Advanced Soft Switching Inverter for Reducing Switching and Power Losses

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Powerex

Azure Dynamics

Project Duration: FY08 to FY10

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Outline

- Purpose of Work
- Problems
- Challenges/Barriers
- Approach
- Accomplishments
- Publications and Patents
- Plans for Next Fiscal Year
- Summary

Purpose of Work

Develop advanced soft switching inverter for traction motor drives to support the following DOE targets

- 105°C coolant temperature – by designing the junction temperature <125°C
- 94% traction drive system efficiency – by designing the inverter efficiency >98%

System and Component Level Cost Trade-off with Consideration of Thermal Management System

- Dual cooling loops
  - Need dual thermal management systems, penalty on **system level cost**, size and weight
- Single cooling loop with 105°C coolant
  - Need to beef up silicon or use wide bandgap devices, penalty on **component level cost**
  - Need to use high temperature bulk capacitors, penalty on **component level cost**, size and weight
  - Need to design circuit with high temperature rating, penalty on **component level cost**

Possible Solutions with Single 105°C Coolant Loop

- **Loss reduction by reducing switching frequency** will result in high motor current ripple and associated loss thus reducing the entire drive efficiency.
- **Loss reduction by increasing device switching speed** will result in high dv/dt, di/dt and associated EMI and common mode current issues.
- **Emerging SiC and wide band-gap devices** for high temperature operation is not cost effective today.
- **Junction temperature reduction by reducing thermal impedance** – it helps but not enough.
- **Advanced soft switching with silicon devices to achieve significant loss reduction** – a cost-effective way.

Challenges/Barriers

- **High temperature operation**
  - Need ultra high efficiency design for low voltage high current
  - Need ultra low thermal impedance package
  - Need high temperature capacitors
  - Need high temperature circuit components (opto coupler is a major problematic component)
- **Integration for cost reduction**
  - Need soft switch module for low cost production
  - Need to integrate high temperature gate drivers
  - Need to integrate low EMI auxiliary power supply
  - Need to integrate current sensor and conditioning circuits

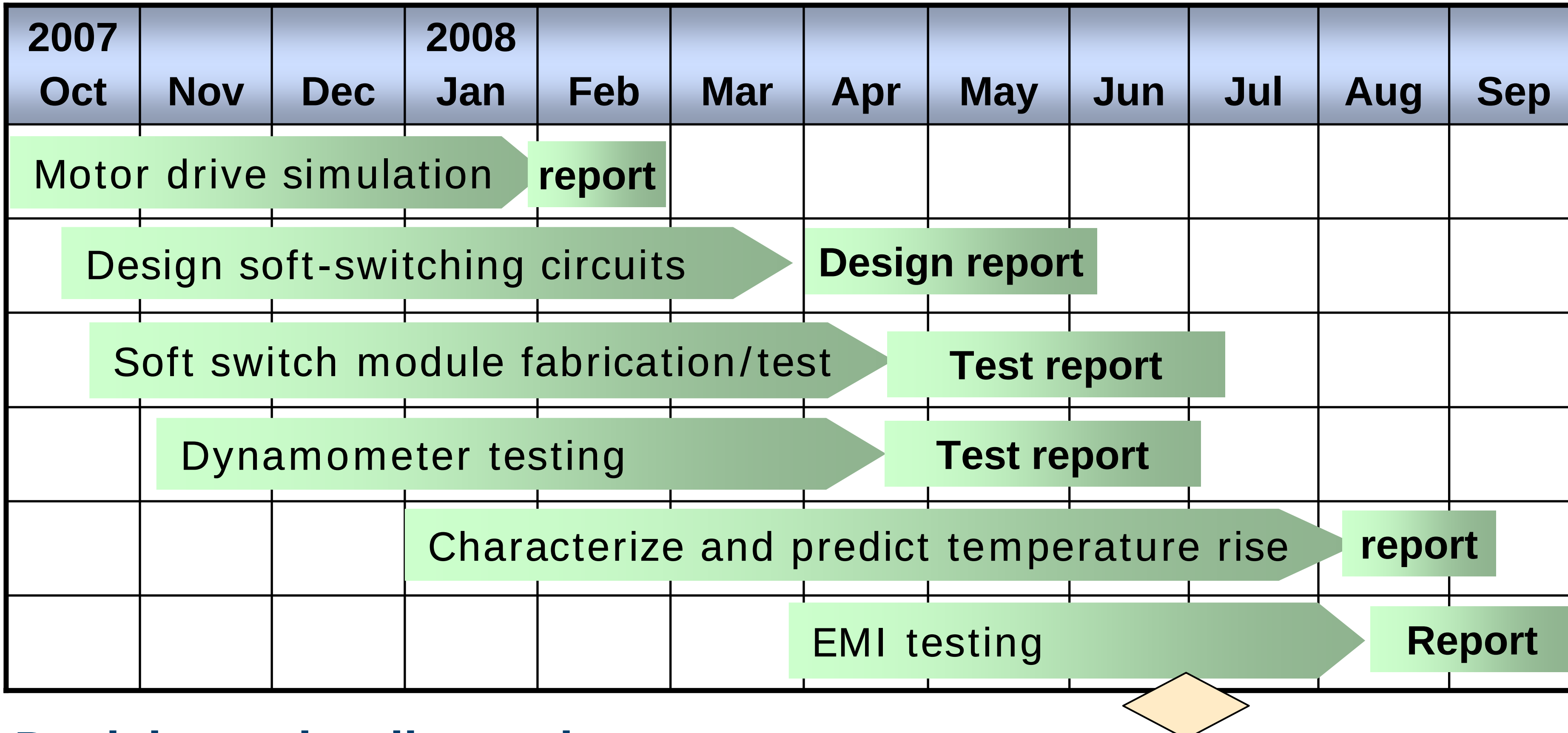
Approach

- Develop a **variable timing controlled soft-switching inverter** for loss reduction.
- Develop **low thermal impedance module with integrated heat sink** for high temperature operation.
- Develop a **highly integrated soft-switch module** for low cost inverter packaging.
- **Modeling and simulation** for design optimization.
- Test the soft-switching inverter with existing EV platform and dynamometer for **EMI and efficiency performance** verification.

Technical Approach for FY08

- **Obtain inverter component V-I stresses through motor drive simulation**
- **Predict device junction temperature through modeling and simulation**
- **Design variable timing control circuit**
- **Design and fabricate high temperature soft switch module for integration**
- **Develop high-accuracy ratio metric calorimeter for ultra high efficiency inverter/dyno testing**
- **Test electromagnetic interference (EMI) performance**
- **Test and validate module level thermal performance**
- **Test and validate Inverter level thermal performance**

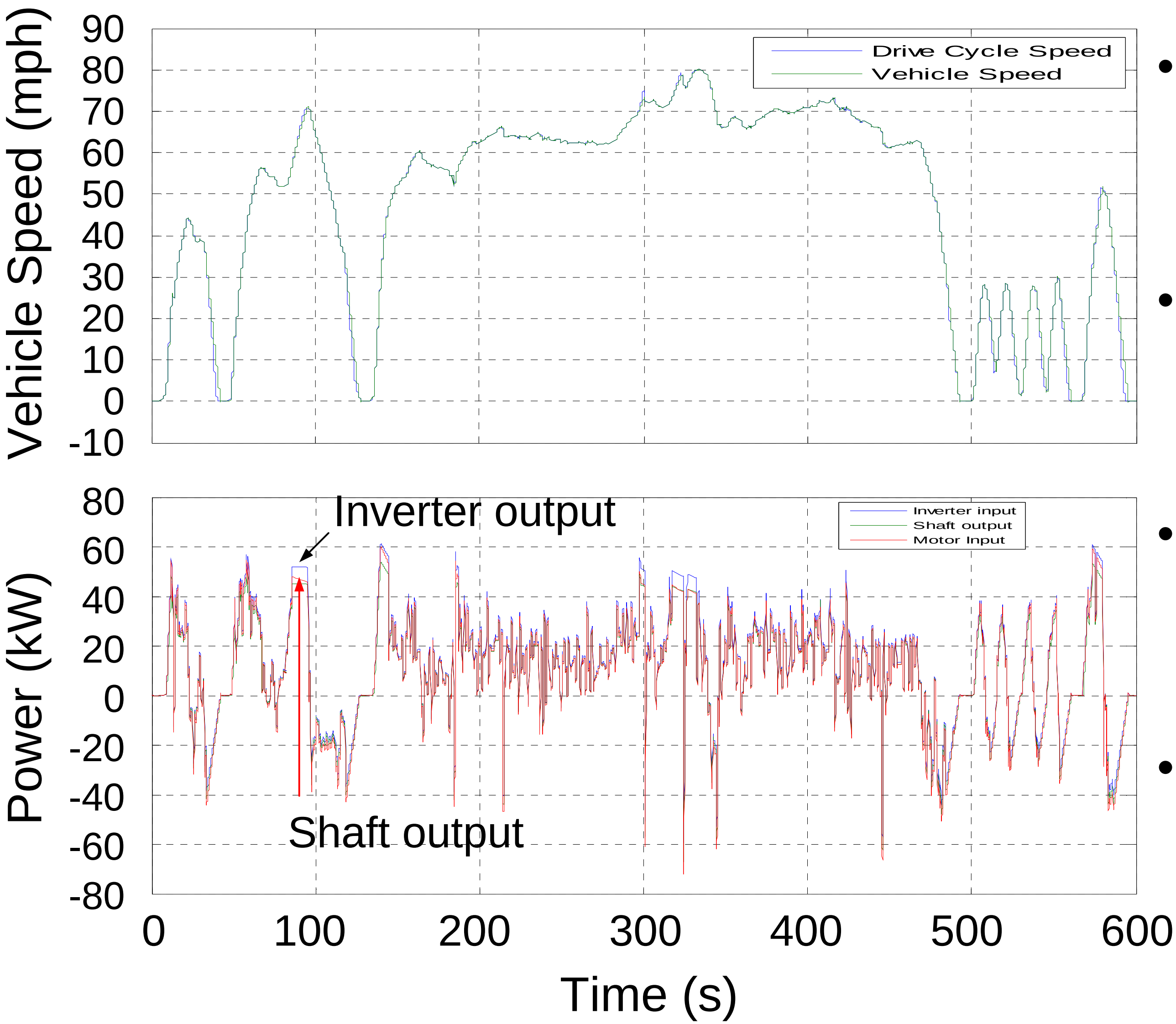
Timeline for FY08



Decision point discussion:

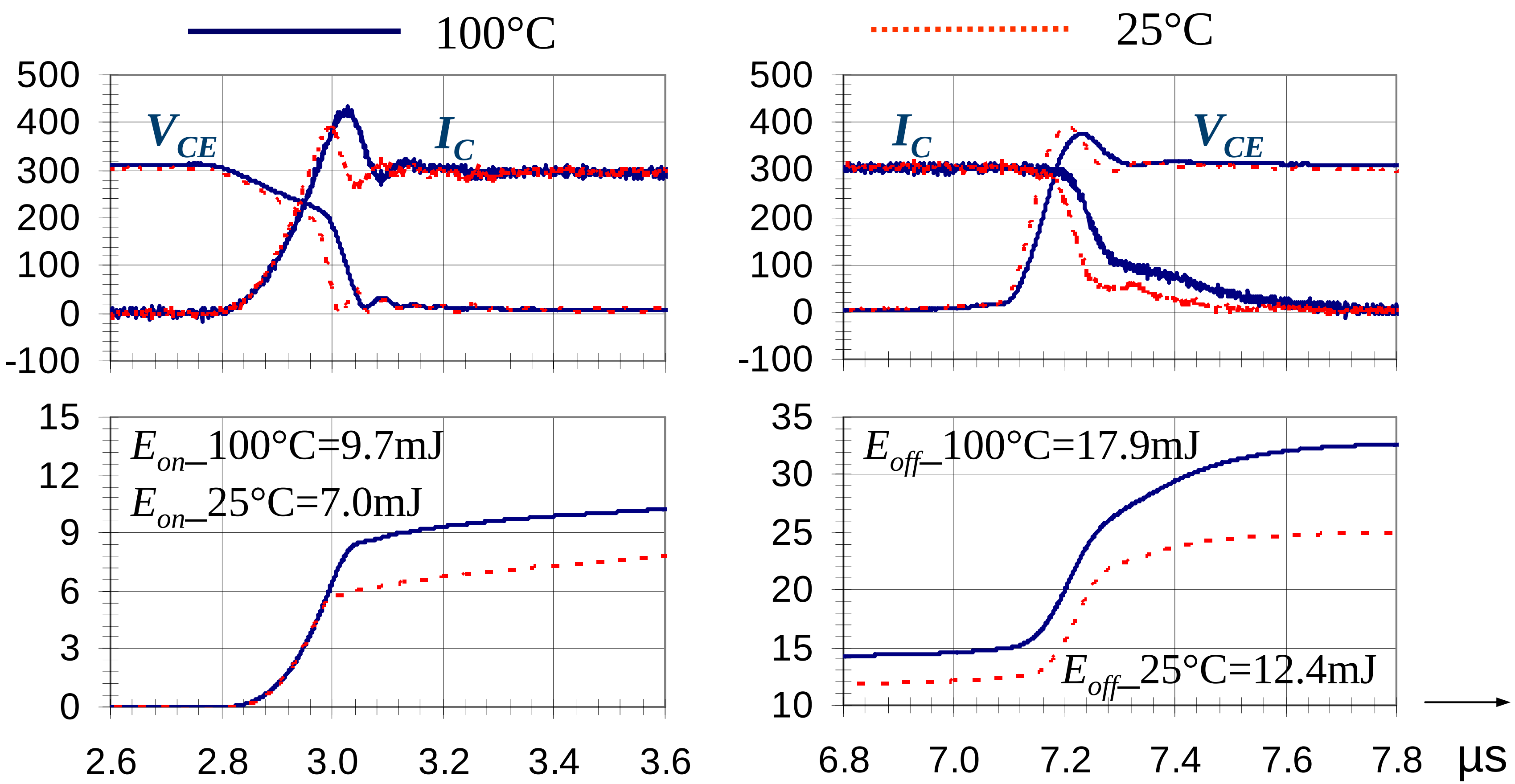
- **Soft-switching inverter efficiency >98%**
- **Low module thermal impedance ensures junction temperature < 125°C under 105° heat sink condition**

Accomplishment – US 06 Vehicle Simulation



- Simulation results show inverter power level, voltage and current stresses
- In a typical driving cycle, vehicle runs below 20 kW most of time.
- Low-power efficiency is crucial to overall drive cycle efficiency
- Inverter peak power reaches 60 kW

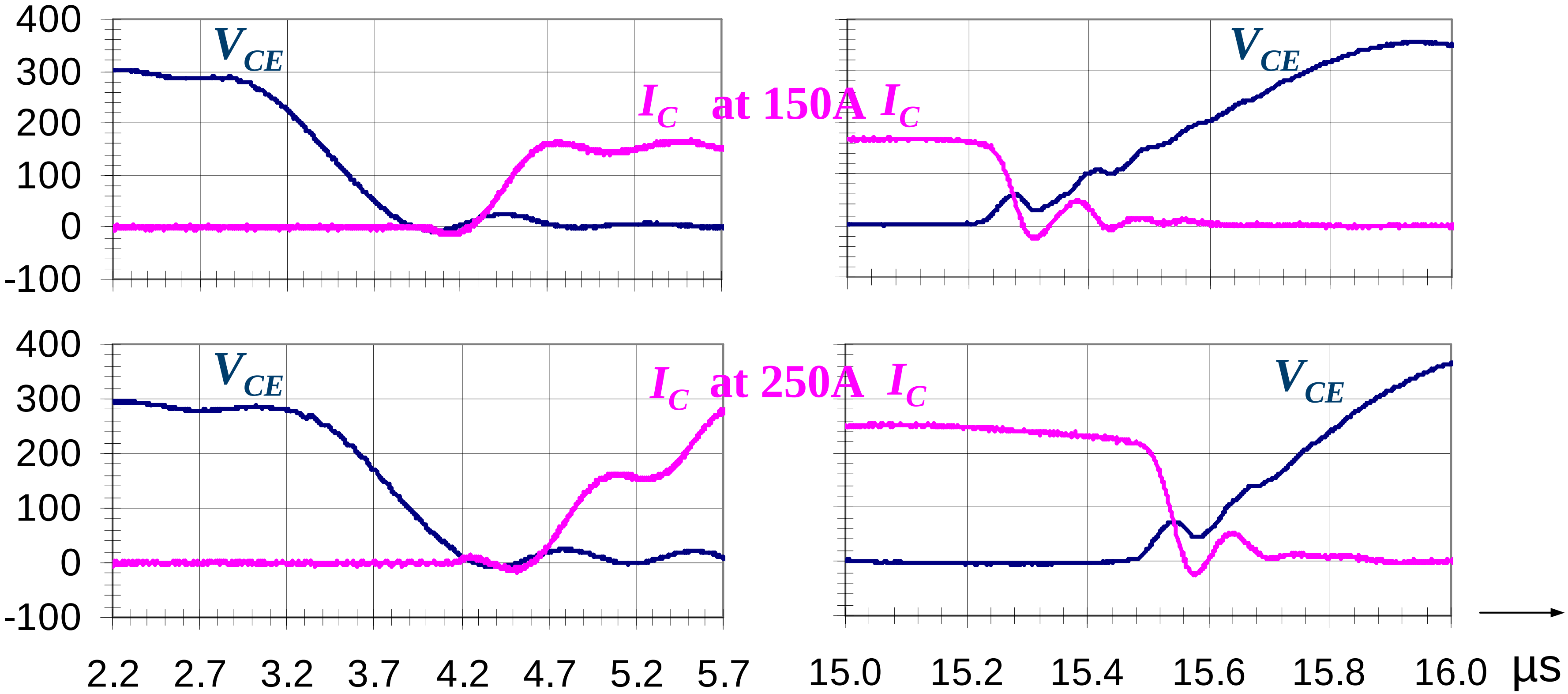
Accomplishment – IGBT Characterization Under Hard-Switching Condition



(a) Turn-on (b) Turn-off

- **Switching speed is significantly lowered under high temperatures**
- **Device switching loss increases by 40% at 100°C condition**

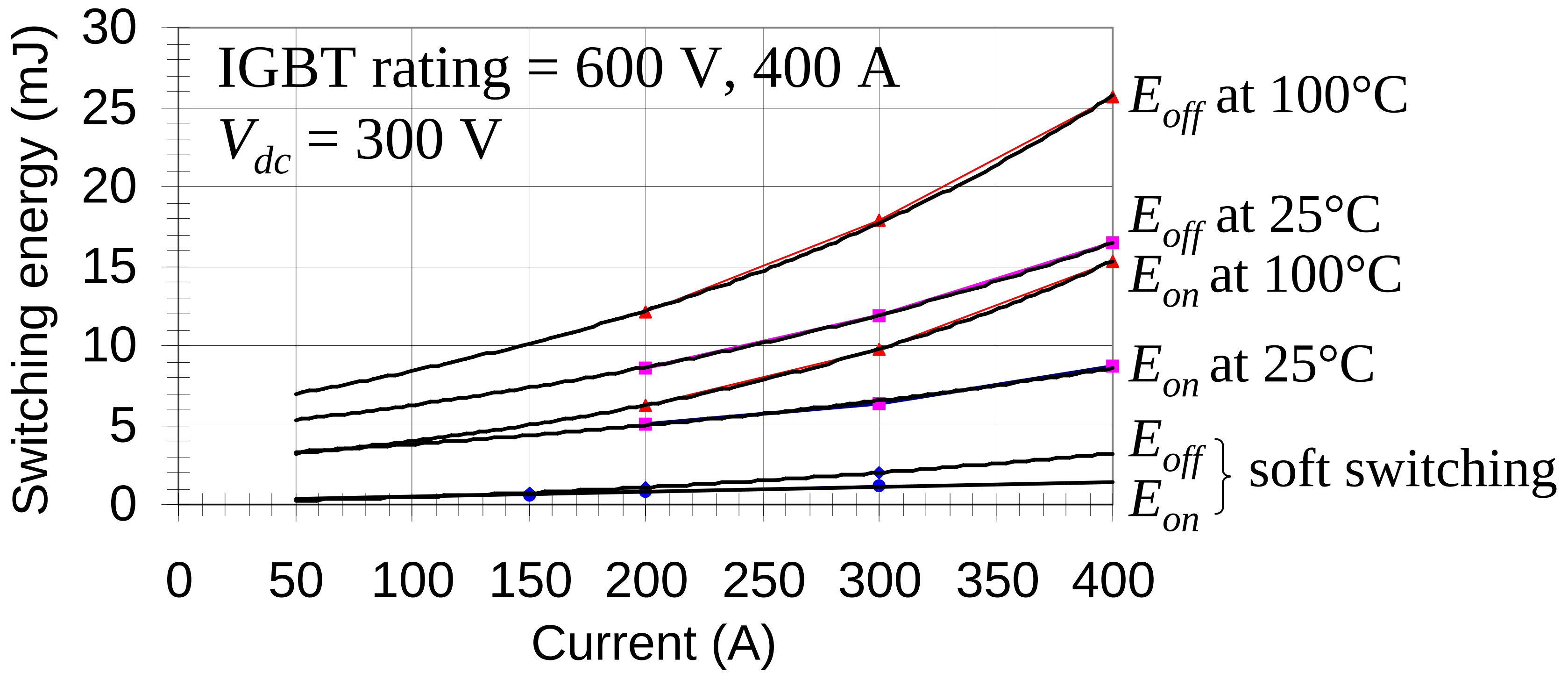
Accomplishment – IGBT Characterization Under Soft-Switching Condition



(a) Turn-on (b) Turn-off

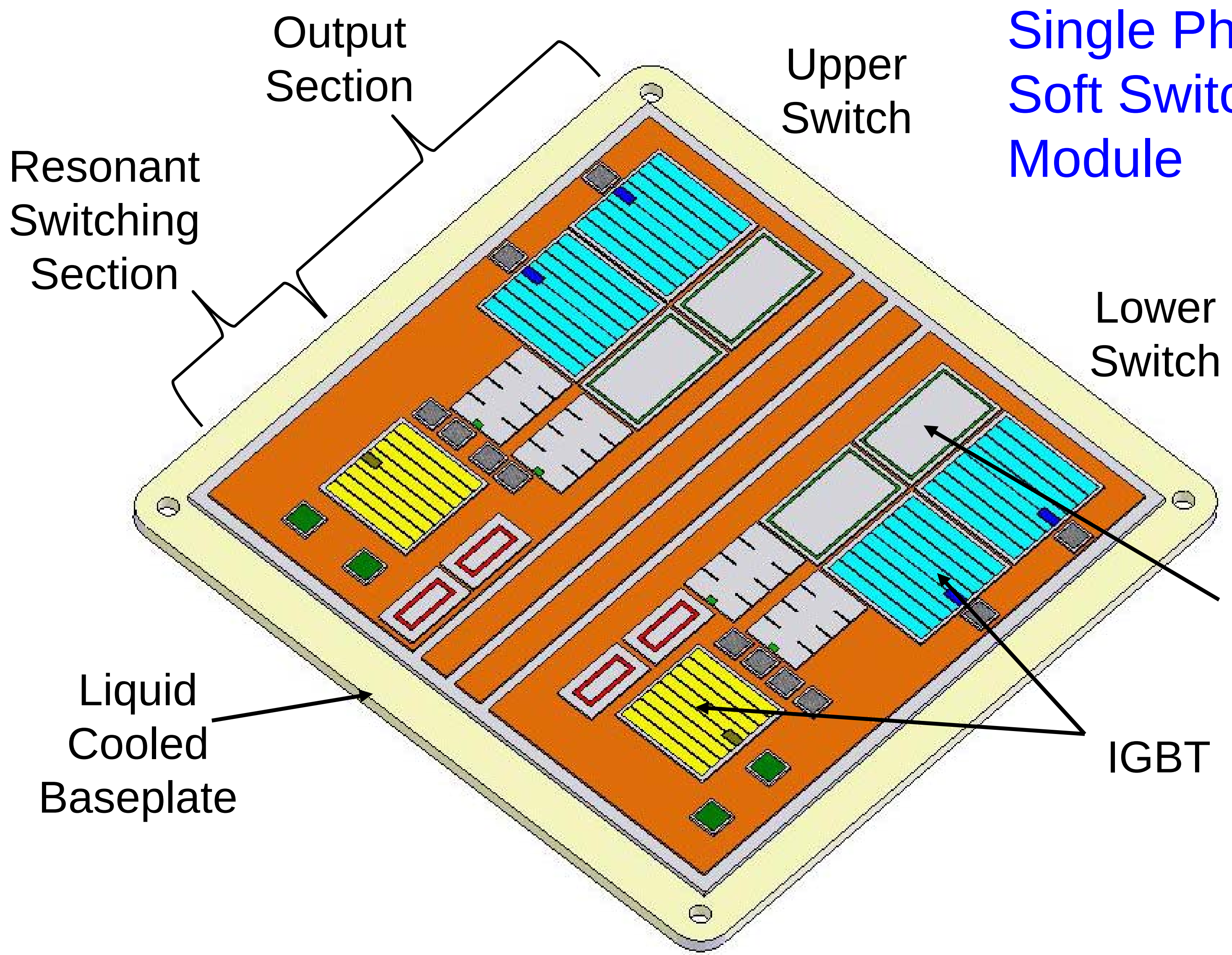
- **During turn-on, current I_C rises after voltage V_{CE} drops to zero**
- **During turn-off, V_{CE} slowly rises after I_C drops to zero**
- **Variable timing achieves soft-switching at all current conditions**
- **Bonus – slow dv/dt that will result in low EMI emission**

Accomplishment – Measured Device Switching Energy Under Different Operating Conditions



- **As compared to 25°C operating condition,**
  - **Device switching loss is increased by 40% at 100°C**
  - **Device switching loss is reduced by 80% under soft switching**
- **Losses in soft switching are due to layout parasitics with discrete components – necessary to integrate the soft switch module**

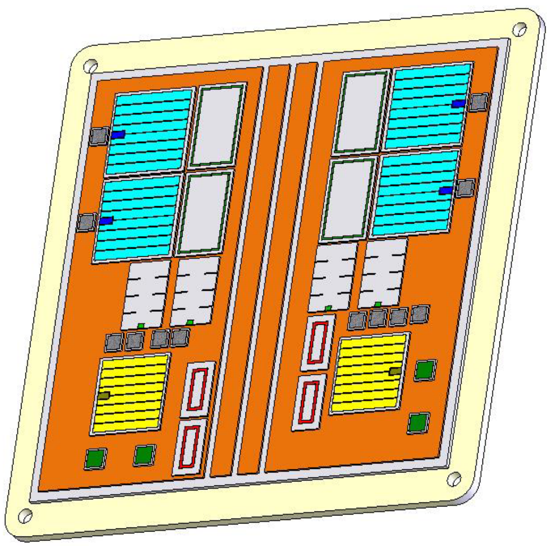
Accomplishment – Half H-Bridge Power Module Chip Layout

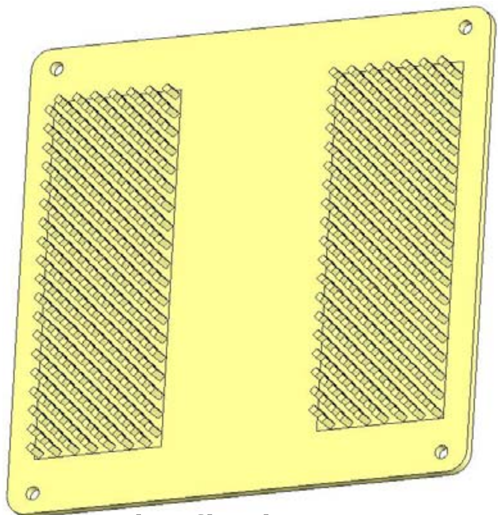


Single Phase-leg Soft Switch Power Module

Accomplishment – 3-D Thermal Simulation Results for Temperature Prediction

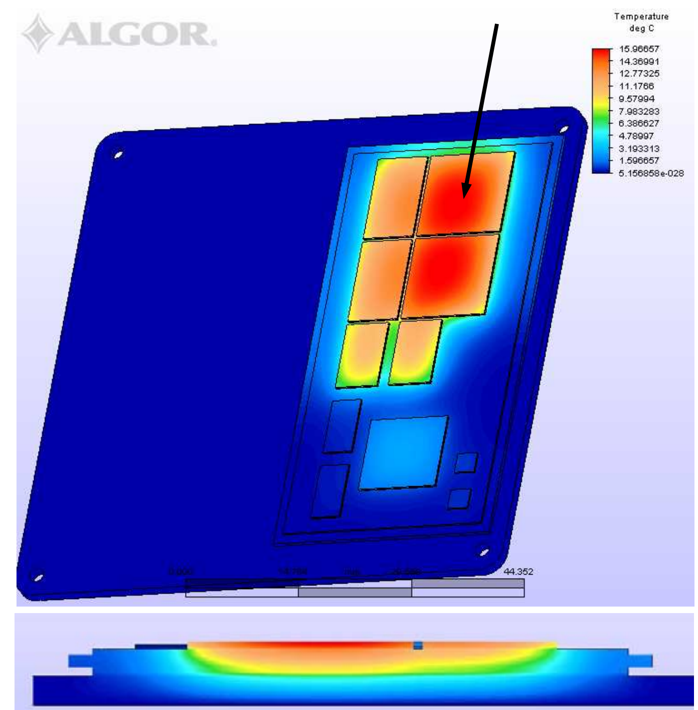
Each die loaded with power dissipations obtained from circuit simulations



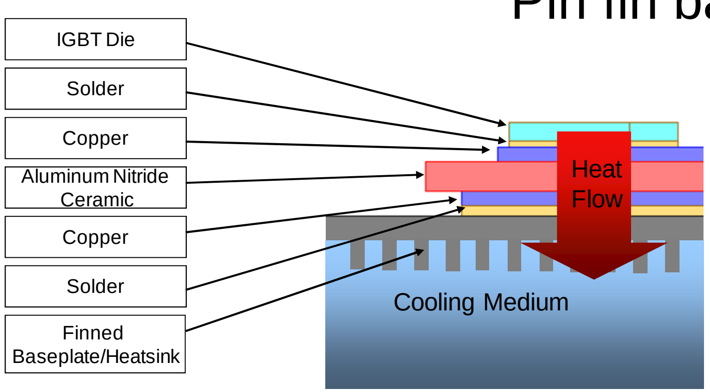


Pin fin base

Output IGBT ΔT = 15 °C above bottom of baseplate

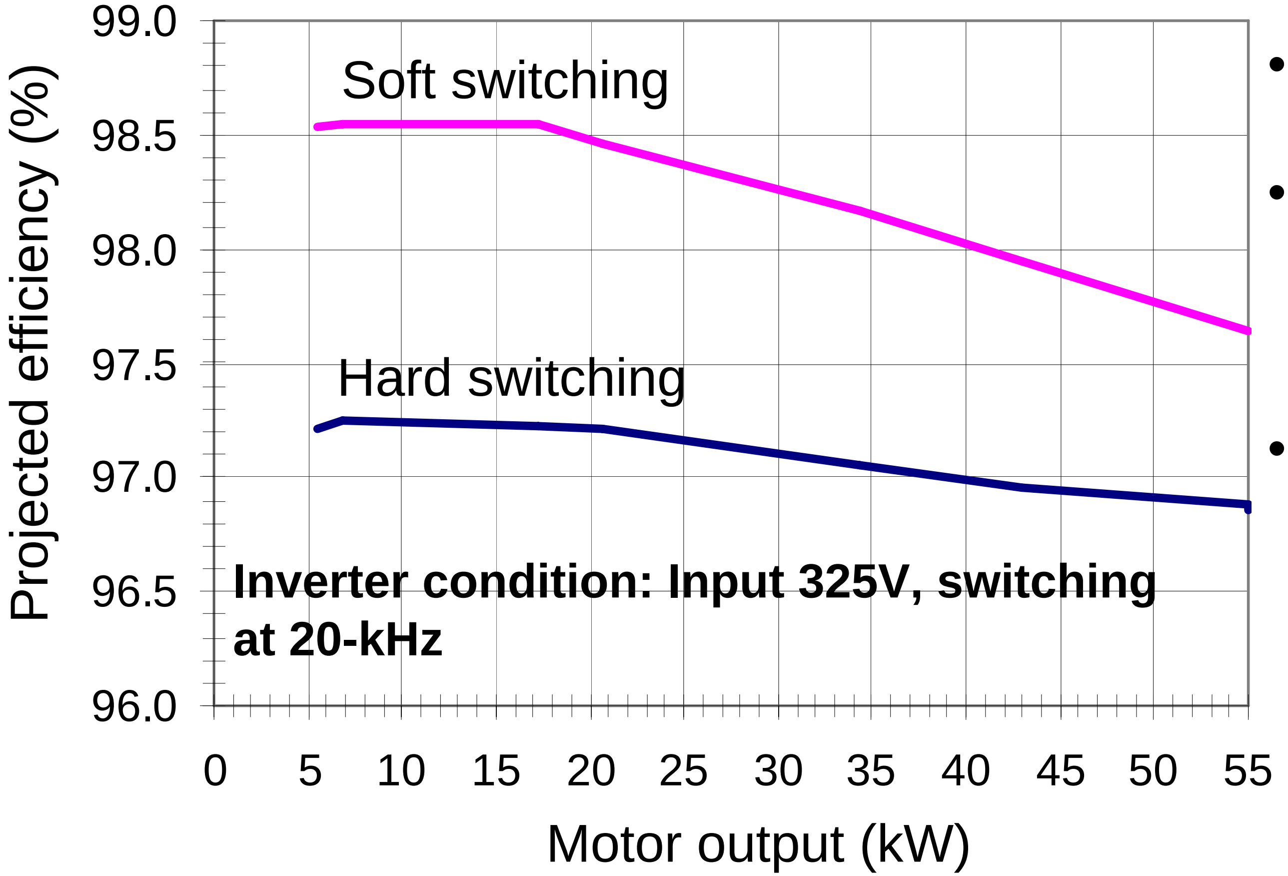


Cross section through IGBT & FWD



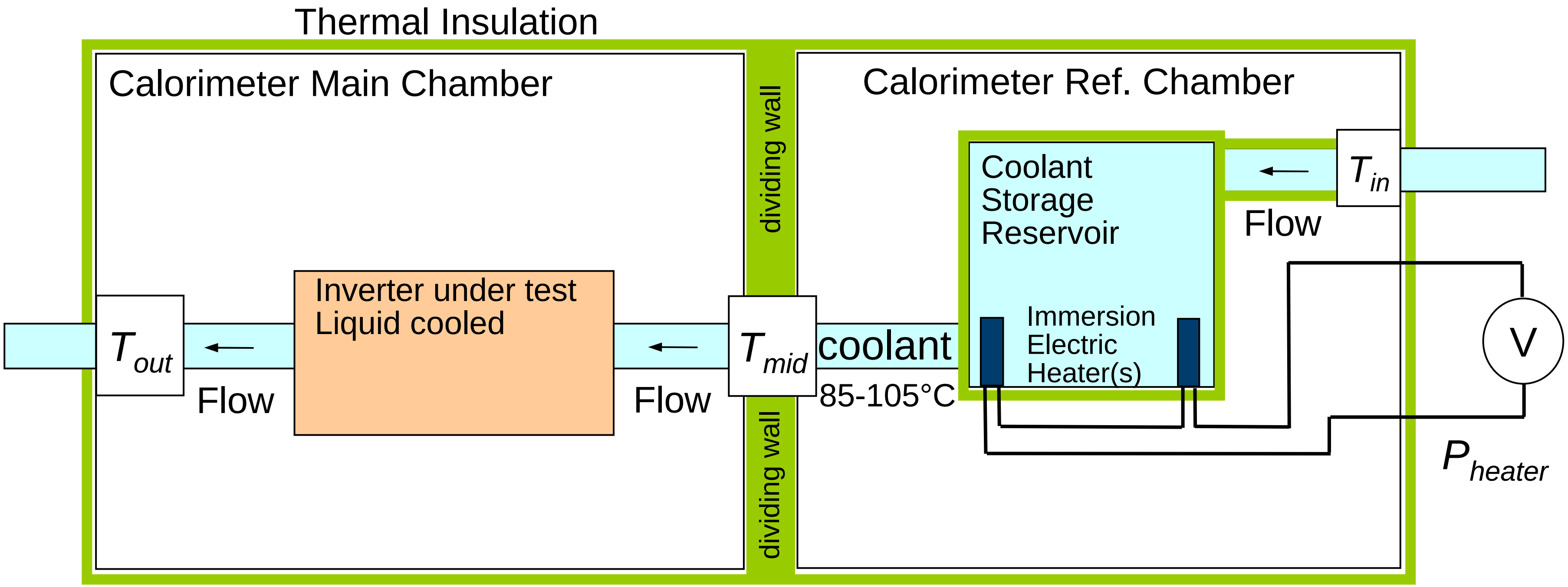
Heat Flow Path

Accomplishment – Soft-Switching Inverter Simulation Results



- Use actual device model in simulation.
- New soft-switching design significantly improves low-power efficiency
- Over 50% loss reduction in low-power region

Accomplishment – Development of Ratio Metric Calorimeter for Ultra High Efficiency Measurement



$$P_{Inverter\_loss} = P_{heater} \frac{T_{mid} - T_{in}}{T_{out} - T_{mid}}$$

- Measure electric power out over power in results in poor efficiency accuracy at this power and efficiency level
- Calorimeter gives accurate power loss
- Provides method to control temperature of coolant

Publications/Patents

- **1 technical paper under preparation**
  - **High temperature hard- and soft-switching device characterization**
- **3 invention disclosures under preparation**
  - **variable timing circuit for soft switching**
  - **new soft switch**
  - **new soft-switching inverter**

Activities for Next Fiscal Year

- Variable Timing Soft-Switching Inverter Demonstration
- Thermal Characterization of Gen-1 Soft-Switch Module
- Gen-2 Soft-Switch Module Design Optimization
- Package 9 Soft-Switch Phase-Leg Modules
- Package 2 Gen-2 Soft-Switching Inverters

Preparation for In-Vehicle Testing

Summary

- Potential for petroleum displacement
  - Advanced soft-switching inverter for significant loss reduction, and thus 105°C operation is possible for system level cost reduction and reliability improvement
- Approach to research
  - Modeling and simulation to predict the device requirement, junction temperature, and inverter efficiency
  - Design of a novel soft switch module and a low-cost variable timing control to achieve soft switching over a wide range
- Technical accomplishments and timeliness thereof
  - Completed most simulations, circuit design for variable timing control, and high-accuracy dyno test setup
- Technology transfer
  - 3 invention disclosures and 1 technical paper under preparation
- Plans for next fiscal year
  - Demonstrate high-efficiency inverter drive with the proposed design

Questions

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