P/O/E/T/S

CENTER FOR POWER OPTIMIZATION OF
ELECTRO-THERMAL SYSTEMS

Enablement of High-Voltage, High-Power Modules via Performance and Durability Validation of Direct Cooling, Voltage Blocking Technologies

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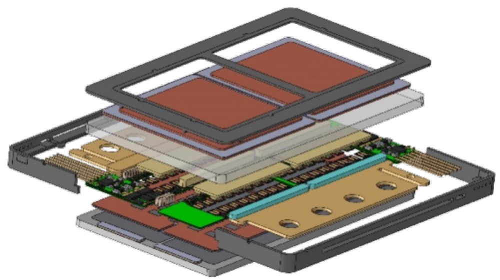
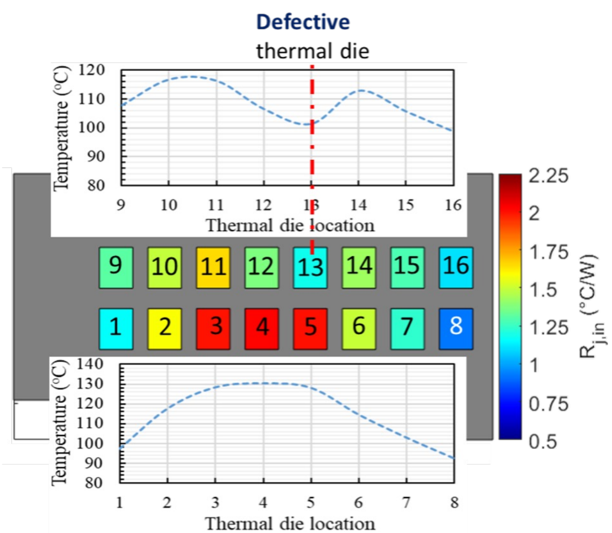
Yuxiang Chen (UA) and Alan Mantooth (UA)

Introduction: Power Densification

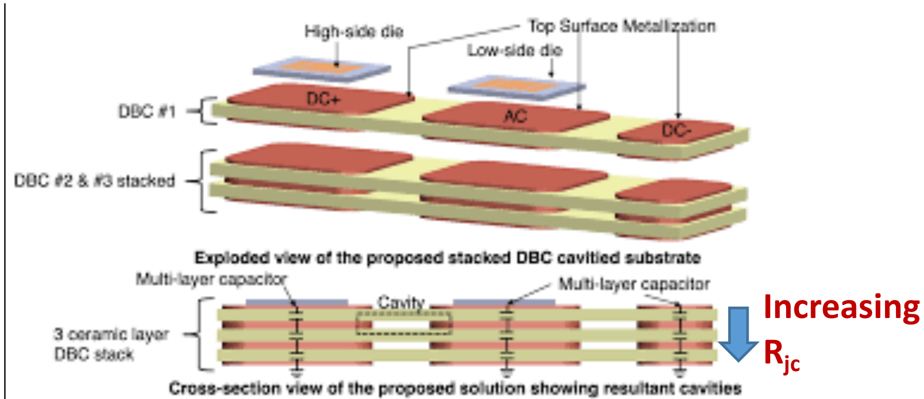
- Power densification and growing module heat losses are rendering traditional "external-to-case" cooling solutions increasingly insufficient



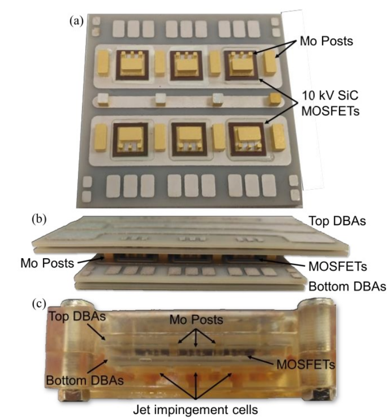
1600A, 1700V Half bridge module under development by Dr. Mantooth's group



Thermal resistance for a ¼ of the module *overlayed with die temperatures for* ***one-sided cooling*** *at T_{inlet} = 55 °C, Q = 6LPM and P = 620W*



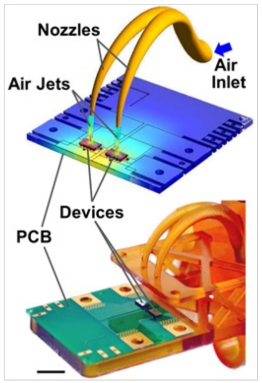
>10kV module concept by Dr. Fang Luo's group [1]



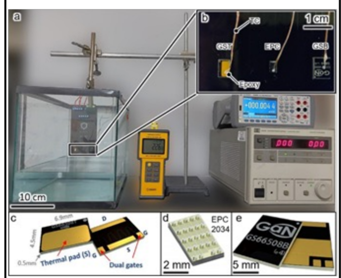
10kV module from Virginia Tech [2]

General Concept: Direct/Integrated Cooling

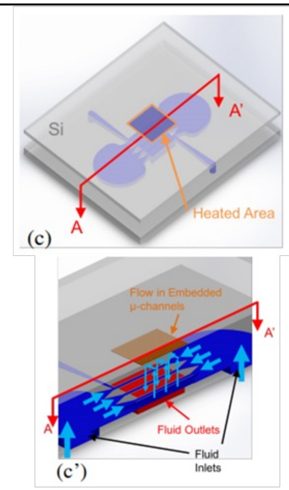
- **Objective:**
  - Enable high density power modules through a direct cooling approach that bypasses the thermally inefficient layers in high voltage packages



Direct air jet impingement cooling of GaN devices [3]



Direct immersion cooling of Parylene C coated devices using de-ionized water [4]



Device integrated microchannels [5]

Limited to low voltage applications

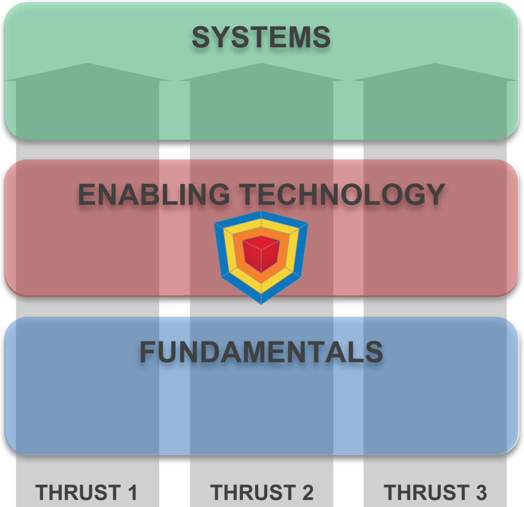
Obj

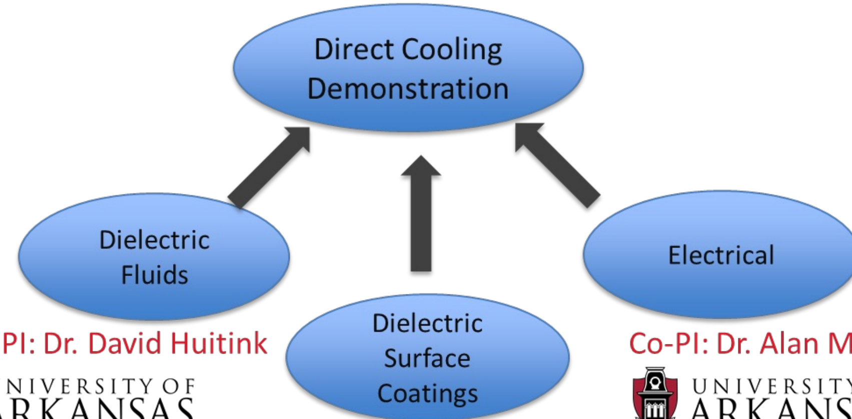
Leverage **dielectric fluids** and/or **dielectric surface coatings** to provide concurrent **cooling** and **voltage isolation**. This requires:

a. Understanding of the voltage blocking characteristics of dielectric fluids under forced convective conditions

b. Development and electro-thermal characterization of high thermal conductivity dielectric coatings

POETS Thrust and Collaborators





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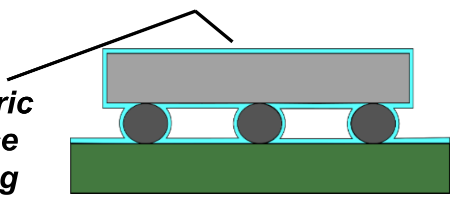
Dielectric surface coating



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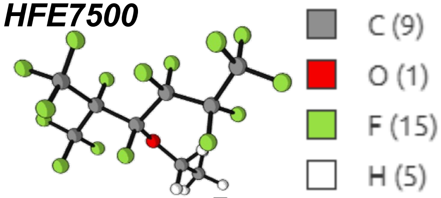
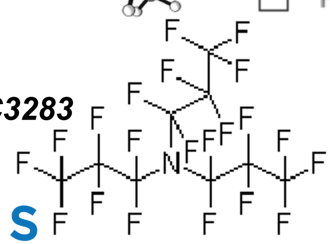
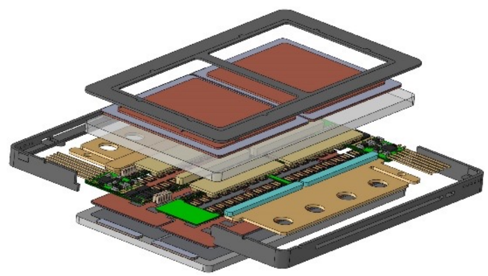
Dielectric fluids

HFE7500

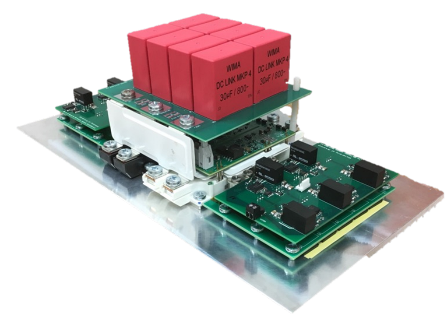


FC3283





Integrated cooling of high-density, high-V module (Basis for the thermal test vehicle that will be used)



Enable high-performance inverter for applications ranging from transportation to power generation

Obj a: DF Characterization Test Setup

Test chamber

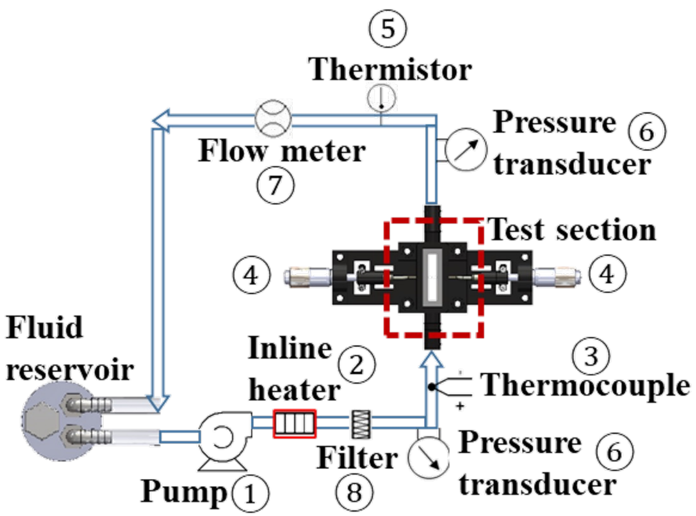
- Additively manufactured using Hi-Temp Resin
- Pair of needle electrodes
- Micrometer for precise control of electrode spacing, thus E-field strength

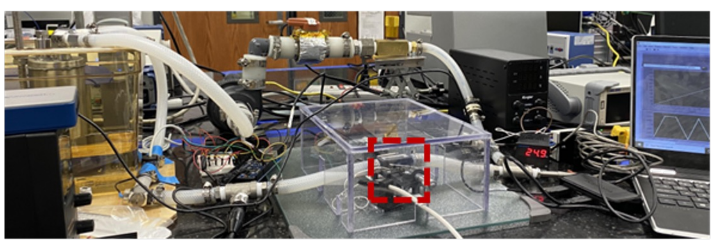
High-V power supply

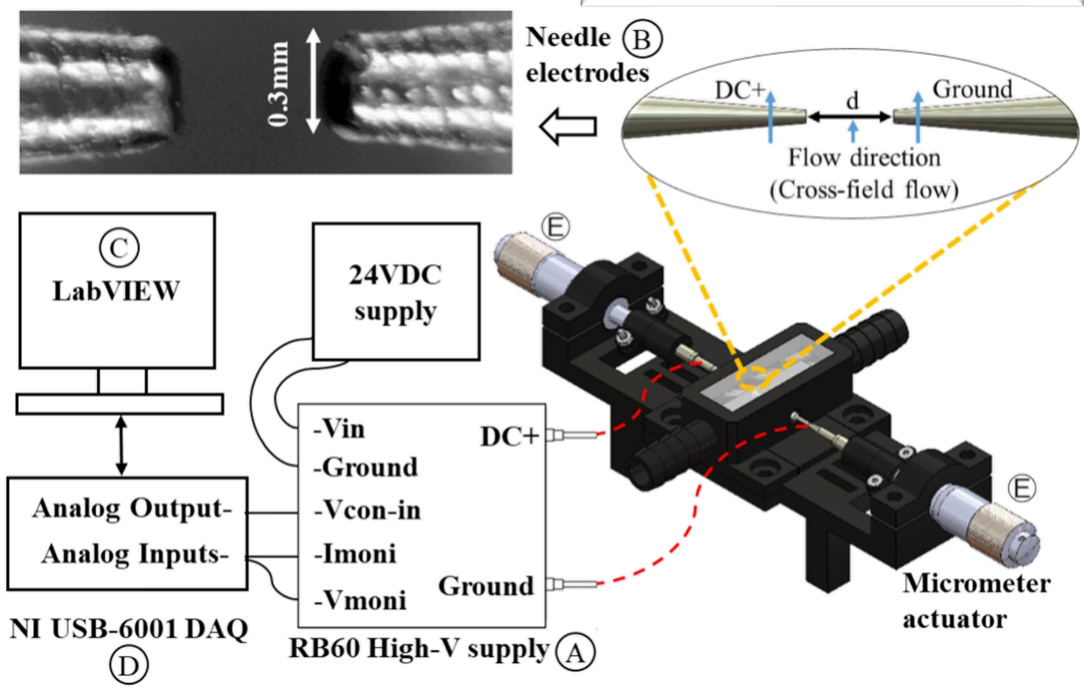
- Matsasuda RB60 model: 30kV/ 2mA rating
- Operated using a Ni Daq system and LabView
- Measurement parameters
  - Ramp rate: 100V/s
  - Trip current: 1mA

Flow loop

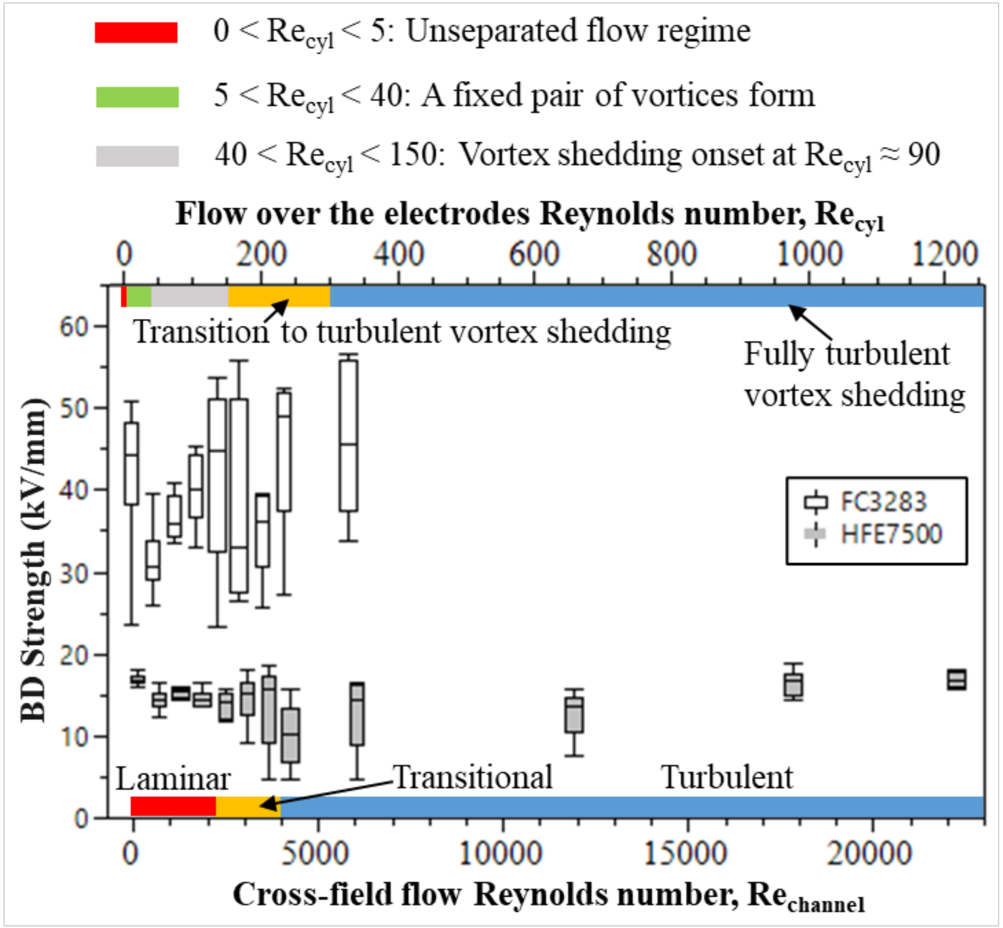
- Pump for flowrate control (Re: 0 to 20,000+)
- Inline heater ($T_{coolant}$ up to 105°C)
- Flow, temperature and pressure sensors read through Arduino



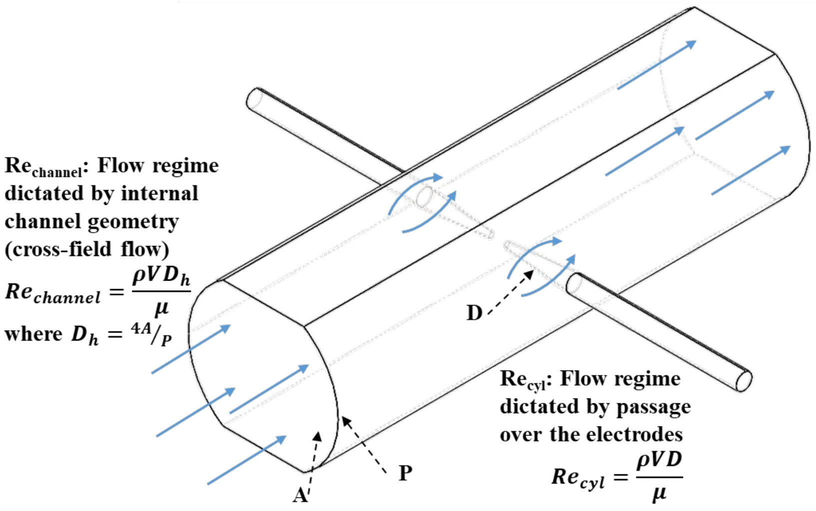




Obj a: Dielectric Fluid Discharge as a Function of Enforced Flow



Breakdown (BD) strength as a function of enforced flow velocity for HFE7500 and FC3283, showing that turbulent conditions overlap for flow over a cylinder and for cross-field flow



The flow regimes governing flow through the test section along with equations for calculating the corresponding Reynolds numbers.

Using flow **velocities** of **$Re_{channel}$ > 10,000** can take advantage of the **sweeping action** of flow to **restore BD strength**

Obj a: Dielectric Fluid Discharge as a Function of Enforced Flow

- The observed changes in breakdown (BD) strength of the fluids due to enforced flow can be attributed to the following factors:

Deterioration of BD strength

Impurities: generation and convection of impurities into the gap

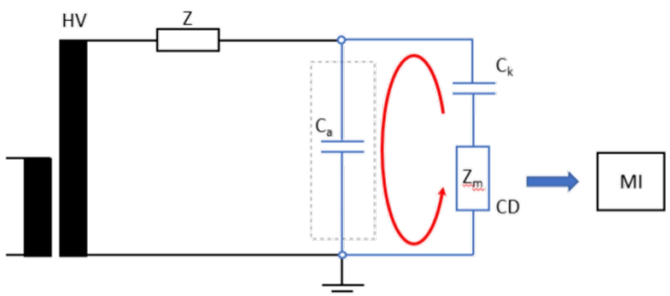
Triboelectric charging: generation of charges that enhance local field

Turbulence: low pressure regions that lead to bubble formation

Augmentation of BD strength

Sweeping Action: on impurities and charge carriers by cross-field flow

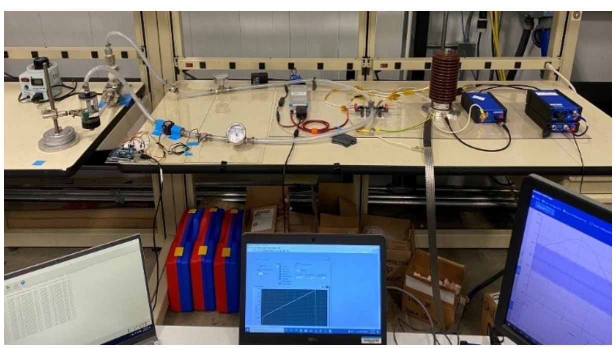
- Turbulence gives rise to low pressure regions that act as nucleation sites for bubble formation
  - Partial discharges can occur inside these bubbles eventually leading to fluid BD
  - The setup below was used to investigate partial discharges due to enforced flow

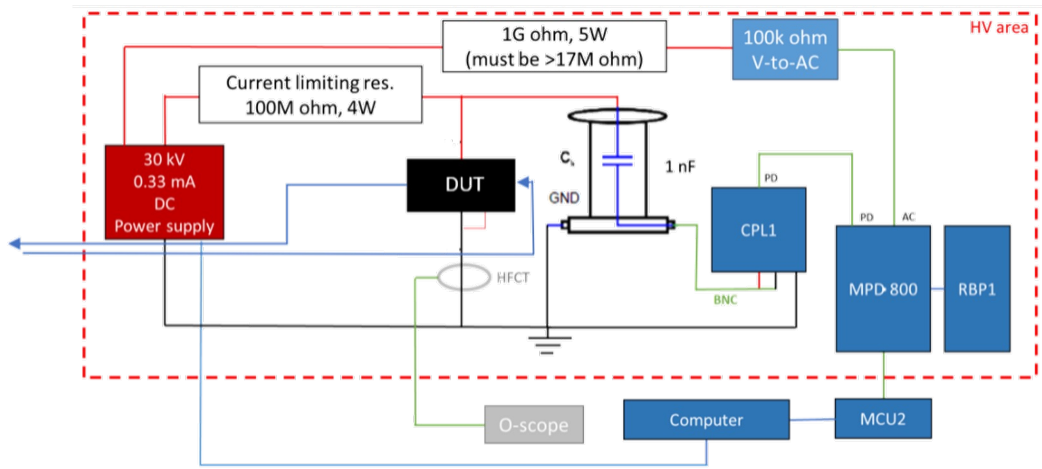


HV	high voltage supply	CD	coupling device
C_a	test object	MI	PD measuring device
C_k	coupling capacitor	Z	filter
Z_m	measuring impedance		

Simplified PD measurement circuit according to IEC60270.

PD Setup

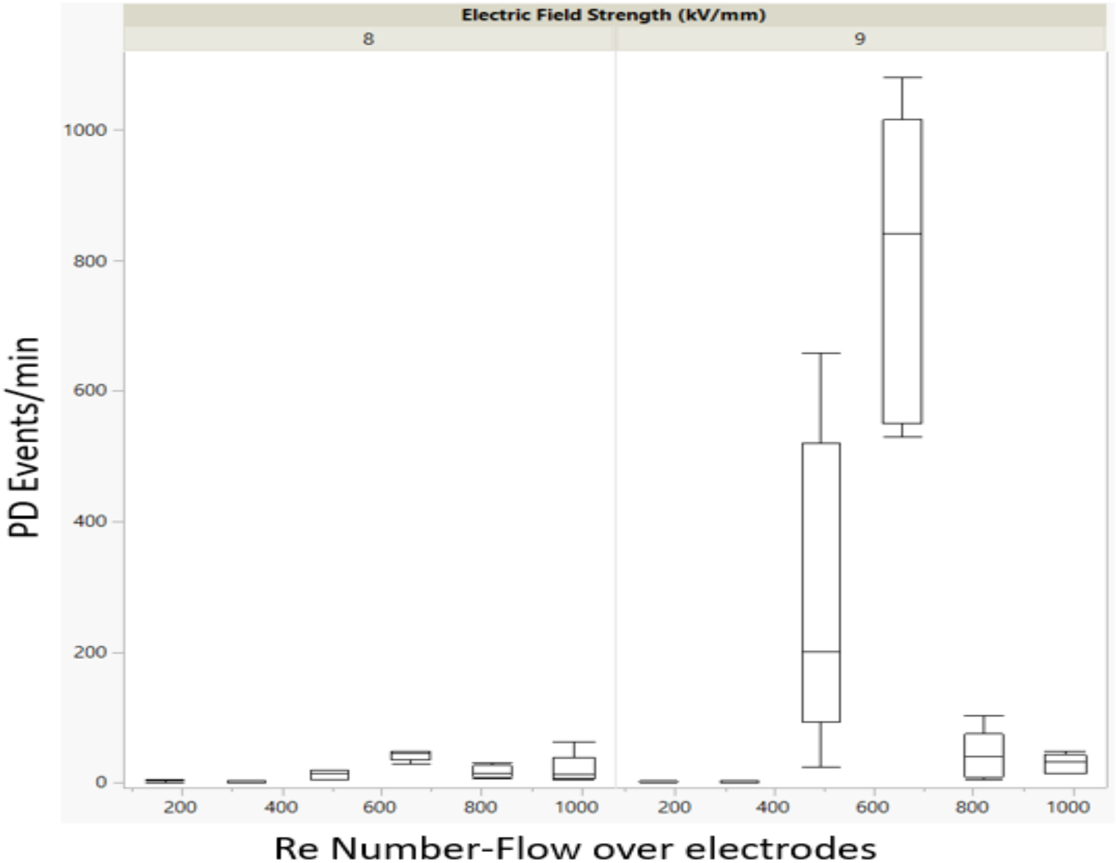




Omicron MPD 800 mathematically integrates current supplied by capacitor to calculate PD charge

Obj a: Turbulence Effects

- Partial discharge measurements to establish a relationship between flow regimes and discharge between electrodes.
  - Measurements are made by ramping voltage to a desired value (100V/s ramp rate) and recording for 2 minutes



0< Re <5: Unseparated flow regime

5< Re <40: A fixed pair of vortices form

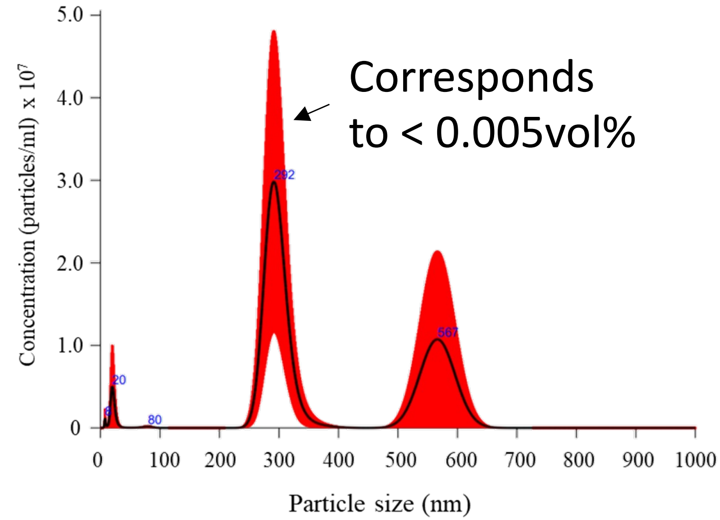
40< Re <150: Laminar vortex street

150< Re <300: Transitional flow

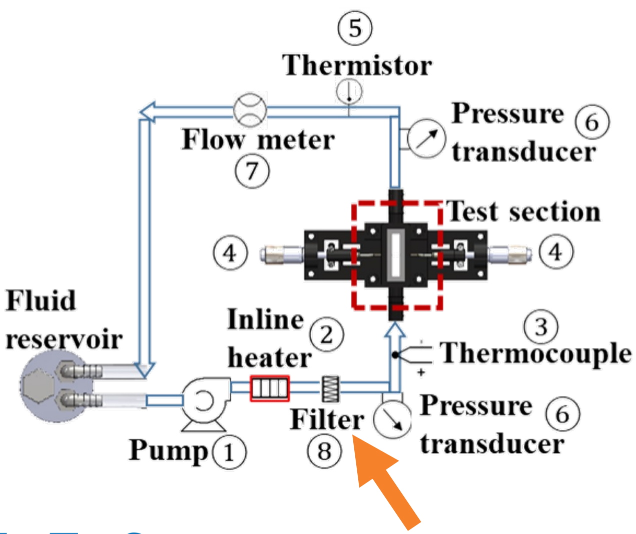
Re >300: Turbulent

Obj a: Impurity Effects

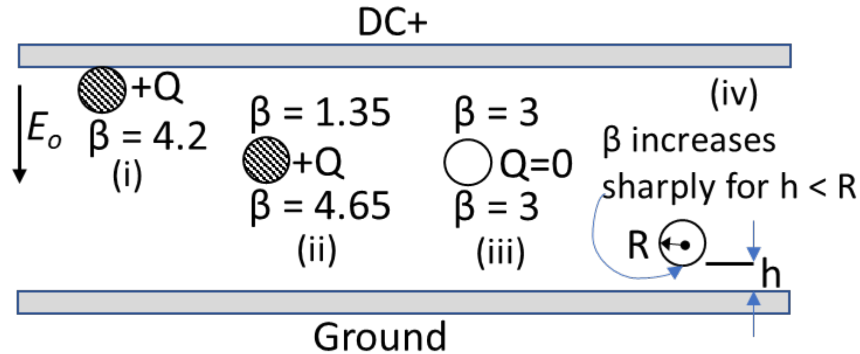
- Steps were taken to minimize and track particulate participation:
  - **Installation** of a **filter** upstream of the test section
  - **Tracking of test sequence** and **statistical analysis** of the data
  - Fluid **chemical characterization**
    - Ultra-violet/visible (UV/Vis) spectroscopy
    - Light Scattering Techniques



Particle tracking analysis on a 95 BD sample



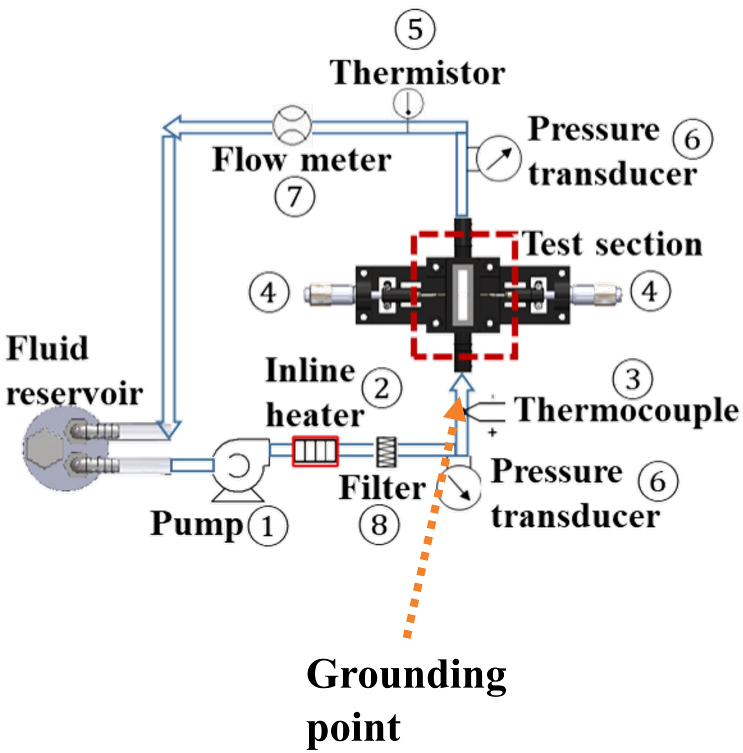
Enhanced Local Field: $\boldsymbol{E = \beta E_o}$

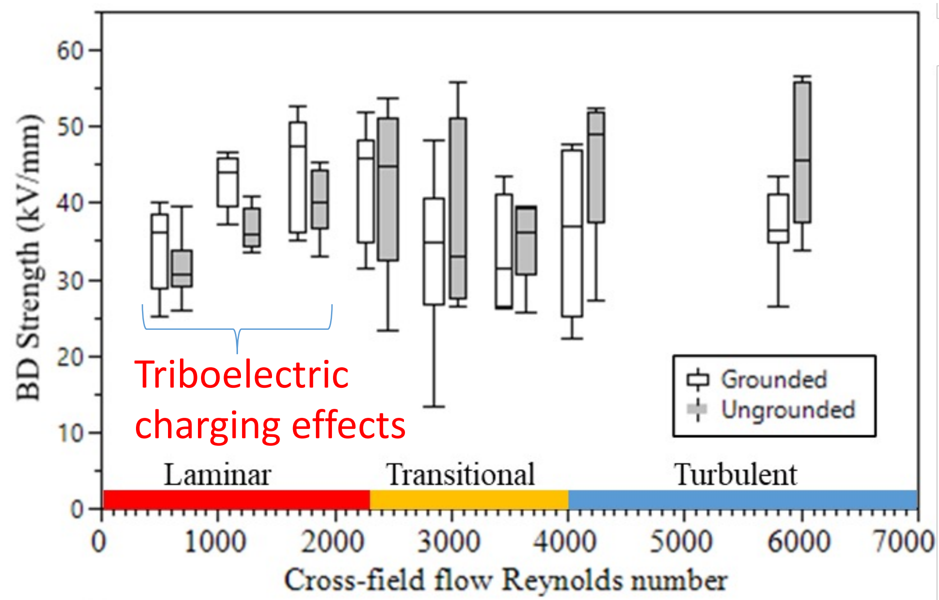


Charged and **uncharged** particles result in **local field enhancement** that can induce **micro-discharges** that **increase probability** of **total BD**. **β depends** on particle **shape**, **location** and **charge** [6 – 8].

Obj a: Triboelectric Charging Effects

- A grounding element was added upstream of the test section to crystallize the effects of triboelectric charging:



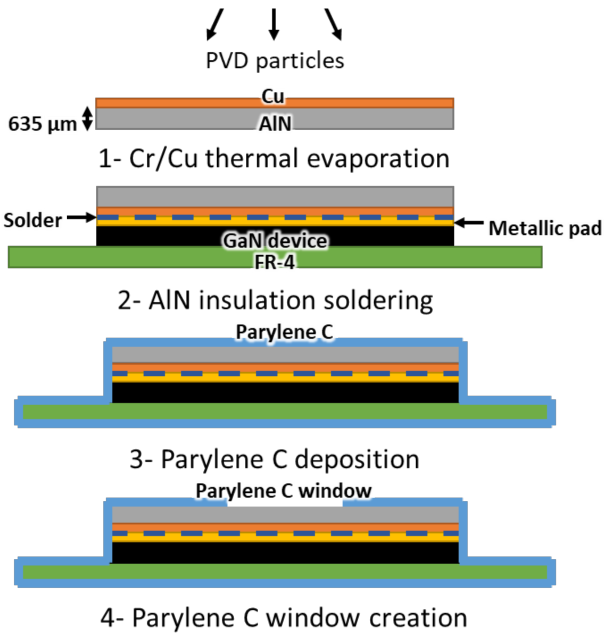


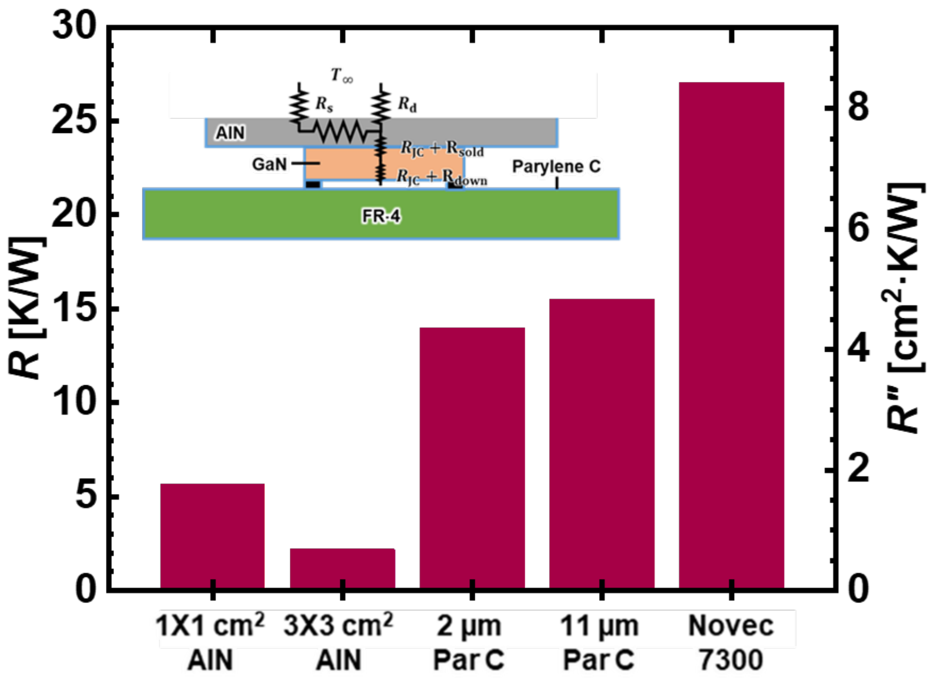
Breakdown strength as a function of enforced flow for FC3283 showing that **grounding** the fluid **reduces** the **effects of triboelectric charging** in the **laminar flow regime**

Objective b:Development and electro-thermal characterization of high thermal conductivity dielectric coatings to enable direct immersion cooling using fluids of improved thermal properties such as DI water

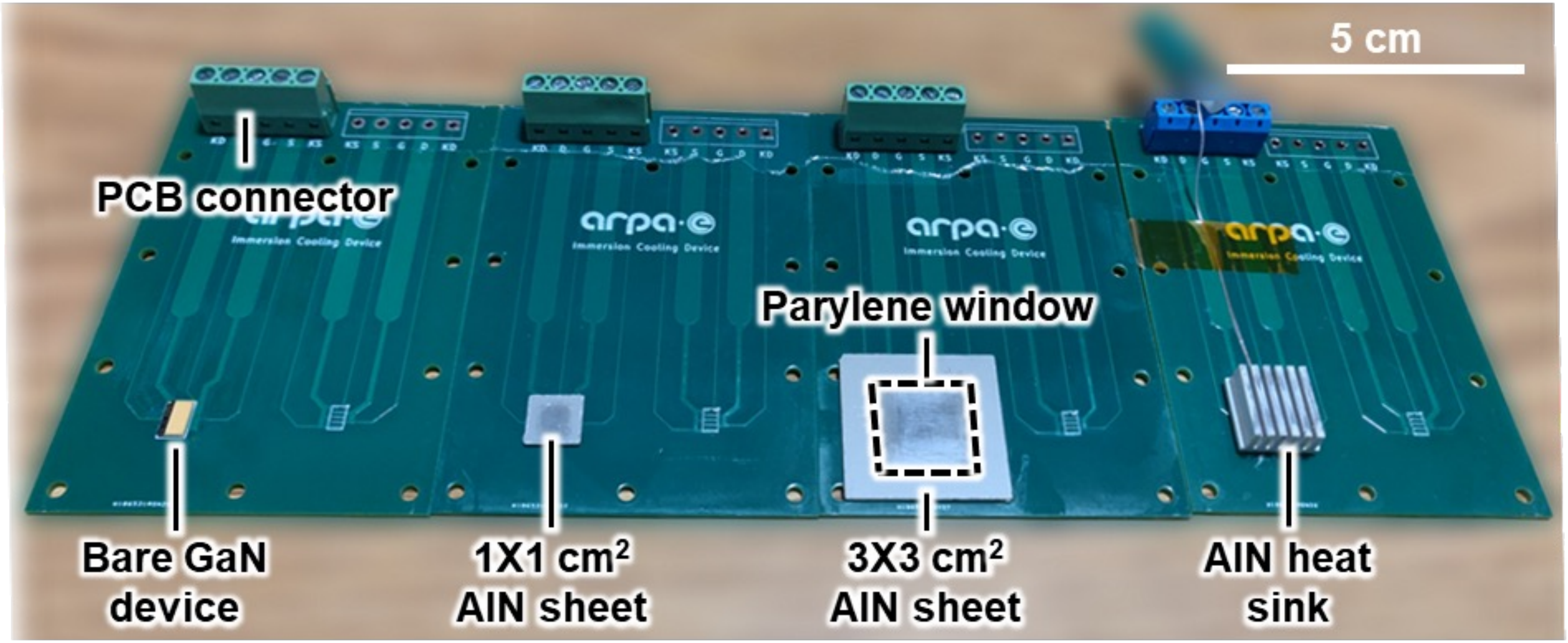
Obj b: Development of High Conductivity Dielectric Surface Coatings

- Initial efforts have explored different insulation techniques using methods such as ALD, CVD, and Dip coating
  - Materials and insulation techniques ranging from Parylene C, SiO_2 and AlN/Parylene window have been explored





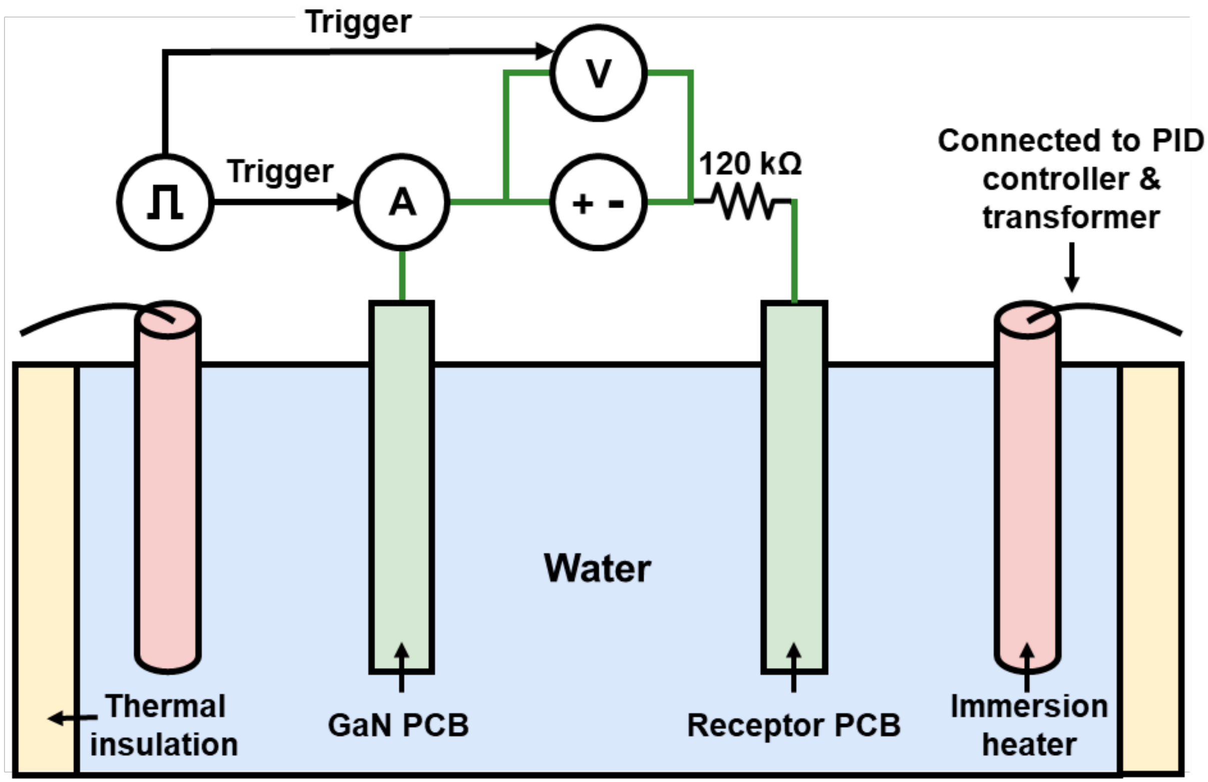
- Parylene C used was 13 µm thick.
- Thermal conductivity of AlN: 180 W/m-K @ 20° C.
- Thermal conductivity of solder: 20 to 70 W/m-K @ 25° C.



- Two different flat AIN sheets were tested: 1x1 and 3x3 cm^2 surface area. They were cut using water jet.

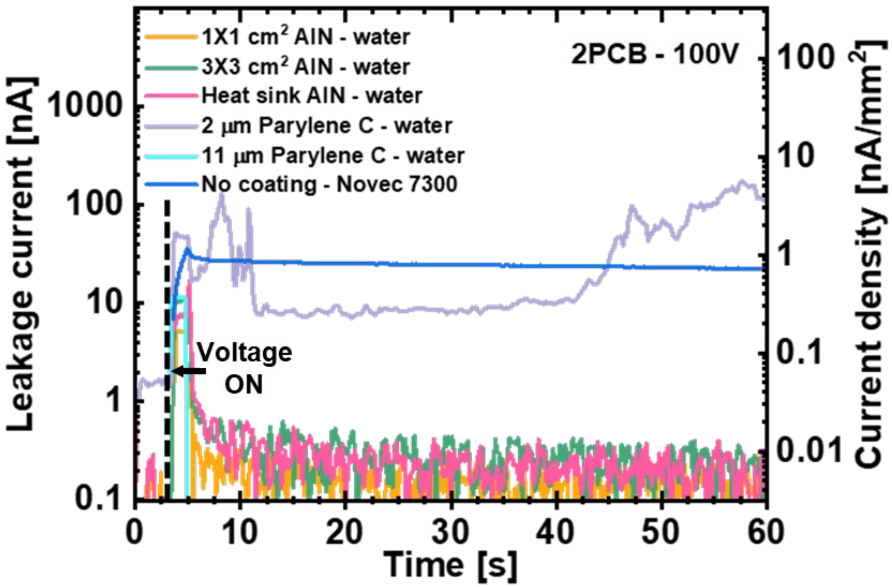
- The heat sink is made by milling a machinable AIN sheet. It has Boron Nitride added to AIN to make it easy to machine.

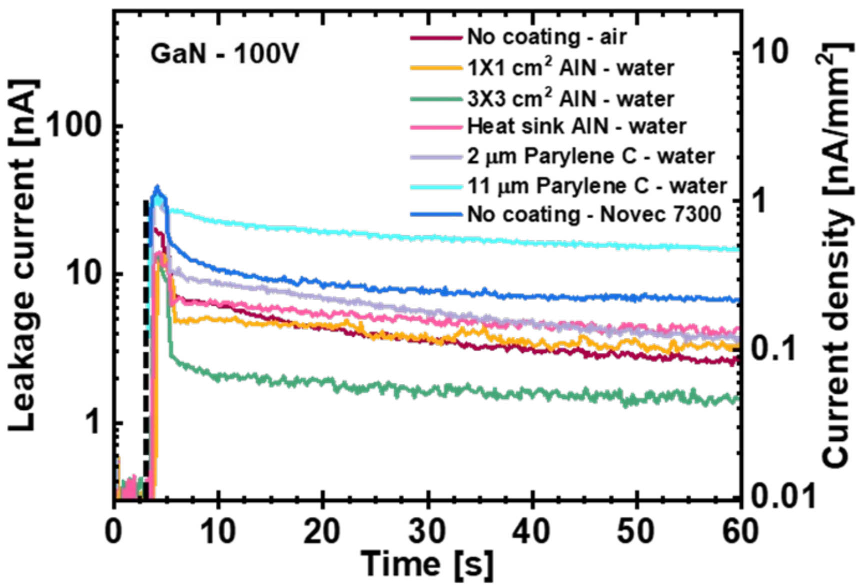
Obj b: Experimental Study – Setup & Electric Circuits



The leakage current in deionized water (DI) drops significantly from the 100s of microampere range for uncoated PCBs, to the nanoampere range for coated PCBs.

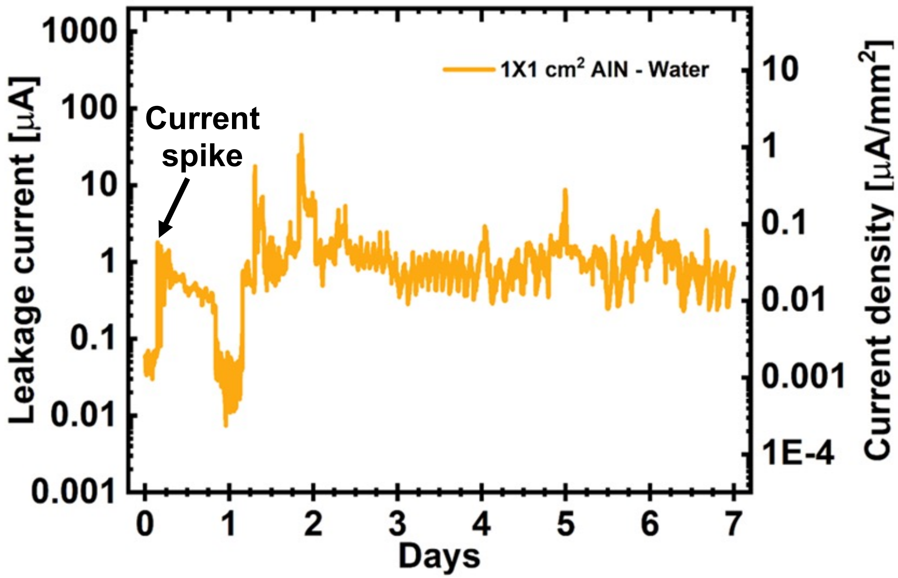
Obj b: Short-Term Leakage Current Results

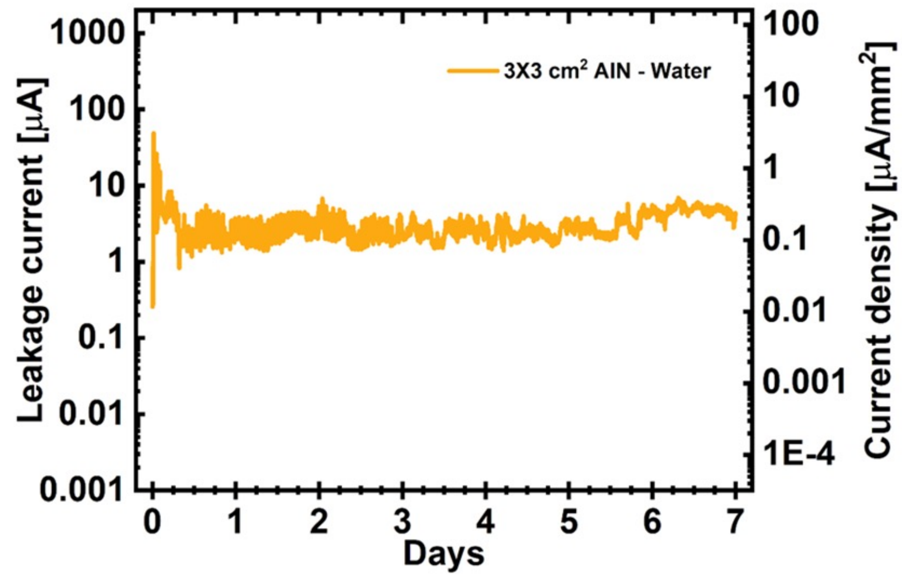




- Short term experiments were done at voltages from 50 to 600 V while the PCBs are submerged in DI water @ room temperature for 60 seconds.
- AlN / Parylene C packages kept the leakage current in the nanoampere range, like thick Parylene C and the dielectric fluid.
- An electrical / interfacial analysis is still needed to understand the value of the leakage current for a specific coating / coolant / voltage scenario.

Obj b: Long-Term Leakage Current Results





- Long term durability experiments were done @ 100 V while the PCBs are submerged in DI water @ 50°C for 7 days.
- The leakage current starts in the nanoampere range but then increases to ~ 1 μA after 1-4 hours after a leakage current spike event.
- Several spikes keep happening but the leakage current stays below the leakage current for uncoated devices (~ 400 μA).

Technology Readiness

TRL of the technology

- Currently at TRL 3
- Achieved proof of concept and electrical characterization of dielectric surface coatings
- Performed electrical characterization of dielectric fluids

Next steps for increasing TRL

- Demonstration of a direct cooled package that leverages the learnings from dielectric fluid characterization and dielectric surface coating development efforts

Conclusion: Project Summary

Progress Summary:

Obj

Leverage dielectric fluids and/or dielectric surface coatings to provide concurrent cooling and voltage isolation.

a. **Measured breakdown strength a hydrofluoroether and fluorocarbon type dielectric fluids to understand the effects of flow (0 < Re < 25000), temperature (22 – 75 °C) and E-field strength. Use the learnings to propose means by which to maintain voltage blocking capacity under convective conditions**

b. **Developed dielectric coatings that provide good electrical insulation as well as improved thermal conductivity including a AlN/Parylene C window approach. Electrical testing showed an ability to block up to 600V for a AlN / 13 µm Parylene C + window**

Upcoming Activities:

Obj a: Dielectric fluid characterization

- ***Flow-dependent measurements for FC3283 at higher Crossfield flow Re > 10,000***
- ***Expand on partial discharge measurements***
- ***Additional testing with plate-plate electrode geometries for better understanding of the factors driving flow-dependent breakdown***

Obj b: Dielectric surface coatings

- ***Temperature-dependent leakage current measurements***
- ***Continue long-term leakage current tests to understand the effects of moisture diffusion***

References

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Thank you! Questions?

Research Area	Personnel	Role	Contact
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