Stony Brook University | Spellman High Voltage Power Electronics Laboratory

Challenges and Potential Solutions for Future Electric Aircraft : from an Academic Point of View

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IEEE L.I.

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A Glance at Spellman HV PE Lab

PI: Fang Luo (Empire Innovation Associate Professor), Ph.D. Student:16, M.S. Students: 3, Undergraduate Students:2

Research Area: High Performance Power Electronics Converter and Systems

Recent Projects:

1. High density power/High efficiency/High Power converters
2. Power Module packaging
3. Converter System Control and lifetime management
4. Ocean Energy and Offshore Wind Energy Systems
5. Electric ground and air vehicles
6. HV Insulation and degradation modeling/testing
7. Microgrid for multi-source/energy storage renewable energy integration

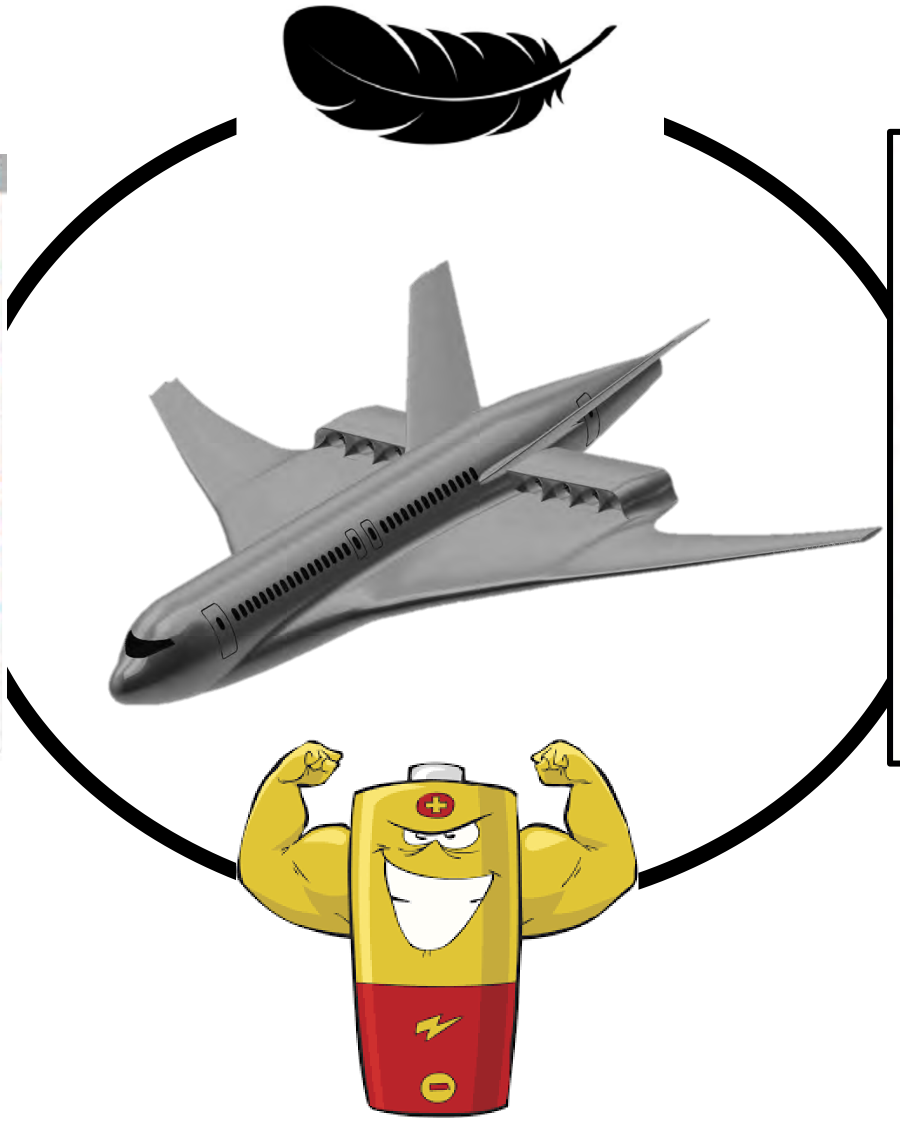
High Performance WBG Modules

High Density Grid Tied Solar Converter (SiC)

Modular Grid-tied Converter for Grid Control (SiC)

Grid-Integration Control

How can I fly it?



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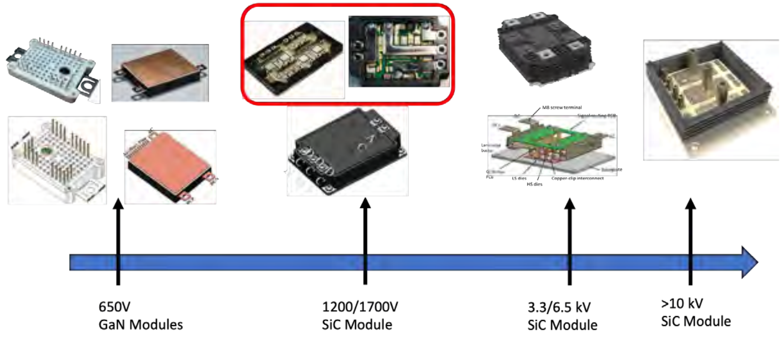
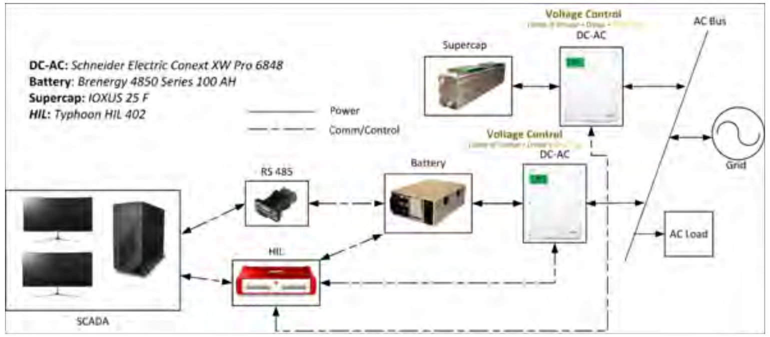
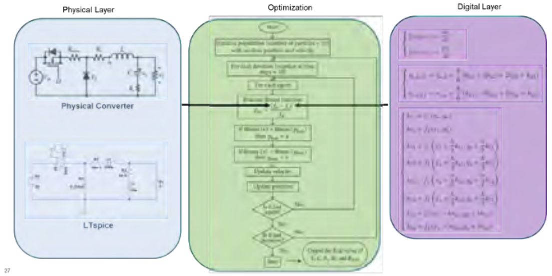
Enabling Technologies

Power Module Packaging





Flying Microgrid Control



Realtime Digital Twin for Prognostic and Diagnostic

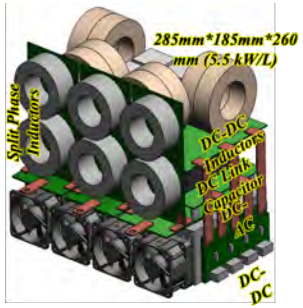
Lifetime Management

1st Order Problem

2nd Order Problem

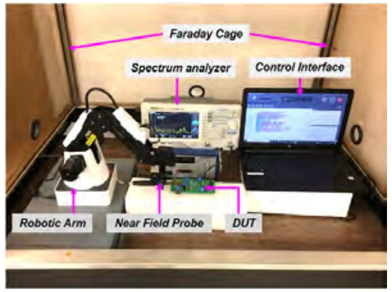
Cryogenic High Density Motor Drive (GaN)

High Density Grid Tied Solar Converter (SiC)

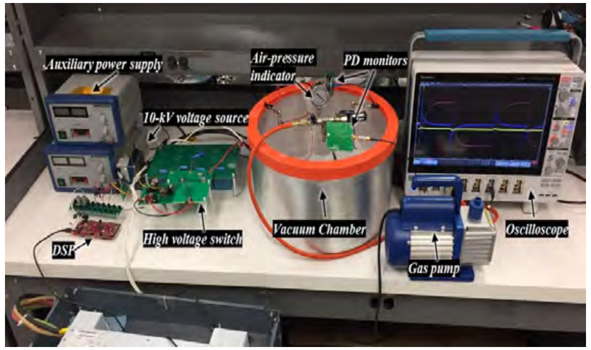


Modular Grid-tied Converter for Grid Control (SiC)

High Performance Power Converters



EMI and Reflected Wave in Flying Microgrid/ Active Filtering

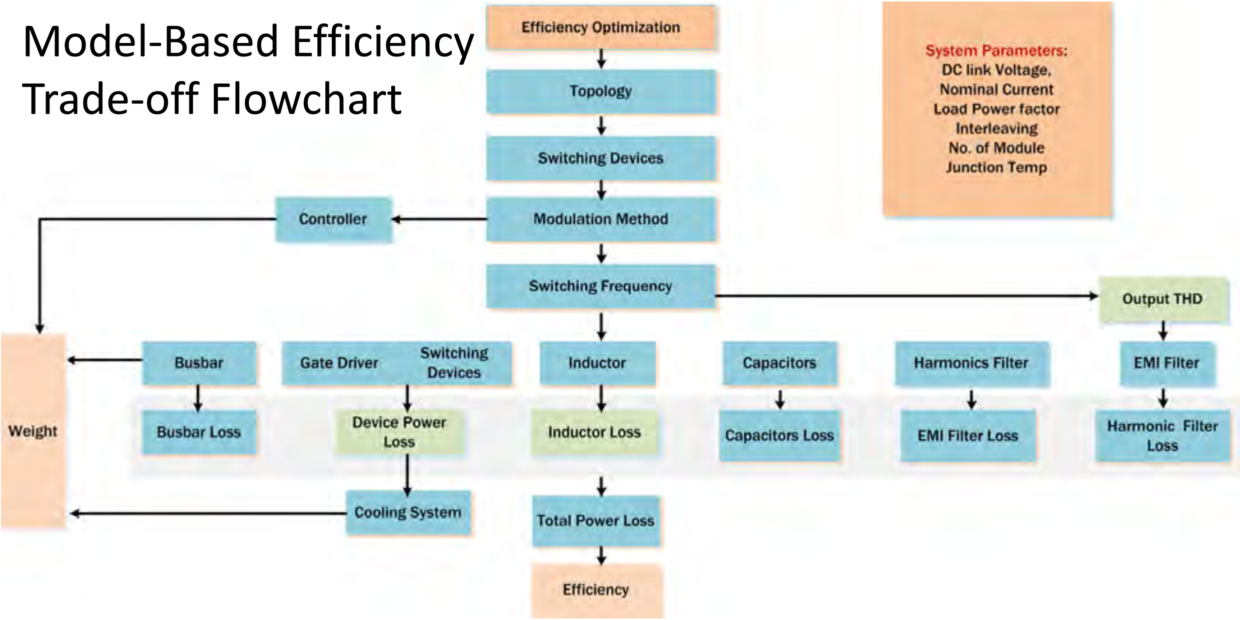


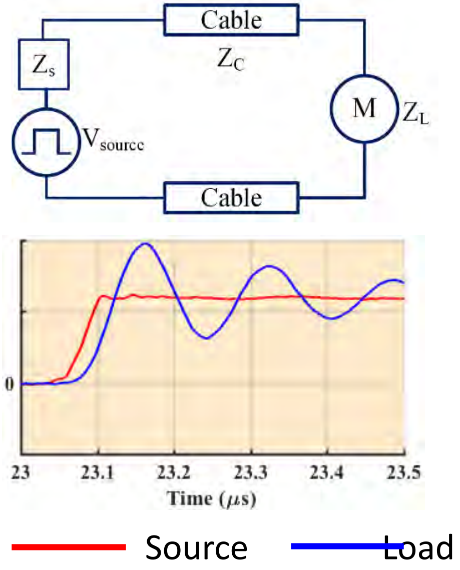
High Attitude Partial Discharge Testing and Modeling

PD/EMI

Multidisciplinary Co-Design Tool

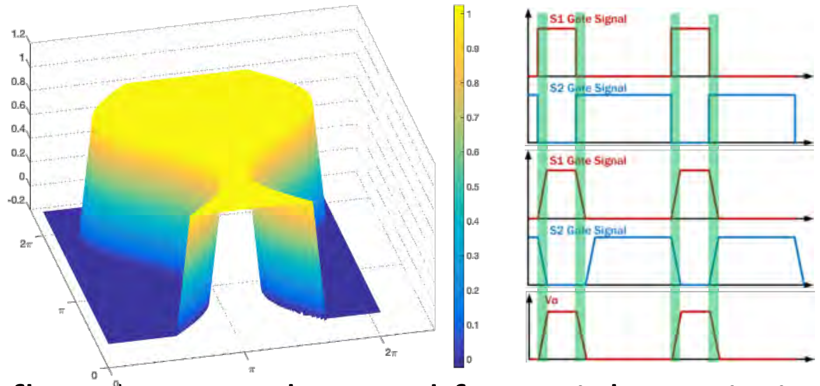
Model-Based Efficiency Trade-off Flowchart

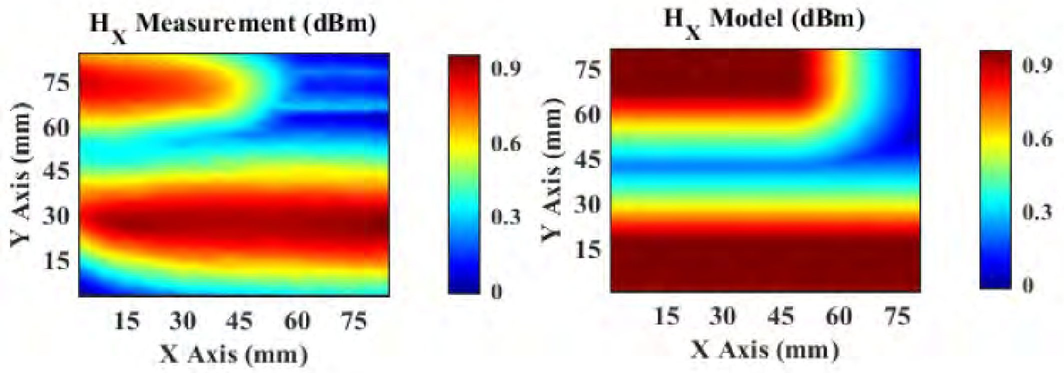




EMI and Reflected Wave Filter Calculator

Math Tool: Improved Double Fourier Integral

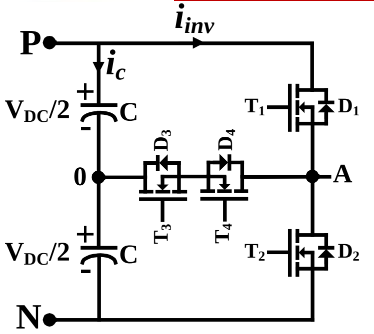




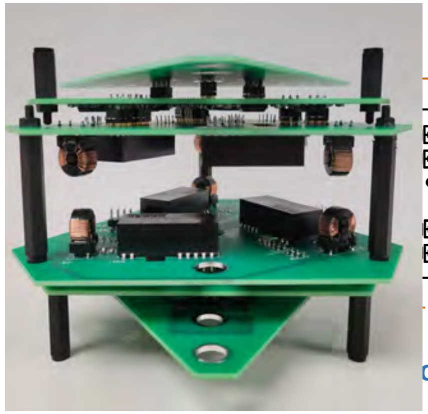
Same flowchart can be used for weight optimization

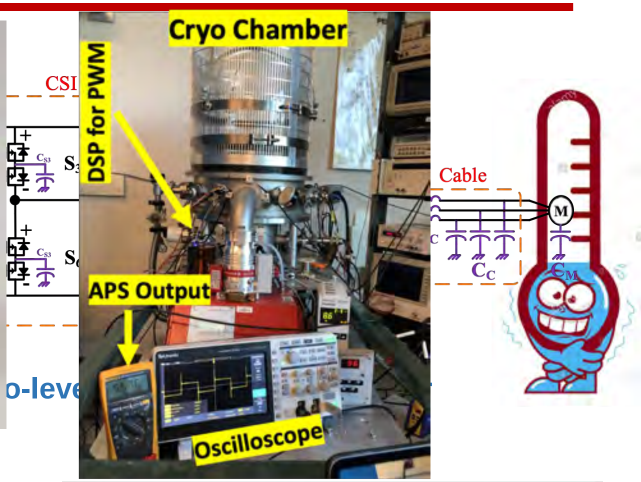
Nearfield Calculator

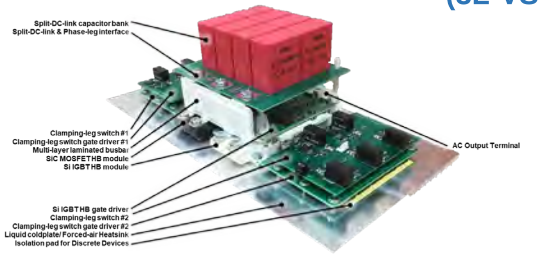
Converter Development



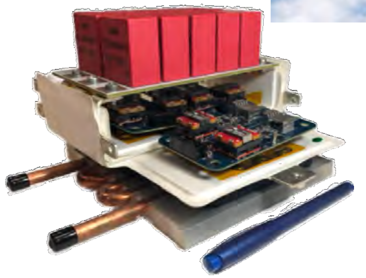
Three Level Voltage Source Inverter (3L-VSI)



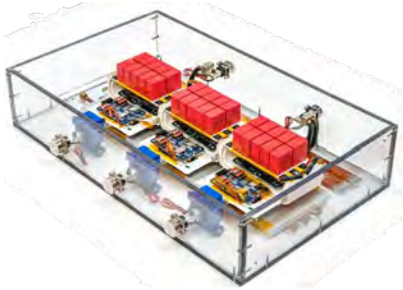


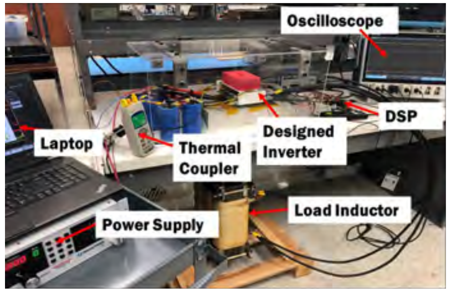


Gen 1: Si IGBT- SiC MOSFET Hybrid 100 kW PEBB, 98.6%, 27.7 kW/kg

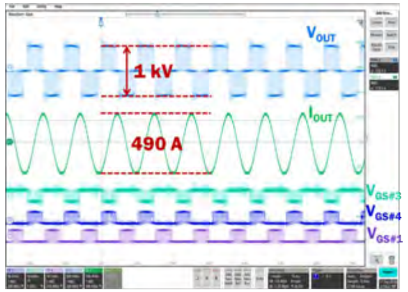


Gen 2: SiC MOSFET 150 kW PEBB, 99.4%, 34 kW/kg



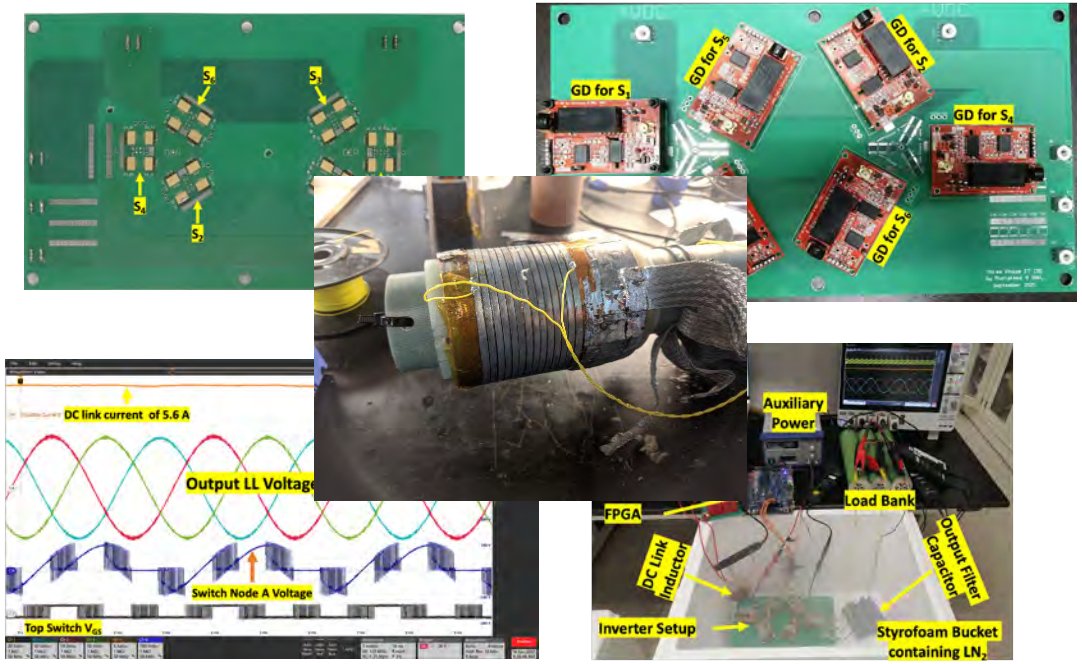


Continuous test setup



Captured Waveform

- *Continuous test at 64.5 kVA, V_{DClink} =1 kV, f_{sw} = 30 kHz*
- *Measured efficiency of 99.45%*



20 kW, 99% efficiency

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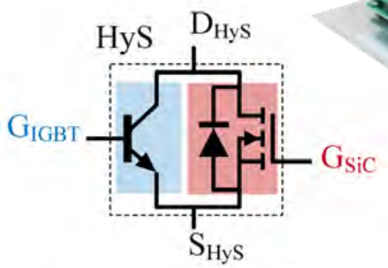
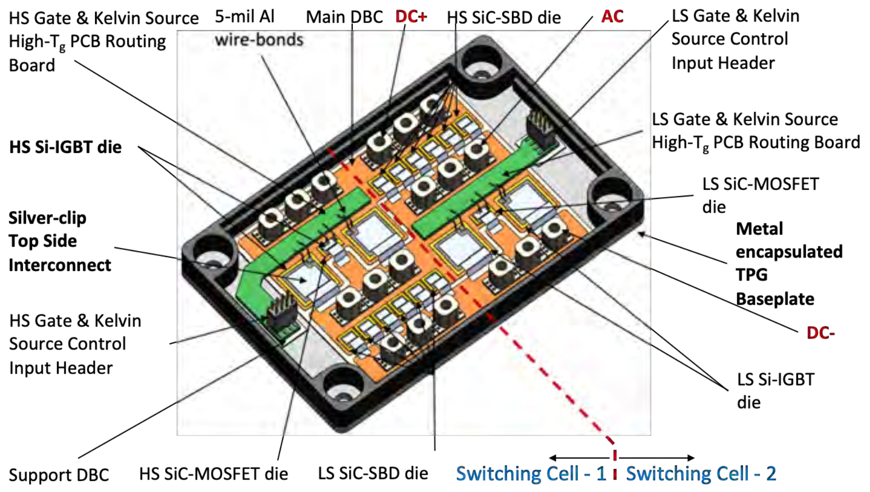
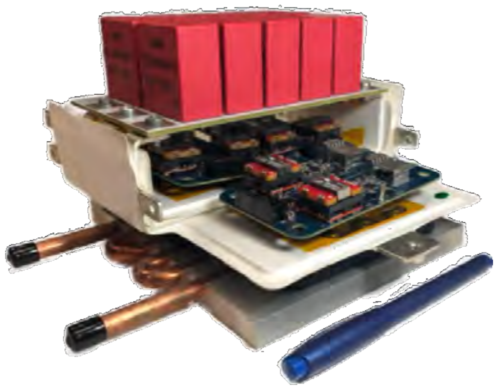
Shrinking the Size: Power Module Development



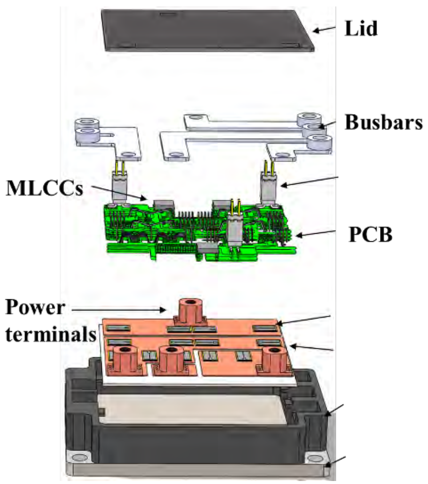
High-current rated Si IGBT
Low-current rated SiC MOSFET



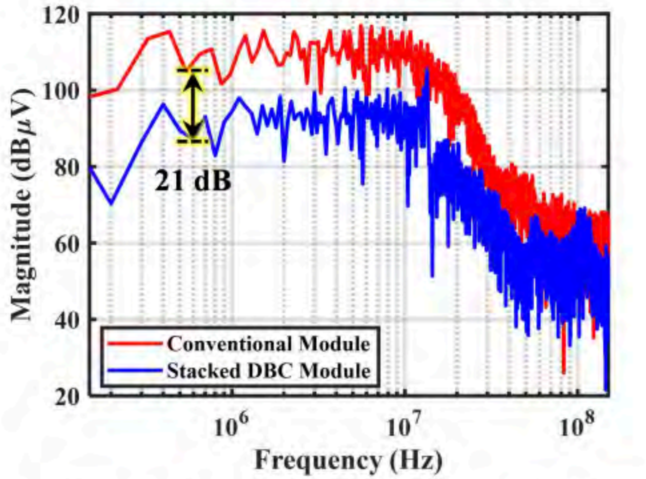
1200V / 350 A HyS TPG Enhanced Thermal Management



3L-TNPC



1200V / 450 A



d) Comparison of CM noise in frequency domain

1200V / 150 A

2022-11-09

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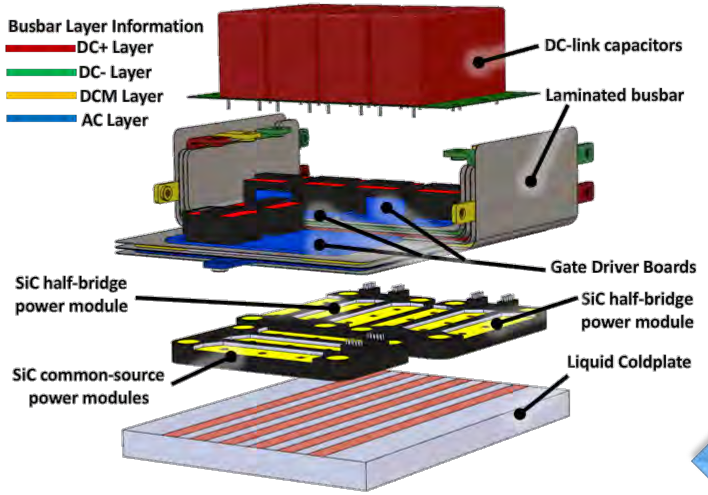
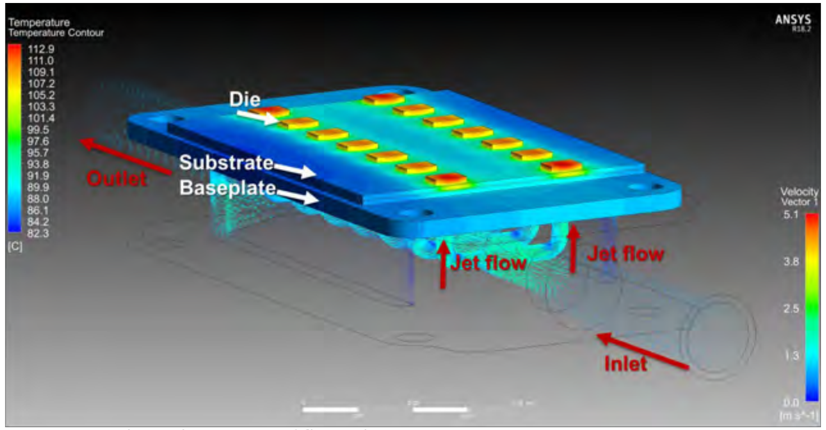
Thermal-Mechanical-Electrical Co-designed Solution



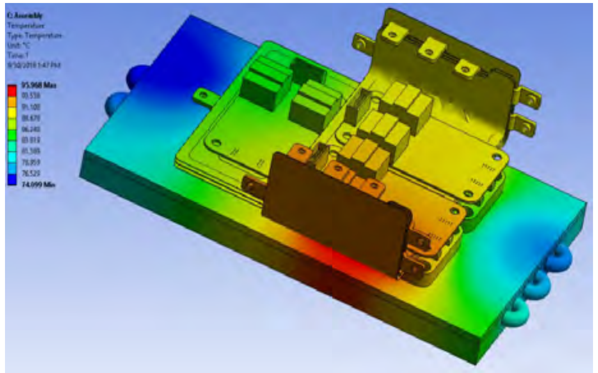
Traditional

Advanced



Thermal mapping and flow velocity mapping, 1.5 GPM @ 70°C

3D Printed Non-metallic coldplate



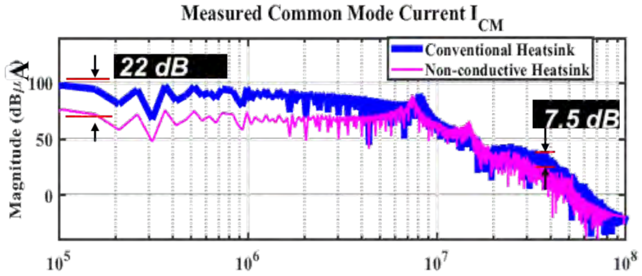
Temperature distribution, 150 kW, 1 GPM @ 70 °C

Gate Driver

Module

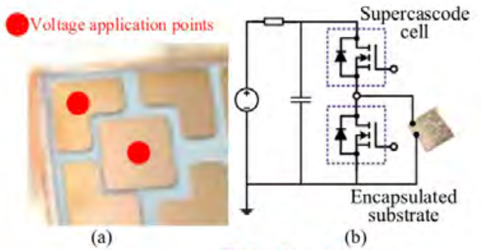
Jet Impingement Cooling System

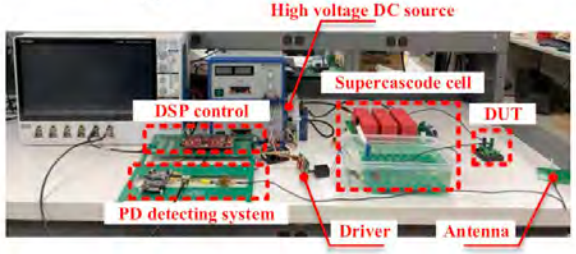
Test Setup ($R_{G,ON}$ = 5 Ω, $R_{G,OFF}$ = 2.5 Ω)

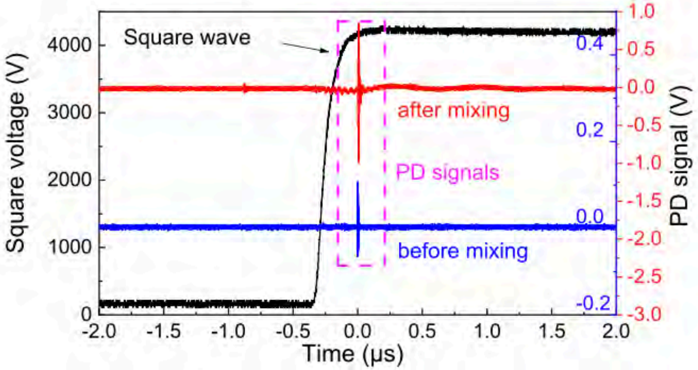


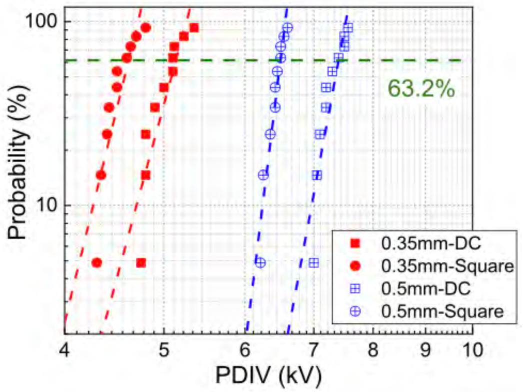
Optimized Jet-Impingement coldplate
3D Printed with non-metallic material for EMI optimization
Busbar is optimized for thermal/stray inductance/ stray capacitance

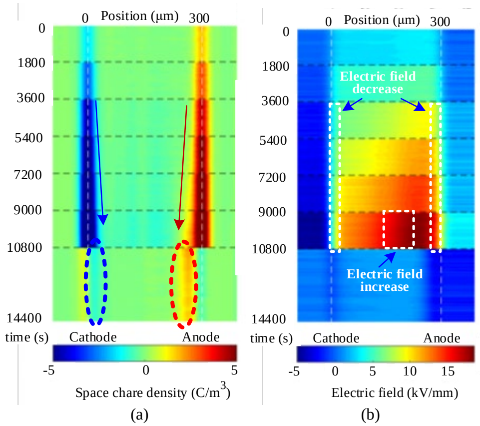
HV PWM Waveform Testing on Power Module Substrate





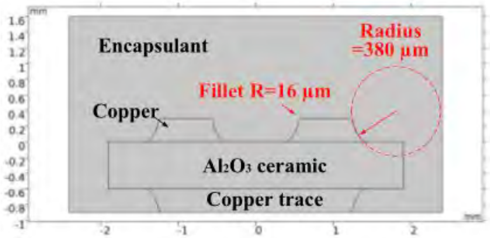


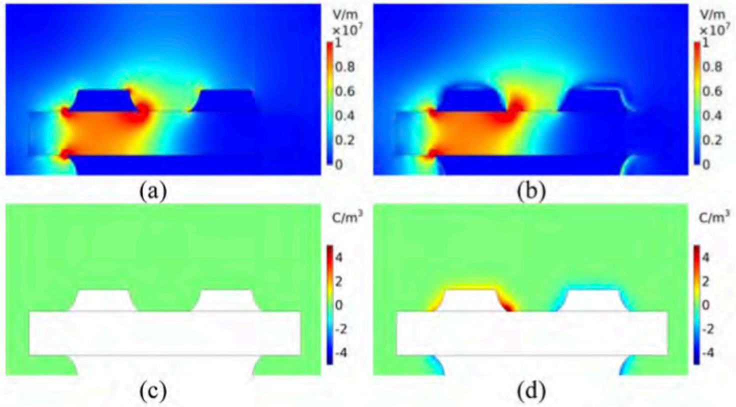




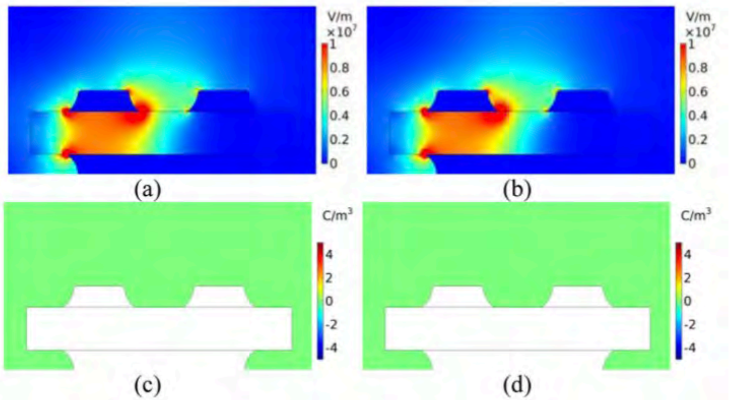
Space Charge

E-field





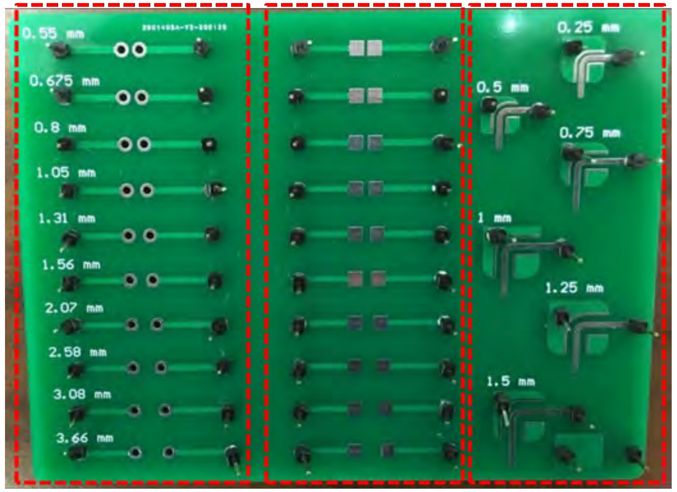
Space-charge simulation results under dc voltage. (a) Electric field distribution at 1 s. (b) Electric field distribution at 1800 s. (c) Space-charge distribution at 1 s. (d) Space-charge distribution at 1800 s.



Space-charge simulation results under dc voltage. (a) Electric field distribution at 1 s. (b) Electric field distribution at 1800 s. (c) Space-charge distribution at 1 s. (d) Space-charge distribution at 1800 s.

- PWM wave will influence space charge distribution in insulator
- Change of space charge will influence E-field distribution

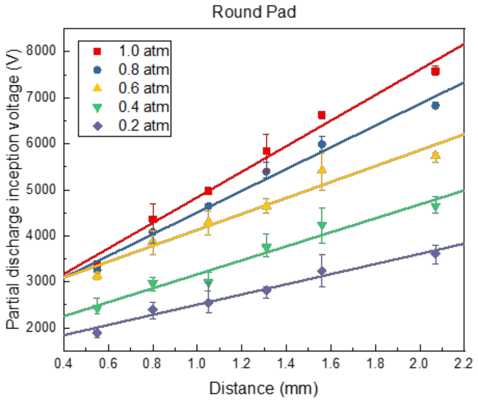
PCB Under DC Excitation at Different Pressure

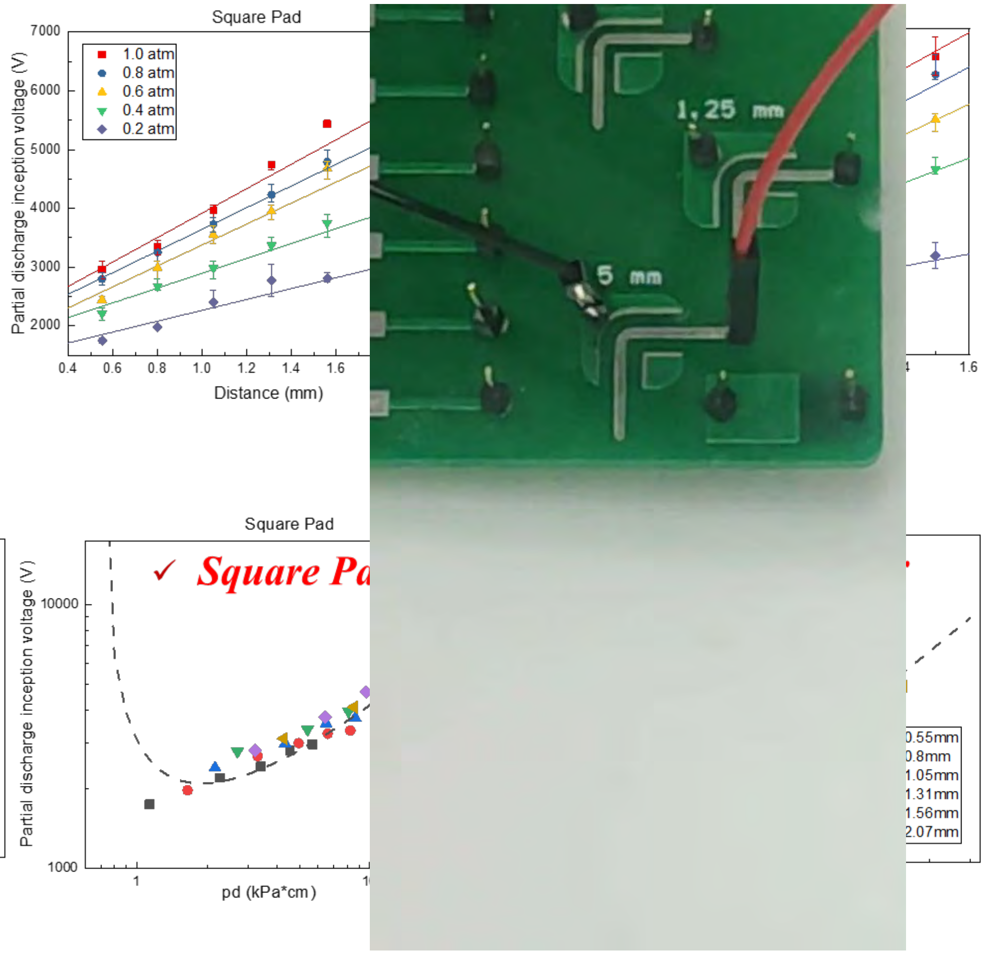


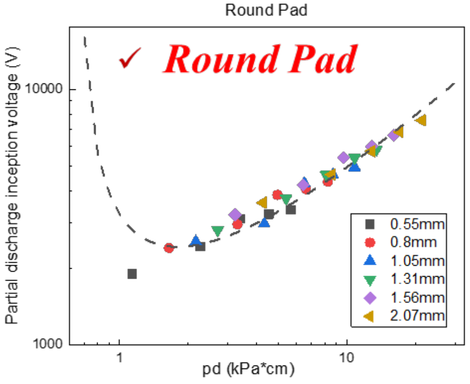
✓ *Round Pad* ✓ *Square Pad* ✓ *Trace Corner*

- ✓ Maximum creepage is ~2 mm
- ✓ PDIV: round pad > square pad > trace corner
- ✓ PDIV linearly increases with creepage at the same pressure
- ✓ The creepage range is not wide enough to see the saturation phenomenon, but the PDIV of round pad with 2 mm creepage is ~7500 V under DC voltage

✓ *Round Pad* ✓ *Square Pad* ✓ *Trace Corner*



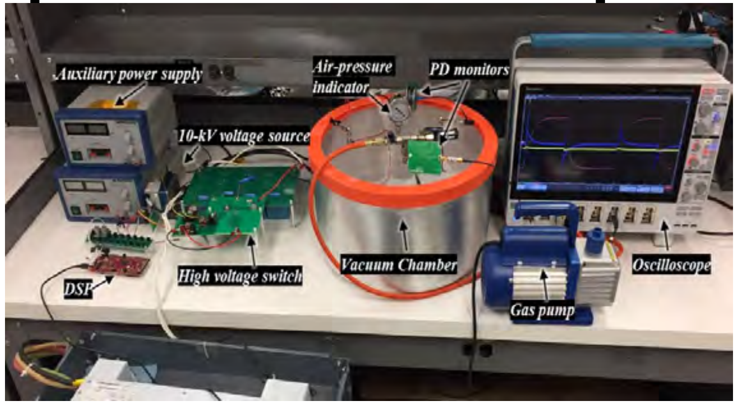




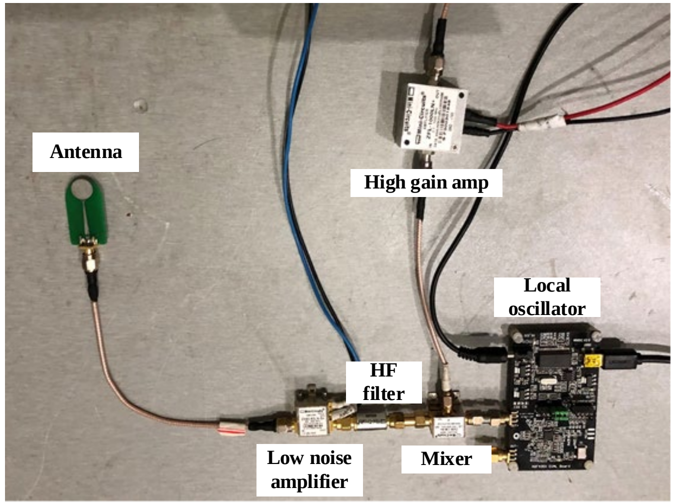
Partial Discharge Measurement & Modeling

➢ Partial discharge under DC and square wave at low pressure

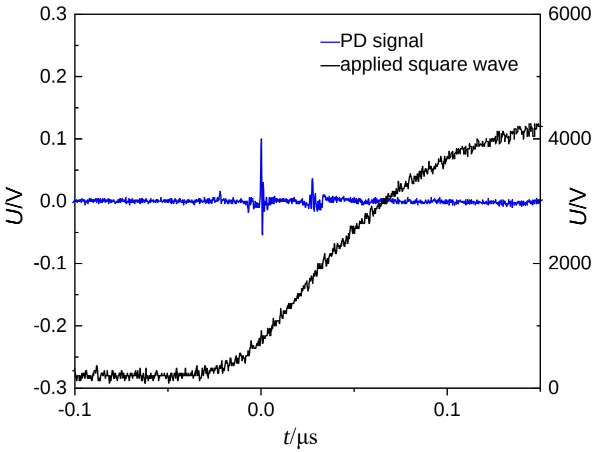
- ✓ High voltage source: AC, DC & square wave
- ✓ Vacuum system: chamber & pump
- ✓ PD measurement: UHF (suitable for AC, DC) or SHF (AC, DC, and square wave)
- ✓ Specimen: surface and void defect (busbar, PCB, and substrate)



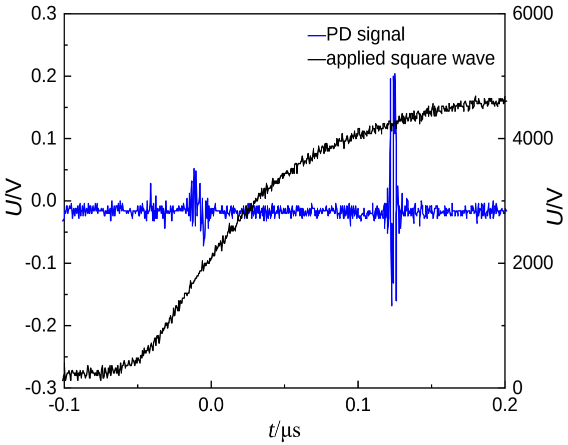
PD measurement testbench



SHF down-mixing measurement system

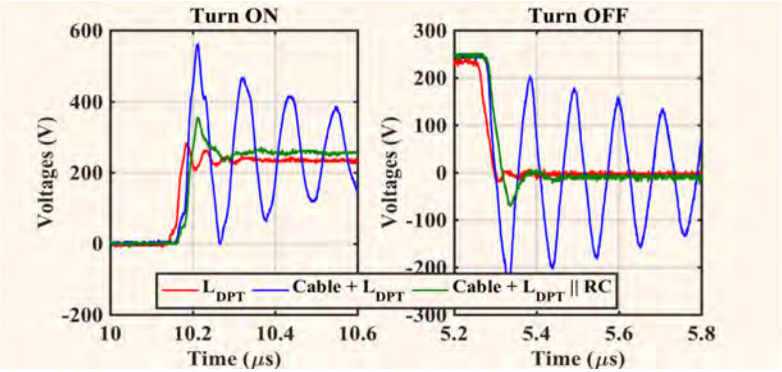


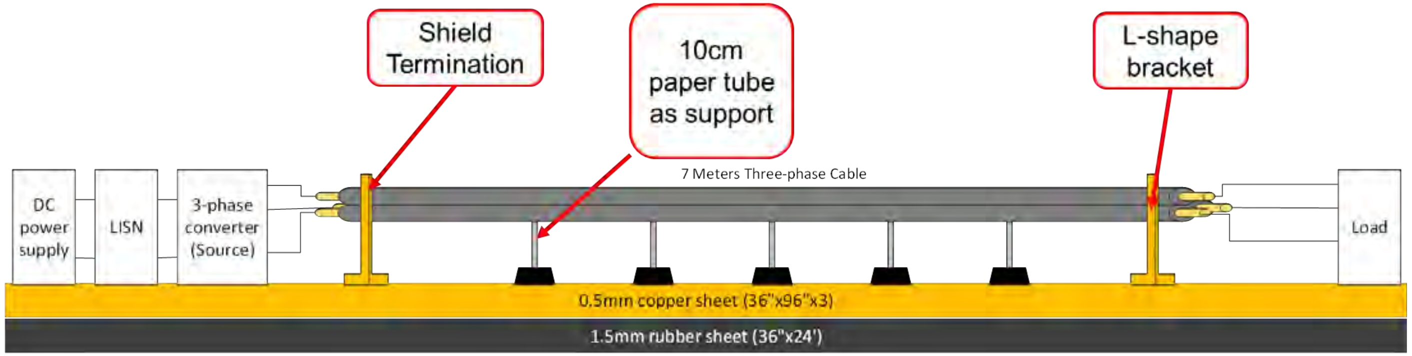
PD signal of silicone elastomer



PD signal of epoxy resin

EMI and Reflected Wave



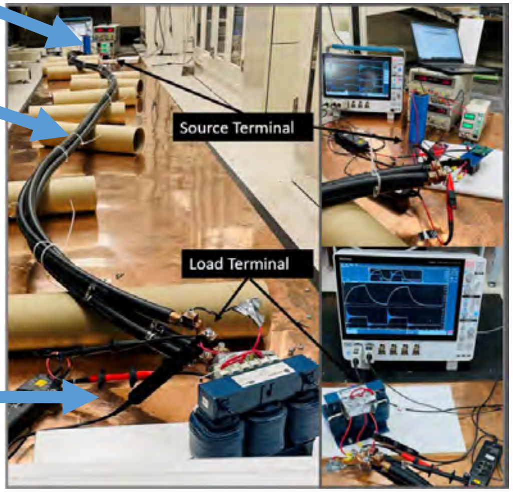


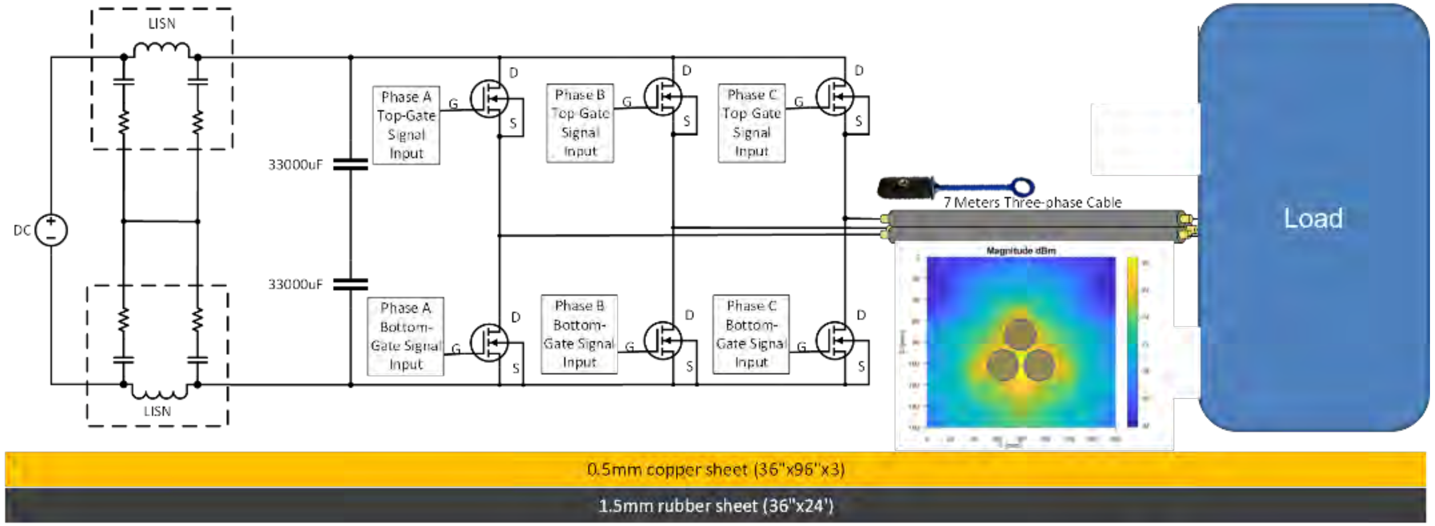
Conducted/Radiated EMI Testing

SiC Converter

Cable

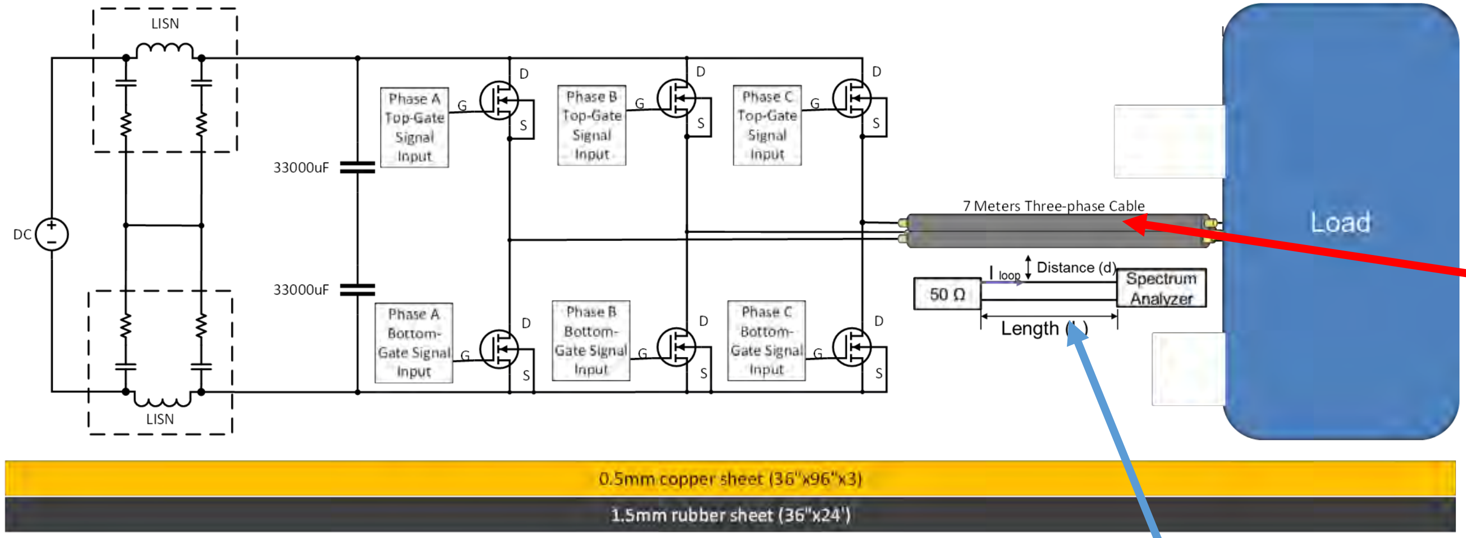
Load

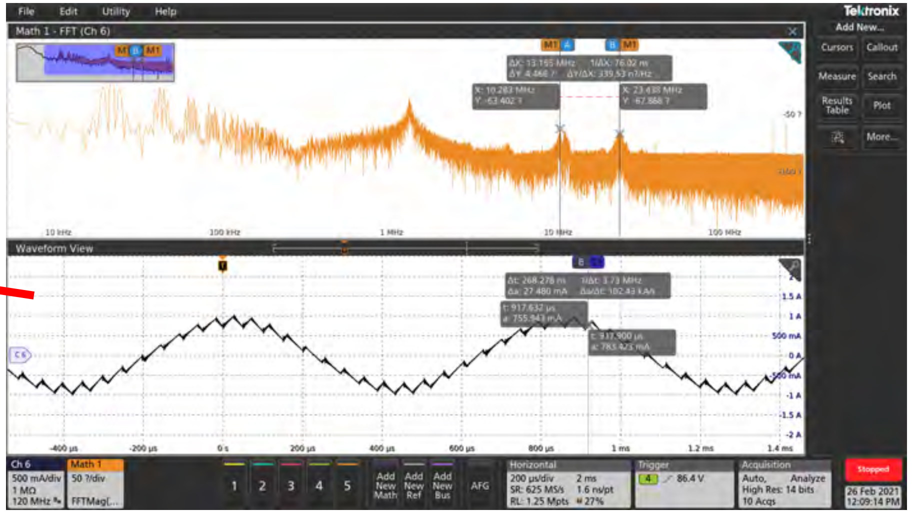




Nearfield EMI Testing

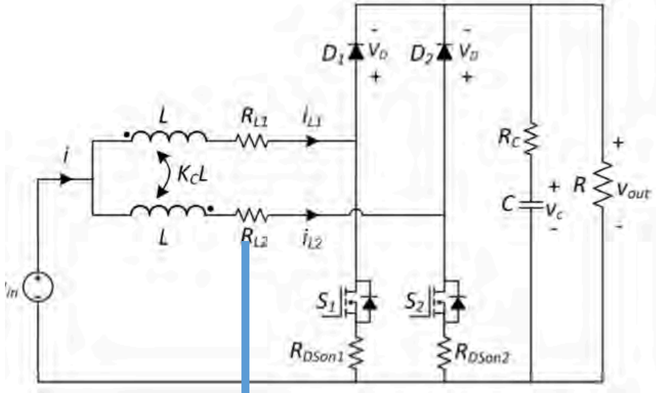
Modified Induced Noise Testing

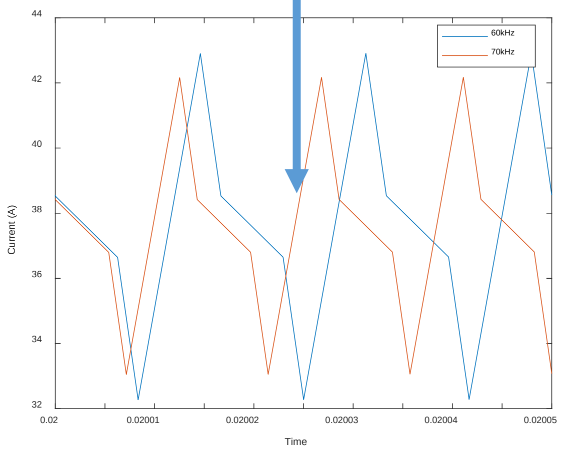


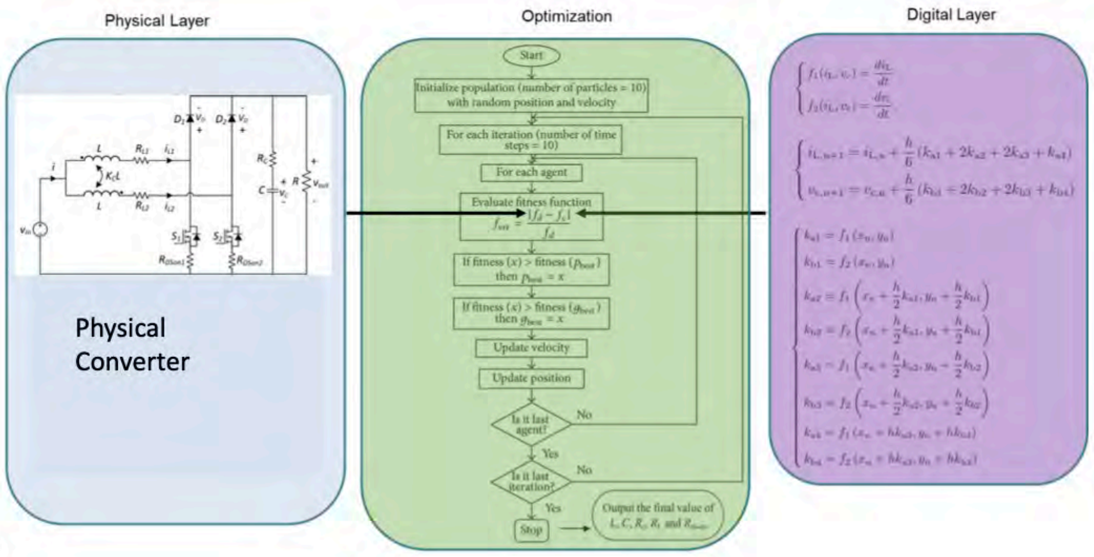


- Power current induced noise can cause damage to signal circuit
- Coupling coefficient is determined by signal loop size, orientation and grounding
- Improved super-positioning in the cabling system

Lifetime Management: Realtime Digital Twin



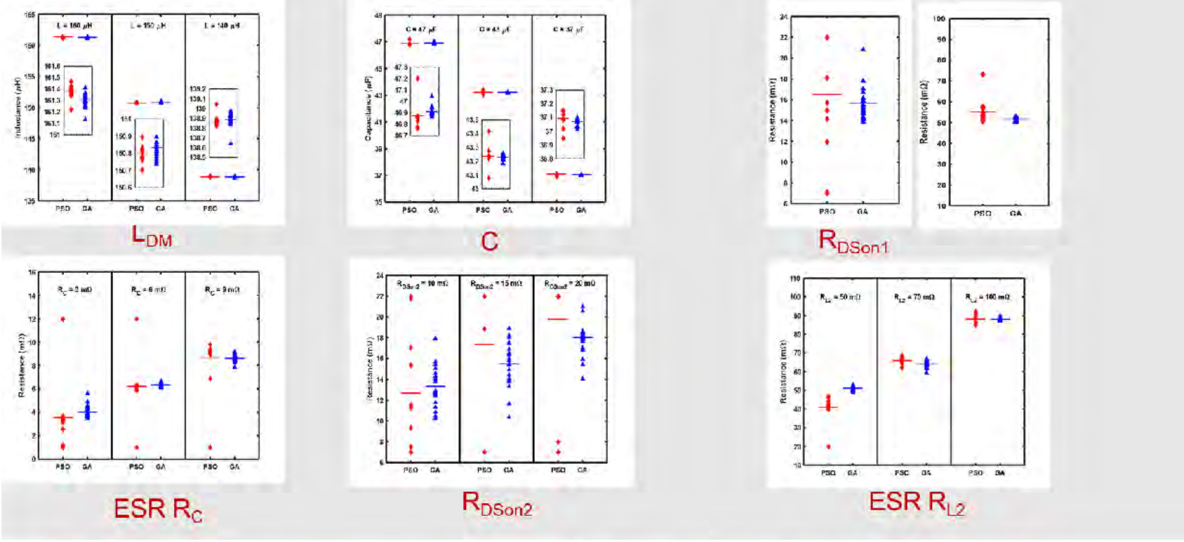




- Converter component parameters can be calculated through the HF slopes in I/O voltage/current
- By estimating the component values, the converter's health condition and its lifetime can be estimated

Self-evolving Realtime Digital Twin at SBU

1. Differential Inductance: L_{DM}
2. Inductors channel resistances: R_{L1} and R_{L2}
3. Switches on Resistances: R_{DSon1} and R_{DSon2}
4. Output Capacitor: C_{out}
5. Capacitor ESR: R_C



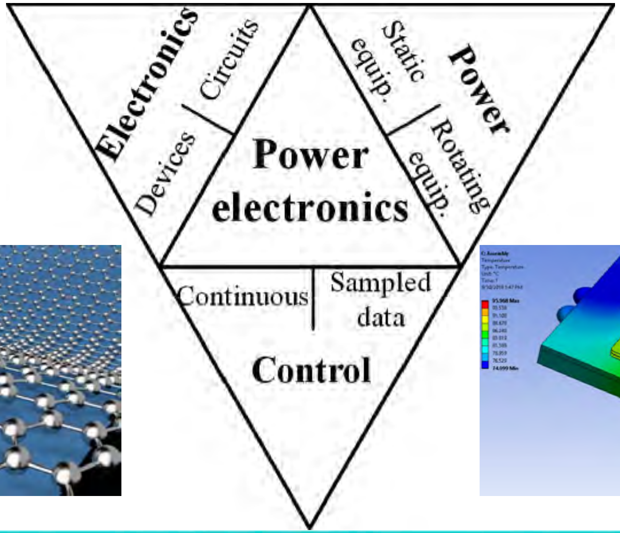
$$\frac{di_{L_1}}{dt} = f_1(i_{L_1}, i_{L_2}, v_c)$$
$$\frac{di_{L_2}}{dt} = f_2(i_{L_1}, i_{L_2}, v_c)$$
$$\frac{dv_c}{dt} = f_c(i_{L_1}, i_{L_2}, v_c)$$

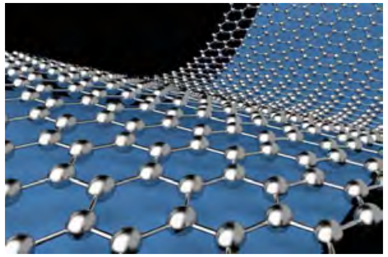
$$i_{L_1}^{n+1} = i_{L_1}^{n} + \frac{h}{6}(k_{a1} + 2k_{a2} + 2k_{a3} + k_{a4})$$
$$i_{L_2}^{n+1} = i_{L_2}^{n} + \frac{h}{6}(k_{b1} + 2k_{b2} + 2k_{b3} + k_{b4})$$
$$v_c^{n+1} = v_c^{n} + \frac{h}{6}(k_{c1} + 2k_{c2} + 2k_{c3} + k_{c4})$$

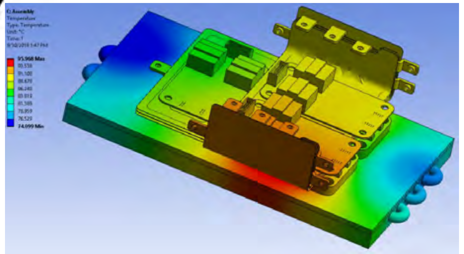
h: time step

Plots compares the parameters estimated for 20 executions with mean value (bar)

What do we need: from a Professor’s Point of view







- Enhanced power engineering courses are in strong demand
- Improved lab sessions are needed
- Interdisciplinary research and education efforts: “learn from the legacy”
- Advanced engineering math tools are needed to address multidisciplinary modeling problem
- No problem is “someone else’s problem”

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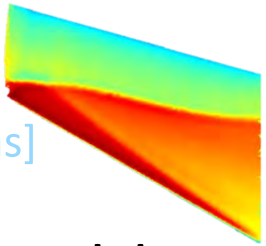
Discussion

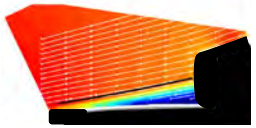
NASA ULI- Cryogenic Power Conversion



[James] [Das]
[Ranjan]

Aero-structural-thermal design optimization

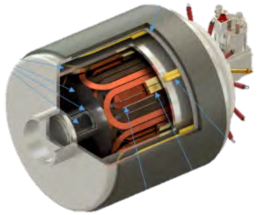
[Greitzer] [Hall]
[Ansell] [Lauer]



Integrated aero-propulsive system

[Falcone]
[Atreya]

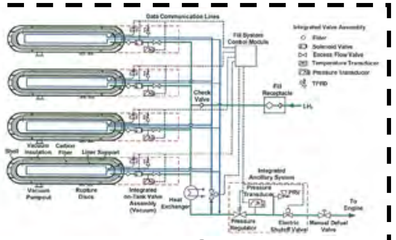
Power system integration



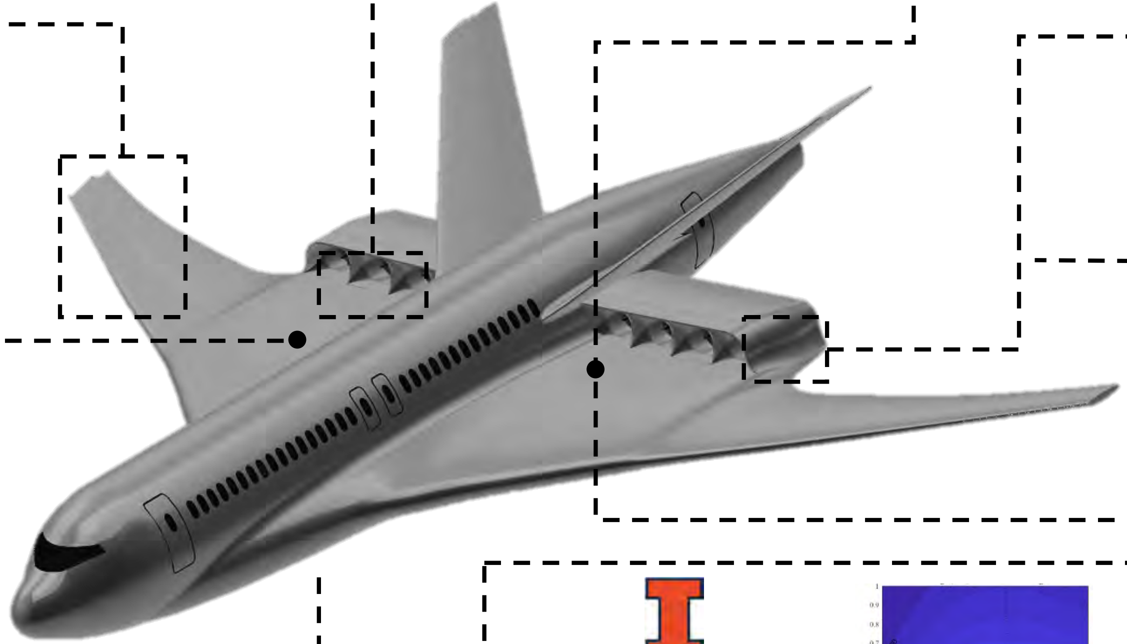
[Haran]
[Banerjee]

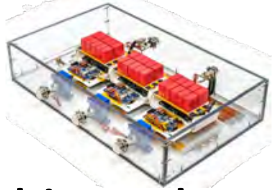
Superconducting machine design and quench dynamics

[Stautner]



Cryogenic energy systems





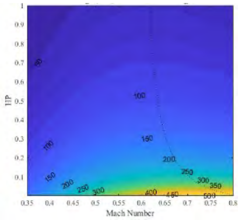
[Mantooth] [Luo]

Cryogenic motor drive and cryo-cooled electronics

[Vanfretti]
[Nademi]
[Podlaski]

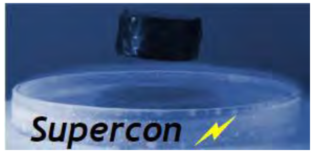
Multi-domain aircraft system modeling

[Merret] [Ansell]
[Waddington]



Aircraft sizing and performance

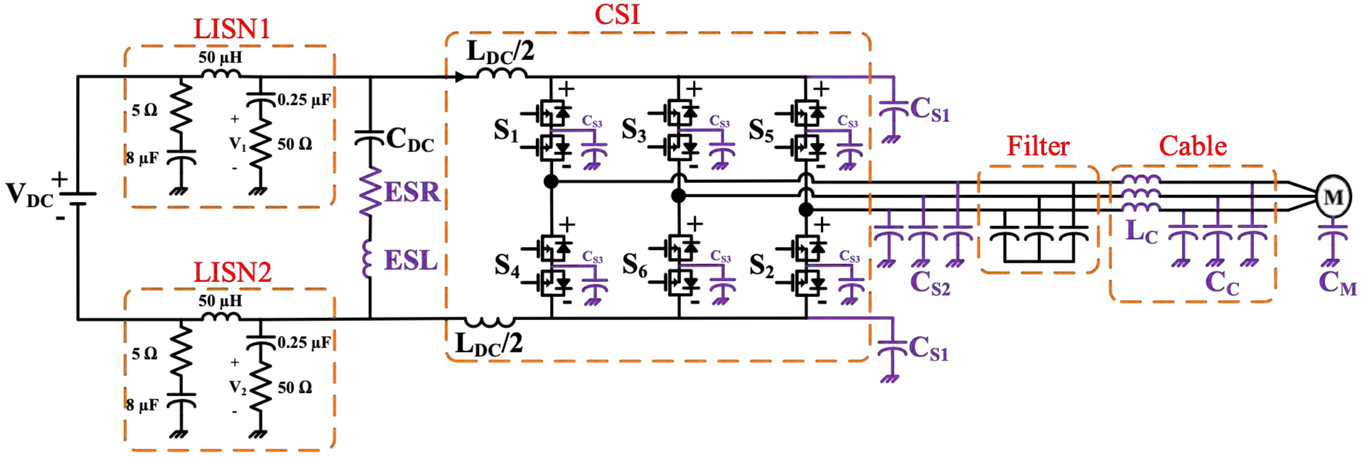
[Sumption] [Haugan]
[Tsao] [Sebastian]

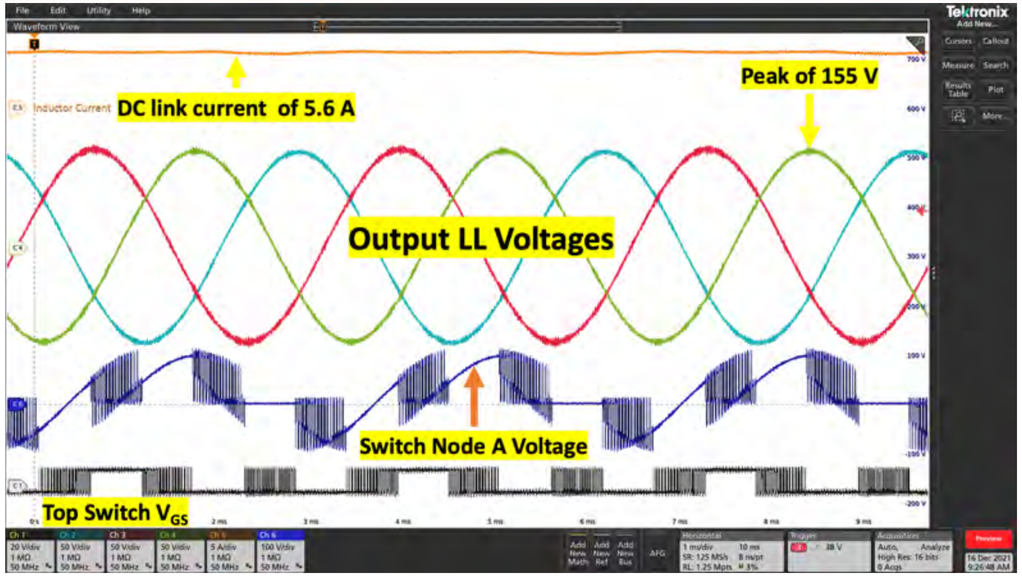


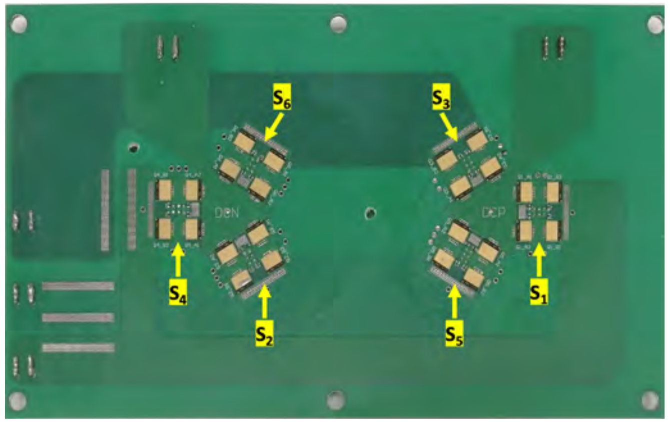
Superconducting materials

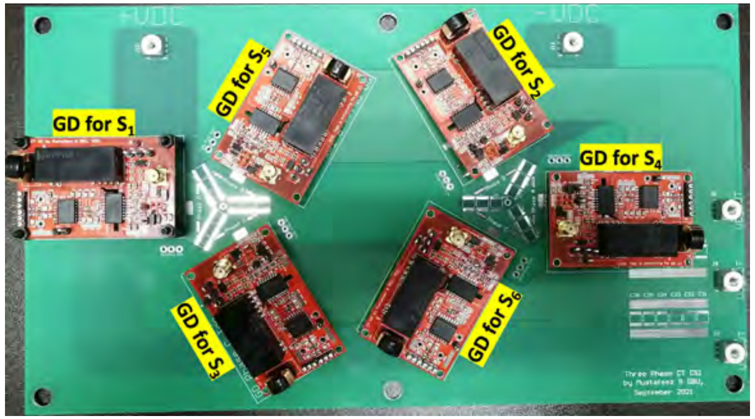
Stony Brook University

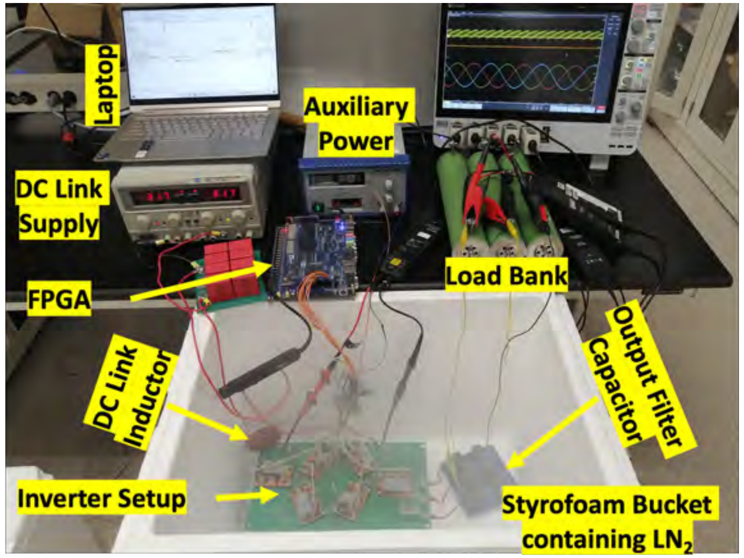
Cryo-Cooled Motor Drive







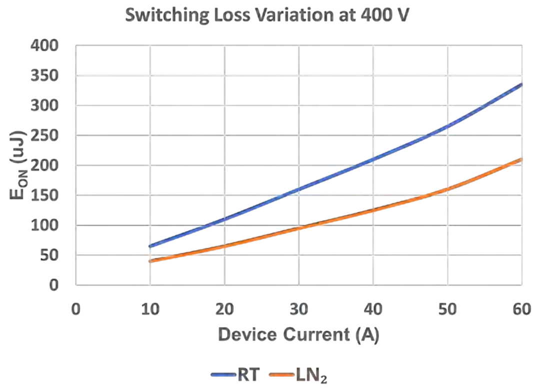


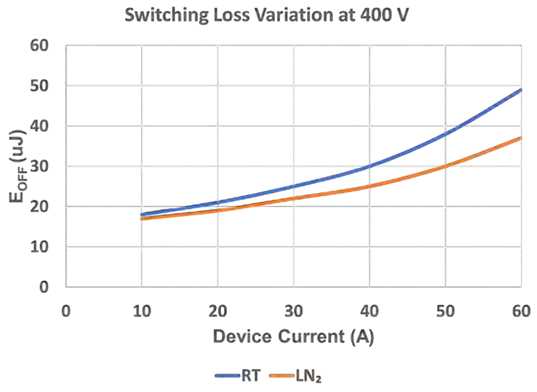


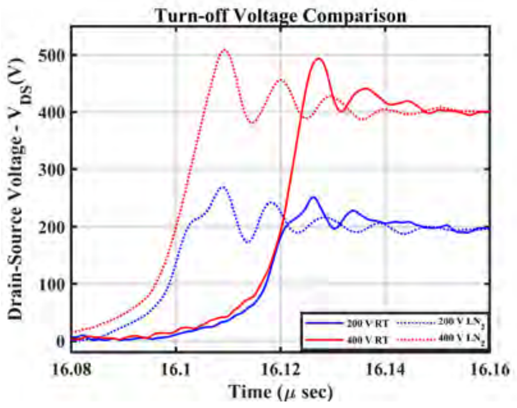
Stony Brook University

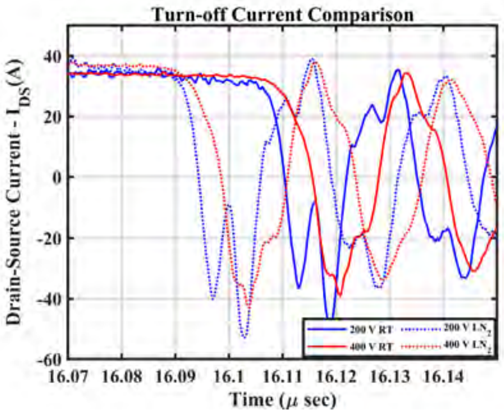
Device and Components at Cryo-Temperature

650 V GaN Device Testing

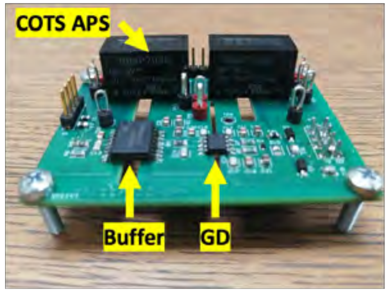


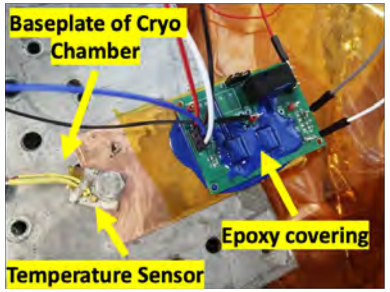


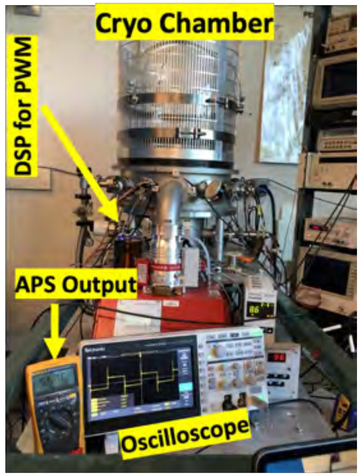




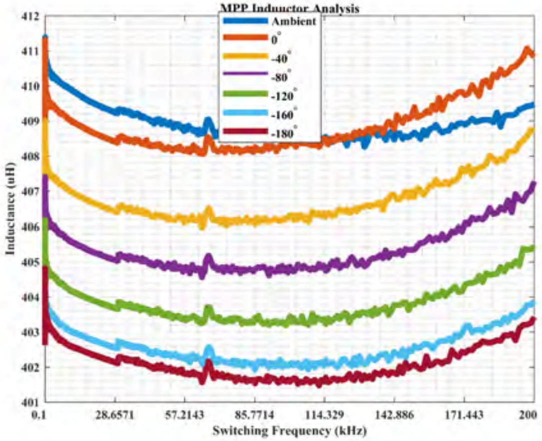
Gate Drive Testing







MPP Inductor Testing



Cryogenic Air Core Inductor