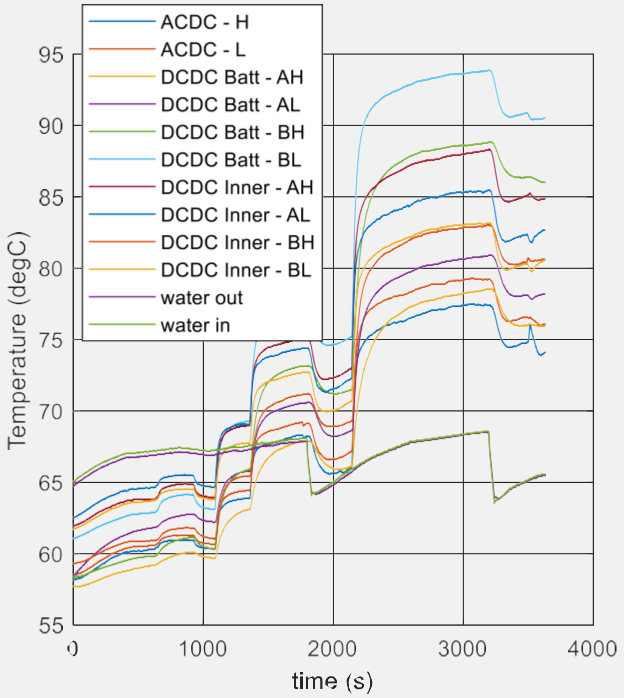
Experimental tests

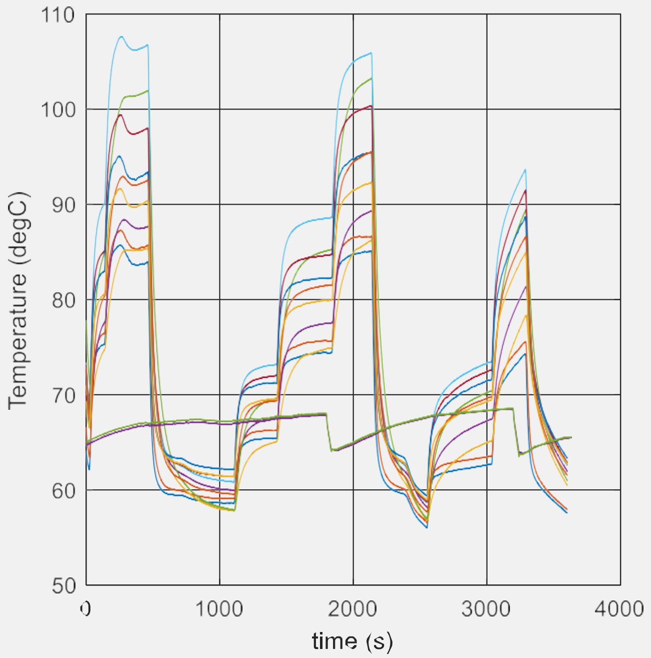
Results of the thermal tests





- To thermally characterize the OBC, 16 thermocouples were installed. 10 of these were installed on the device case.
- Tests were performed changing the OBC operating conditions as well as the cooling performance (both water inlet temperature and flowrate were varied).
- The test results were then used by Newtwen to calibrate the Virtual Thermal Sensors in order to achieve an unprecedented accuracy in the real time temperature monitoring.





Interface with Twin Fabrica by Newtwen

Hexagon input data:

- CAD Geometry
- Mesh
- Material properties and boundary conditions
- Loss model for the power devices
- CFD solution
- Test data

Virtual Thermal Sensors by Newtwen

Building OBC VTS

What is a virtual thermal sensor?

A software solution with no sensing placement limitations, capable of accurately estimating temperature dynamics and predicting future outcomes, across the **entire spectrum of operating conditions**.

VTS are as accurate as physical sensors and can either complement or replace them entirely.

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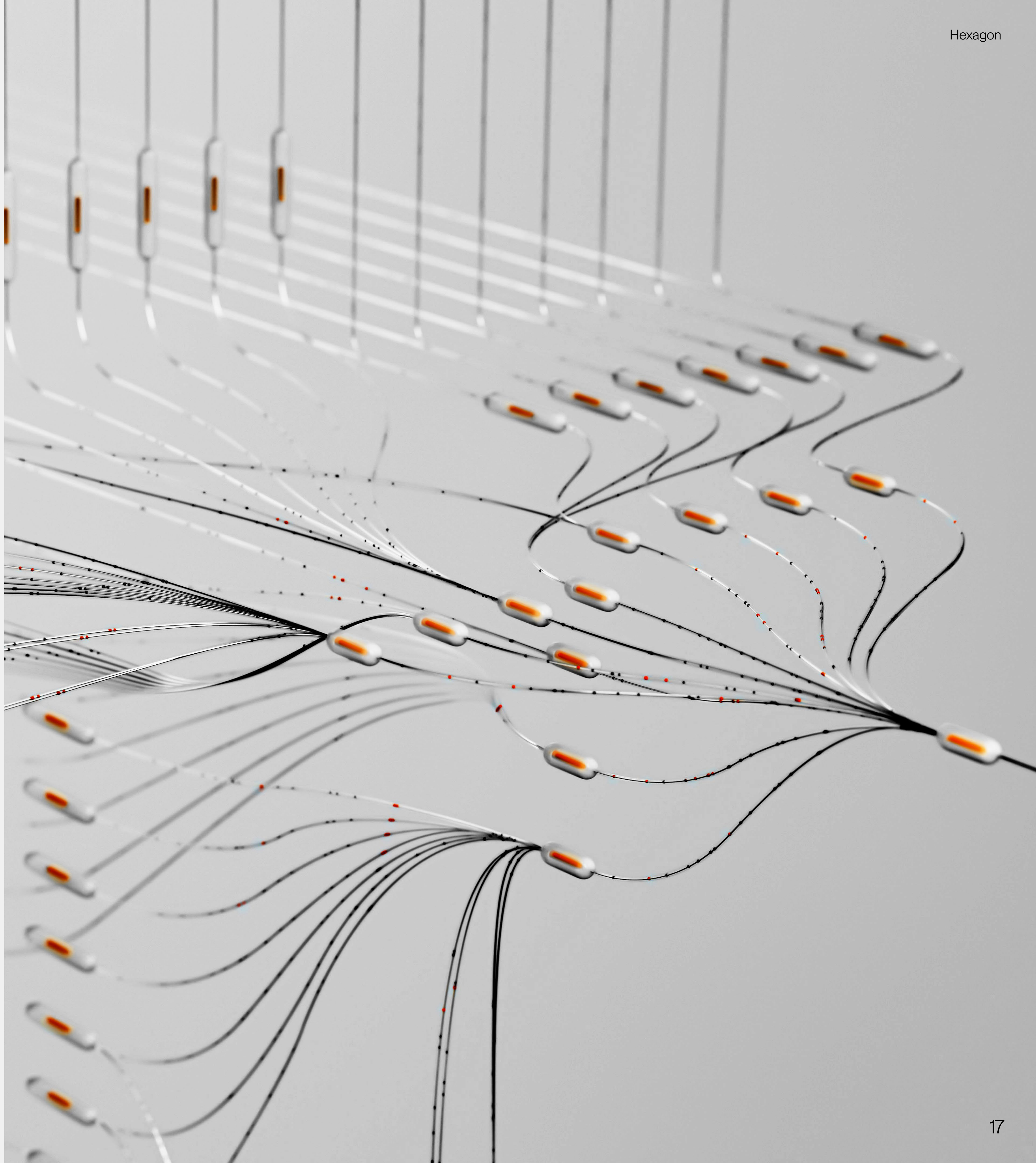
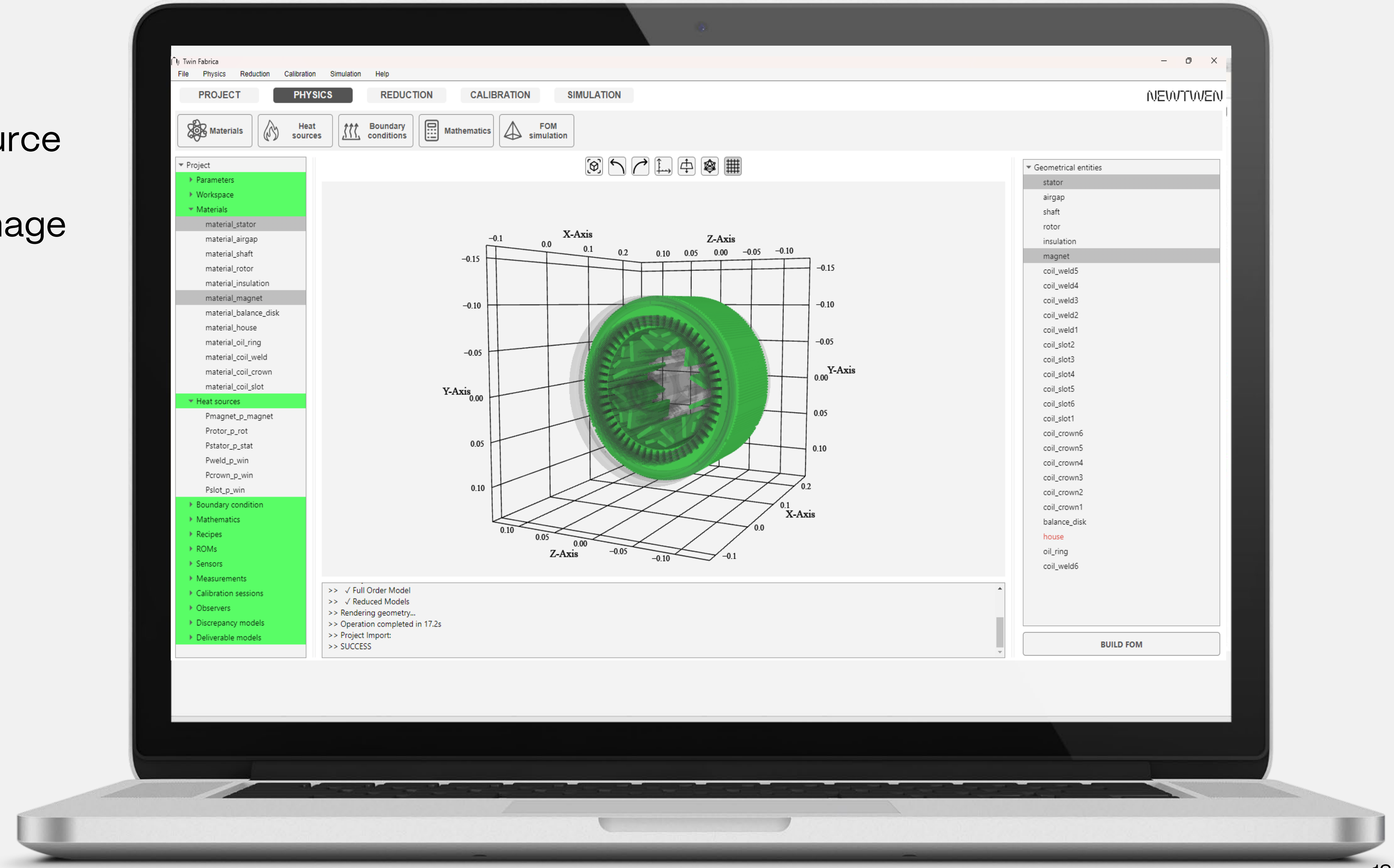


Twin Fabrica™

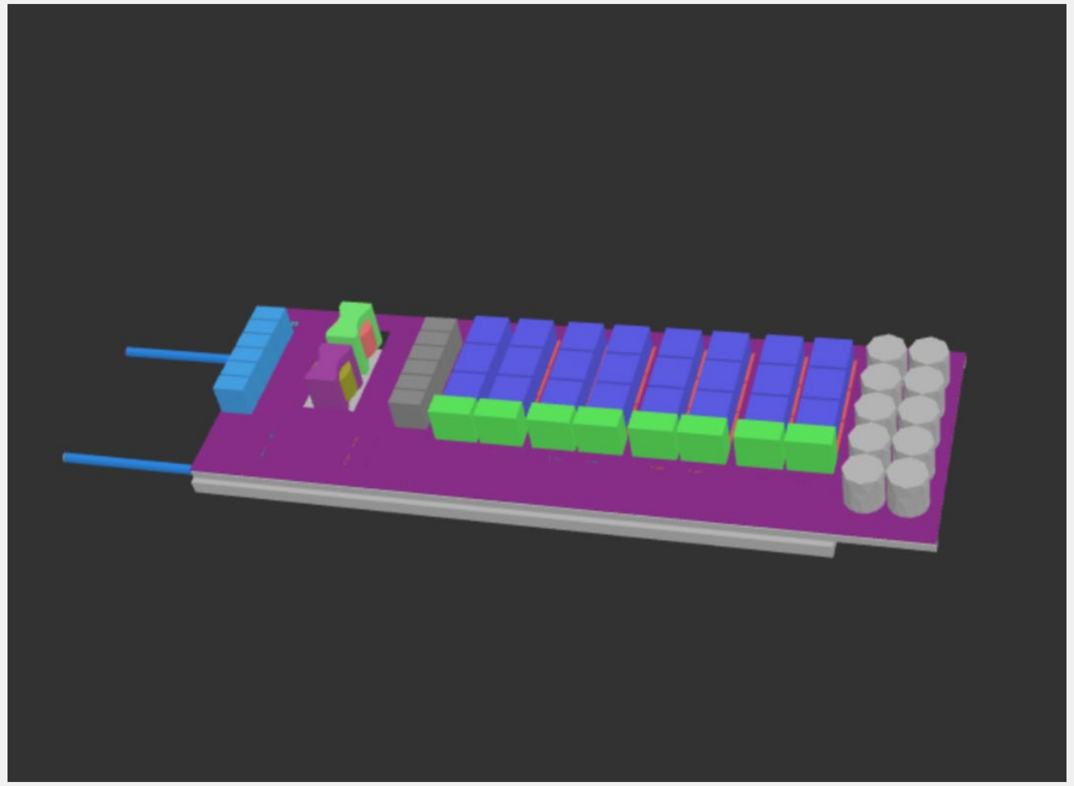
The best tool to build and deploy VTS at scale.

The VTS methodology is very effective, but also resource consuming. Different data and skills need to be well integrated to succced. With Twin fabrica you can manage the whole workflow in a very cost effective way.

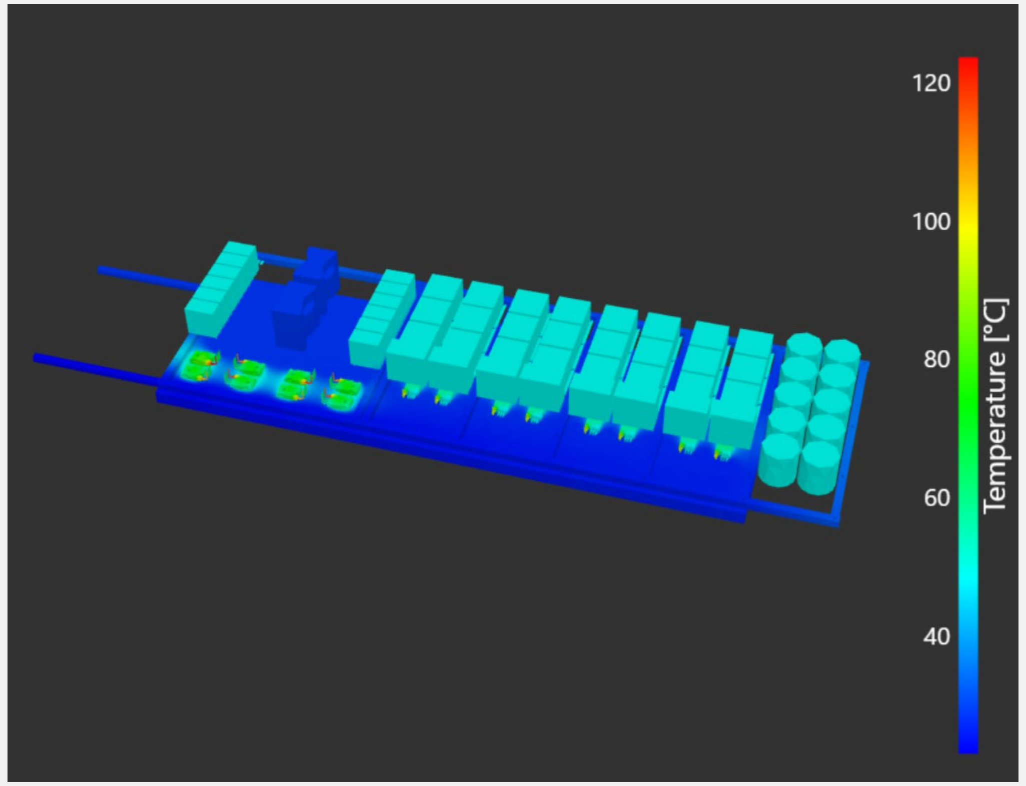


Thermal Management & Control

- The fast time, compact size of components and user safety requirements during battery charging for electric vehicles require proper thermal management of the power electronics system.
- **The hotspot temperature** of the system **cannot be directly measured** without high manufacturing costs.
- As a result, large safety margins are applied significantly reducing the on-board charger performance.

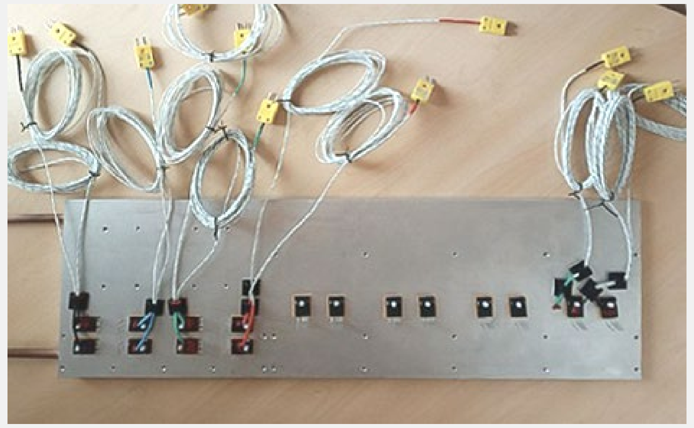


On-board Charger geometry



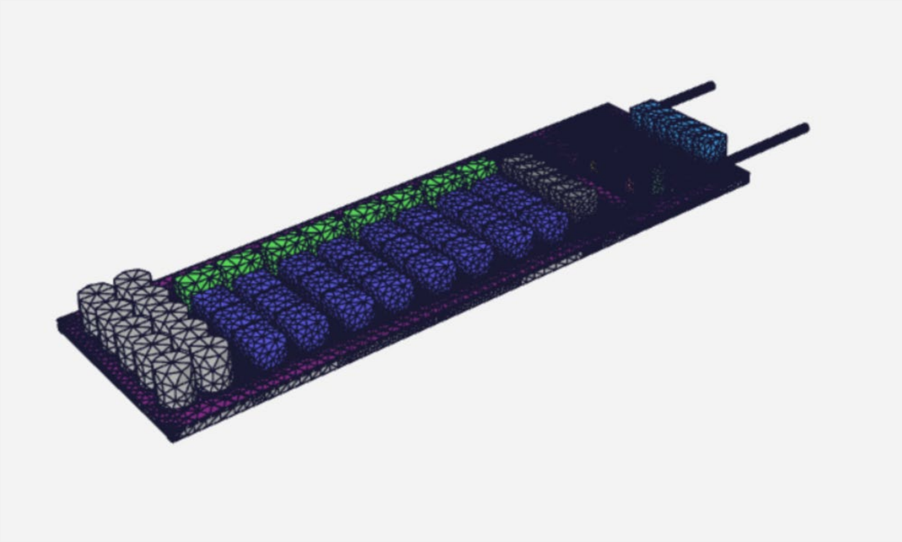
How the Temperature is distributed

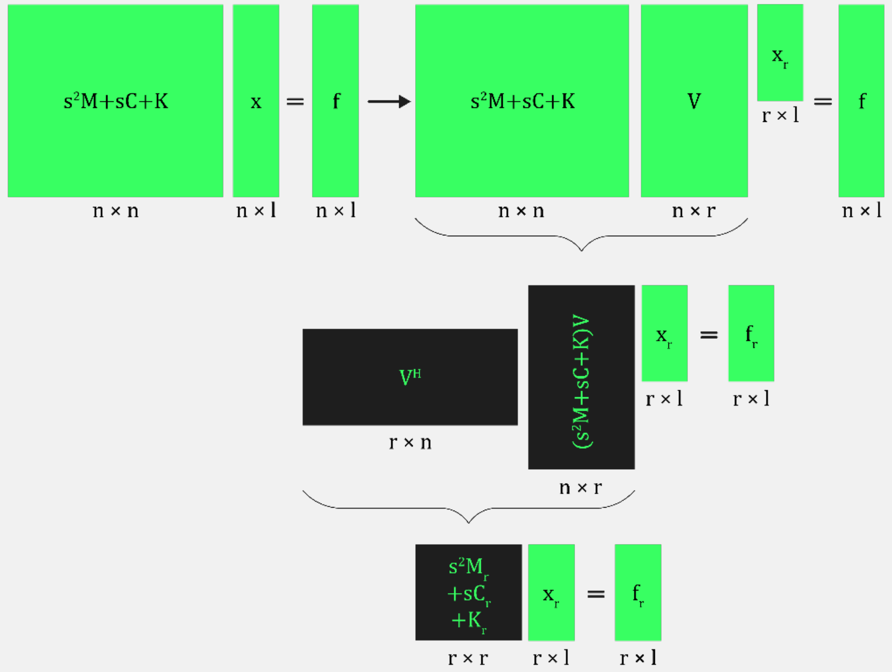
Twin Fabrica™: Pipeline

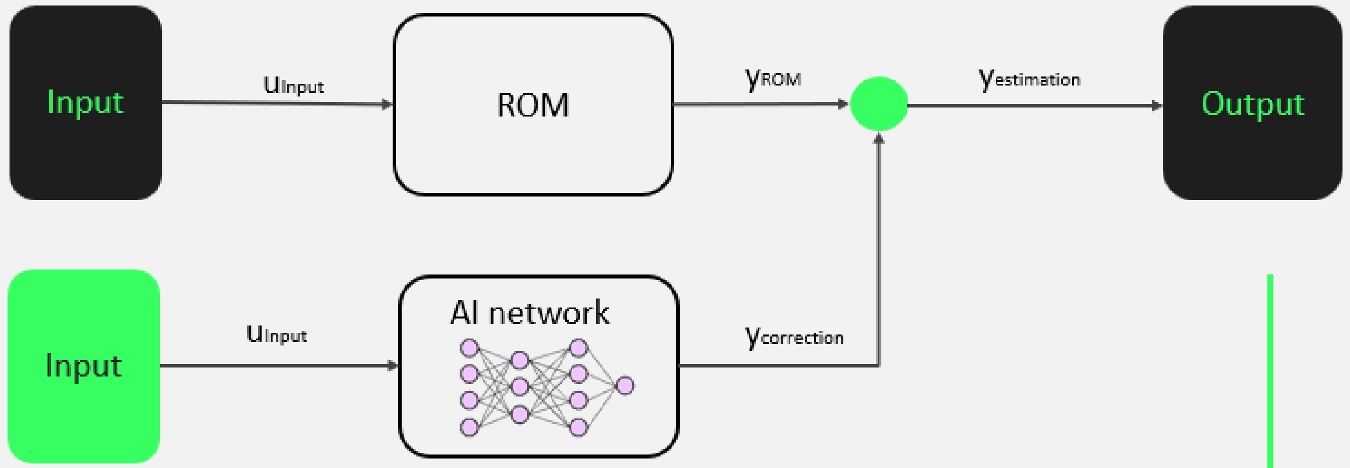


Input
CAD, material properties, and power loss characterization

Input
Measurement from testbench







Finite element models
~ 0.4 milion of degrees of freedom (DOF)

Model order reduction
From 0.4 milion DOF to just 30 DOF reduced order model (ROM)

Physics AI virtual sensors
Calibration with real sensor measurements

Output
Final software architecture to be embedded into third party platforms

KPIs & Activities

KPIs defined by Hexagon:

- VTS Position: 10 thermal sensor in the MOSFETs (8 for DC/DC and 2 for AC/DC).
- Accuracy: real sensors estimation versus virtual sensor difference of maximum ±5 ˚C both in steady-state and transient
- Model size: < 40 kB as target for memory footprint
- Runtime: < 200 us of execution time for the virtual sensors, suitable for the 10 ms task implementation in the TI C2000.

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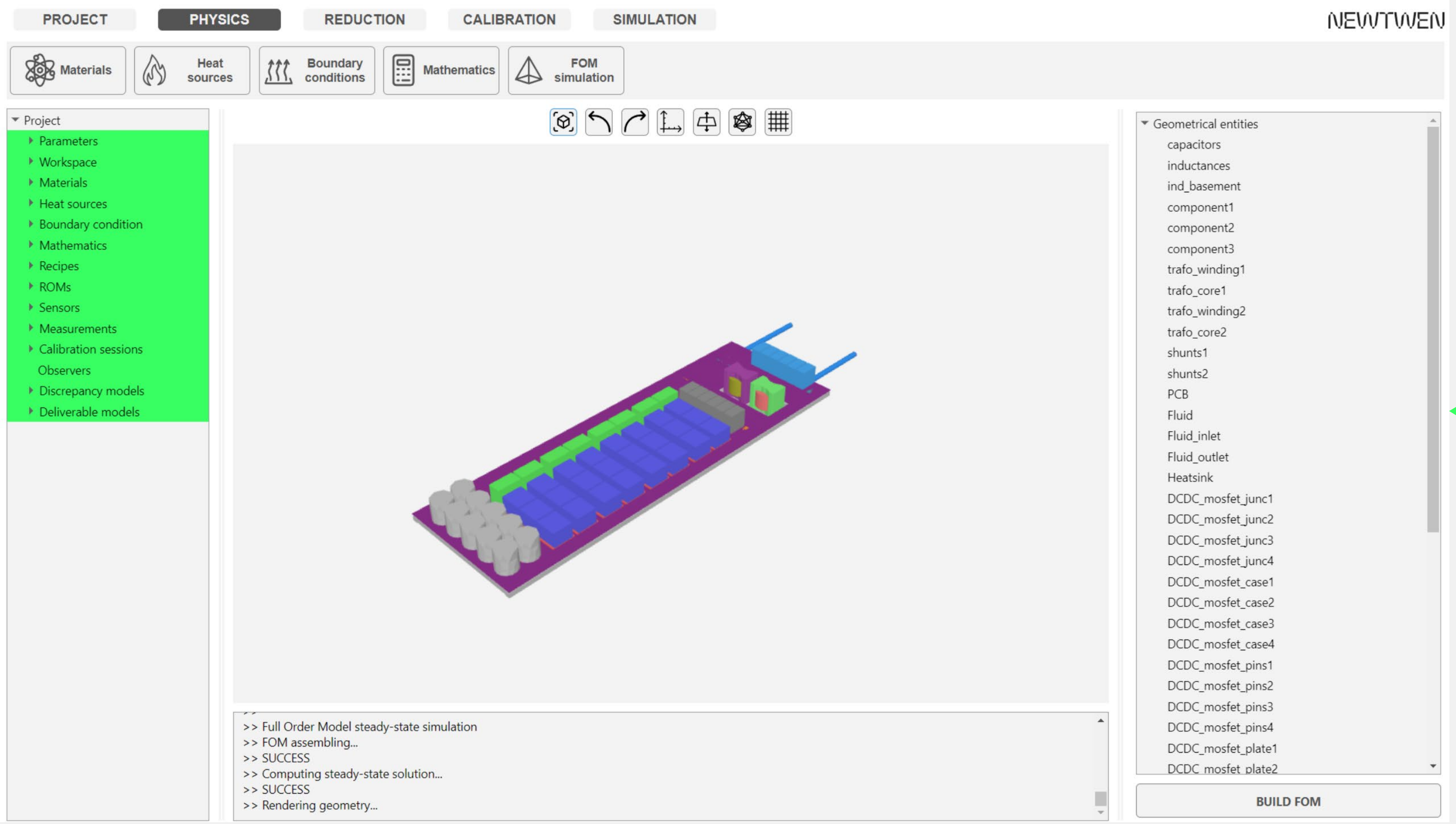
Twin Fabrica™: Geometry and CFD integration

In Twin Fabrica it is possible to load **3D CAD geometry** and mesh, as well as CFD results of **velocity field** from other software, e.g. **Cradle CDF.**



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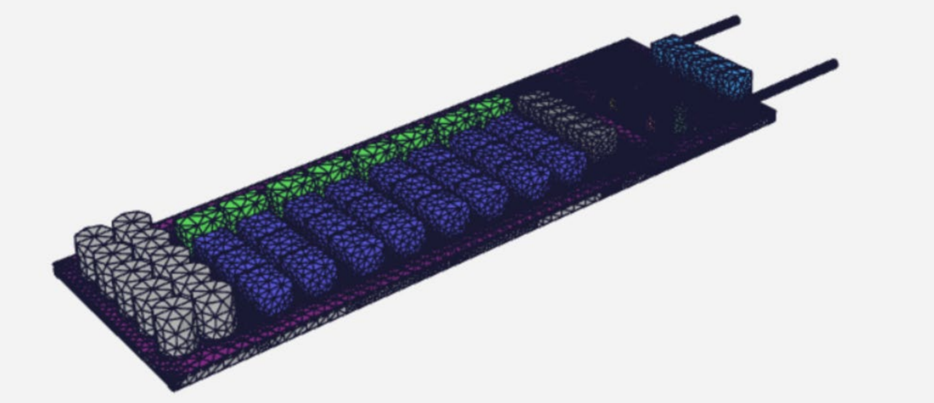
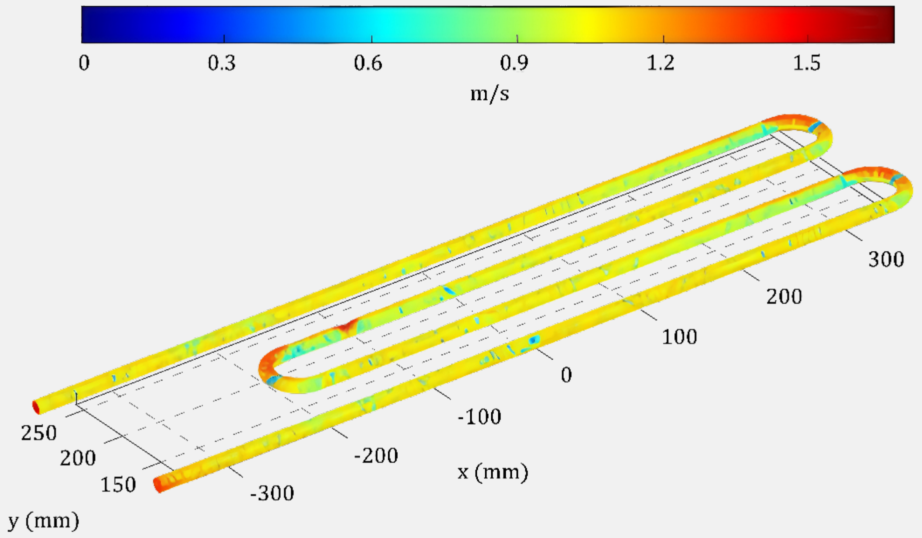
Twin Fabrica™: Homepage



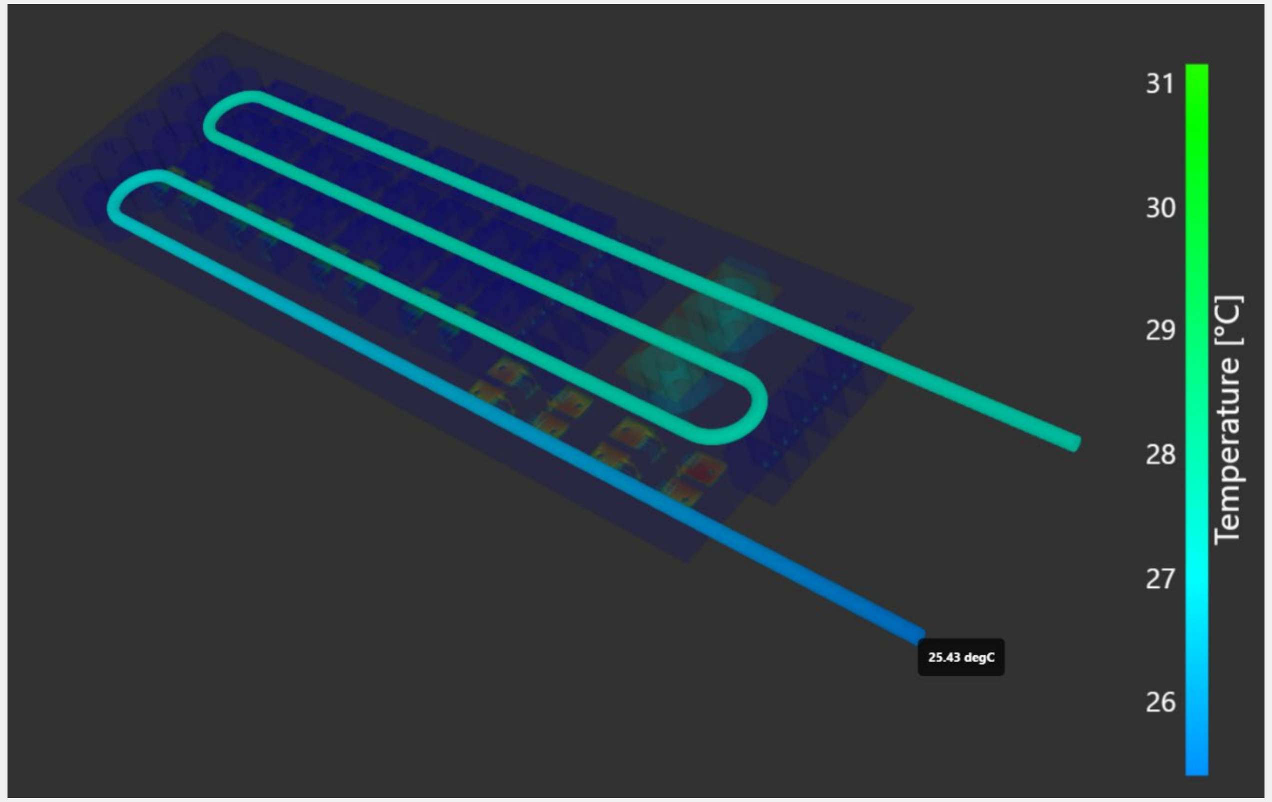
3D CAD geometry



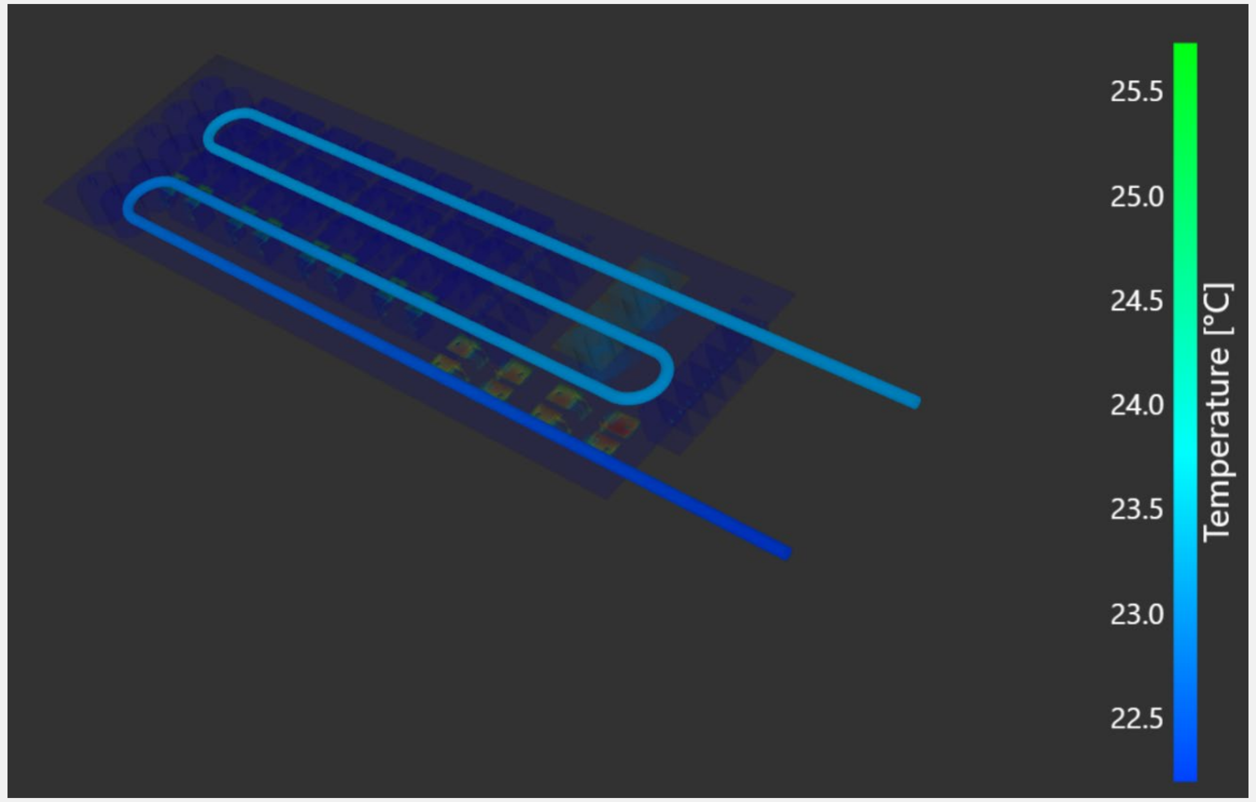
Fluid velocity field

Twin Fabrica™: Advective heat transfer

- The advective heat transfer $\rho c \vec{v} \nabla T$ can be directly considered in the partial differential heat equation with inflow boundary condition.



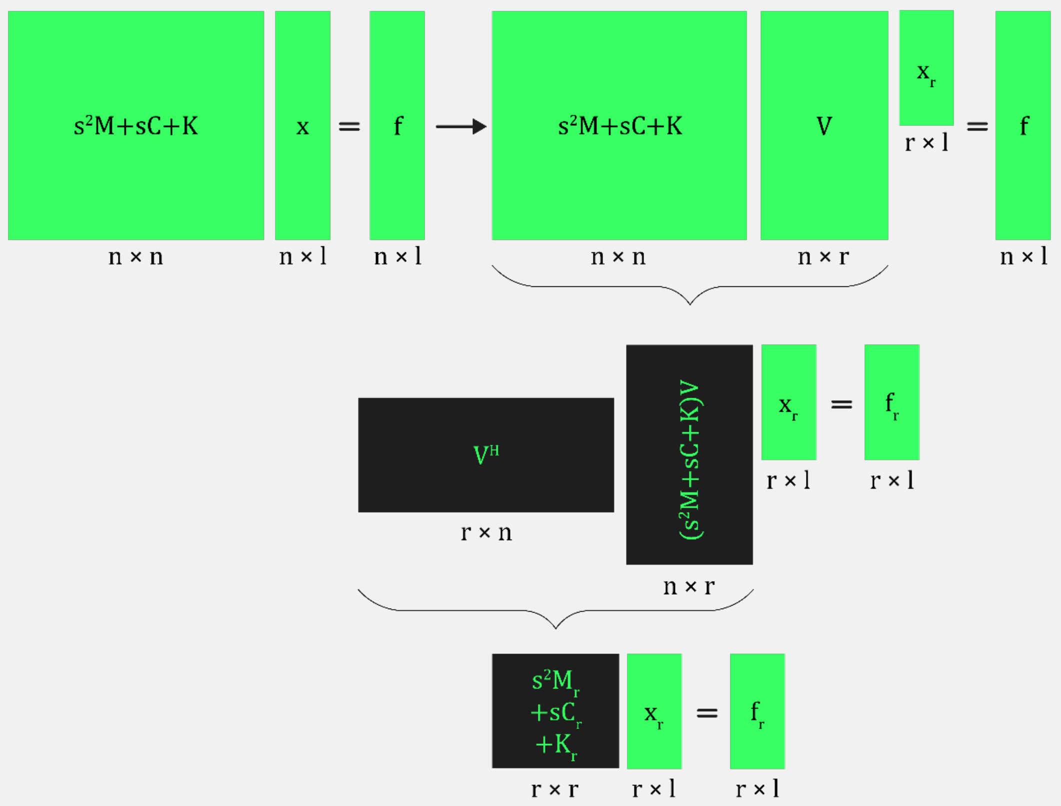
Thermal Temperature adopting lower fluid flowrate



Thermal Temperature adopting higher fluid flowrate

Twin Fabrica™: ROM

FOM simulation

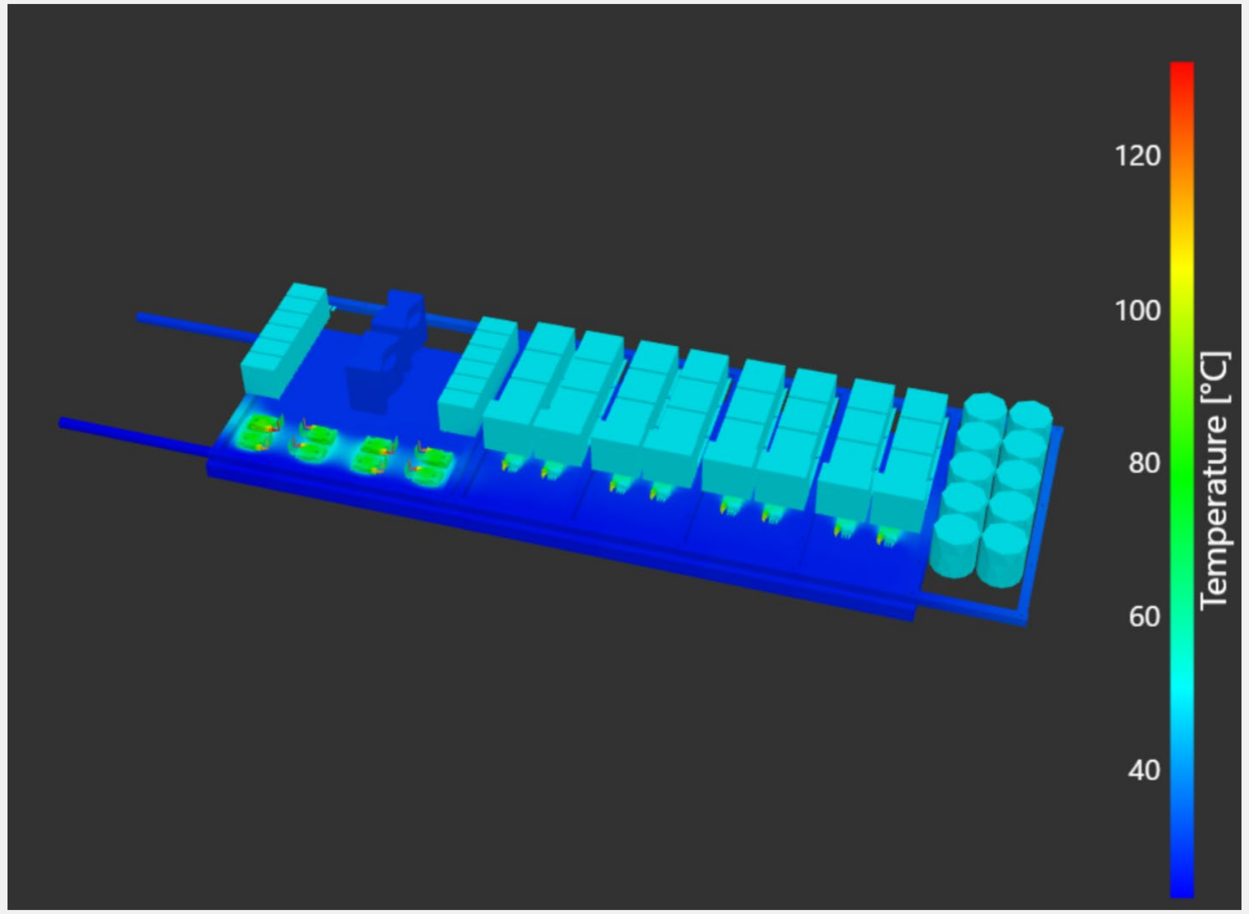


ROM Simulation

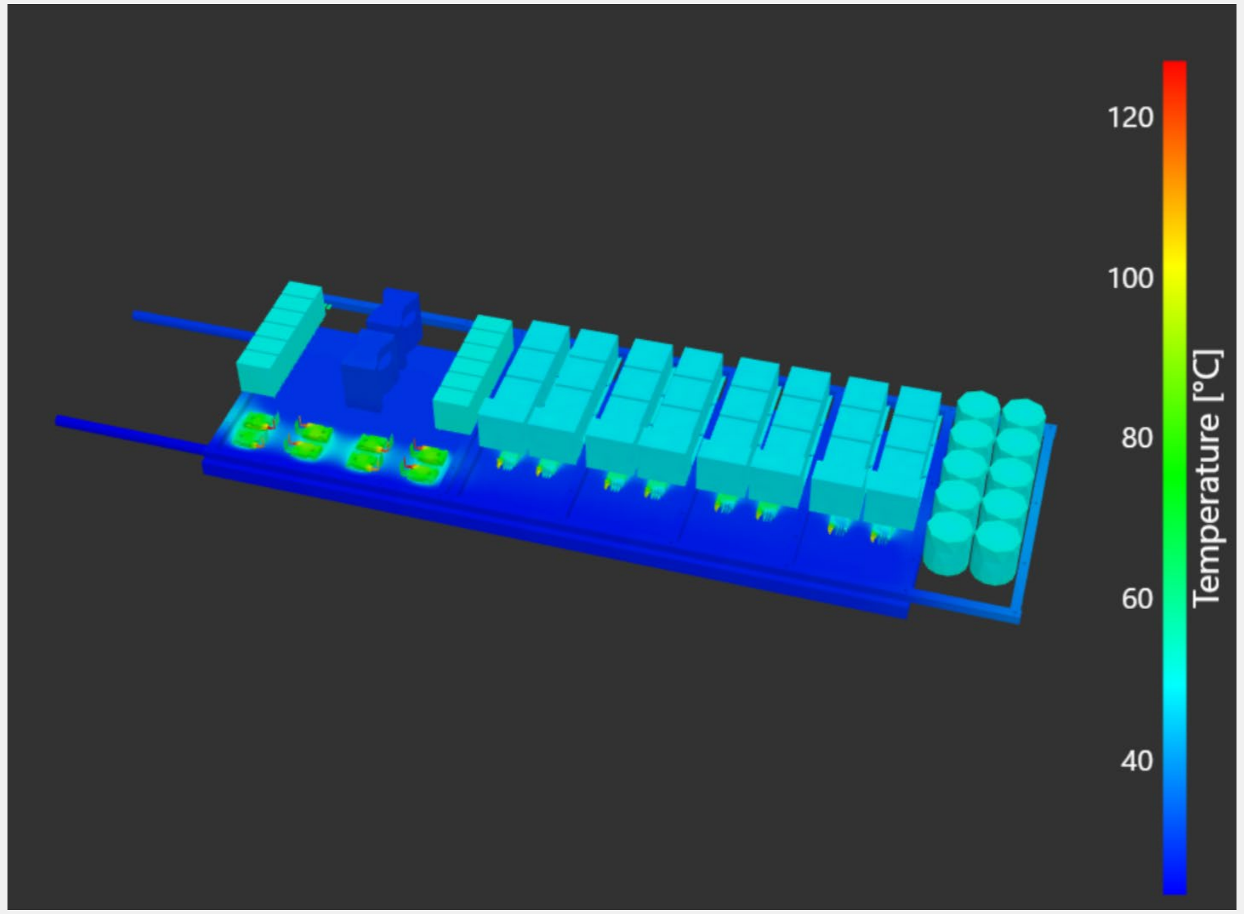
- Advection is considered in the model order reduction
- Decreasing from 416118 DOF of the FOM to **30** of the **ROM** without loosing of accuracy and resolution
- FOM Vs ROM Error analysis toolbox
- **Real time** feasibility

Twin Fabrica™: FOM vs ROM

- FOM vs ROM Temperature comparison in a steady-state simulation considering a random set of parameter material properties, boundary conditions, and heat sources. As can be seen, ROM preserve high temperature distribution accuracy:



FOM Model Temperature plot

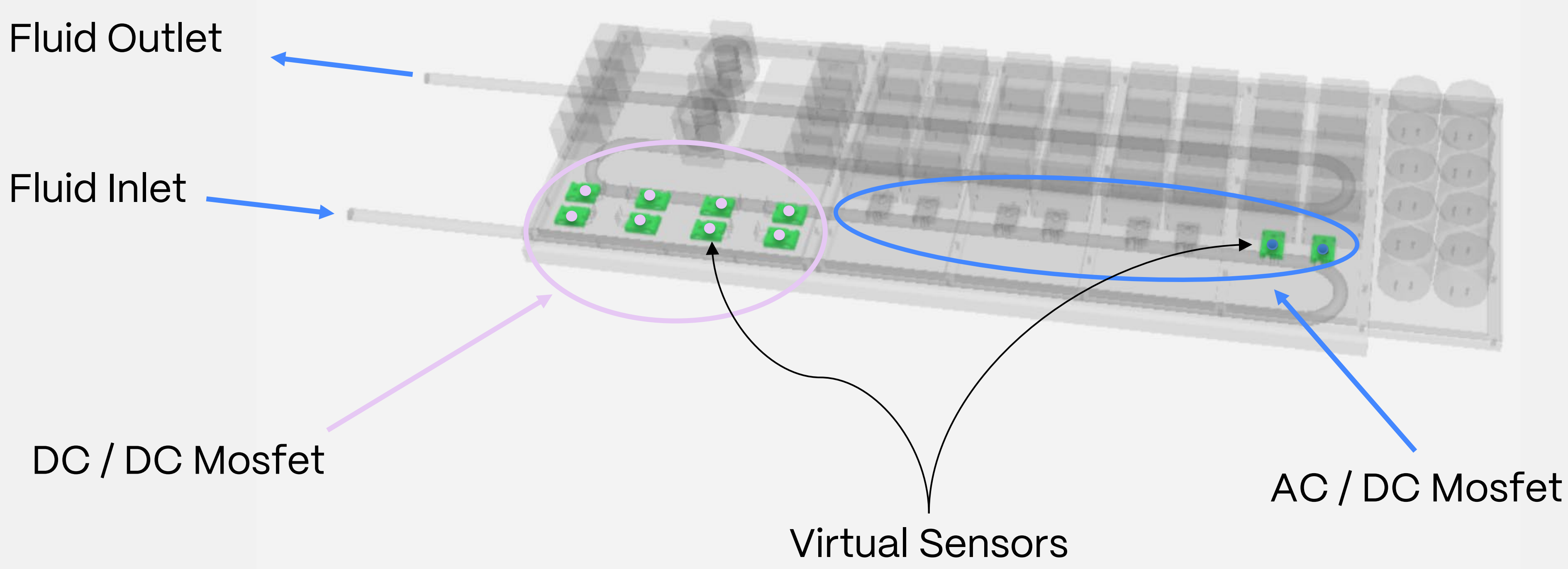


ROM Model Temperature plot

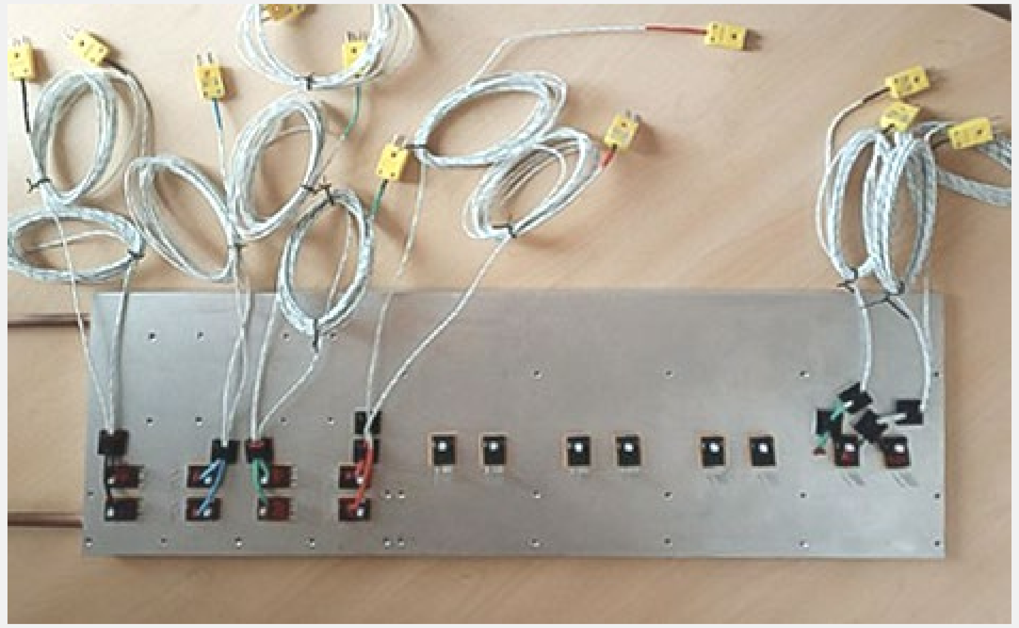
Test Bench: Sensor placement

Sensor probes

- 2x AC/DC Mosfet junction
- 8x DC/DC Mosfet junction



Virtual Sensor location



Real Sensor location

Test bench: Measures

Data pool overview

4 different test conditions

3+ hours of recording on testbench

10+ different load conditions

4 different fluid flowrates

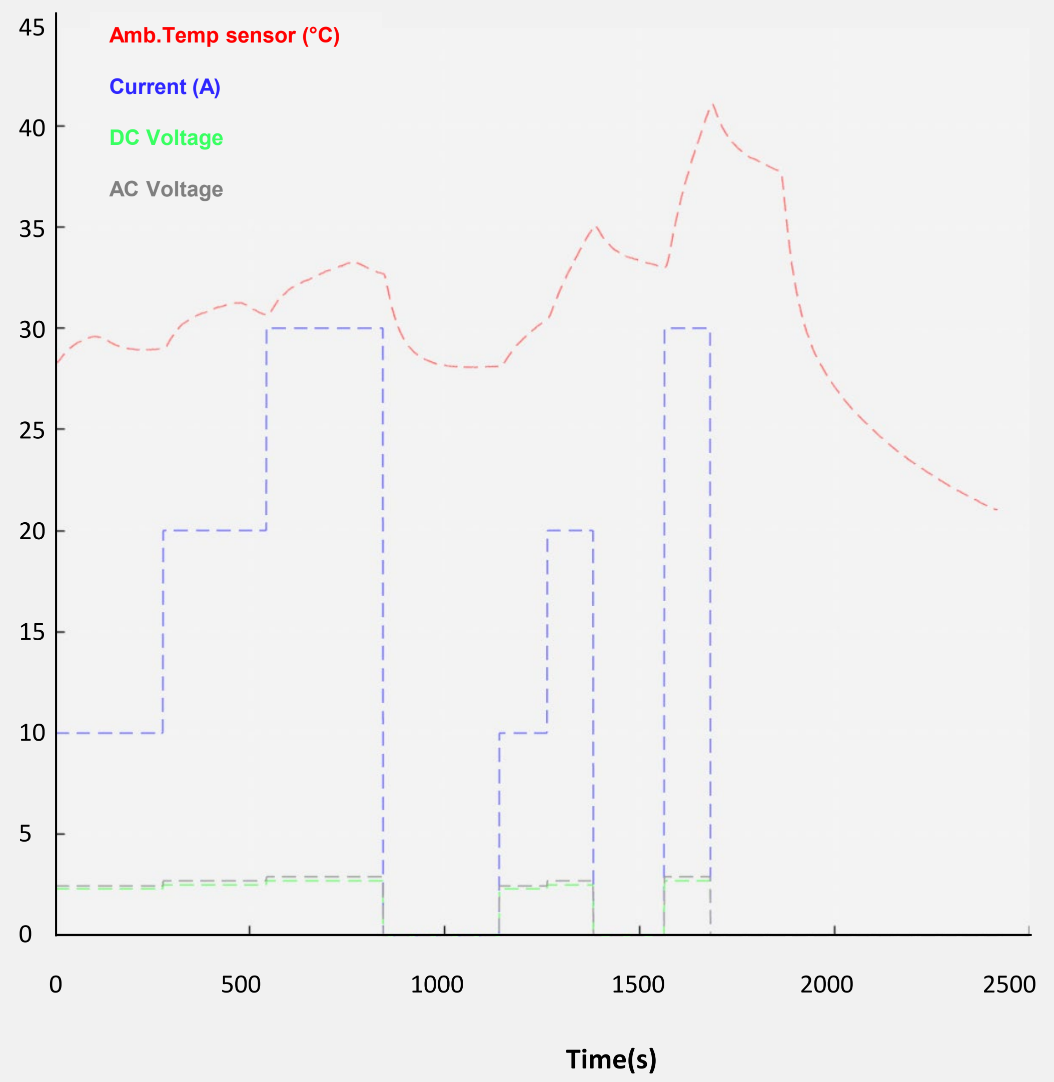
10 sensors available

GOAL

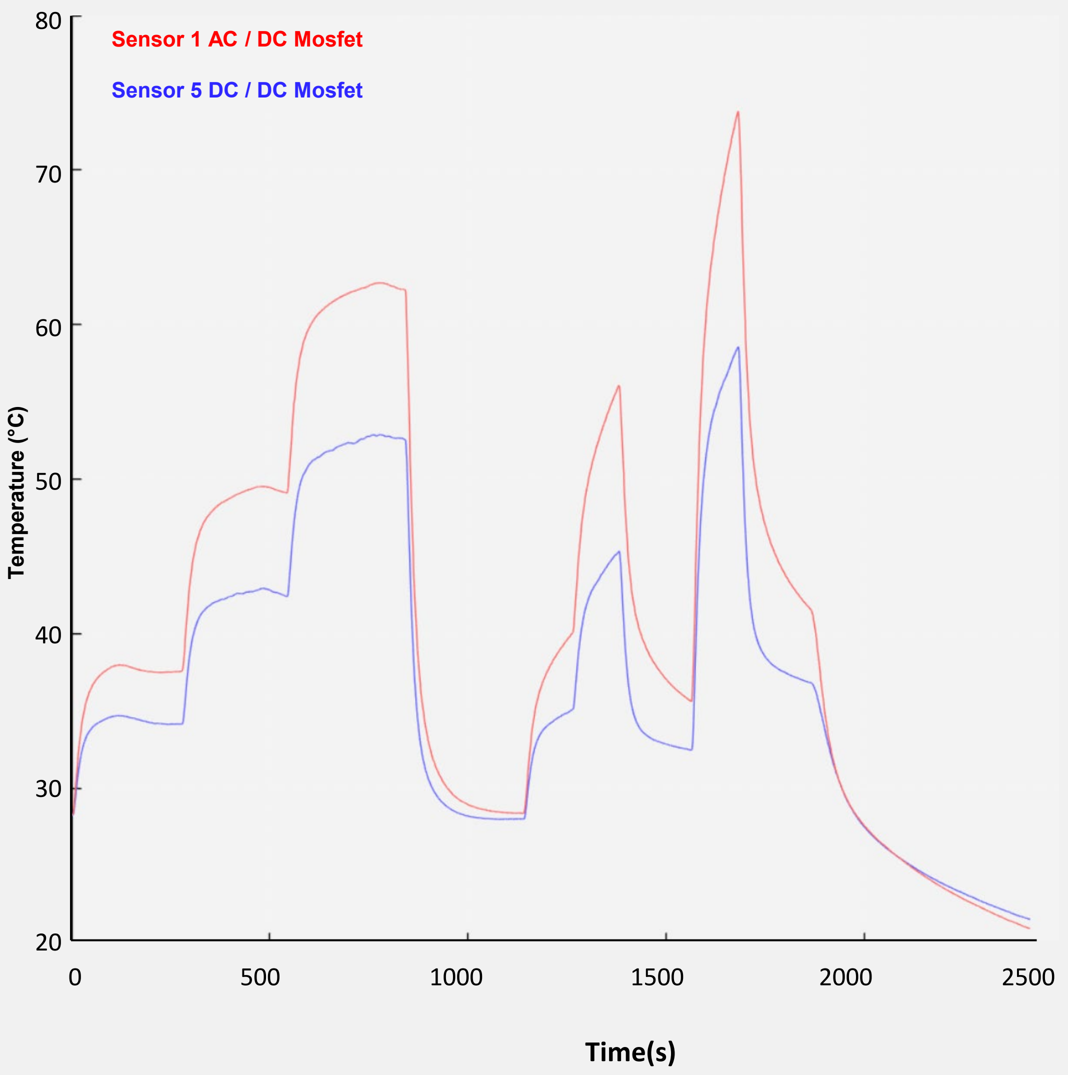
A **unique** model capable of predicting with high accuracy in real-time the dynamic temperature behavior of the modelled virtual thermal sensors

Example: Test bench measurements

Data Input



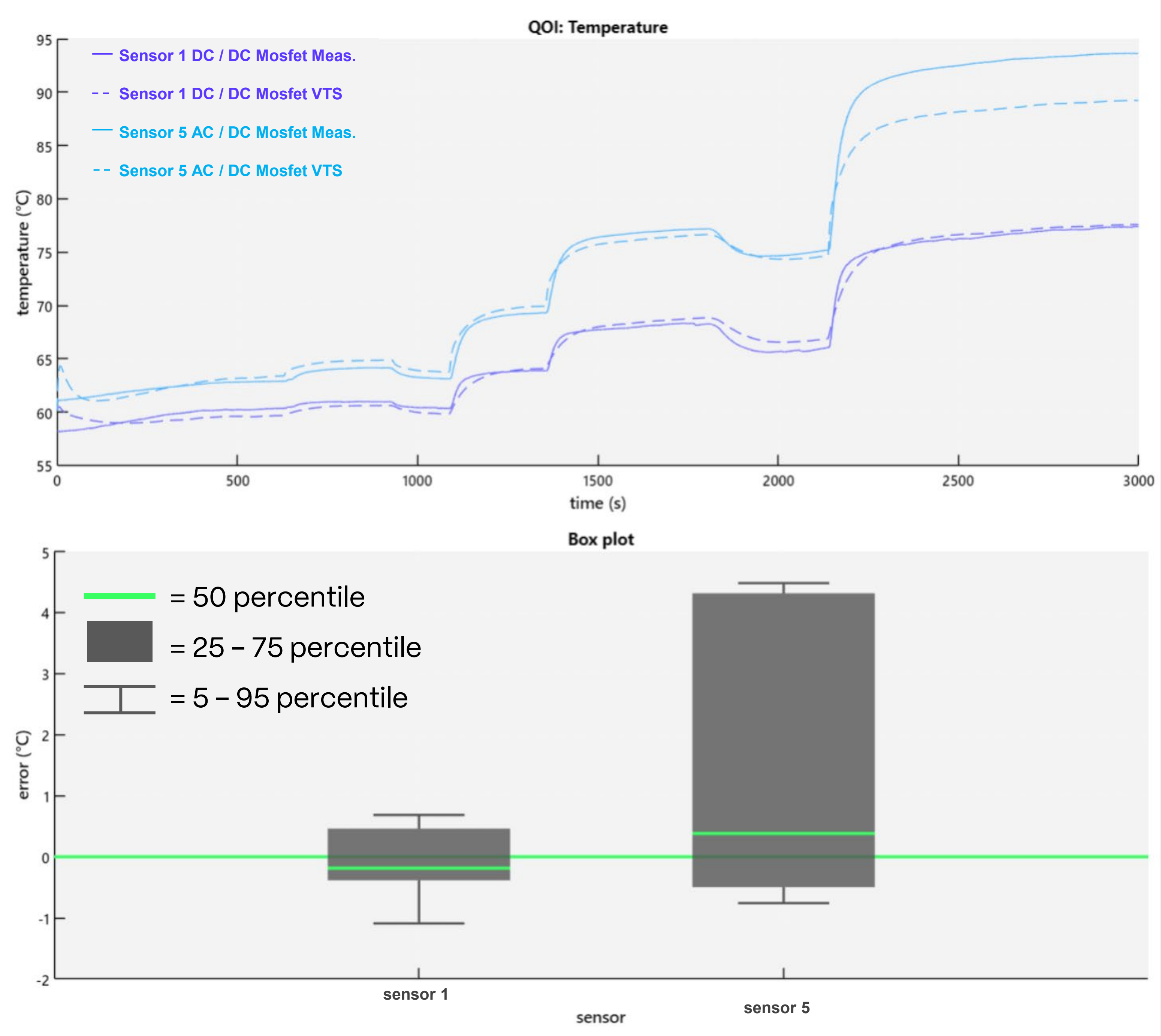
Data Output



Testbench Calibration Results

- **Test: calibration**
- **Error: 5 °C maximum** along all the operating range
- Model: Physics-based ROM

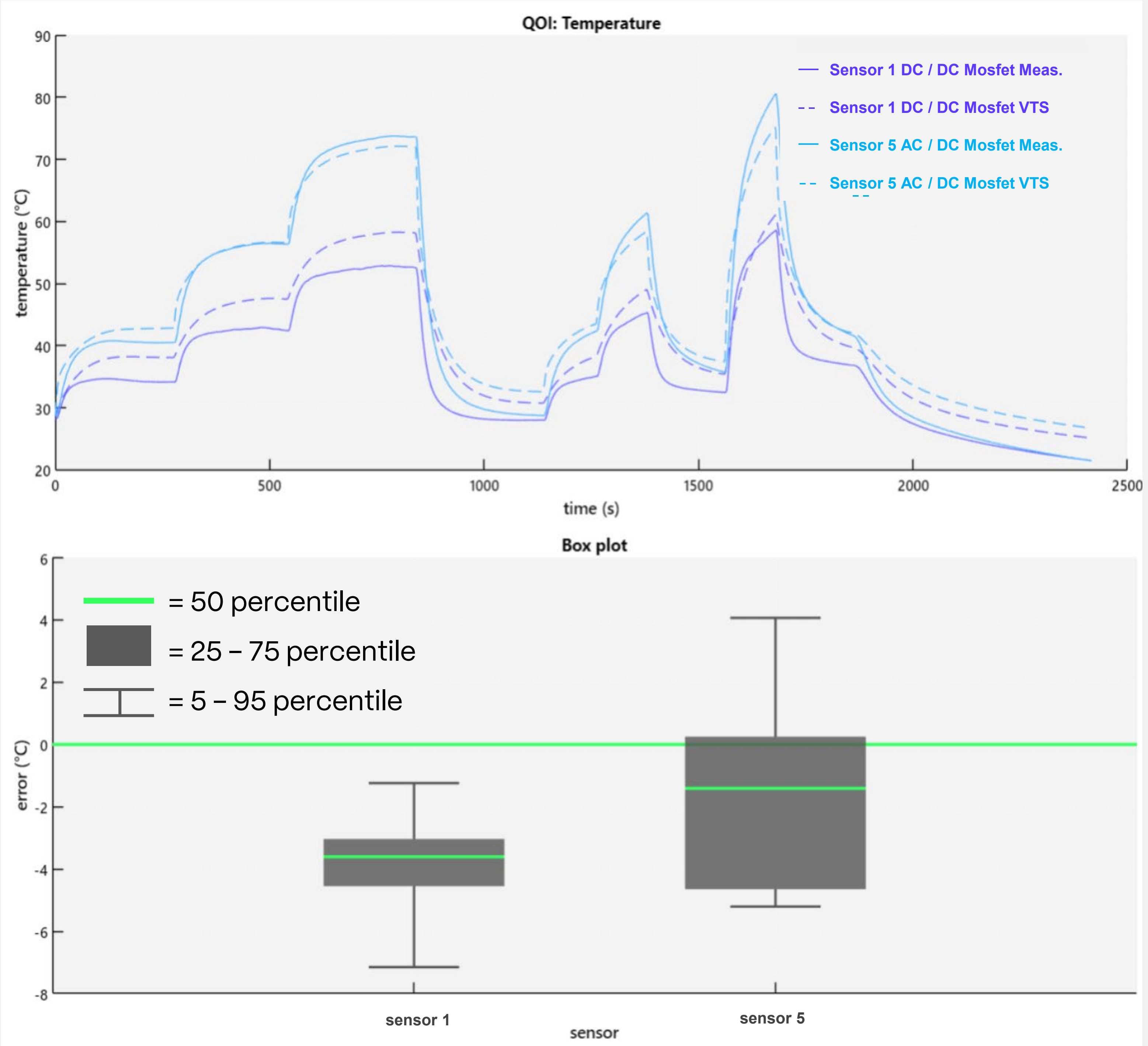
CALIBRATION



Testbench Validation Results

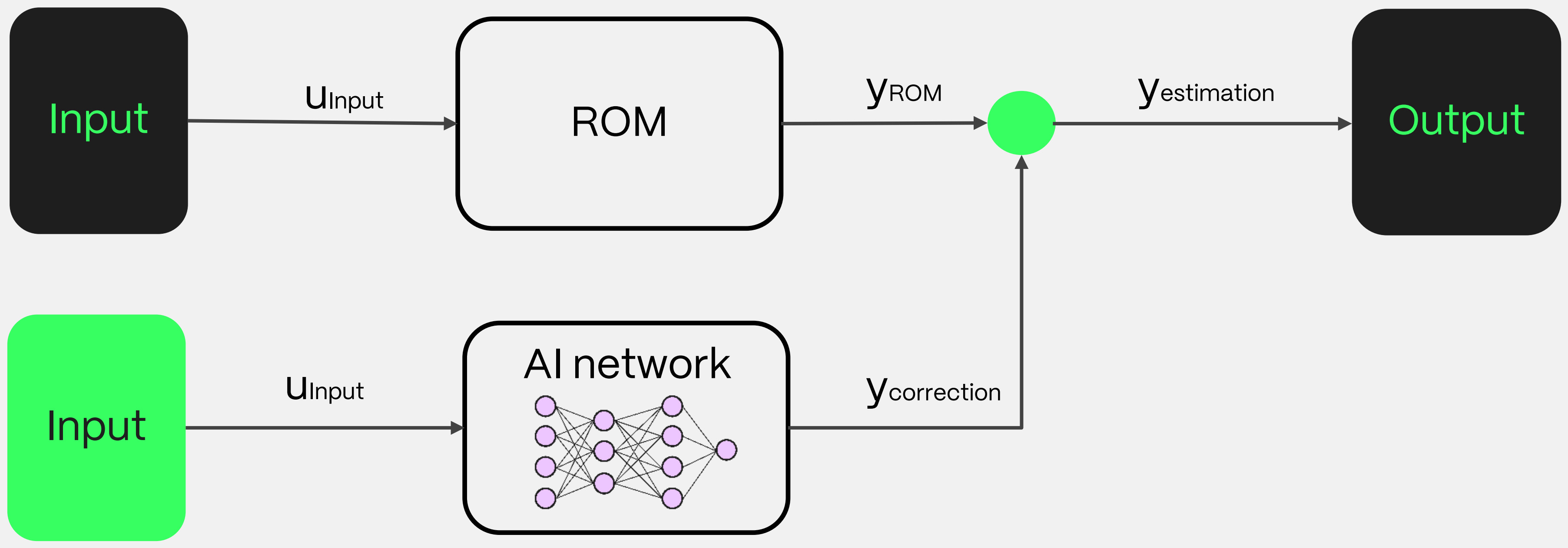
- **Test: validation**
- **Error: 7 °C maximum** along all the operating range (above the KPI requirements)
- Model: Physics-based ROM

VALIDATION



Discrepancy model: to improve accuracy

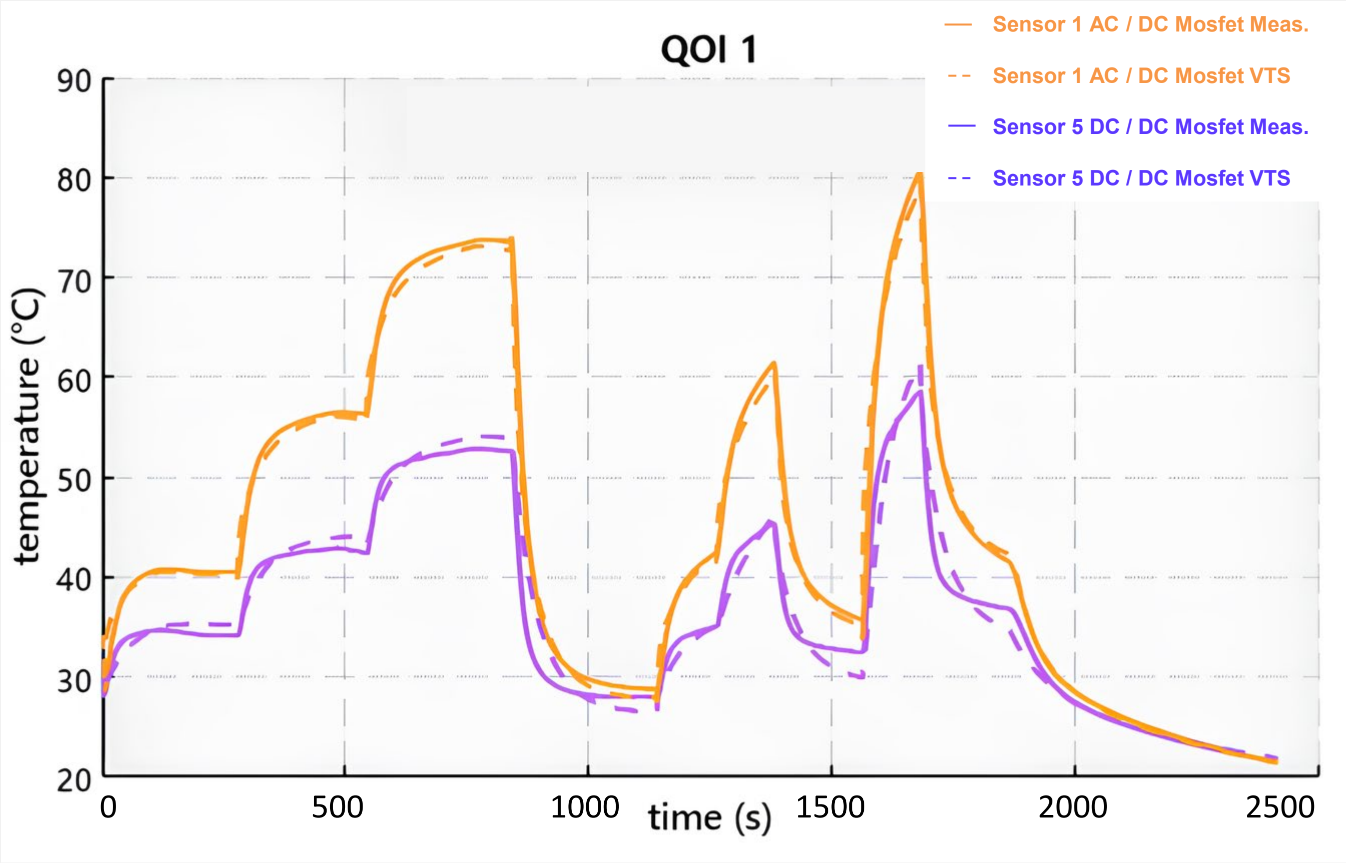
Discrepancy model:



- **AI Neural network** is used to compensate discrepancy between physics-based ROM and real measures acquired from the real device under test
- It needs **calibration** and **validation processes provided automatically inside Twin Fabrica**

Discrepancy model: validation

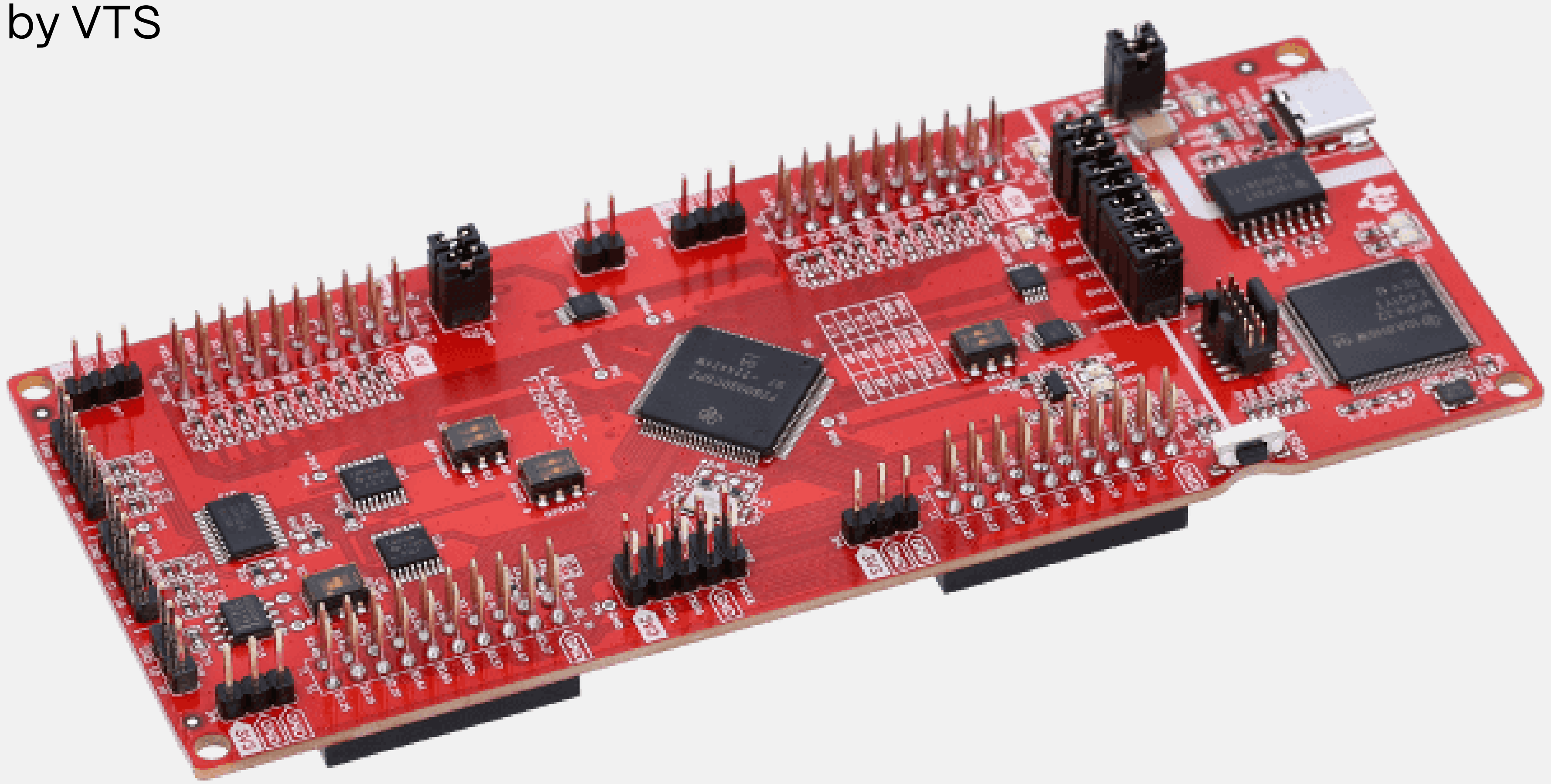
- Test: **validation**
- **Error: <5 °C** maximum along all the operating range (satisfying the KPI requirements)
- Model: Physics-based ROM + AI Discrepancy Model



Real-time implementation

Digital Twin based virtual thermal sensing implementation on TI C2000:

- RAM: approx. ~1kB
- Flash: approx. ~ 20kB
- Execution time: approx. ~ 170us
- Accurate control of system hot spot temperatures enhanced by VTS



VTS for On-board charger

Hexagon case study

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