Design for Additive Manufacturing of Wide Band-Gap Power Electronics Components

ERCAN M. DEDE, MASANORI ISHIGAKI, SHAILESH N. JOSHI, & FENG ZHOU

TOYOTA RESEARCH INSTITUTE OF NORTH AMERICA

JUNE 13, 2016

INTERNATIONAL SYMPOSIUM ON 3D POWER ELECTRONICS INTEGRATION AND MANUFACTURING (3D-PEIM)

Acknowledgements

- **National Renewable Energy Lab**
  - Mr. Kevin Bennion
  - Dr. Gilbert Moreno
  - Dr. Sreekant Narumanchi
- **Purdue University – CTRC**
  - Professor Suresh V. Garimella
  - Dr. Matthew J. Rau
- **Toyota Central R&D Labs**
  - Dr. Tsuyoshi Nomura
- **Toyota Motor Corporation**
  - Mr. Tomohiro Takenaga
- **Toyota Technical Center**
  - Dr. Yan Liu
- **Wolfspeed**
  - Dr. Kraig J. Olejniczak
  - Dr. Brandon Passmore

Outline

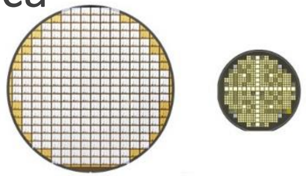
- Overview of Research Group
- Motivation for 3D Integration
- Why Explore Additive Manufacturing?
- Applications for Additive Manufacturing
  - Circuit-Level Concepts
  - System-Level Concepts
- Future Opportunities & Challenges
- Conclusions
- References

Overview of Research Group

- Toyota Research Institute of North America
  - Electronics Research Department

Research focused on environment, safety, and human interaction

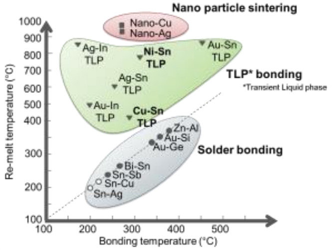
Development of 14X Power Density SiC Charger Prototype



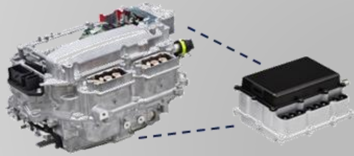
Investigation of Next Gen. SiC, GaN Devices

Intelligent & WBG Devices
(Lab E-1 & E-2)

Development of Automotive Phased Array Radar

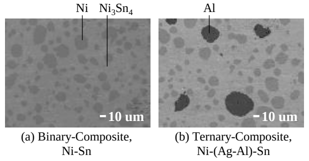


Optimized Electro-Thermal Power Systems

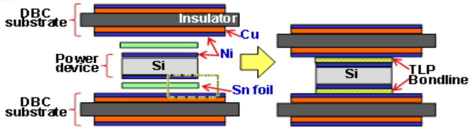


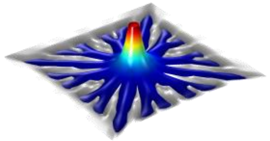
Advanced Circuit & Control
(Lab E-1 & E-2)

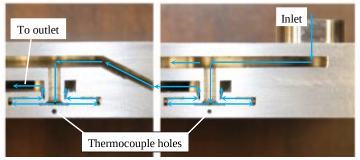
High Temperature Packaging
(Lab E-2)



Research on TLP for Advanced Packaging



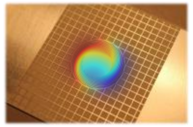


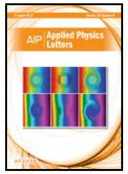


Optimization for Air, Single, Two-Phase Cooling

Thermal Energy Management
(Lab E-2)

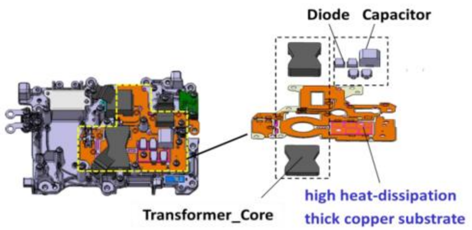
Heat Flow Control for Electronics





Motivation for 3D Integration

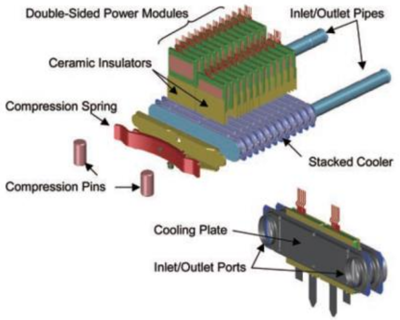
- Current Power Control Unit (PCU) architecture – compact, highly integrated packaging



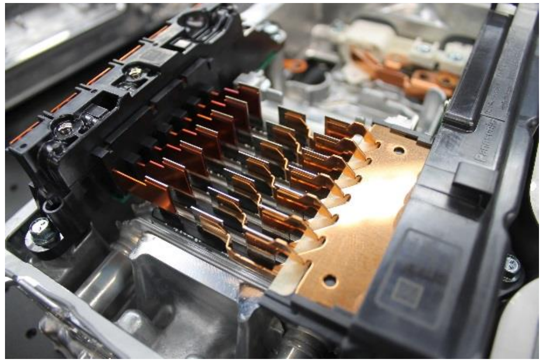
Ref.: Shimadu, H., et al., EVTeC 2016

DC-DC Converter with High Frequency Integrated Magnetics

4th Gen. PCU



Ref.: Okamoto, K., et al., Denso Tech. Rev. 2011



Power Card Structure with Interleaved Double-Side Cooling

Why Explore Additive Manufacturing?

- Core ideas behind Additive Manufacturing (AM)
  - Expand design space →
    Enhance integration & create new function
    - "…multimaterial…"
    - "…lightweight structures…"
    - "…internal cooling passages…"
    - "…unparalleled geometric complexity…"
    - "…functionally grade material compositions…"

Ref.: Rosen, D.W., et al., J. Mech. Design 2015 (Guest Editorial, Special Issue: Design for Additive Manufacturing)

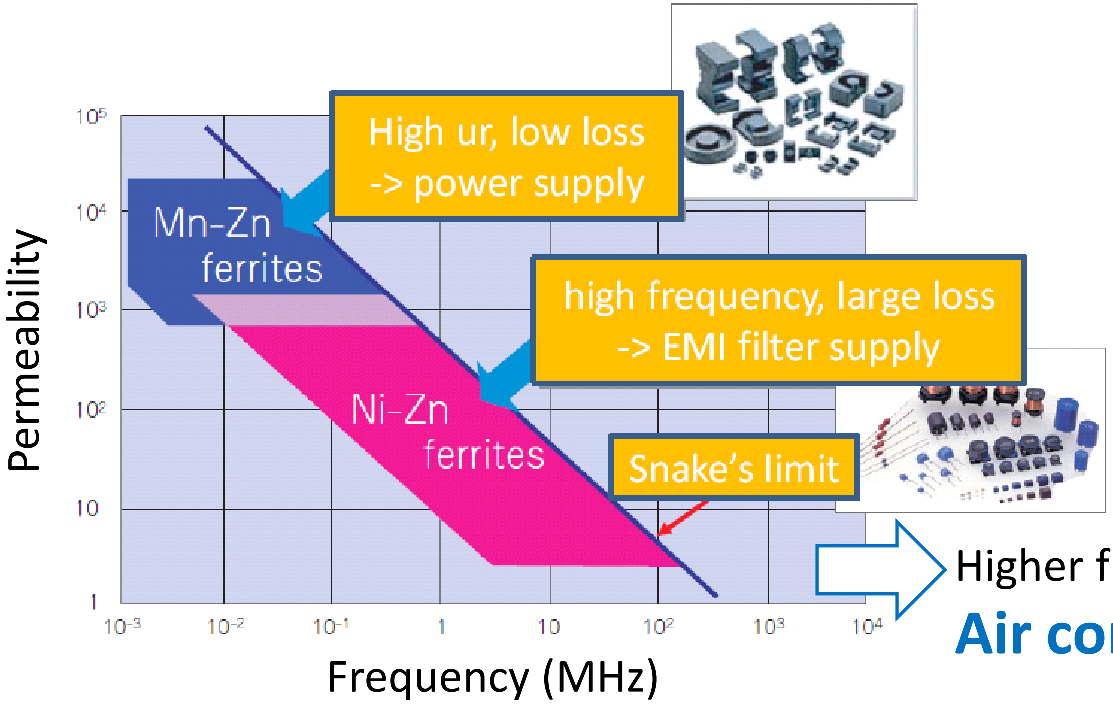
Above characteristics highly sought in future power-dense wide band-gap (WBG) electronics systems

Applications for Additive Manufacturing

CIRCUIT-LEVEL CONCEPT – CURRENT SENSOR

High Frequency Passives

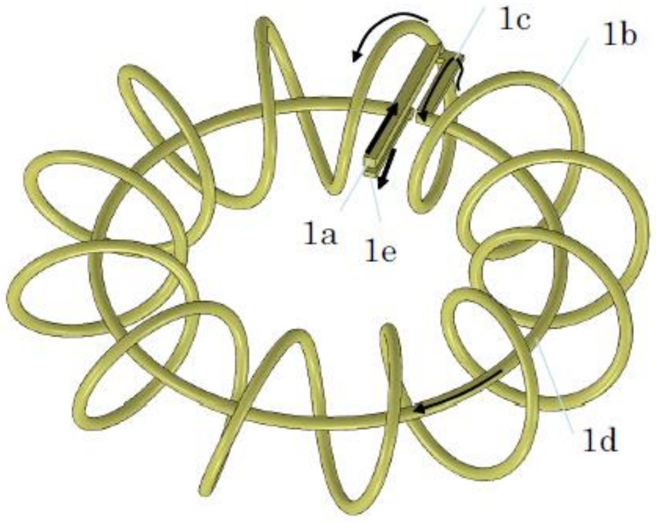
- High operational frequency expected with WBG devices → Paradigm shift in magnetics design



*Ref.: https://product.tdk.com/ja/products/emc/guidebook/jemc_basic_06.pdf

Higher frequency:

Air core device



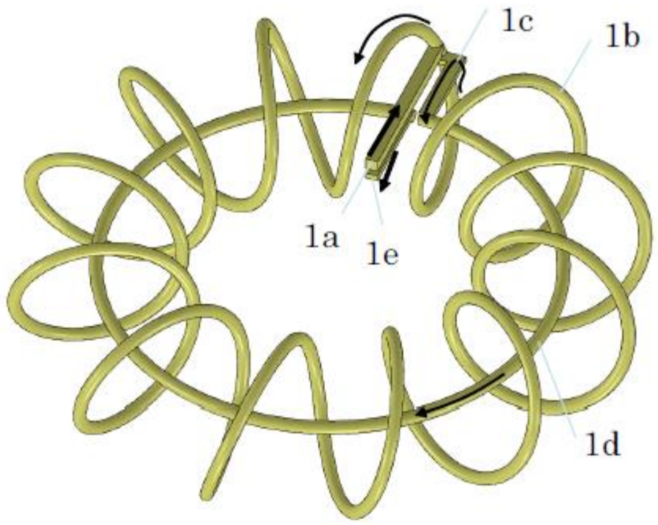
Ex: Rogowski-coil

Pros:
- Linear (air core)
  - No frequency dependence
  - No saturation
- Simple
- Low cost

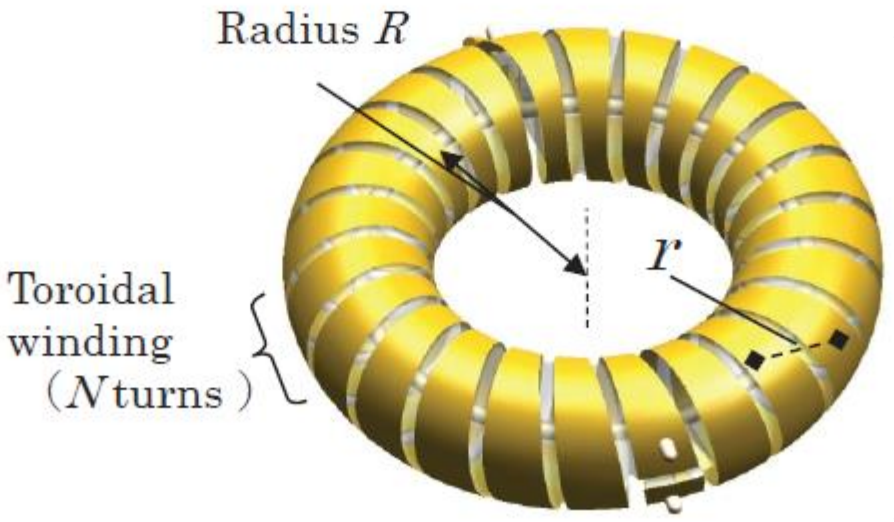
Cons:
- Manufacturing dependency

Sheet-Wound Coil Concept

- Re-conceptualize the traditional wire-based structure

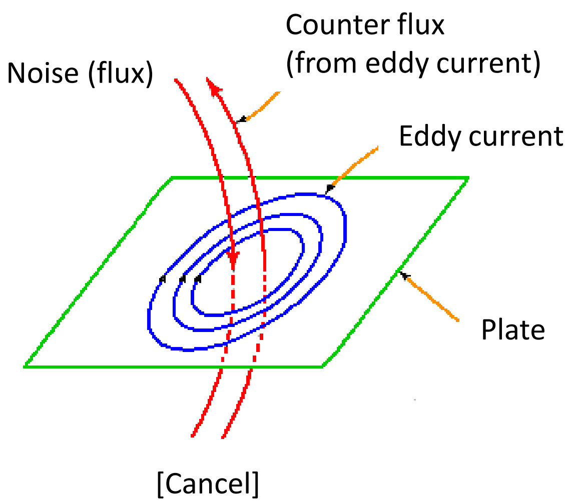


Wire-Based Toroid Structure



Sheet-Wound Structure

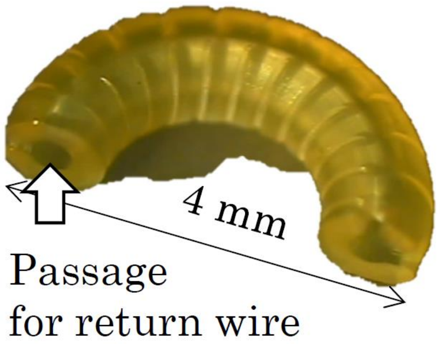
- ✓ Less noise in/out
- ✓ Design inductance accurately



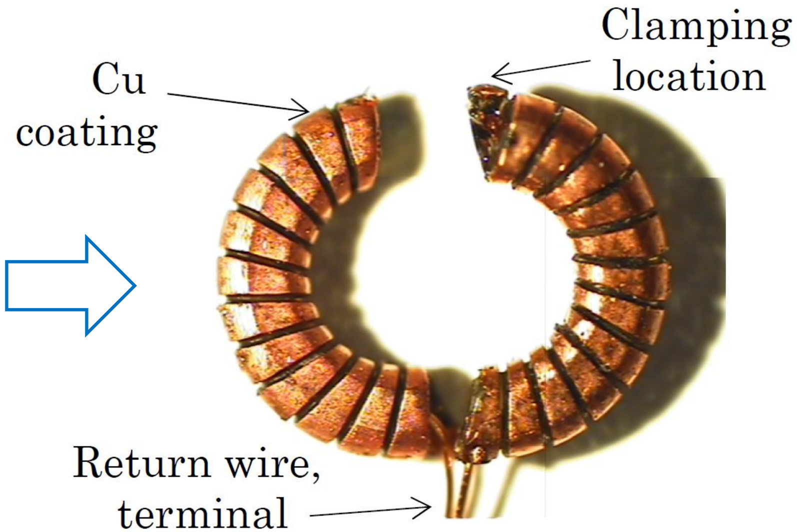
Electromagnetic Shielding Effect

Sheet-Wound Coil Fabrication

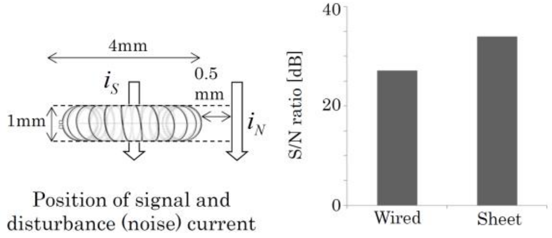
- Metal plating of 3D AM bobbin for structure realization



Bobbin



Assembled Sensor



Experimental Result &
Final Custom Sensor Image

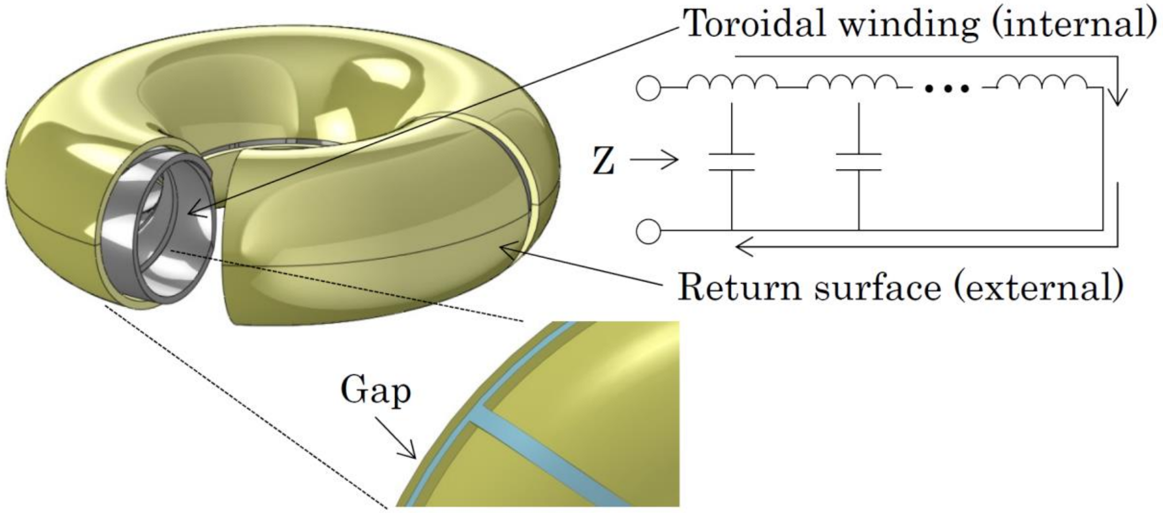
Fewer turns fabricated with greater precision enables high frequency, accuracy measurement in compact space

Applications for Additive Manufacturing

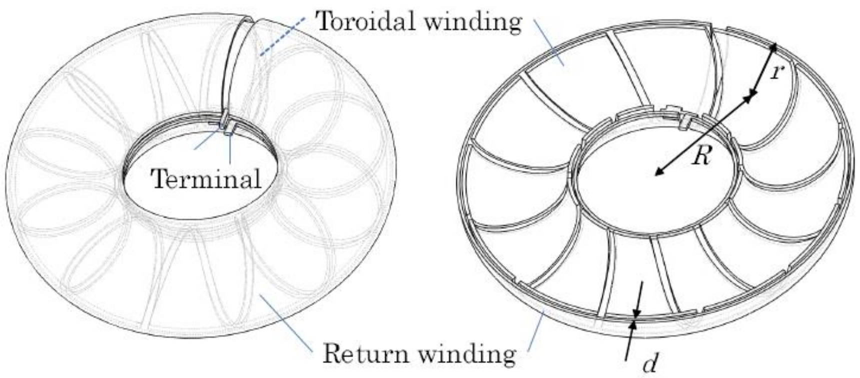
CIRCUIT-LEVEL CONCEPT – LC RESONANT TANK

Extension to LC Resonant Tank

- Integrate resonant capacitance into structure
  - Magnetic flux “packed” inside due to shielding effect, while capacitance conserves magnetic flux



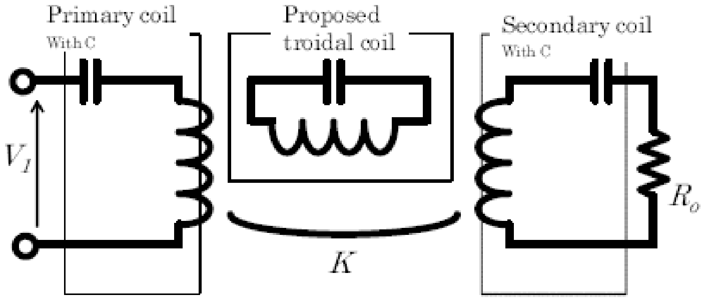
3D Isometric View & Equivalent Circuit



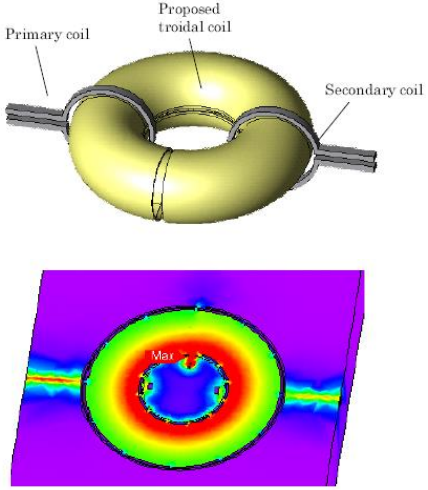
Transparent & Sectioned Views

Extension to LC Resonant Tank

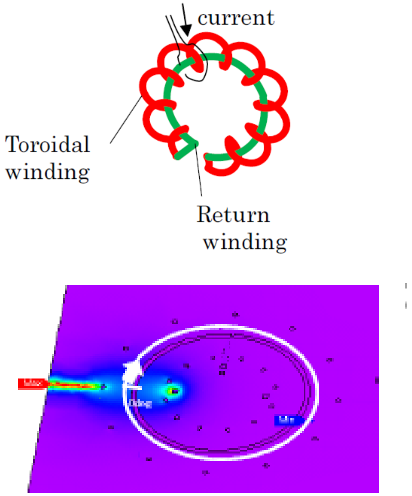
- Application to air core transformer
  - Improve power transfer from primary to secondary coil with air core (i.e. no traditional ferrite core)



Circuit Diagram
(Wireless Power Transfer using Resonant Inductive Coupling)



Sheet-Wound LC Tank Simulation Result*



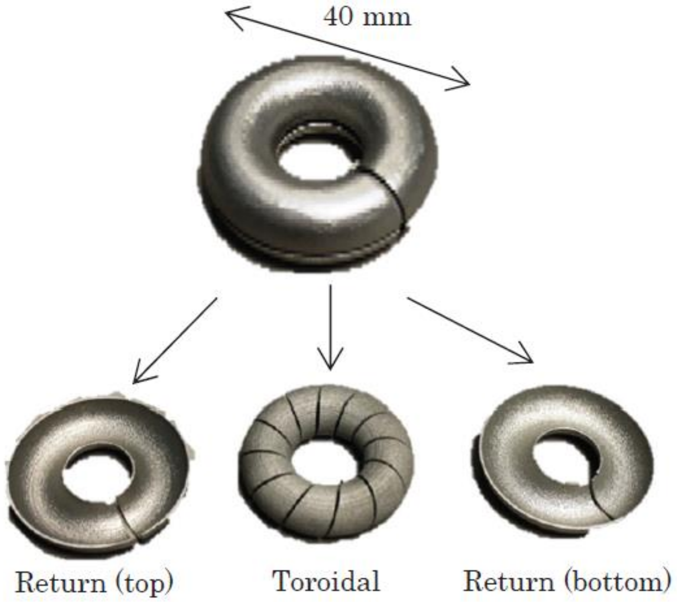
Wire-Based Toroid Simulation Result*

*Magnetic Flux Density Contours Shown

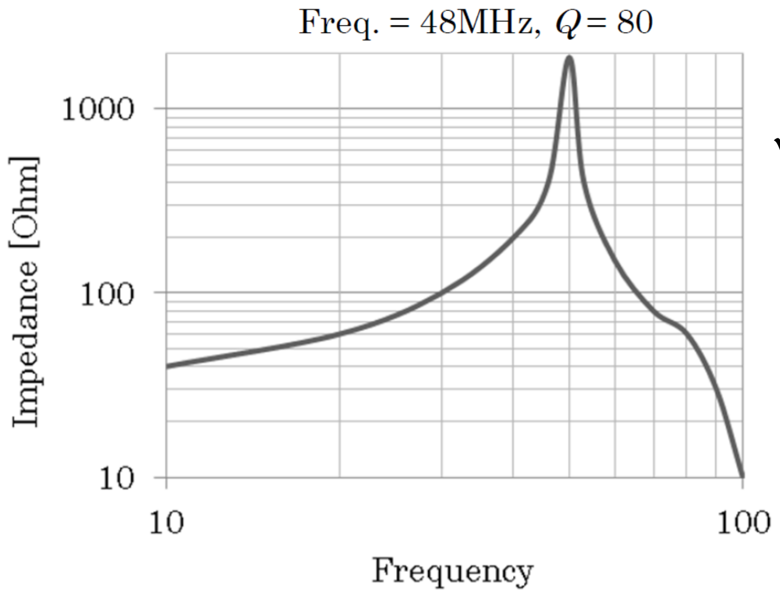
LC Resonant Tank Fabrication

- Direct Metal Deposition (DMD) 3D printing
  - Fabricated using three components to properly construct air gap →

Multi-material (metal-plastic) 3D printer technology required for one-piece construction!



AM Manufacturing Strategy



✓ Sharp resonance with high quality factor

Experimental Results for 3D Resonant Tank

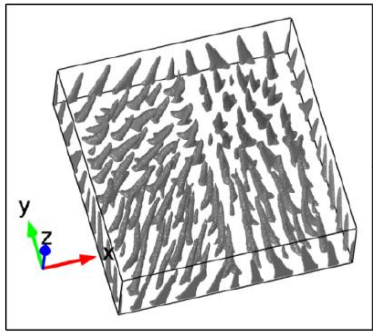
Applications for Additive Manufacturing

SYSTEM-LEVEL CONCEPT – AIR COOLING

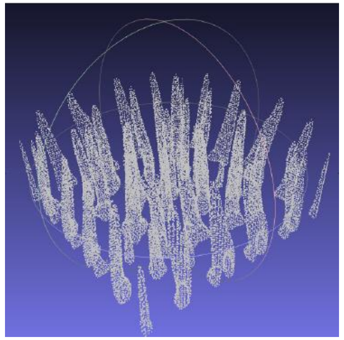
Air-Cooled Heat Sink Design

- Structural optimization plus AM applied to study performance limits
  - Optimization for steady-state heat conduction plus side-surface convection

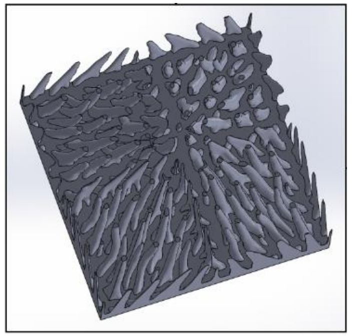
Movie of Example 2-D Structural Optimization Design Evolution



3D Topology Optimization Result



Quarter-Symmetry Point Cloud Data



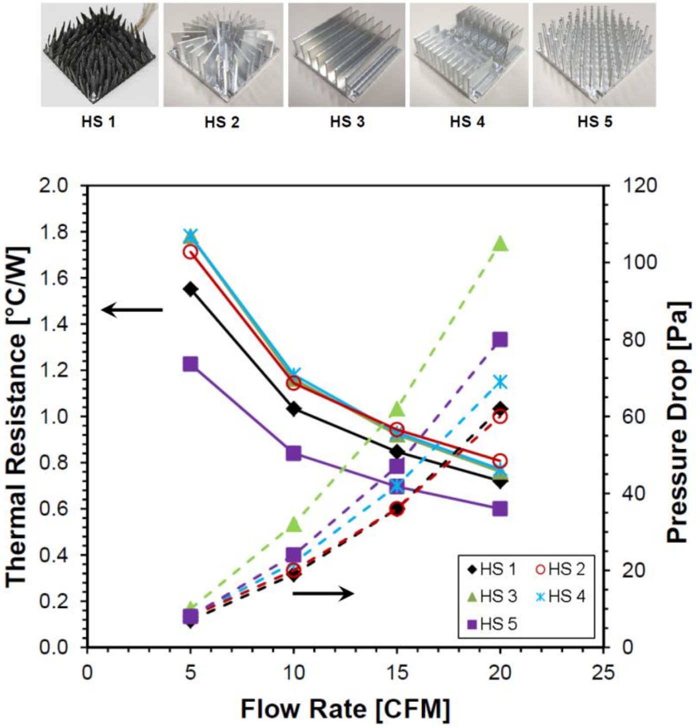
Synthesized Solid Model CAD Geometry

AlSi12 Rapid Prototype

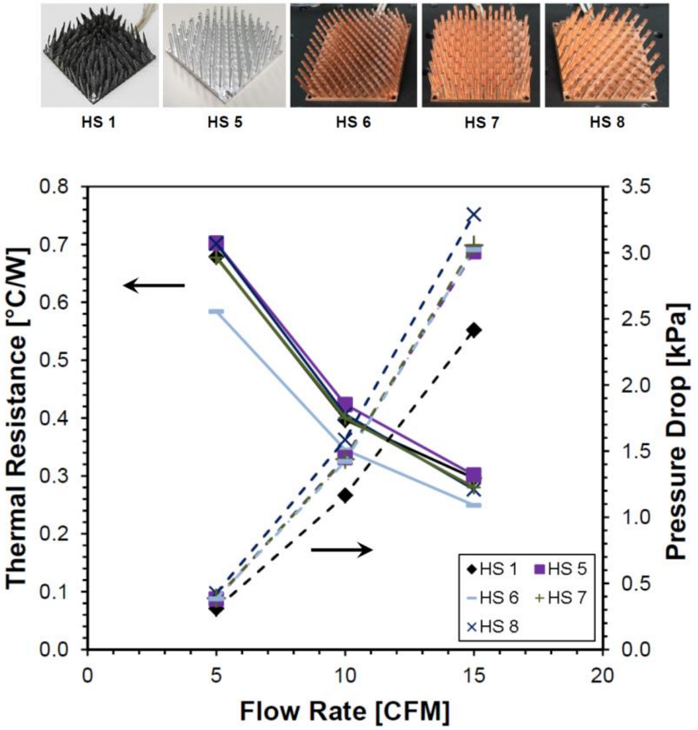
Extension to 3D Design

Variable geometry pin fin design obtained to maximize heat transfer

Heat Sink Performance Evaluation



Case 1 experimental results for Al alloy heat sinks, HS 1–HS 5, with Ø38.1 mm orifice at 12.7 mm jet-to-target spacing
(Re ~ 4,700-19,000)



Case 2 experimental results for pin-fin heat sinks, HS 1 & HS 5–HS 8, with Ø12.7 mm orifice at 12.7 mm jet-to-target spacing
(Re ~ 14,000-43,000)

* $\mathrm{COP} = 1/(R_{\mathrm{th(cnv)}}\Delta P\dot{V})$

HS No.	COP [1/°C] (Case 1)	% Difference (Case 1)
	$d = 38.1$ mm; $H/d = 0.33$	
1	2.37	-
2	2.19	−7.81%
3	1.33	−44.1 %
4	1.99	−16.1 %
5	2.21	−7.02%
6	-	-
7	-	-
8	-	-

Case 1

HS No.	COP [1/°C] (Case 2)	% Difference (Case 2)
	$d = 12.7$ mm; $H/d = 1$	
1	0.197	-
2	-	-
3	-	-
4	-	-
5	0.156	−21.1%
6	0.187	−5.13%
7	0.165	−16.5%
8	0.155	−21.4%

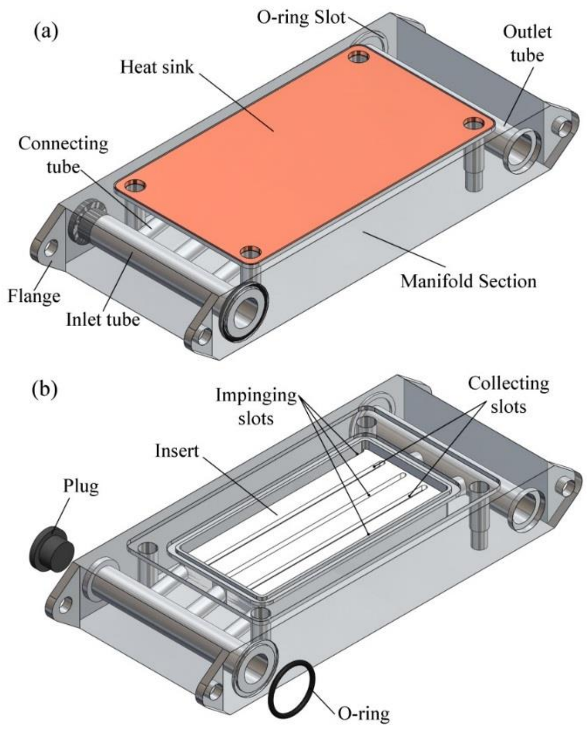
Case 2

Applications for Additive Manufacturing

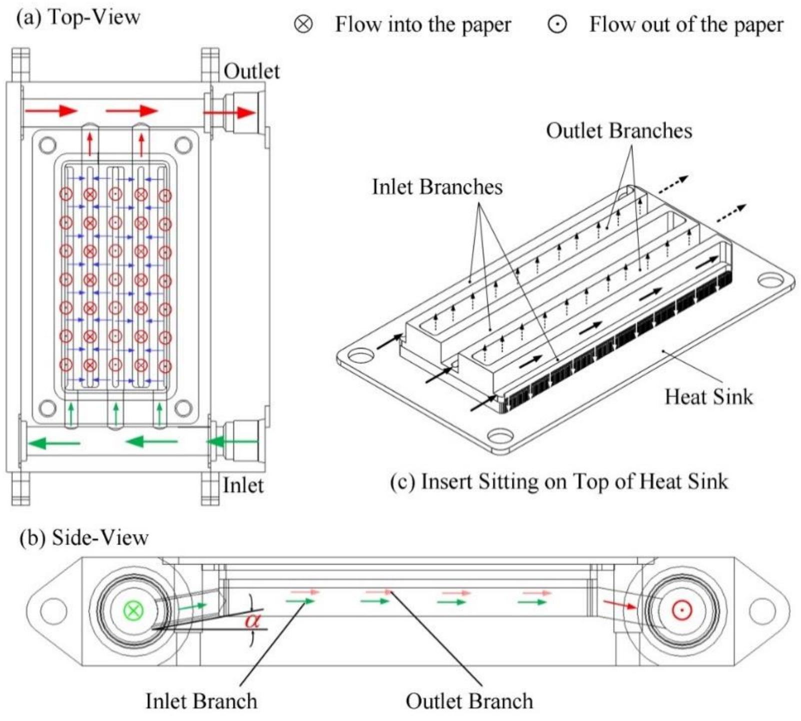
SYSTEM-LEVEL CONCEPT – LIQUID COOLING

Modular Liquid Cooling for Power Electronics

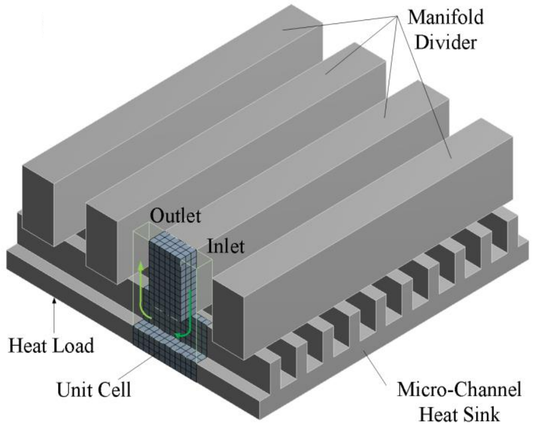
- Manifold microchannel (MMC) system for high performance single-phase liquid cooling



Manifold Section plus Insert & Heat Sink



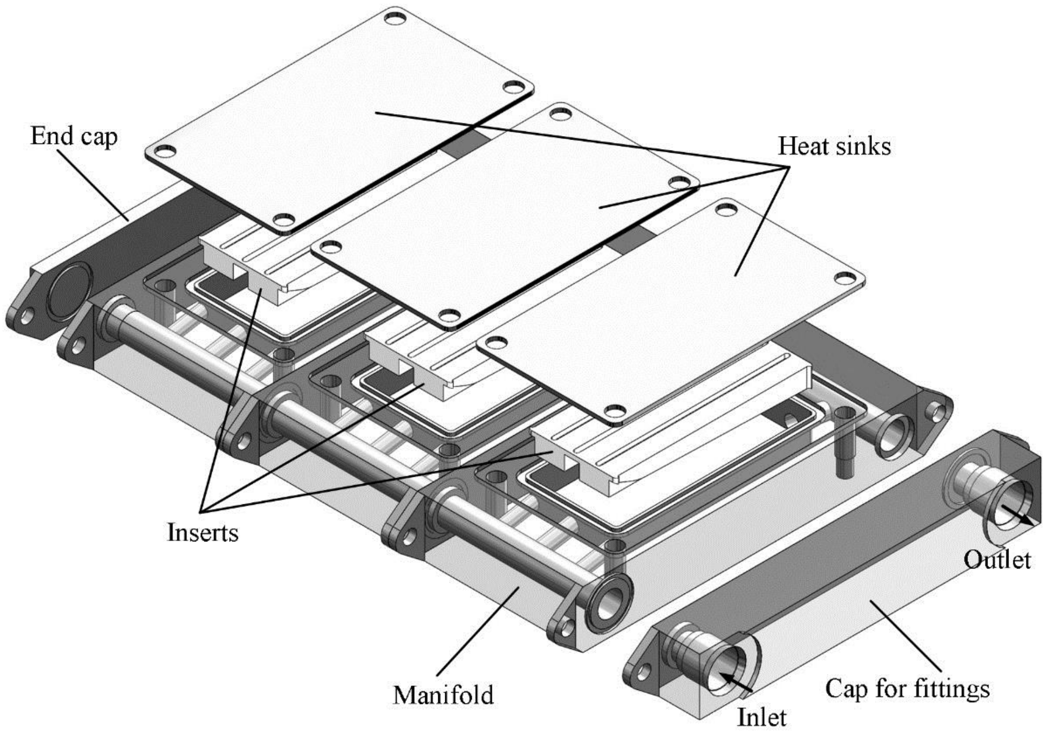
Transparent Views with Flow Operation



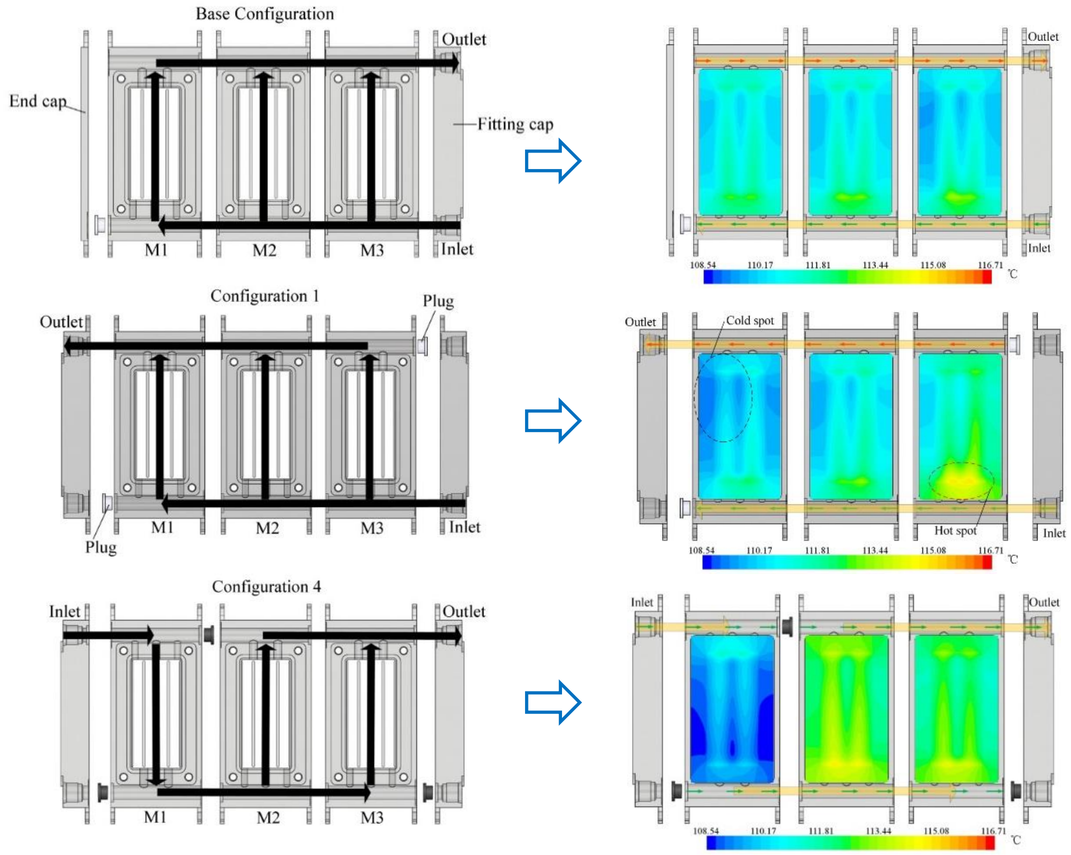
MMC Detailed View

Modular Liquid Cooling for Power Electronics

- Cold plate flow configurations considering three power modules

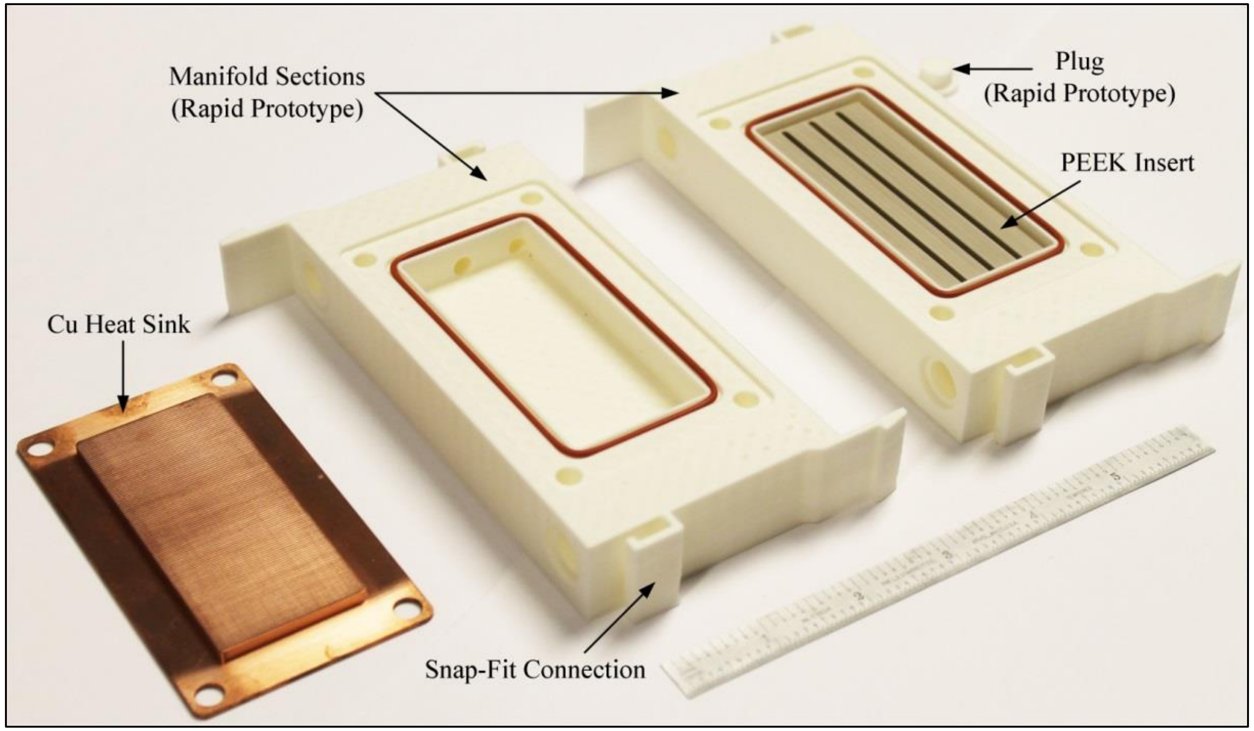


Exploded View of Cold Plate

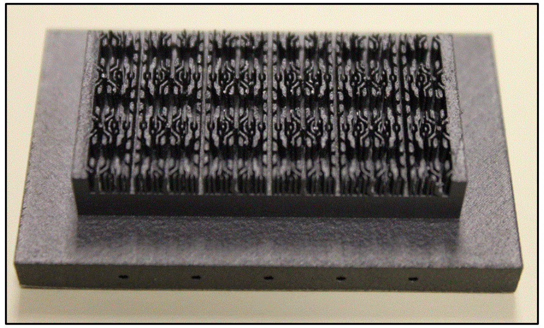


Modular Cold Plate AM Rapid Prototype

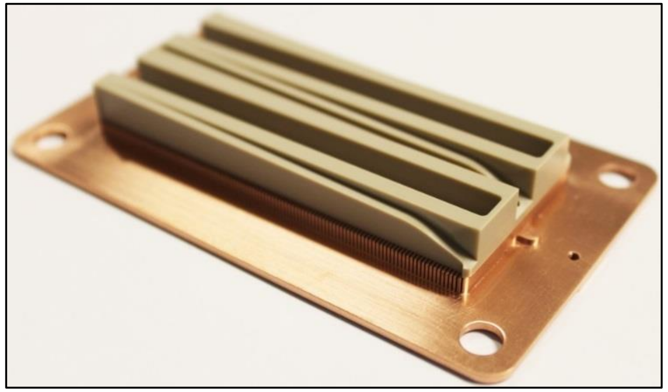
- Polymer prototype manifold system with snap-fit connections



Disassembled Cold Plate Showing Two AM Manifold Sections



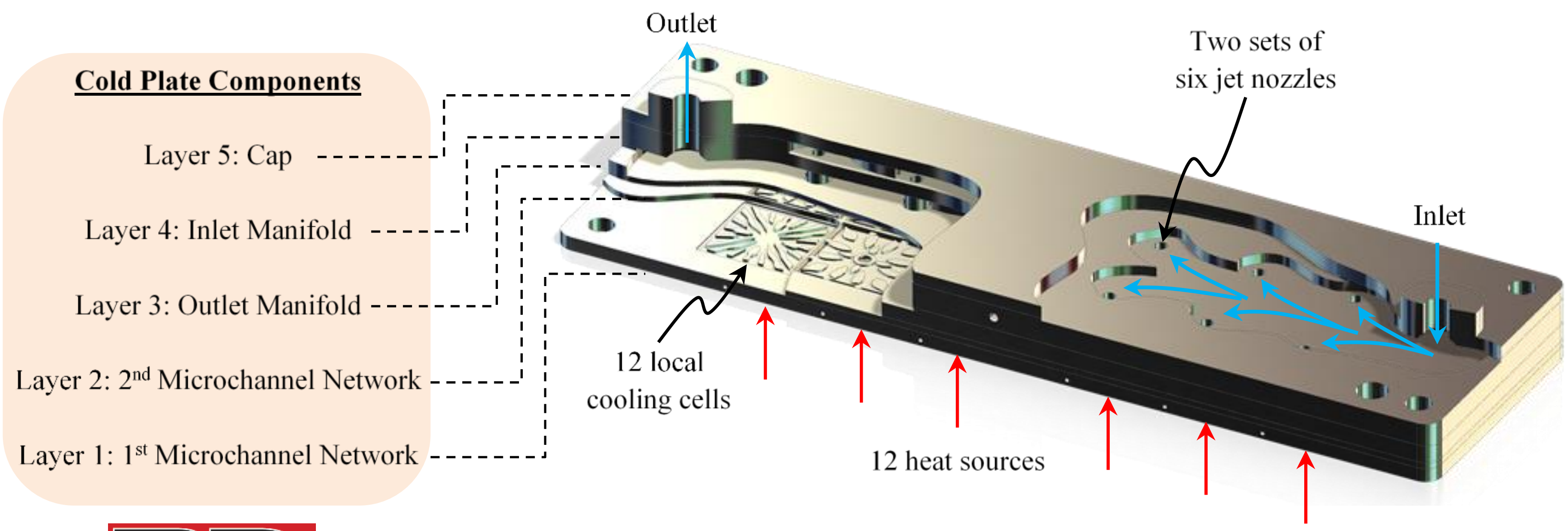
3D AM Optimized MMC Heat Sink Concept



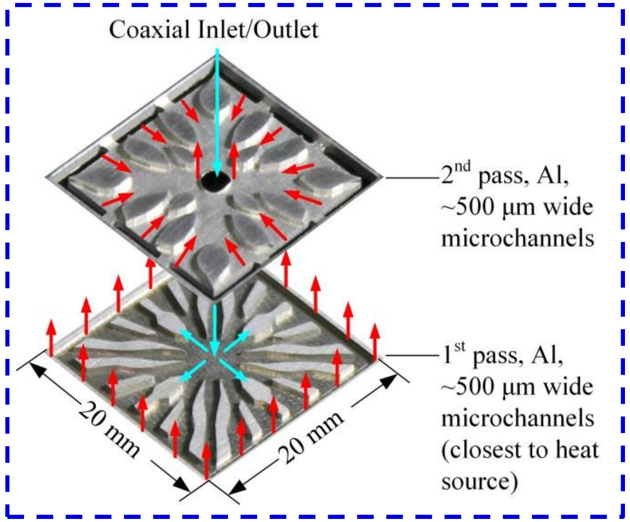
Insert on Top of Fin Structure

Liquid Cold Plate Design – Another Quick Note

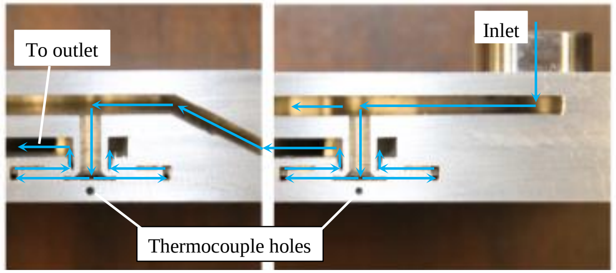
- Precision machined & diffusion bonded, *but why not 3D print?*



12-Piece Single-Phase Liquid Cold Plate



Multi-Pass Microchannel System



Cross-Section View

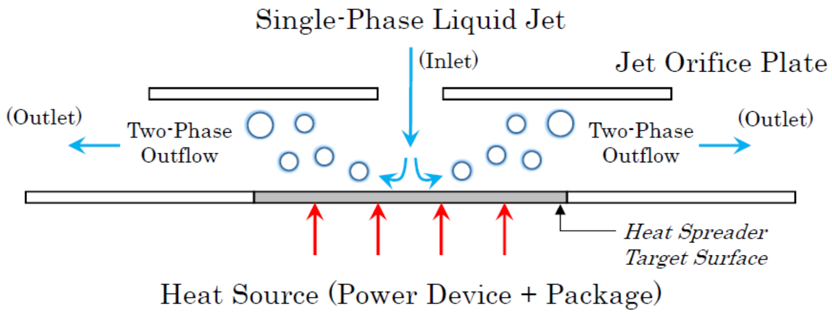
R&D 100 Award Winner (2013)

Applications for Additive Manufacturing

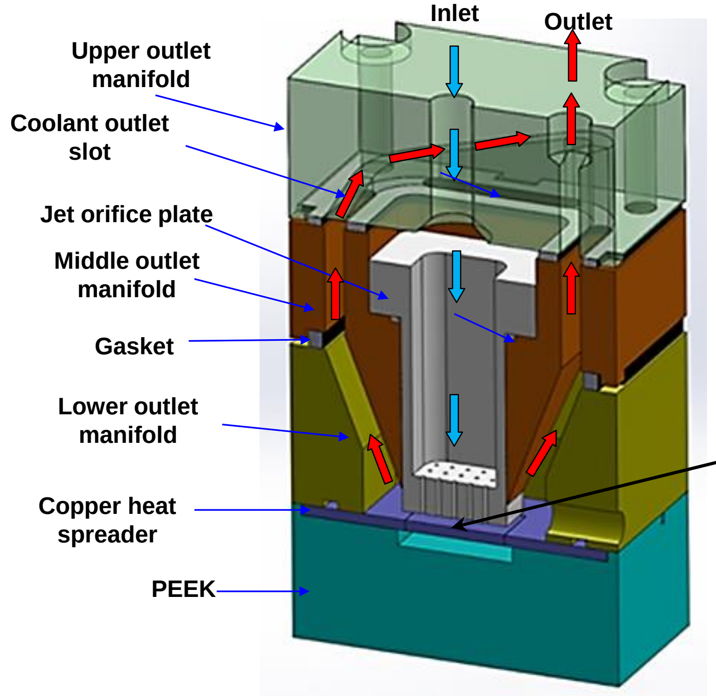
SYSTEM-LEVEL CONCEPT – TWO-PHASE COOLING

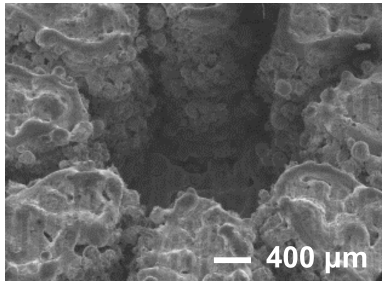
Two-Phase Cooling for Enhance Performance

- High power density systems → single-phase liquid cooling reaching fundamental limit
  - Design of high performance two-phase cooling technology



Operational Concept for Two-Phase Jet Impingement Cooling





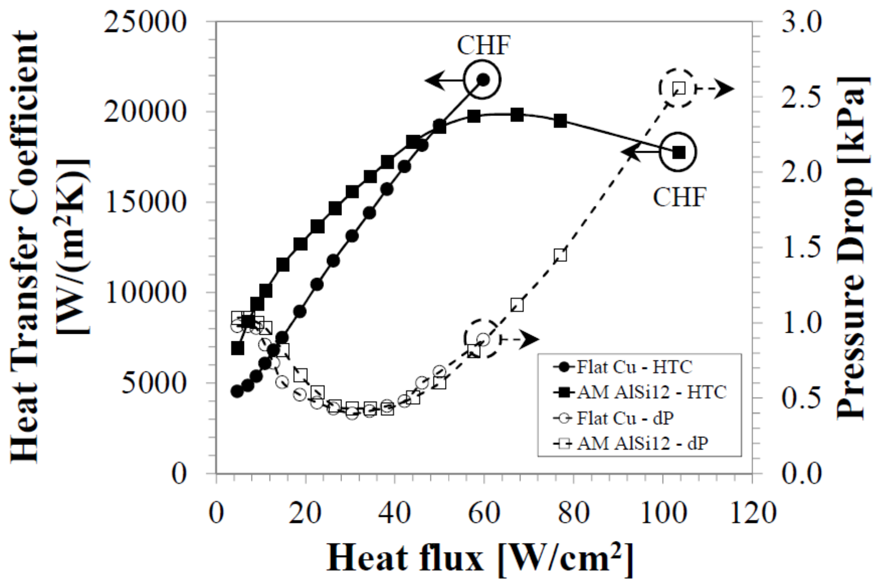
Porous Structure Detail

AM AlSi12 Heat Spreader

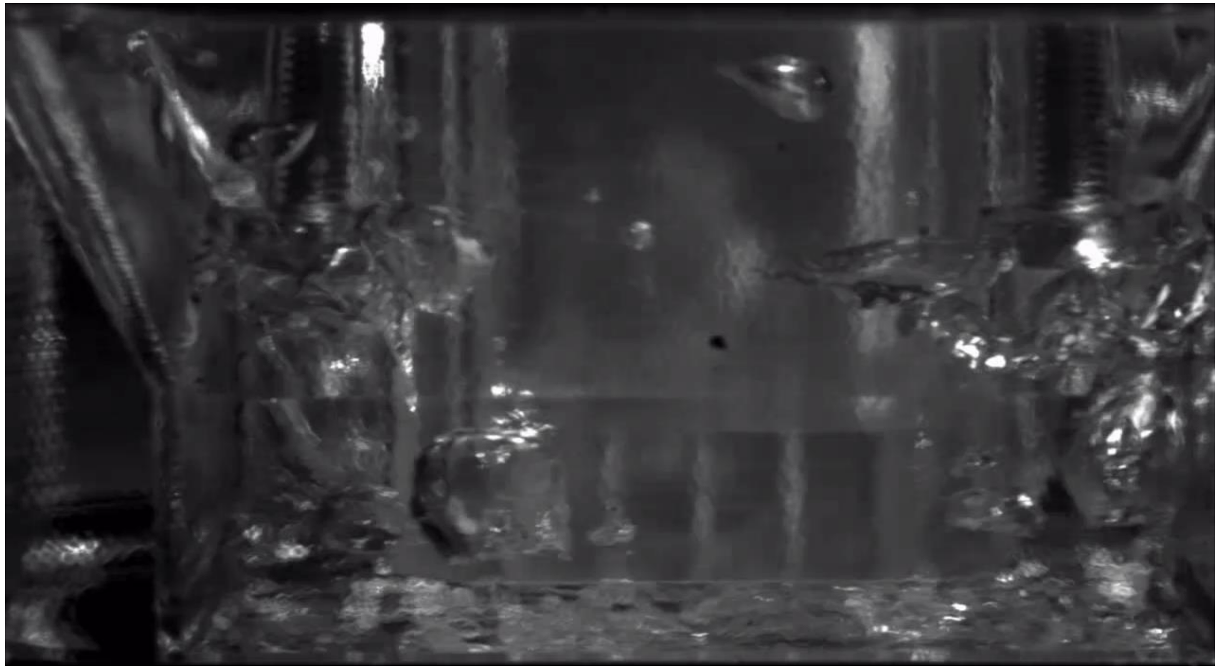
Cold Plate with Vapor Extraction Manifold

Performance Characteristics

- Flow visualization and understanding heat transfer and pressure drop comparison



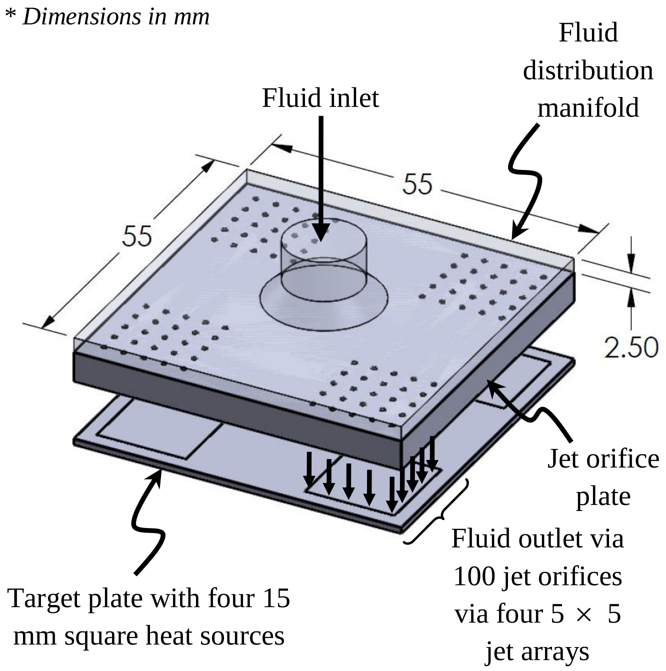
Inherent porosity of AM surface extends CHF



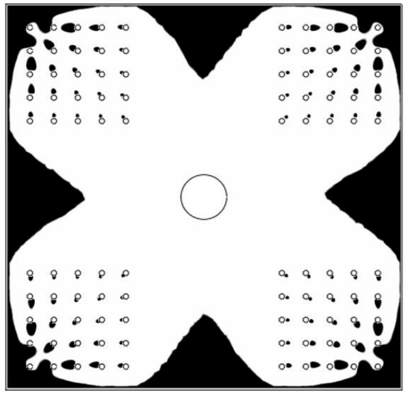
Two-Phase Jet Impingement Movie – Approaching Critical Heat Flux (CHF)

Compact Manifold Design

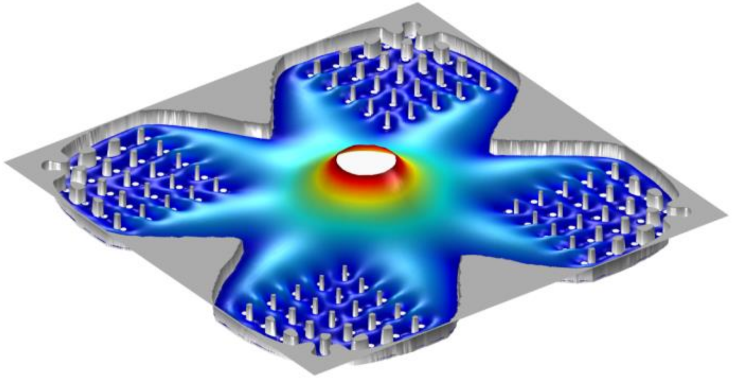
- Exploit optimization of single-phase inlet manifold for size reduction of cold plate



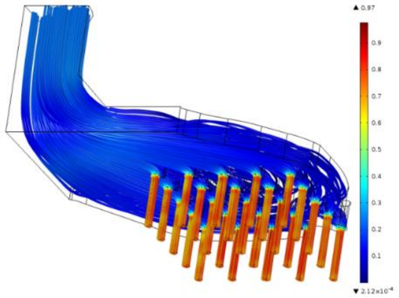
Manifold Layout for Four Power Devices



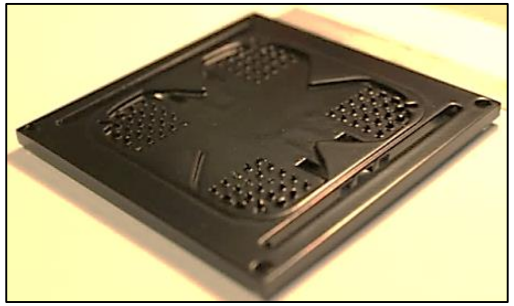
Design Evolution Movie



Final Design



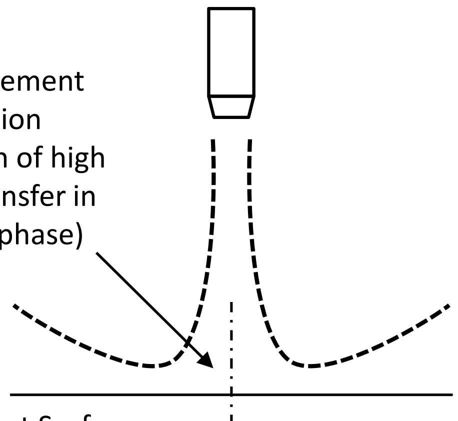
Design Verification by Simulation



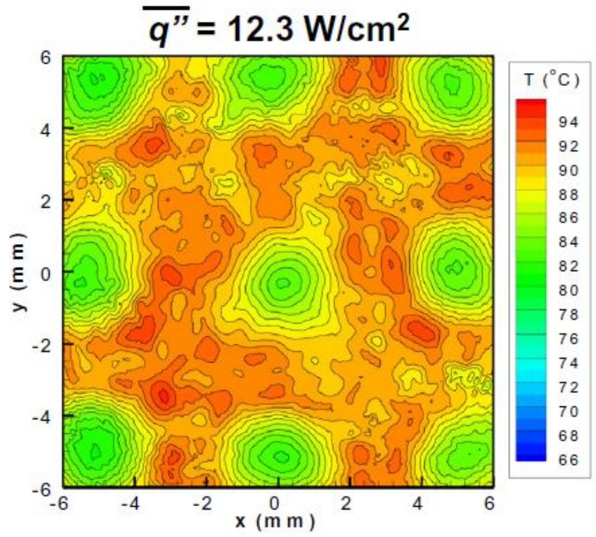
AM Rapid Prototype for Design Visualization

Future Possibilities – Target Surface Design

- Opportunity for structural design optimization as two-phase conjugate simulation evolves

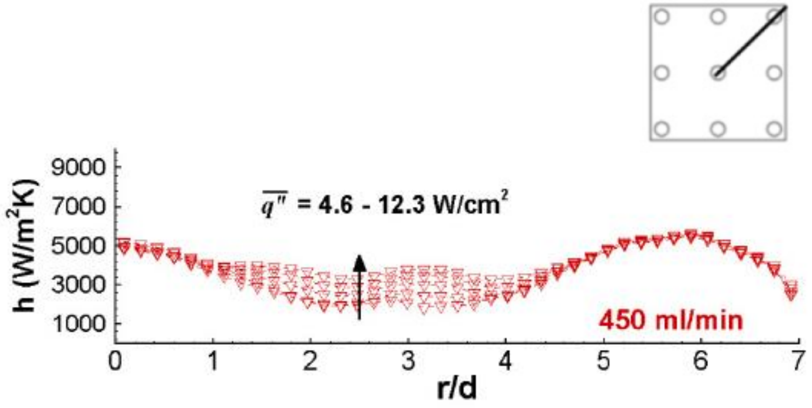


Typical Jet Impingement Scenario



*Ref.: Rau, M.J. and Garimella, S.V., 2013. IJHMT

Two-Phase Temperature Map (3 x 3 jet array)

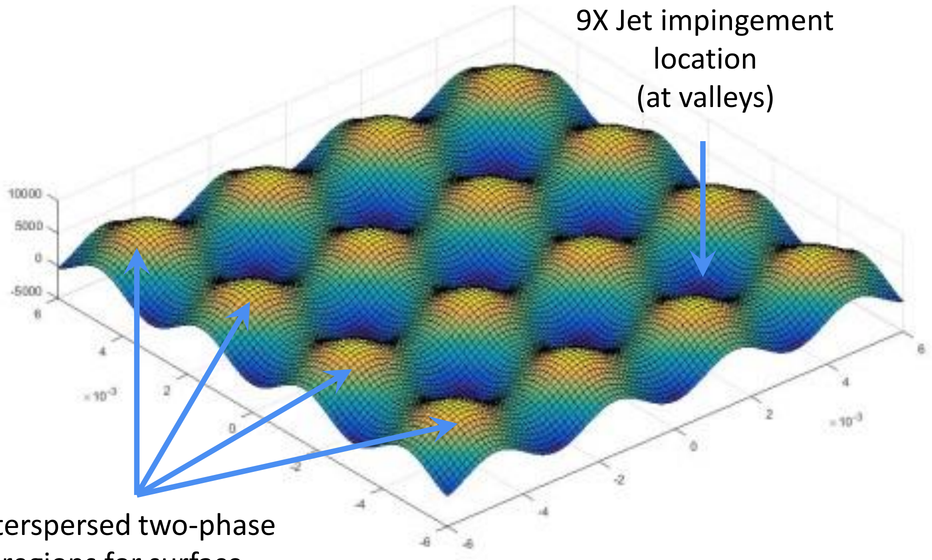


*Ref.: Rau, M.J. and Garimella, S.V., 2013. IJHMT

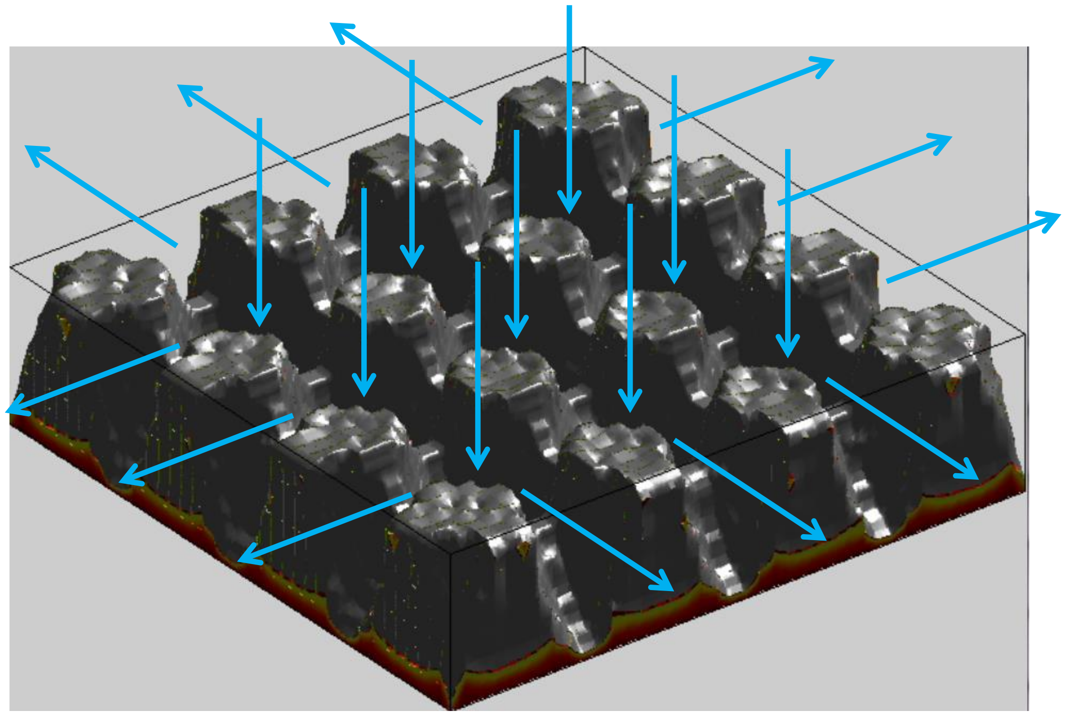
Variation in Local Heat Transfer Coefficient (3 x 3 jet array)

Future Possibilities – Target Surface Design

- Example optimization study for heat conduction plus side-surface convection (following air cooling study)
  - Assume *inverse* spatial heat transfer coefficient distribution is known *a priori*



Impose Heat Transfer Coefficient Profile to Optimize Two-Phase Surface Regions



Movie of Evolution of Surface Structure → AM Possibility?

Challenges & Future Opportunities

- AM material related challenges – in context of present work
  - Multi-material printing combining metals and plastics for 3D circuits
    - Technologies now starting to emerge
  - High thermal conductivity (e.g. copper) and high temperature materials
    - NASA demonstrated → need transition to wider commercial space
  - Fully dense metal deposition (heat transfer) & plastic printing (flow)

- Comprehensive design methods that address AM
  - Re-think traditional design paradigms and re-phrase methods to remove traditional manufacturing limitations

- Democratization of manufacturing → logical byproduct of AM
  - But, will low cost, high volume production become a reality?

Conclusions

- AM supports exploration of future 3D power electronics integration and manufacturing
  - New compact, high performance electrical device and circuit concepts realizable
  - Benefits rapid investigation of unique thermal management technologies
- Synergy with advanced structural optimization methods
  - Complex topologies no longer limited by traditional fabrication
- How to realize full potential of AM for power-dense electronics systems?
  - Further research and development for multi-material printing technologies, finished material quality, and new material compositions
- What is applicability for high volume manufacturing?

References

1. Zhou, F., Liu Y, Liu, Y., Joshi, S.N., and Dede, E.M., 2015. “Modular design for a single-phase manifold mini/microchannel cold plate.” Journal of Thermal Science and Engineering Applications, 8: 021010 (13 pages).
2. Dede, E.M., Joshi, S.N., and Zhou F., 2015. “Topology optimization, additive layer manufacturing, and experimental testing of an air-cooled heat sink.” Journal of Mechanical Design, 137: 111403 (9 pages).
3. Joshi, S.N. and Dede, E.M., 2015. “Effect of sub-cooling on performance of a multi-jet two phase cooler with multi-scale porous surfaces.” International Journal of Thermal Sciences, 87: 110-120
4. Rau, M.J., Dede, E.M., and Garimella, S.V., 2014. “Local single- and two-phase heat transfer from an impinging cross-shaped jet.” International Journal of Heat and Mass Transfer, 79: 432-436.
5. Dede, E.M., Lee, J., and Nomura, T., 2014. *Multiphysics simulation – electromechanical system applications and optimization.* Springer, London.
6. Dede, E.M. and Nomura, T., 2014. “Topology optimization of a hybrid vehicle power electronics cold plate – application to the design of a fluid distribution structure.” EVTeC and APE 2014, Yokohama, Japan.
7. Rau, M.J. and Garimella, S.V., 2013. “Local two-phase heat transfer from arrays of confined and submerged impinging jets.” International Journal of Heat and Mass Transfer, 67: 487-498.
8. Ishigaki, M., et al., 2011. “Proposal of high accurate and tiny rogowski-coil current sensor.” IEEJ Annual meeting (Japanese), 4: 265.