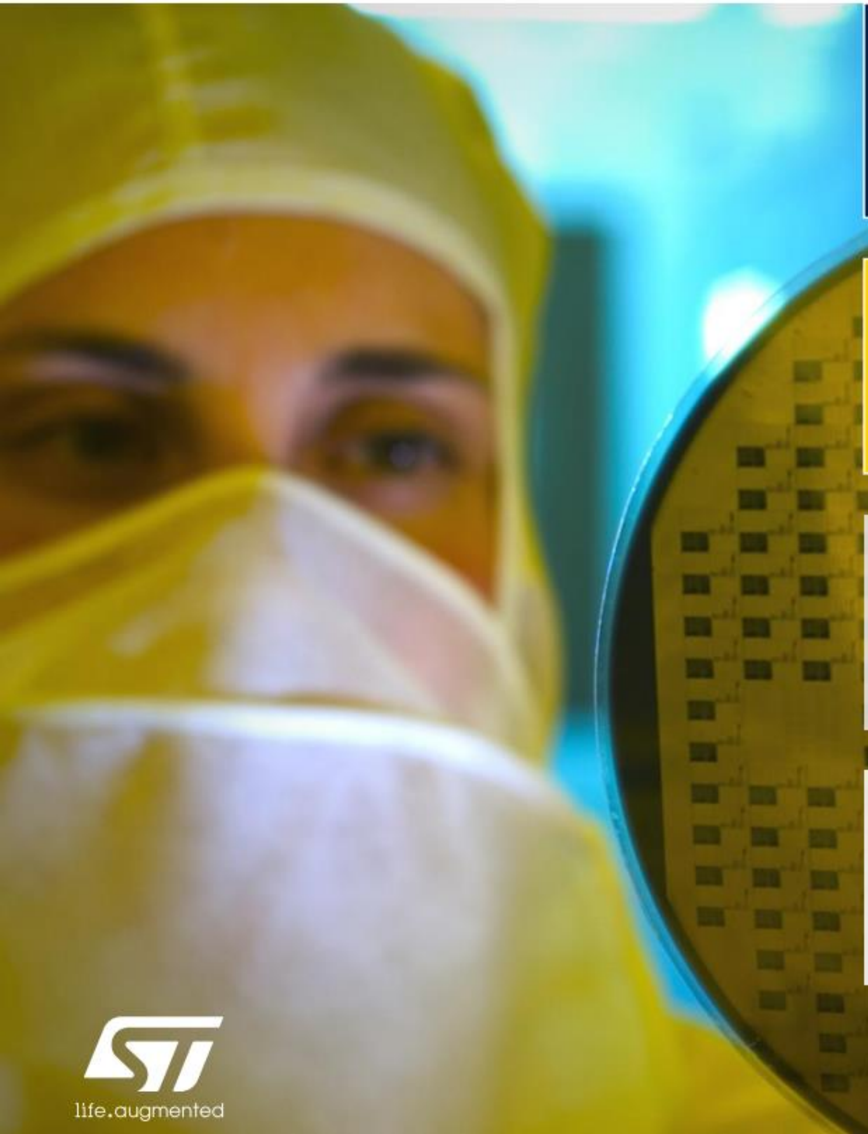
Thermally aware high-power inverter board for battery-powered applications

Enrico POLI

life.augmented

We are creators and makers of technology



One of the world's largest semiconductor companies

50,000+ people of which **9,000+** in R&D

$16.1 billion revenues in 2022

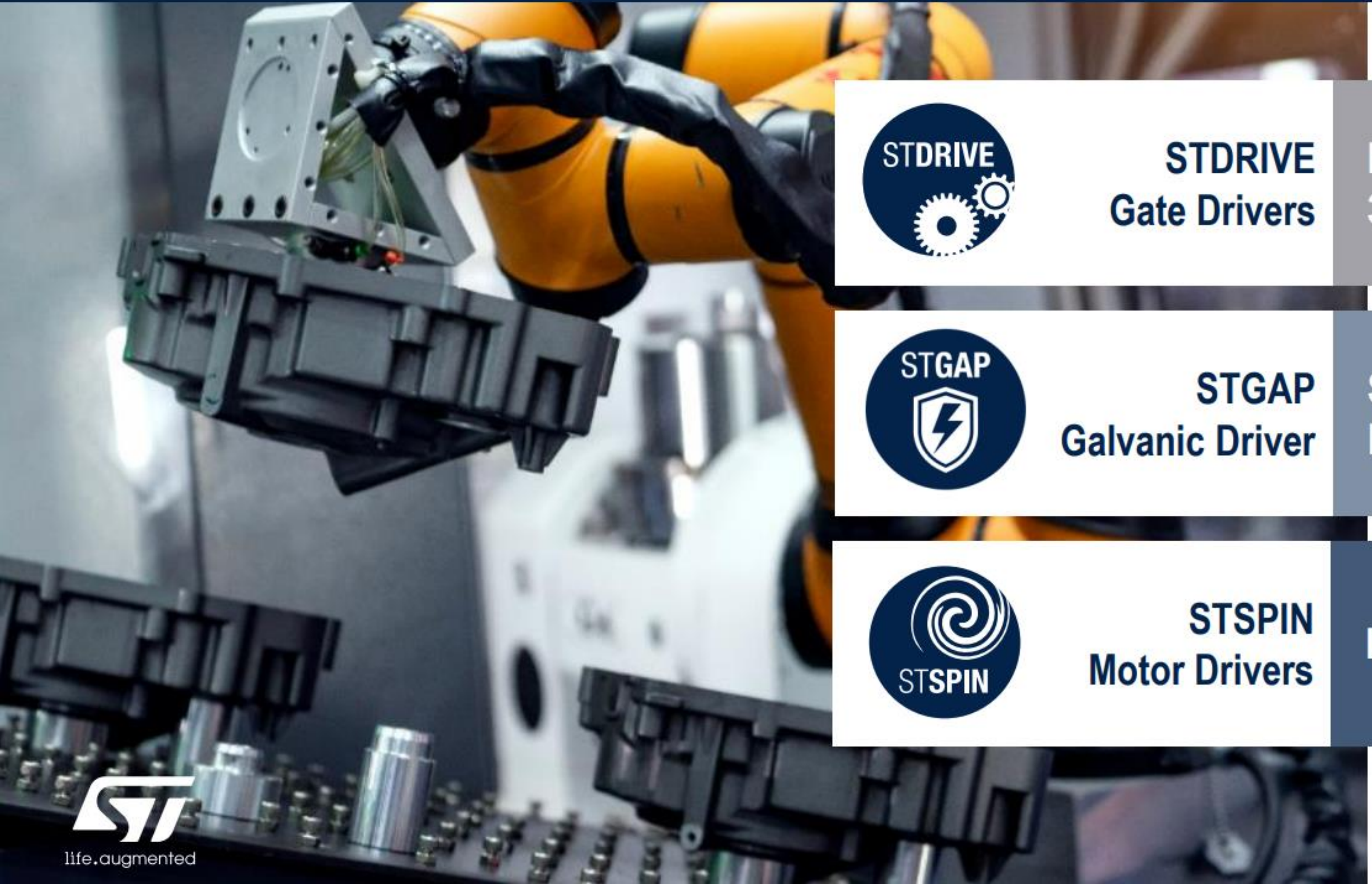
Over **80** sales & marketing offices serving over **200,000** customers across the globe

14 manufacturing sites

Signatory of the United Nations Global Compact (UNGC)
Member of the Responsible Business Alliance (RBA)

ST addresses the industrial market with application driven, high added-value ASSPs & ASICs

Motor control leadership areas



STDRIVE Gate Drivers	**From single to 3-phase**	Best-in-class motor driving, high efficiency and robustness
STGAP Galvanic Driver	**Safety & High voltage**	6 kV galvanic isolated drivers optimized for SiC, GaN & IGBT
STSPIN Motor Drivers	**Digital motion**	High system integration, Flexibility, performance

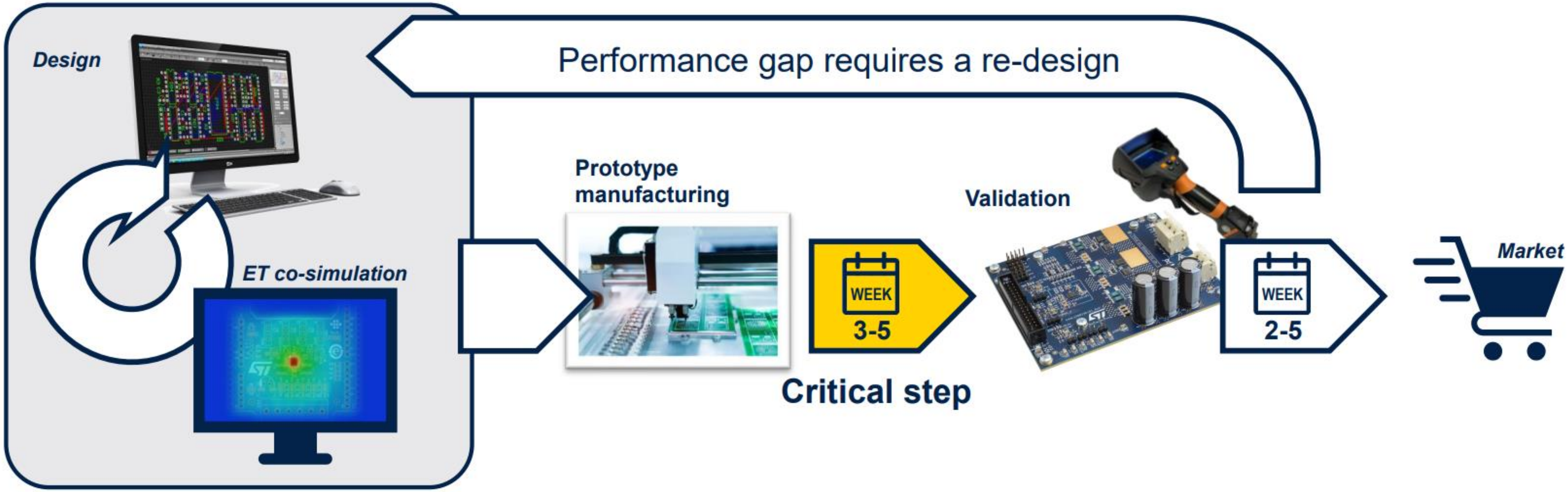
Introduction

High power at low voltage

Best efficiency and reliability

Compact form factor

Challenging PCB design



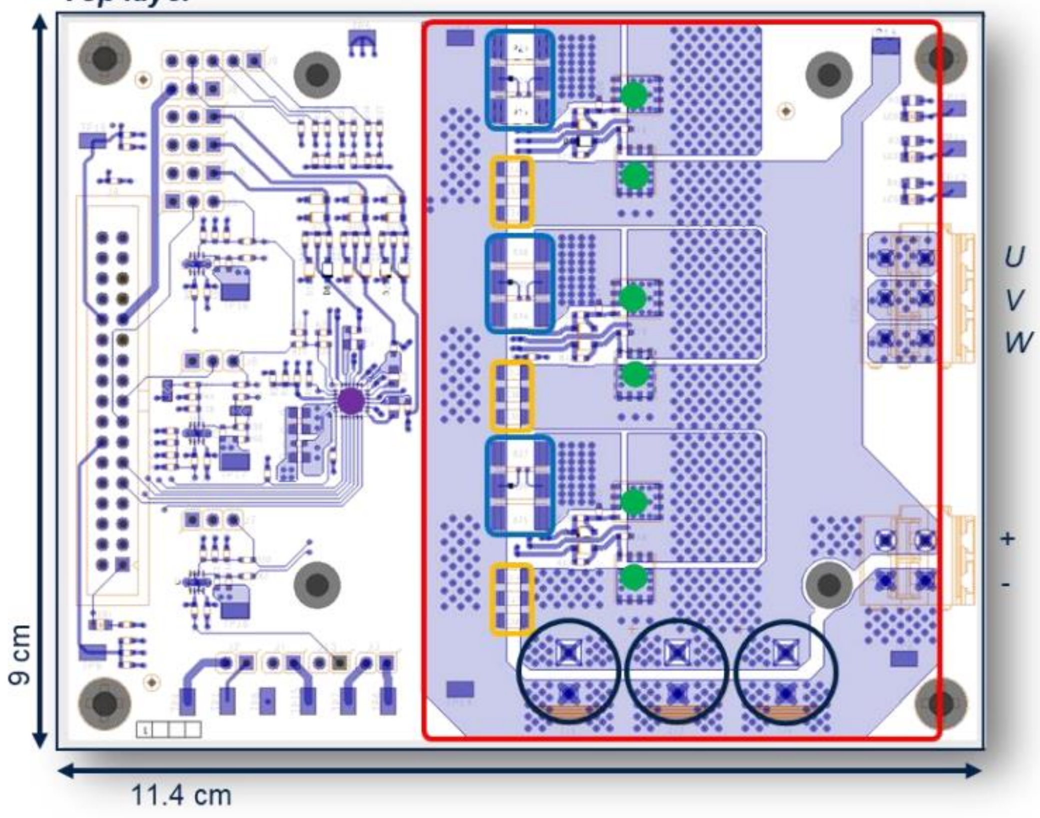
EVALSTDRIVE101

High power Three-Phase Motor Driving Board

- STDRIVE101 gate driver and STL110N10F7 MOSFETs
- 15 A_{rms} output current (20 A_{rms} with heatsink) at 75V
- Three or single shunt current sensing topology
- Sensor and sensor less algorithms
- Bus voltage and temperature monitoring
- Overcurrent / short circuit protection
- Free software libraries for Field-Oriented Control and 6STEP

Layout improvements

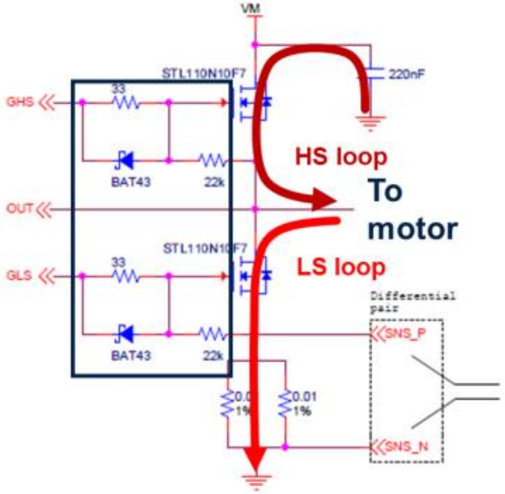
Top layer

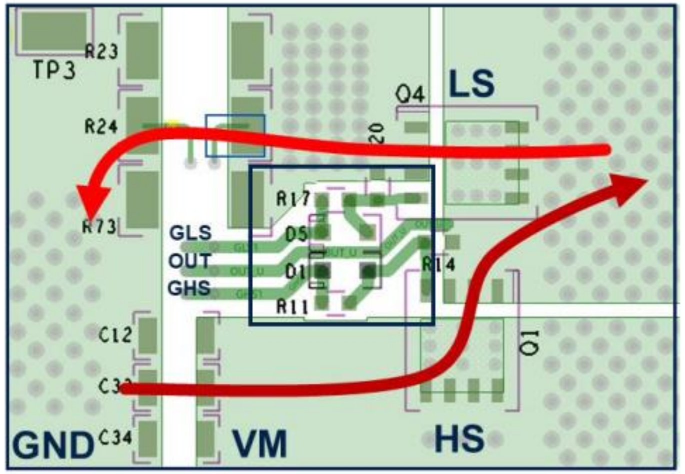


- STDRIVE101
- STL110N10F7
- 50 cm^2 power stage
- Shunt resistors
- Ceramic capacitors
- Electrolytic capacitors

- Better heat spreading
- Max dissipation area
- Dual side cooling

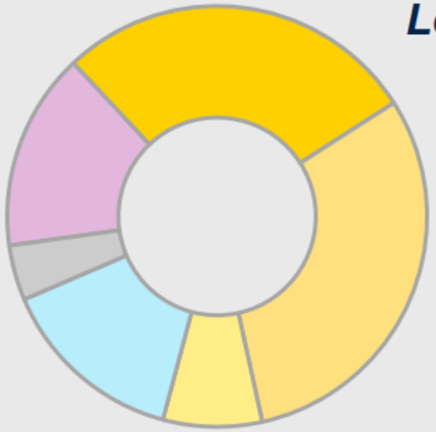
- Reduced current density
- Small loops placement
- Fast switching





life.augmented

Estimate of power losses



Losses composition

- PCB traces → By Celsius™ from layout data
- MOSFETs:
  - Conduction
  - Switching
  - Body diode
- Shunt resistors
- Others

(MOSFETs and shunt resistors) By formulae with datasheet parameters

551 mW

$$P_{cond} \sim \frac{R_{on} \cdot I_l^2 \cdot (1 - 2 \cdot t_{dt} \cdot f)}{2}$$

602 mW

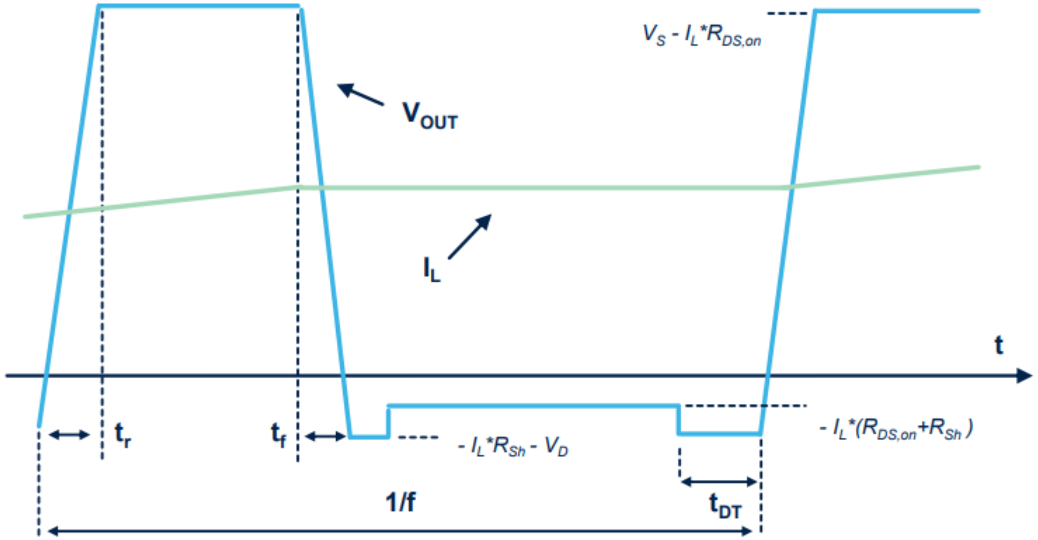
$$P_{sw} \sim \frac{f \cdot V_s \cdot I_l \cdot \left(\frac{Q_p \cdot R_g}{V_{gd} - V_p} + \frac{Q_p}{I_{gd}} + R_g \cdot C_{iss} \cdot ln\left(\frac{V_{gd} - V_{th}}{V_{gd} - V_p} \right) + \frac{C_{iss} \cdot (V_p - V_{th})}{I_{gd}} \right)}{4}$$

150 mW

$$P_{dt} \sim V_d \cdot I_l \cdot t_{dt} \cdot f$$

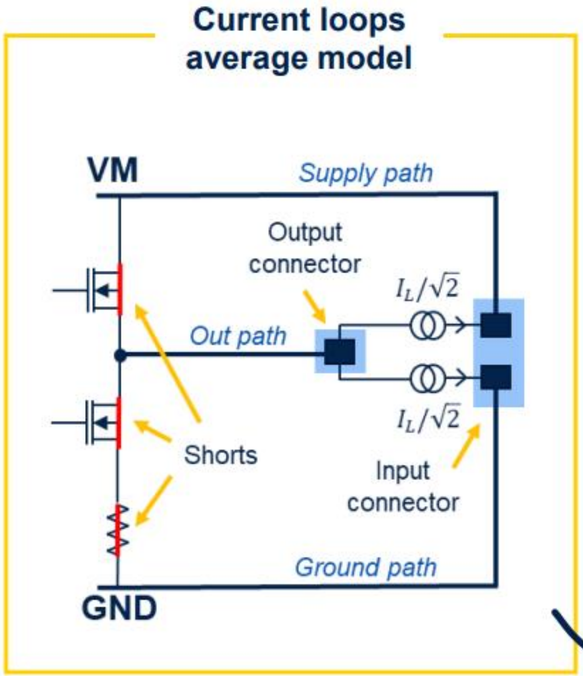
281 mW

$$P_{sh} = \frac{R_{sh} \cdot I_l^2}{2}$$

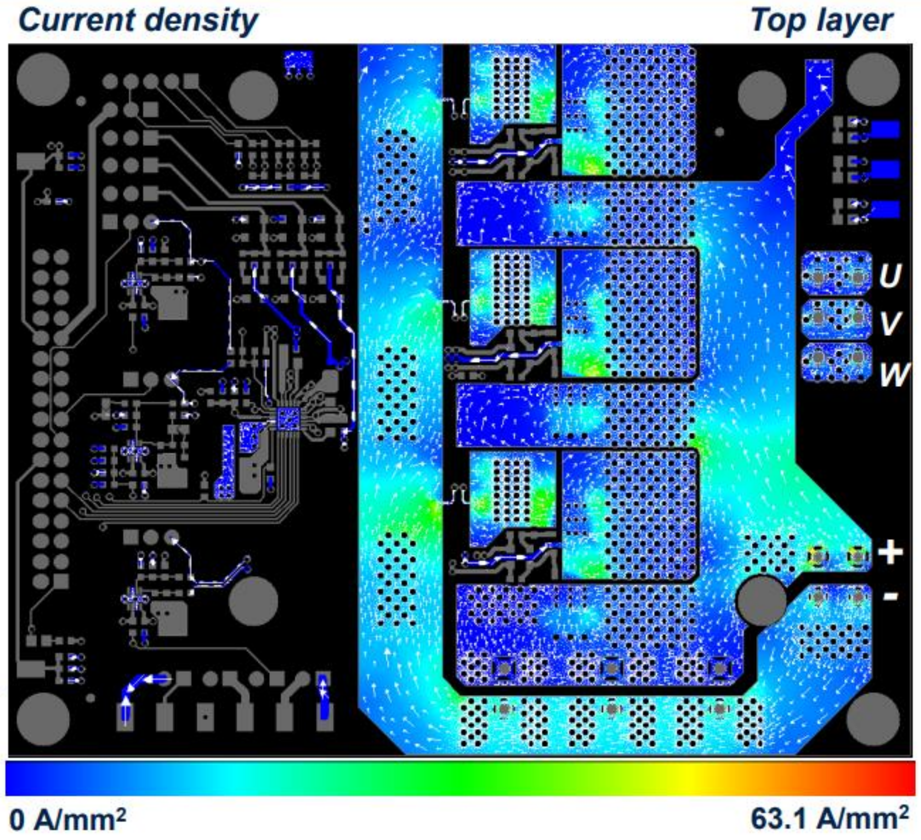


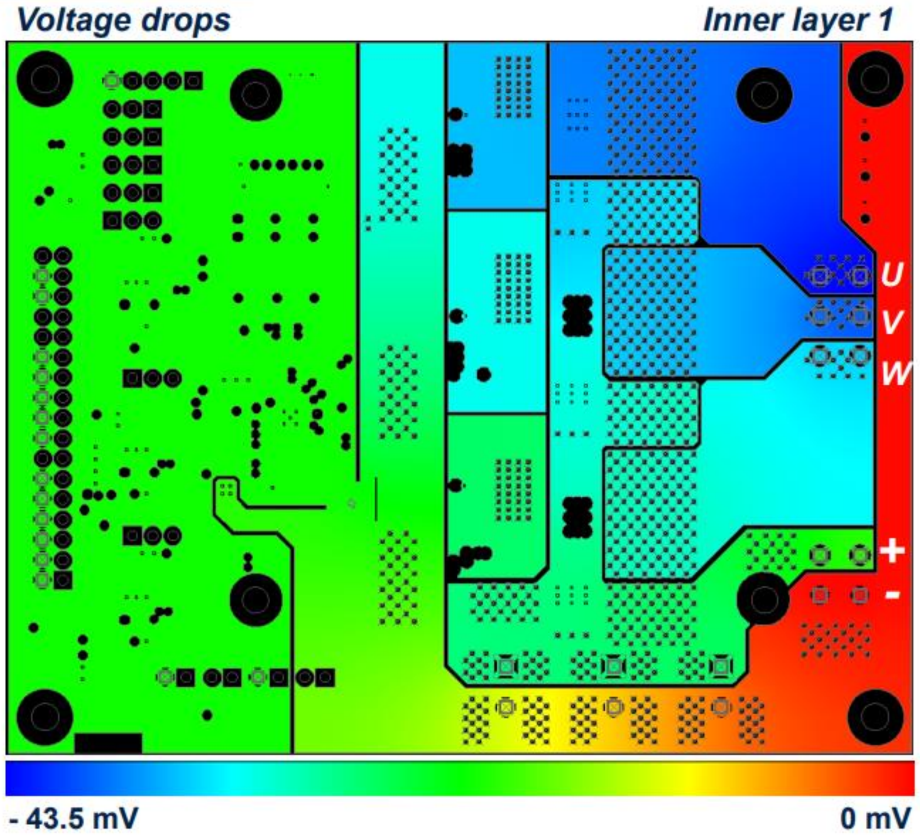
Celsius simulation

Electrical analysis @ 15 Arms



Only effects on traces





- Current density below 25 A/mm2
- Hotspots not of concern
- No bottleneck and balanced outputs

life.augmented

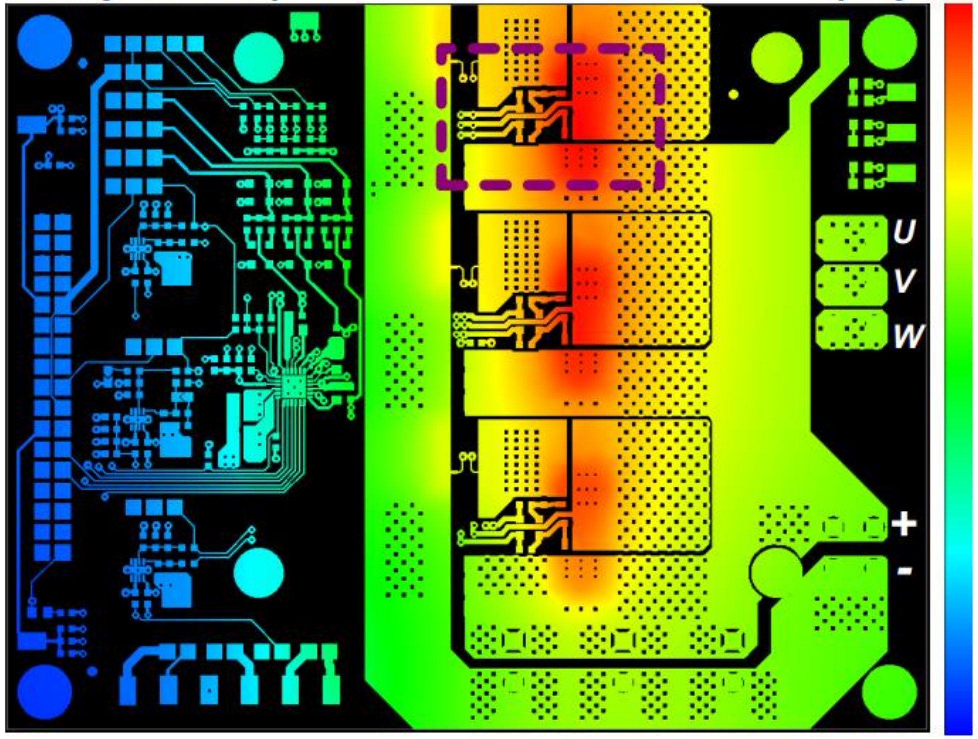
Celsius simulation

Thermal analysis @ 15 Arms

Settings

- 28 °C ambient temperature
- Fixed heat transfer coefficients
- 2-R model for MOSFETs
- Step functions for sources

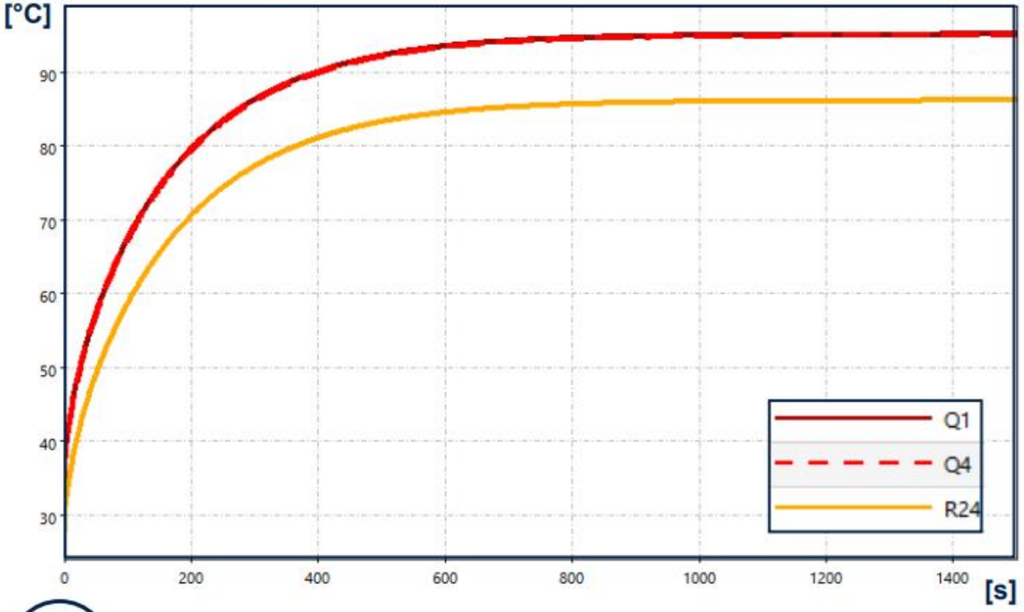
Steady state temperatures ***Top layer***



93.6 °C

58.1 °C

Transient temperatures



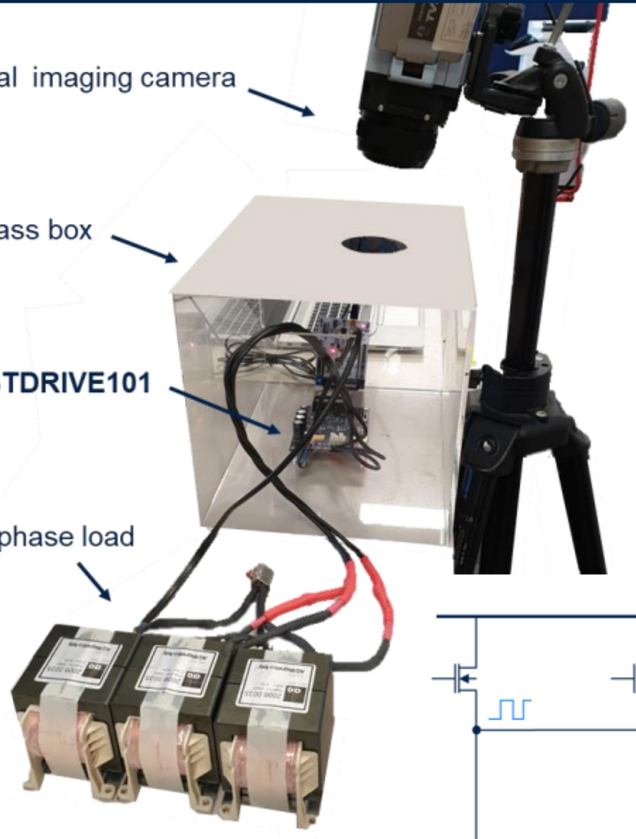
- Hottest U half bridge
- MOSFETs at 95 °C and shunts at 86 °C
- 13 minutes warm up
- 5 °C delta - top vs bottom

Very good design margin

life.augmented

Bench validation

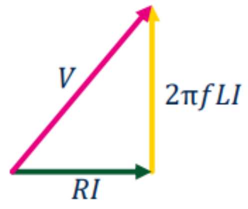
Setup description

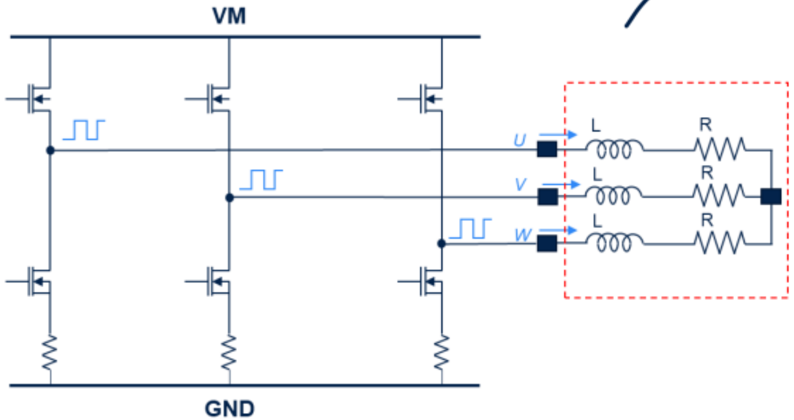


Equivalent to motor

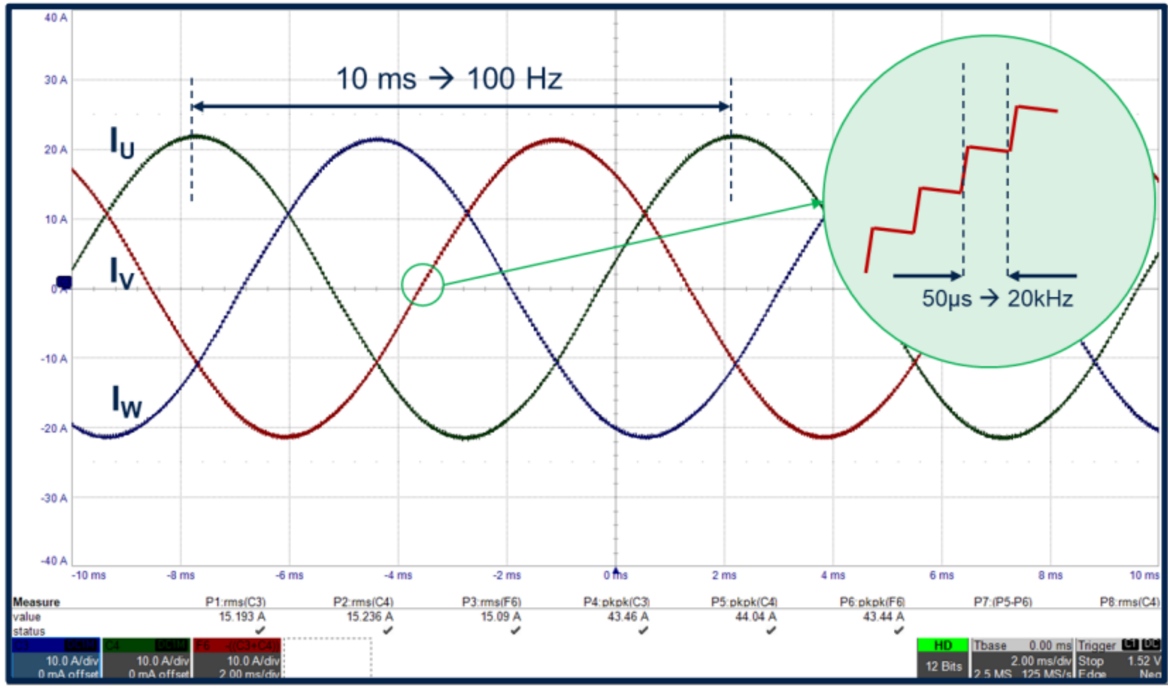
V - I drops

$$I = \frac{V}{\sqrt{(2\pi f L)^2 + R^2}}$$





Configurable sinusoidal currents



- Power stage as in application
- Easier to implement
- Fast tuning

Bench validation

Power losses measurement

Correlate estimated data with real losses

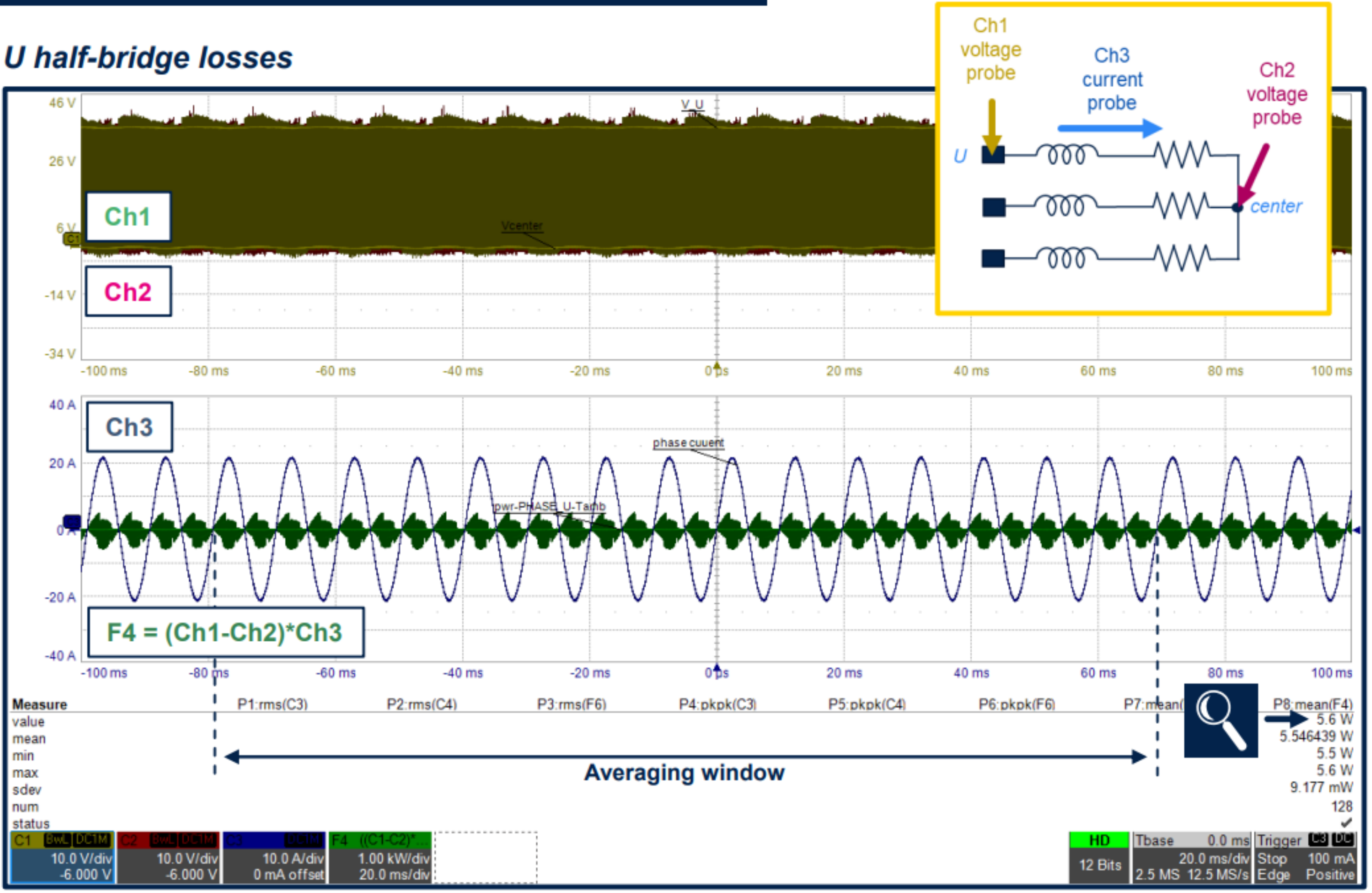
By oscilloscope

$$P_{loss} = P_{in} - P_{out} = \overline{V_{in} \cdot I_{in}} - \overline{\sum_{i=1}^{3} (V_i - V_c) \cdot I_i}$$

Power	Estimate [W]	Measure @ T_{amb} [W]	Measure @ T_{hot} [W]
P_{in}	-	27.51	28.39
P_{out}^{U}	-	5.6	5.7
P_{out}^{V}	-	6.5	6.6
P_{out}^{W}	-	6.1	6.2
P_{loss}	9.5	9.36	9.89

- Spread hot vs ambient
- Slight load unbalancing
- Estimate in line with measures

U half-bridge losses

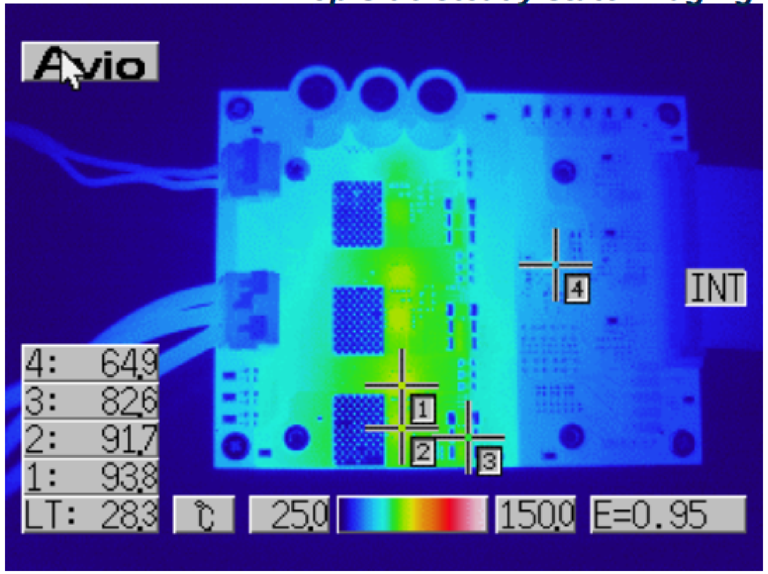


Bench validation

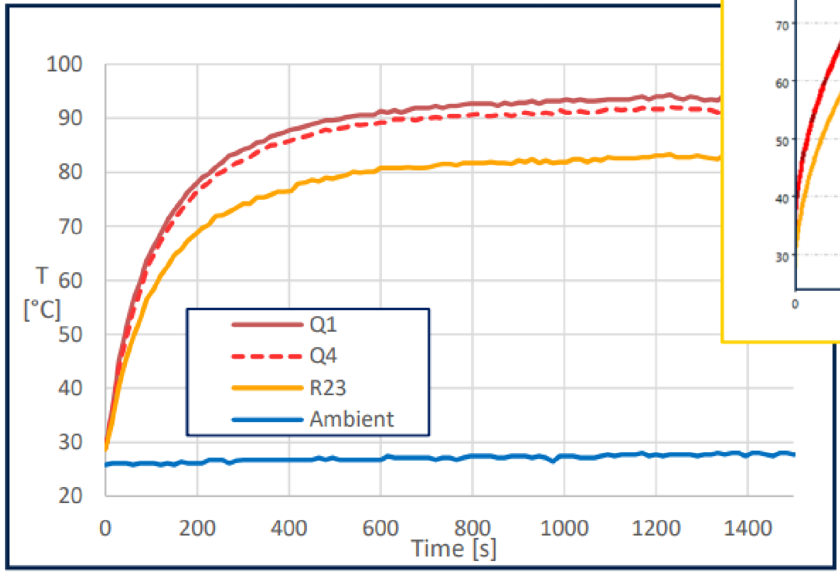
Thermal characterization

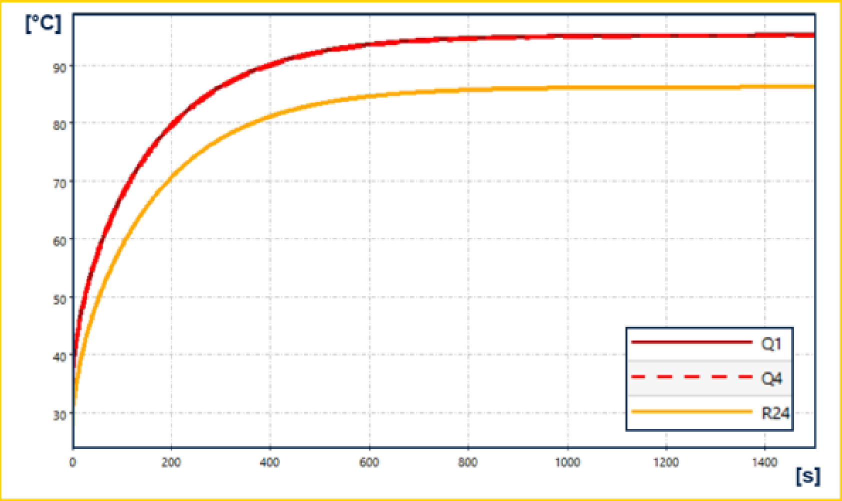
Correlate simulations with real heating

Top side steady state imaging



Half-bridge U components warm up





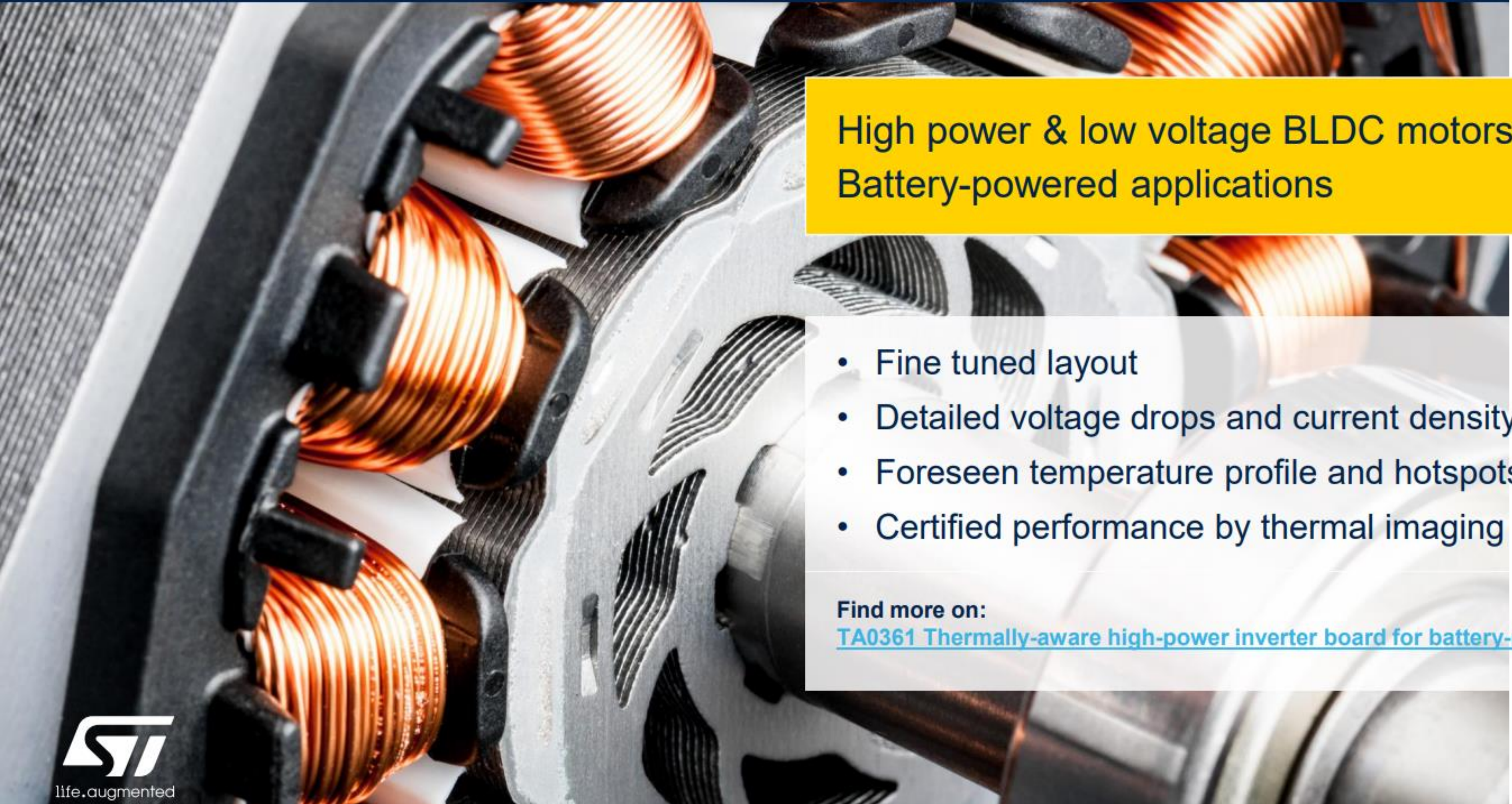
Simulated transient temperatures

Component	Simulation [°C]	Measure [°C]
HS MOSFET Q1	95.1	93.8
LS MOSEFT Q4	94.9	91.7
Shunt resistor R23	86.3	82.6

- Confirmed hottest half bridge
- Same transient
- Very good temperatures matching

Conclusions

EVALSTDRIVE101 optimized by Celsius™



High power & low voltage BLDC motors
Battery-powered applications

- Fine tuned layout
- Detailed voltage drops and current density
- Foreseen temperature profile and hotspots
- Certified performance by thermal imaging

Find more on:
[TA0361 Thermally-aware high-power inverter board for battery-powered applications]

life.augmented

Our technology starts with You

Find out more at www.st.com

life.augmented

EMA Design Automation®

FlowCAD

Designing for High Current / High Power PCB Applications

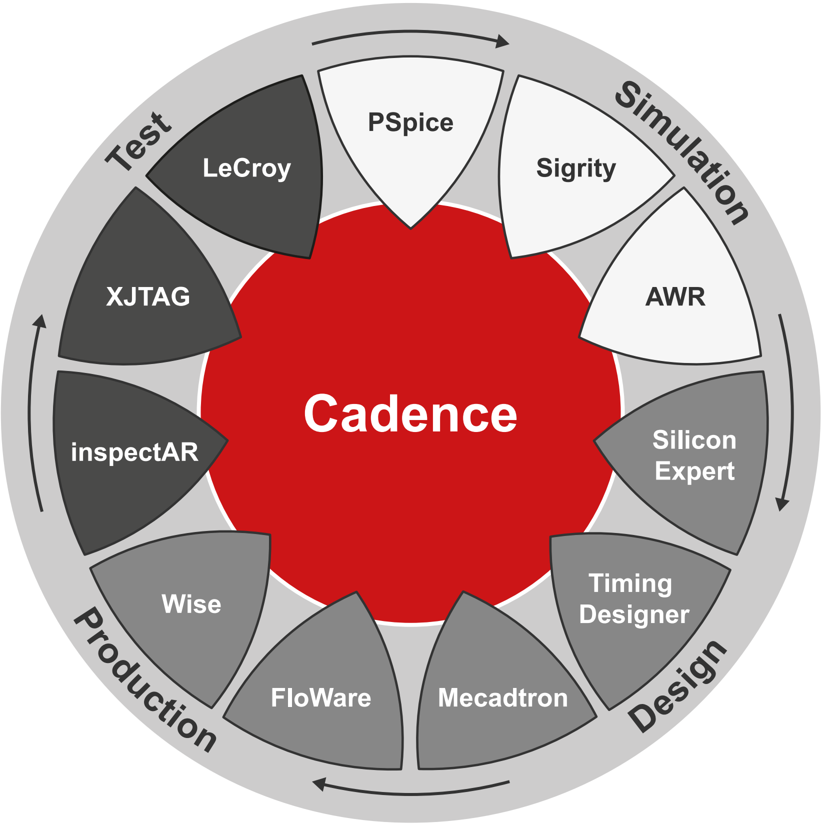
Dirk Linnenbrügger / Jerry Long

Webinar

Products / Solutions for Electronic Designers

Solutions

- PCB Layout
- PSpice-Simulation
- SI- and PI-Simulation
- EMI and Antenna Simulation
- Timing Analysis
- Thermal Simulation
- 3D mCAD-eCAD Integration
- CAM Verification
- Boundary Scan Test
- Protocol Analysis
- Electronic Data Management
- PLM and ERP-Connection



Focus on Customer Satisfaction

Sales

- Fair, competent advice
- Long term solutions

Support

- Hotline, Fastviewer
- Survey

Service

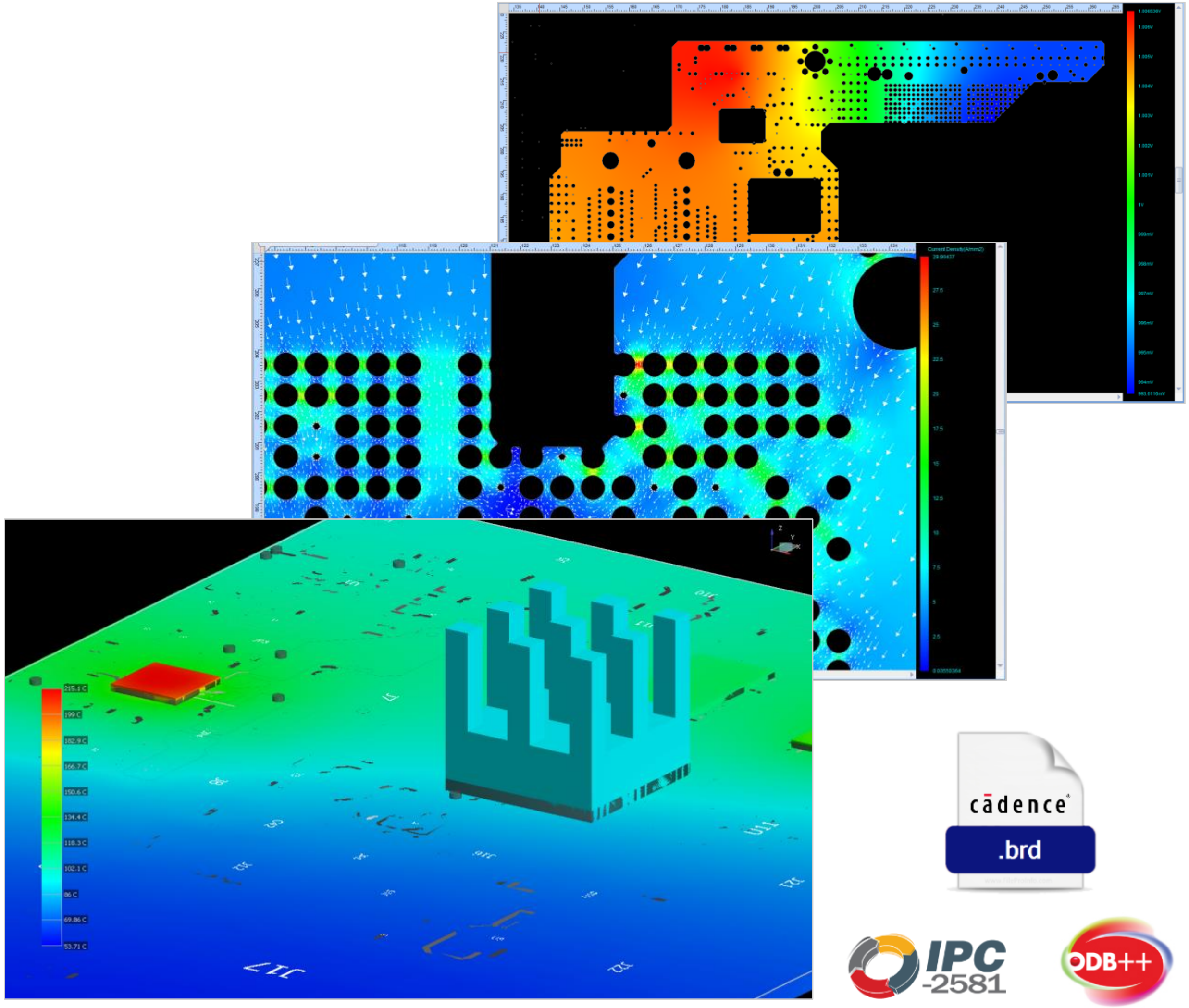
- PCB Design Services
  (Layout, Simulation, Migration)

Training

- Trainings center, on-site
- Workshops

Electrical and Thermal Co-Simulation & Analysis

- **Electrical DC Analysis**
  - Tracks down the voltage distribution along the power delivery path
  - Finds out if there’s any critical location of large amount of current
- **Thermal Analysis**
  - Consider Joule heating on PCB and package
  - Locates current and temperature hot spots to avoid risk of failure
- **E/T Co-Simulation**
  - Ensures the thermal stability of your design
  - Increases your PCB reliability
  - Enables you to make necessary design decisions in time



cādence .brd

IPC-2581

ODB++

Transient E/T Co-Simulation Workflow

Initial Setup

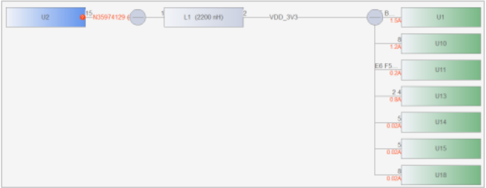
- Check layer stackup
- Set up plating thickness
- Choose / edit PCB material

Stack Up | Pad Stack

Layer #	Color	Layer Icon	Layer Name	Thickness(mm	Material
1			Signal$TOP	0.07	copper
			Medium$41	0.25	FR4
2			Signal$2INN	0.07	copper
			Medium$43	0.8	FR4
3			Signal$3INN	0.07	copper
			Medium$45	0.25	FR4
4			Signal$BOTTOM	0.07	copper

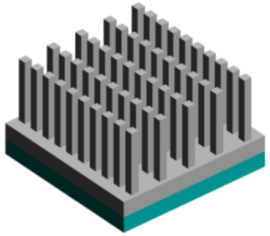
E-Setup

- Set up VRMs (sources)
- Set up sinks
- Set up discrete components



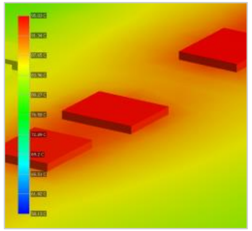
T-Setup

- Set up ambient conditions
- Select & set up thermal components
- Define external heat sink (opt.)



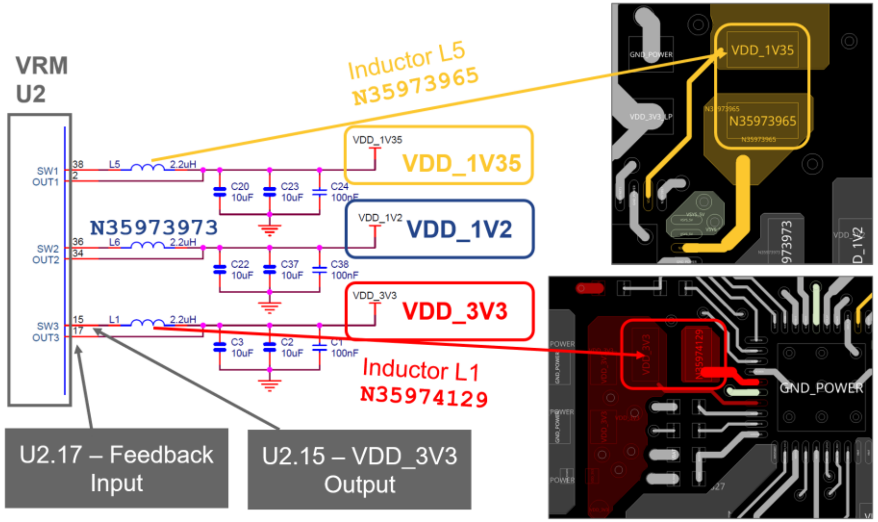
Simulation & Results

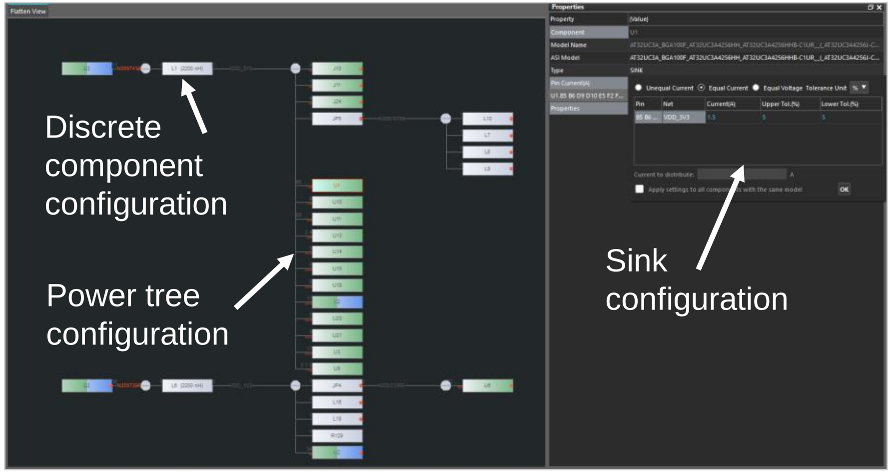
- E/T result tables
- E/T 2D/3D distributions
- Generate report



Setup of VRMs, Sinks and Discrete Components

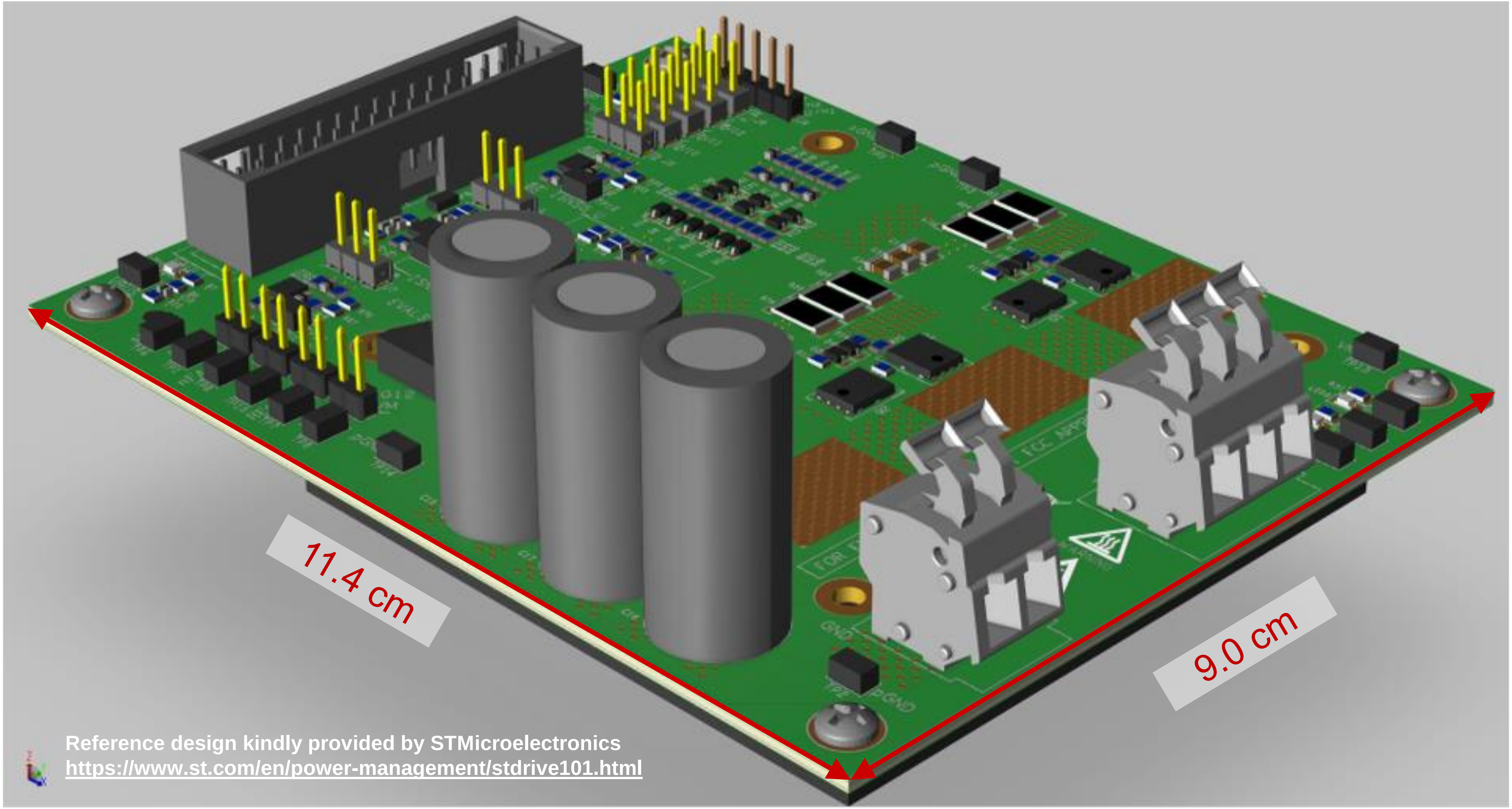
- Power rail configuration capabilities
  - – Wizard based setup
    - Used for simple power rail structures
  - – PowerTree
    - Used for complex power supply structures
    - Configuration of:
      - – Sources (starting point)
      - – Discrete components
      - – Sinks (ending point)
    - Supports DC-DC LDO configuration
  - – Current source configuration
    - Used for 3 phase MOSFET gate drivers





STMicroelectronics STDRIVE Demonstration Board for Three-Phase Brushless Motors

STDRIVE101 Triple Half-Bridge Gate Driver



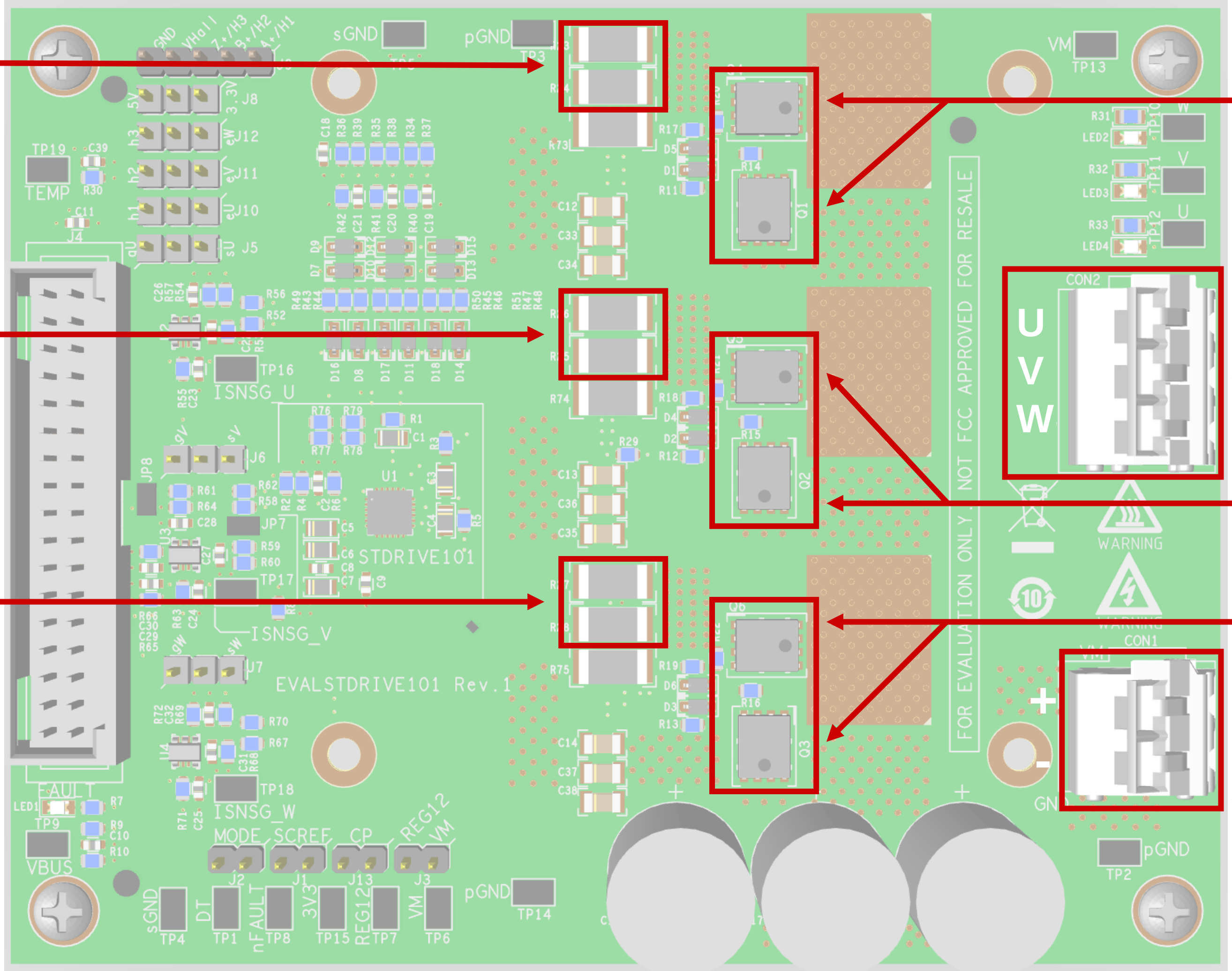
Reference design kindly provided by STMicroelectronics
https://www.st.com/en/power-management/stdrive101.html

Board Layout

Shunt resistor
R23, R24

Shunt resistor
R25, R26

Shunt resistor
R27, R28



MOSFET Half Bridges
Q1 and Q4

Motor phases connector
CON2

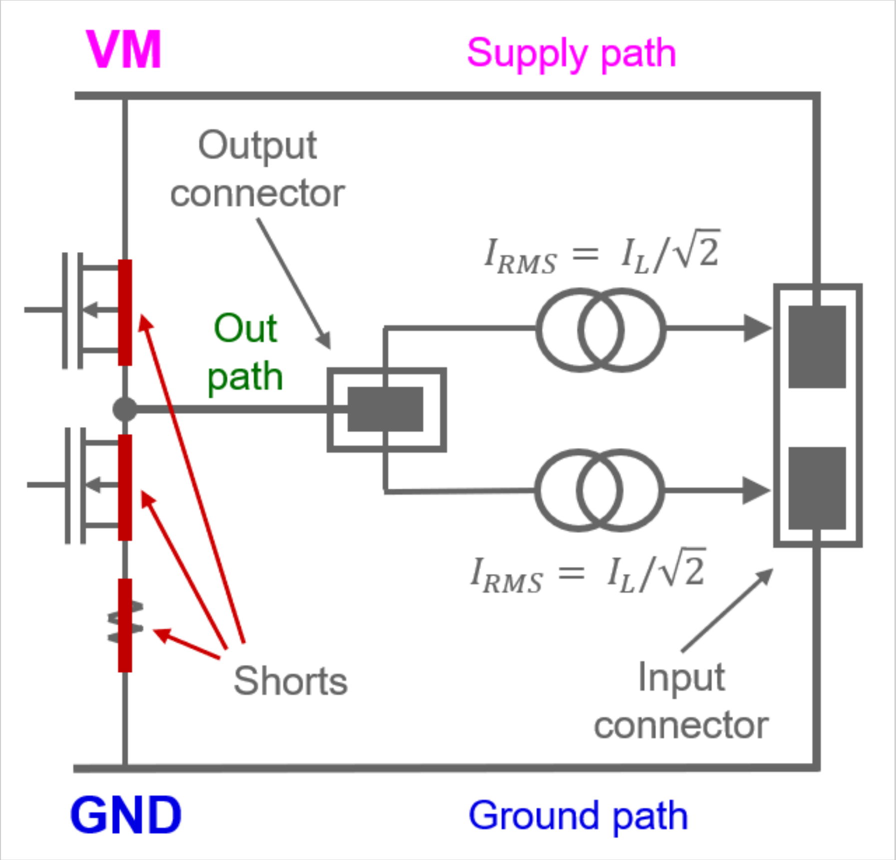
MOSFET Half Bridges
Q2 and Q5

MOSFET Half
Bridges Q3 and Q6

Power supply connector
CON1

Simplified PCB Current Loop Model

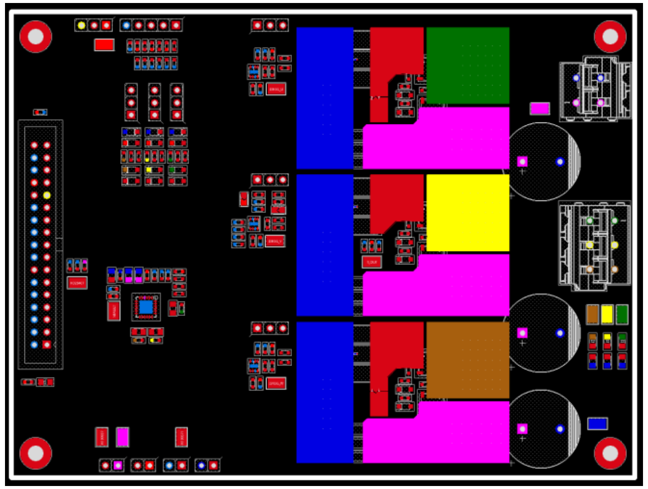
- Average current loops modeled by a supply rail and a ground path loop
  - Each half bridge simplified modeled by a constant current source placed between output power connector and supply power connector
  - Power MOSFETs modeled by short circuits
  - Shunt resistors modeled by short circuits
  - Good fitting with real case average currents



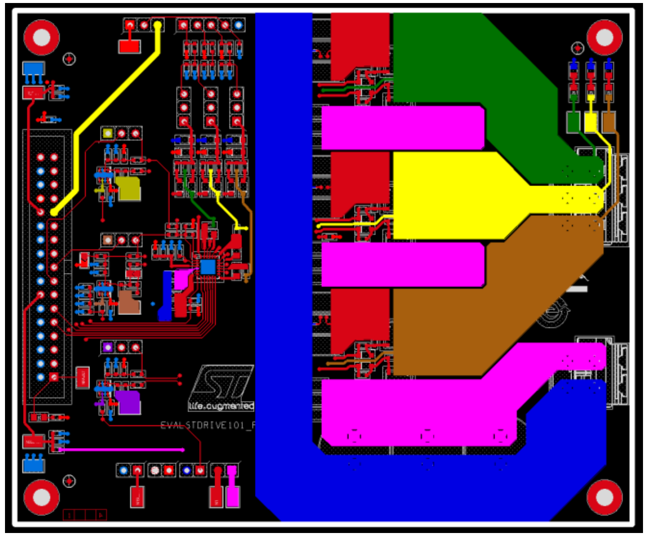
Reference: Cadence/STMicroelectronics Whitepaper

Development Stages

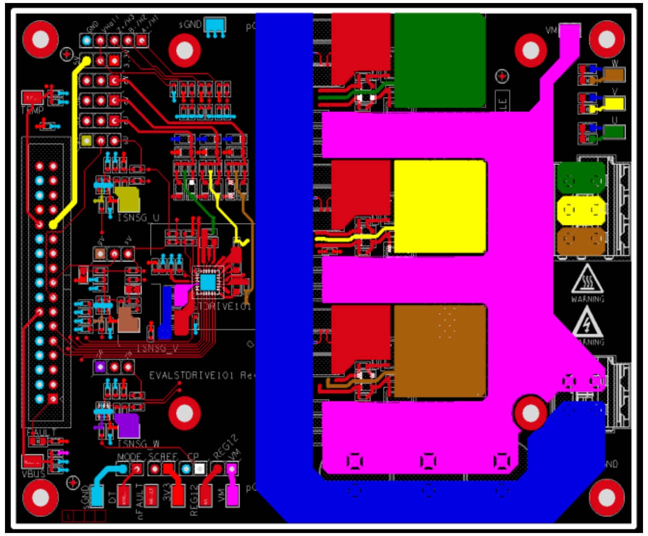
- **Initial Layout**
  - Not fully placed
  - Rough thermal analysis of top layer only



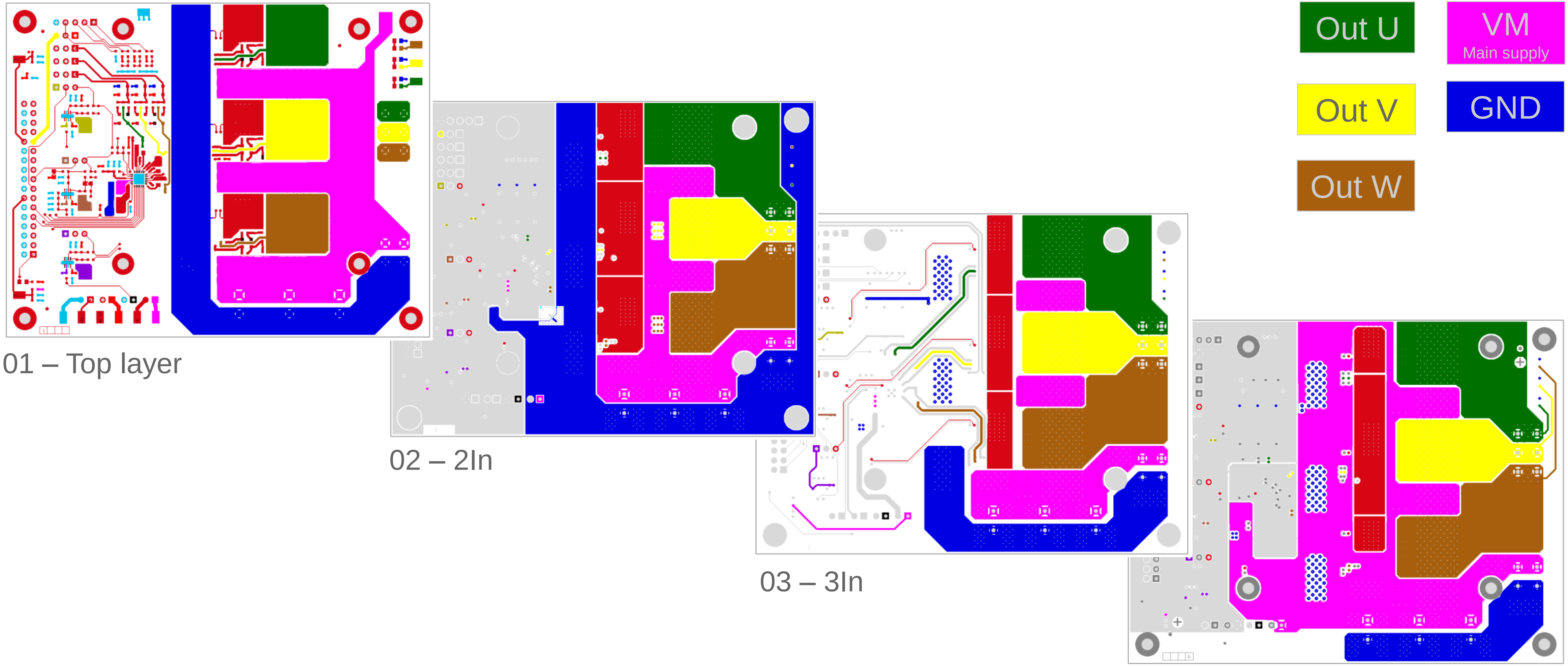
- **Interims2 Layout**
  - Analyzing and optimizing current paths
  - Modify layout to improve heat transmission from top to bottom board surface



- **Final Layout**
  - Optimized layout without bottlenecks
  - Increased copper thickness
  - Well balanced output voltages



Final Layout – Layout Plots



01 – Top layer

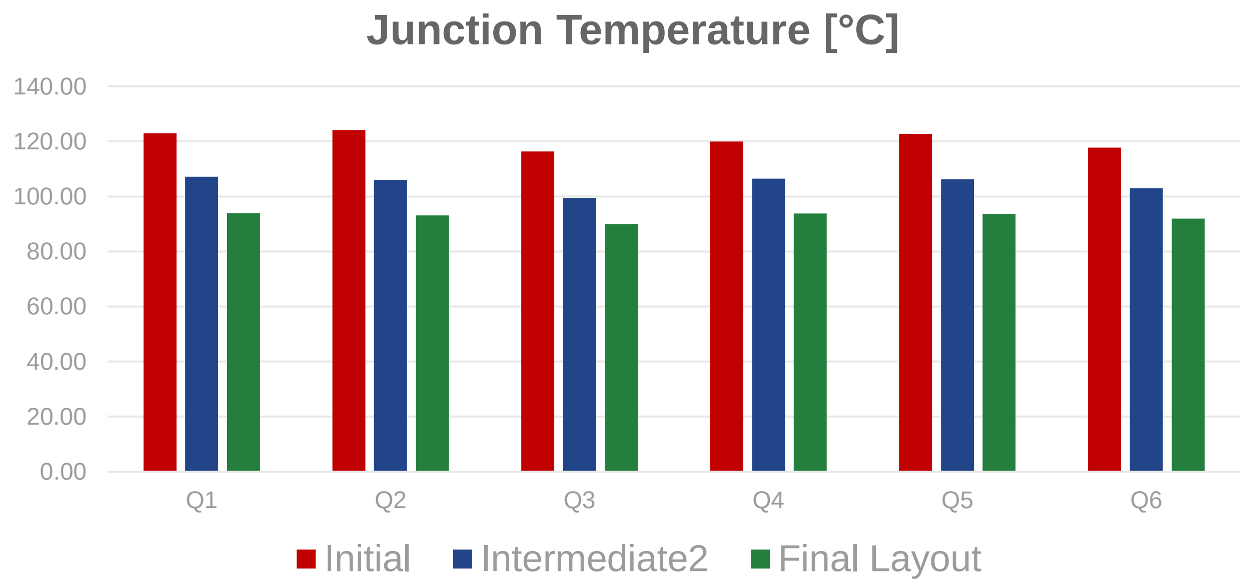
02 – 2In

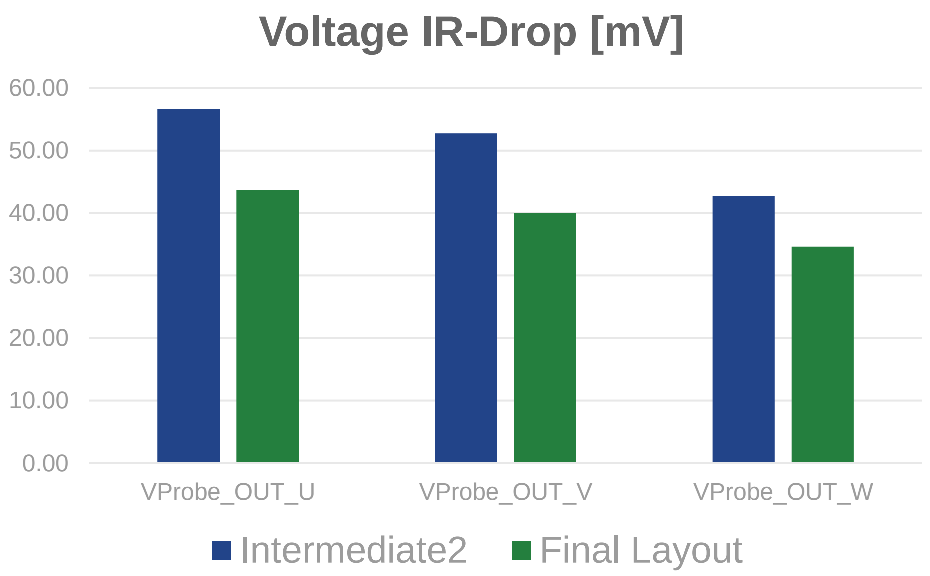
03 – 3In

04 – Bottom layer

Junction Temperature & IR-Drop vs. Copper Thickness

	Initial	Intermediate2	Final Layout
Layer 01	1 oz copper	1 oz copper	2 oz copper
Layer 02	½ oz copper	½ oz copper	2 oz copper
Layer 03	½ oz copper	½ oz copper	2 oz copper
Layer 04	1 oz copper	1 oz copper	2 oz copper

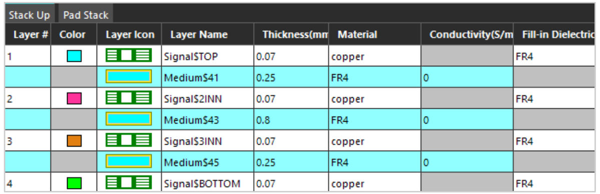




Celsius Thermal Solver – Initial Setup

- Load layout file
- Check layer stackup
- Check padstack
- Check PCB material configuration

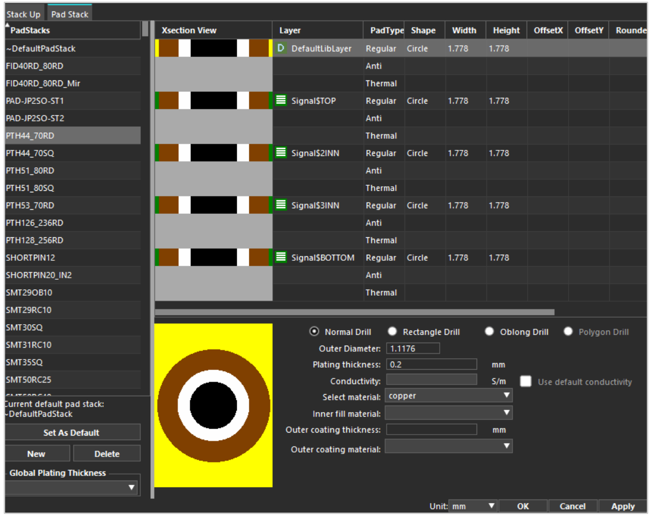
cadence .brd · IPC-2581 · ODB++



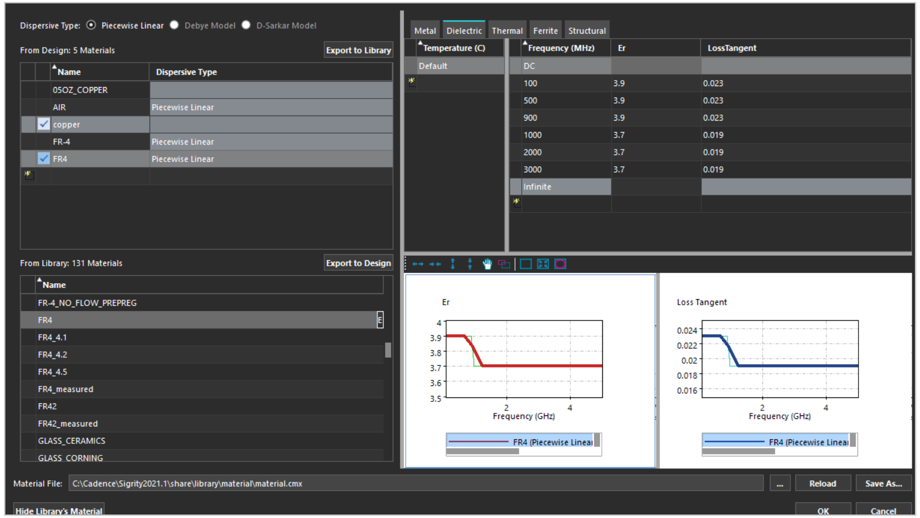
Layer #	Color	Layer Icon	Layer Name	Thickness(mm)	Material	Conductivity(S/m)	Fill-in Dielectric
1			Signal$TOP	0.07	copper		FR4
			Medium$41	0.25	FR4	0	
2			Signal$2INN	0.07	copper		FR4
			Medium$43	0.8	FR4	0	
3			Signal$3INN	0.07	copper		FR4
			Medium$45	0.25	FR4	0	
4			Signal$BOTTOM	0.07	copper		FR4

Layer stackup editor

DEMO



Padstack stackup editor



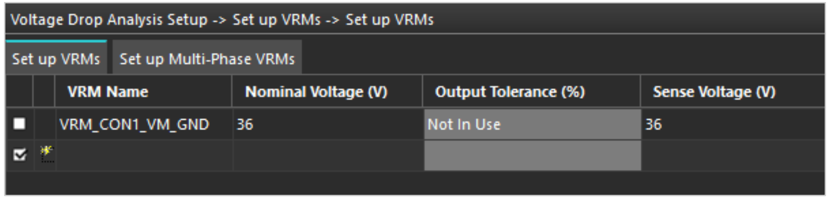
Material database

Initial Setup → E-Setup → T-Setup → Simulation & Results

Celsius Thermal Solver – E-Setup

- Set up VRMs
- Set up Sinks
- Set up Discrete components
- Set up V/I Probes

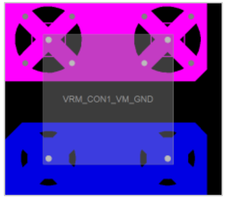
DEMO



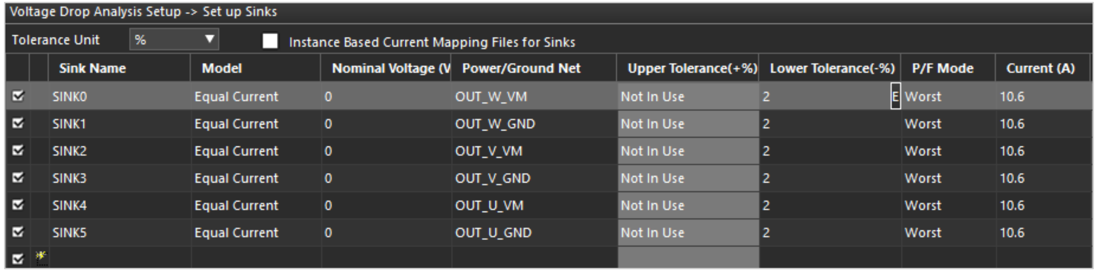
Voltage Drop Analysis Setup -> Set up VRMs -> Set up VRMs

Set up VRMs | Set up Multi-Phase VRMs

	VRM Name	Nominal Voltage (V)	Output Tolerance (%)	Sense Voltage (V)
☐	VRM_CON1_VM_GND	36	Not In Use	36



Voltage Regulator Modules VRMs

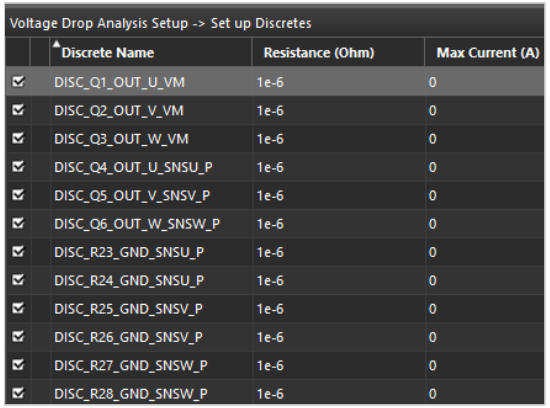


Voltage Drop Analysis Setup -> Set up Sinks

Tolerance Unit % ☐ Instance Based Current Mapping Files for Sinks

	Sink Name	Model	Nominal Voltage (V	Power/Ground Net	Upper Tolerance(+%)	Lower Tolerance(-%)	P/F Mode	Current (A)
☑	SINK0	Equal Current	0	OUT_W_VM	Not In Use	2	Worst	10.6
☑	SINK1	Equal Current	0	OUT_W_GND	Not In Use	2	Worst	10.6
☑	SINK2	Equal Current	0	OUT_V_VM	Not In Use	2	Worst	10.6
☑	SINK3	Equal Current	0	OUT_V_GND	Not In Use	2	Worst	10.6
☑	SINK4	Equal Current	0	OUT_U_VM	Not In Use	2	Worst	10.6
☑	SINK5	Equal Current	0	OUT_U_GND	Not In Use	2	Worst	10.6

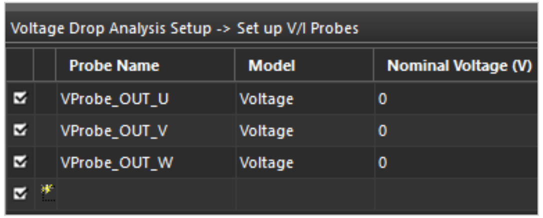
Sinks



Voltage Drop Analysis Setup -> Set up Discretes

	Discrete Name	Resistance (Ohm)	Max Current (A)
☑	DISC_Q1_OUT_U_VM	1e-6	0
☑	DISC_Q2_OUT_V_VM	1e-6	0
☑	DISC_Q3_OUT_W_VM	1e-6	0
☑	DISC_Q4_OUT_U_SNSU_P	1e-6	0
☑	DISC_Q5_OUT_V_SNSV_P	1e-6	0
☑	DISC_Q6_OUT_W_SNSW_P	1e-6	0
☑	DISC_R23_GND_SNSU_P	1e-6	0
☑	DISC_R24_GND_SNSU_P	1e-6	0
☑	DISC_R25_GND_SNSV_P	1e-6	0
☑	DISC_R26_GND_SNSV_P	1e-6	0
☑	DISC_R27_GND_SNSW_P	1e-6	0
☑	DISC_R28_GND_SNSW_P	1e-6	0

Discrete components



Voltage Drop Analysis Setup -> Set up V/I Probes

	Probe Name	Model	Nominal Voltage (V)
☑	VProbe_OUT_U	Voltage	0
☑	VProbe_OUT_V	Voltage	0
☑	VProbe_OUT_W	Voltage	0

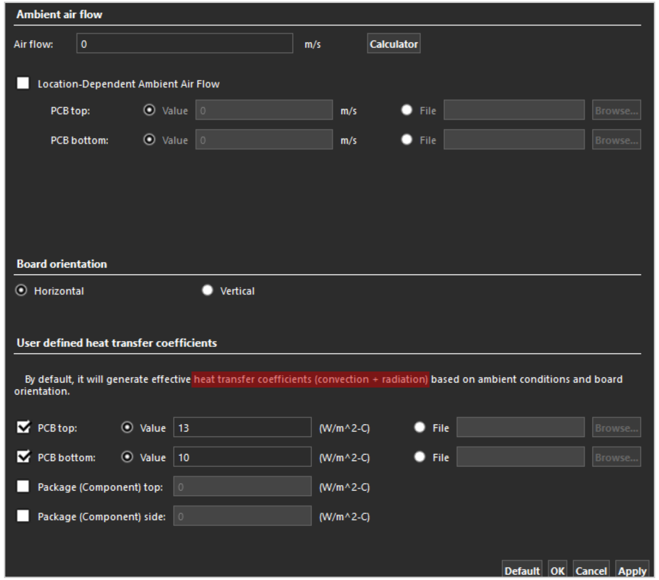
Voltage probes

Initial Setup → E-Setup → T-Setup → Simulation & Results

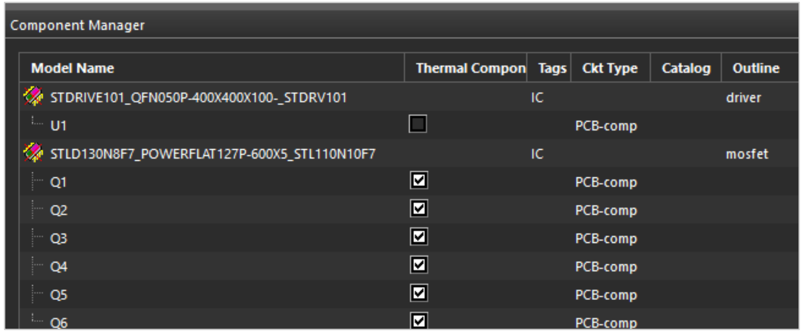
Celsius Thermal Solver – T-Setup (I)

- Set up ambient temperature & ambient conditions
  (i.e. heat transfer coefficient HTC)
- Select thermal components

DEMO



Ambient conditions



Thermal component selection

Initial Setup → E-Setup → T-Setup → Simulation & Results

Celsius Thermal Solver – T-Setup (II)

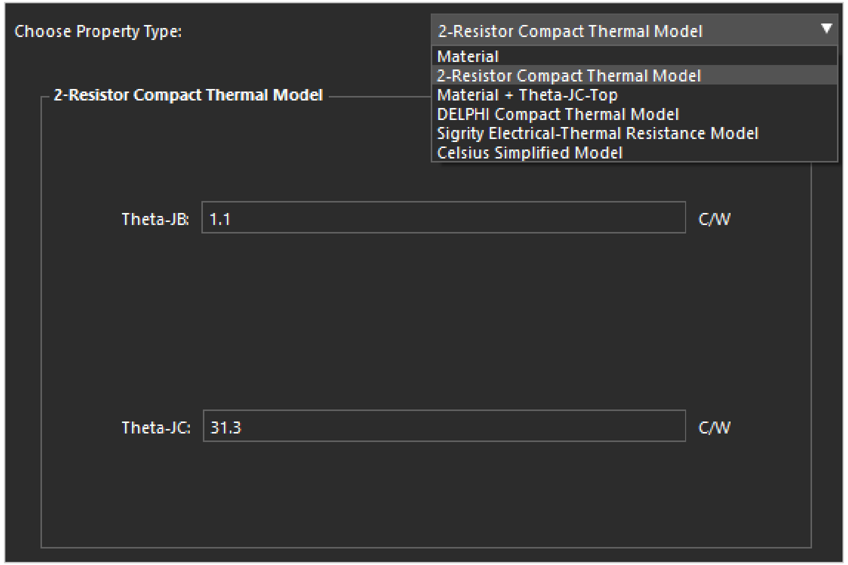
- Set up thermal components

DEMO

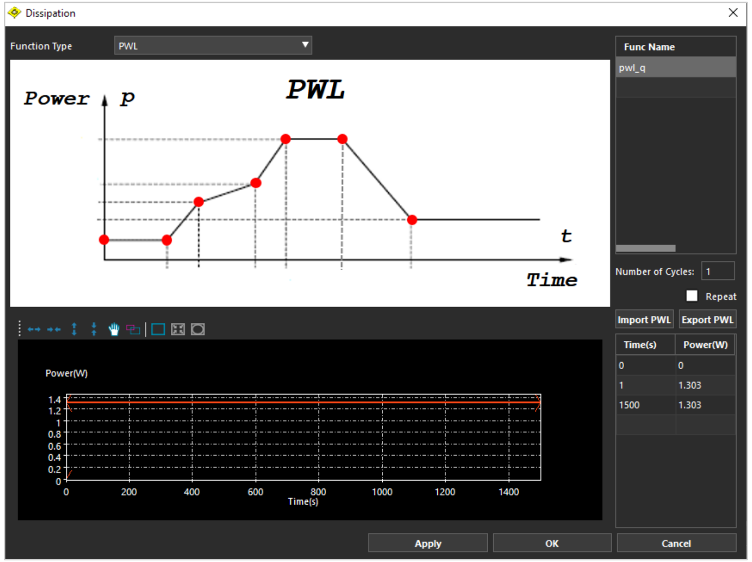
Component Manager

RefDes	Model Name	Tags	X(mm)	Y(mm)	Rotation	Flip	Property	MaxDieTemperat	Dissipation
Q1	STLD130N8F7_P...	IC	71mm	76mm	270.000000	No	2-Resistor Comp...	95.000000	Transient Function : pwl_q
Q2	STLD130N8F7_P...	IC	71mm	50.75mm	270.000000	No	2-Resistor Comp...	95.000000	Transient Function : pwl_q
Q3	STLD130N8F7_P...	IC	71mm	25.5mm	270.000000	No	2-Resistor Comp...	95.000000	Transient Function : pwl_q
Q4	STLD130N8F7_P...	IC	71.25mm	85.5mm	0.000000	No	2-Resistor Comp...	95.000000	Transient Function : pwl_q
Q5	STLD130N8F7_P...	IC	71.25mm	60.25mm	0.000000	No	2-Resistor Comp...	95.000000	Transient Function : pwl_q
Q6	STLD130N8F7_P...	IC	71.25mm	35mm	0.000000	No	2-Resistor Comp...	95.000000	Transient Function : pwl_q
R23	R-2512_RESC-25...	IC	56.75mm	91.5mm	0.000000	No	Material		0.281W
R24	R-2512_RESC-25...	IC	56.75mm	87.5mm	0.000000	No	Material		0.281W
R25	R-2512_RESC-25...	IC	56.75mm	62.25mm	0.000000	No	Material		0.281W
R26	R-2512_RESC-25...	IC	56.75mm	66.25mm	0.000000	No	Material		0.281W
R27	R-2512_RESC-25...	IC	56.75mm	41mm	0.000000	No	Material		0.281W
R28	R-2512_RESC-25...	IC	56.75mm	37mm	0.000000	No	Material		0.281W

Set up PCB components table



Thermal component material selection



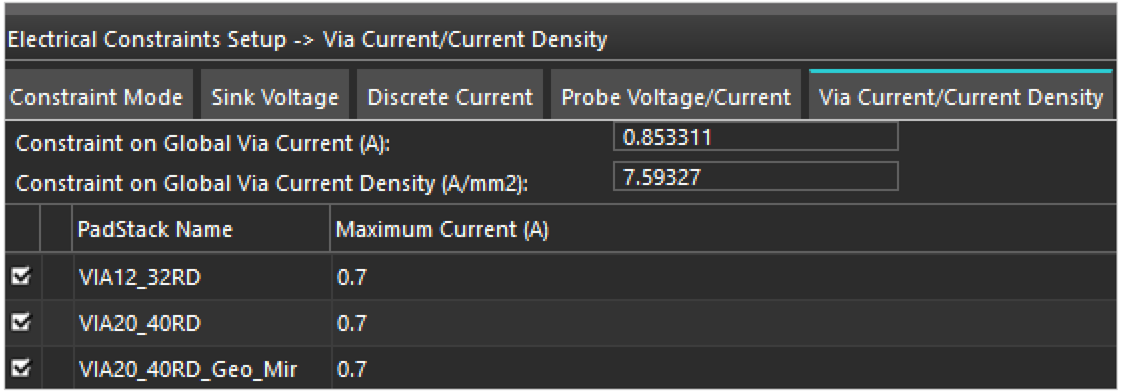
Transient thermal dissipation function definition

Initial Setup → E-Setup → T-Setup → Simulation & Results

Celsius Thermal Solver – Constraints-Setup

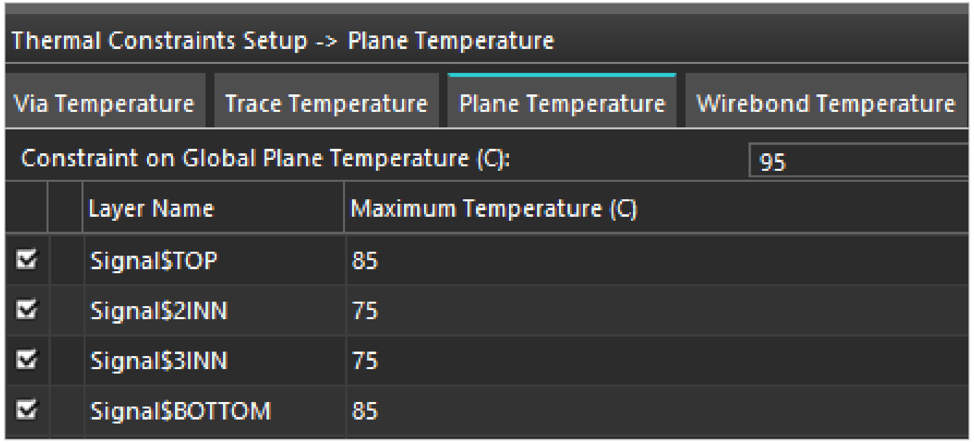
DEMO

- Set up E-Constraints
  - max. IR-drop
  - max via current
  - max. current density
- Set up T-Constraints
  - max. plane temperature



PadStack Name	Maximum Current (A)
VIA12_32RD	0.7
VIA20_40RD	0.7
VIA20_40RD_Geo_Mir	0.7

Max. via current



Layer Name	Maximum Temperature (C)
Signal$TOP	85
Signal$2INN	75
Signal$3INN	75
Signal$BOTTOM	85

Max. plane temperature

Celsius Thermal Solver – E-Simulation & Results

DEMO

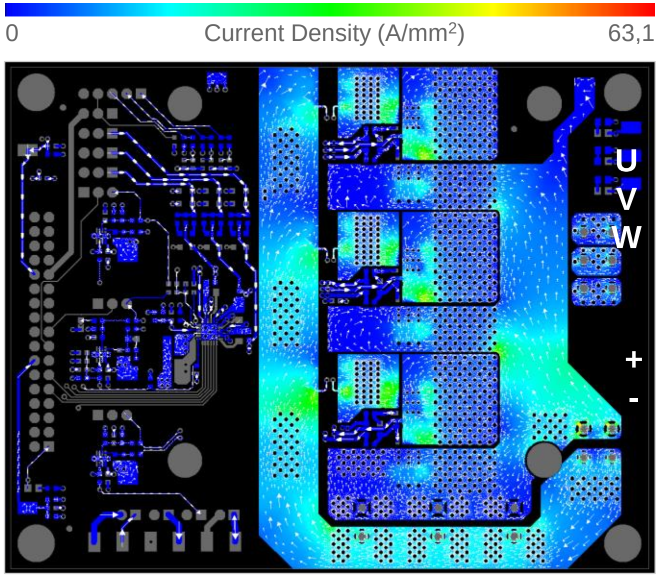
- View electrical result tables and current / voltage distributions
- Simulation time
  – single static analysis: 30 sec.
  – complete transient: 16 min.

Results and Report -> Probes Measurements

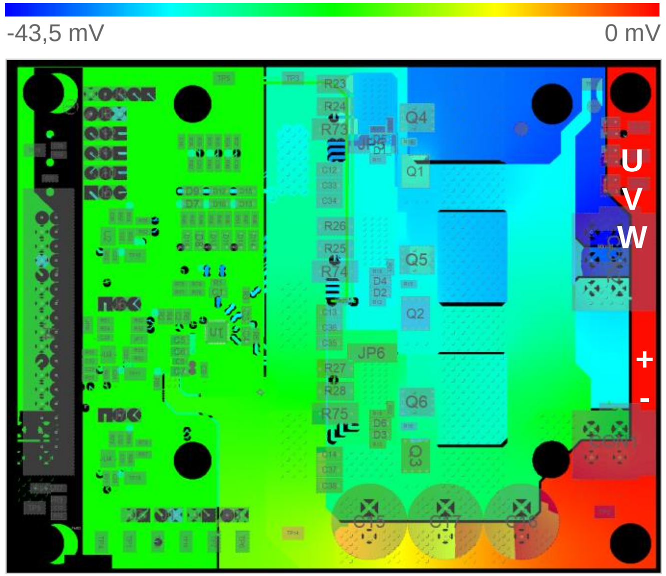
VRM Voltage | Sink Voltage | Discrete Current | Other Component Voltage | Power Loss

Probe Name	Model	Nominal Voltage (V)	Actual Voltage (V)
VProbe_OUT_U	Voltage	0	-0.0437187
VProbe_OUT_V	Voltage	0	-0.0399944
VProbe_OUT_W	Voltage	0	-0.0346542

Voltage probes results table



2D current density distribution, top layer



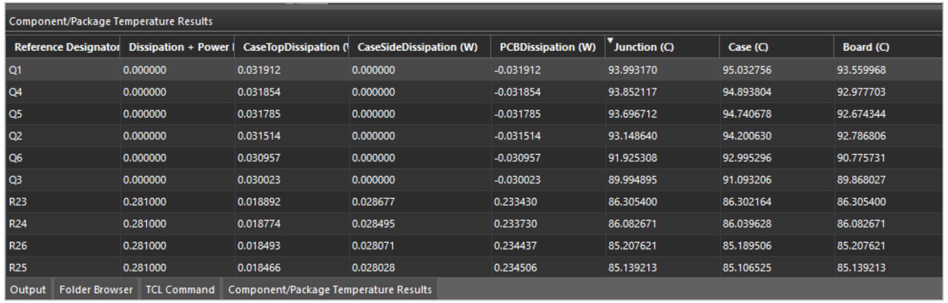
2D IR-drop distribution, all layers

Initial Setup → E-Setup → T-Setup → Simulation & Results

Celsius Thermal Solver – T-Simulation & Results

- View thermal steady state result tables and distributions

DEMO

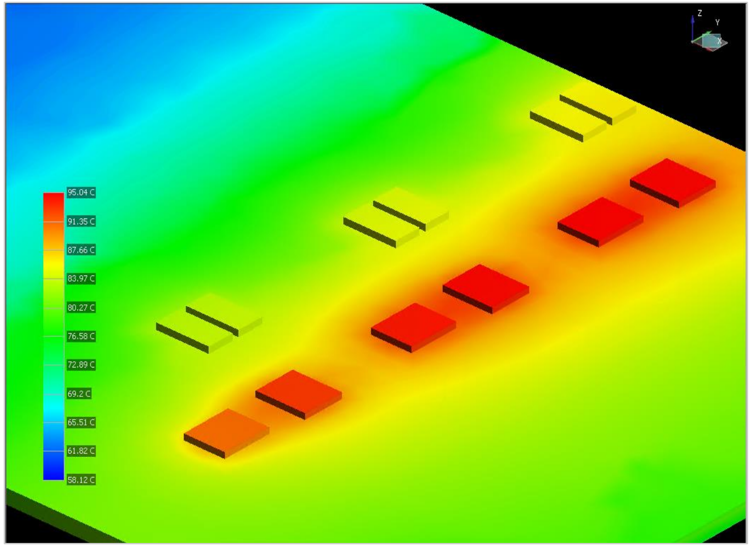


Component/Package Temperature Results

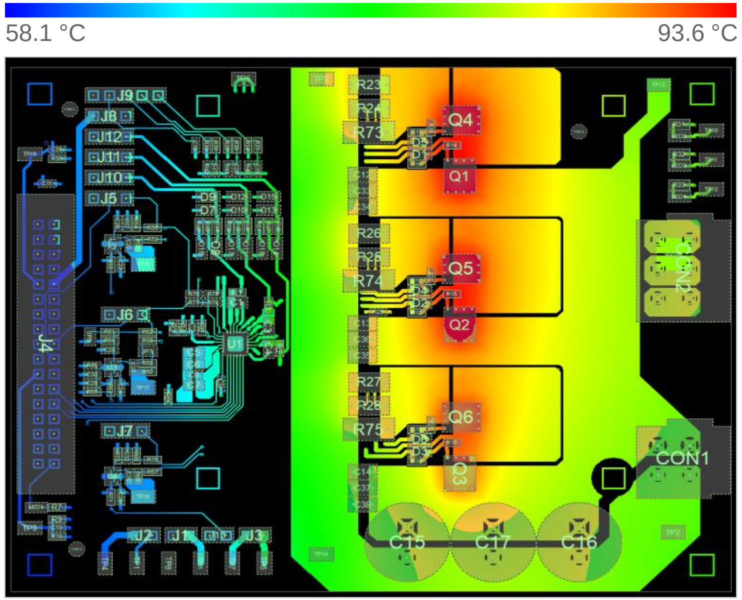
Reference Designator	Dissipation + Power	CaseTopDissipation (	CaseSideDissipation (W)	PCBDissipation (W)	Junction (C)	Case (C)	Board (C)
Q1	0.000000	0.031912	0.000000	-0.031912	93.993170	95.032756	93.559968
Q4	0.000000	0.031854	0.000000	-0.031854	93.852117	94.893804	92.977703
Q5	0.000000	0.031785	0.000000	-0.031785	93.696712	94.740678	92.674344
Q2	0.000000	0.031514	0.000000	-0.031514	93.148640	94.200630	92.786806
Q6	0.000000	0.030957	0.000000	-0.030957	91.925308	92.995296	90.775731
Q3	0.000000	0.030023	0.000000	-0.030023	89.994895	91.093206	89.868027
R23	0.281000	0.018892	0.028677	0.233430	86.305400	86.302164	86.305400
R24	0.281000	0.018774	0.028495	0.233730	86.082671	86.039628	86.082671
R26	0.281000	0.018493	0.028071	0.234437	85.207621	85.189506	85.207621
R25	0.281000	0.018466	0.028028	0.234506	85.139213	85.106525	85.139213

Output | Folder Browser | TCL Command | Component/Package Temperature Results

Component temperature results table



3D thermal distribution



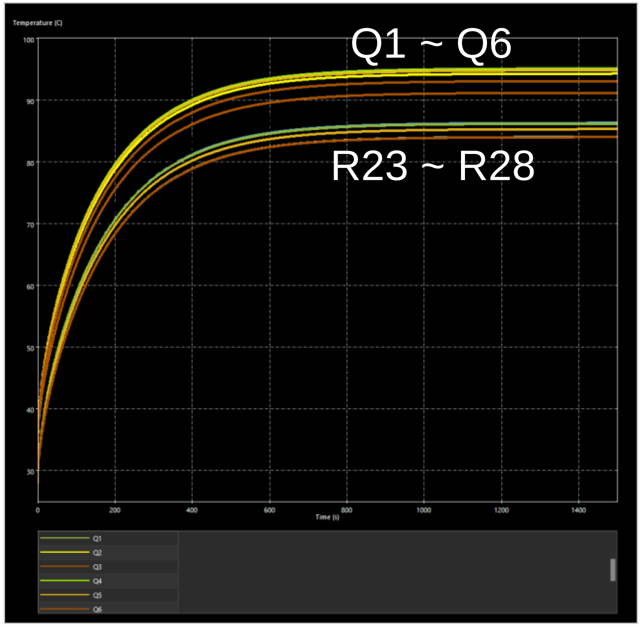
2D steady state temperature distribution

Initial Setup → E-Setup → T-Setup → Simulation & Results

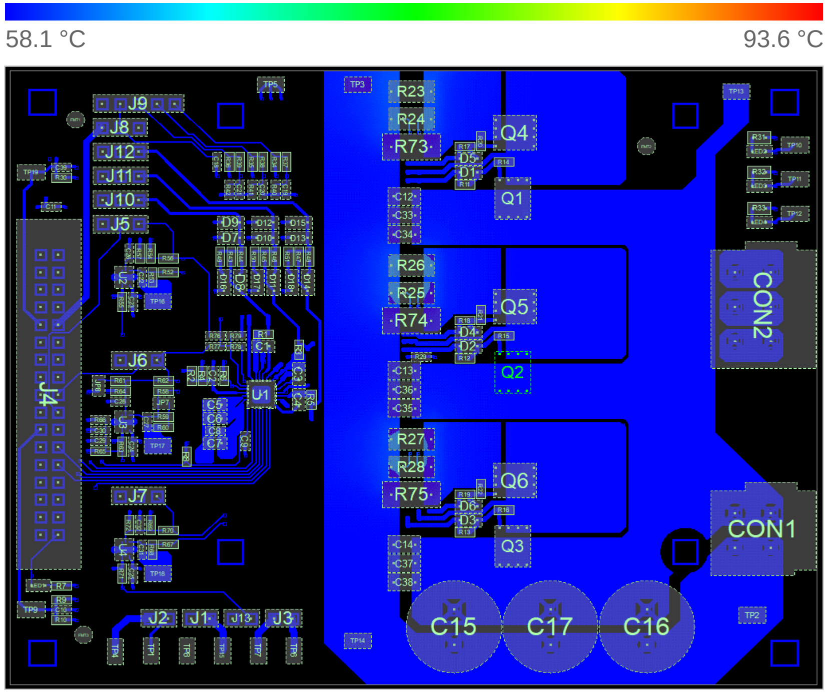
Celsius Thermal Solver – Transient T-Simulation & Results

- View thermal transient result curves and transient thermal distribution

DEMO



Transient temperature warmup curve



2D transient thermal distribution

Initial Setup | E-Setup | T-Setup | Simulation & Results

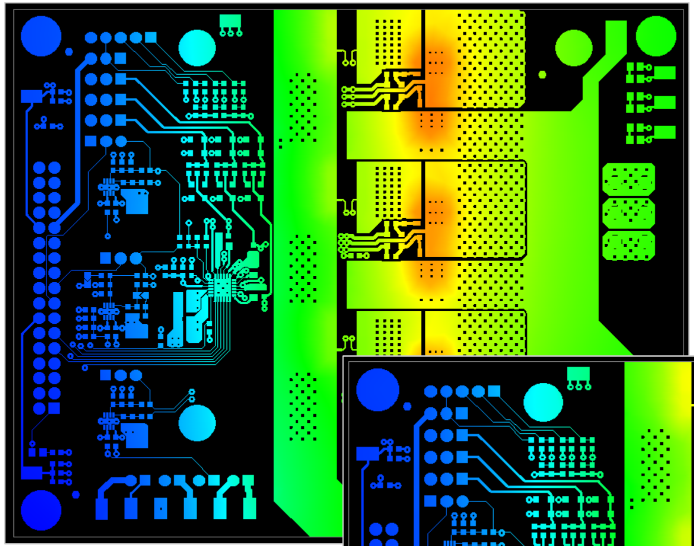
Exploring Different What-if Configurations (I)

Choose high thermal glass composite PCB laminate

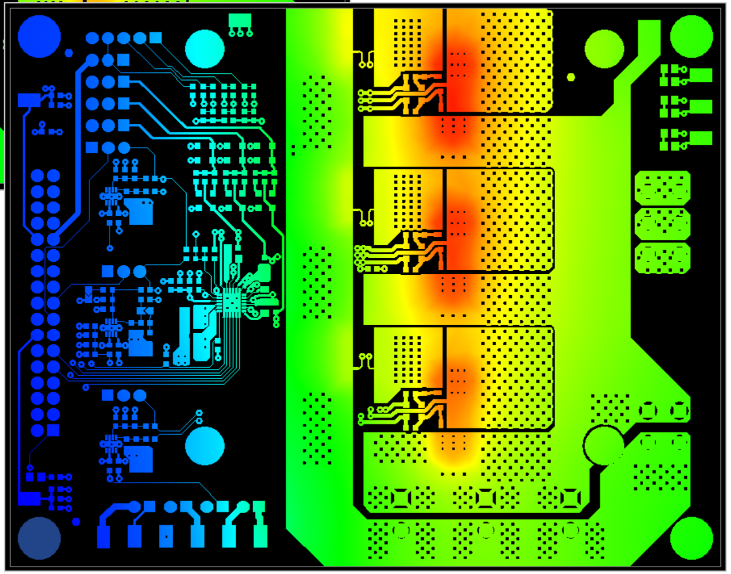
	Junction Conductivity 1.5 W/m · K	Junction Conductivity 1.1 W/m · K	Junction Conductivity 0.4 W/m · K
	Junction Temperature (°C)		
Q1	91.5	91.8	92.6
Q2	90.5	90.8	91.5
Q3	87.8	88.1	88.7
Q4	91.5	91.8	92.5
Q5	91.0	91.3	92.1
Q6	89.4	89.7	90.4

Item	Unit	ECOOL R-1586(H)	ECOOL R-1787	Conventional FR-4, R-1705
UL / ANSI grade	-	CEM-3	CEM-3	FR-4.0
Glass transition temp. (Tg)	°C	148	148	140
Thermal conductivity @ 85°C	W/m · K	1.5	1.1	0.4
Thermal resistance	°C / W	5.0	6.7	17.5

Source: Panasonic



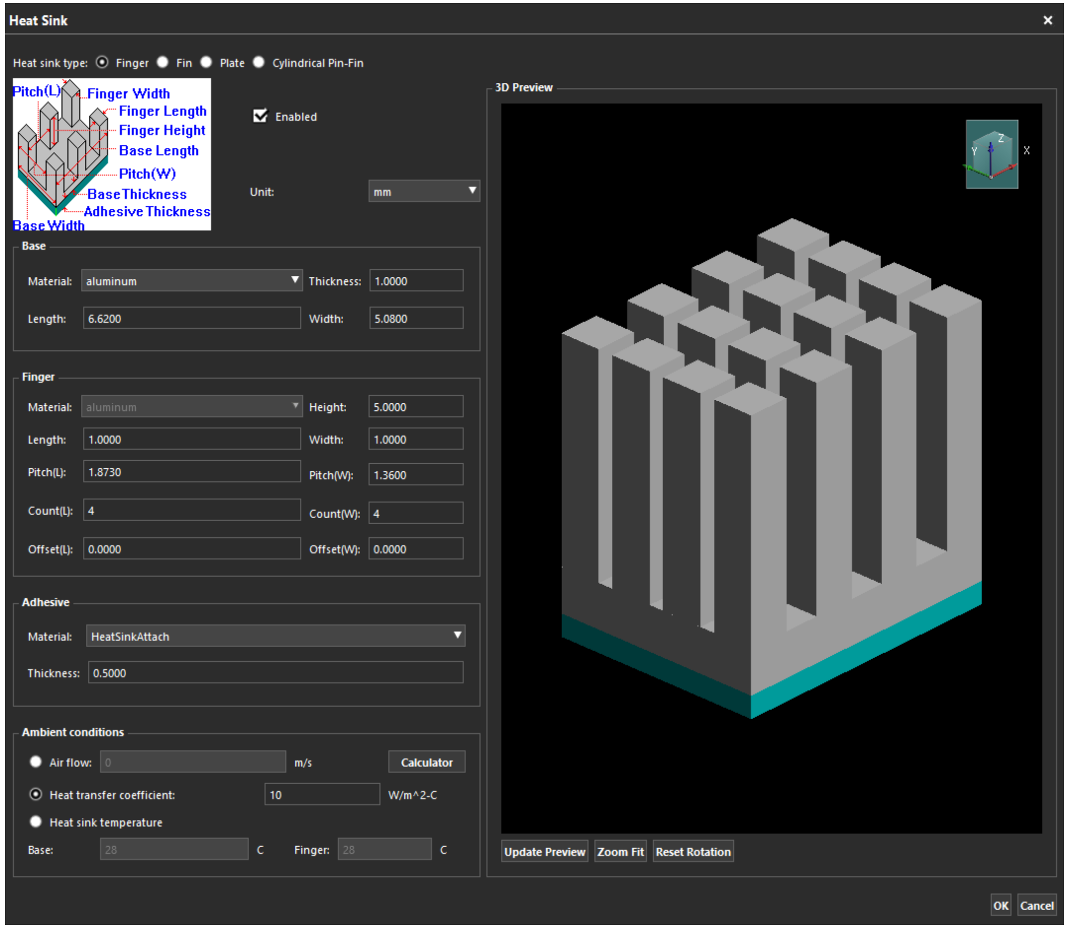
Conductivity
1.5 W/m · K



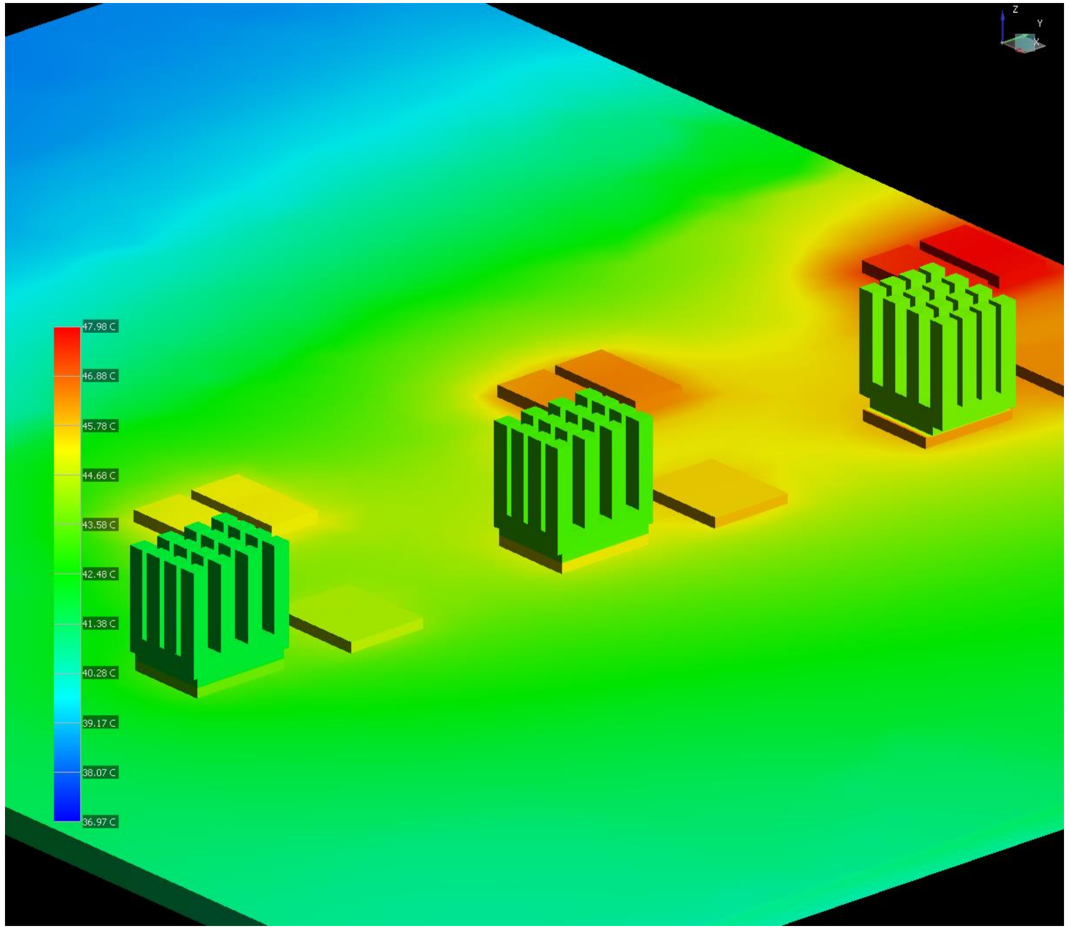
Conductivity
0.4 W/m · K

Exploring Different What-if Configurations (II)

Define individual heat sinks to components

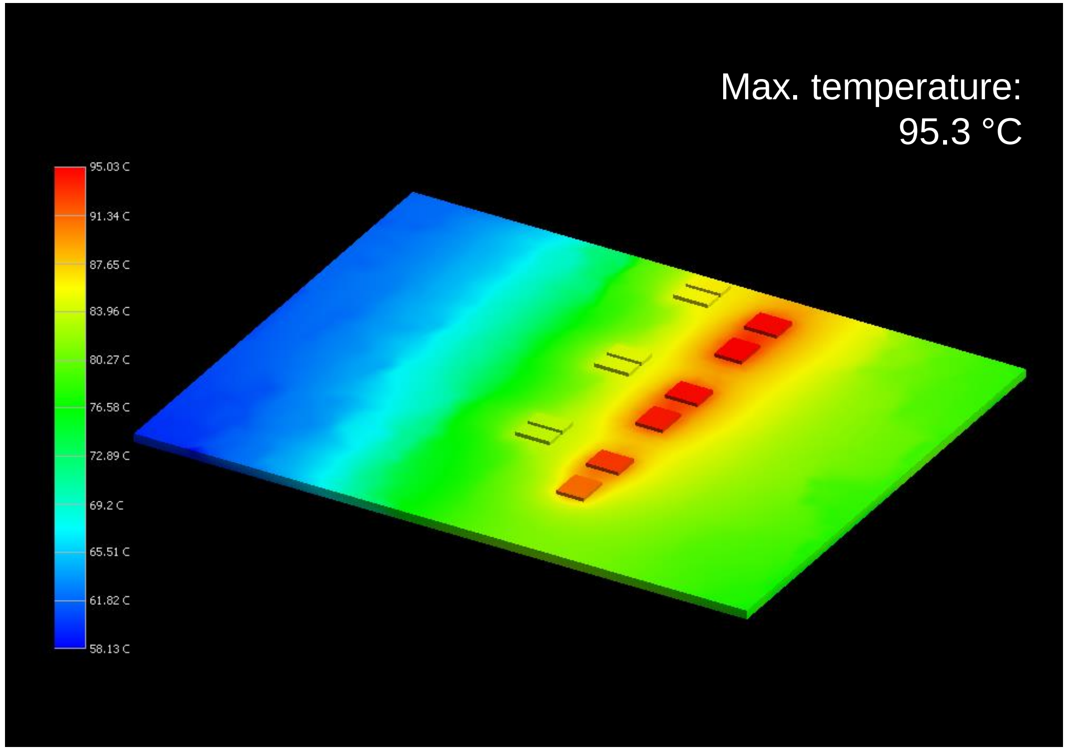


3D thermal distribution with heat sinks

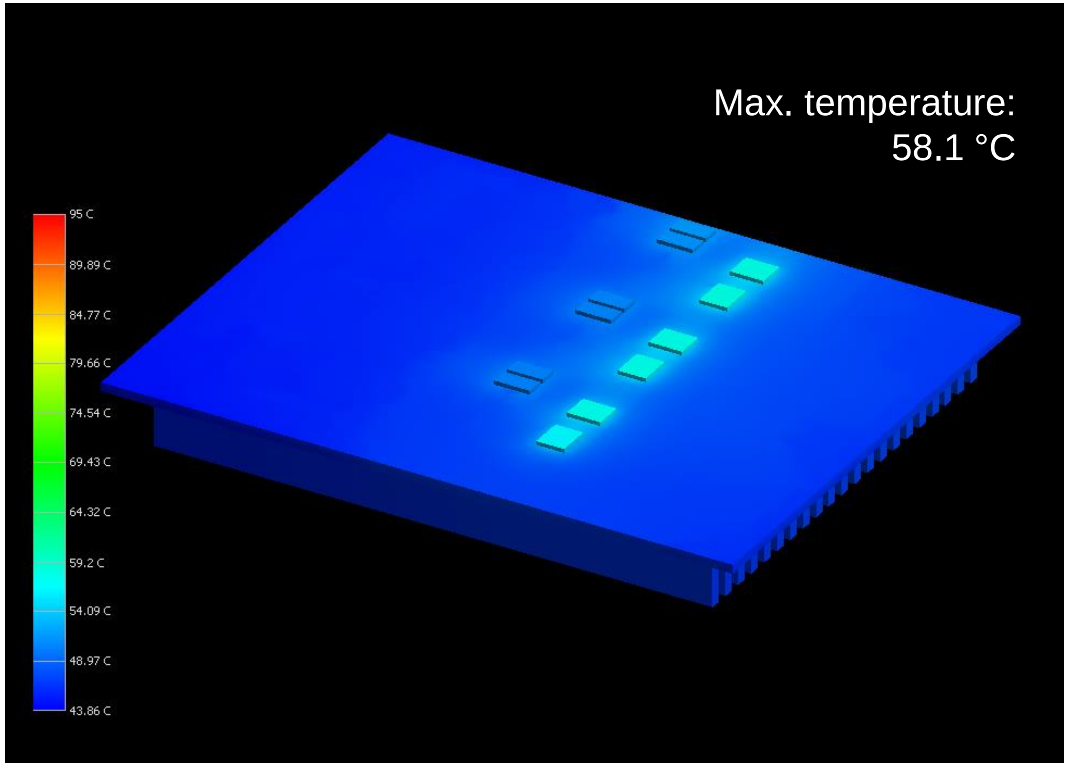


Exploring Different What-if Configurations (III)

3D thermal distribution without heatsinks

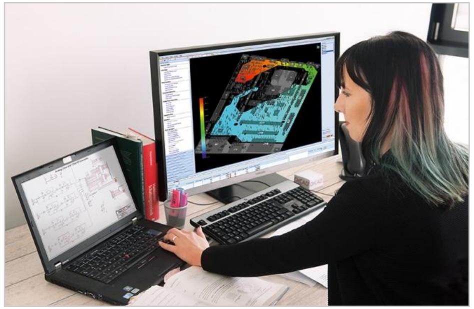


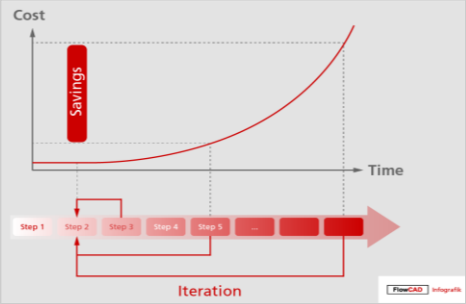
3D thermal distribution with heat sink plate

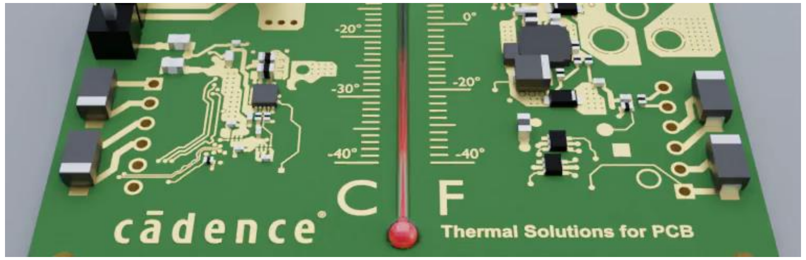


Summary & Key Takeaways

- With the Celsius Thermal Solver, you can easily simulate the thermal behavior of your design
  - Complete solution with detailed modeling of the PCB
  - Find temperature hot spots in your design
  - Eliminate high voltage drops and current bottlenecks
- E/T co-simulation helps to make any necessary changes during design development
- Simulation “only” costs time; no costs for prototypes
- Experiment! Nothing breaks! ☺
- Deliver a first-time-right solution for the given challenge







FlowCAD.com/Thermal

Contact us / Kontakt zu FlowCAD

Please do not hesitate to contact us.
Für weitere Fragen und Informationen stehen wir gerne zur Verfügung.

FlowCAD Deutschland
Mozartstr. 2
85622 Feldkirchen bei München
T +49 89 45637-770
info@FlowCAD.de

FlowCAD Schweiz
Hintermättlistr. 1
5506 Mägenwil
T +41 56 485 91 91
info@FlowCAD.ch

FlowCAD Polska
ul. Sąsiedzka 2A
80-298 Gdańsk
T +48 58 727 90 90
info@FlowCAD.pl

Follow Us

» [FlowCAD.com]

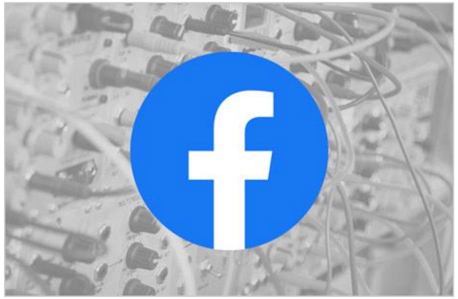
» [FlowCAD.com/newsletter]

» [youtube.com/FlowCAD]

» [linkedin.com/FlowCAD]

» [twitter.com/FlowCAD]

» [instagram.com/FlowCAD]



» [facebook.com/FlowCAD]

» [xing.com/FlowCAD]

Don’t forget to subscribe, share and like!

EMA Design Automation®

FlowCAD