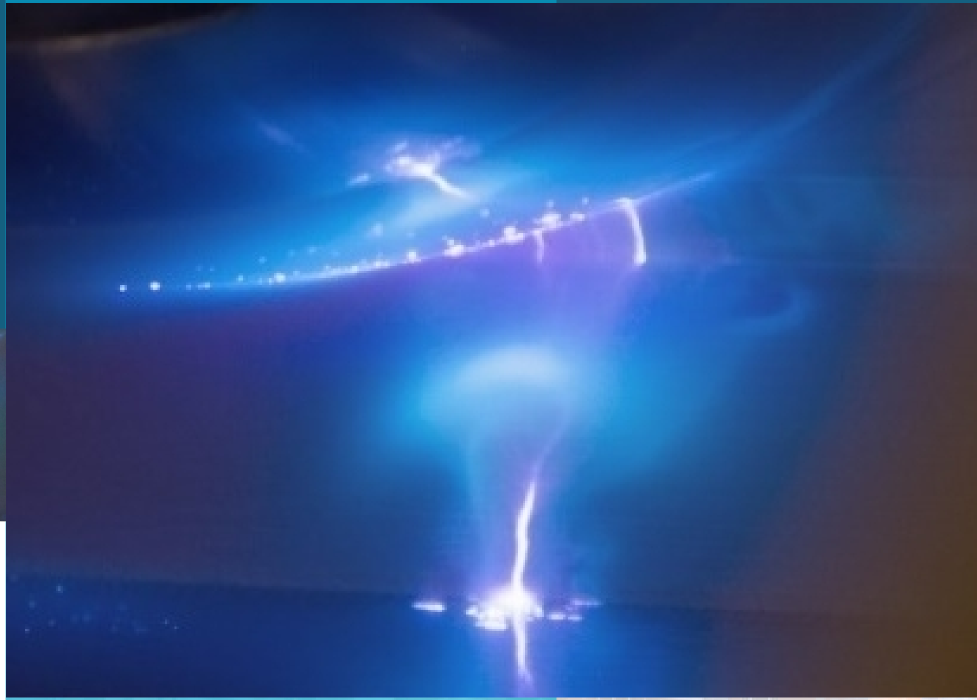
SAND2022-12343C

Mechanisms of Anode-Initiated Vacuum Insulator Flashover for Pulsed Power Applications



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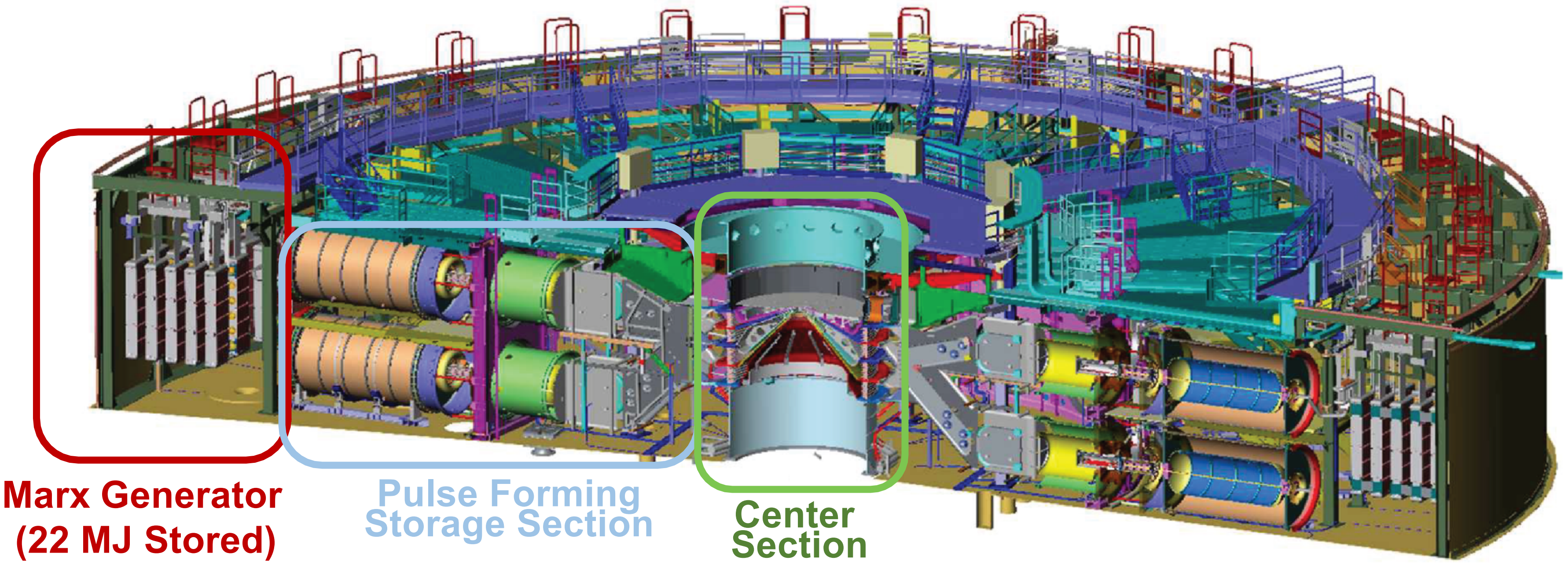
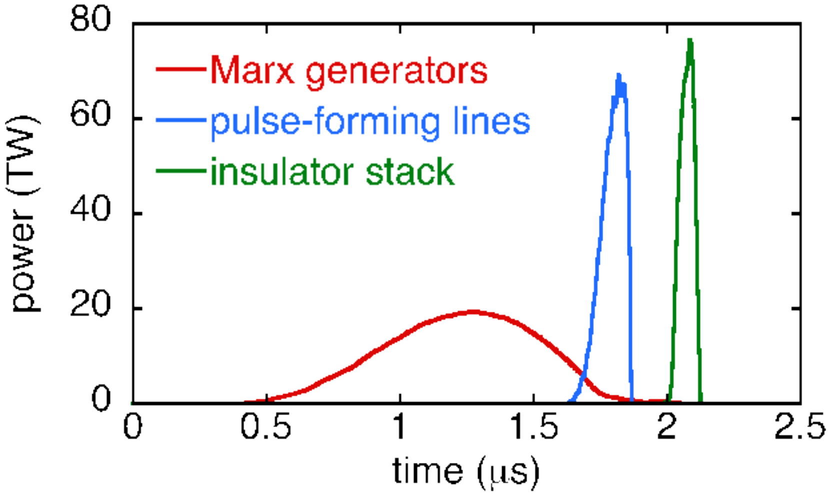
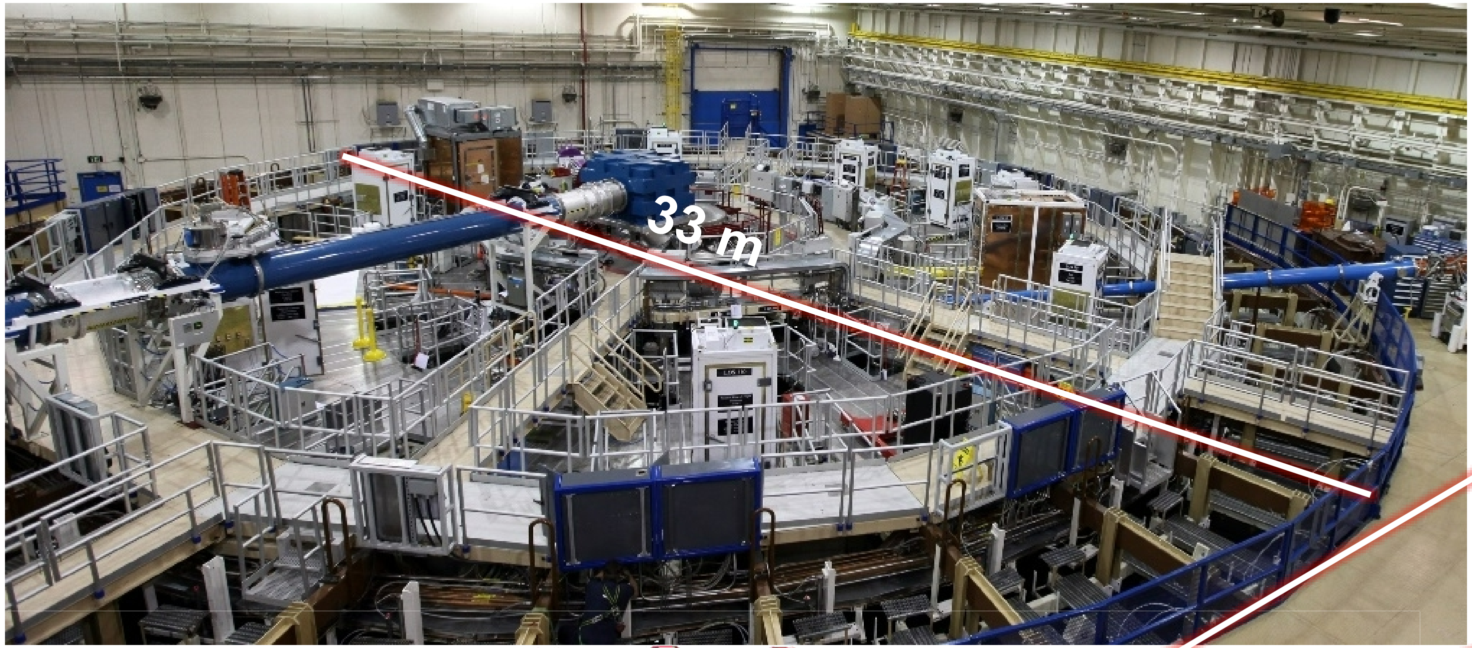
Sandia's Z Machine

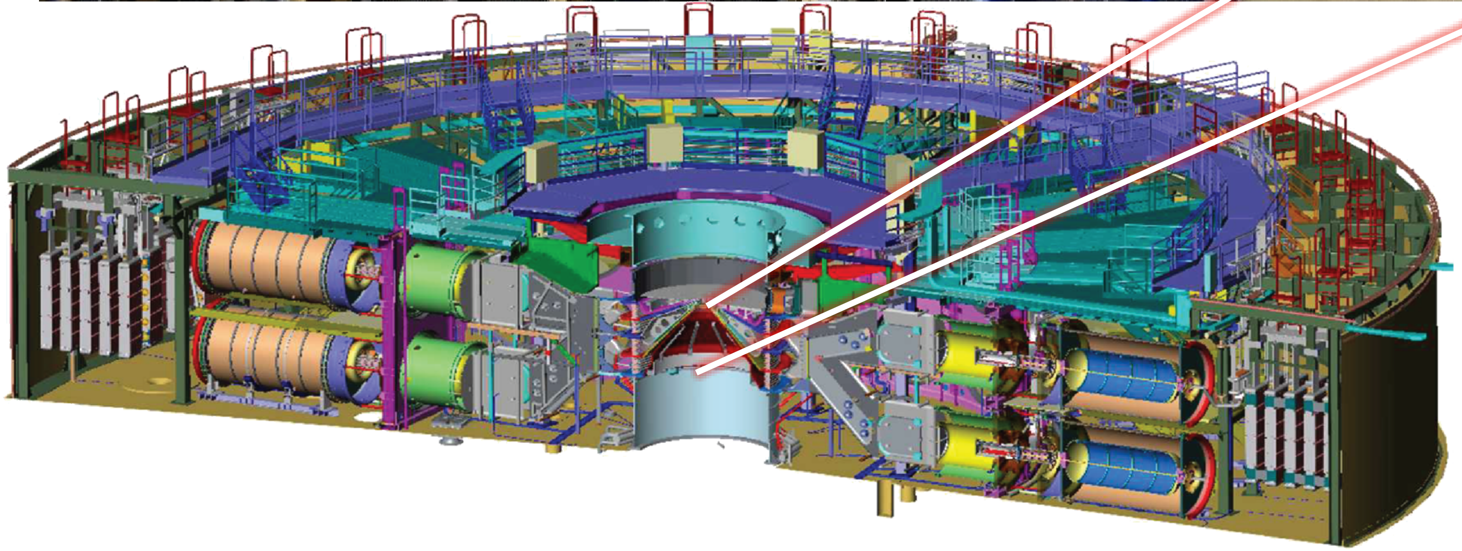


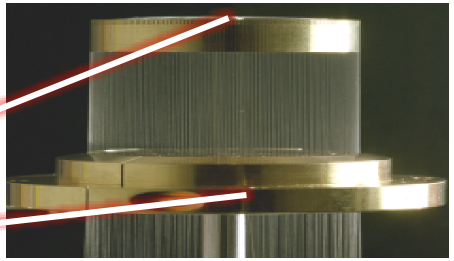


Z, the world's largest pulsed power machine, delivers 80-100 TW and 6 MJ of electrical energy to its center section in ~150 ns. X-ray pulse has ~300 TW. World's power grid is ~4 TW.

Sandia’s Z Machine

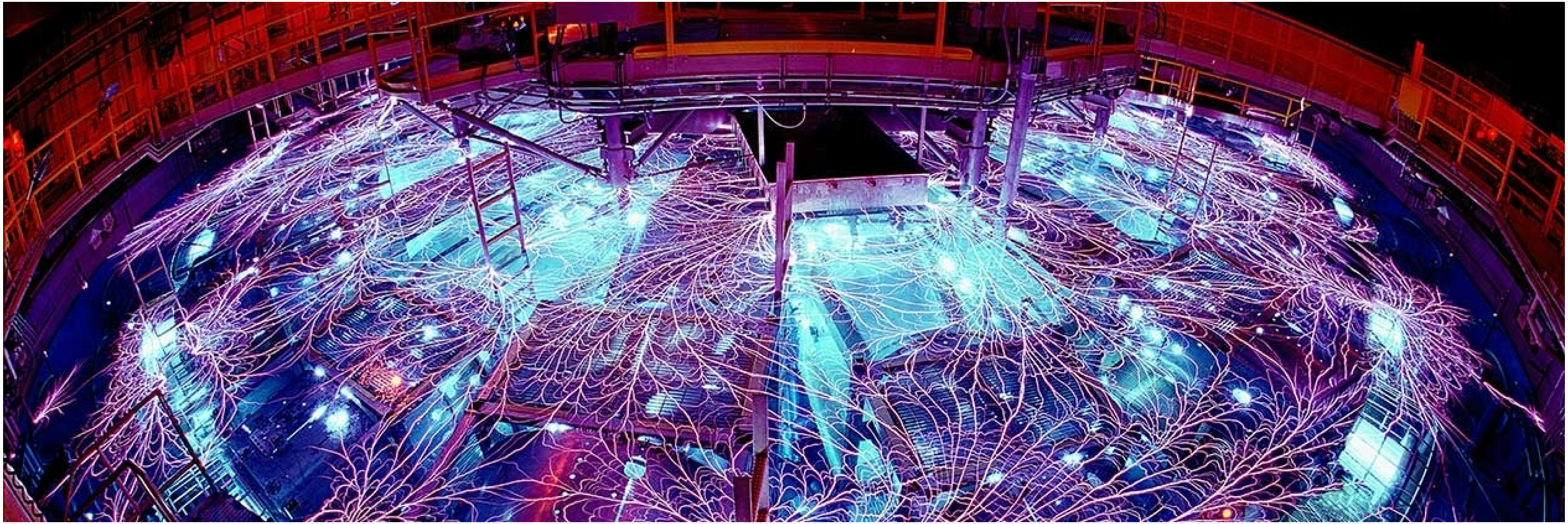




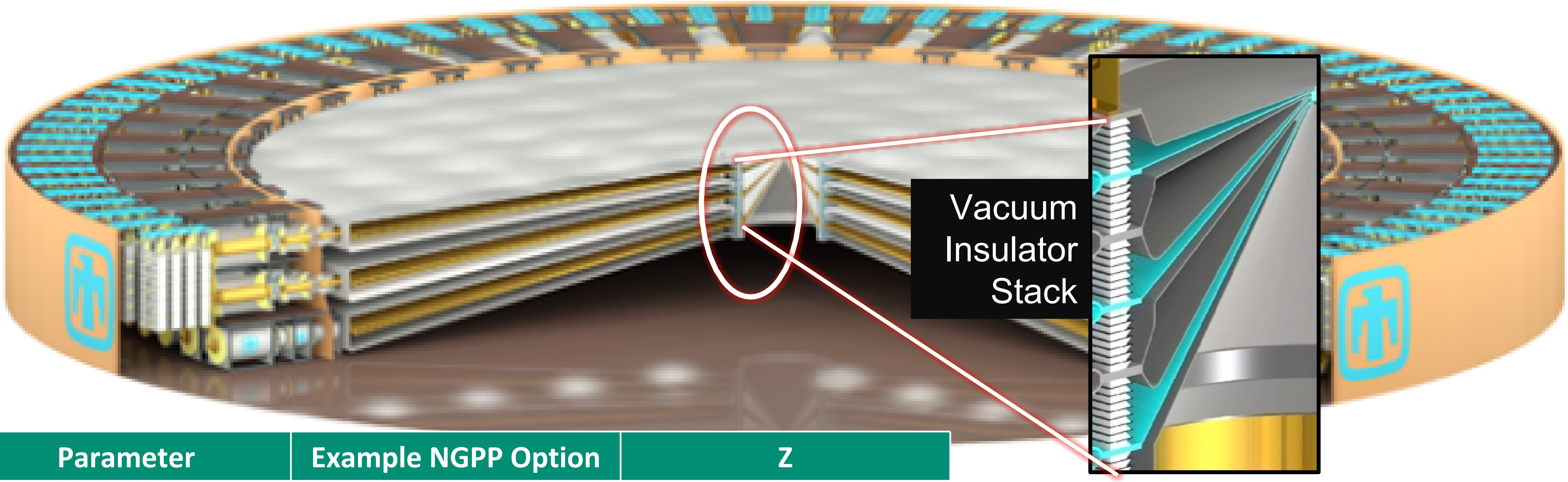


Send 20 MA through this 2 cm radius x 1.4 cm height hohlraum!

Sandia's Z Machine



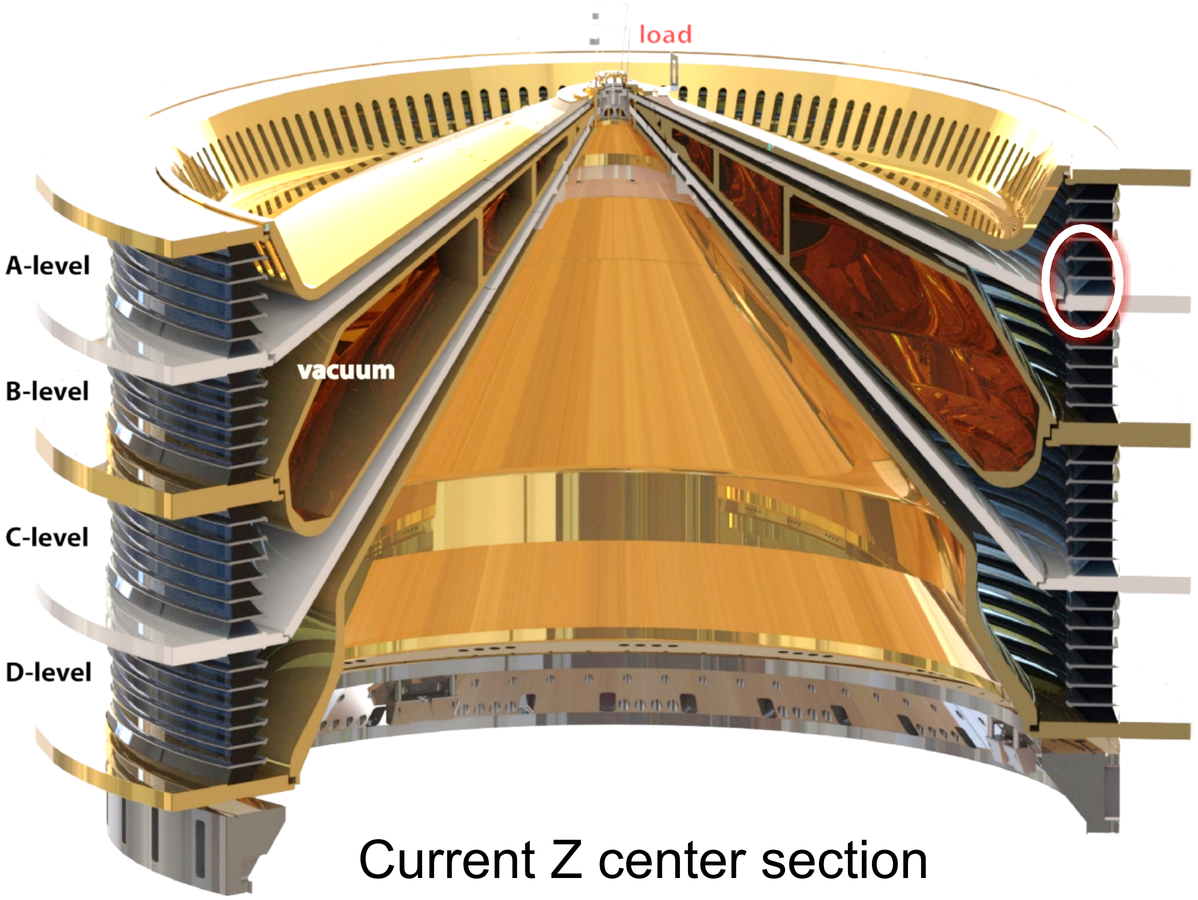
Sandia's "Next Z Machine": Next Generation Pulsed Power (NGPP)



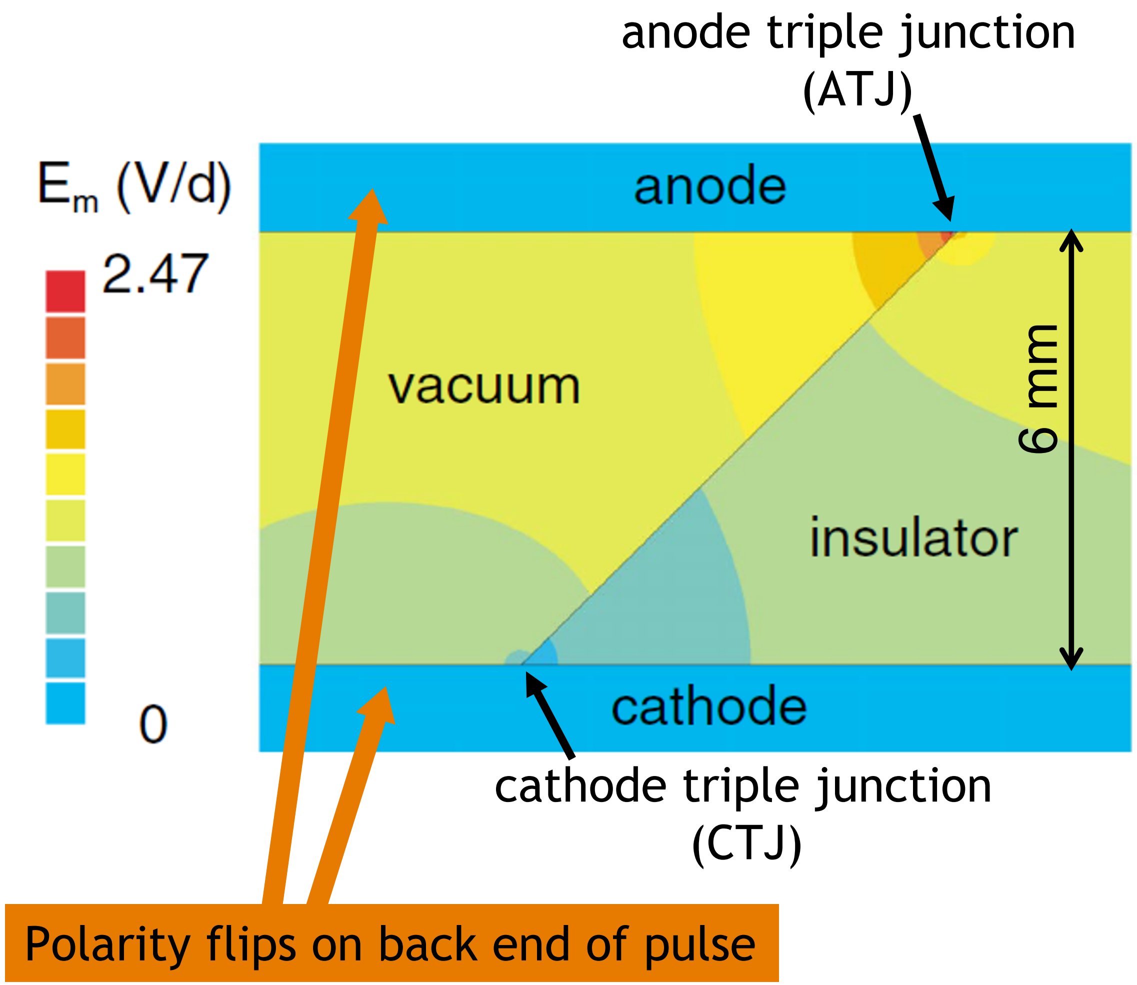
Parameter	Example NGPP Option	Z
Diameter	90 m	30 m
Marxes	75 @ 2400 kJ (180 MJ)	36 @ 600 kJ (22 MJ)
Capacitors	13,500 @ 2.95 µF	2,160 @ 2.65 µF
Power at Stack	602 TW	85 TW
Forward Energy at Stack	54 MJ (short pulse)	6 MJ (short pulse)

Height of vacuum insulator stack is a critical constraint. Smaller gaps – requiring higher breakdown strengths – will lead to $100M's of savings and enable new class of designs.

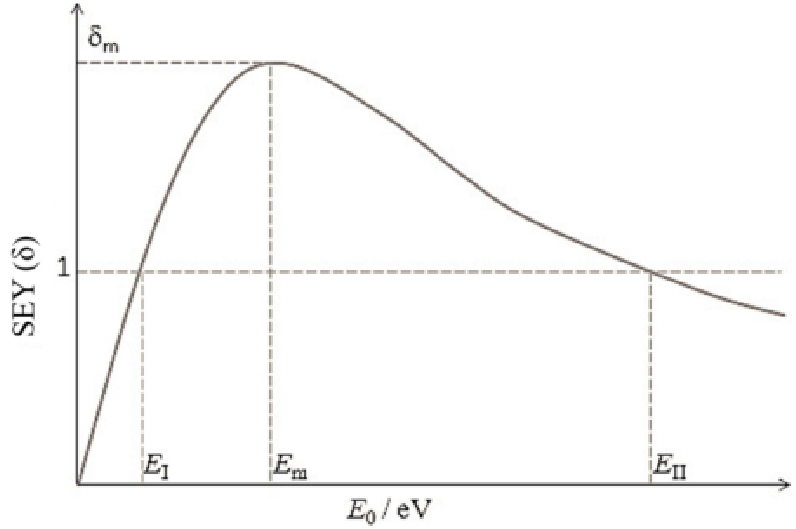
Vacuum Insulator Flashover

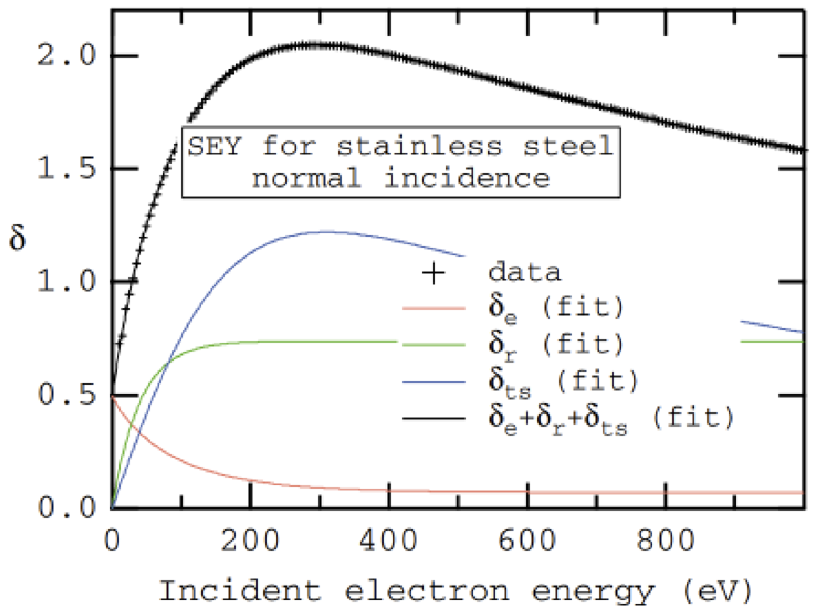


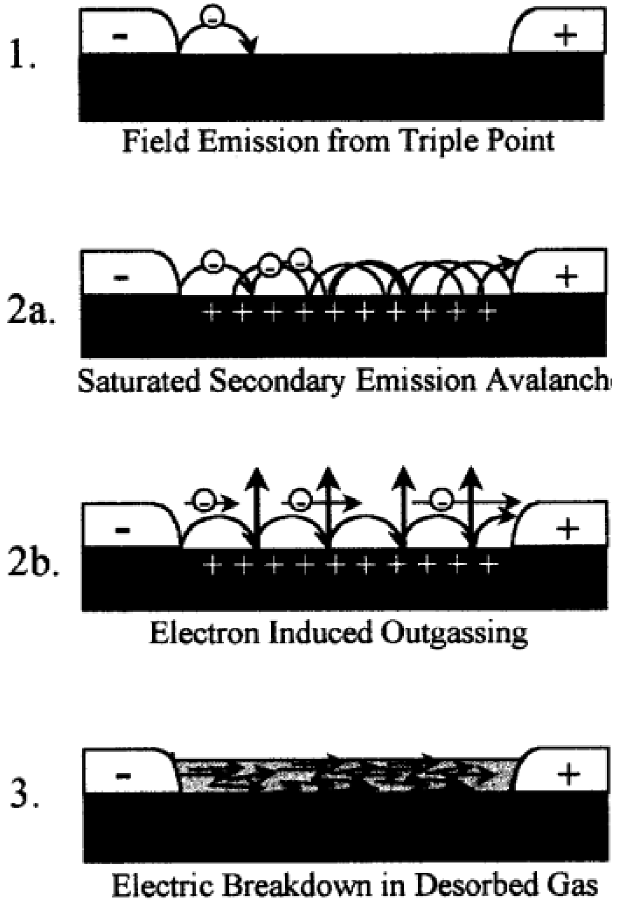
Current Z center section

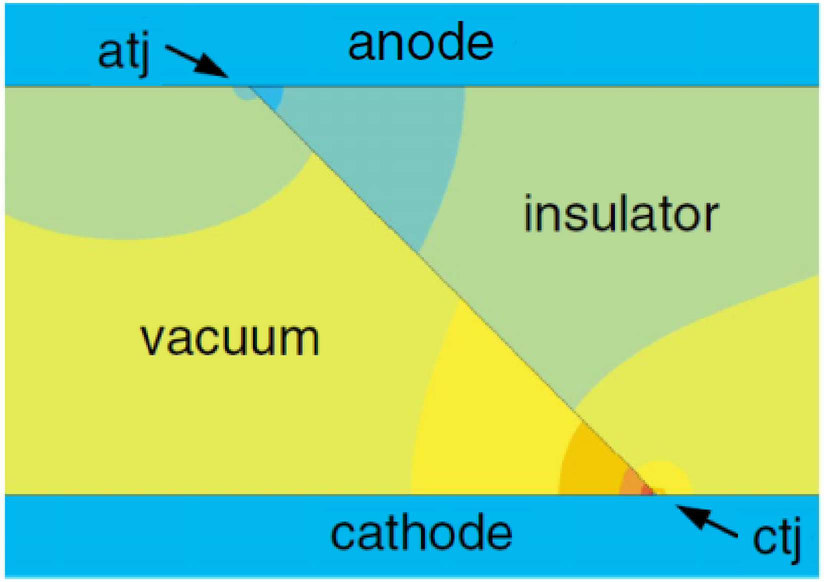


Cathode-Initiated Breakdown



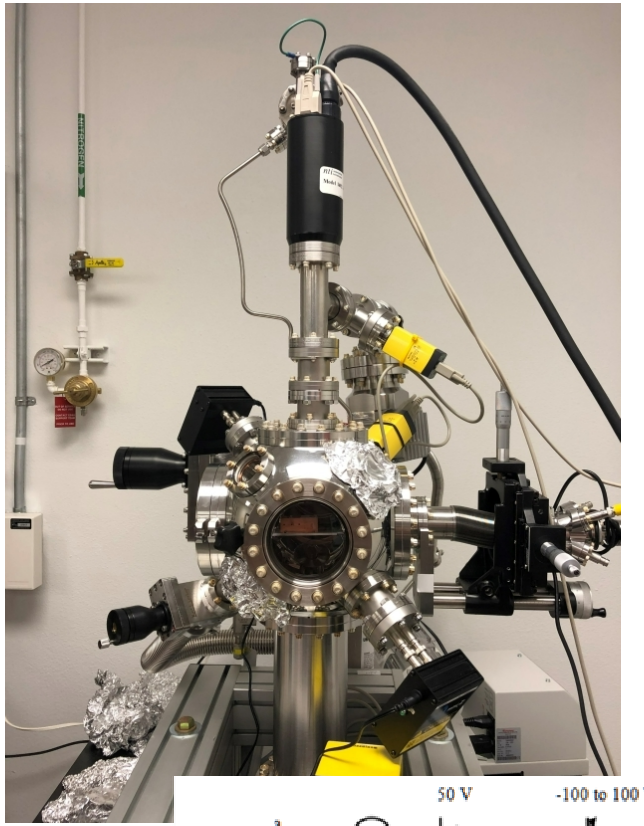






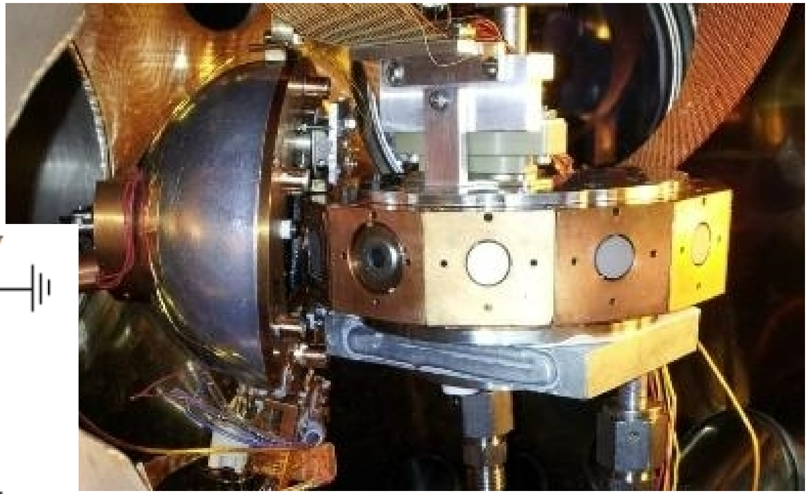
Furman, Phys. Rev. STAB, 2002
Jenkins, Electron and Ion Emission from Solids, 1965
Neuber, IEEE Trans. Plasma Sci., 2000
Stygar, Phys. Rev. STAB, 2005

Cathode-Initiated Breakdown: Measuring Yields

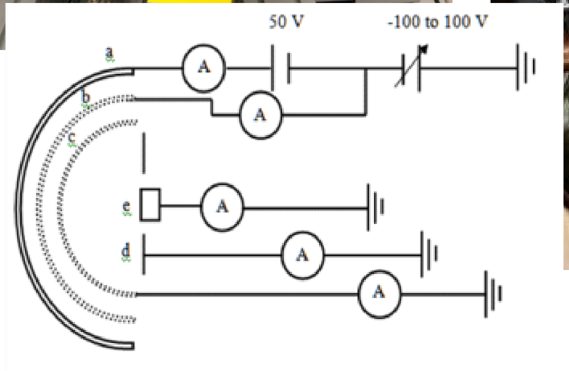


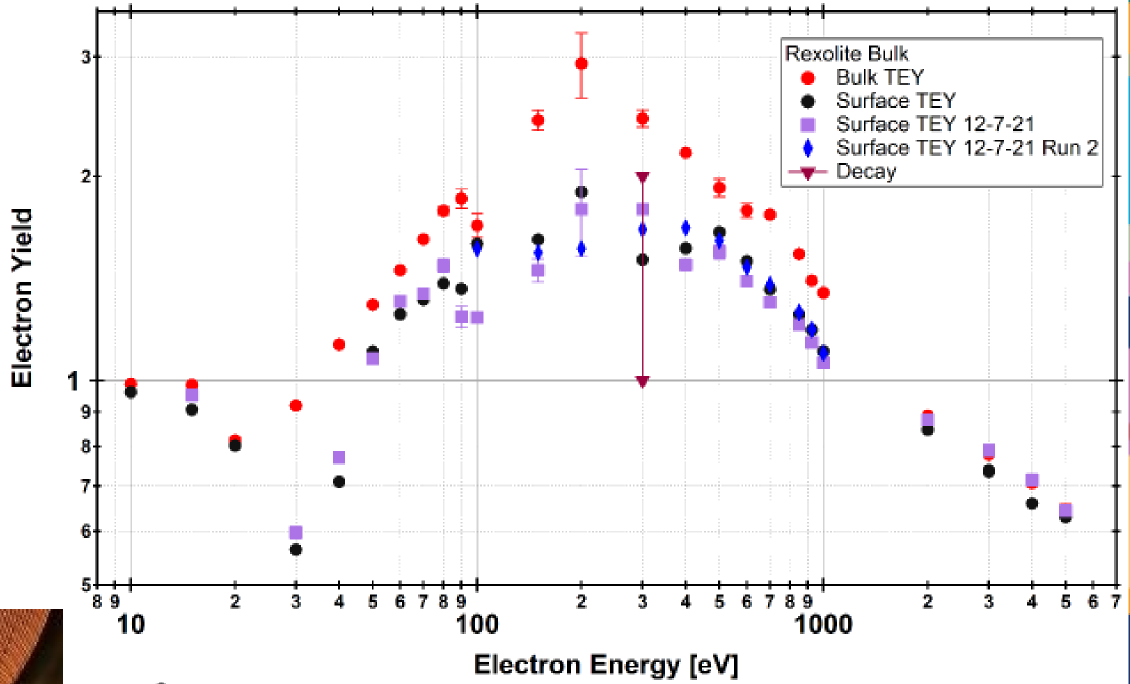
Ion gun with 0.02 - 3 keV ions and beam blanking for pulsed operations on insulators.

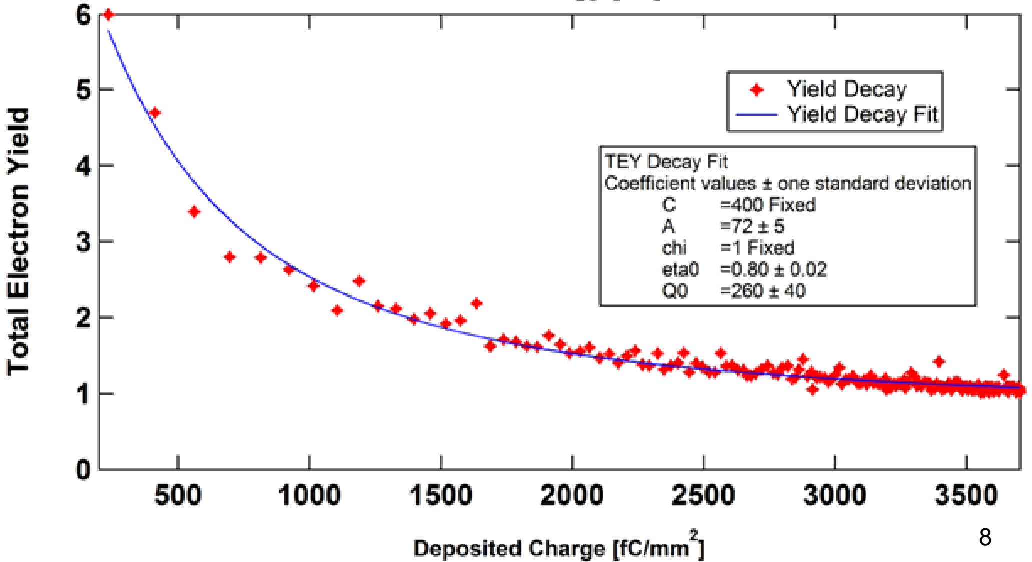
Electron gun 0.05 - 5 keV electrons with speed pulsing capability.



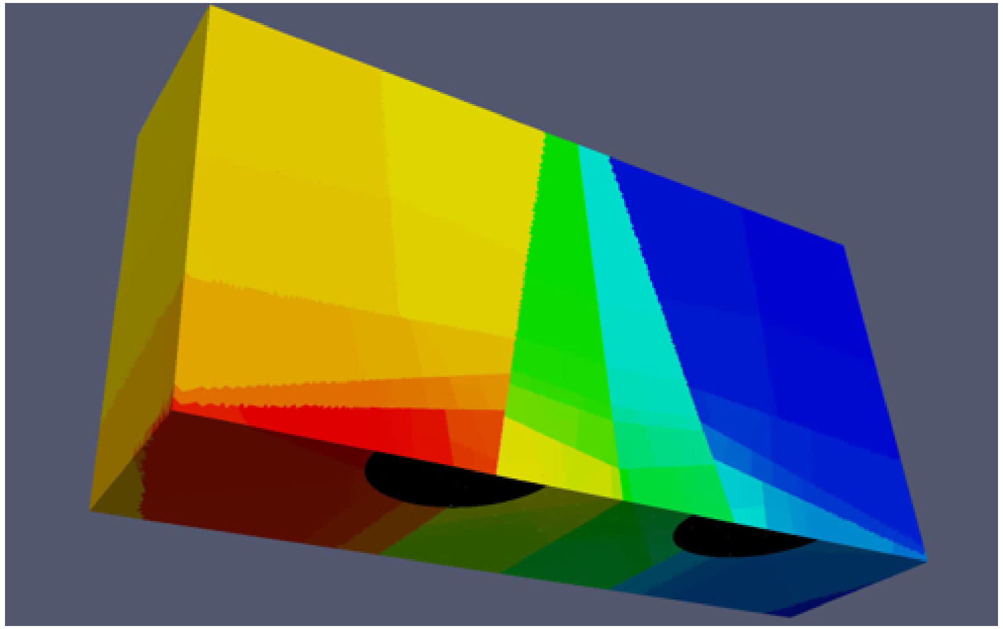
Primary beam





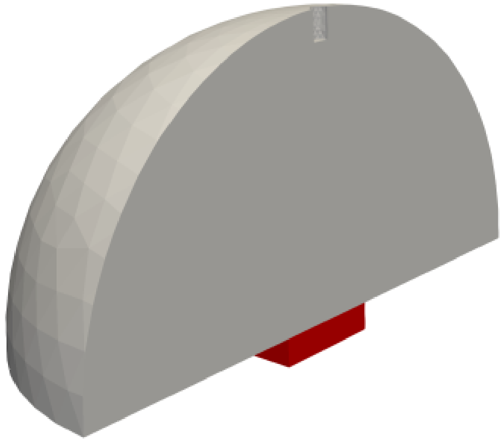


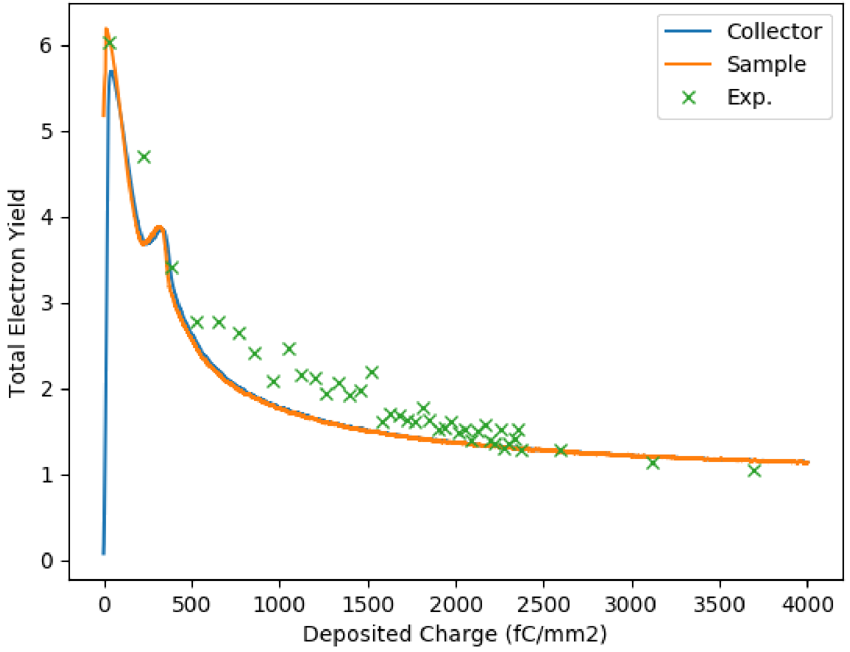
Aleph Simulation Tool

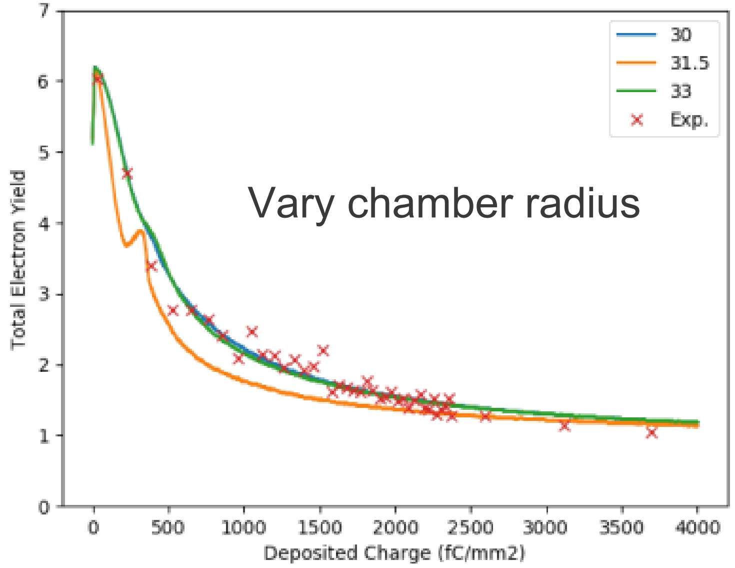


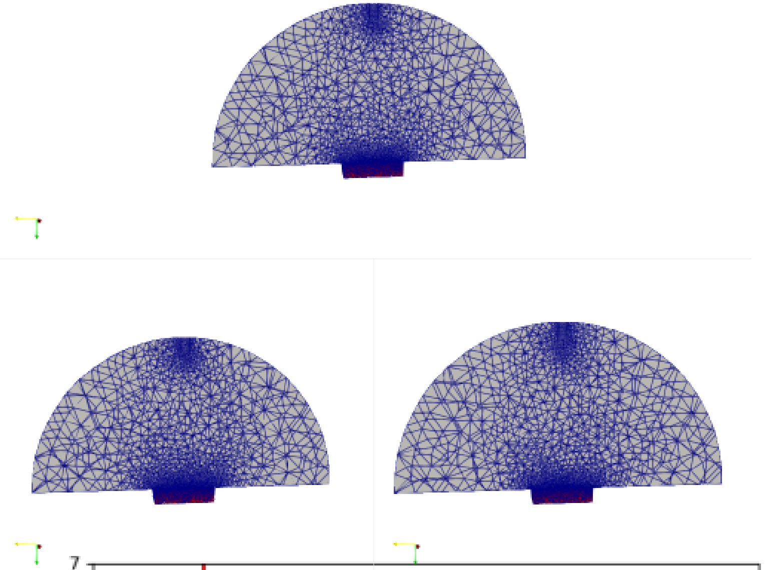
1, 2, or 3D Cartesian
Unstructured FEM (compatible with CAD)
Massively parallel
Hybrid PIC + DSMC (PIC-MCC)
Electrostatics
Fixed B field
Solid conduction
Advanced surface (electrode) models
e- approximations (quasi-neutral ambipolar, Boltzmann)
Collisions, charge exchange, chemistry, excited states, ionization
Photon transport, photoemission, photoionization
Advanced particle weighting methods
Dual mesh (Particle and Electrostatics/Output)
Dynamic load balancing (tricky)
Restart (with all particles)
Agile software infrastructure for extending BCs, post-processed quantities, etc.
Currently utilizing up to 64K processors (>200M elements, >1B particles)

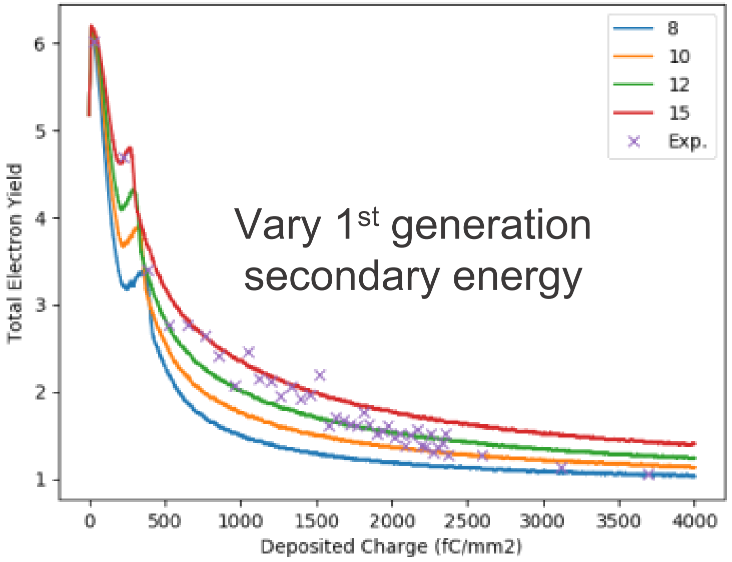
Cathode-Initiated Breakdown: Secondary Yield Simulation

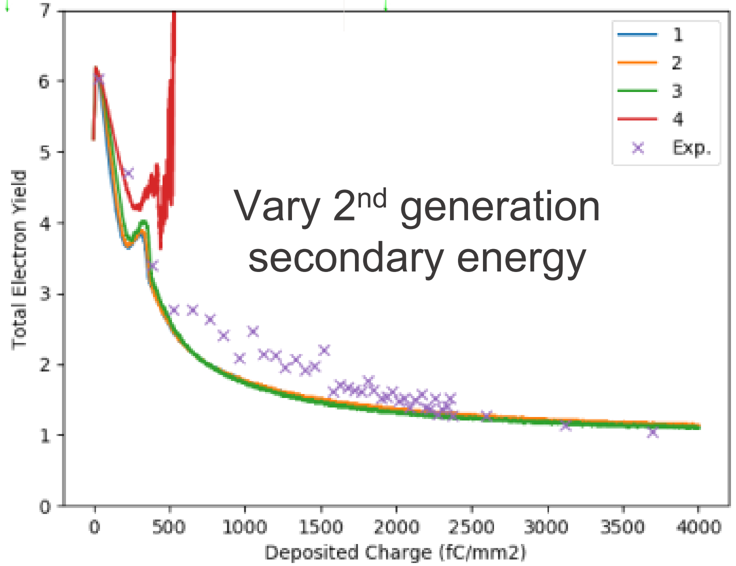




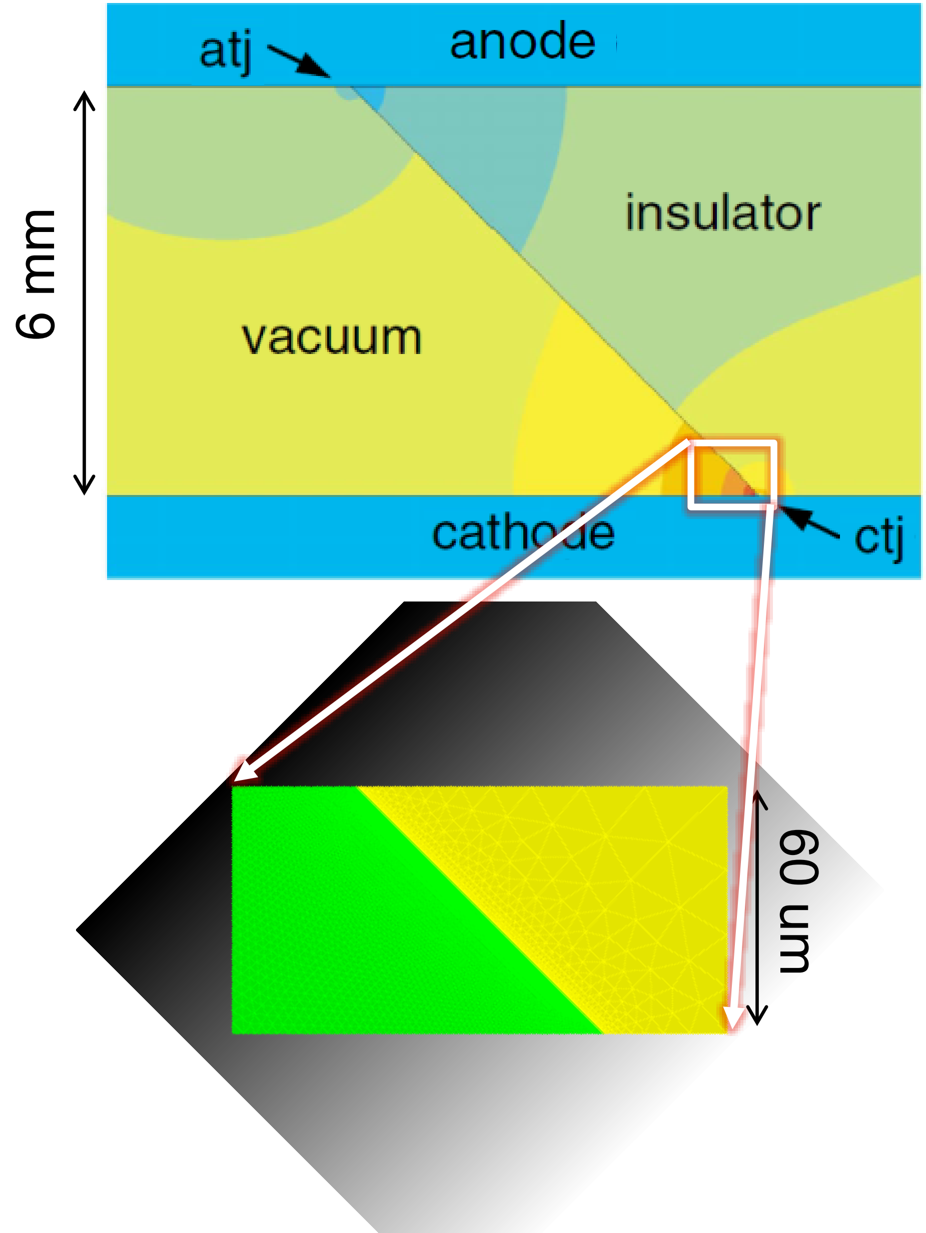


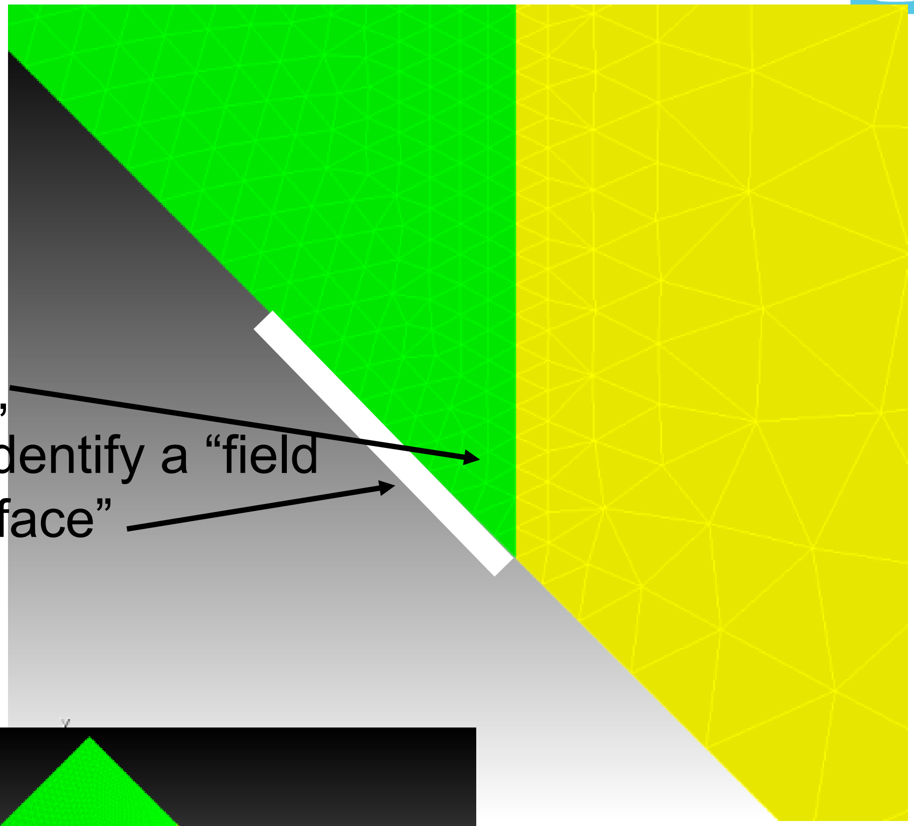






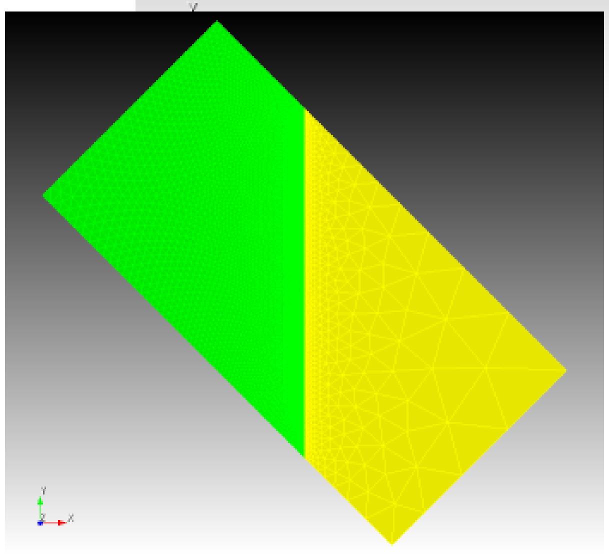
Cathode-Initiated Breakdown: Cascade Simulation



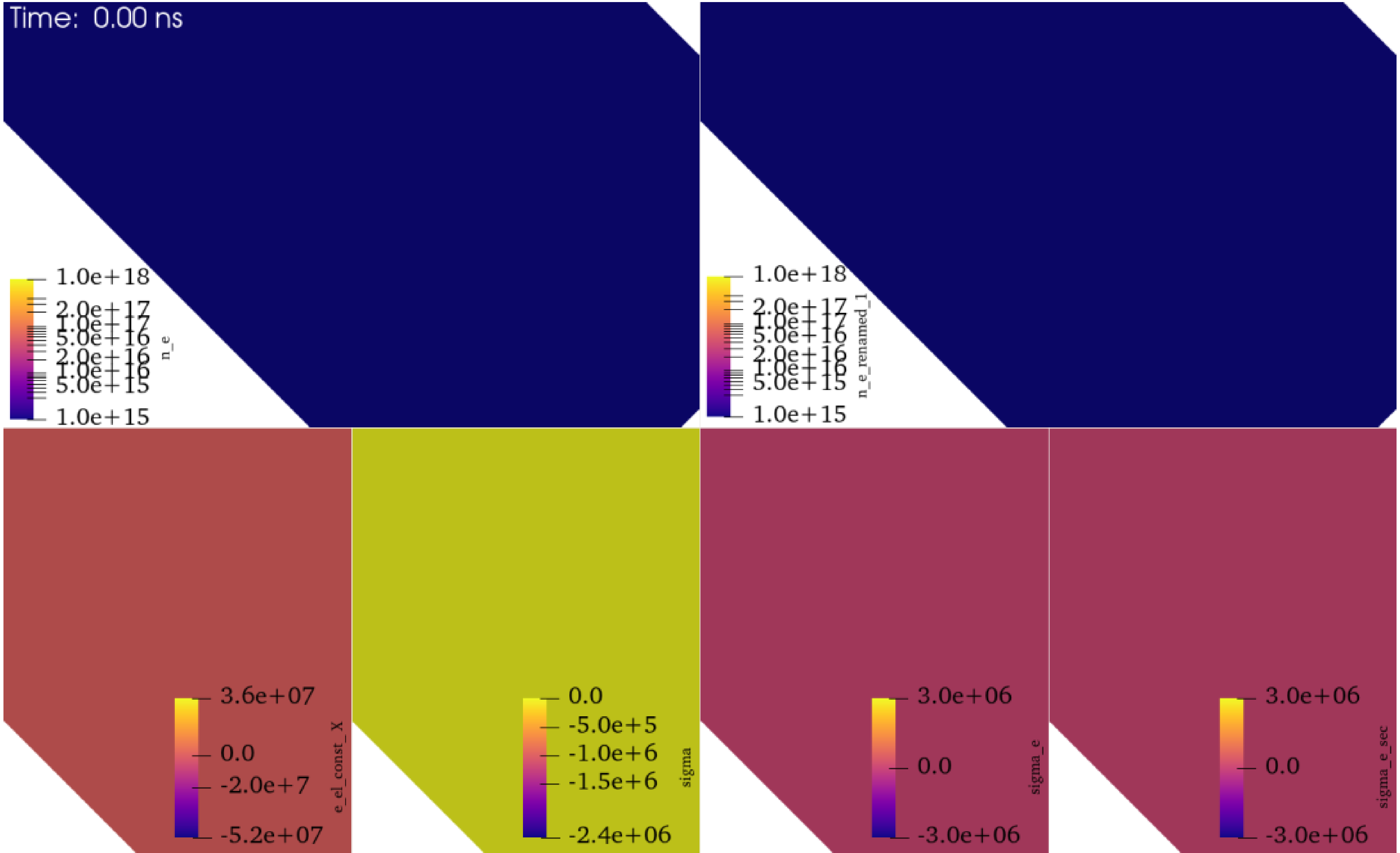


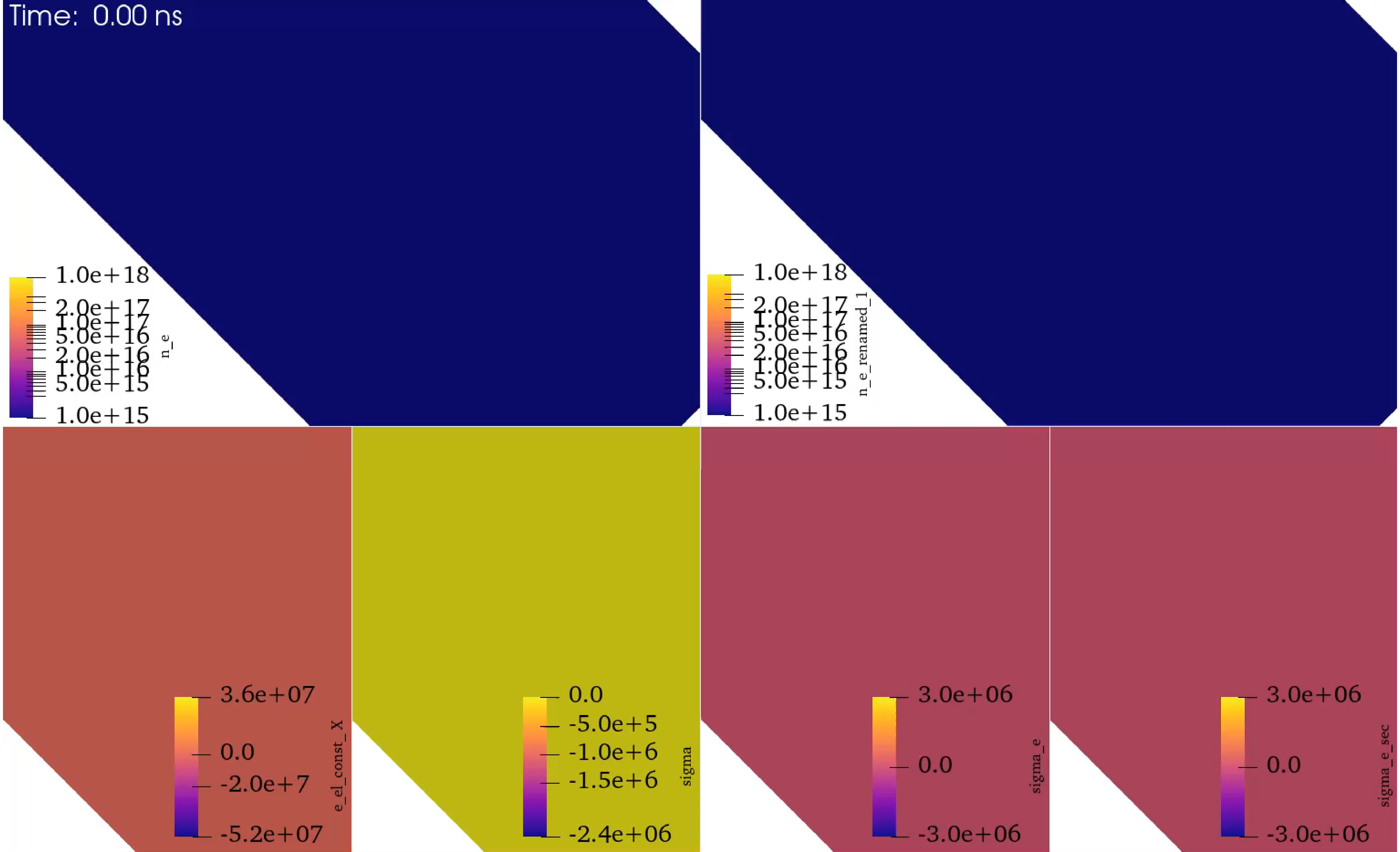
Δx ~ 300 nm,
Sometimes identify a "field emission surface"

Rotate 45 so $E_x = E_{normal}$, $E_y = E_{tangent}$



Cathode-Initiated Breakdown: Cascade Simulation

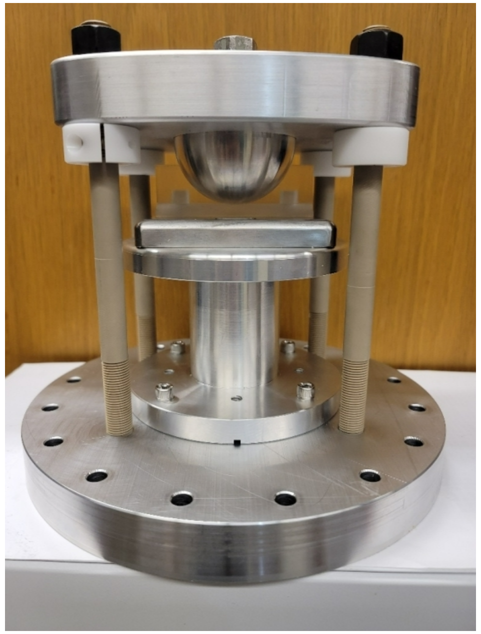



Time: 0.00 ns
1.0e+18
2.0e+17
1.0e+17
5.0e+16
2.0e+16
1.0e+16
5.0e+15
1.0e+15
n_e
1.0e+18
2.0e+17
1.0e+17
5.0e+16
2.0e+16
1.0e+16
5.0e+15
1.0e+15
n_e_renamed_1
3.6e+07
0.0
-2.0e+7
-5.2e+07
e_el_const_X
0.0
-5.0e+5
-1.0e+6
-1.5e+6
-2.4e+06
sigma
3.0e+06
0.0
-3.0e+06
sigma_e
3.0e+06
0.0
-3.0e+06
sigma_e_sec

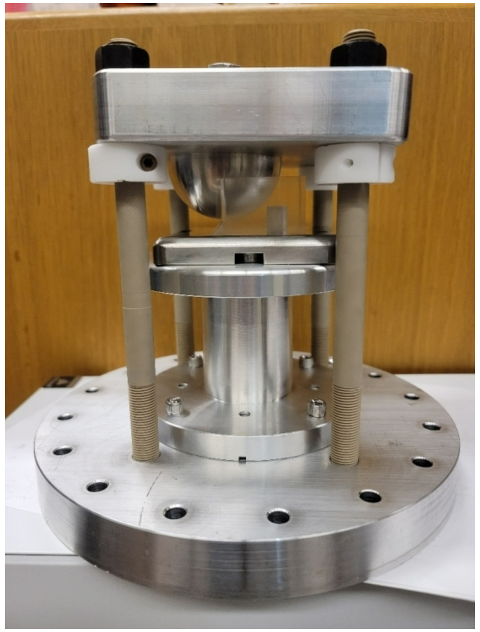
Anode-Initiated Flashover: Experiments

Wish to reproduce some of the environment on Z. Do achieve fields ~400 kV/cm. Have shorter pulse (~25 ns vs. ~150 ns). Would also like to be amenable to modeling for validation.

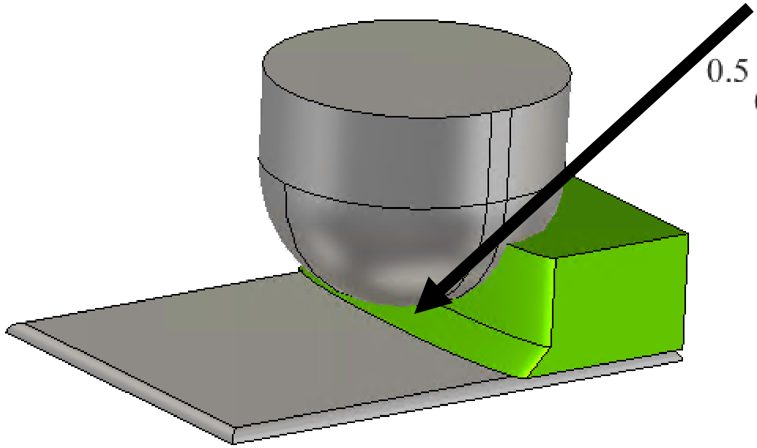
Use new diagnostics on system!

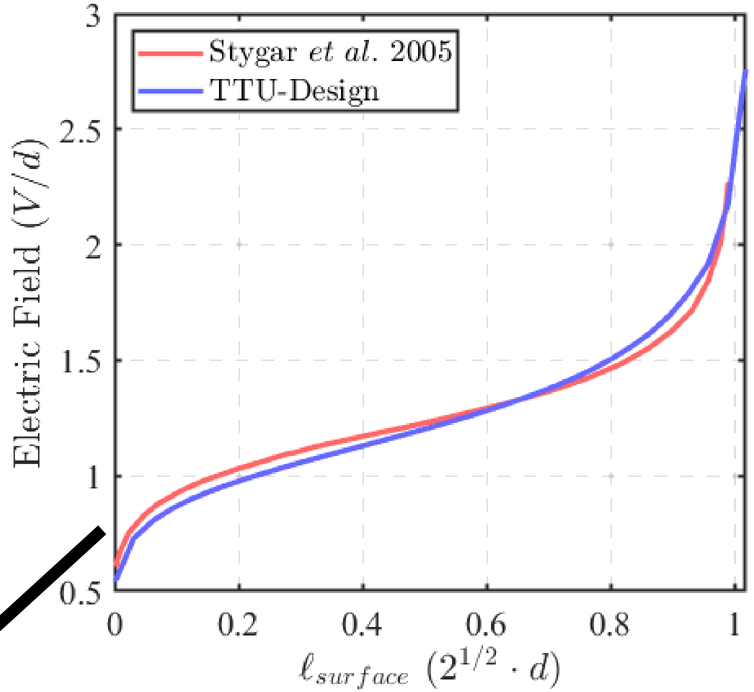


Front



Side

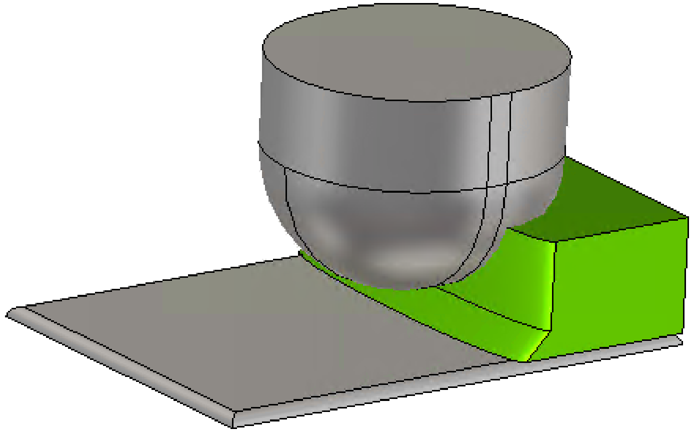




240 kV/0.6 cm = 400 kV/cm
(hope for 500 kV by end)

Refining Insulator Configurations

1st Generation

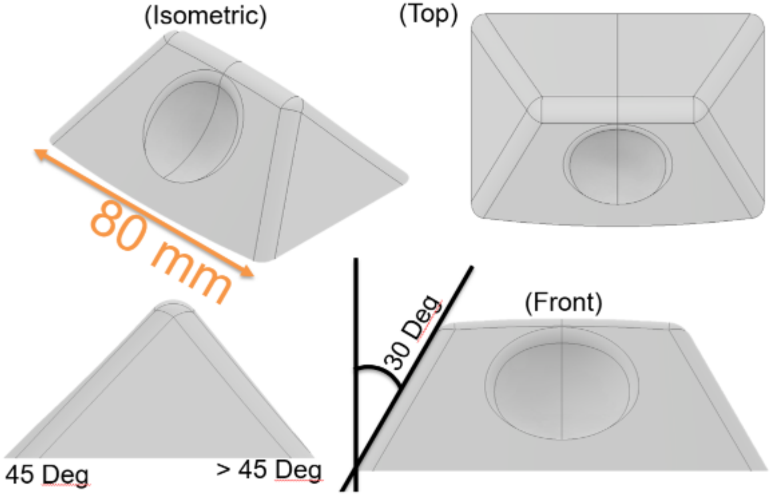


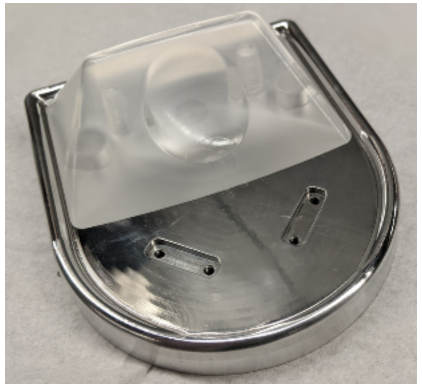
45° wedge, straight sides. Subject to breakdown along back/side

2nd Generation

Entire front is angled. Smoothed edges. Still some breakdown along back/side. Requires wire "field enhancer"

3rd Generation



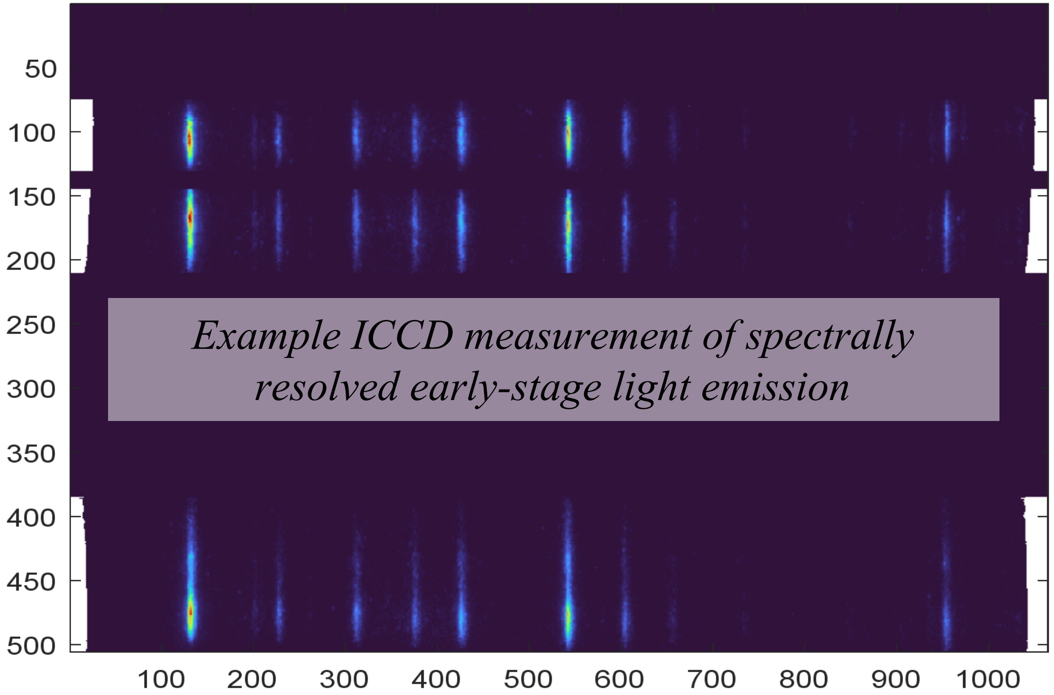


Fully seated anode. Variable fillet around anode. No wire?

Spatially, Spectrally, and Temporally Resolved Light Emission

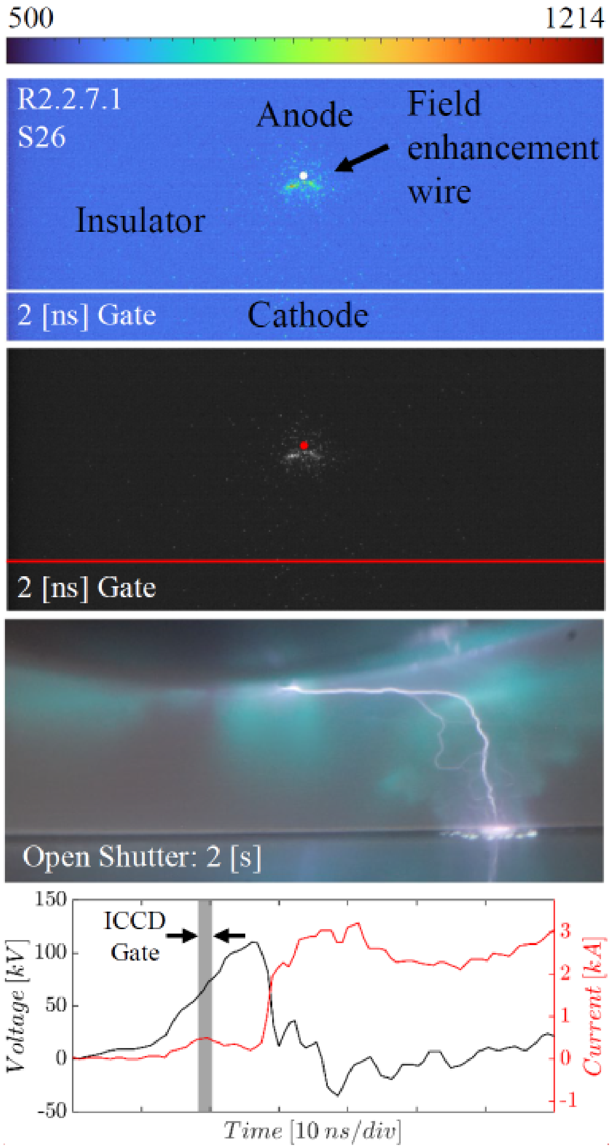
- Light from the cathode and anode regions are collected via a pair of fibers
- Fibers connect to a spectrograph with ICCD detector
    - Use a 5 ns ICCD gate to observe light in the *early-stage* of flashover formation

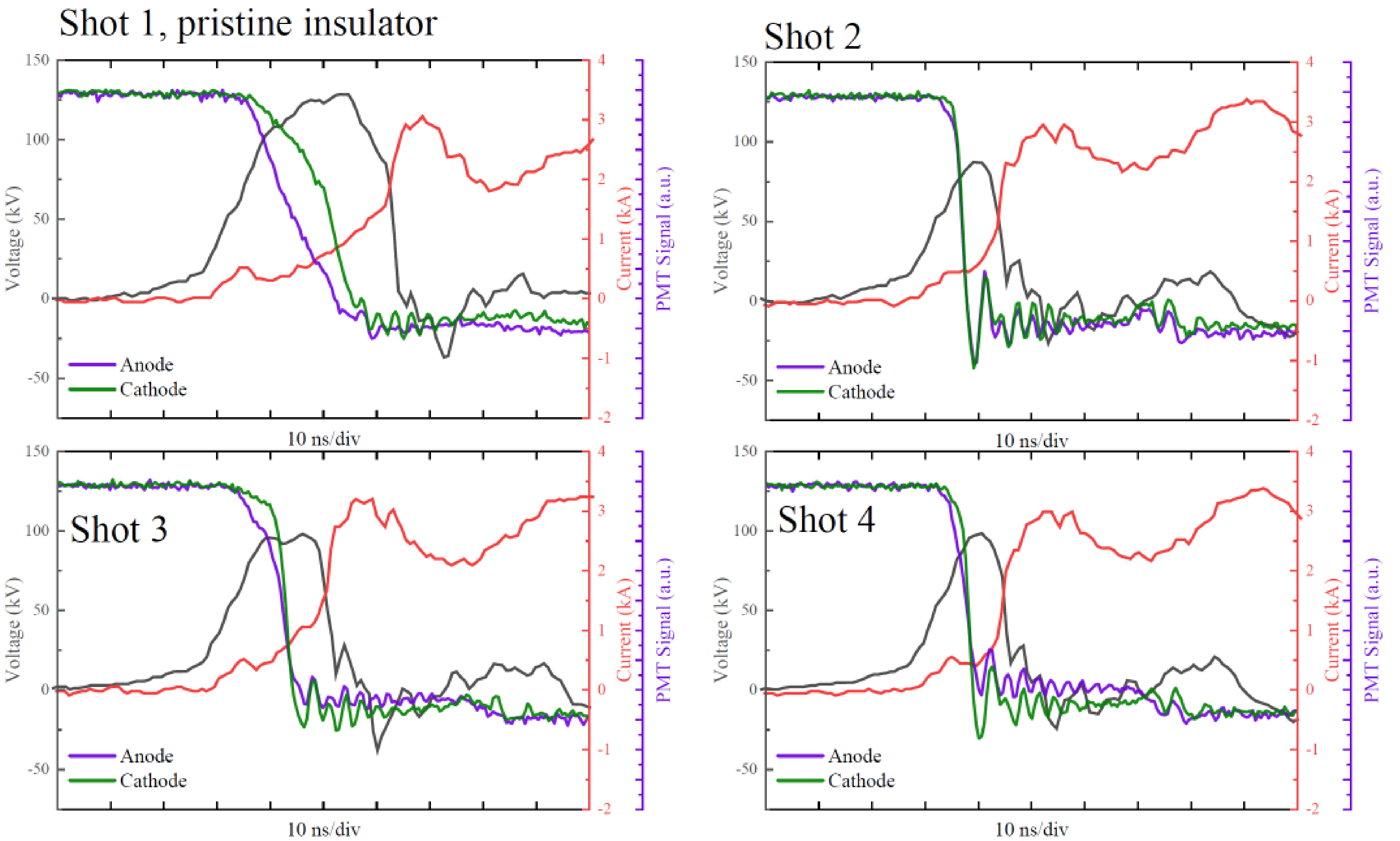
Observation window of the anode and cathode fibers



Example ICCD measurement of spectrally resolved early-stage light emission

Anode-Initiated Breakdown: Early Light

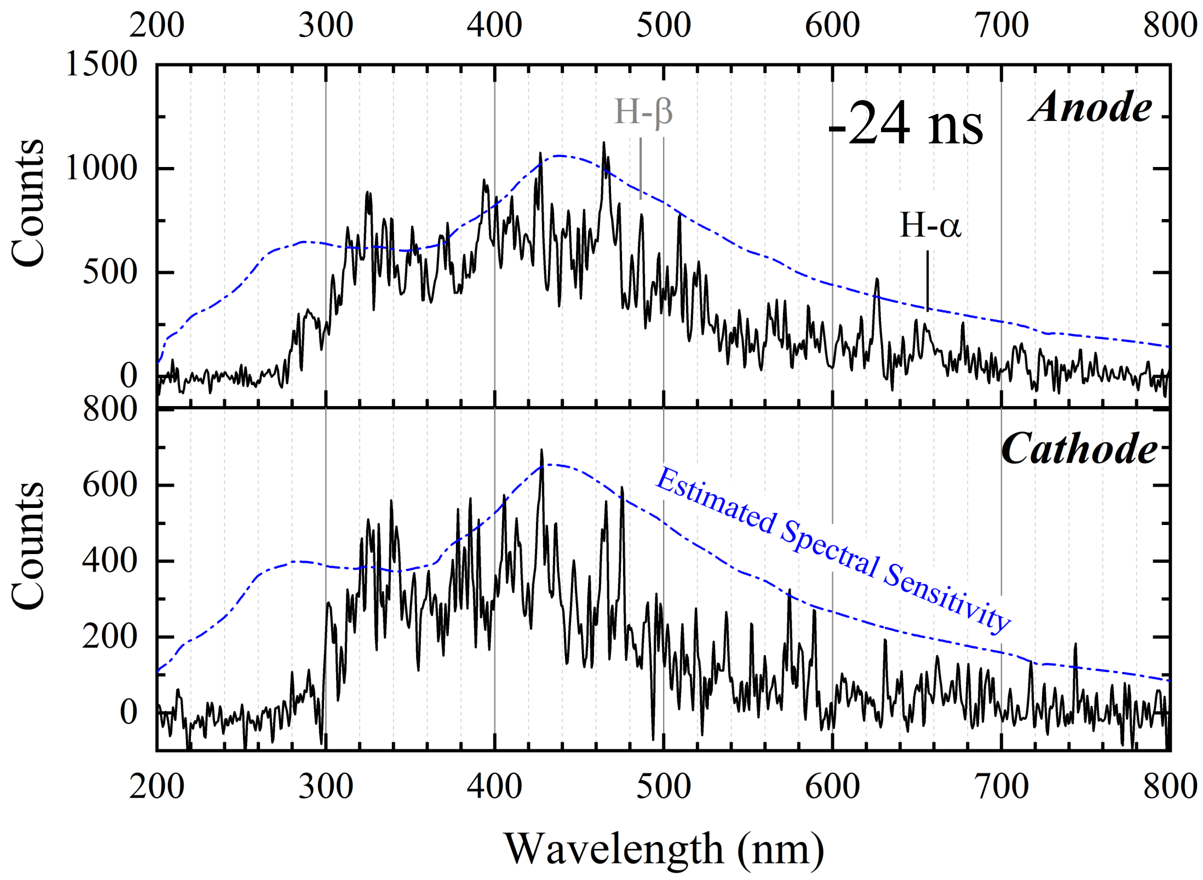




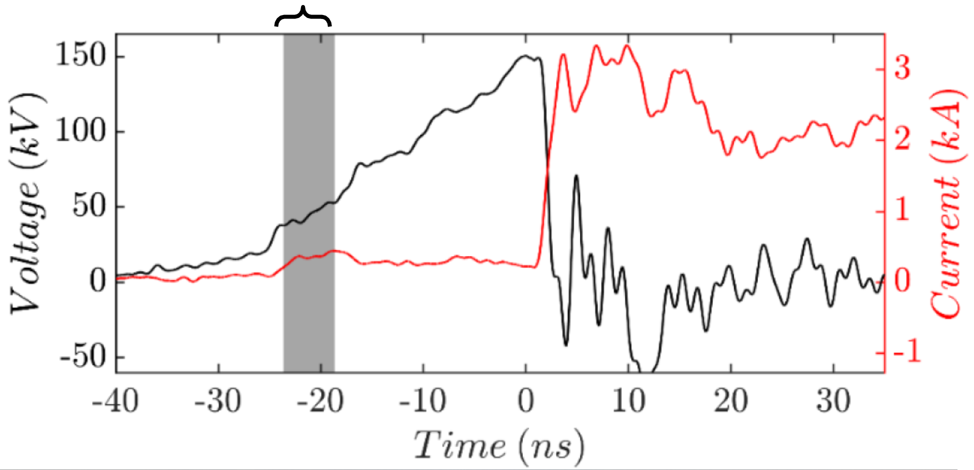
OES Time Series (t = -24 ns)

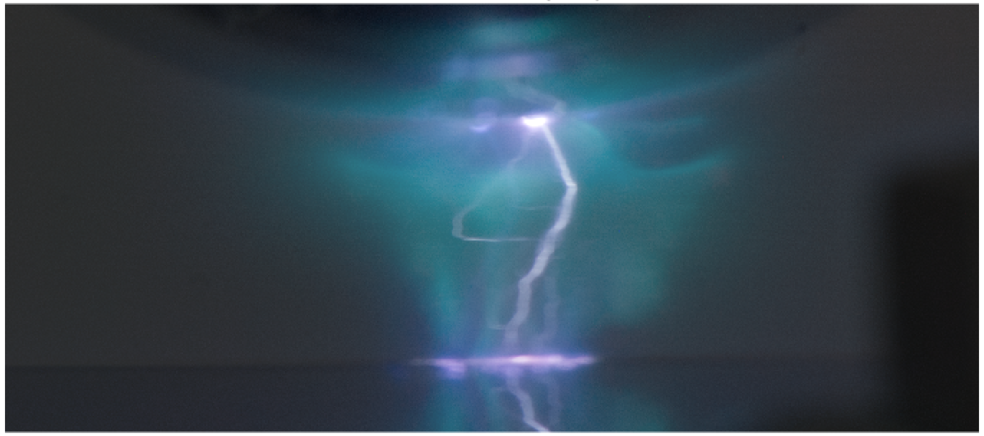
Broadband background characteristic of cathodoluminescence or similar

- Governed by optical characteristics of polystyrene toward the UV



Optical gate (5 ns width)





Black: High degree of confidence

Gray: Lesser degree of confidence

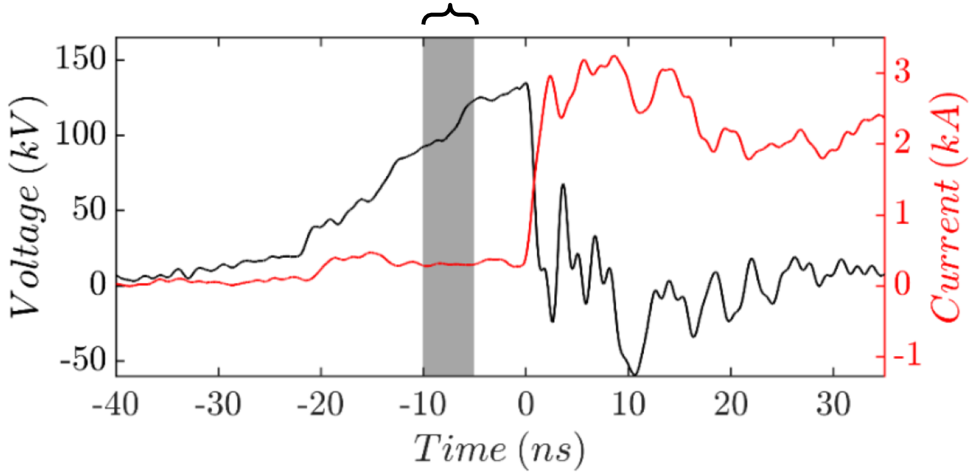
OES Time Series (t = -10 ns)

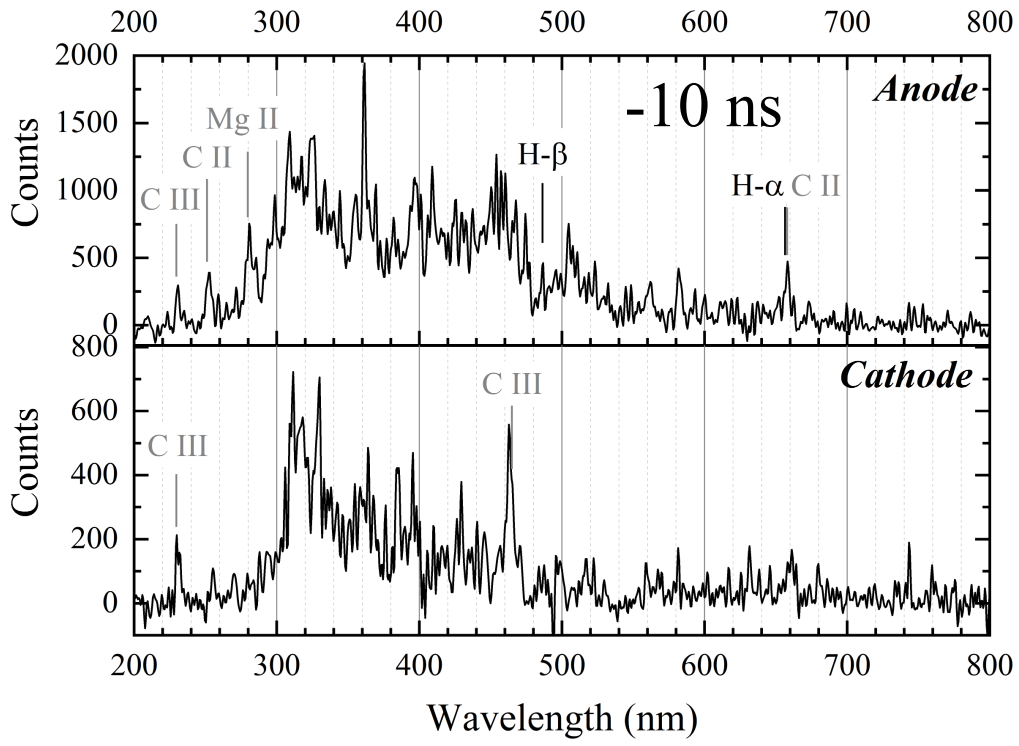
High confidence transitions (nm): H - **486.1**, **656.3**

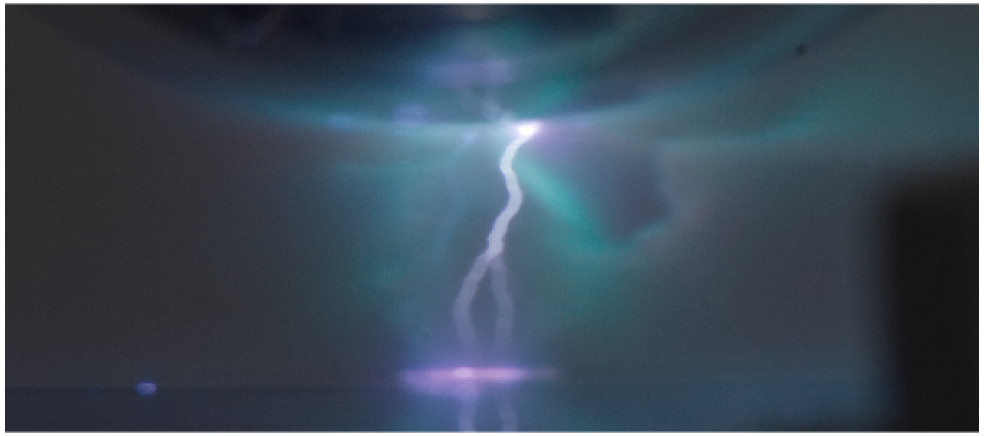
Possible transitions (nm):

- C II – **251.1**, 283.7, 392.0, 426.7, 514.5, 589.0, **657.9**
- C III – **229.7**, 406.9, 418.7, 464.8
- Mg II – **279.7**, 448.1

Optical gate (5 ns width)







Black: High degree of confidence

Gray: Lesser degree of confidence

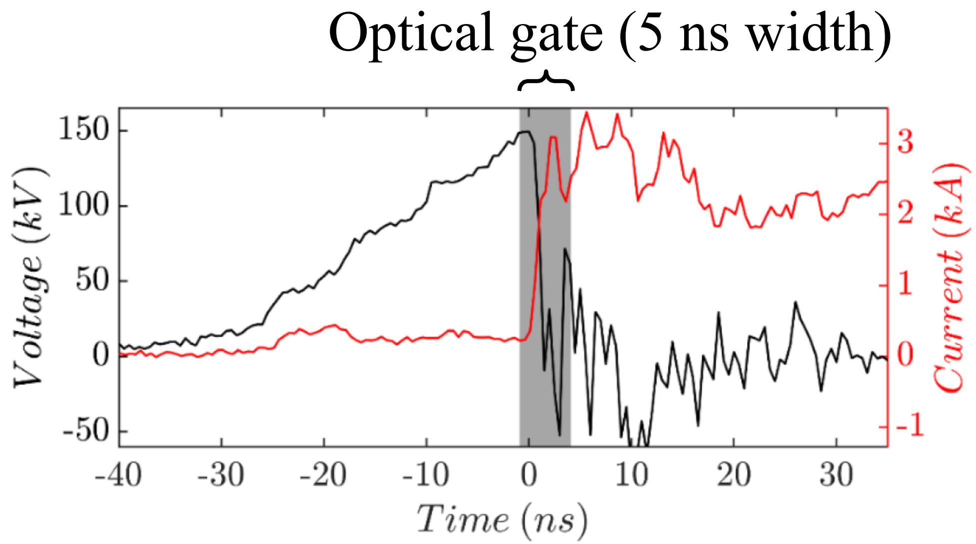
OES Time Series (t = -1 ns)

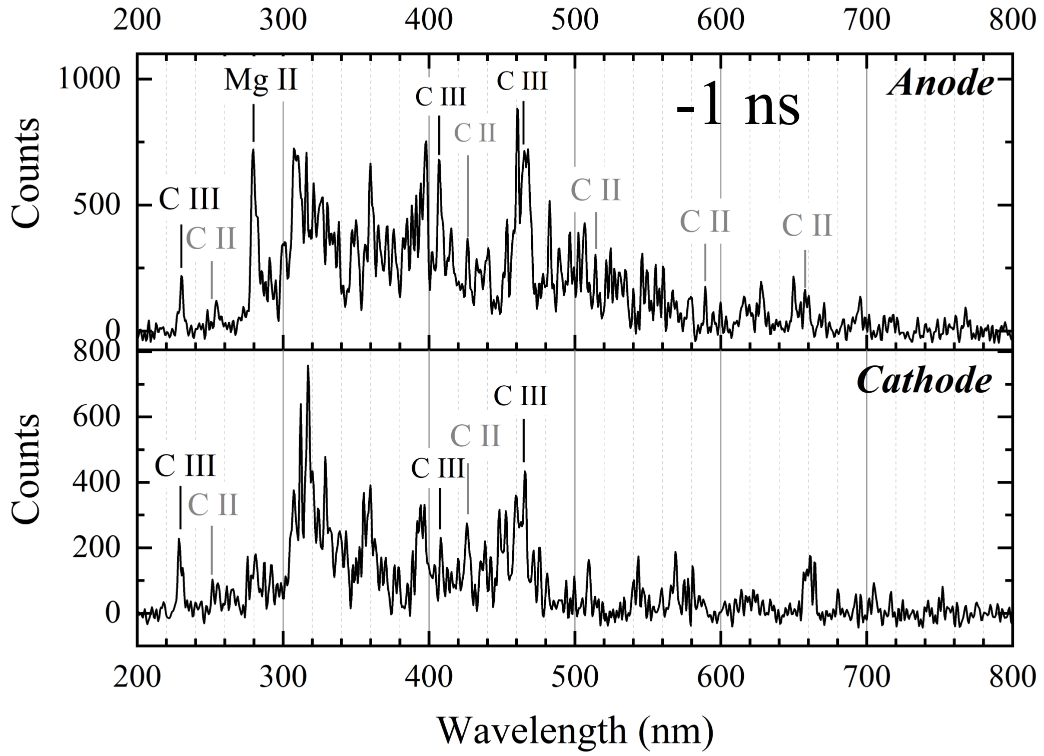
High confidence transitions (nm):

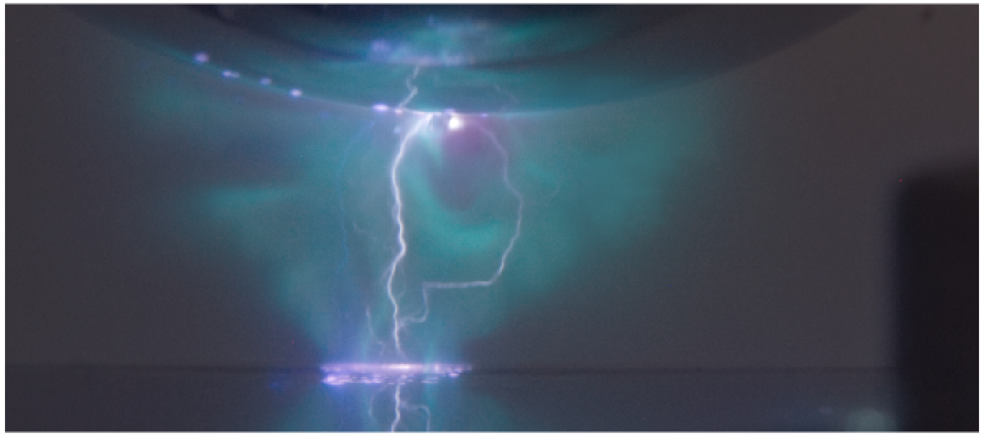
- C III – **229.7**, **406.9**, 418.7, **464.8**
- Mg II – **279.7**, 448.1

Possible transitions (nm):

- C II – **251.1**, 283.7, 392.0, **426.7**, **514.5**, **589.0**, **657.9**







Black: High degree of confidence

Gray: Lesser degree of confidence

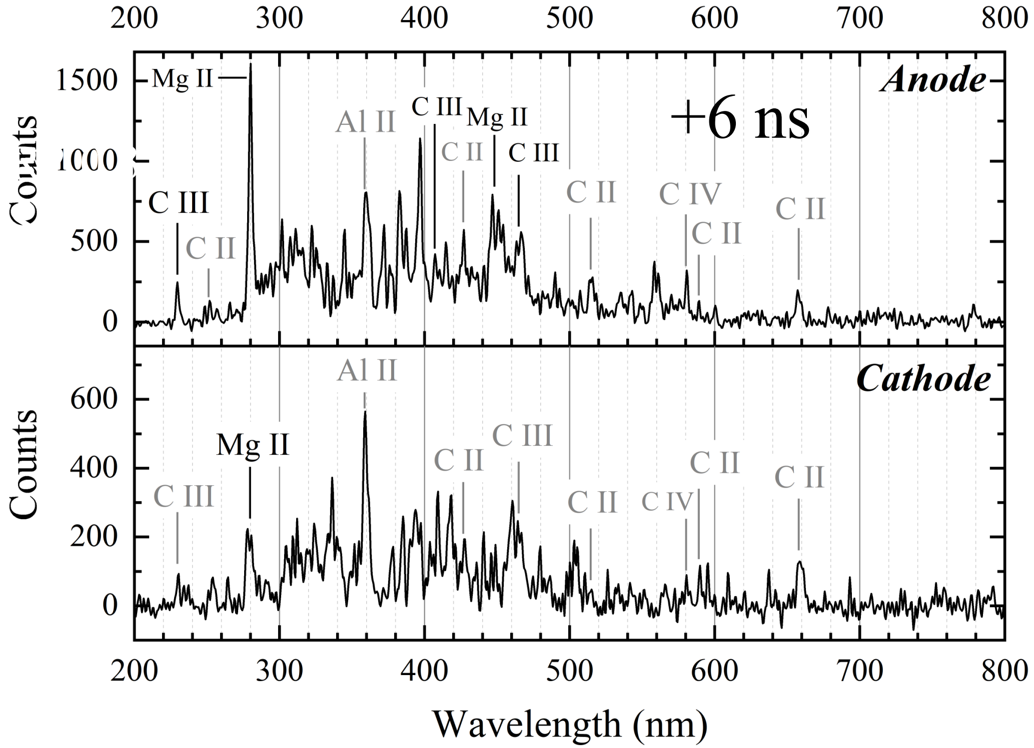
OES Time Series (t = +6 ns)

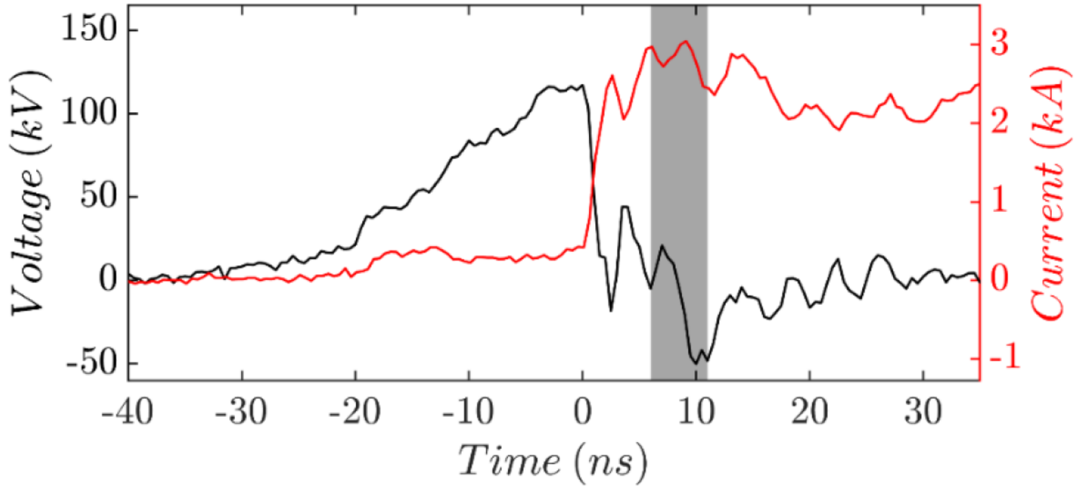
High confidence transitions (nm):

- C III – **229.7**, **406.9**, 418.7, **464.8**
- Mg II – **279.7**, **448.1**

Possible transitions (nm):

- C II – **251.1**, 283.7, 392.0, **426.7**, **514.5**, **589.0**, **657.9**
- C IV – **580.3**
- Al II – **358.7**





Black: High degree of confidence

Gray: Lesser degree of confidence

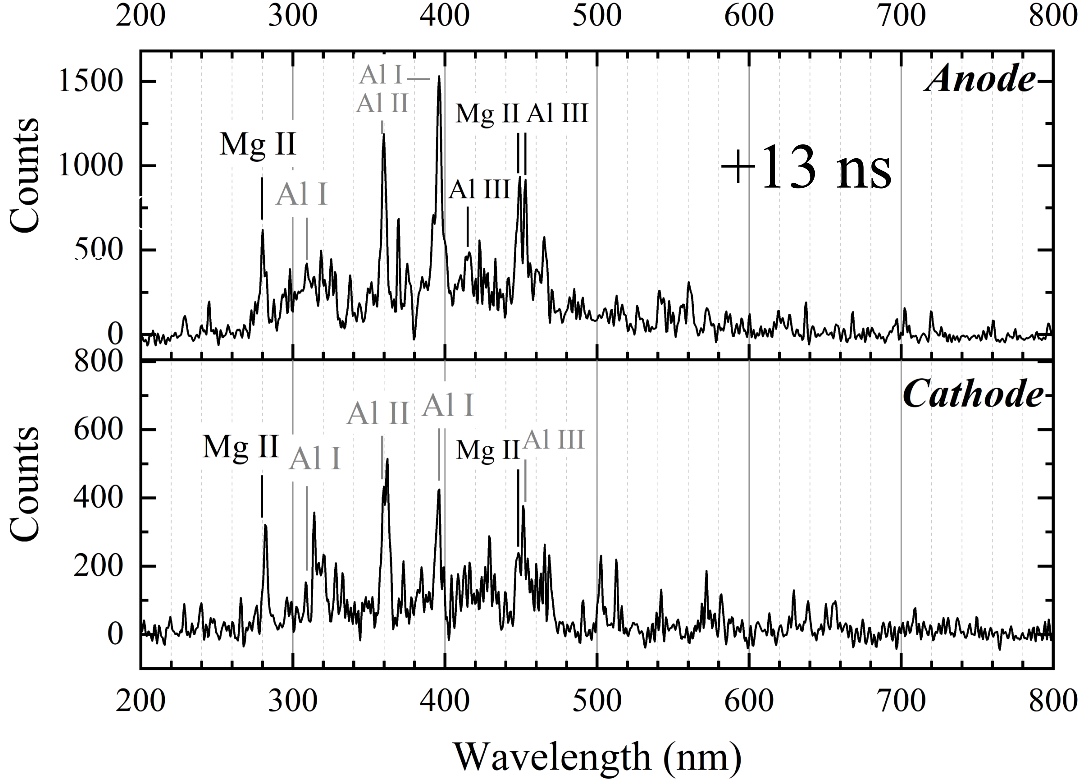
OES Time Series (t = +13 ns)

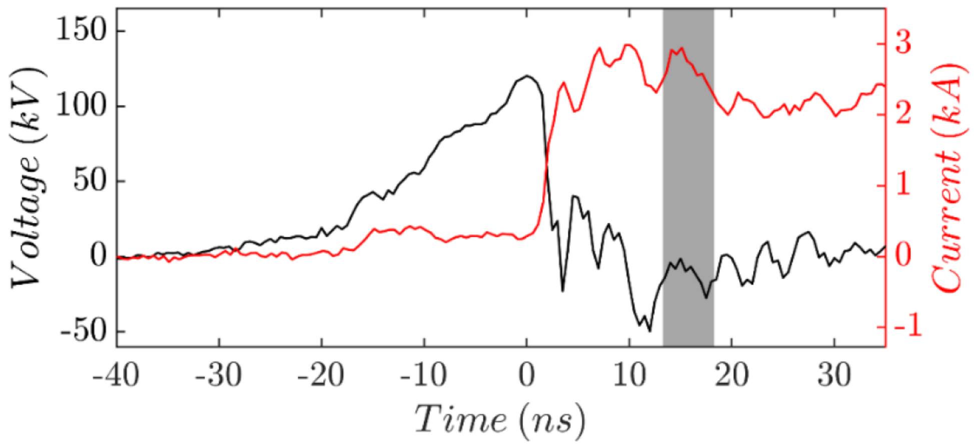
High confidence transitions (nm):

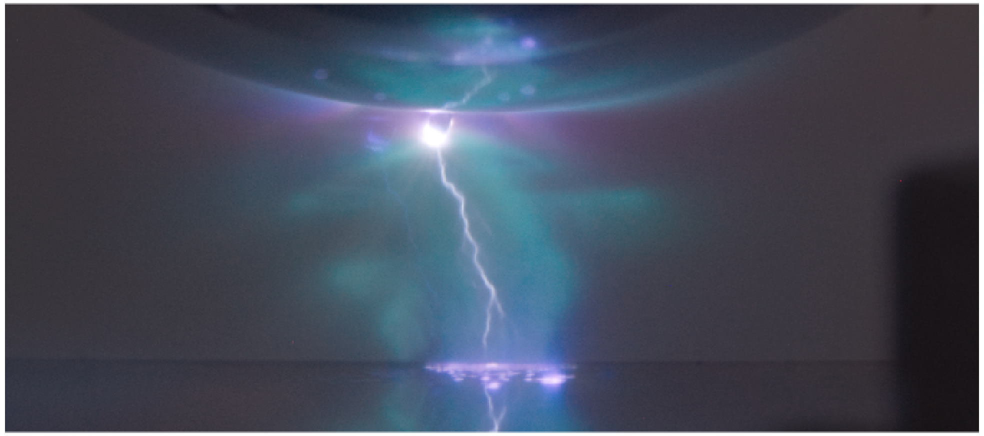
- Mg II – **279.7**, **448.1**
- Al III – **415.0**, **452.9**

Possible transitions (nm):

- Al I – **309.2**, **396.2**
- Al II – **358.7**







Black: High degree of confidence

Gray: Lesser degree of confidence

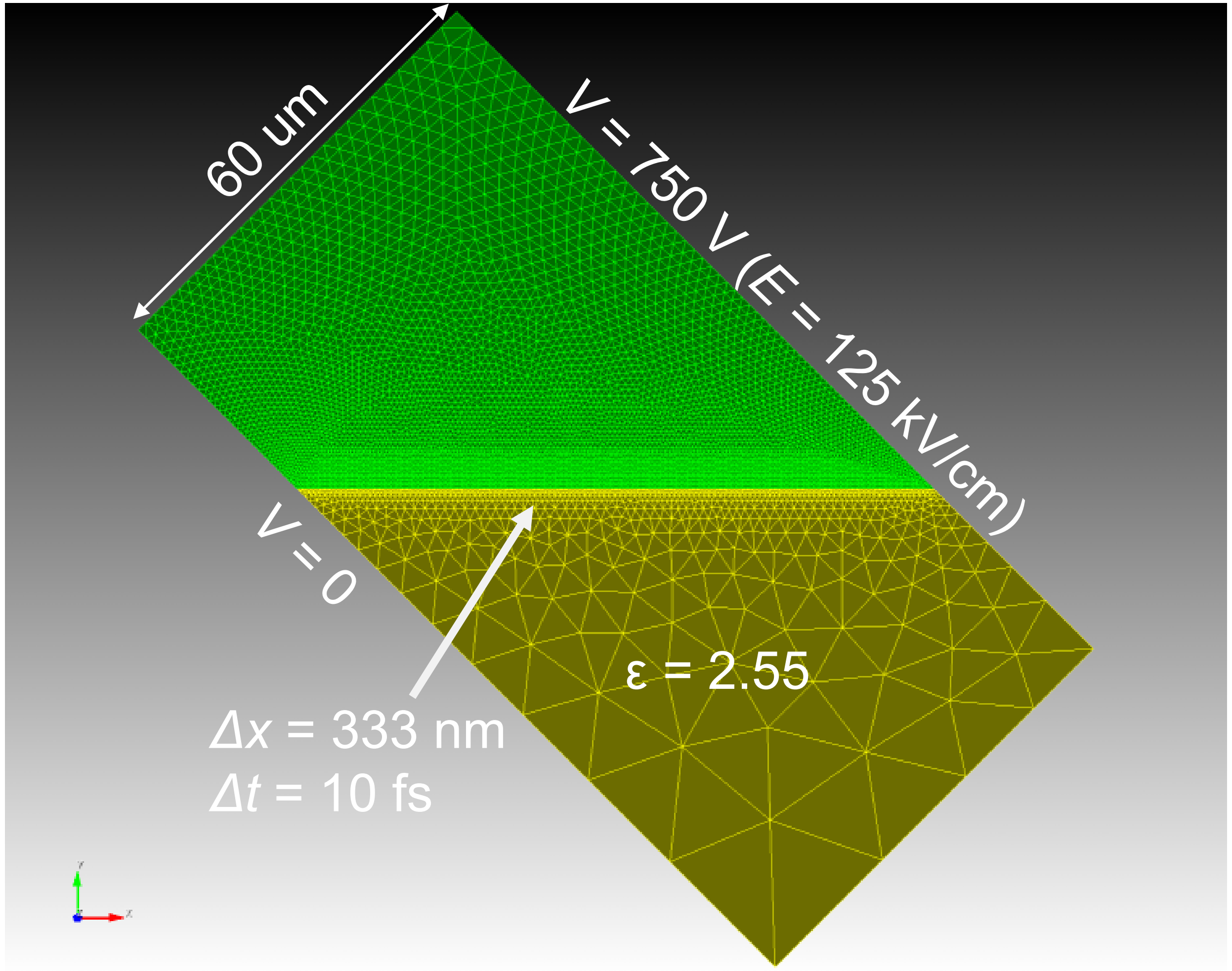
Anode-Initiated Breakdown: Simulations

Goals:

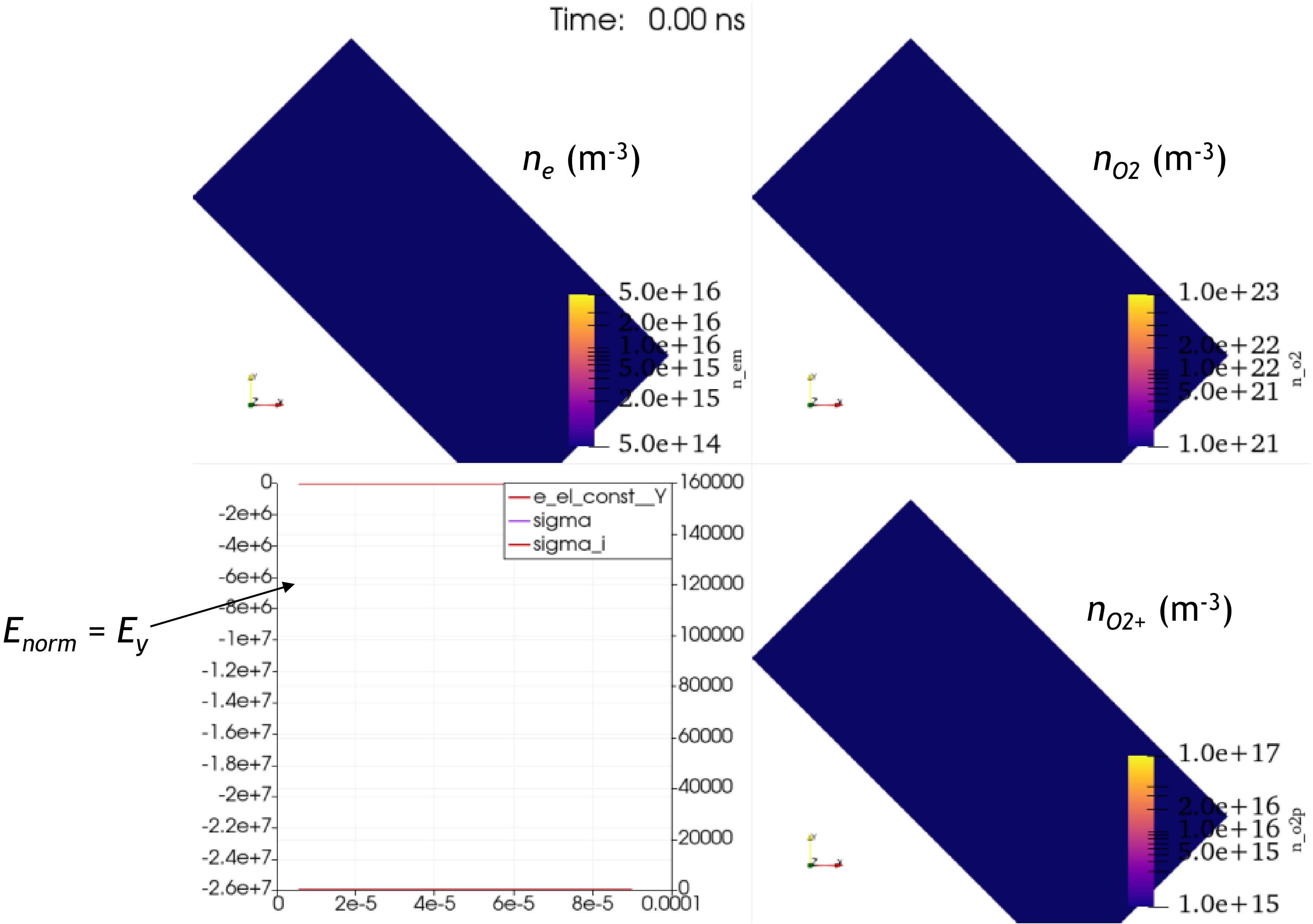
- Provide insights into breakdown phenomena roles
- Provide framework to study design ideas (predict impacts on operation)

Anode Triple Junction (ATJ) Aleph modeling:

- Fowler-Nordheim emission of e-, with surface charging on dielectric
- Neutral emission scaled to Fowler-Nordheim emission on dielectric for H_2, C, O_2, H_2O, CO_2 (1e3)
- e-heavy ionization
- e-heavy dissociations
- e-heavy elastic/excitation for H, H+, C, C+, O, O+, CO2, CO2+, CO, CO+, H2, H2+, H2O, H2O, H2O+, O2, O2+, OH
- e- secondary emission from above ion species



Anode-Initiated Breakdown: Simulations



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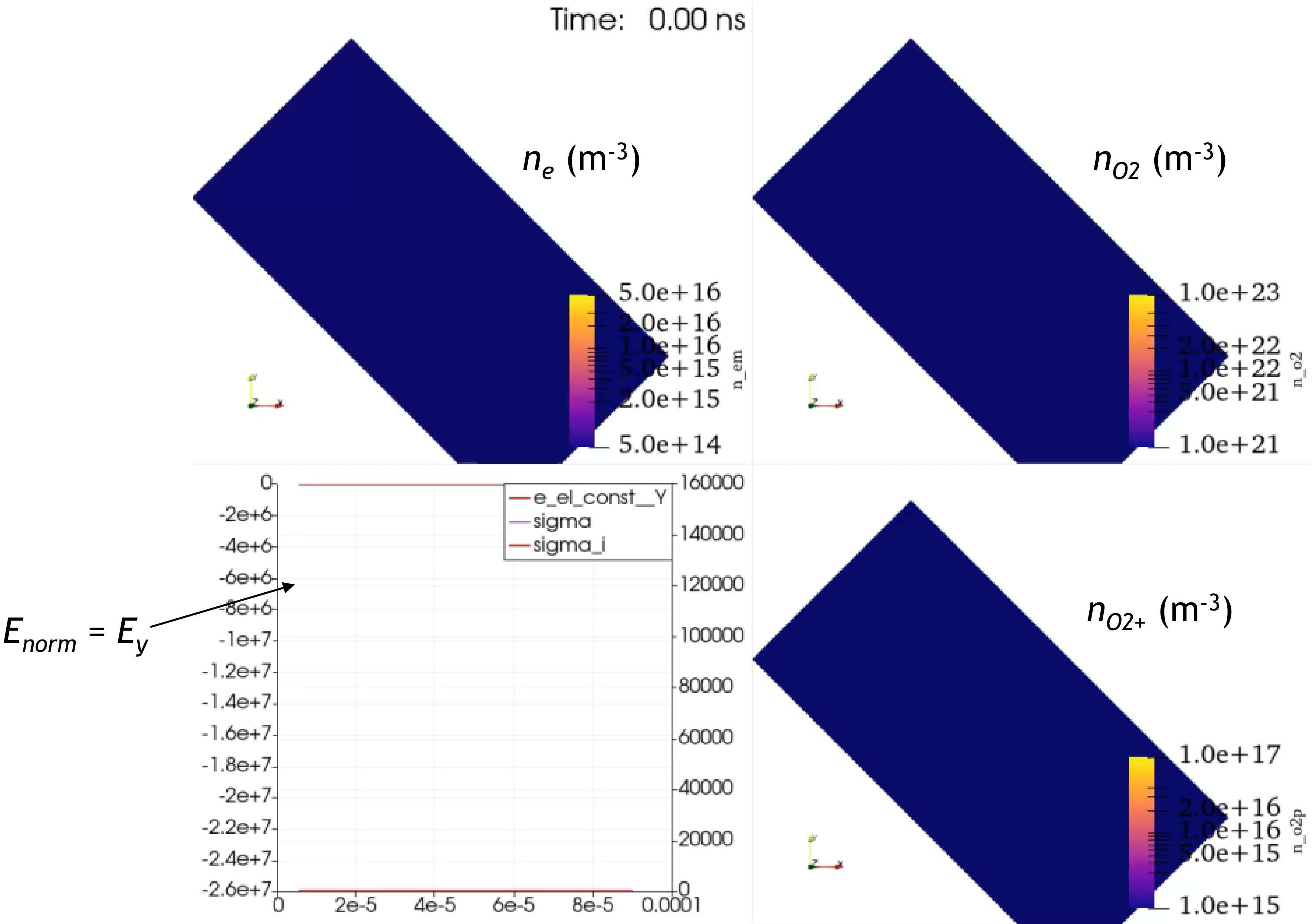


Summary

Developing multiple approaches to investigate anode- and cathode-initiated breakdown for pulsed power systems. Mechanisms of anode-initiated are not understood. We are identifying time-resolved species to indicate material source.

Other project investigating different insulator materials (inclusions).

Experiments not discussed here:

- X-ray measurement for high energy electron locations
- Laser deflection measurements for n_e and n_n
- Ion-induced and photon-induced secondary electron emission

Modeling not discussed here:

- Full geometry (maybe 3D)
- Photon processes
- More detailed species chemistry

THANK YOU!

BACKUP SLIDES FOLLOW

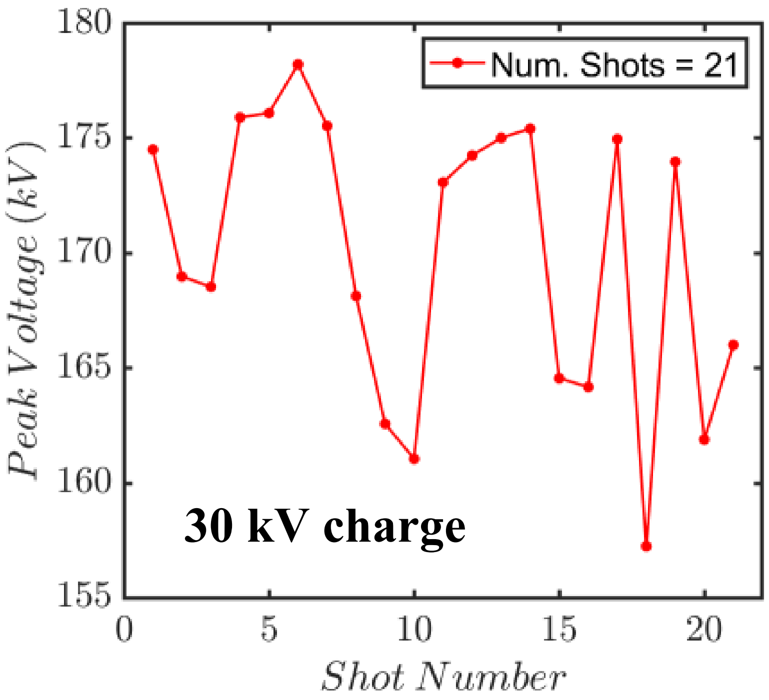
Small Gaps Lead to Cathode-Initiated?

Experimental conditions

- 4 mm gap (vertical dimension)
- Vacuum at ~$7.1 \cdot 10^{-6}$ Torr
- Vertical sanding on front face in flashover region

Experimental Results

- 21 of 21 shots flashed over on front face
- Transition to cathode-initiated flashover (?)

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S2

S3

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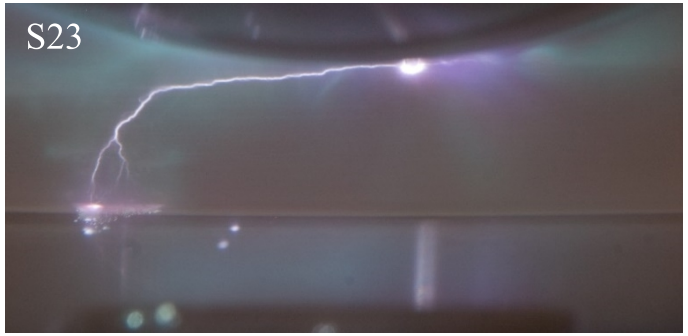
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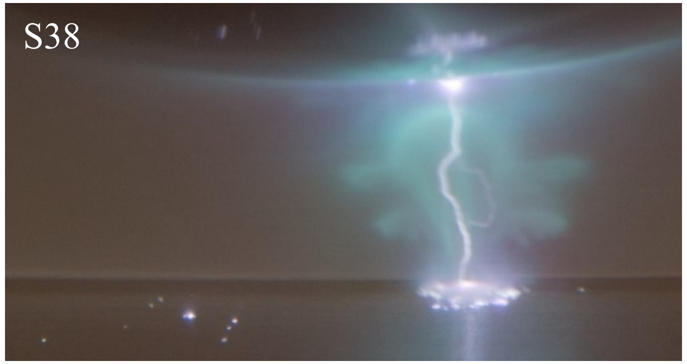
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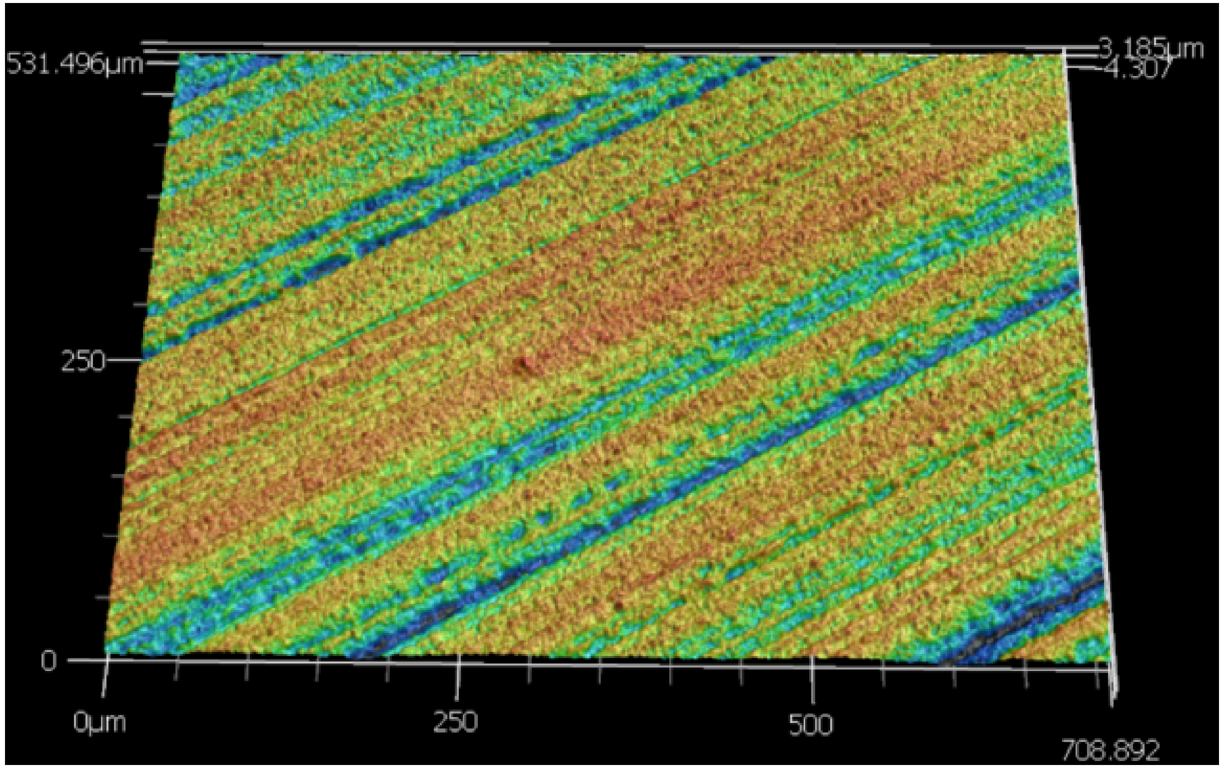
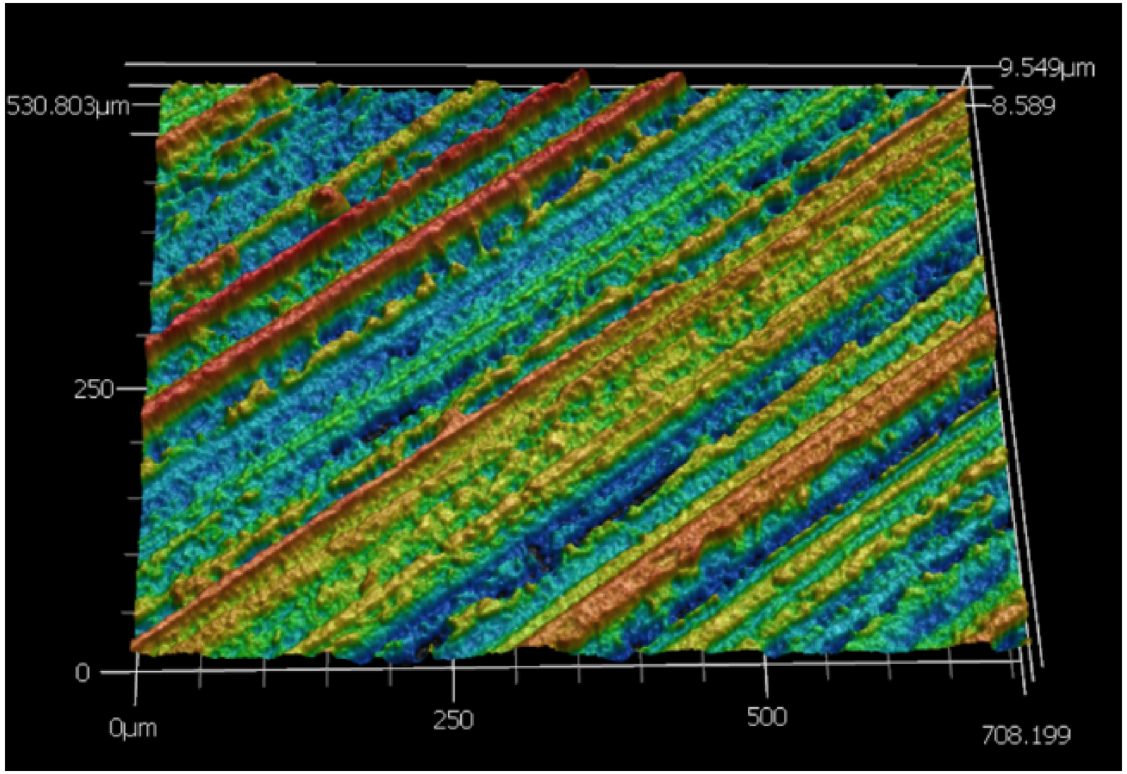
SNL Surface Roughness Measurements

Cut piece of bulk Rexolite
Sa Roughness = 0.674 μm



Rexolite Surface from Z-machine
Sa Roughness = 1.861 μm



Aleph Simulation Tool

Basic algorithm for one time step of length Δt:

1. Given known electrostatic field $\mathbf{E}^n$, move each particle for $\frac{\Delta t}{2}$ via:

$$v_i^{n+1/2} = v_i^n + \frac{\Delta t}{2}\left(\frac{q_i}{m_i}\mathbf{E}^n\right)$$

$$x_i^{n+1} = x_i^n + \Delta t v_i^{n+1/2}$$

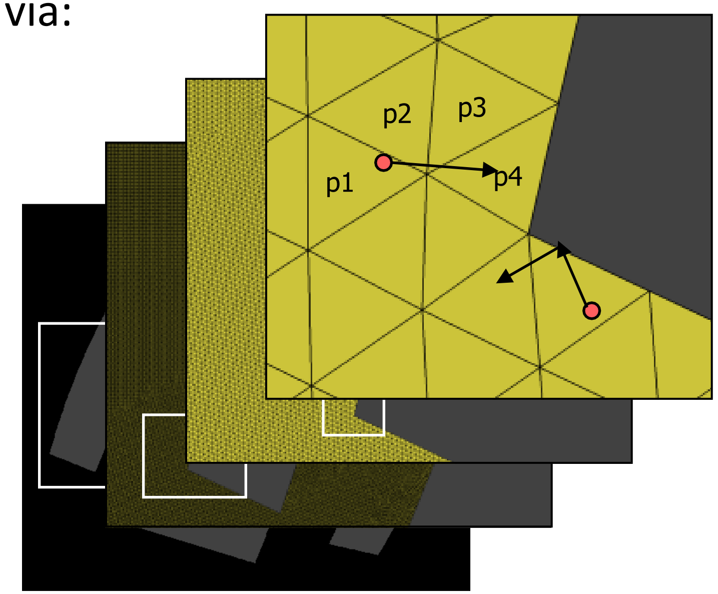
2. Compute intersections (non-trivial in parallel).
3. Transfer charges from particle mesh to static mesh.
4. Solve for $\mathbf{E}^{n+1}$,

$$\nabla \cdot \left(\epsilon \nabla V^{n+1}\right) = -\rho(\mathbf{x}^{n-1})$$

$$\mathbf{E}^{n+1} = -\nabla V^{n+1}$$

5. Transfer fields from static mesh to dynamic mesh.
6. Update each particle for another $\frac{\Delta t}{2}$ via:

$$v_i^{n+1} = v_i^{n+1/2} + \frac{\Delta t}{2}\left(\frac{q_i}{m_i}\mathbf{E}^{n-1}\right)$$



7. Perform DSMC collisions: sample pairs in element, determine cross section and probability of collision. Roll a digital die, and if they collide, re-distribute energy.
8. Perform chemistry: for each reaction, determine expected number of reactions. Sample particles of those types, perform reaction (particle creation/deletion).
9. Reweight particles.
10. Compute post-processing and other quantities and write output.
11. Rebalance particle mesh if appropriate (variety of determination methods).