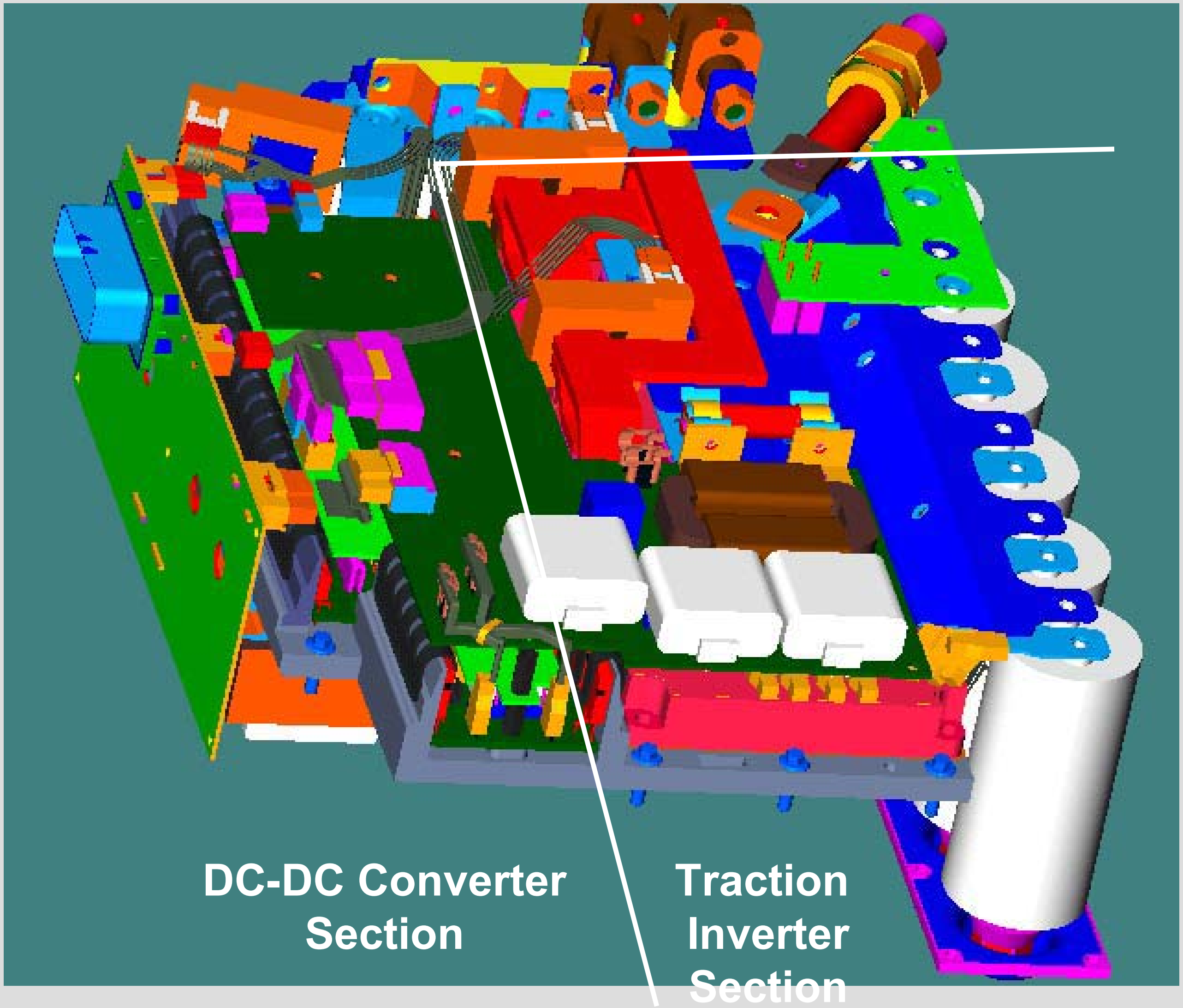
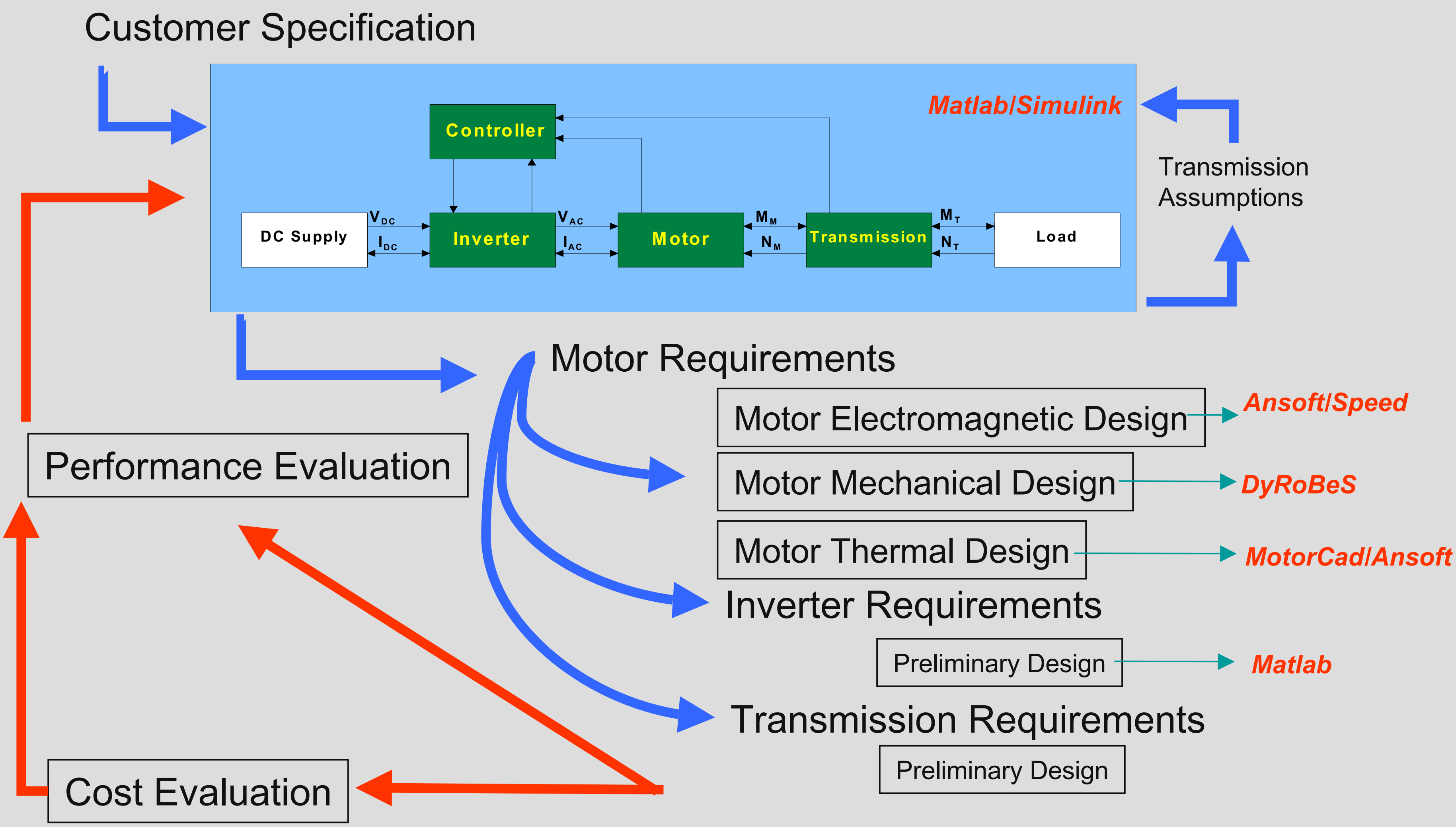
IPT Electronics : High Power Density Inverter



- 65kW at 250V (80kW at 300V)
- 500ARMS at 57C coolant, 450ARMS at 72C coolant
- 22kg => 3000W/kg (includes 3/2kW bidirectional DC-DC converter)
- Advanced power control circuits
- High accuracy torque control
- Designed for automotive reliability

System Simulation Framework – E-Drives



Customer Specification

Matlab/Simulink

Transmission Assumptions

Motor Requirements

Motor Electromagnetic Design → *Ansoft/Speed*

Motor Mechanical Design → *DyRoBeS*

Motor Thermal Design → *MotorCad/Ansoft*

Inverter Requirements

Preliminary Design → *Matlab*

Transmission Requirements

Preliminary Design

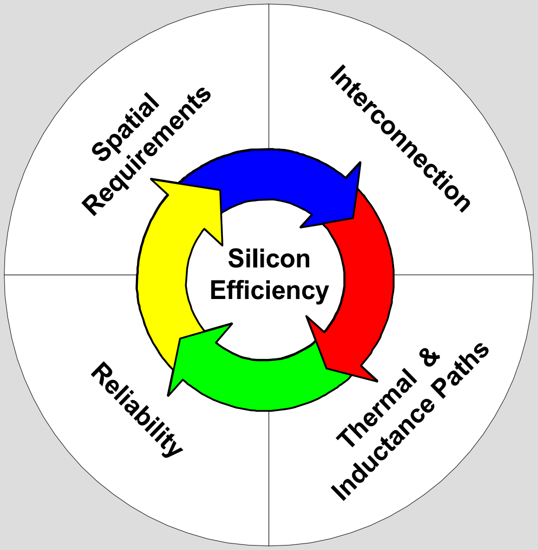
Performance Evaluation

Cost Evaluation

Advanced Technology Developments

Power Semiconductor Packaging Design & Manufacturing

ECOSTAR POWER MODULE FACILITY



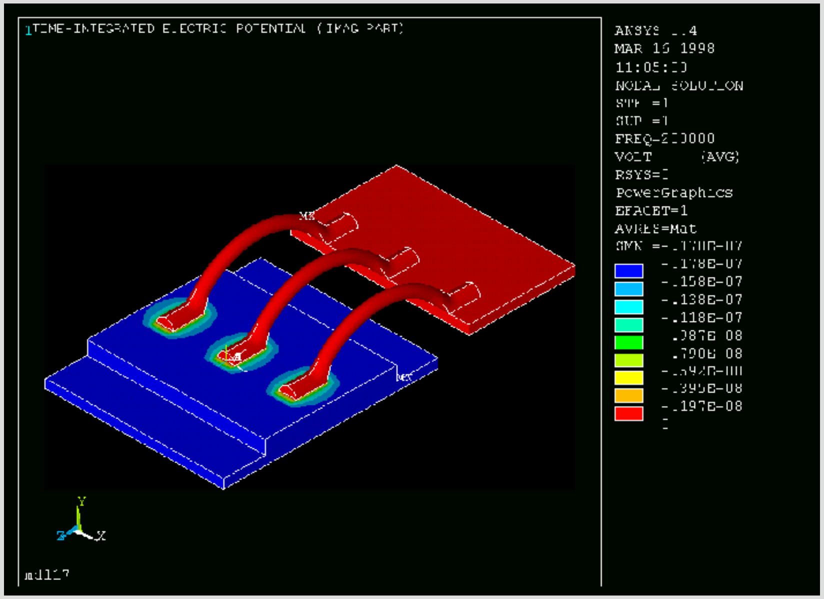
Spatial Requirements

Interconnection

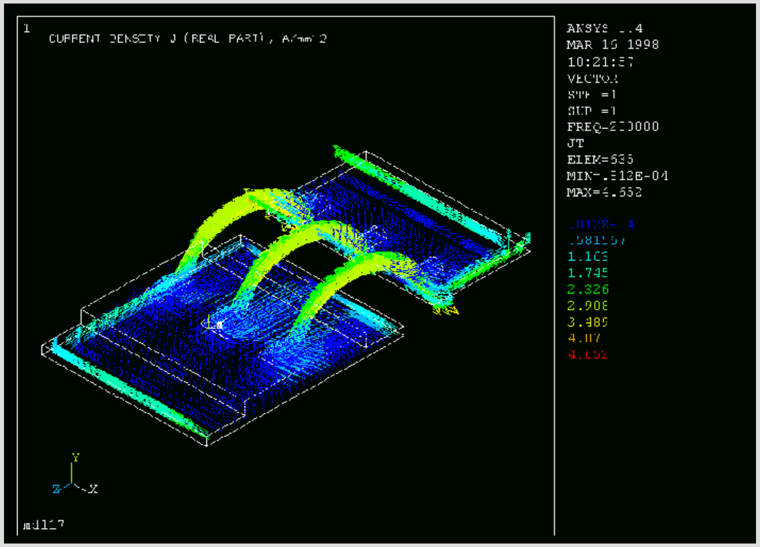
Silicon Efficiency

Reliability

Thermal & Inductance Paths



- Thermal Stress on wire bonds



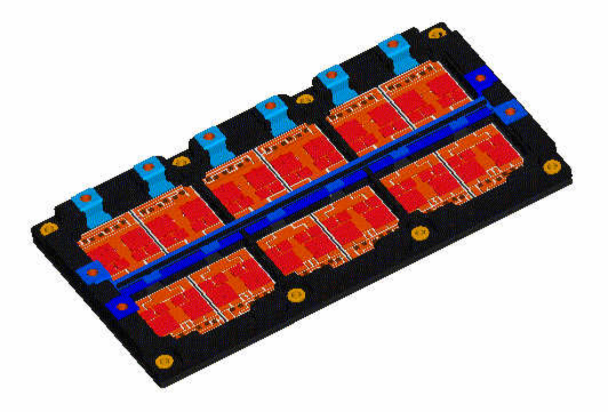
- Inductive effects in Power Module

Thermal and Mechanical Properties of Each Layers

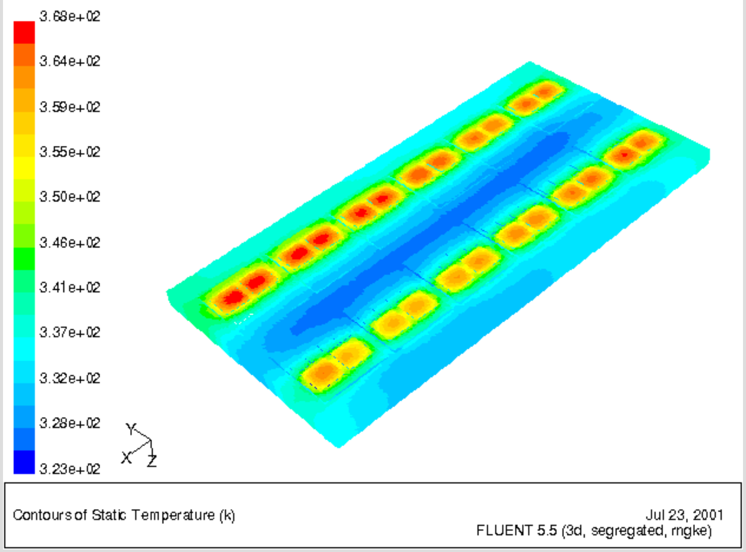
Material	Density (kg/m^3)	Thermal condutivity (W/m K)	Specific heat (J/kg K)	Young's modile (GPa)	CTE (ppm/K)
Copper	8979	389 🔴	381	112.9	16.4
AlSiC	3100	🟡 150	880	227	6.8
60Sn/40 Pb solder	8470	50	364.5	29.8	21.1
DBC AlN	8930	🟡 170	431	327	2.5
95Pb/5Sn solder	11100	35	133.7	20.4	25.1
Thermal grease	2703	0.735	796	0.011	16.4
Aluminum	2760	237	858.8	70	23.6
Silicon	2330	🟡 153 @ 25 ^oC 119 @ 77 ^oC 98.9 @ 127 ^oC 76.2 @ 227 ^oC	702	112.9	2.54

Thermal Resistance Predicted Using Numerical Tools

- **In developing Ballard Custom Power Module with integrated pinfin baseplate, computational fluid dynamics (CFD) was used to simulate fluid flow along fins and heat transfer within solids.**
- **The predicted maximum junction-to-coolant thermal resistance is 0.09 °C/W per switch, and the average number is about 0.08 °C/W per switch.**



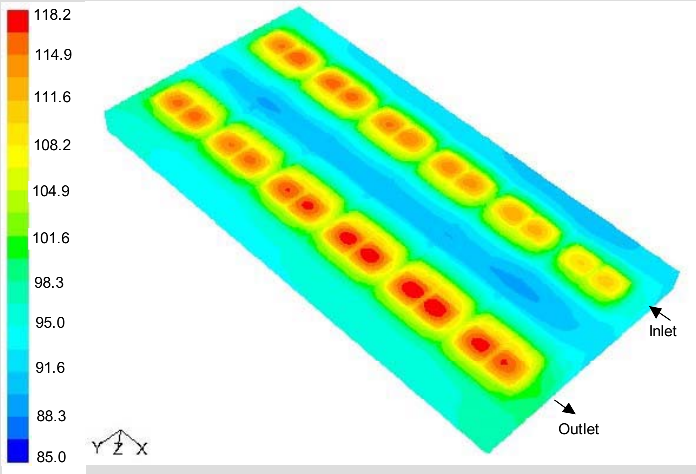
CAD model



Temperature predicted from CFD simulation

Junction Temperature of IGBT and Diode

- Application condition similar to IPT “Full Torque Stall”.
- Power loss is 350W for IGBT and 105W for Diode per switch.
- Coolant inlet temperature is 85 ^{o}C, flow rate is 2 gpm.



Temperature predicted from CFD simulation for CPM with pinfin baseplate

IGBT and Diode Temperature for CPMs with Flat and Pinfin Baseplates

	CPM with flat AlSiC baseplate	CPM with pinfin AlSiC baseplate
T_{jIGBT} (^{o}C)	**139**	**118**
T_{jDiode} (^{o}C)	**127**	**112**

Comparison

- **Thermal resistance reduced by 40% for integrated pin-fin power module.**

	Standard flat baseplate	Integrated pin-fin baseplate	Percentage reduction
Average thermal resistance per switch	**0.12 °C/W**	**0.07 °C/W**	**40%**
Average IGBT junction temperature	**97 °C**	**81 °C**	**40%** *
Maximum measured IGBT temperature	**105 °C**	**84 °C**	**47%** *

* Note: Percentage reduction refers to temperature difference between junction and coolant that has inlet temperature of 60 °C in this test.

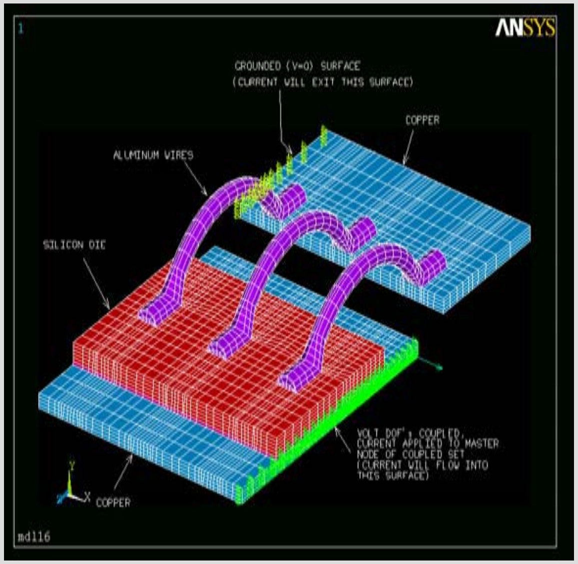
Problem Approach to Inductance Challenge

1.00 Simulation & Modeling of Structure

2.00 Inductance formulae for current paths

3.00 Physical Systems Test

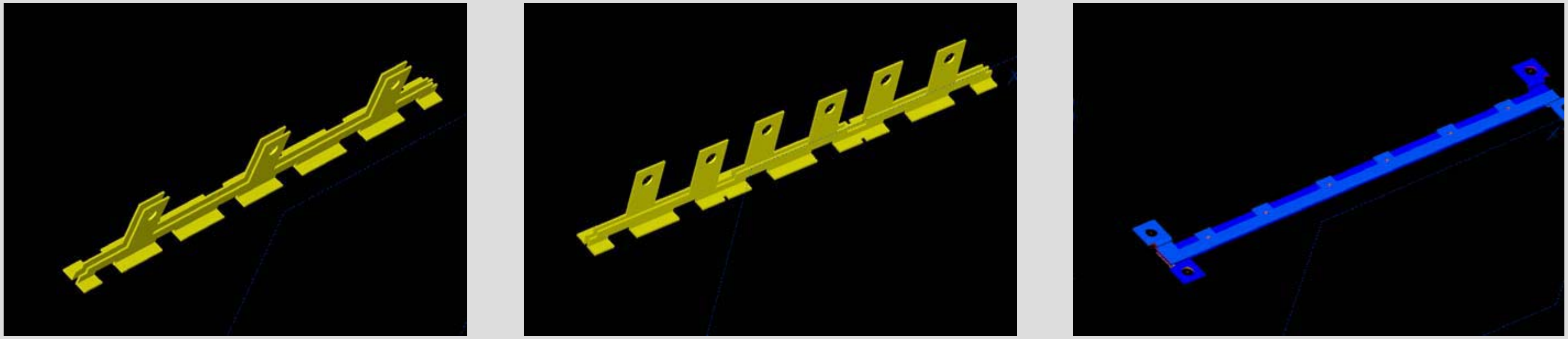
Inductance Analysis



OBJECTIVES

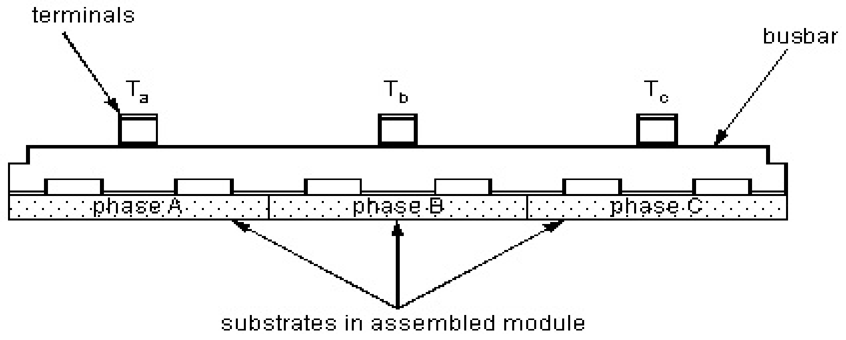
- Optimize layout for minimum inductance
- Reduce Parasitics
  - Lower switching losses
  - Minimize effects of body diode recovery
  - Reduce bond wire stress
  - Minimize EMI

- **Alternative Embedded Busbar Structures**

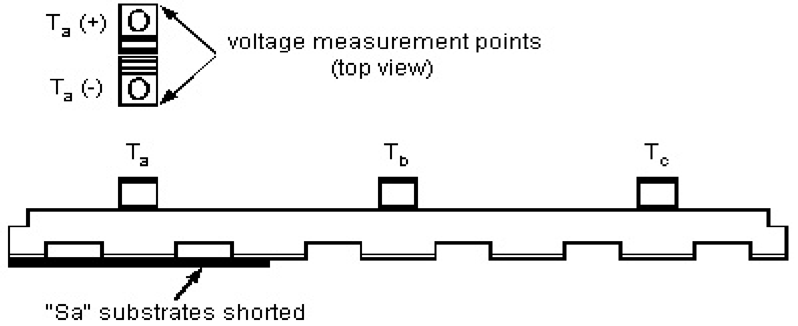


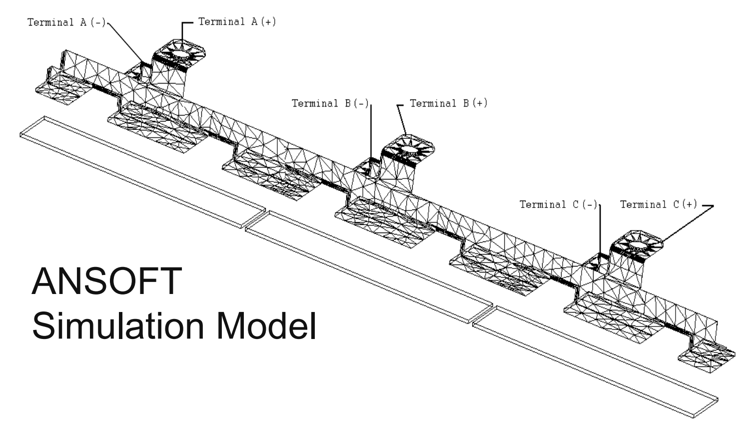
Inductance Analysis of the D.C. Link

Busbar Shown as Assembled in Three-Phase Module



Busbar Shown as Connected During Inductance Measurement





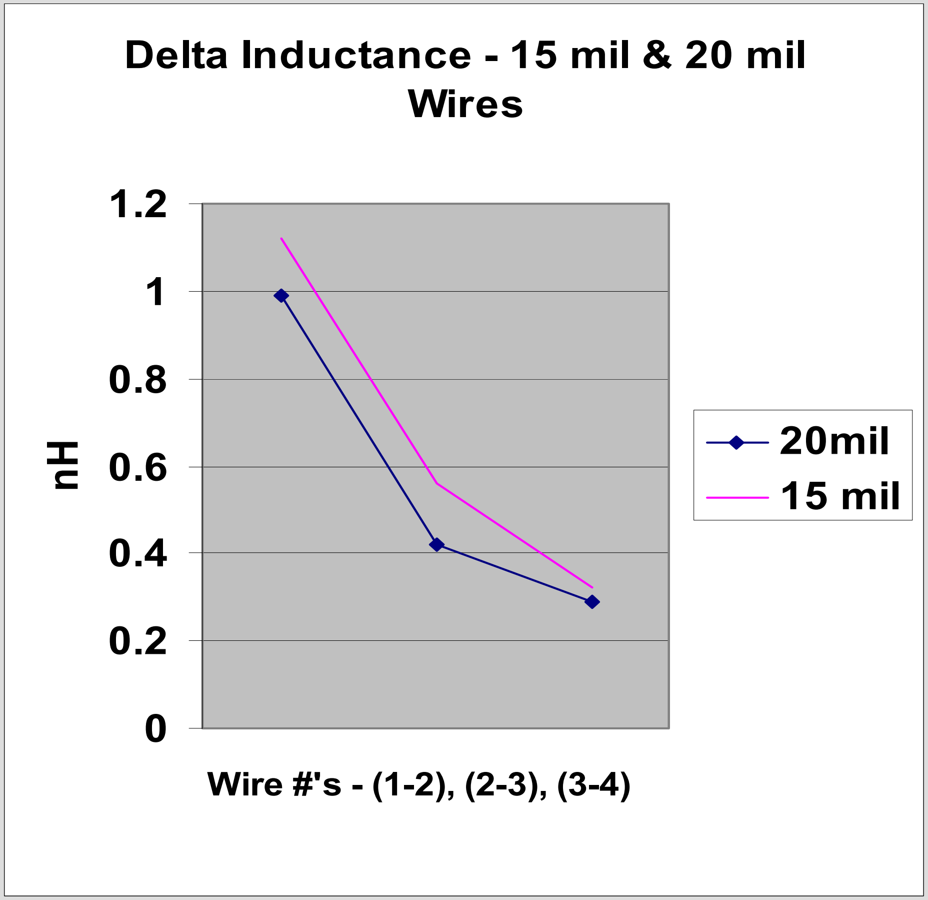
ANSOFT
Simulation Model

Measured Results

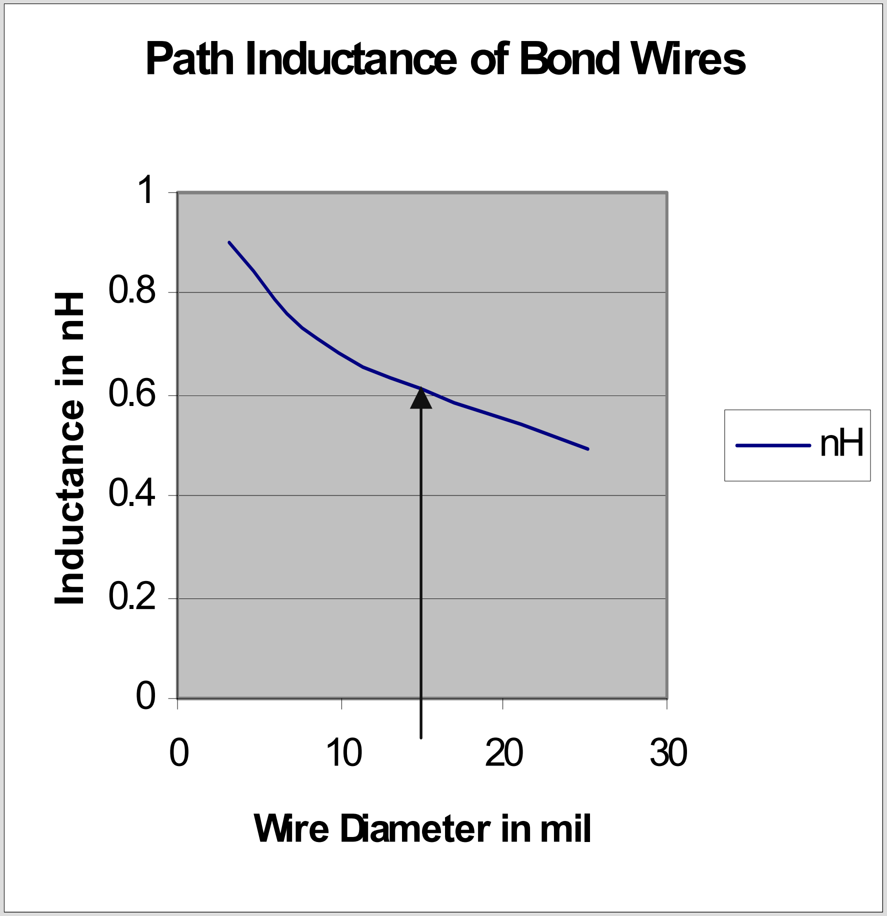
Units = nH

	Terminals		
shorted phase	**Ta**	**Tb**	**Tc**
Sa	4.5	7.2	9.2
Sb	6.0	4.1	6.0
Sc	9.2	7.2	4.5

Path Inductance - The Bond Wires



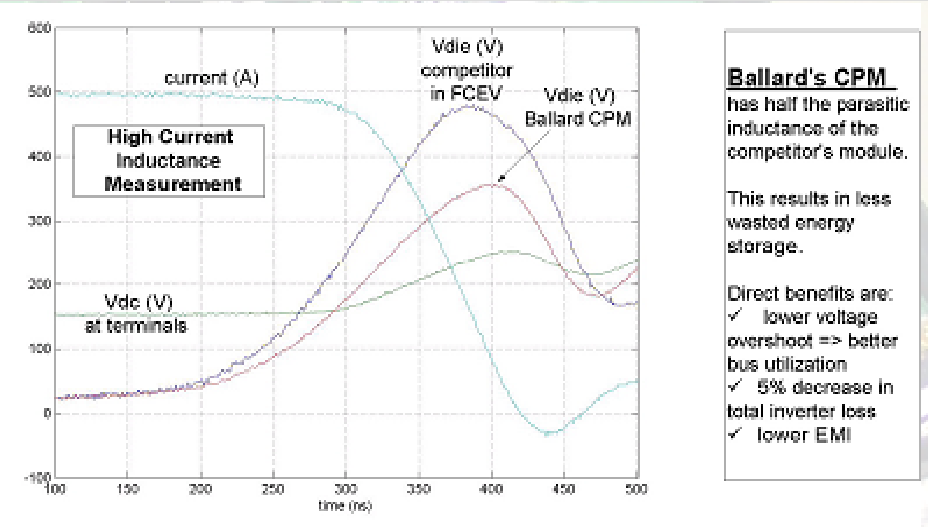
Physical Testing



Formulae Based
15 mil wire

Achieved Benefits

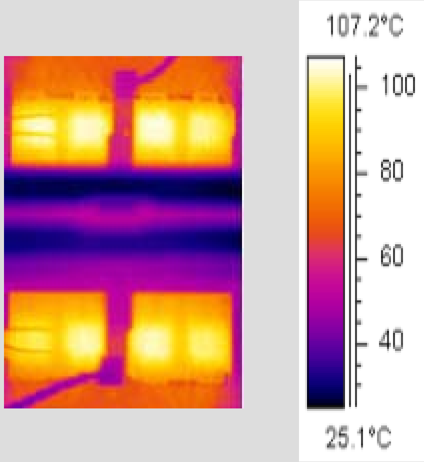
- Increased package performance:
  - Significant reduction in parasitic inductance
  - Significant reduction in thermal resistance
  - Increased power density
- Increase packaging integration
- Reduced system packaging space
- Reduced system cost
- Improved reliability



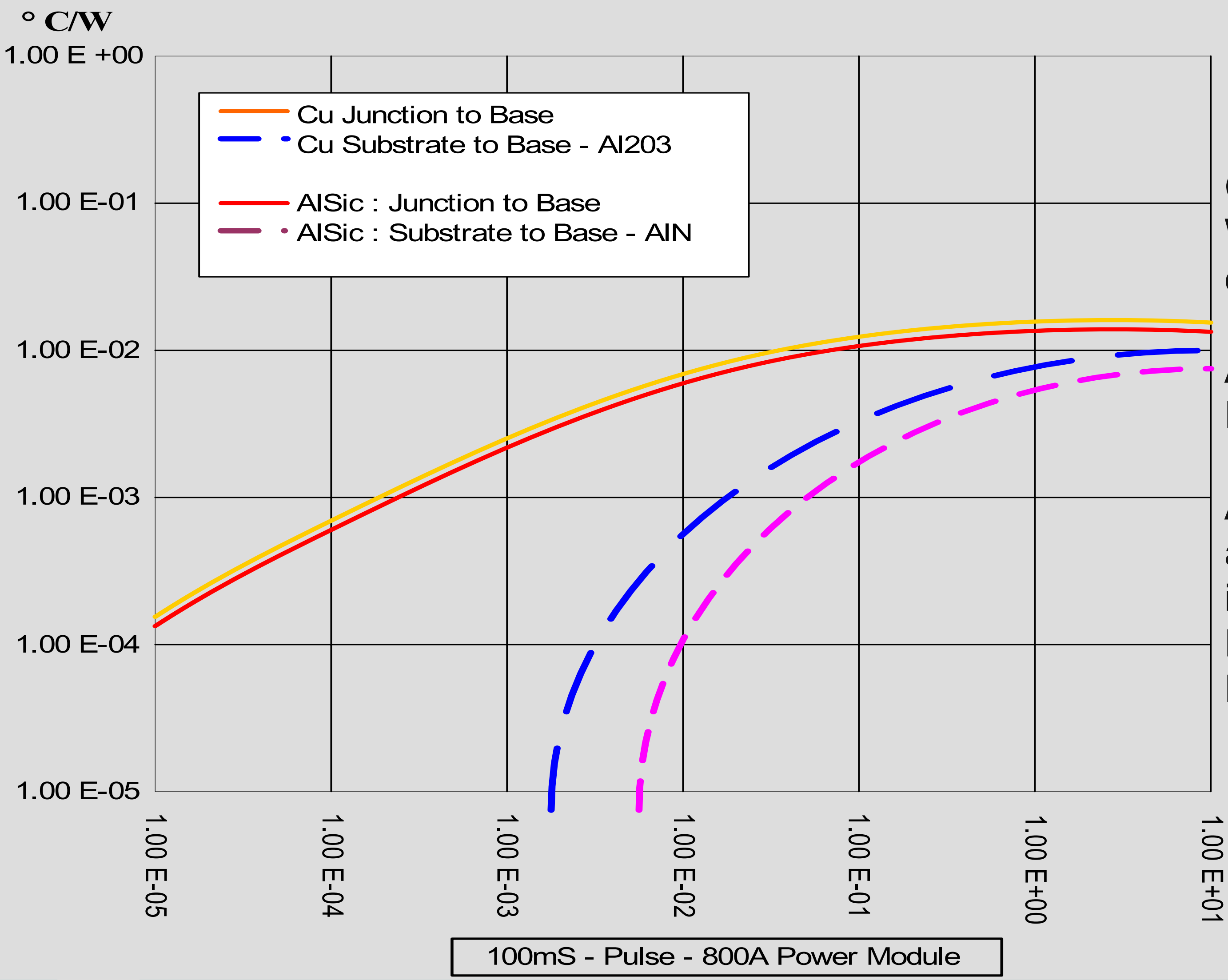
Ballard's CPM has half the parasitic inductance of the competitor's module.

This results in less wasted energy storage.

Direct benefits are:
- ✓ lower voltage overshoot => better bus utilization
- ✓ 5% decrease in total inverter loss
- ✓ lower EMI



Transient Thermals



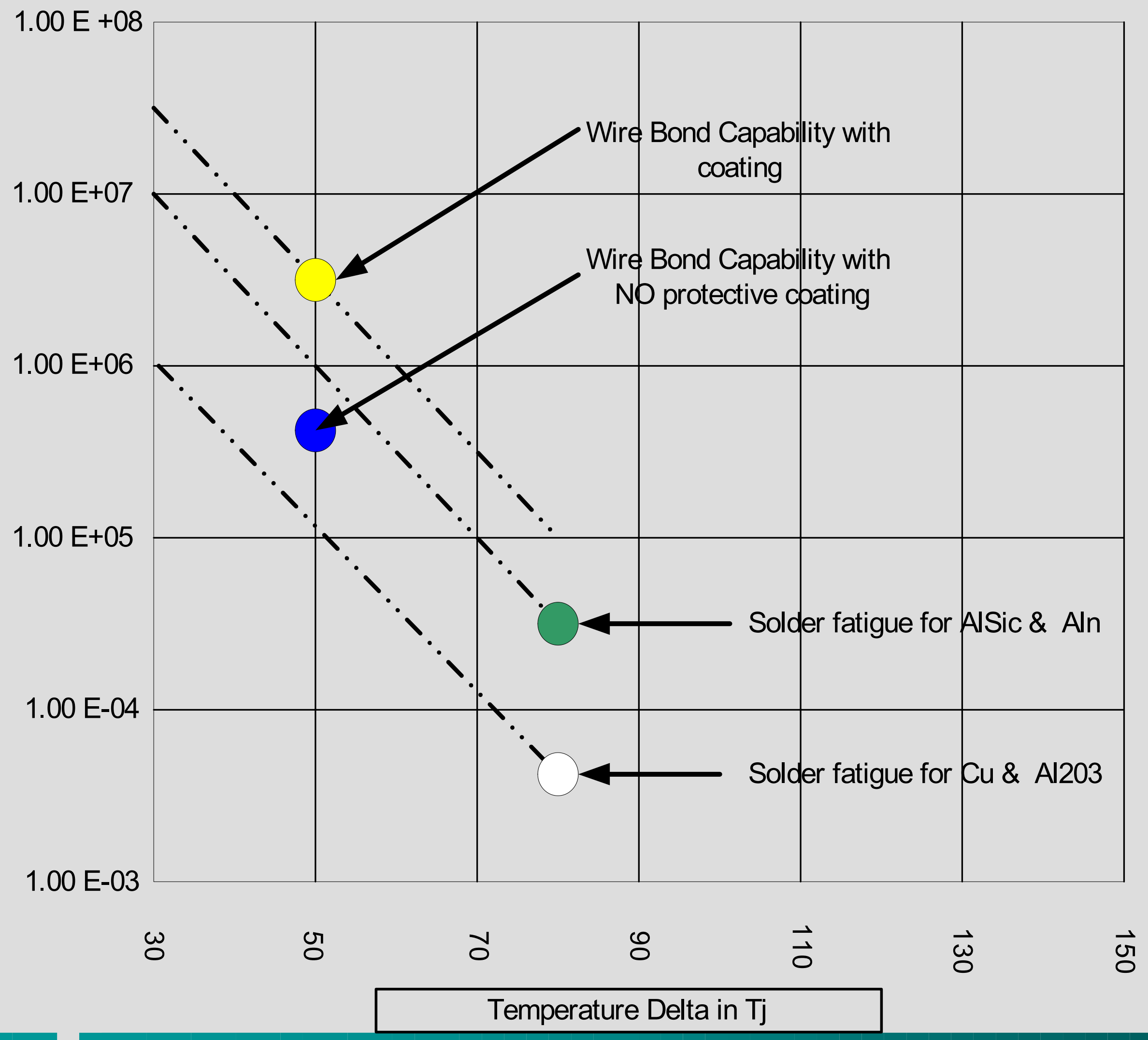
Comparison

Cu baseplate
With Al203 DBC
compared to

AlSic and Aln
DBC.

AlSic & Aln offers
a 10% improvement
in thermal resistance
Due to the Aln
DBC substrate

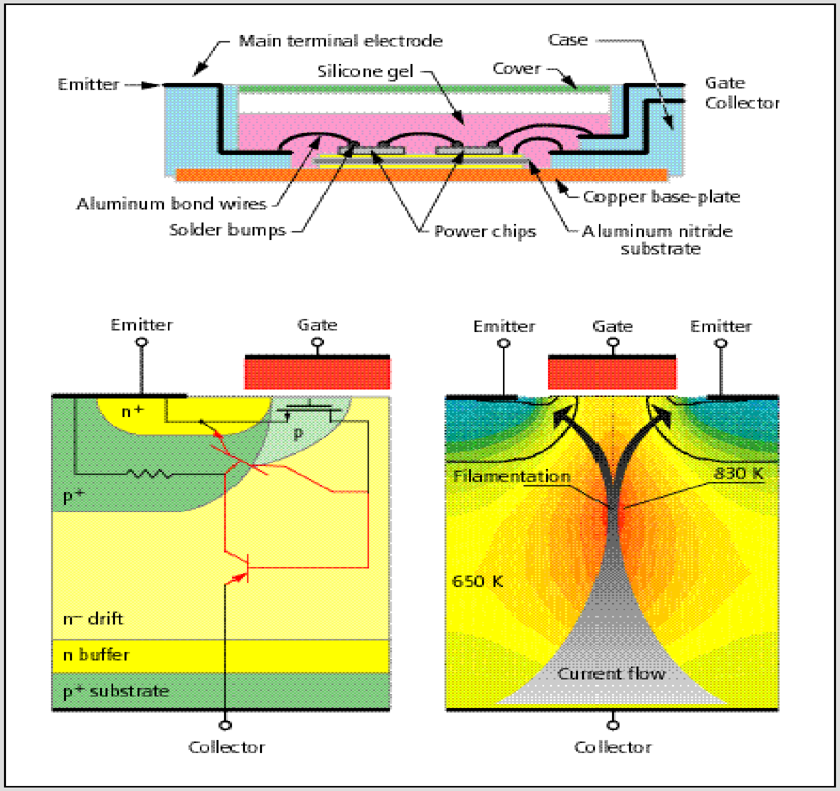
Materials Reliability



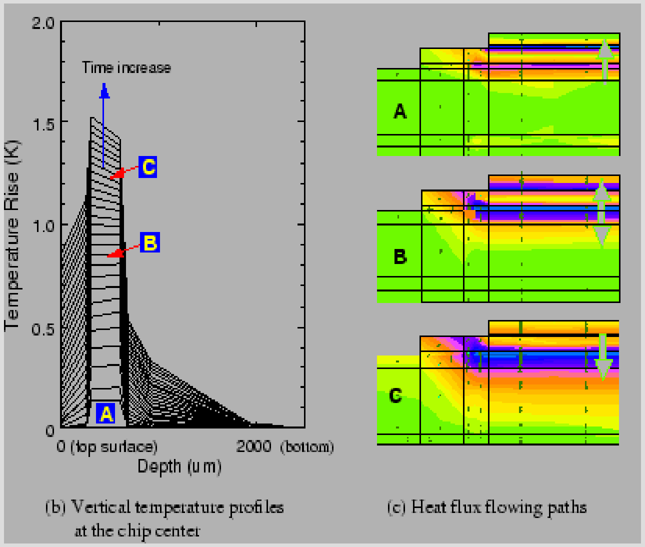
Comparison

- Cu with Al203
- AlSic with Aln
- Wire Bond Coating improvement

POWER SILICON



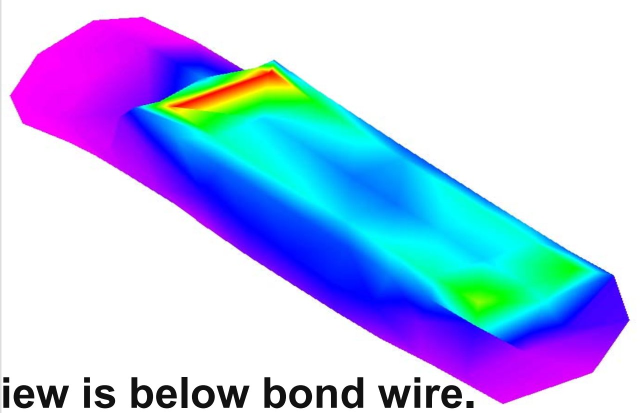
- IGBT Heat Diffusion



(b) Vertical temperature profiles at the chip center

(c) Heat flux flowing paths

- Stress in bond wire.



This view is below bond wire.

- IGBT Devices evaluated -
Eupec, Semikron, ABB, Toshiba, Hitachi, Fuji

IGBT Technical Trend for Cross Section (600V – 1700V)

Conventional Design

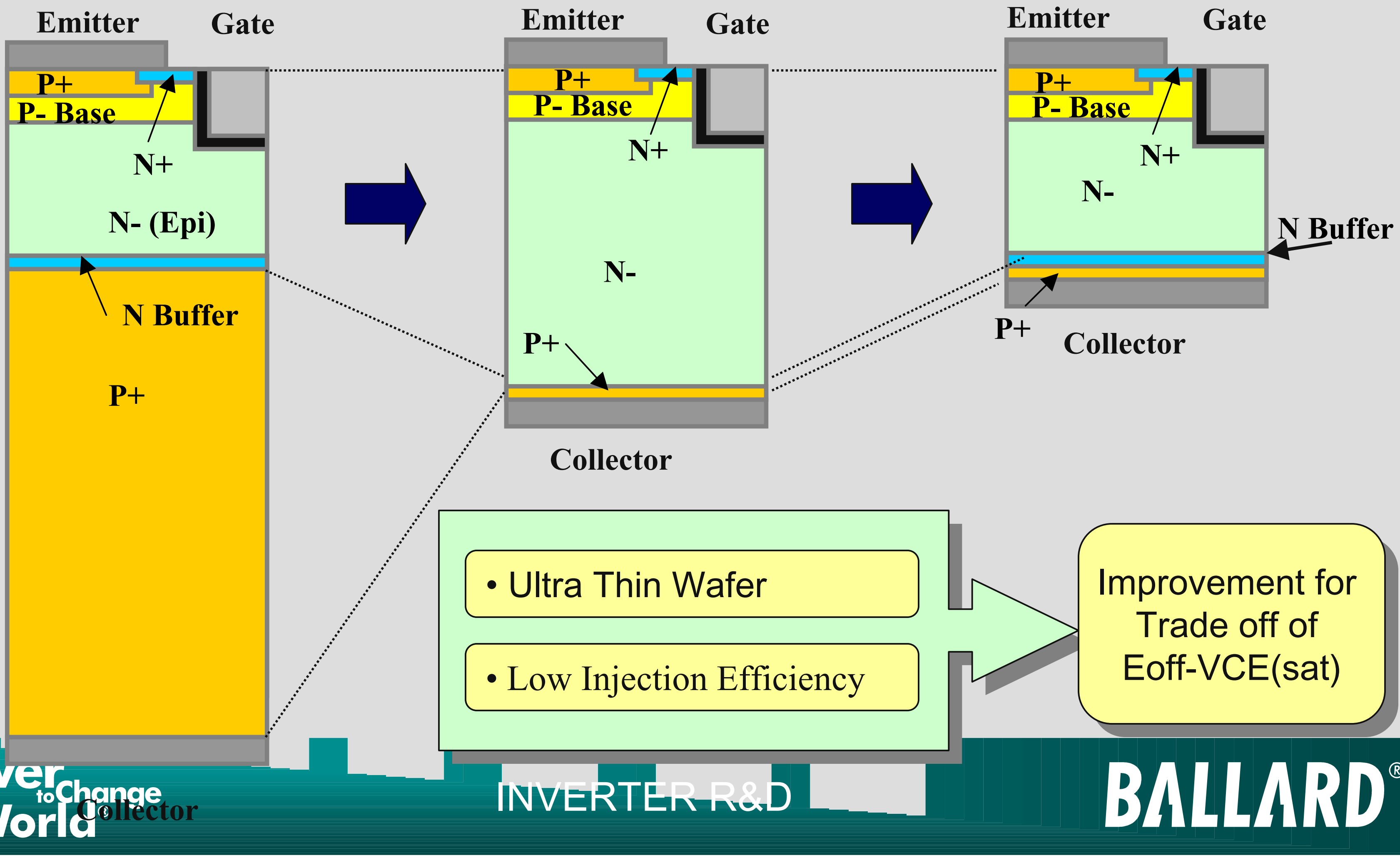
PT-Trench

Current Design

Thin NPT-Trench

Future Design

Ultra Thin PT-Trench

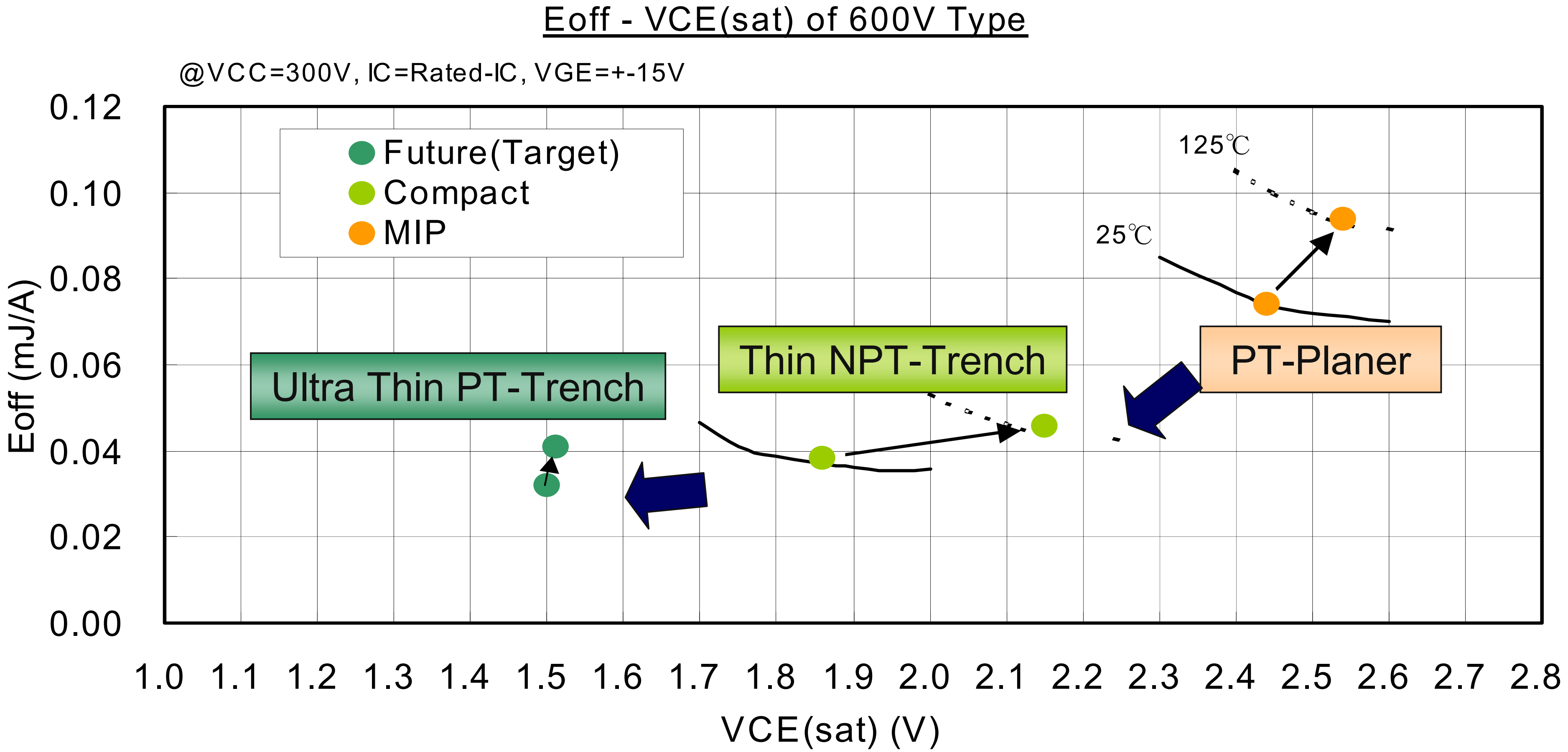


- Ultra Thin Wafer
- Low Injection Efficiency

Improvement for Trade off of Eoff-VCE(sat)

600V IGBT Eoff-VCE(sat) Trade-off

Ultra Thin PT-Trench (Future) VS Thin NPT-Trench (Latest) VS PT-Planer (Conventional)

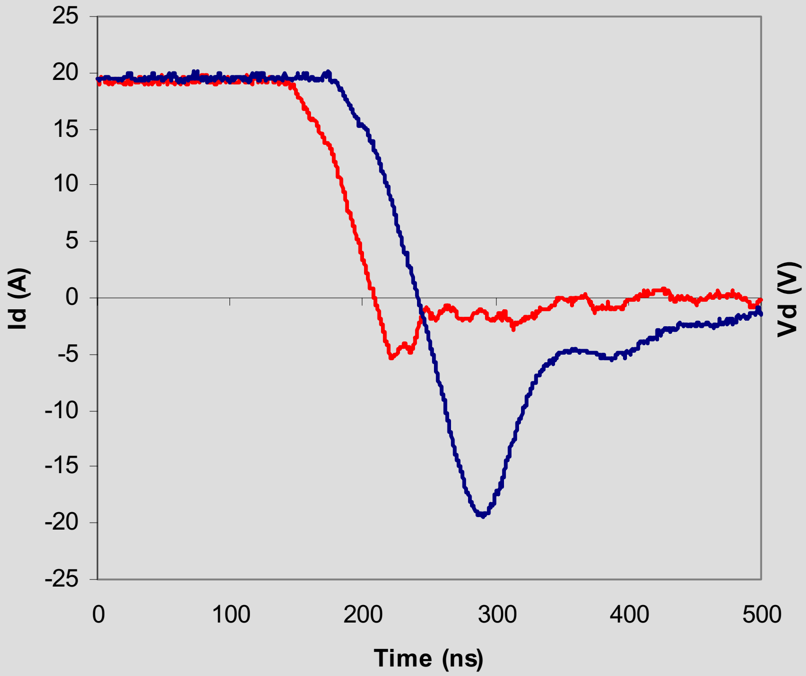


Eoff - VCE(sat) of 600V Type

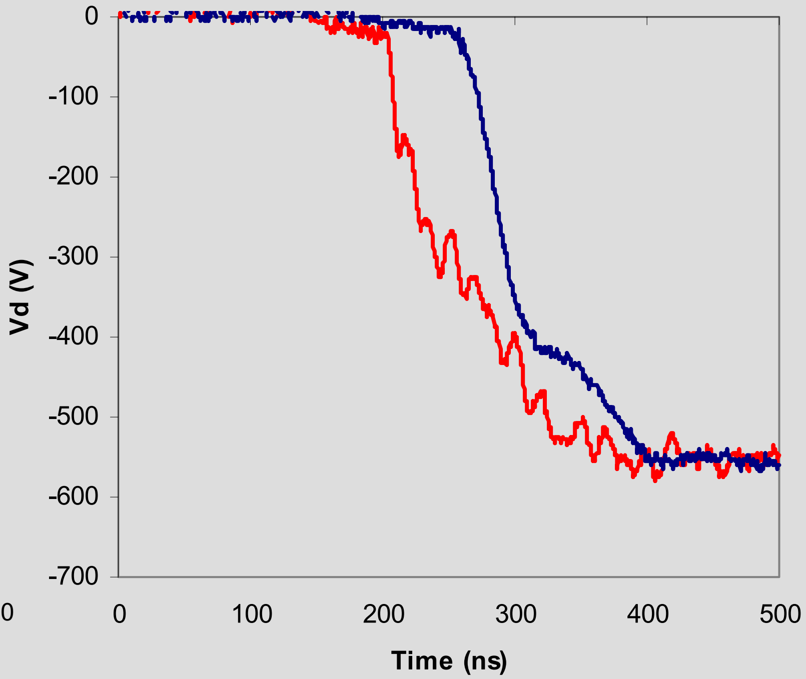
@VCC=300V, IC=Rated-IC, VGE=+-15V

Switching Waveforms

Clamped inductive load switching at 25C.
Red trace SiC, blue trace 1200V hyperfast Si pin diode



current



voltage

Reverse Recovery Summary

25C

		Si PiN	SiC	SiC vs Si
Peak reverse current	Ipr (A)	12.5	3	24%
Reverse recovery time	Trr (ns)	37	19	51%
Recovered charge	Qrr (nC)	231	28	12%
Diode loss	Eoff Diode (µJ)	69	9	13%
IGBT loss	Eon IGBT (µJ)	173	149	86%

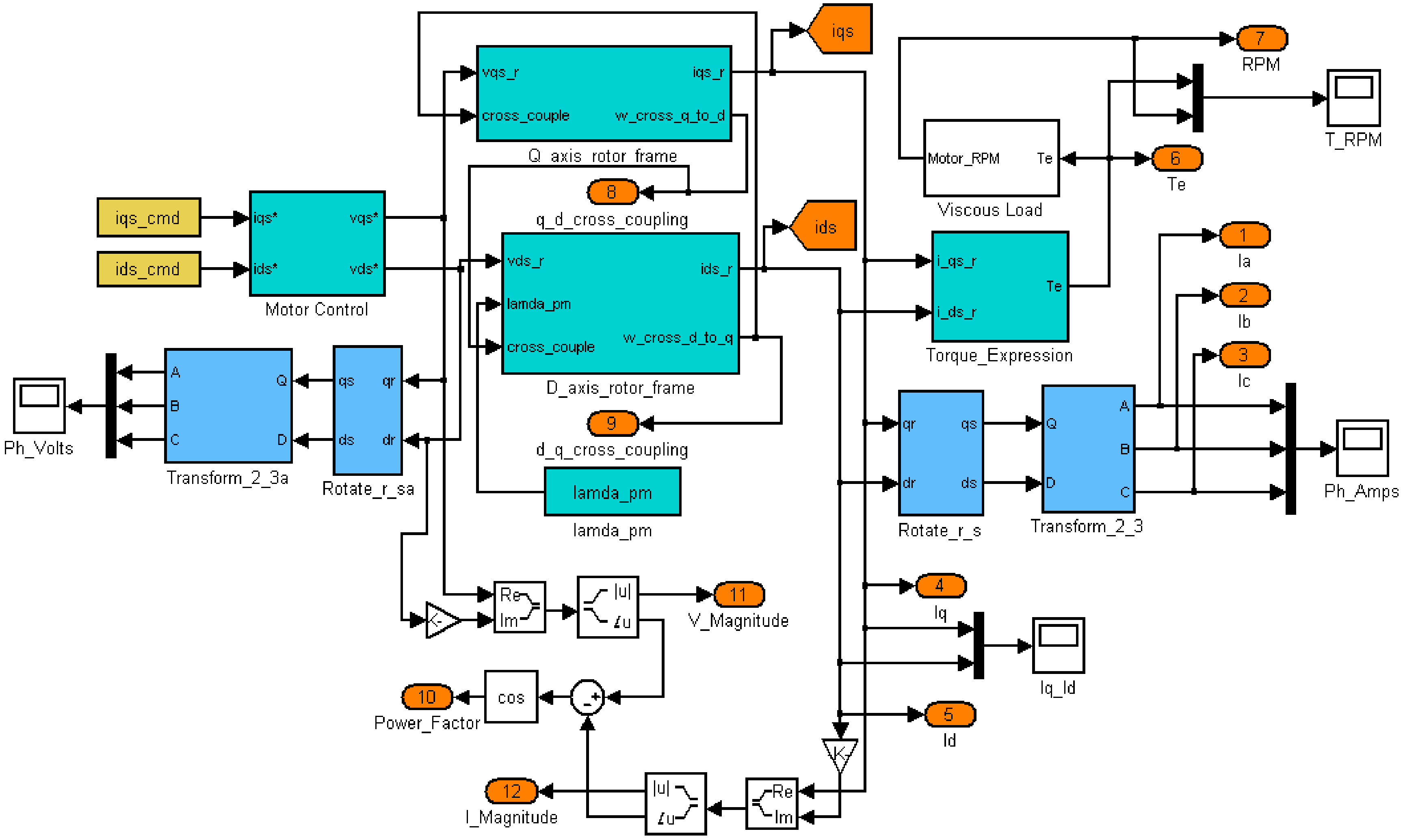
125C

		Si PiN	SiC	SiC vs Si
Peak reverse current	Ipr (A)	17.5	3	17%
Reverse recovery time	Trr (ns)	51	19	37%
Recovered charge	Qrr (nC)	446	28	6%
Diode loss	Eoff Diode (µJ)	139	9	6%
IGBT loss	Eon IGBT (µJ)	198	149	75%

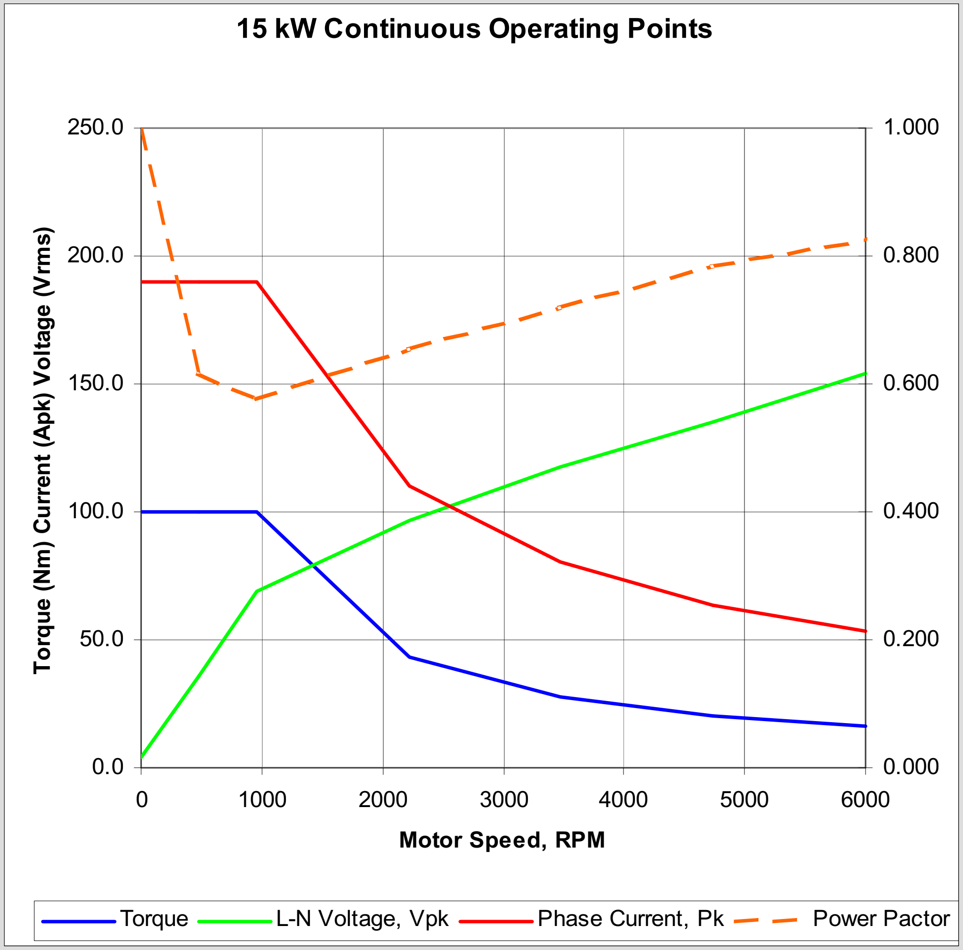
Hybrid Power Inverter Development

Power Inverter Hardware & Analysis for a Hybrid Vehicle Platform

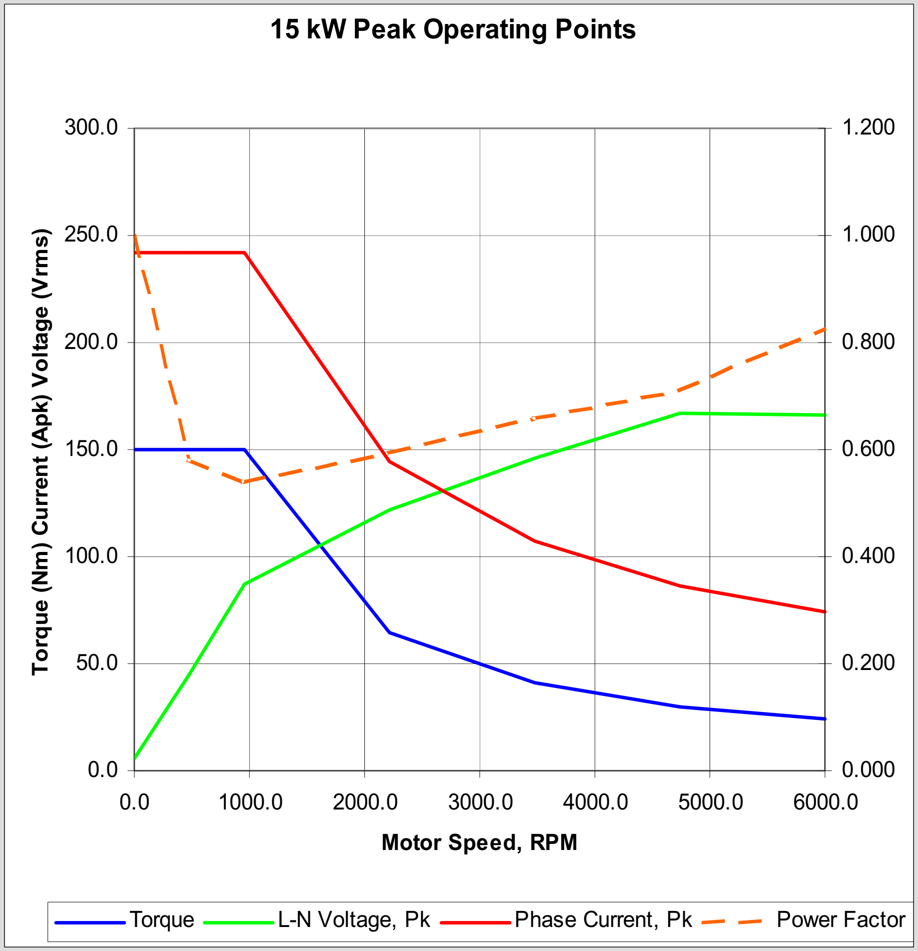
PM Synchronous Motor Model



PM Synchronous Motor – 15 kW Operation

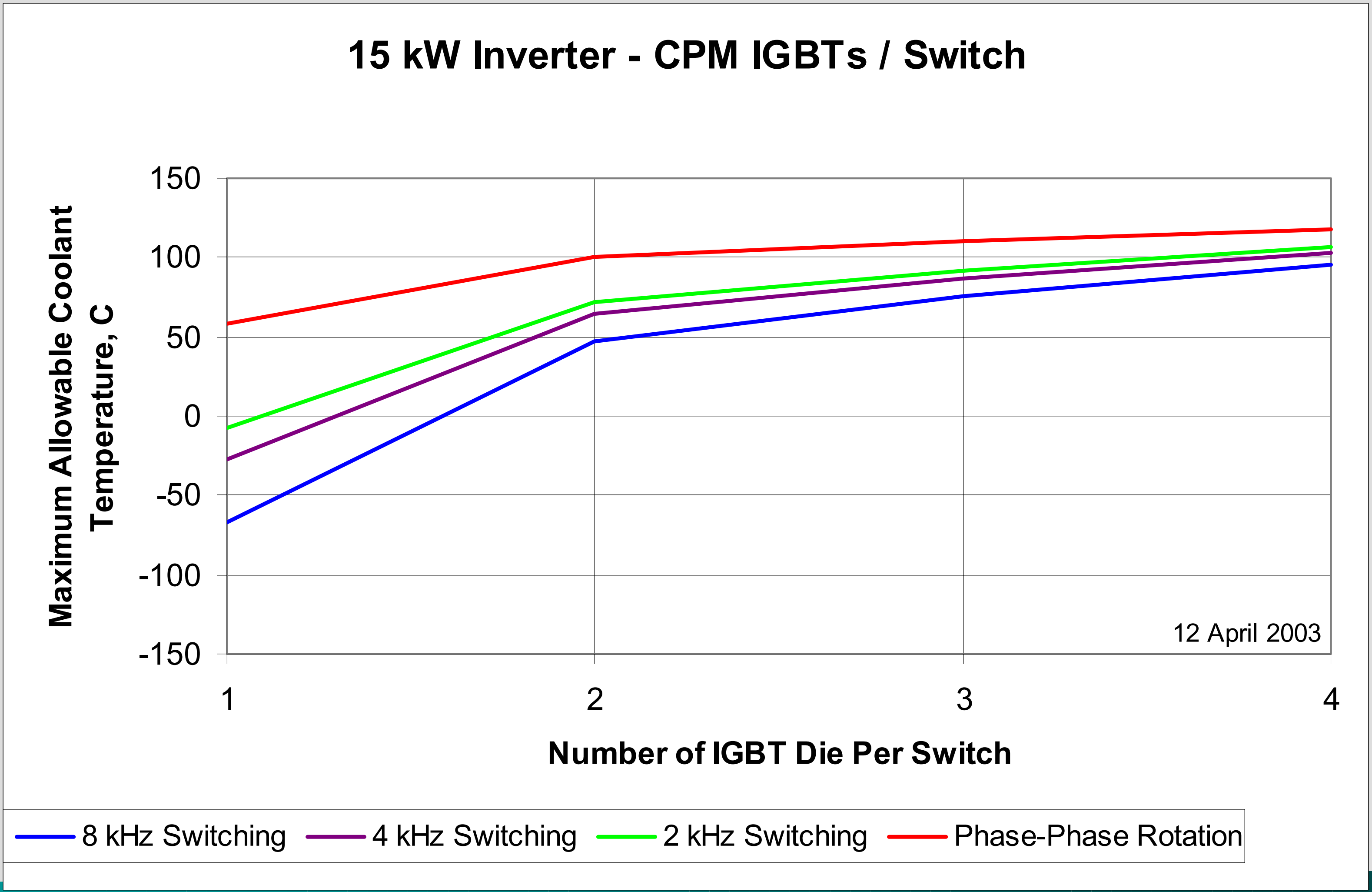


15 kW Continuous Operating Points

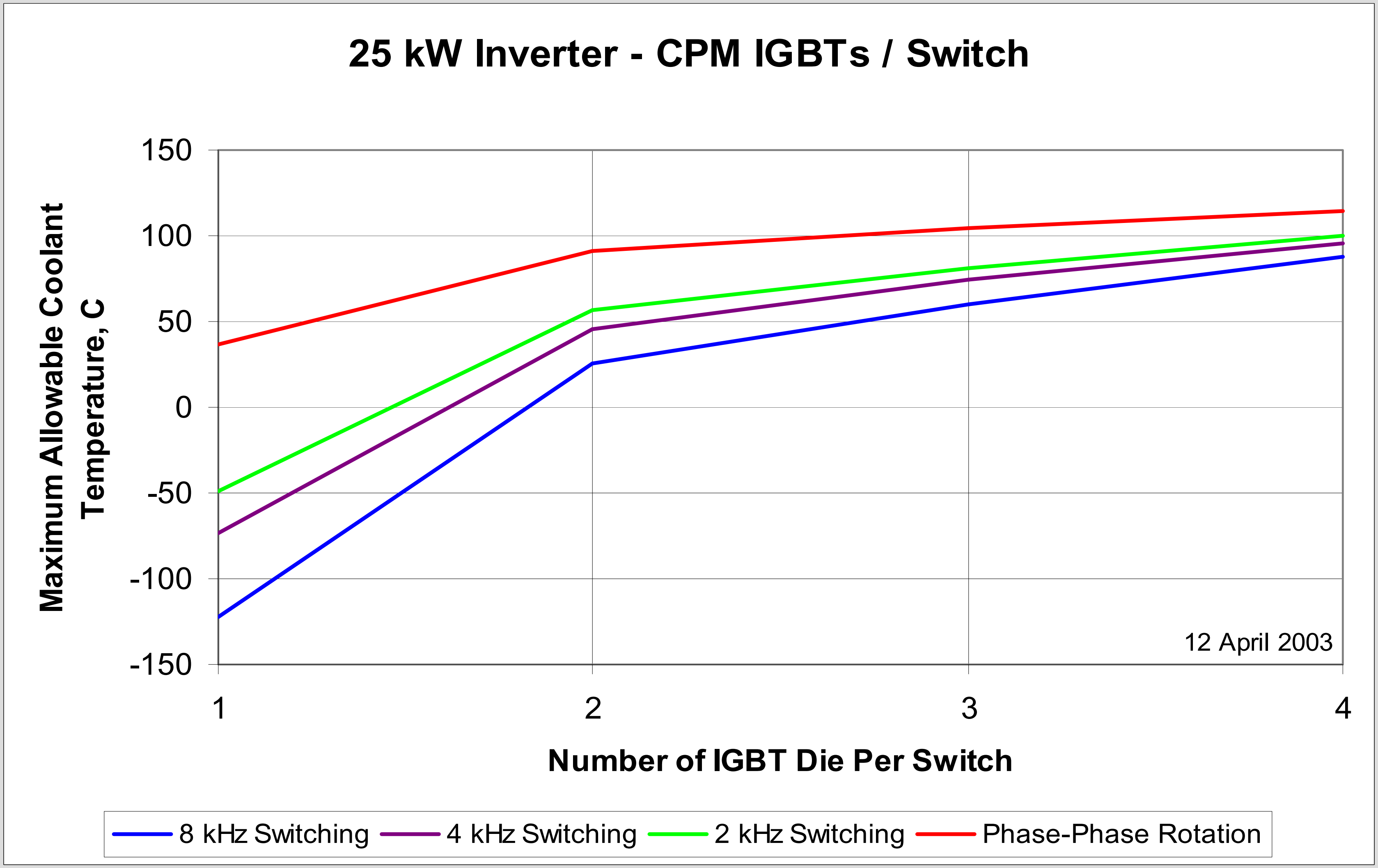


15 kW Peak Operating Points

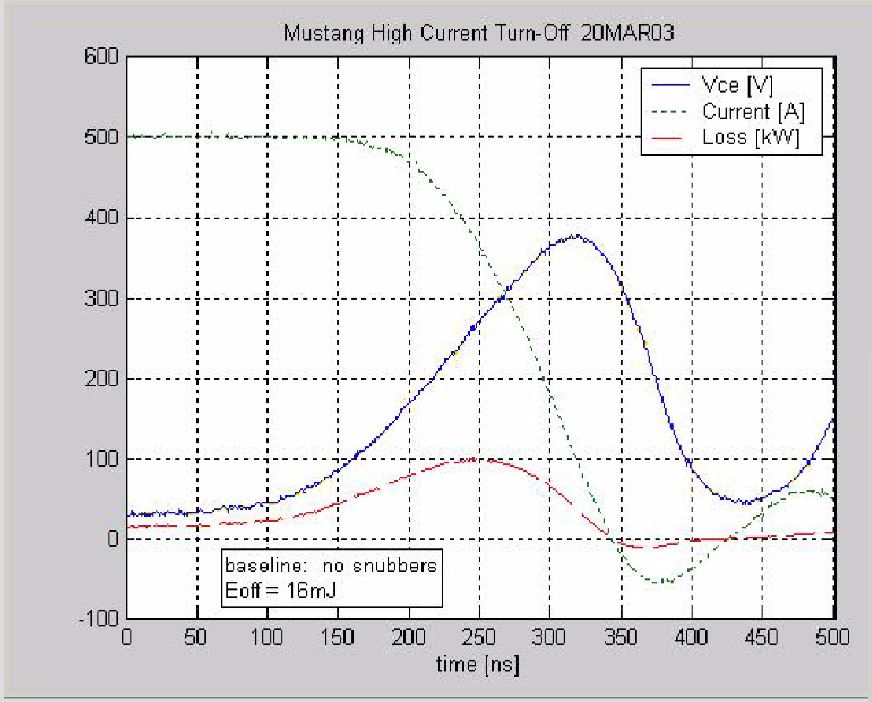
Maximum Coolant Temperature – 15 kW Drive



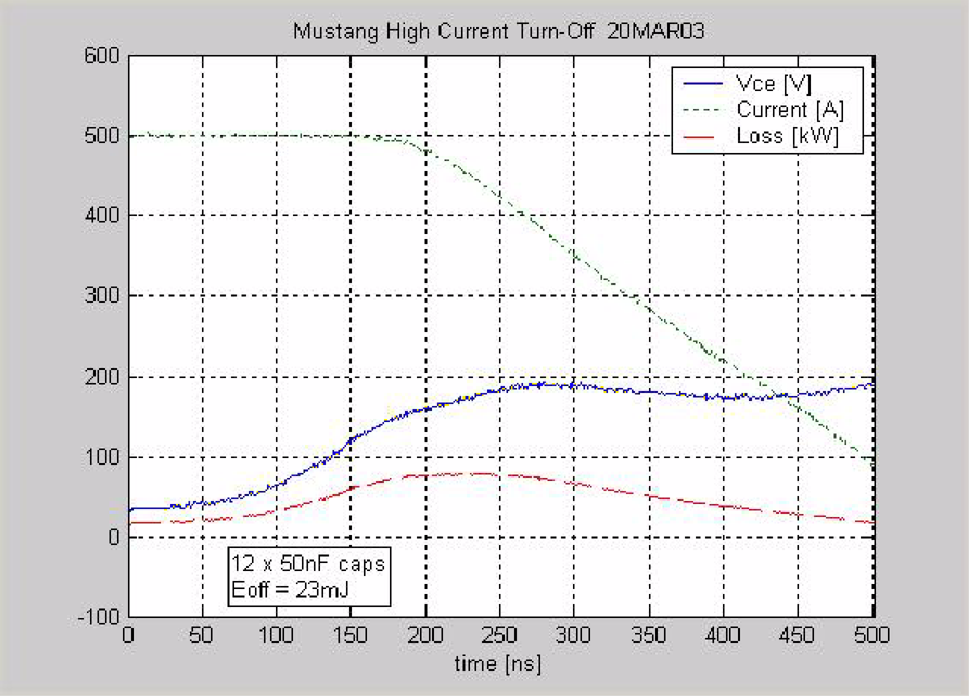
Maximum Coolant Temperature – 25 kW Drive



Voltage Overshoot Reduction

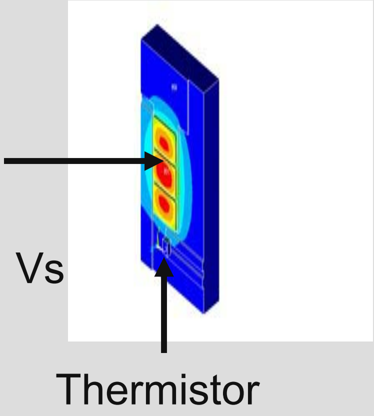


Integrated DC-Bus Snubbers



Further Work

- Faster Temperature Sensing of Silicon Junction.



- Silicon integration of gate drive and sensing circuits.

- EMI containment
  - Turn-on speed and diode recovery.
  - DC Bus Capacitance integrated with Busbar in module.