18th International Forum on Advanced Microsystems for Automotive Applications (AMAA 2014)
Berlin, 24. June 2014

Reliability of New SiC BJT Power Modules for Fully Electric Vehicles

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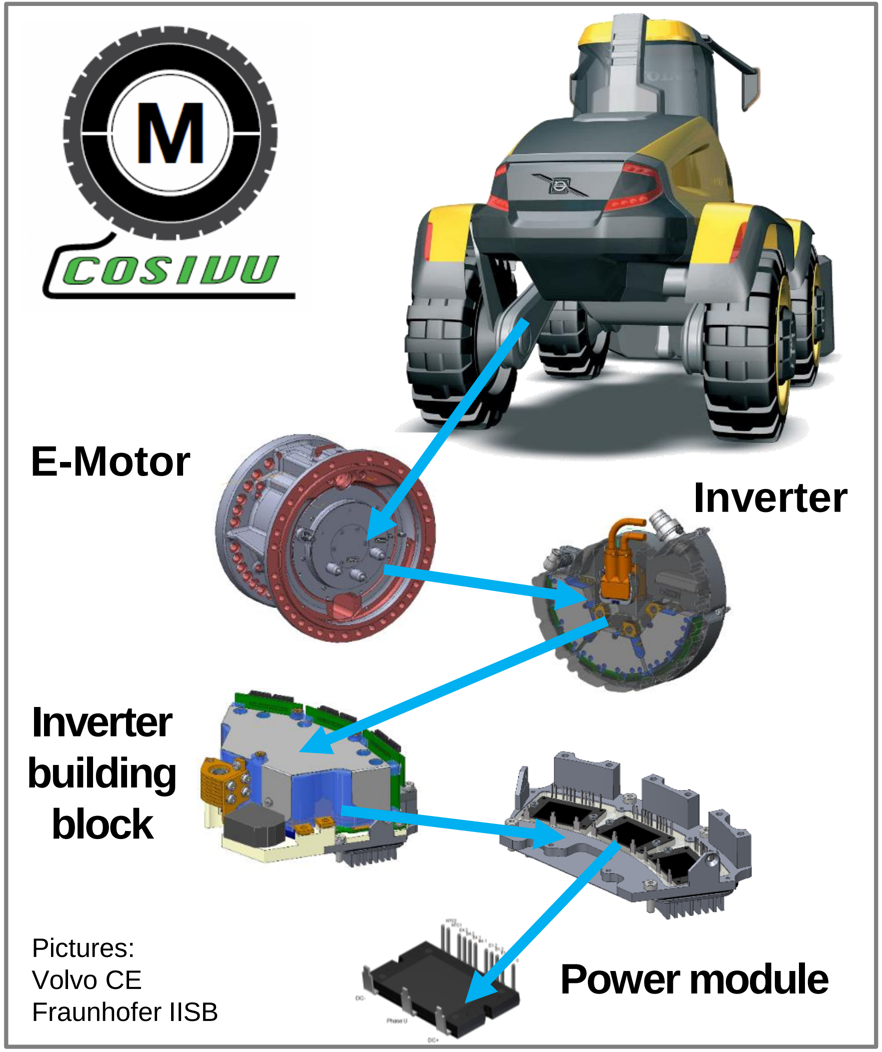
Micro Materials Center
Prof. B. Michel, Prof. S. Rzepka

Project duration:
Oct'12 – Sep'15

I. COSIVU project | Overview

Project objectives:

- Development of a novel electric drive-train system architecture by realizing a smart, compact, and durable single-wheel drive unit including:
  - integrated electric motor
  - 2-stage gear system
  - inverter with SiC based power electronics
  - novel control and health-monitoring system with wireless communication
  - advanced ultra-compact cooling solution
- Validation platform: commercial vehicle (VOLVO) + passenger car (Elaphe)



Pictures:
Volvo CE
Fraunhofer IISB

VOLVO
Fraunhofer ENAS + IISB
elaphe
swerea IVF
SENSITEC
NANOTEST Berliner Nanotest und Design GmbH
HELLA
TECHNISCHE UNIVERSITÄT CHEMNITZ
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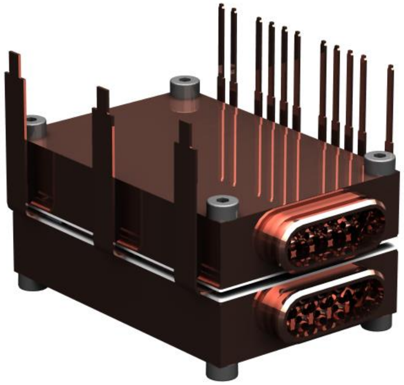
II. SiC power module | General information

Power module in half-bridge configuration with full SiC components:

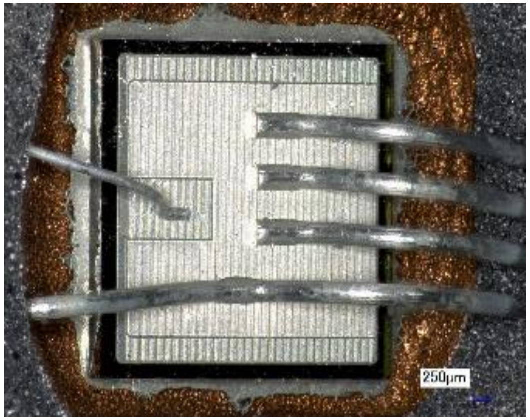
- 4x SiC bipolar junction transistors (BJT) from FCS
- 4x SiC diodes from Cree
- 1200V, 50A (diode: 54A)
- Substrate: DCB with aluminum nitride (AIN) as ceramic isolator
- Lead-free solder; Alu wire-bonds (E: 300µm, B: 150µm)
- Encapsulation: epoxy mold compound (EMC)

FCS SiC power module:

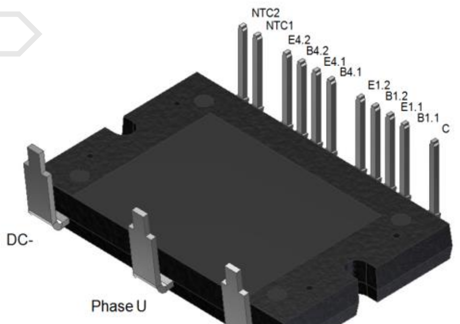
Double-sided cooled SiC power module:



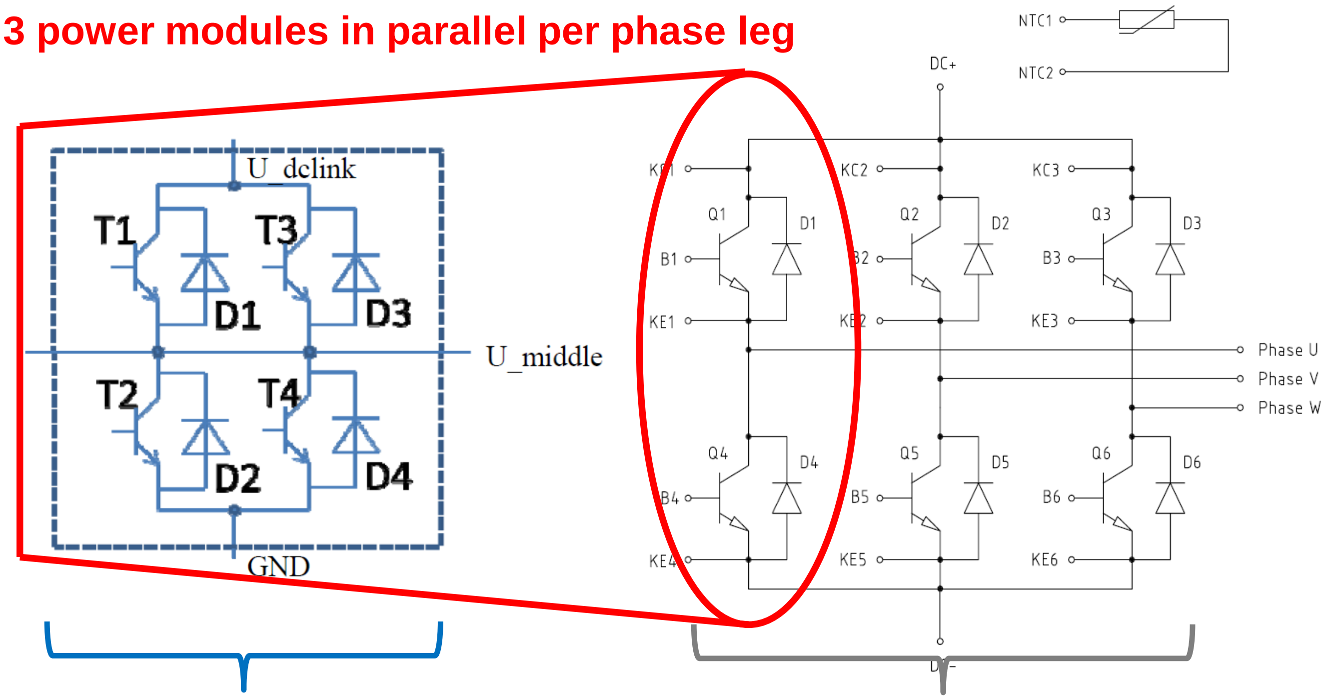
SiC bipolar junction transistor:



II. SiC power module | Schematic



3 power modules in parallel per phase leg

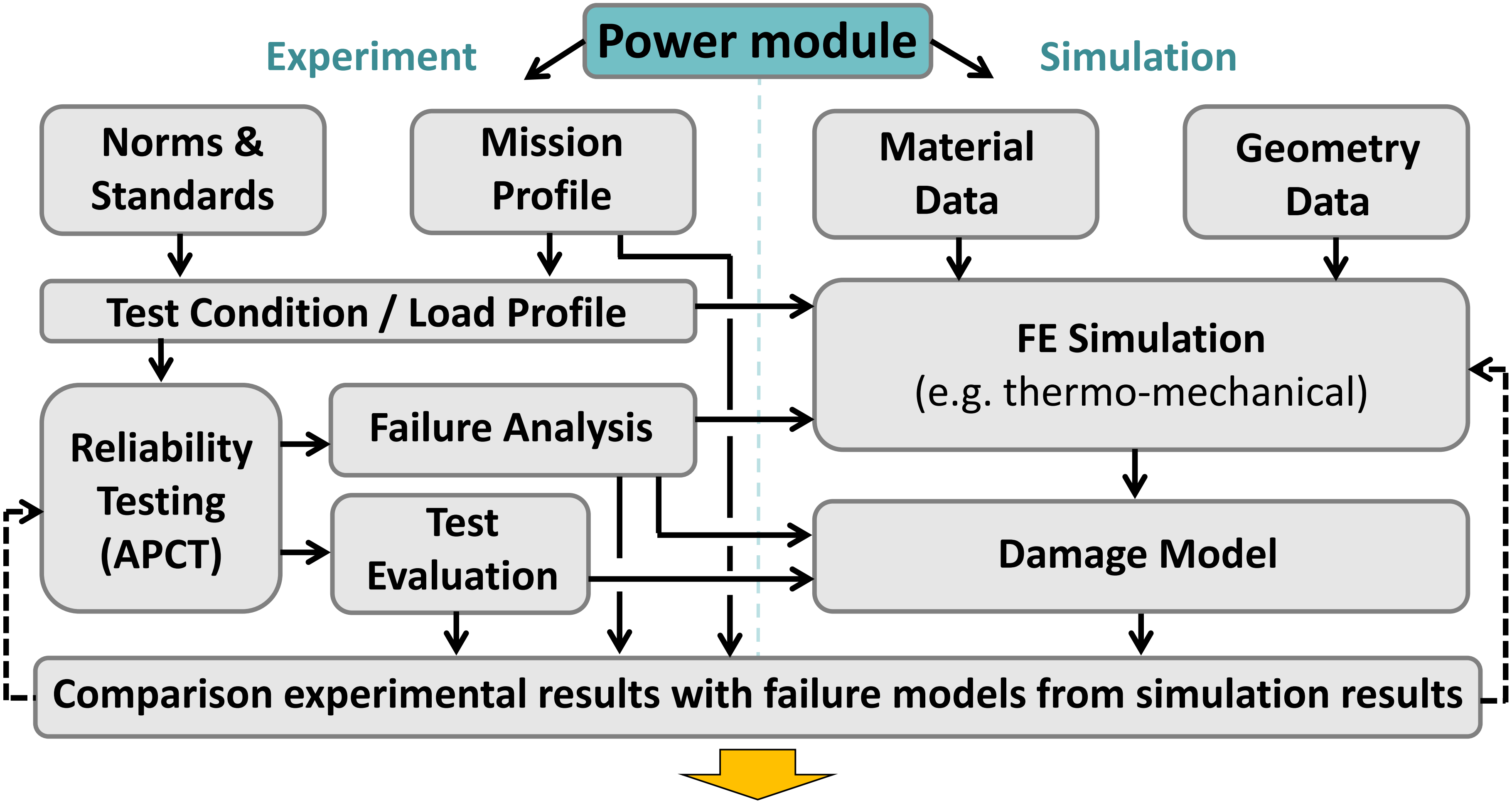


Power module

(half bridge configuration)

Inverter with 3 phase legs

III. Reliability | General approach for reliability assessment of power module



Power module

Experiment

Simulation

Norms & Standards

Mission Profile

Material Data

Geometry Data

Test Condition / Load Profile

FE Simulation
(e.g. thermo-mechanical)

Reliability Testing (APCT)

Failure Analysis

Test Evaluation

Damage Model

Comparison experimental results with failure models from simulation results

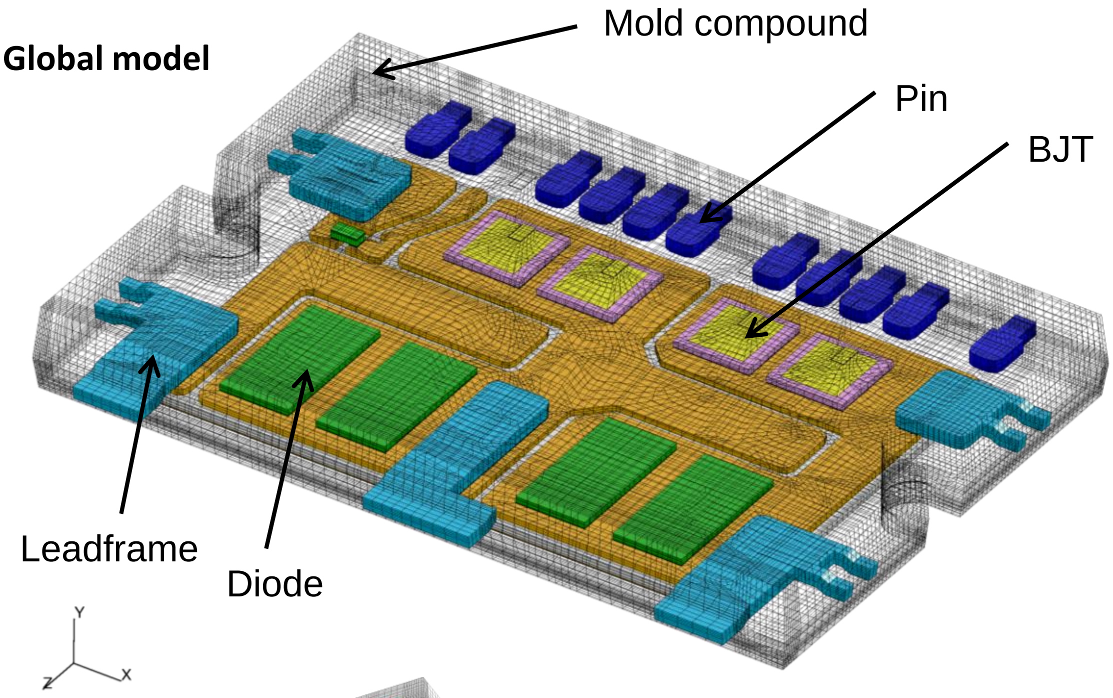
Lifetime estimation

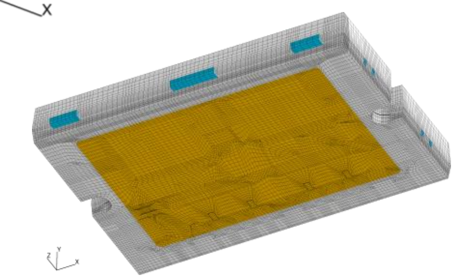
III. Reliability | FE simulation: Geometry model

FE simulation targets:

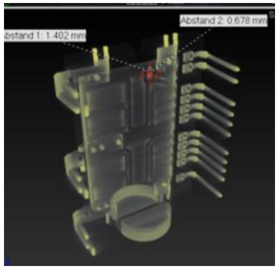
- Investigation of mechanical stress concentration and accumulating plastic and creep strain induces by:
    - Manufacturing process (soldering of DCB, transfer molding)
    - Internal and external thermal loads
- Replication of the corresponding physical effects

Global model



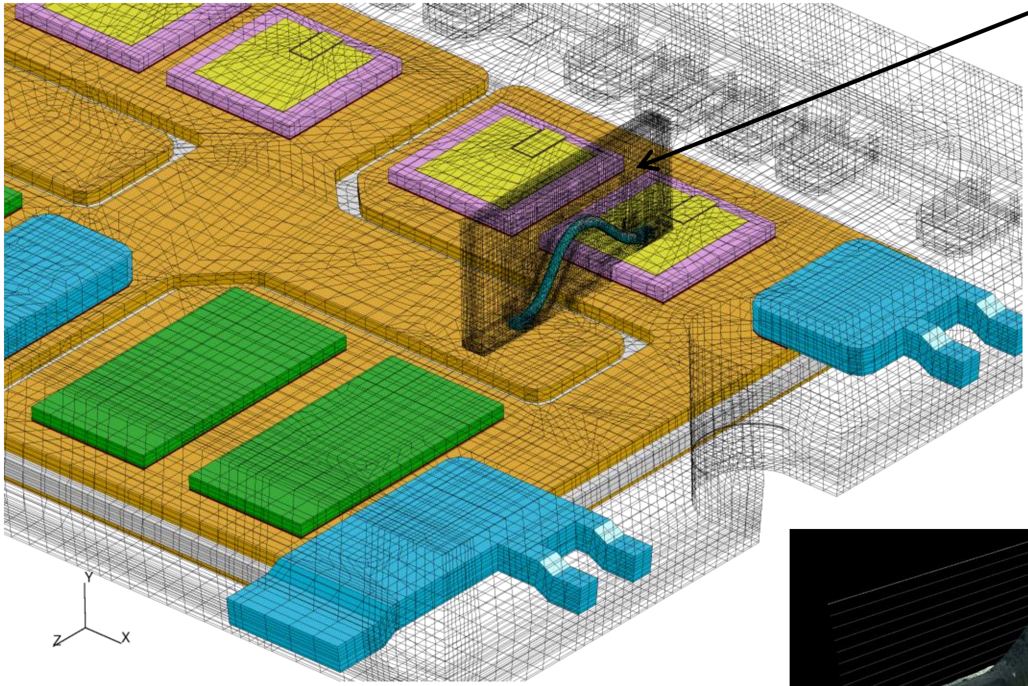


Non destructive CT inspection and measurement @ power module – determination of input for 3D simulation

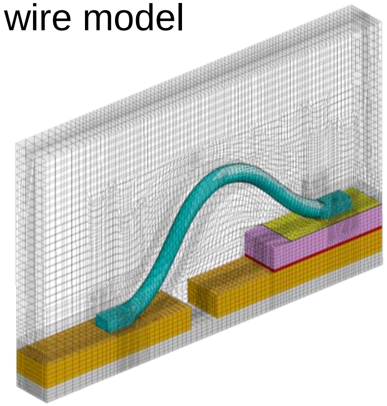


III. Reliability | FE simulation: Geometry model

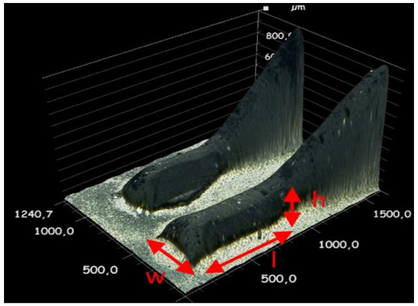
Local geometry model of wire bond:



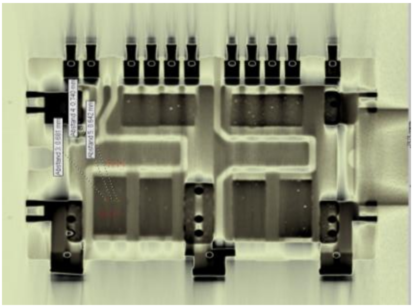
Position of local bond wire model



3D image of wire-bonds:



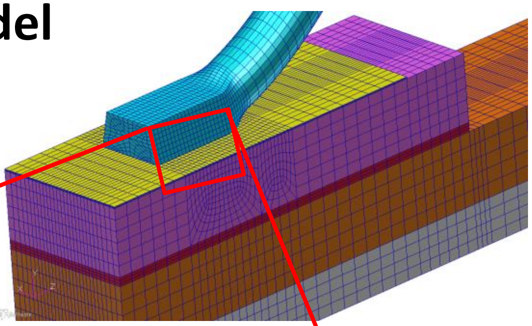
Position of bond wire derived from CT scan:



III. Reliability | FE simulation: Geometry model

Cohesive zone approach for wire bond:

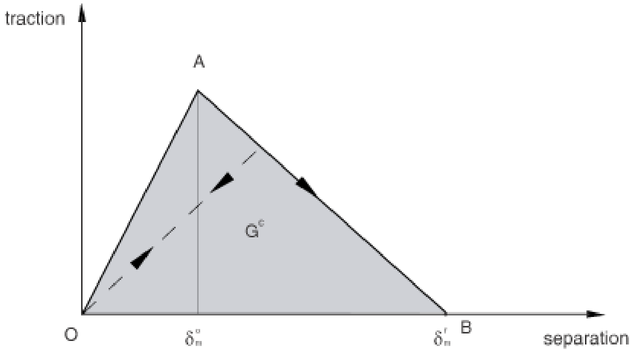
- Geometry information derived from 3D digital microscope images

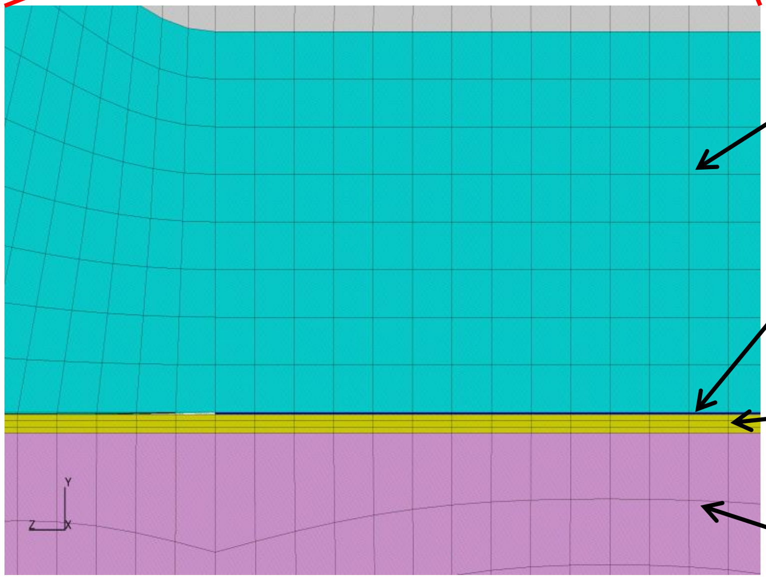


Crack growth law
(Paris and Erdogan):

$$\frac{\mathrm{d}a}{\mathrm{d}N} = C\Delta K^m$$

Linear traction-separation response:





Bond wire base
(200µm)

Cohesive zone area
(1µm)

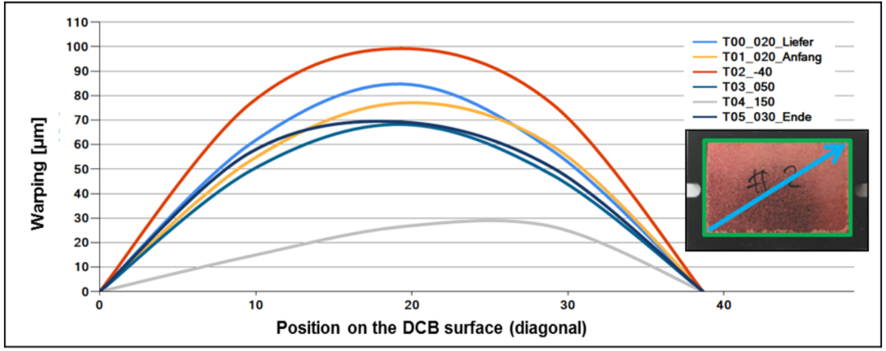
Metallization
(10µm)

Die
(380µm)

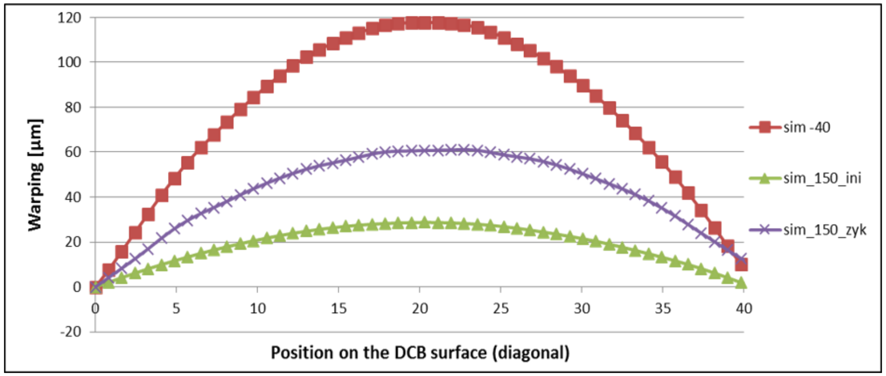
III. Reliability | FE simulation: Calibration

Calibration result: Good compliance between warpage measurement and simulation

Warpage measurement results:



Simulation results:

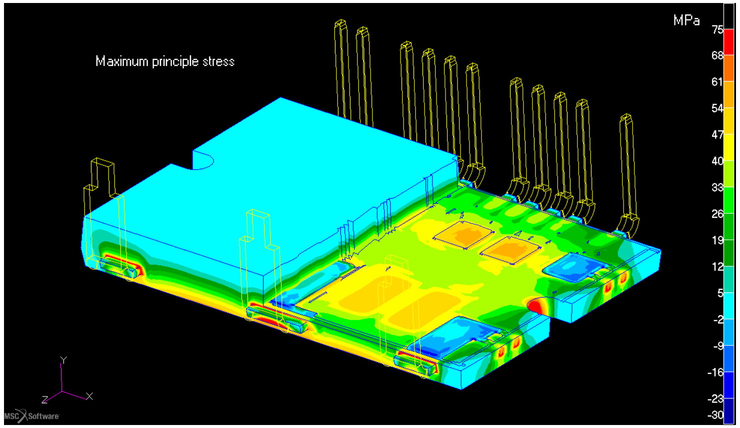


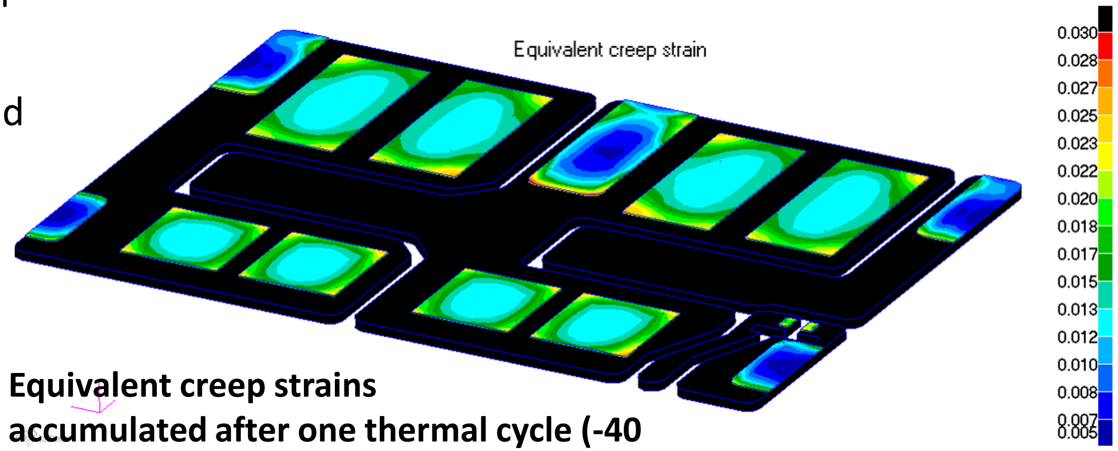
OMI Equinox:

III. Reliability | FE simulation: First simulation results

FE simulation results:

- Quantifying of creep strains in the die attach of the SiC dies accumulated over the process steps and through thermal cycling already by global model
- Significant strains and stress can be observed in the die attach
- Results indicate that creep strain are primarily influenced by the high CTE mismatch between DCB and SiC dies
- Accumulating equivalent creep strain (=failure criterion) in die attach may lead to solder fatigue





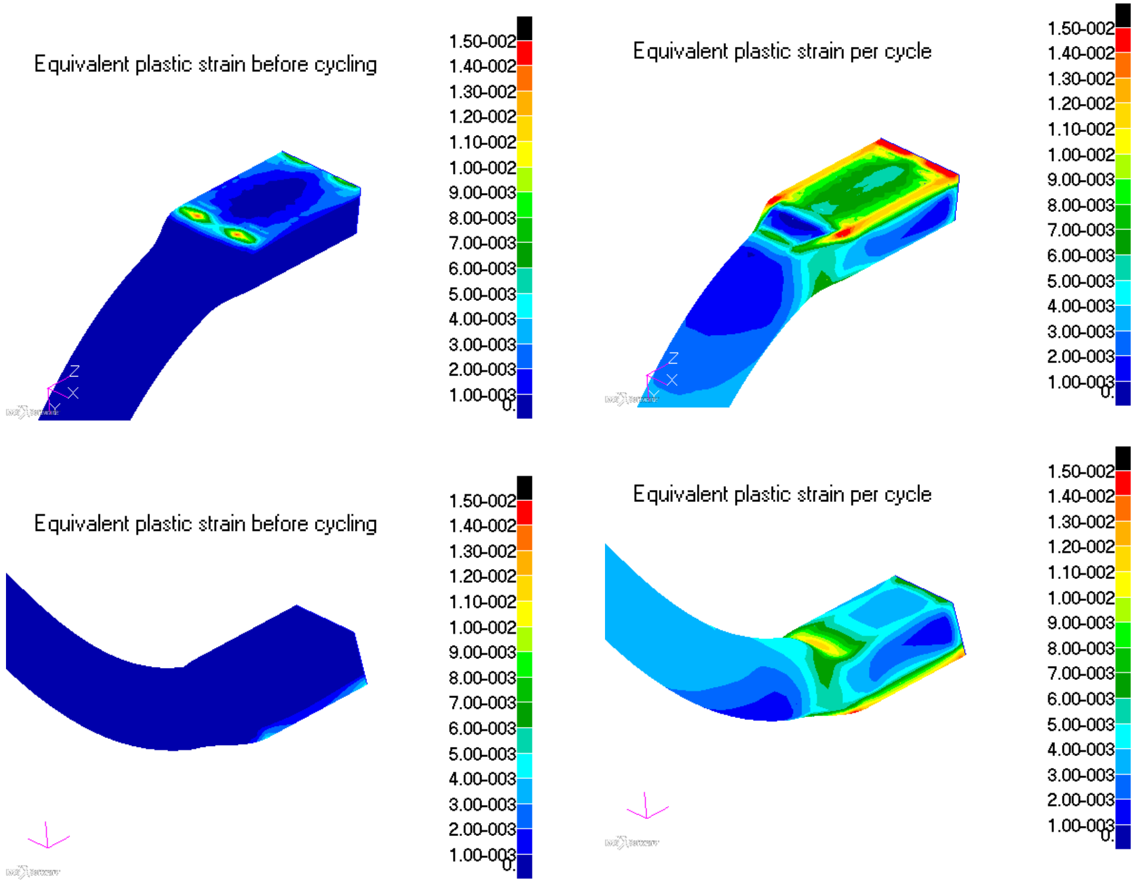
Equivalent creep strains accumulated after one thermal cycle (-40 to 150°C)

III. Reliability | FE simulation: First simulation results

FE simulation results:

- Monitoring of mechanical stress concentration and plastic deformation at the bond wires have been performed by using the local model
- Strain values are significant, but conclusions can only be made together with the testing results

→ **Further investigations are needed**



Equivalent plastic strain before cycling

Equivalent plastic strain per cycle

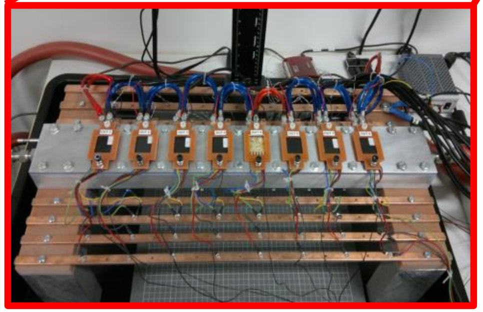
Equivalent plastic strain before cycling

Equivalent plastic strain per cycle

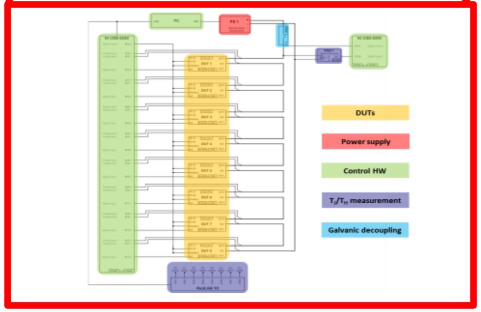
III. Reliability | Active power cycling: Test bench adaption

Starting point: Existing APC test bench dedicated to MOSFET / diode based power modules

APC test bench at Fraunhofer ENAS:



1. Sample holder

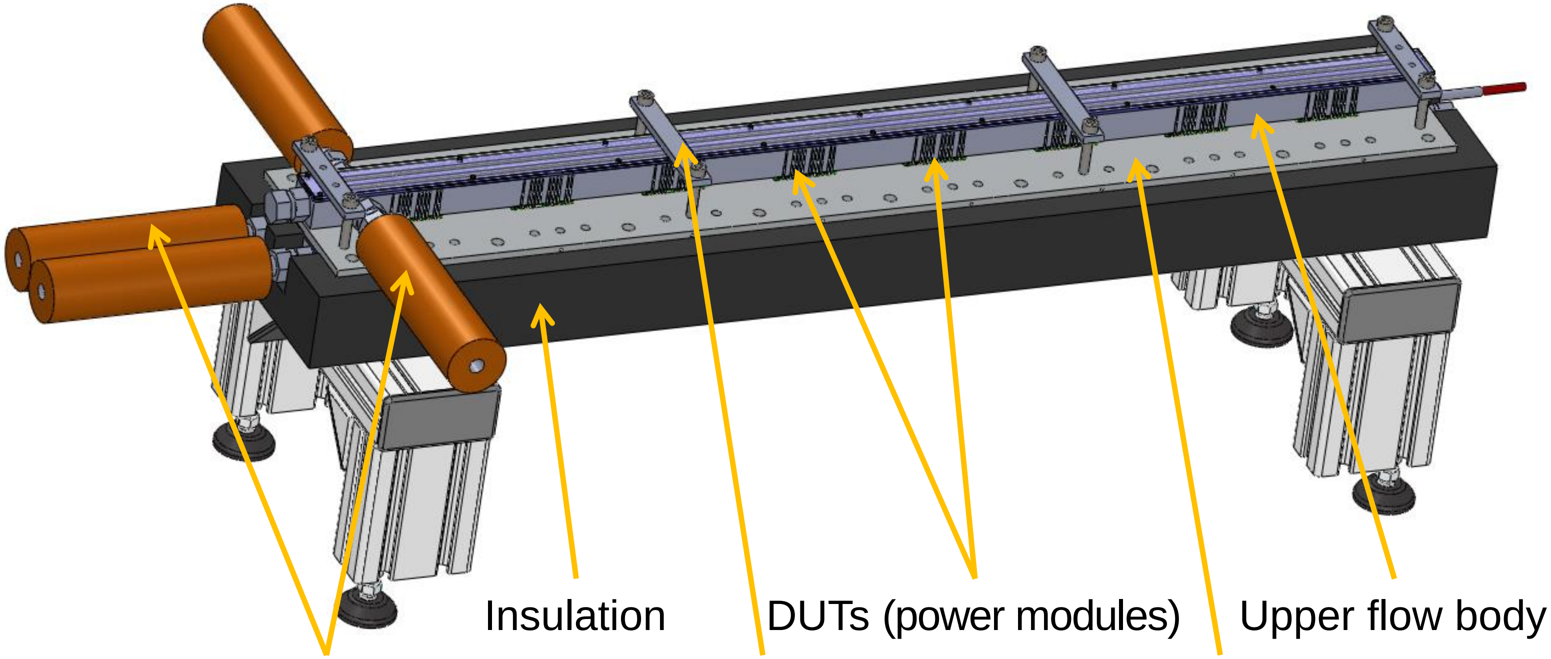


2. Electrical HW / connection plan

3. LabVIEW control SW

III. Reliability | Active power cycling: New sample holder design

For single-sided + double-sided cooling



Insulation

DUTs (power modules)

Upper flow body

Coolant in- and outlets

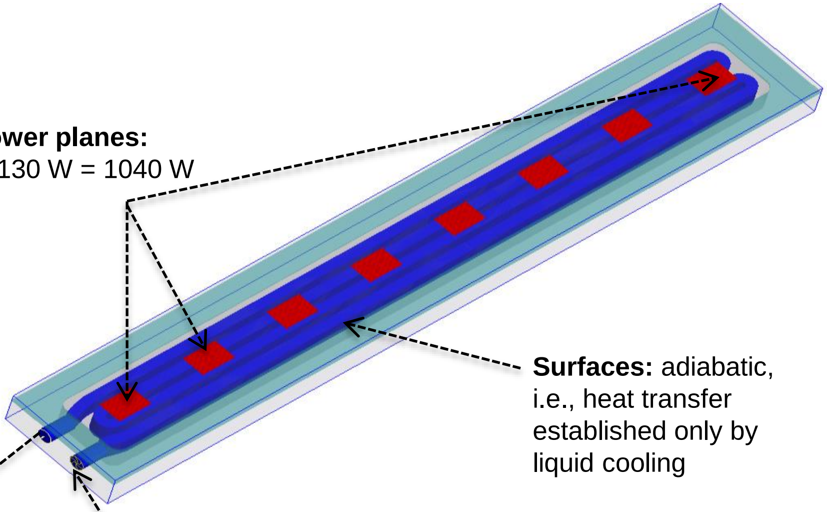
Pressure plate

Main (lower) flow body

III. Reliability | Active power cycling: Thermal analysis of cooling body

Thermal-fluid analysis of cooling body

- Simulation of single-sided cooling case
- Power modules replaced by simple heat sources (130W@50A/1,3V) with constant power
- Employment of steady-sate simulation
- Fluid flow rate is determined by the pump system curve



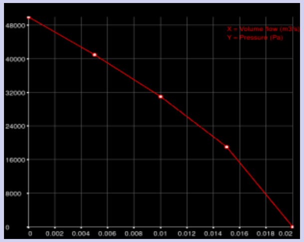
Power planes:
8x130 W = 1040 W

Surfaces: adiabatic, i.e., heat transfer established only by liquid cooling

Outlet: no BCs

Inlet:
dV/dt refers to pump curve (see below)
T_in = const = 60°C

Pump curve of used thermostat (Level 4):



Properties of flow body:

	Chasis material (Alu)	Sealing material (Noaflon 100)
Coeef. of thermal conductivity	313,0 W/mK	0,25 W/mK
Density	19281,0 Kg/m³	1700,0 Kg/m³
Doeff. of spec. heat	131 KJ/KgK	1300 KJ/KgK

Properties of coolant (Silicon oil Kryo 51):

Temaperature	kin. viscosity	dyn. viscosity	Density	Spec. Heat Capacity
degC	mm²/s	kg/(m s)	kg/m³	KJ/(KgK)
20	5	4.63E-03	925	1.61
40	4.1	3.79E-03	905	1.65
60	3.4	3.15E-03	895	1.68
80	2.6	2.41E-03	875	1.71
100	2	1.85E-03	865	1.73

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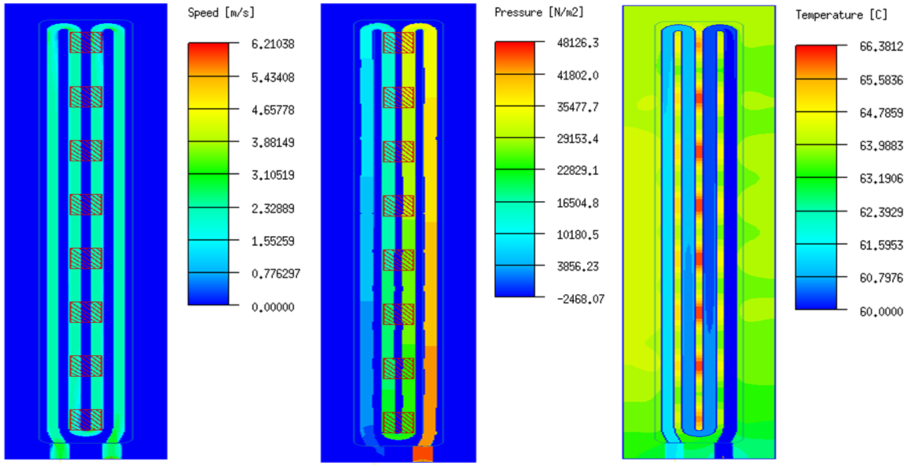
III. Reliability | Active power cycling: Thermal analysis of cooling body

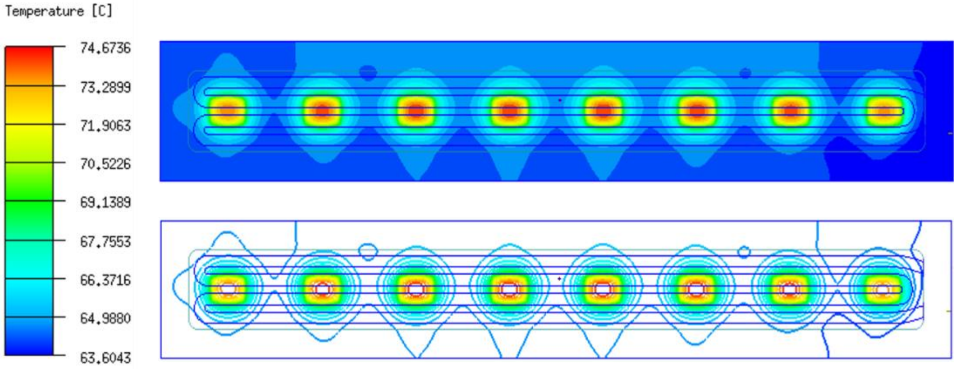
Simulation results:

- Temperature contour plot and iso-thermal indicates low temperature gradient among the heat sources
- Sources 2 – 6 are at the same max. temperature (within 1 k deviation)
- Source 1 and source 8 max temperatures are slightly below
- The max temperatures show a temperature rise above ambient of less then 25 K

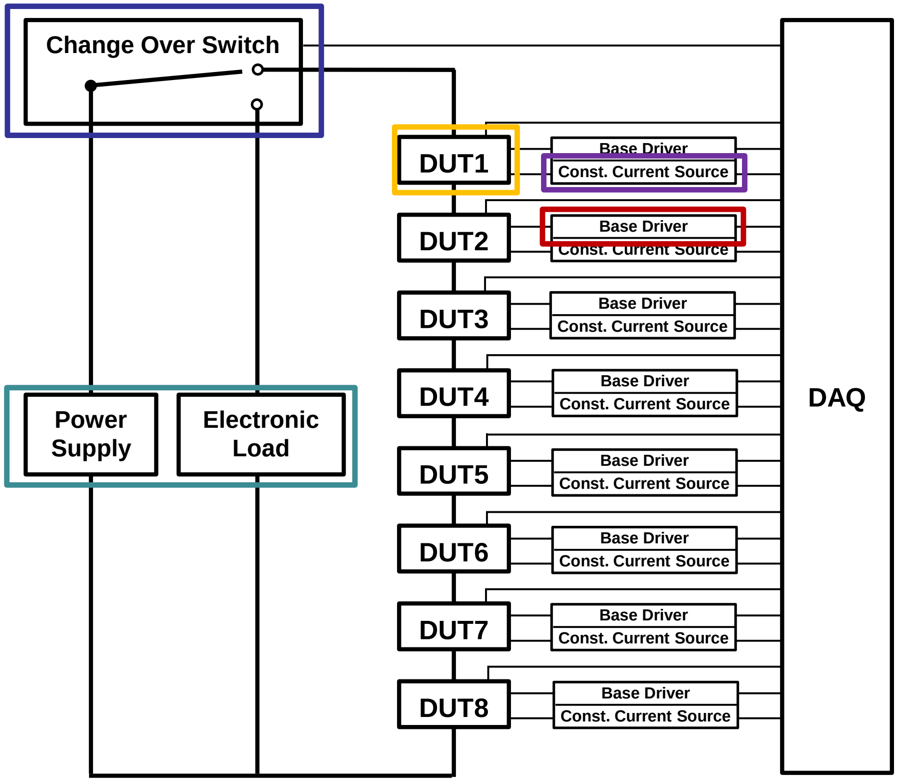
Mid plane contour plots (top view):



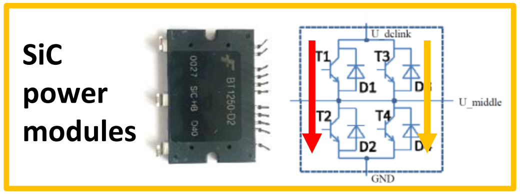
Top plane (heat sources) contour:

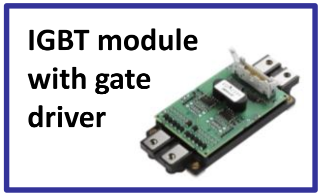


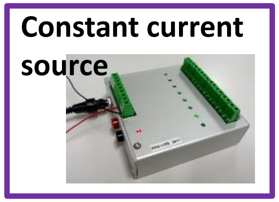
III. Reliability | Active power cycling: Connection plan

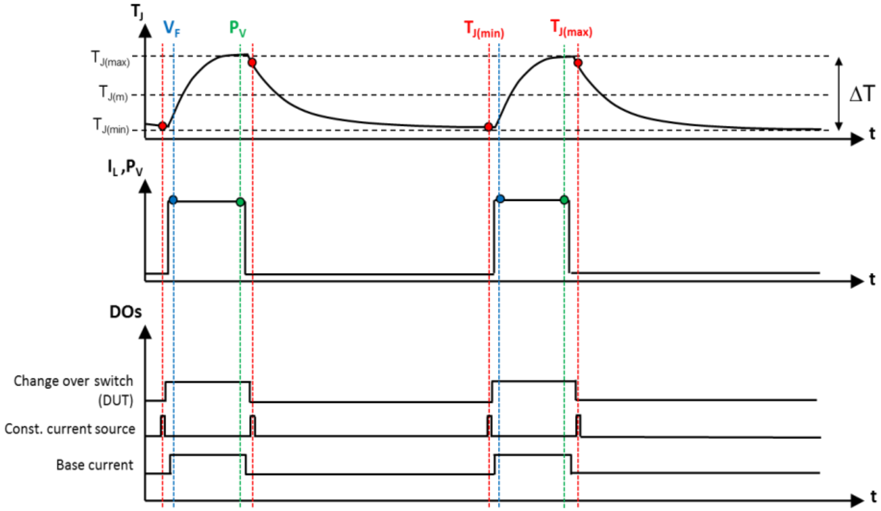


Test 1 **Test 2**

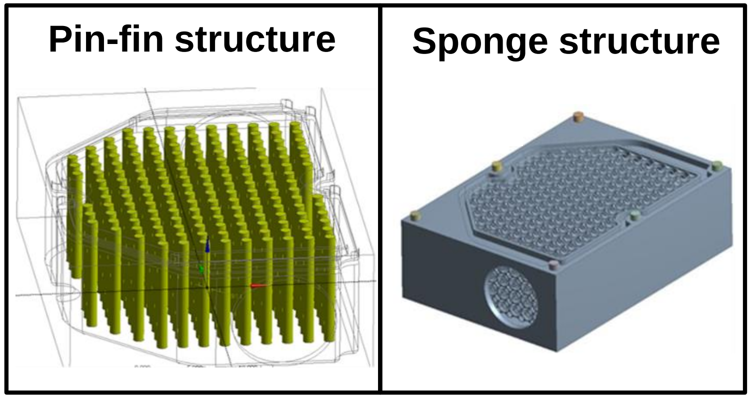








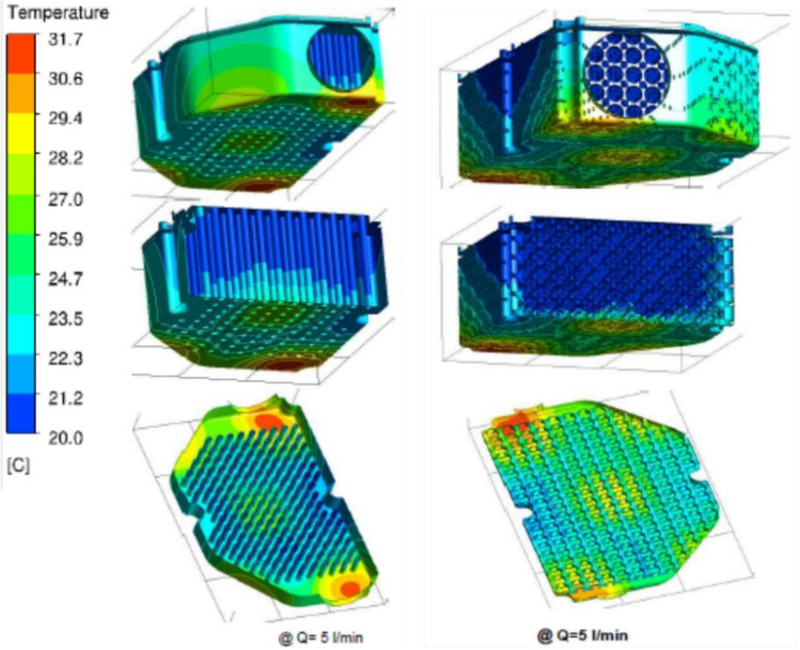
IV. Novel cooling concepts



Investigation of double-sided cooling concept (^{2}COOL) by Swerea IVF:

- Thermal computational fluid dynamics (CFD) analyses on simple inline pin-fin structure as well as on sponge-like structure
  - Coolant flow: 5 – 15 l/min; Temp.: 20°C
  - Heat source: Single-sided scenario, 30W each
  - Results: see picture on the right; higher pressure drop for sponge-like structure

Conclusion: Further improvements needed in terms of reduced height and tilted sponge structure for better vertical mixing of coolant



V. Next steps in COSIVU (reliability work for SiC power module)

FE simulation:

- Simulation of active power cycles for single-sided power module
- Likewise, FE simulation for double-sided cooled power module
- Simulation at system level (inverter building block) with detailed sub-models of critical components (power module, current sensor, …)

Active power Cycling:

- Test bench adaptation:
  - Sample holder: Thermal fluid analysis on double-sided cooling system
  - Connection plan / HW: i) Finalization ii) Fully galvanic decoupled constant current sources iii) Base driver
  - Adaption of LabVIEW control software
- Power cycling tests and failure analysis on single-sided and double-sided cooled power modules

Thank You for Your attention!