



ASSESSING THERMAL BUFFERING HALF-BRIDGE INTERCONNECTS FOR ENGINE COMPARTMENT TRACTION INVERTER

Power Electronic Thermal Buffering Interconnects

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PICHOT OVERVIEW: WHAT AND WHY?



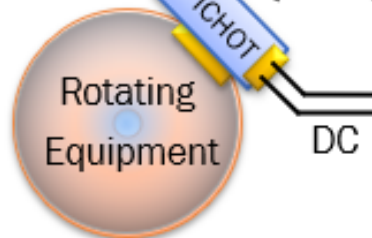
Power Inverter, Compact and High Operational Temperature

WHAT

200kW Power Inverter

No Extra Cooling
Equipment

105°C Engine
Coolant



RF quiet

4x Power

Density
200,000 W

Wireless
Gate Drivers

Advanced
Heat Flow

Reliable
SiC Health

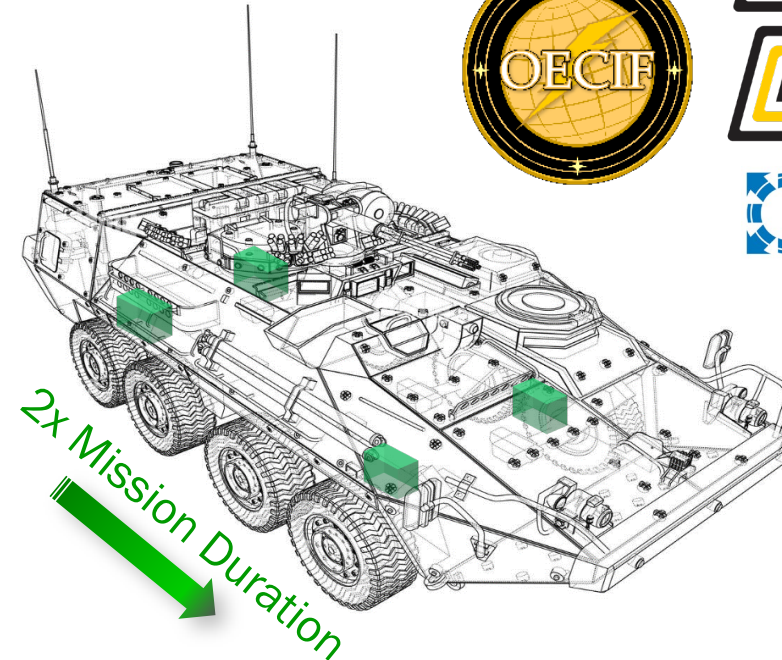
200kW Bidirectional DC $\leftrightarrow$ 3- Φ Motor & Generator

Technology Improvements:

- Quadrupled power density
- Eliminates RF-emitting bulky AC cables
- SiC health prediction (PPMX)

WHY

Warfighter Impact: Enables fuel longevity,
power export, and silent operation





PICHOT LEVERAGING ADVANCED TECHNOLOGY – ZEUS 200

2018 → Development effort to prove GVSC's design concept

Gen1 SiC used to prove 200kW capability

2021 → Design kickoff with dedicated laboratory and team leads owning major systems

Upgraded to Gen2 SiC for increased reliability

Zeus 200 planned for use in developmental vehicle hybridization programs

Family of Inverters concept developed using Zeus 200 architecture & patent

2023 → Successful testing to 200kW continuous power

Kick-off Zeus 200 Inverter Licensing with Focused Industry Day (55 Companies in Attendance)

Upgraded to Gen3 SiC for increased reliability, stability, and module life

2024 → 4 Zeus 200 non-exclusive license agreements in-progress

LRIP units built supporting ongoing hybridization efforts

PICHOT Kick-off using Zeus 200kW design as foundation



ZEUS 200

Advanced SiC Inverter

KEY FEATURES

- Patented Advanced Silicon Carbide (SiC) Technology
- 200kW (400kW Peak) Power @ 105°C Coolant
- Power Density: 10.46kW/L Nom, ~21kW/L @ 105°C (Peak)
- Bi-Directional for Motoring/Generation
- Size 435x268x164 mm (L x W x H)
- Weight 30 kg

HARDWARE FEATURES

- High Temperature (121°C) Ambient Operation
- 3-Phase AC SiC Stage with High Voltage Interlock (HVIL)
- Dual DC Power Distribution Ports (600A Continuous)
- HVIL and Pre-charge
- Integrated EMI Filter (MIL-STD-461)
- Dual J1939 CAN Interfaces
- Inverter Parallelization and Sync Interface
- Motor/Generator Resolver Interface

SOFTWARE FEATURES

- Dynamic Control and Status Reporting Over CAN
- Temperature, Voltage, Current Sensing for System Protection
- Advanced Diagnostic Capabilities and Fault Protection
- Configurable Voltage, Frequency, Motor/Generator Parameters
- MISRA-C Compliant Codeset

Inverter Model	Electrical Output Power	Peak Efficiency	Output Current Cont/Peak (Amps)	Input DC voltage	Max switching frequency	Control voltage
Z200	200kW / 400kW Peak	99.5%+	334 / 667	300 - 800VDC	50kHz	17 - 32VDC

ENABLING HYBRIDIZATION

The Zeus Inverter development is part of GVSC's electrification efforts to control new motors, generators, and import/export power for vehicles. Whereas the automotive industry is electrifying vehicles for fuel efficiency improvements, the military is additionally focused on enabling new capabilities such as silent mobility, directed energy weapons, vehicle to vehicle (V2V), vehicle to grid (V2G), extended mission duration, autonomy, and mobile command and control.

FOR FURTHER INFORMATION:
U.S. ARMY COMBAT CAPABILITIES DEVELOPMENT COMMAND
GROUND VEHICLE SYSTEMS CENTER
DEVCOM.ARMY.MIL

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- Zeus power density
10.46 kW/L continuous,
21 kW/L peak

- PICHOT
42 kW/L continuous (T)
60 kW/L continuous (O)

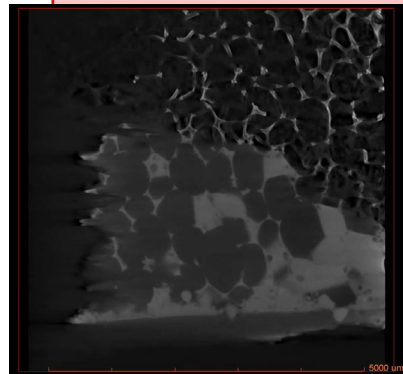
- Design constraint –
 $T_j \leq 150^\circ\text{C}$

- ARL focus on
opportunities for
transient mitigation

THERMAL BUFFERING INTERCONNECTS

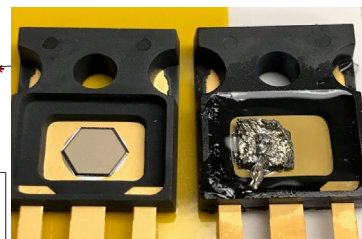
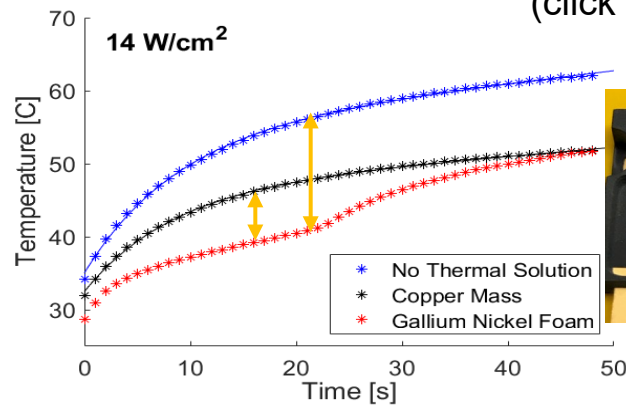


COTS-compatible intervention – deepens thermal magazine on 6 sec shots by 8.7%



Scales w/ diode efficiency
 η_{eo} : 51% $\rightarrow$ 60% gives
 E_{th} : +8.7% $\rightarrow$ +10.7%

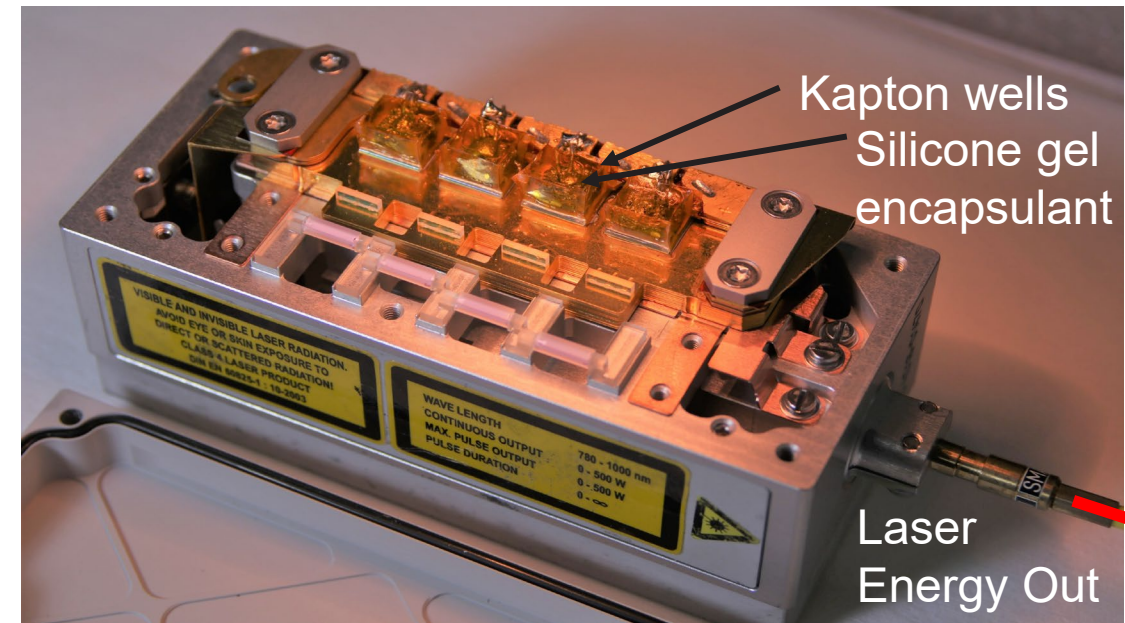
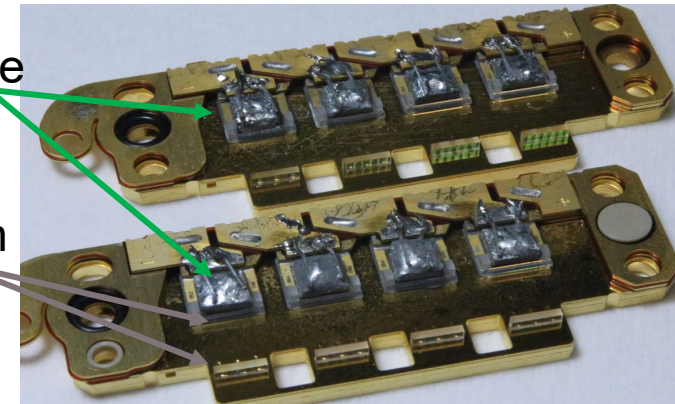
← Metal Foam /
Liquid Metal Composites
(click to play)



Surge
suppression
Zener diodes

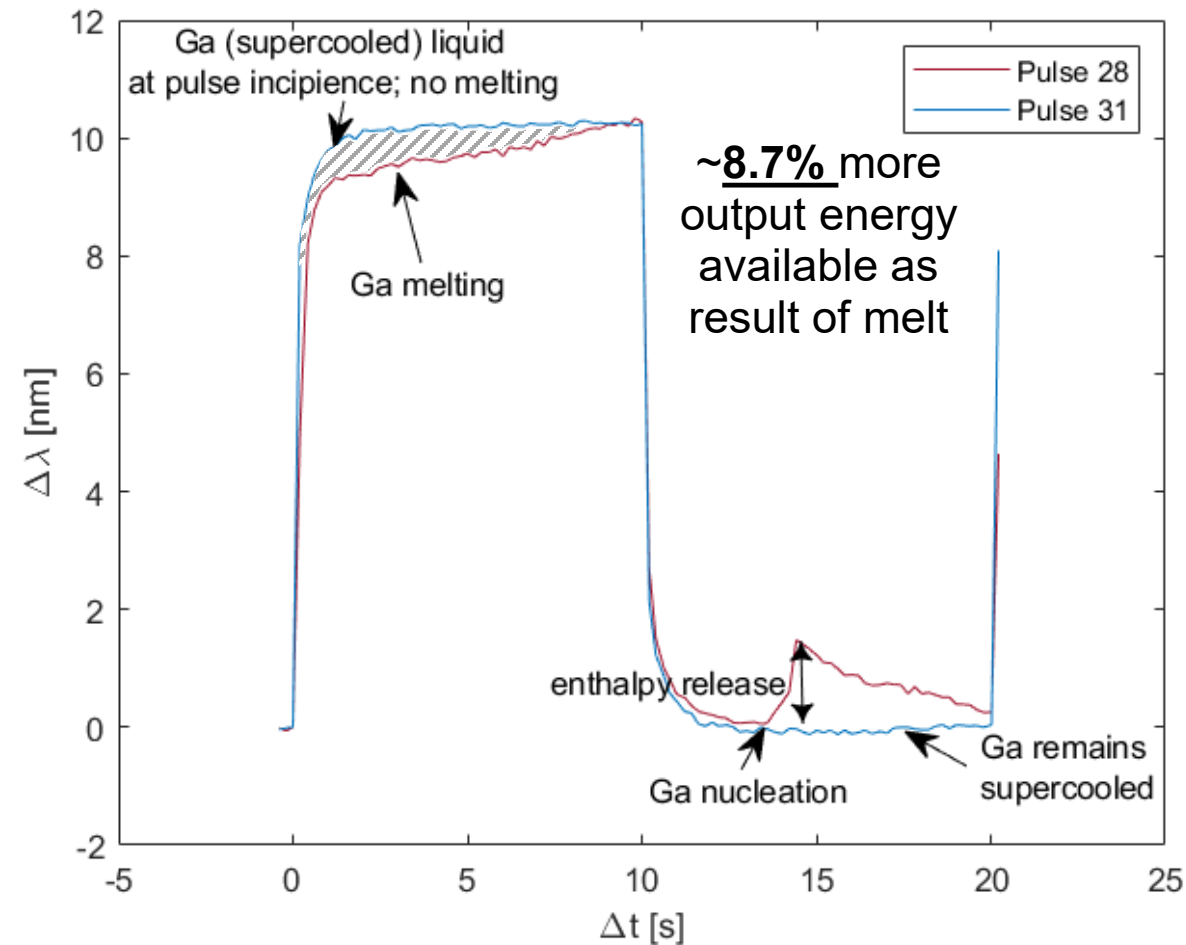
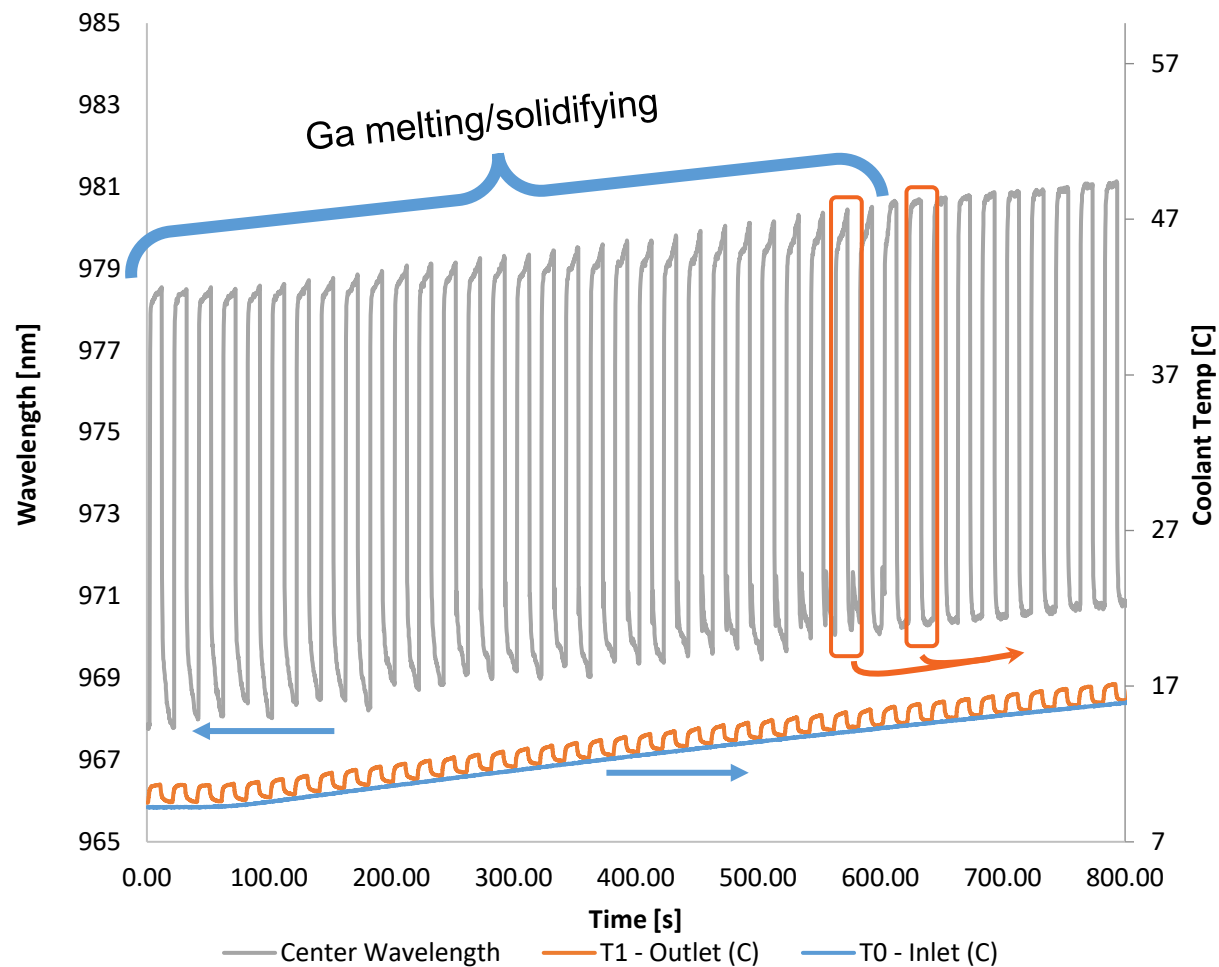
LMPM-composite
PCM

Collimation
Optics

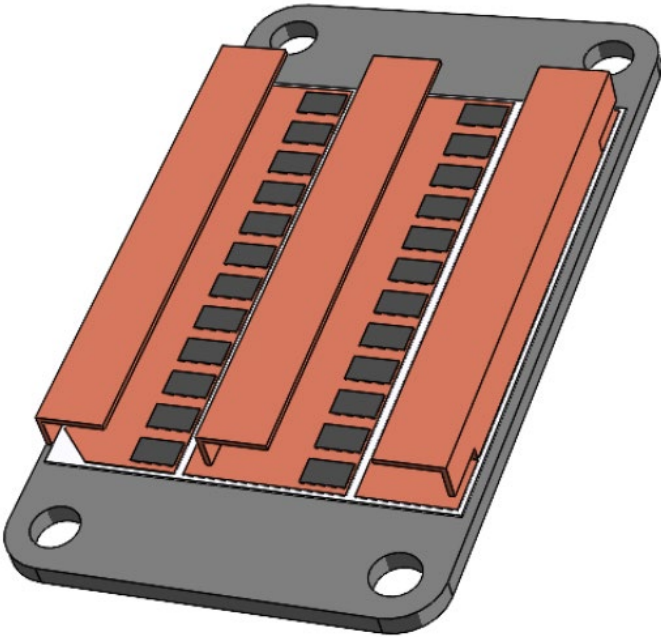


Laser
Energy Out

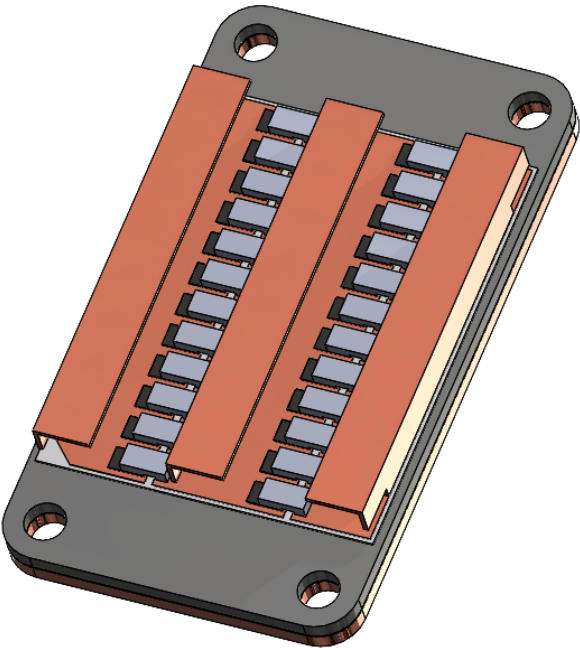
BUFFERING INTERCONNECTS ON LASER DIODES



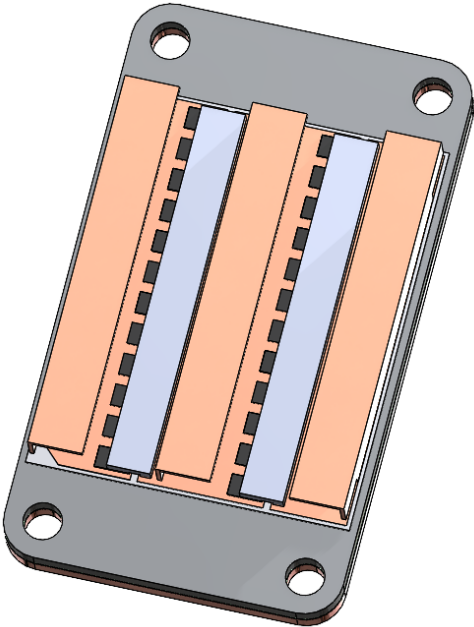
FOAM INTEGRATION OPTIONS



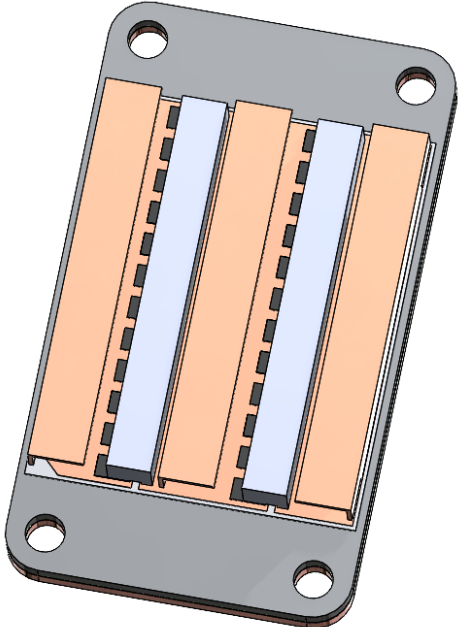
CAB760 Layout



CAB760 with Single
PCM-Foam Bonds



CAB760 with Combined
PCM-Foam Bonds



CAB760 with Combined
PCM-Foam Bonds Max PCM

Interconnect	Conventional Wire bonds
Total Volume	0.0 mm ³
Ind 174 Energy Storage	36.4 J/g
Max Energy Storage	0 J

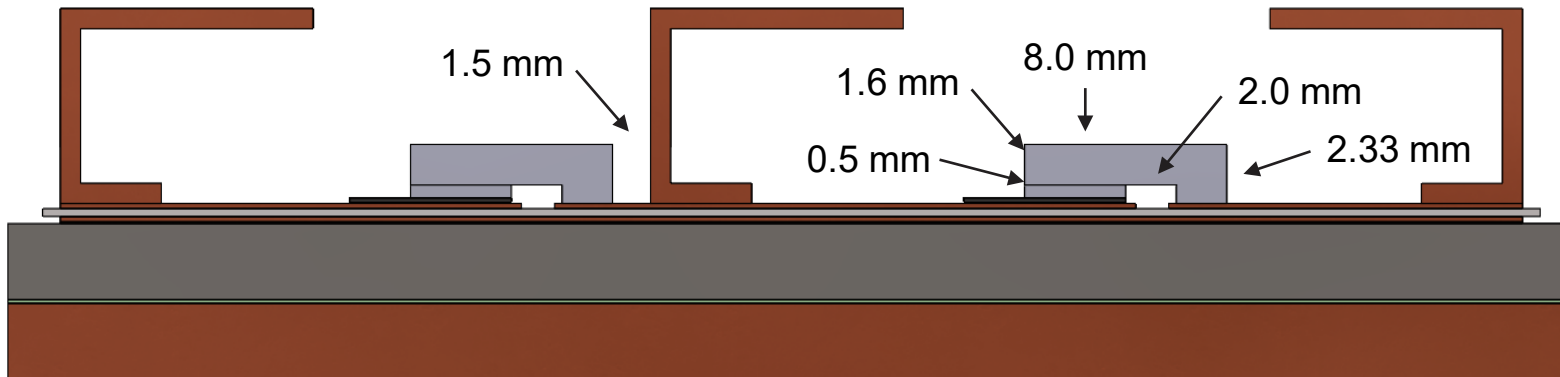
Interconnect	Conventional Wire bonds
Total Volume	1560.96 mm ³
Ind 174 Energy Storage	36.4 J/g
Max Energy Storage	485.23 J

Interconnect	Conventional Wire bonds
Total Volume	2176.16 mm ³
Ind 174 Energy Storage	36.4 J/g
Max Energy Storage	676.47 J

Interconnect	Conventional Wire bonds
Total Volume	7741.84 mm ³
Ind 174 Energy Storage	36.4 J/g
Max Energy Storage	2406.57 J

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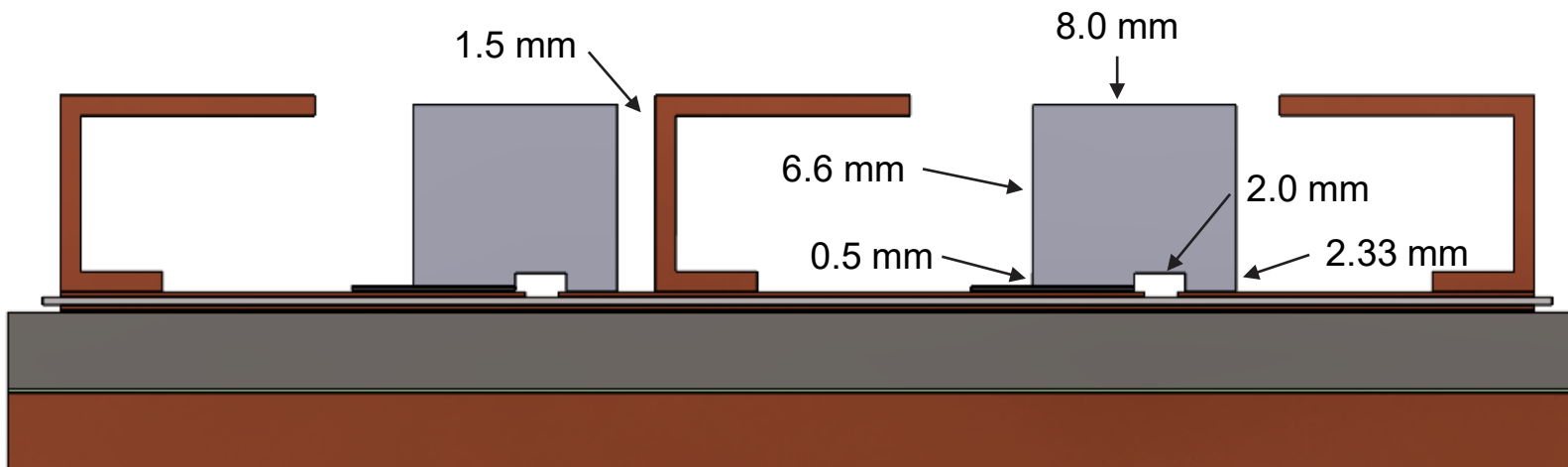
FOAM INTEGRATION CROSS SECTION



CAB760 with Single PCM-Foam or
Combined PCM-Foam Bond

Single Foam Layer (~1.6 mm)

Individual Foam Connects = 4.0 mm wide
12 individual bonds on each side



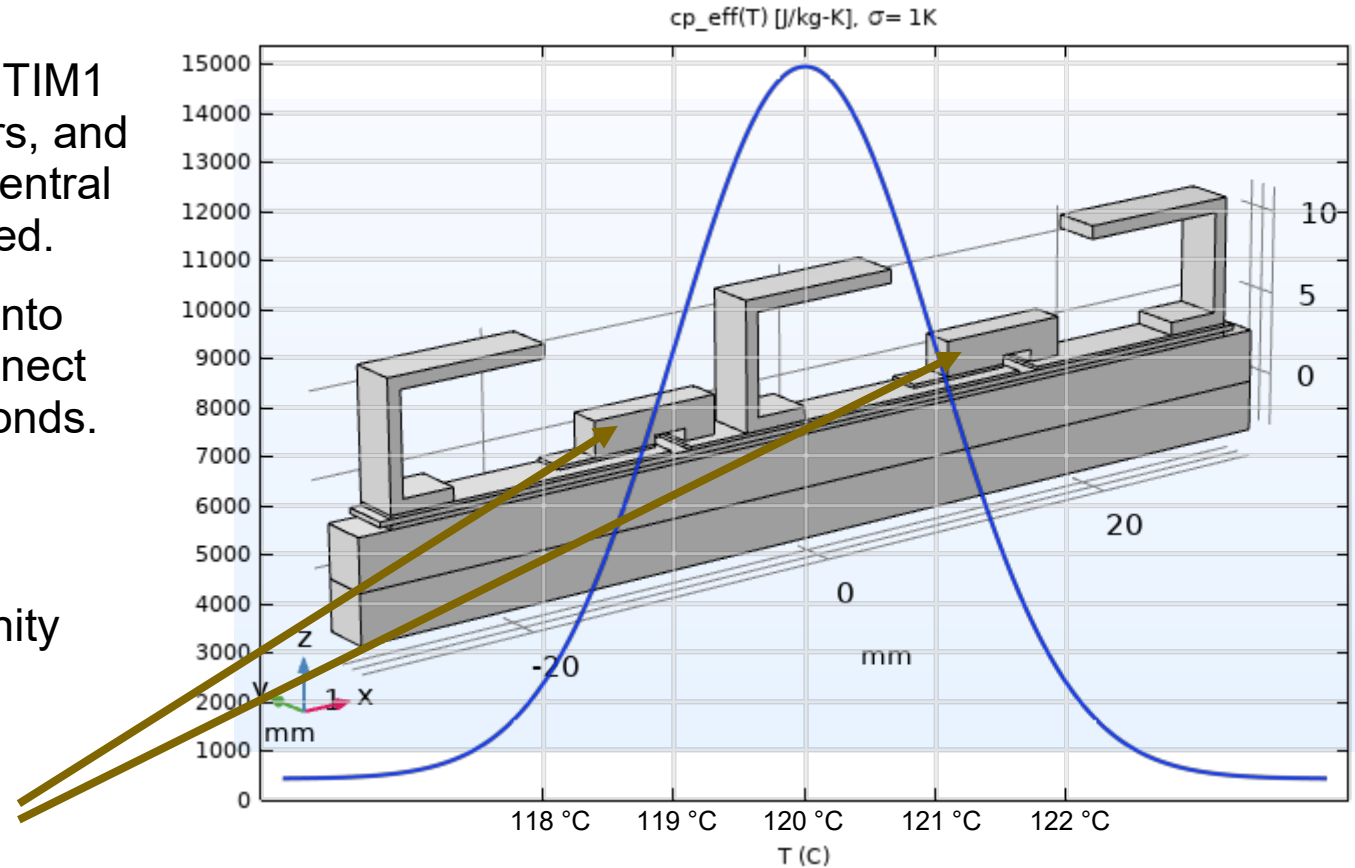
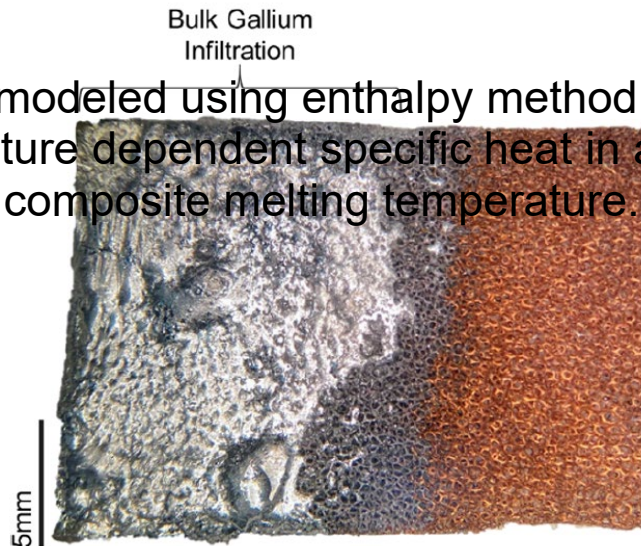
CAB760 with Single PCM-Foam or
Combined PCM-Foam Bond

Max PCM Height 6.6 mm

Provides additional 5 mm PCM height vs
single PCM-foam layer stack

MODULE GEOMETRY AND INTEGRATED THERMAL BUFFERING

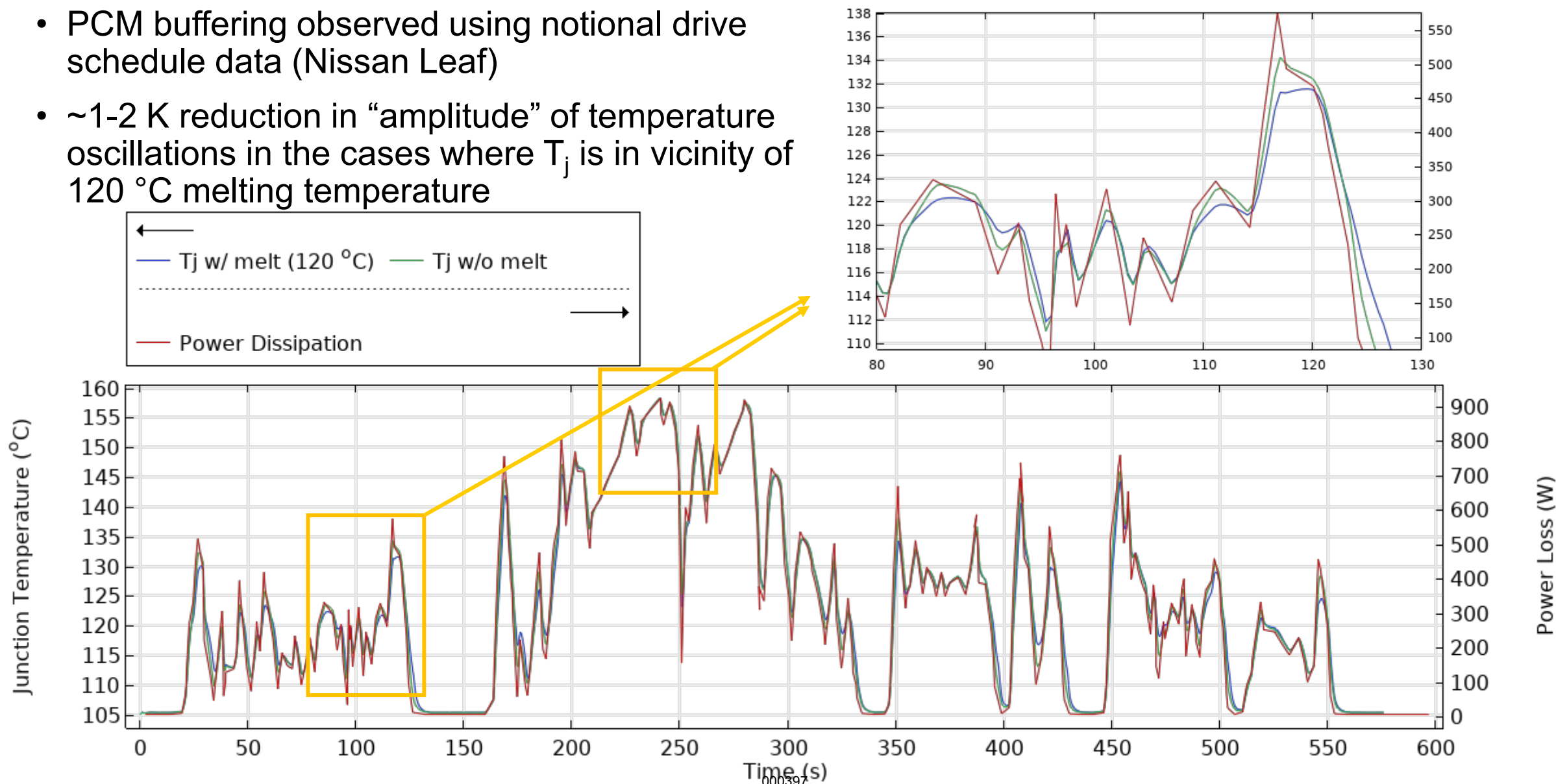
- CAB760 Module, with thin layers (Die Attach, TIM1 an TIM2) abstracted as 2D conductance layers, and geometry reduced to linear periodic about a central pair of MOSFET switches. Diodes not modeled.
- Composite low-melting point metal infiltrated into porous metal foam used as electrical interconnect material in region formerly occupied by wirebonds.
- Melting modeled using enthalpy method – temperature dependent specific heat in a vicinity close to composite melting temperature.



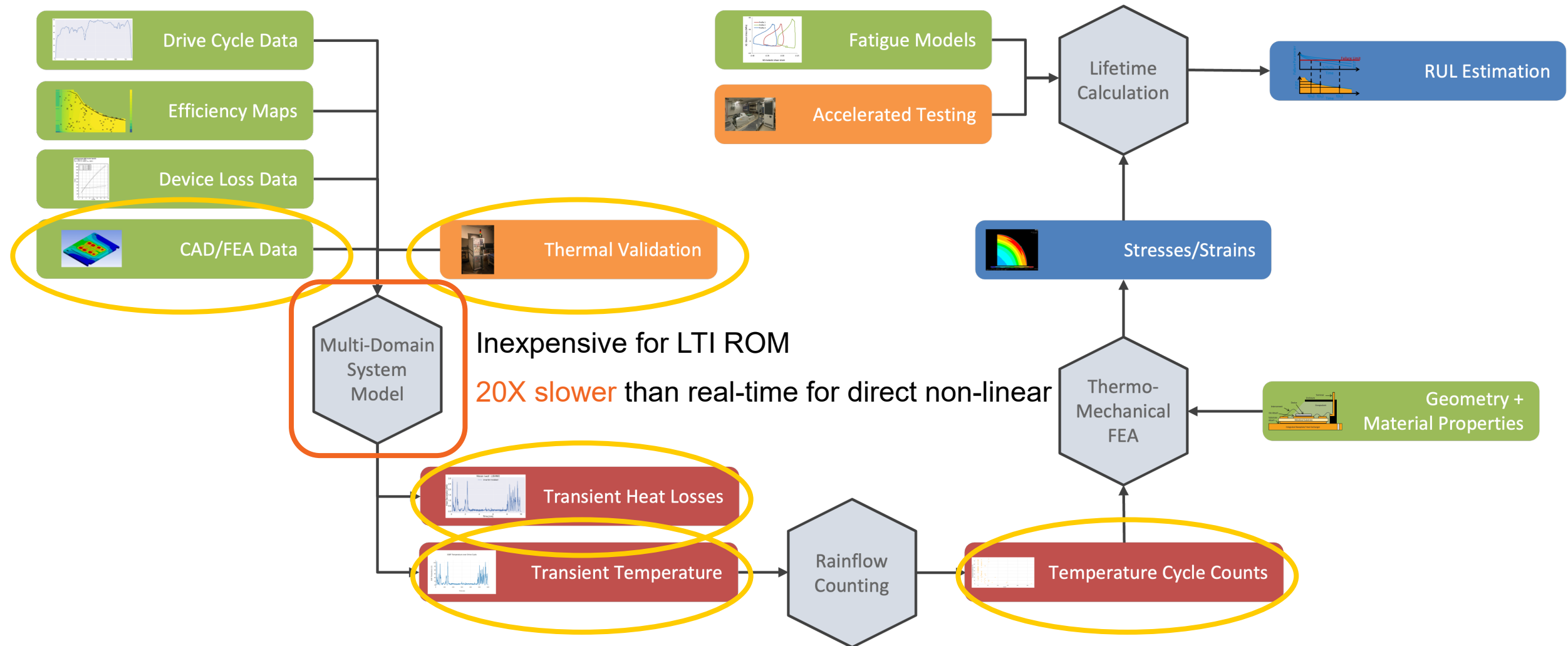


TRANSIENT NONLINEAR BEHAVIOR

- PCM buffering observed using notional drive schedule data (Nissan Leaf)
- ~1-2 K reduction in “amplitude” of temperature oscillations in the cases where T_j is in vicinity of 120 °C melting temperature



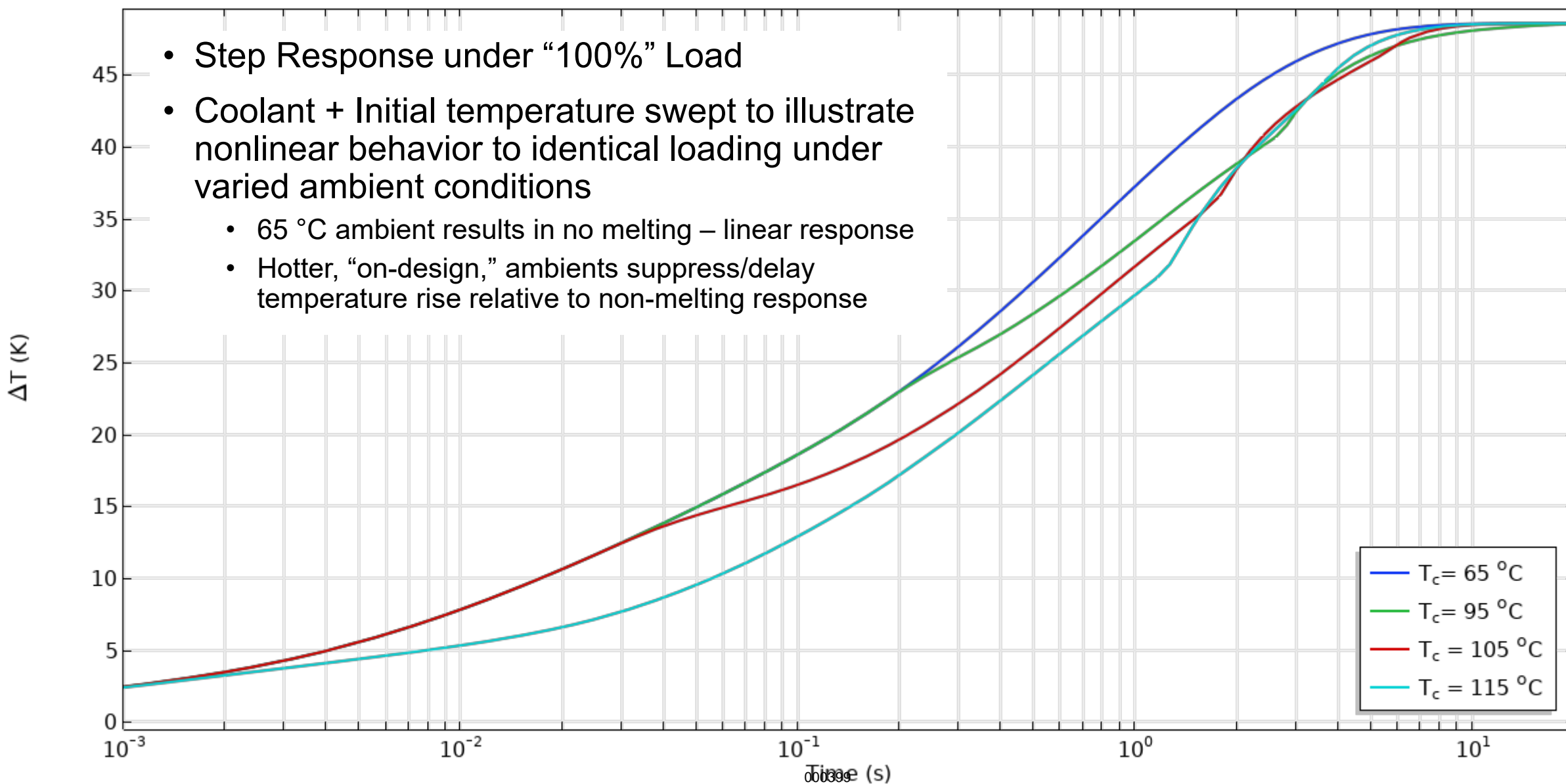
ONRAMPS INTO NREL LIFETIME CALCULATION





TRANSIENT STEP RESPONSE

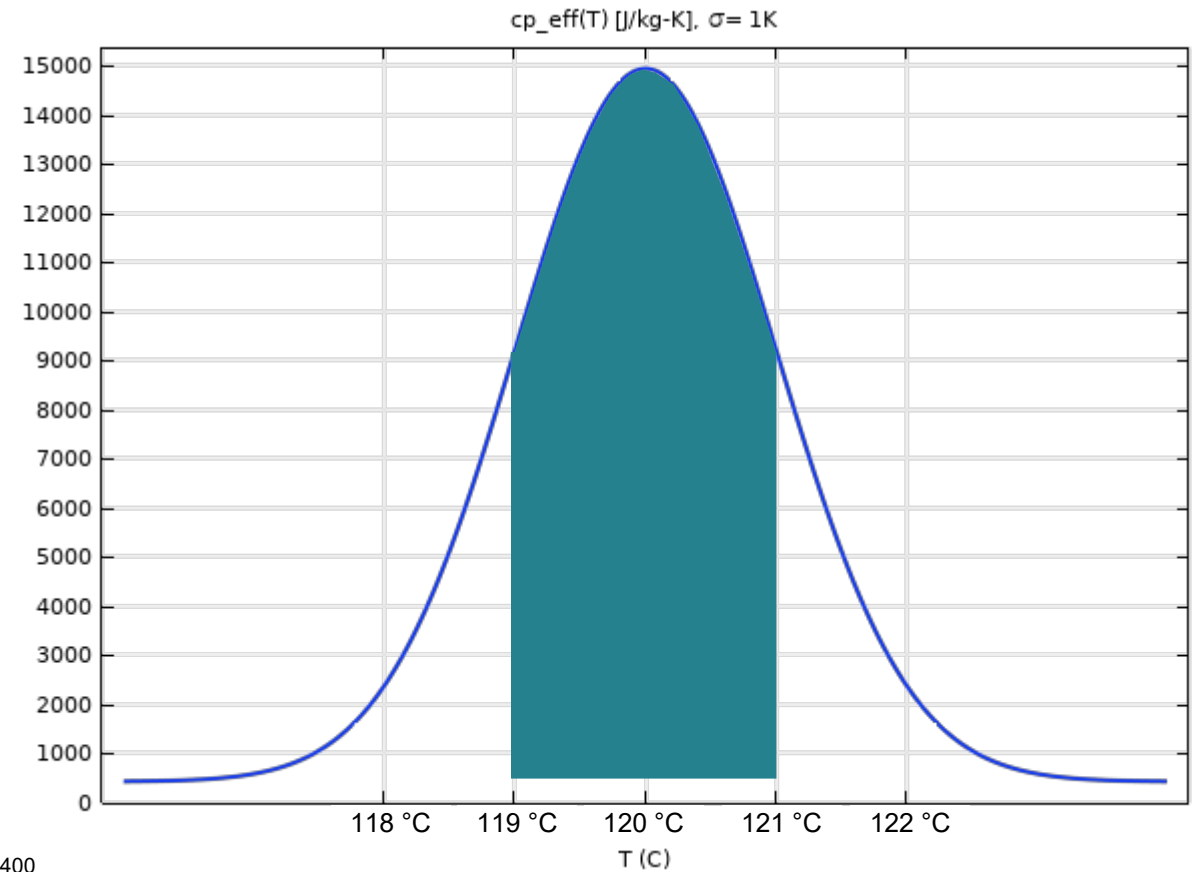
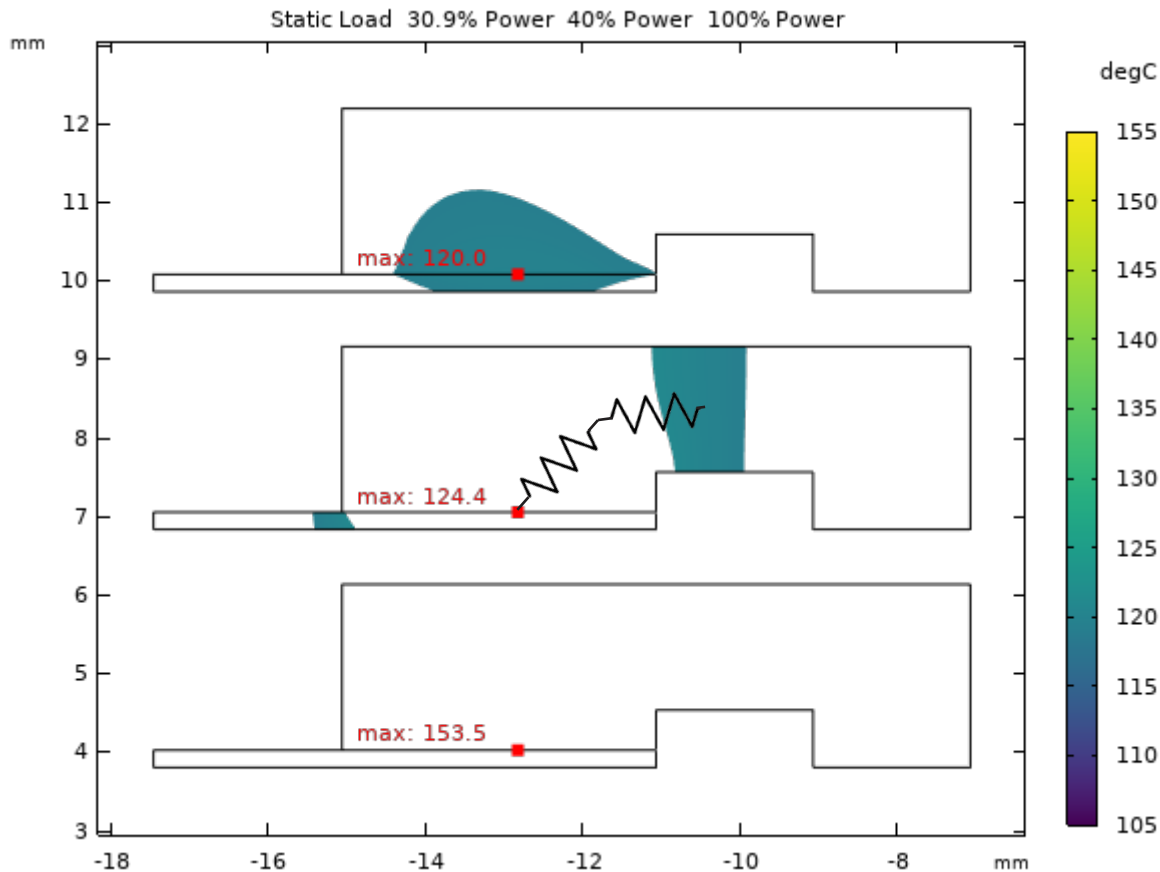
- Step Response under “100%” Load
- Coolant + Initial temperature swept to illustrate nonlinear behavior to identical loading under varied ambient conditions
 - 65 °C ambient results in no melting – linear response
 - Hotter, “on-design,” ambients suppress/delay temperature rise relative to non-melting response





“ACTIVE” PCM

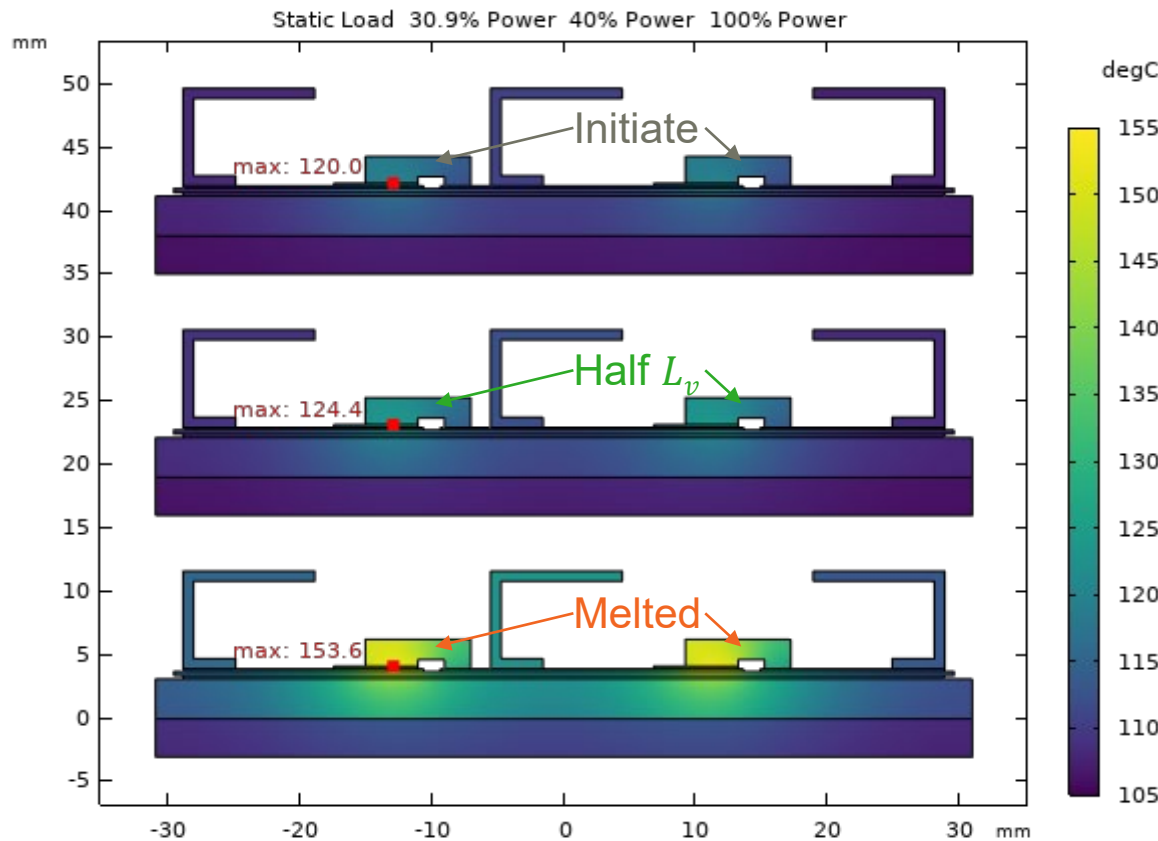
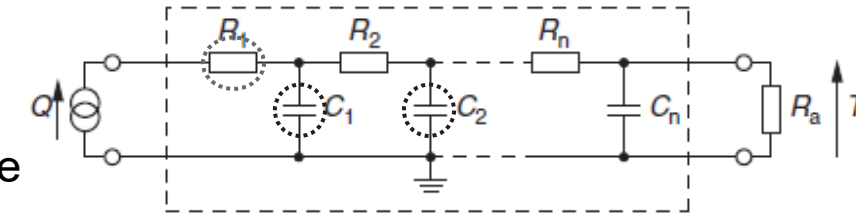
- Plotted: bands of PCM within 1σ of the smeared melting temperature at each loading
 - SiC material included for context
- Linear FD analysis treats material as having fixed C_p as determined by static load





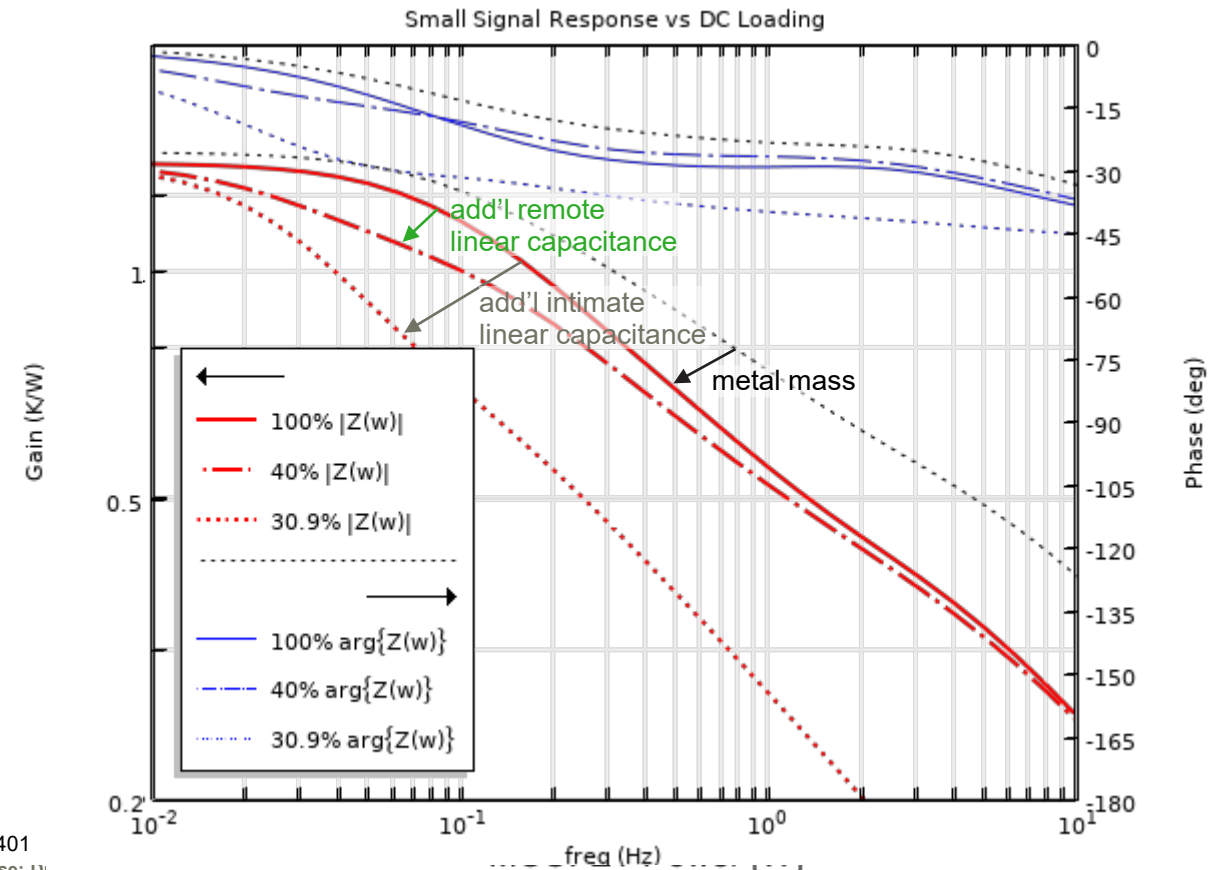
FREQUENCY-DOMAIN PERTURBATION (LINEARIZED)

- DC Response (of all junctions ganged together) – 1.395 K/W
- 34.8 W per chip (100% load) melts all PCM ($T_{\text{melt}} = 120^{\circ}\text{C}$) at steady state
- 40% load (13.92 W) leads to $T_j = 124.4^{\circ}\text{C}$, partially “active” PCM damps small signal gain
- 30.9% load brings “active” PCM directly adjacent to junction
- (black dotted – no PCM interconnect at all)



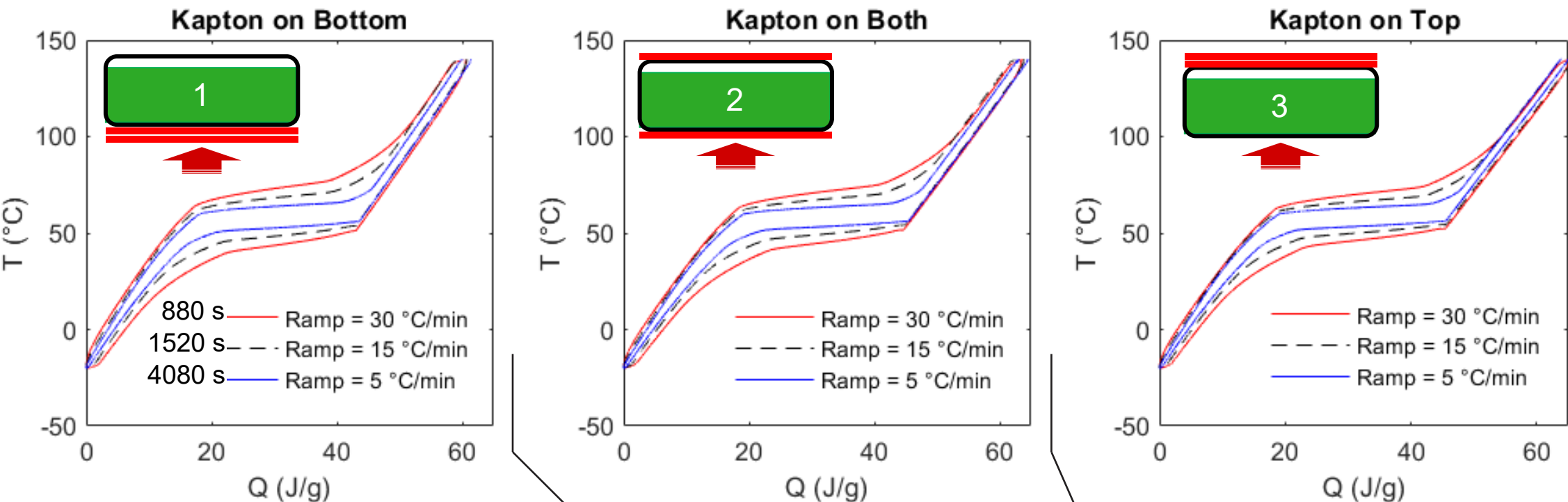
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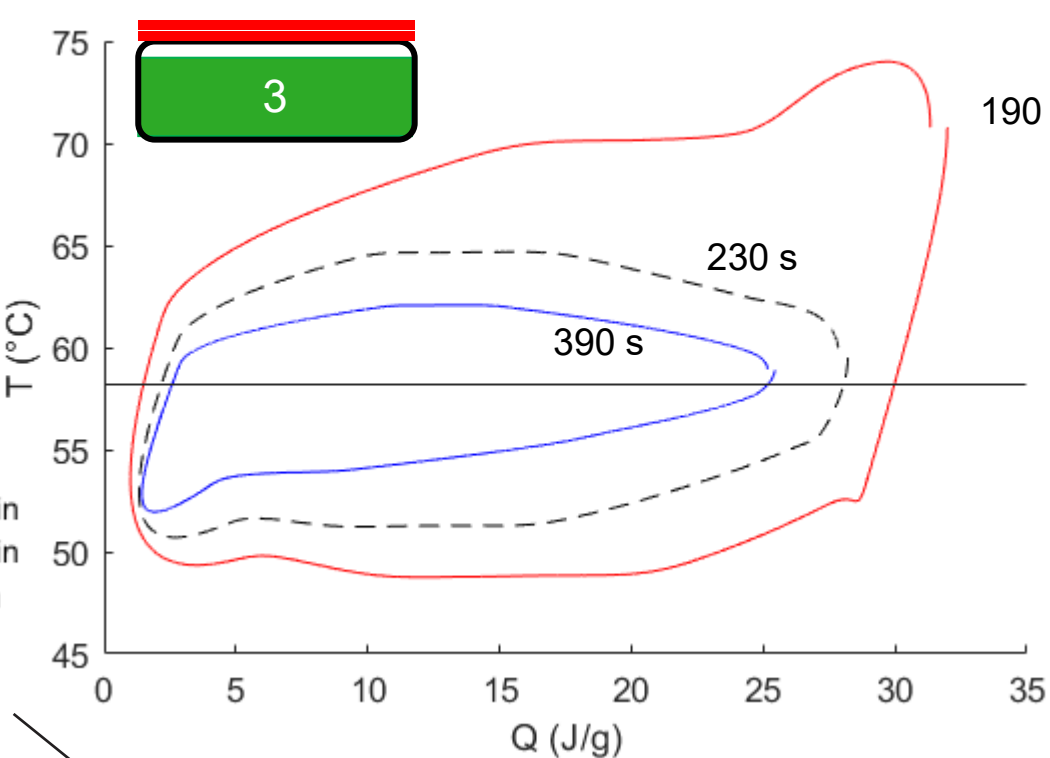
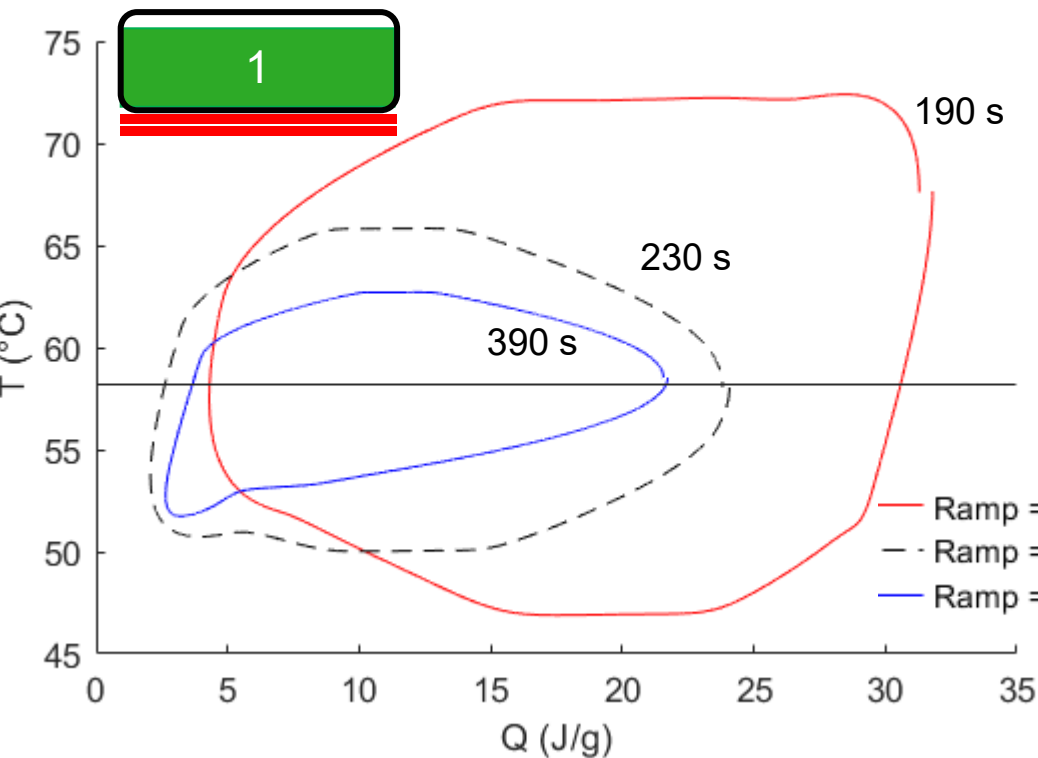


NEXT STEPS? EGM: FROM HEAT FLOW TO EXERGY FLOW



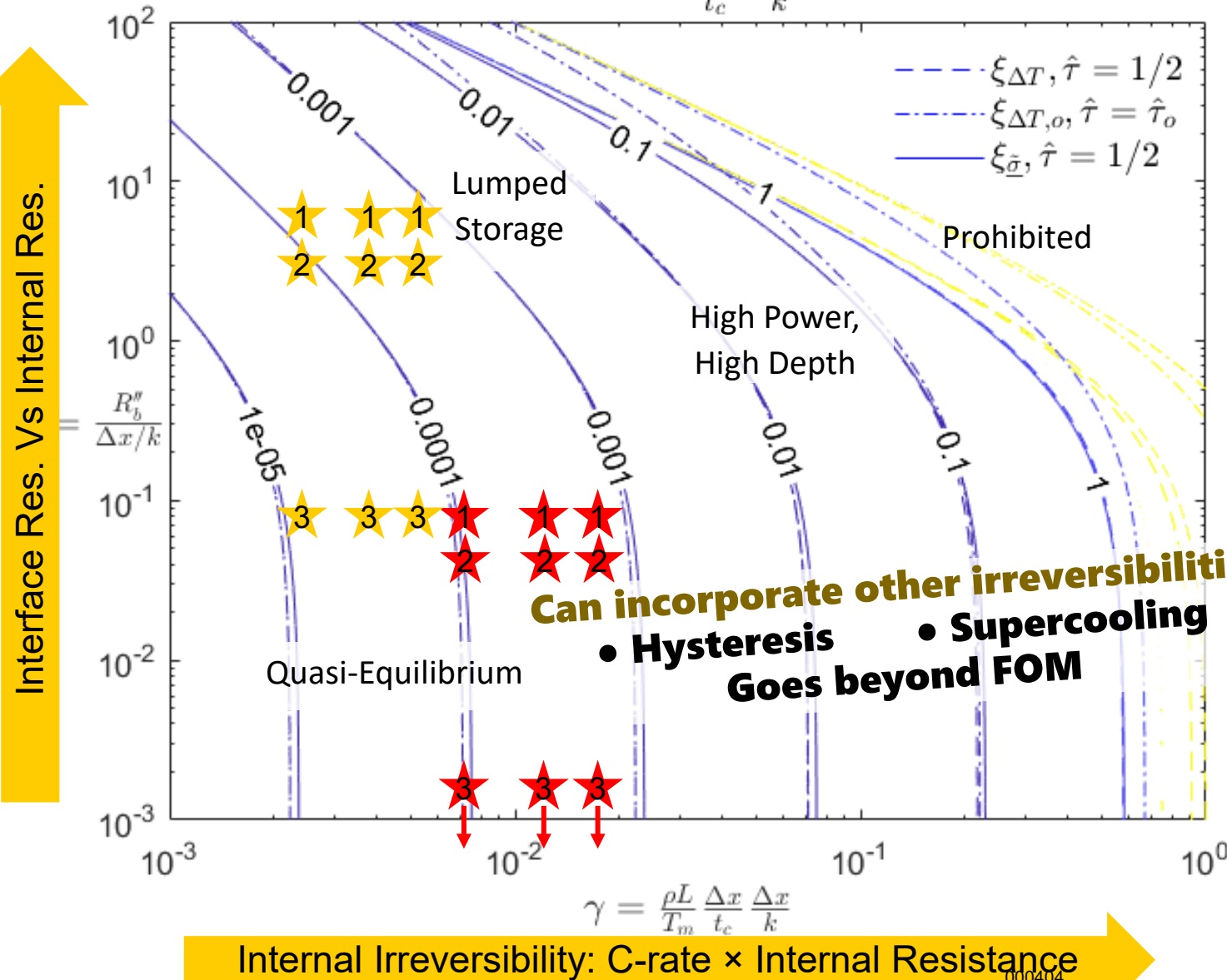
$\frac{c_p \Delta T}{L} \approx 1.5$	$\frac{\dot{S}_{gen}''}{P_c}$ [μW/cm ² -K] / [mW/cm ²]	$1 - X_d/X_s$	$\frac{\dot{S}_{gen}''}{P_c}$ [μW/cm ² -K] / [mW/cm ²]	$1 - X_d/X_s$	$\frac{\dot{S}_{gen}''}{P_c}$ [μW/cm ² -K] / [mW/cm ²]	$1 - X_d/X_s$
30 °C/min	19.8 / 163	36.5%	16.0 / 173	51.8%	15.7 / 176	53.5%
15 °C/min	9.0 / 94	50.1%	9.0 / 98	52.5%	8.2 / 101	57.6%
5 °C/min	2.4 / 36	65.0%	2.4 / 37	66.5%	2.0 / 37	72.2%

LOW STEPHAN TES EXERGY



$\frac{c_p \Delta T}{L} < 0.23$	$\frac{\dot{S}_{gen}''}{P_c}$ [$\mu\text{W}/\text{cm}^2\text{-K}$] / [mW/cm^2]	$1 - X_d/X_s$	$\frac{\dot{S}_{gen}''}{P_c}$ [$\mu\text{W}/\text{cm}^2\text{-K}$] / [mW/cm^2]	$1 - X_d/X_s$
30 °C/min	41.4 / 342	38.2%	43.5 / 385	42.3%
15 °C/min	16.9 / 227	62.0%	19.0 / 277	65.0%
5 °C/min	5.1 / 116	77.5%	6.5 / 146	77.2%

Latent Heat-TES Performance



Markers: numbered by Kapton configuration



- Colored by material
- Left to right: 5, 15, 30 °C/min
- Field's Metal (Yellow)
- Paraffin (Red)

Entropy production categorizes mode

Quasi-Equilibrium

- Insignificant Exergy costs in TES
- TES underutilized

High Power, High Depth

- TES heavily exercised
- Goal: balance Exergy cost in TES vs package

Lumped Storage

- Interface resistance > Material res.
- Poorer performance, easy to model

Internally Dominated

- PCM conductivity is limiting factor
- R varies w/ SoC, charge profile matters

SUMMARY



- Thermal Buffering Interconnects provide near-junction capacitance that enable new capabilities and/or enhanced thermomechanical reliability
- Long-term material reliability, shock and vibration resistance still to be explored
- Latent Heat Thermal Energy Storage (LH-TES) challenging to model economically in the context of multiscale, multi-physics system assessment
- Solutions not portable between applications. Can Entropy Generation Minimization (EGM) provide application-agnostic assessment of LH-TES performance envelope beyond material FOM?



THANK YOU.

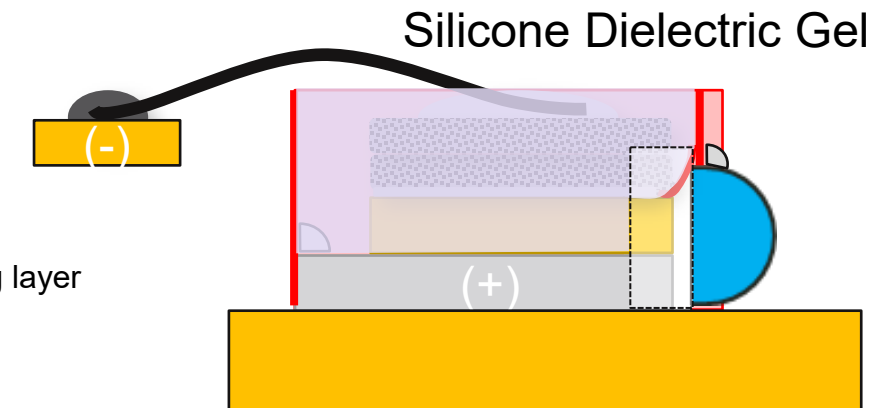
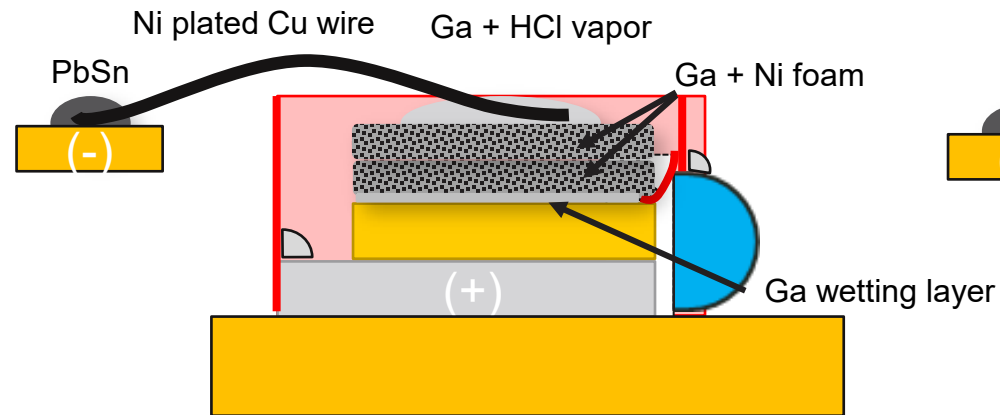
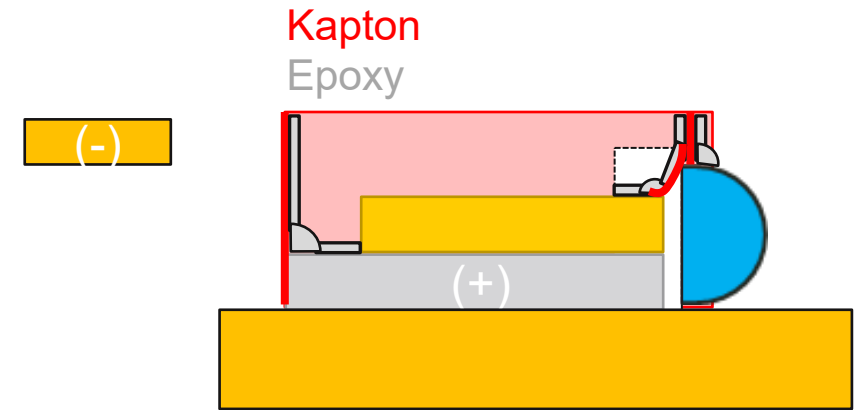
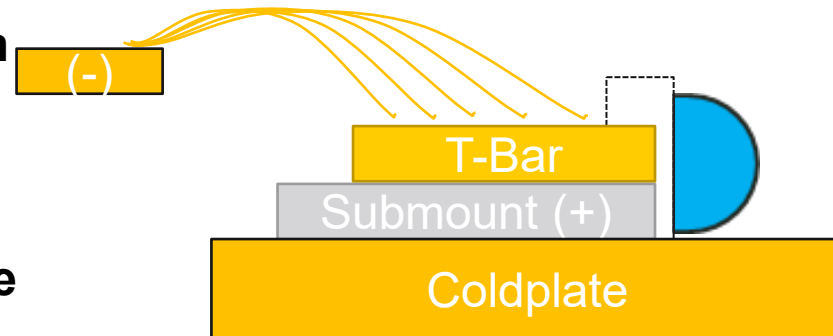
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Power Integration and Architectures Branch
Energy Sciences Division
DEVCOM Army Research Laboratory

CURRENT PROCESS FLOW – LASER DIODE



- Basic premise - replace wirebonds with Ga/Ni foam PCM interconnect
- Foam keeps Ga from beading up or migrating when liquid, helps nucleate on cooldown
- HCl vapor strips GaO skin, needed to wet, but leaves residue that facilitates corrosion outside of N2 drybox
- Encapsulating in DE gel prevents corrosion, provides compliant mechanical adhesion

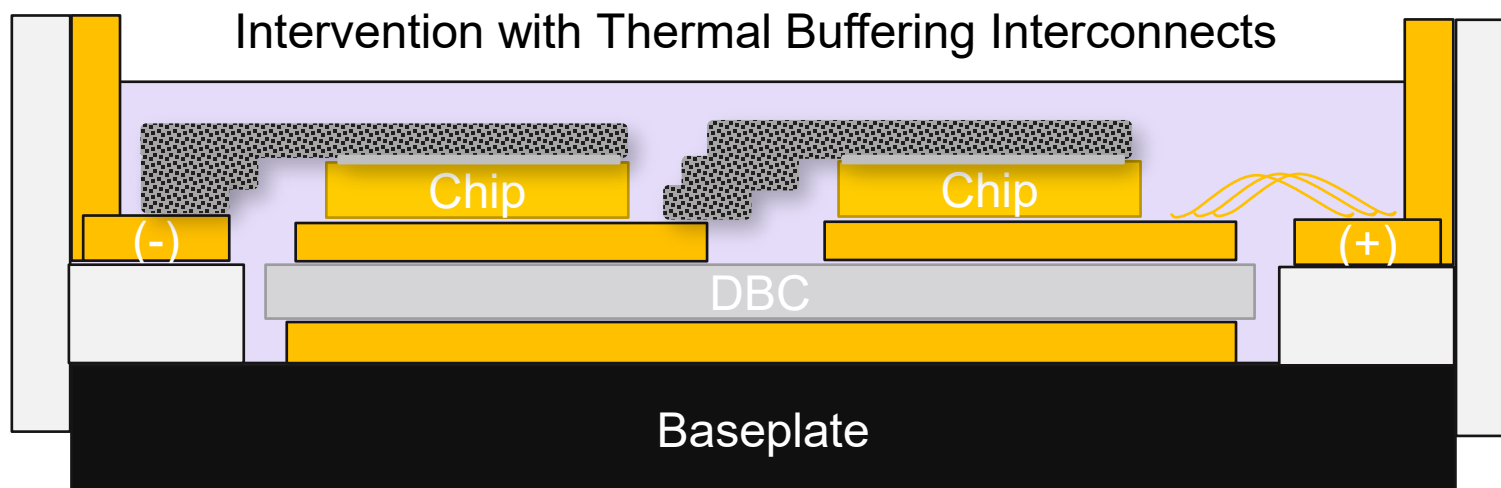
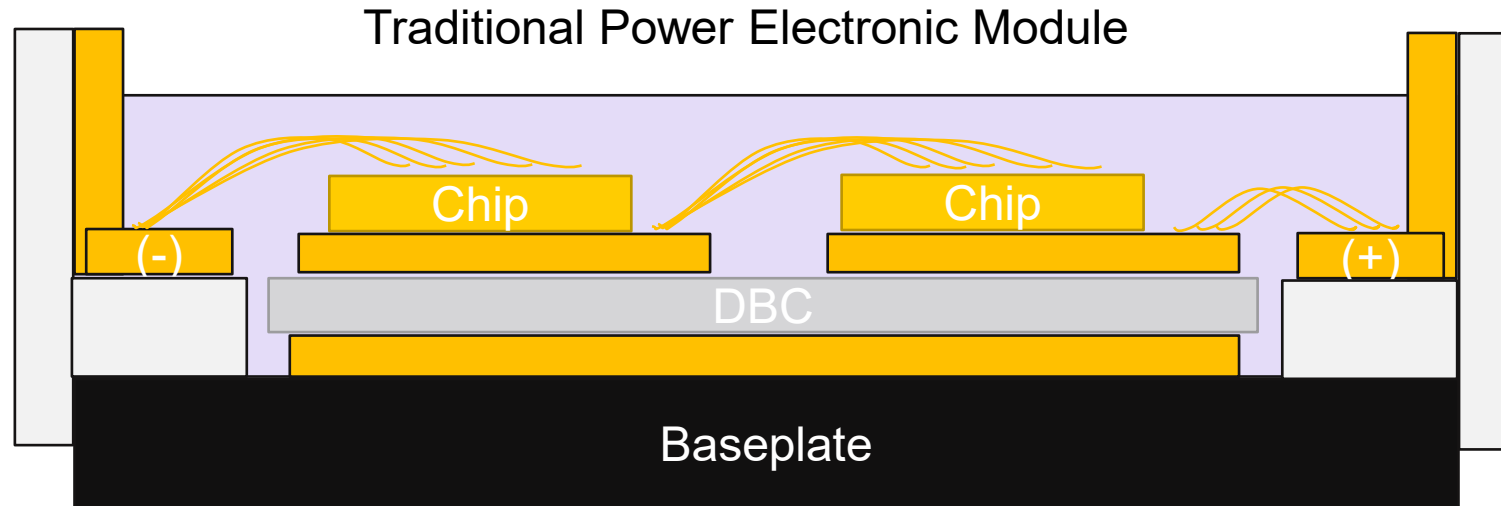


~ 500mg Ga per T-Bar, equivalent to 40J of storage

POSSIBLE INCARNATIONS



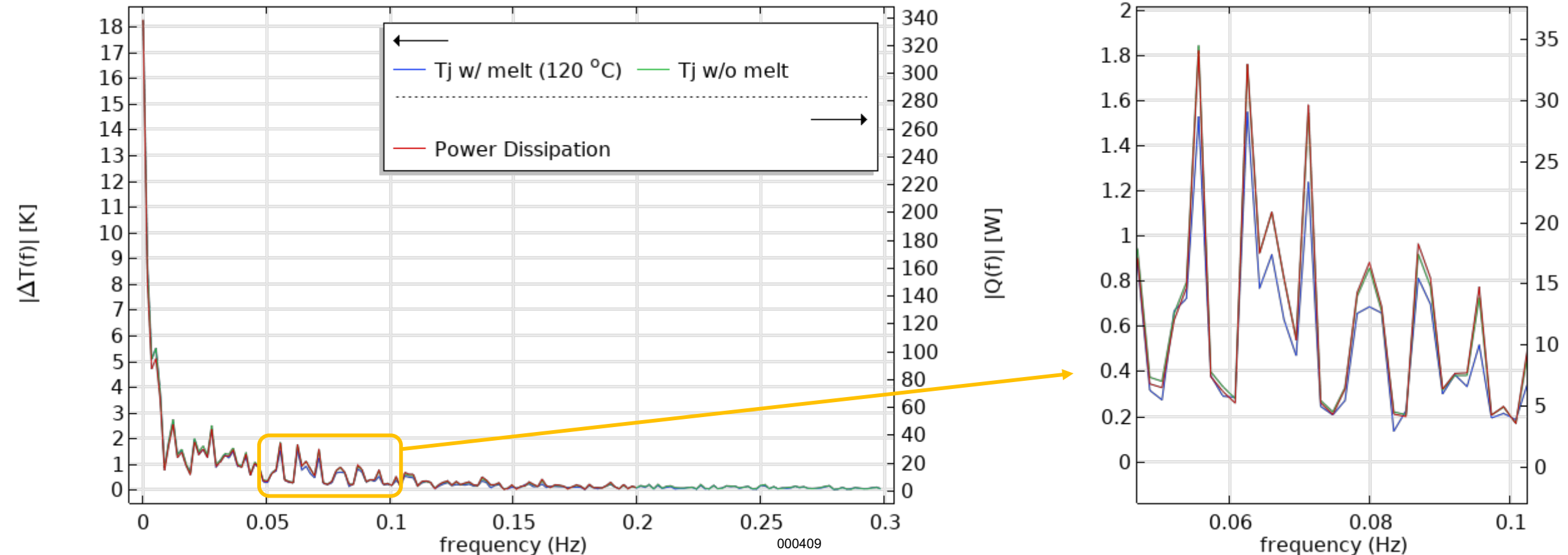
- Could be used to replace wirebond interconnects in a variety of contexts
- Infiltrated PCM could be any low-melting point metal depending on target temperature
- Attaches to terminals or chips could be rigid (solder /brazed/ conductive epoxy) or PCM attach (either same as in foam or different depending on mechanical needs)
- Arbitrary foam 3D shapes can be created using EDM before/after infiltration
 - Could be used in the context of novel 3D packaging





BACKUP - FREQUENCY CONTENT OF TRANSIENT RESPONSE

- Fourier Analysis of transient response shows evidence of melting damping oscillations having 10-20 sec cycle periods

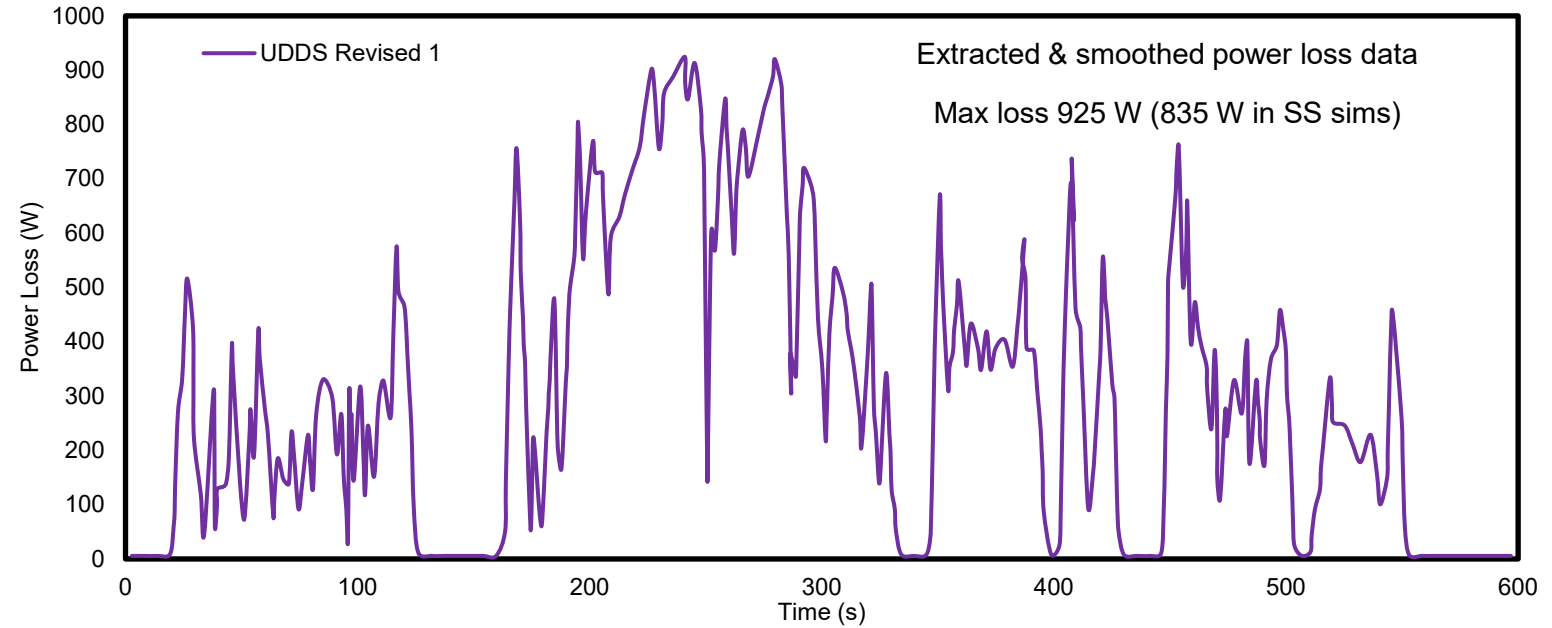
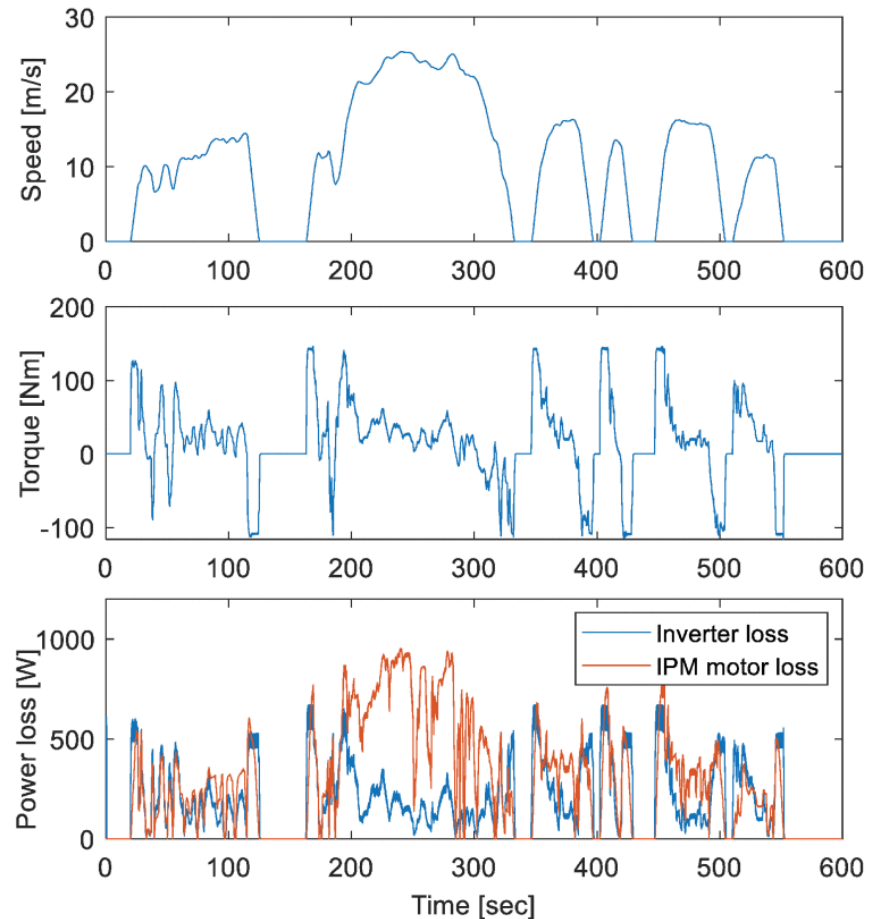


CAB760 MODULE – TRANSIENT PROFILE 1

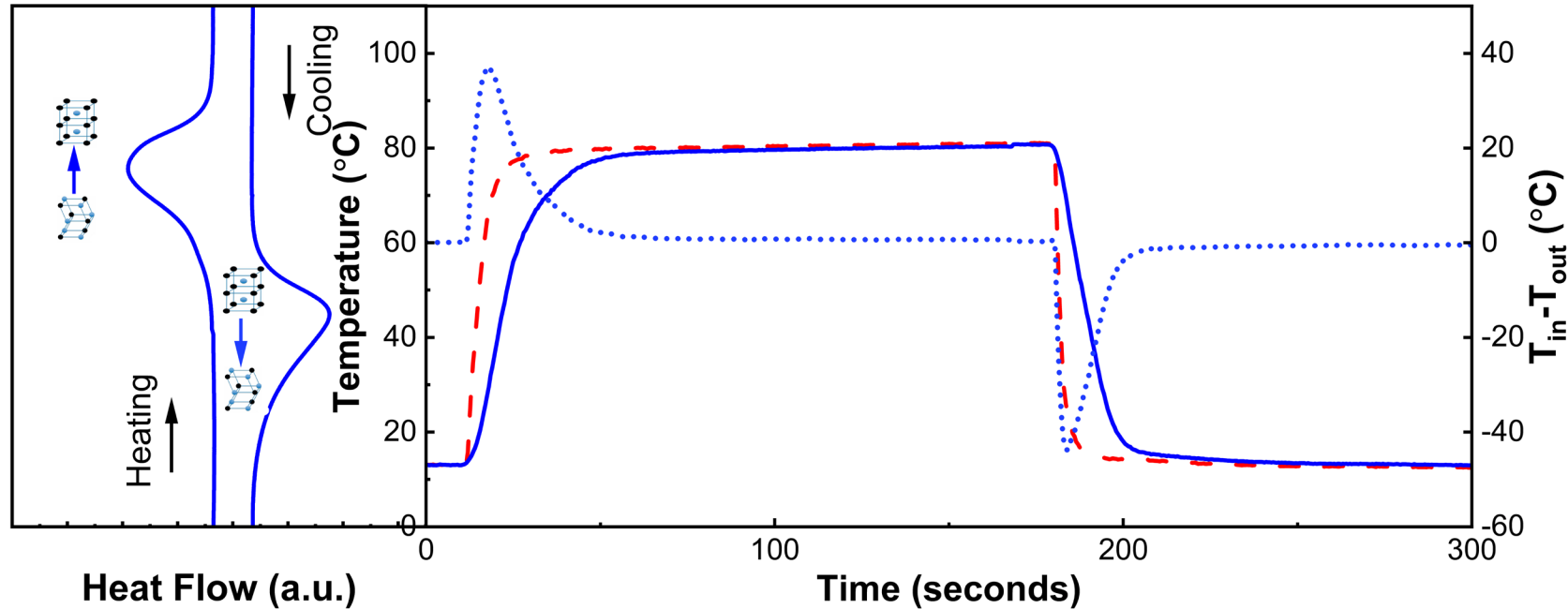


UDDS (Urban Dynamometer Drive Schedule)

Based on Nissan Leaf



OBSERVING IRREVERSIBILITY – NITI HX



$$\frac{dS}{dt} = \dot{m}(s_{in} - s_{out}) - \frac{\dot{Q}_{loss}}{T} + \dot{S}_{gen}$$

$$\frac{dU}{dt} = \dot{m}C_p(T_{in} - T_{out}) - \dot{Q}_{loss}$$

16.7 J/K over cycle

45 mW/K $\dot{S}_{gen}$

111kJ charge, discharge

601 W P_c

$$\frac{X_{out}}{X_{in}} = 52.8\%$$

$$(T_0 = 293.15K)$$



Wilson, et. al. "High power thermal energy storage from ordered-pore additively manufactured phase-transforming nickel-titanium porous cubes," *ITHERM 2024*