Integrated Liquid Metal Based Cooling – An Ultimate Cooling Strategy for Electronics

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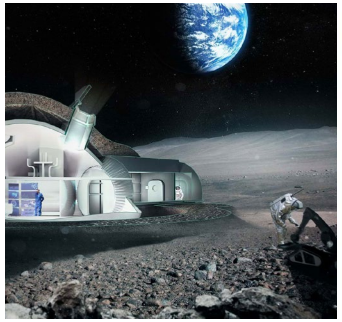


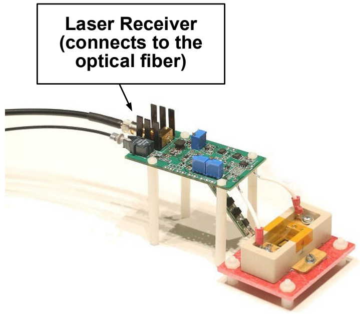
CHPPE | The Ohio State University College of Engineering

Examples of Past Medium Voltage Projects at OSU

2014-2015

Power over fiber base gate drive for 15-kV SiC MOSFET

- Ultra-high isolation capability
- Elimination of cross talks among gate drives and control circuits at high dv/dt



- First Place Award at the IEEE Student Demonstration Competition of ECCE2015
- Patent granted

2016-2021

7-kV 1-MVA Modular Multilevel Converter for Industrial Motor Drives

- Based on 1.7-kV SiC power modules
- Peak efficiency: 99.3%
- 3 times of loss reduction
- 4 times power density improvement

2016-2019
DoE NGEM

PowerAmerica
2019-2021

From University Research to Industry Product

OSU Research Prototypes

Toshiba North America Product

The first SiC based medium voltage Mega-watt industry motor drive product

https://youtu.be/Jz3Ikd734Pc

Examples of Past Medium Voltage Projects at OSU

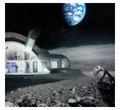
2019-2023

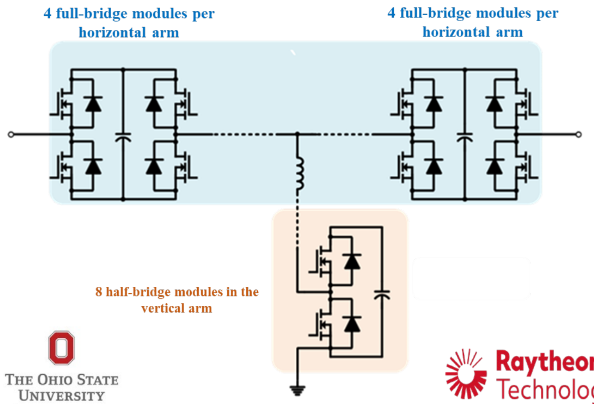
20-kV T-Type Modular DC Circuit Breaker (T-Breaker) for Future DC Networks

ARPA-E CHANGING WHAT'S POSSIBLE

- A 20-kV solid state circuit breaker with 500 A breaking capability
- 60.2 MW/m^3 active power density
- 99.977 % measured efficiency
- Unmatched ancillary functions
- High immunity towards control signal misalignments

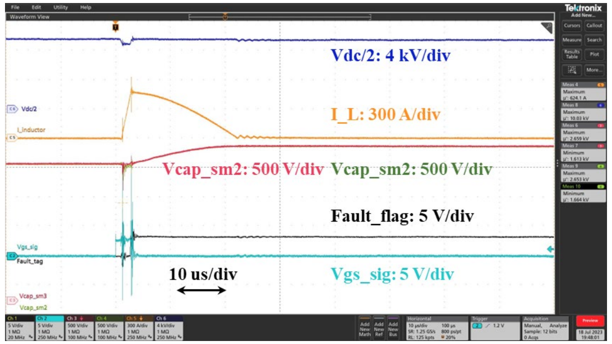
The validation of the T-Breaker topology at 1-kV 5000-A in the early stage of the project has led to a new project for microgrids on the lunar surface.





The Ohio State University

Raytheon Technologies



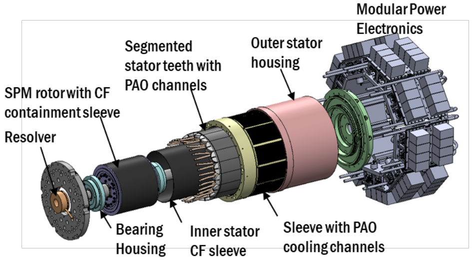
Breaking a 500-A fault current at 20-kV

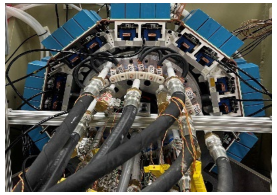
2017-2023

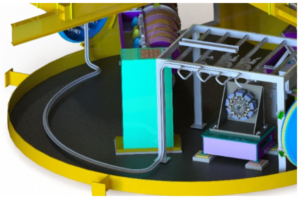
2-kV 1-MVA Integrated Modular Motor Drive for Turbo Electric Aircraft

NASA

- Modular structure for high fault tolerance and voltage stress reduction
- Vol. Power Density : 13.5 kW/L
- Mass. Power Density: 9.0 kW/kg
- A half-day workshop is planned on Sept. 6th







Tests were concluded successfully at NASA's NEAT facility on June 30th, 2023

The Ohio State University · Wisconsin · University of Maryland · North Carolina A&T State University

Outline

- Introduction of Liquid Metal based Cooling
- Three types of Magnetohydrodynamic (MHD) Pumps

Liquid Metal for Cooling Purposes

Gallium alloy in liquid state *

Property	$Ga_{61}In_{25}Sn_{13}Zn_{1}$	Water
Density ($Kg \cdot m^{-3}$)	6370	1000
Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	15	0.6
Melting point ($^{\circ}C$)	7.6	0

- Very safe and easy to handle in university lab environment
- High cost, $545 per kilogram when purchased in 2020**

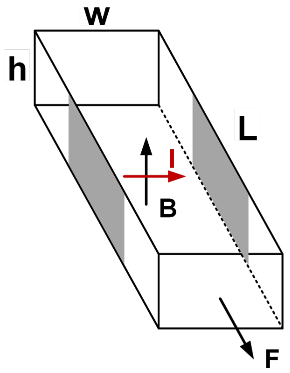
* https://www.indium.com/products/alloys/liquid-alloys/#image-2

** What is the per kilogram cost of SiC power modules?

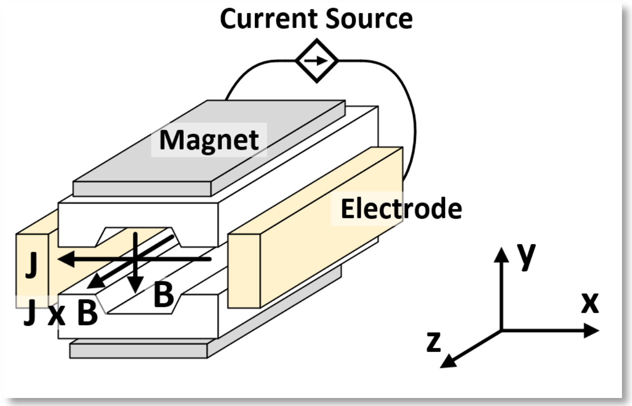
How to Create the Flow

Magnetohydrodynamic (MHD) Pump

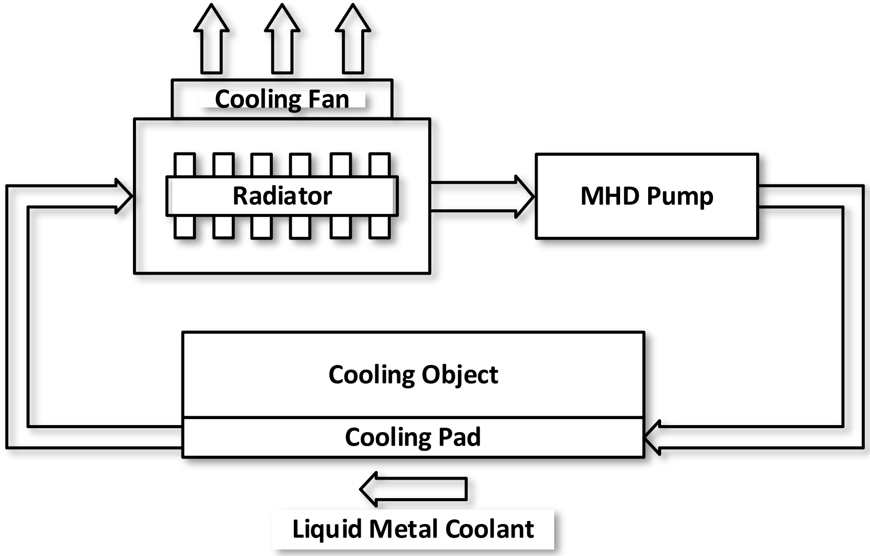
Lorentz force is generated inside a MHD pump with the presence of perpendicular magnetic field and current;



Vector diagram of Lorentz force

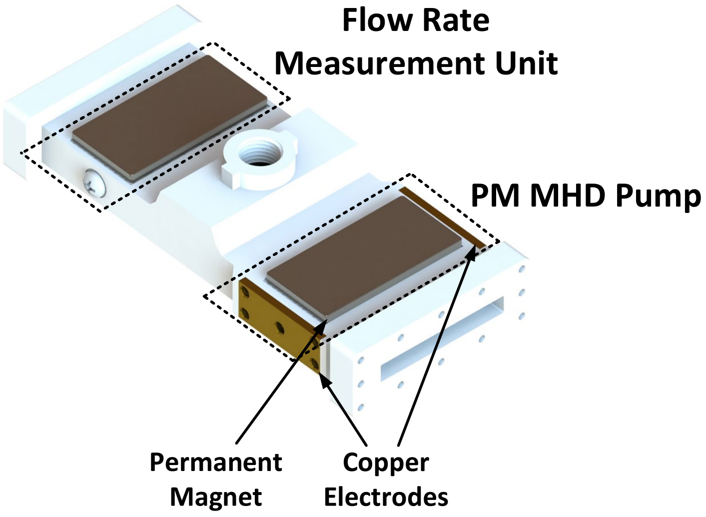


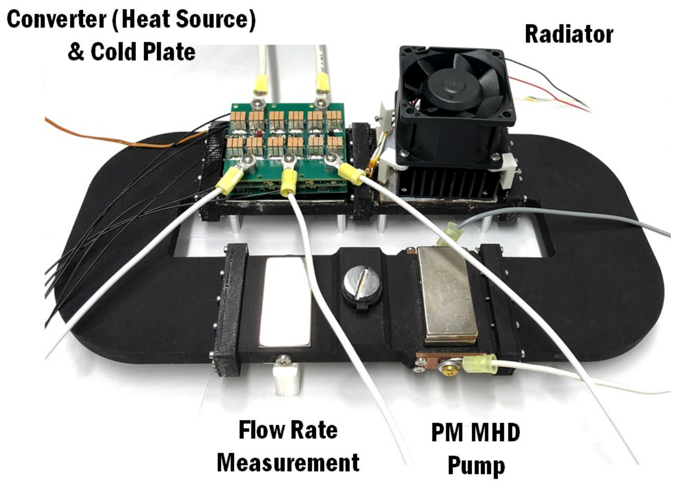
Structure of a Typical MHD Pump

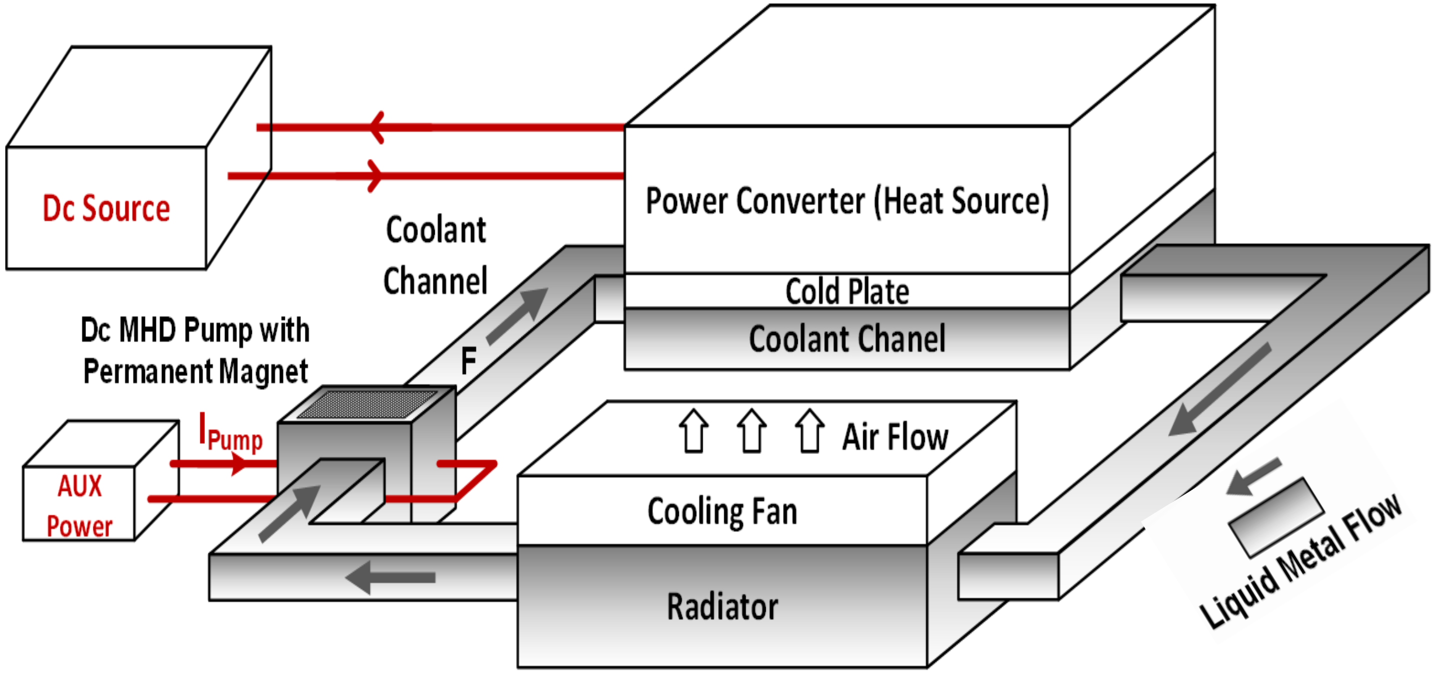


Generic structure of liquid metal-based cooling with a MHD pump

Permanent Magnet MHD Pump



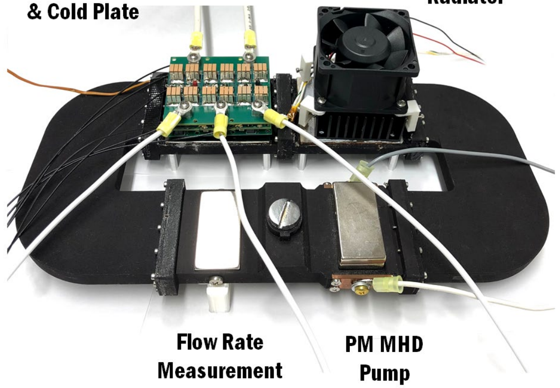




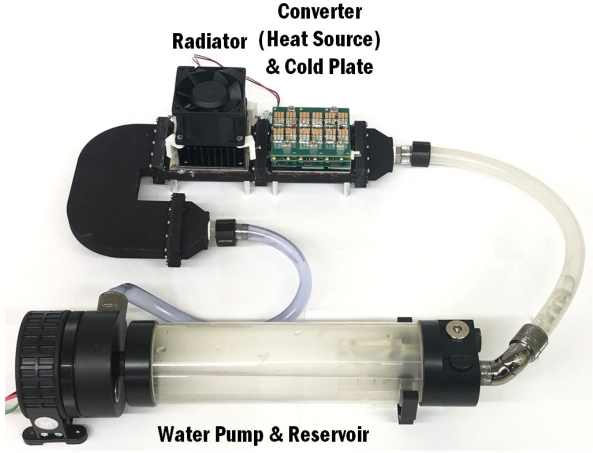
Liquid metal cooling loop with PM MHD pump

- Less numbers of rotatory components in the cooling loop.
- Low acoustic noise.
- Excellent cooling capability with ultra-low power loss.

Prototypes for Evaluation



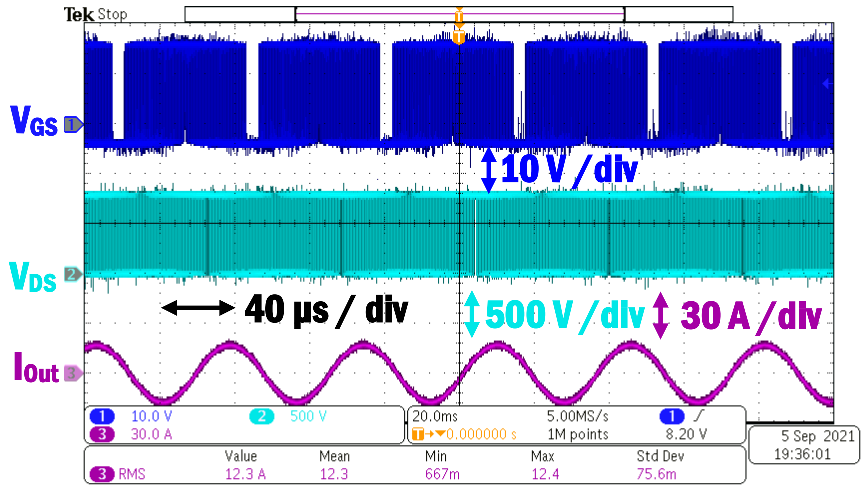
PM MHD based cooling



Water-based cooling

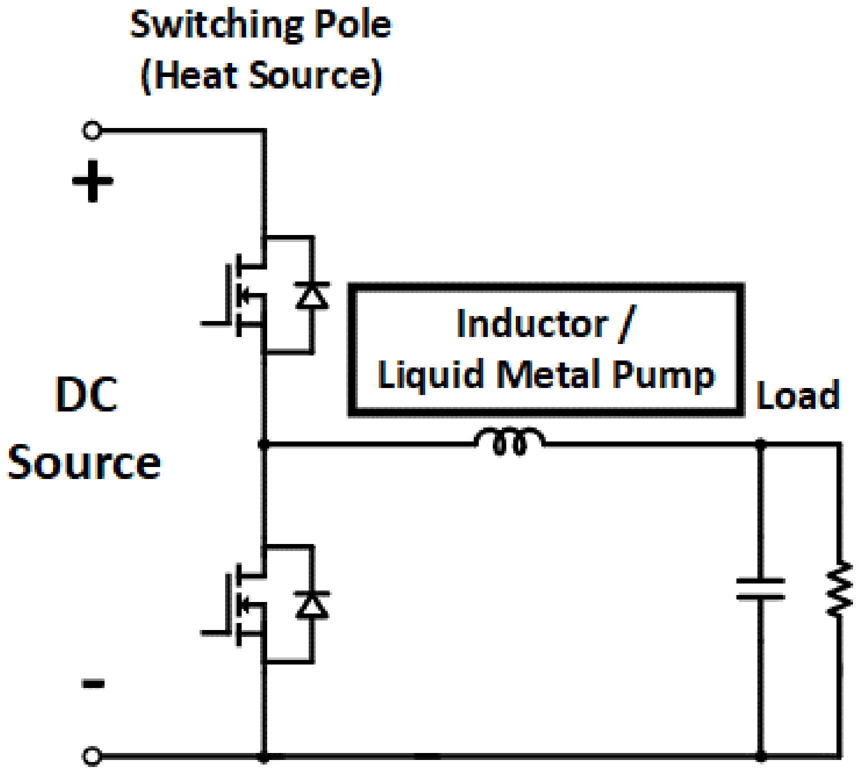
Both prototypes share the **same cold plate, radiator, and a 3-phase converter** as the heat source.

Parameter	Liquid Metal	Water
Converter Output Power	10.5 kW	
Estimated device T_J	54.0 °C	59.0 °C
Coolant flow rate	0.2 - 0.5 L/min	4.8 L/min
Measured P_{Pump} (W)	less than 0.1 W	8 W

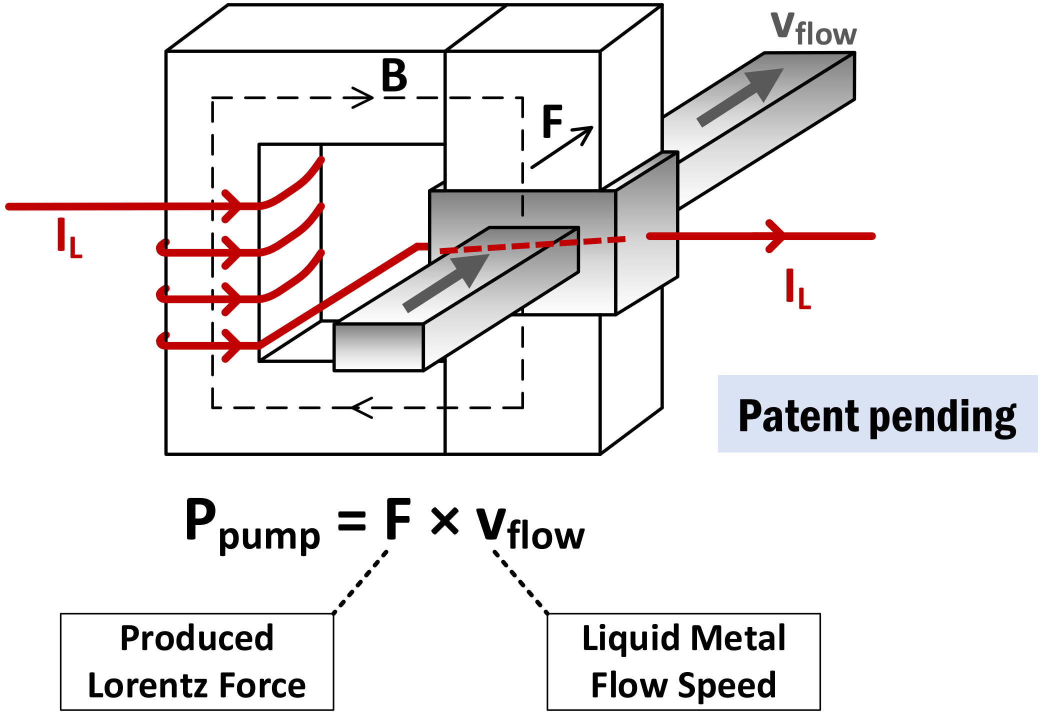


Converter (heat source) operation waveforms at 15 kHz f_{SW}

Inductor Integrated MHD Pump (i²MHD)



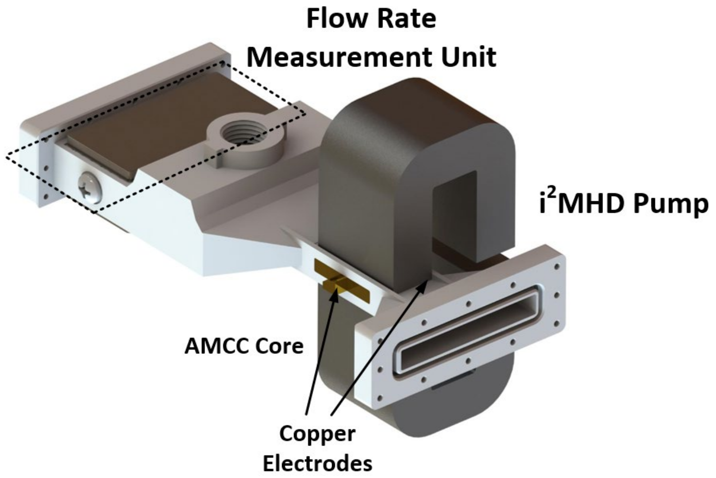
Buck converter circuit diagram

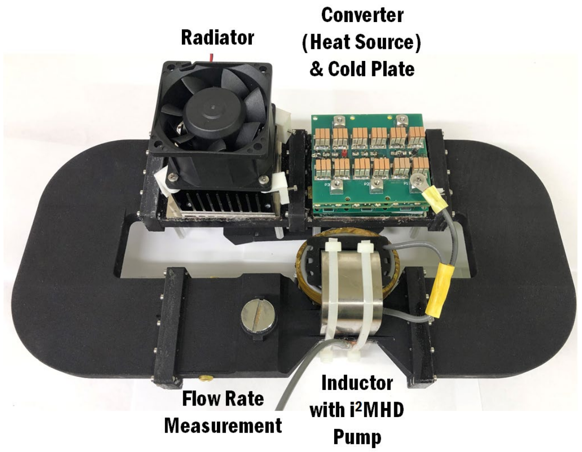


- Inductors are essential components of many power electronics circuits;
- By substituting the airgap of an inductor with liquid metal and connecting winding current to the liquid metal, an inductor integrated MHD pump (i²MHD) can be realized.

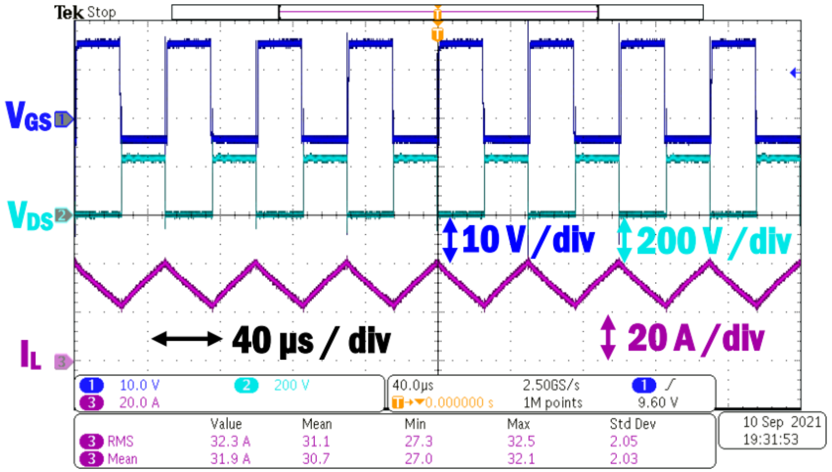
Idea formed during a project sponsored by the TRAC program.

Design Details of i^2MHD Pump

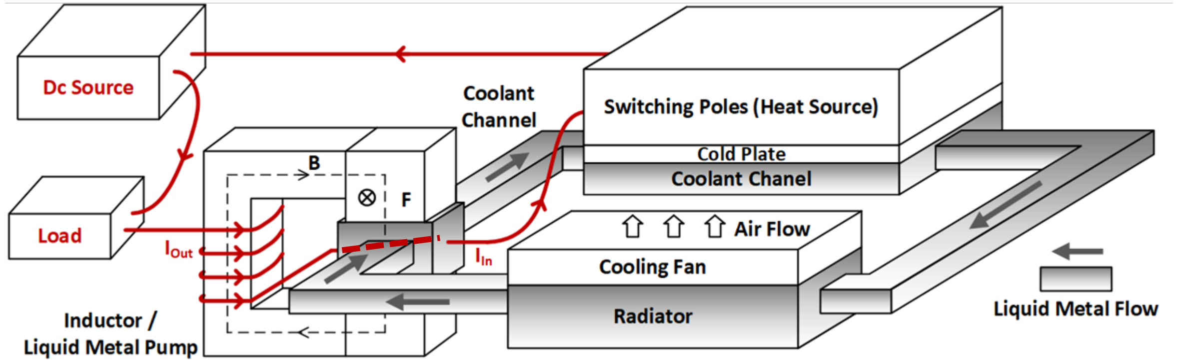




Cooling loop with i^2MHD pump

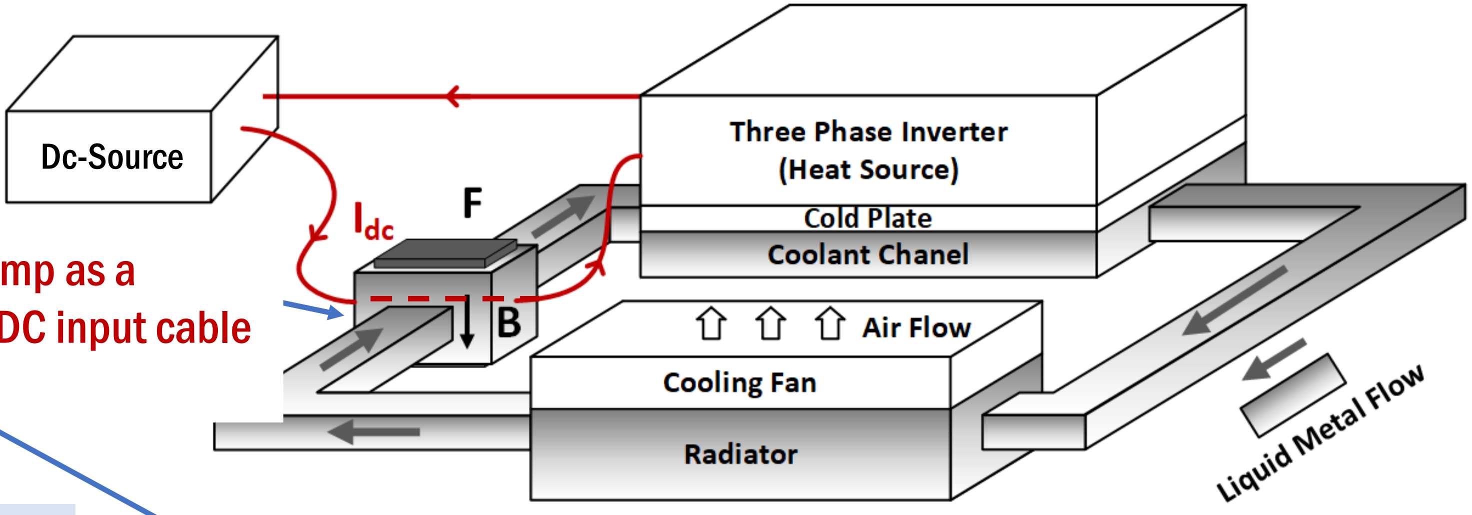


Inductor/ i^2MHD Pump operation waveforms at 20 kHz f_{SW}

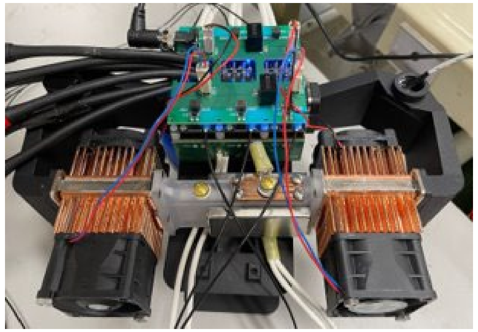


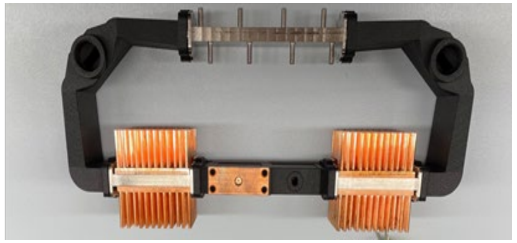
- The inductor not only functions as an essential component of the dc/dc converter but also as an MHD pump;
- No auxiliary power supply and permanent magnets are needed;
- The flow rate of liquid metal will be self adaptive to the load condition because the Lorentz force is generated by the inductor magnetic field and the winding current

Hybrid Integrated MHD Pump

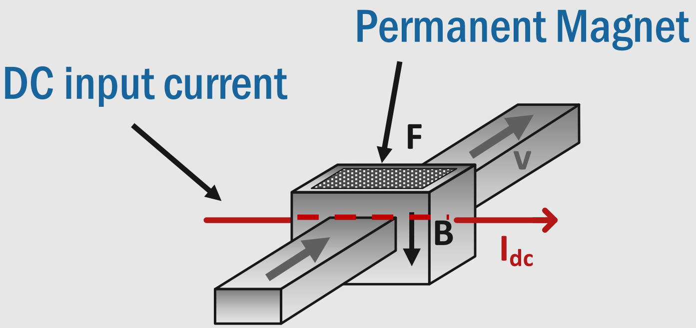


Liquid metal pump as a segment of the DC input cable or busbar





Patent pending



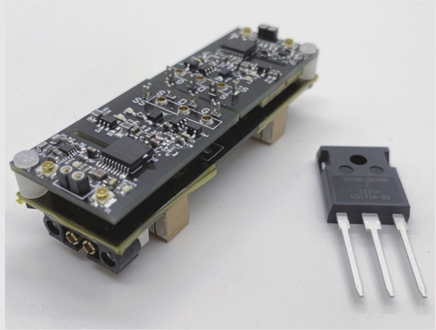
Liquid metal flow driven by Lorenz force

Flow rate is self-adaptive with the DC input current to the inverter

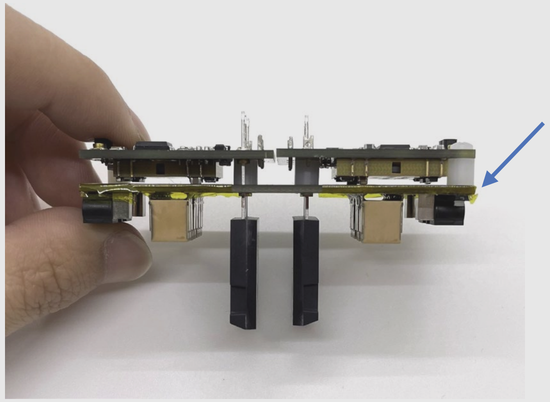
SiC Inverter with Hybrid MHD Pump

- Modular structure
- High common mode noise immunity
- Coolant system with ultra-low power consumption
- Coolant flow rate is self-adaptive to load power
- Fin-less cold plate with liquid metal as coolant
- Low acoustic noise

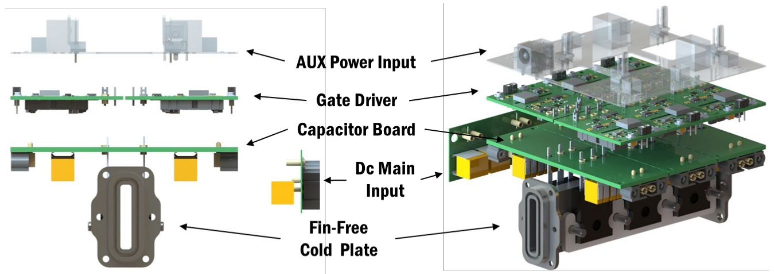
Measurements & Estimations	Value
Output Power	20 kVA
Measured T_{Case}	103.4 °C
Estimated P_{Loss}	41 W (Per Device)
Estimated T_J	132.1 °C (The Hottest One)
Measured $T_{Coolant}$	62.4 °C
Measured flow rate	0.55 L/min



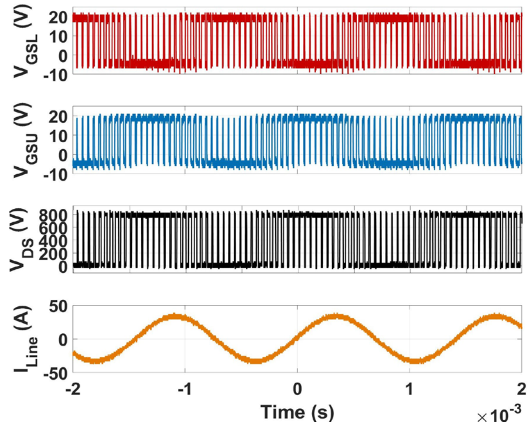
One Phase Leg



The top layer of the main power board serves as a shielding layer



Power Density: 120 kVA/L, calculated based on box volume



Operation Waveforms at 20 kVA (23.5 Arms)

Challenges and Remaining Questions

- High melting temperature (7 °C for the Gallium Indium Alloy that was used in OSU prototypes)
- High material cost
- Impact of magnetic field and current (ac and dc) to the characteristics of the liquid metal including viscosity, thermal conductivity, permeability, erosion (reaction with heatsink material), etc.
- Overall cost/benefit evaluation in terms of efficiency, response to heat load fluctuations, reliability, weight and size, acoustic noise, etc.
- What would be the impact to the thermal management and power electronics in general if LK-99 if fully validated?

Thank you for your attention!

Questions?

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