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2017
JULY 9-13
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Cryogenic Power Electronics for Superconducting Power Systems

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CREATING THE NEXT

MOTIVATION

- Superconducting power devices are expected to **increase the power density** for applications such as all-electric ships and airplanes.
- Propulsion motors, generators, and power cables operate at **cryogenic temperature**.
- Power electronic devices at room temperature lead to substantial **heat flux into the cryogenic system**.
  - There is renewed interest to investigate power electronic devices that operate at cryogenic temperature.
  - The cryogenic environment is challenging since it impacts material properties.


EADS VoltAir, eCO2avia


Airbus eConcept airliner


NASA N3-X


DDG-1000

RESEARCH PROJECTS (PARTIAL LIST)

NASA Glenn Research Center: **Low-Temperature Power Electronics Program**

Patterson, Richard L., John E. Dickman, Ahmad Hammoud, and Scott Gerber. "Low-Temperature Power Electronics Program," January 1, 1997. http://ntrs.nasa.gov/search.jsp?R=19980237413.

Jet Propulsion Laboratory

Das, R. S. L., S. Krauthamer, and R. H. Frisbee. "Evaluation of Cryogenic Power Conditioning Subsystems for Electric Propulsion Spacecraft." In *Energy Conversion Engineering Conference, 1996. IECEC 96., Proceedings of the 31st Intersociety*, 1:605–10 vol.1, 1996.

DARPA: **SuperHype Program**

Curcic, T., and S. A. Wolf. "Superconducting Hybrid Power Electronics for Military Systems." *IEEE Transactions on Applied Superconductivity* 15, no. 2 (June 2005): 2364–69.

GE Corporate Research and Development

Mueller, O. M., and K. G. Herd. "Ultra-High Efficiency Power Conversion Using Cryogenic MOSFETs and HT-Superconductors." In , *24th Annual IEEE Power Electronics Specialists Conference, 1993. PESC '93 Record*, 772–78, 1993.

RESEARCH PROJECTS (PARTIAL LIST)

Airbus Group, Rolls-Royce Strategic Research Centre, Cranfield University: DEAP Project

Berg, F., J. Palmer, P. Miller, M. Husband, and G. Dodds. “HTS Electrical System for a Distributed Propulsion Aircraft.” *IEEE Transactions on Applied Superconductivity* 25, no. 3 (June 2015): 1–5.

Siemens AG

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American Superconductor Corporation

Schempp, E., and C. Russo. “Applications of High-Temperature Superconducting Coils as Inductors in Switching Power Supplies.” *IEEE Transactions on Applied Superconductivity* 3, no. 1 (March 1993): 563–65.

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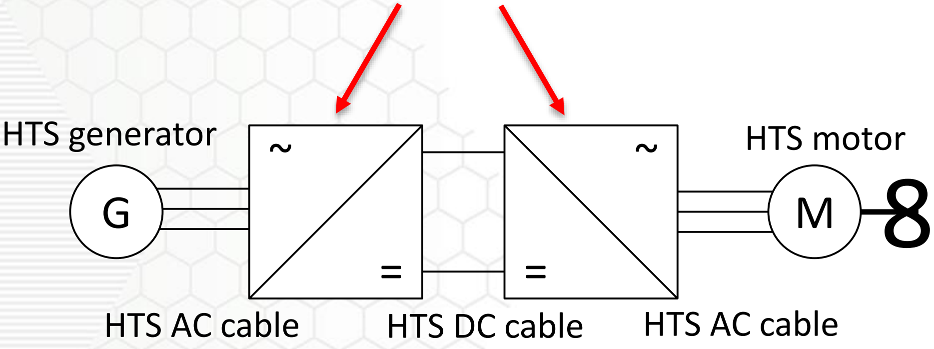
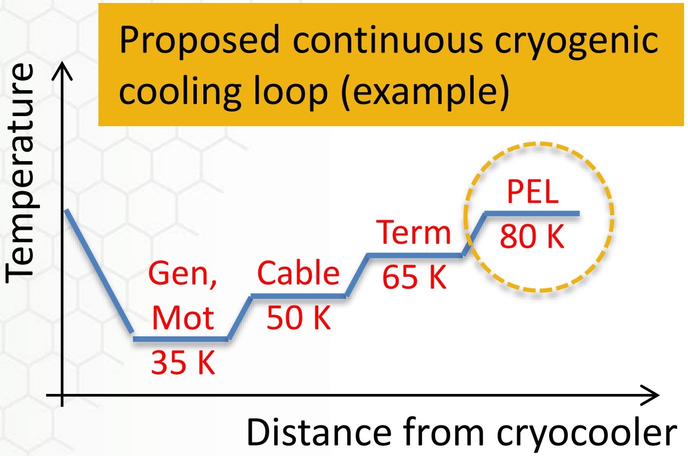
THE CRUX WITH HEAT INFLUX

- Advantages
  - Minimize heat influx from ambient/cryogenic interfaces
  - Increased power density and efficiency
  - Continous loop of cryogen
- Disadvantages:
  - Resistive devices in cryogenic environment come with cooling penalty
  - Only limited experience with cryogenic power electronics



Traditionally warm components in the cryogenic power system

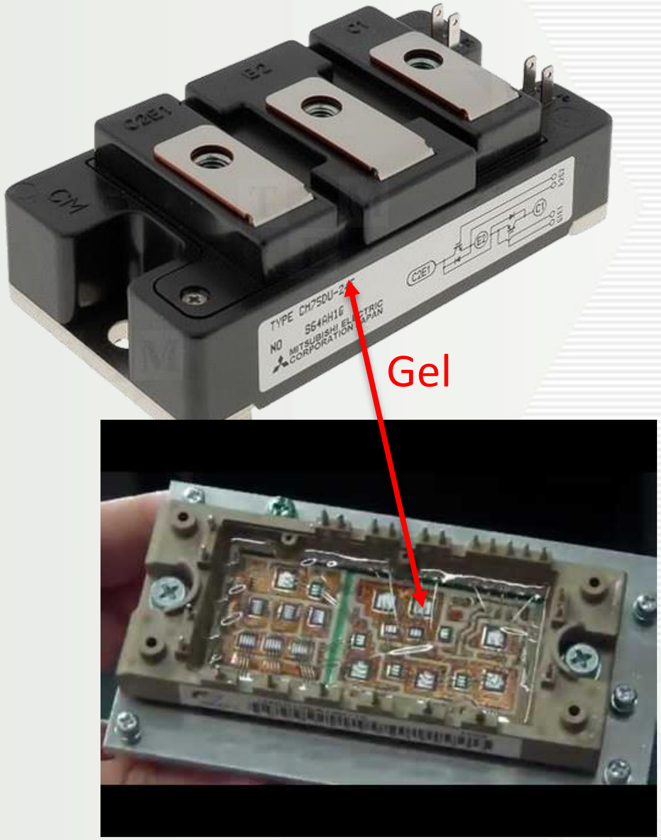


Proposed continuous cryogenic cooling loop (example)

SEMICONDUCTORS: PACKAGING

Not suitable for cryogenic applicactions:

- Contains plastics and silicone gels
- CTE mismatch

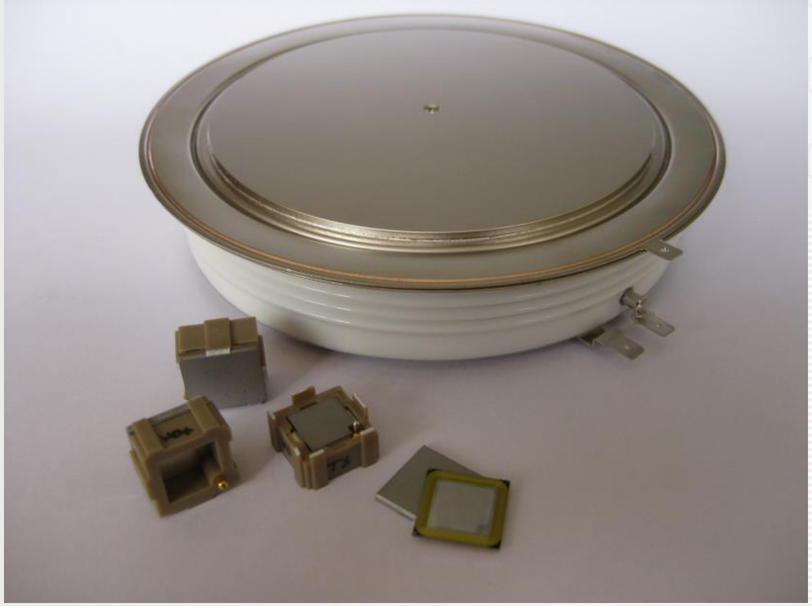


Gel

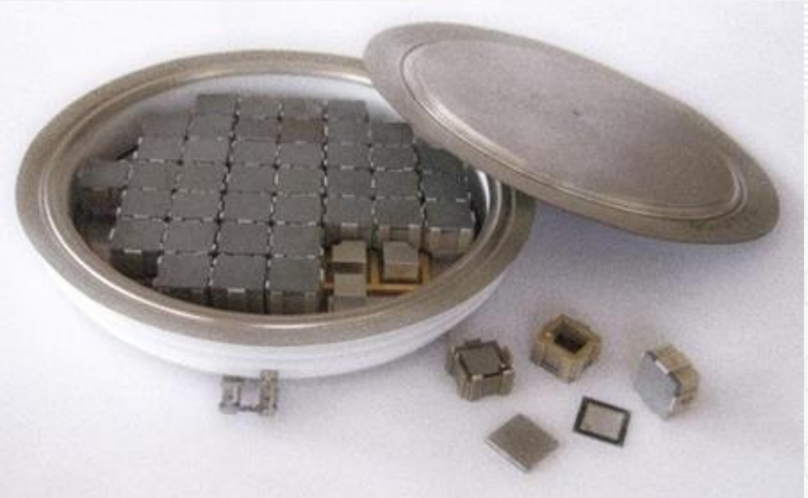
More suitable in cryogenic environment:

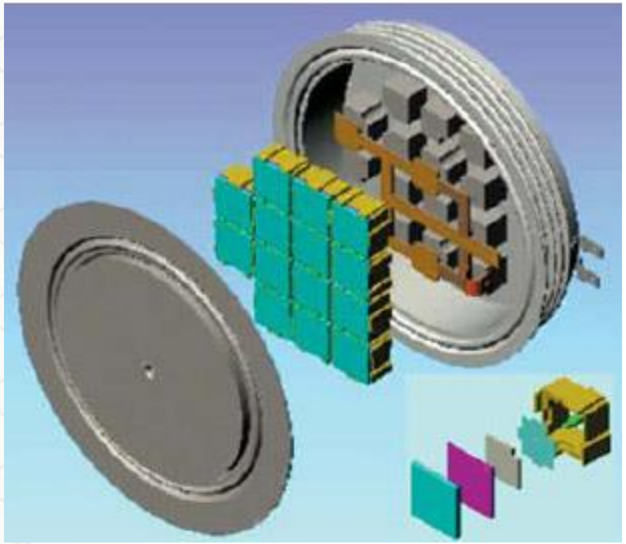
- Ceramics press-pack modules
- Braze joints

PRESS-PACK IGBT



Currently up to 6500 V, 3000 A, and reverse blocking or conducting variants.





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SEMICONDUCTORS: PERFORMANCE

- Bipolar semiconductors like BJTs and thyristors/GTOs are not suitable
  - Carrier freeze out
  - Current gain β drops

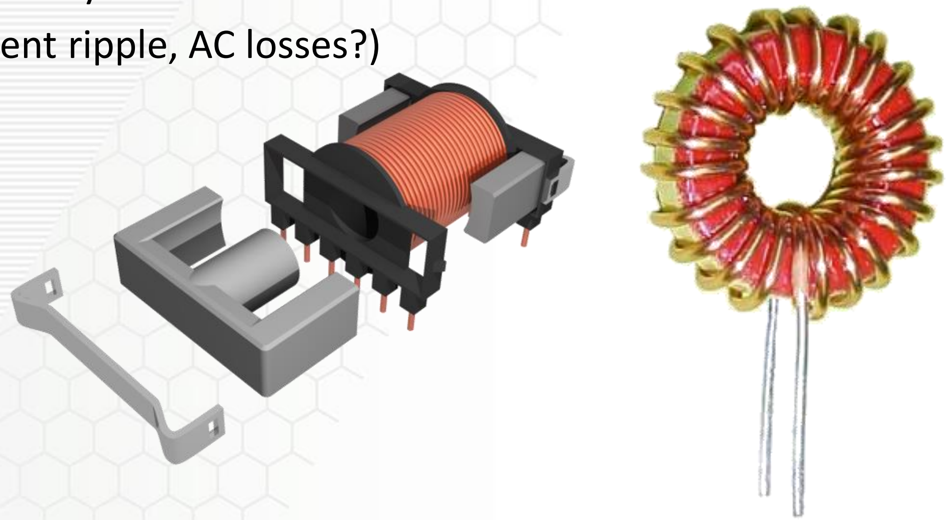
- Medium power IGBTs (up to 1700 V, 200 A) successfully tested over 50K-300K and over 4.2K-295K
  - Bare semiconductor without package

- Semiconductor physics (IGBT):
  - $V_{CE} \downarrow$ @ same I_{CE}… (increase in carrier mobility)
  - Threshold voltage V_T ↑ (carrier freeze out)
  - $V_{BR} \downarrow$ (typ 20-30%)
  - Reduced tail current (reduced carrier lifetime)

INDUCTORS AND TRANSFORMERS

- Increased core losses due to higher conductivity of steel (larger eddy currents)
    - Compensate by thinner sheets of steel?
    - Core-less (“air core”) design?
    - Core at RT, winding at cryogenic temperature
- Reduced conductor losses
    - Thinner wire → higher winding density
    - Potentially superconducting (current ripple, AC losses?)

Laminated core (increased core losses)



Powder core (compatibility with cryogenic temperatures unclear)

CAPACITORS AND VARISTORS

- Capacitors are problematic due to mismatch of CTE between polymeric film and metal film (large interface surface)
  - Size matters
  - Low capacitance or low voltage?
  - Type of dielectric (ceramic?)


Ceramic capacitors


Electrolytic capacitors

- Metal oxide varistors (MOVs)
  - Similar issues with interface as capacitors
  - Drop in specific heat capacity at cryogenic temperature
  - Better avoid

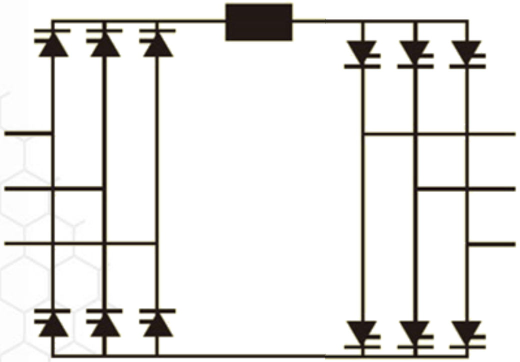

Tantalum capacitors

- Capacitor-limited and MOV- free converter design
  - No DC link capacitors
  - Filter capacitors – at room temperature?

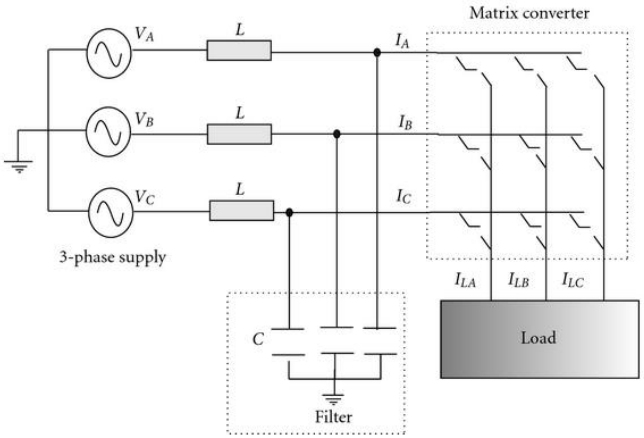
SYSTEM ASPECTS: TOPOLOGY

Objective: minimize the number and size of capacitors in the converter design

- Promising topologies
  - Current source converters (inductor in DC link) – requires reverse-blocking semiconductors
  - Matrix converters (direct AC-AC, no DC link)
- Reduce filters requirements
  - Multilevel topologies
  - Cascaded converters - Interleaving
  - Minimum capicitance in the filter design
- Might require reverse blocking IGBTs



Current source converter

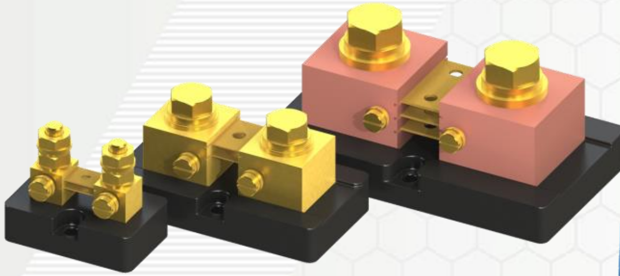


Matrix converter

CONTROL

- Controller including auxiliary power supply and communication at RT
    - Gate driver at RT
    - Physical separation between gate driver and IGBT can be problematic

- Instrumentation
    - Current sensing
    - Voltage sensing
    - Temperature sensing



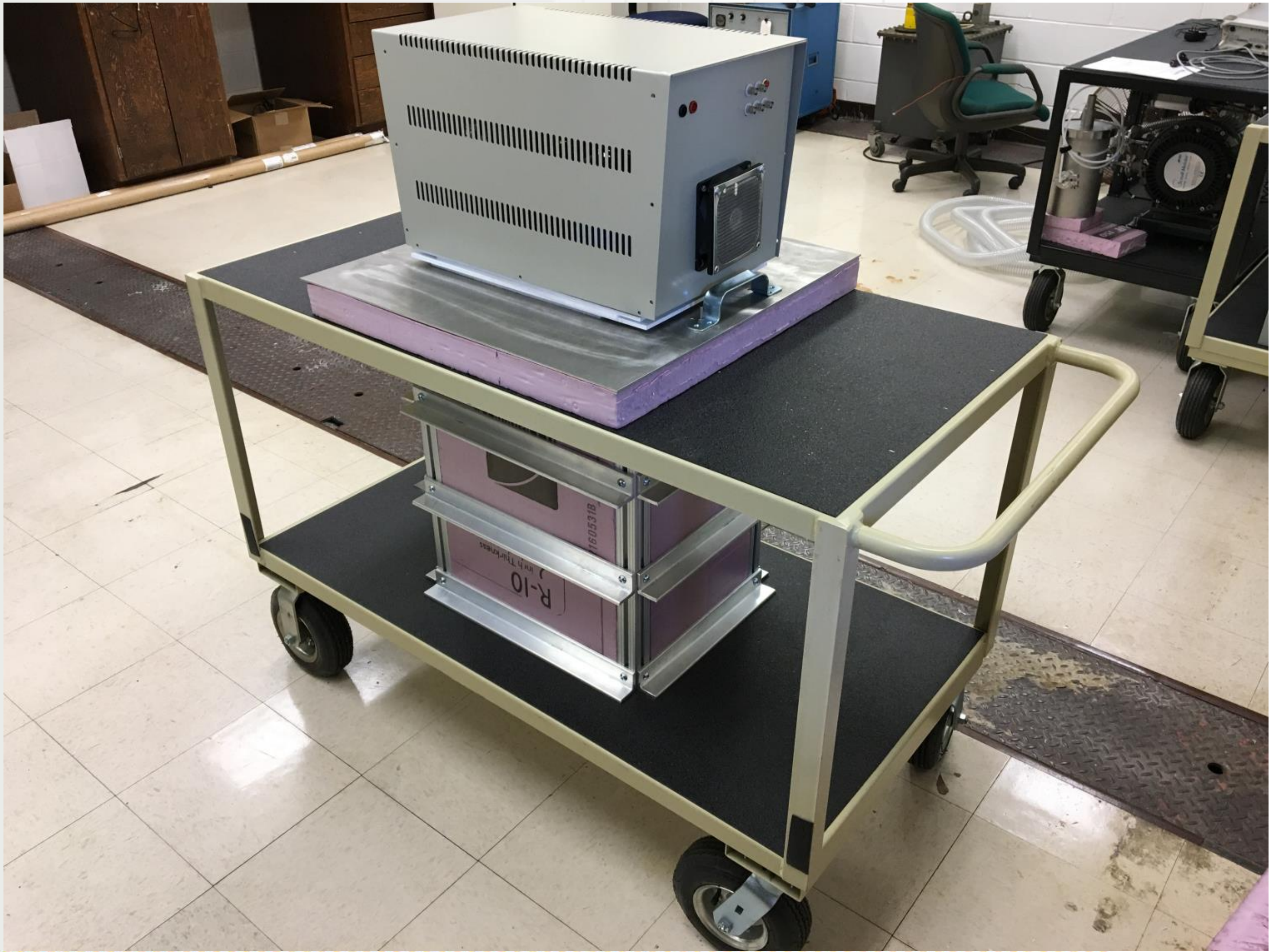
EXPERIMENTAL SETUP

IXYS UK WESTCODE

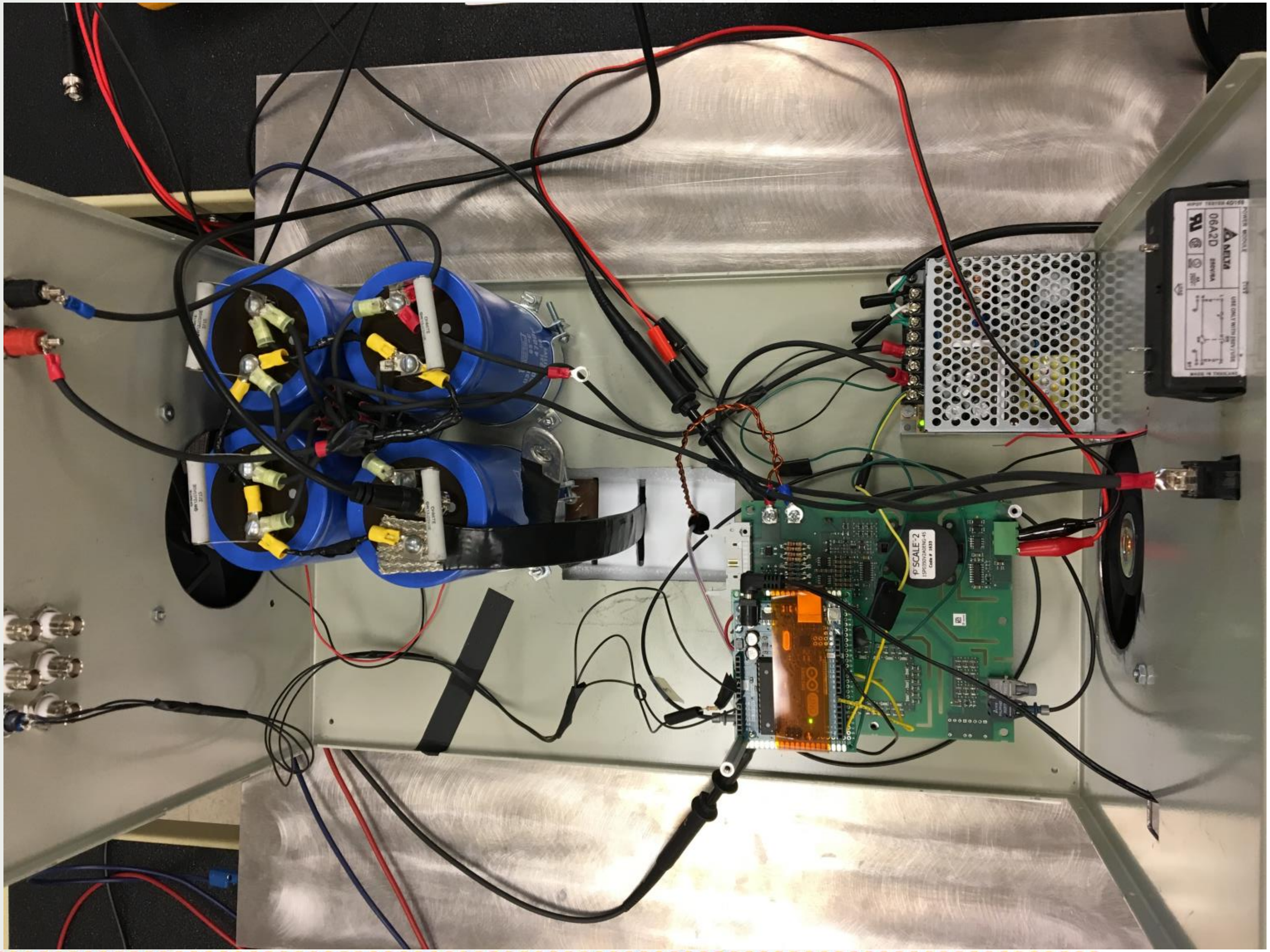
FLORIDA STATE UNIVERSITY 1851

Georgia Tech

EXPERIMENTAL SETUP

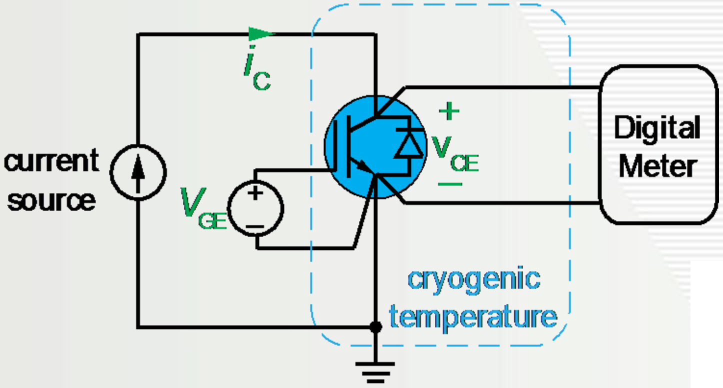


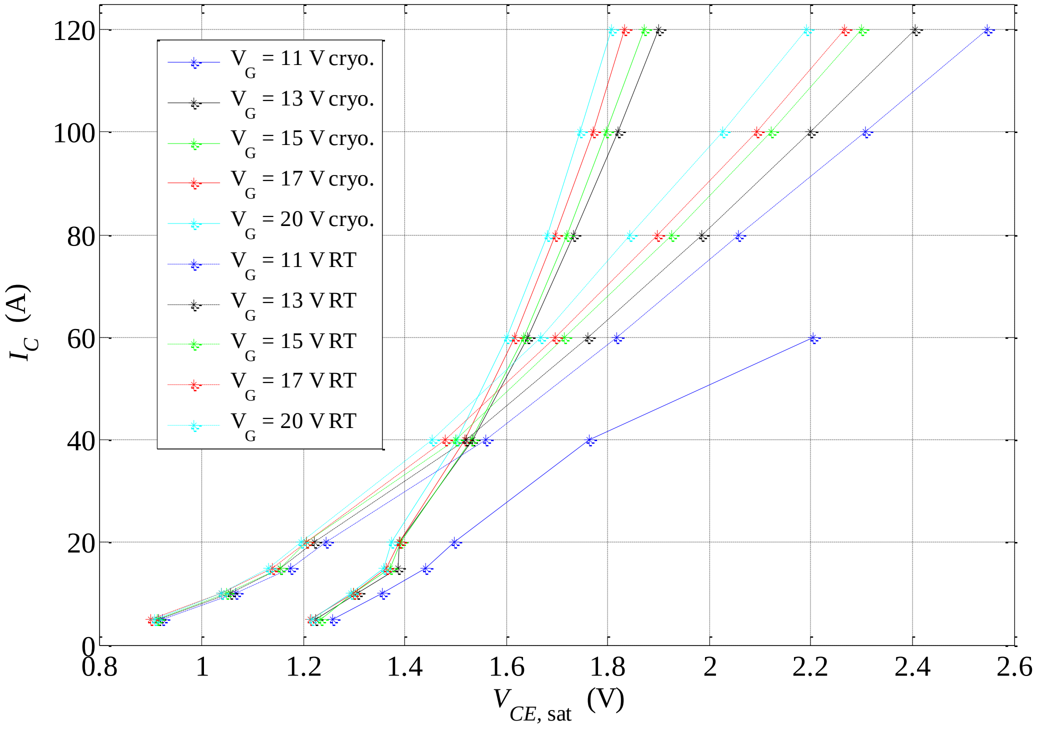
EXPERIMENTAL SETUP



EXPERIMENTAL SETUP

STATIC CHARACTERIZATION

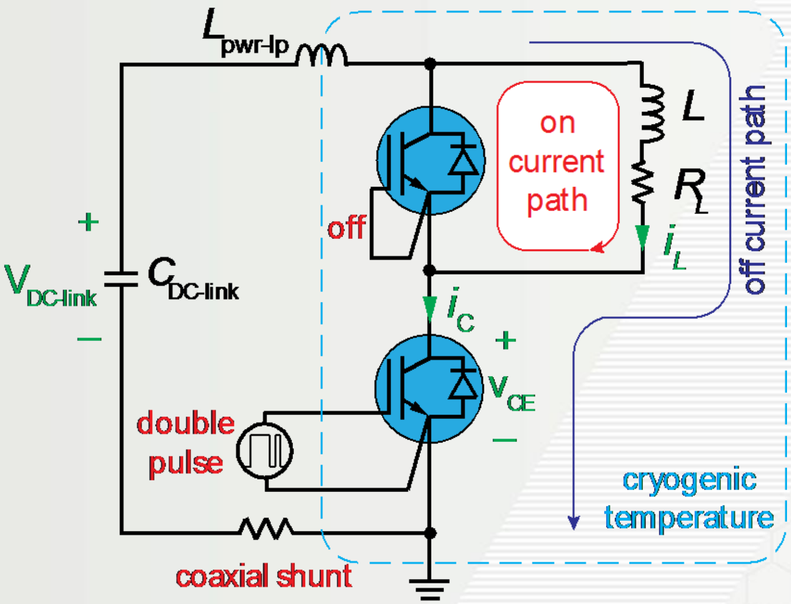


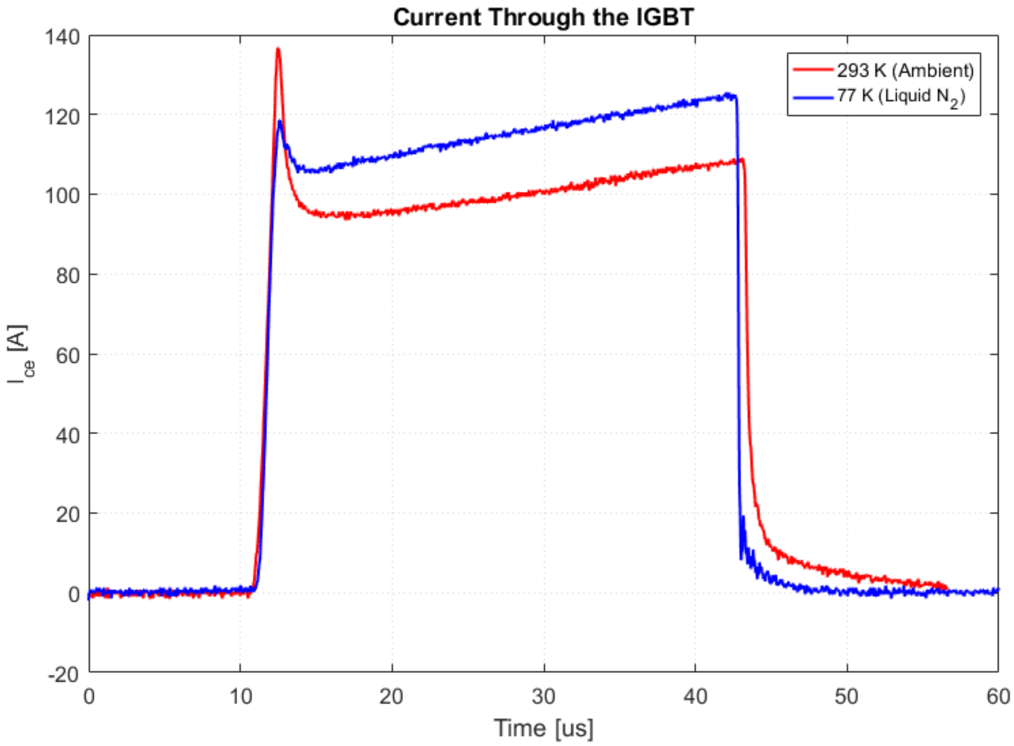


- Test was short, i.e. T_j ~77 K
- 4-wire method to avoid measuring voltage drop in the leads
- Reduction of conduction losses of 5-20% if I_C is larger than 50 A

DOUBLE PULSE TEST

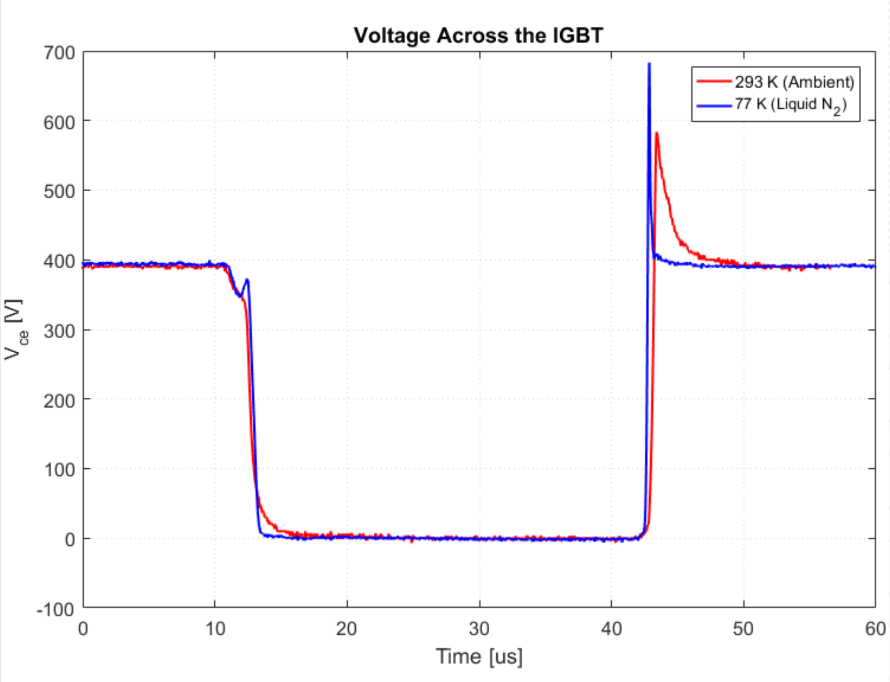
- Dynamic characterization of IGBTs in a bath of LN2 and at RT
- 50 cm gate leads
- Inductor in a bath of LN_2 (resistance changes)

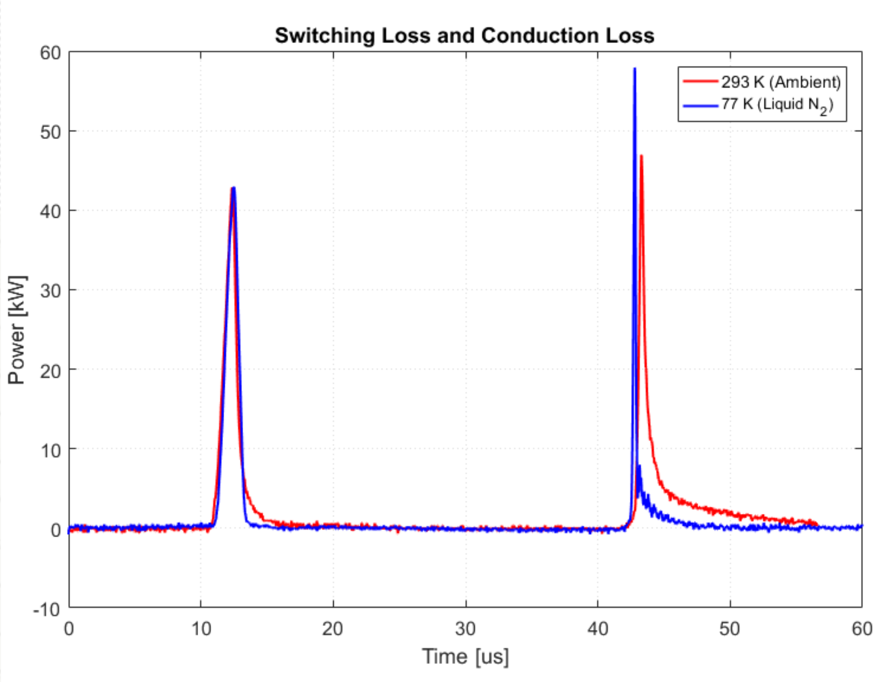




DOUBLE PULSE TEST

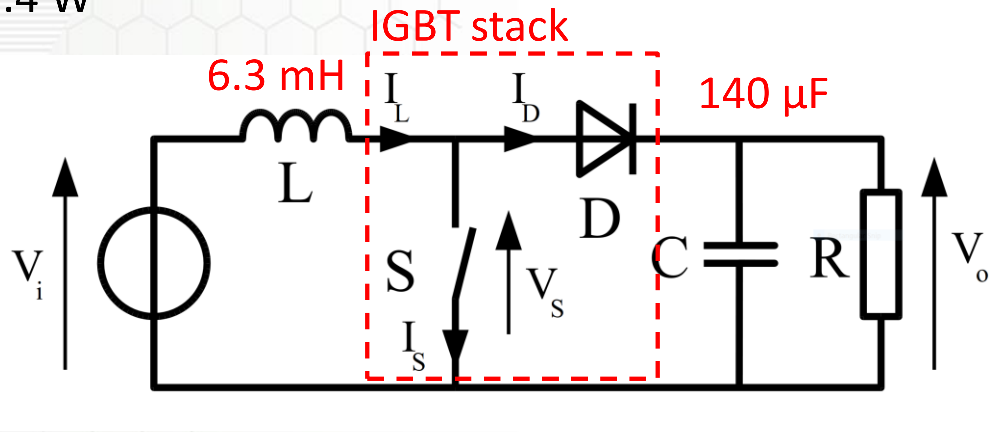
- At 77 K:
  - Reduced I_C overshoot (anti-parallel diode stores less charge)
  - Higher I_C (due to lower resistance of the inductor and wiring)
  - Higher turn-off voltage overshoot (due to faster current decay)
  - Shorter tail current





MODELING A BOOST CONVERTER

- What can we do with a single phase stack? – A 225 kW boost converter!
  - Input: 1,500 V / 150 A
  - Output: 2,000 V / 113 A
  - Switching frequency: 2 kHz
- Results from PLECS computer model
  - Switching losses: 373 W → 148 W
  - Conduction losses: 96.1 W → 73.4 W
- Stay tuned...



CONCLUSION

- Cryogenic power electronics have the potential to increase efficiency and power density of a fully cryogenic power system.
  - At the System level: reduced heat flux and system optimization (continuous cryogenic loop)
  - At the converter level: enhanced semiconductors properties and reduced conductor losses (inductors)
- Many of the earlier studies focused on characteristics of semiconductors
  - Semiconductors are only one part of a converter
  - Packaging needs to be considered
  - Topology of the converter is important (e.g., to avoid large capacitors)
- A system level approach is needed (cryogenics + converter + control)
  - Multi-disciplinary team

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Space Applications

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SMES

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E-Ships

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Electrical Aircrafts

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Capacitors

Pan, Ming-Jen. “Performance of Capacitors under DC Bias at Liquid Nitrogen Temperature.” *Cryogenics* 45, no. 6 (June 2005): 463–67.

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