CHARGED
VIRTUAL CONFERENCE
EV ENGINEERING

Innovative cooling concepts for enhanced power density in electrified vehicles





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AGENDA

01 Tiny Power Box Project

02 Evolution from System Integration to Simulation

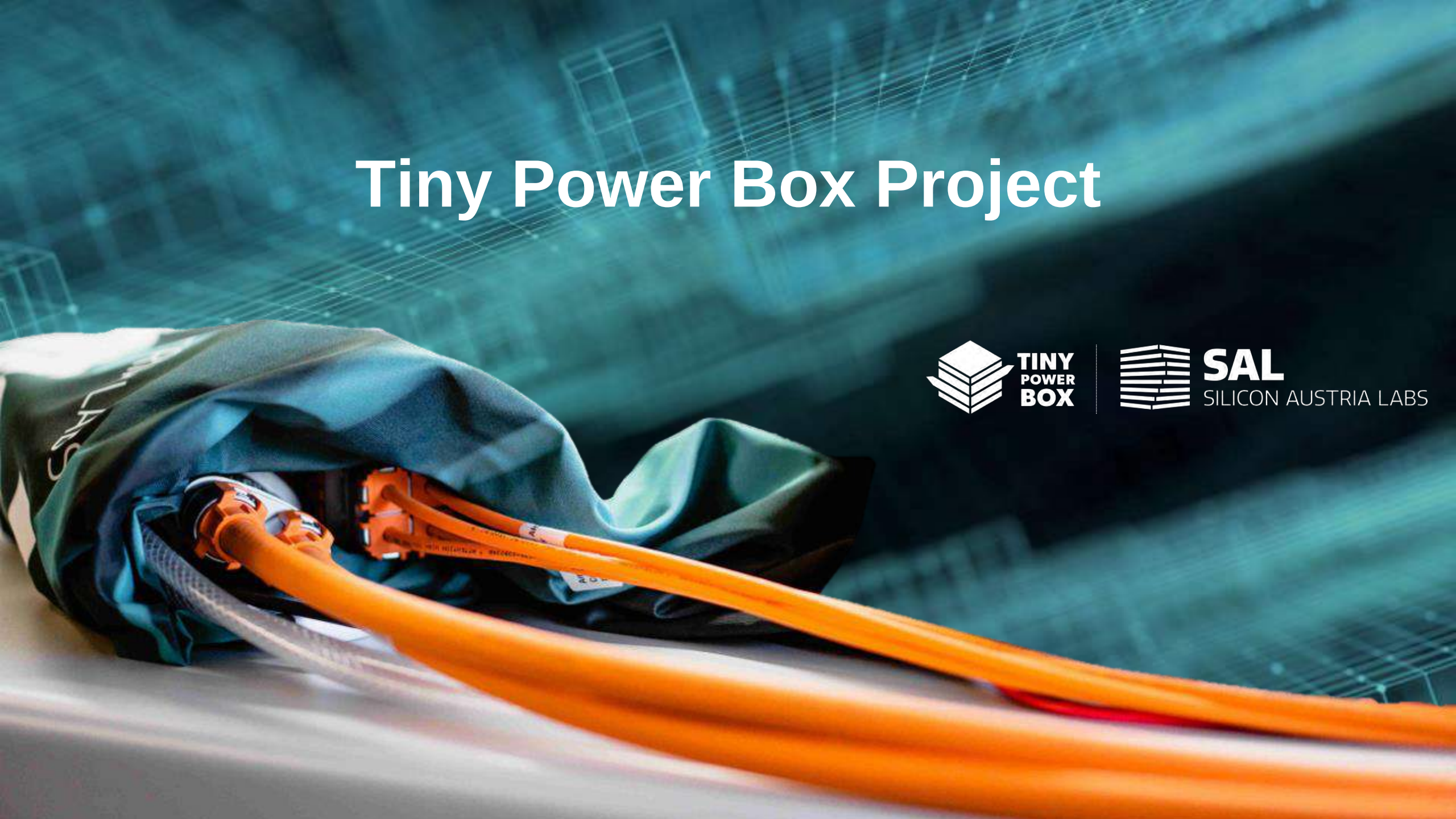
03 Enhancing System Integrity

04 Topology and Isolation

05 Optimal Component Layout

06 Thermo/Mechanical Simulations

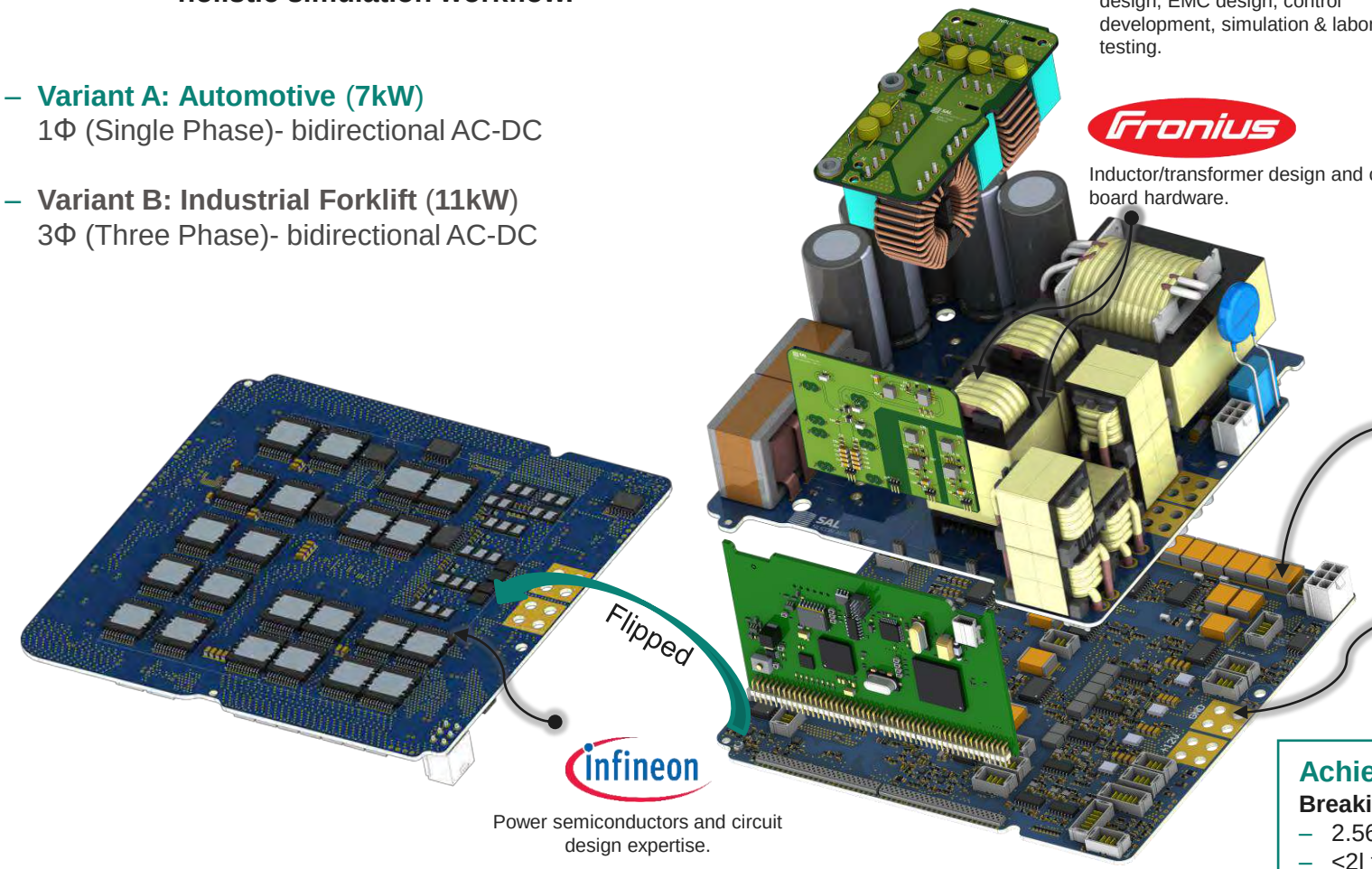
Tiny Power Box Project



Role model for cooperative projects

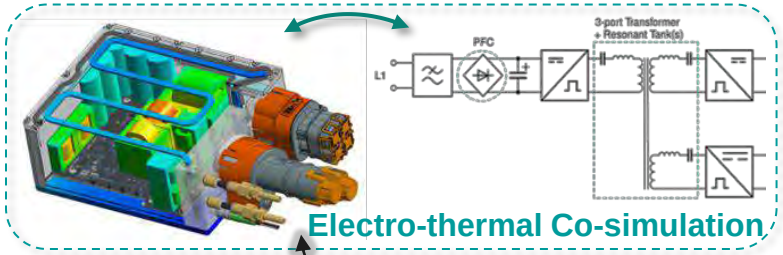
Bi-directional Onboard Charger with **integrated LVDC** featuring beyond **state-of-the-art power density** and a **holistic simulation workflow.**

- **Variant A: Automotive (7kW)**
  1Φ (Single Phase)- bidirectional AC-DC
- **Variant B: Industrial Forklift (11kW)**
  3Φ (Three Phase)- bidirectional AC-DC



SAL SILICON AUSTRIA LABS
Topology optimization, system design, EMC design, control development, simulation & laboratory testing.

Fronius
Inductor/transformer design and control board hardware.



Electro-thermal Co-simulation

+ develop path for:
System Lifetime

TDK
Ceralink™ modelling, capacitor expertise & potting assembly.

AVL
Thermal, system and reliability simulation expertise.

AT&S
Embedded MOSFET benchmarking and simulation.

Infineon
Power semiconductors and circuit design expertise.

PhD and Master Students
TU Graz
KÄRNTEN University of Applied Sciences

Achievements:
Breaking state-of-the-art OBC power density
- 2.56l actual total volume with case
- <2l target volume for re-design step

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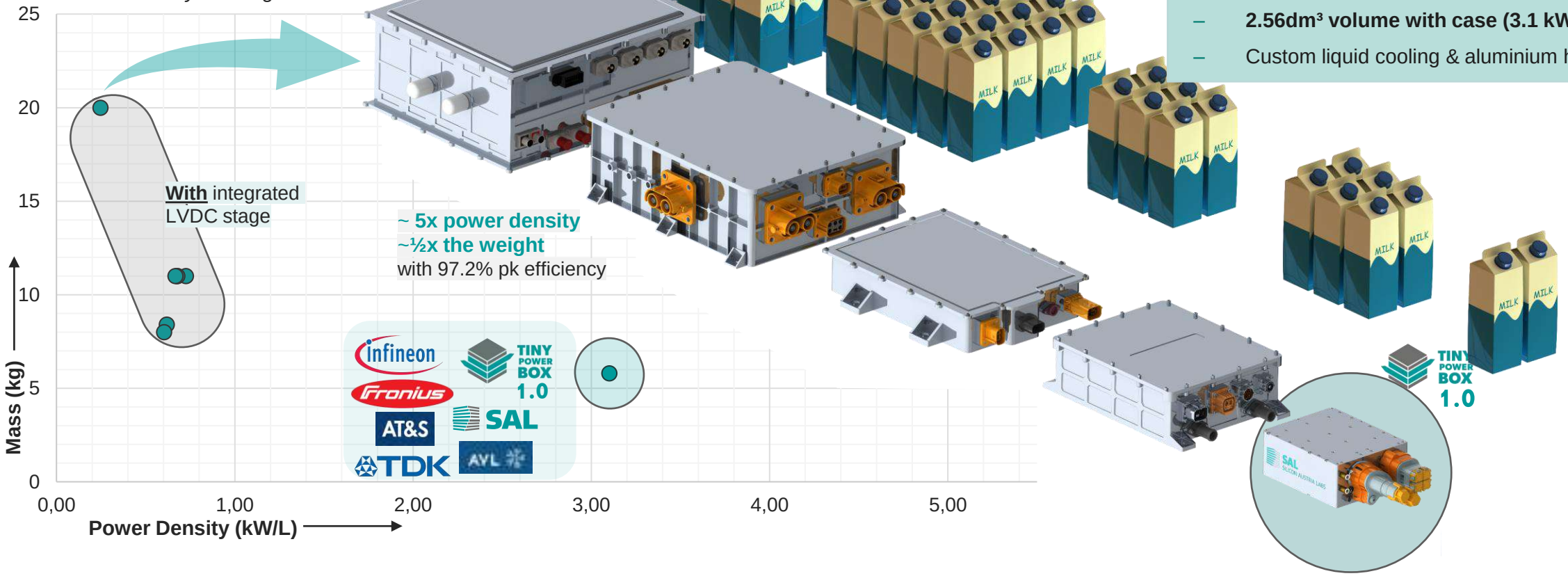
Tiny Power Box 1.0 vs Market

What we achieved in the first adventure

- 1Φ (Single Phase)- 7.0 kW bidirectional AC-DC
- 250 V – 460 V HV output
- 2.4 kW, 12 V LV output
- 97.5% peak total efficiency
- No derating @ ambient 70°C
- **2.56dm³ volume with case (3.1 kW/L)**
- Custom liquid cooling & aluminium housing

Comparison of 7kW OBC
<u>with</u> integrated LV stage
Power Density vs Weight



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Tiny Power Box 2 vs Market

The next step in power density and further innovation



- 1Φ **and** 3Φ Phase operation
- ~ **2x power density**
- ~ **2x** more power at LV
- **12V** auxiliary port
- **Active** EMI Filter
- **Active DC Bus Stabilization**

Bi-directional OBC Concept for Automotive Applications

11kW (3.5kW)/ 3 (1)phase;
> 5kW/L power density;
Optimized water cooling;
3phase /1phase operation.

TINY POWER BOX 2.0

SAL, Infineon, Fronius, TDK, META SYSTEM, AVL, TU Graz

beyond 5kW/L power density

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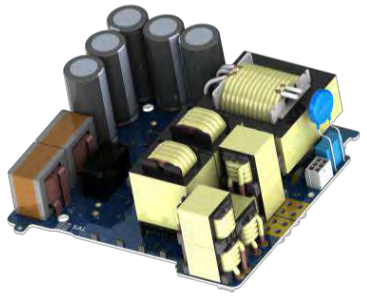
Evolution from System Integration to Simulation



Evolution from system integration to simulation

Next-Gen electrified vehicles: Innovative cooling and converter approaches to maximize power density



- 1:1 3D Components Modeling
- System layout
- Cooling concept
- Implementation of Cutting-Edge Components
- Optimize the placement and configuration of components
- Requirements review and feasibility studies

System Integration

MCAD

- Conceptualization of Space Requirements
- Component Positions
- Layout Design
- Board Outline Definition
- Intersection Detection

Mechanical (3D CAD)

Coupling

Electrical (2D Layout)

ECAD

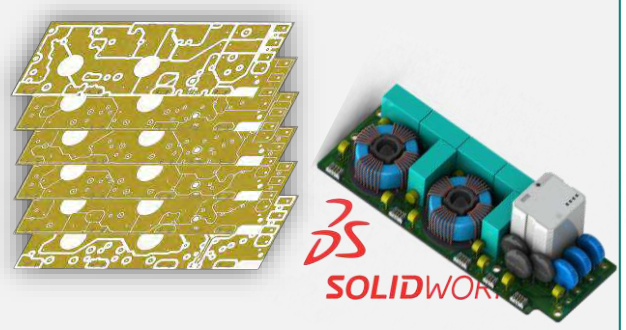
- Board Outline Definition
- Collision Detection
- 2D Layout Design

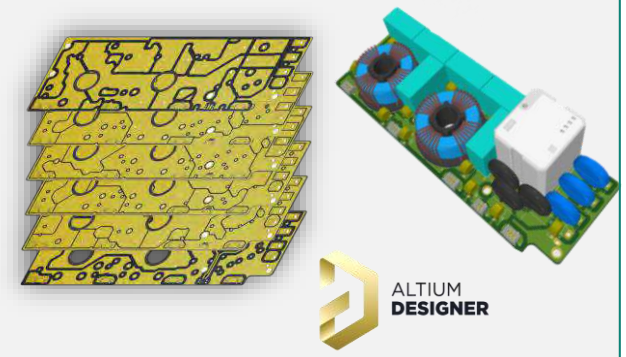
- Mechanical Environment Evaluation
- PCB Assembly Process
- Connection Axis Alignment
- Component Distance from Housing

System-Level Multi-Board Design: Design Rule Checking and Assembly

- PCB Layer Stack and Thickness Specification
- Import of 3D Geometries and Layouts
- Footprint Definition
- Routing and Schematic Design

- High-Fidelity Geometry Details for Mechanics and Electronics
- Mechatronics and Electronics Libraries Management
- Manufacturing Data Generation
  - Bills of Materials (BOM)
- Assessment of Manufacturing Capabilities
- Creation of Drawings and Schematics





https://www.altium.com/solutions/by-technology/ecad-mcad

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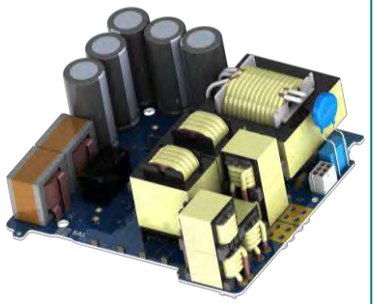
Evolution from system integration to simulation

Next-Gen electrified vehicles: Innovative cooling and converter approaches to maximize power density



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- System layout
- Cooling concept
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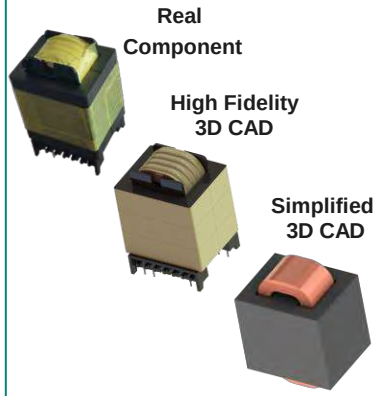
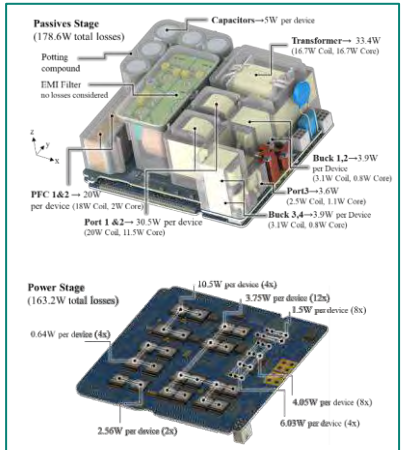
System Integration



- 3D CAD Model Simplification
- Defeature Non-Essential Components
- Components Features Simplification

Simulation Preparation



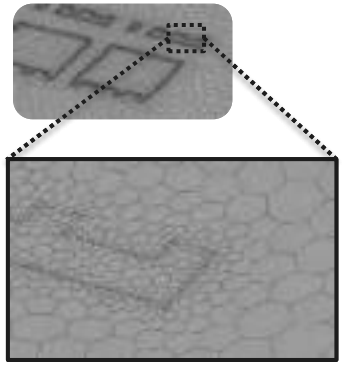
- Application of Loads and Thermal Inputs
- **Power Stage:** losses assigned to the semiconductor die
- **Passive Stage:** losses assigned to the ferrite core and winding

Simulation Scenarios and Case Studies



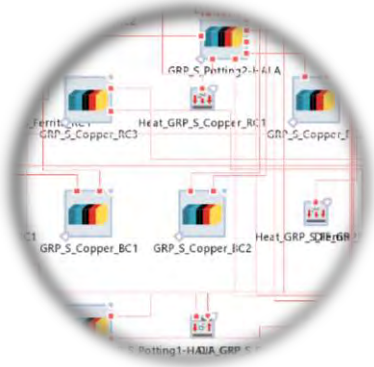
- Material Property Assignment
- Boundary Condition Definition
- Initial Condition Setup

Material Property Assignment



- Validation of Geometry and Mesh
- Convergence Criteria
- Selection of Simulation Parameters

Discretization and Meshing



- Develop a reduced order model (ROM) to simplify the thermal simulation
- Post-processing steps to analyze thermal simulation results

3D and 1D Simulation (Reduced Order Model)

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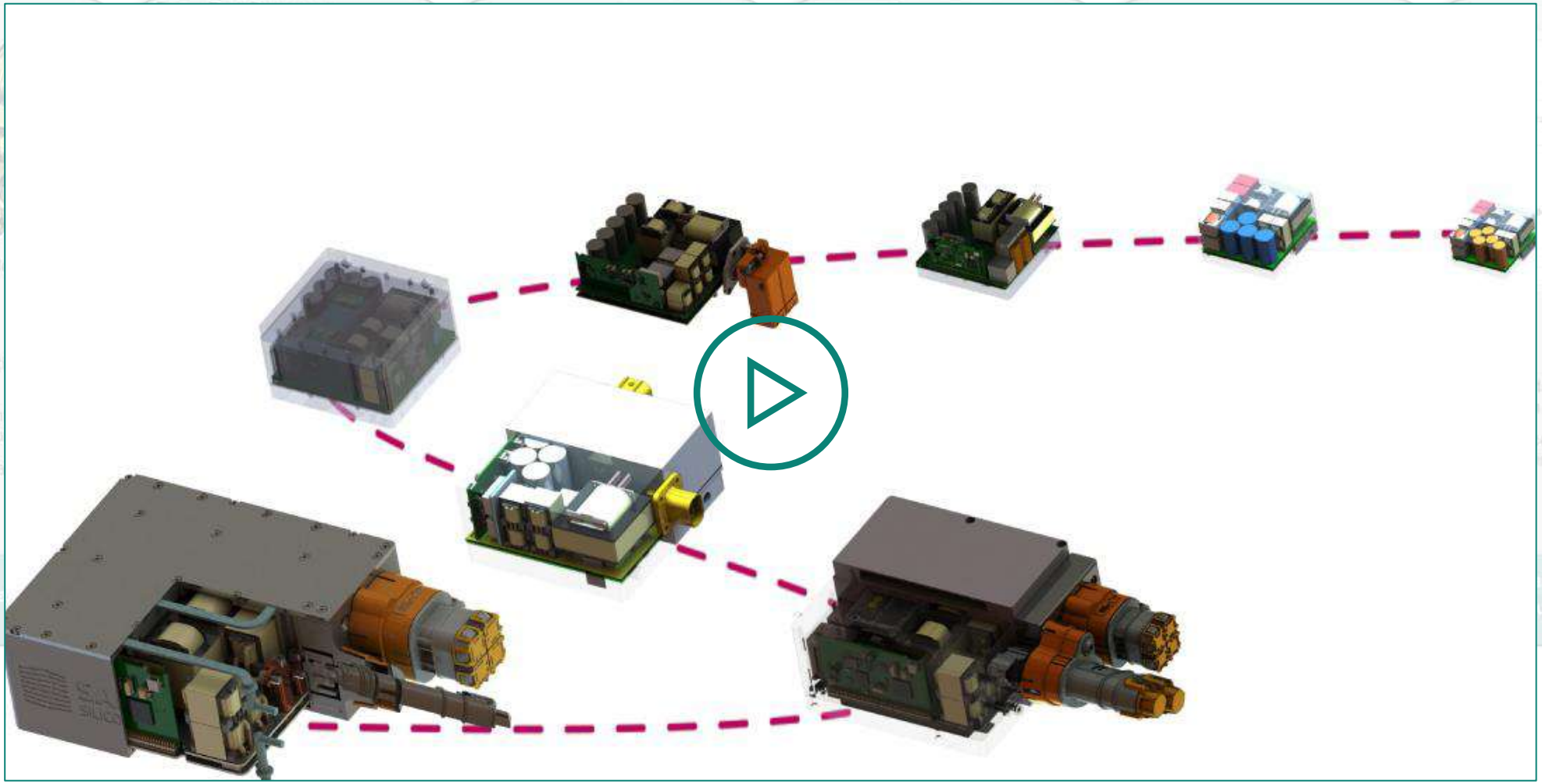
Evolution from system integration to simulation

Next-Gen electrified vehicles: From zero to hero



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Evolution from system integration to simulation

Next-Gen electrified vehicles: Innovative cooling and converter approaches to maximize power density

- **Requirements for Electro-Thermal Co-Simulation:**
  - Precise geometrical models of components along with accurate material data.
  - Electrically accurate component models (both active and passive) with comprehensive thermal characterization.

- **When to Use Electro-Thermal Co-Simulation:**
  - **High-density designs:** As the component density on substrates or PCBs increases, thermal interactions between components become significant.
  - **Thermal interactions:** Observable thermal interactions occur between passive components and semiconductors.
  - **Package-induced coupling:** Housing or packaging components often thermally couple different sections of an electronic assembly, leading to heat flux interference between various stages.

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Enhancing
System Integrity
TINY
POWER
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Enhancing system integrity
A different assembly concept for more efficient cooling

The proposed setup for **OBC novel approach** shows how **top-side cooled** and **double-side cooled** power components can be utilized to achieve **efficient cooling**, **highest mechanical integrity** when **compressing a TIM**, and finally achieving **very high-power density** and electrical **efficiency**.

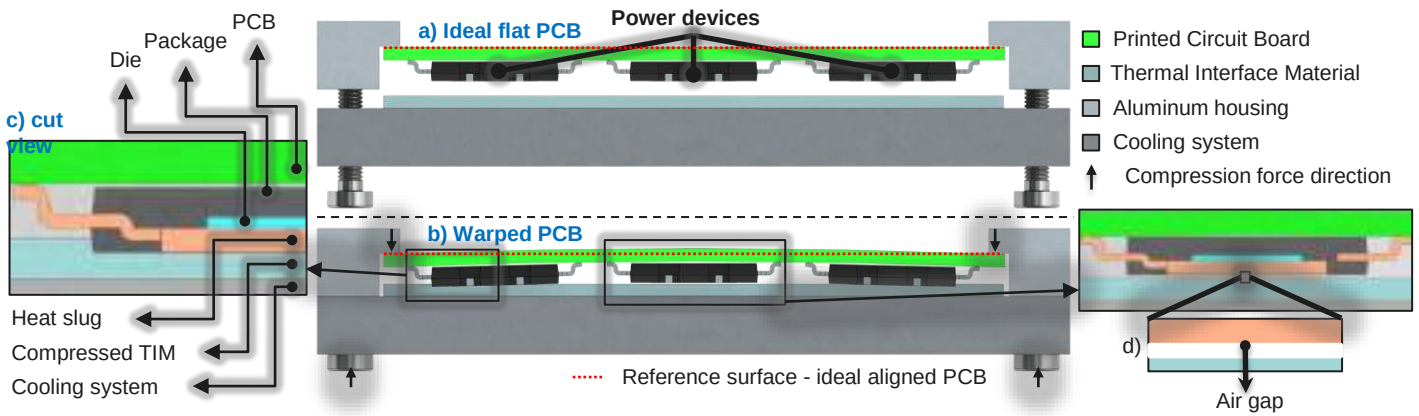

Figure 1:

a) Ideal Flat PCB: no compression force applied
b) PCB Warpage: Uneven compression forces can warp the PCB, leading to partial over-compression of the TIM.
c) and in the worst case leads to weak or no thermal connection for some power devices (d).

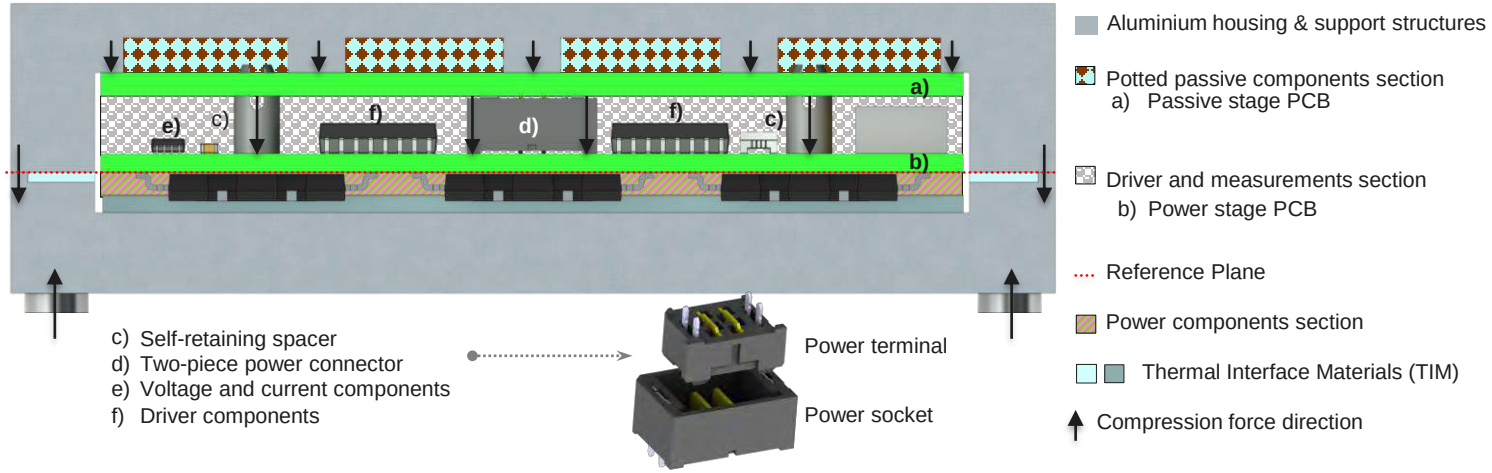

Figure 2:

Compression forces from the aluminum housing and support structures are directed towards the power stage PCB, ensuring minimal warpage, effective thermal attachment of semiconductor components, and uniform TIM compression.

I. Recepi, C. Mentin, P. Matzic and R. A. Garcia Mora, "Tiny Power Box – Mechanical Investigations for Automotive Very High Power Density Onboard Chargers," PCIM Europe 2023; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management, Nuremberg, Germany, 2023, pp. 1-9, doi: 10.30420/566091234.

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Enhancing system integrity
Thickness and compression impact of the TIM

To ensure that power devices operate safely within their thermal limits, it is crucial that the Thermal Interface Material (TIM) is effectively compressed and forms a secure thermal bonding with the corresponding surfaces.
This proper compression and attachment maximize heat transfer efficiency, preventing overheating and maintaining optimal device performance.

Δt1 Pre-compression TIM thickness: 1.5 mm
Δt2 Post-compression TIM thickness: 1.23 mm
a) The cold plate profile before assembly.
b) The TIM profile before assembly of the complete structure.
c) The TIM profile after assembly of the complete structure.

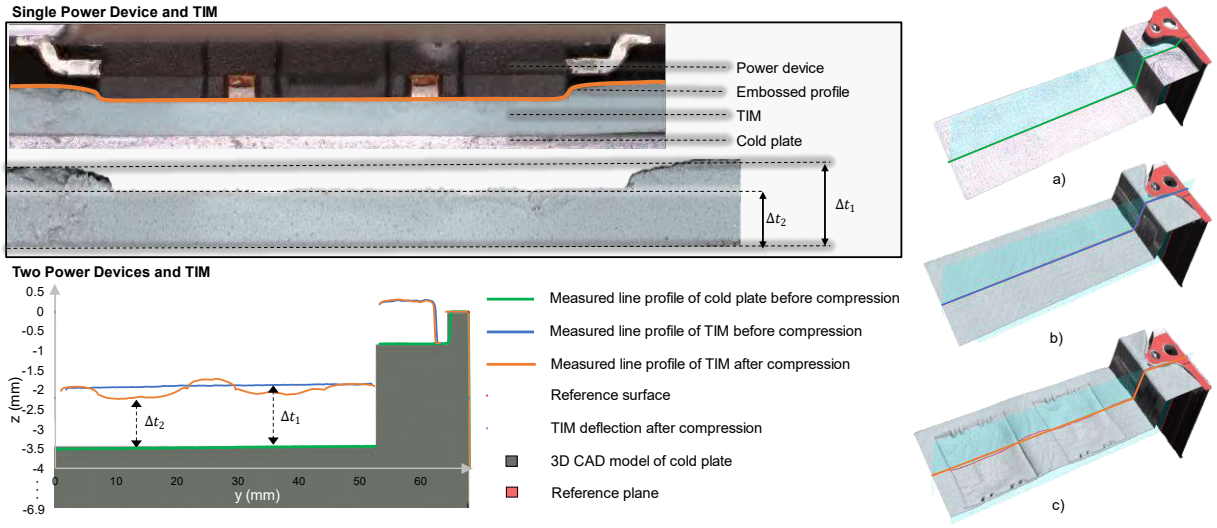

Figure 3: Thickness and deflection of TIM before and after assembly

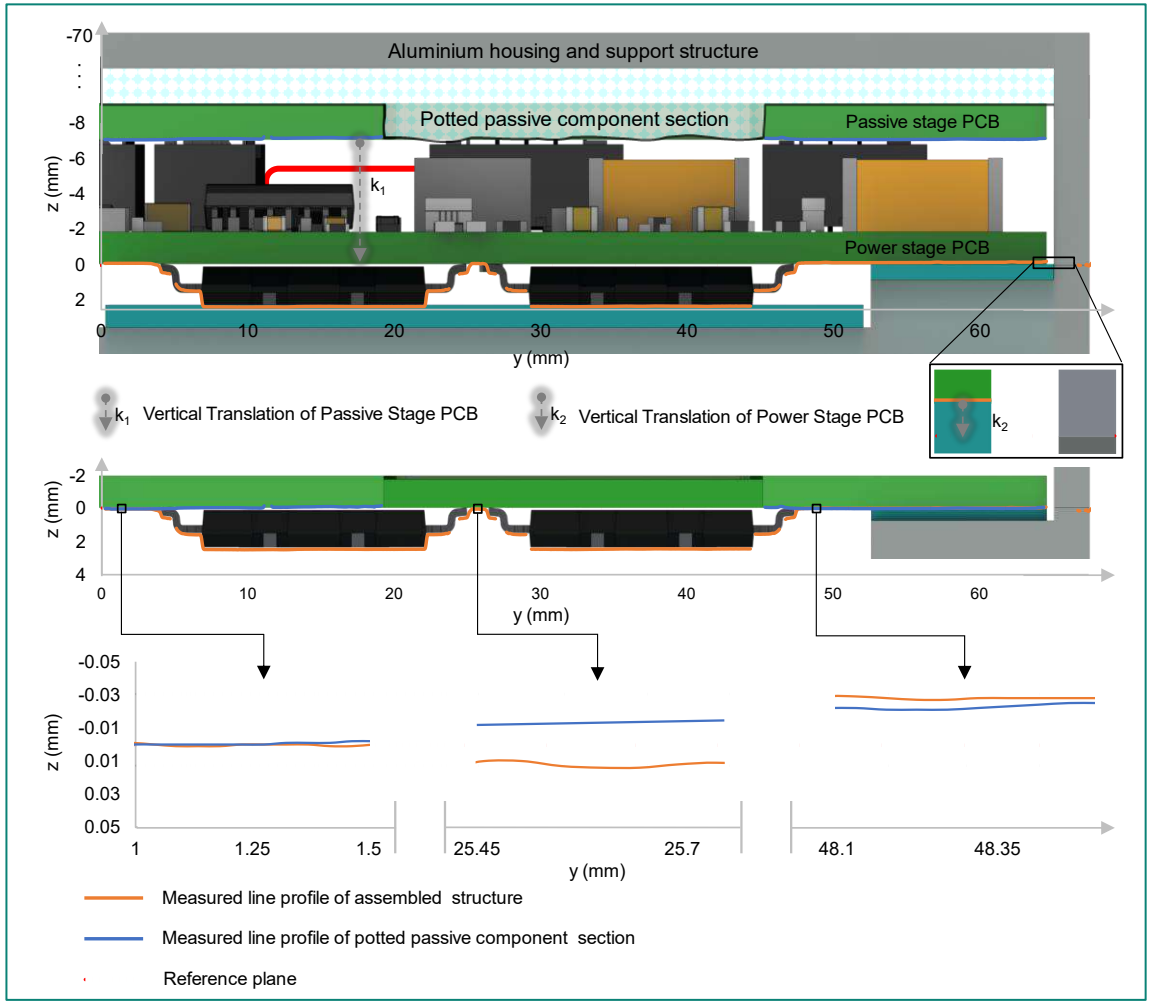

Figure 4: Measured line profiles for warpage analysis of the Passive and Power PCB stages.

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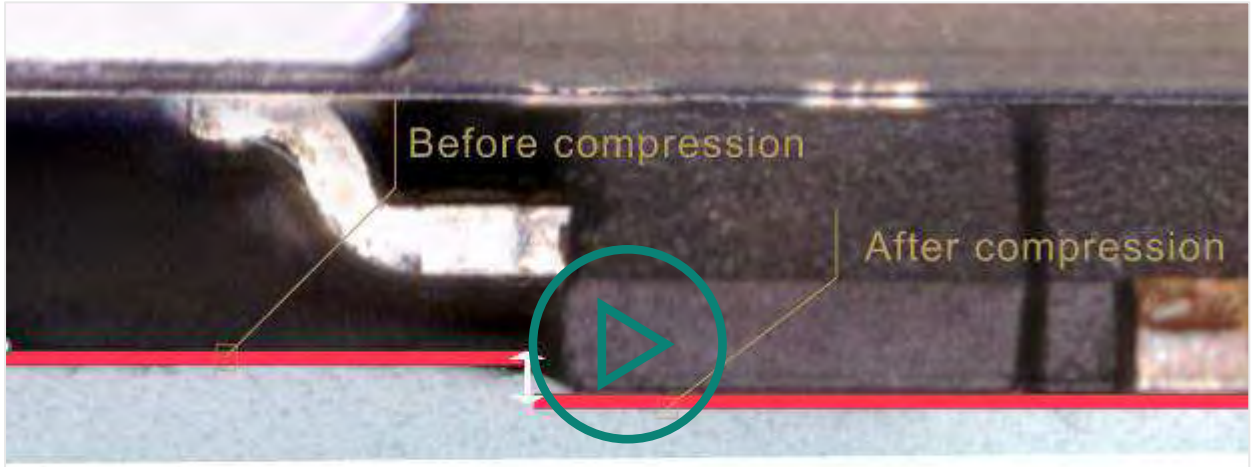
Enhancing system integrity
Thickness and compression impact of the TIM



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Enhancing system integrity
Cooling plate profile and mounting all together

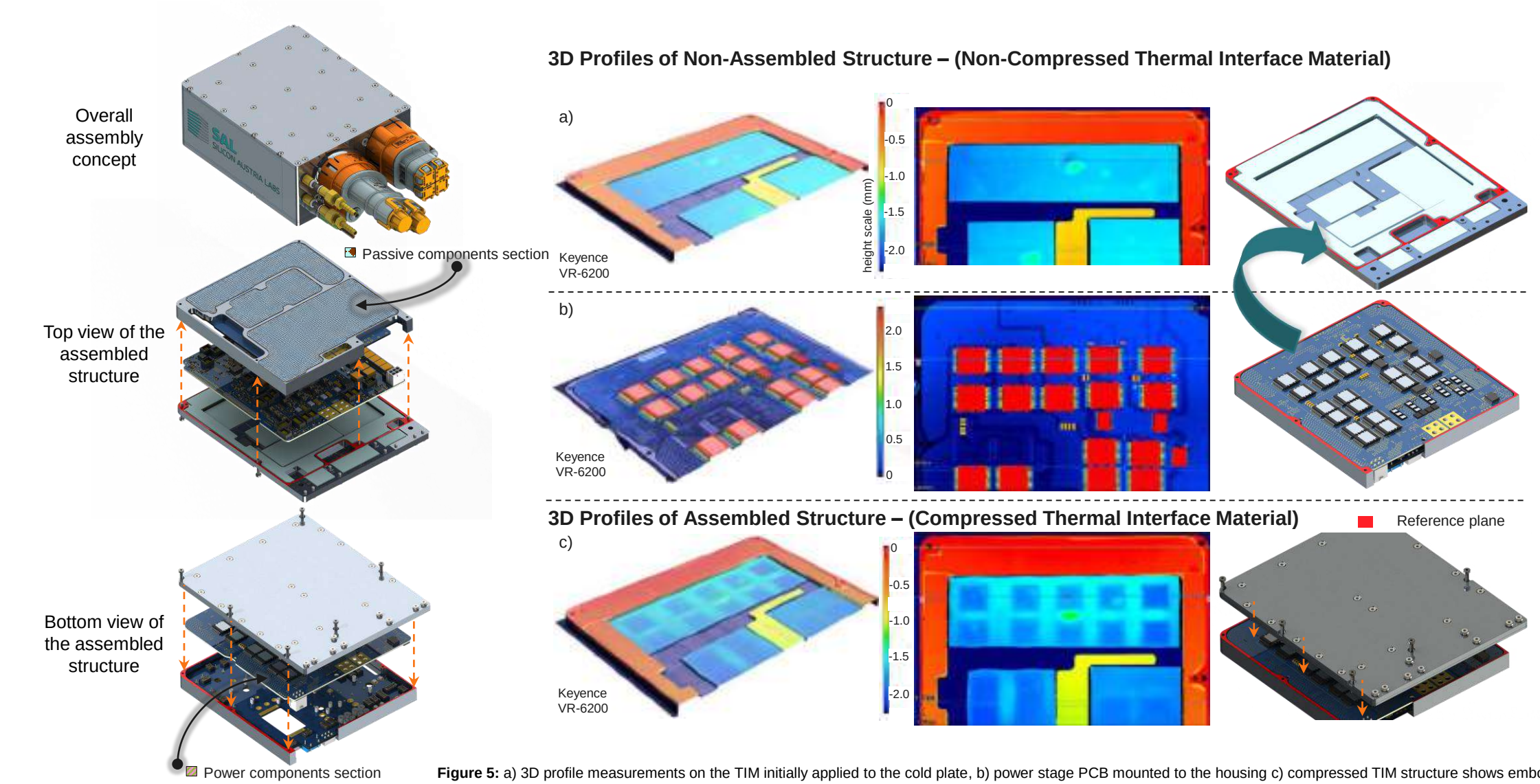

Figure 5: a) 3D profile measurements on the TIM initially applied to the cold plate, b) power stage PCB mounted to the housing c) compressed TIM structure shows embossed power devices.

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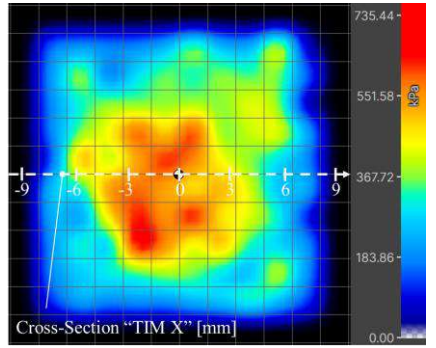
Enhancing thermo-mechanical integrity
Ideal vs real mechanical assembly scenarios

- **Ideal scenario:**
  - The PCB and cold plate remain perfectly flat, with no deformation.
  - The TIM is compressed evenly across the entire surface.

- **PCB warpage scenario:**
  - PCB warpage causes uneven compression of the TIM, leading to areas with poor thermal contact.
  - The uneven contact increases thermal resistance in certain areas, reducing overall heat dissipation.

- **Cold plate warpage scenario:**
  - Cold plate warpage can result in non-uniform compression of the TIM, similar to PCB warpage.
  - Areas of poor contact between the cold plate and the power device can create localized hot spots, increasing the risk of overheating components.



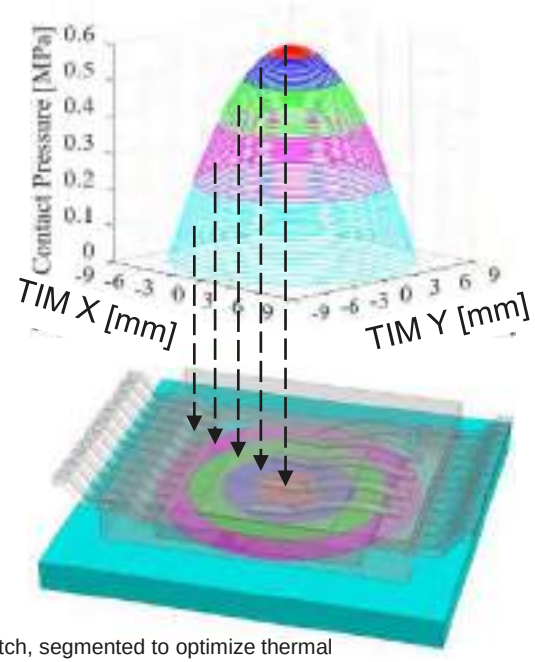


Figure 6: TIM patch, segmented to optimize thermal resistance based on varying contact pressures.

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Enhancing thermo-mechanical integrity
The important role of potting for stability and cooling

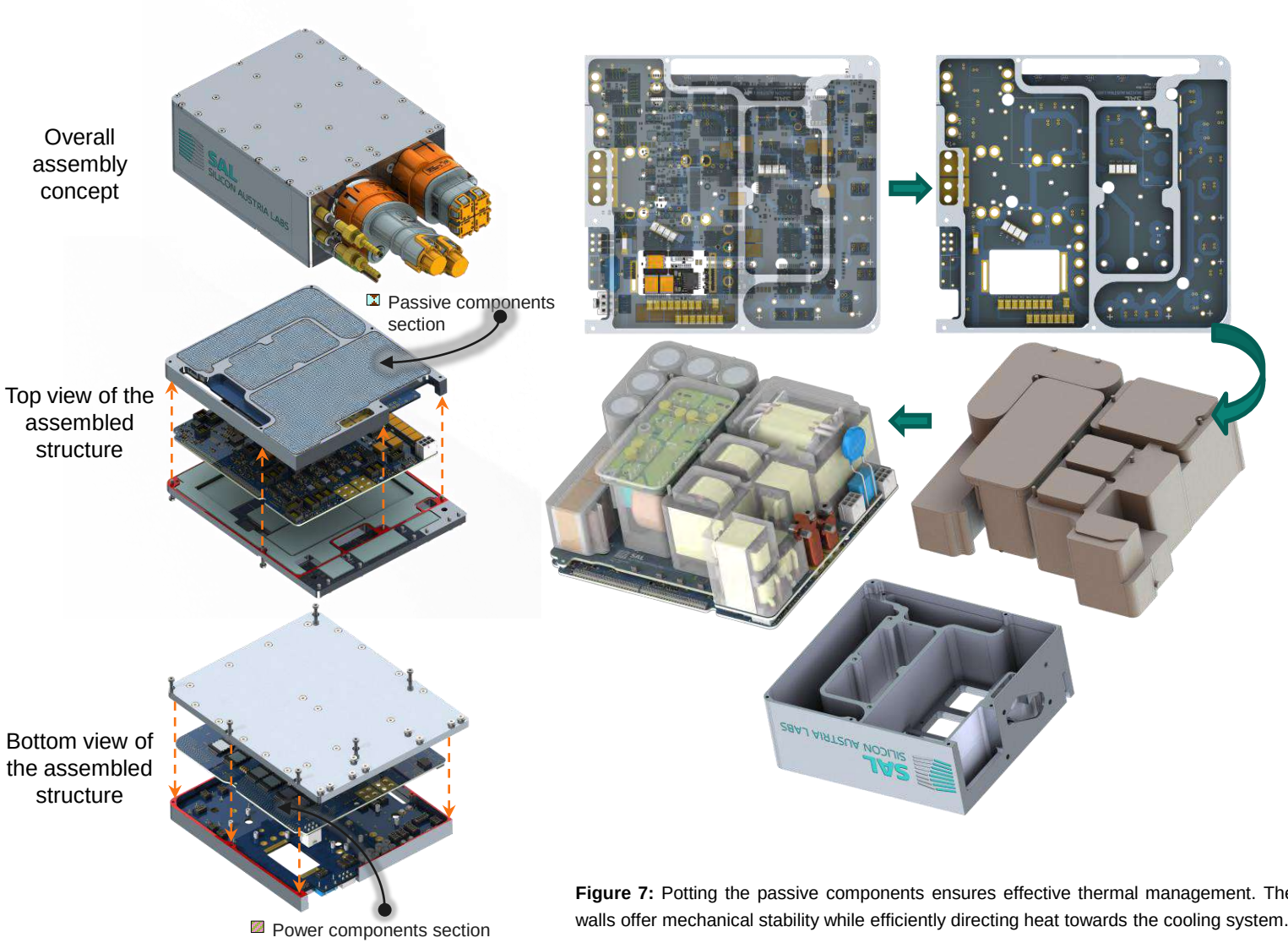

Figure 7: Potting the passive components ensures effective thermal management. The aluminum walls offer mechanical stability while efficiently directing heat towards the cooling system.

- Potting a system offers several advantages beyond thermal management and mechanical stability.
- **Vibration and Shock Resistance:** The potting material can absorb and dissipate vibrations and shocks, protecting the components from mechanical stresses that could lead to failure.
- **Electrical Insulation:** Potting can serve as an electrical insulator, preventing short circuits and improving the overall safety of the system.
- **Reduced Noise and Interference:** Potting can help dampen acoustic noise and reduce electromagnetic interference, leading to more stable and reliable system performance.

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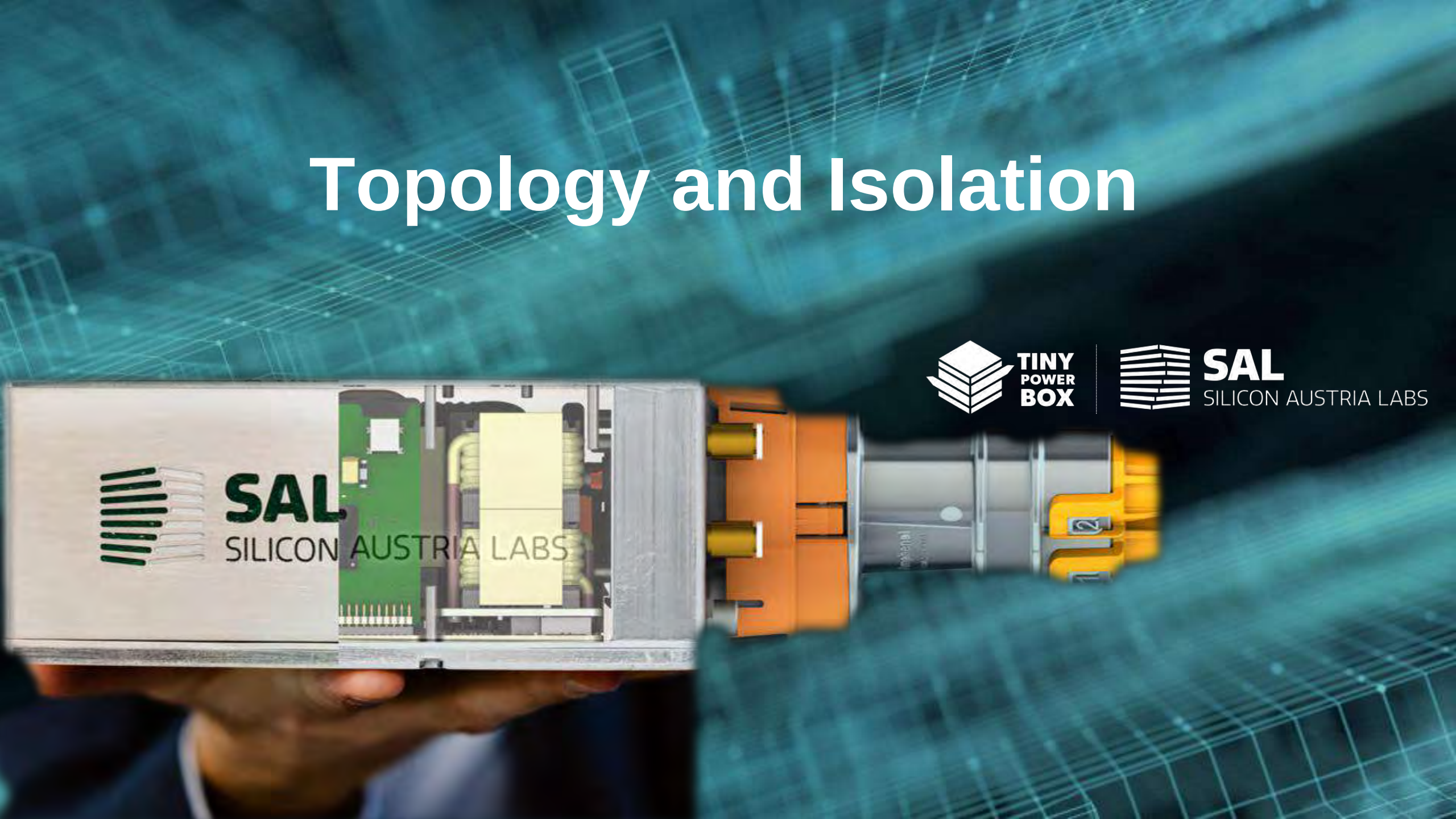
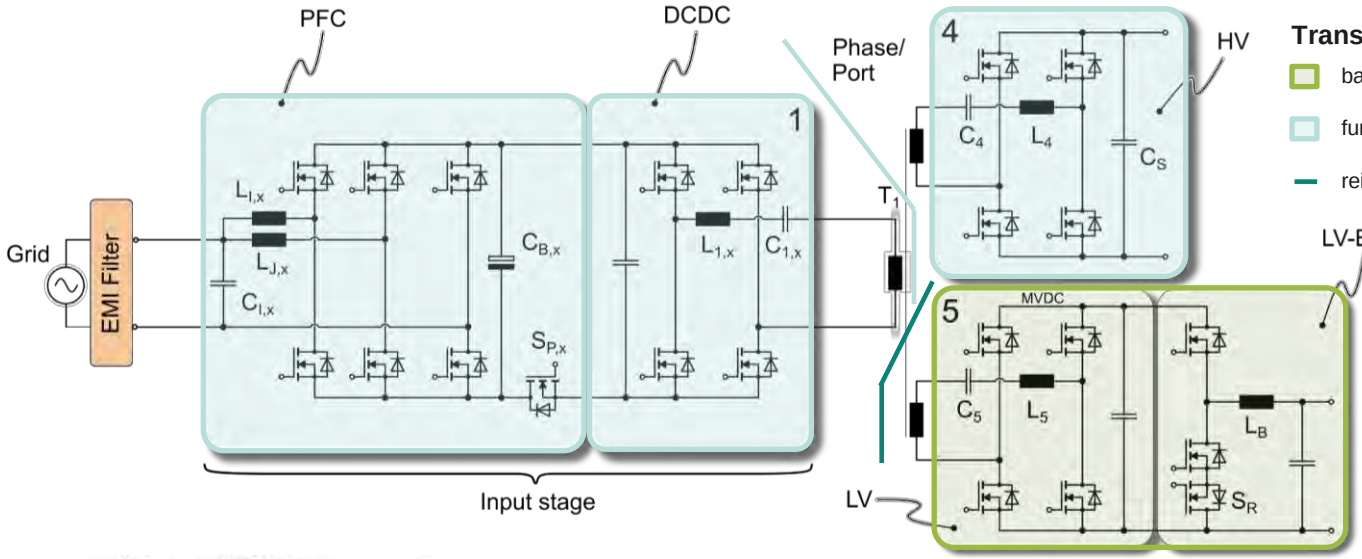
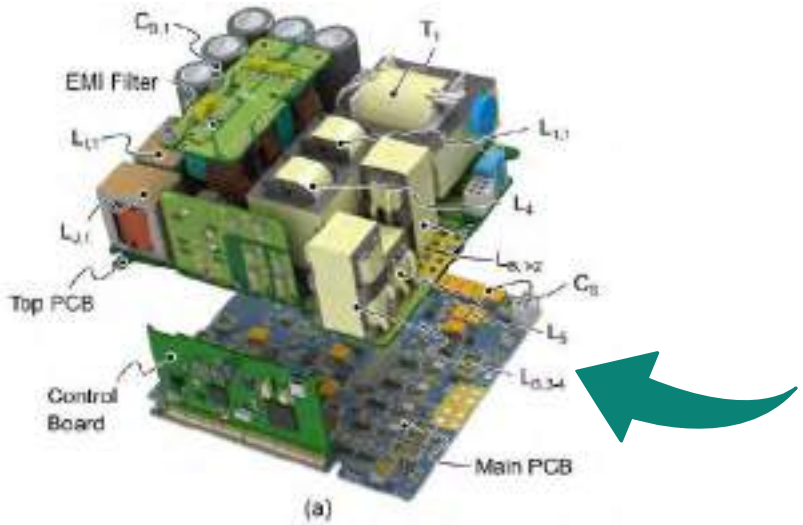
Topology and Isolation

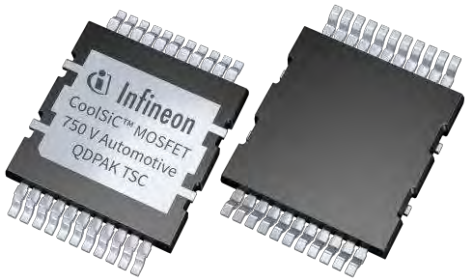


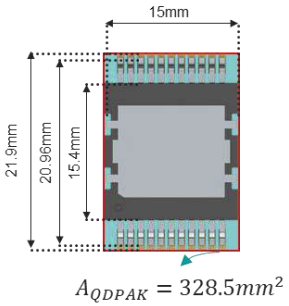
Topology and isolation
Single phase OBC + DCDC automotive version





Top side cooled 750 V SiC MOSFETs





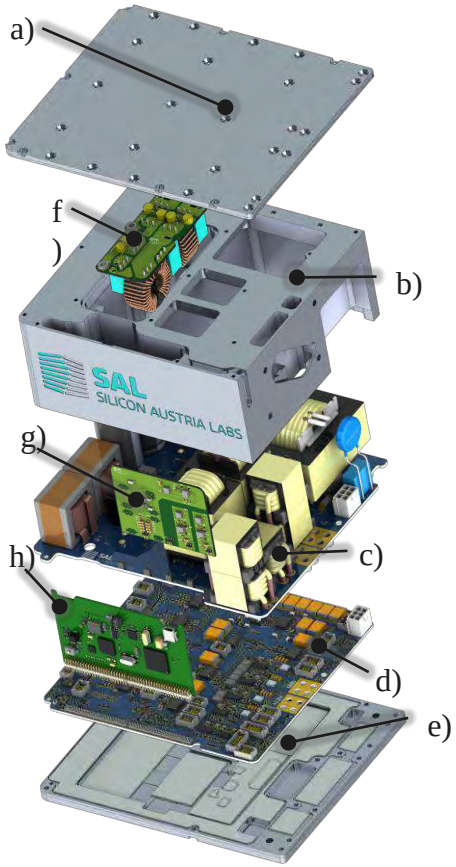


Fig. 8: Overall assembly concept with integrated liquid cooling for an automotive OBC application. **a)** top side cooling system, **b)** aluminum housing, **c)** passive stage, **d)** power stage, **e)** bottom side cooling system thermal interface material, **g)** auxiliary supply board, **h)** control board, **f)** EMI filter board.

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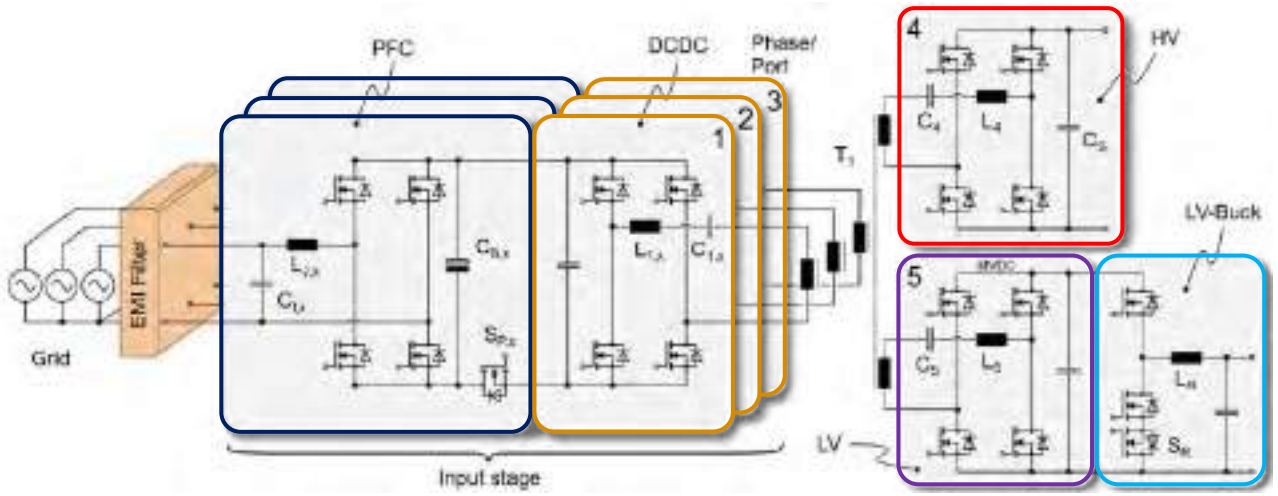
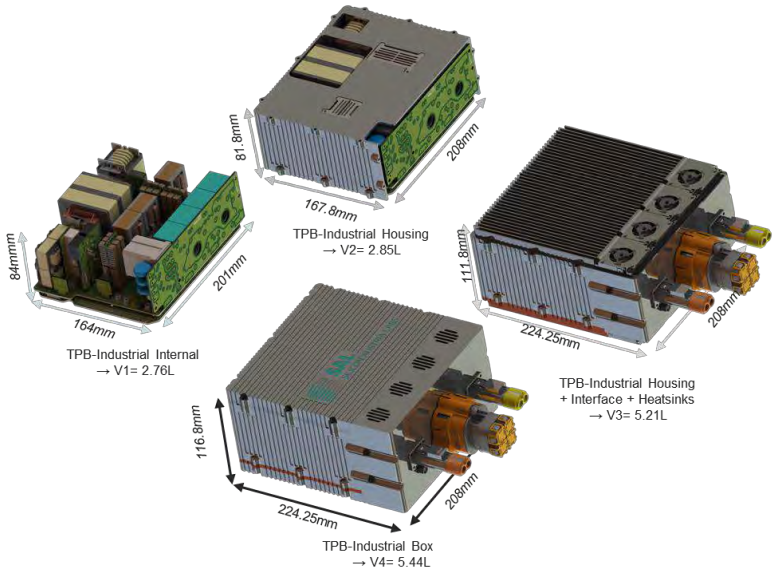
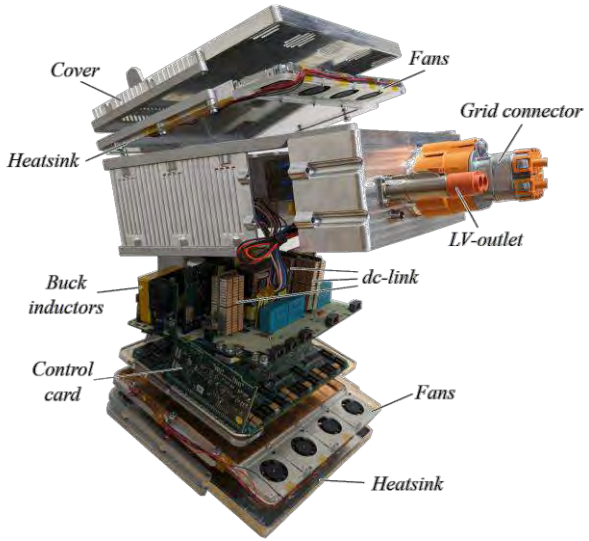
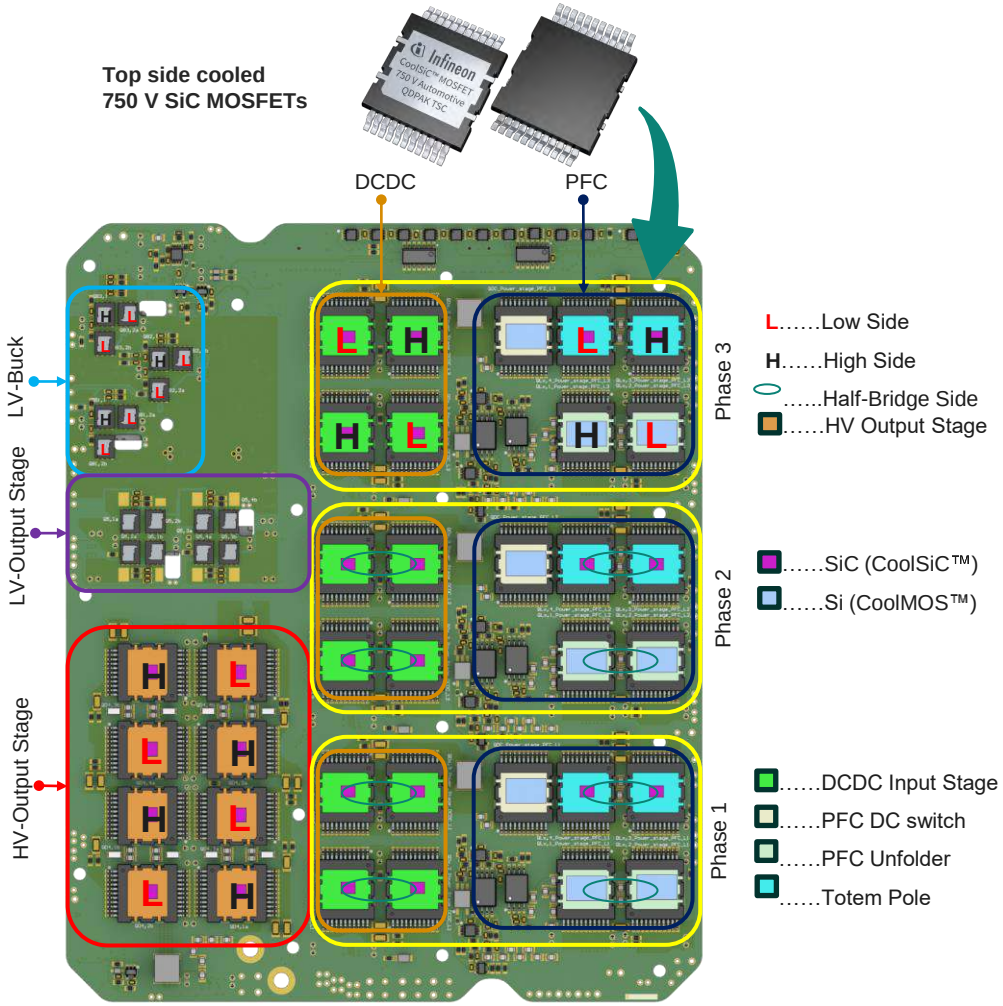
Topology and isolation
Three phase OBC + DCDC industrial version









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Topology and Isolation
Different thermal interface approaches & impact in cooling

– Non-isolation foil version generally have lower thermal resistance, allowing more efficient heat transfer from the power device to the heat sink, improving cooling performance.

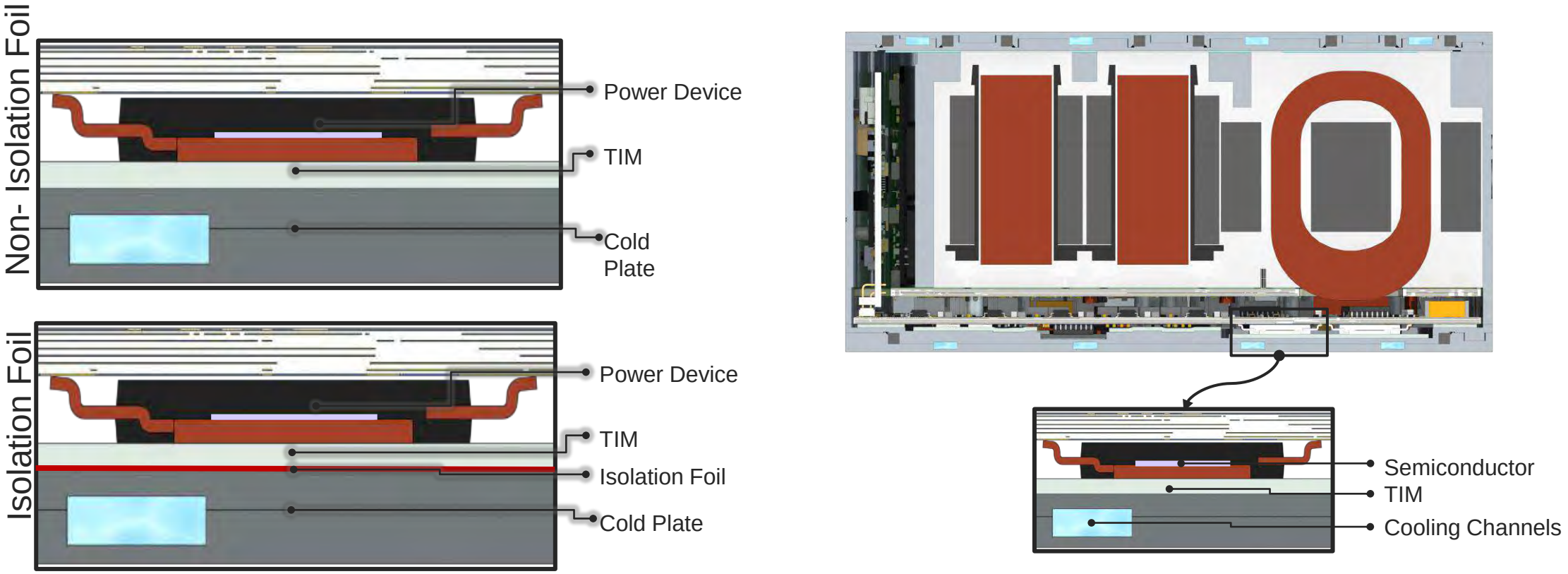

Figure 9: Cross-sectional comparison of the assembly with and without isolation foil, highlighting the addition of the isolation layer for electrical insulation.

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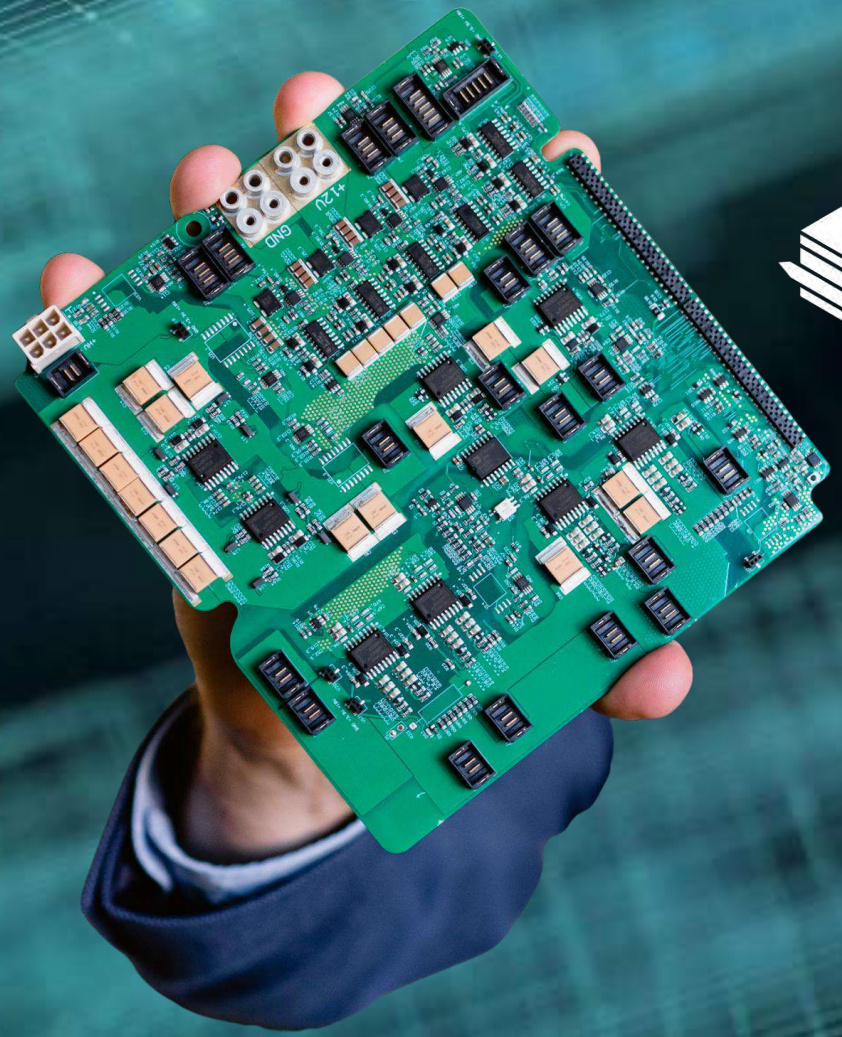
Optimal Component Layout



TINY POWER BOX

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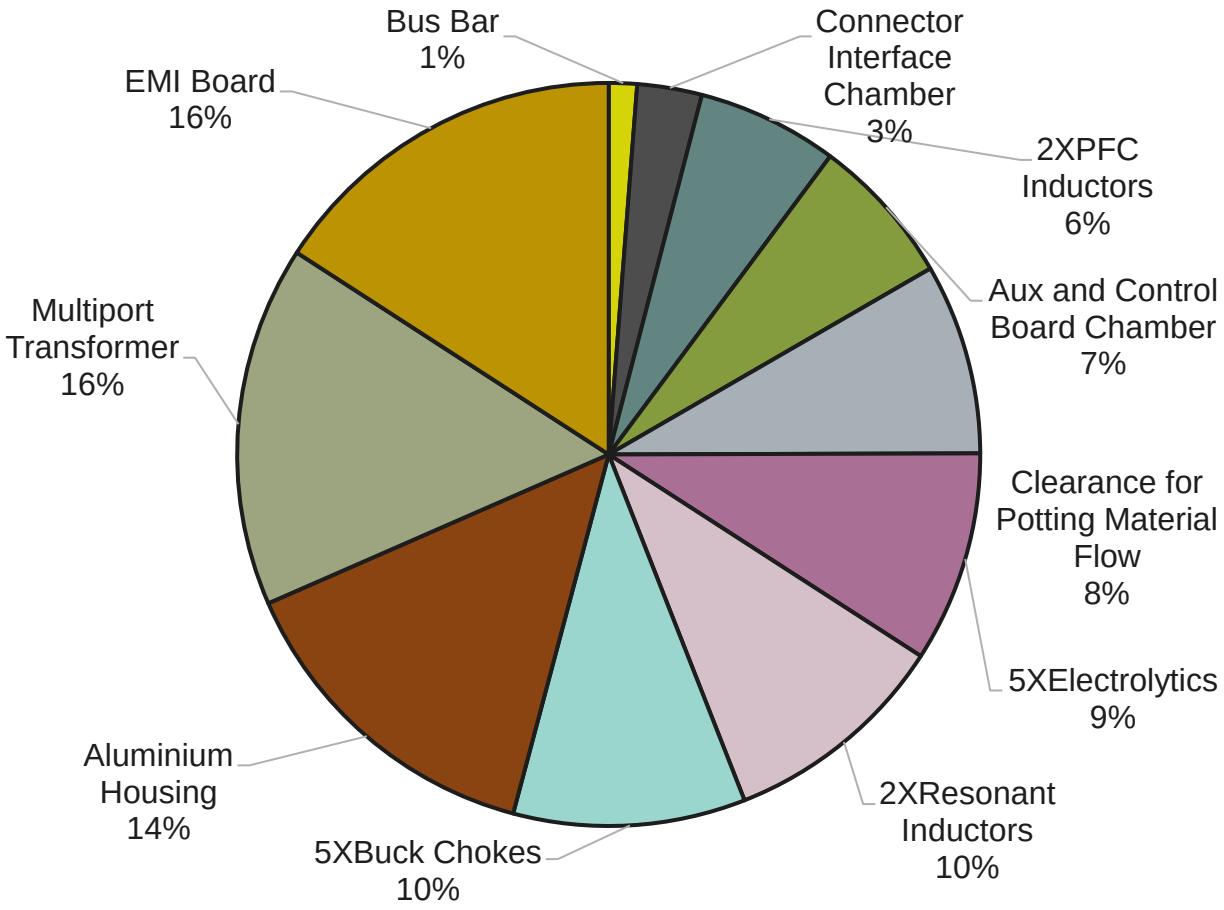
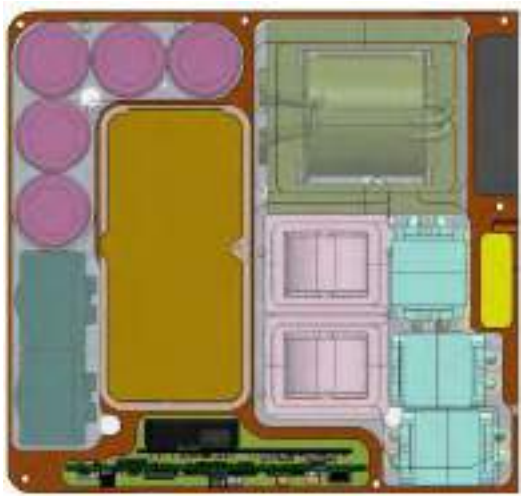
Optimal Component Layout for Passive Stage Area







- The passive stage determines the geometry of the surface area occupied by the components of whole system.
- It sets size limitations based on the bulkiness of passive components.
- In unpopulated areas, a minimum clearance of 1 to 2 mm between the housing and the electronics is necessary to allow the potting material to flow evenly around the components.
- This is why the inclusion of passive components in the proposed OBC leaves no room to further reduce the overall volume.

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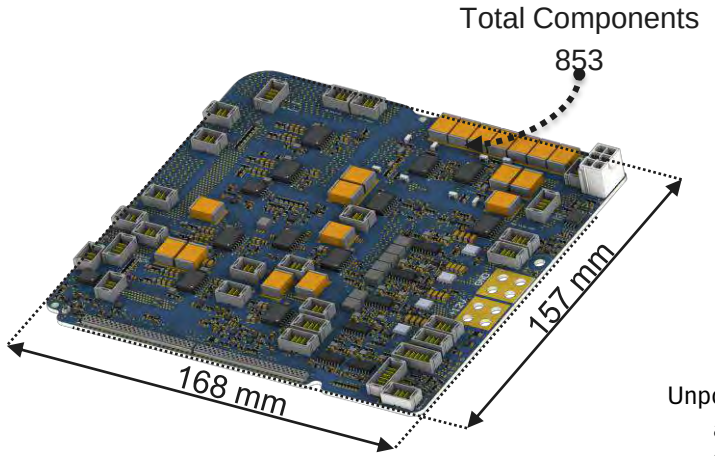
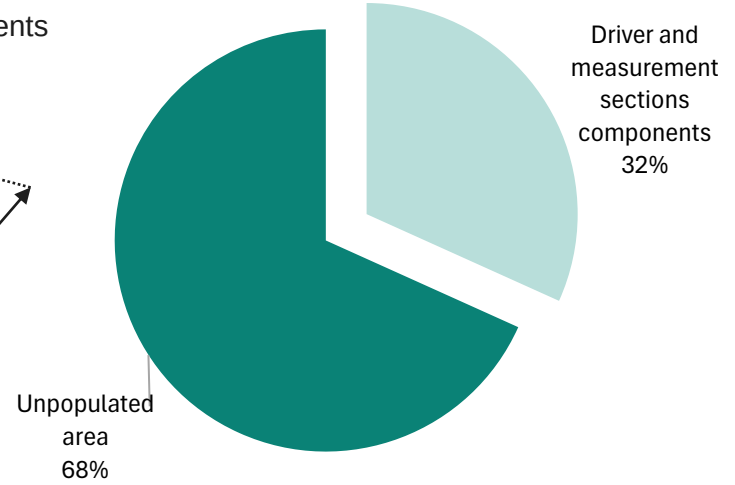
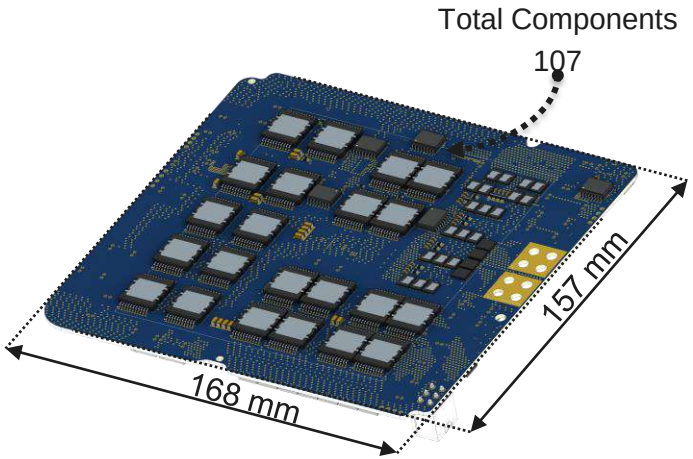
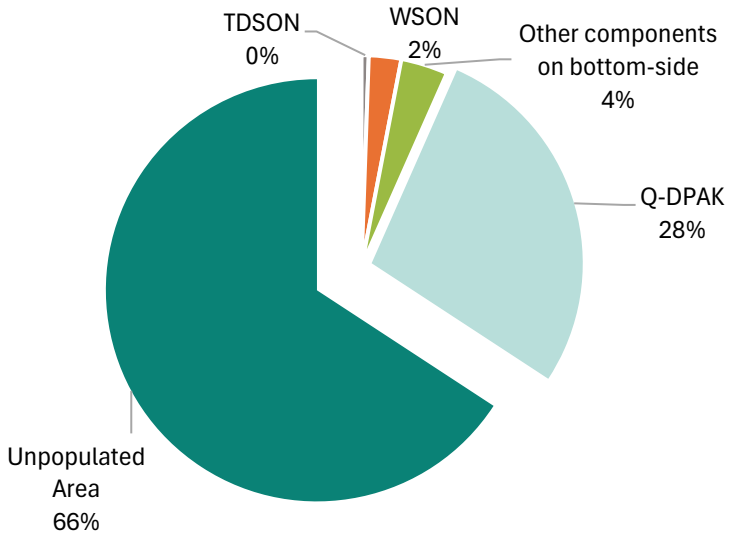
Optimal Component Layout for Active Stage Area

- The passive stage determines the available space, which directly influences the size of the PCB in the active stage.
- Unpopulated areas on a PCB are deliberately left empty to increase the creepage and clearance distances.
- Unpopulated areas ensure that creepage and clearance distances are maintained, reducing the risk of electrical breakdown or failure.









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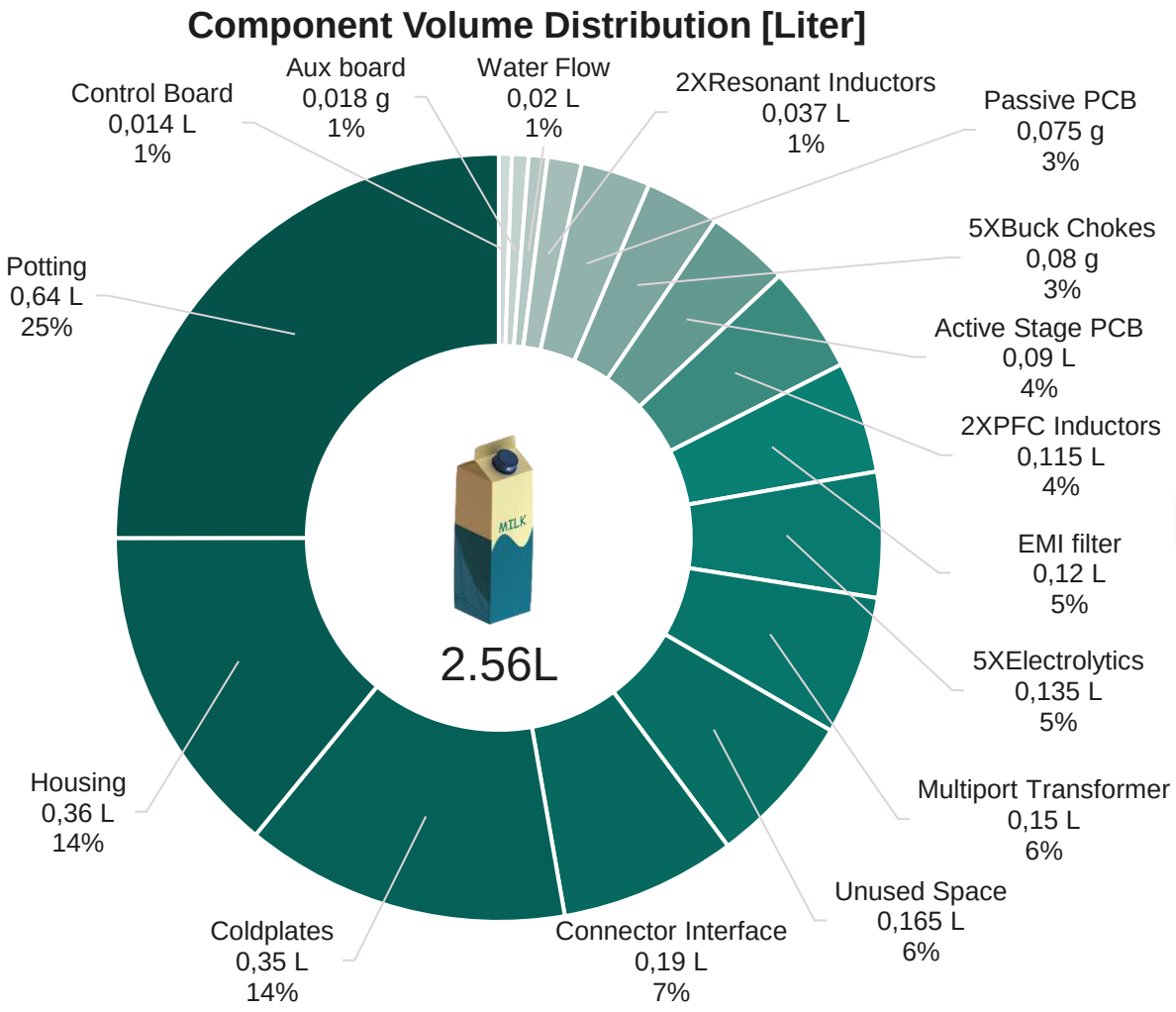
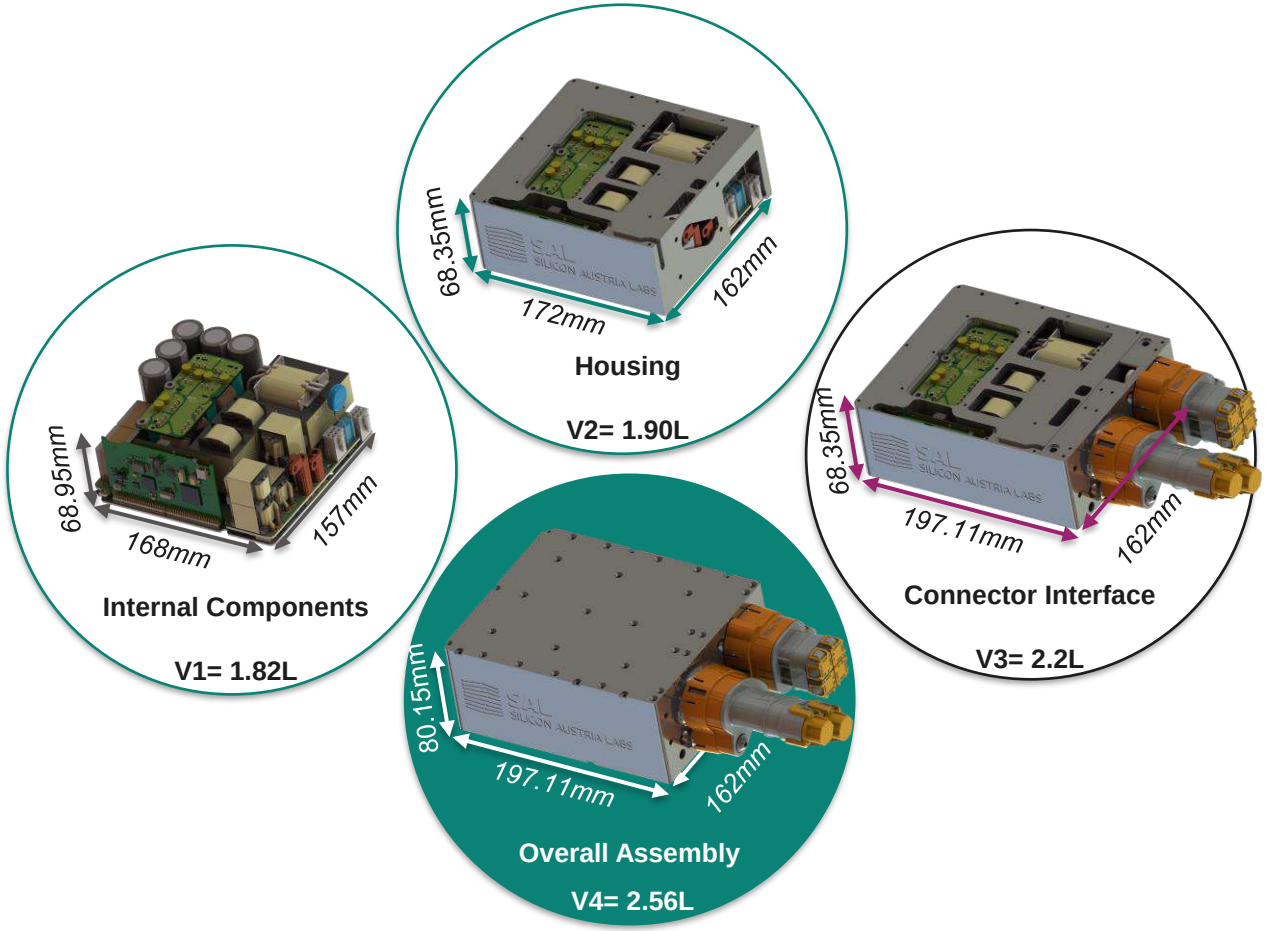
Volume distribution of components
Including internal, housing and connectors





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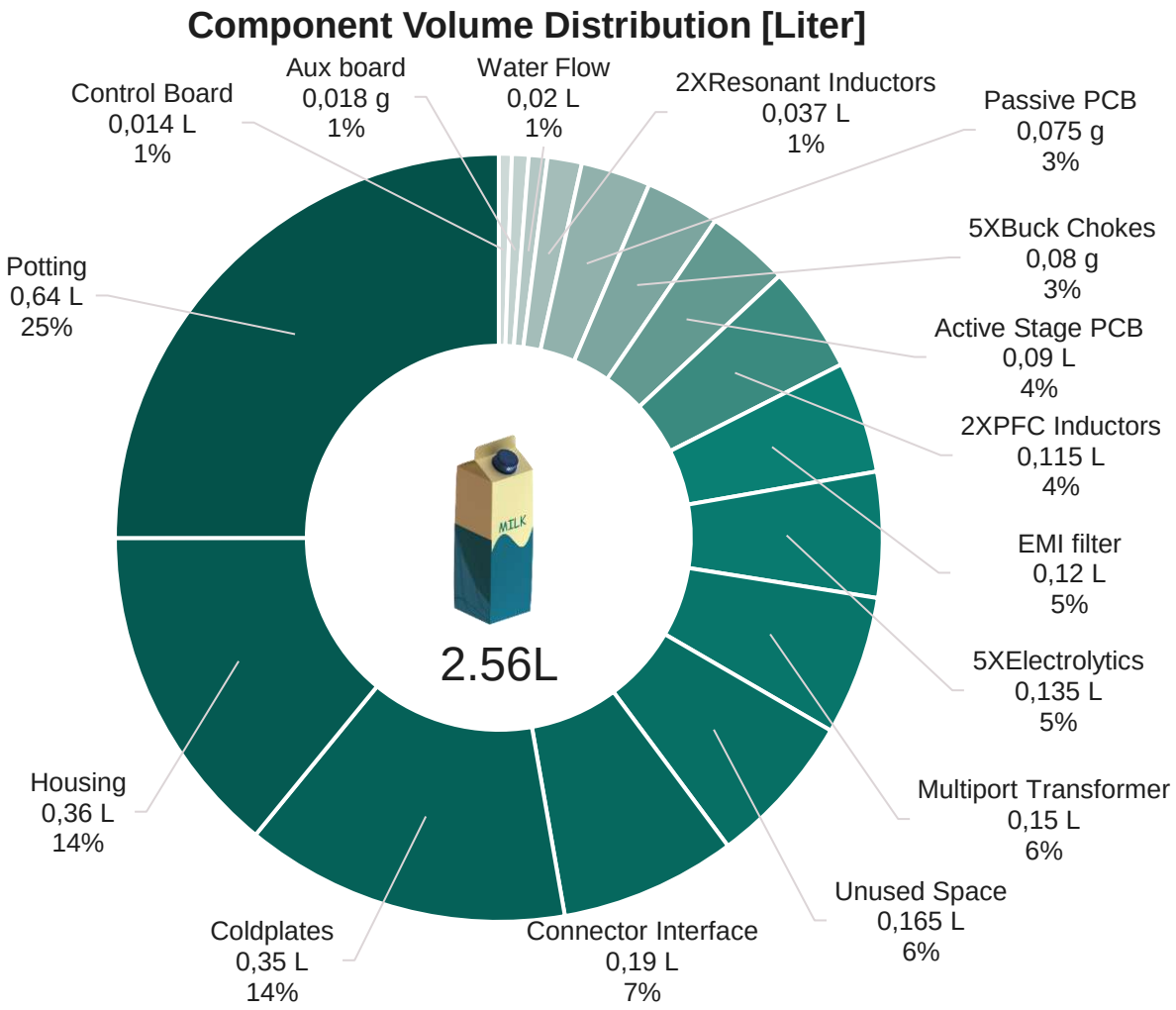
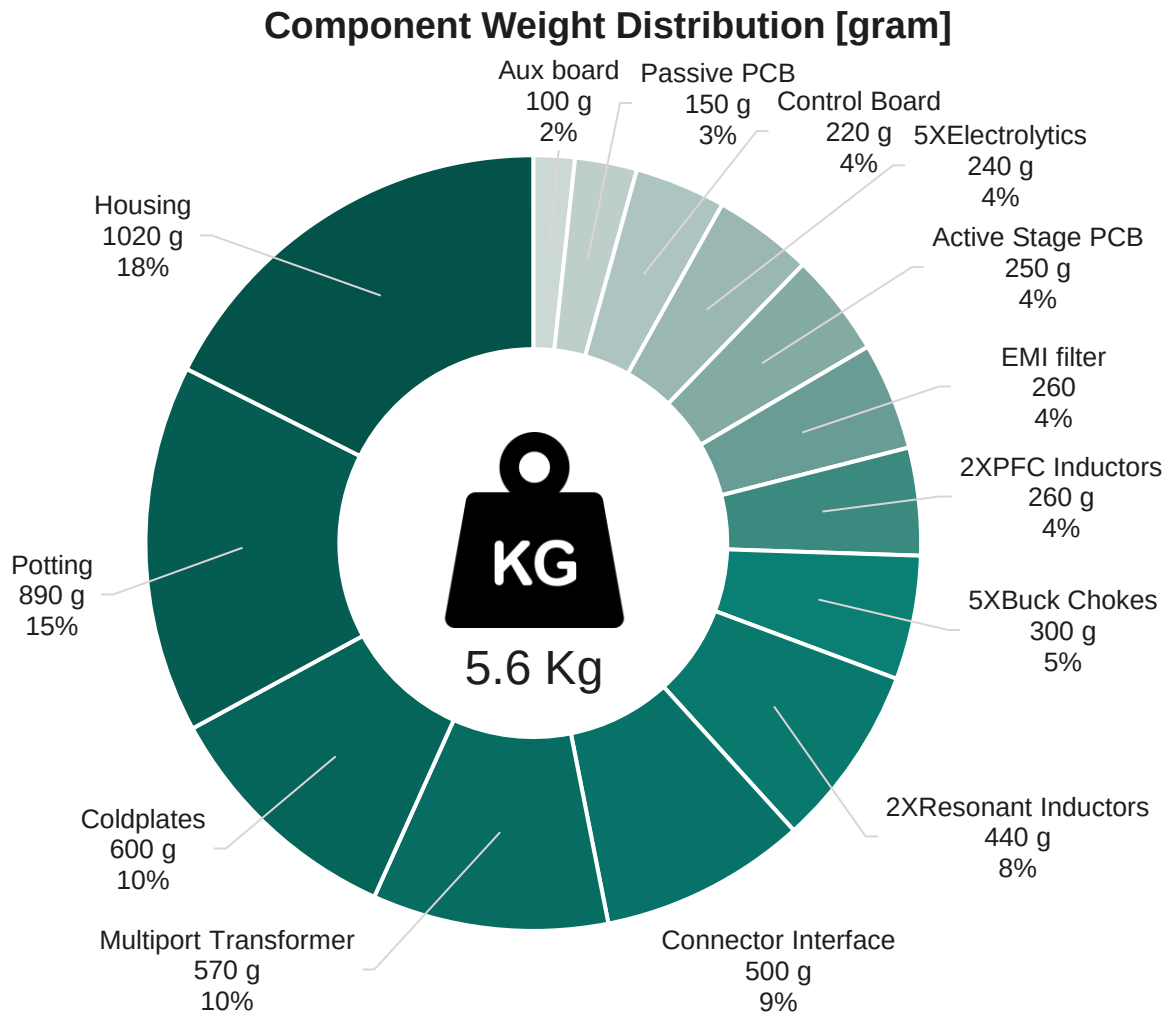
F. Vollmaier et al., "Tiny Power Box - Exploiting Multiport Series Resonant Topologies for Very High Power Density Onboard Chargers," PCIM Europe 2022; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management, Nuremberg, Germany, 2022, pp. 1-9, doi: 10.30420/565822017.

Volume and weight distribution of components
Overall view of the demonstrator





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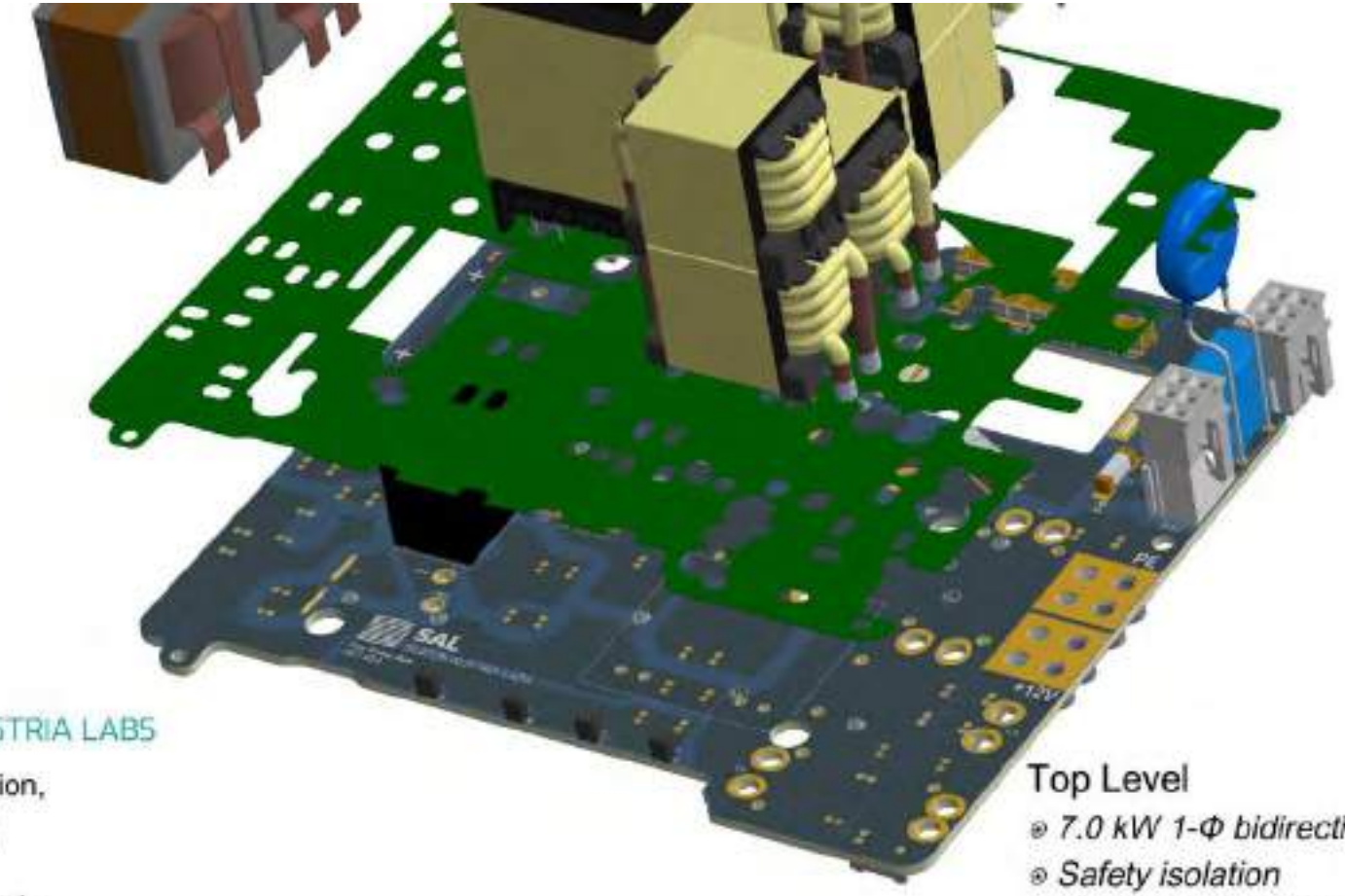
Detailed system assembly procedure



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Topology optimization,
system design,
EMC design,
control development,
simulation &
laboratory testing

Top Level

- *7.0 kW 1-Φ bidirectional AC-DC/DC-DC*
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- *97.5% peak total efficiency*
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- *1.95-liter incl. case (3.6 kW/L)*

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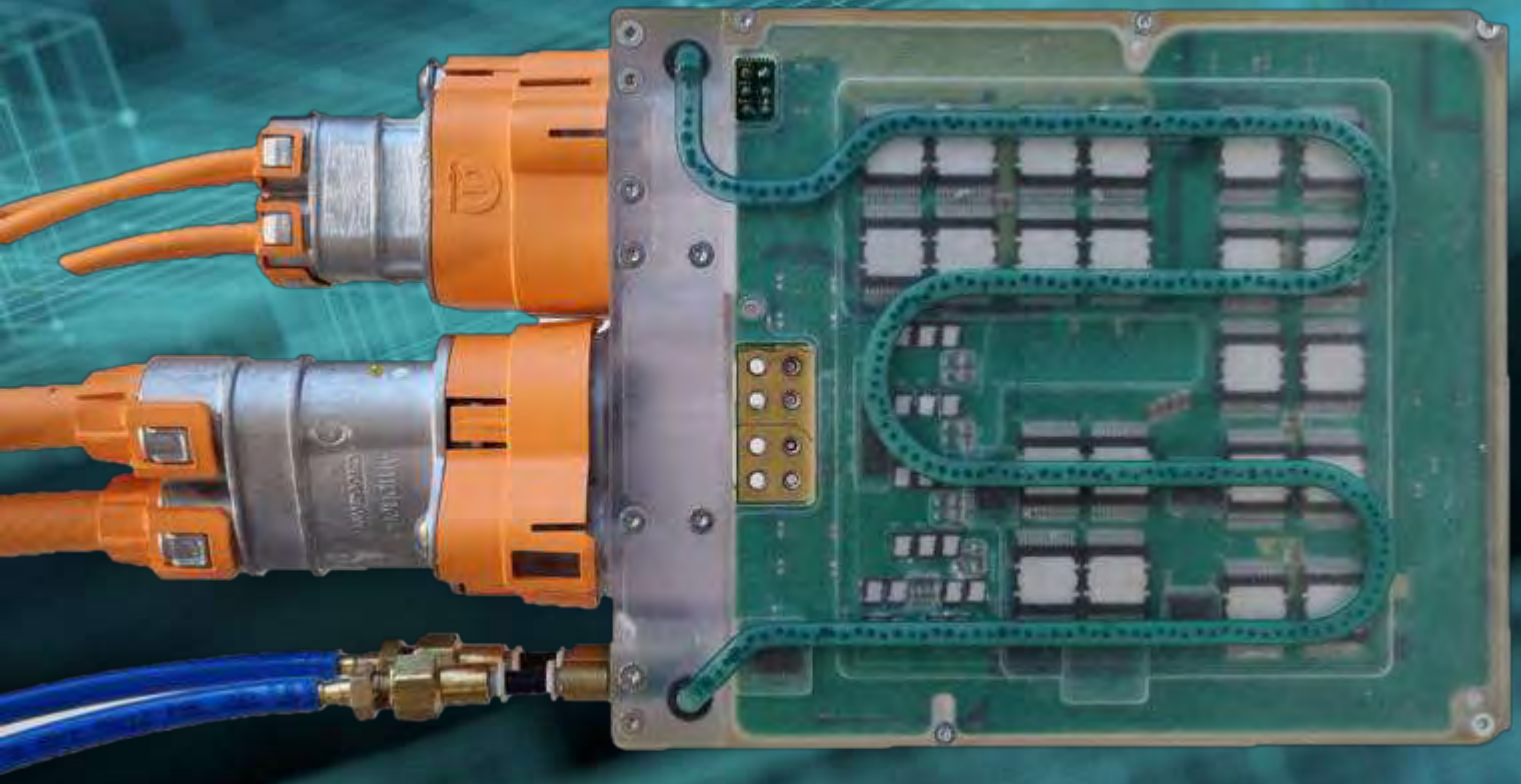
Thermo / Mechanical Simulations



TINY POWER BOX

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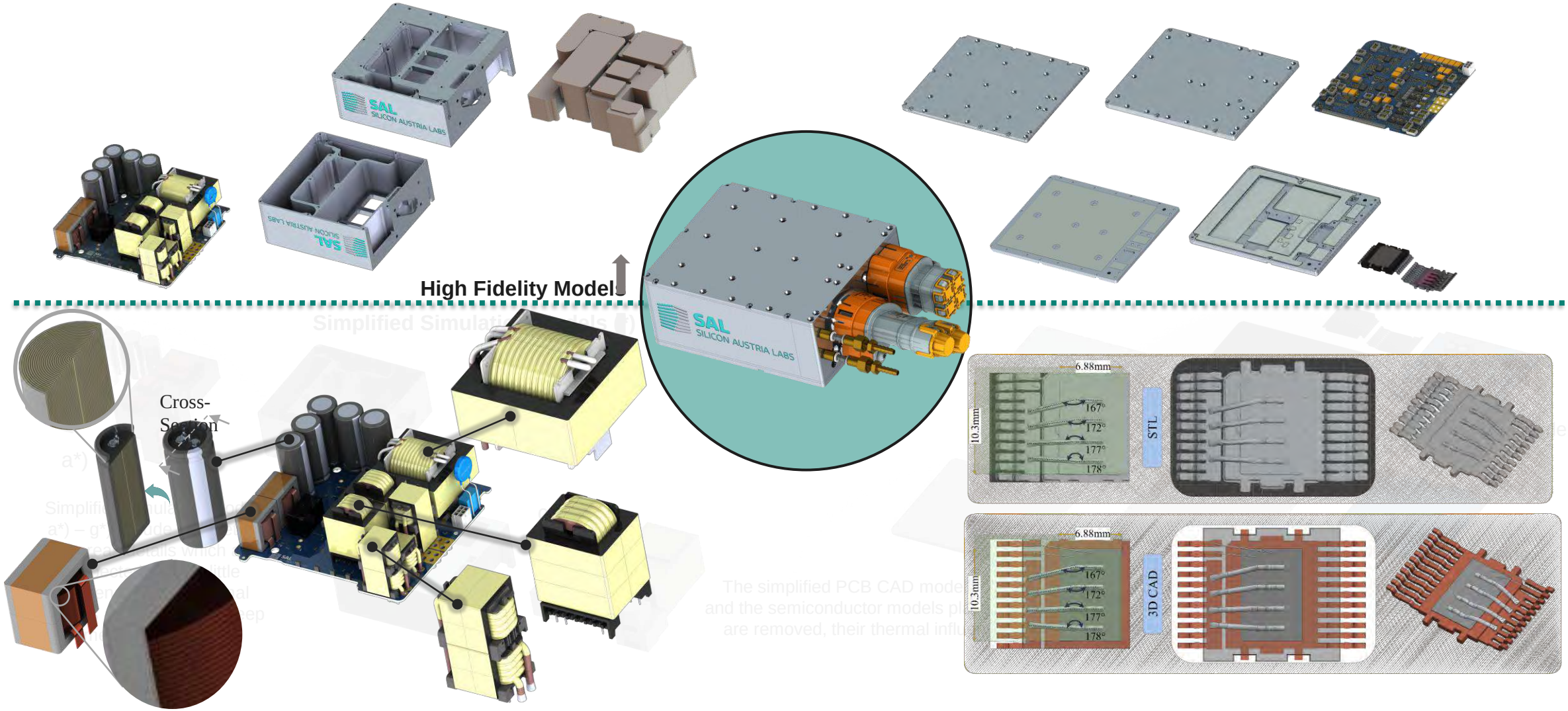
Thermo / mechanical simulations



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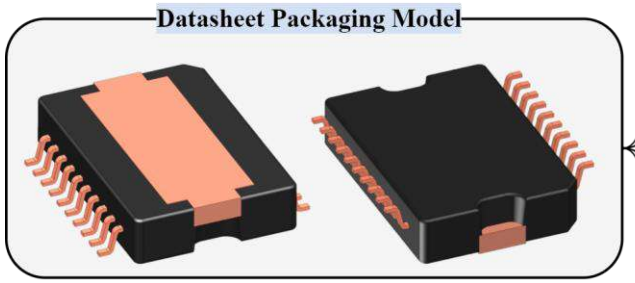
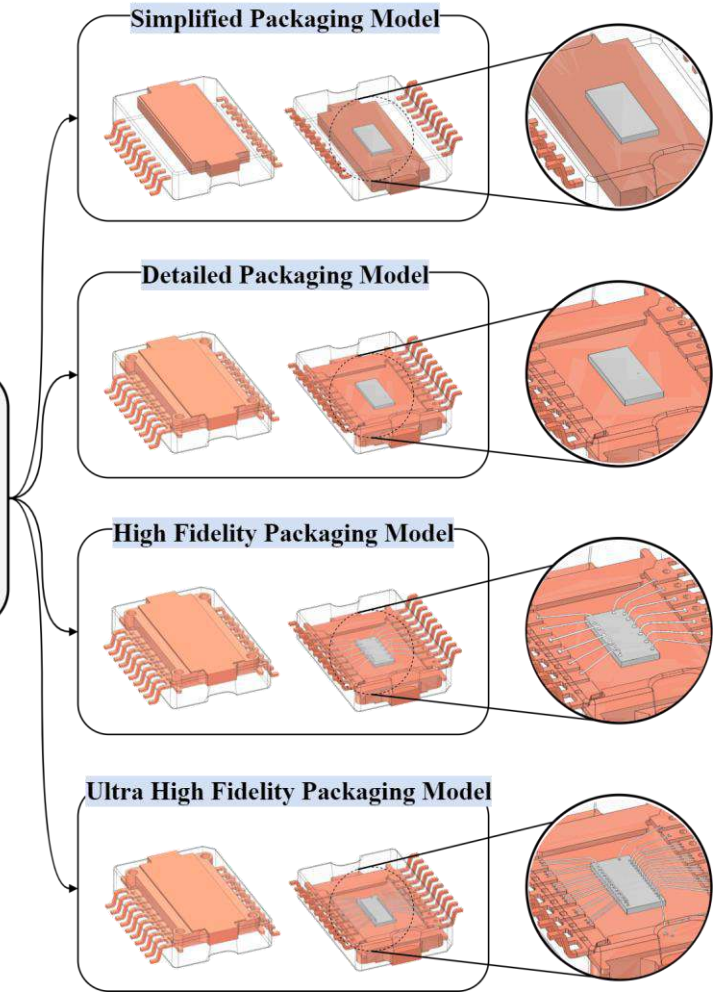
Thermo / Mechanical simulations
The impact of the depth in modeling devices

The steady-state thermal analysis results obtained by implementing the models with:

- different grades of details
- the same boundary conditions
- material properties
- and mesh settings





Assembly Test Setup	Temperature in °C			
	Die	Difference %	Capacitor	Difference %
Simplified Model	126.5	100%	60.0	100%
Detailed Model	124.8	↓1.34%	83.9	↑39.8%
High Fidelity Model	124.7	↓1.42%	85.0	↑41.6%
Ultra-High-Fidelity Model	124.9	↓1.26%	85.0	↑41.6%

- **Simplified packaging models**, based on data sheet information alone fail to capture secondary heat flows.
- **High-fidelity packaging models,**
  - include features such as bond wires, lead frame, and heat slug, required for accurate thermal simulation analyses.
  - capturing thermal cross-talk much better than simplified models do, as shown in an example where the **temperature of a nearby placed ceramic capacitor** is significantly raised .
- An accurately modelled lead frame can severely influence the amount of heat flux delivered into the surroundings.

C. Mentin, I. Recepi and T. Polom, "High Fidelity Package Simulation Models Capturing Accurate Thermal Cross-Coupling," 2020 26th International Workshop on Thermal Investigations of ICs and Systems (THERMINIC), Berlin, Germany, 2020, pp. 97-103, doi: 10.1109/THERMINIC49743.2020.9420498. keywords: {Heating systems;Analytical models;Capacitors;Predictive models;Lead;Electronic packaging thermal management;Data models},

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Thermo / Mechanical simulations
The impact of the depth in modeling devices

The steady-state thermal analysis results obtained by implementing the models with:

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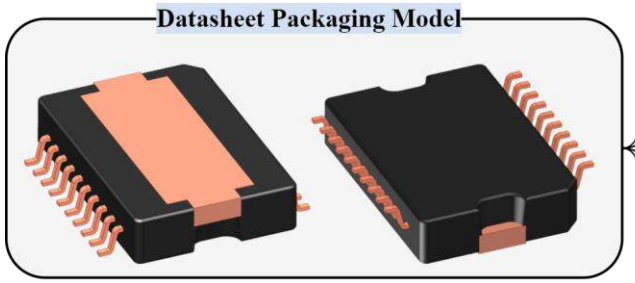

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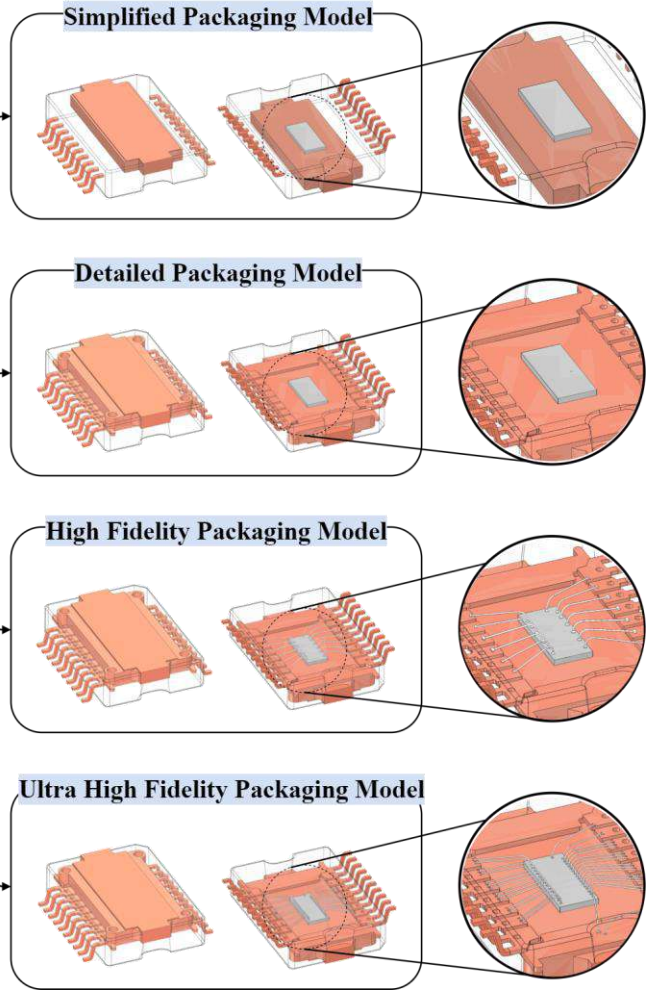

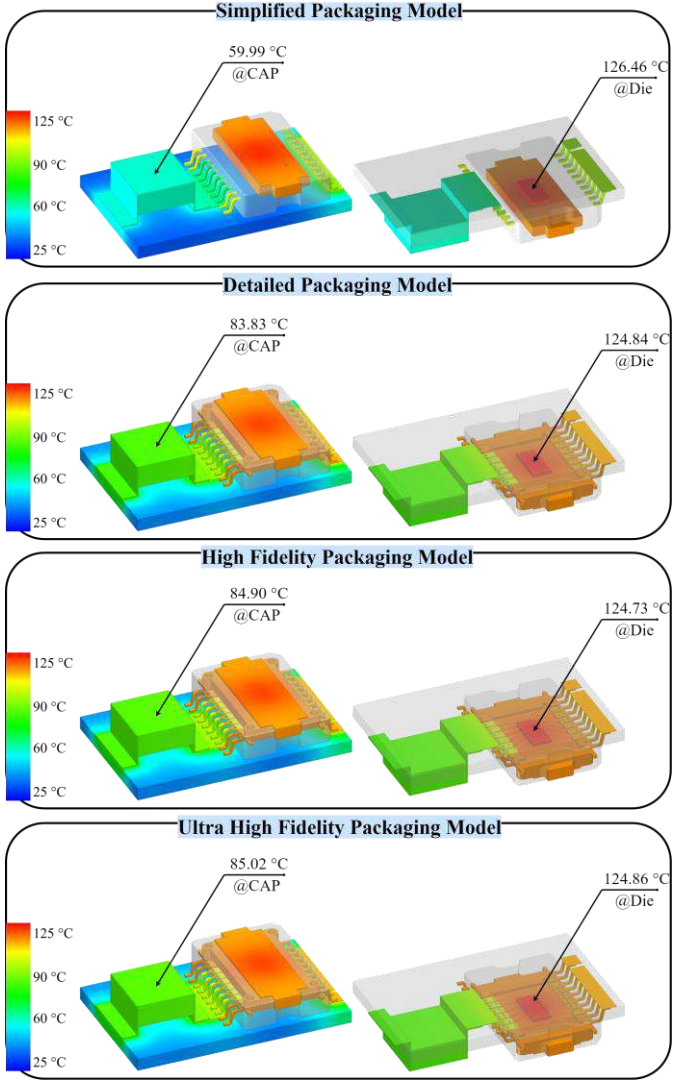

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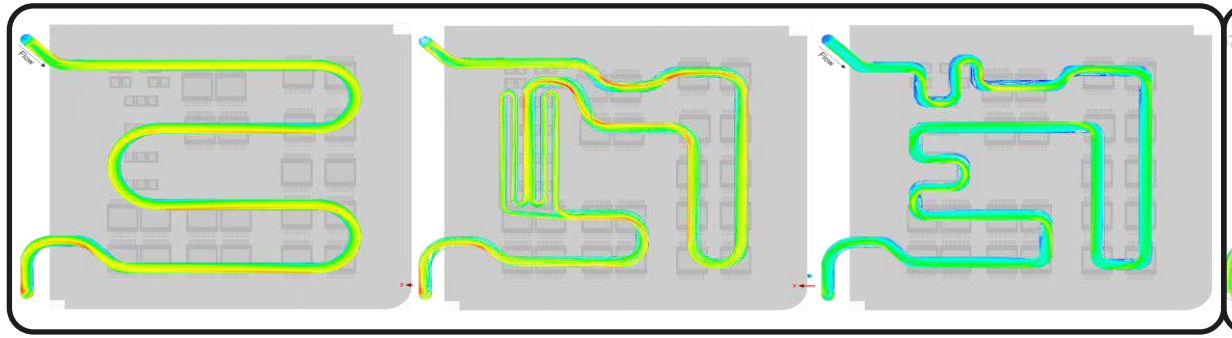
Thermo / Mechanical simulations

Cooling plates and channels design variations - I

- **Base Plate:** Constructed from highly thermally conductive Aluminum 6063, the base plate serves as the primary interface between the heat source and the cooling liquid.
- **Cooling Channel:** Embedded within the base plate, these channels guide the cooling liquid flow. The channel designed with different variants, including patterns and pin structures.
- **Sealing Mechanism:** Rubber seals created a watertight barrier, ensuring that the cooling liquid remains contained within the cold plate.
- **Mounting Mechanism:** Cold plate featured with mounting holes, allowing secure attachment to Thermal Interface Material and the Aluminum housing.

Patterns Channels



Pin Structures



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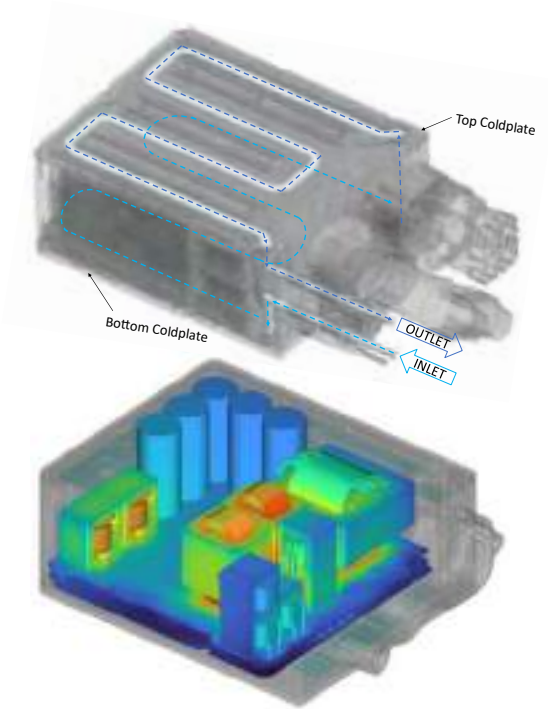
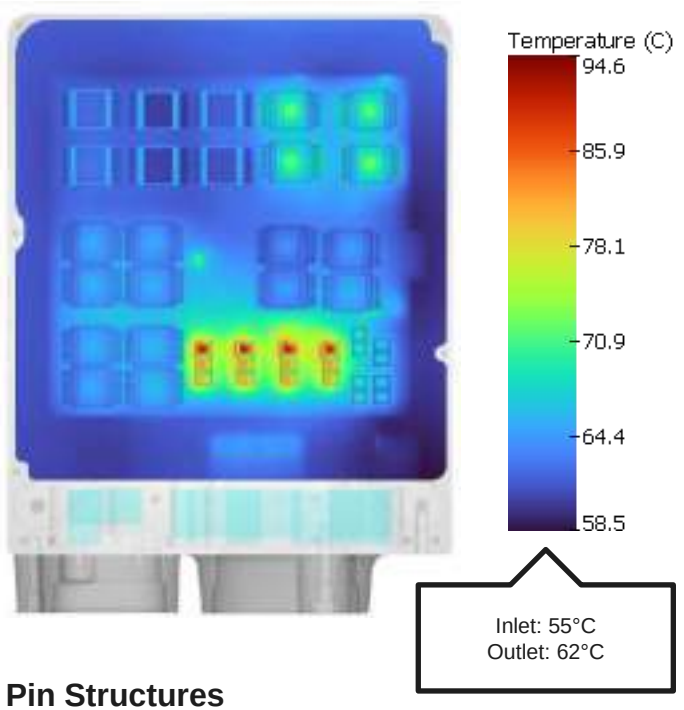
Thermo / Mechanical simulations

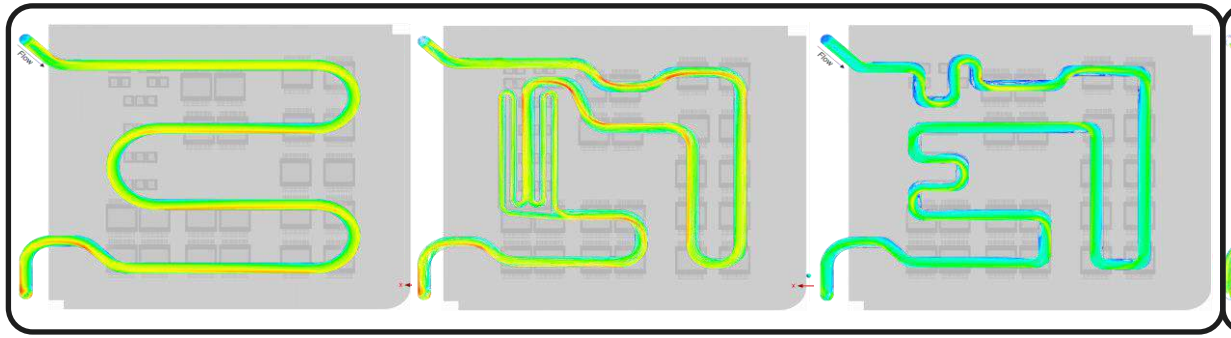
Cooling plates and channels design variations - II

- The cooling fluid is introduced to the system, starting at the bottom cold plate.
  - The **Bottom Cold Plate** cools the **Active Stage**.
- The fluid then moves through a channel to reach the top cold plate.
  - The **Top Cold Plate** cools the **Passive Stage.**
- This cooling process follows as single input - single output to utilize the 3D flow path.





Patterns Channels



Pin Structures



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Thermo / Mechanical simulations
Final animation



Overall assembly concept with integrated liquid cooling
for an automotive OBC application

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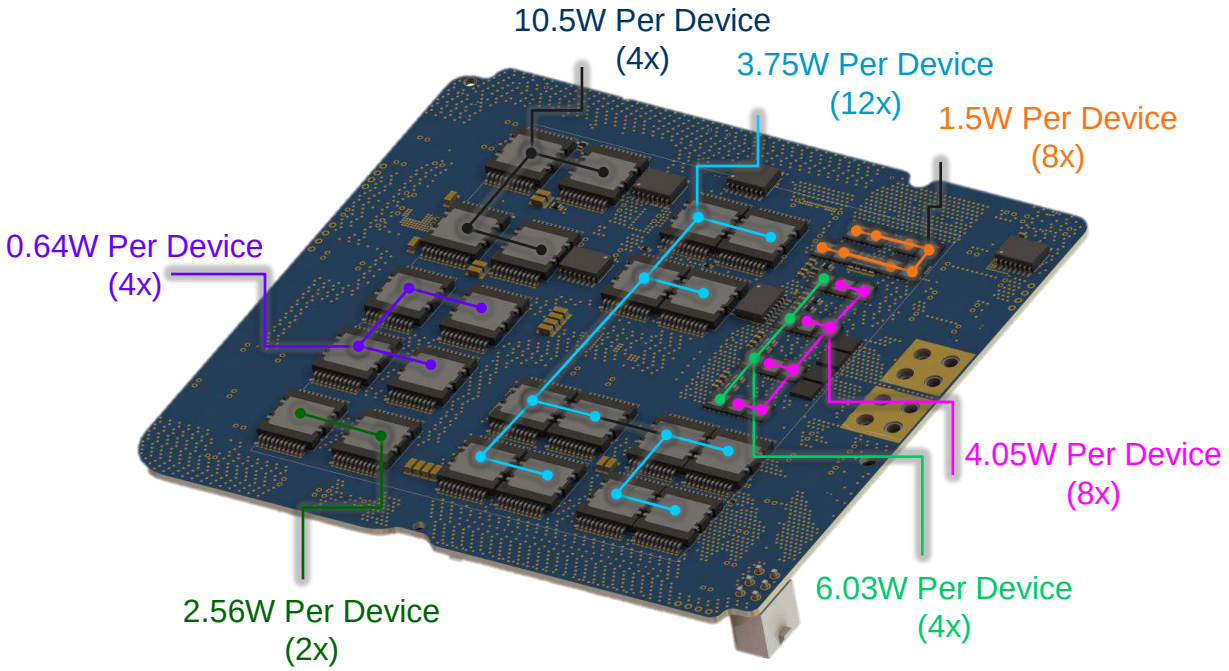
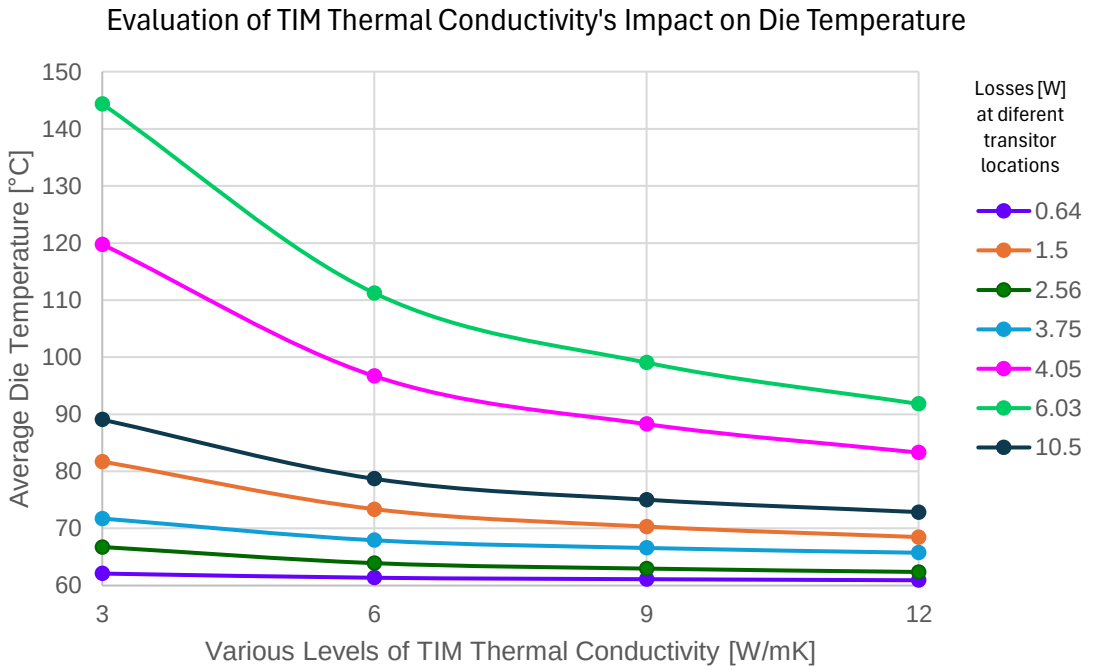
Thermo / Mechanical simulations

Impact of the thermal conductivity of TIM into the semiconductors





Losses [W]	*Thermal Conductivity of TIM* $\lambda K = 3\ W/mK$		*Thermal Conductivity of TIM* $\lambda K = 6\ W/mK$		*Thermal Conductivity of TIM* $\lambda K = 9\ W/mK$		*Thermal Conductivity of TIM* $\lambda K = 12\ W/mK$	
	Max Die T [°C]	Avg Die T [°C]	Max Die T [°C]	Avg Die T [°C]	Max Die T [°C]	Avg Die T [°C]	Max Die T [°C]	Avg Die T [°C]
0.64	62.9	62.1	62.1	61.4	61.9	61.1	61.7	61.0
1.5	83.9	81.7	75.6	73.4	72.6	70.3	71.0	68.7
2.56	67.0	66.7	64.2	63.9	63.2	62.9	62.8	62.5
3.75	72.9	71.7	69.1	67.9	67.8	66.6	67.1	65.9
4.05	122.0	119.8	99.2	96.7	90.9	88.3	86.6	83.9
6.03	148.1	144.4	114.2	111.2	101.9	99.0	95.5	92.6
10.5	90.1	89.1	79.8	78.7	76.1	75.0	74.2	73.1

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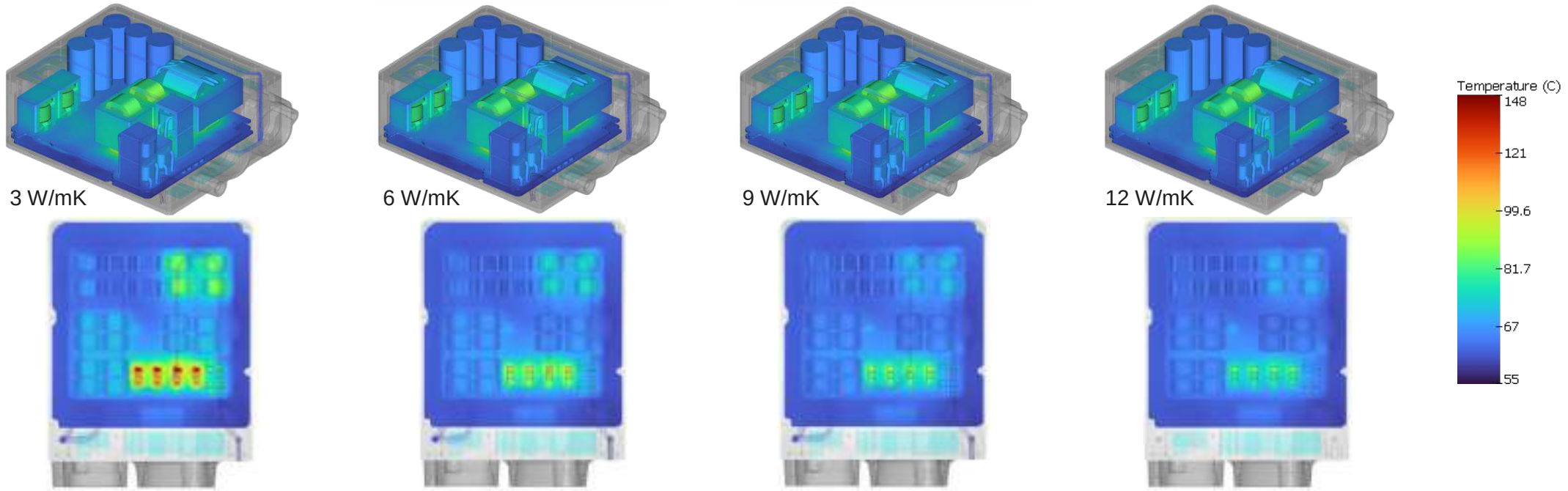
Thermo / Mechanical simulations

Impact of the thermal conductivity of TIM to the system



Losses [W]	$Thermal\ Conductivity\ of\ TIM$ $\lambda K = 3\ W/mK$		$Thermal\ Conductivity\ of\ TIM$ $\lambda K = 6\ W/mK$		$Thermal\ Conductivity\ of\ TIM$ $\lambda K = 9\ W/mK$		$Thermal\ Conductivity\ of\ TIM$ $\lambda K = 12\ W/mK$	
	Max Die T [°C]	Avg Die T [°C]	Max Die T [°C]	Avg Die T [°C]	Max Die T [°C]	Avg Die T [°C]	Max Die T [°C]	Avg Die T [°C]
0.64	62.9	62.1	62.1	61.4	61.9	61.1	61.7	61.0
1.5	83.9	81.7	75.6	73.4	72.6	70.3	71.0	68.7
2.56	67.0	66.7	64.2	63.9	63.2	62.9	62.8	62.5
3.75	72.9	71.7	69.1	67.9	67.8	66.6	67.1	65.9
4.05	122.0	119.8	99.2	96.7	90.9	88.3	86.6	83.9
6.03	148.1	144.4	114.2	111.2	101.9	99.0	95.5	92.6
10.5	90.1	89.1	79.8	78.7	76.1	75.0	74.2	73.1

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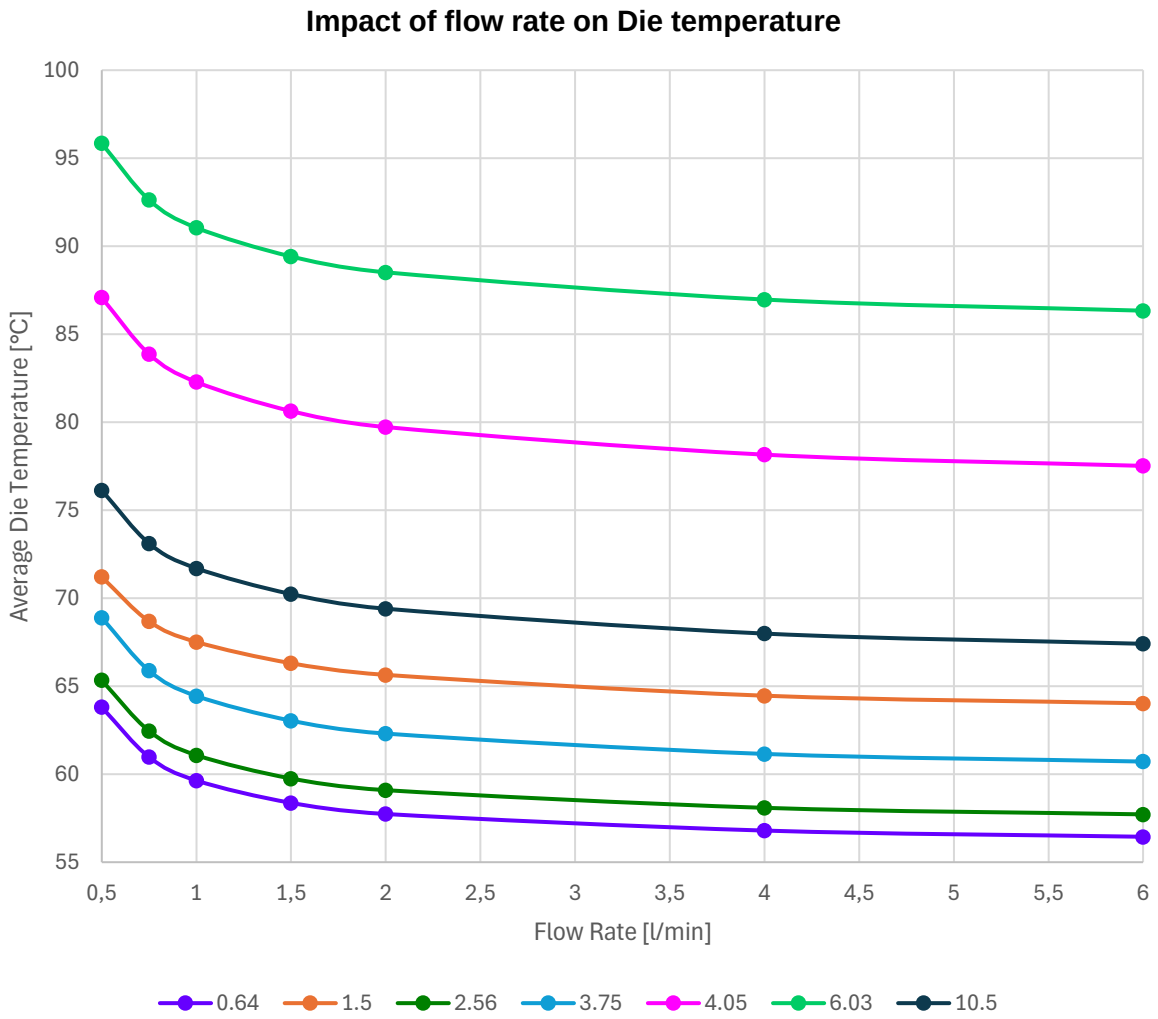
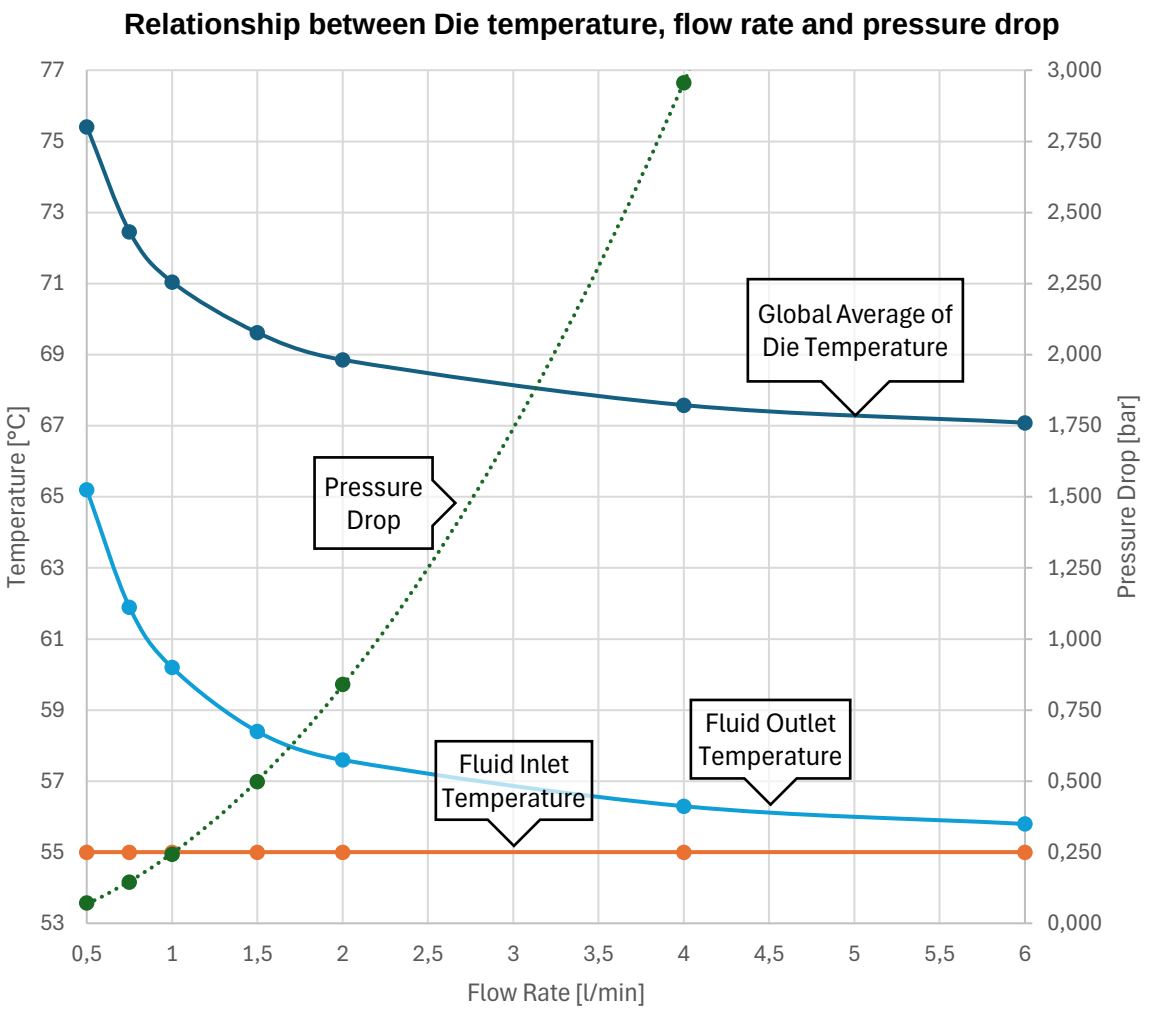
Relationship among flow rate, die temperature and pressure drop and why it matters





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