PASSIVE COMPONENTS FOR A 3D ENVIRONMENT

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Commercial Power Electronics - drawbacks

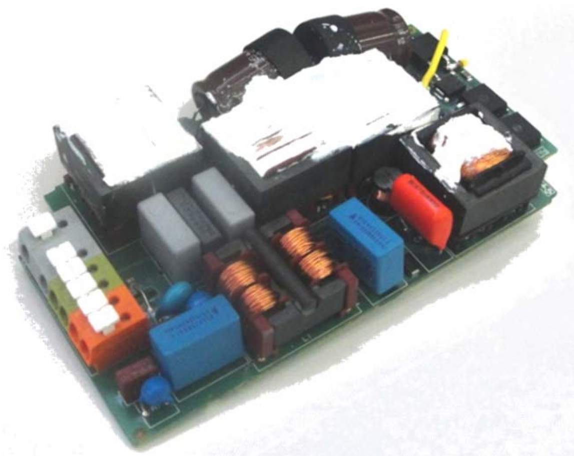
2D layout + Non-uniform height + Poor thermal properties =
= LOW POWER DENSITY

Mixed technology THT & SMT + "Odd shape" assembling parts =
= LABOUR INTENSIVE MANUFACTURING

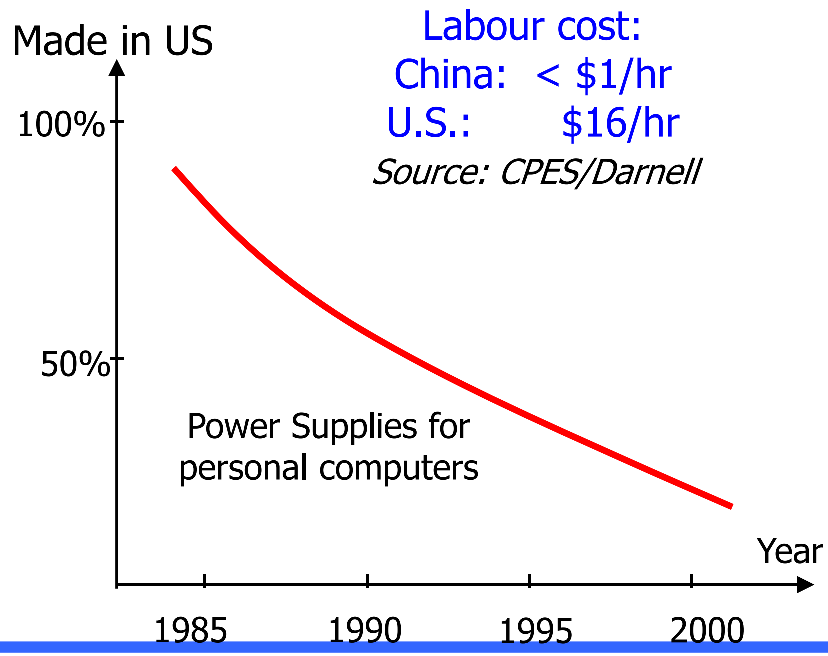
PE examples – commercial products

2.2kW Industrial drive

150W HID Lamp
Electronic ballast



Labour intensive construction



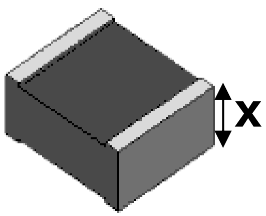
Outline

- Background ✓
- Power Sandwich concept for manufacturability
- X-dim Components
- Automated manufacturing
- Multilayer Thermal Management Concept
- Natural Convection demonstrator
- Forced air Cooling demonstrator
- Conclusion

Power Sandwich concept for manufacturability

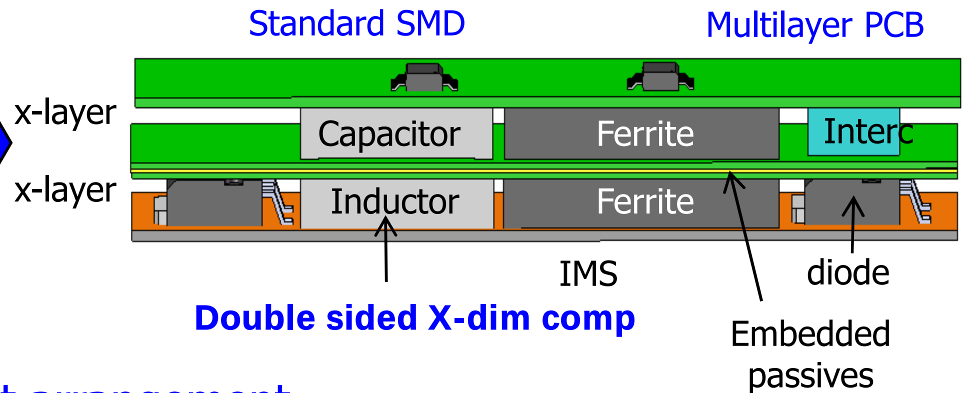
- **X-dim components**
  - Uniform (or compatible) height – x=14mm
  - Double sided SMT components
  - Enhanced thermal properties
- **Power Sandwich system integration**
  - Double sided and multi-layer soldering
  - Components active in the heat removal from each others
  - 3D loss density dependent components arrangement

x-dim components

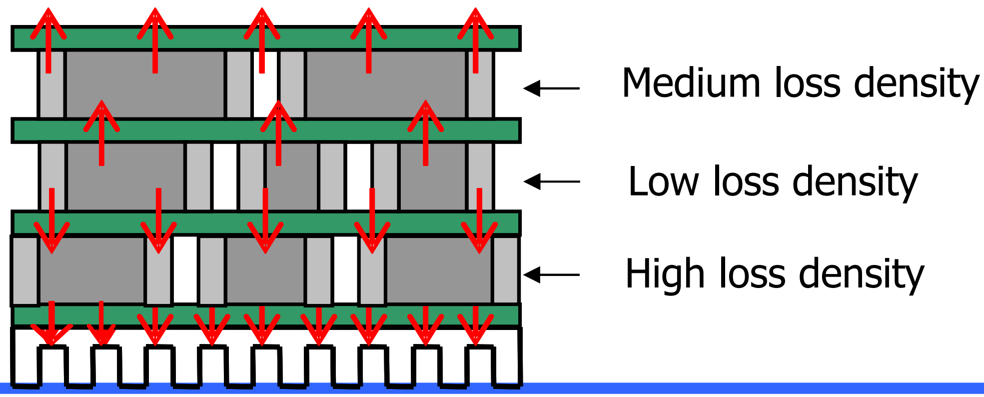


Automated assembly

POWER SANDWICH



Loss density dependent arrangement

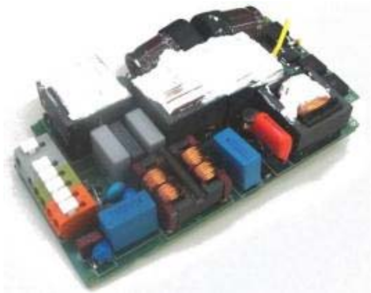


Power Sandwich Case Studies

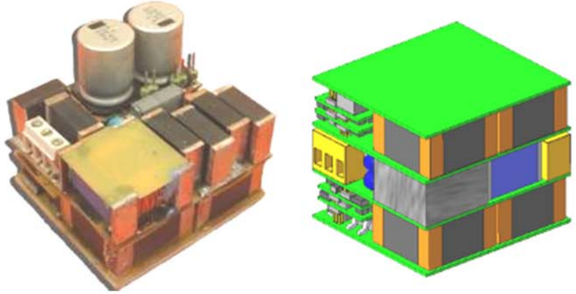
150W HID Lamp Electronic Ballast

- Power Density Increased by 2X
- Footprint reduced by 3.4X (Important for ballasts)

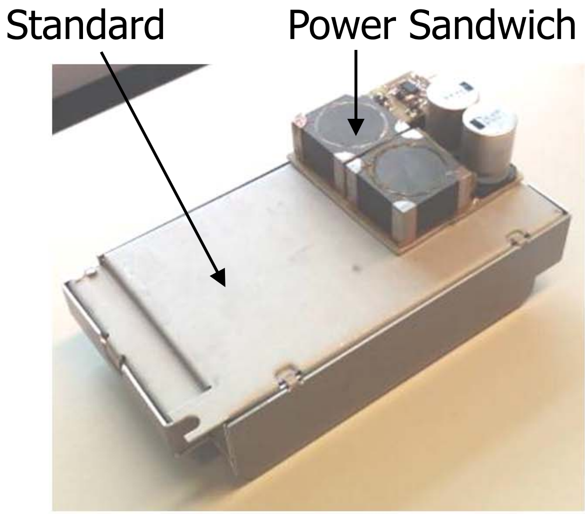
Standard (0.46 kW/l)



Power Sandwich (1kW/l)



Standard
VS
Power Sandwich



2.2KW Inverter for Motor Drive

- Power Density Increased by 3.8X
- Very Simple Thermal Management

Standard

1kW/l
Big Heat Sinks

Power Sandwich

3.8kW/l
No typical heat sinks

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X-dim Components Samples – Inductors

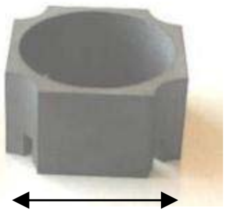
- Drum and shield construction, x=14mm
    - Reduced packaging - No coil formers
    - Double sided SMT
- Thermal performance improvements
    - Integrated SMT tabs
    - Potting

Construction parts

Drum

23 mm

Shield



26 mm

Cu SMT tabs

Inductor Samples

L=240µH

Standard vs. X-dim

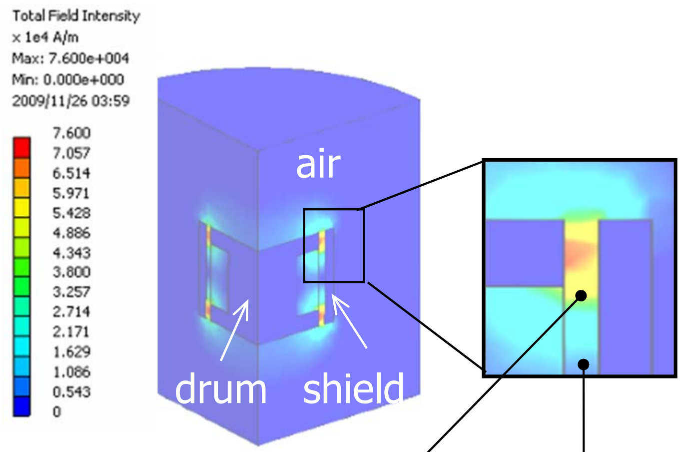
(L=240µH, I_{max}=4A)

Vol. reduced by ~30%.

X-dim Components Samples – Inductors Thermal Performance

- Temperature rise measured at two points in the winding
- Low ΔT (max 3.8ºC) in x-dim inductor.

Measurement points



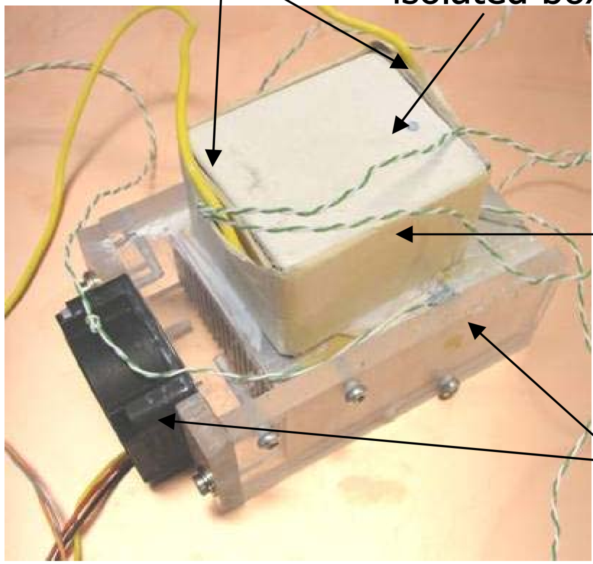
$\Delta T_2 = 3.8^oC$

$\Delta T_1 = 3.1^oC$

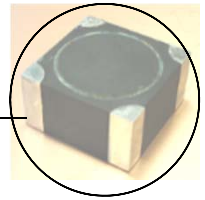
Experimental set-up

Power terminals

Thermally isolated box



X-dim inductor inside box



Heat sink/fan assembly

Heat sink (Al)+kapton+TIM

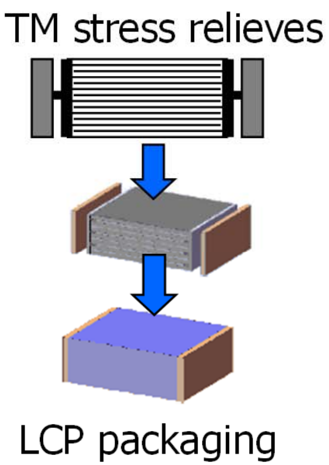
Interfaces equivalent to the real assembly

X-dim Components Samples – Capacitors

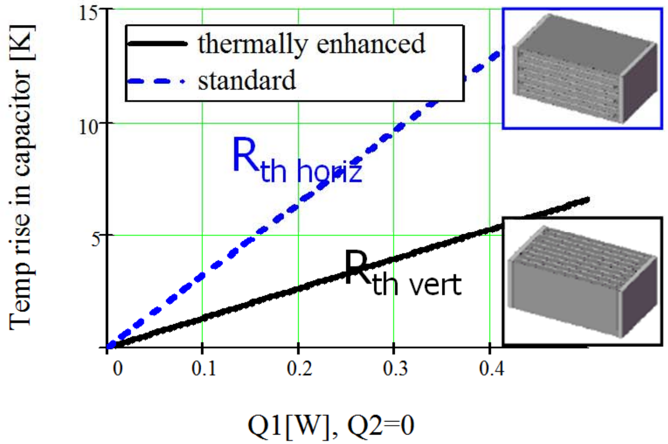
METAL-FILM CAPACITORS , X=14mm

- TM stress relieves
- Reduced packaging, vertical film orientation

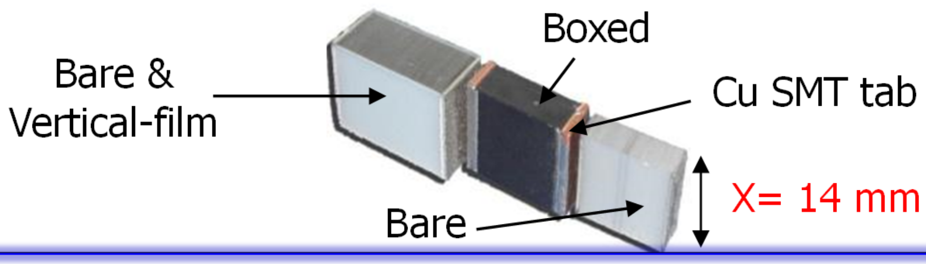
Construction



Thermal behavior



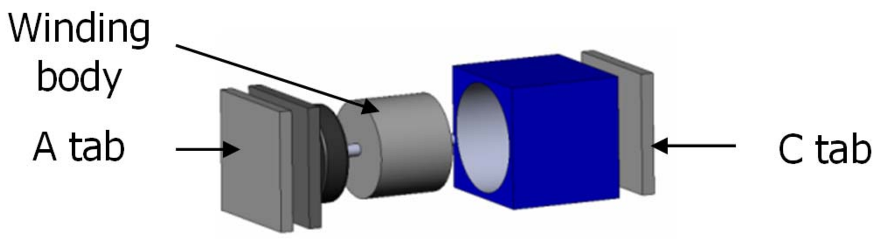
Samples



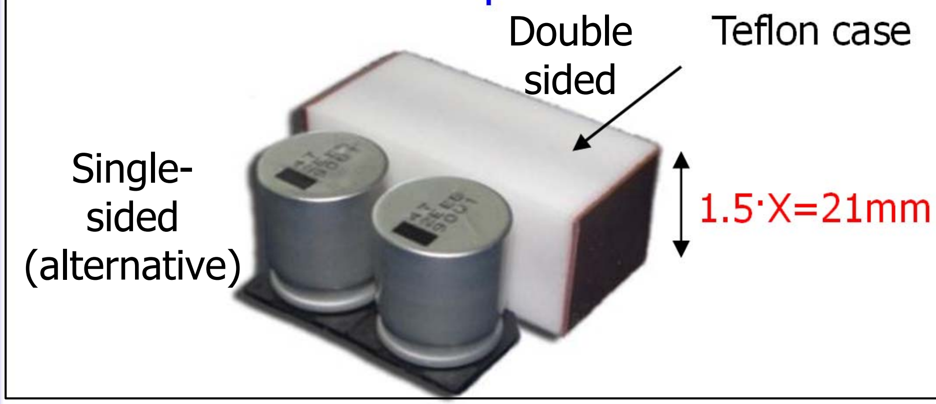
ELECTROLYTIC CAPACITORS, 1.5X

- Axial leaded double sided construction
- Teflon sleeve

Construction



Samples



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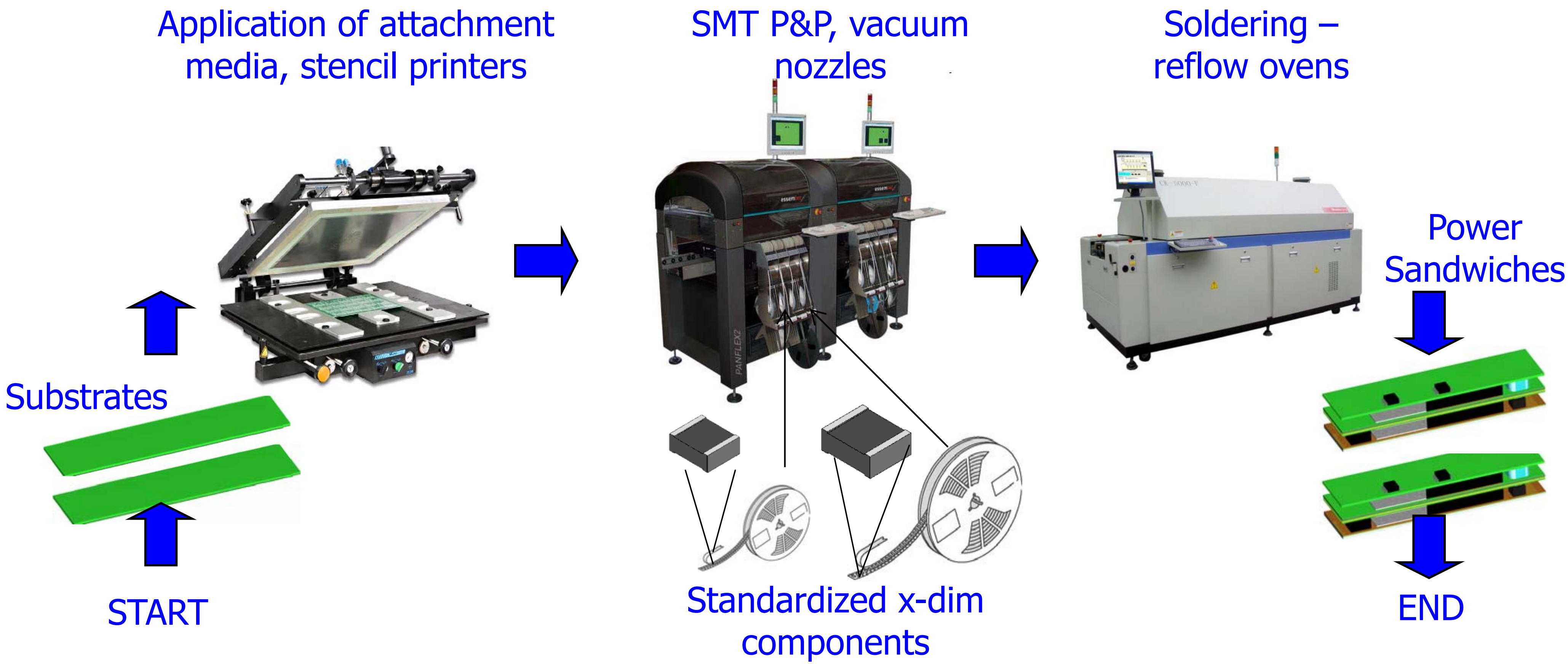
Power Sandwich SMT automated manufacturing features

- Multilayer SMT assembly and stacking
  - Gluing x-dim components to the PCB, P&P x-dim components, P&P of populated substrate
- Double sided soldering
  - Solder paste application on PCBs and x-dim components, Soldering of x-dim components from top and bottom
- Multilayer soldering
  - Double sided soldering in a few stack layers, Soldering different thermal capacitances



Power Sandwich - process flow/manufacturing sections

- Components assembly
    - Components assembled on single substrates (Similar to standard SMT assembly)
- Layers stacking and soldering
    - P&P populated substrates, Double-sided and Multi-layer soldering

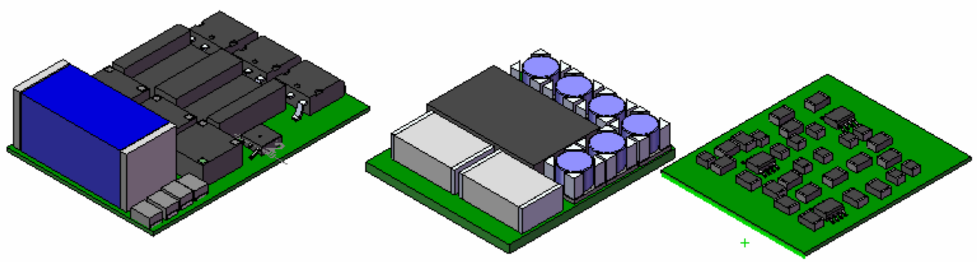
Components assembly

START → Apply solder paste and glue on PCBs → P&P x-dim components → Glue curing

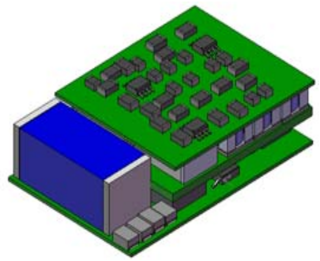
→ Apply solder paste on x-dim components → P&P populated PCBs - stacking → Vapour-phase soldering → Cleaning, inspection → END

Layers stacking and soldering

Components assembly



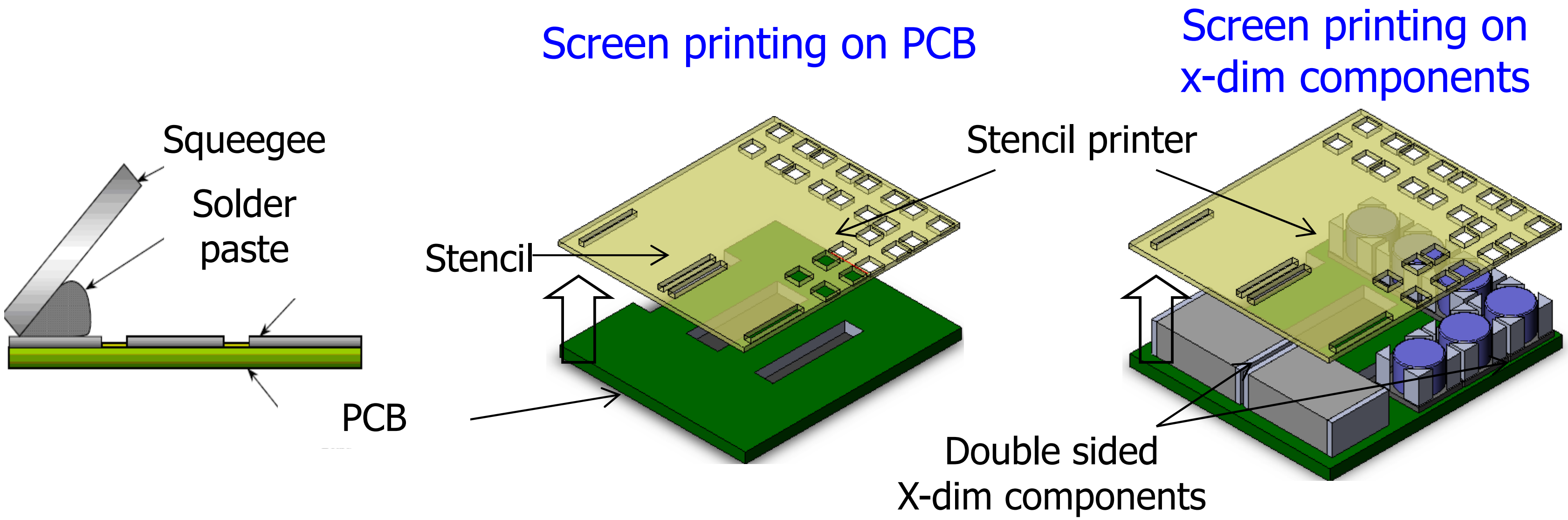
Layers stacking and soldering



Power Sandwich – application of attachment media

- Stencil printers, screen printing
- The same height of x-dim components → screen printing on x-dim components enabled
- Double sided x-dim components → the same stencil used for substrates and x-dim components

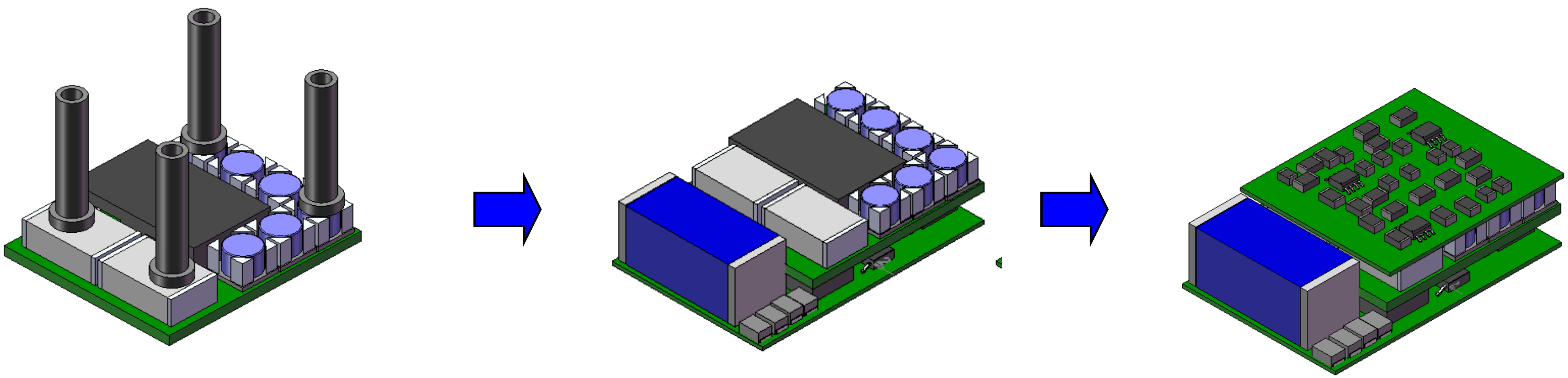
Application of attachment media



Power Sandwich – Pick and Place

- Vacuum nozzles for P&P
- Coo-planarity inherent to Power Sandwich → P&P of populated substrates enabled (by vacuum nozzles)

P&P of populated substrates



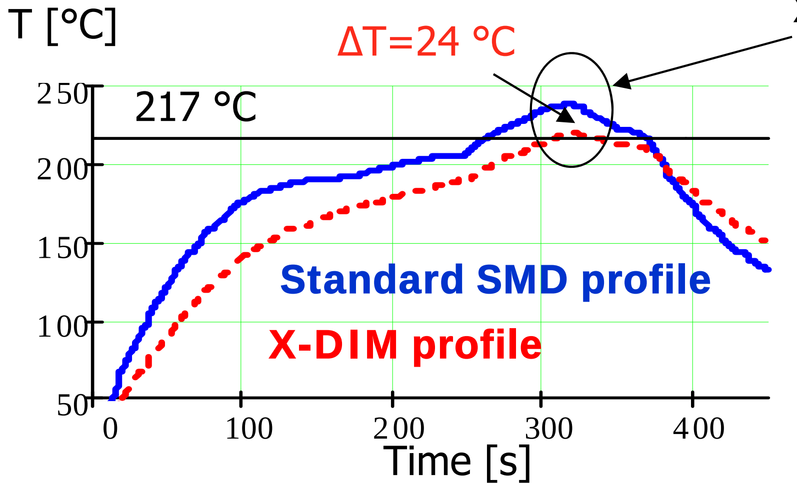
Power Sandwich – Soldering

- Soldering large and different thermal capacitances (X-dim vs. standard SMT)
- Solution:
  - Enable faster temperature response of the components
  - Enable more uniform heat distribution
  - Limit maximum temperature (overheating)

→ **VAPOUR-PHASE SOLDERING**

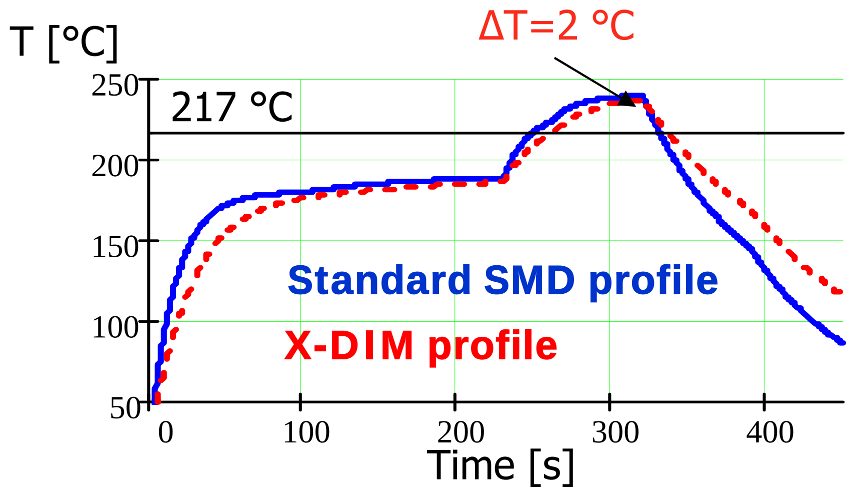
Temperature profiles - Simulation results

CONVECTION SOLDERING



X-dim component not kept sufficiently long above solder paste melting point

VAPOUR-PHASE SOLDERING

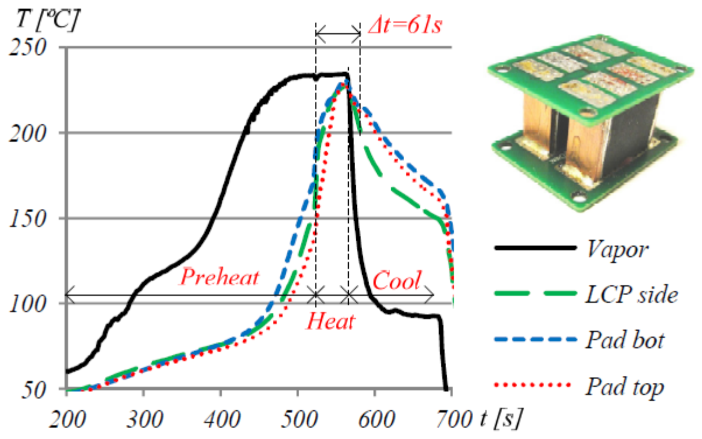


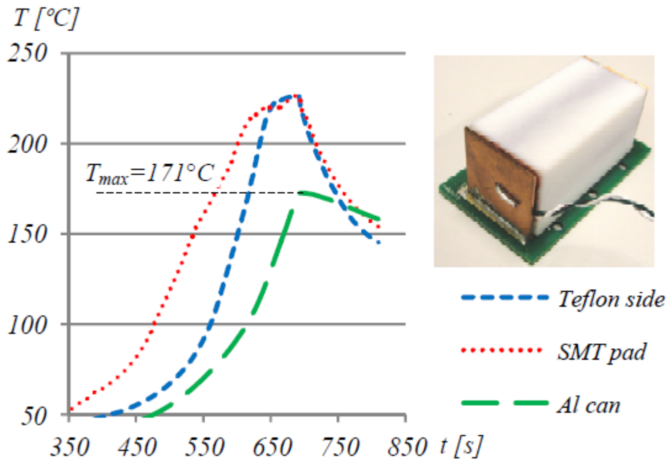
With the vapour-phase ovens, greater and more uniform heat transfer results in smaller temperature difference between small and large thermal capacitances (*2°C* at peak temperature)!

IOP ECPE TU Delft

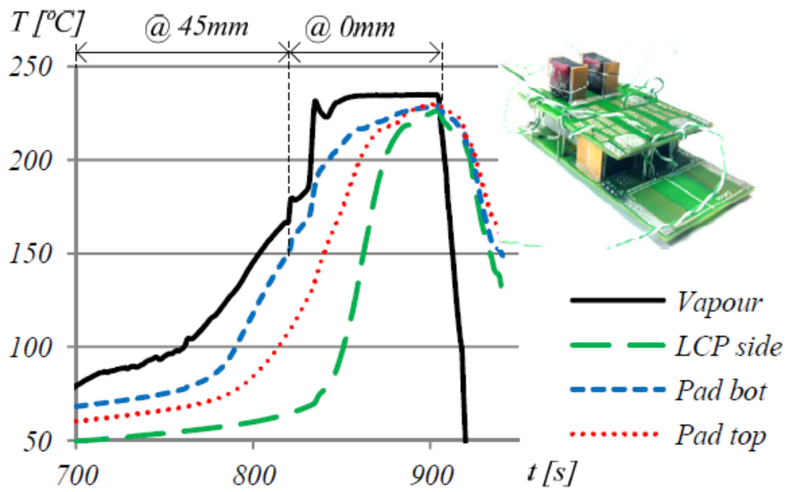
Power Sandwich – Soldering experimental results

- Temperature rise experiments on X-dimension components





- Temperature rise experiments on X-dimension assembly



Temperature-time profiles during soldering of CM choke and 4 metal-film capacitors on two sides and 2 metal-film capacitors on one side with assembly preheated at 45mm above minimum position in the oven.

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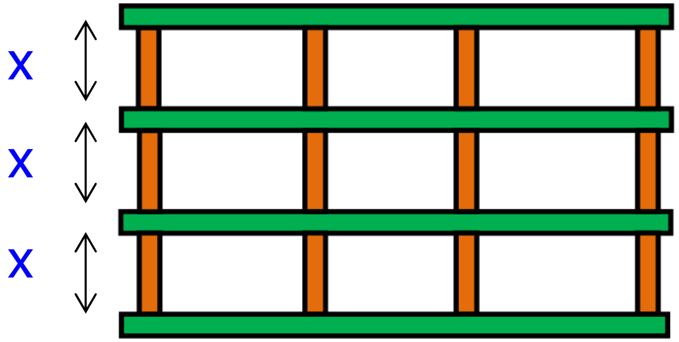
Multilayer Thermal Management Concept – Power Sandwich

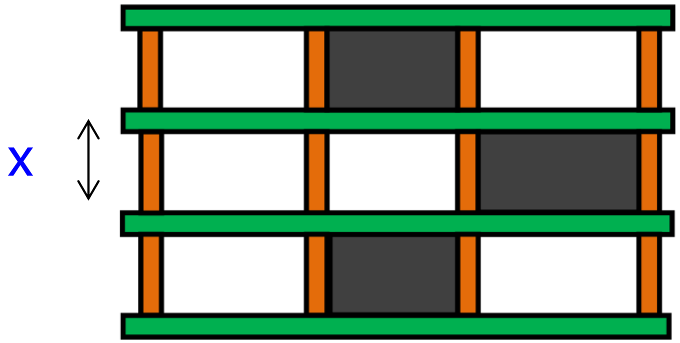


3D multilayer thermally conductive structure

Structure carries thermo-mechanical stresses

PCBs and IMSs spaced by Cu tabs soldered at both sides

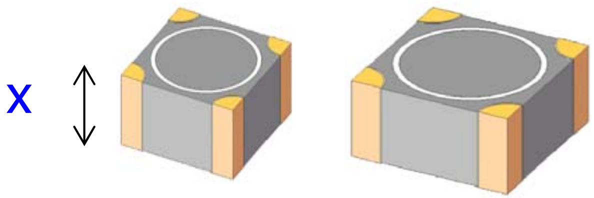
Empty spaces for adding functionality



Circuit functionality

Semiconductors and passive components

Cu SMT tabs: mechanical, thermal, electrical



X-dim components

Integrated Cu tabs – double sided SMT

Compatible in height (x) & Thermally enhanced

Multilayer Thermal Management Concept – Power Sandwich

- Multi-sided Cooling
  - Heatflow to more surfaces
  - X-dim components participate in heat exchange between layers
- X-dim Components Contribution
  - Reduce R_{th} inside converter
  - Facilitate more uniform T in the system

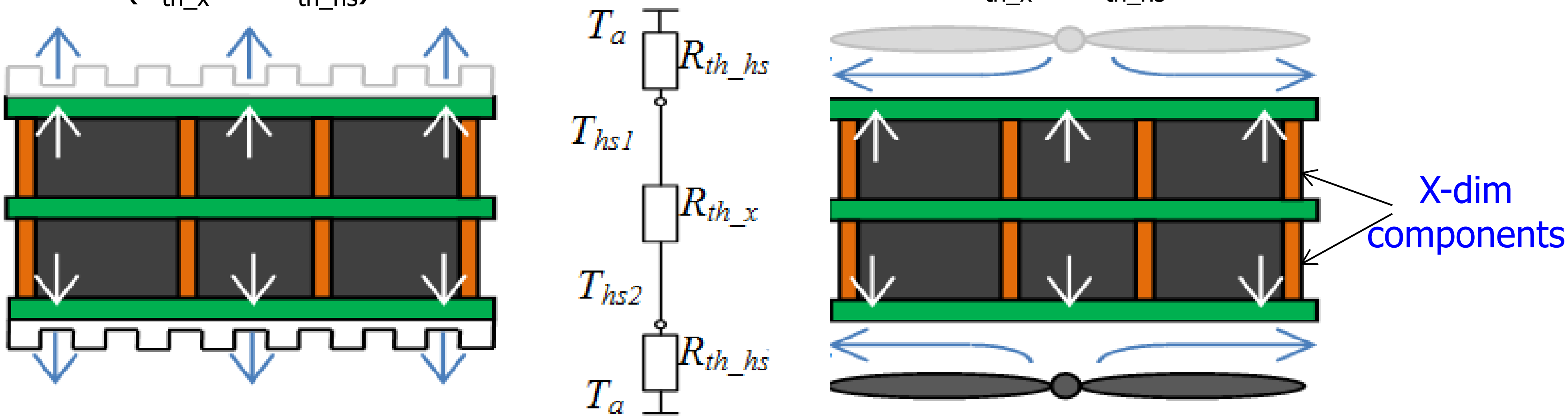
Smaller heat sinks to keep components bellow specified limits

Natural Convection

$(R_{th\_x} << R_{th\_hs})$

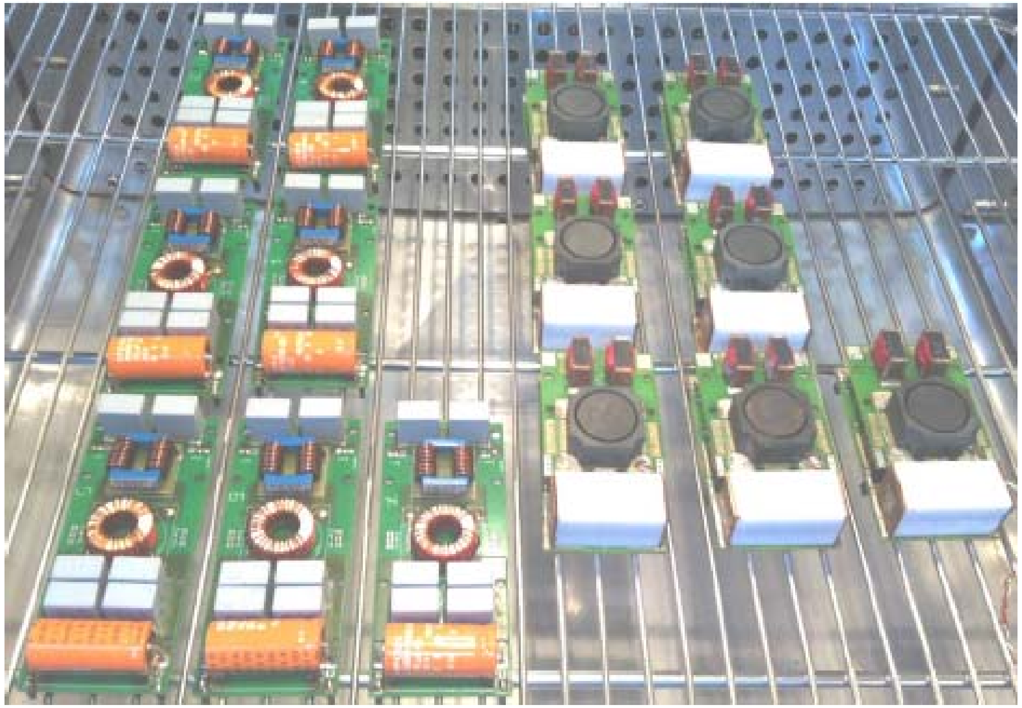
Forced Convection

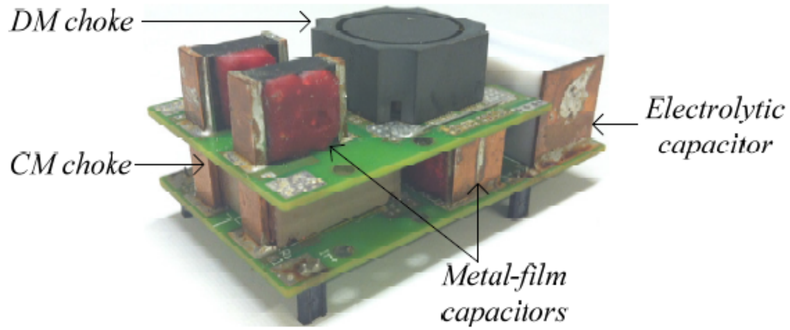
$(R_{th\_x} \approx R_{th\_hs})$



Multilayer Thermal Management Concept – Thermal Cycling

- EMI filters with standard passive components and Power Sandwich EMI filter with x-dimension components used in temperature cycling experiments.





Initial thermal cycling tests did not reveal component destruction and failure of solder joints.

After 900 temperature cycles single- and doublesided soldering of SMT x-dimension components did not shown weakness.

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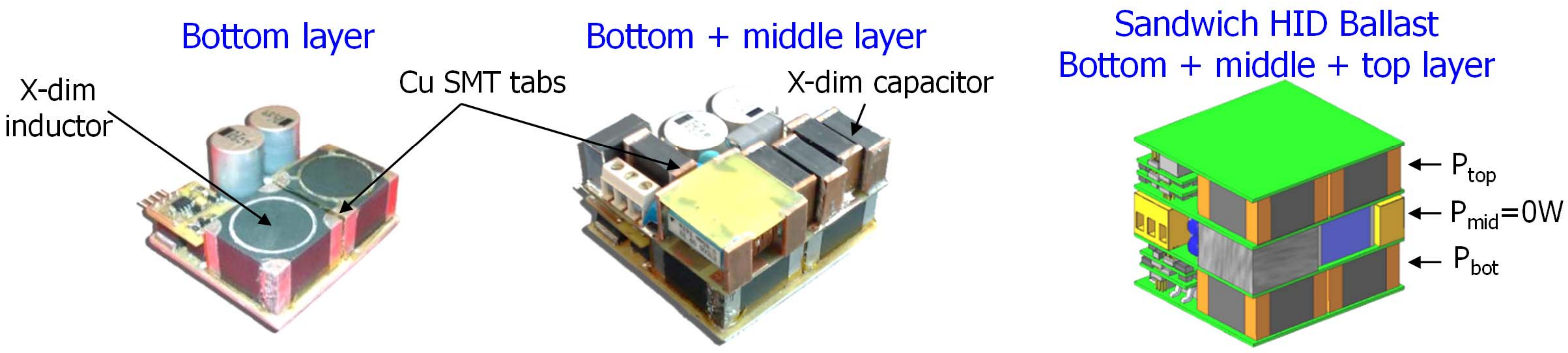
Temperature Distribution Analysis – Natural Convection

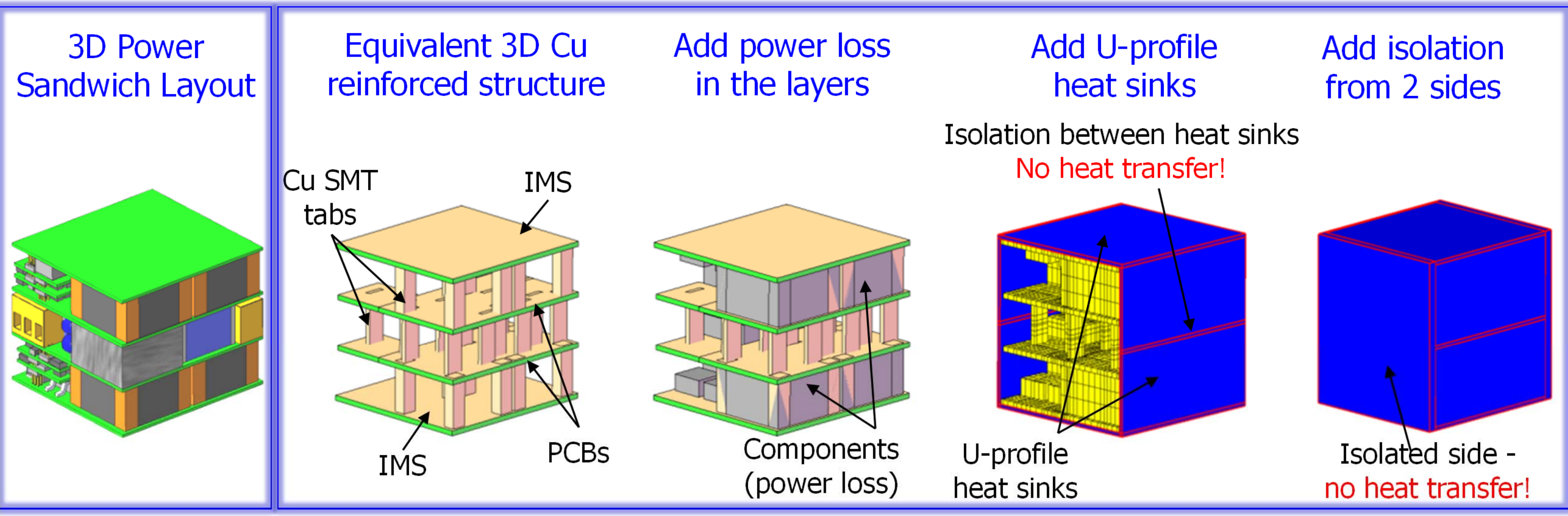
- Power Sandwich HID Ballast Case Study
  - 3-layers assembly
  - Total power loss P=9W
  - Real power loss distribution: P_{top}=4.2W, P_{bot}=4.8W
- Find Temperature Distribution for Two Cases by CFD Simulations
  - Nearly the same (real) power loss distribution at top and bottom: P_{top}=4.2W, P_{bot}=4.8W
  - Different power loss distribution at top and bottom: $P_{bot}=2P_{top}$; P_{bot}=6W, P_{top}=3W

3D Layout Case Study



Temperature Distribution Analysis – Natural Convection

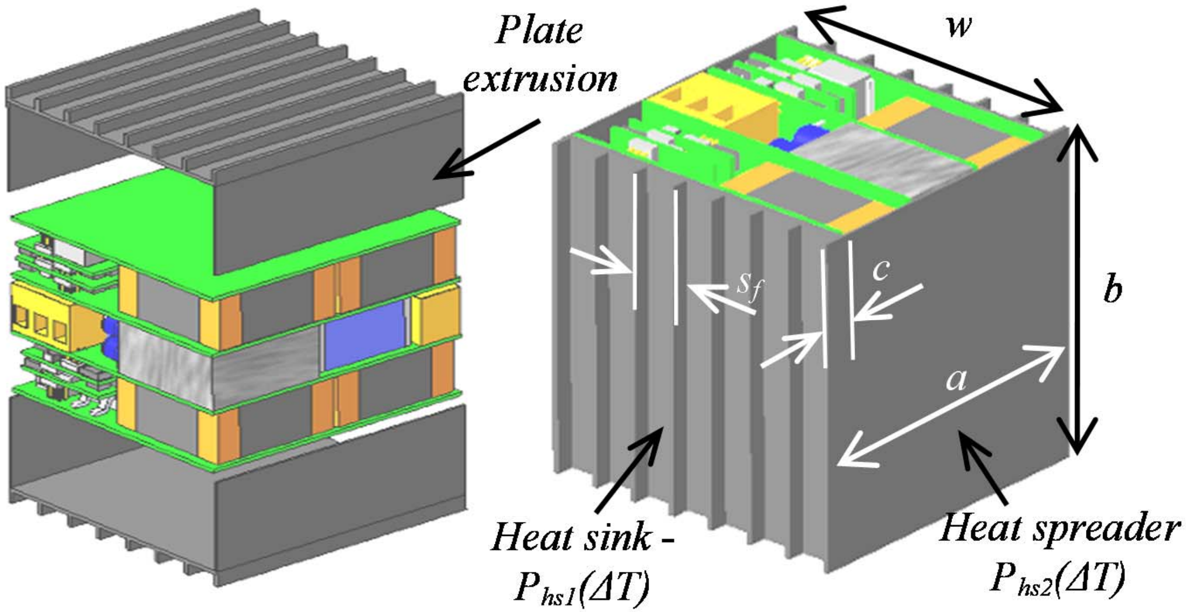
- CFD Modeling Steps
  - Create equivalent 3D Copper Reinforced Structure
  - Add components exhibiting power loss, no loss in the middle (EMI filter components)
  - Add 2 U-profile heat sinks covering 4 sides
  - Add isolation layers from sides not active in heat removal



Natural Convection Cooling – Thermal Design

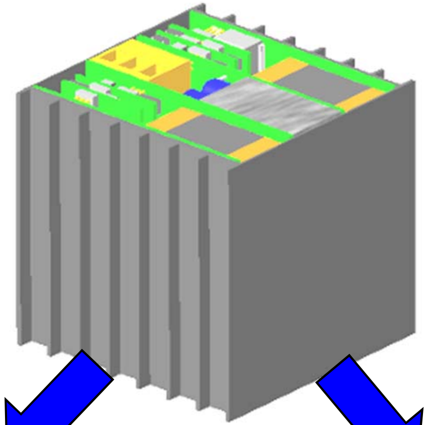
- 150W HID Lamp Electronic Ballast
- 4-sided heat removal concept

Thermal Management Method



Natural Convection Cooling – Modeling Results

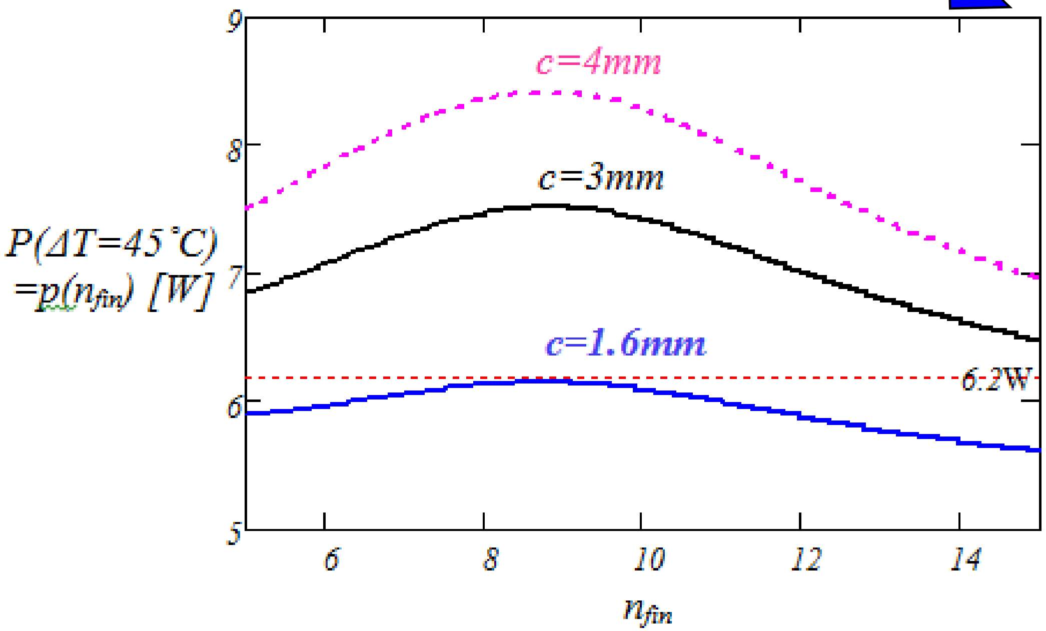
P_{total}=9W



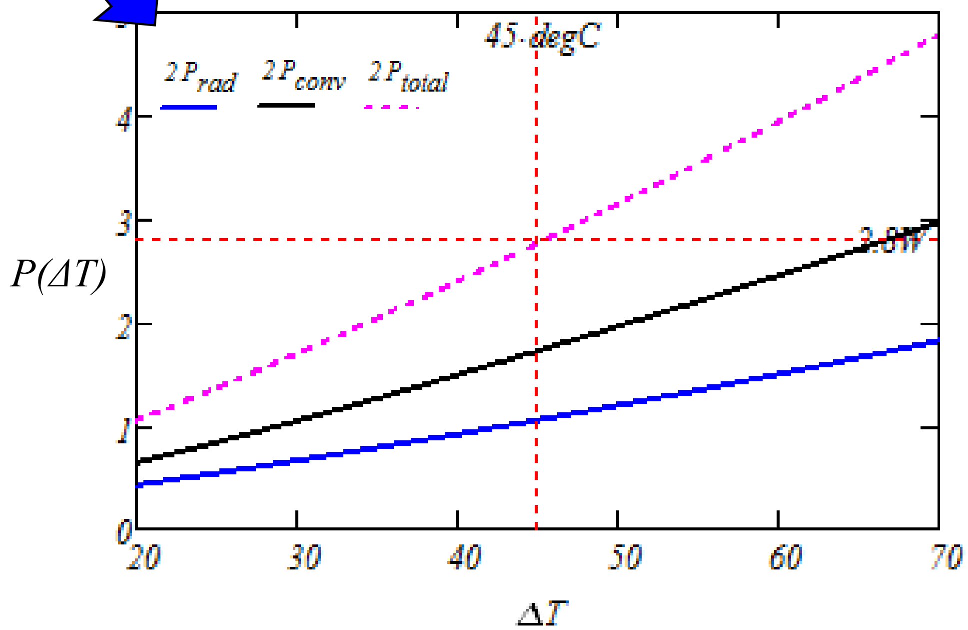
$2P_{heat\text{-}sink}$ =6.2W

$2P_{plate}$ =2.8W

Optimized heat sink model
natural convection + radiation



Vertical plate model
natural convection + radiation

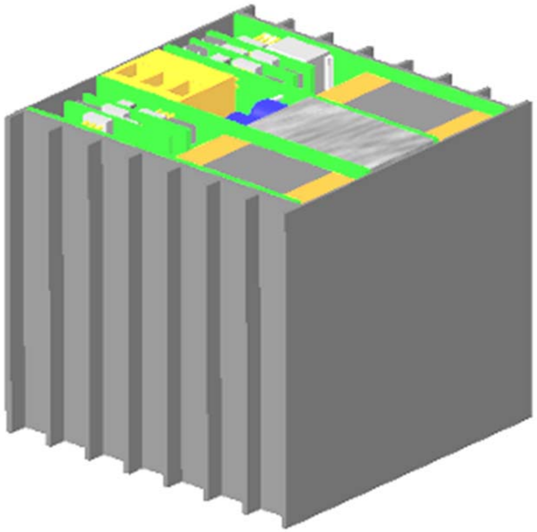


Natural Convection Cooling – Modeling Results Summary

Ambient temperature T_a=55°C

Heat Sink temp: $T_{h\text{-}sink}$ =100°C

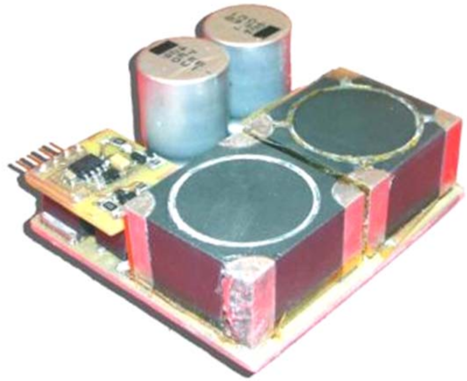
X-dim Component temp: $T_{x\text{-}dim}$=103°C



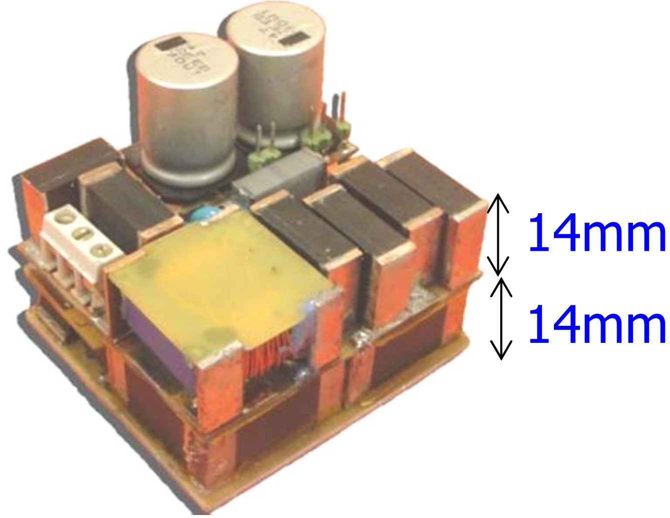
0.9kW/l
(2x)

Compared to the state of the art construction power density is increased by factor of 2 (0.9kW/l)

Stacked buck x-layer



Stacked buck &
Low loss density x-layers



Natural Convection Cooling – Experimental Results

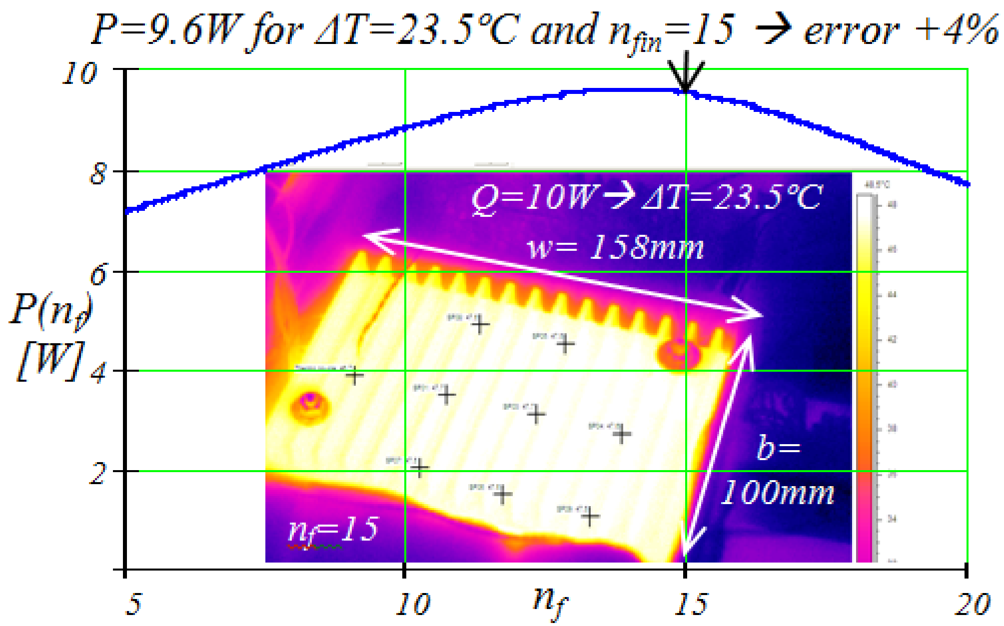
Ambient temperature T_a=22˚C

Power Sandwich vertical orientation

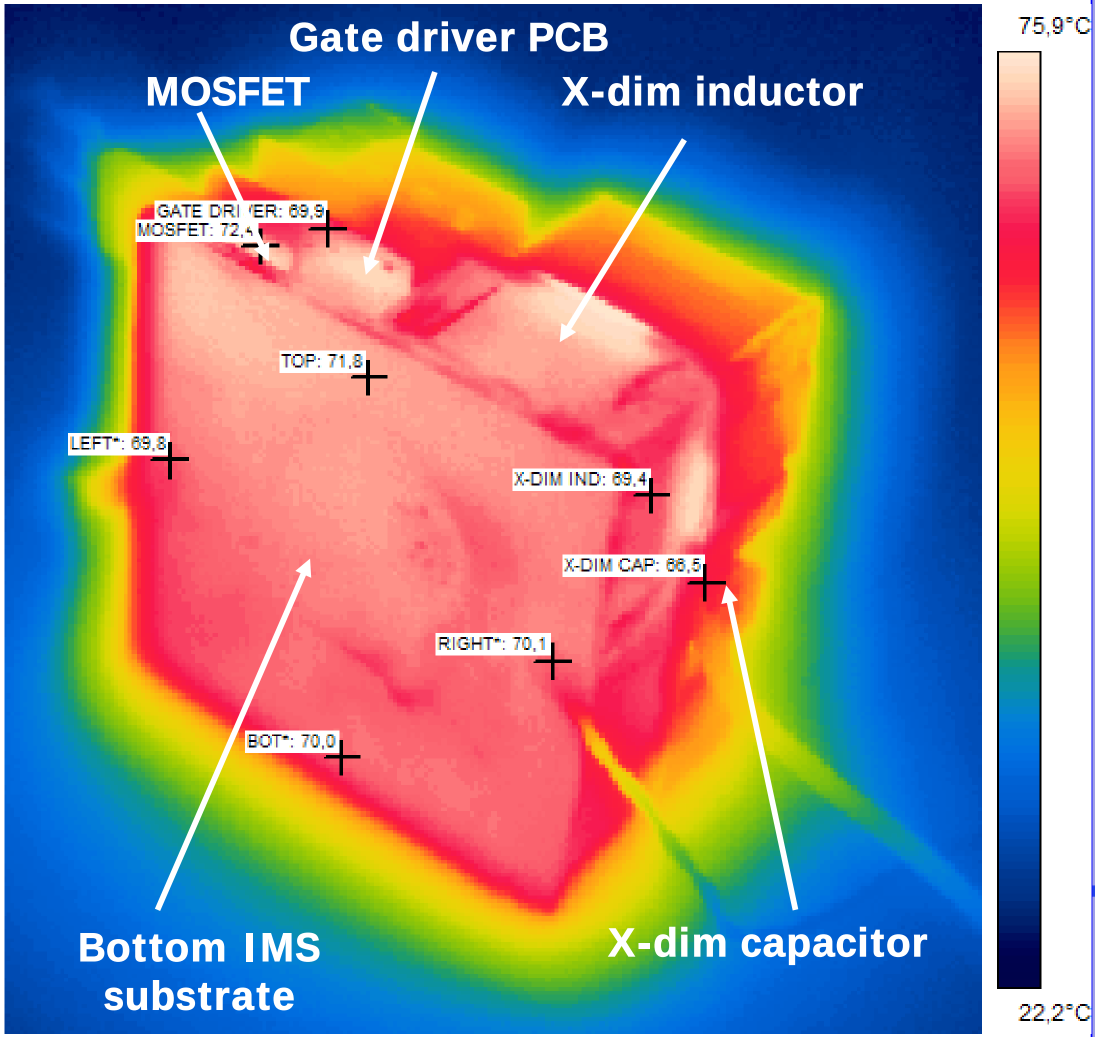
The temperature at IMS uniform at 70 ˚C

ΔT in x-dim components low

Heat Sink Model Verification



HID Ballast Thermal Image (after 3 hours)



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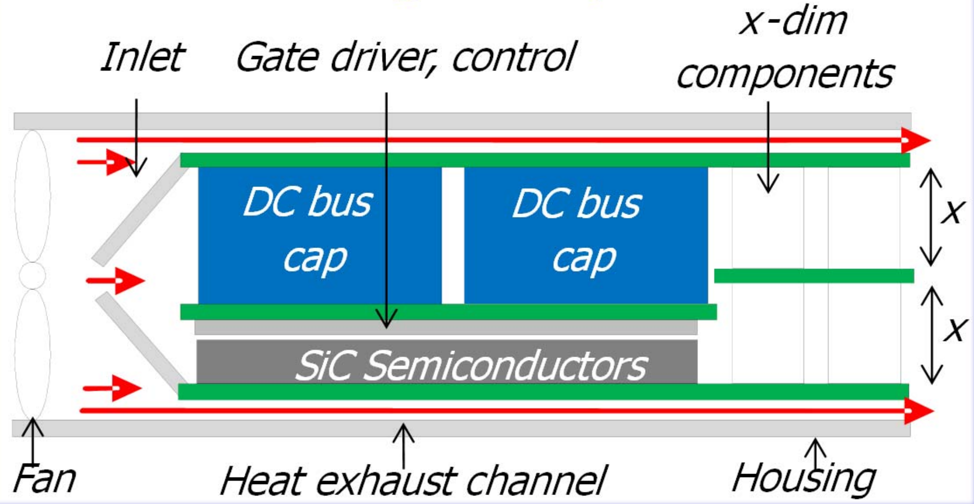
Forced Convection Cooling - Concept

- 2.2kW Inverter for Motor Drive with SiC JFETs
- Heat sources separated at two sides
    - Rectifier top side
    - Inverter bottom side
- High density packaging of x-dim passives
    - Low power loss

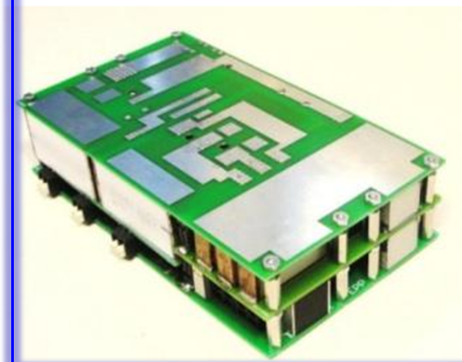
Double-sided Heat Removal
&
Low Power Loss of SiC Inverter

GOAL: No Use of typical Heavy/Complex Heat Sinks

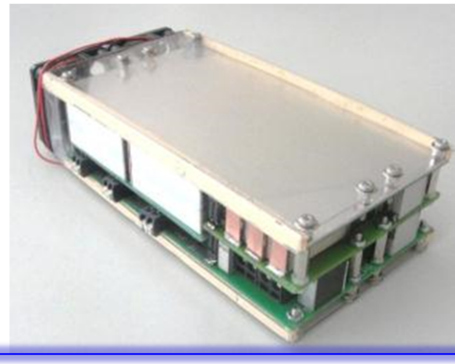
Thermal Manag. Concept - Side View



Sandwich 2.2kW Inverter



Added channels
NO Heat Sinks



Forced Convection Cooling – Spatial Design

- Loss density dependent components packaging
- 2-layers power sandwich assembly

SMT Sub-assemblies

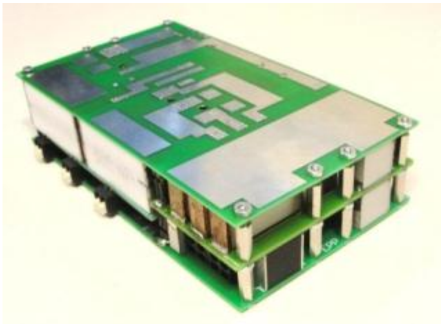
Assembly steps

1. SiC inverter

2. Control board

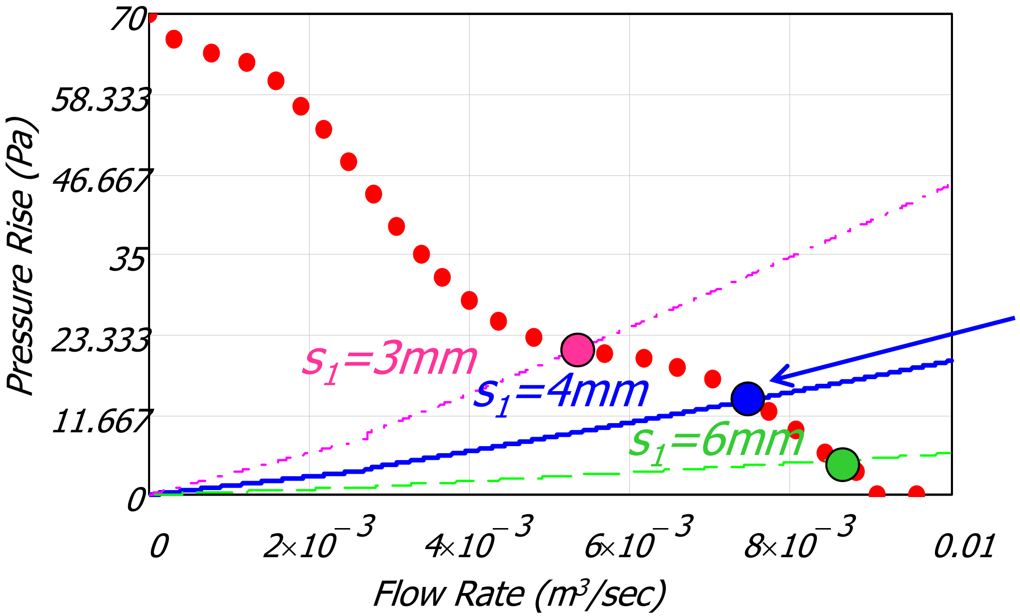
3. EMI filter

4. Rectifier

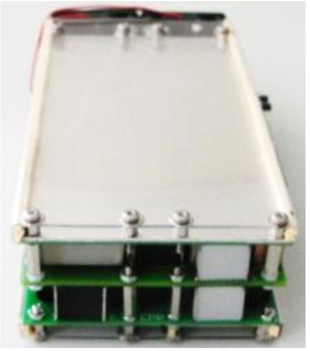


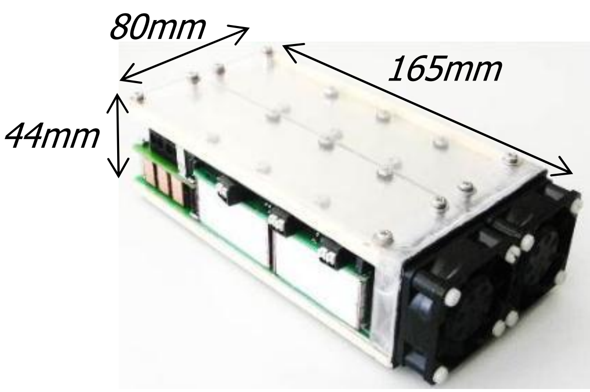
Forced Convection Cooling – Thermal Design & Modeling Results

- Thermal Management Optimization
  - Fan selection
  - Independent channel heights (s_1, s_2) adjustment



Optimal channel height s_1=4mm yielding the highest heat transfer coefficient h≈70 W/(m²·K)

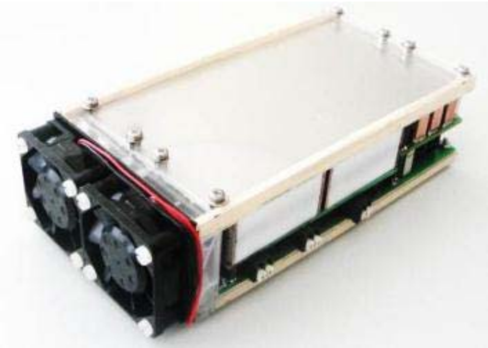




Compared to the state of the art construction power density is increased by factor of 3.8 (3.8kW/l)

Forced Convection Cooling – Experimental Results

3.8kW/L (3.8X)

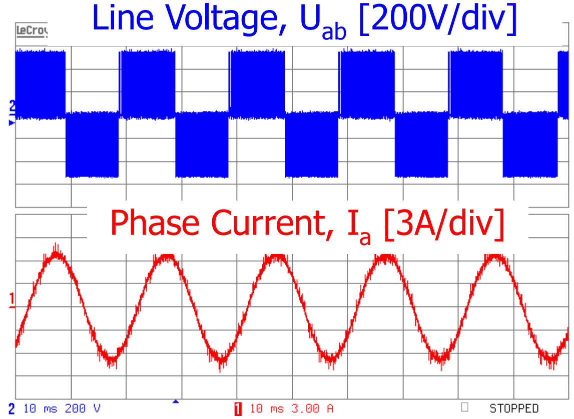


Ambient temperature T_a=22°C

Heat Sink temp: $T_{h\text{-}sink}$ =44°C

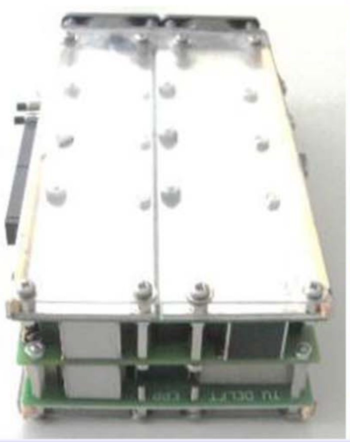
Components: T_{comp}<50°C

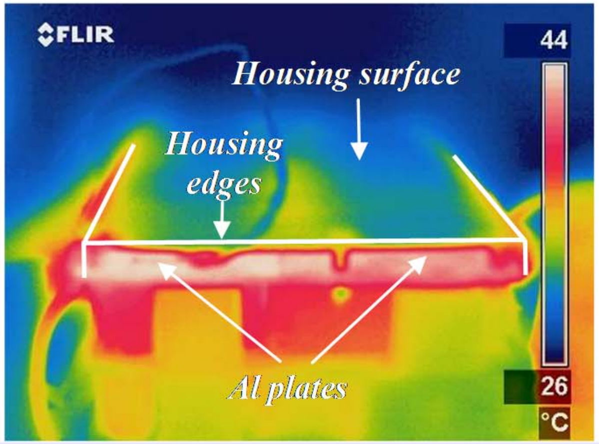
Waveforms



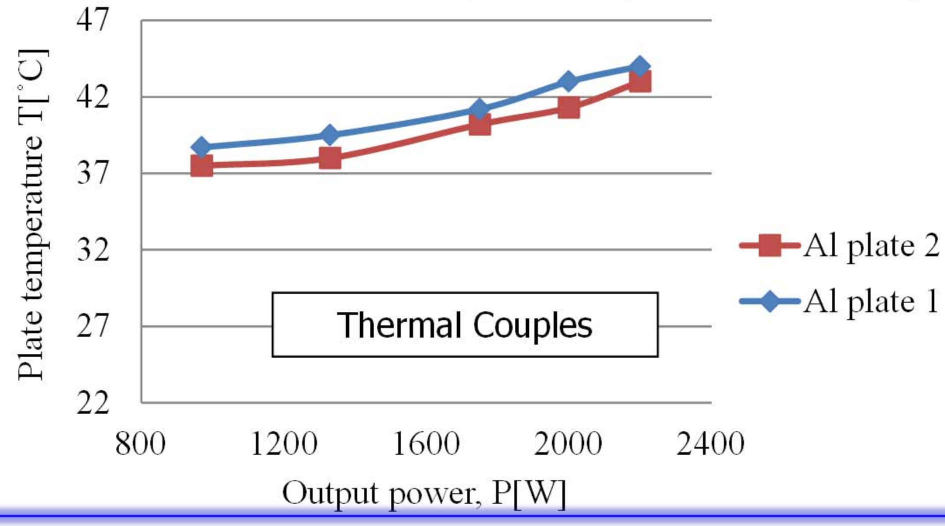
THERMAL MEASUREMENTS

IR Image (SiC Inverter Channel)





Measured T of Al plates (SiC Inverter)



Outline

- Background ✓
- Power Sandwich concept for manufacturability ✓
- X-dim Components ✓
- Automated manufacturing ✓
- Multilayer Thermal Management Concept ✓
- Natural Convection demonstrator ✓
- Forced air Cooling demonstrator ✓
- Conclusion

- Power Sandwich technology benefits
  - PCB based
  - Standardised SMT components
  - Automated assembly
  - Effective thermal management
  - High density packaging

Cost (component & assembly)

High power density