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COMPOSITE INSULATOR MATERIALS FOR VACUUM FLASHOVER HOLDOFF

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OVERVIEW

- Problem description: ns-scaled pulsed flashover of vacuum-insulator interface
- Material modification methods
- Experimental facilities used to investigate pulsed flashover
- Initial data on epoxy-CB_4 composite
- Materials characterization measurements
- Revisiting epoxy-CB_4 on new Caeculus 500 kV Pulsed Flashover Test Stand
- Interpretation of experimental data
    - Higher than predicted sample conductivity at high fields
    - Absence of electrical impulse with flashover on composite sample
- Future work

FLASHOVER ACROSS VACUUM-INSULATOR INTERFACES CONSTRAINS TRANSMITTED POWER AND EFFICIENCY

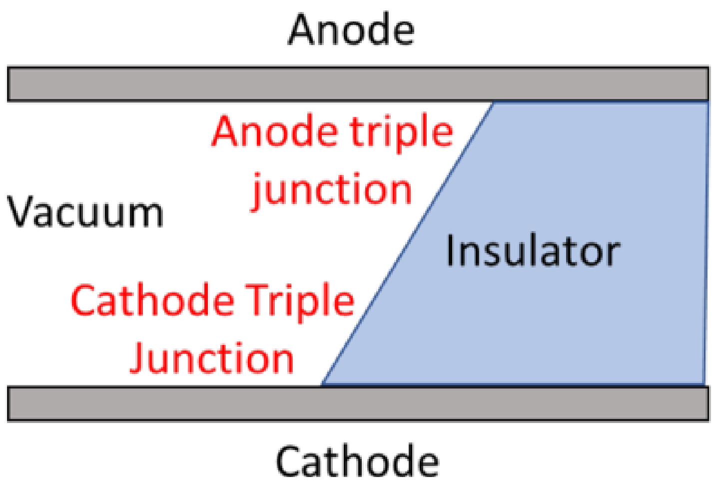
Surface breakdown at vacuum-insulator interface (flashover) occurs at fields many times lower than bulk breakdown or vacuum breakdown [1]

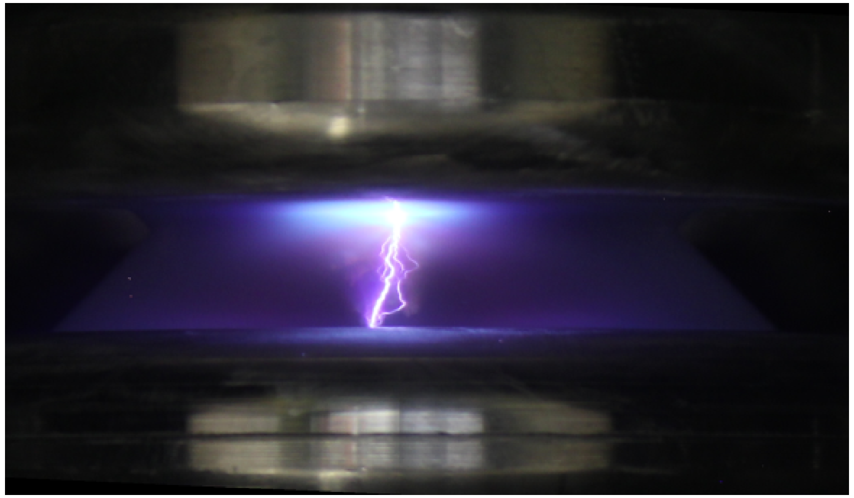
Multiple physical mechanisms are believed to be responsible, depending on the interface profile and pulse length [2]

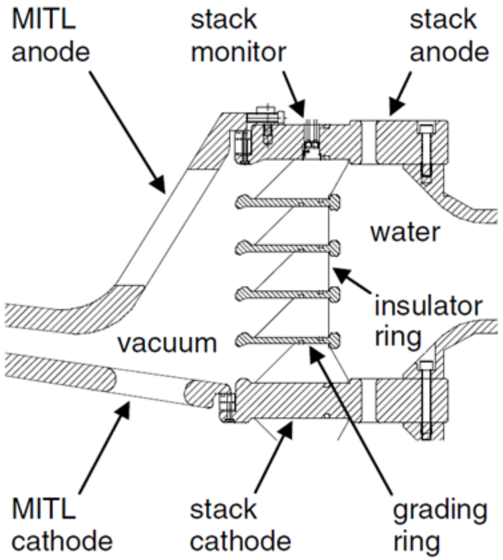
- Cathode-initiated [3], Anode-initiated [4], Sub-surface processes [5]

Large accelerators employ stacks of insulators with field-grading rings and optimized 45-degree profiles to minimize size [6]

Further optimization requires machined field-shaping [7] (difficult at large scales) or intrinsically stronger insulators







From *Phys. Rev. ST Accel. Beams*, vol **7**, 070401, 2004 [6]

FLASHOVER DEPENDS ON APPLIED VOLTAGE, DIMENSIONS, AND MATERIAL PROPERTIES

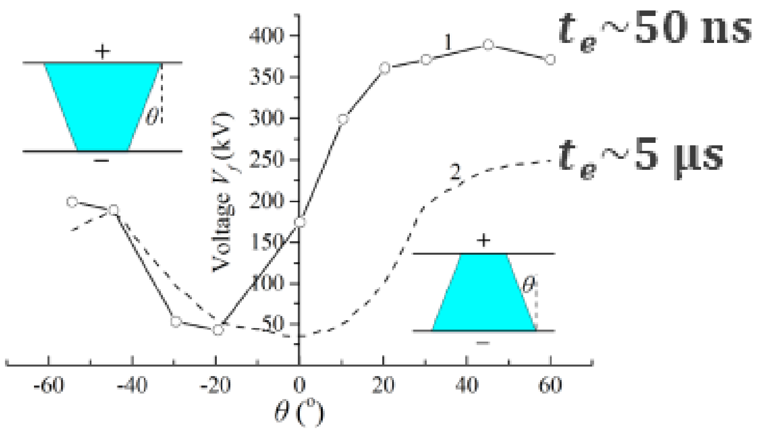
For an insulator interface of circumference C and height d subject to a voltage pulse with peak field E_p and effective time t_e:

- Stygar model of insulator flashover [6] $\gamma = V_p\, d^{-1}\, (Ct_e)^{\frac{1}{\beta}}\, e^{-\frac{\lambda}{d}}$ with β and λ fit parameters

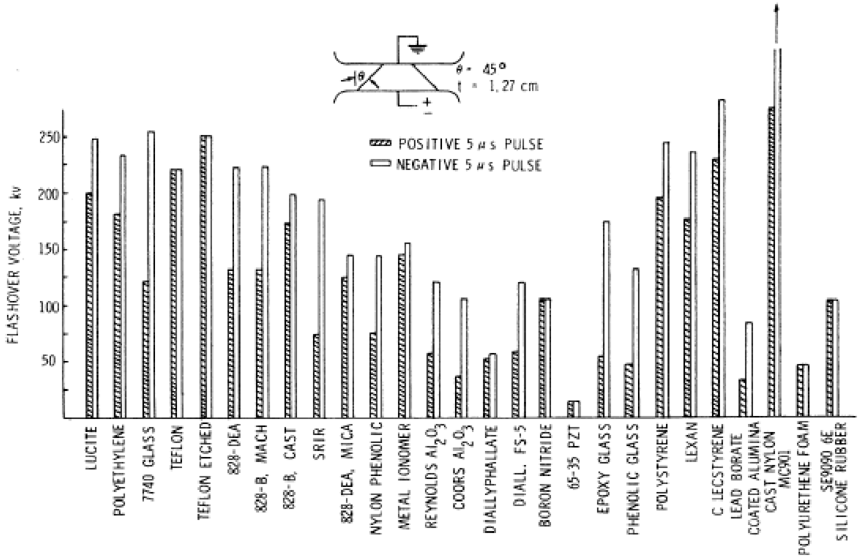
- J. C. Martin model of insulator flashover [8] $\gamma = V_p\, d^{-\frac{9}{10}}\, t_e^{\frac{1}{6}}\, C^{\frac{1}{10}}$

For experiments comparing samples of the same size and applying a consistent pulse shape,
peak holdoff voltage ∝ **material-dependent flashover strength**

On large pulsed power facilities (e.g. Z), peak fields are typically 100-200 kV/cm and t_e ~ 20-50 ns.



From *IEEE Trans. on Diel. and Electr. Insul.* **25**, no. 6, pp. 2321-2339, 2018 [9] cf. [1]



From *IEEE Trans. Electr. Insul.*, vol. **7**, no.1, pp. 9-15, 1972 [1]

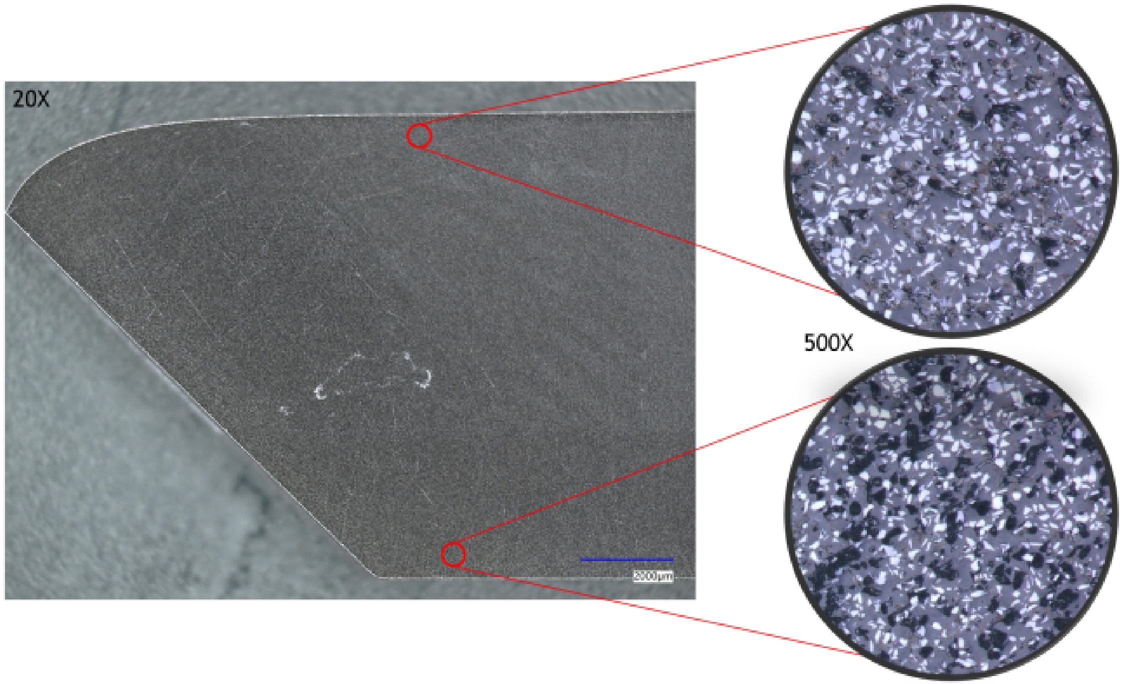
WE INVESTIGATE TWO CLASSES OF MATERIAL MODIFICATIONS

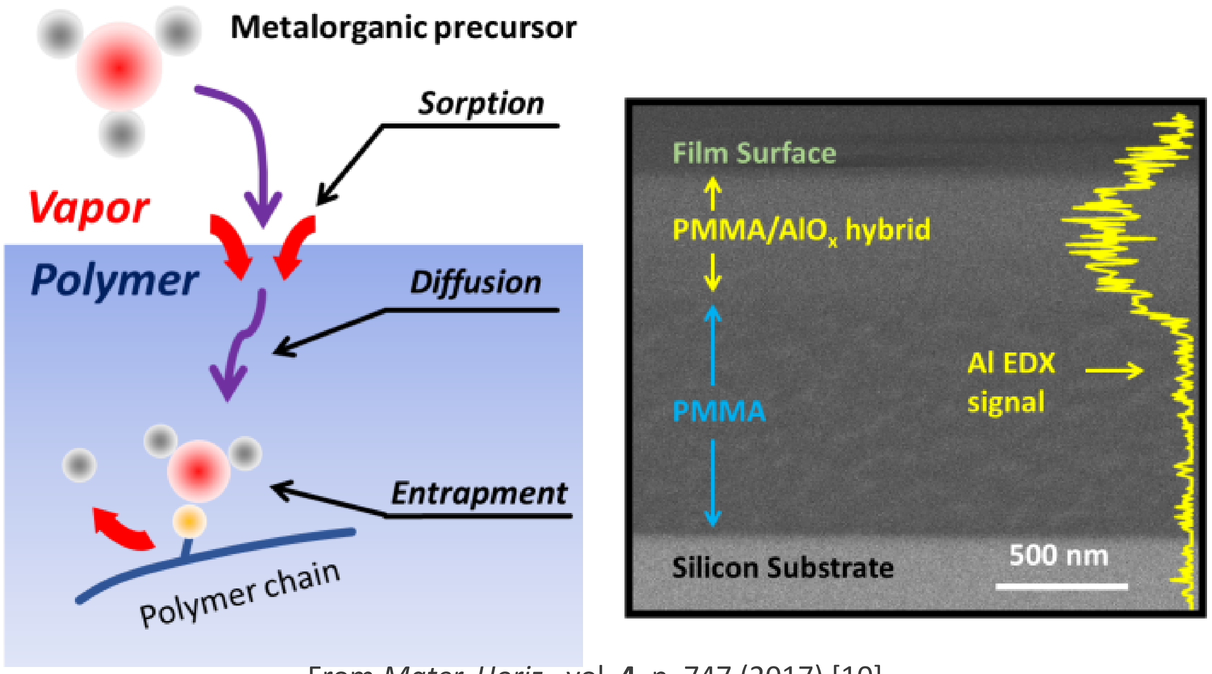
Volumetric Blending

- Baseline material: EPON828/DEA (100:12)
- Dopant material blended with uncured resin via planetary mixer and/or ultrasonic agitation
- Produces nearly uniform composite throughout entire sample

Vapor Phase Infiltration

- Baseline material: Poly(methyl)-methacrylate
- Dopant material infiltrated into near-surface polymer via exposure to metalorganic under elevated temperatures
- Produces high dopant concentrations near surface which exponentially decay into bulk



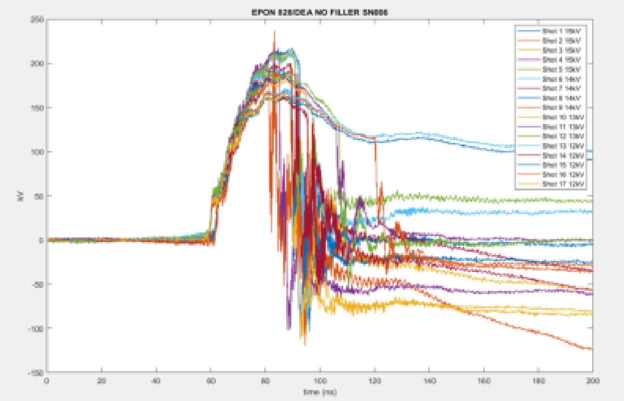


From *Mater. Horiz.*, vol. **4**, p. 747 (2017) [10]

THREE TEST FACILITIES HAVE ENABLED MEASUREMENTS OF FLASHOVER CONDITIONS AT COUPON SCALES

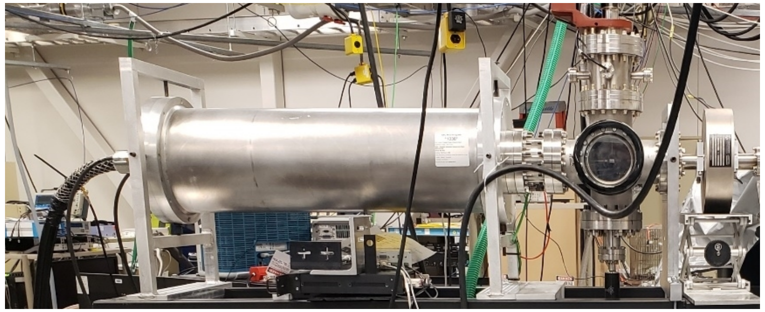
UNM Marx Test Bed

- 30-stage, 40 kV charge Marx
- 400 kV max operating voltage into vacuum
- 30 ns risetime
- Overdamped matching load



Ion Beam Laboratory PPEG

- 15-stage, 40 kV charge Marx
- 240 kV max operating voltage into vacuum
- 15 ns risetime
- Critically damped matching load
- Modified from pulsed power E-gun (PPEG) to accommodate vacuum insulator testing



Caeculus “son of Vulcan”

- 30-stage, 50 kV charge Marx
- 500 kV max operating voltage into vacuum
- 20 ns risetime
- Slightly underdamped matching load

INITIAL TEST DATA APPEARED TO INDICATE CB_4-EPOXY BLEND HAD UNPRECEDENTED FLASHOVER RESISTANCE

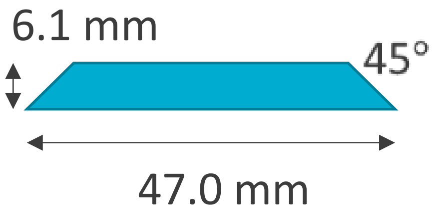
Samples of undoped EPON828/DEA, Rexolite cross-linked polystyrene, and 25 vol% CB_4 in EPON828/DEA were tested for flashover on the UNM and IBL PPEG test stands

- Forward bias on UNM test stand
- Reverse bias on IBL PPEG

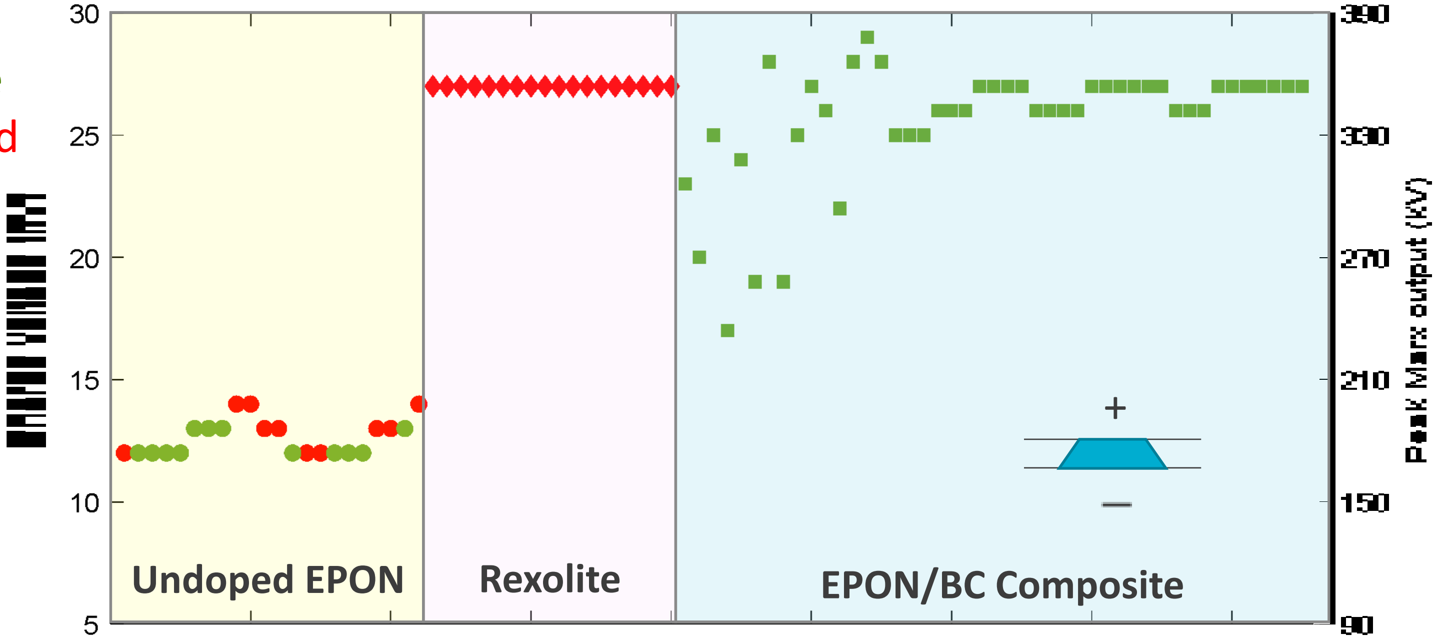
The carbide composite never broke down under highest achievable test conditions

Green: Held off full pulse

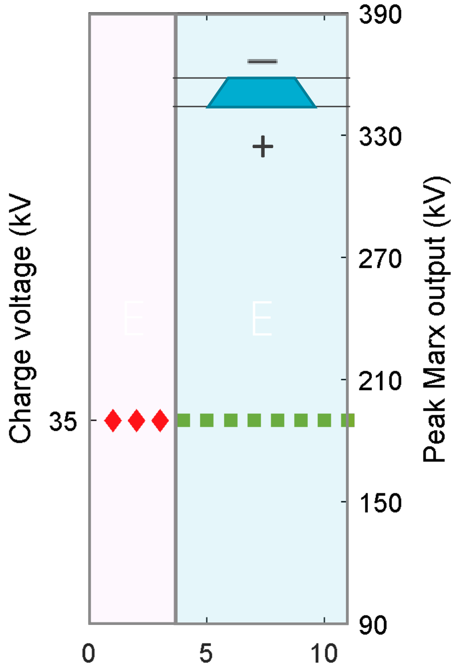
Red: Breakdown occurred



UNM Marx



IBL PPEG



SAMPLE MEASUREMENTS INDICATE LITTLE CHANGE AT THE SURFACE DUE TO THE CB_4 INCLUSIONS

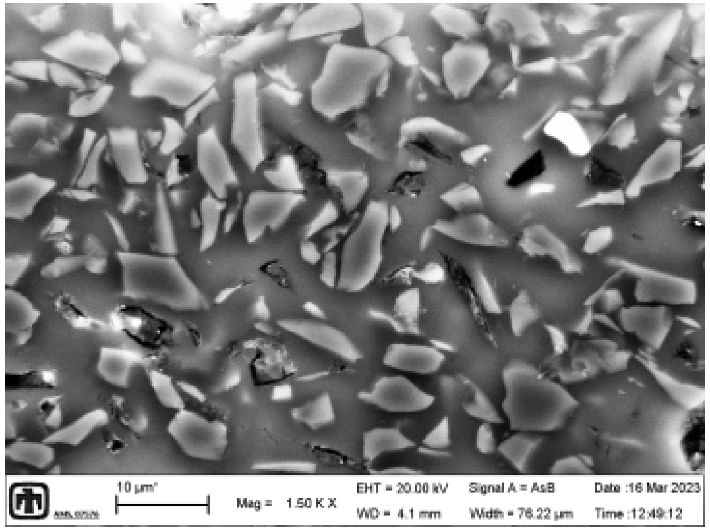
Secondary emission yield measurements similar between carbide blend and undoped epoxy

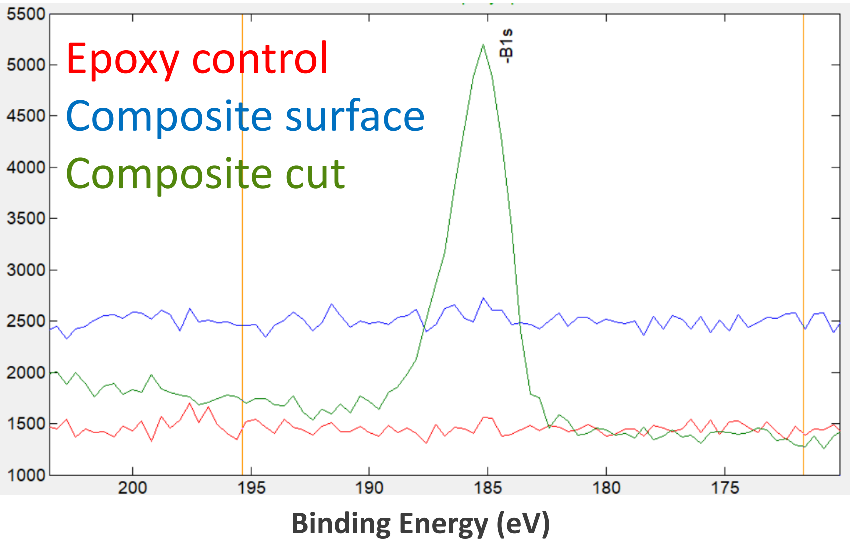
- First crossover energy, peak yield slightly more favorable in *undoped* sample (see poster by Kern)

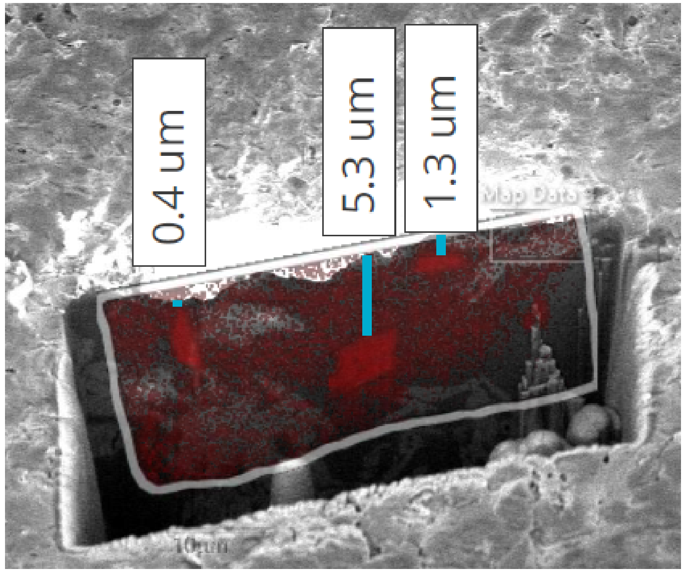
X-ray photoelectron spectroscopy (XPS) showed boron only detected on cut surface (detection depth ~10nm)

- Laser-induced breakdown spectroscopy (LIBS) indicated large jump in boron concentration between 2 and 3 μm

Interface difficult to resolve on SEM images; focused ion beam extracted sample under TEM showed CB_4 particles at least several hundred nm from surface



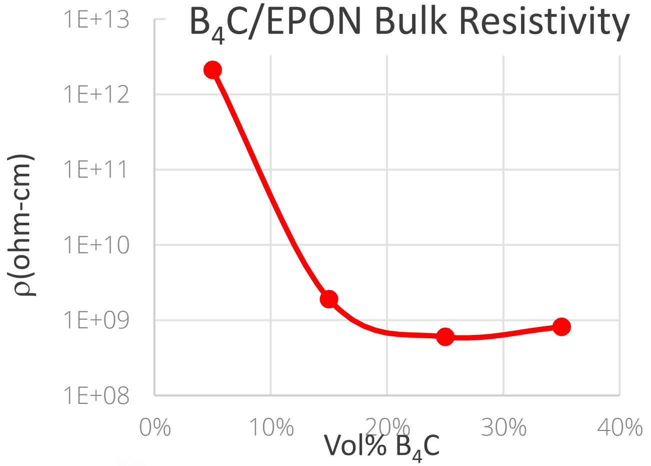


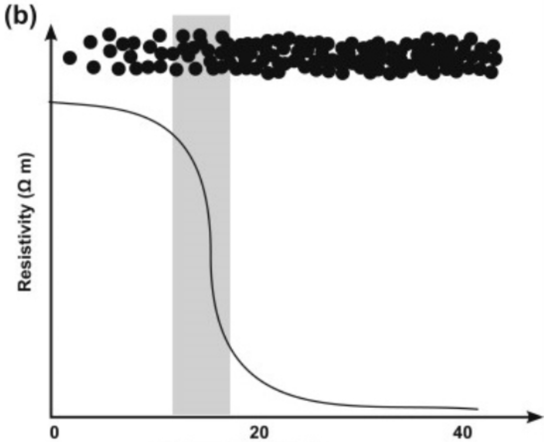


CONDUCTIVITY MEASUREMENTS INDICATE A PERCOLATION-ENHANCED SAMPLE CONDUCTANCE WHICH CAN SELF-GRADE FIELD

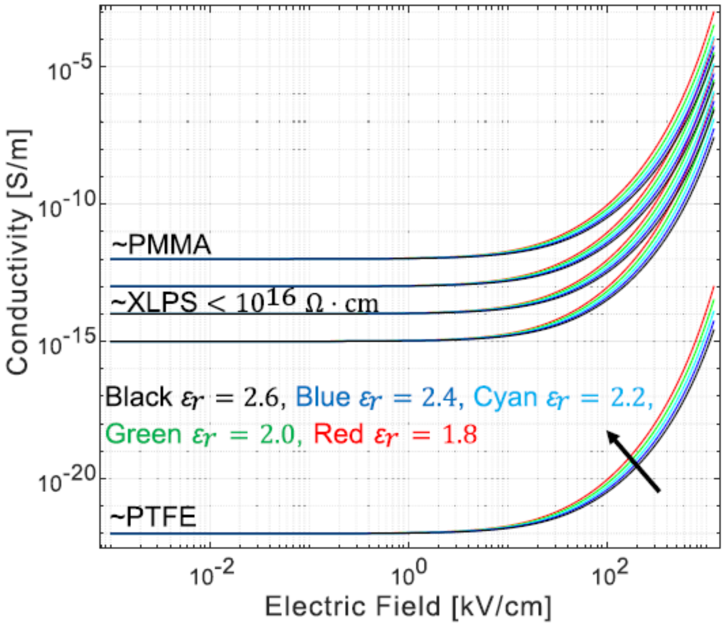
Measurements made at 1,100 V with 1mm spacing electrodes (11 kV/cm)

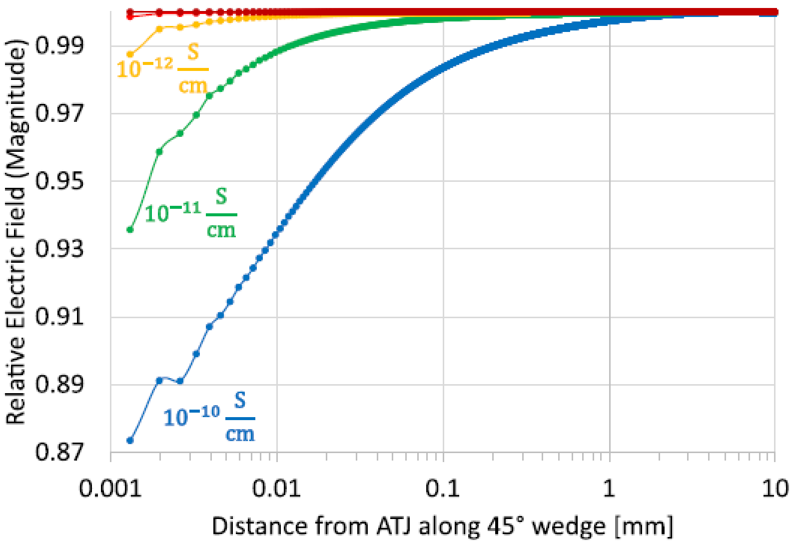
Theoretical percolation threshold for α ~ 3-4 CB_4 microparticles around 12-17%





Carbide composite $\epsilon_r \approx 3.5$ (CB_4 $\epsilon_r = 6.4$)

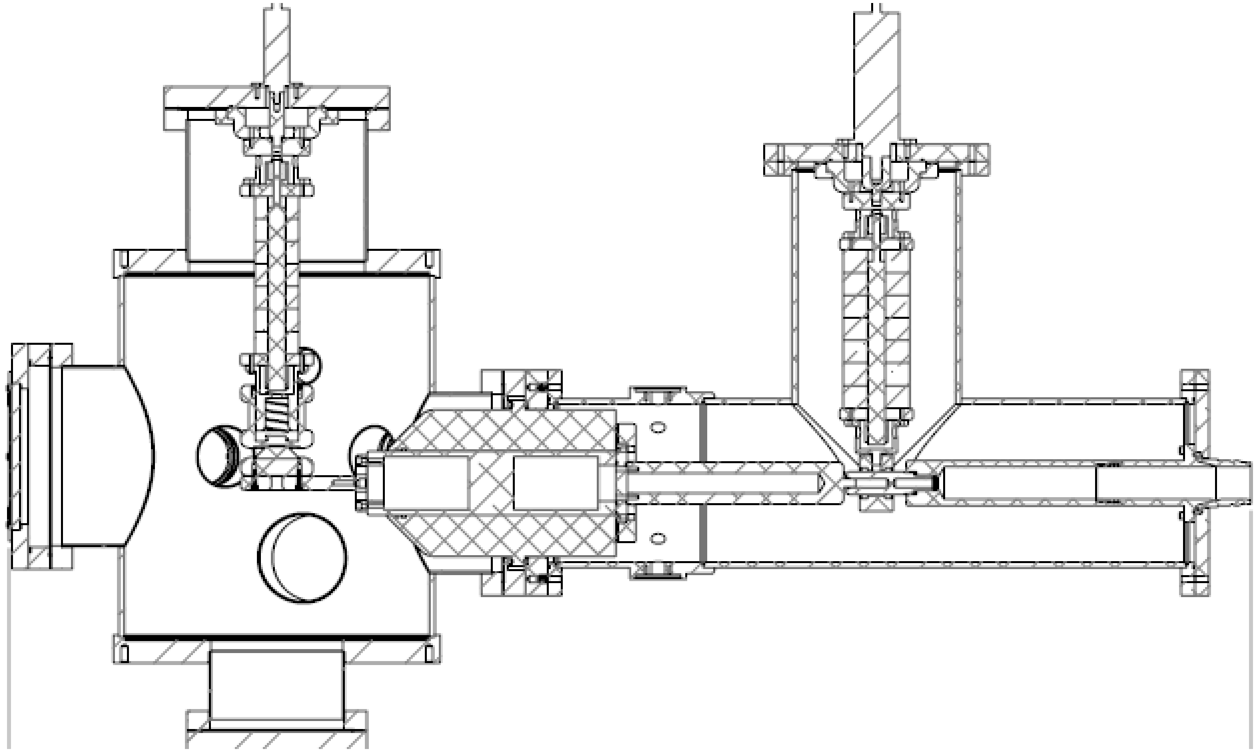




(left) From *Carbon Nanotube Reinforced Composites : CNT Polymer Science and Technology* (2014) [11]

(top middle, top right) From *IEEE Trans. Plasma Sci.*, vol. **50**, no. 10, pp. 3361-3370 (2022) [2] cf. [12]

EXPERIMENTS ON CAECULUS INDICATE SAMPLE RESISTANCE DROPS MORE THAN PREDICTED AT ACCELERATOR-RELEVANT FIELDS



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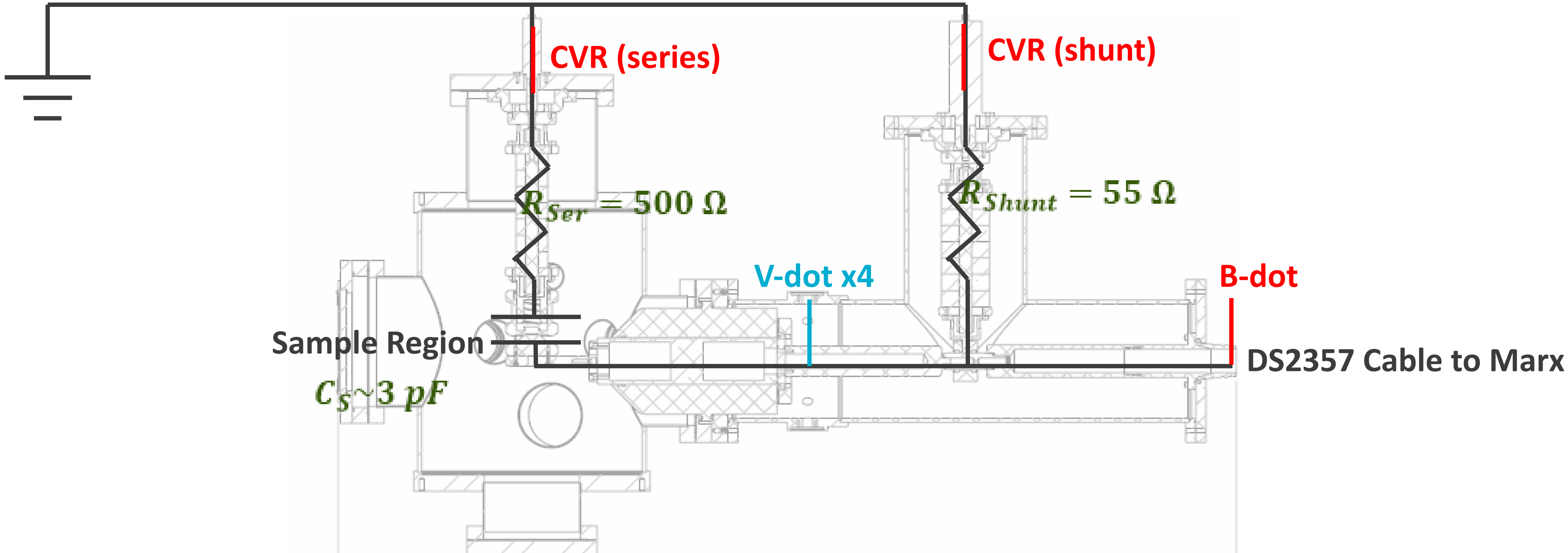
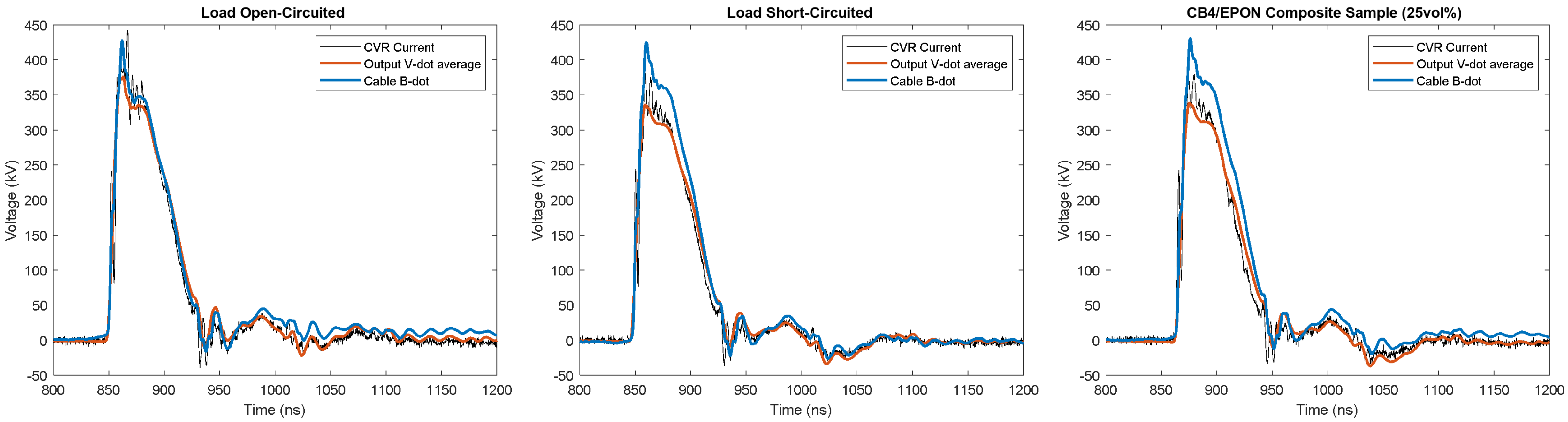


EXPERIMENTS ON CAECULUS INDICATE SAMPLE RESISTANCE DROPS MORE THAN PREDICTED AT ACCELERATOR-RELEVANT FIELDS

Composite sample nearly indistinguishable from a short-circuit load region

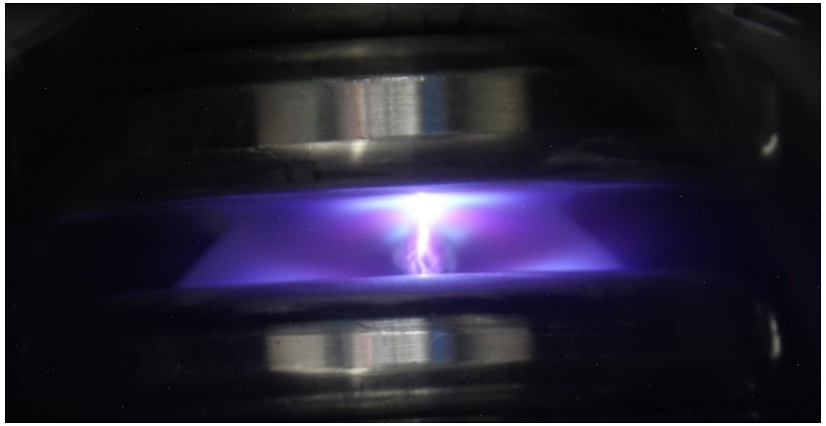
Estimated sample resistance with series resistor shorted is 20-30 ohms

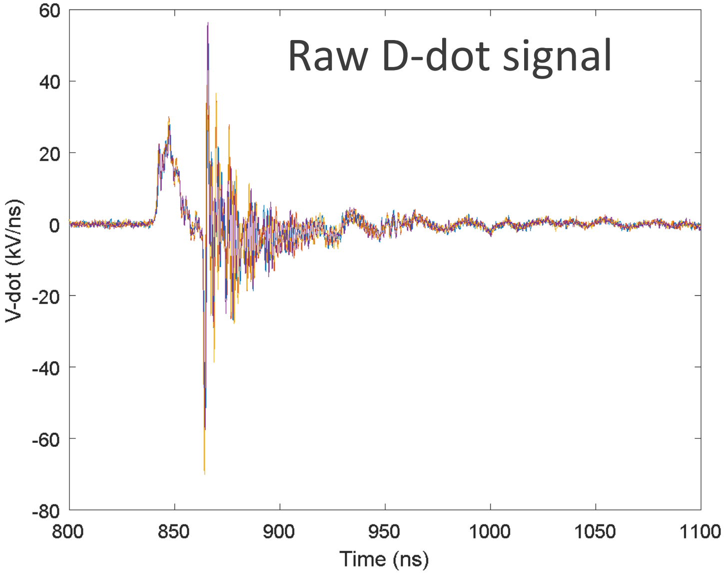
- Too low to drive to the 300 kV/cm fields that break down Rexolite

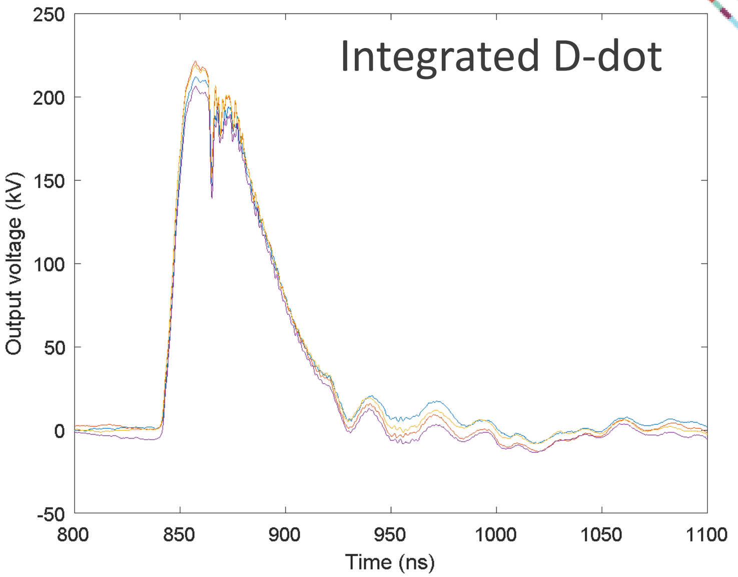


ENHANCED CONDUCTIVITY OF CB_4 COMPOSITE APPEARS TO DISRUPT ELECTRICAL IMPULSE FROM FLASHOVER ARC

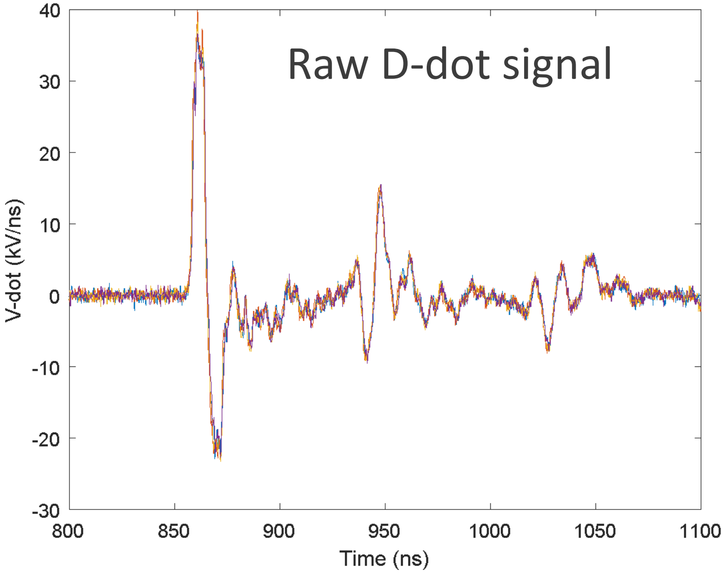
Neat EPON828/DEA

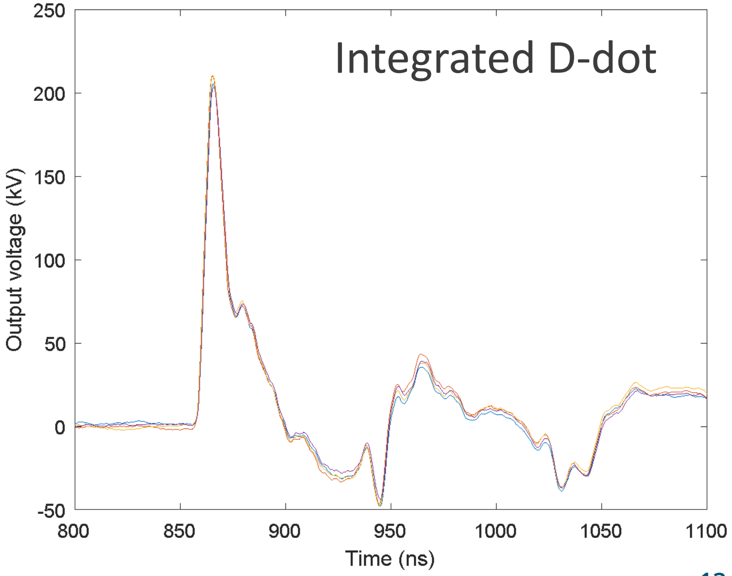






Boron carbide composite





CONCLUSIONS AND FUTURE WORK

We compared flashover behavior between EPON828/DEA, Rexolite, and a carbide/epoxy composite on multiple test fixtures

The apparent superiority of the carbide-epoxy composite is attributable to an enhancement in field-dependent conductivity which lowers the peak field on the sample for a given output Marx voltage

When the carbide material undergoes flashover, the flashover plasma is optically dimmer and electrically “quiet,” suggesting the arc does not become as conductive as flashovers of pure insulators

Future planned experiments:

- Look at other dopant materials and concentrations (we have a backlog of samples)
- Compare VPI modified and unmodified acrylic samples
- Explore coatings of composites on bulk insulating materials

REFERENCES

[1] O. Milton, "Pulsed Flashover of Insulators in Vacuum," *IEEE Trans. Electr. Insul.*, vol. **7**, no.1, pp. 9-15, 1972.

[2] W. Brooks *et al.*, "Exploring the Basic Physical Mechanisms of Cathode- and Anode-Initiated High-Voltage Surface Flashover," *IEEE Trans. Plasma Sci.*, vol. **50**, no. 10, pp. 3361-3370, 2022.

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