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Exploring the basic physical mechanisms of cathode and anode directed high voltage surface flashover

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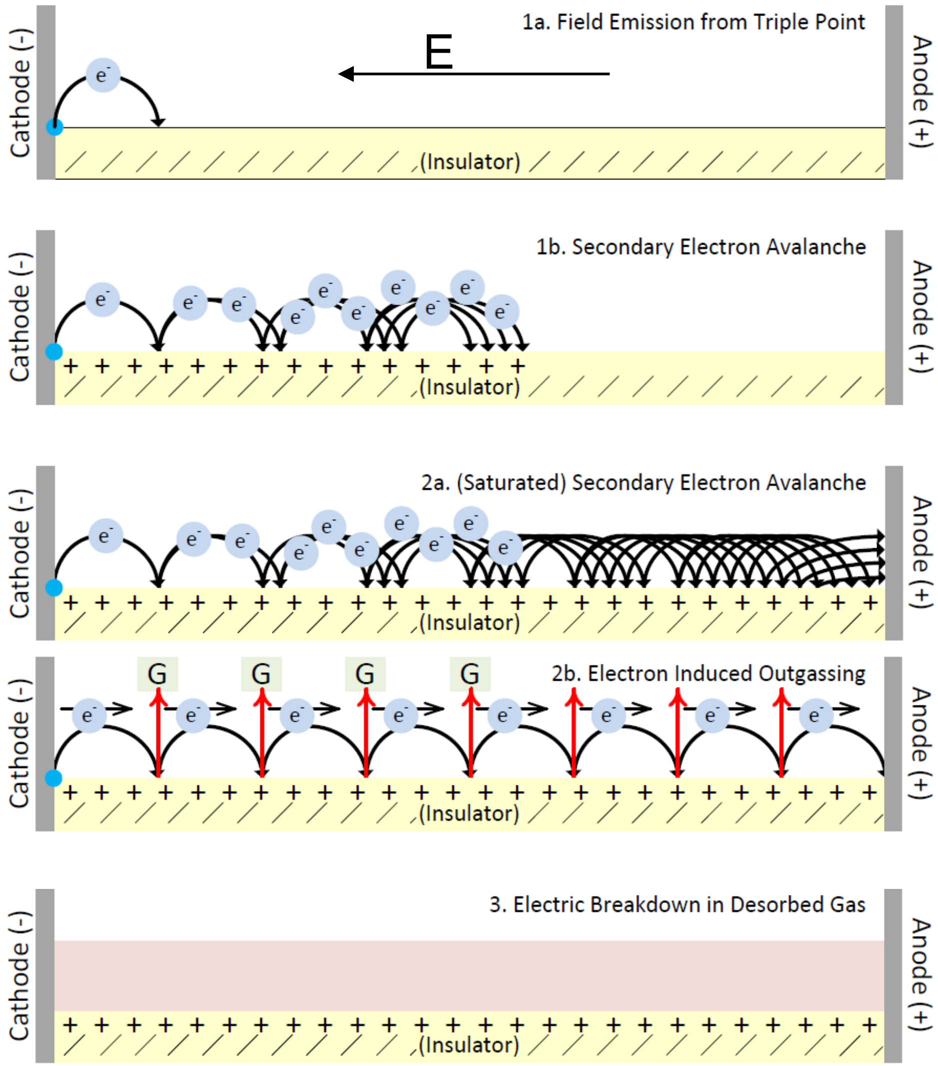
1 Recipient of DOE NNSA LRGF support, provided under cooperative agreement DE-N0003960

Cathode Initiated Surface Flashover



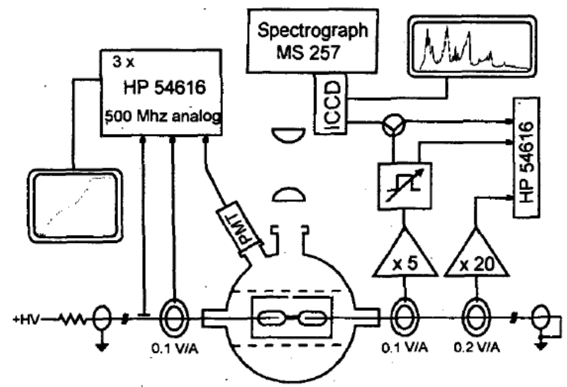


Figure 1. Schematic of the experimental setup for unipolar surface flashover. One way transit time of charging and load coaxial line is approx. 135 ns.

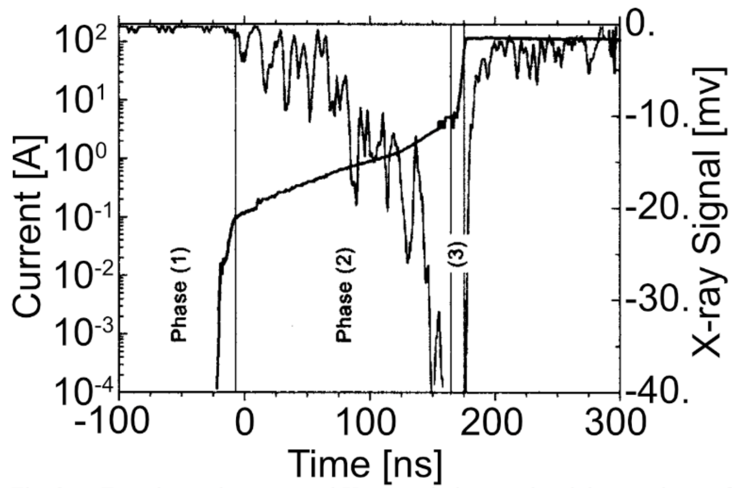


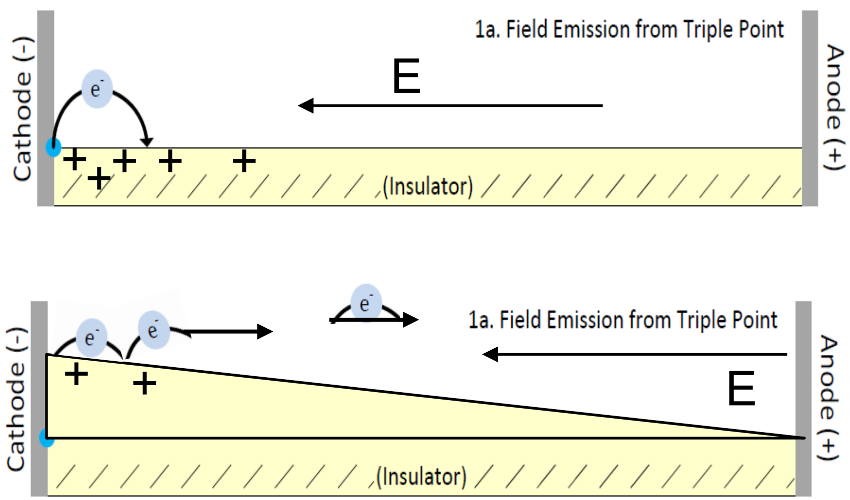
Fig. 2. Experimental current and X-ray emission at a breakdown voltage of 11.4 kV.

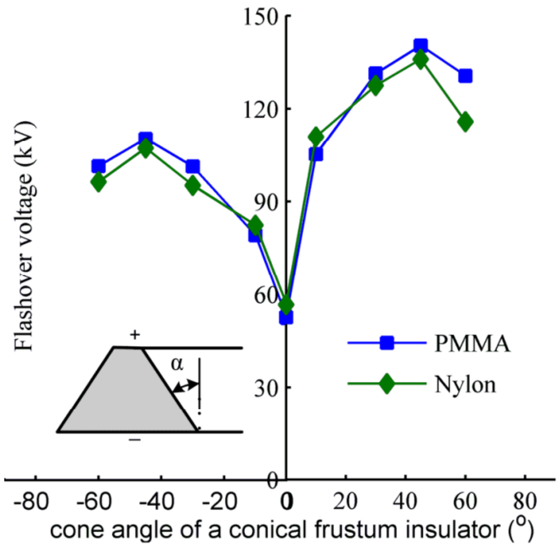
[1] Neuber, A. et al. The role of outgassing in surface flashover under vacuum *IEEE TPS 28, No. 5, 2000*

Increasing Flashover Potential

- **Electric field parallel to surface** → SEE easily forms, followed by electron induced outgassing and gaseous breakdown
  LOW THRESHOLD

- **Electric field in angle with the surface** → SEE cannot easily form electrons are pulled away from the surface
  HIGHER FLASHOVER THRESHOLD



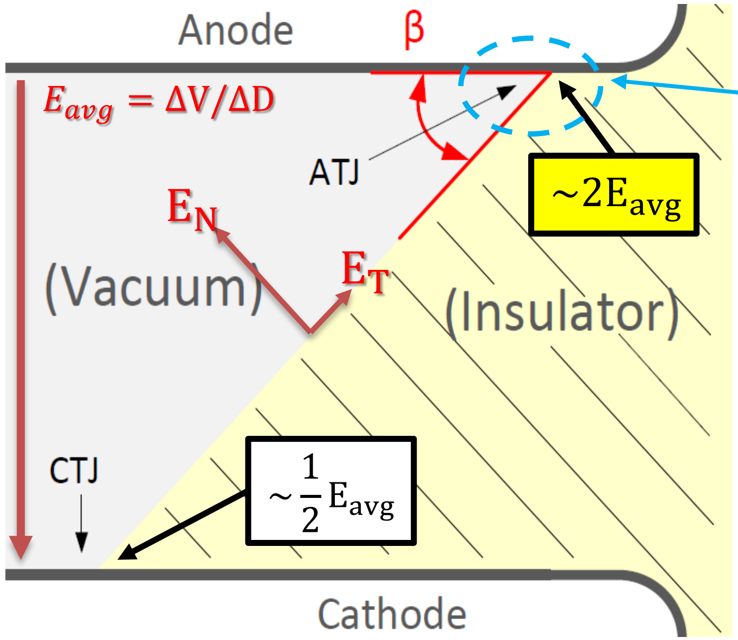


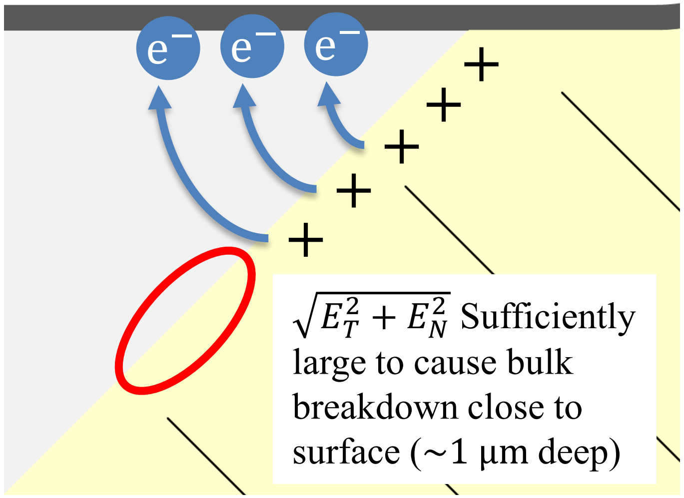
[5] Yan et al. "Experimental investigation of surface flashover in vacuum using nanosecond pulses," IEEE TDEI 14, 634-642, 2007

For 45 degree positive angle: Field at anode much higher (~ factor 4) than at cathode → **Anode initiated flashover**

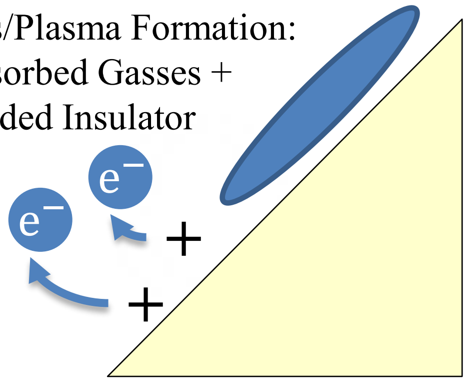
Anode Initiated Surface Flashover

(Working Theory)





Gas/Plasma Formation: Desorbed Gasses + Eroded Insulator



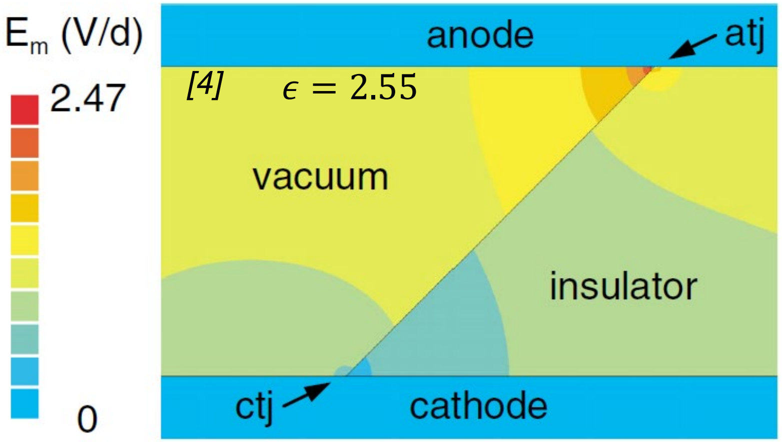
Note:

- 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.

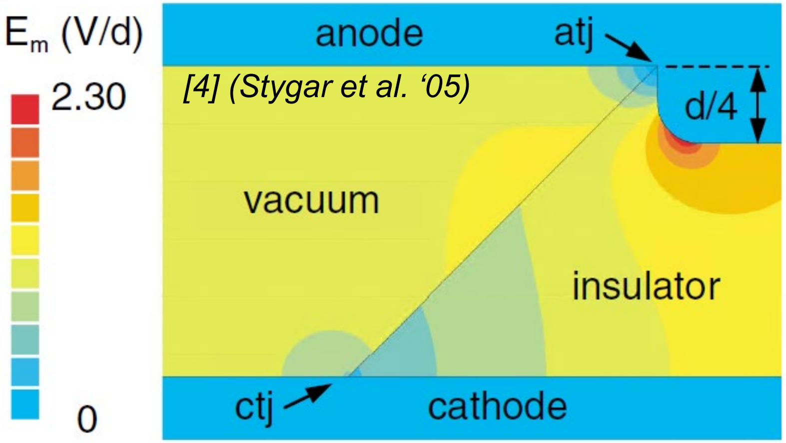
- [2] R. A. Anderson, Surface flashover measurements on conical insulator suggesting possible design improvements, SAND75 0667, 1976
- [3] Stygar et al. Flashover of a vacuum-insulator interface: a statistical model *Phys. Rev. ST Accel. Beams, American Physical Society,* 2004, 7, 070401
- [4] Stygar et al. Improved design of a high-voltage vacuum-insulator interface *Phys. Rev. ST Accel. Beams, American Physical Society,* 2005, 8, 050401

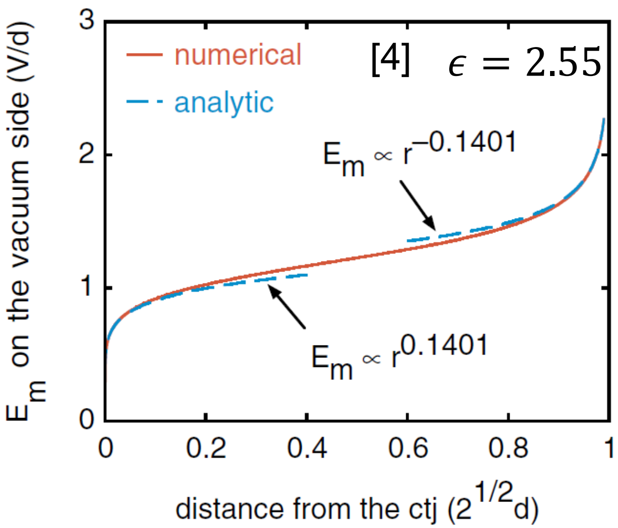
Positive Wedge / Anode Initiated Flashover

Base Wedge Geometry



Anode Plug Geometry



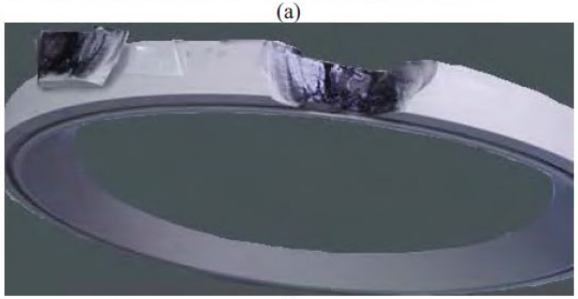


Anode plug offered $21\% +$ improvement in flashover strength ($630\ kV/cm$ vs $522\ kV/cm$) limited by bulk breakdown.

- The anode plug slightly enhances fields:
  - CTJ to midpoint
- The anode plug reduces fields:
  - ATJ to midpoint
- Suggest breakdown is initiated from the upper half of the insulator, likely the ATJ

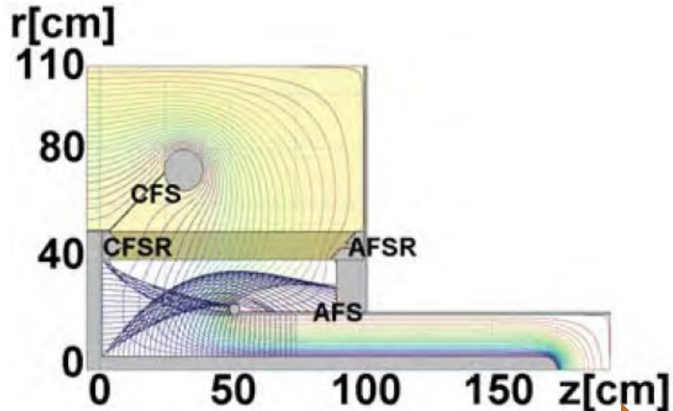
Suppressing SEE / Multipactor

(a)

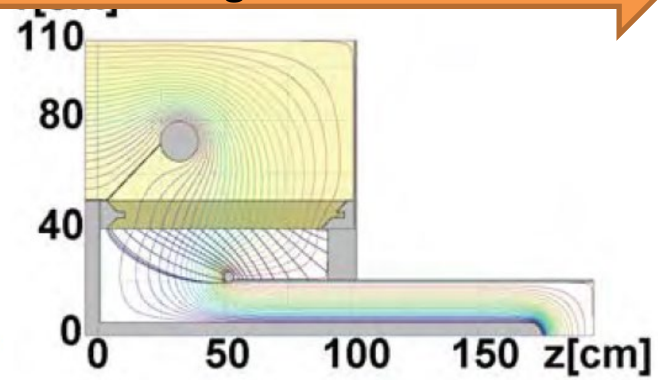


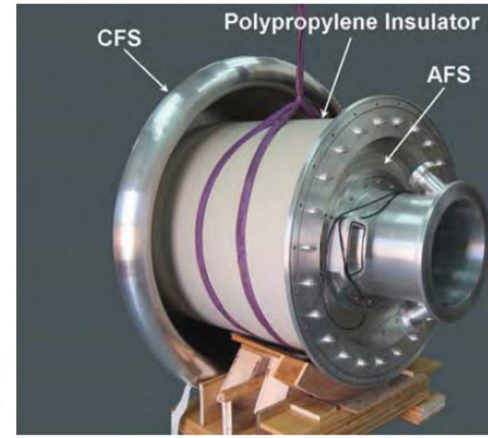
(b)

Figure 4. (a) The stacked ring insulator in our 2MV pulsed power machine as described in Fig. 3. (b) A polypropelene ring damaged by breakdown.

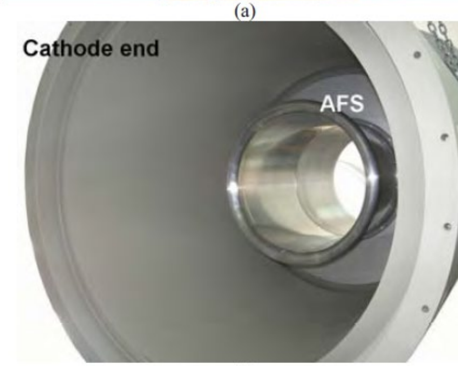


Redesigned Insulator





(a)



Field shaping configured to prevent field emission from CTJ, insulator from striking insulator. Optimized placement resulted in superior performance to insulator stack.

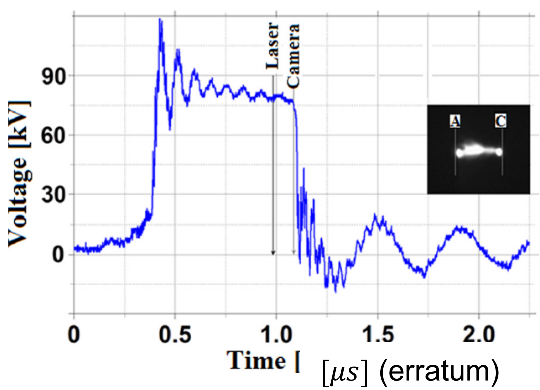
[6] J. G. Leopold, R. Gad, E. Hillel, C. Leibovitz, M. Markovits and I. Navon, "Applying a different approach to pulsed high-voltage insulation," *2010 IEEE International Power Modulator and High Voltage Conference*, 2010

(See also) [7] Different approach to pulsed high-voltage vacuum-insulation design, John G. Leopold, Chaim Leibovitz, Itamar Navon, and Meir Markovits, Phys. Rev. ST Accel. Beams 10, 060401

Electron Seeding by Photoemission

[8] Ya. E. Krasik and J. G. Leopold , "**Initiation of vacuum insulator surface high-voltage flashover with electrons produced by laser illumination**", Physics of Plasmas 22, 083109 (2015) https://doi.org/10.1063/1.4928580

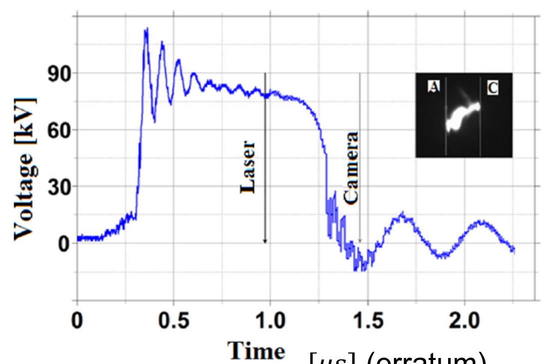
50 mm Polyetherimide Cylinders, 15 mm long; 213 nm $(10^6 \text{ to } 10^8)\ \mathrm{W/cm^2}$



$[\mu s]$ (erratum)

FIG. 4. The voltage waveform across the insulator. The arrows indicate the starting time of the laser beam followed by the synchro-pulse of the 4QuikE camera (frame duration 2 ns, camera amplification 850 V). Inset: light radiation from the surface flashover plasma. Here, the laser beam is applied in the vicinity of the CTJ of a 1.5 cm-long cylindrical sample. The applied voltage amplitude is 90 kV and the laser beam power density is $\sim 10^5\ \mathrm{W/cm^2}$.

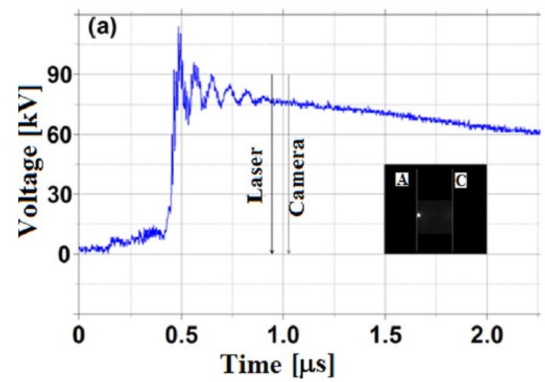
Operated at $60\ \mathrm{kV/cm}$ (breakdown threshold $\sim 165\ \mathrm{kV/cm}$), $\sim 10^5\ \mathrm{W/cm^2}$ laser pulse on CTJ would trigger breakdown. $(90\ \mathrm{kV}$ applied)



$[\mu s]$ (erratum)

FIG. 6. The voltage waveform across the insulator inclined at 45°. The arrows indicate the starting time of the laser beam and synchro-pulse of the 4QuikE camera (frame duration 2 ns, camera amplification 650 V) application. Inset: light radiation from the surface flashover plasma. The laser beam is applied in the vicinity of the CTJ of sample inclined at 45°. The applied voltage amplitude is 90 kV and the laser beam power density is $\sim 5 \times 10^7\ \mathrm{W/cm^2}$.

The 45-degree cone shows a high degree of resiliency, requiring $\sim 500 \times$ greater $(\sim 5 \times 10^7\ \mathrm{W/cm^2})$ laser pulse intensity on CTJ. $(90\ \mathrm{kV}$ applied)



(Figure 5a)

$\sim 5 \times 10^9 \frac{\mathrm{W}}{\mathrm{cm^2}}$ pulse, plasma generation found necessary to trigger breakdown from ATJ. $(150\ \mathrm{kV}$ applied)

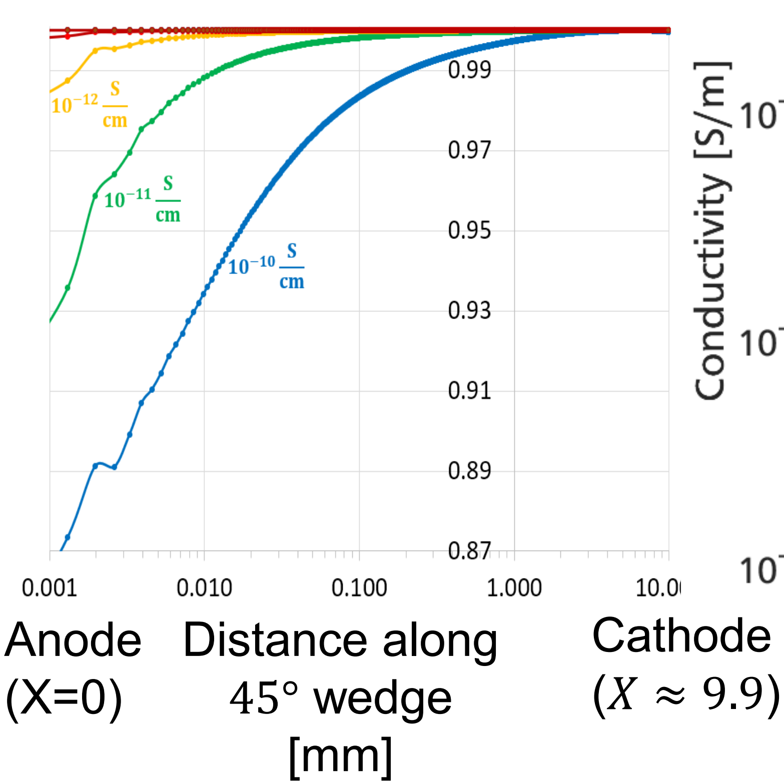
Field in Bulk is largely unaffected by field-dependent conduction. No significant self-grading observed.

2D Axisymmetric

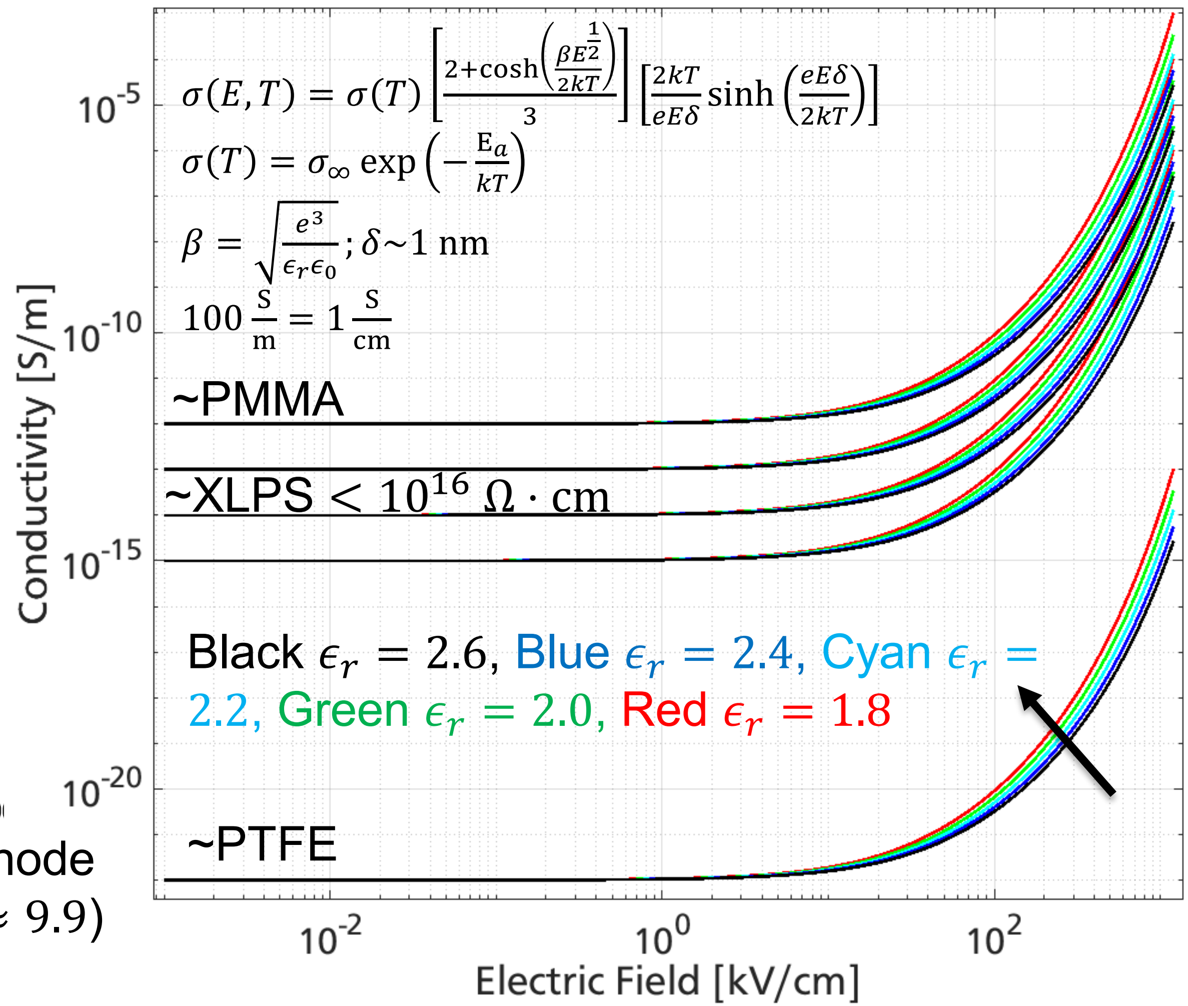
Peak Fields ($\sigma = \sigma_{DC}$) $\approx 1.036 \frac{\text{MV}}{\text{cm}}$

$\epsilon_r = 2.3$; $T = 293$ K

Relative Electric Field



Equation(s) from [9] Lai, S. T. "Deep dielectric charging," in Fundamentals of spacecraft charging: spacecraft interactions with space plasmas



Critical Insulator Material Parameters

Ceramics

- Bakeout Compatible
- Vacuum Compatible
- Low Tolerance for Mechanical Shock

Plastics

- Low thermal tolerance
- Outgassing is a concern
- Tolerant of Mechanical Shock
- Low dielectric constant (ϵ) (Stygar et al. 2005)
  - E_{atj} increases with increasing ϵ
  - E_{ctj} decreases with increasing ϵ
- High breakdown strength (Stygar et al. 2005)

- PMMA
  - Originally Used
- XLPS (Cross-linked Polystyrene) Investigated
  - Predicted to be about 11% better than PMMA (Stygar et al. 2004)

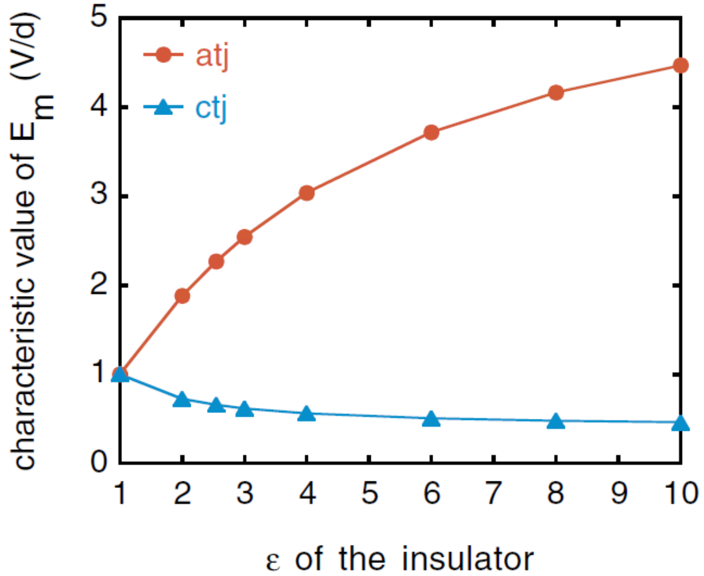
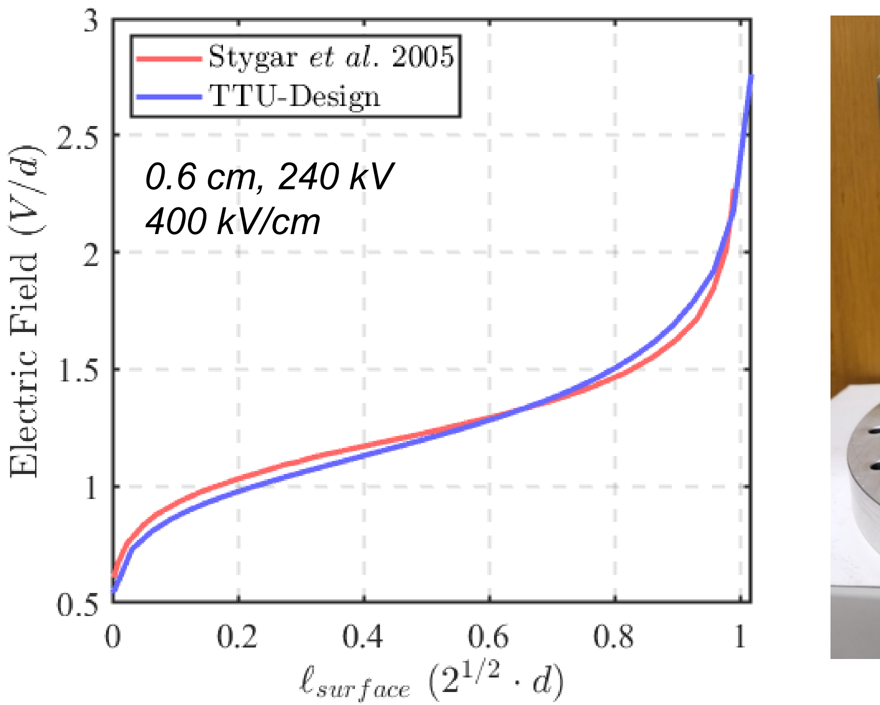
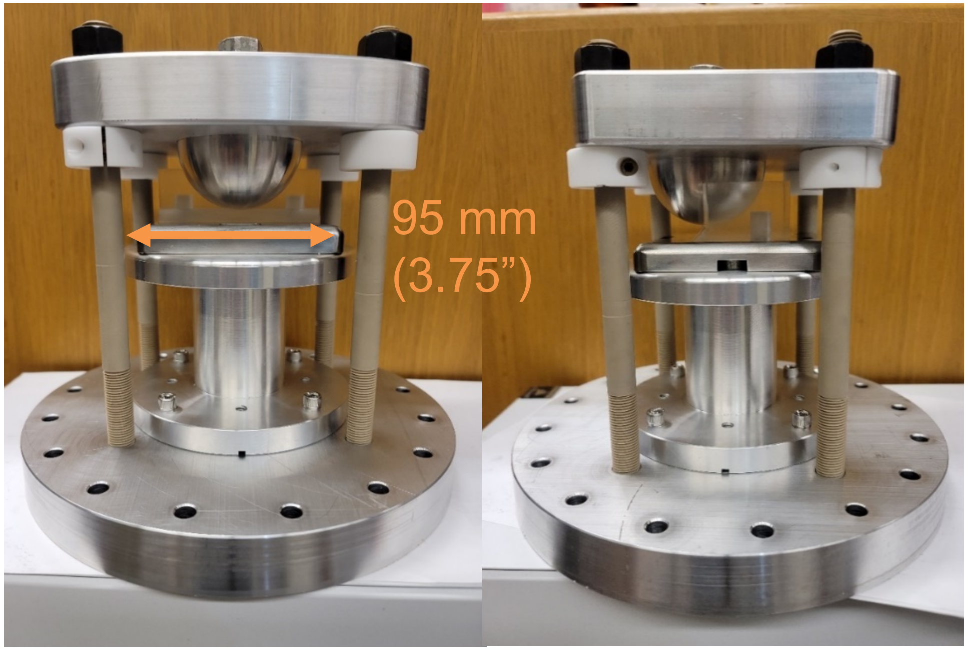


FIG. 6. (Color) The characteristic value of E_m near the anode and cathode triple junctions for the idealized 45° vacuum-insulator interface outlined in Figs. 1 and 2. Plotted is the field on the vacuum side of the interface as a function of the dielectric constant ε. We arbitrarily define the characteristic field to be that at the interface, at a distance $(0.01)2^{1/2}d$ from a junction.

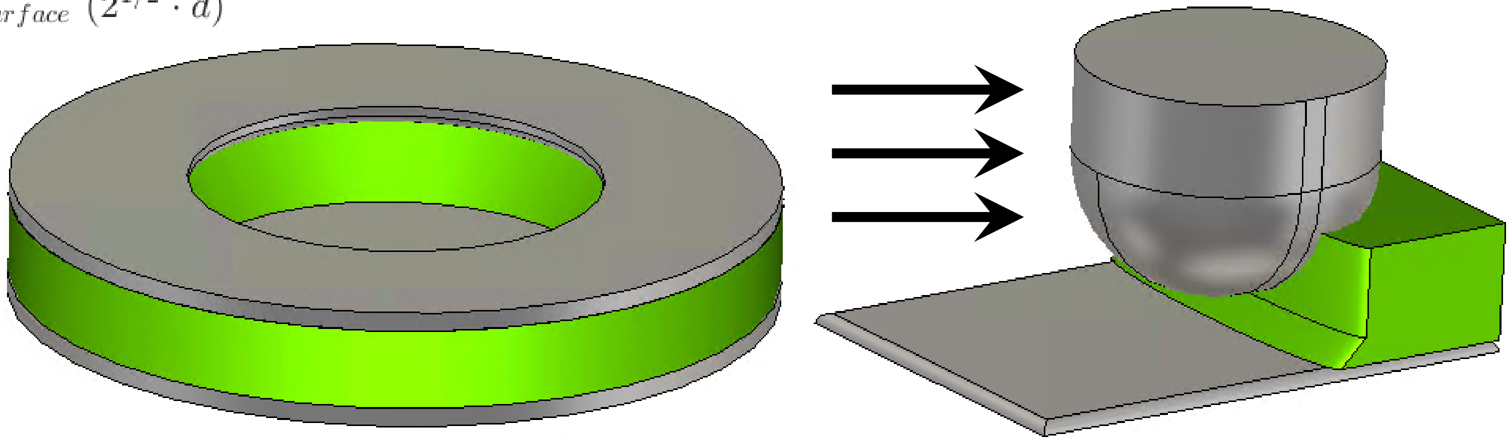
(Stygar et al. 2005) Suppression of CTJ is rapidly diminishing; ATJ grows aggressively

Experimental Apparatus

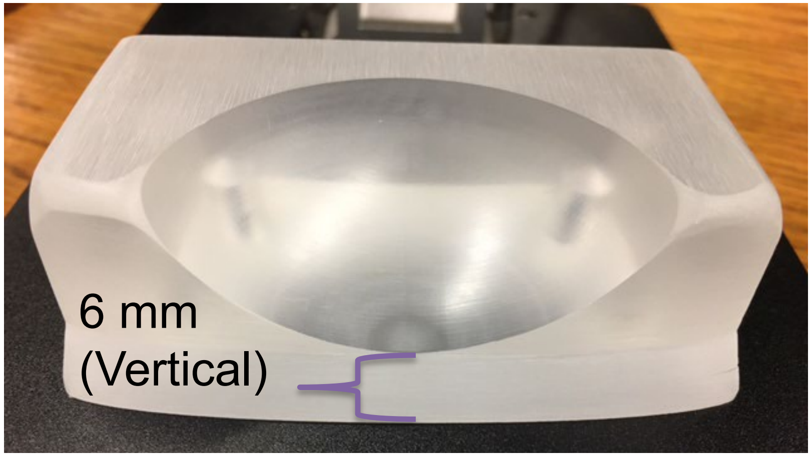


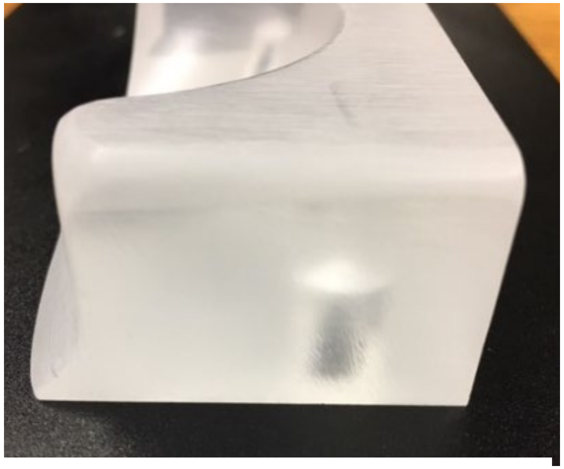


Stygar-like topology for localization of breakdown to a repeatable, central spot.



1st Generation Insulator Test Geometry





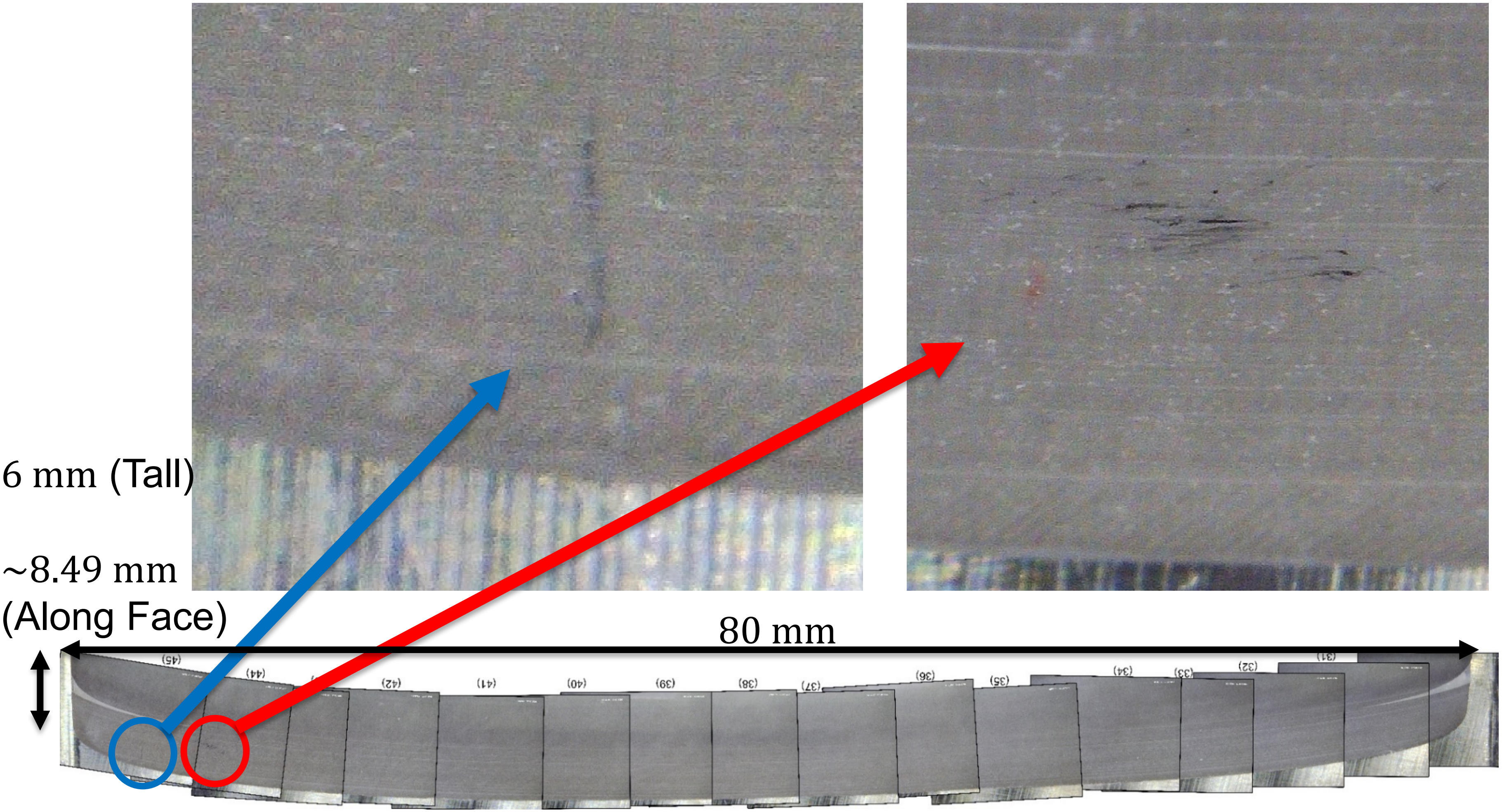
Earliest tests breakdown along the sharp edges was the dominant pathway

Breakdown along back (top surface, and down) was a persistent issue.

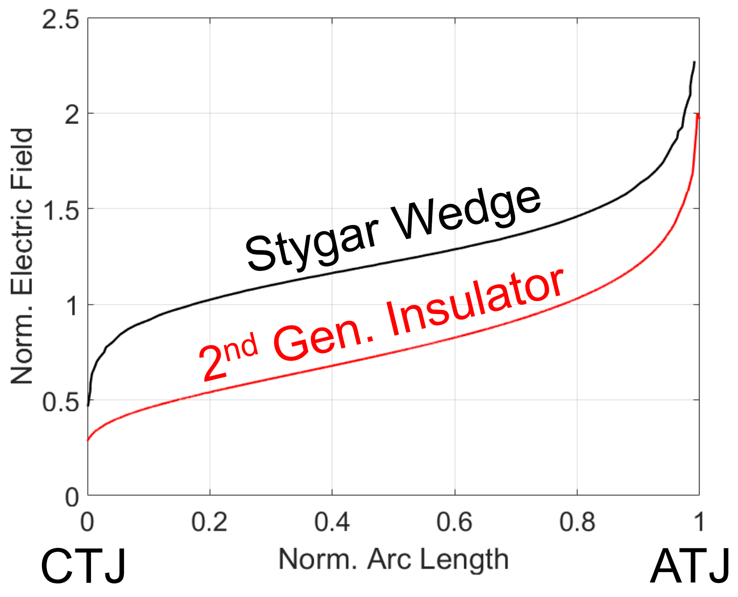
- Breakdown along the vertical surfaces proved to be far more likely than breakdown in the center (45° Wedge)
- Non-Critical Edges were rounded off to prevent breakdown along the edges of the structure.

Flashover of PMMA

Dark Scarring on Acrylic Insulator (Most Likely Carbon)

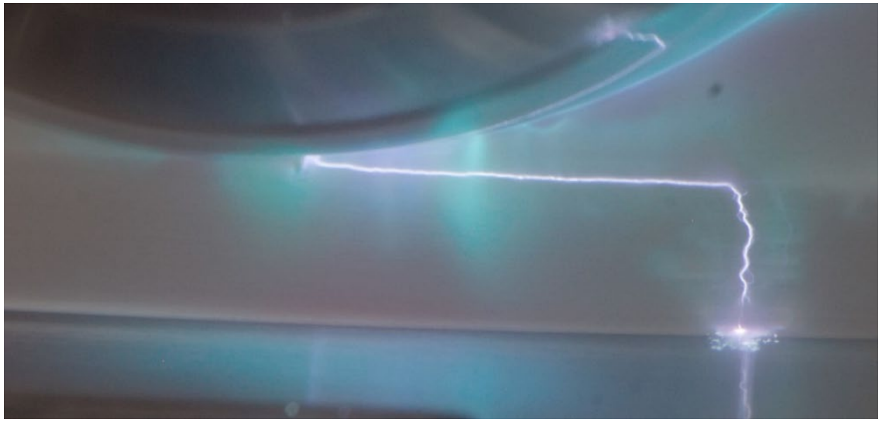


2^{nd} Generation Insulator Test Geometry

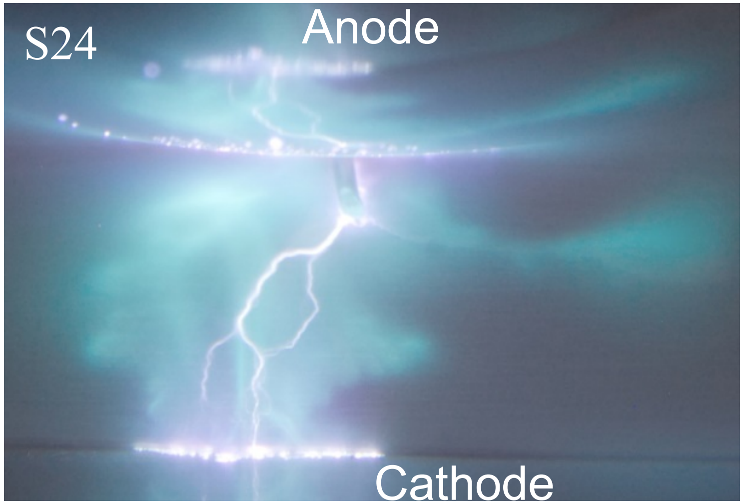


- Extended wedge improved voltage hold-off.
- Flashover across back (top) surface still is an issue.

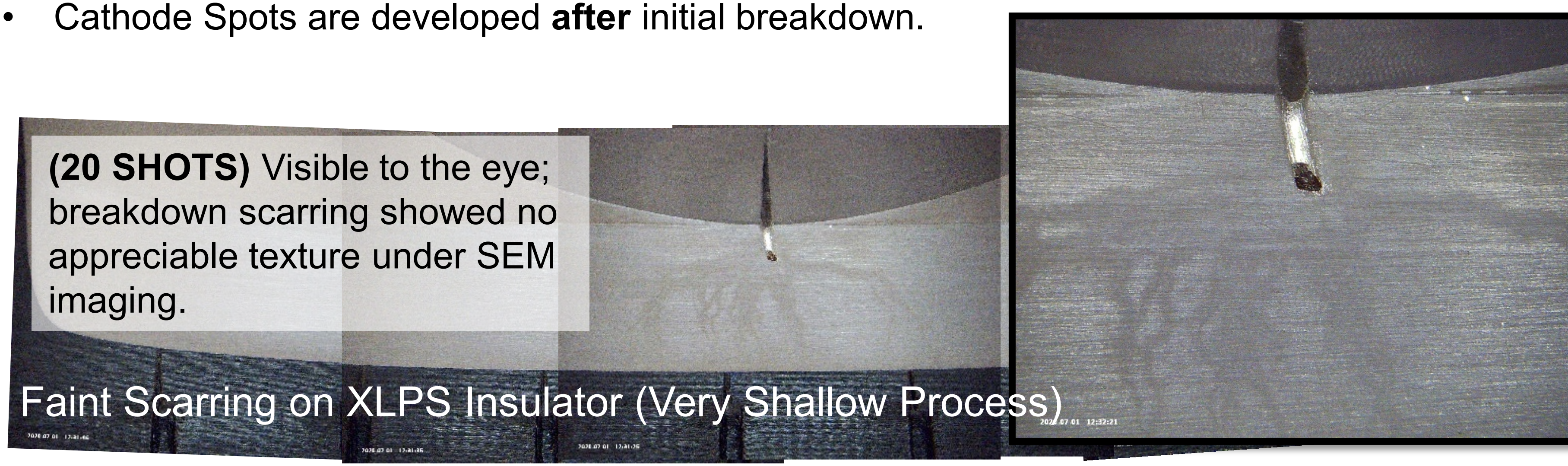
- Flashover of mechanical defects provided a striking contrast to breakdown directly in the gap.



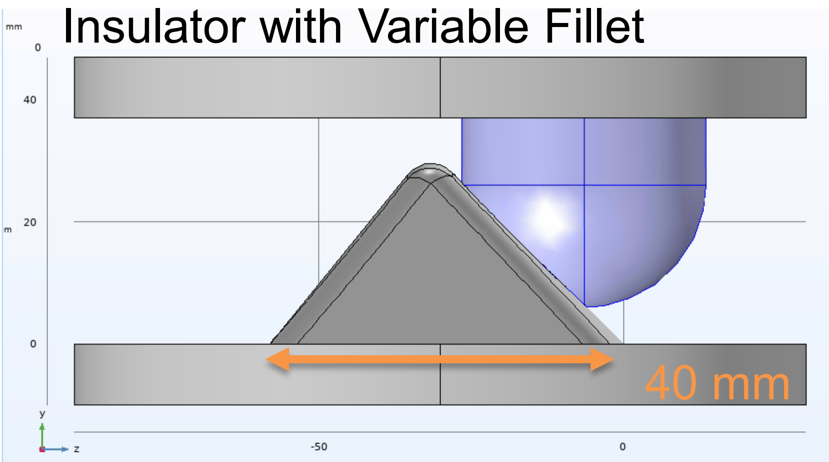
Anode Initiated Flashover

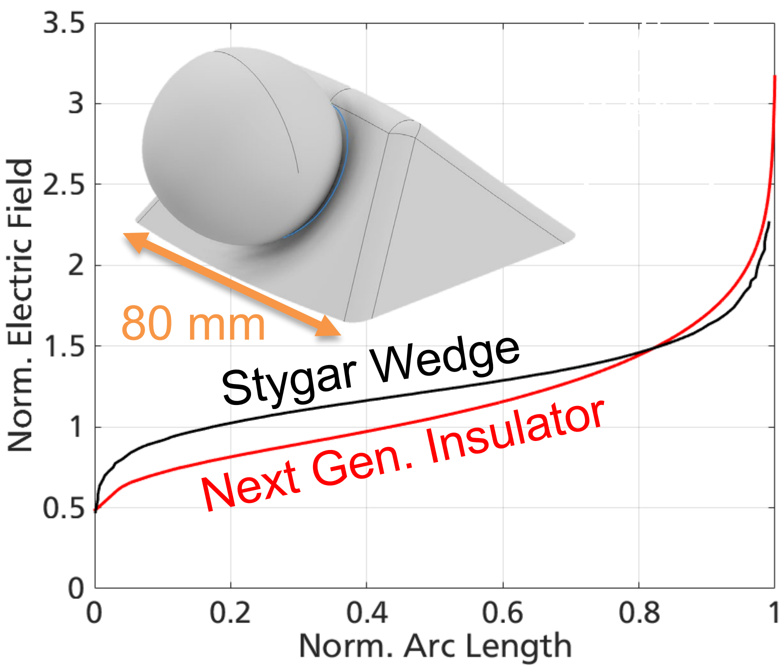


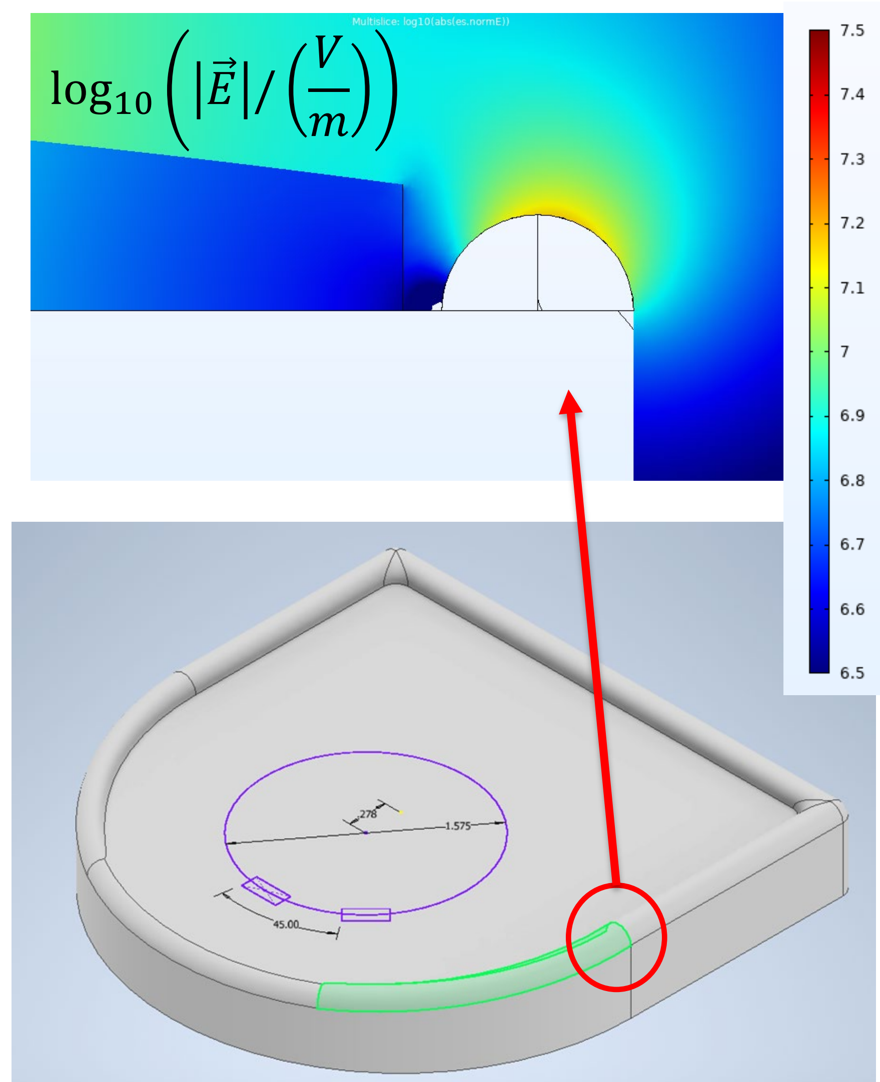
- Initiation was localized by use of the aluminum wire
- Cathode Spots are developed **after** initial breakdown.



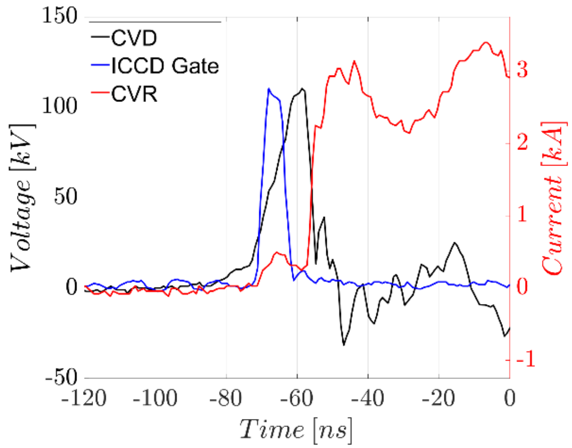
Next Generation Insulator

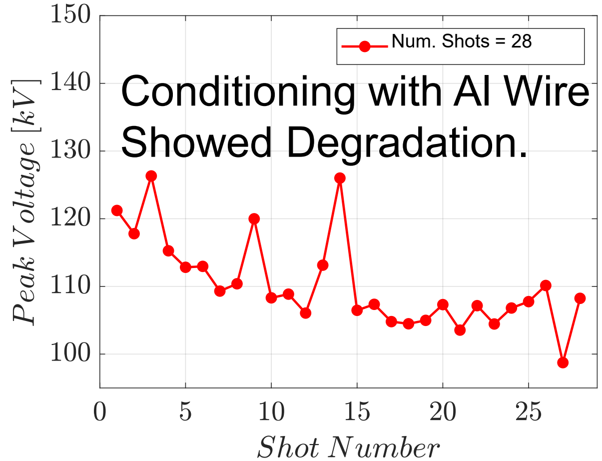


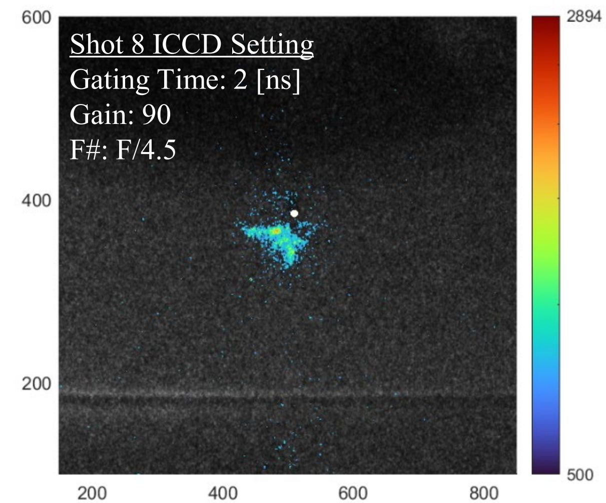




Additional Results of Interest

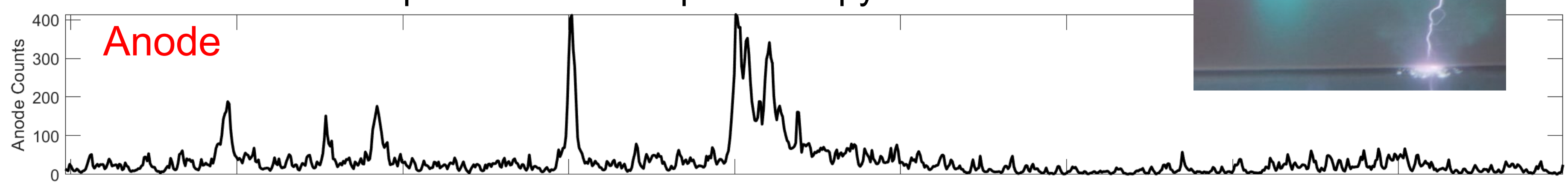




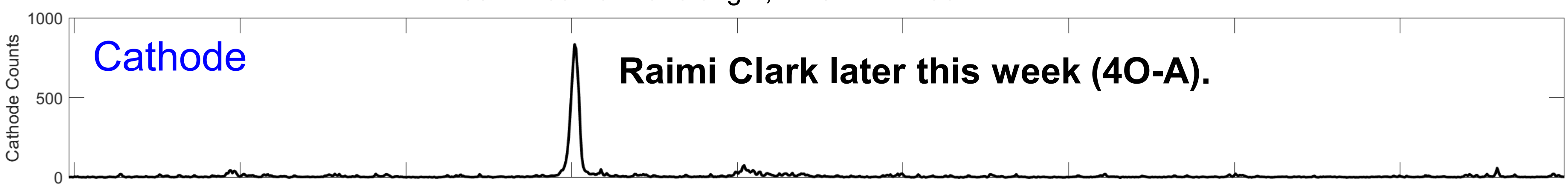


See Jacob Young (1O-A, Here Next)

> Optical Emission Spectroscopy <



~ 465 nm center wavelength, ~ 45 nm window



Raimi Clark later this week (4O-A).

Conclusions

Conclusions:

- Cathode initiated flashover typically occurs first
  - Hide the CTJ
  - Suppress the field at the CTJ
- Positive 45-degree wedge
  - High flashover voltage
  - Anode initiated flashover
- Bulk conduction is not believed to contribute any significant field grading.
  - External doping necessary if desired
- Anode initiated flashover
  - Observed early light and treeing from the anode
  - Detected carbon spectra near anode which may indicate breakdown of insulator near anode

Future Work:

- Refine the Insulator Test Bed
  - Add a CVD directly under the insulator
  - Move to a larger chamber and test fixture (scaling mechanics)
- Continued development of insulator geometry
  - Localize the breakdown **without** the need for the wire
  - Explore the impact of differing materials
- Continued measurements
  - Voltage & Current Diagnostics
  - Gated & Long Exposure Photography
  - Optical emission spectroscopy
- Develop additional diagnostics
  - Temporally resolved gas densities

Citations

- [1] Neuber, A. et al. The role of outgassing in surface flashover under vacuum *IEEE Transactions on Plasma Science, Vol 28, No. 5, October 2000*
- [2] R. A. Anderson, Surface flashover measurements on conical insulator suggesting possible design improvements, SAND75 0667, 1976
- [3] Stygar et al. Flashover of a vacuum-insulator interface: a statistical model *Phys. Rev. ST Accel. Beams, American Physical Society,* 2004, 7, 070401
- [4] Stygar et al. Improved design of a high-voltage vacuum-insulator interface *Phys. Rev. ST Accel. Beams, American Physical Society,* 2005, 8, 050401
- [5] P. Yan et al., "Experimental investigation of surface flashover in vacuum using nanosecond pulses," in IEEE Transactions on Dielectrics and Electrical Insulation, vol. 14, no. 3, pp. 634-642, June 2007
- [6] J. G. Leopold, R. Gad, E. Hillel, C. Leibovitz, M. Markovits and I. Navon, "Applying a different approach to pulsed high-voltage insulation," *2010 IEEE International Power Modulator and High Voltage Conference*, 2010
- [7] Different approach to pulsed high-voltage vacuum-insulation design, John G. Leopold, Chaim Leibovitz, Itamar Navon, and Meir Markovits, Phys. Rev. ST Accel. Beams 10, 060401
- [8] Ya. E. Krasik and J. G. Leopold , "Initiation of vacuum insulator surface high-voltage flashover with electrons produced by laser illumination", Physics of Plasmas 22, 083109 (2015) https://doi.org/10.1063/1.4928580
- [9] Fundamentals of spacecraft charging: spacecraft interactions with space plasmas, Princeton University Press, 2012
- [*] Fundamental Study of High Electric Field Surface Flashover in Vacuum, Neuber, Andreas and Stephens, Jacob and Brooks, William and Clark, Raimi and Young, Jacob and Mounho, Michael and Hopkins, Matthew, EAPPC BEAM 2020

- Modelled in Commercial FEM Solver (COMSOL)
  - Time Dependent (Axisymmetric) Model Using Electric Currents Interface and Circuit Excitation
    - $\nabla \cdot \vec{J} = Q$
    - $\vec{J} = \sigma\vec{E} + \frac{\partial\vec{D}}{\partial t} + \vec{J_e}$
    - $\vec{E} = -\nabla\phi$
  - Field Dependent Insulator Conductivity
    - $\beta^2 = \frac{|q_e|^3}{\epsilon_0}$; $\delta = 1$ nm; $T = 293$ k; $\sigma(T) = \sigma_T$
    - $\sigma(E,T) = \sigma(T)\left[2 + \cosh\left(\frac{\beta|\vec{E}|^{\frac{1}{2}}}{2kT}\right)\right]\left[\frac{2kT}{|q_e\vec{E}|\delta}\sinh\left(\frac{|q_e\vec{E}|\delta}{2kT}\right)\right]$
    - (Fundamentals of Spacecraft Charging: Spacecraft Interactions with
    - Space Plasmas, Chapter 16: Deep Dielectric Charging by Shu T. Lai,
    - p.152 (16.14), Princeton University Press)
  - Solver Settings
    - Fully Coupled, Direct Solver (MUMPS)
    - Nonlinear Method: Constant (Newton)
    - Jacobian update: On Every Iteration
    - Stabilization: Anderson acceleration
    - Adaptive Mesh Refinement

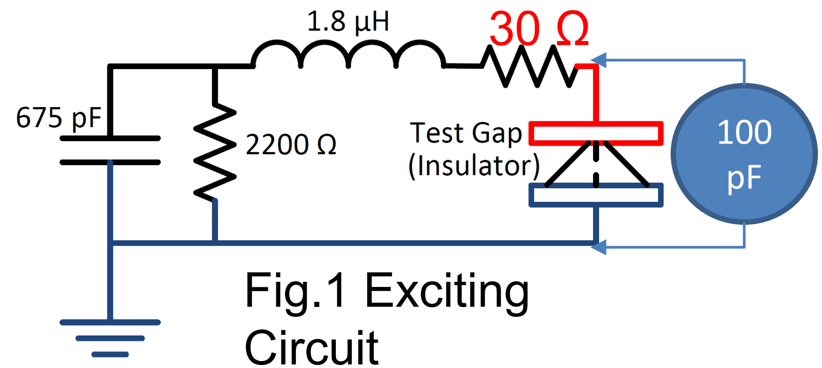


Fig.1 Exciting Circuit

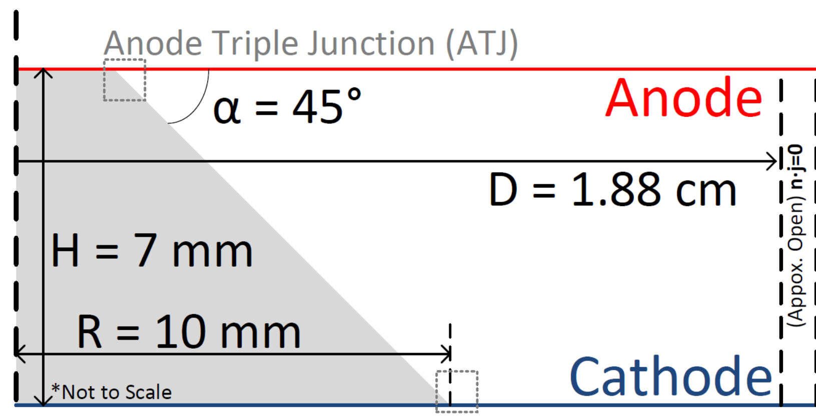
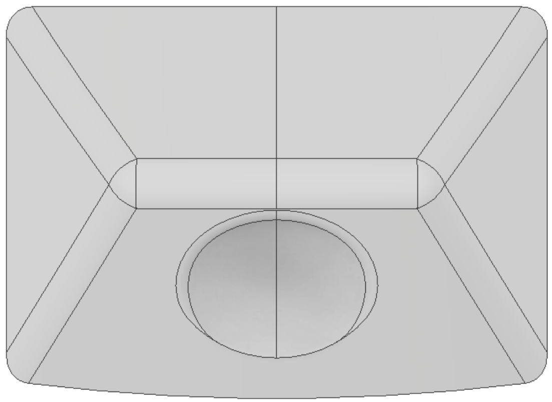


Fig.2 Geometry

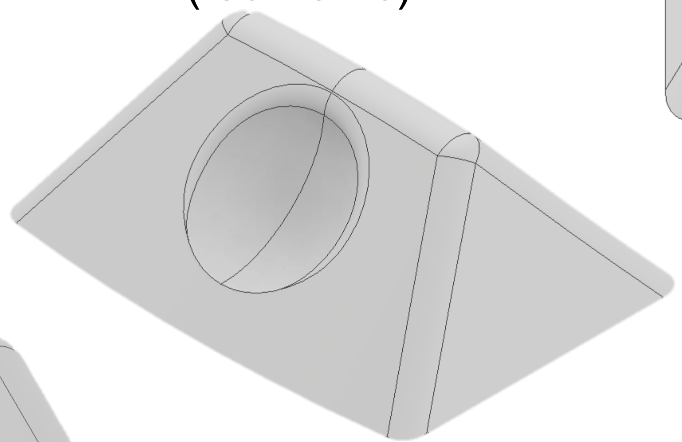
Appendix: CAD Model

(Top)

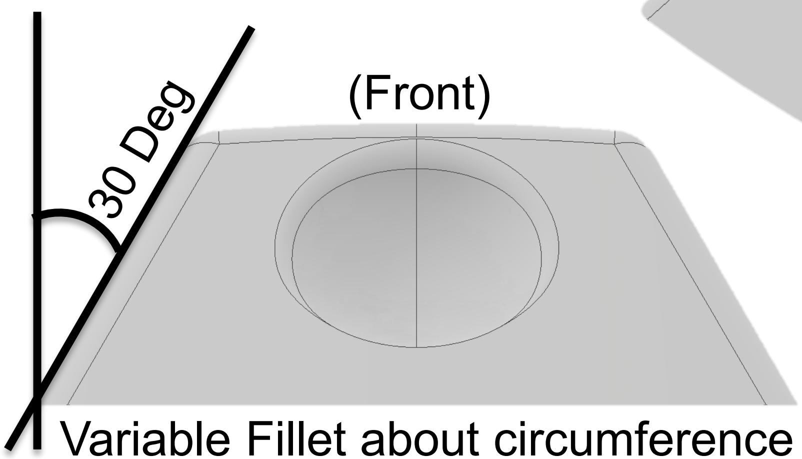


Receives 20 mm R Sphere Electrode
5 mm Fillet (Top, Sides)
Variable Fillet (Sphere)

(Isometric)



(Front)



<u>Variable Fillet about circumference</u>

5 mm @ 0 % (Top)
4 mm @ 20 %
3 mm @ 40 %
2 mm @ 60 %
0 mm @ 80 %
0 mm @ 100 %

(Side)