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)

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

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

Polarity flips on back end of pulse
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!

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
Anode-Initiated Breakdown: Early Light

Shot 1, pristine insulator

Shot 2

Shot 3

Shot 4
OES Time Series \( (t = -24 \text{ ns}) \)

- Broadband background characteristic of cathodoluminescence or similar
  - Governed by optical characteristics of polystyrene toward the UV

**Graphical Data**

- **Anode**
  - H-\( \beta \)
  - H-\( \alpha \)
- **Cathode**
  - Estimated Spectral Sensitivity

**Optical gate (5 ns width)**

**Legend**

- **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

Black: High degree of confidence
Gray: Lesser degree of confidence

Optical gate (5 ns width)
OES Time Series ($t = -1 \text{ ns}$)

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

[Graph showing time series data]

**Black**: High degree of confidence
**Gray**: Lesser degree of confidence
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
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)
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 H₂, C, O₂, H₂O, CO₂ (1e3)
- e-heavy ionization
- e-heavy dissociations
- e- secondary emission from above ion species
Anode-Initiated Breakdown: Simulations

\[ E_{\text{norm}} = E_y \]
Anode-Initiated Breakdown: Simulations

\[ E_{\text{norm}} = E_y \]
Cathode-Initiated Breakdown

1. Field Emission from Triple Point

2a. Saturated Secondary Emission Avalanche

2b. Electron Induced Outgassing

3. Electric Breakdown in Desorbed Gas

Furman, Phys. Rev. STAB, 2002
Jenkins, Electron and Ion Emission from Solids, 1965
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.
Cathode-Initiated Breakdown: Secondary Yield Simulation

- Vary chamber radius
- Vary 1st generation secondary energy
- Vary 2nd generation secondary energy
Cathode-Initiated Breakdown: Cascade Simulation

\[ \Delta x \approx 300 \text{ nm,} \]

Sometimes identify a “field emission surface”

Rotate 45 so

\[ E_x = E_{\text{normal}}, \]
\[ E_y = E_{\text{tangent}} \]
Cathode-Initiated Breakdown: Cascade Simulation
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 \( \sim 7.1 \cdot 10^{-6} \) 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 (?)
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 $\Delta t$:

1. Given known electrostatic field $E^n$ move each particle for $\frac{\Delta t}{2}$ via:
   \[
   v_i^{n+1/2} - v_i^n = \frac{\Delta t}{2} \left( \frac{q_i}{m_i} E^n \right)
   \]
   \[
   x_i^{n+1} = x_i^n + \Delta t v_i^{n+1/2}
   \]
2. Compute intersections (non-trivial in parallel).
3. Transfer charges from particle mesh to static mesh.
4. Solve for $E^{n+1}$,
   \[
   \nabla \cdot (\varepsilon \nabla V^{n+1}) - \rho(x^{n-1}) = 0
   \]
   \[
   E^{n+1} = -\nabla V^{n+1}
   \]
5. Transfer fields from static mesh to dynamic mesh.
6. Update each particle for another $\frac{\Delta t}{2}$ via:
   \[
   v_i^{n+1} - v_i^{n+1/2} = \frac{\Delta t}{2} \left( \frac{q_i}{m_i} E^{n-1} \right)
   \]
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).