Analysis of a Thermally Integrated 3D Package for SiC-Based DC-DC Full Bridge Converter

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CEEE AHXPI Consortium

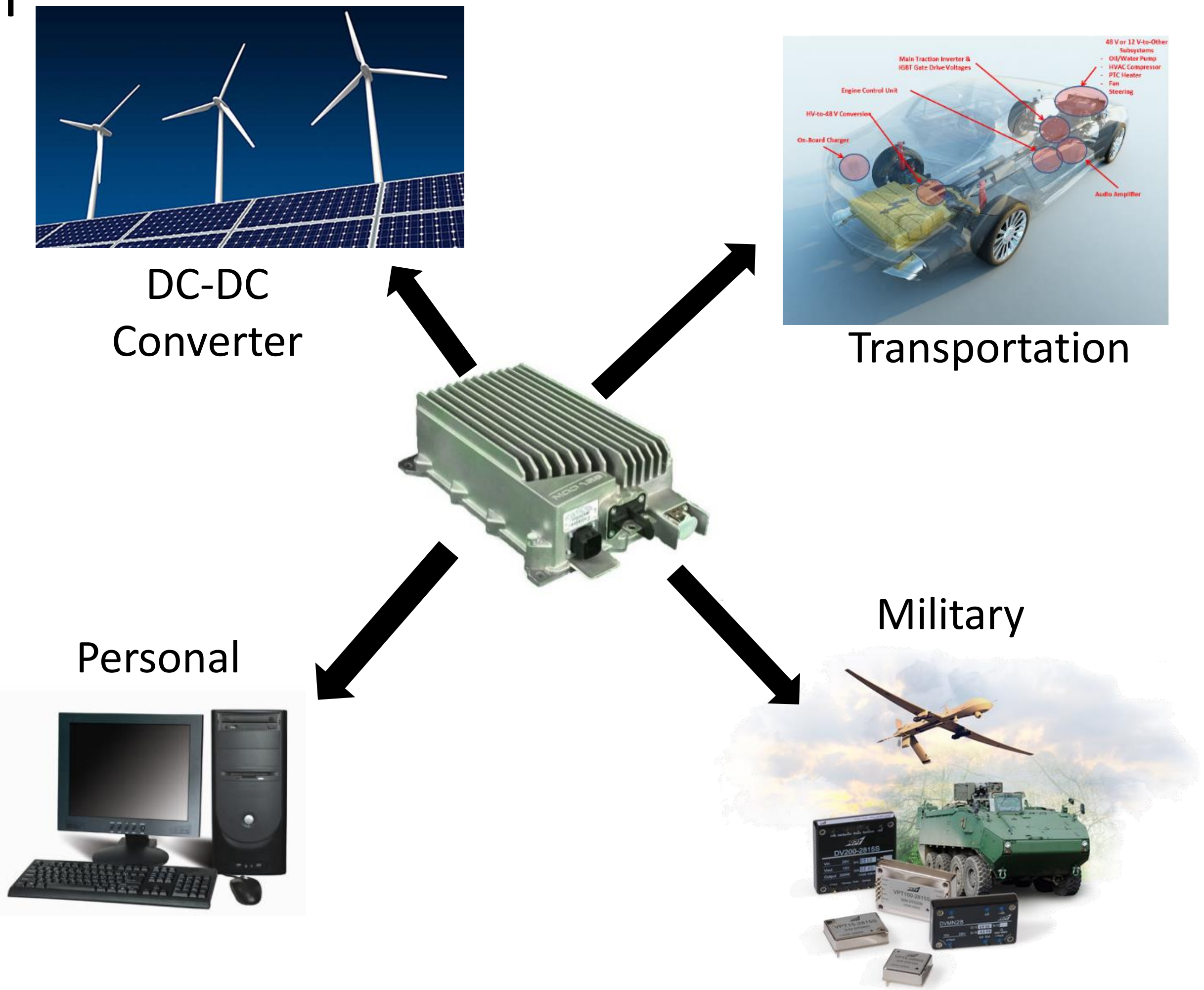
CENTER FOR ENVIRONMENTAL ENERGY ENGINEERING

Outline

- Motivation/Introduction
- Project Objectives and Review
- Transformer Cooling
- System Design
- Summary and Major Accomplishments

Motivation - High Power DC-DC Converters

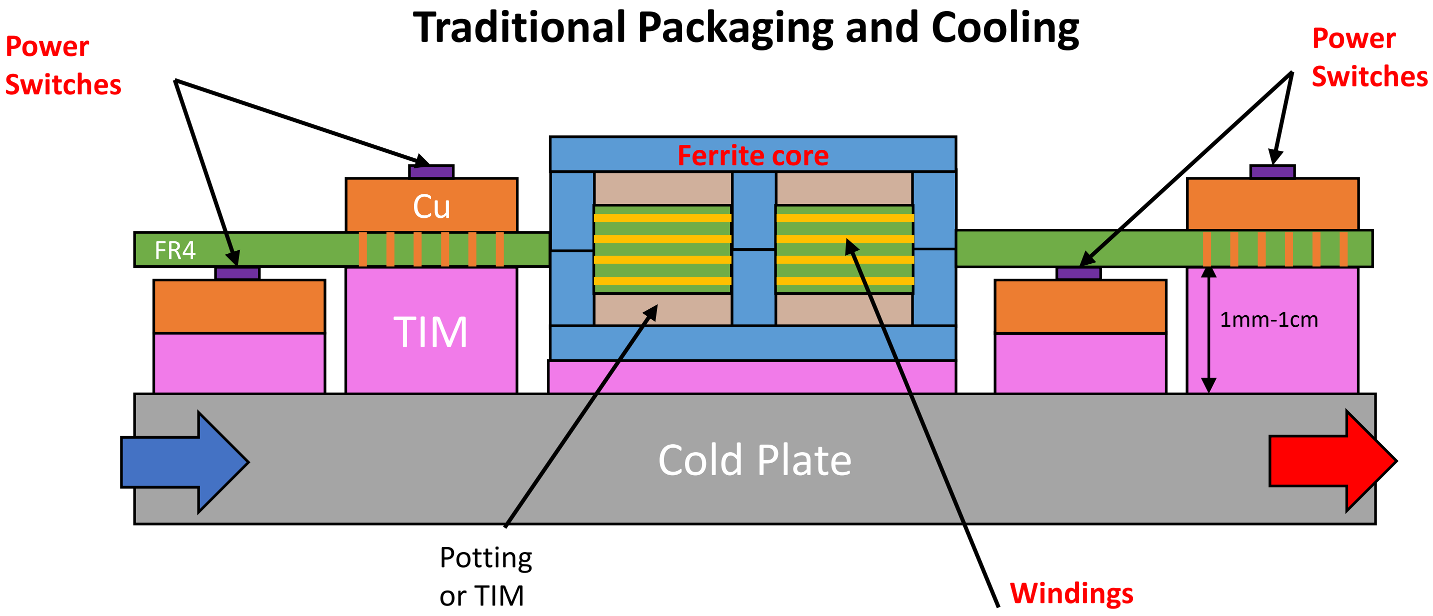
- Converts a source of direct current (DC) from one voltage level to another
- Used in a variety of applications
- Typical efficiency 90-92%
- Typical power density < 1kW/L
- SWAP - Size weight and power
  - Increased power and voltage req.
  - Increased compactness
  - Increased heat fluxes
- Thermal management becomes the bottleneck!
  - Air-cooling is predominantly utilized for heat removal in most cases no longer sufficient

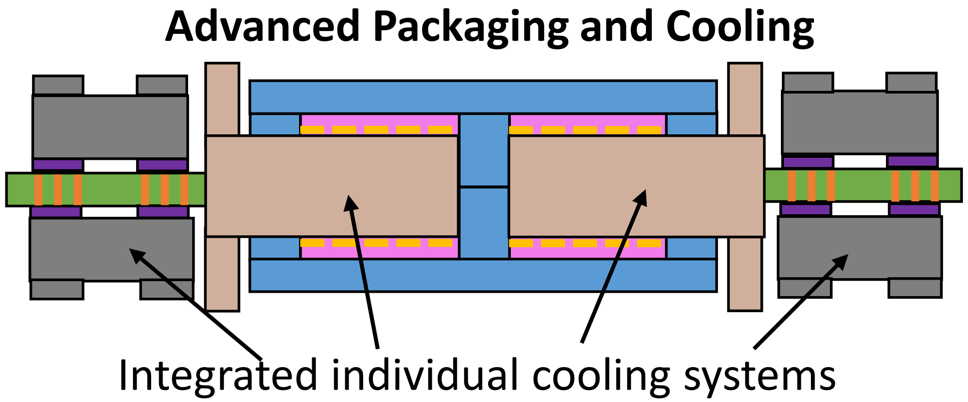


Motivation - High Power DC-DC Converters

- 3 major heat dissipating components
  - Switches
  - Magnetic core
  - Windings
- Traditional cooling involves TIM and cold plate
- Advanced packaging can integrate cooling into components

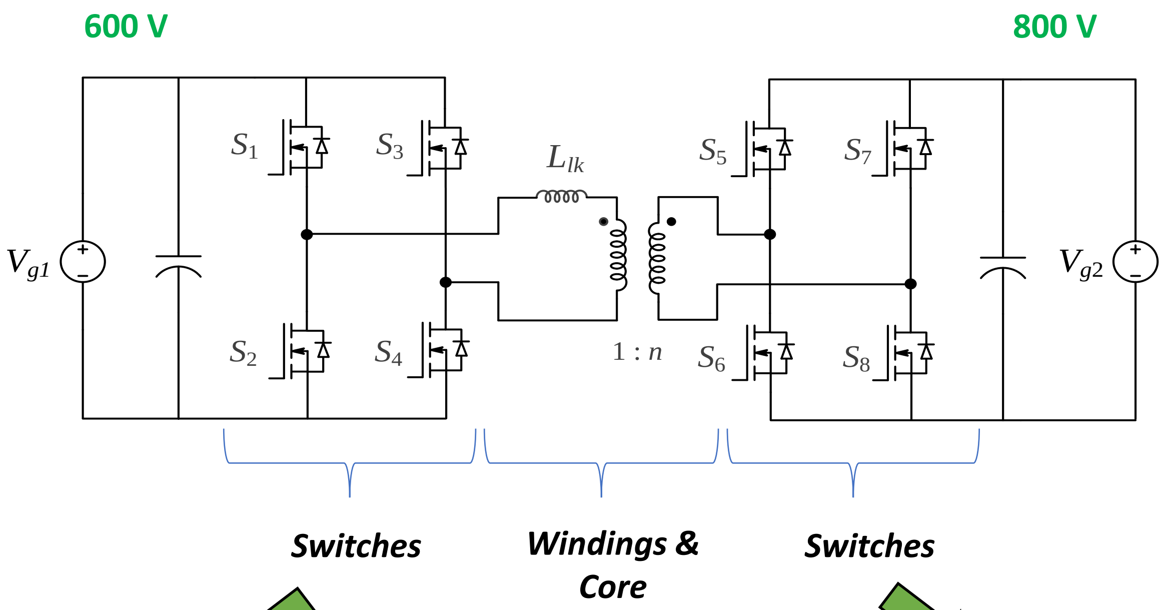
<u>Significant potential to reduce size and improve thermal performance!</u>

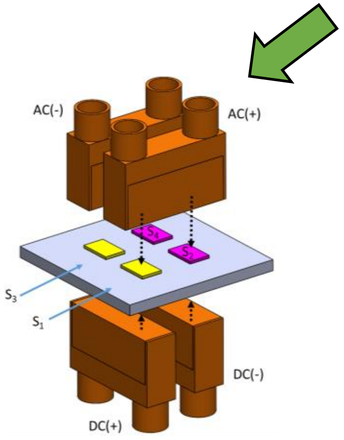




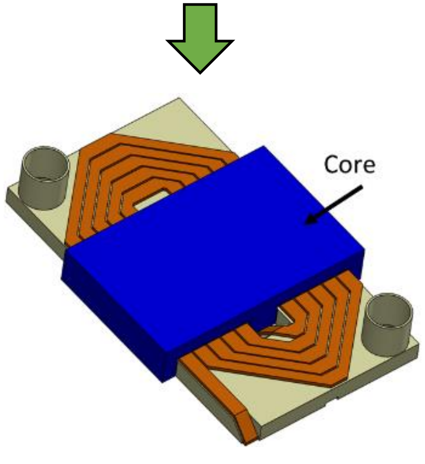
SCAPOPS-II Project Objectives

- Silicon Carbide Advanced Packaging of Power Semiconductors II (SCAPOPS-II)
  - 10 kW High efficiency (≥ 97 %), high-voltage (800 V) DC-DC converter for electric vehicles
- Key thermal design concepts enabling increased power density
  - Advanced packaging configurations
  - Double-functioning components
  - Extensive use of additive manufacturing
  - Advanced thermal management techniques

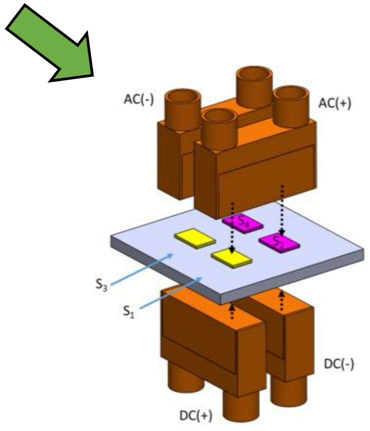




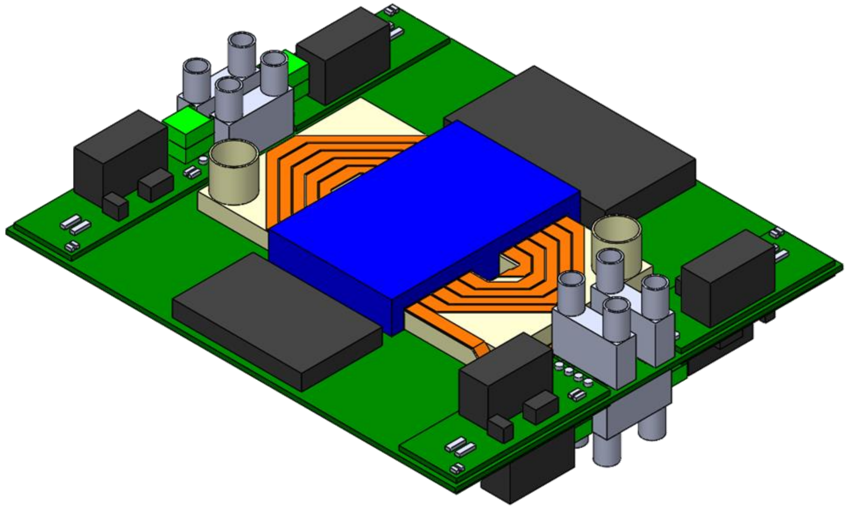
VEMMS Cooler



C3 Cooler

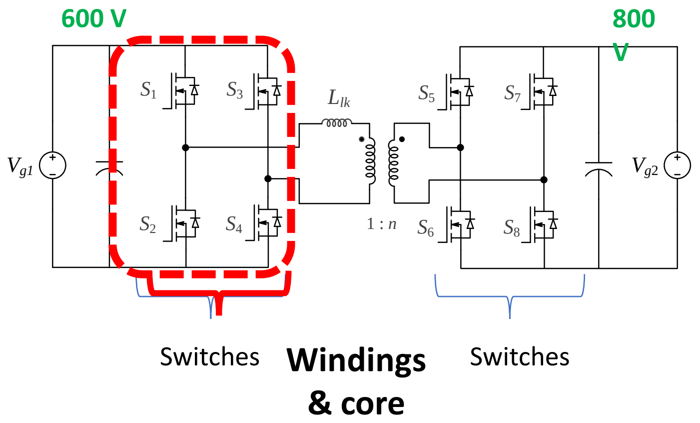


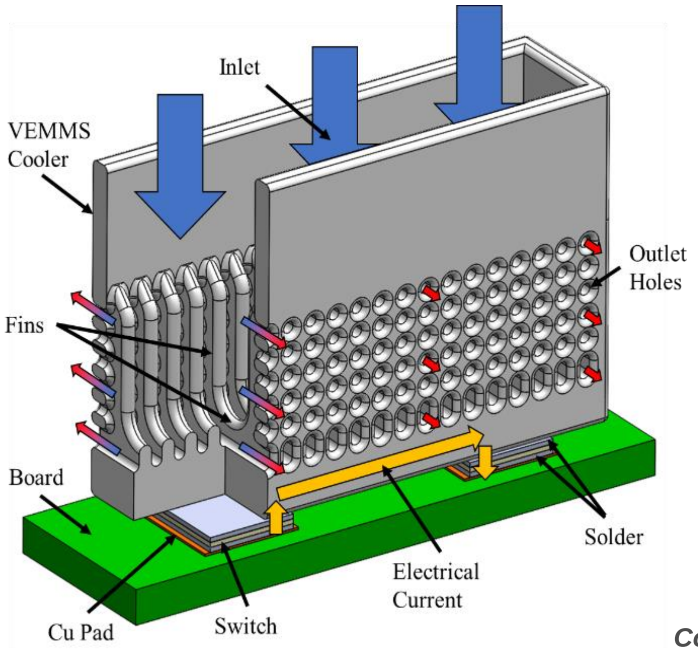
VEMMS Cooler



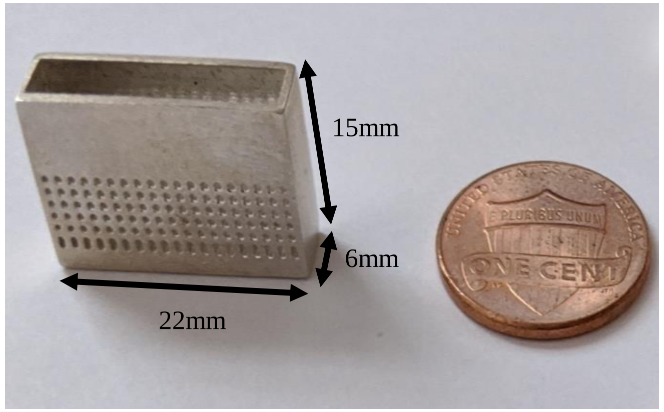
Review: Switch Cooling with VEMMS

- <u>V</u>ertically <u>E</u>nhanced <u>M</u>anifold <u>M</u>icrochannel <u>S</u>ystem
  - Heat spreading is isotropic
  - Design for minimum footprint on the board
  - Utilize available vertical space
- Designed air and liquid VEMMS
- Additively manufactured air VEMMS coolers
- Experimentally tested
- Good agreement between numerical and experimental data

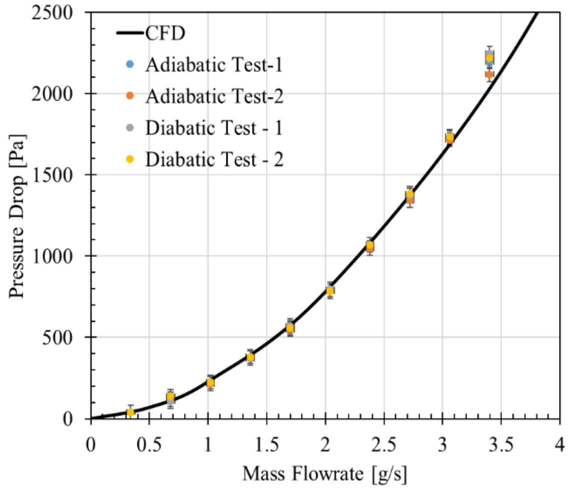




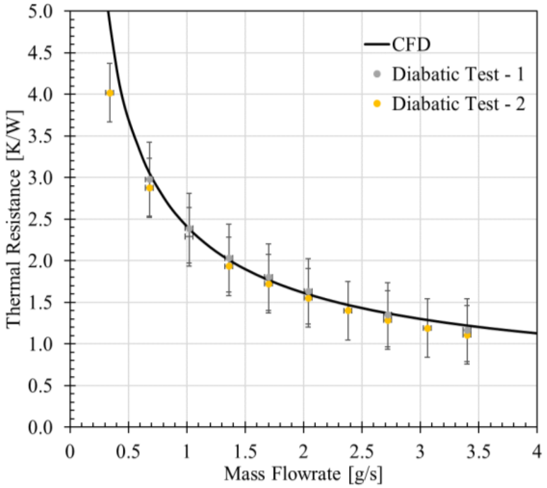
Additively Manufactured VEMMS Cooler



Pressure Drop Results

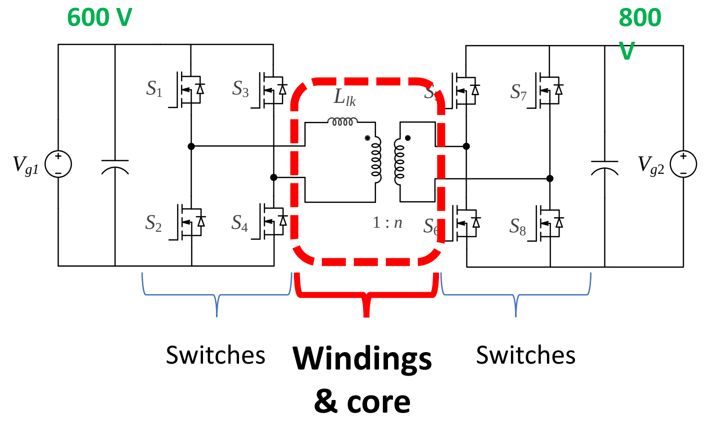


Heat Transfer Results

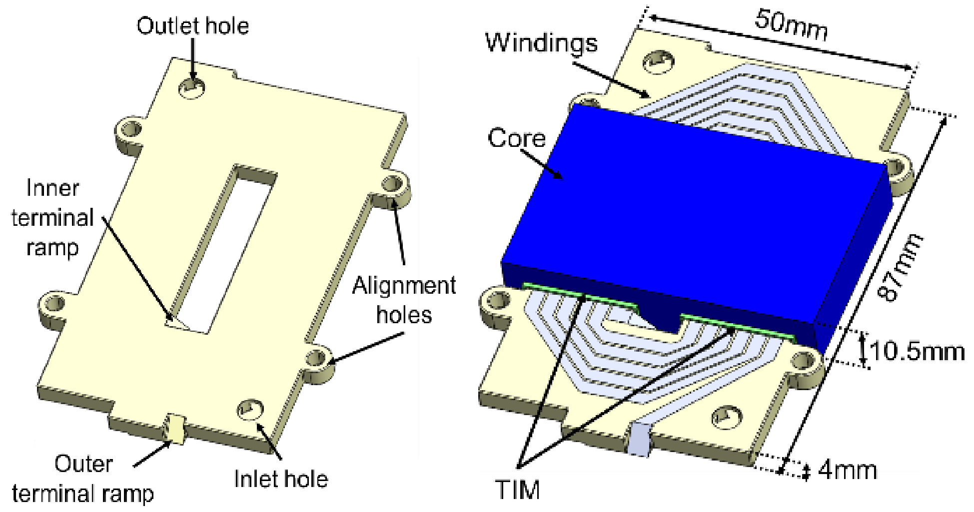


Transformer Thermal Management – C3 Cooling

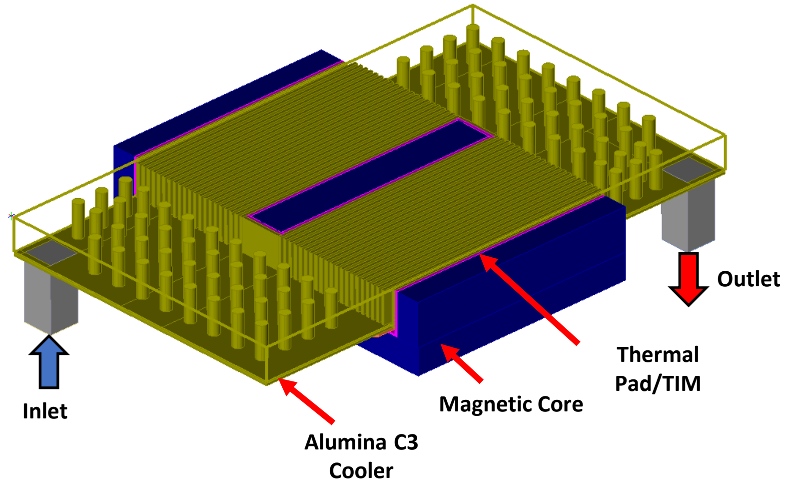
- **C**ombined **C**ore and **C**oil (C3) Cooling
  - 3D printed from Alumina
  - Coils 2D printed directly on alumina
  - Cools coil and core together
  - Cooling located close to heat generation
    - Core legs are actively cooled
  - Microchannels in high heat generation area
  - Tube banks in low heat generation area
    - Also serve as supports for additive manufacturing



C3 Cooler	Transformer Assembly



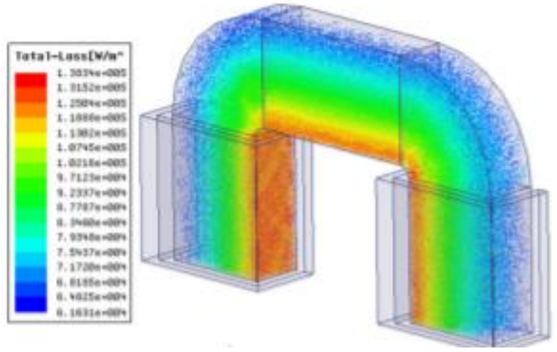
C3 Cooler CFD Model and Internal View



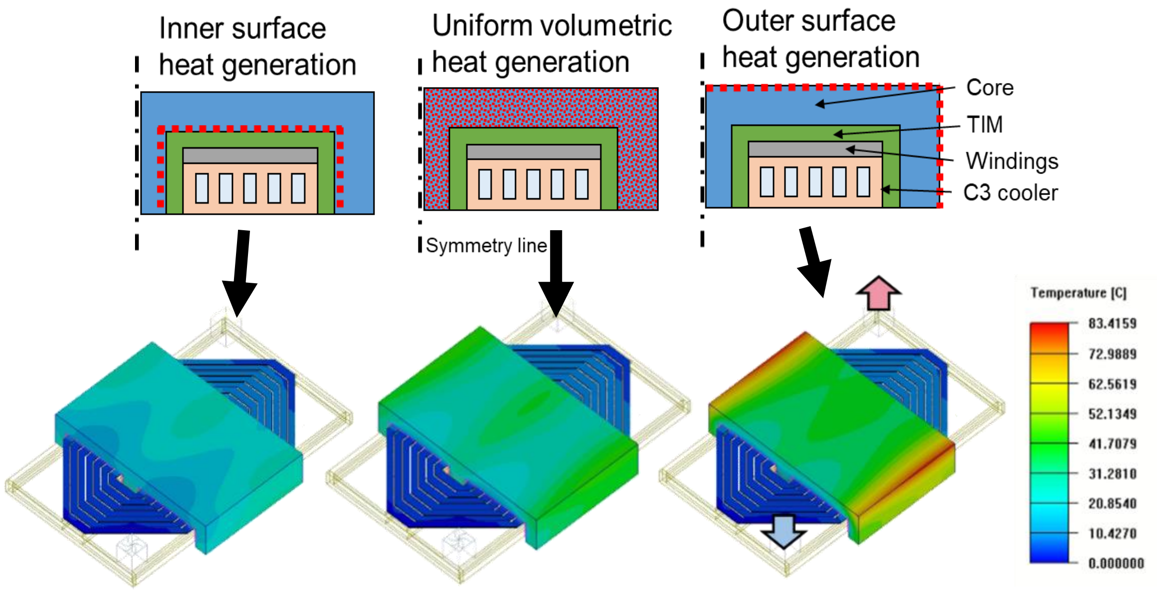
Investigation of Spatial Heat Generation

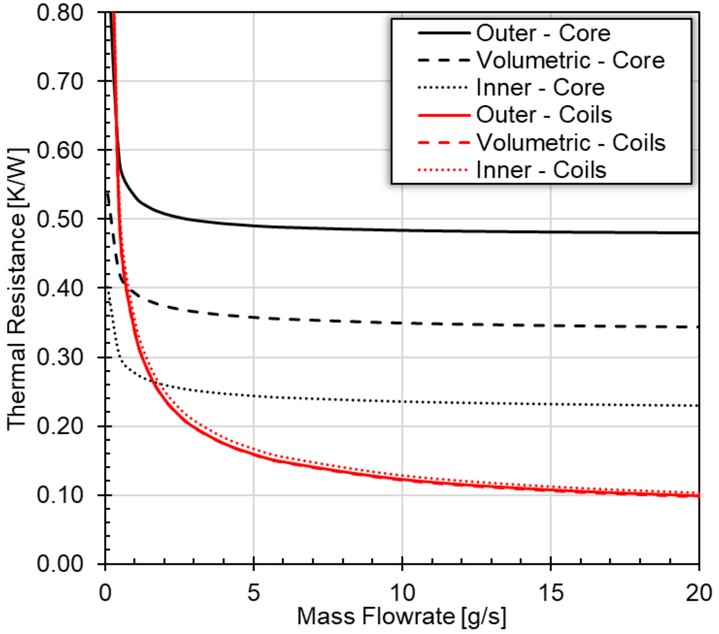
- Heat generation is non-uniform in real high frequency application
- Extreme cases are investigated to bound performance
  - Easiest to test with outer surface heat (DC)
  - More realistically, heat is generated close to inner surface (AC)
- From simulation, inner surface has lowest thermal resistance, as expected
  - Coil thermal resistance not affected, as expected

Actual heat load distribution [83]



Thermally Investigated bounding cases

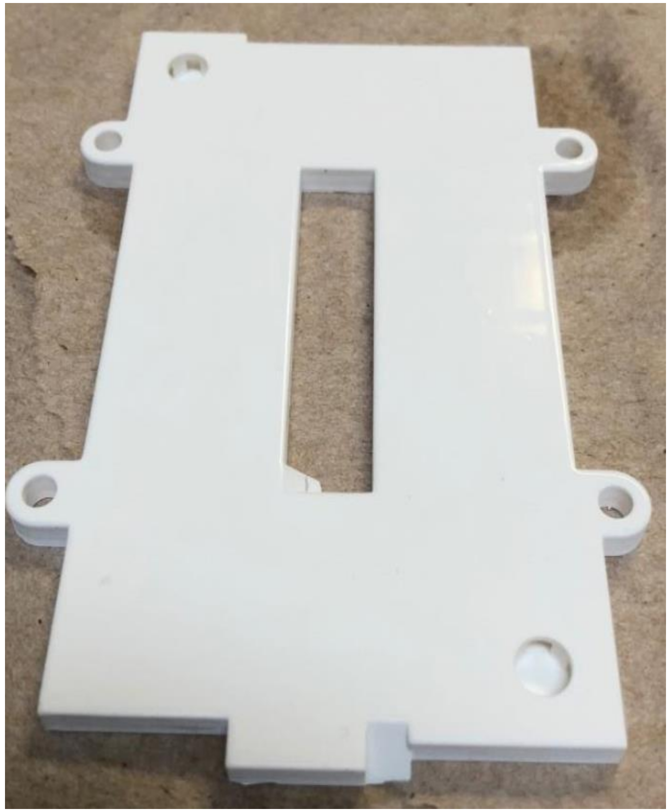




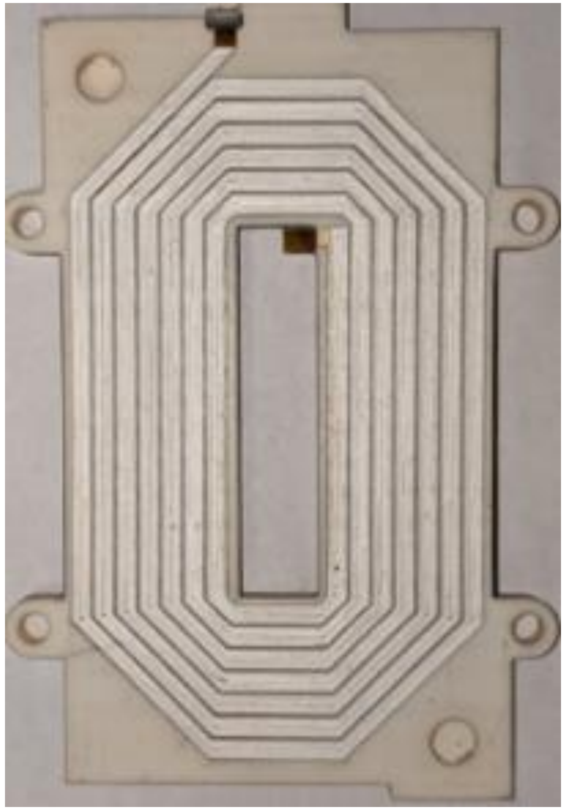
C3 Cooler Prototype and Experimental Setup

- A prototype was additively manufactured out of Alumina
- Silver windings were inkjet printed by the packaging team
- A test loop was assembled for experimentation

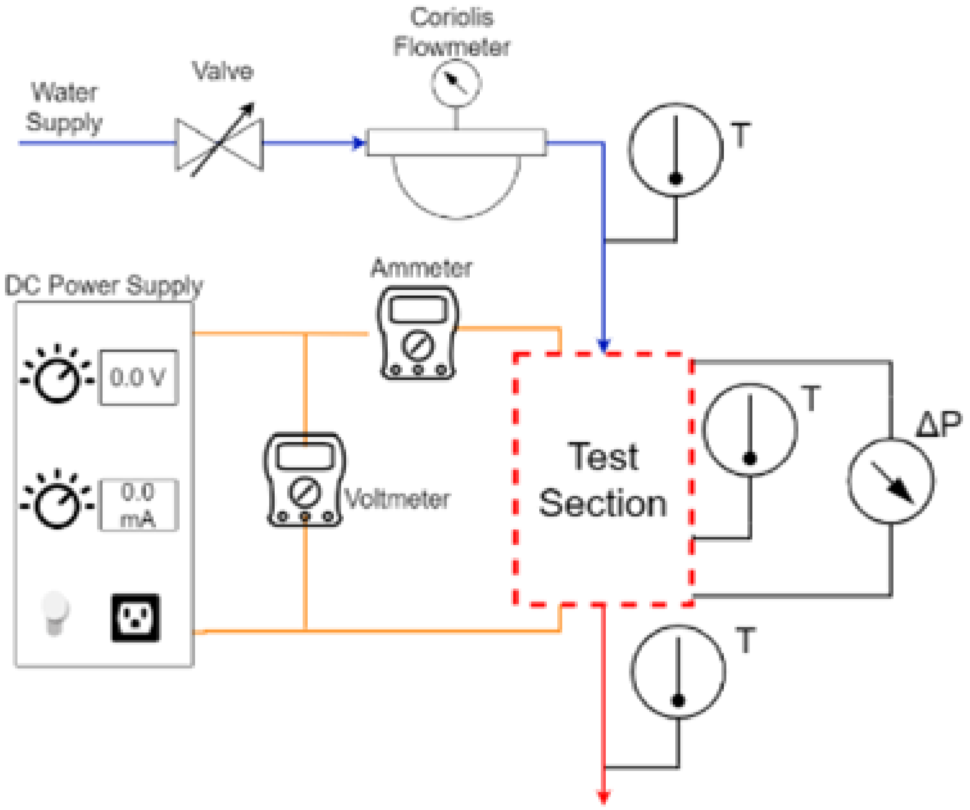
C3 Prototype



Silver windings



Test Loop



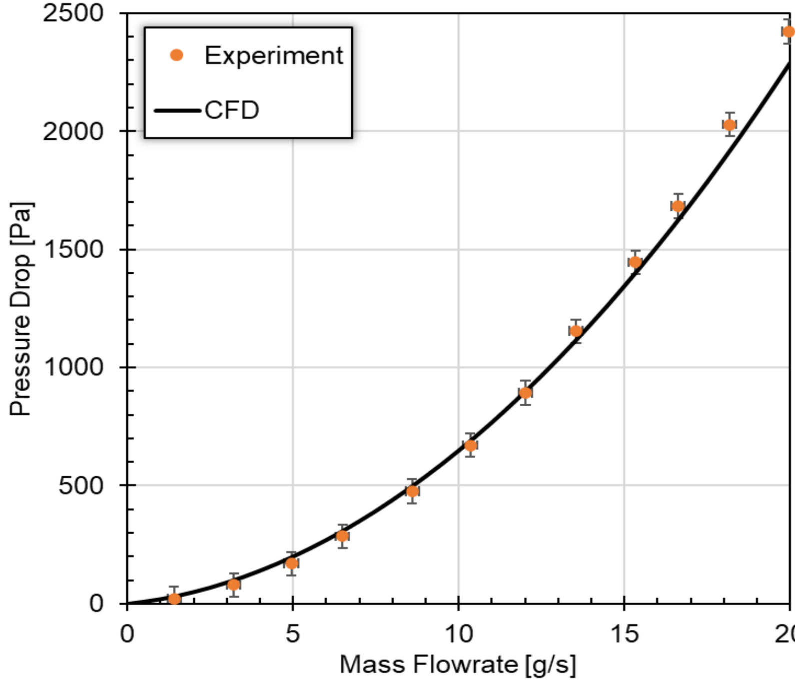
C3 Cooler Experimental Results

- Pressure drop and temperatures are monitored as a function of flow rate
- Good agreement obtained with CFD predictions
  - Comparison done at the locally measured points

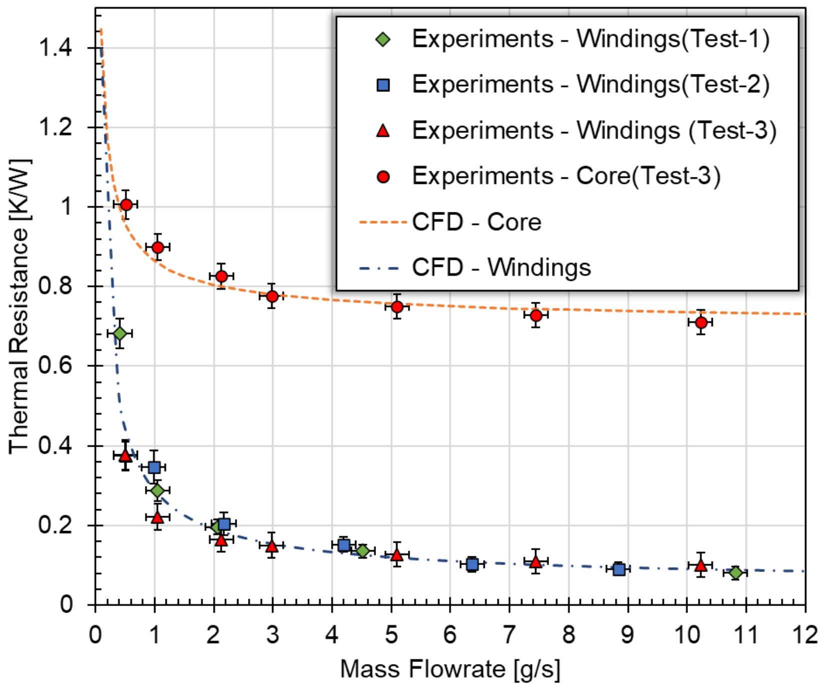
$$R_{coil} = \frac{T_{coil,measured} - T_{fluid,in}}{Q_{core} + Q_{coil}}$$

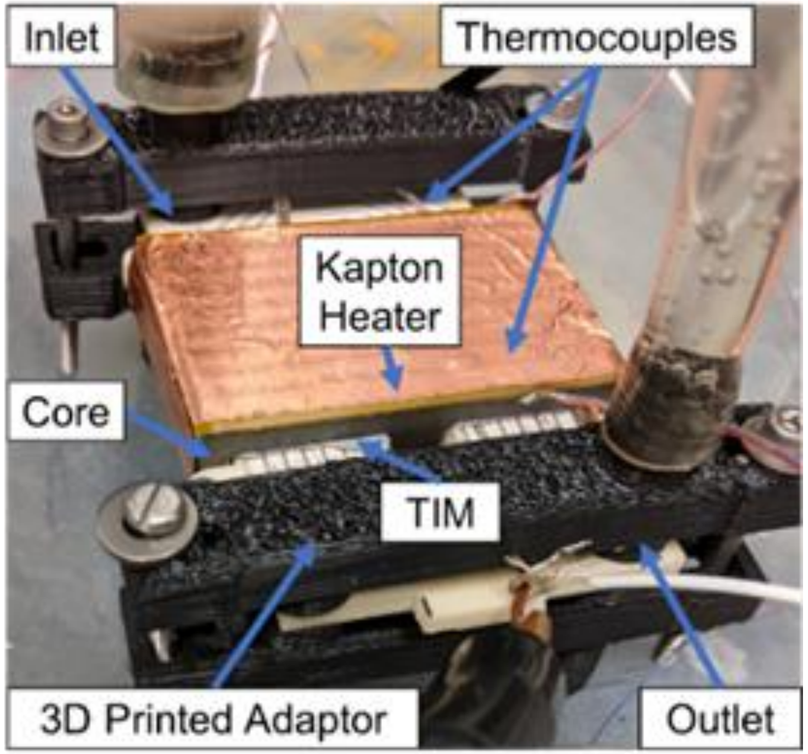
$$R_{core} = \frac{T_{core,measured} - T_{coil,measured}}{Q_{core}}$$

Pressure Drop Results



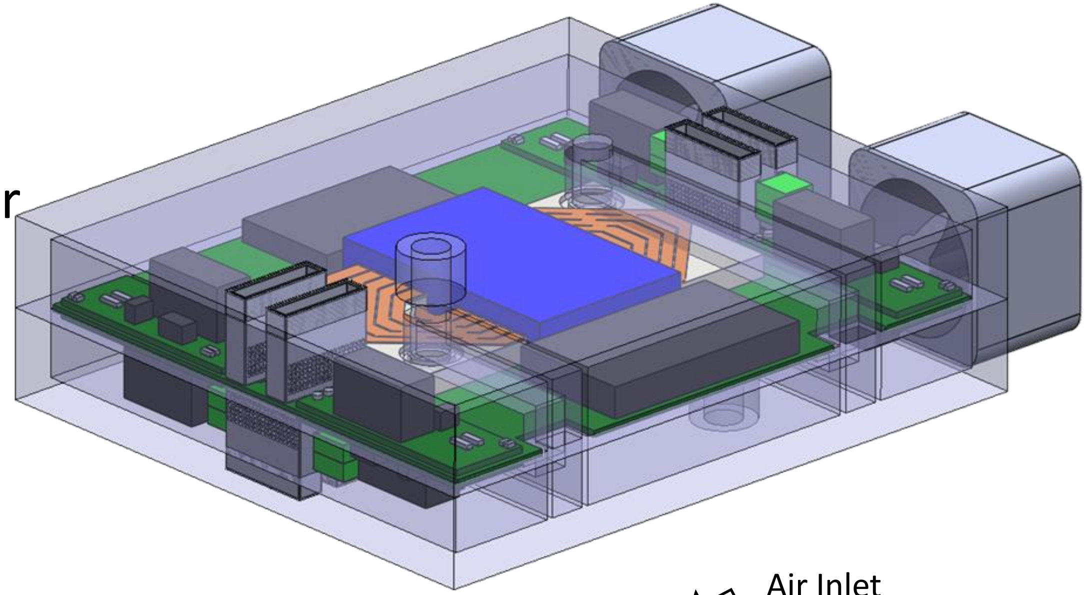
Thermal Results

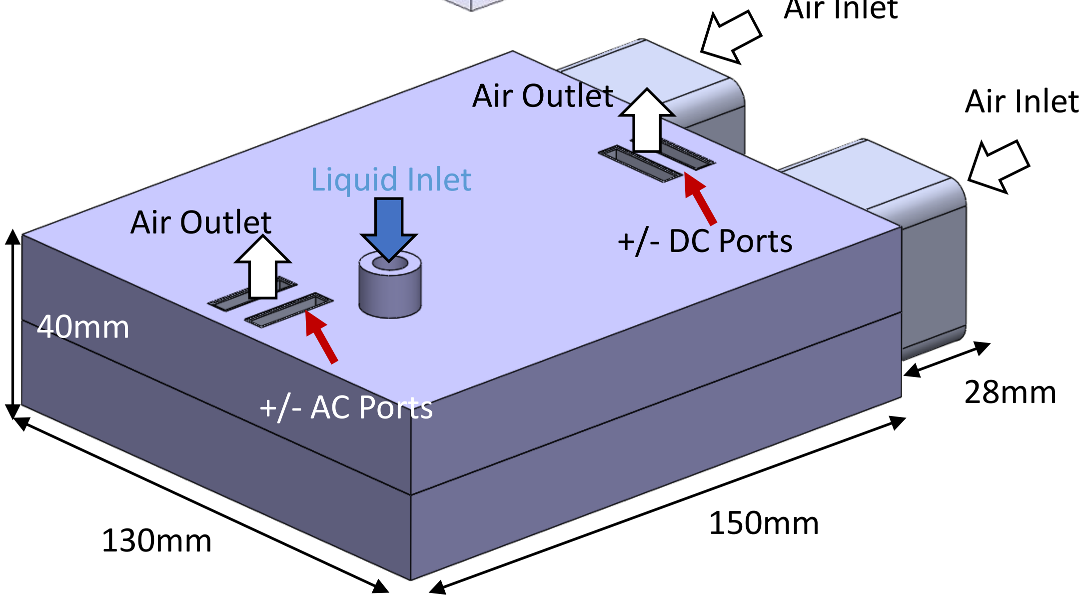




System Design

- Hybrid heat rejection approach where:
  - Single-phase, WEG from vehicle is used for C3 coolers
    - Air cooling was found insufficient
  - Single-phase, air from ambient is used for VEMMS coolers via fans
    - Requires only two fans (reduced volume)
    - Air outlet ports will be used as electrical terminals





✓**Total volume = 0.54 L**

✓**Power Density = ~20kW/L (for 10kW converter)**

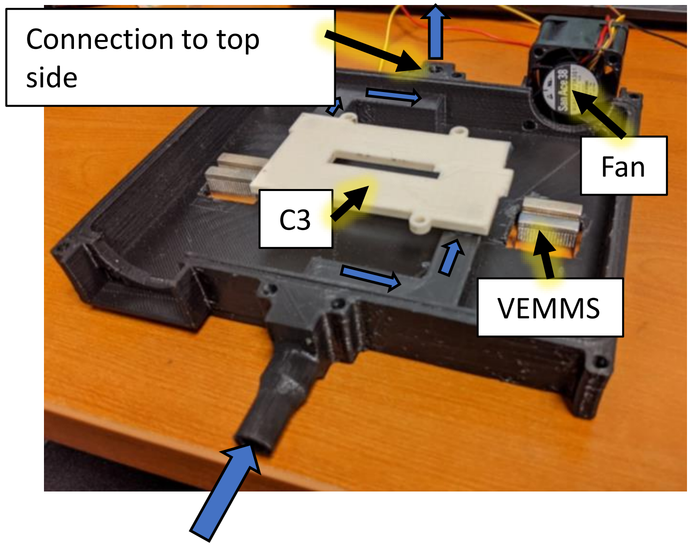
✓**At 60°C ambient/inlet and 2 fans**

✓T_{coils}<110°C
✓T_{core}<120°C
✓$T_{switches}$<165°C

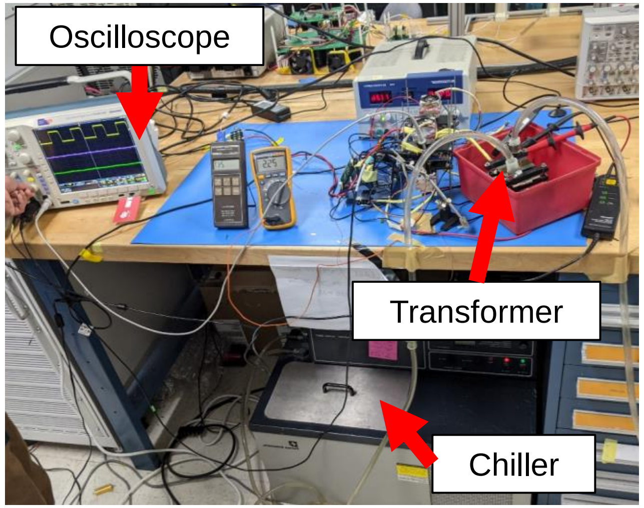
Integration to Electrical System and Final Results

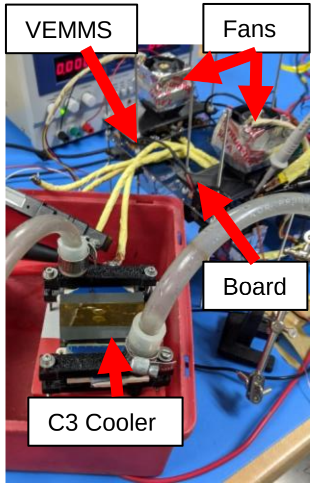
- Enclosure with internal flow routing channels is additively manufactured out of polymer
  - Parts are kept unpacked for safety
- The heatsinks are integrated to the electrical team's setup
- AC Losses were applied
  - Up to 8.4 kWe (out of 10kWe target)
- Thermal management of switches and transformers in the presence of AC losses is experimentally achieved
  - 16 kWe/L

3D Printed Enclosure (Bottom side)



Electrical/Thermal Experimental Setup

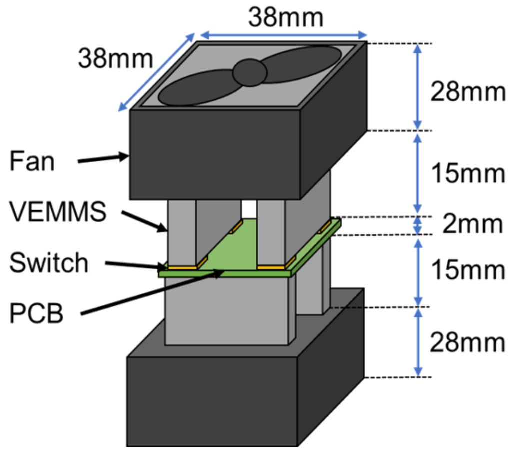




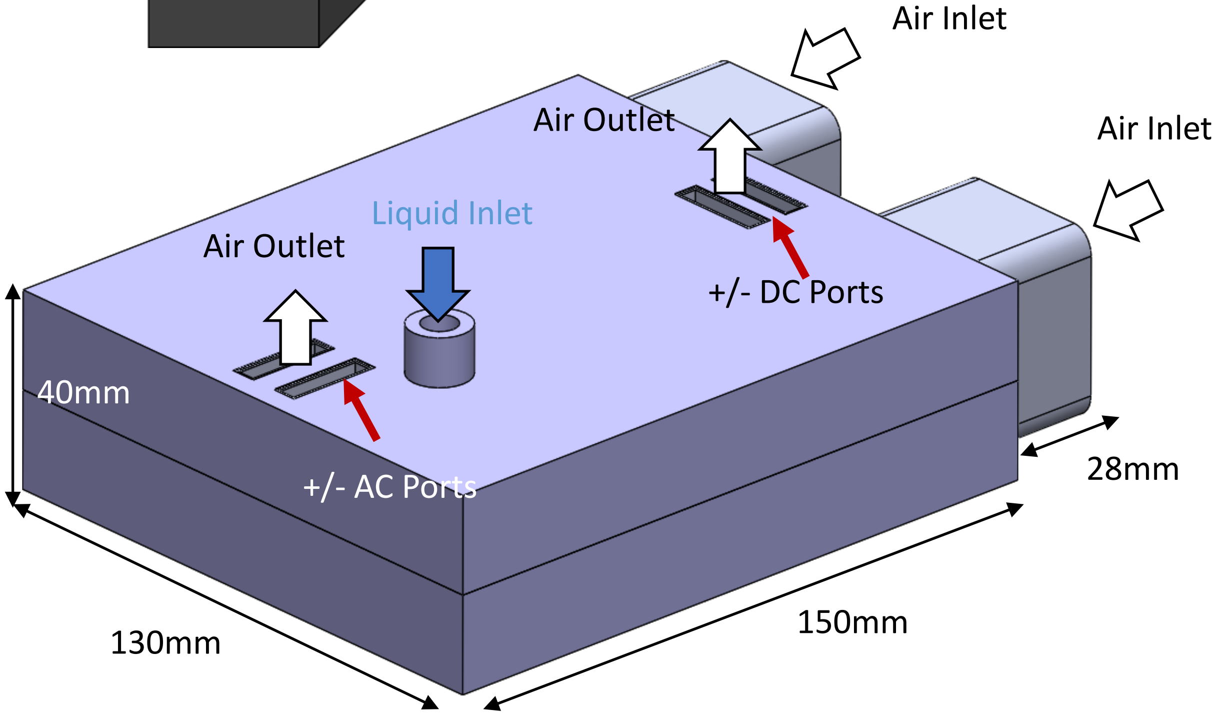
Summary and Major Accomplishments

- Designed, tested, and validated models for:
  - Switches
    - Full bridge based on this has a power density of 286 kWe/L
  - Transformer
    - Thermal resistances of 0.4 K/W for the core and 0.1 K/W for the coils
  - Hybrid System
    - WEG for transformer; air for switches
      - Single phase cooling is sufficient
    - 0.54 Liter volume
    - 16-20 kWe/Liter

Expected Full Bridge Assembly Dimensions



Study	Fluid	R_{th} [K/W]	Heatsink Volume [cm^3]	Conductance Density [W/K-L]
Gillot et.al. [29]	Liquid	0.101	70.8	140
Gillot et.al. [30]	Liquid	0.08	36.7	340
Lee et.al. [31]	Liquid	0.15	13.3	500
Boteler et.al. [4]	Liquid	0.52	3.75	513
Current Work	**Liquid**	**0.3**	**1.98**	**1684**
Liang et.al [32]	Air	2	161.3	3
Xu et.al. [5]	Air	0.5	144.6	14
Current Work	**Air**	**2**	**1.98**	**253**



Acknowledgements

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Q&A

THANK YOU!