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Fundamental Study of High Electric Field Surface Flashover in Vacuum

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National Nuclear Security Administration

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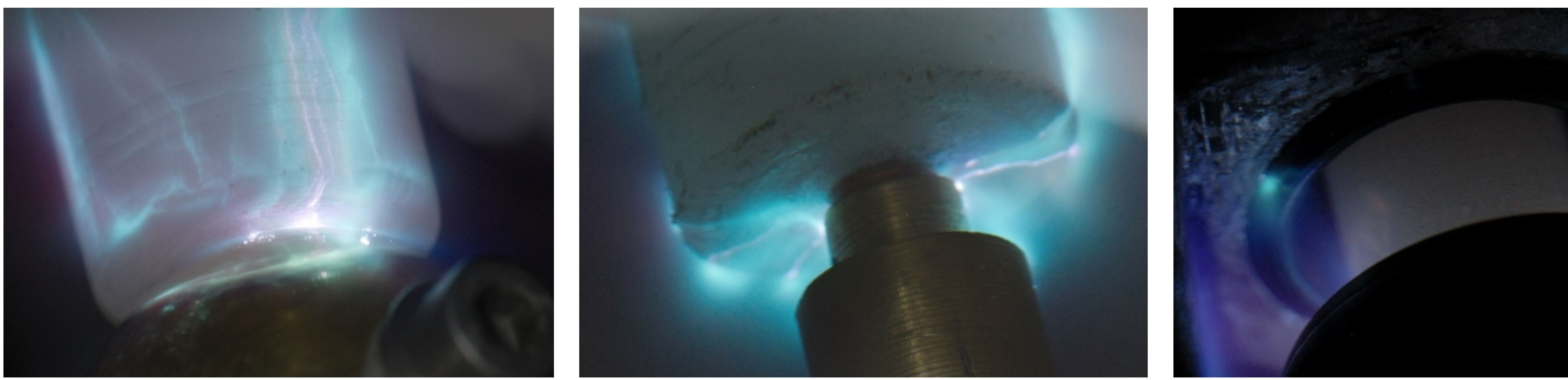
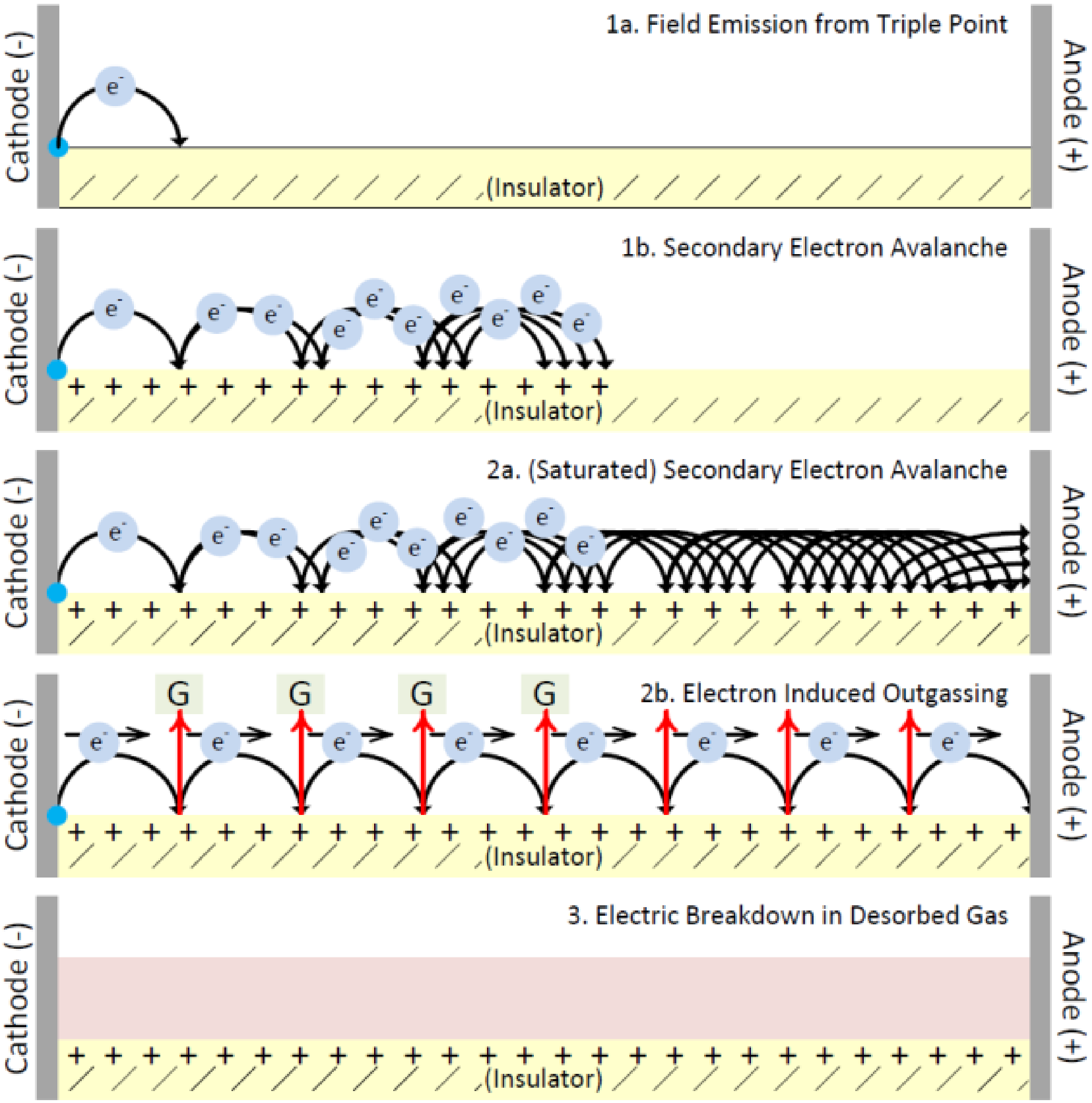
Motivation

- Dielectric hold-off of vacuum is much greater than the surface flashover threshold of insulators.
  - Improve body of evidence for anode initiated vacuum flashover.
  - Large pulsed power machines are geometrically constrained.
  - Inform design of large pulsed power infrastructure.



Selected images of pulsed breakdown of high-voltage vacuum feed-though initially used in experimental setup. Issue became apparent when pushing to higher voltages of latest insulator geometry.

Cathode Initiated Surface Flashover



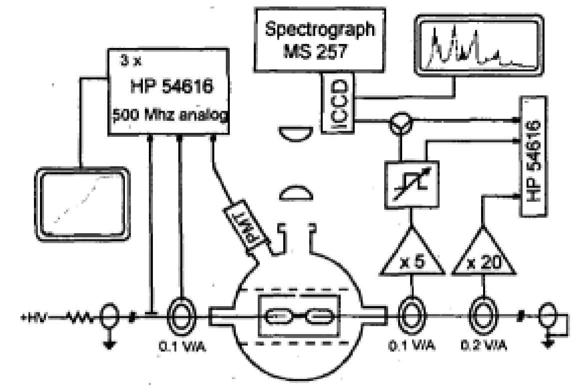


Figure 1. Schematic of the experimental setup for unipolar surface flashover. One way transit time of charging and load coaxial line is approx. 135 ns.

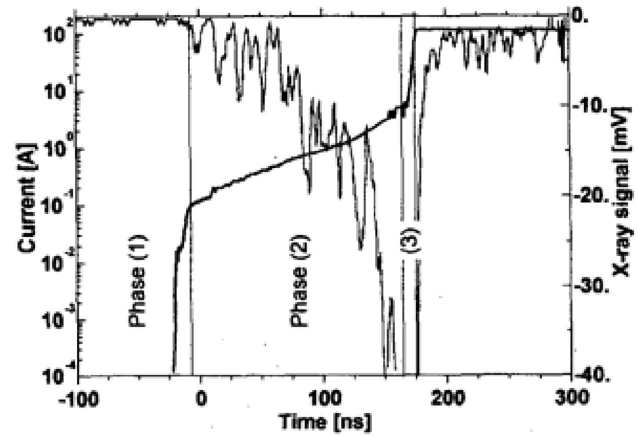
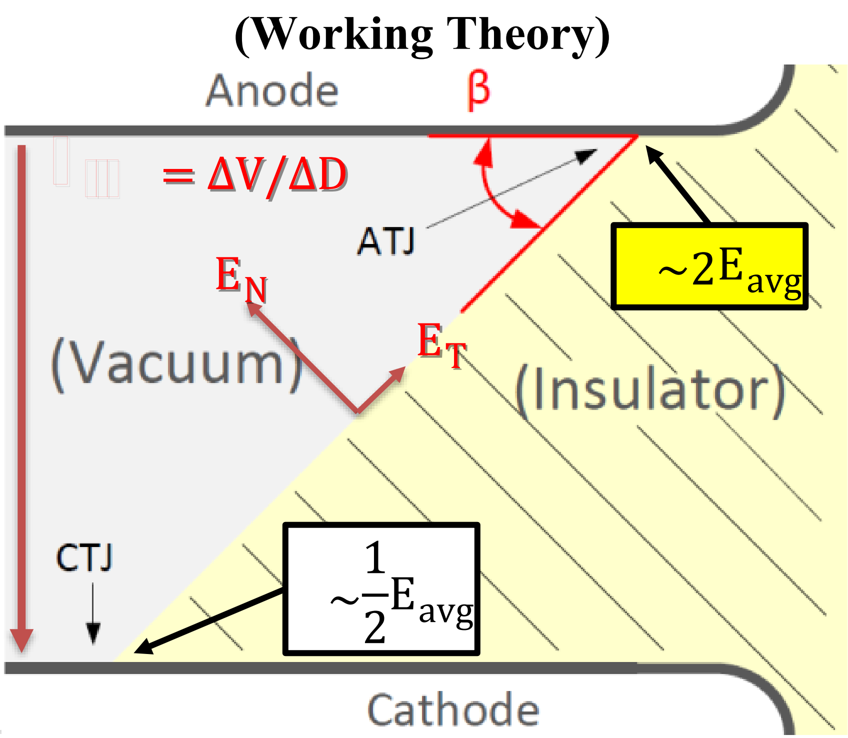
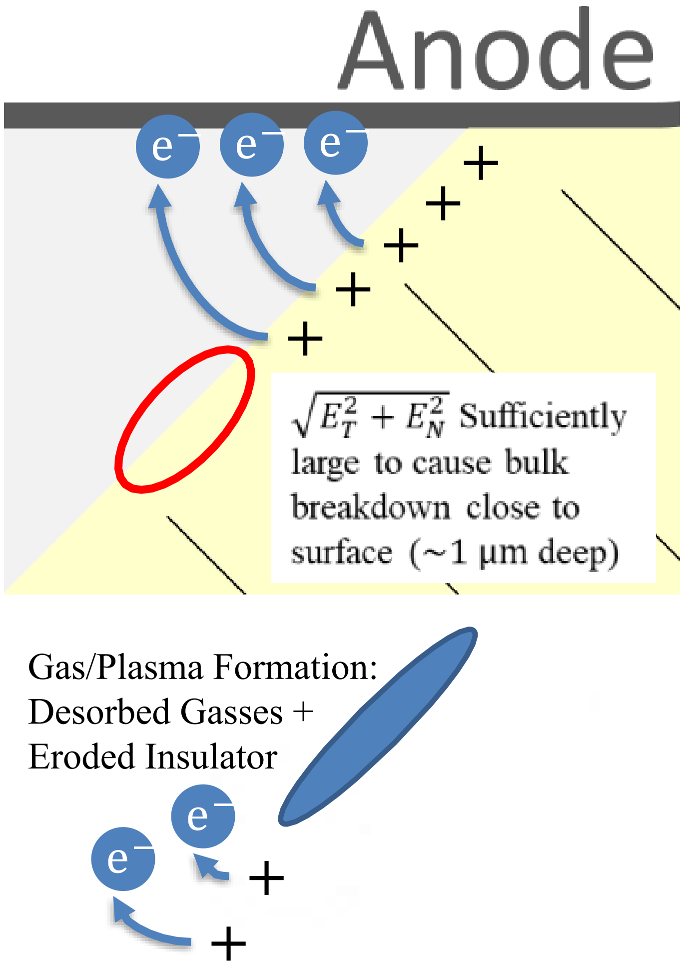


Figure 2: Experimental current and x-ray emission at a breakdown voltage of 11.4 kV.

Neuber, A. et al. The role of outgassing in surface flashover under vacuum *Digest of Technical Papers. 12th IEEE International Pulsed Power Conference. (Cat. No.99CH36358)*, **1999**, *1*

Anode Initiated Surface Flashover





Note:

- Anode initiated flashover dominates due to (ATJ, CTJ)
- Initiation *may* be due to degassing, not surface breakdown
- Interest in whether field-emitted electrons liberate adsorbed gasses on the dielectric surface.

- Stygar et al. Flashover of a vacuum-insulator interface: a statistical model *Phys. Rev. ST Accel. Beams, American Physical Society,* 2004, 7, 070401
- Stygar et al. Improved design of a high-voltage vacuum-insulator interface *Phys. Rev. ST Accel. Beams, American Physical Society,* 2005, 8, 050401

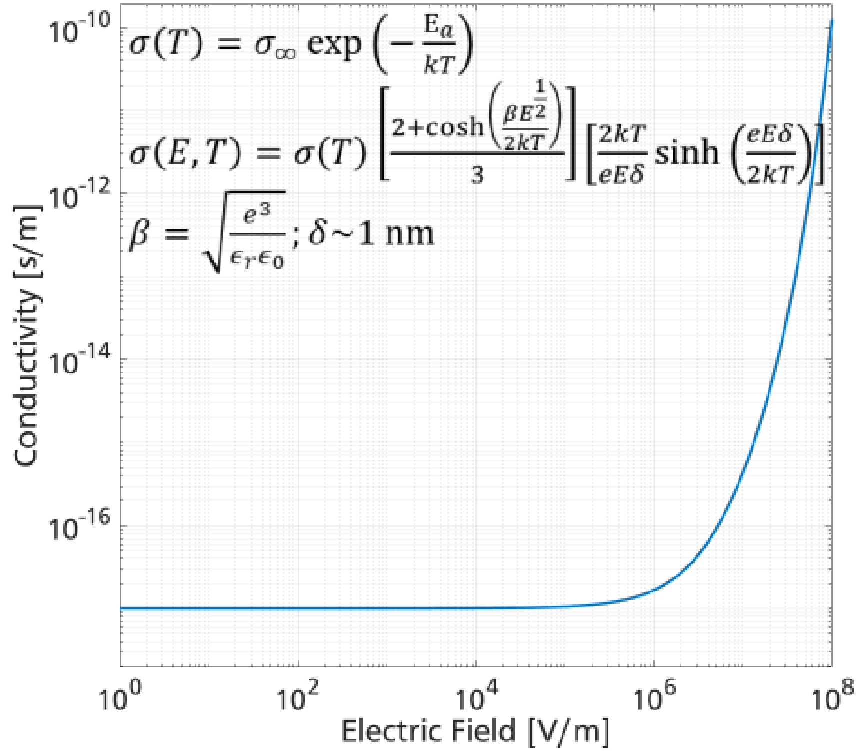
Role of Material Selection

Materials of Interest

- Acrylic (PMMA)
- Polystyrene (PS)
- Rexolite 1422 (XPS)
- Nylon MC901

Conduction in the Insulator

Lai, S. T. “Deep dielectric charging,” in Fundamentals of spacecraft charging: spacecraft interactions with space plasmas , Princeton University Press,**2012**. pp. 151-152

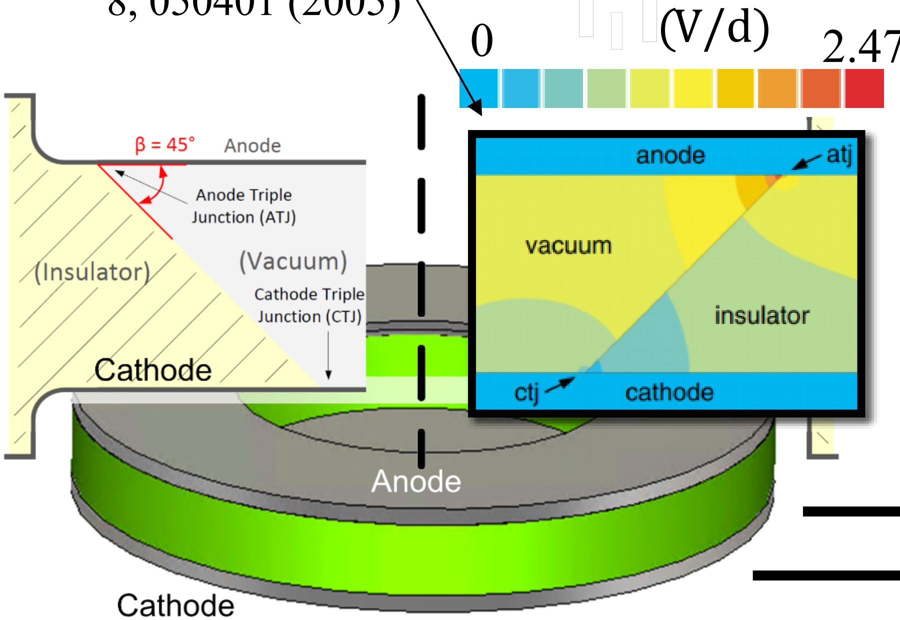


Qualitative plot of the equation above for typical insulator.

Vacuum Interface Design

Improved design of a high-voltage vacuum-insulator interface

- W. A. Stygar et al. 2005, Physical Review Special Topics – Accelerators and Beams 8, 050401 (2005)



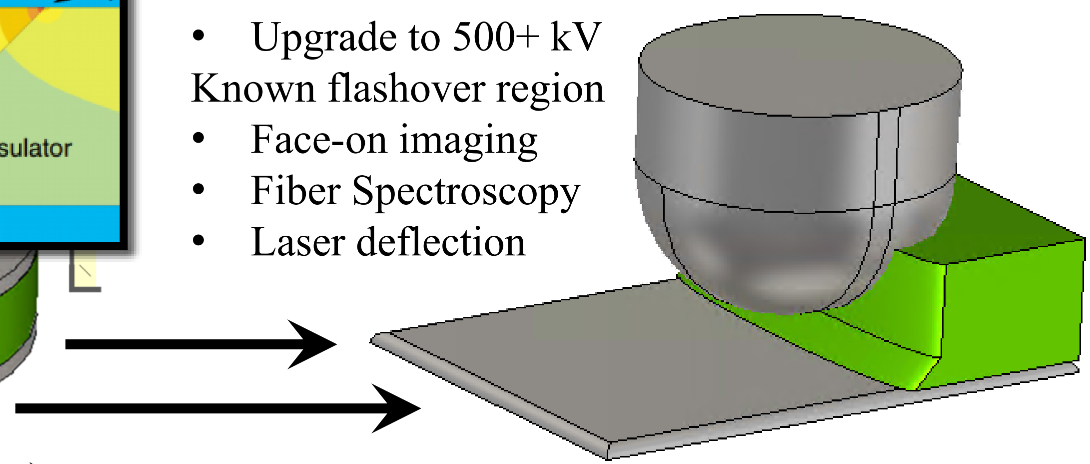
(Stygar-Like Topology)

TTU Design with Improved Diagnostic Accessibility

Smaller insulator
- 4 cm x ~40 cm OD versus 5 cm x 10 cm x 4 cm
- Faster/cheaper turn-around

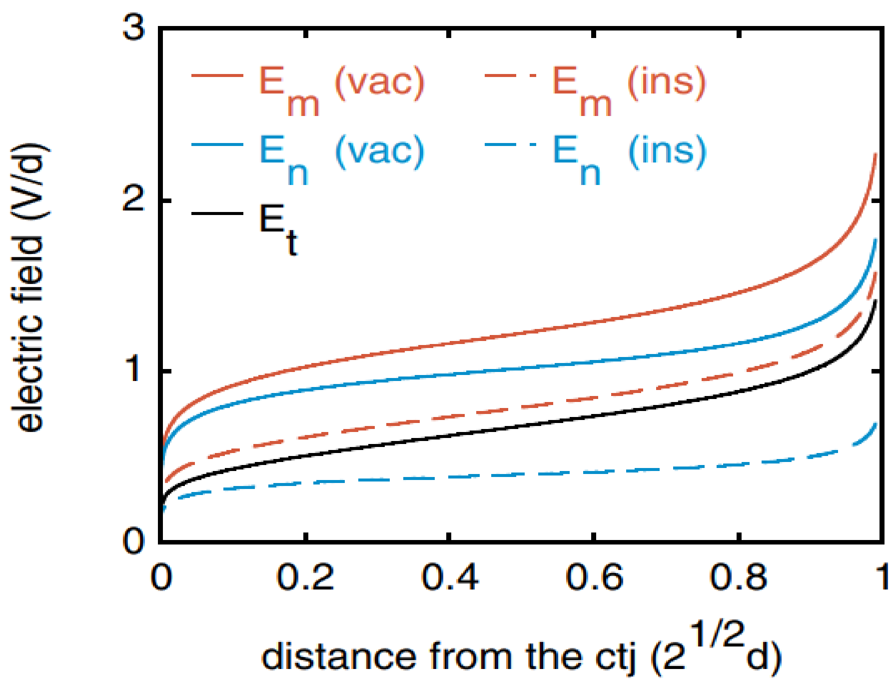
Smaller gap (0.6 cm versus 4.3 cm)
- 240 kV versus 2.2 MV
- Upgrade to 500+ kV

Known flashover region
- Face-on imaging
- Fiber Spectroscopy
- Laser deflection

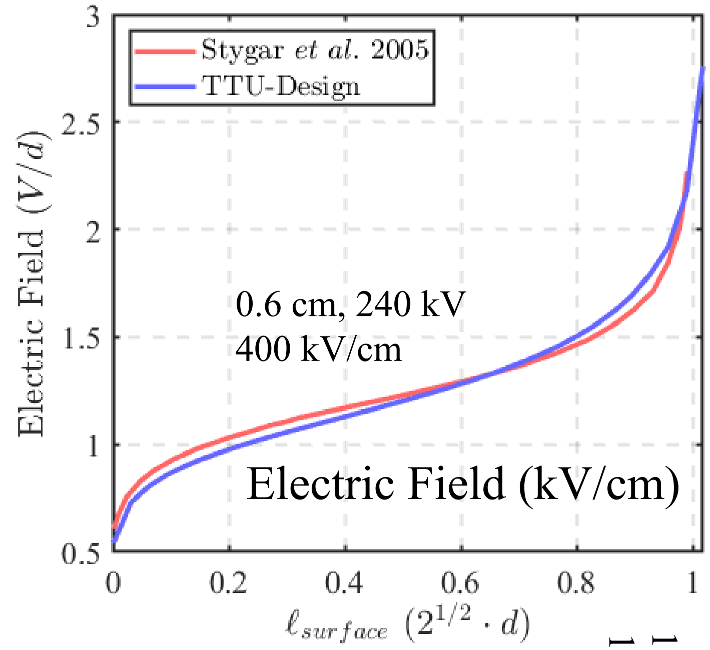


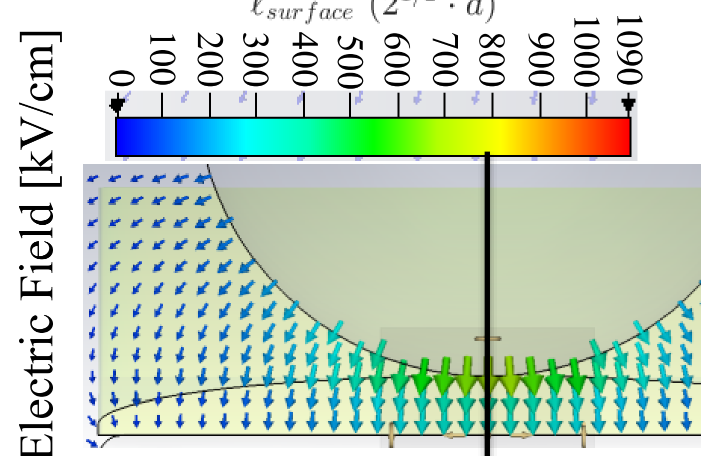
Fields Along the Insulator Surface

W. A. Stygar et al. 2005, Physical Review Special Topics – Accelerators and Beams 8, 050401 (2005)



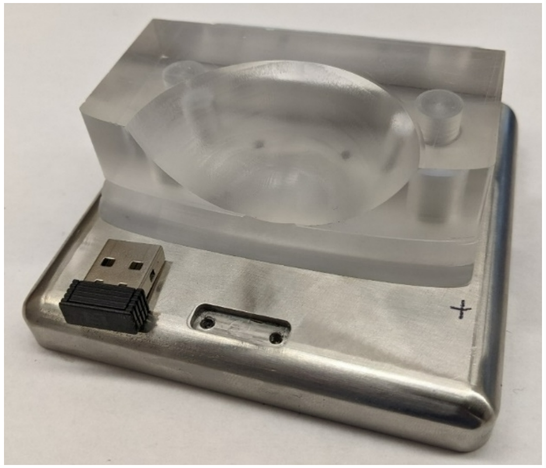
"The quantity E_n is the absolute value of the electric field normal to the interface, Et is the absolute value of the field tangent to the interface, and $E_m = (E_n^2 + E_t^2)^{1/2}$. The fields are given in units of V/d, where V is the voltage across the insulator and d is the insulator thickness […]"





*240 kV applied (without breakdown)

Insulator Testbed



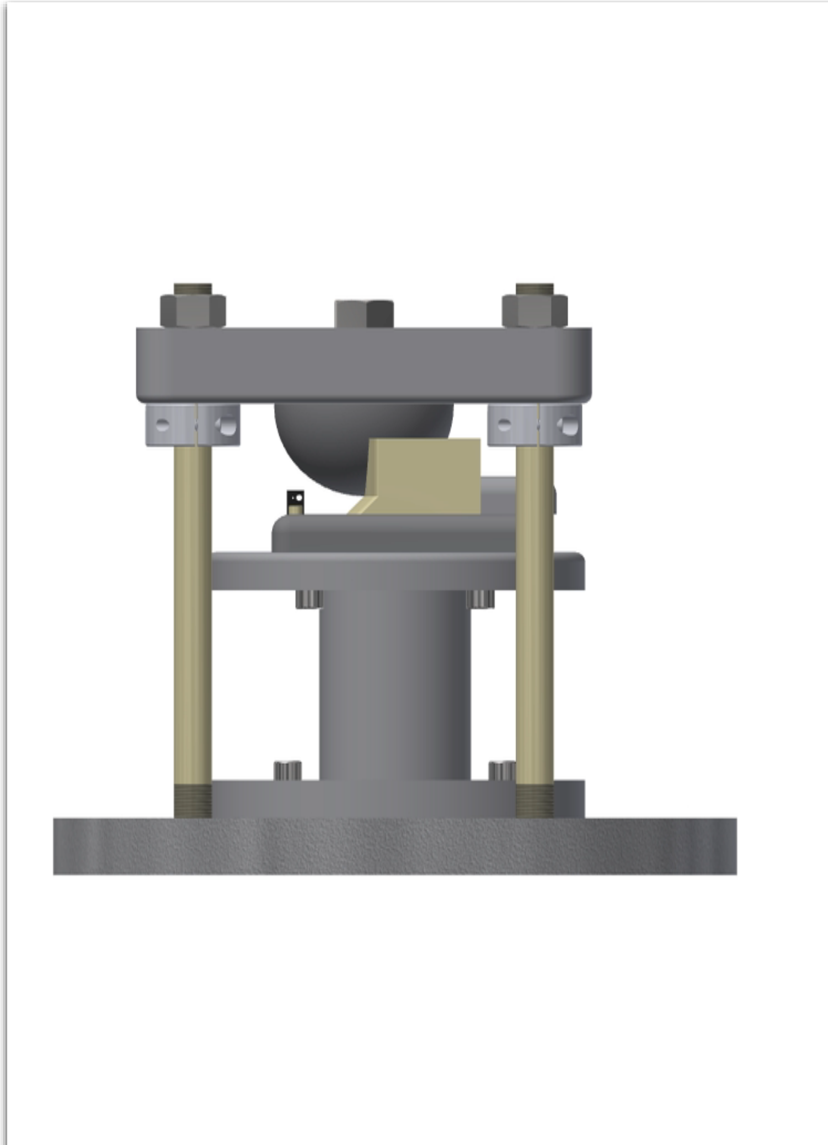
Physical Dimensions

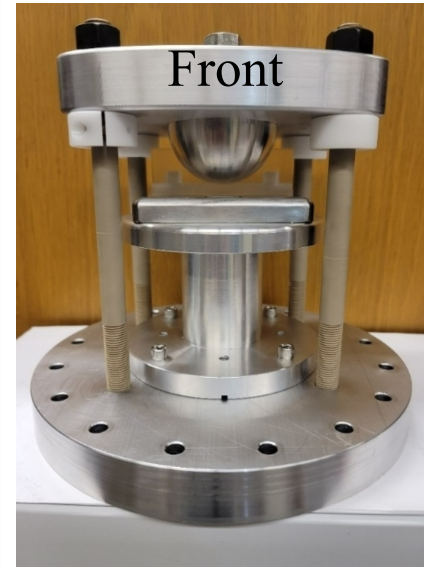
Insulator
79.38 mm (3.125 in) Wide
25.40 mm (1.00 in) Tall

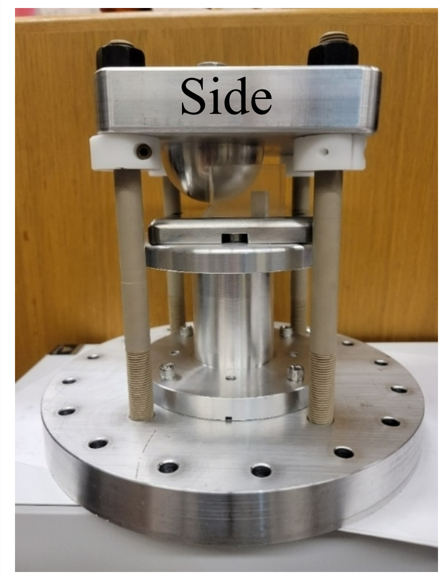
Wedge
45 Degrees
6 mm Vertical

Anode
30 mm radius

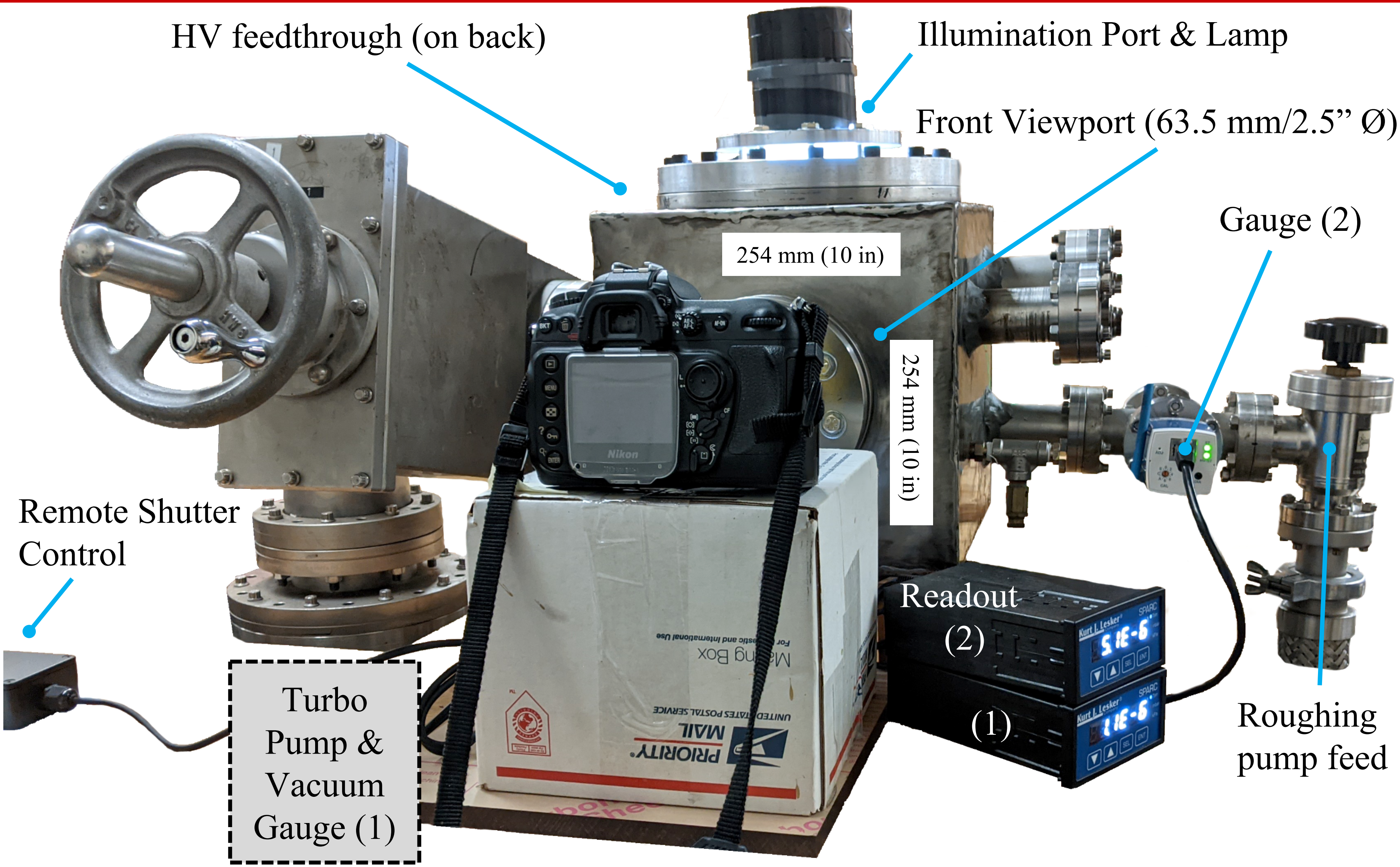
Cathode
95.25 mm (3.75 in) Wide
88.90 mm (3.50 in) Deep







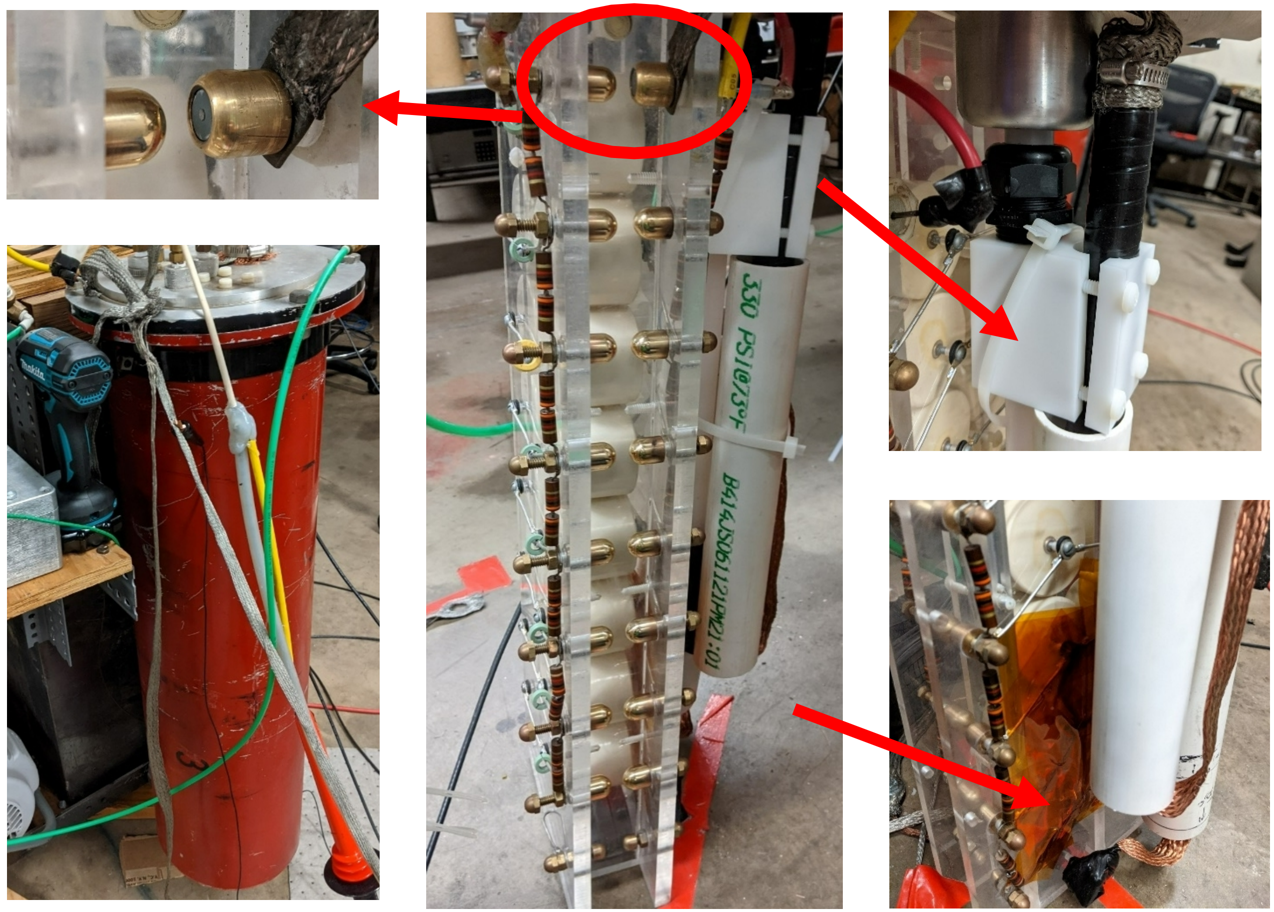
Experimental Apparatus (R.0)

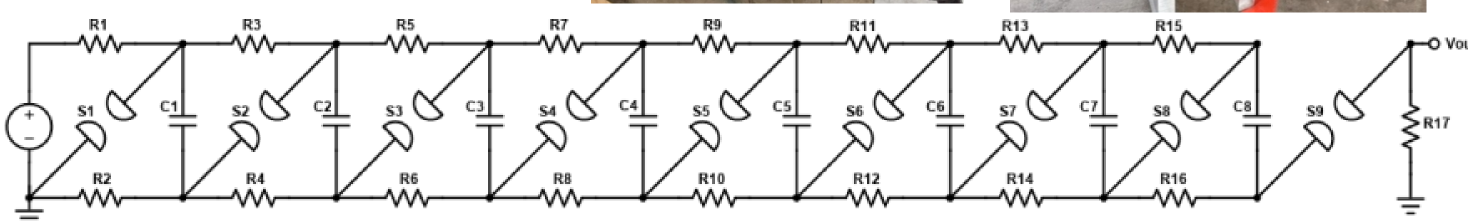


Marx Generator (Source)

Pressurized Marx
- 18 PSI_G N_2
- Triggered First Gap
- 8 Stages
  - 5.4 nF / Stage
- 675 pF Erected
- Negative Charge
  - Typical (−)30 kV
- Positive Discharge
  - ~18 ns Rise Time
  - > 180 kV Output

Output
- Internal 2200 Ω Shunt
- (System) ESR 30 Ω
- (System) ESL 1.8 μH

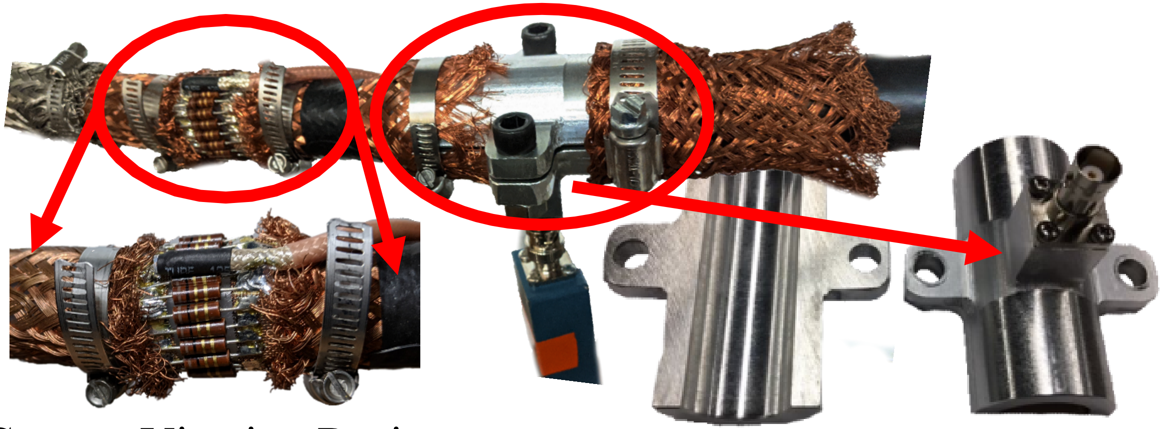




Top: Selected Image of Marx Generator

Left: Corresponding Schematic

Current and Voltage Diagnostics



Current Viewing Resistor
~ 50 mΩ

Capacitive Voltage Divider

CVR Calibration

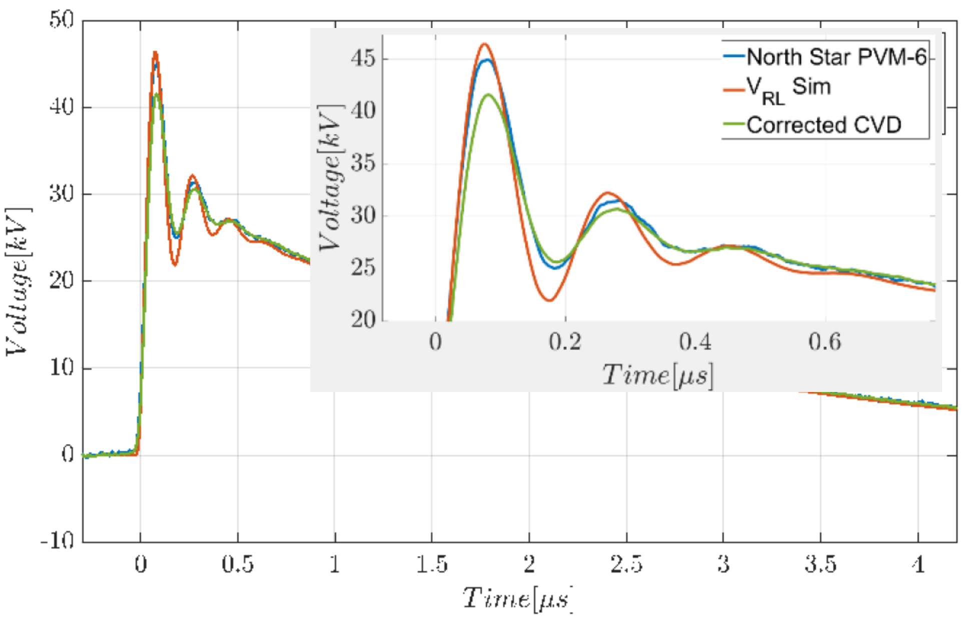
- Pearson 110
- Pearson 6585

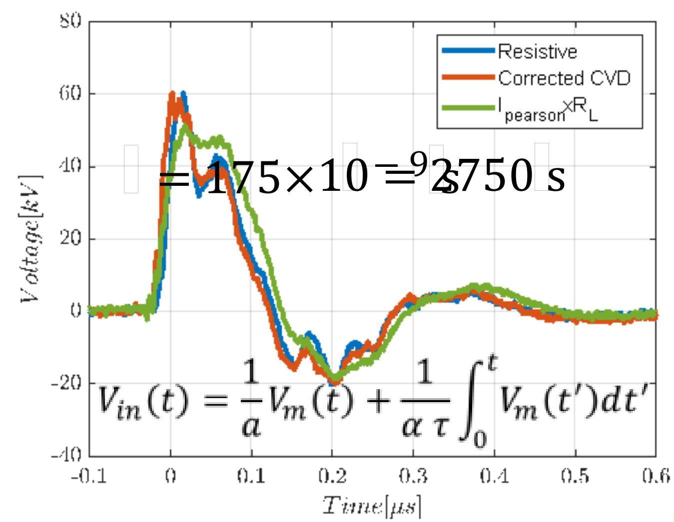
CVD Calibration

- NorthStar PVM-6
- Current * Load

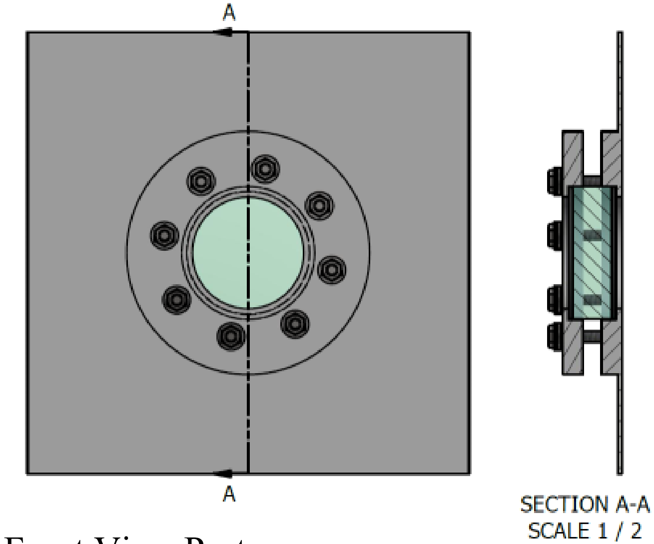
External Cabling

- Length Matched
- *OTT*: (70.72 ± 0.28) *ns*





Optical Imaging of Flashover



Front View Port
- (Present) PMMA, 2.5" Diameter
- (Future) Optical-UV Transmissive

Nikon D200
Sigma 18-300 mm F3.5-6.3 DC Macro
Edmund Optics 75 mm x 300 mm FL
(VIS 0 Ar. Coated, Achromatic Lens, 88-594)

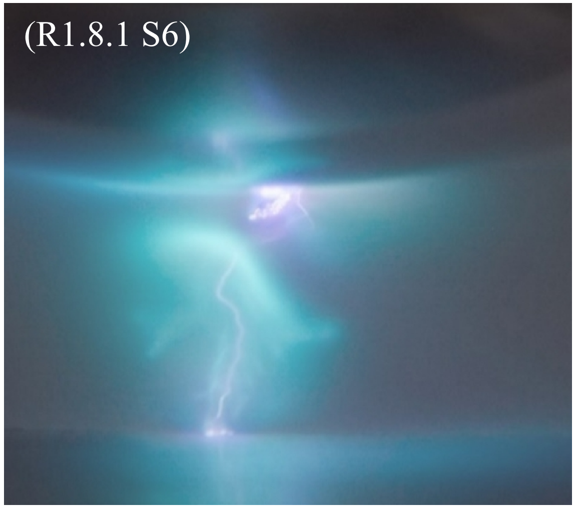
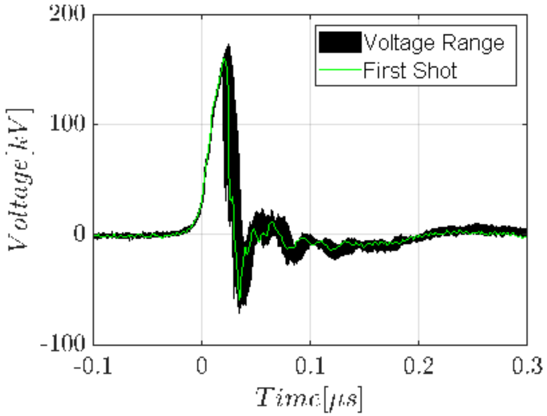
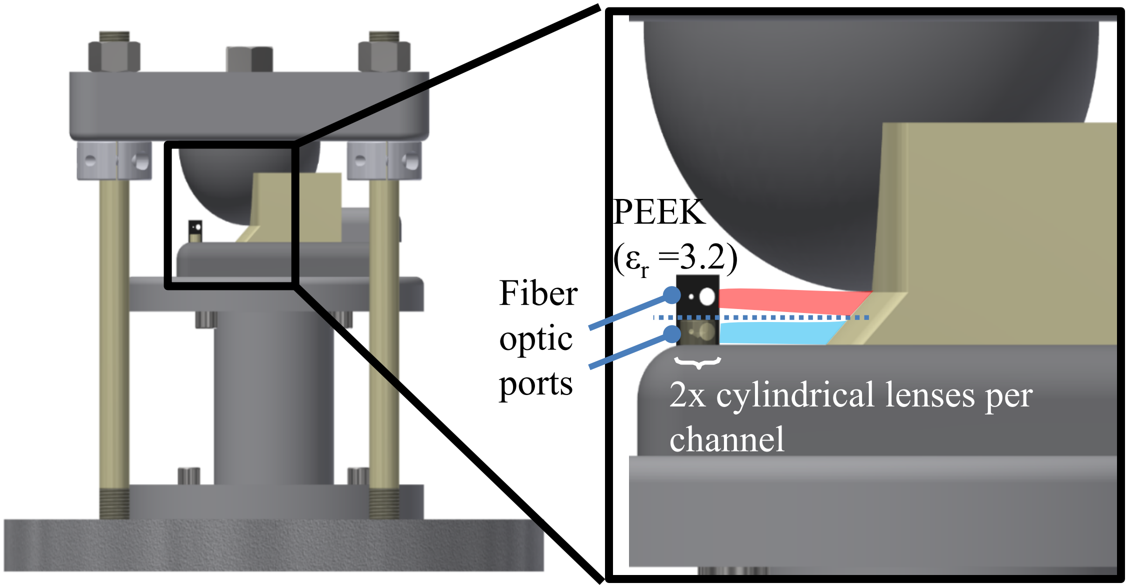


Image R1.8.1 S6
Variable focus allows an image to resolve between: (a) the full width of the insulator and (b) just the wedge.

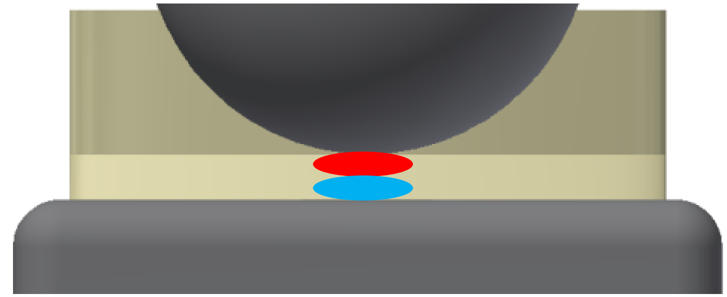
In Progress
- Optical Trigger by Spark Gap Light
- Time Resolved Photography

Princeton Pi-MAX 4
- Intensified CCD
- Sub-500 ps gate

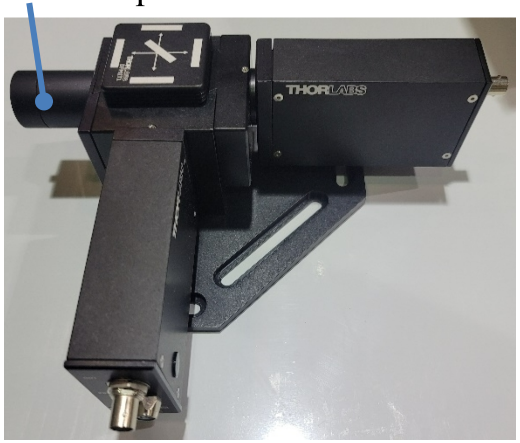




Forms ~3 mm Height regions
- Allows spatially resolved light
- Dedicated: anode; cathode view

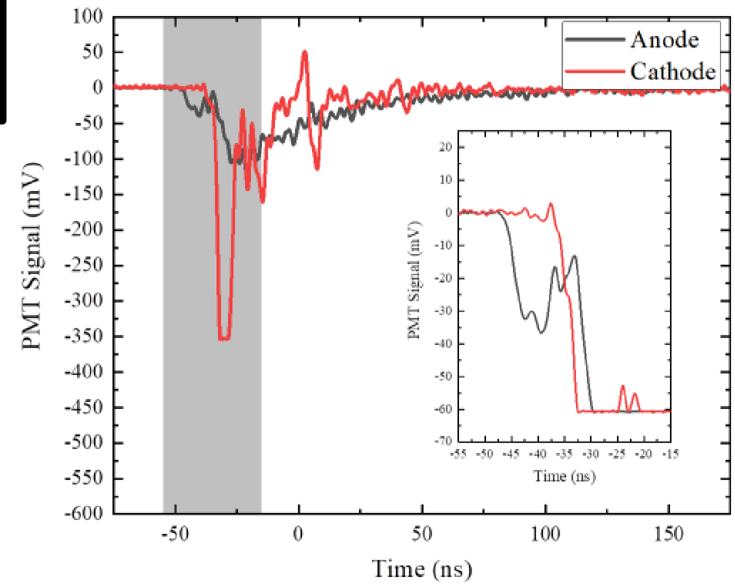


Fiber input



2x Dual-Channel PMTSS
- Temporally resolved light intensity
- Spectral response (185 to 900) nm
- Optional beam splitter for limited spectral resolution

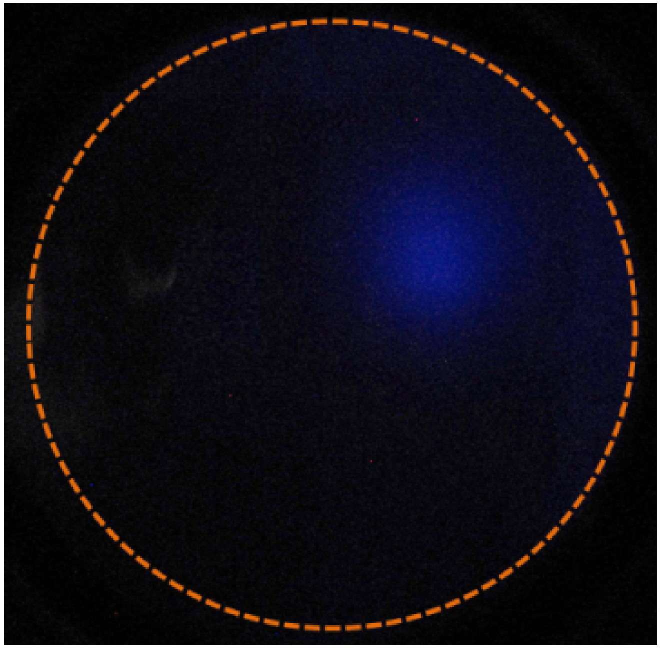
Planned:
- ns gated spectrography with Pi-MAX ICCD



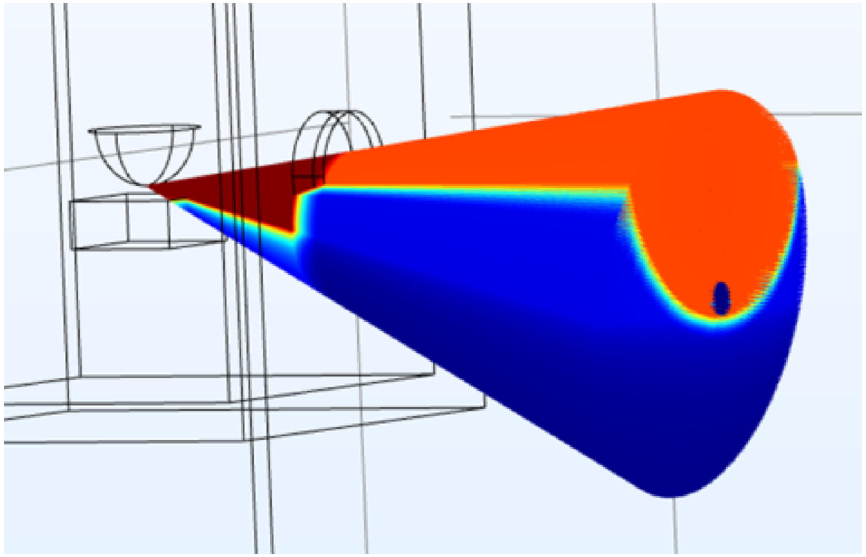
(Prelim.) Early light activity at the anode for breakdown in atmospheric air for 1 cm gap.

X-Ray Diagnostics

- Spatiotemporally resolve X-ray emission from anode
  - Scintillator images using high-speed ICCD camera
- (Initial) approach: pinhole in the chamber sidewall
- (Present) minimal light output from the scintillator.
  - Exploring insertion of scintillation material into the anode to increase x-ray intensity incident on the scintillator.



Initial photograph of scintillator operation inside vacuum chamber. Origin of X-Rays unclear, suspect breakdown to Aluminum covering.

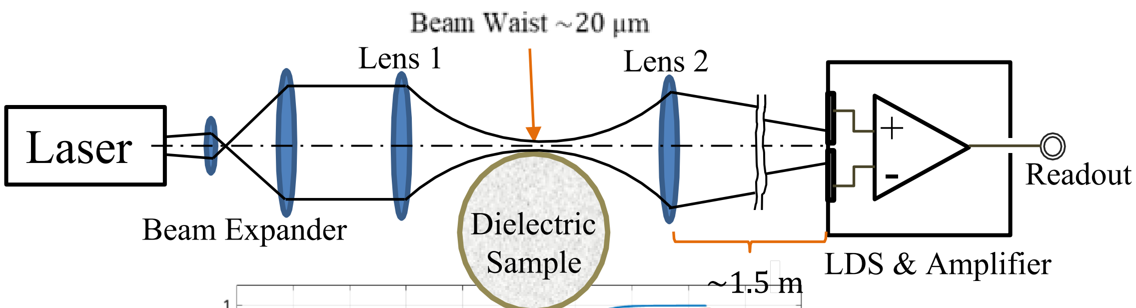


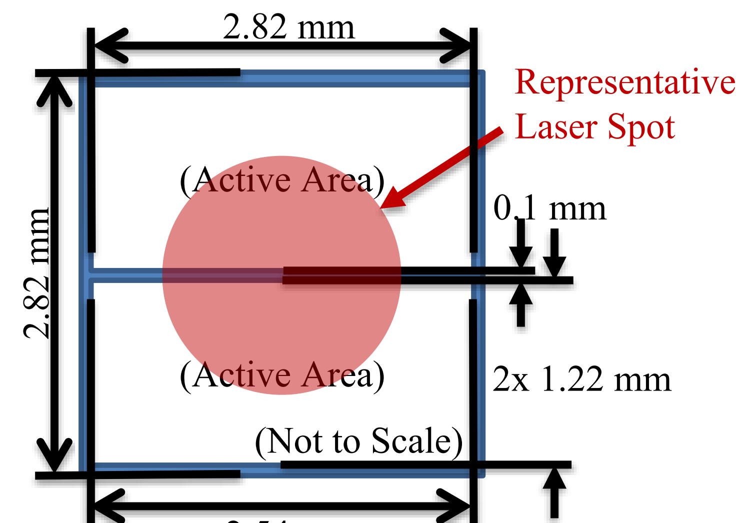
COMSOL Ray-Tracing simulation of X-Ray emission from anode.

Laser Deflection by Gas Desorption

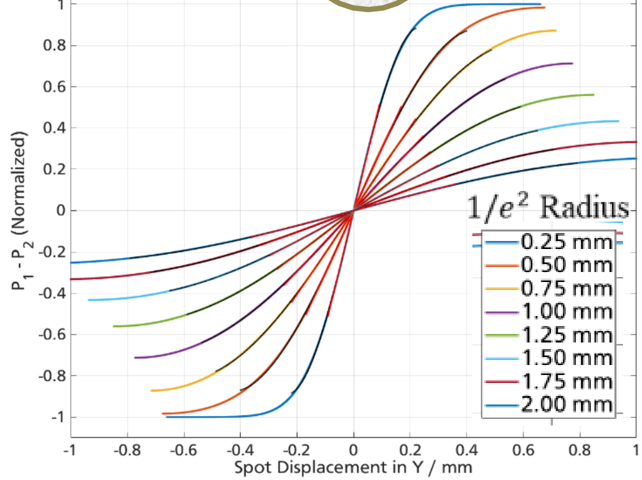
Originally proposed by Enloe et al. in "Fast, sensitive laser deflection system suitable for transient plasma analysis":

$$\delta\varphi = \frac{1}{n_0}\left|\int_{path} \nabla n \, ds\right| = \frac{D\,|\langle \nabla n \rangle|}{n}$$



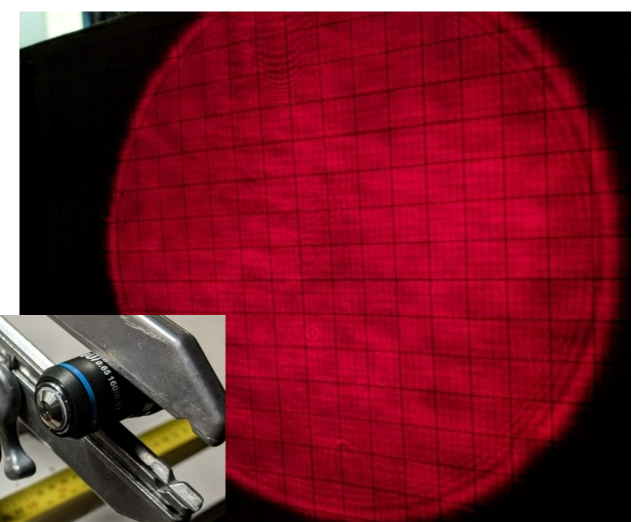


Recreated from Opto Diode ODD-3W-2 Datasheet.

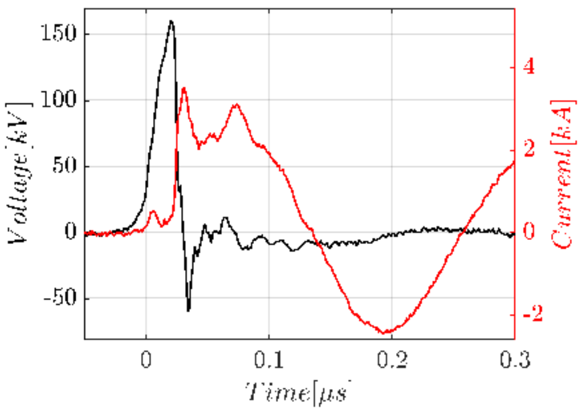


Theoretical response of Bi-Cell Photodiode; Red Linear Regime and Black is 3rd-Order Fit

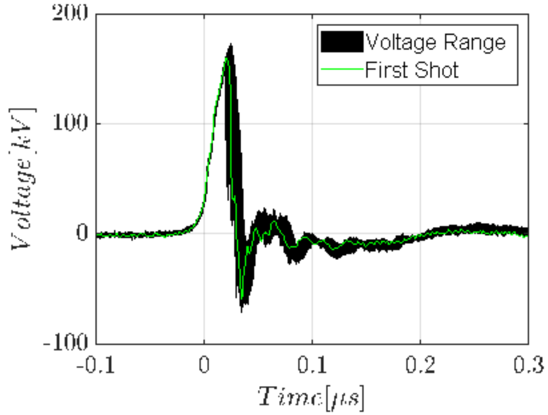
Interferogram depicting laser beam expanded using microscope objective lens.



Preliminary Results

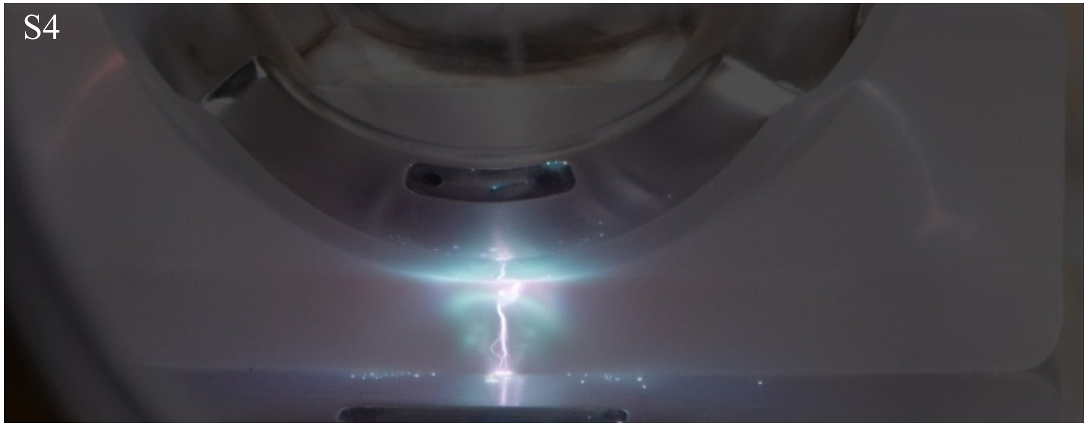


- CVD: 700 mV/div, 23 dB in attenuation
- CVR: 2.5 V/div, 23 dB in attenuation



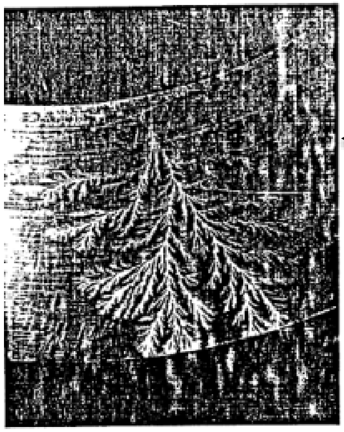
- Aggregate of 20+ Shots on insulator

Ongoing efforts to control breakdown position are a focus.



Central breakdown does occur; note side flashes attributed to voltage reversal.

Postmortem Characteristics



Postmortem dendrite "surface trees" *

Trees are typically shallow (same depth at stem as anywhere else) indicating that current is shunted to the developing plasma.

"… surface layer less than 1 mm.."**

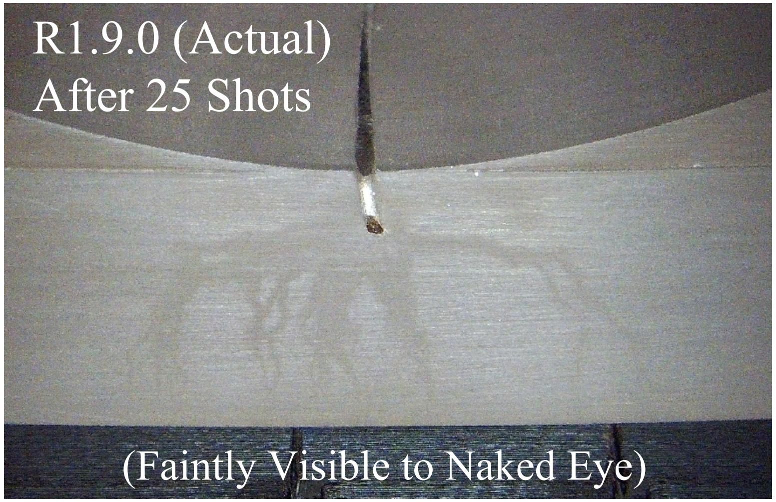
"… tends to follow hairline scratches.."**

*G.E. Vogtlin, W. W. Hofer, and M. J. Wilson. *Insulator design options*. No. UCRL-98704; CONF-8805132-2. Lawrence Livermore National Lab., CA (USA), 1988.

**R.A. Anderson, "Surface flashover measurements on conical insulators suggesting possible design improvements". United States: Sandia Lab Report SAND-75-0667, 1976.

(TTU 2021) Sample was imaged with scanning electron microscopy (SEM).

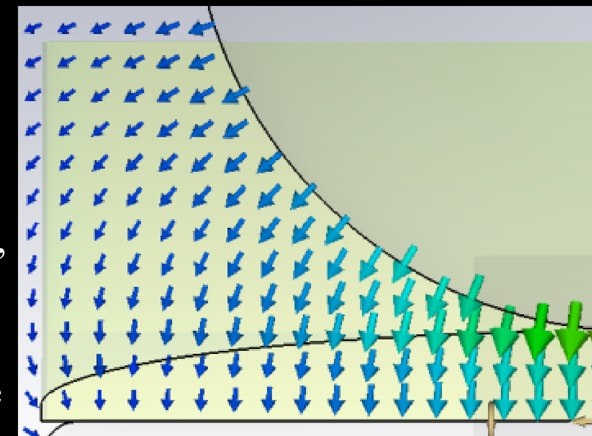
- Platinum sputtering used
- No appreciable surface texture. Resolution is limited by surface charging.
- It is believed the breakdown effectively polishes the surface.



(TTU 2021)
Visible surface of Rexolite insulator.

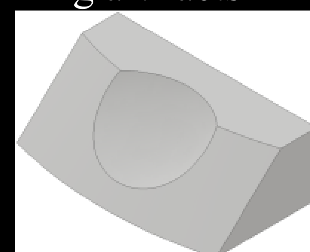
Geometry Revision

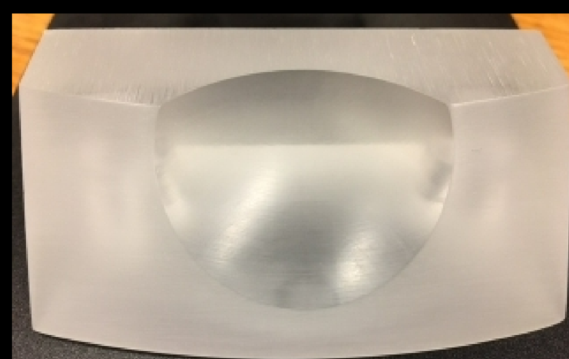
Flashover with initial geometry attracted to 45°-90° transition, edges, etc. despite various treatment efforts

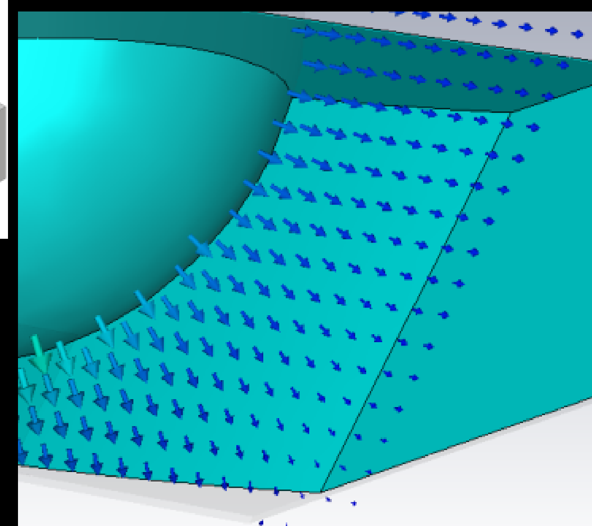


- High tangential field component on vertical face permits diagonal SEY avalanche toward anode →
- Manufacturability somewhat poor, machining artifacts possible

Extending wedge past anode contact results in field lifting electrons off the surface, limits machining artifacts



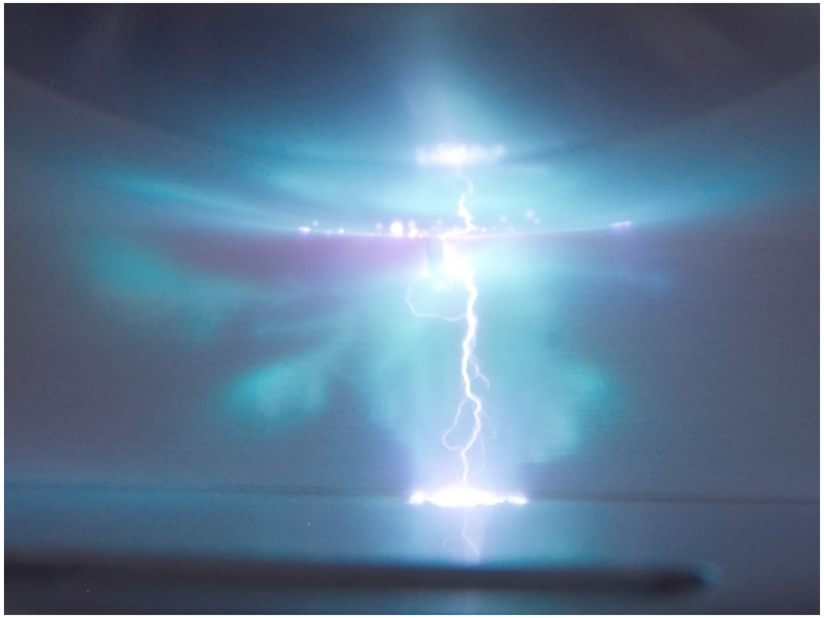




Conclusions

- Conclusions:
  - Early into the research effort; producing several inroads...
  - Mature Diagnostics:
    - Current
    - Voltage
  - Developing Diagnostics:
    - Imaging of anode and cathode
      - Temporospatial diagnostics
    - X-Ray detection
    - Laser deflection
  - Behavior of insulator bulk will play a role in flashover

- Future Work:
  - Continued development of diagnostics
  - Investigate the behavior of different materials.
  - Gather data for modelling efforts.



Selected breakdown triggered off thin wire representing a large defect