Exceptional service in the national interest

Sandia
National
Laboratories

Photos placed in horizontal position
with even amount of white space
between photos and header

Paschen Concepts in Non-Uniform Gas

Christopher H. Moore, Matthew M. Hopkins,
Jeremiah J. Boerner, Paul S. Crozier, Stan G. Moore

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

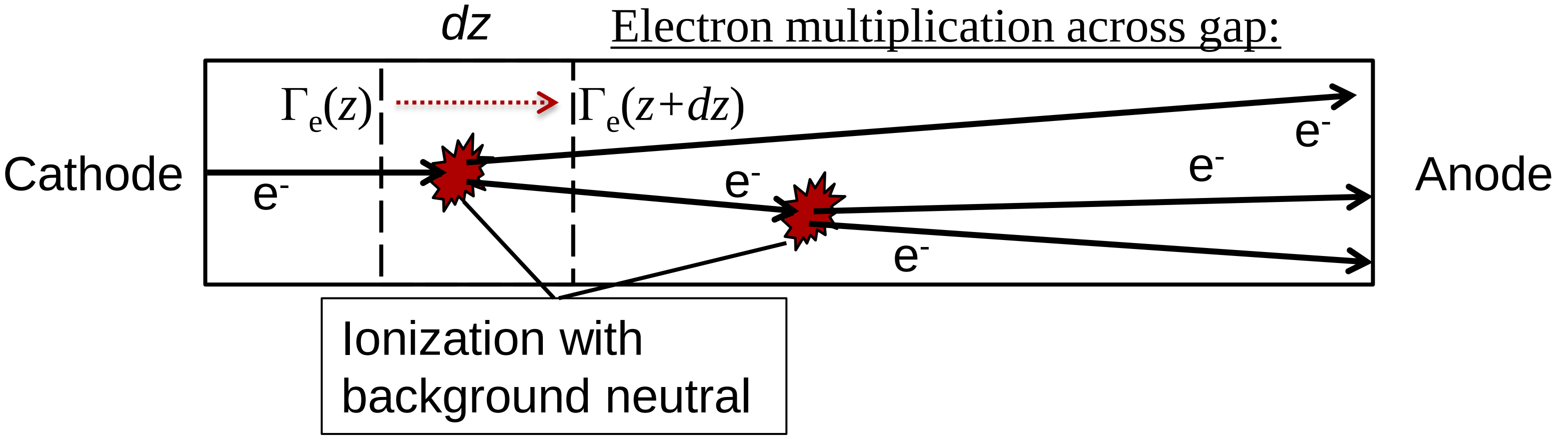
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2013-9299C

Outline

- Paschen Background
- Large gap vs. small gap, or Auger neutralization vs. Cold Field Emission (CFE)
- Effect of non-uniform background neutral gas density

Can We Predict Breakdown Analytically?

- Obtain analytic breakdown criteria (limited by assumptions)
- Paschen breakdown:



- Change in e^- flux across *dz* due to ionization with mean free path, λ_{iz}:

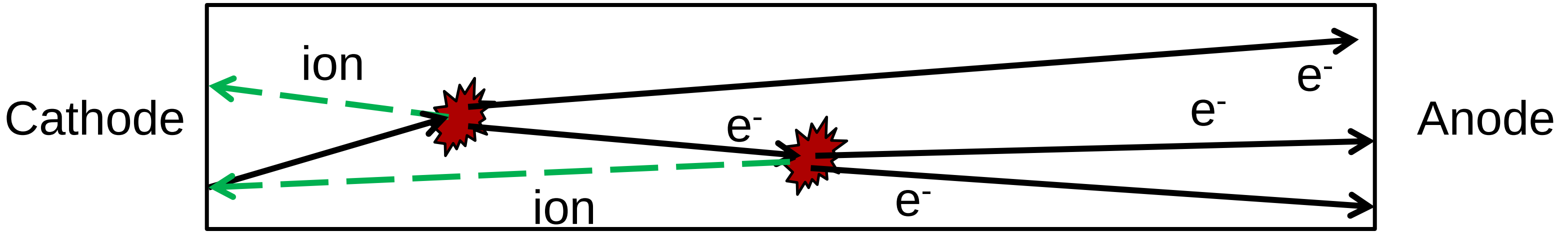
$$d\Gamma_e = \Gamma_e \frac{dz}{\lambda_{iz}(z)} = \alpha(z)\Gamma_e \mathrm{dz}, \qquad \alpha(z) \equiv \frac{1}{\lambda_{iz}(z)}$$

- Assume form for α(z): $\alpha(z) = const = A_p p \; exp\left(-\frac{B_p p}{E}\right)$
  - A_p & B_p fit to breakdown data and ≈ constant over range of E/n
  - Fails when background gas is non-uniform, field is non-uniform, or when ionization significantly depletes the background neutral gas density

Can We Predict Breakdown Analytically?

- Electron-neutral ionization doesn't just multiply electrons… it creates ions which then stream to the cathode:

<u>Electron production at cathode via ion impact:</u>



- The breakdown is self-sustaining → Auger neutralization of ions produces e^- flux at cathode:

$$\Gamma_e(0) = \gamma_{se}\Gamma_i(0)$$

Assumes γ_{se} is constant – not valid for microscale gaps with Fowler-Nordheim CFE or for dirty surfaces

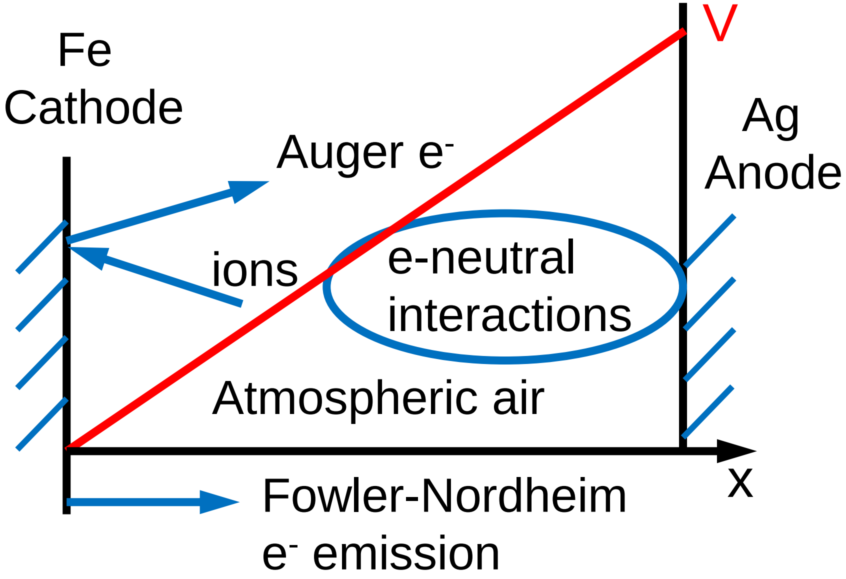
- Further assume space charge negligible ($E = {}^{V_b}/_{d_{gap}}$) and put it together to obtain Paschen's curve:

$$V_B = \frac{B_p pd}{ln(A_p pd) - ln[ln(1 + 1/\gamma_e)]}$$

Paschen Curve: Summary

- Basic physical mechanism of breakdown:
  - Electron multiplication across gap via electron-neutral ionization
  - Ions occasionally generate an electron at the cathode
- Main Paschen assumptions:
  - Constant electron yield per ion approaching the surface (γ_e)
  - Negligible space charge
  - Electric field is constant
  - Constant A_p and B_p coefficients based on electron energy distribution function (EEDF) across the gap and the resultant electron-neutral interactions
- Simulation allows for analysis where assumptions are not valid
  - When Cold Field Emission (CFE) of electrons matters
    - Microscale gaps
    - Vacuum gaps with very high applied voltages
  - Spatially non-uniform background neutral gas densities like those developed during vacuum breakdown or when a vacuum seal fails
  - Nonlinear electric fields from realistic geometries

1D Breakdown in Air



- PIC-DSMC simulations – 1D spatial, 3D velocity (1D3V)
  - Simulate various gap sizes → Find breakdown voltage
  - Uniform grid, $\Delta x < \lambda_D$ at $n_e = 10^{21}$ m^{-3} (typical "breakdown"density)
  - Timestep = 5×10^{-15} s < CFL < mean collision time < $1/\omega_{pe}$

- "Trigger" breakdown with an initial, very low density uniform electron & ion plasma of 10^{17} m^{-3} ($\sim 10^{-9} * n_{N2}$)

Surface Model

- Include Auger neutralization
  - Upon approach to surface, ion is neutralized and liberates secondary electron with probability γ_e
  - γ_{e,N_2^+} = 0.026, γ_{e,O_2^+} = 0.018 (Lieberman & Lichtenberg, 2005)
    - Function of the ion species' ionization potential & surface work function (use ϕ=4.5 for Fe)
    - Independent of kinetic energy below ~500 eV
    - Dependent on surface contamination
- Include Fowler-Nordheim field emission
  - Quantum tunneling through surface potential barrier accounting for local surface E-field, E_s

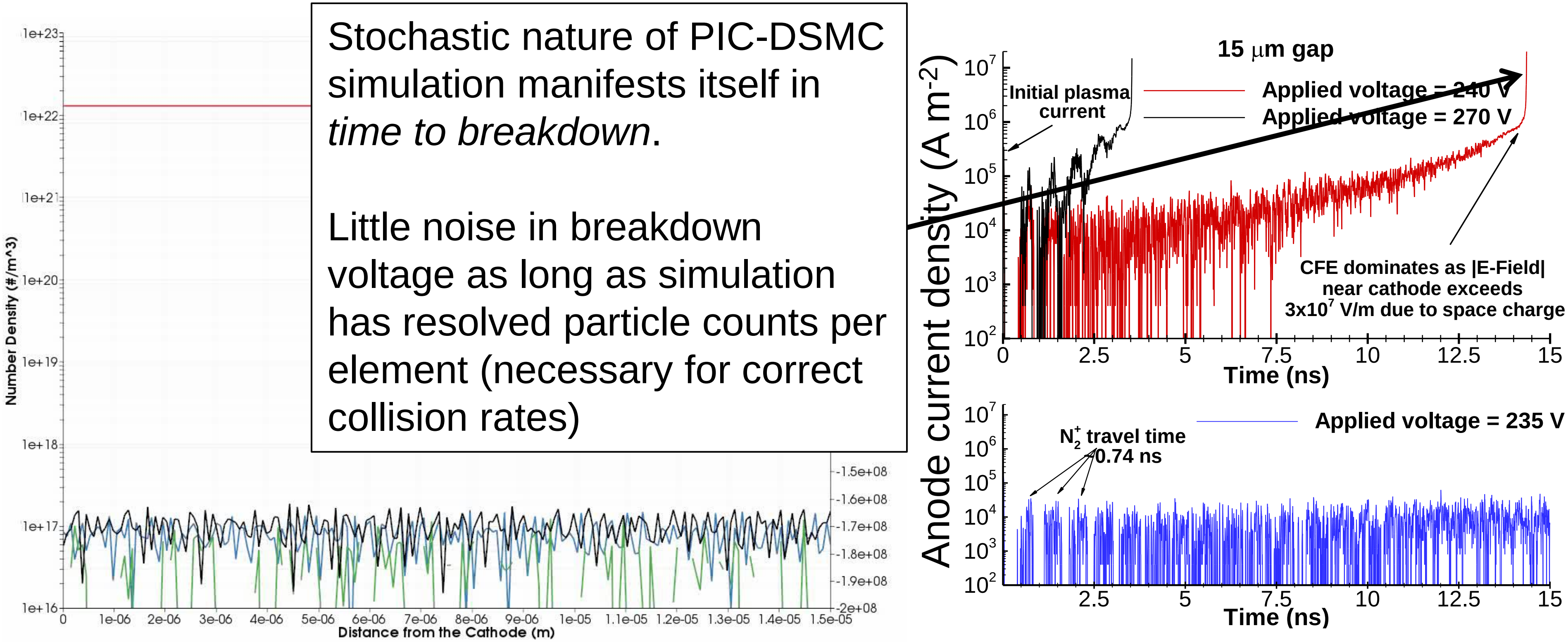
$$j = \frac{A[\beta E_s]^2}{\phi} exp\left(-\frac{B\phi^{1.5}v(y)}{[\beta E_s]}\right); \;\; v(y) \approx 0.95 - \left(\frac{C[\beta E_s]^{0.5}}{\phi}\right)^2$$

  - Assume β=50, typical for polished metal but dependent on surface conditions
- **In present work no attempt is made to calibrate γ or β to exp. data. More rigorous validation with better exp. data can be done in future.**

Gas Interaction Model

- Include e^--N_2, e^--O_2, e^--N_2^+, and e^--O_2^+ interactions
  - Elastic, Excitation
    - Alter electron energy distribution
    - Elastic collisions can be either isotropic or preferentially forward scattering
  - Ionization: $N_2 \rightarrow N_2^+$ and $O_2 \rightarrow O_2^+$
    - Source of ions & secondary electrons
    - Use *total* ionization cross section
    - Do not include double ionization ($N_2 \rightarrow N_2^{++}$ & $O_2 \rightarrow O_2^{++}$)
    - Do not include dissociative ionization ($N_2 \rightarrow N + N^+$ & $O_2 \rightarrow O + O^+$)
  - Recombination ($O_2 \rightarrow O + O^-$), Attachment ($N_2^+ \rightarrow 2N$ & $O_2^+ \rightarrow 2O$)
    - Sink for electrons, ions
- Ignore ion-neutral and e^--ion collisions for computational speedup
  - During breakdown gas < 0.01% ionized → negligible momentum transfer to neutral gas, comparatively few electron-ion collisions

Large Gap Breakdown

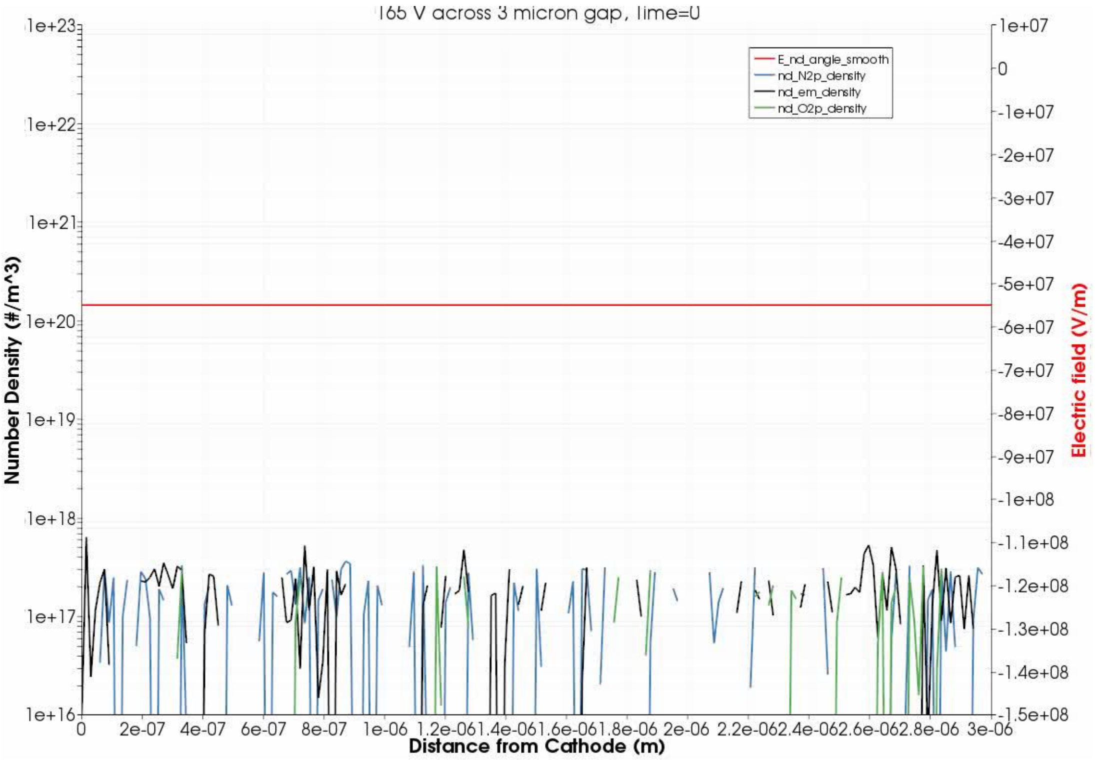


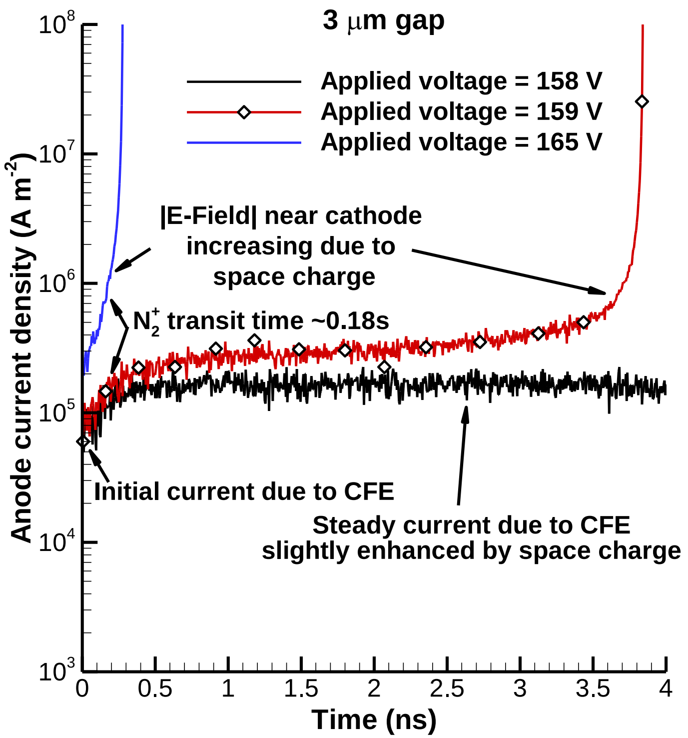
Stochastic nature of PIC-DSMC simulation manifests itself in *time to breakdown*.

Little noise in breakdown voltage as long as simulation has resolved particle counts per element (necessary for correct collision rates)

- Initial pulsing of current as ions transit gap and release electrons from cathode which then generate more ions
- Eventually quasi-neutral plasma established
  - Gap voltage drop only across sheath → Fowler-Nordheim emission accelerates breakdown
  - Most ionization events occur at edge of sheath

Small Gap Breakdown





|E-Field| near cathode increasing due to space charge

N_2^+ transit time ~0.18s

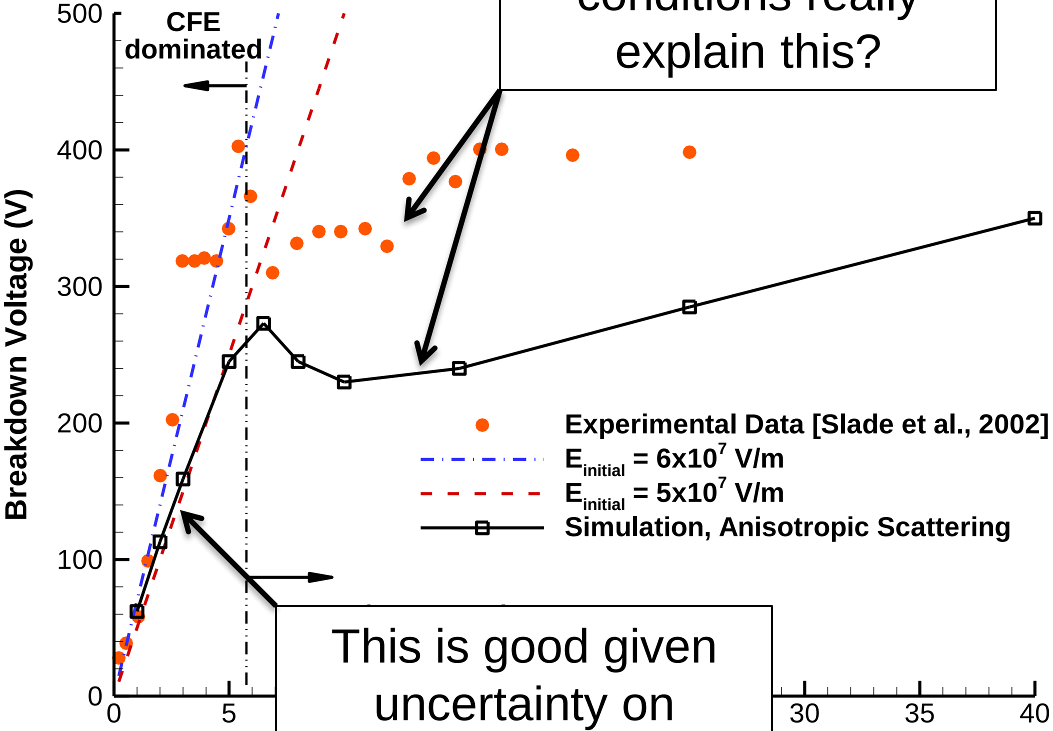
Initial current due to CFE

Steady current due to CFE slightly enhanced by space charge

- For small enough gaps, Fowler-Nordheim field emission dominant source of electrons
- Ionization of gap gas → Net charge buildup across gap leads to increased field emission and breakdown

Breakdown vs. Gap Size: Experiment

- Small gaps: Fowler-Nordheim emission
  - Sensitive to β (field enhancement factor) due to microscopic roughness & φ (cathode work function)
  - Experiment requires initial E-field across the gap of ~6 × 10^7 V/m to breakdown (blue dash-dot line)
  - Simulation requires smaller initial E-field of ~5 × 10^7 V/m (while still in CFE regime)



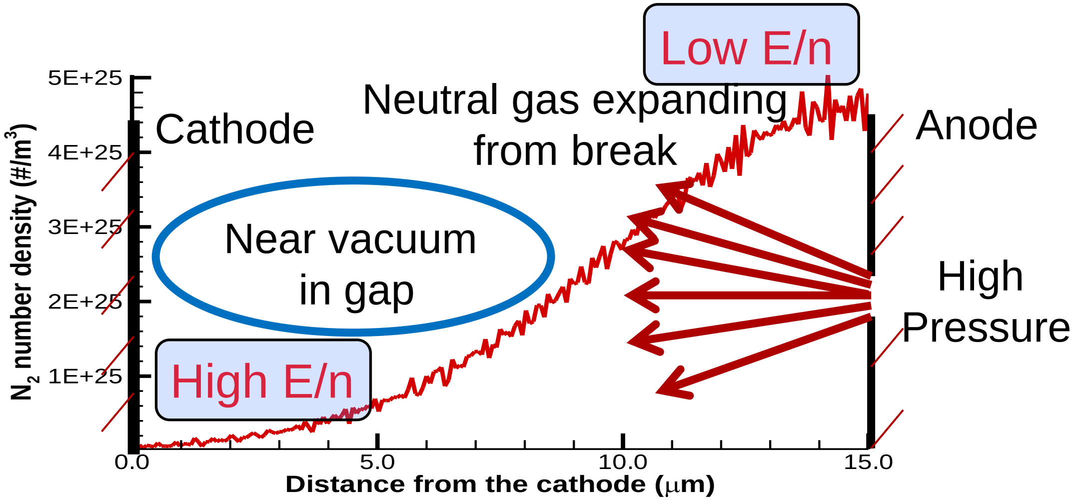
But can surface conditions really explain this?

This is good given uncertainty on experimental surface conditions…

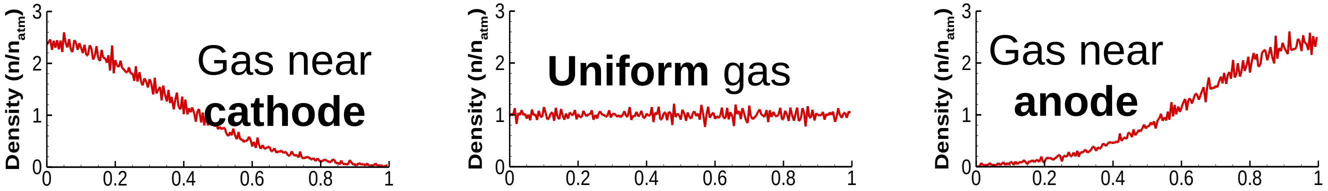
- Large Gaps: Auger neutralization electron emission
  - Sensitive to secondary emission coefficient and e^- - neutral interactions

Non-Uniform Gas Model

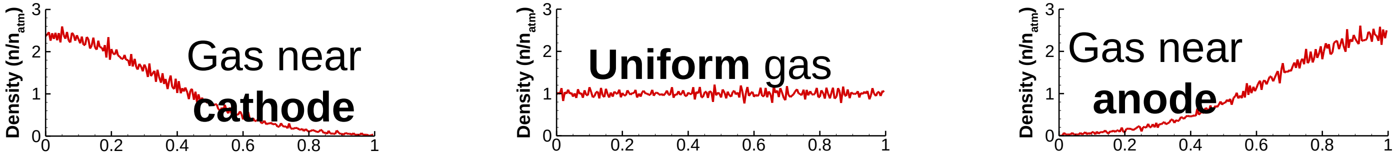
- Paschen curve predicts V_b well for large gaps with a uniform background of neutrals
- What if the gas is non-uniform across the gap?
  - Vacuum breakdown proceeds via production of neutral gas “fuel” from surfaces usually acting as cathode or anode
  - Mechanical damage or contamination are also sources of neutral “gas”
  - This affects the EEDF entering the gas → Different V_b



- Consider a normal distribution (σ=d_{gap}/3) near each electrode:



Electron Energy Distributions

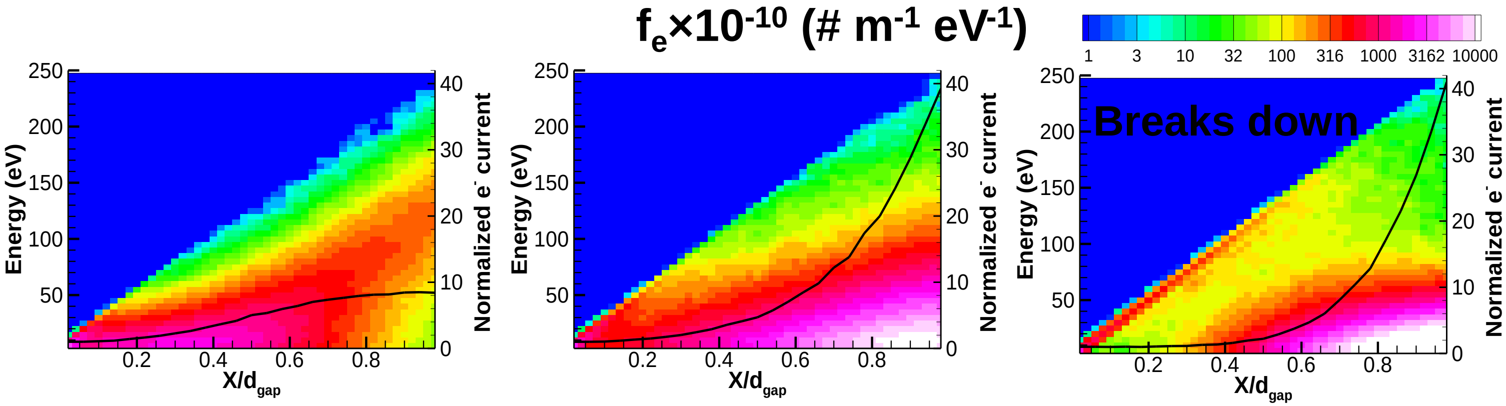


6.5µm

250V

At n_{ATM}:

$$\frac{d_{gap}}{\lambda_{mfp}} \approx 7$$

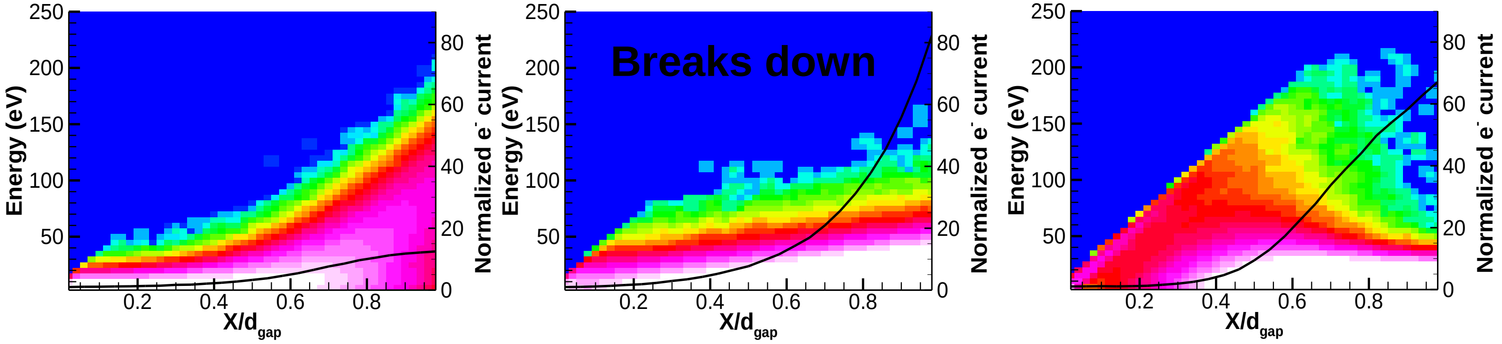


25µm

300V

At n_{ATM}:

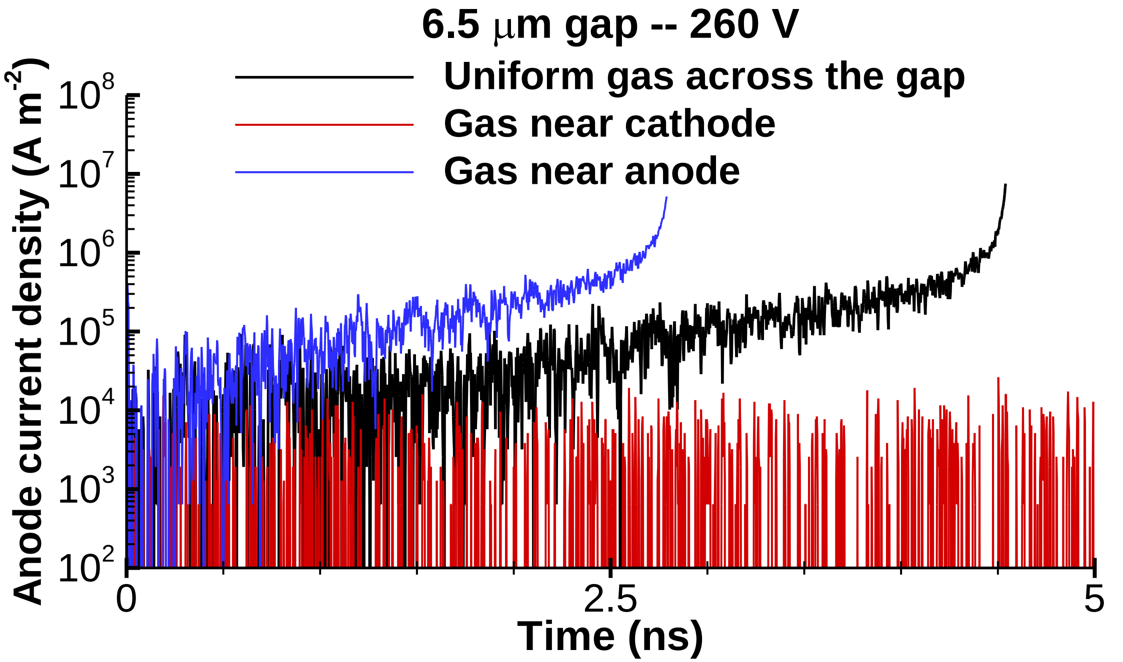
$$\frac{d_{gap}}{\lambda_{mfp}} \approx 30$$



- Energy dependent cross sections + applied field that accelerates electrons across the gap → Location of high density region matters!

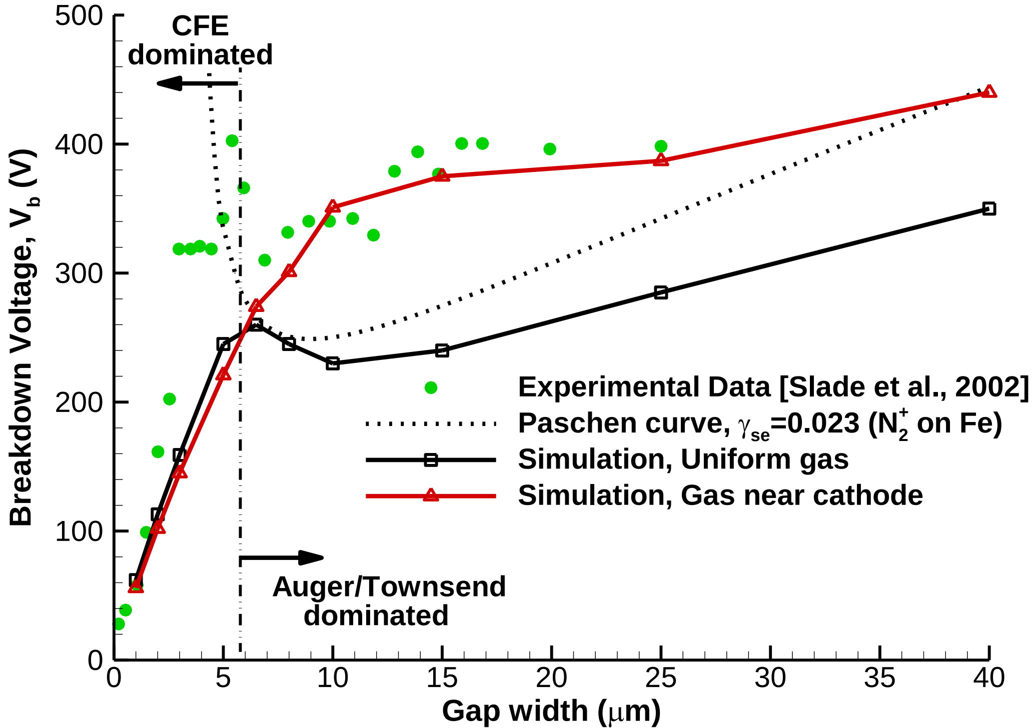
Current Across 6.5 μm Gap

- Changes in EEDF directly affect current growth!
- Increased gas density near the cathode suppresses breakdown
- Increased gas density near anode speeds up breakdown for smaller gaps (Kn_{gap} ~ 0.2)
  - Ionization rate increased, fewer ion pulses needed to generate quasi-neutral plasma and the associated sheath → CFE



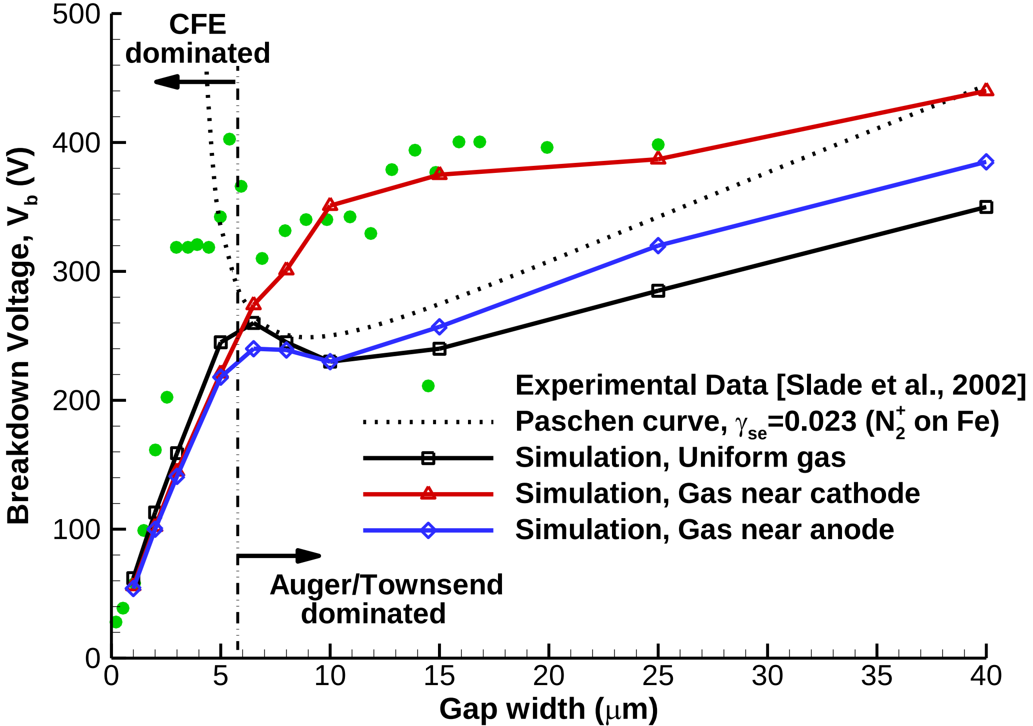
Breakdown vs. Gap size

- CFE dominated gaps: V_b not significantly affected by gas distribution.
- Auger/Townsend dominated gaps:
  - Gas near cathode → V_b increases by ~50%
  - Close to cathode low energy electrons likely to lose energy to excitation & don’t have energy for ionization. Collision rate (~density) smaller once electrons gain sufficient energy → Less ionization per electron across the gap.



Breakdown vs. Gap size

- Auger/Townsend dominated gaps:
  - Gas near anode → V_b can decrease by ~10% relative to uniform gas distributions, but it also increases for larger gaps – Why?
    - V_b increases when gap width > several mean free paths
    - In high density region the e^- don't gain as much energy from the field between collisions resulting in increased energy lost to excitation and less ionization.
  - V_b decreases when gap width < several mean free paths
    - Relatively fewer collisions so e^- gains more energy from field between collisions
    - Higher average collision energy for the e^- → More ionization collisions relative to inelastic

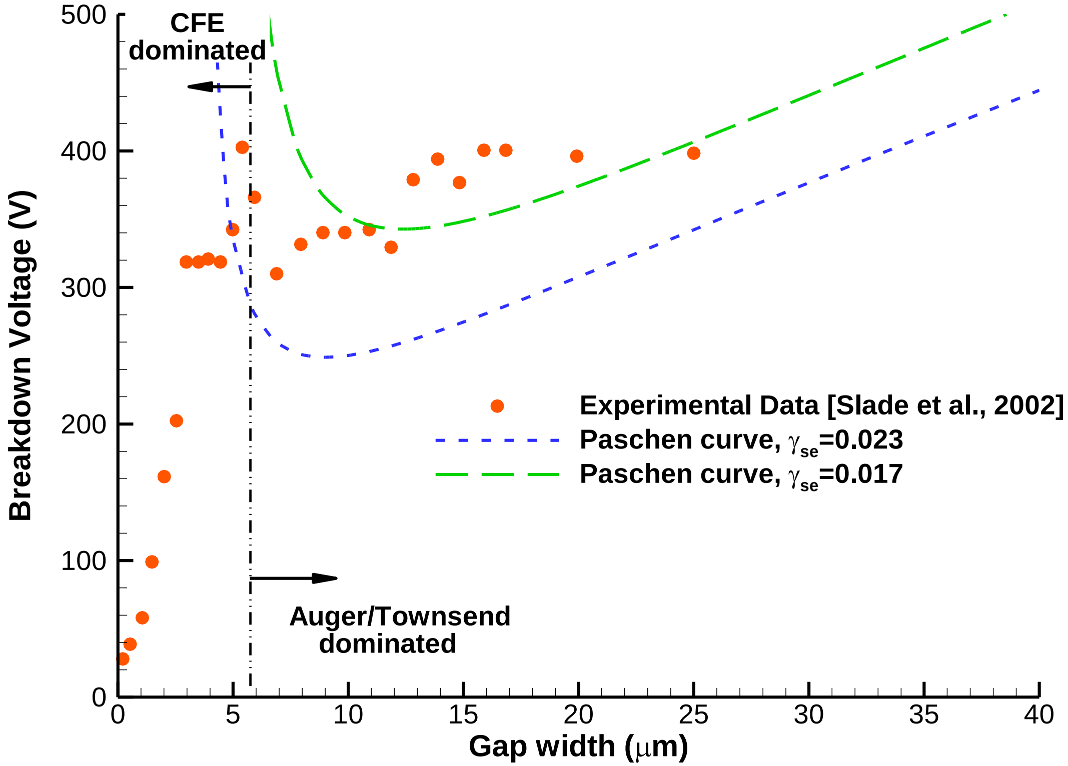


Conclusions: Non-Uniform Neutral Gas

- Neutral background gas distribution not as important for breakdown in microscale gaps dominated by Fowler-Nordheim cold field emission of electrons from the cathode
  - For larger gaps the background gas distribution effects the EEDF through an interplay between energy gained from the field and energy lost due to inelastic collisions → net ionization rate changes with gas distribution
- Gas density higher **near cathode**:
  - V_b increased by ~50%
  - Collision rate slower once electrons gain sufficient energy to ionize → Less ionization per electron across the gap.
- Gas density higher **near anode**:
  - V_b increases when gap width > several mean free paths. In high density region electrons don't gain as much energy between collisions and thus have higher chance to lose energy via excitation vs. ionization
  - **V_b decreases when gap width < several mean free paths.** Fewer collisions across gap → e^- energy near peak ionization cross section

Breakdown vs. Gap size: Paschen

- Experimental breakdown voltages in large gaps (where Paschen should be valid) “fit” by $\gamma_e \cong 0.017$
- Small change in γ_e gives large change in Paschen curve



Electron production across gap

- EEDF changes if there is a non-uniform background gas
  - More energy-losing excitation collisions if denser gas located in region where electrons are ~10 eV (near cathode)
  - Ionization efficiency changes → More/Less daughter electrons from a single electron created at cathode (Auger-neutralization)
- Thus different background neutral gas density distributions result in different electron multiplication across the gap for a given voltage
  - Complex interplay between energy gained from the field, lost due to inelastic collisions, and the ionization rate