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Electrical diagnostics and nanosecond imaging of vacuum surface flashover

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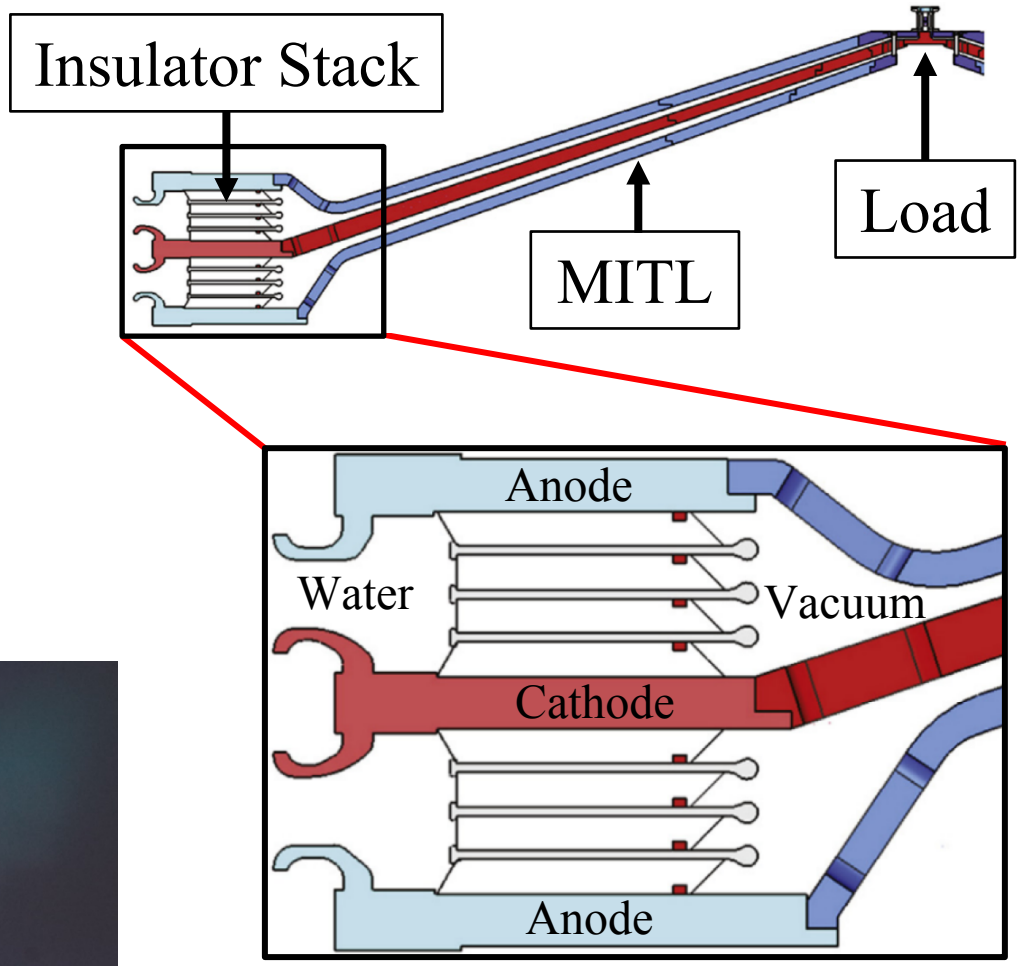
Motivation

- Engineer a moderate-scale emulation of the conditions and geometry of insulators in large-scale pulsed power machines.
- Characterize anode-initiated flashover in vacuum
  - Engineer a repeatable flashover location
  - Explore and identify the indicators of the breakdown event
  - Measure breakdown with a high degree of accuracy

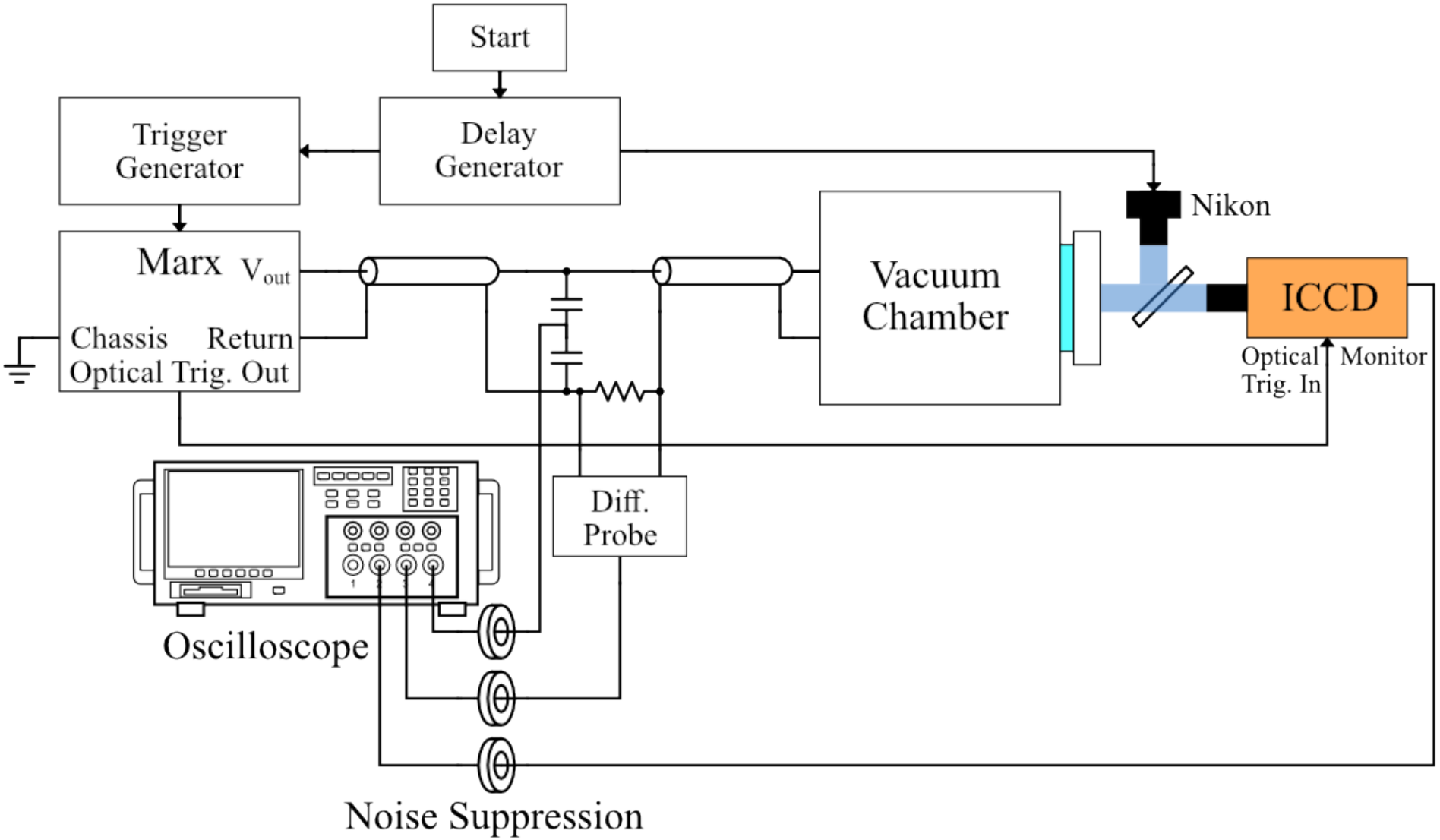
Time integrated image of surface flashover with branching primarily reaching towards the cathode. (~ 240 kV)

Large Scale Pulsed Power System [1]



[1]. R. B. Spielman et al., "Conceptual design of a 15-TW pulsed-power accelerator for high-energy-density–physics experiments," Matter and Radiation at Extremes, vol. 2, no. 4, Art. no. 4, Jul. 2017, doi: 10.1016/j.mre.2017.05.002.

System Overview



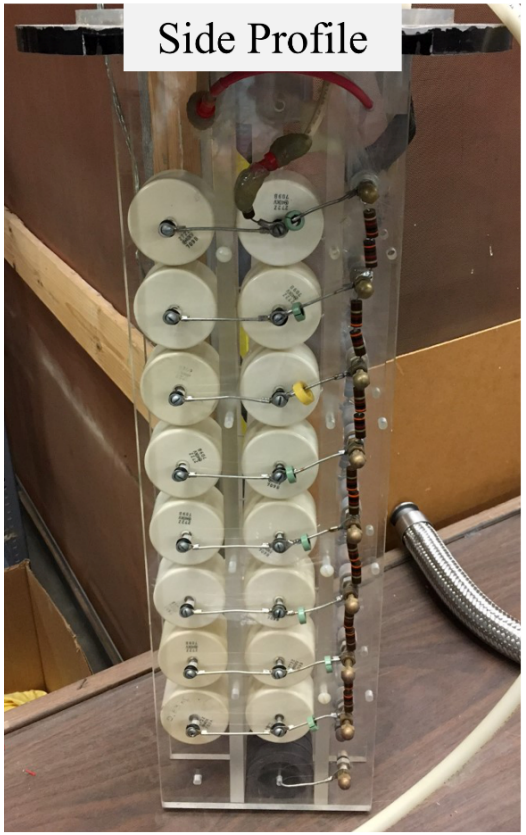
Marx Generator (Source)

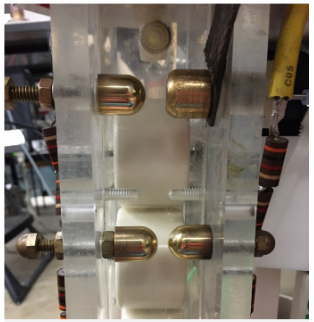
Pressurized Marx

- 16 psig 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

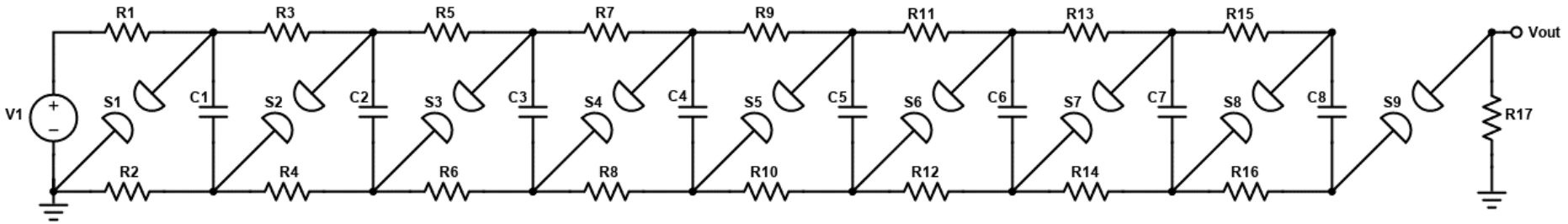
- Internal 2.2 kΩ Shunt
- (System) ESR 30 Ω
- (System) ESL 1.8 µH





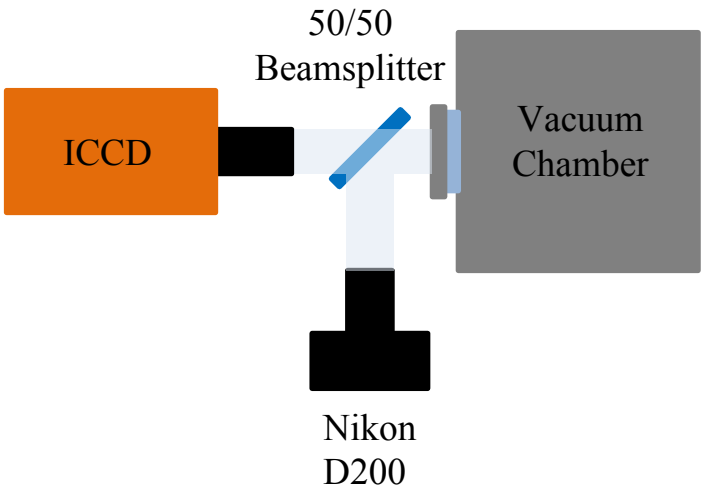
Spark Gap Configuration

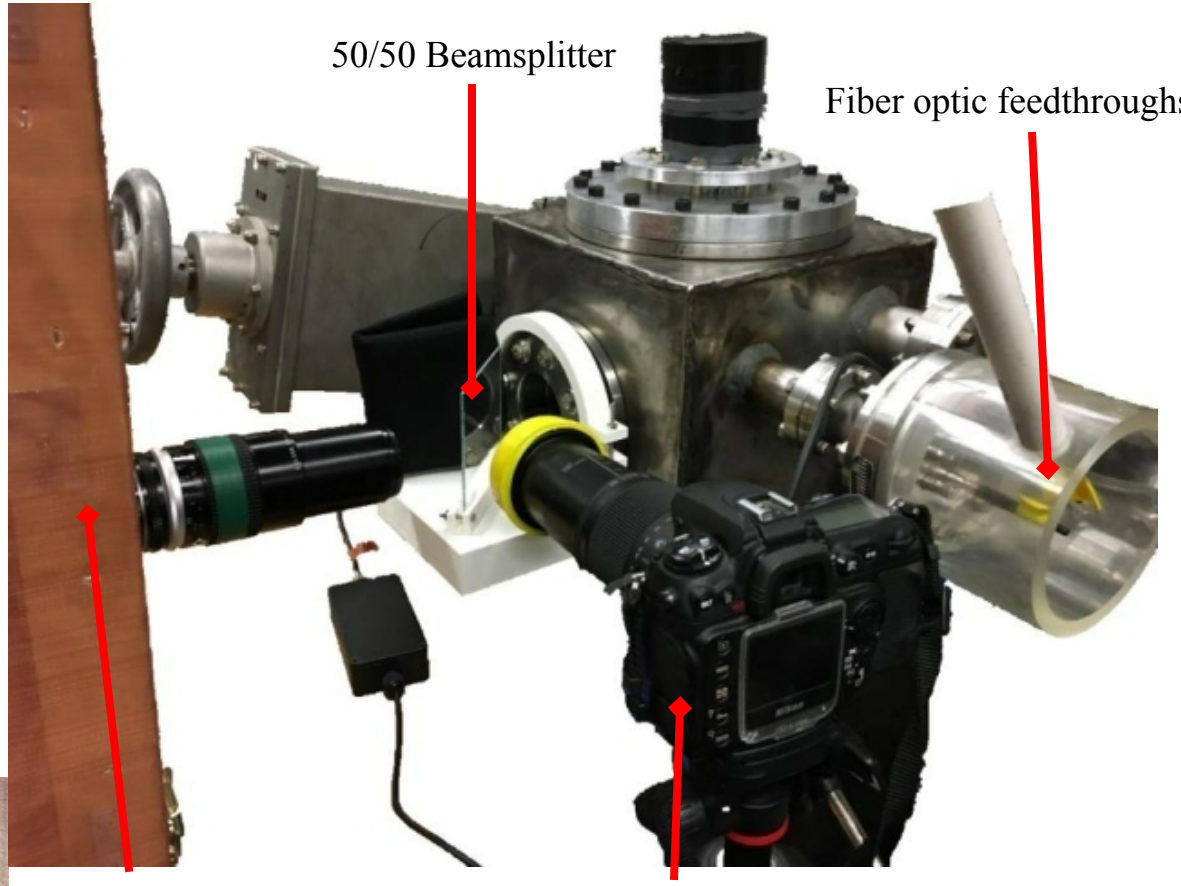
Trigatron



Optical Imaging Apparatus

Top-Down View of Imaging Apparatus





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

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)

Current and Voltage Diagnostics

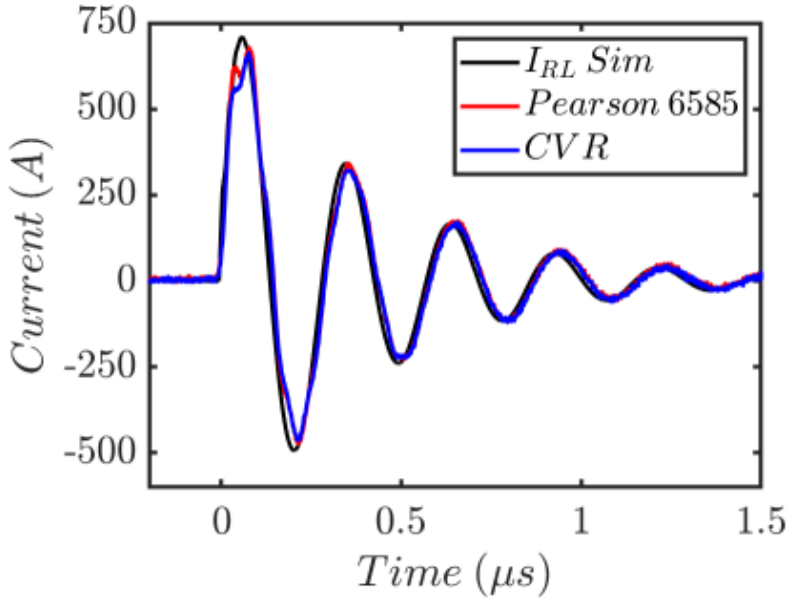
Current Viewing Resistor
~ 42 mΩ

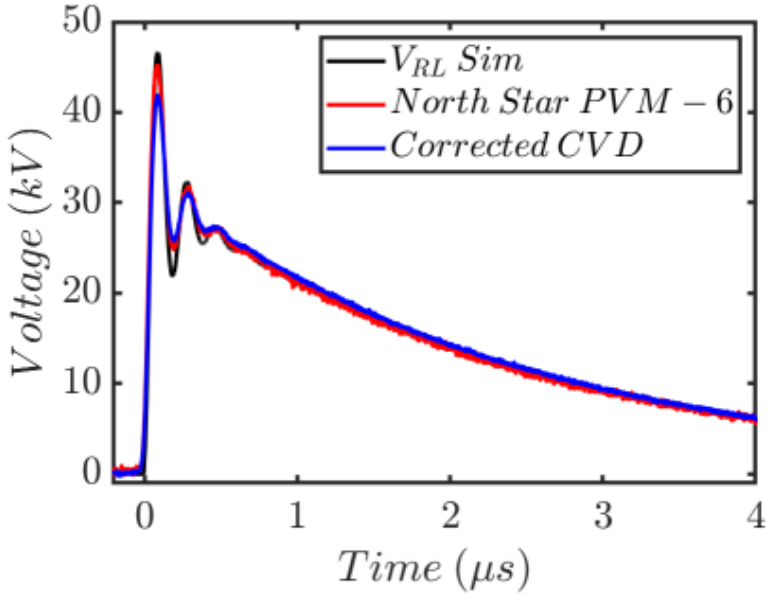
Capacitive Voltage Divider

CVR Calibration
- Pearson 110
- Pearson 6585

CVD Calibration
- NorthStar PVM-6
- Current * Load

$$V_{in}(t) = \frac{1}{a}V_m(t) + \frac{1}{\alpha\,\tau}\int_0^t V_m(t')dt'$$





Insulator Testbed

Physical Dimensions

Insulator

79.38 mm (3.125 in) Wide
29.21 mm (1.15 in) Tall

Wedge

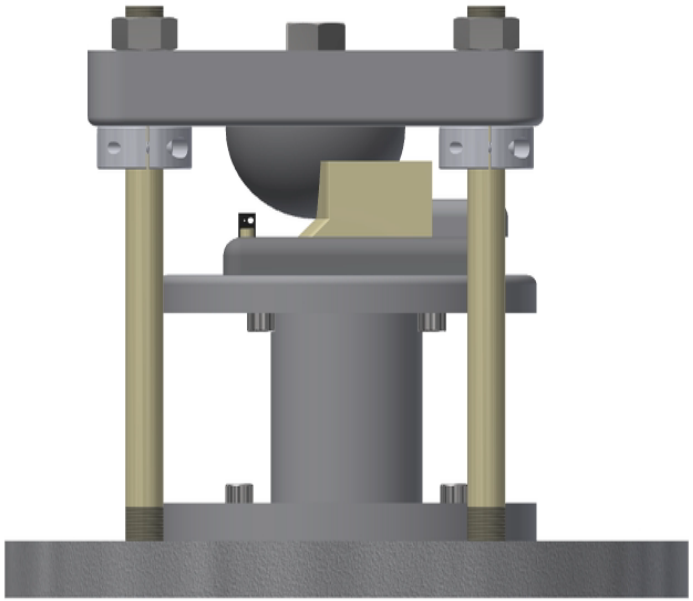
45 Degrees
6 mm Vertical

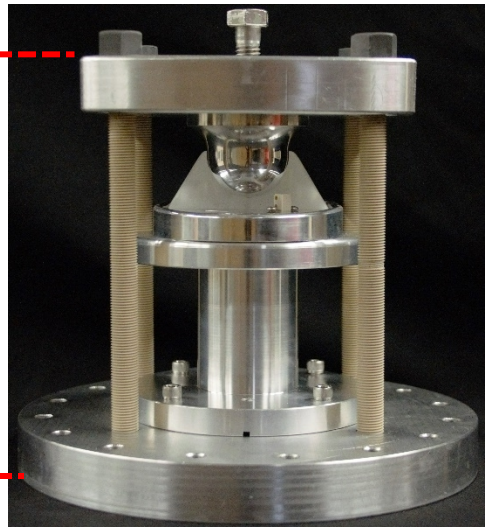
Anode

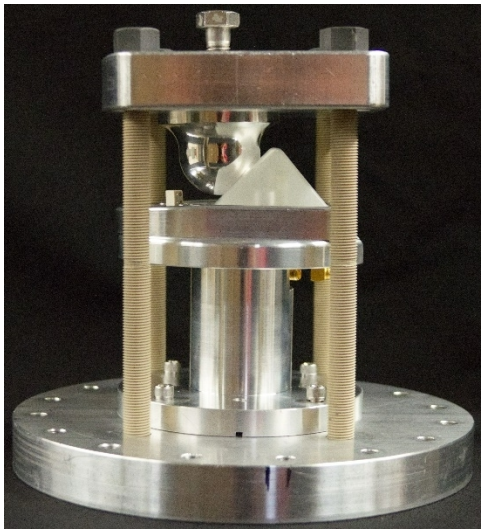
20 mm radius

Cathode

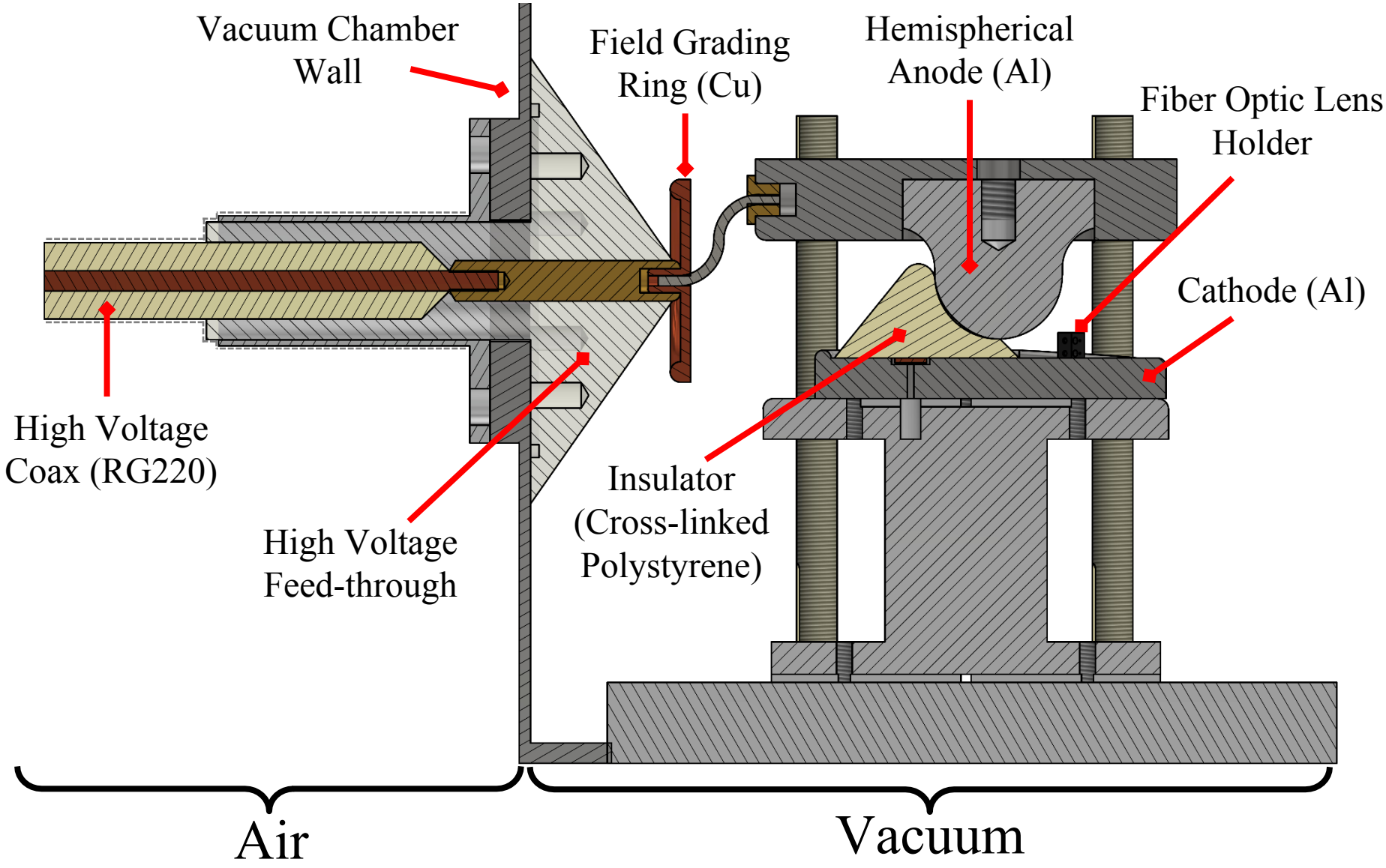
92.0 mm (3.622 in) Wide
110.0 mm (4.332 in) Deep







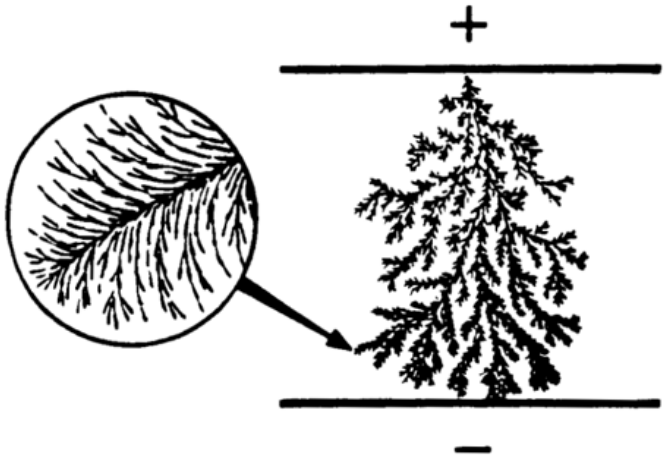
Insulator Testbed Cross-Section



Anode vs Cathode-Initiated Flashover

Anode-initiated flashover

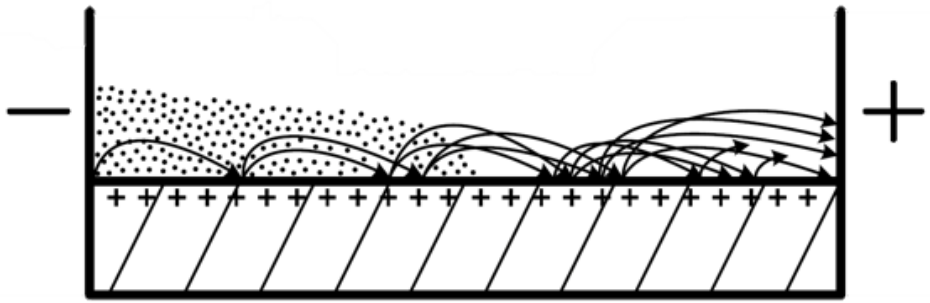
1. Plasma formation near the anode triple junction distorts and enhances electric fields.
2. Localized bulk dielectric breakdown fuels further plasma formation
3. Propagation towards cathode in a treeing pattern



R. A. Anderson, "Anode-initiated surface flashover," in Conference on Electrical Insulation & Dielectric Phenomena, United States, 1979, no. SAND–79-0581C, p. 9.Available: http://inis.iaea.org/search/search.aspx?orig_q=RN:11511747

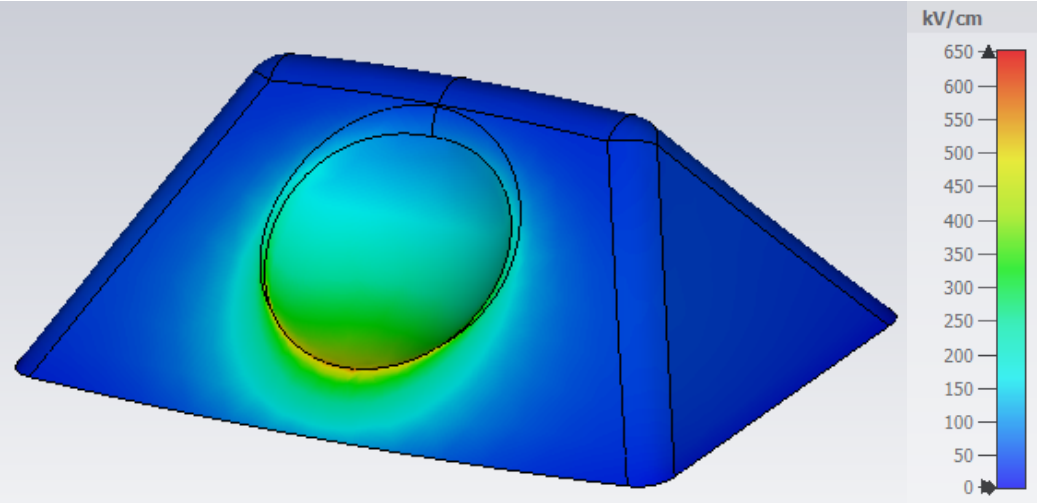
Cathode-initiated flashover

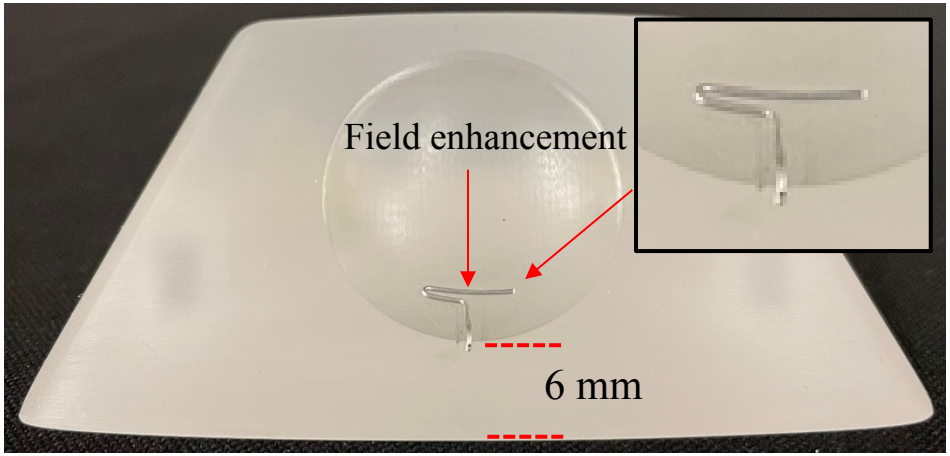
1. Field electron emission near cathode triple junction
2. Surface is bombarded by free electrons resulting in secondary electron emission, positive surface charging, and gas desorption
3. Desorbed gas cloud provides medium for plasma development



3rd Gen. Insulator Topology

- Initial testing showed the insulator's ability to hold off flashover at voltages over 270 kV
- Field enhancement at anode triple junction simulates a preferential breakdown location due to a flaw
- Material: Aluminum wire 0.5 mm diameter

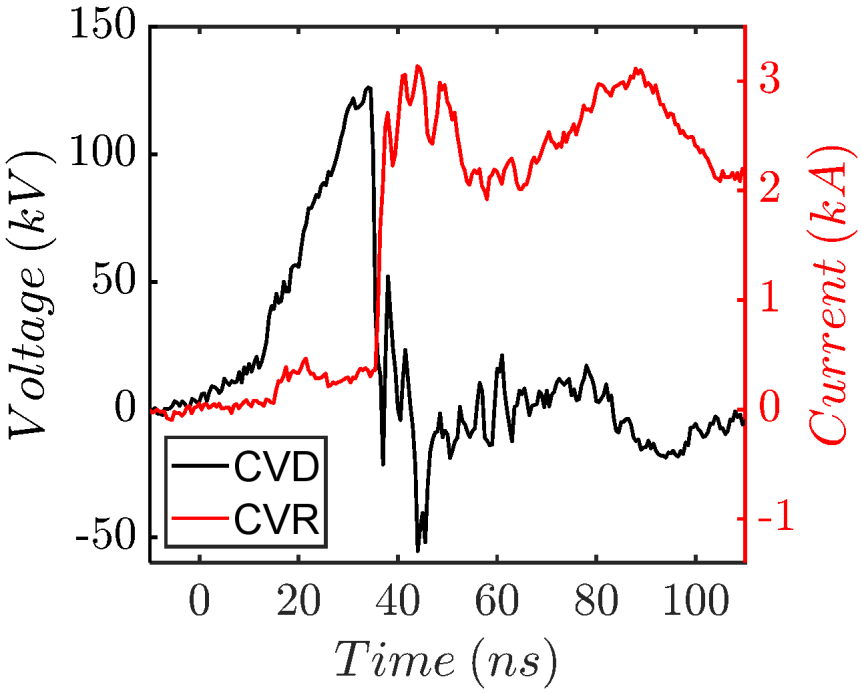


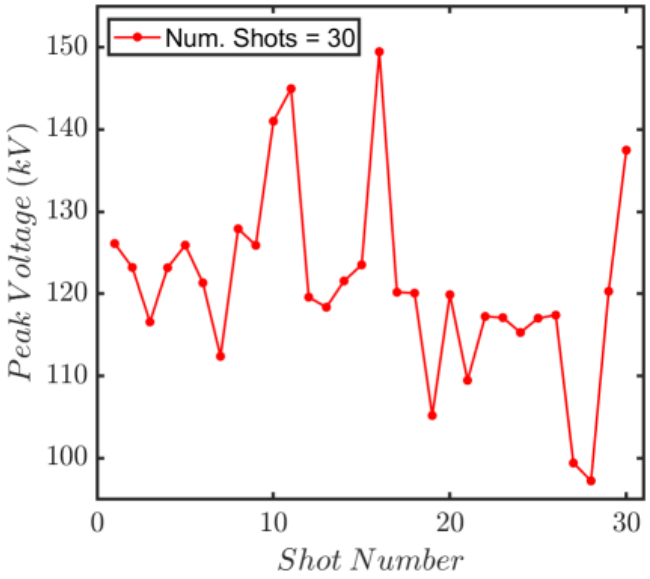


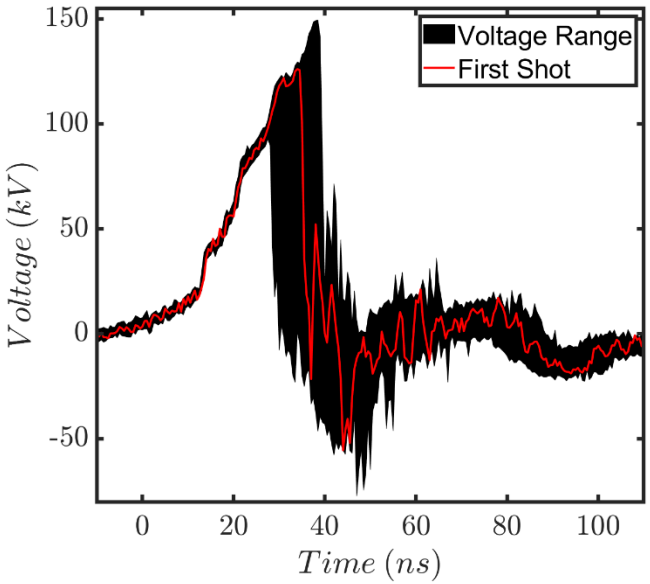
3rd Gen. Voltage-Current Measurements

Waveform Characteristics

- Rise Time = 20.68 ± 1.78 [ns] (std.)
- V_{peak} = 121.14 ± 11.45 [kV] (std.)
- V_{peak} ranges (97.24 to 149.46) [kV]

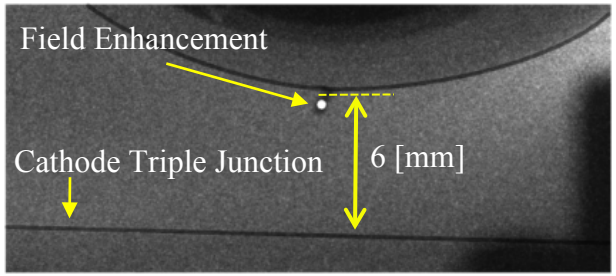






3rd Gen. Temporally Resolved Imaging

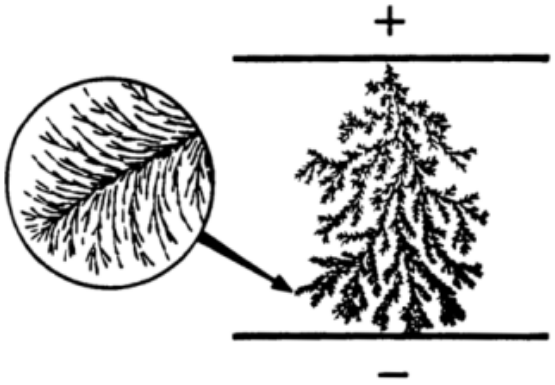
Reference Image



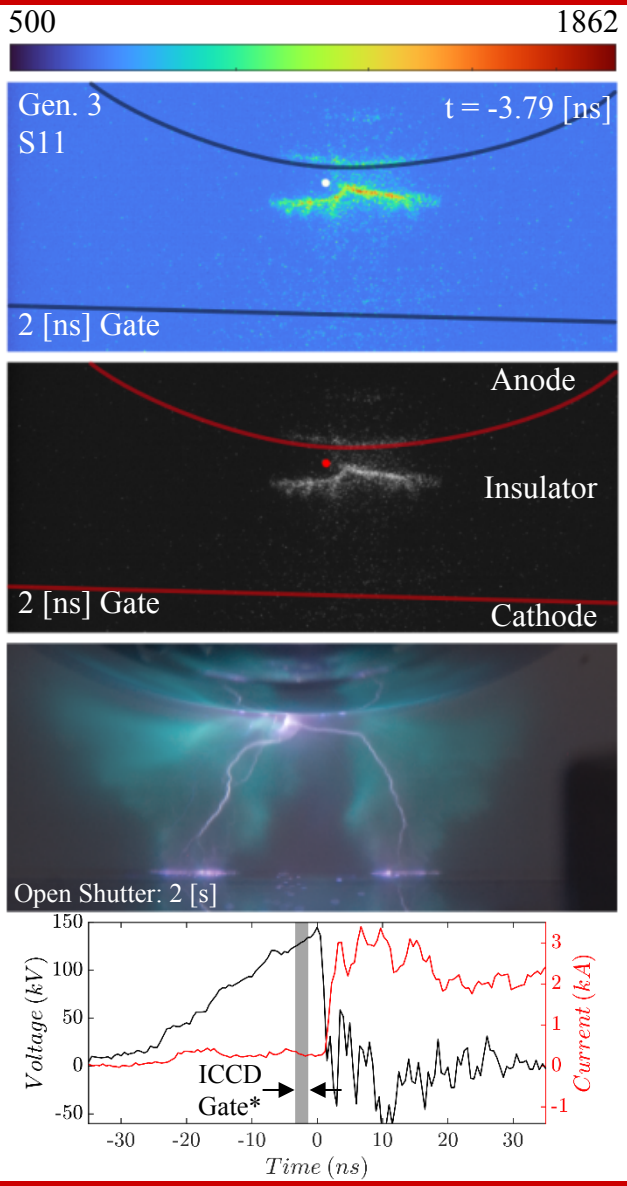
ICCD Settings

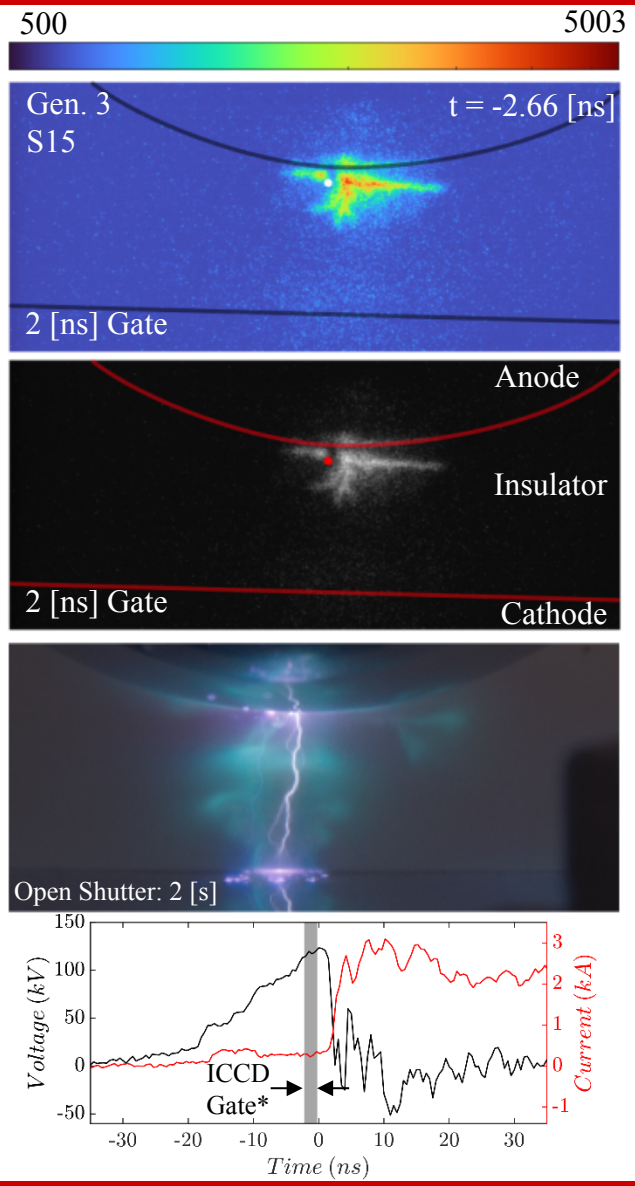
Gating Time: 2 [ns]
Gain: 95
F#: F/4.5

- Imaging demonstrates that flashover is anode-initiated

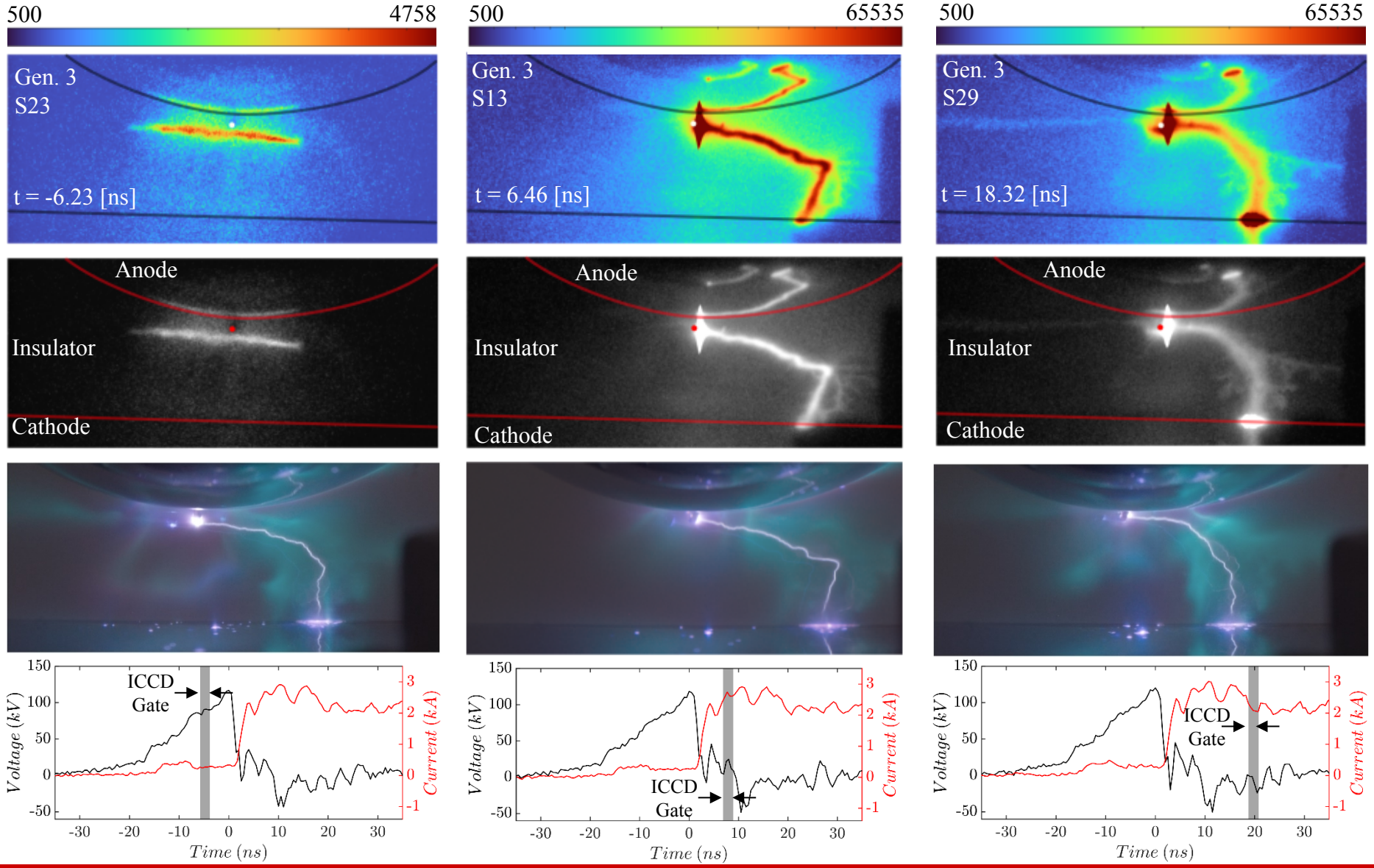


R. A. Anderson, "Anode-initiated surface flashover," in Conference on Electrical Insulation & Dielectric Phenomena, United States, 1979, no. SAND–79-0581C, p. 9.Available: http://inis.iaea.org/search/search.aspx?orig_q=RN:11511747



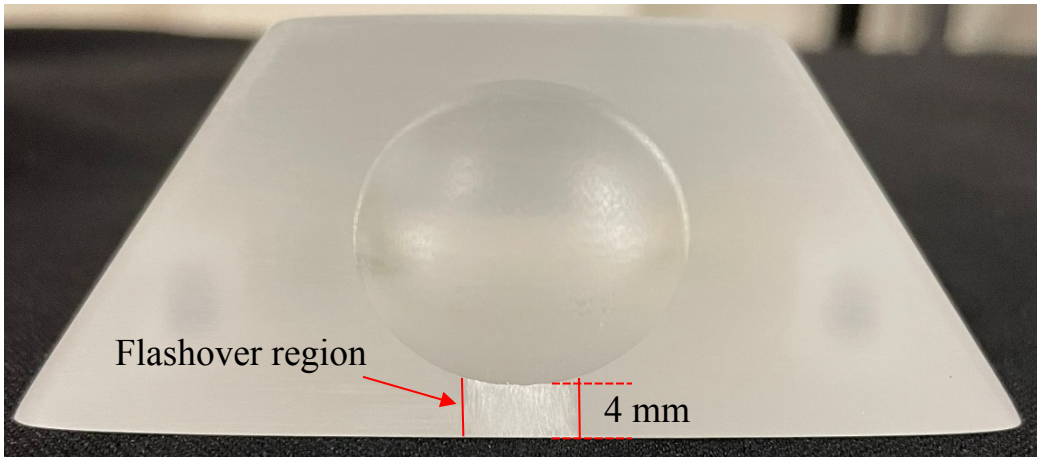


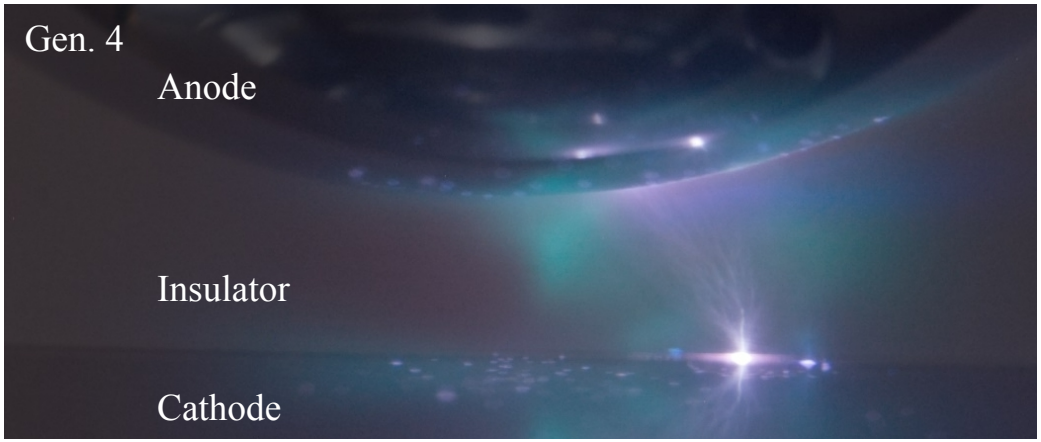
3rd Gen. Temporally Resolved Imaging



4th Gen. Insulator Topology

- The vertical gap was reduced to 4 mm
- Flashover achieved with vertical sanding (280 grit) in the flashover region (~170 kV)
  - Inconsistencies in repeatability

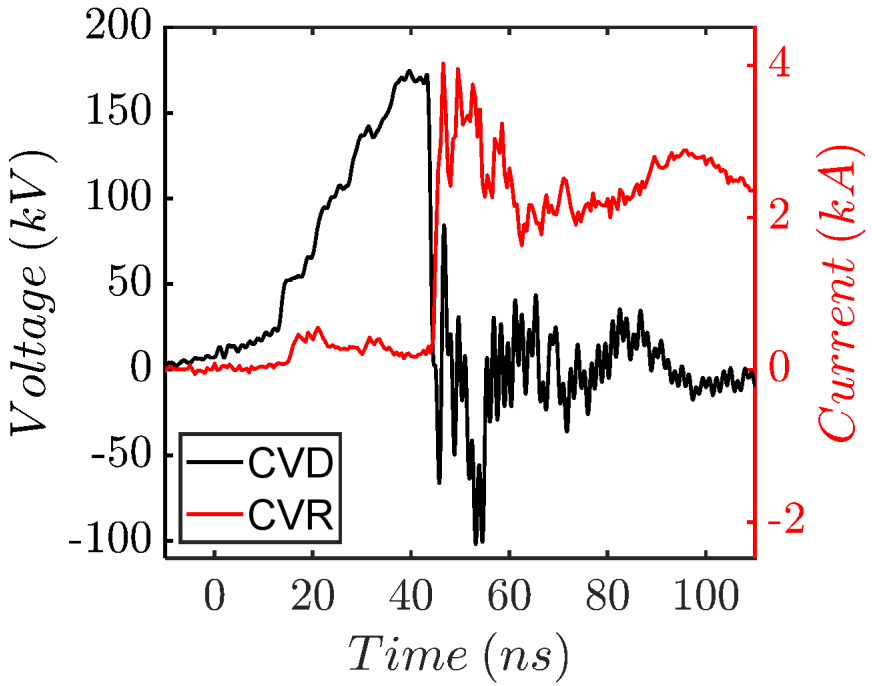


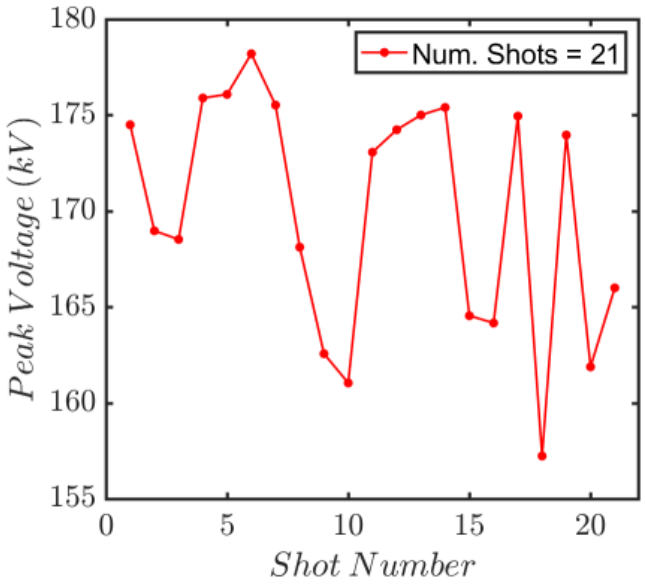


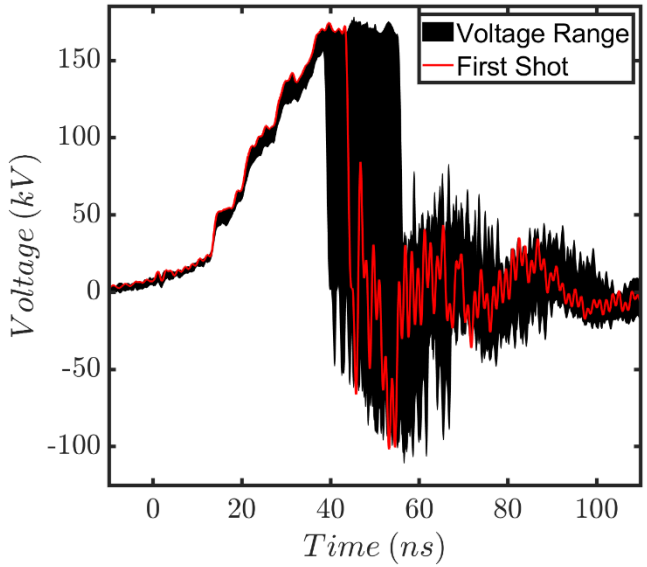
4th Gen. Voltage-Current Measurements

Waveform Characteristics

- Rise time = 27.24 ± 0.92 [ns] (std.)
- V_{peak} = 170.01 ± 6.18 [kV] (std.)
- V_{peak} ranges (157.25 to 178.22) [kV]

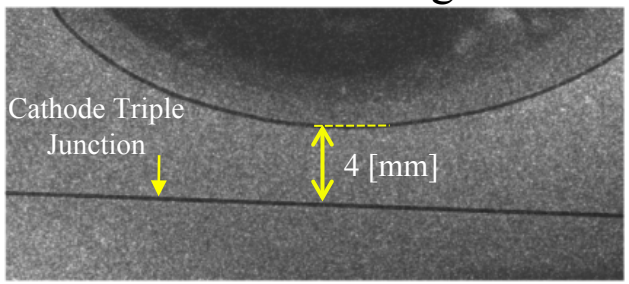


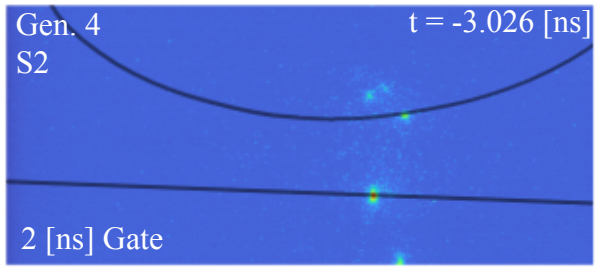


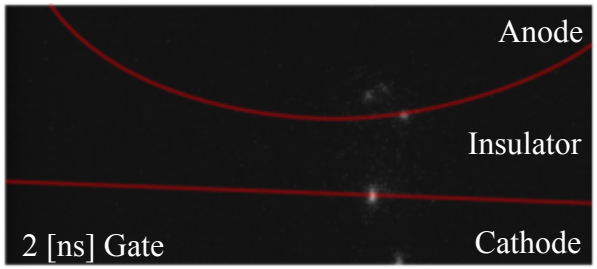


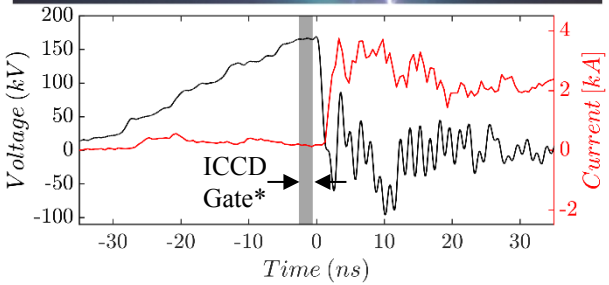
4th Gen. Temporally Resolved Imaging

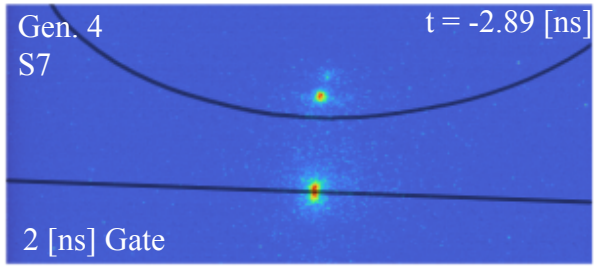
Reference Image

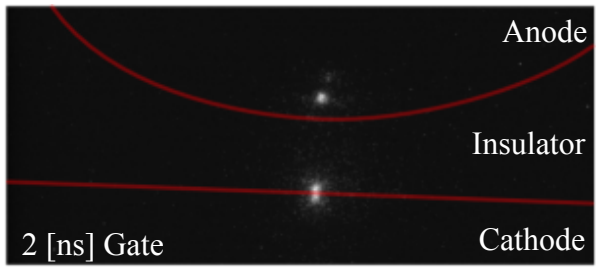


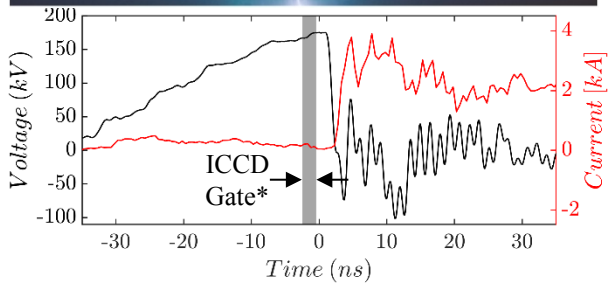








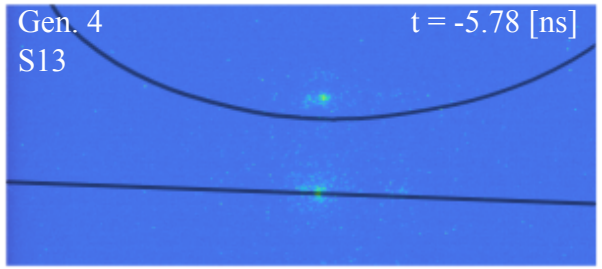


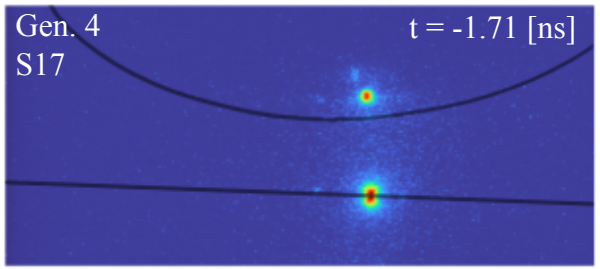


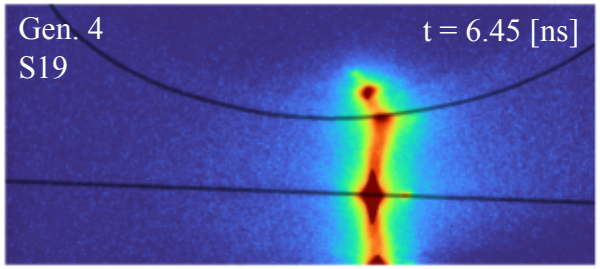
ICCD Settings
Gating Time: 2 [ns]
Gain: 95
F#: F/4.5

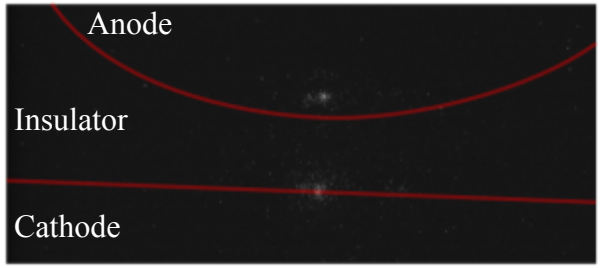
- Imaging observed mostly cathode-initiated flashover
  - Anode-initiated flashover was observed in only a few shots

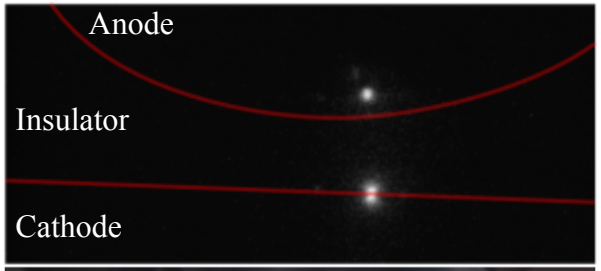
4th Gen. Temporally Resolved Imaging

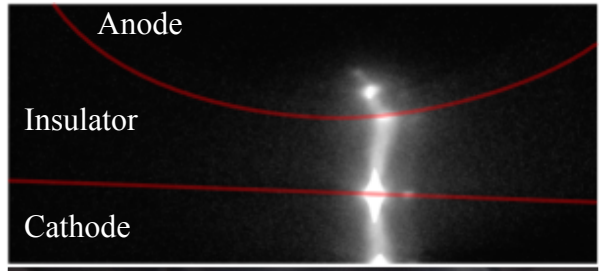


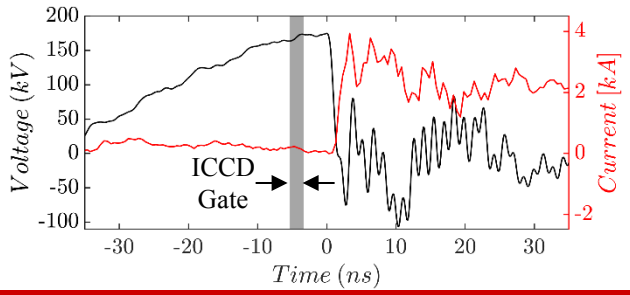


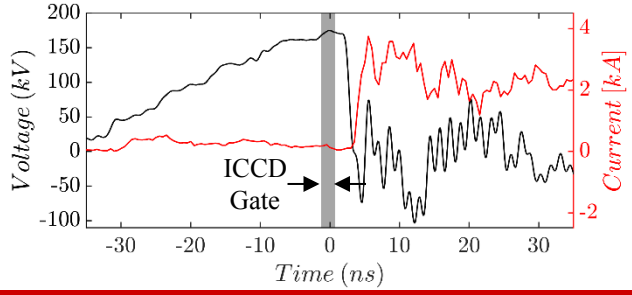


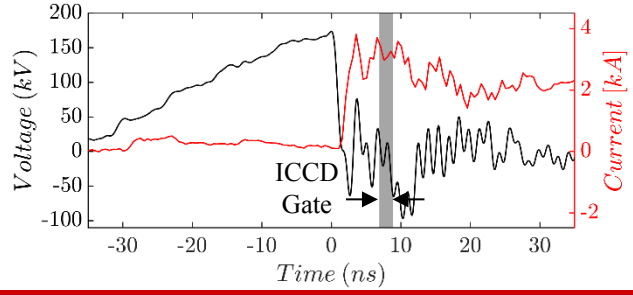






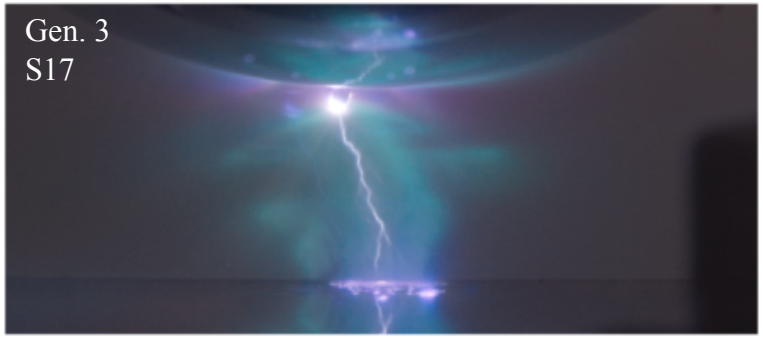


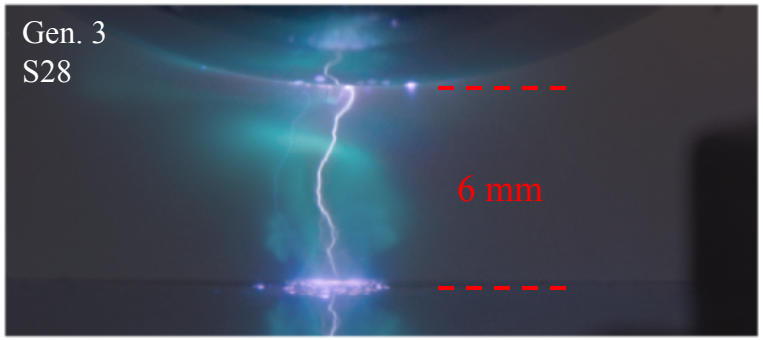


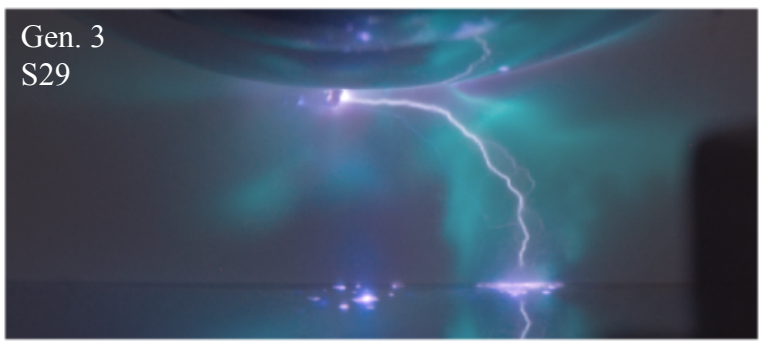


Anode vs Cathode Initiation

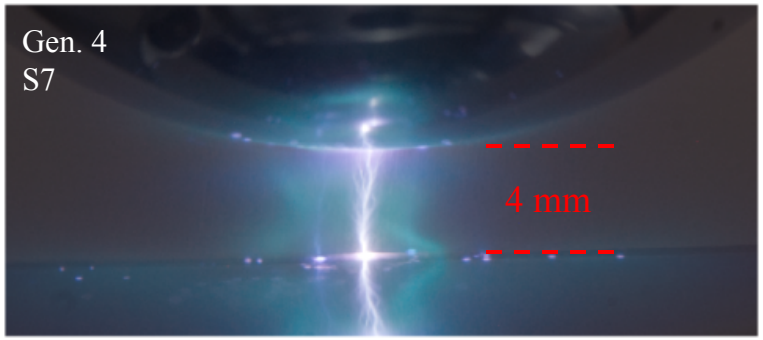
- Gen. 3 (6 mm vertical gap) resulted in <u>exclusively</u> anode-initiated flashover







- Gen. 4 (4 mm vertical gap) <u>primarily</u> cathode-initiated flashover



Conclusions

- Conclusions:
  - **6 mm gap with field enhancement:** Early-stage light emission originates near anode
  - **4 mm gap with no field enhancement:** Early-stage light emission originates near cathode primarily

- Future Work:
  - Further explore insulator gap distance vs flashover initiation process
  - Investigate the behavior of different insulator materials