P/O/E/T/S

CENTER FOR POWER OPTIMIZATION OF ELECTRO-THERMAL SYSTEMS

Technology Roadmapping Template

2022 Annual Meeting

October 19, 2022

Goals of Session

As POETS moves into year 8, there have been many achievements and breakthroughs that have contributed to the goal of increasing power density by 100x when measured against 2014 State-of-the-Art. In recent years, there have been new companies join the center as well as new employees participating from the existing POETS industry partners. This presents an opportunity to quantify, demonstrate, and re-baseline efforts in both fundamental research and enabling technologies within POETS.

Outcomes:

- Establish new baseline of POETS Research for Industry
- Establish benchmarks against SOA w/ Industry input
- Identify focus areas of **fundamental research** and **enabling technologies** moving forward
- Owen will compile session notes into a graphic for the annual report and future presentations
- Get industry feedback

Session Agenda – 2 PARTS

- **Part 1 - Current state of POETS –** 8:30 to 11:00am PDT
  - **30 Min** - >10x Improvement of Power Density of Electrified Systems (**Dr. Haran**)
  - **45 Min – Breakout Sessions**
    - Materials and Devices(**Dr. Miljkovic**)
      - Electrical/thermal conductivity
      - Advanced passives
      - High temp
      - High-Density thermal energy storage
    - Components and Subsystems(**Dr. Huitink**)
      - Electric machines
      - Fabrication methods
      - Power electronics
    - Systems and Testbeds(**Dr. Allison**)
      - Packaging
        - Spatial optimization
        - Power module layout
      - Integrated sensing
      - Integrated cooling
      - Testbeds
  - **15 Min – Break**
  - **30 Min – Facilitators Panel Discussion**

Tasks for Each Breakout Session

- Identify baseline targets for technology w/ Industry Input
- Highlight current state of POETS research in each topic area
- Showcase specific projects that demonstrate the current state
- Get industry feedback

- **Part 2 – 60 Min – Looking Ahead -** 1:00 to 2:00pm PDT
  - Panel led discussion on the topics explored in session 1 and the direction of both fundamental research and enabling technologies research within POETS (**Dr. Krein and Thrusts**)

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CENTER FOR POWER OPTIMIZATION OF ELECTRO-THERMAL SYSTEMS

Intro

Materials Workshop

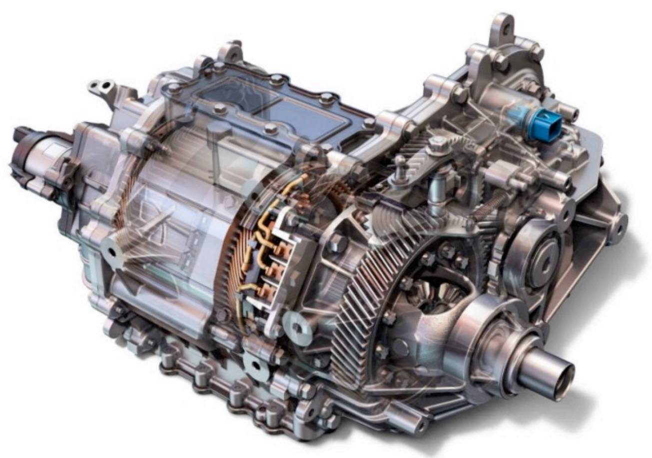
Power Density Improvements

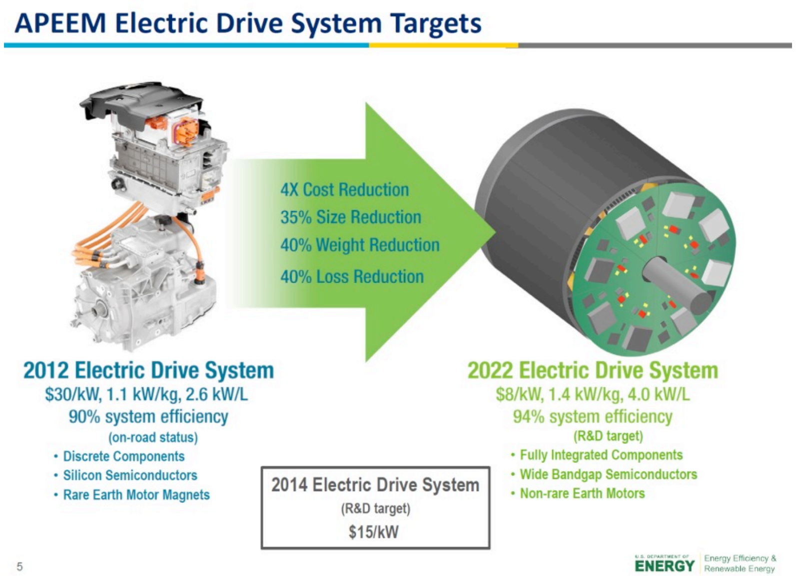
POETS goal: “10-100X improvement in power density” over 2014 baseline

Power electronic converters and electric motors are two technology demonstrators which integrate the thermal and electrical advances from all thrusts

SOA of power electronics and electric motors for the different applications are being benchmarked by various institutions and agencies

POETS will continue to advance the SOA to meet or exceed targets set by industry roadmaps





S. Rogers, S. Boyd, Advanced Power Electronics and Electric Motors, Vehicle Technologies Office

Inverter example

High-Voltage Power Electronics Technical Targets

ETDS Targets			
Year	2020	2025	Change
Cost ($/kW)	8	6	25% cost reduction
Power Density (kW/L)	4.0	33	88% volume reduction

Power Electronics Targets			
Year	2020	2025	Change
Cost ($/kW)	3.3	2.7	18% cost reduction
Power Density (kW/L)	13.4	100	87% volume reduction

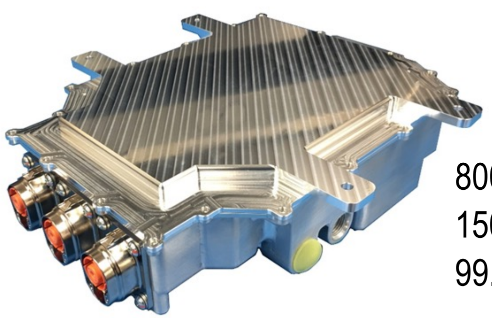
Electric Motor Targets			
Year	2020	2025	Change
Cost ($/kW)	4.7	3.3	30% cost reduction
Power Density (kW/L)[1]	5.7	50	89% volume reduction

2017 US Drive Electrical and Electronics, Technical Team Roadmap

POETS team has developed two generations of an all SiC traction inverter over the past three years

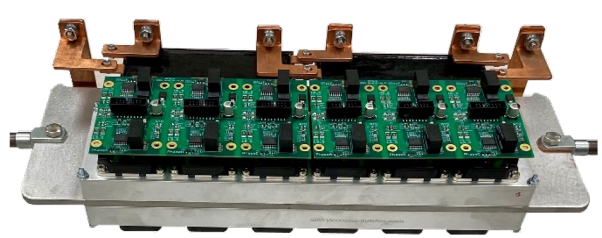
Generation 2 traction inverter has achieved 150 kW maximum power with a power density of 86 kW/L.

POETS researchers are working together to meet the DOE 2025 target



800V SiC Inverter
150 kW
99.4% Peak Efficiency

[Zhao, Mantooth]

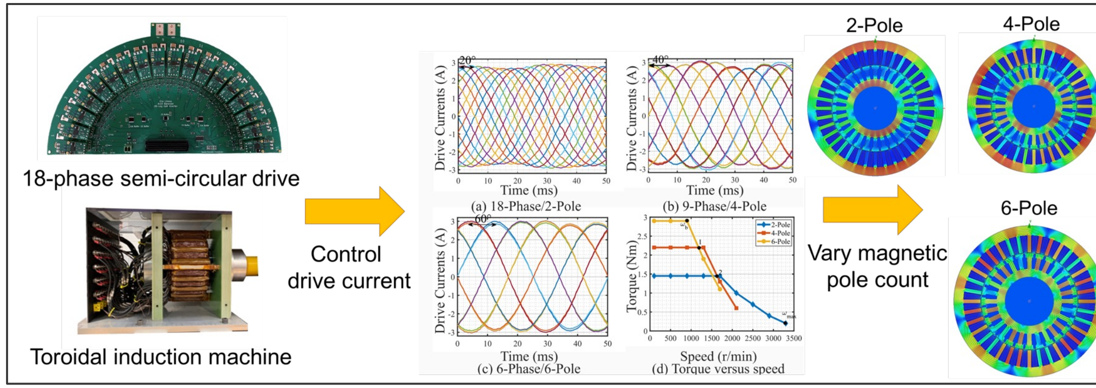


6-Phase SiC Inverter System
Capable for SRM
105°C coolant compatible
20 kW/L

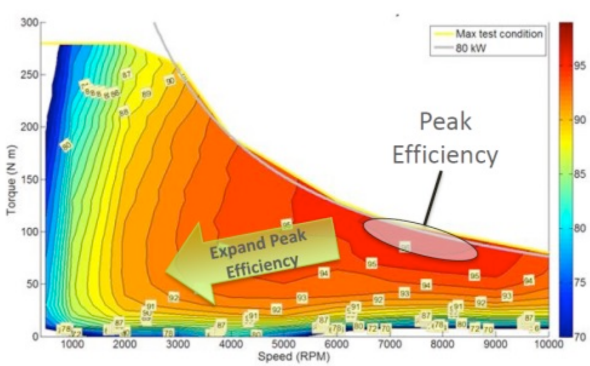
[Balda, Mantooth]

Variable-pole Induction

[Bannerjee, Miljkovic, Krein]



Additional considerations: Cost, efficiency, reliability, supply chain risks, charging

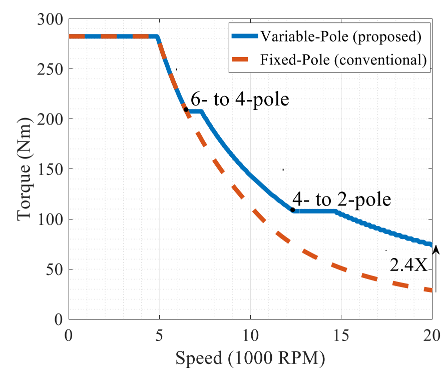


Typical On-road Traction Motor Efficiency Map

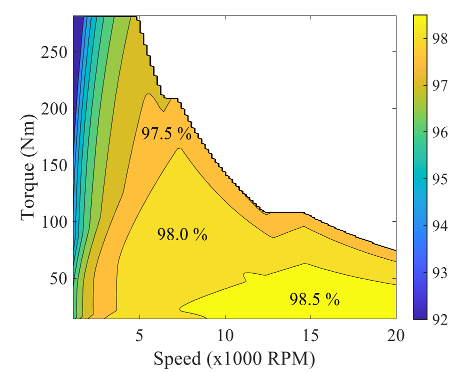
Expand regions of high efficiency operation

- Current peak efficiency regions do not match the most frequent operating points

Susan Rogers
Steven Boyd
Advanced Power Electronics and Electric Motors
Vehicle Technologies Office



A variable pole-count induction machine has 2.4X more torque capability compared to its fixed-pole counterpart at the maximum speed.



Combined machine-inverter efficiency color map of the proposed variable-pole induction machine based traction drive.

Aircraft

For electrified aircraft, benchmarking against targets in 2016 NAE report on low carbon aircraft

Threshold metrics established for electrical systems to enable different classes of aircraft

Power > 1MW, and specific power > 3 - 6.5kW/kg for regional jets.

Similar metrics from NASA's AATT program

The SOA technology is 250kW of power at a specific power of ~1-2kW/kg.

POETS is in the process of validating electric motors at 1 MW power with a specific power of 13kW/kg and efficiency above 96%.

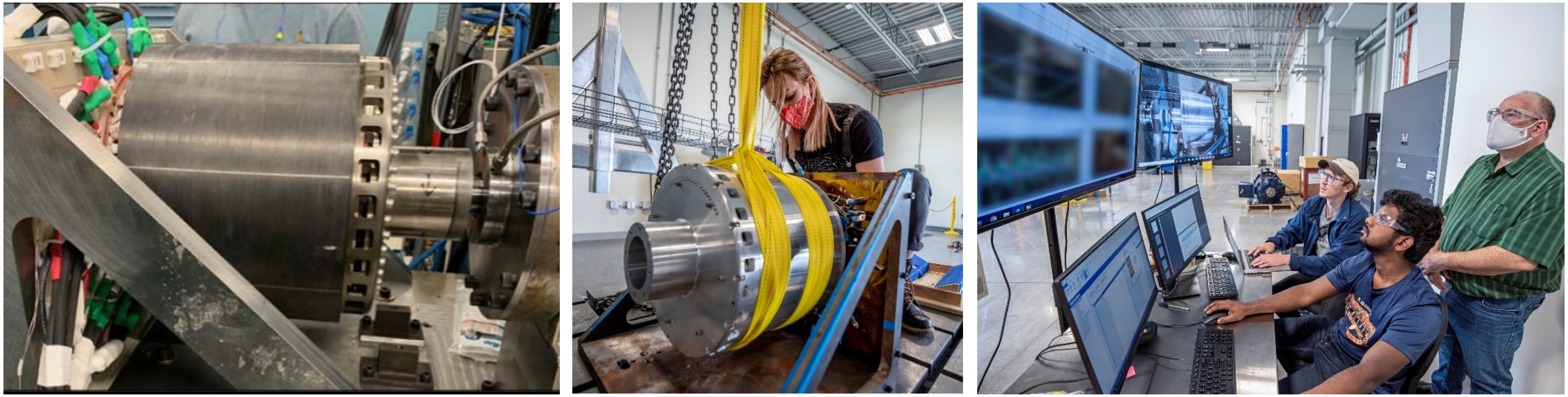
TABLE 4.2 Electrical System Component Performance Requirements for Parallel Hybrid, All-Electric, and Turboelectric Propulsion Systems

Aircraft Requirements	Electric System [a] Power Capability (MW)	Electric System [a] Specific Power (kW/kg)[c]	Battery [b] Specific Energy (Wh/kg)
General aviation and commuter			
Parallel hybrid	Motor <1	>3	>250
All-electric	Motor <1	>6.5	>400
Turboelectric	Motor and generator: <1	>6.5	n/a
Regional and single aisle			
Parallel hybrid	Motor 1-6	>3	>800
All-electric [b]	Motor 1-11	>6.5	>1,800
Turboelectric	Motor 1.5-3; Generator 1-11	>6.5	n/a
Twin-aisle			
Parallel hybrid	Not studied		
All-electric	Not feasible		
Turboelectric	Motor 4; generator 30	>10	n/a
APU for Large Aircraft	Generator 0.5-1	>3	Not studied

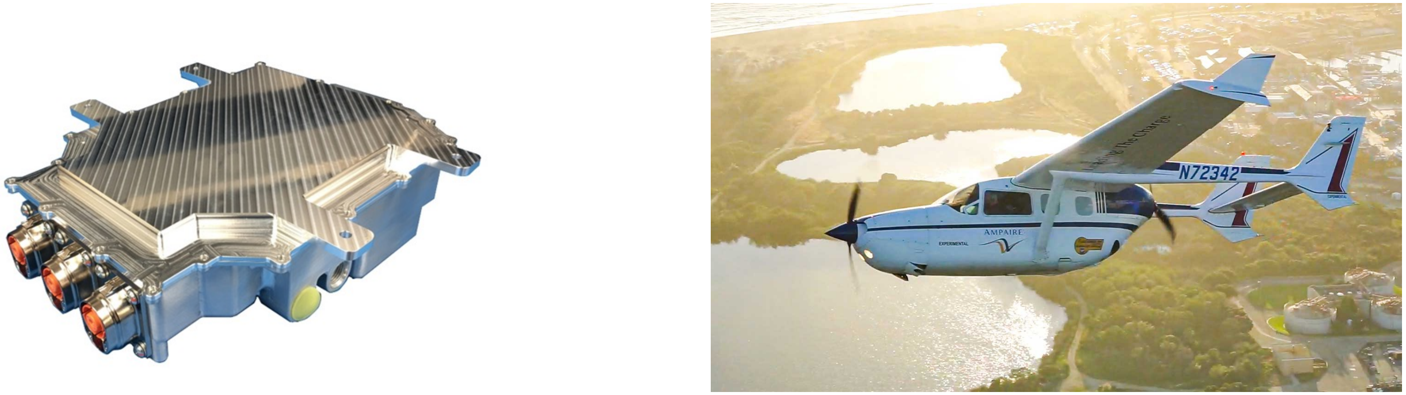
[a] Includes power electronics.
[b] Total battery system and usable energy for discharge durations that are relevant to commercial aviation flight times, nominally 1-10 hours. Values shown are for rechargeable batteries; primary (nonrechargeable) batteries are not considered relevant to commercial aviation.
[c] Conversion factors: 1 kW/kg = 0.61 HP/lb; 1 kg/kW = 2.2 lb/kW = 1.64 lb/HP.

Source: Commercial Aircraft Propulsion and Energy Systems Research: Reducing Global Carbon Emissions (2016), NAP
Bowman, C., R. Jansen, G. Brown, K. Duffy, and J. Trudell. "Key Performance Parameter Driven Technology Goals for Electric Machines and Power Systems." (2015).

Technology maturation through associated projects



(left) 15,000 rpm, 1-MW slotless PM motor, (center) 300KW machine assembled and (right) tested on PRDC testbed



Gen-2 SiC inverter from UArk being tested on Ampaire flying testbed

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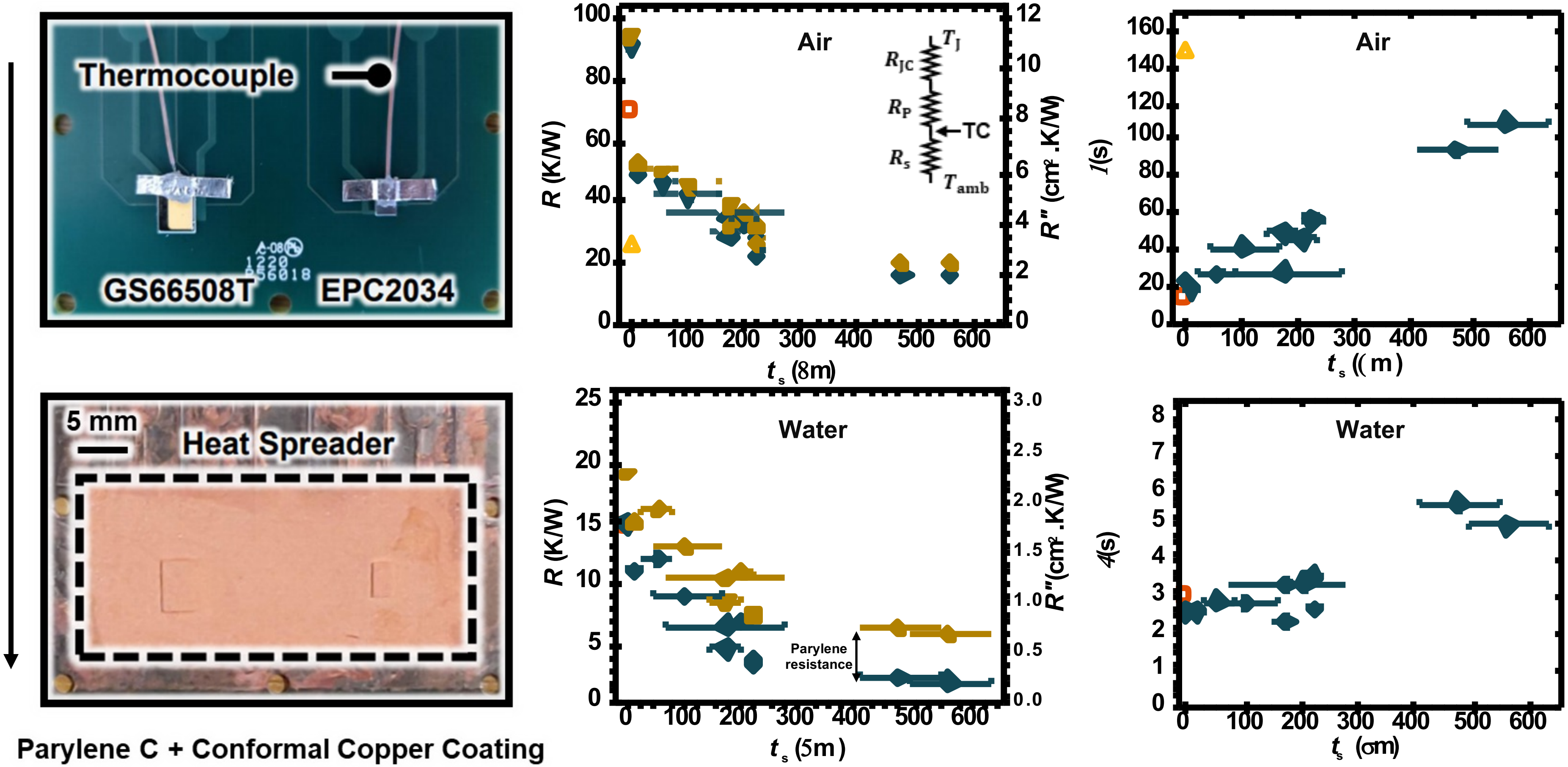
Materials and Devices

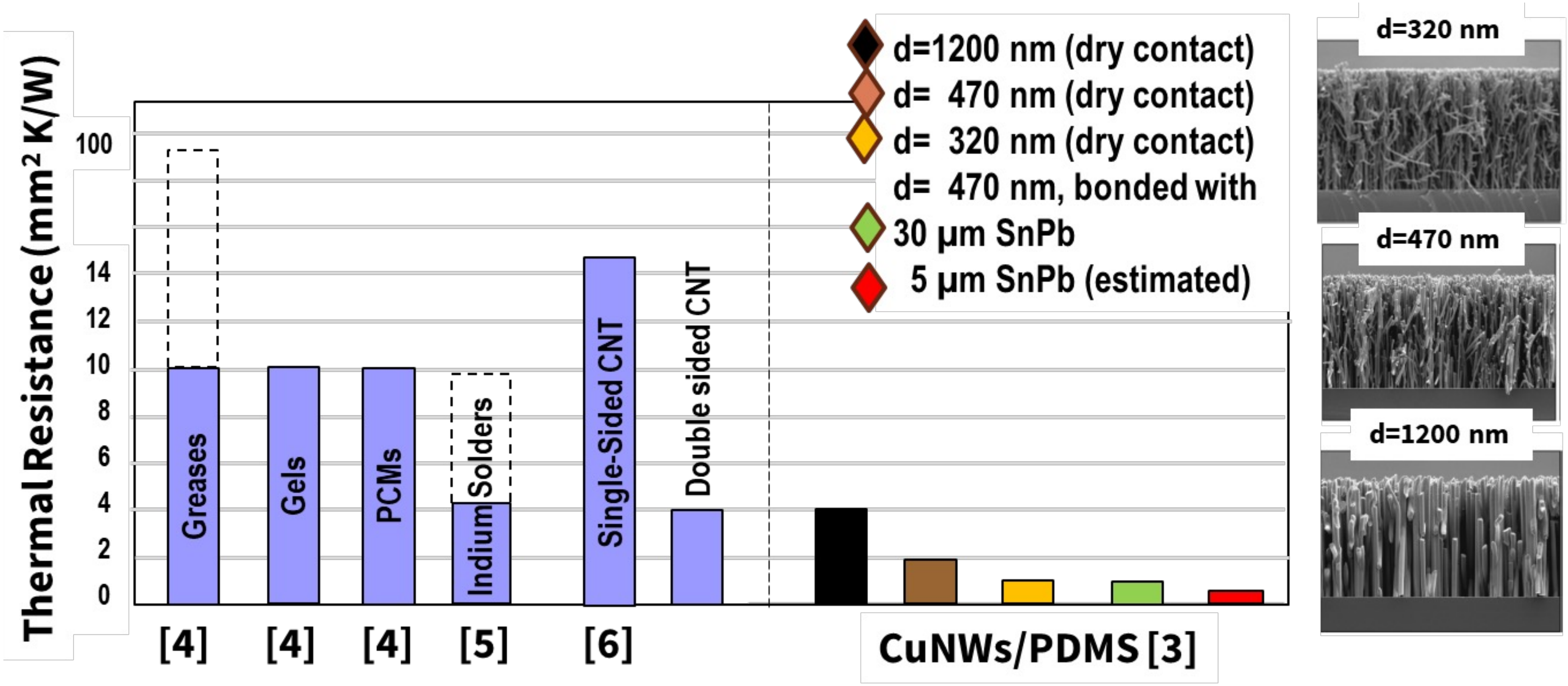
Materials Workshop

Gebrael, Tarek, et al. "High-efficiency cooling via the monolithic integration of copper on electronic devices." Nature Electronics (2022): 1-9.



Conformal copper coatings enhance heat spreading in air cooling and liquid cooling involving water, water/ethylene glycol, dielectric liquids…

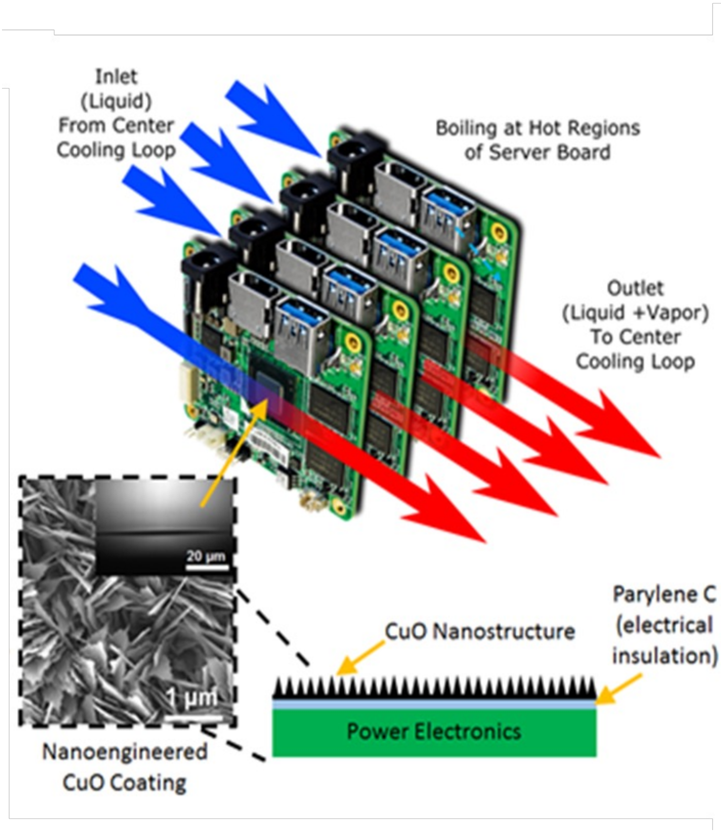
Goodson, Asheghi

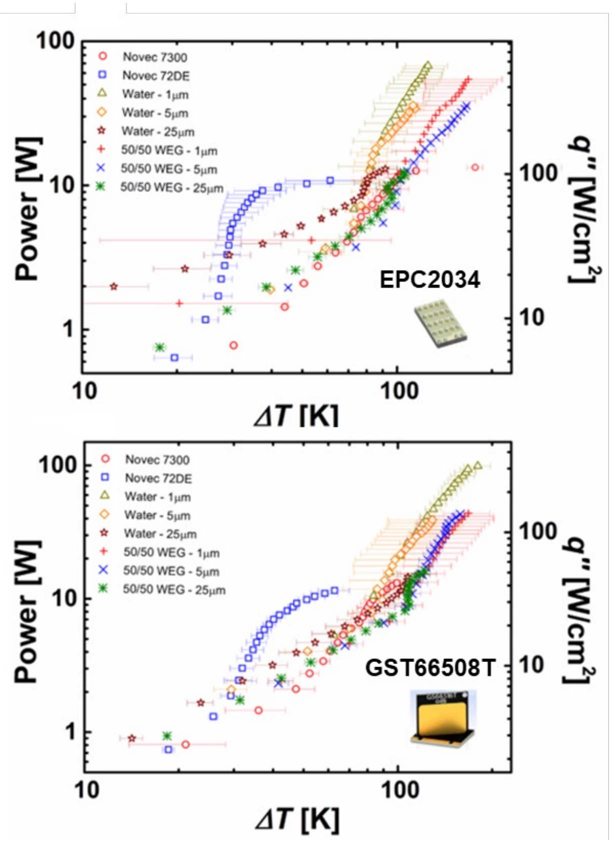


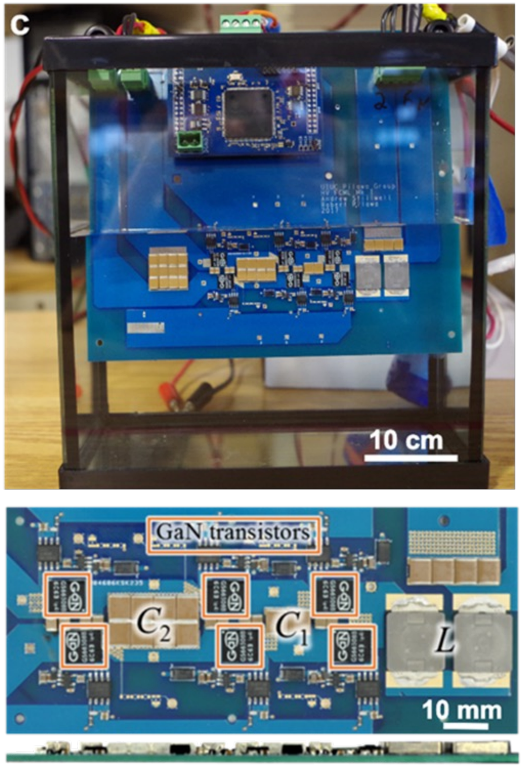
Comparison of thermal resistance of State-of-the-Art commercial and laboratory demo [4] thermal interface materials (CNT: carbon nanotubes, PCM: phase-change material; greases, gels, PCMs: [4]; Indium solders [5], CNTs: [6], with that of the proposed CuNWs/PDMS TIMs tape (1 cm^2). The thermal resistance of the CuNWs/PDMS composite of various nanowire volume fractions and diameters (dry contact: 320 ♦, 470 ♦, 1190 ♦, and 470 nm ♦ bonded with 30 µm thick SnPb). The SnPb bonded CuNWs/PDMS composite performs better although the thermal resistances are nearly a factor 2-4 smaller than the stand-alone (without filler) CuNWs [1]. The CuNWs/PDMS TIMs tape performs a factor of 4 better than CNTs [6], with a potential to achieve thermal resistances as low as 0.5 mm^2-K/W ♦.

Miljkovic, King, Pilawa

Birbarah, Patrick*, Gebrael, Tarek*, et al. "Water immersion cooling of high power density electronics". International Journal of Heat and Mass Transfer 147 (2020): 118918.







- Water provides a 5X increase in the critical heat flux (CHF) compared to SOA dielectric liquids.
- Converter circuit coated with 25 μm thick Parylene C operated successfully in DI water. DC-DC conversion with an input voltage of 500 V and a 167 kHz switching frequency produced 56 Watts of loss from the power components (efficiency > 97%) for a duration of 1 hour.

Dr. Heungdong Kwon, Qianying Wu, Sougata Hazra, Dr. Chi Zhang, Katherine Jiang, Adjunct Prof. Mehdi Asheghi, Prof. Ken Goodson

"Convective-based" vs. "Capillary-based cooling"

Micro-coolers: Combinations of different Wicks and 3D-Manifolds

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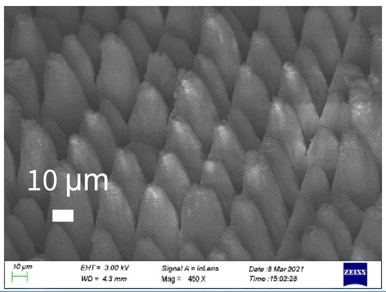
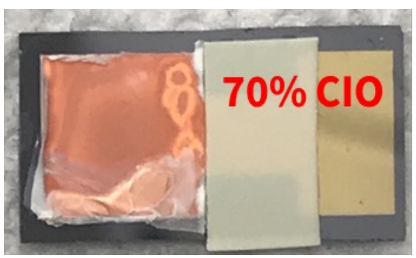
Nanoheat Lab | Mechanical Engineering

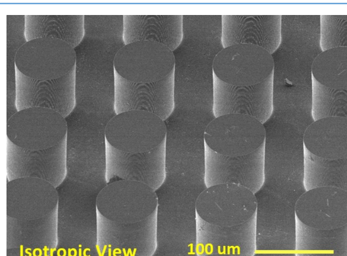
Stanford ENGINEERING



AlN pyramid Fins



Copper Inverse Opals (CIOs)



Silicon Pin Fins

X
Y
Z

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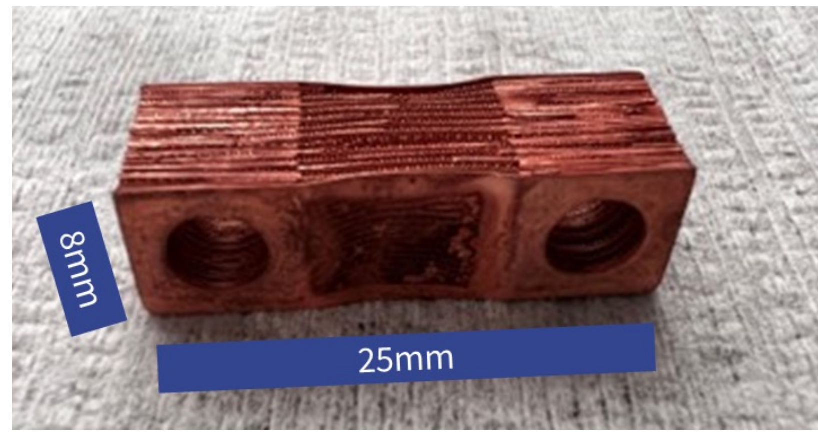
Additive manufacturing of Wiremesh 3D-Manifold

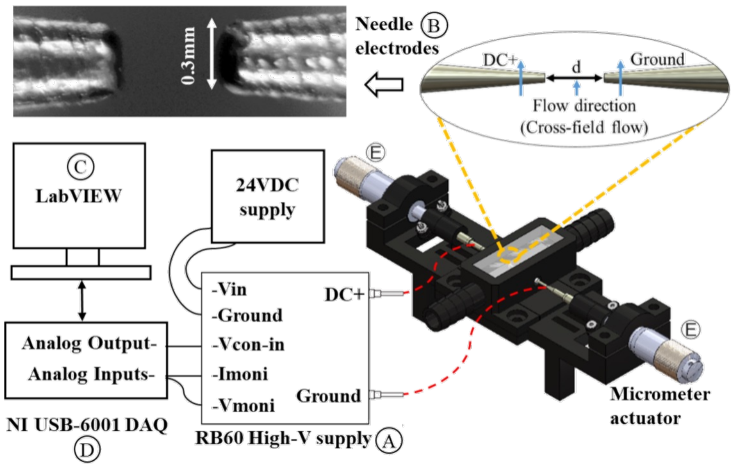


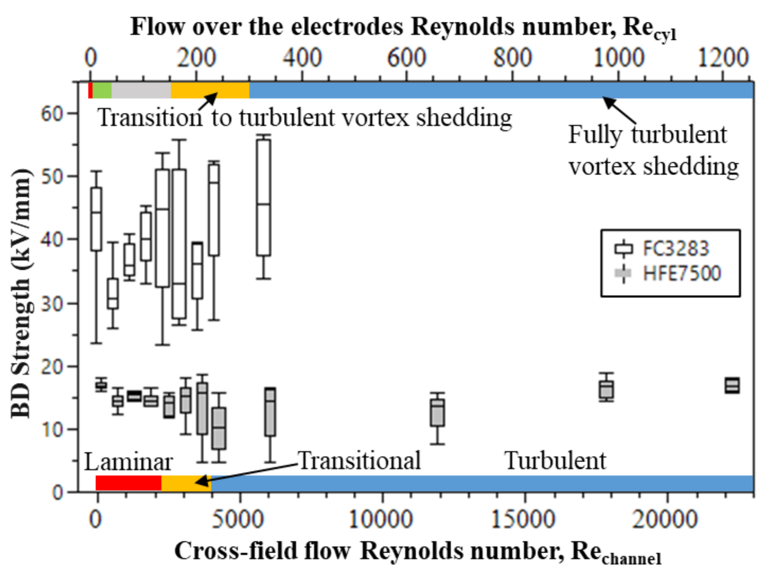
Prof. James Palko, Neda Tehrani (Ph.D. Student), Souvik Roy (Ph.D. Student), Muhammad Shattique (Ph.D. Student), Roman Giglio (Ph.D. Student)

Protection & Reliability in Immersion Cooling

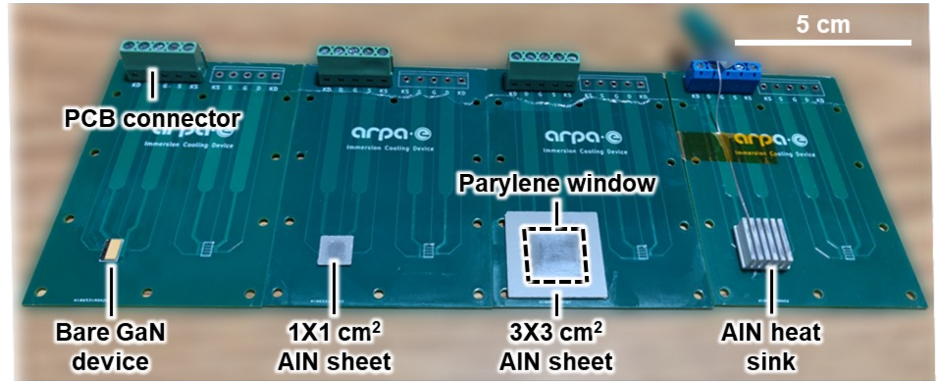
Huitink, Miljkovic

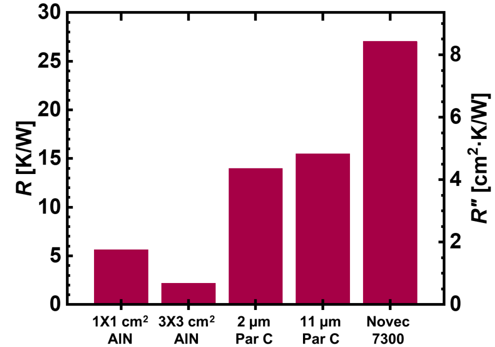
Dielectric liquid reliability characterization

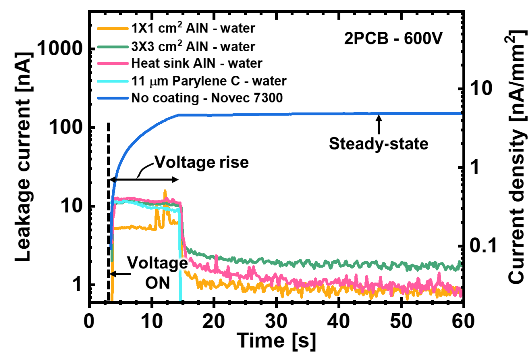


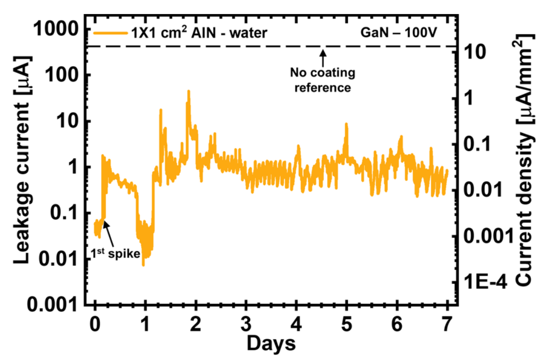


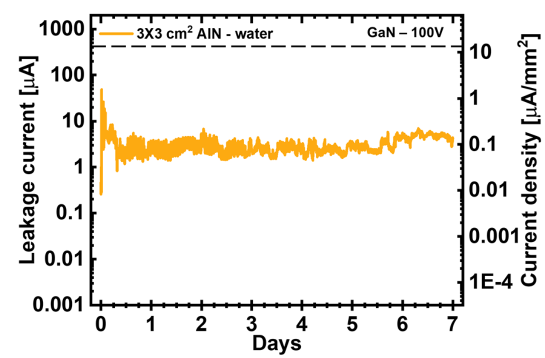
Protective coating electrical and thermal characterization







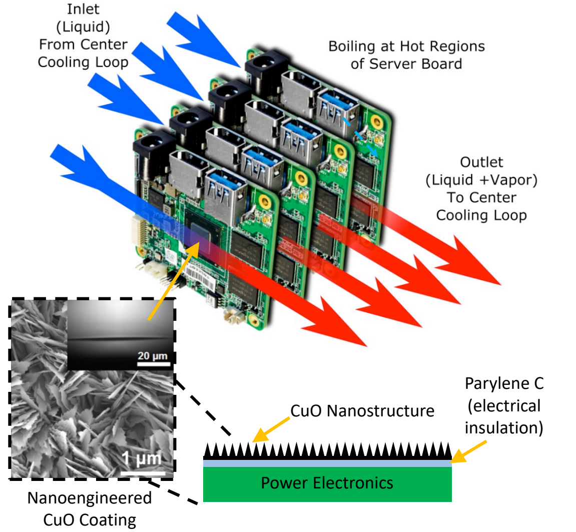




Flow Immersion cooling of RF electronics

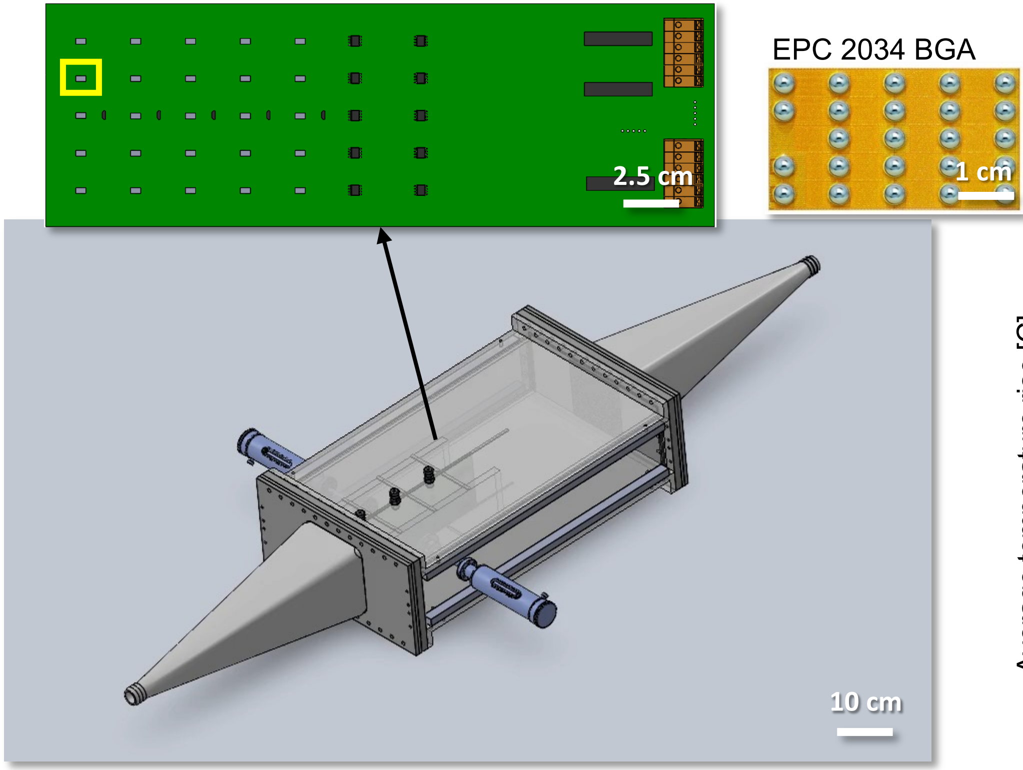
Huitink, Miljkovic

- Single and two-phase flow **immersion cooling** allows **high heat transfer coefficients** suitable for reliable, power-dense electronics
- The **coupling of thermal and hydraulic phenomena** when directly flow cooling PCBs has not been rigorously studied or optimized
- We need a fundamental understanding of the coupled physics to develop design tools for novel cooling systems for **steady state and transiently operated power-dense electronics**

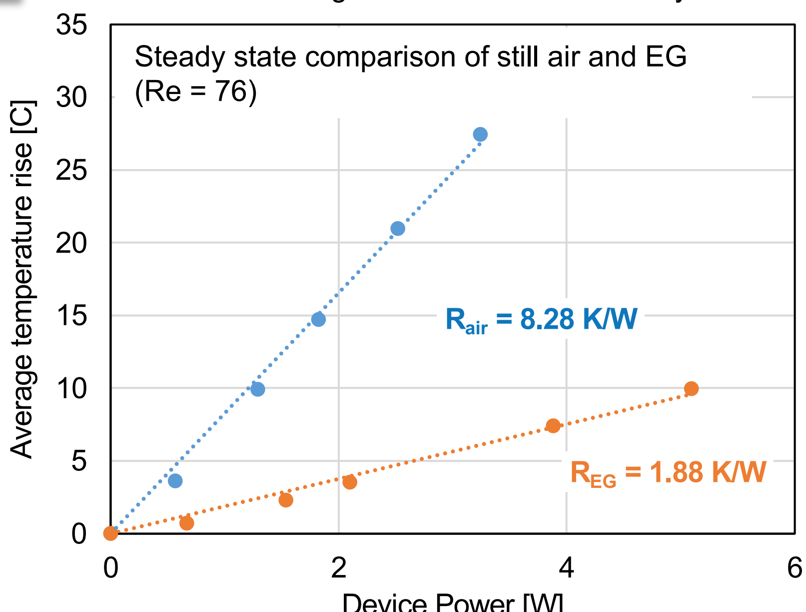


Flow boiling of electronics enhanced by CuO

DUT: PCB with grid of GanFETs and sensors (T, I)



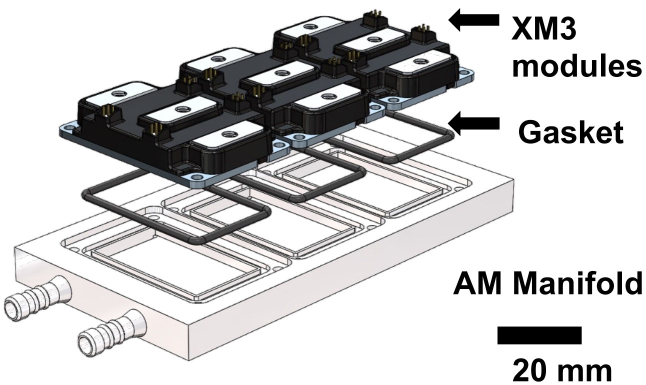
Schematic of dynamically changing liquid tunnel test section

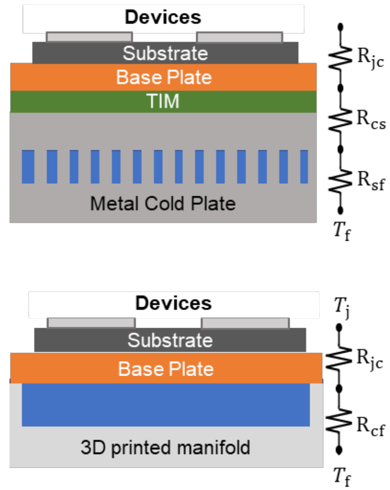


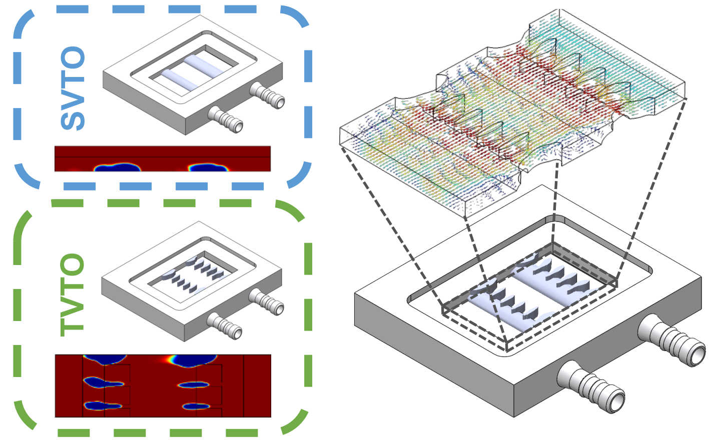
Additive Manufacturing Enabled Thermal Management

Zhao, Mantooth, Balda, Huitink, Miljkovic

- Direct Cooling of power modules

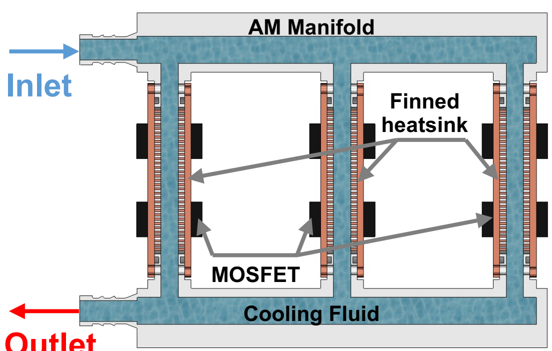


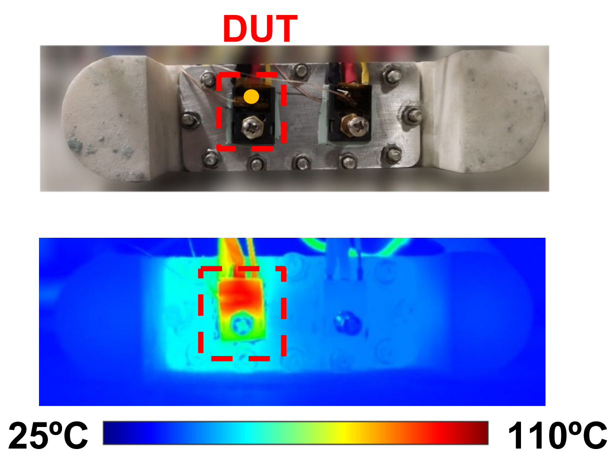




- Hybrid thermal management solutions

Polymer *(AM Manifold) –* ***Metal*** *(Finned heat sink)* ***Hybrid Cooler***





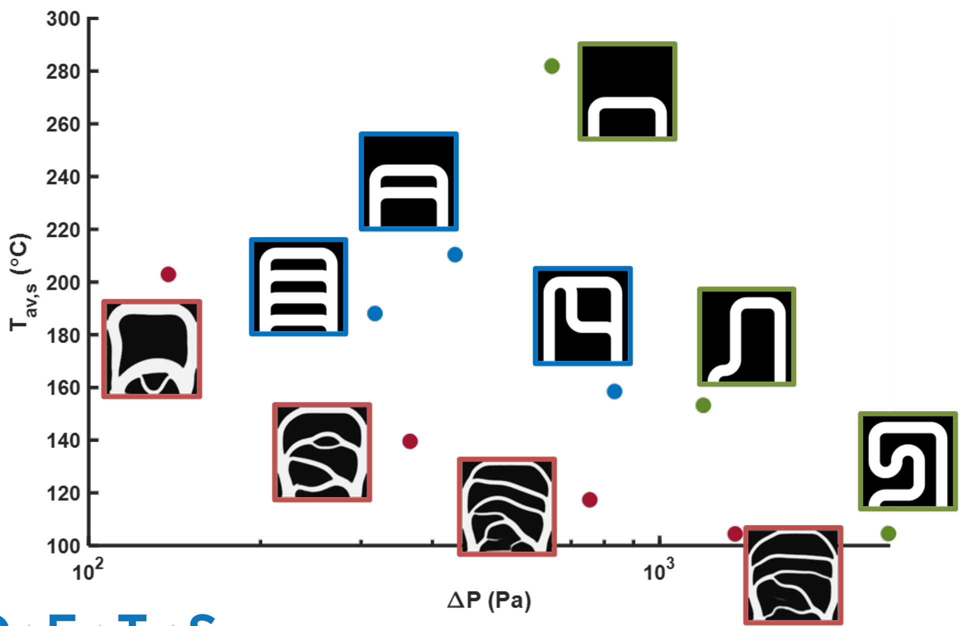
Three Phase Traction Inverter Using TO-247 SiC discrete MOSFETs

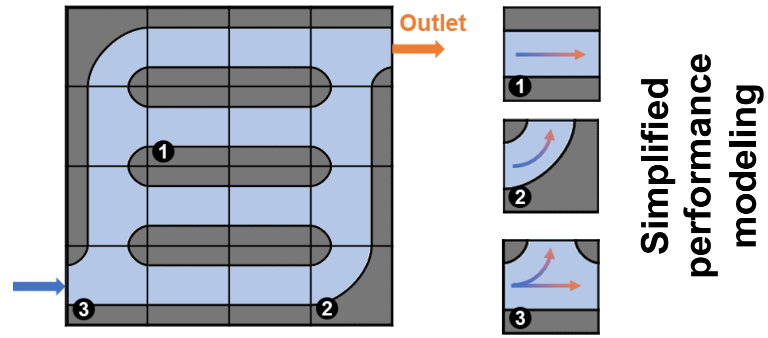
0.16 ºC/W	225 W	>100 kW/L
Heat sink thermal resistance	Heat Dissipation Per MOSFET	Estimated volumetric power density

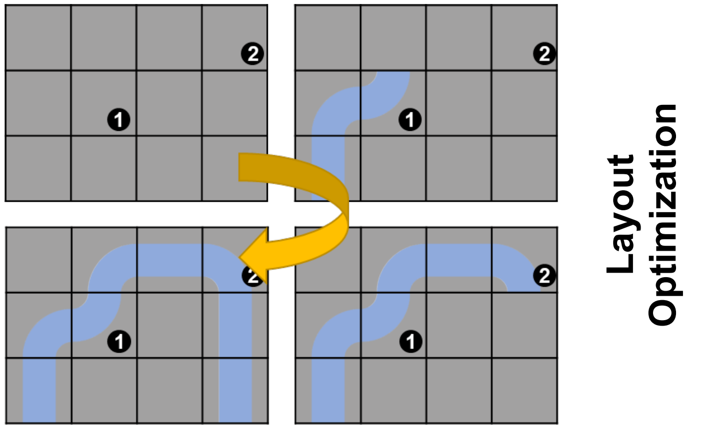
Reduced Order Optimization of Cold Plates

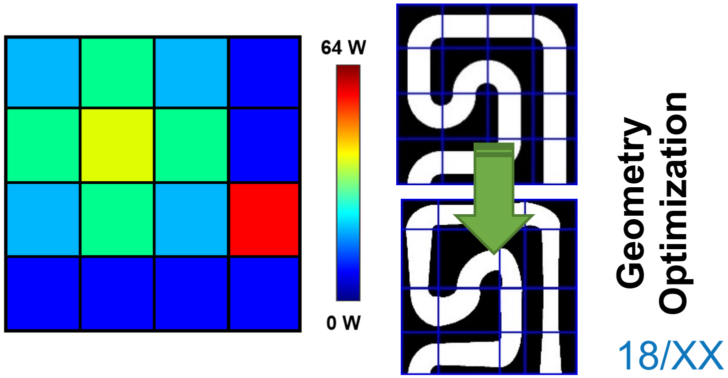
James, King, Mantooth, Miljkovic

- Rapid **(60-120s)** optimization of cold plate designs enabled by -
  - Simplified performance modeling using elementary flow blocks
  - Flow layout optimization using path search algorithm coupled with randomized search
  - Optimization of element size and diameters
- Optimized performance compared against Topology Optimization



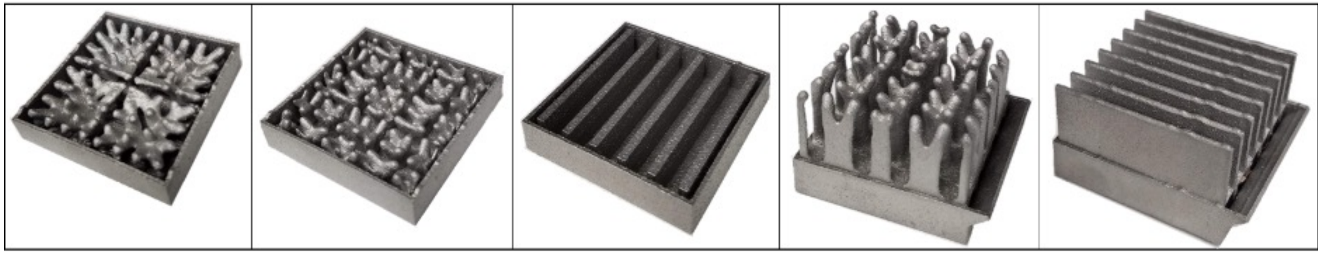


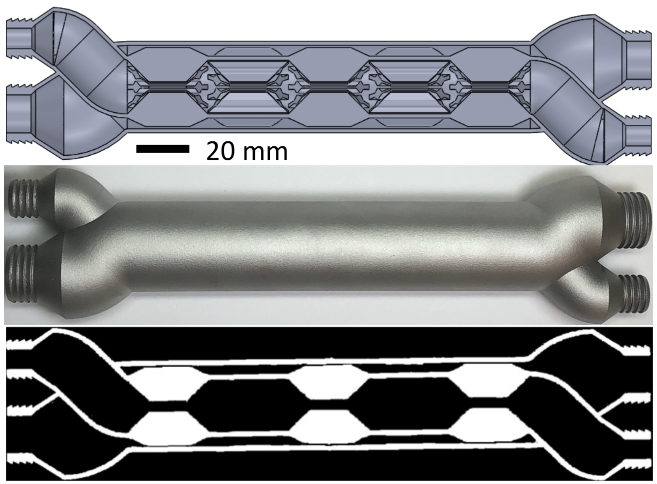


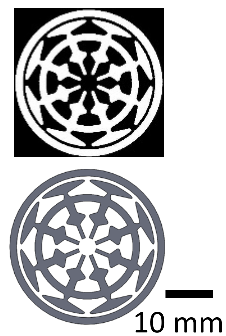


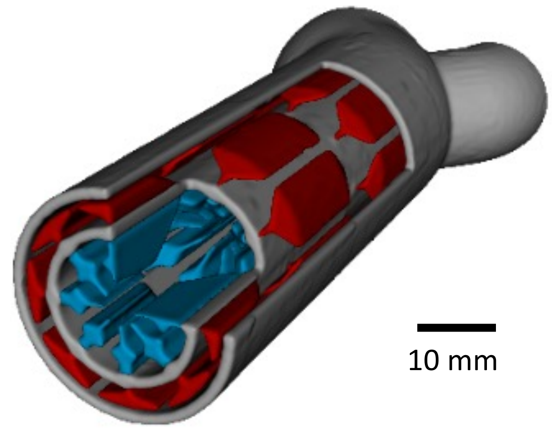
High Fidelity Optimization of Cold Plates

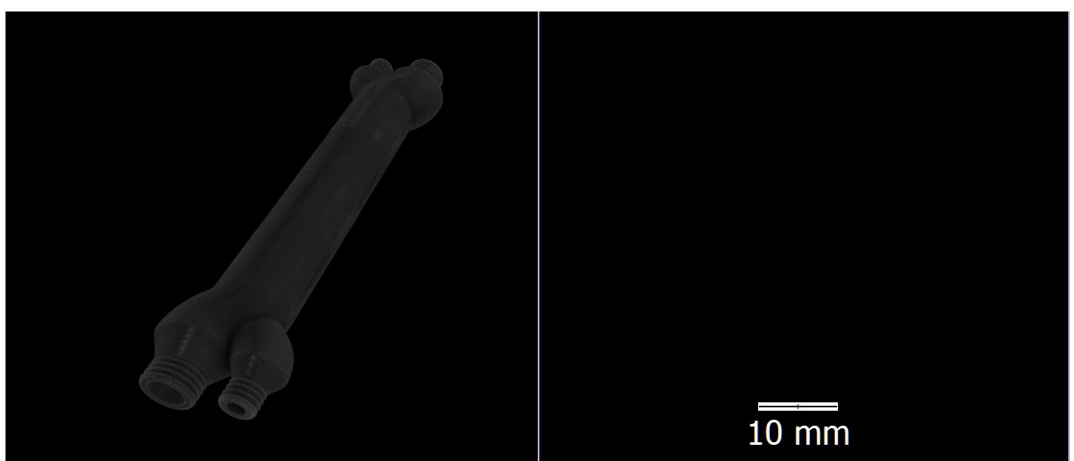
King, Huitink







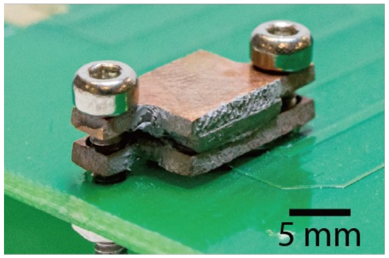


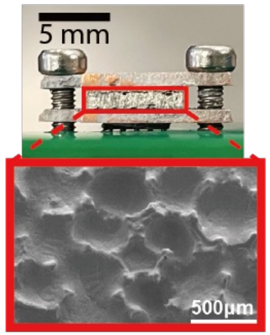


Phase Change Materials

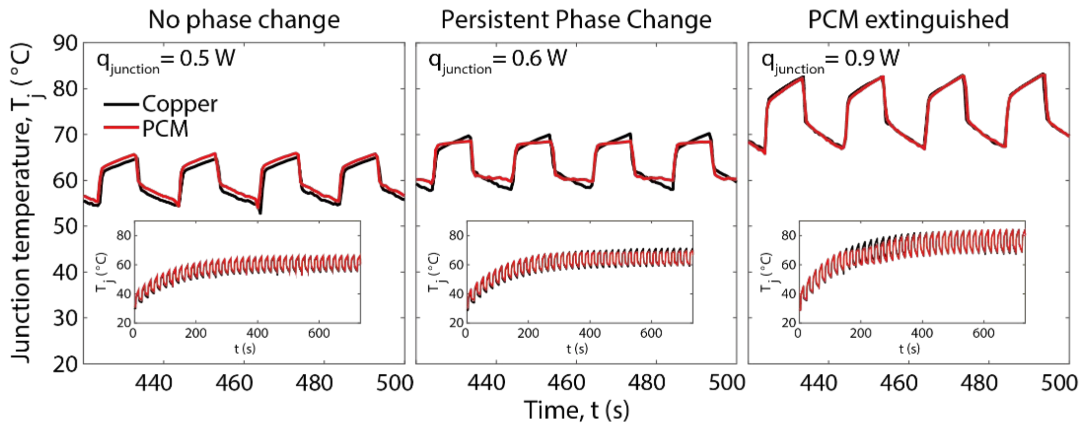
King, Zhao, Mantooth, Miljkovic

- Phase change materials (PCM) for transient thermal buffering in electronics.

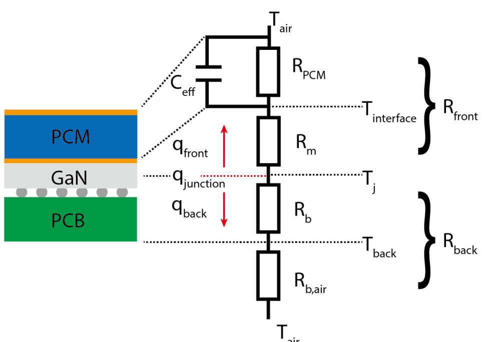


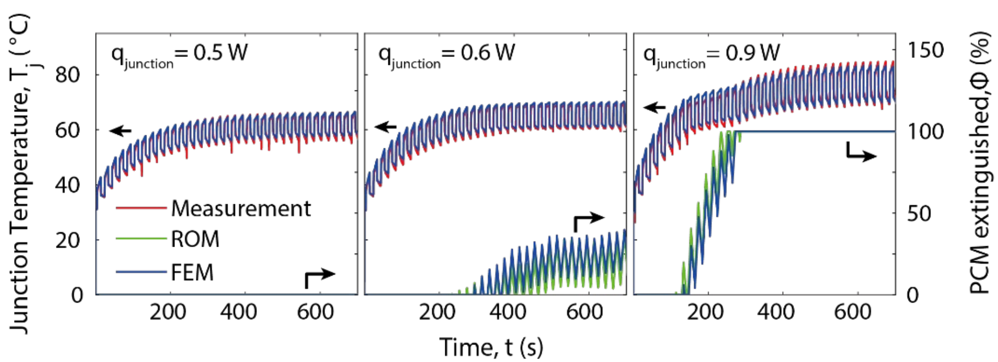


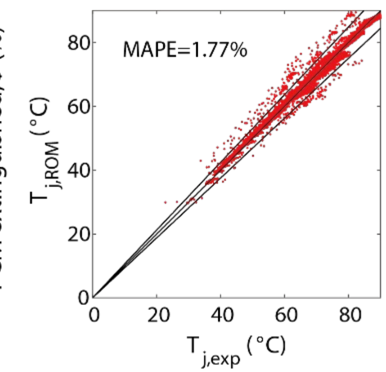
Field's metal/Cu foam composite



- Achieved up to **21% junction temperature swing reduction** compared to copper reference.

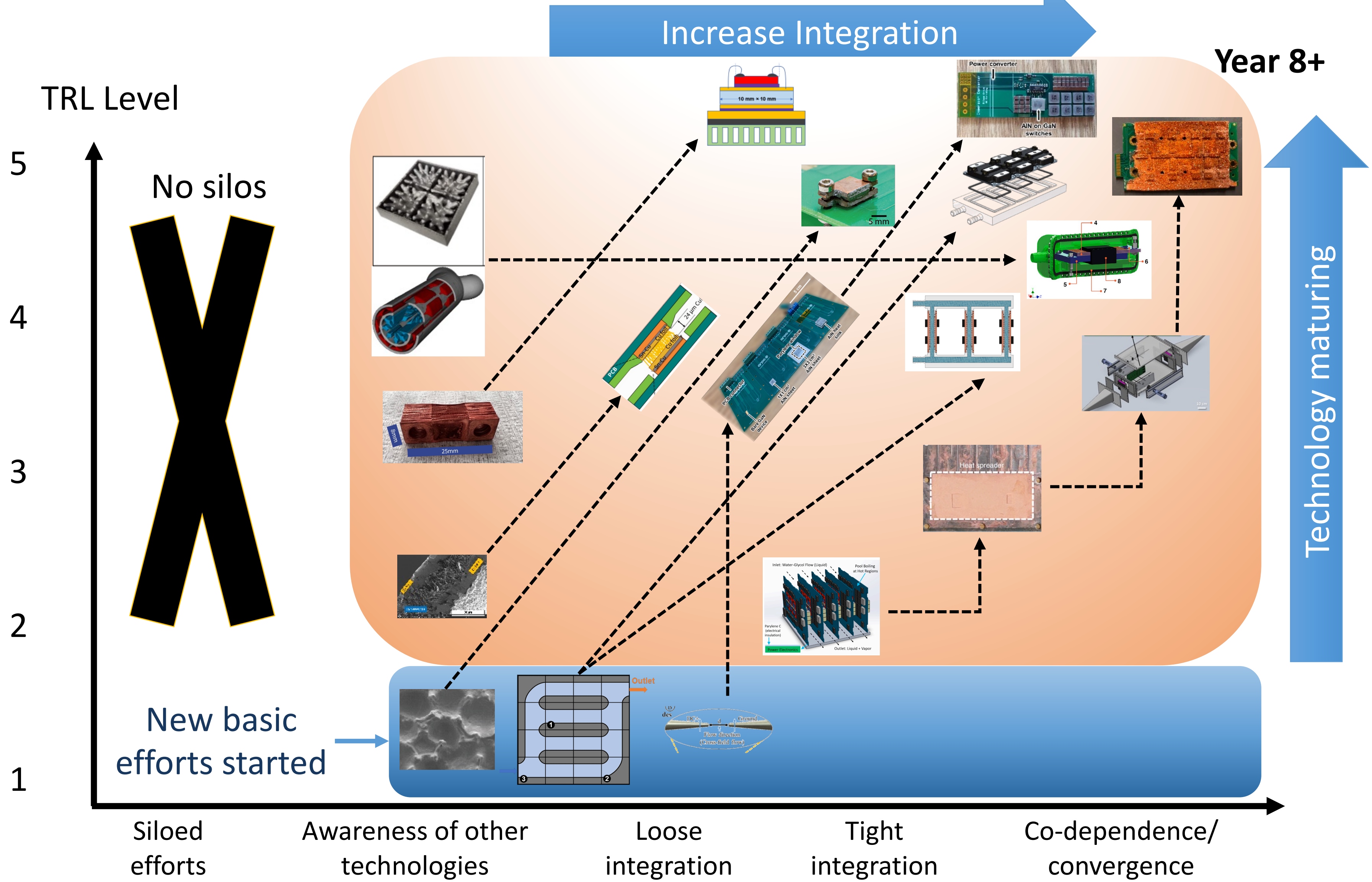




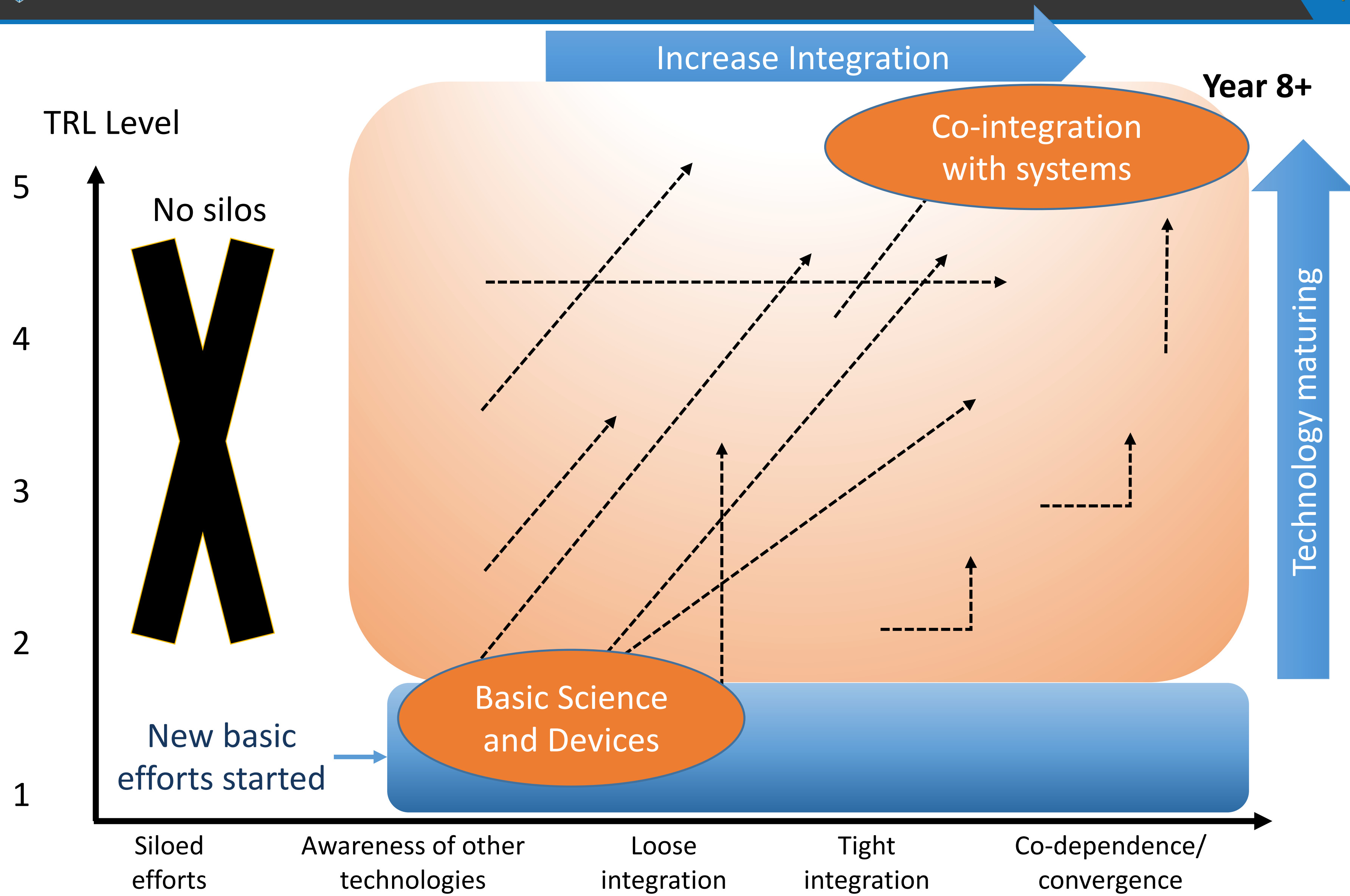


- Reduced-order model (ROM) provides expedited prediction tool for PCM integrated cooling optimization.
- ROM model solution takes **99.9% less time** when compared to finite element method simulations tools.

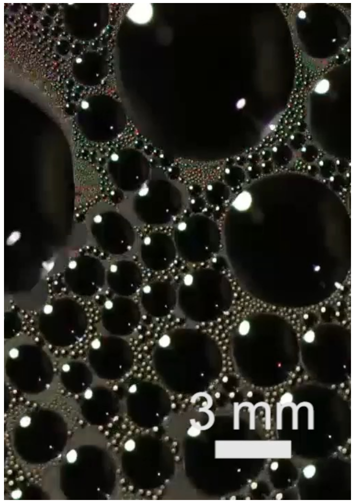
Research Advancement Graphic

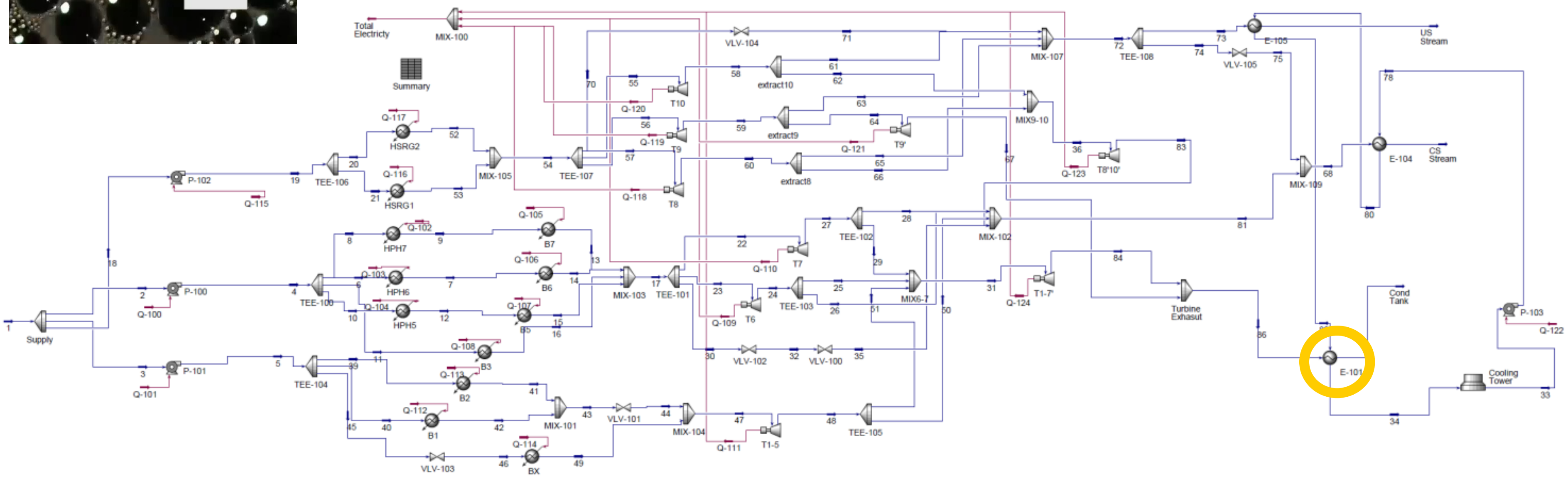


Research Advancement Graphic



What do we really need at POETS to help us?





- What does it mean when we put it in the system? A 10X component level improvement may make a 1% impact on the system.

P/O/E/T/S

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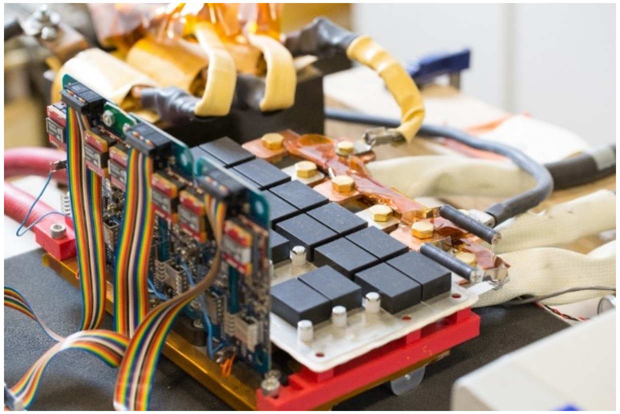
ELECTRO-THERMAL SYSTEMS

Power Electronics

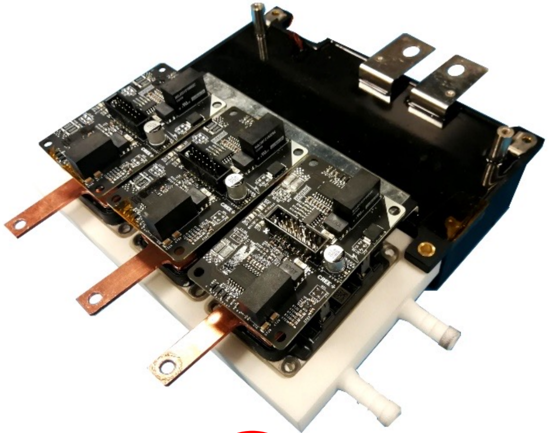
Materials Workshop

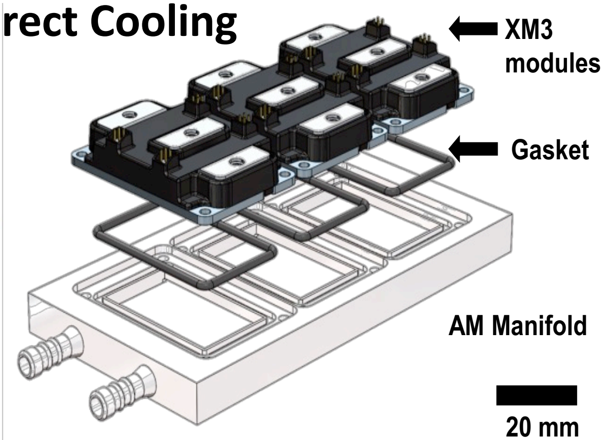
800V SiC Traction Inverters for EVs

GEN 1 (2018): 75 kW, 13 kW/L

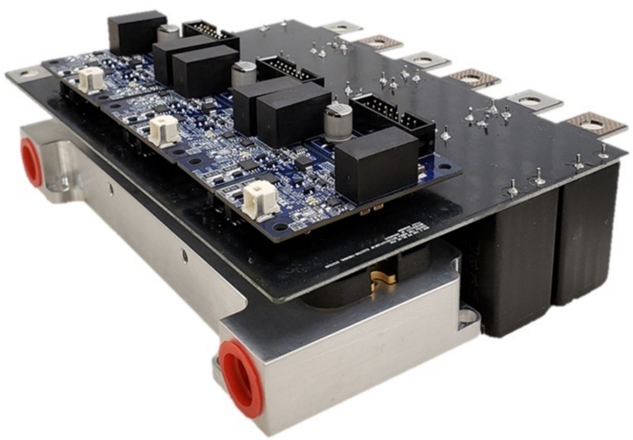


XM3 Inverter (2021) with Direct Cooling

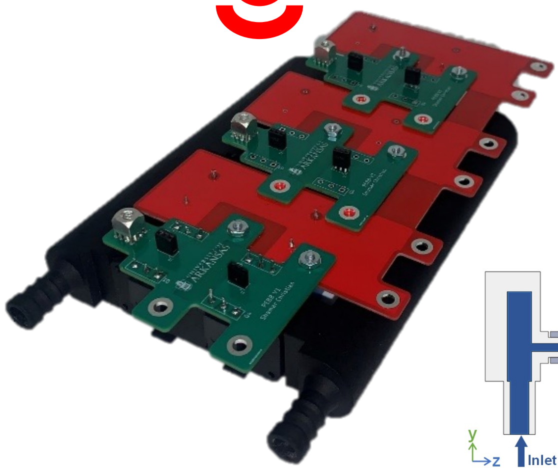




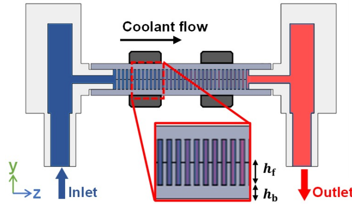
AM Manifold for Direct Cooling



GEN 2 (2019): 150 kW, 86 kW/L



AM Cooler for Discrete Devices



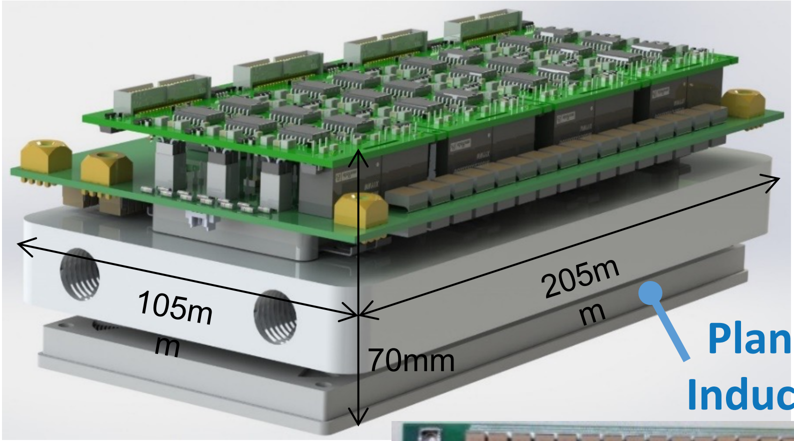
Latest Design (2022) 80 kW w/ Discrete Devices, 155 kW/L

Balda
Zhao
Miljkovic

DC/DC Converter: Topology, Magnetics & Ctrl.

80 kW Boost Converter, 56 kW/L

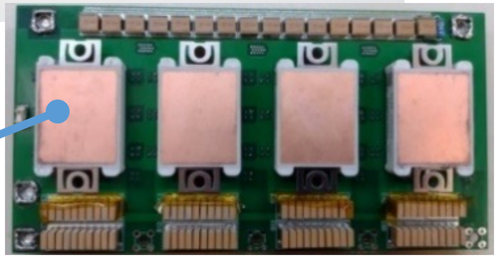
12-phase Interleaved Boost Converter with 600kHz equivalent switching frequency

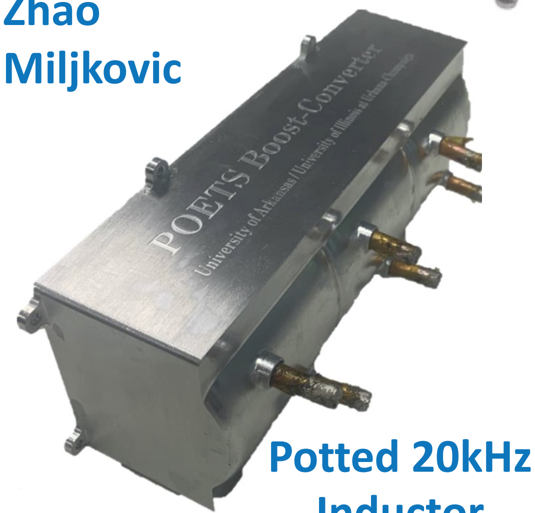


Planar Inductor

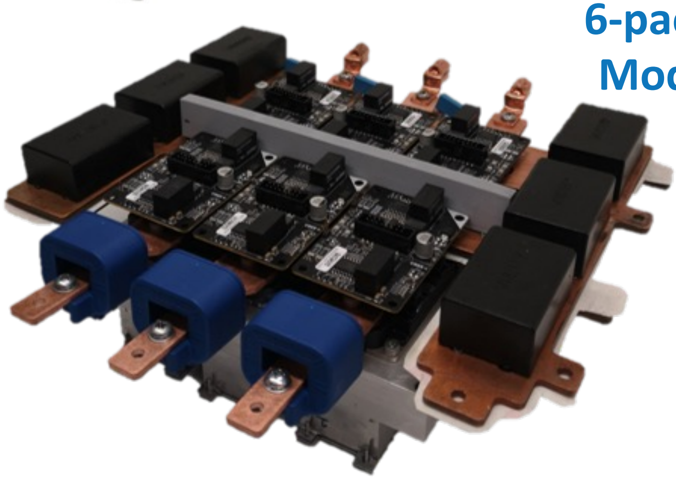
Balda
Zhao
Miljkovic

6-pack SiC Modules

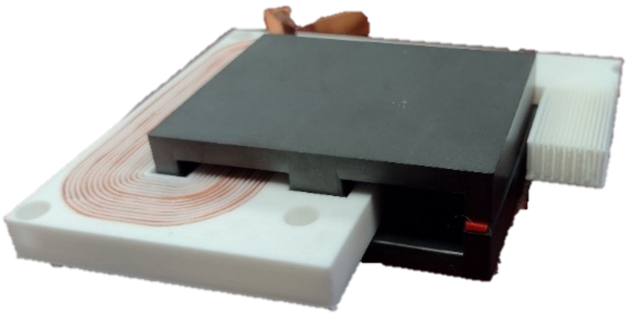




Potted 20kHz Inductor

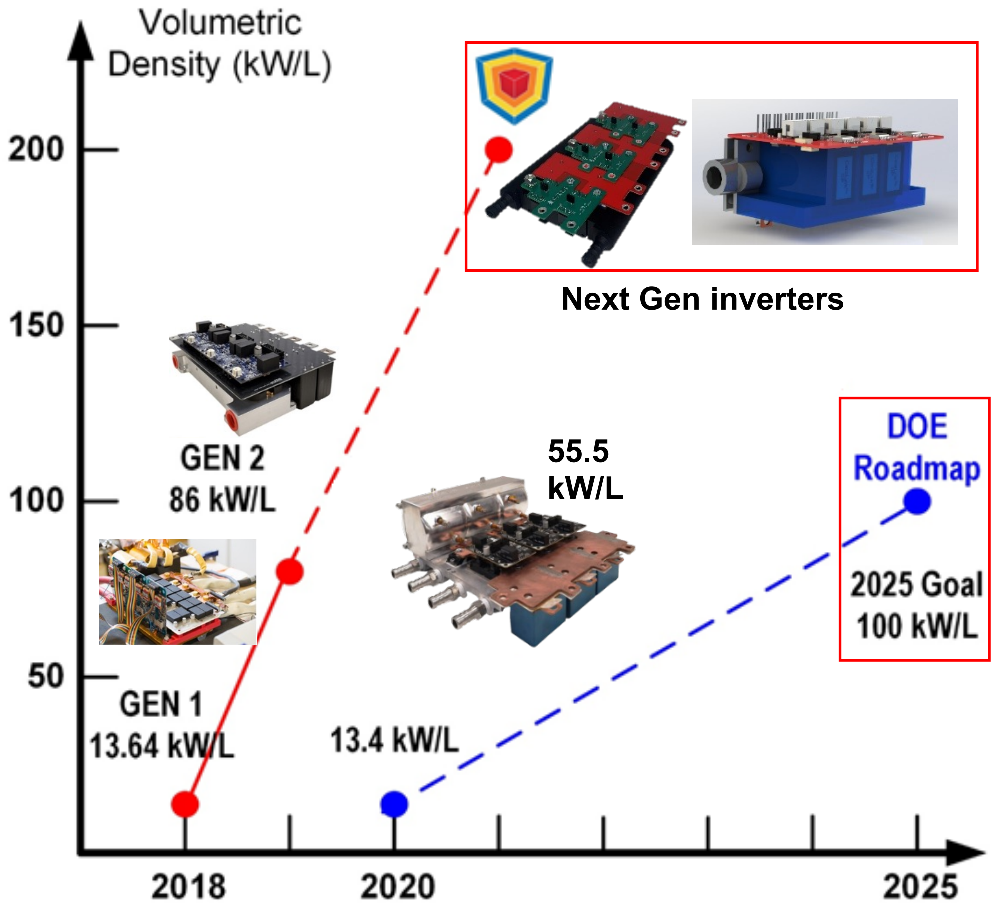


50 kW/L POETS PCU: Boost Converter + Traction Inverter



Planar Inductor w/ AM Bobbin

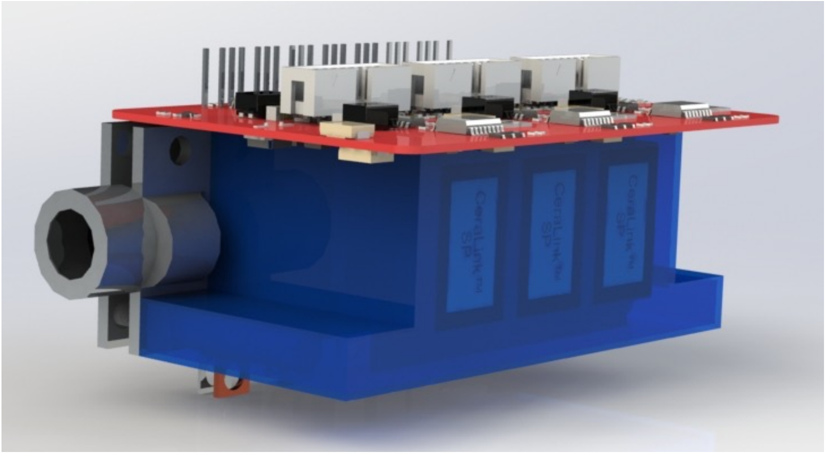
Towards Higher Power Density



Conceptual Design –

50 kW Inverter w/ Double-Sided Cooling (DSC) Modules

170+ kW/L



Consistent advance towards higher power density for traction applications!

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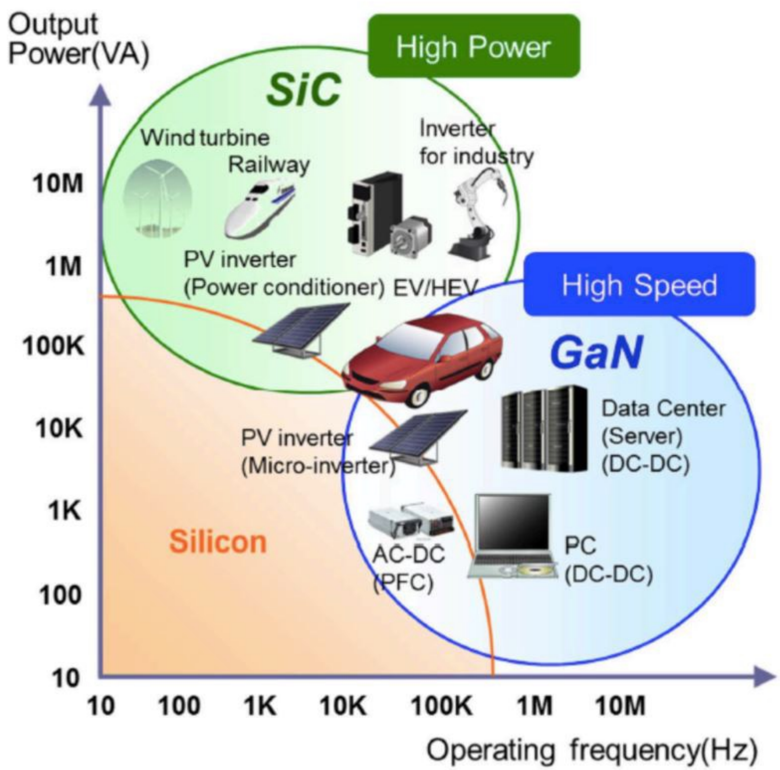
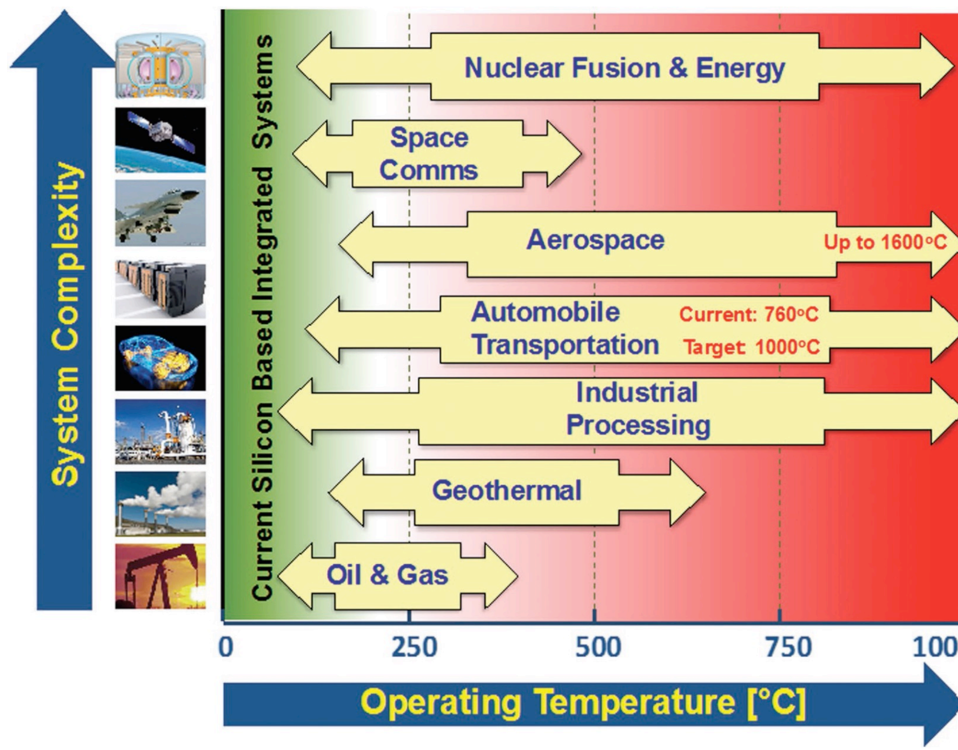
High Temp Materials

Materials Workshop

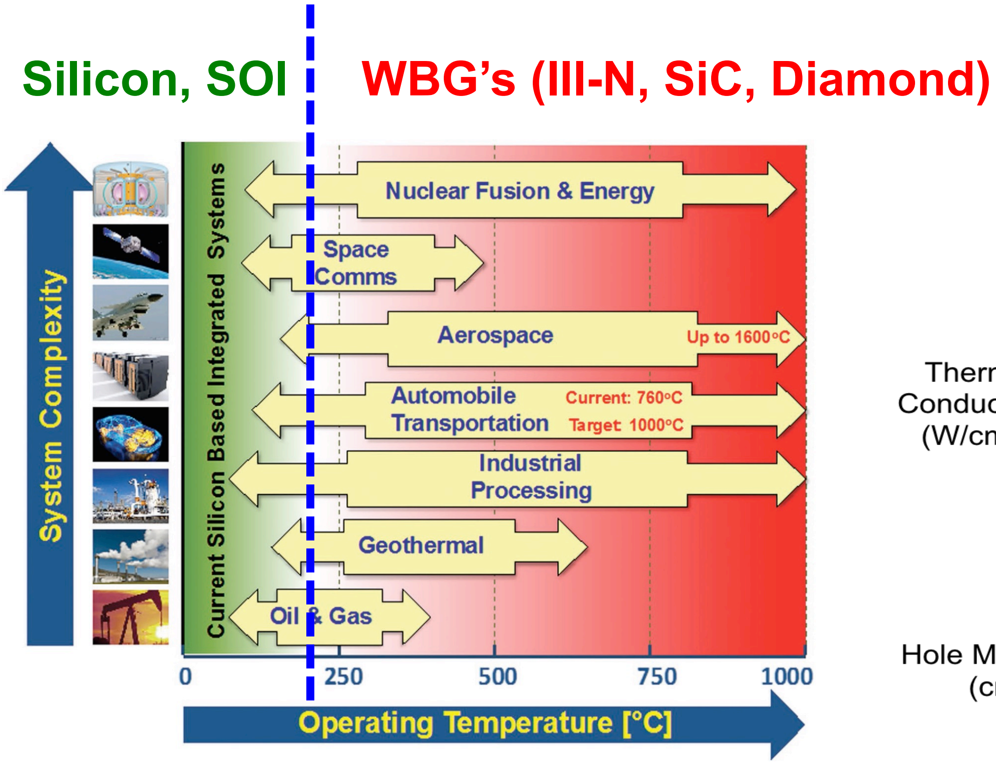
Applications & Future High-temperature Systems



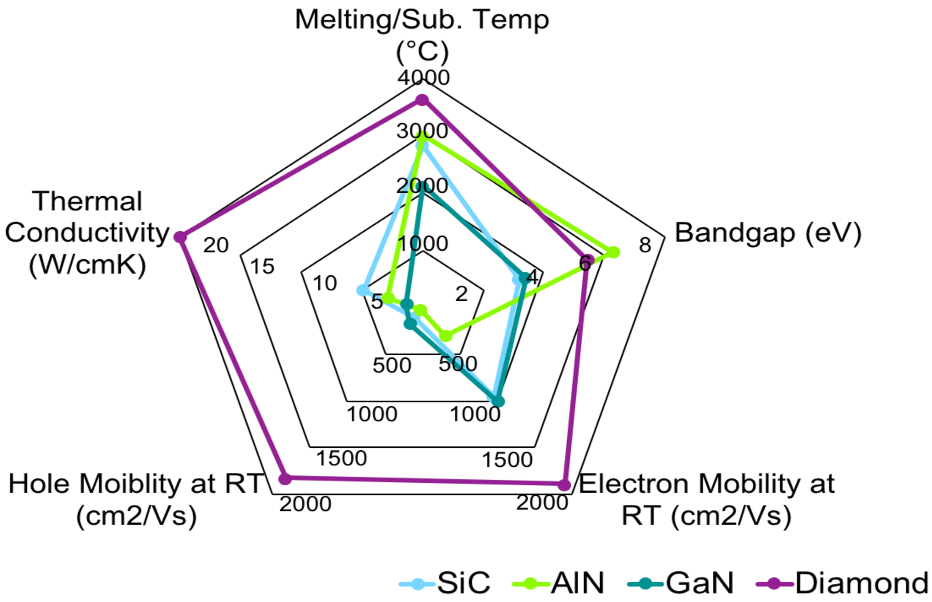


[1] Tsao, J. Y. et al., *Advanced Elec. Materials* (2017)
[2] Image credit: Panasonic

Temperature Limitations in the Current State-of-the-art

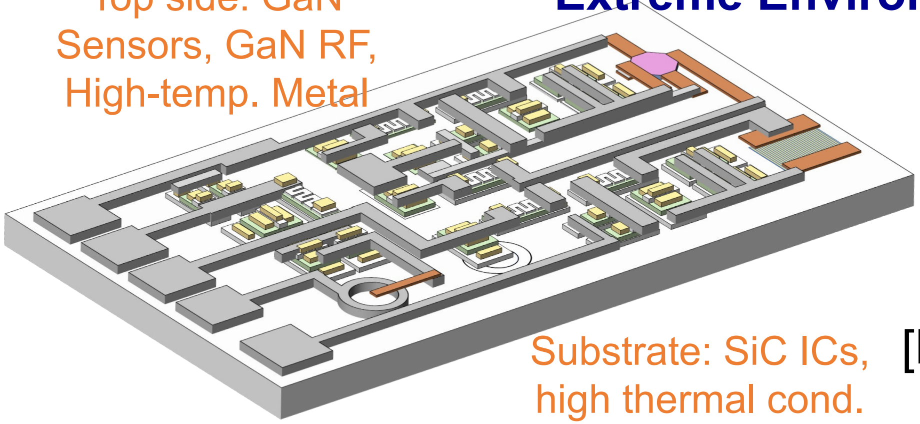


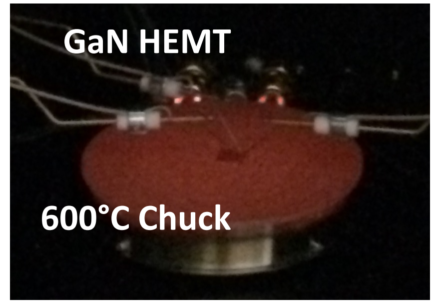
Tsao, J. Y. et al., *Advanced Elec. Materials* (2017)



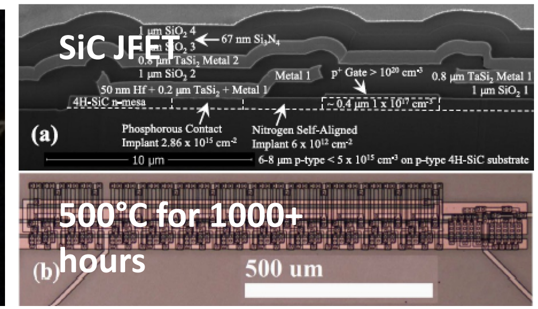
GaN + SiC (via UArk's MUSiC?)

Extreme Environment Microelectronics





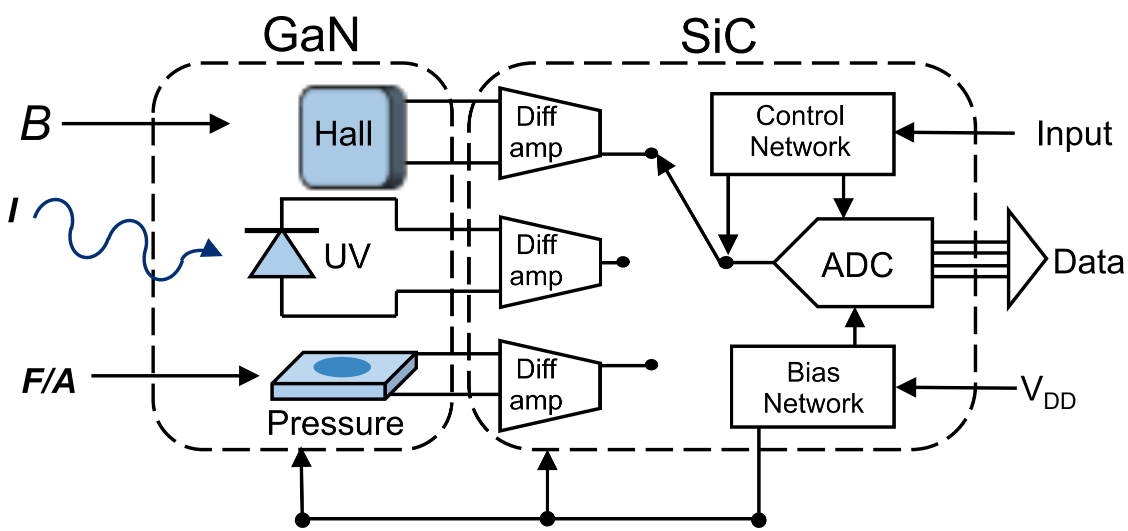
[D.G. Senesky, **2016**]



[NASA Glenn, **2016**]

-Recent advancements in GaN & SiC microfab. (including high-temp. interface materials) has enabled **extreme temp. operation > 400°C**.

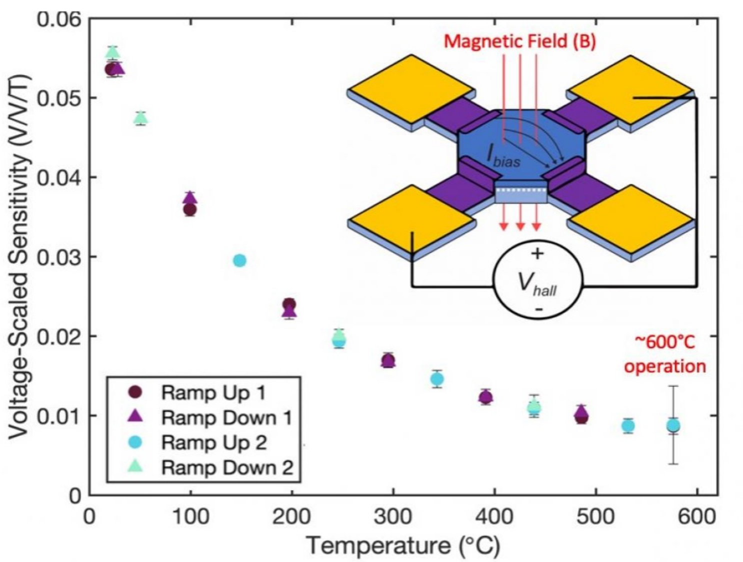
-Heterogeneous integrated GaN/SiC devices enables co-located sensing, data amplification, & processing.



AlGaN/GaN Hall-effect Plates at 600°C

D. Senesky, D. Huitink, G. Salamo, & A. Mantooth

- Demonstration of GaN-based Hall-effect sensor operation up to **600°C** and **stable operation at 450°C (in air)**
- Activation energies of failure mechanisms found to be **~0.36 eV**
- Significant degradation observed under argon-based, high-temperature storage conditions at 200°C over a 72-hour period, suggesting strain-relaxation in non-oxidizing environments.



Voltage-scaled sensitivities vs. temperature for InAlN/GaN Hall-effect sensor developed via the POETS program.

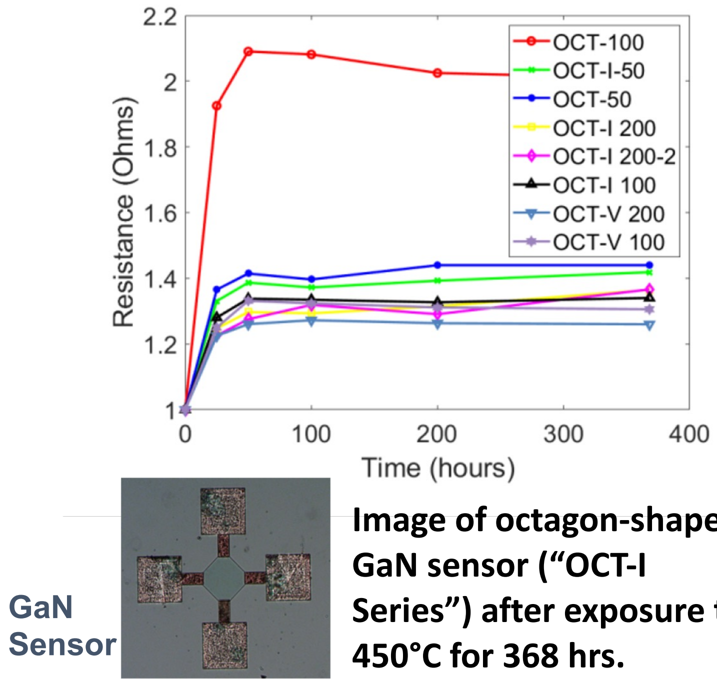
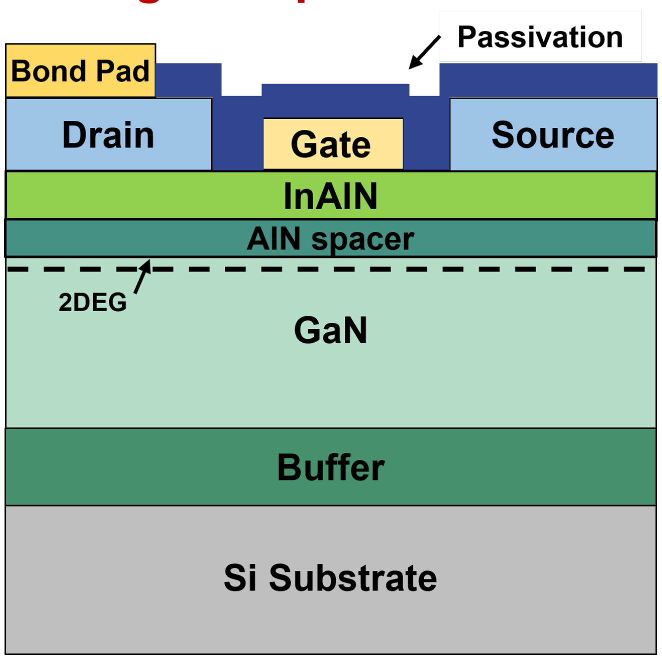
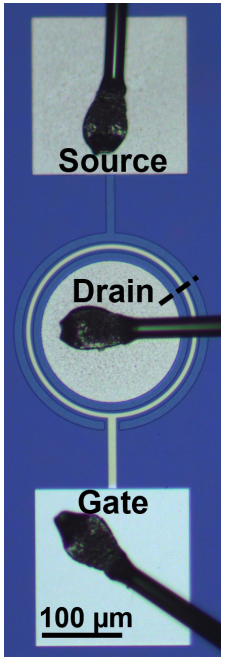


Image of octagon-shaped GaN sensor ("OCT-I Series") after exposure to 450°C for 368 hrs.

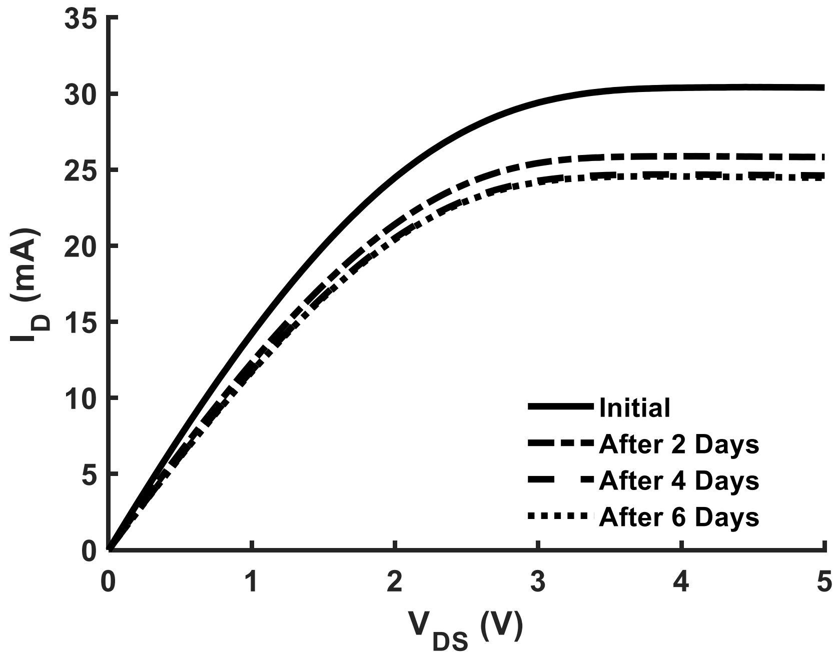
High-temperature Evolution

High-temperature GaN Platform





476°C in Air

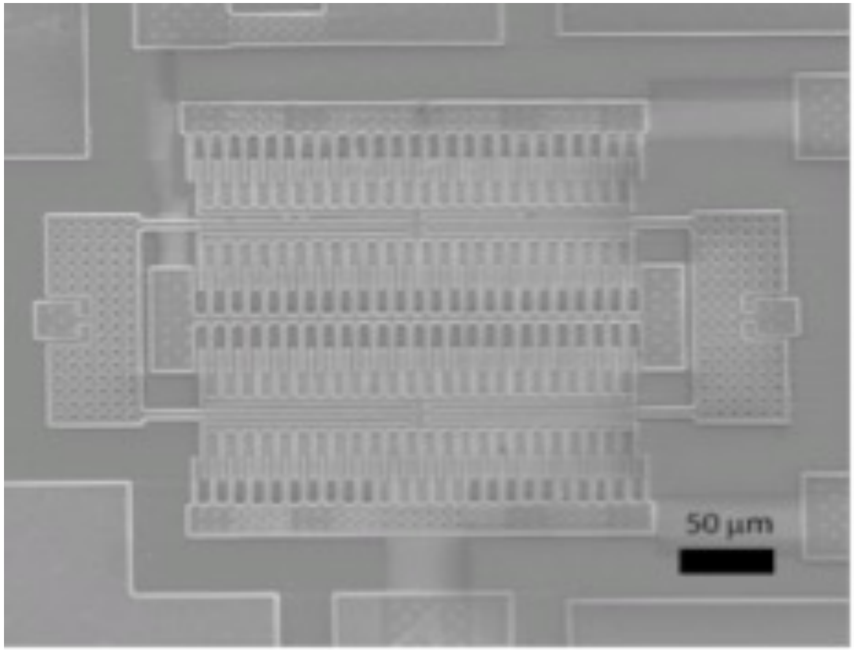


Question: Slight drain current reduction initially – why?

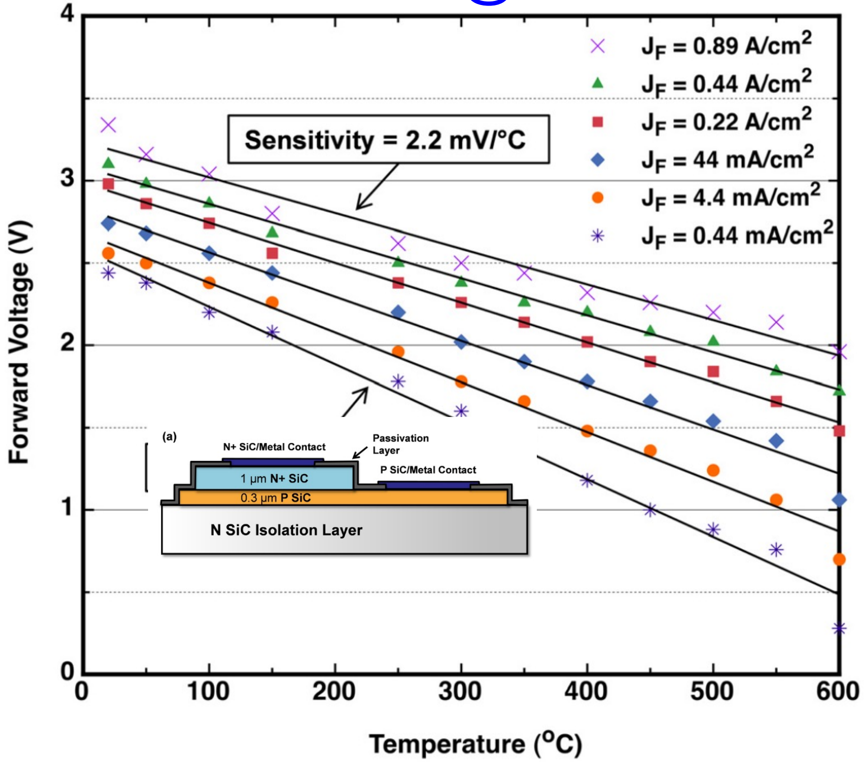
Eisner, S.R., … , & Senesky, D.G., Prepublication Data

High-temperature SiC Sensors

3C-SiC-on-Si MEMS Strain Sensor @ 600˚C



4H-SiC pn Diode Temperature Sensor @ 600˚C



1.) D.G. Senesky,…A.P. Pisano et al., IEEE Sensors (2009)
2.) N. Zhang,…D.G. Senesky, A.P. Pisano et al., Applied Physics Letters (2014)

P/O/E/T/S

CENTER FOR POWER OPTIMIZATION OF ELECTRO-THERMAL SYSTEMS

Electrified Machines

Materials Workshop

Requirements for electric propulsion

TABLE 4.2 Electrical System Component Performance Requirements for Parallel Hybrid, All-Electric, and Turboelectric Propulsion Systems

Aircraft Requirements	Electric System [a] Power Capability (MW)	Electric System [a] Specific Power (kW/kg)[c]	Battery [b] Specific Energy (Wh/kg)
General aviation and commuter			
Parallel hybrid	Motor <1	>3	>250
All-electric	Motor <1	>6.5	>400
Turboelectric	Motor and generator: <1	>6.5	n/a
Regional and single aisle			
Parallel hybrid	Motor 1-6	>3	>800
All-electric [b]	Motor 1-11	>6.5	>1,800
Turboelectric	Motor 1.5-3; Generator 1-11	>6.5	n/a
Twin-aisle			
Parallel hybrid	Not studied		
All-electric	Not feasible		
Turboelectric	Motor 4; generator 30	>10	n/a
APU for Large Aircraft	Generator 0.5-1	>3	Not studied

[a] Includes power electronics.
[b] Total battery system and usable energy for discharge durations that are relevant to commercial aviation flight times, nominally 1-10 hours. Values shown are for rechargeable batteries; primary (nonrechargeable) batteries are not considered relevant to commercial aviation.
[c] Conversion factors: 1 kW/kg = 0.61 HP/lb; 1 kg/kW = 2.2 lb/kW = 1.64 lb/HP.

National Academies of Sciences, Engineering, and Medicine. *Commercial aircraft propulsion and energy systems research: reducing global carbon emissions.* National Academies Press, 2016.

Regional and single-aisle

Parallel hybrid:

- Motor rated power: 1-6 MW
- ‘Electric System’ specific power: > 3 kW/kg
- Battery specific energy: > 800 Wh/kg

Turboelectric/’series hybrid’:

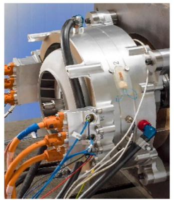
- Motor rated power: 1.5-3MW
- Generator rated power: 1-11 MW
- ‘Electric System’ specific power: > 6.5 kW/kg

State-of-the-art

Electric Machine SOA: Power = 0.25 MW; 2.2 kW/kg

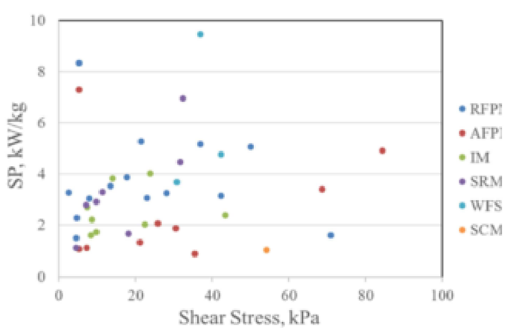
Main features:
High Speed, high frequency
Aggressive cooling
Synchronous machines

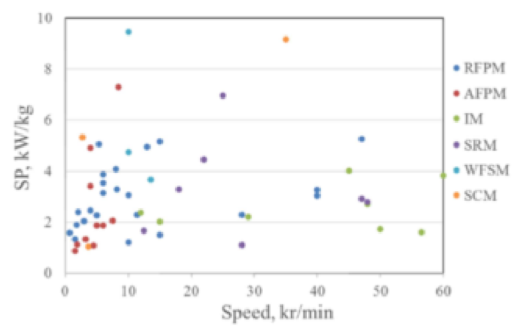
UTAS Starter generator
250 kVA,
7200–16000 rpm

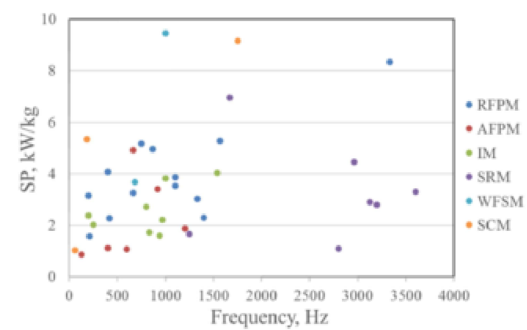


Siemens SP260D
260kW
2500RPM
1000 Nm
50 kg
Si Inverter

Siemens SP200D
204kW
1300 RPM
1500 Nm
49 kg
SiC Inverter

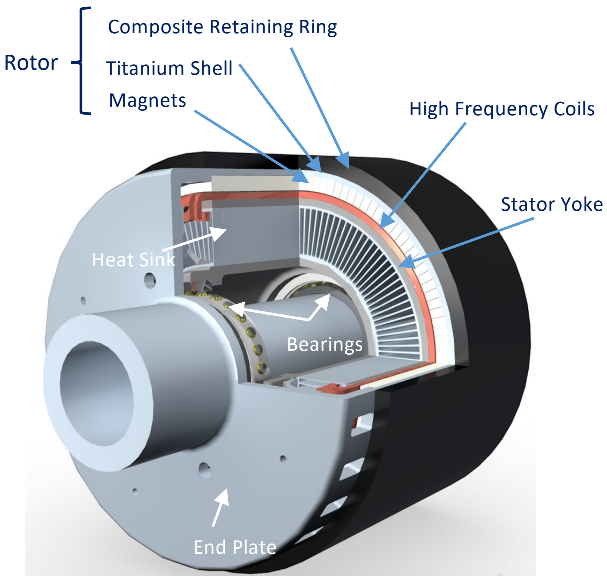


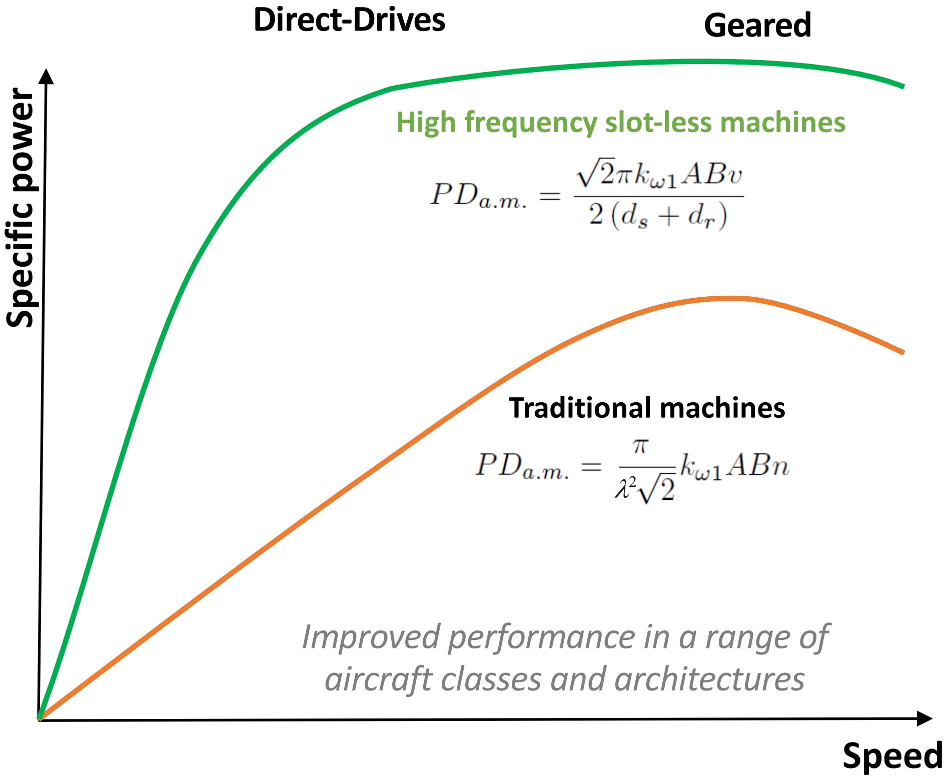




Zhang X, Bowman CL, O'Connell TC, Haran KS. Large electric machines for aircraft electric propulsion. IET Electric Power Applications. 2018 Jan 22;12(6):767-79.

High Frequency Slot-less Machines



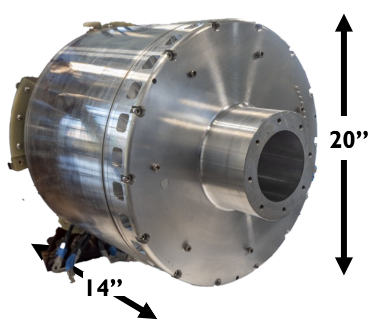


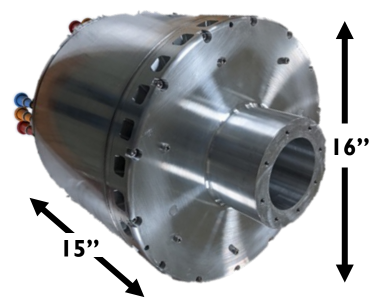
Yoon, A., Xiao, J., Lohan, D., Arastu, F. and Haran, K., 2019. High-frequency electric machines for boundary layer ingestion fan propulsor. IEEE Transactions on Energy Conversion, 34(4), pp.2189-2197.

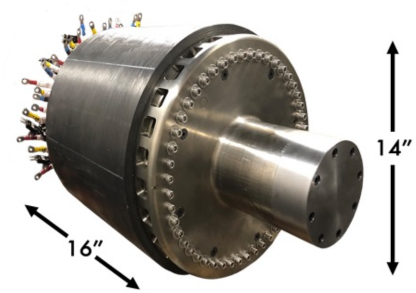
Megawatt Motors

- Efficiency: **98% EM efficiency, 97% incl mechanical losses**
- Specific power: **24kW/kg (13kW incl cooling & structure**)
- Potential to reduce weight further with liquid cooling

Model	AIR1000L	AIR1000M	AIR1000H
Rated Power	1 MW	1 MW	1 MW
Rated Speed	3600 rpm	8000 rpm	15000 rpm
Motor OD	500 mm	410 mm	340 mm
Axial Length	350 mm	380 mm	400 mm
Active weight	66 kg	59 kg	55 kg
Total weight*	104 kg	90 kg	78 kg
Efficiency	97%	97%	97%
Voltage	1 kV	1 kV	1 kV
Cooling	Air	Air	Air





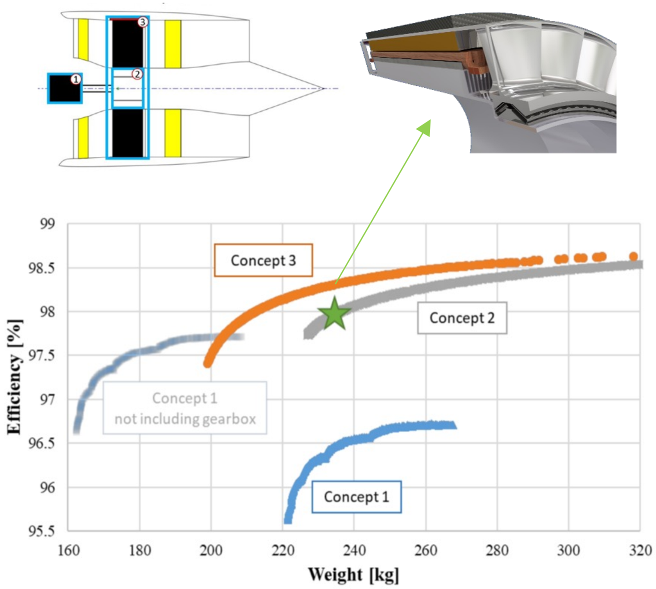


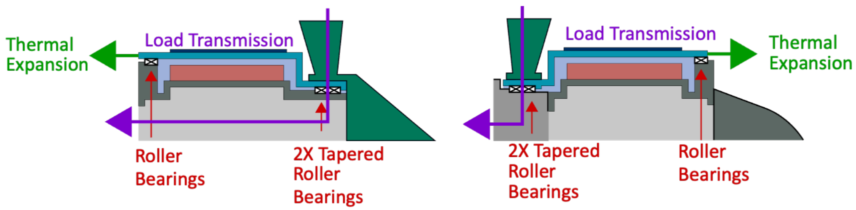
Validation

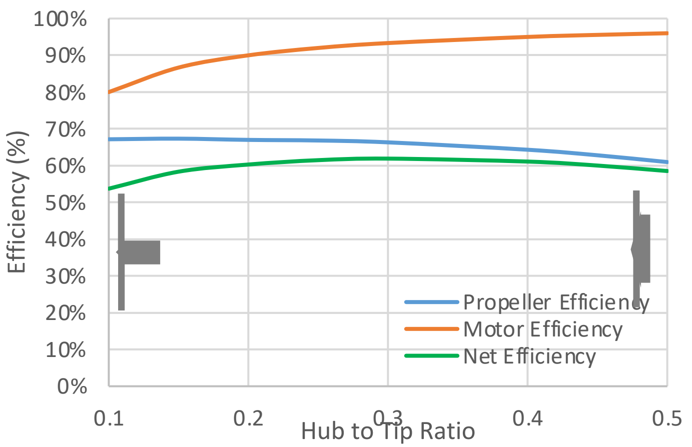
(left) 15,000 rpm, 1-MW slotless PM motor, (center) 300KW machine assembled and (right) tested on PRDC testbed

Mechanical Integration

- Geared or direct-drive
- Ring motor or shaft mounted
- Bearing arrangements



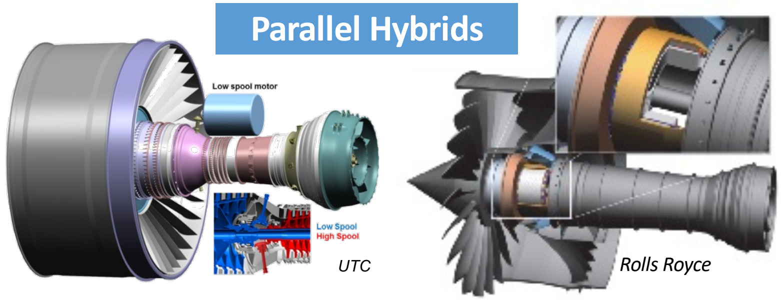




Propulsor system "efficiency" as function of hub to tip ratio

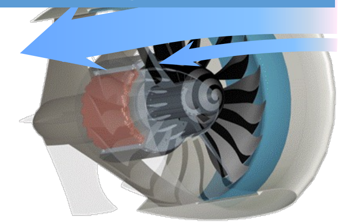
Use Cases

Parallel Hybrids



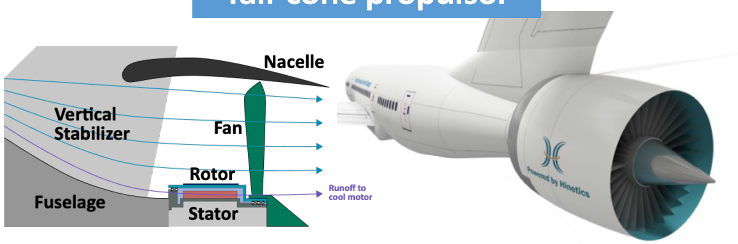
- High speed - gearbox and lube system available
- Up to 4000 hp, embedded in engine
- Potential to reduce weight further with liquid cooling

Integrated Propulsors



- Direct air-cooling with self pumped air; eliminate liquid lines
- ‘LP’ compressor + embedded heatsink
- Incorporate power conditioning components

Tail-cone propulsor



- Relatively low speed, 3-4 MW, large diameter
- E.g. NASA’s STARC-ABL
- Geared or direct-drive

eVTOL

- Extreme duty cycle and stringent noise requirements
- Lower altitude, lower voltage, system level redundancy
- Different orientation with respect to vehicle/flight

Acknowledgment

Appendix A - POETS Vision (Annual Report)

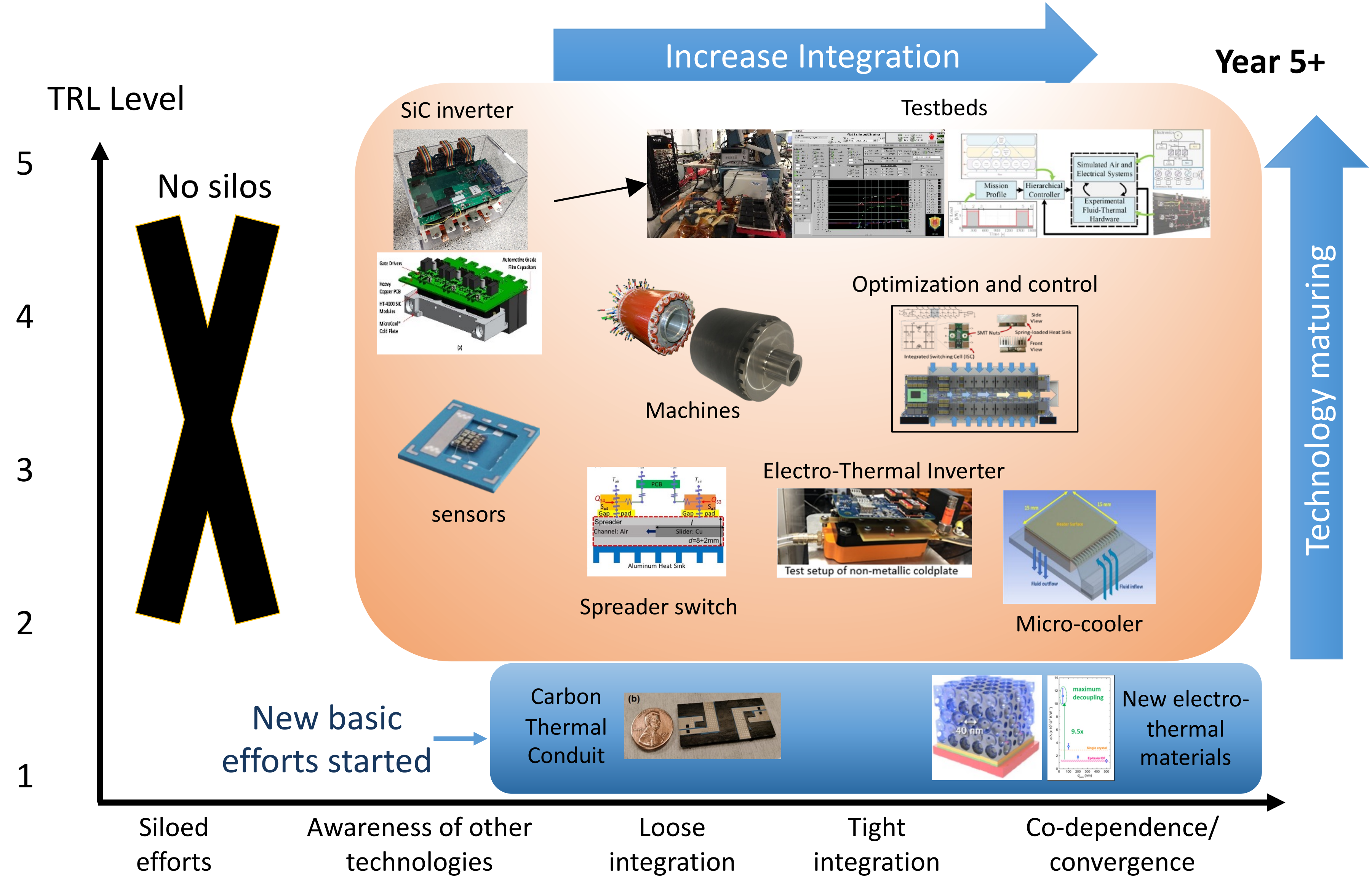
Fundamental Research

- >10X improvement in power density vs state of the art at the start of POETS
- Materials that have unique properties such as being electrically conductors but thermal insulators.
- Spatial Packing and Routing optimization algorithms to handle complex designs while observing mass and power flow constraints.
- Novel materials for high density thermal energy storage
- Advanced passives and magnetics utilizing novel materials and fabrication methods
- New fabrication methods such as Additive Manufacturing for integrated thermal and electrical systems
- Integrated sensing within power modules and machines
- Integrated cooling for high power density power modules

Enabling Technologies

- 10X to 100X increase in power converters over 2014 State of the Art.
- Power module layout that promotes heterogenous integration in modules
- High power density machines and drives.
- High ambient temperature electronics.
- Reliability and life cycle safety for electrified powertrains

Appendix B – Research Advancement Graphic



Center Table 3-1: Intellectual Property

IP License #	IP License Title or Name	Brief Description of Technology
16/161,260	Micro-Hall Effect Devices for Simultaneous Current and Temperature Measurement	Relates to improvements in hall effect sensors.
16/416,556	A 3D Wire Bondless power Module with Integrated Gate Driver	Module integrates a SiC gate driver and SiC power device.
62/674,988	Schottky-Hall Effect and Sensor	Hall sensor that takes advantage of a Schottky contact to achieve a sensitivity that exceeds the current technology.
16/277,934	Chip Warpage Reduction via Raised Free Bending Trace Geometries	A new layered production method for microchips allows for increased trace freedom, relieving pressure due to thermal expansion.
US20190307025	Active thermal management system for electronic devices and method of achieving device-to-device isothermalization	This patent pertains to the development of a millimeter scale thermal switch
16/434,524	Capillary Ferrofluid-Core Integration Method for High Performance On-chip Self-rolled-up Nanomembrane Magnetic Devices	Rolled-up magnetic component for on-chip applications and method of making a rolled-up magnetic component
62/834,031	Additively manufactured, non-conducting, convective heat removal device	A more efficient, non-metallic localized device for cooling down high-powered electronics
US10490328	Self-Rolled-Up Graphene-On-Diamond Nanomembrane On-Chip Power Inductors	The inductor is self-rolled nanomembrane technology and has a small footprint along with high power inductance and high heat dissipation. This structure can be arranged into arrays to meet specific power converting needs, in a smaller size than current methods
16/948,858	Immersion Cooling of Electronics in Water	Immersion Cooling of Electronics in Water
63/007,023	Carbon nanotube-metal oxide composite fiber and thin film electrodes for high performance electrochemical supercapacitors	High Performance electrochemical supercapacitors
63/093,363	Posts-rolling Electroplating for Efficiency and Bandwidth Enhancement of S-RUM based passive Components	This technology allows for the fabrication of high-quality-factor milliTesla- and Tesla-level inductors for high density circuit applications and allows for the precise tuning of the inductor performance.
US10720380B1	Flip-chip Wire Bondless Power Device	The present invention relates to semiconductor devices and, in particular, to converting bare die to flip-chip wire bondless power devices and methods of assembly.