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POWER ELECTRONICS PACKAGE MODELLING FOR ADVANCED THERMAL SIMULATIONS

CHRISTIAN MENTIN

RESEARCH UNIT PACKAGING & MULTIPHYSICS

DIVISION POWER ELECTRONICS

christian.mentin@silicon-austria.com

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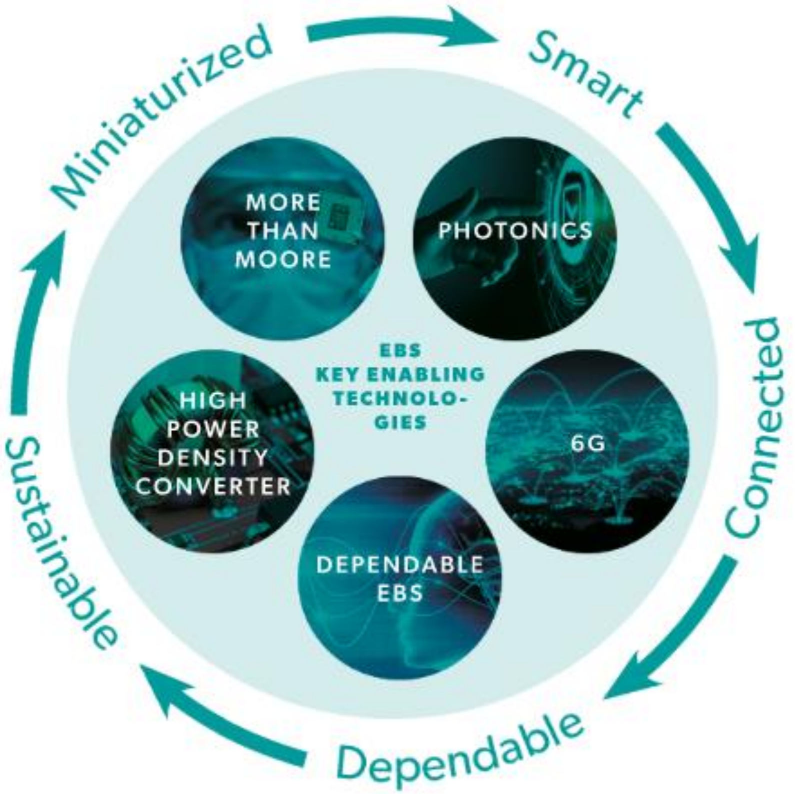
SILICON AUSTRIA LABS (SAL)

What drives us?

As a **high-level research center** and **pioneer in EBS**, we offer the industry, access to top-class R&D infrastructures & research services to give them the decisive competitive advantage on both domestic and on international soil.

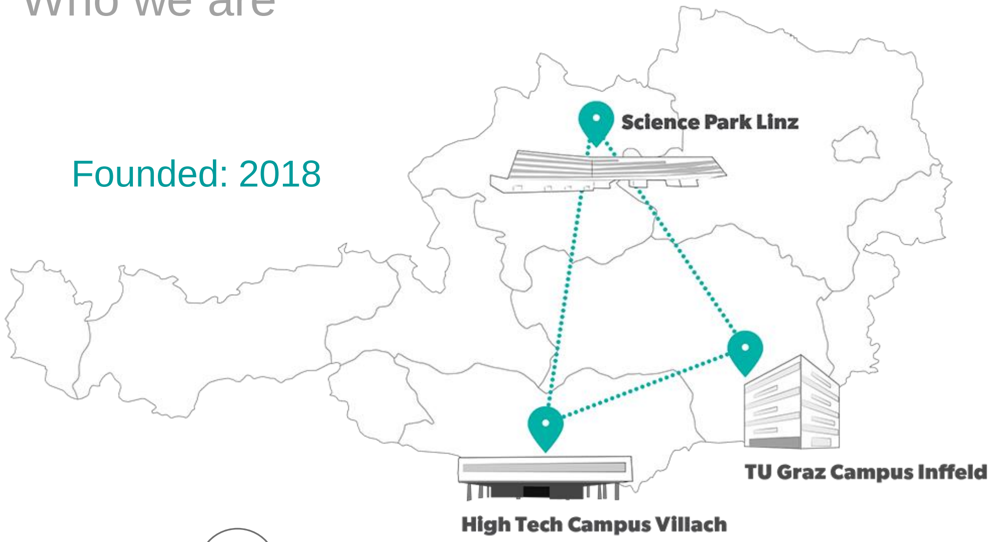
- We provide **EBS Key Enabling Technologies** for Smart, Connected, Dependable, Sustainable and Miniaturized Solutions
- We offer cost-effective research through the lighthouses. **More-than-Moore, Photonics, 6G, High Power Density Converter** and **Dependable EBS**



KEY FACTS*

Who we are

Founded: 2018



3

LOCATIONS

- Graz (HQ)
- Villach
- Linz

> 90

PARTNER NETWORK

- From Industry & Research

> 300

EXPERTS

- Experienced team
- 40 nations
- Multidisciplinary

128

PUBLICATIONS

32 Mio. €

PROJECT VOLUME

- Total volume for research projects

5

SHAREHOLDER

- 50,1 % Republic of Austria (BMK)
- 24,95 % FEEI
- 10 % Styria (SFG)
- 10 % State of Carinthia
- 4,95 % Upper Austria (UAR)

*2022

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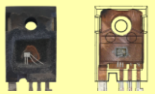
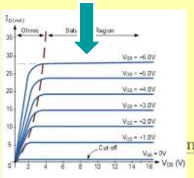
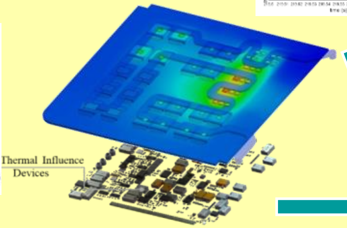
Packaging & Multiphysics (PM)

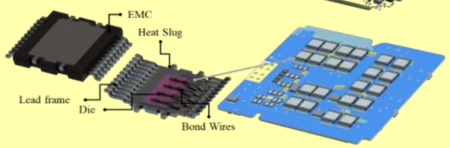
Device characterization





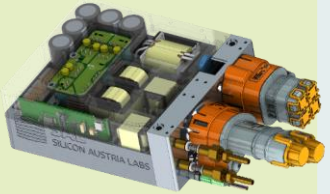
Thermal/mechanical cycle analysis



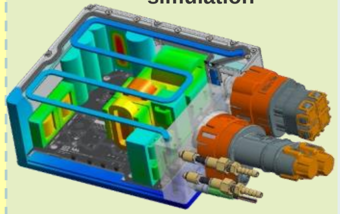


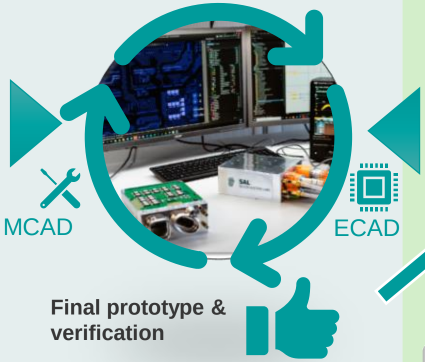
Component modelling & system integration

ECAD-MCAD design Subsystem integration



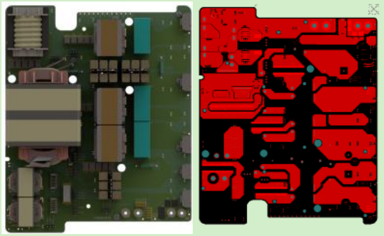
Thermal + CFD simulation

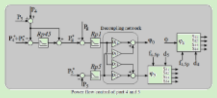




Final prototype & verification

PCB layout design

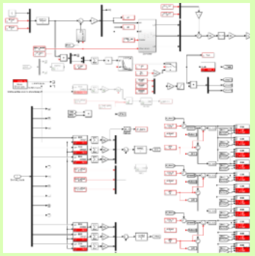




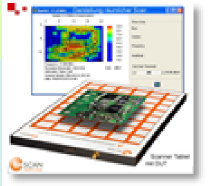
Controller design and rapid prototyping

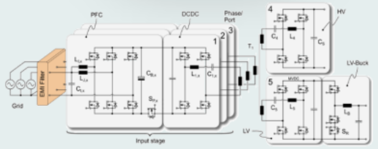
Instrumentation and Test (IT)

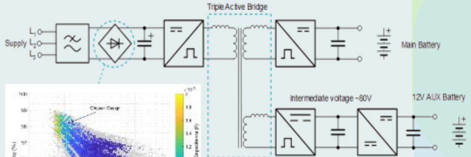
MPSoCs for P-HIL & control algorithm implementation

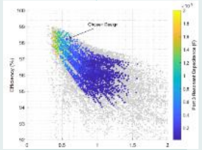


High-bandwidth sensing and high-precision measurement for high switching frequency converters

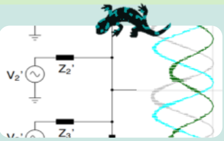




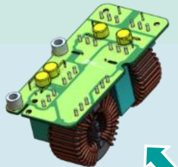




Converter system architecture & topology optimization



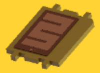
Circuit analysis & simulation

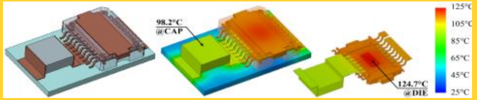


EMI modelling and EMI filter optimization

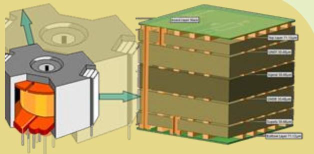
Architecture and Topologies (AT)

Integration technologies for active & passive components

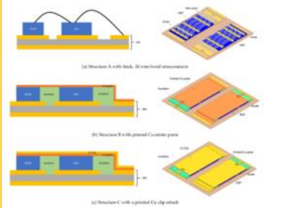


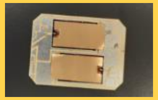


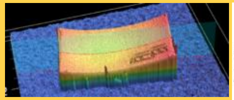
Multi-domain modelling of discrete & power module packages

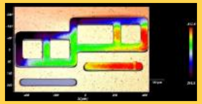


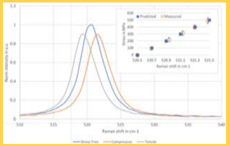
Passive components design, optimization











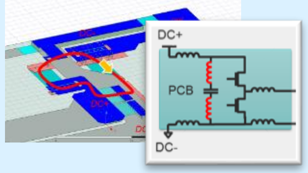
Warpage Analysis (from die to package)

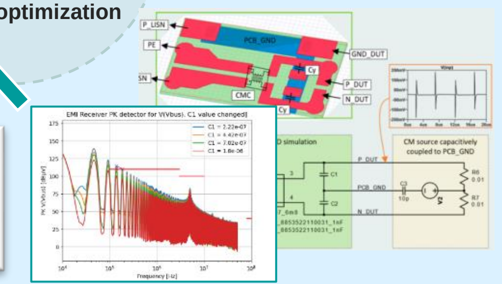
Interconnection technologies for power modules

Heterogenous Integration (HIT)

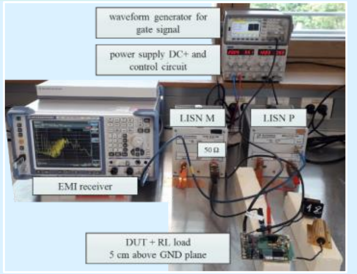
Multidisciplinary research needs multidisciplinary competences!

Automated & time-efficient simulation-workflows





System level EMC simulation of PE converters



Broadband component measurement and modelling

Coexistence and Electromagnetic Compatibility (CEMC)

AGENDA

01 **Motivation**

02 Introduction

03 Methodology

04 Simulation use-cases

05 Conclusions

SIMULATION CHALLENGES

HIGH-FIDELITY MODELS

MULTIPHYSICS

MODEL INTEGRATION

INTERACTIONS

Environmental conditions
Control systems
Other system components
Electromagnetic interference
Thermal / electrical
Degradation mechanisms

DESIGN

Large-scale multi-objective optimization

Automation on virtual platform

Optimal component selection and sizing

VIRTUAL TESTING

Simulate realistic operating conditions

MODEL-BASED DEVELOPMENT

MOTIVATION

VIRTUAL POWER ELECTRONICS DEVELOPMENT

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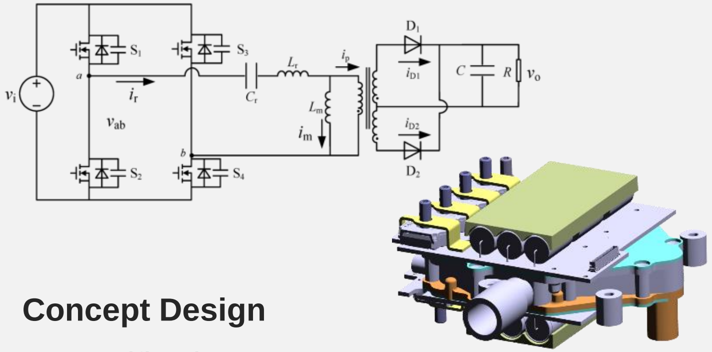
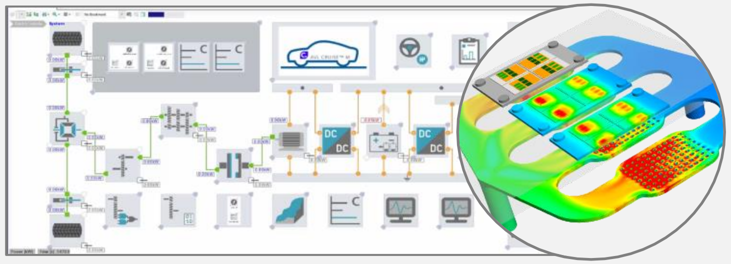


Concept Design

- Specifications
- System layout
- Packaging concept
- Cooling concept
- Component selection and design
- Requirements review and feasibility studies

FEASIBILITY & CONCEPT



Virtual design validation

- Operation performance
- Cooling performance
- Scenarios
  - **Start-up**
  - **Continuous/discontinuous load/derating**
  - **Environment Conditions**

BUT HOW TO START?

DESIGN VALIDATION

Virtualization of test procedures

- Identify most critical operation modes and routes
- Optimize reliability, operation strategy, charging, control
- Optimize for EMI

Test result review

- Investigation of failures and deficiencies
- Understand and improve process chain

TESTING

i Scalable models from **concept phase** through **optimization** up to the **test bench simulation**

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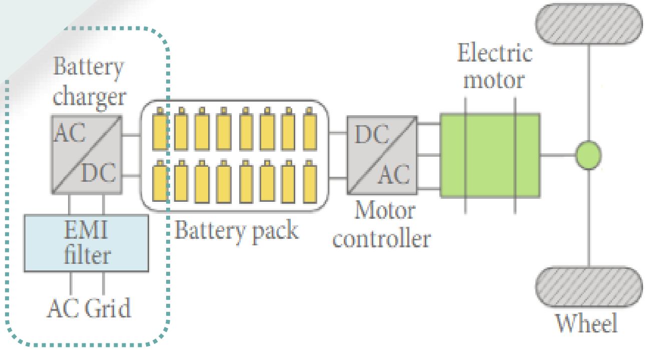
INTRODUCTION

THE SIMULATION USE CASE

THE BEGINNING

- **Tiny Power Box** project @ SAL 7kW bi-directional on-board charger (OBC) for automotive application
  water cooled
  +2.4kW LV DCDC output



- Specifications:
  - As small as possible
  - Efficiency > 98%
  - Power rating 7 kW
  - Liquid cooling

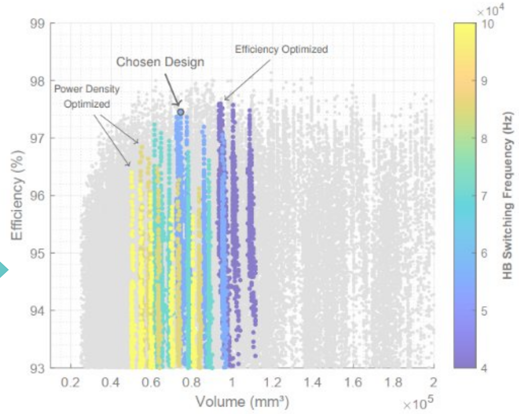
Very hi
> 4k

We need accurate simulations!

SAL Co-Simulation

MATLAB SIMULINK + **SALamander**Circuits

Customized for Pareto-front style simulations.



: Coupled Thermal + Simulink (Control) + Electrical Simulations

Today's focus:
Thermal modelling aspects

MAIN OBC ASSEMBLY

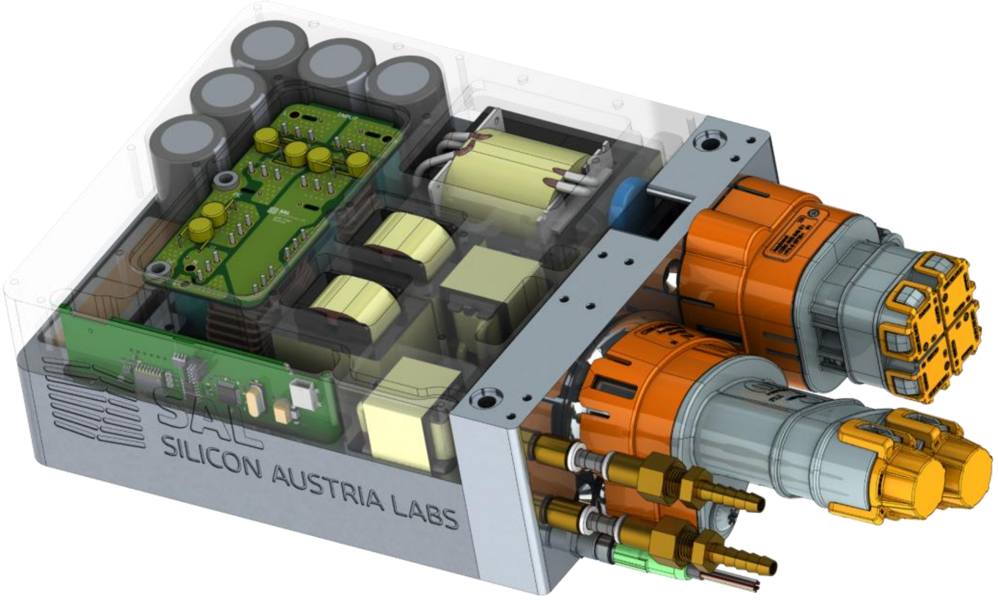


Figure 1 – Transparent Tiny Power Box assembly

Fig.2 Overall assembly concept with integrated liquid cooling for an automotive OBC application. The sytem setup includes **a)** top side cooling system, **b)** aluminum housing which is filled with potting material, **c)** passive components PCB, **d)** power stage PCB, **e)** bottom side cooling system thermal interface material, **g)** auxiliary supply board, **h)** control board, **f)** EMI filter board. The potting material (not shown) help to increase the heat transfer towards the liquid cooling system and improve cooling of the components. Thermal interface materials are used to thermally attach the coldplates to the semiconductors the aluminum housing.

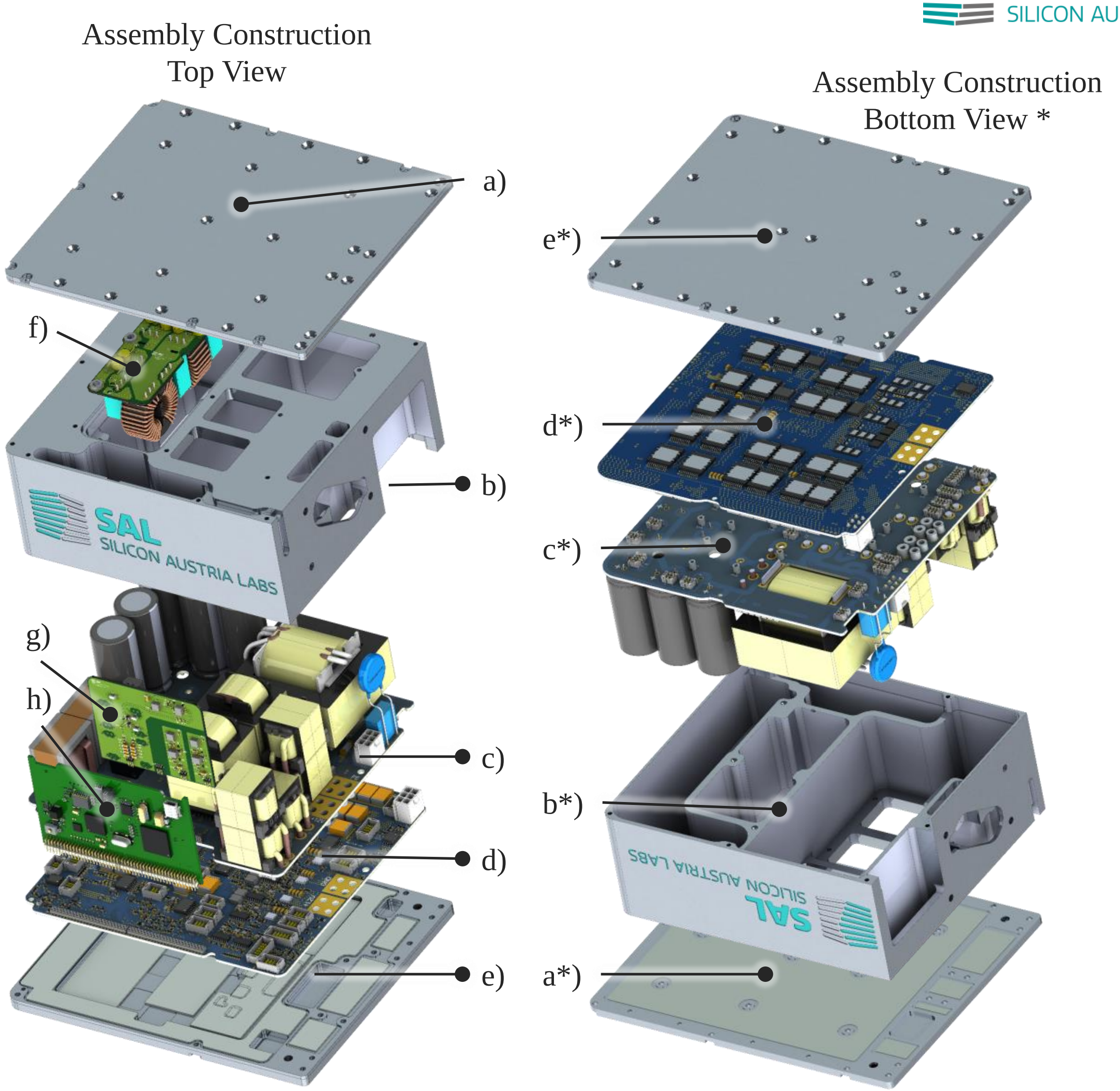
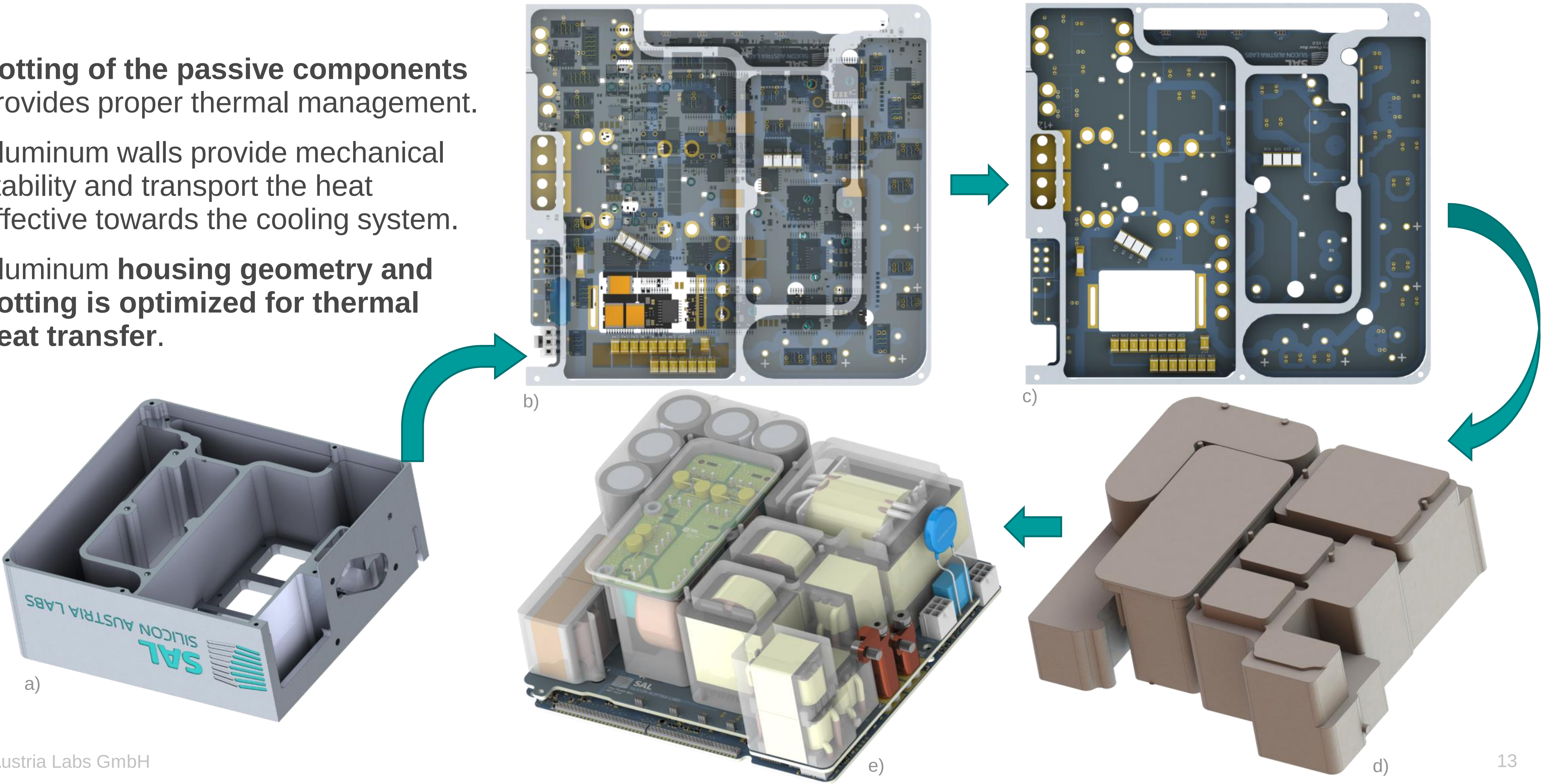


Figure 2 – Overall assembly concept

OBC POTTING FOR OPTIMUM COOLING

- **Potting of the passive components** provides proper thermal management.
- Aluminum walls provide mechanical stability and transport the heat effective towards the cooling system.
- Aluminum **housing geometry and potting is optimized for thermal heat transfer**.

Figure 3 – Potting Chambers and Aluminum housing wall structures

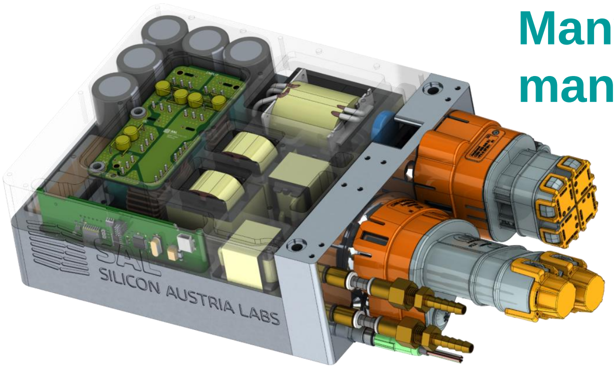


INTRODUCTION

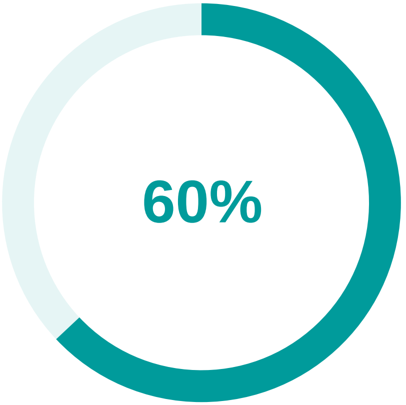
SIMULATION EXPERTS SURVEY

A few years ago, one of our partners conducted an internal and external survey, one of the questions being:

“How simulation engineers distribute their time when working in projects?”



Many details, many components!



About 60% of the time is consumed in data handling and preparation.

> This is just one of the reasons why we are focusing on developing **seamless workflows**.
>
> In a nutshell the developed tools and workflows **enable simulation team to concentrate on their work** instead of dealing with data exchange and compatibility issues.

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- 03 **Methodology**
- 04 Simulation use-cases
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METHODOLOGY

HIGH FIDELITY SYSTEM MODELLING

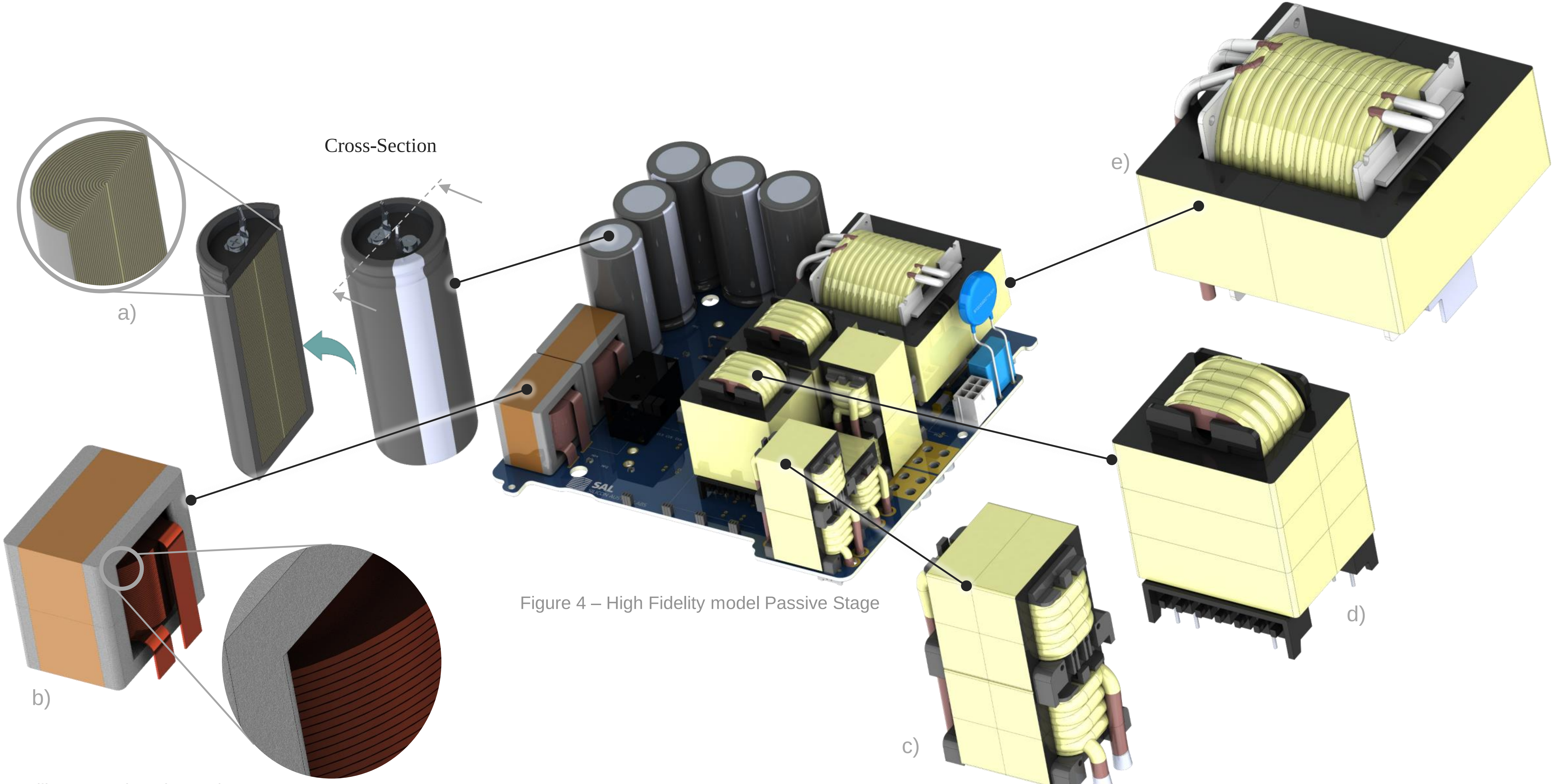

Figure 4 – High Fidelity model Passive Stage

HIGH FIDELITY SYSTEM MODELLING

High fidelity component models are an enabler for high density system integration and accurate multi-domain simulations.

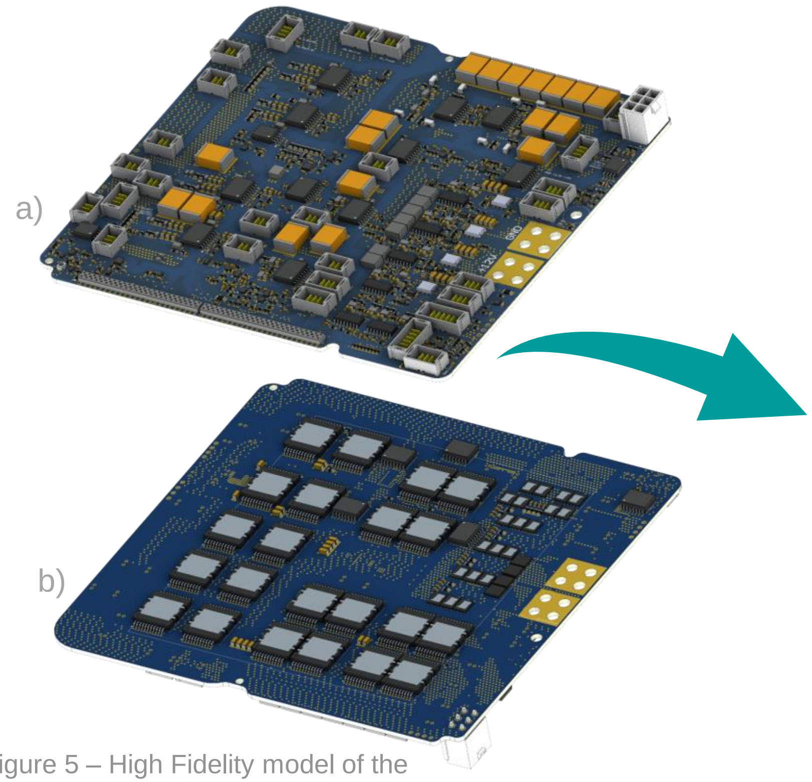

Figure 5 – High Fidelity model of the PCB with all components placed a) top View and b) bottom View

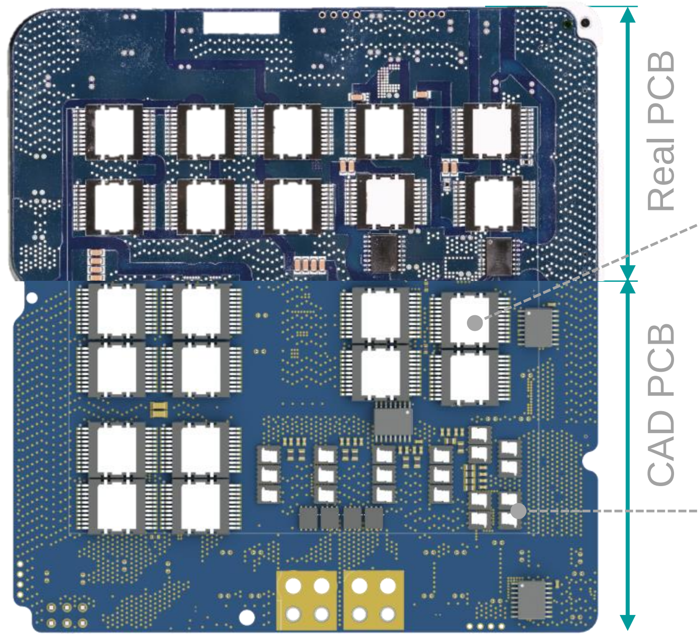

Figure 6 – Internal Structure of Power Stage PCB showing top copper layer with vias, traces and power devices.

Package model including structures as bondwires, die size and accurate leadframe geometry

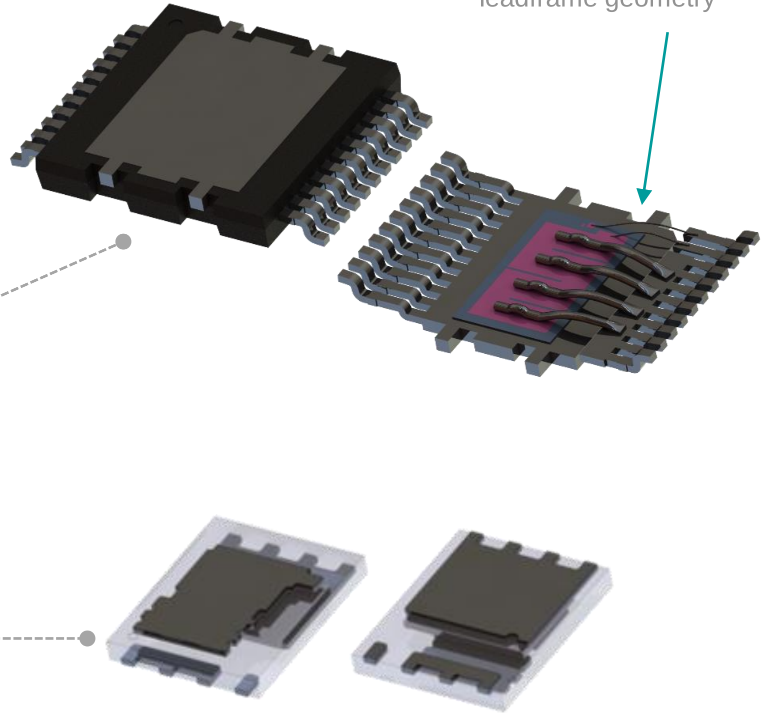

Figure 7 – High Fidelity semiconductor models generated by device package inspection (SAL inhouse process)

PCB COPPER STRUCTURE

- Copper structures of a PCB:
  - Power stage PCB has 8 copper layers.

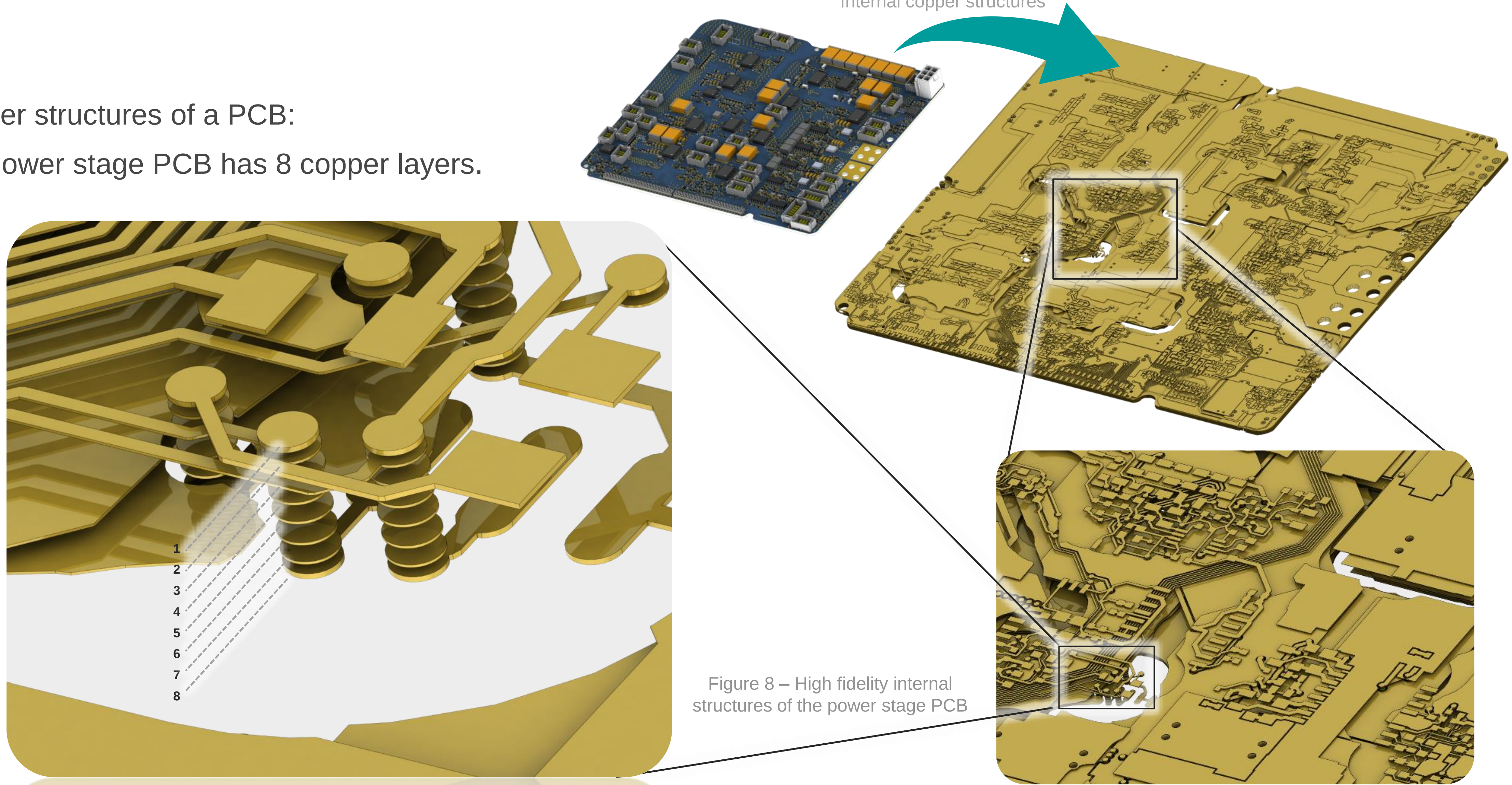

Figure 8 – High fidelity internal structures of the power stage PCB

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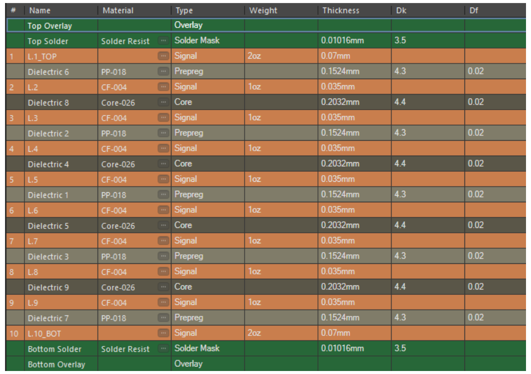
SIMPLIFICATION OF PACKAGE DETAILS

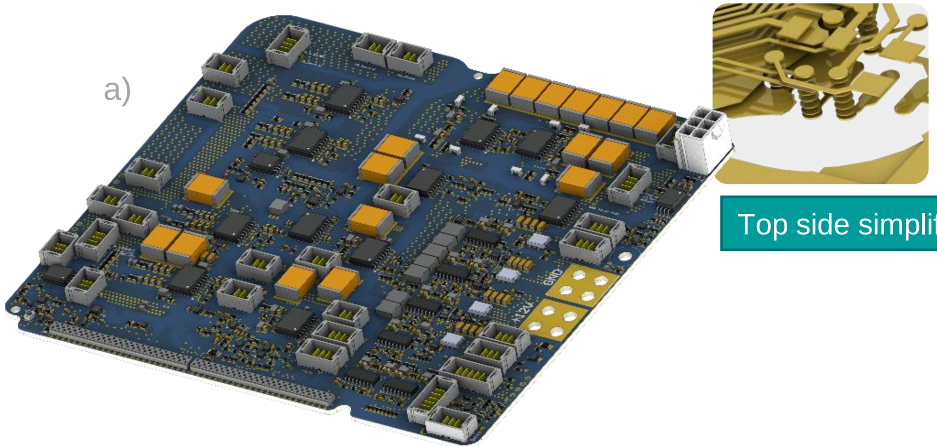
PCB COPPER STRUCTURE SIMPLIFICATION

- Copper structures need a simplification step. Detailed structures are not feasible for simulation.

PCB layer stackup
(copper and dielectric layers)



#	Name	Material	Type	Weight	Thickness	Dk	Df
	Top Overlay		Overlay				
	Top Solder	Solder Resist	Solder Mask		0.01016mm	3.5	
1	L.1_TOP		Signal	2oz	0.07mm		
	Dielectric 6	PP-018	Prepreg		0.1524mm	4.3	0.02
2	L.2	CF-004	Signal	1oz	0.035mm		
	Dielectric 8	Core-026	Core		0.2032mm	4.4	0.02
3	L.3	CF-004	Signal	1oz	0.035mm		
	Dielectric 2	PP-018	Prepreg		0.1524mm	4.3	0.02
4	L.4	CF-004	Signal	1oz	0.035mm		
	Dielectric 4	Core-026	Core		0.2032mm	4.4	0.02
5	L.5	CF-004	Signal	1oz	0.035mm		
	Dielectric 1	PP-018	Prepreg		0.1524mm	4.3	0.02
6	L.6	CF-004	Signal	1oz	0.035mm		
	Dielectric 5	Core-026	Core		0.2032mm	4.4	0.02
7	L.7	CF-004	Signal	1oz	0.035mm		
	Dielectric 3	PP-018	Prepreg		0.1524mm	4.3	0.02
8	L.8	CF-004	Signal	1oz	0.035mm		
	Dielectric 9	Core-026	Core		0.2032mm	4.4	0.02
9	L.9	CF-004	Signal	1oz	0.035mm		
	Dielectric 7	PP-018	Prepreg		0.1524mm	4.3	0.02
10	L.10_BOT		Signal	2oz	0.07mm		
	Bottom Solder	Solder Resist	Solder Mask		0.01016mm	3.5	
	Bottom Overlay		Overlay				



Top side simplification

PCB mixture material with thermal conductivity dependent on copper content and direction

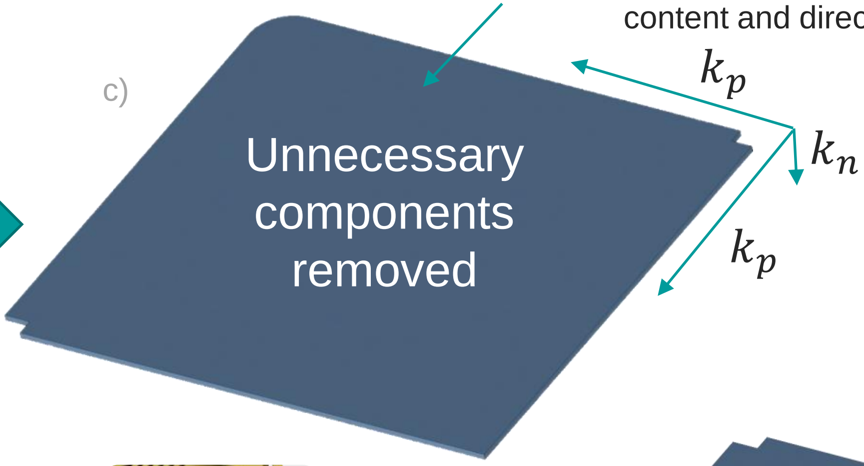
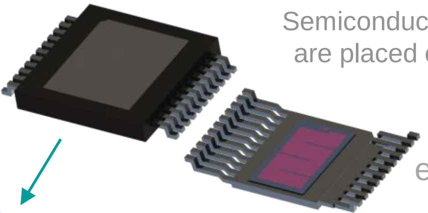
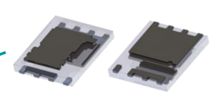


Figure 9 – High Fidelity model
a) Top View and b) Bottom View

Bottom side Simplification

Semiconductor models are placed on the PCB





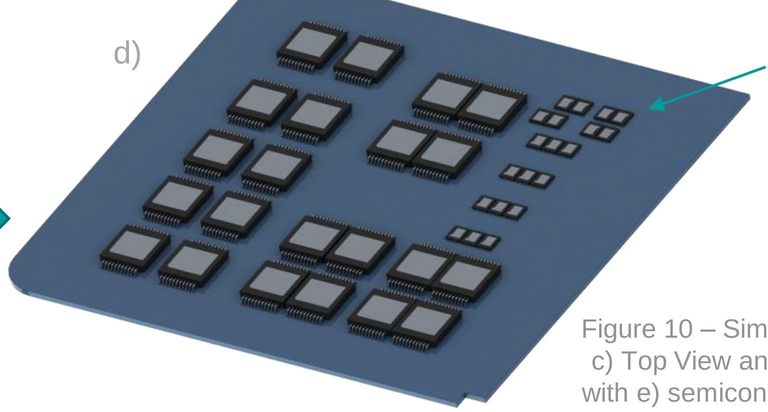
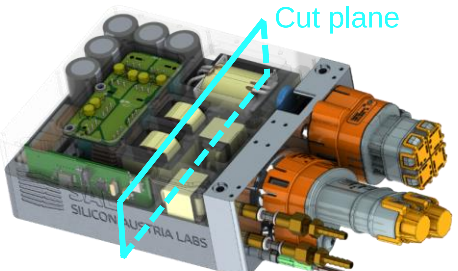


Figure 10 – Simplified PCB model
c) Top View and d) Bottom View
with e) semiconductor component details

METHODOLOGY

CUT VIEW



- Cut view of the Tiny Power Box OBC model.
- Lots of connectors and distance holders are used as support structures. In combination with the aluminum housing this results in a mechanically stiff setup providing very little possible mechanical PCB movements between supports.

Simplified Electrolytic Capacitor [3]

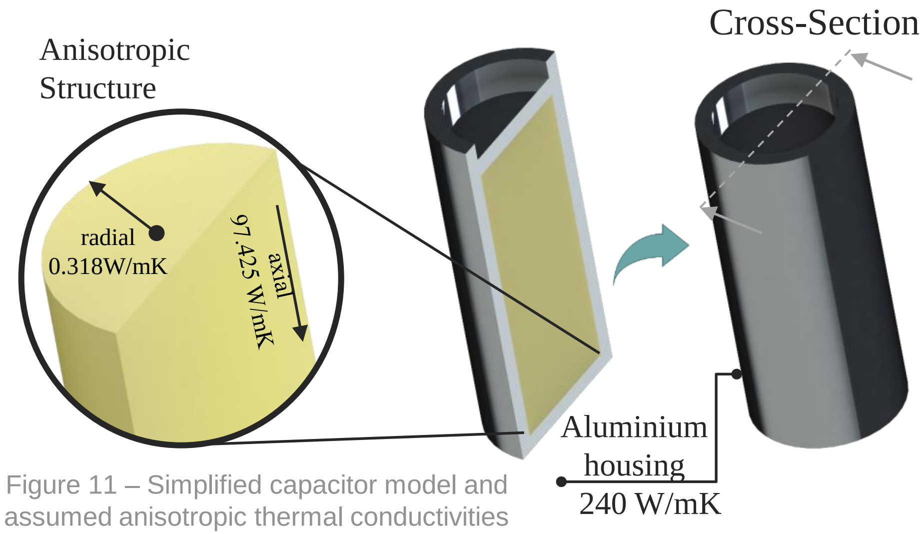


Figure 11 – Simplified capacitor model and assumed anisotropic thermal conductivities

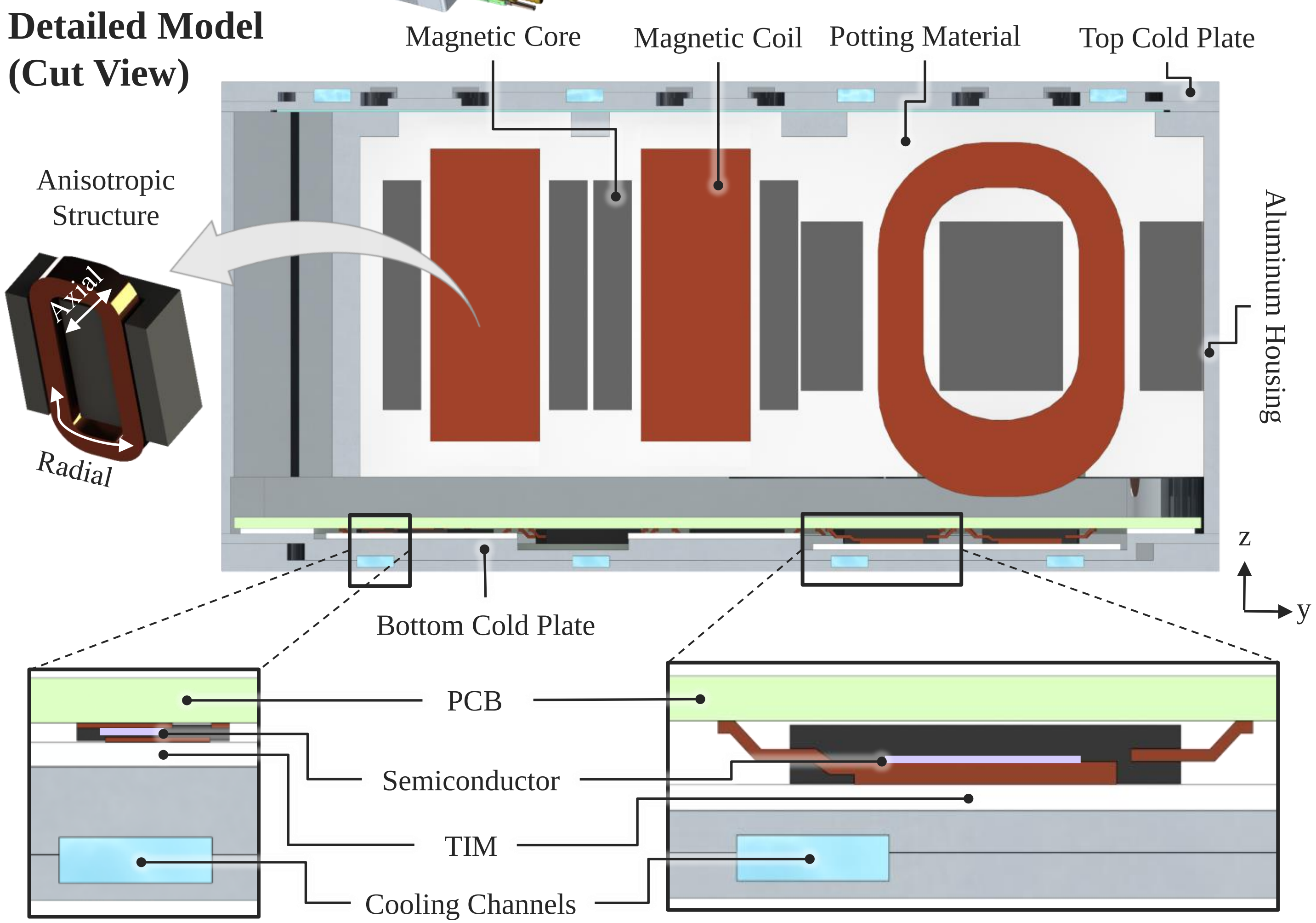


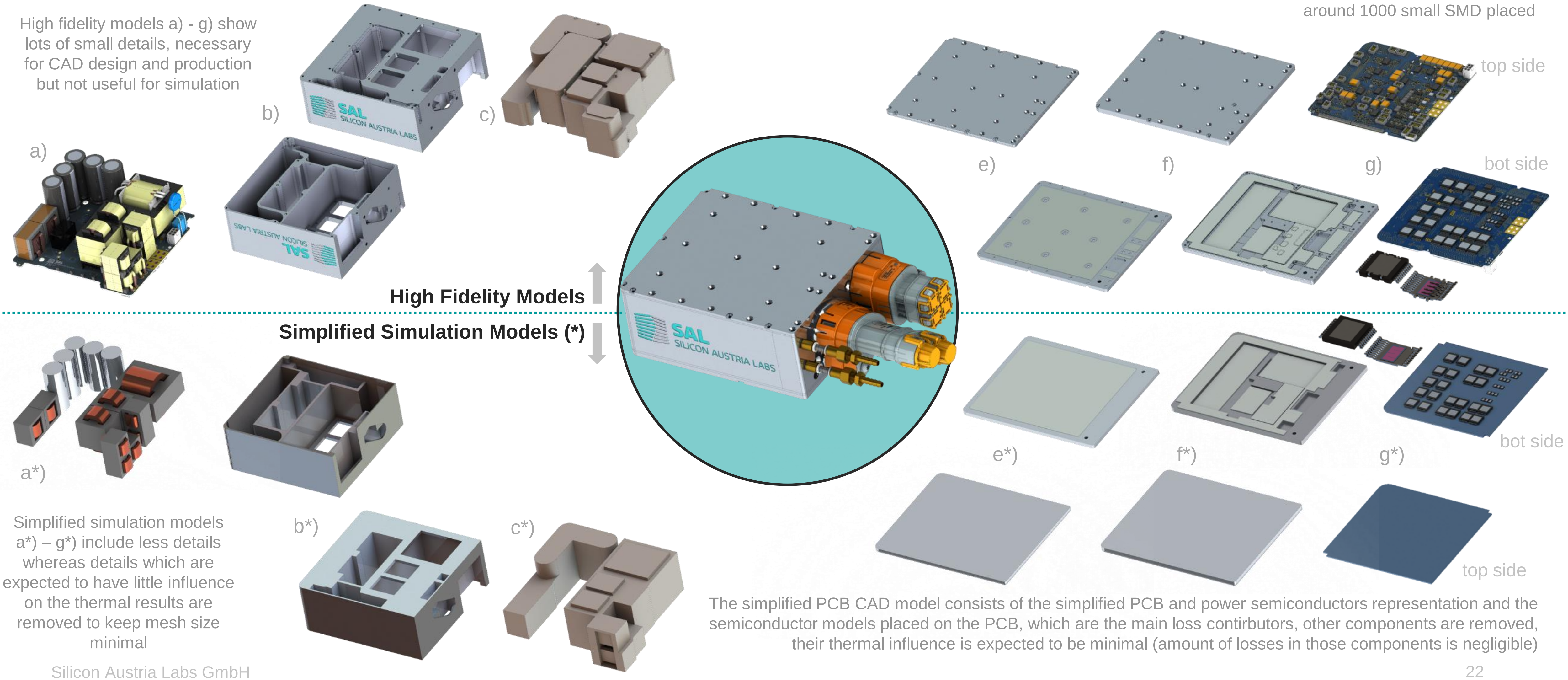
Figure 12 – Cut view of the simplified simulation model

SIMPLIFICATION FOR SIMULATION

Fig. 11 High Fidelty Models vs. Simplified Simulation Models

High fidelity models a) - g) show lots of small details, necessary for CAD design and production but not useful for simulation

The PCB CAD Data shows around 1000 small SMD placed



Simplified simulation models a*) – g*) include less details whereas details which are expected to have little influence on the thermal results are removed to keep mesh size minimal

The simplified PCB CAD model consists of the simplified PCB and power semiconductors representation and the semiconductor models placed on the PCB, which are the main loss contirbutors, other components are removed, their thermal influence is expected to be minimal (amount of losses in those components is negligible)

AGENDA

- 01 Motivation
- 02 Introduction
- 03 Methodology
- **04 Simulation use-cases**
- 05 Conclusions

SIMULATION USE-CASES

SEMICONDUCTOR PACKAGE ANALYSIS

SIMPLIFIED SIMULATION SETUP

- Mimicking a typical PCB setup with a semiconductor and heatsink
- **Several variants of semiconductor models** are compared.
    - Variant 3 is the most accurate replicate of the real semiconductor package
- In a later step, also the copper content in the PCB is varied.
    - Since the copper content directly influences the thermal conductivity of the PCB this is taken into account with the proposed copper volume based PCB simplification approach.

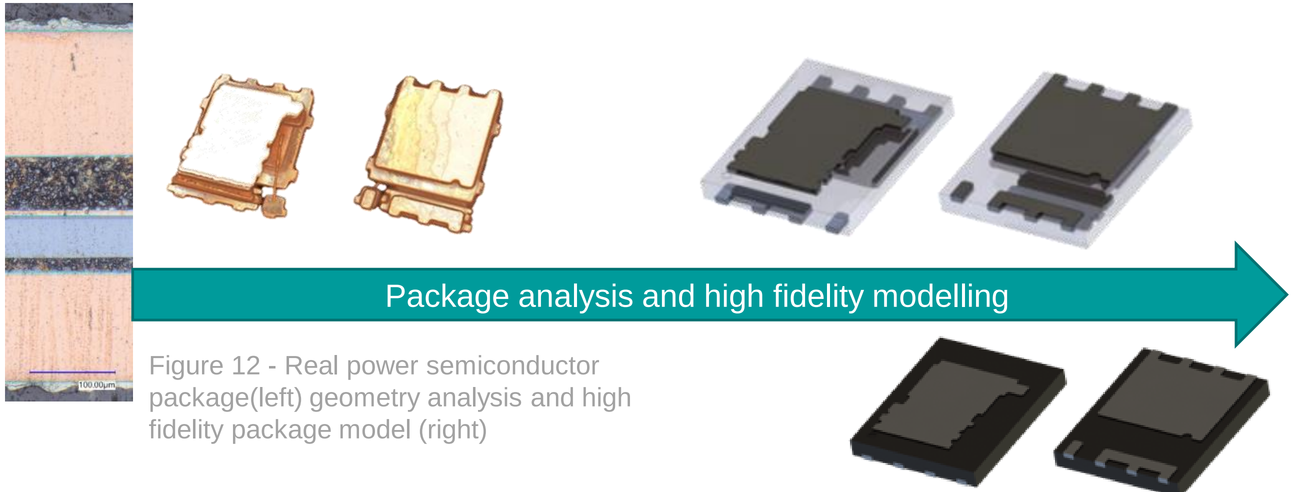


Figure 12 - Real power semiconductor package(left) geometry analysis and high fidelity package model (right)

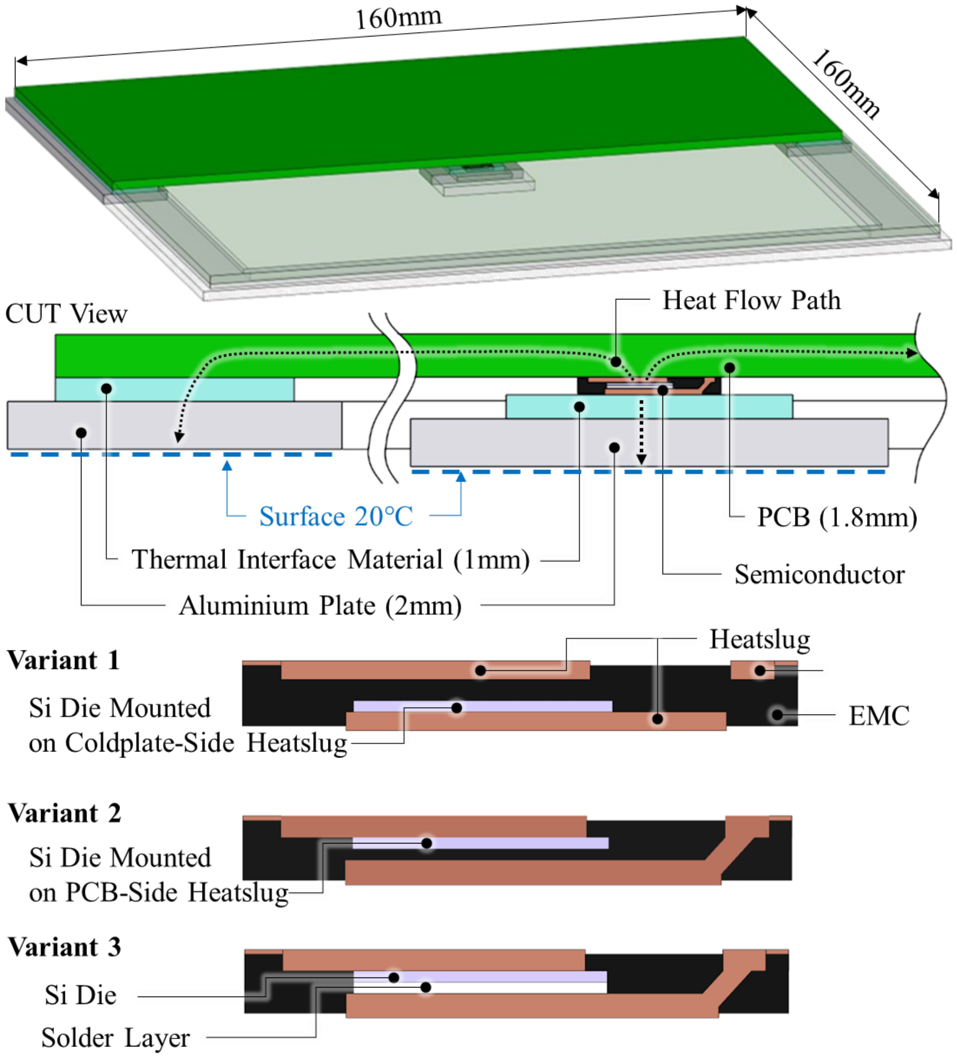
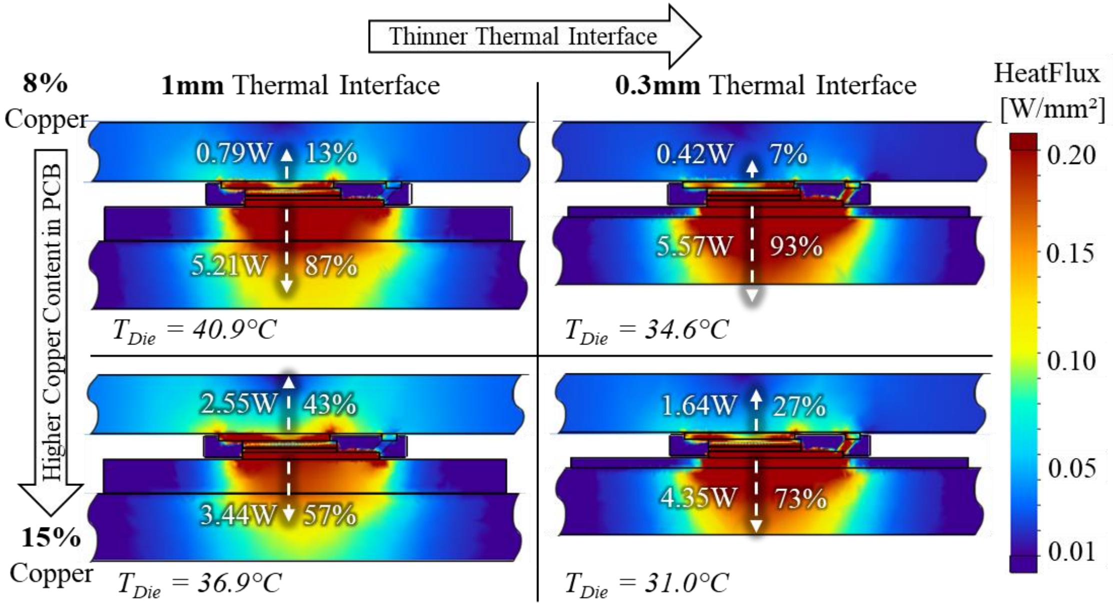


Figure 13 – Simplified simulation setup with three different variants of the (typically unknown) semiconductor packaging model.

COMPARISON OF DIFFERENT SETUPS

Figure 15 – Thermal heat transfer through device leadframe with different PCB copper content and thermal interface thickness



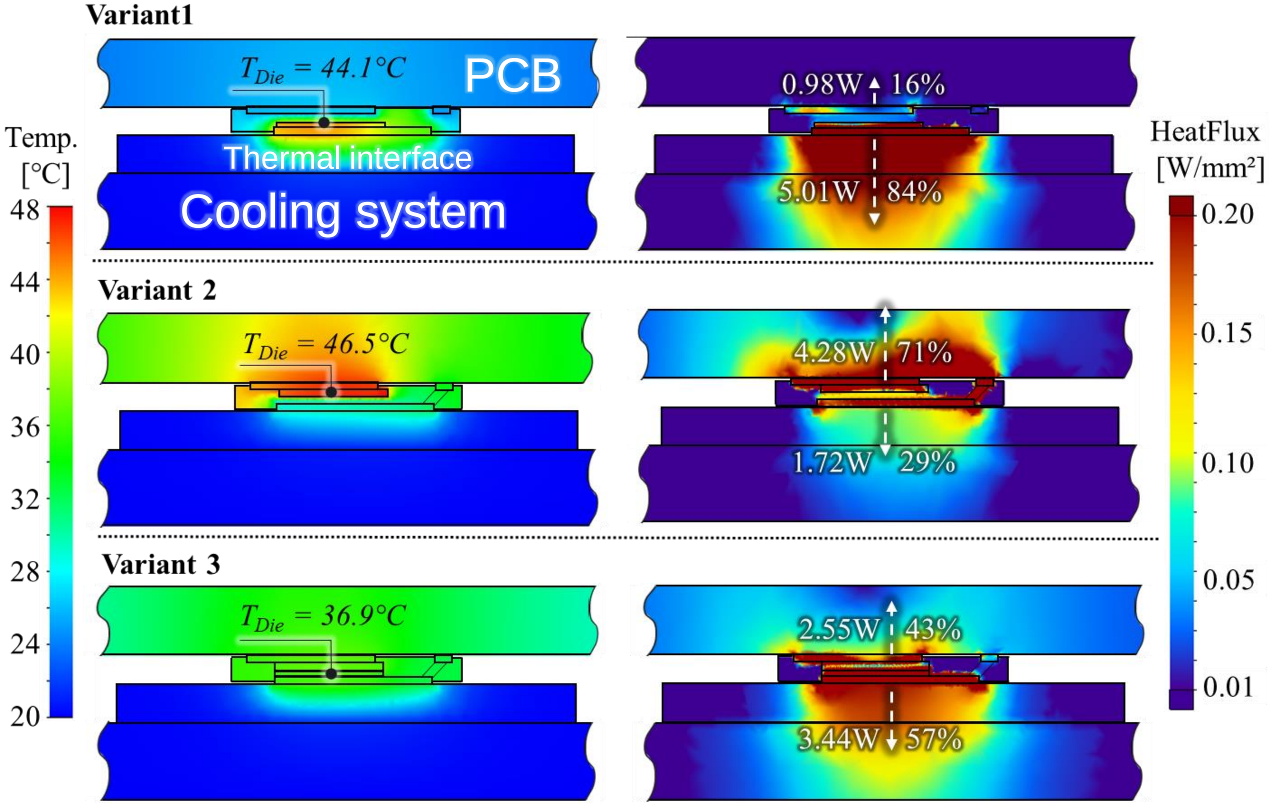


Figure 14 – Thermal heat transfer through device leadframe (right) and resulting semiconductor temperatures (left)

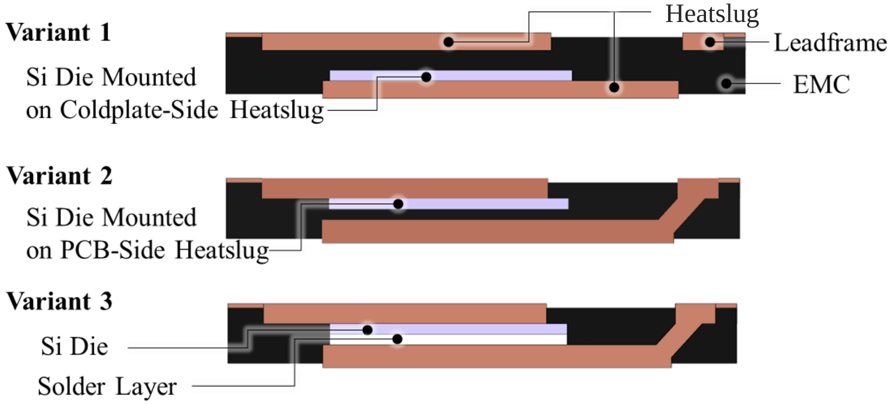


Figure 16 – Three different variants of the semiconductor packaging model.

SIMULATION USE-CASES

SYSTEM LEVEL THERMAL SIMULATION

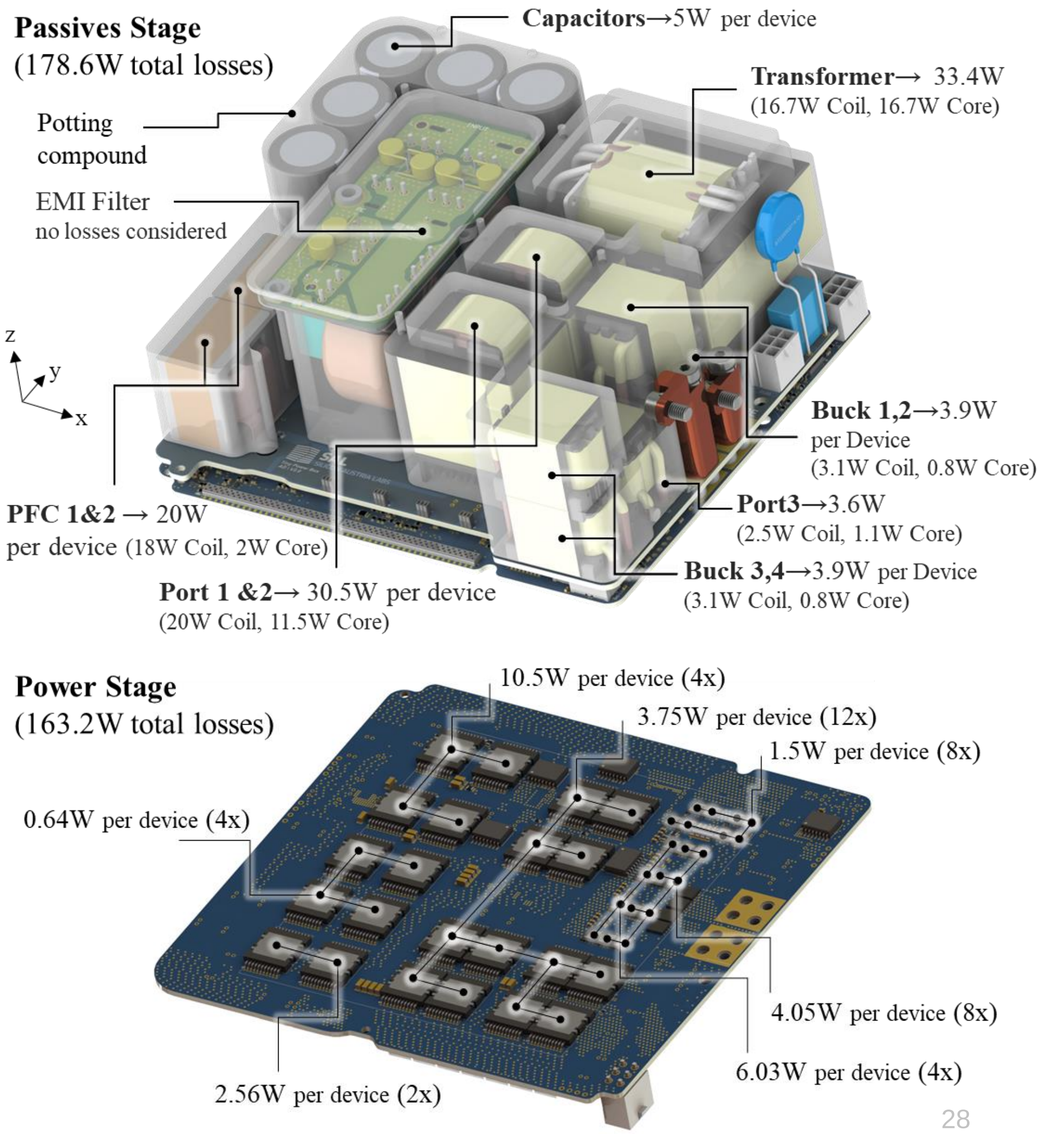
BOUNDARY CONDITIONS

- Loss estimates for components known from electrical simulations:
  - Loss in semiconductors distributed to **semiconductor die**,
  - Loss in magnetics distributed to **ferrite core** and **winding**.

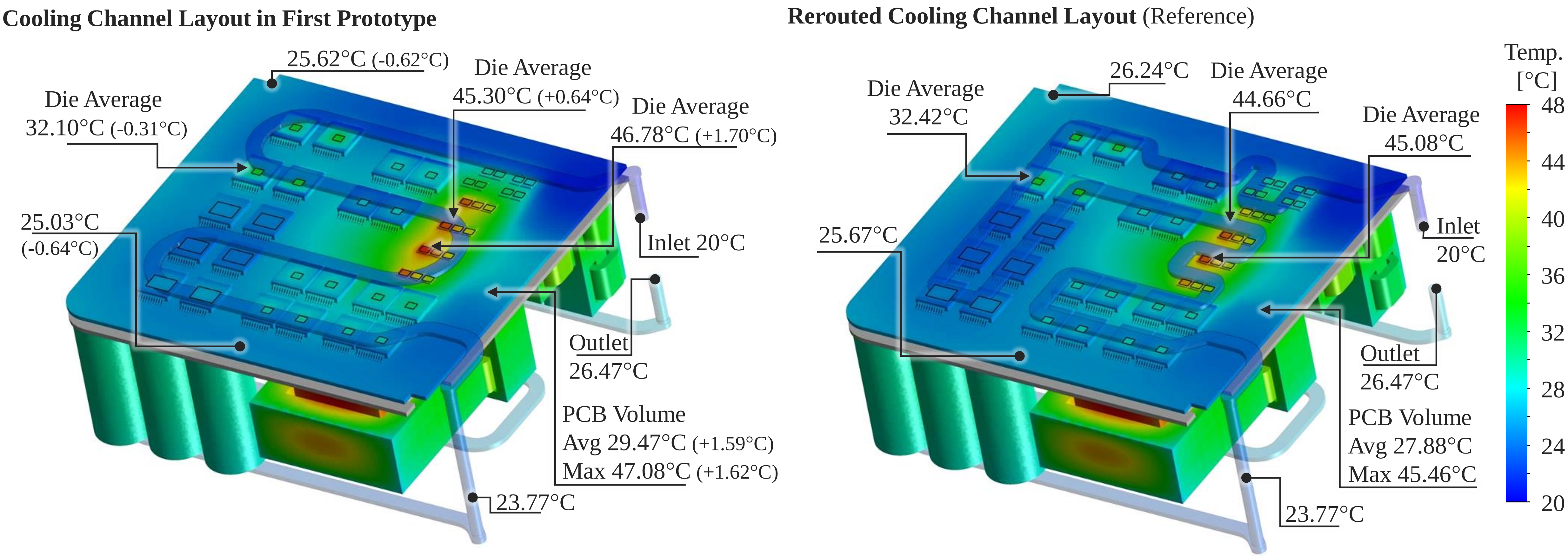
TABLE II MATERIAL PROPERTIES USED FOR SIMULATIONS

Material	**Thermal Conductivity [W/(m K)]**	
	Radial	**Axial**
Silicon (Si-die)	148	
Silicon Carbide (SiC-die)	490	
Epoxy mold compund (EMC)	0.881	
Copper (Heat Slug)	384	
Copper (Winding)	380	10
Aluminium 6063	190	
Ferrite	4	
PCB (FR4 + Copper)	56 (k_p)	0.286 (k_n)
Capacitor Winding	0.318	97.42
Capacitor Aluminium Housing	240	
TIM (TG-A 1250)	12.5	
Conductive Tape	0.7	
Potting (TCR-L-PU-2C-LV-AR)	2.1	
Solder layer (SnAgCu)	60	

Figure 17 – Losses shown for all components in the setup



FULL SYSTEM SIMULATION



Cooling Channel Layout in First Prototype

Rerouted Cooling Channel Layout (Reference)

Figure 18 - Comparison of thermal simulation results for two cooling channel layouts and full-system to single-PCB simulation.
The cooling channels are shown as a transparent layer on top of the PCB. In general a proper cooling channel layout can achieve lower die temperatures.

FULL SYSTEM SIMULATION

- There is a significant amount of heat flow **(36W, 20%)** from the top side components transferred towards the bottom side cooling system.
  - This **leads to higher temperatures** on the bottom side of the setup (semiconductors and PCB)
  - Additionally the **temperatures of the passives stage** are lower since the bottom cold plate is accounted
  - The **water channel geometry** cannot just only be adopted, also there may be an advancement by **changing in-and outlet**, in case the cool inlet water can reach the hottest components first.

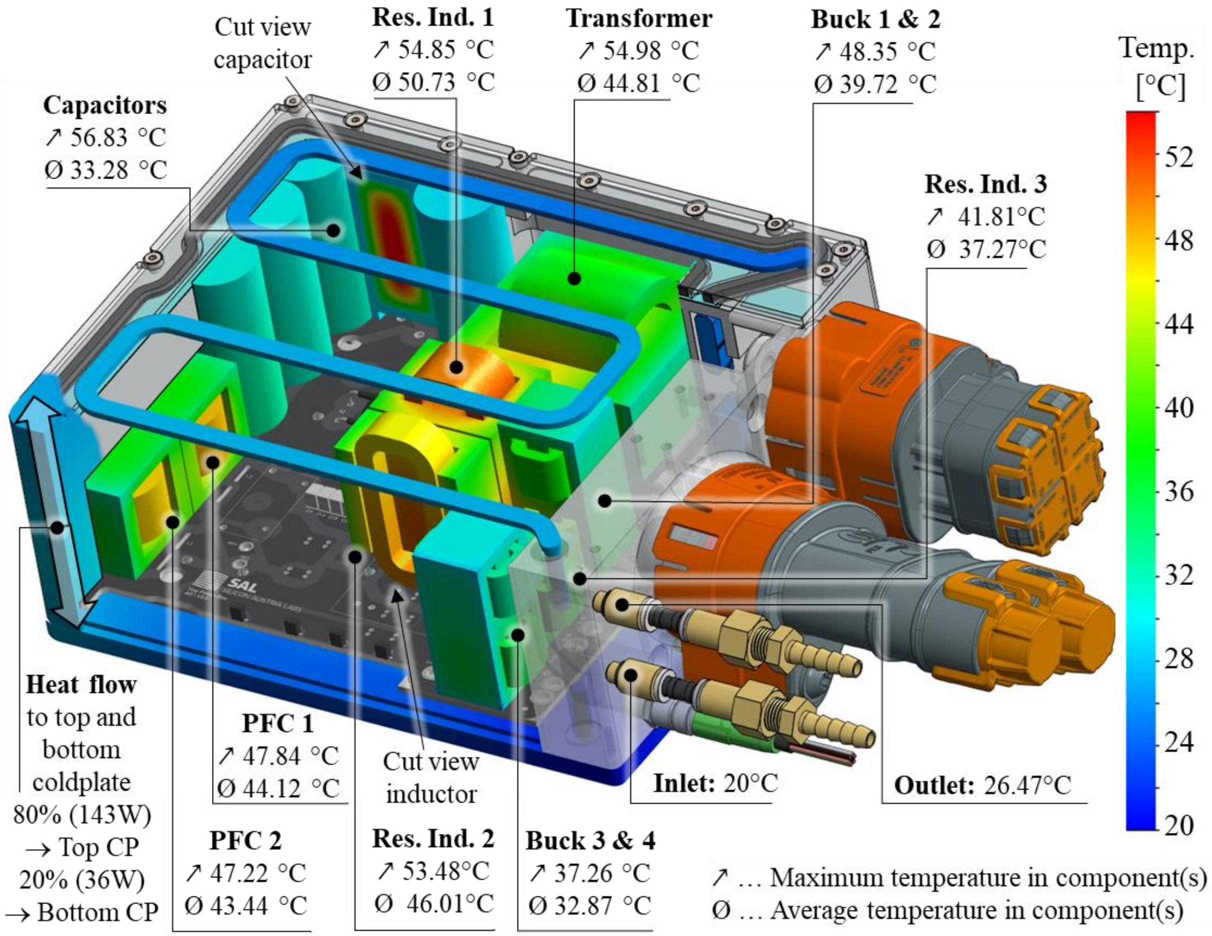


Figure 19 – System simulation results showing average and maximum temperatures of components.

AGENDA

01 Motivation

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04 Simulation use-cases

05 Conclusions

DO WE REALLY CARE ABOUT SEMICONDUCTOR PACKAGING?

*At SAL we derive high fidelity packaging models for individual modelling of semiconductor devices.

Indeed it depends on the package…

Device models for simulation may reconstructed using:

- Simple datasheet information or
- High fidelity package structures*

High fidelity semiconductor models influence the heat propagation into their surroundings.

Thermo-sensitive electrical parameters of closely placed passive components can be influenced by the semiconductor model used.

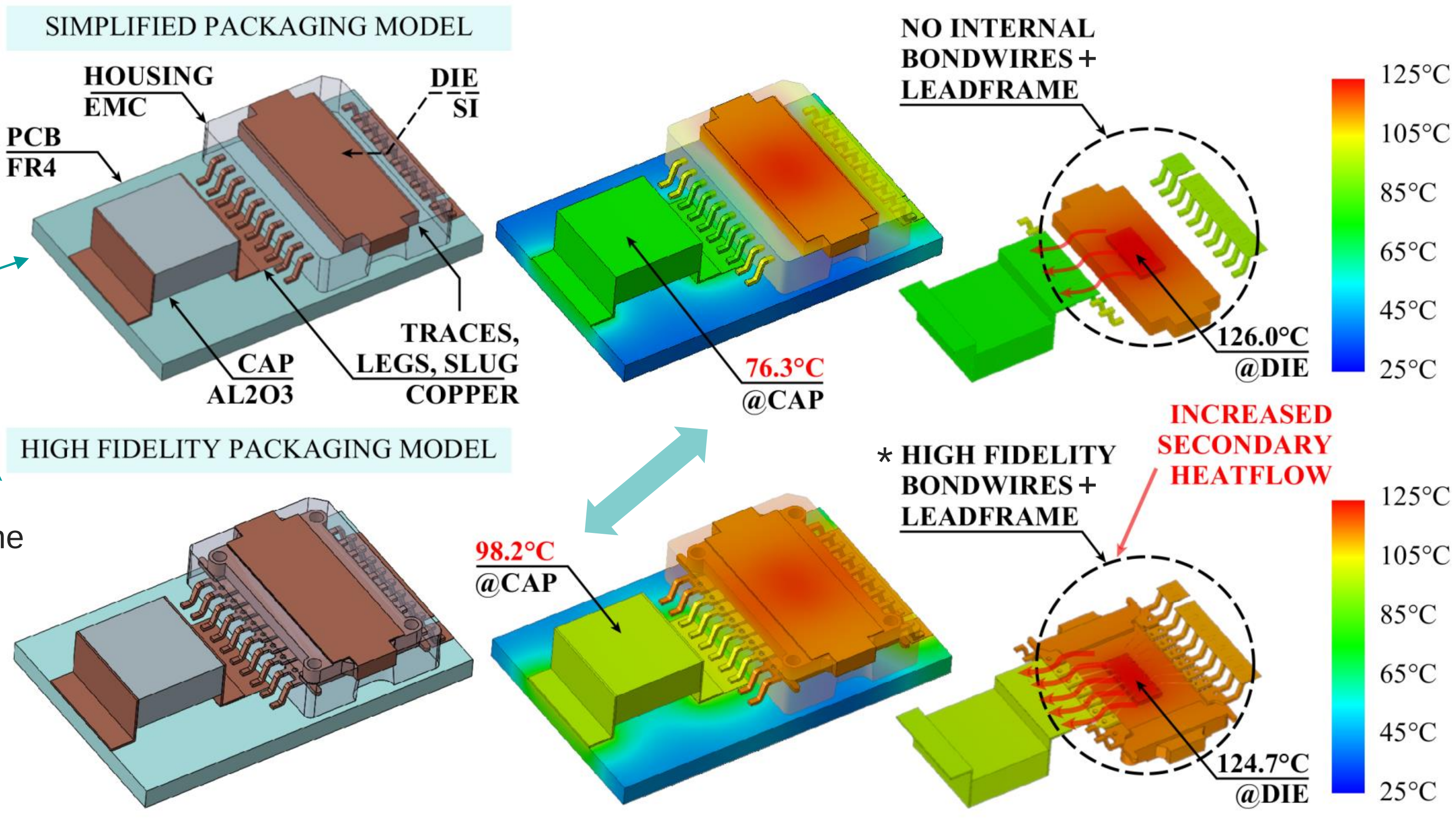
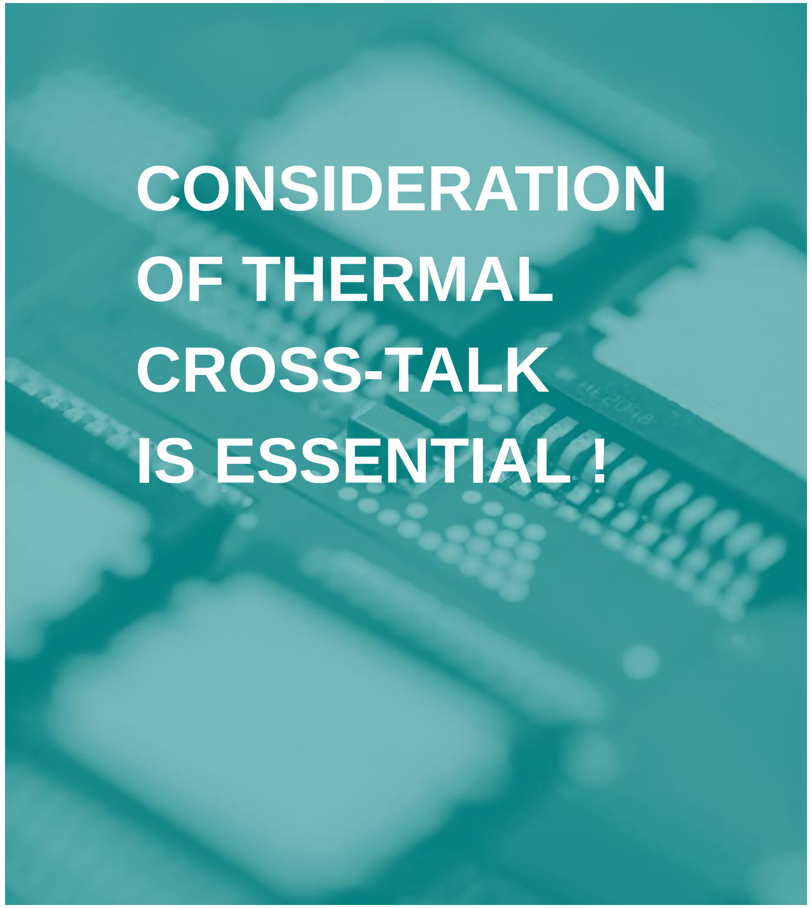


Figure 20 - Datasheet semiconductor device model simulation results (top) compared with high fidelity model with accurate leadframe and bond wire structures (bottom)

SIMULATION ASPECTS

- **When do we need proper package models for system simulation?**
  - As soon as the density on the substrate or PCB gets higher, the thermal interactions between components start to increase.
  - **Thermal interactions** in between the system components can be observed:
    - **Often housing (package) parts thermally couple the different sections** in an electronic assembly -> the heat flux of different stages interferes -> the system packaging design actively can control the direction of the heat flux and prevent thermal cross-talk.
  - Electrical accurate component models (active and passive components) can be influenced by thermal cross-talk thereof they need proper temperature input.



CONSIDERATION OF THERMAL CROSS-TALK IS ESSENTIAL !

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[1] C. Mentin, I. Recepi and P. Matzick, "**Tiny Power Box - Thermal Investigations for Very High Power Density Onboard Chargers**," *2022 28th International Workshop on Thermal Investigations of ICs and Systems (THERMINIC)*, Dublin, Ireland, 2022, pp. 1-6, doi: 10.1109/THERMINIC57263.2022.9950663.

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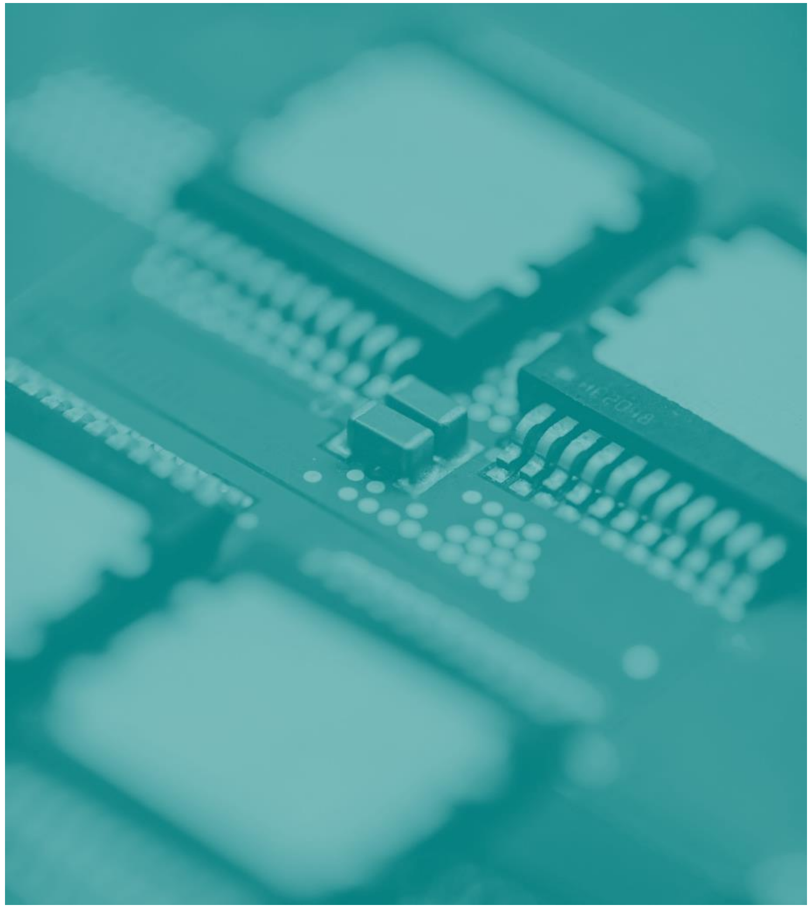

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