Exceptional service in the national interest

Sandia National Laboratories

SAND2015-8936C

2D vs 1D: A PIC/DSMC Model of Breakdown in Triggered Vacuum Spark Gaps

Stan Moore, Chris Moore, Jeremiah Boerner

Gaseous Electronics Conference (GEC)

October 15, 2015

Honolulu, Hawaii

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. 2014-19378 C

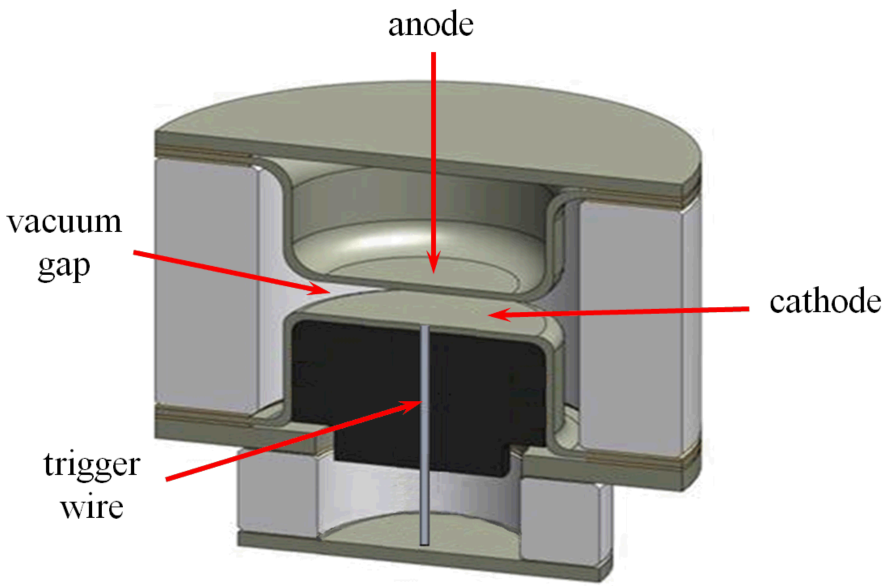
Introduction

- Triggered vacuum spark gaps (TVSGs) are useful as high voltage, high current switches with:
  - a fast switching time
  - a variable operating voltage

- Example applications of TVSGs are:
  - pulsed power
  - crowbar circuits which prevent overvoltage

Breakdown Mechanism

- Electrodes are initially separated by a vacuum gap with a potential difference across the gap
- Trigger current pulse causes metal vapor arc to form [1]
- This plasma expands and leads to breakdown of the main gap



[1] Boxman R L, *IEEE Trans. Electron Devices* **24**, 122-8 (1977)

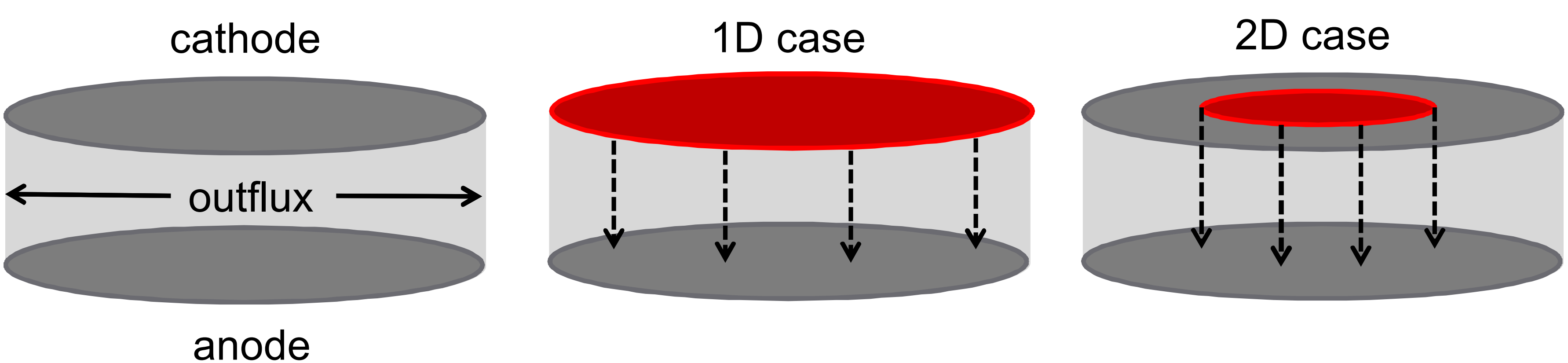
How useful are 1D Models?

- 1D models run fast and require less computing resources
- However, 1D models may have fundamental limitations compared to 2D and 3D
- Are 2D simulations of TVSGs worth the extra computational cost?

“Essentially, all models are wrong, but some are useful.” ~ George Box

Differences between 1D vs 2D

1. Outflux BC—particles are lost at the outer edge
   - Reduces the current to the anode
   - This effect depends on temperature vs drift velocity
2. 2D effects—emit particles from only a fraction of the cathode surface
   - Hold total injection rate (not flux) constant
   - Increases the density of emitted particles in the injection region



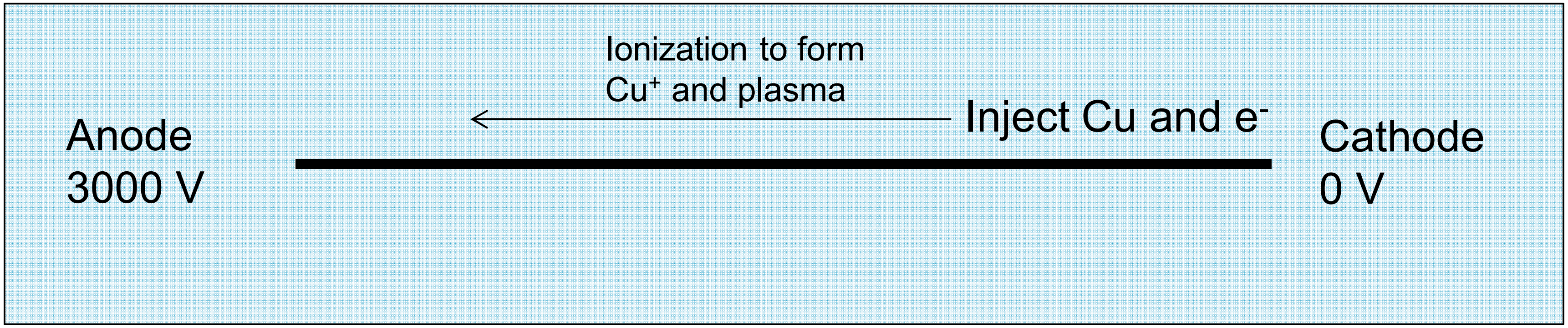
TVSG Design Parameters for Simulations

- Electrode and trigger material → **copper** [1]
- Electrode diameter → 7 cm, [1], 2.5 cm [2], choose **0.2 mm** to reduce computational cost
- Voltage across the gap → **3 kV** [1]
- R, L, C external circuit parameters → **R = 5 Ω**, **L = 250 nH**, **C = 34 μF** [1]
- Gap size → not specified by Boxman [1], 0-10 mm [2], choose a value of **0.1 mm**

[1] Boxman R L, *IEEE Trans. Electron Devices* **24**, 122-8 (1977)
[2] Raju *et al*., J. Appl. Phys. **48**, 1101 (1977)

Model

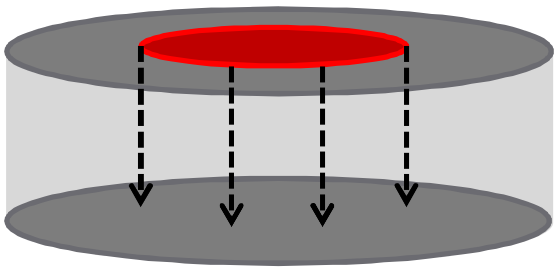
- Particle-in-cell (PIC) [1] and Direct Simulation Monte Carlo (DSMC) [2] simulations
- Ionization, excitation, elastic, and charge exchange collisions
- Sputtering and secondary electron emission are also included
- Particle influx is held constant (crude approximation to thermionic/field emission of electrons and evaporation of Cu neutrals)



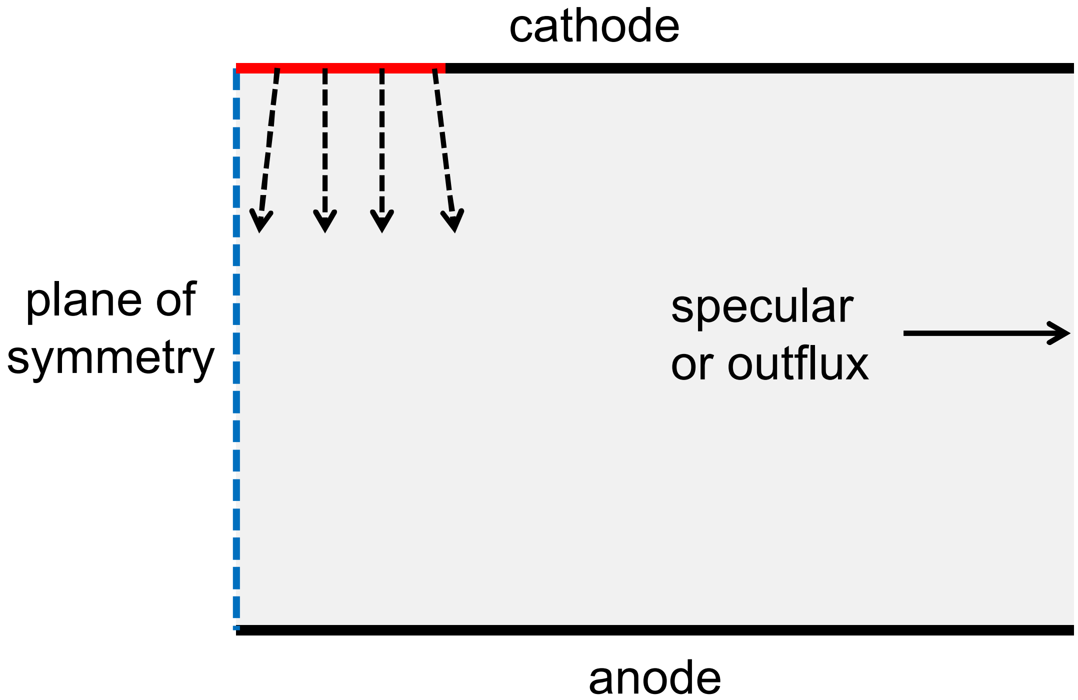
[1] C. K. Birdsall and A. B. Langdon, Plasma Physics via Computer Simulation, McGraw-Hill, New York (2005).
[2] G. A. Bird, Molecular Gas Dynamics and the Direct Simulation of Gas Flows, Oxford University Press, Oxford, UK (1994).

2D Model

- Use straight 2D (not axisymmetric)
- Use plane of symmetry at x = 0 to reduce computational cost
- In some cases, only a fraction of the cathode emits particles



axisymmetric
analogue



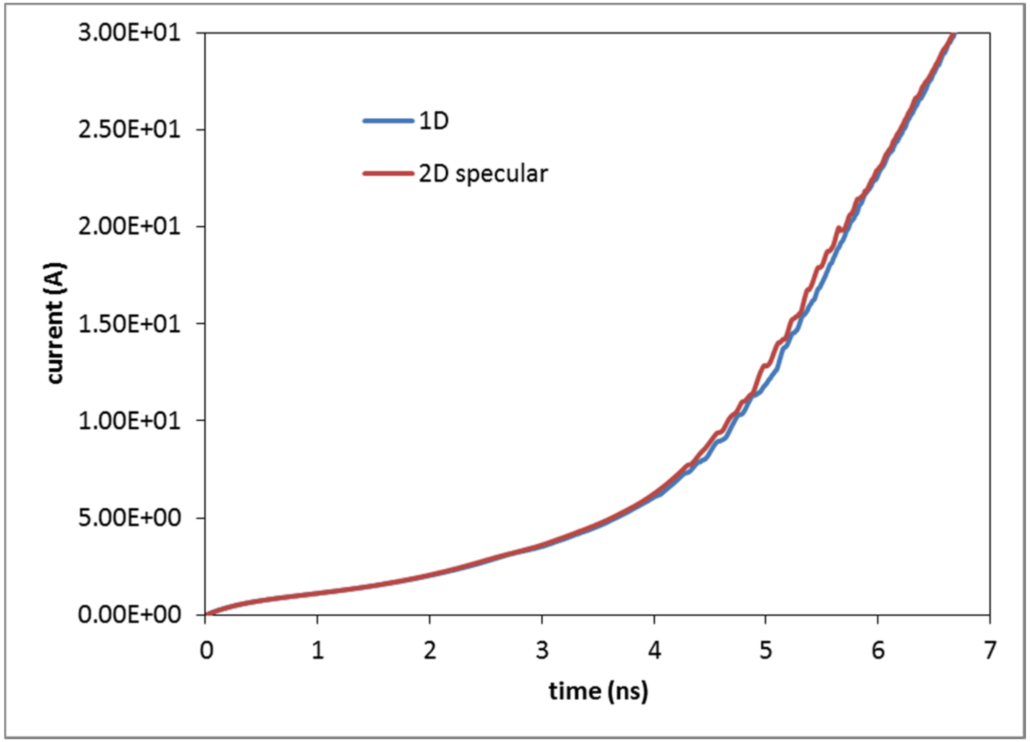
Simulation Parameters

- Mesh spacing—**~0.333 µm** (0.1 mm/300 elements in 1D)
- Timestep—**50 fs**
- Constant Flux of neutrals
  - **Temperature**—assume **2840 K** for injection (melting point of copper)
  - **Drift velocity**—assume **12,227 m/s** for injection (speed of copper ions in arc is about 13,200 m/s [1] due to vaporization, cathode spots with explosive emission, etc.)
  - **Density**—constant value, varies from **0.75e22 to 4e22 m^{-3}**
- Time-dependent flux of electrons
  - **Temperature**—assume **5 eV** for injection
  - **Flux rate**—**space-charge limited** injection based on Child-Langmuir law

[1] A. Anders, Cathodic Arcs: From Fractal Spots to Energetic Condensation Springer, New York, 2008

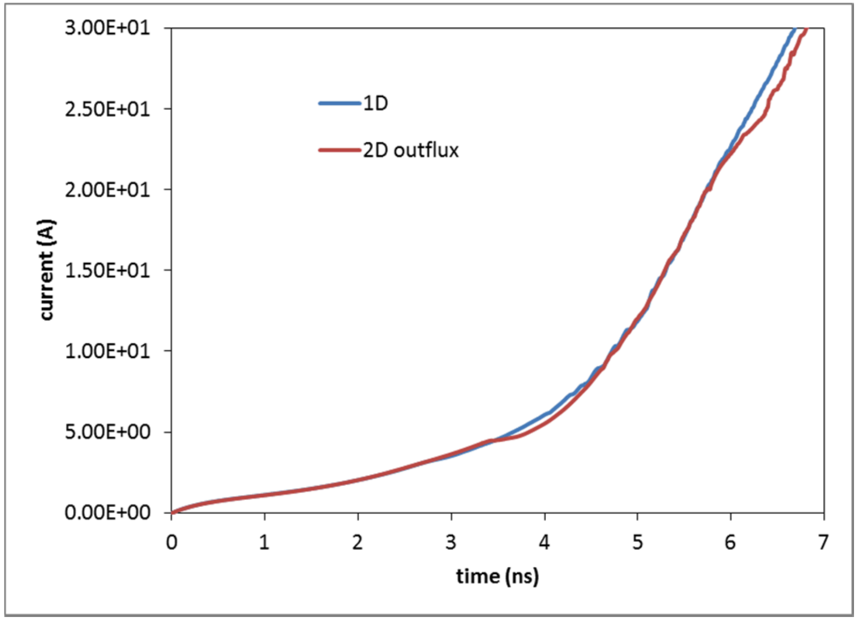
Sanity Check

- 1D vs 2D simulation with specular BC and injection over the entire cathode region (injection n_{Cu} = 1e22 m^{-3})
- Results are comparable



Outflux BC

- 1D vs 2D simulation with outflux BC and injection over the entire cathode (injection n_{Cu} = 1e22 m^{-3})
- In this case, outflux BC has little effect on current waveforms and time to breakdown

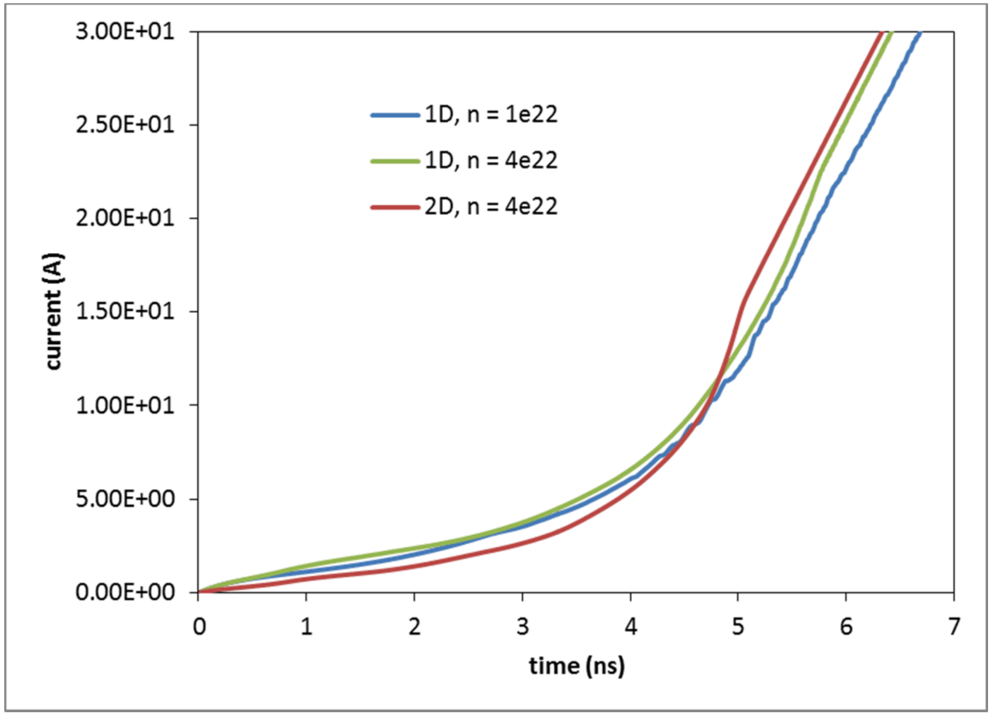


2D Effects

- For the 2D case, only allow 1/4 of the cathode area to emit particles
- Increase the density of the 2D case so the total injection rate remains constant
- Compare two different neutral injection rates
- Case 1
  - 1D: n_{Cu} = 7.5e21 m^{-3}
  - 2D: n_{Cu} = 3e22 m^{-3}
- Case 2
  - 1D: n_{Cu} = 1e22 m^{-3}
  - 2D: n_{Cu} = 4e22 m^{-3}

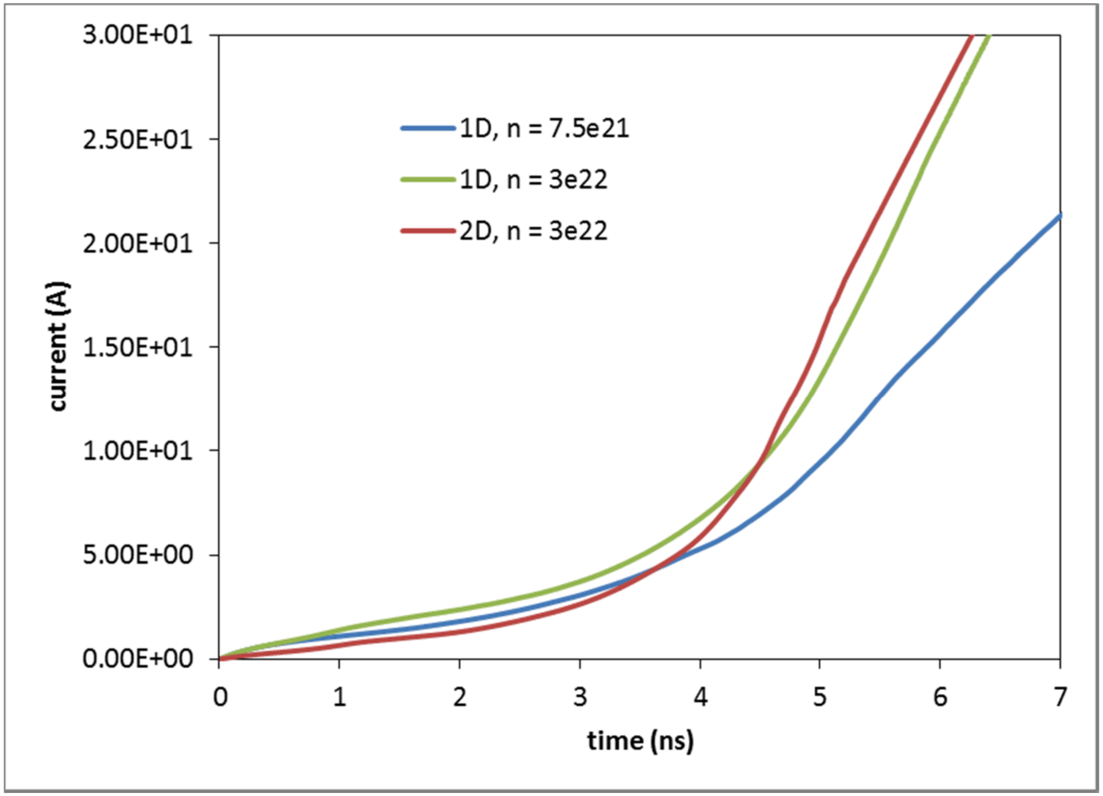
Simulation Results, Case 1

- 2D effects lead to a faster slightly breakdown time
- Difference cannot be explained by the increase in neutral density (changing E/n and α_{iz}) alone

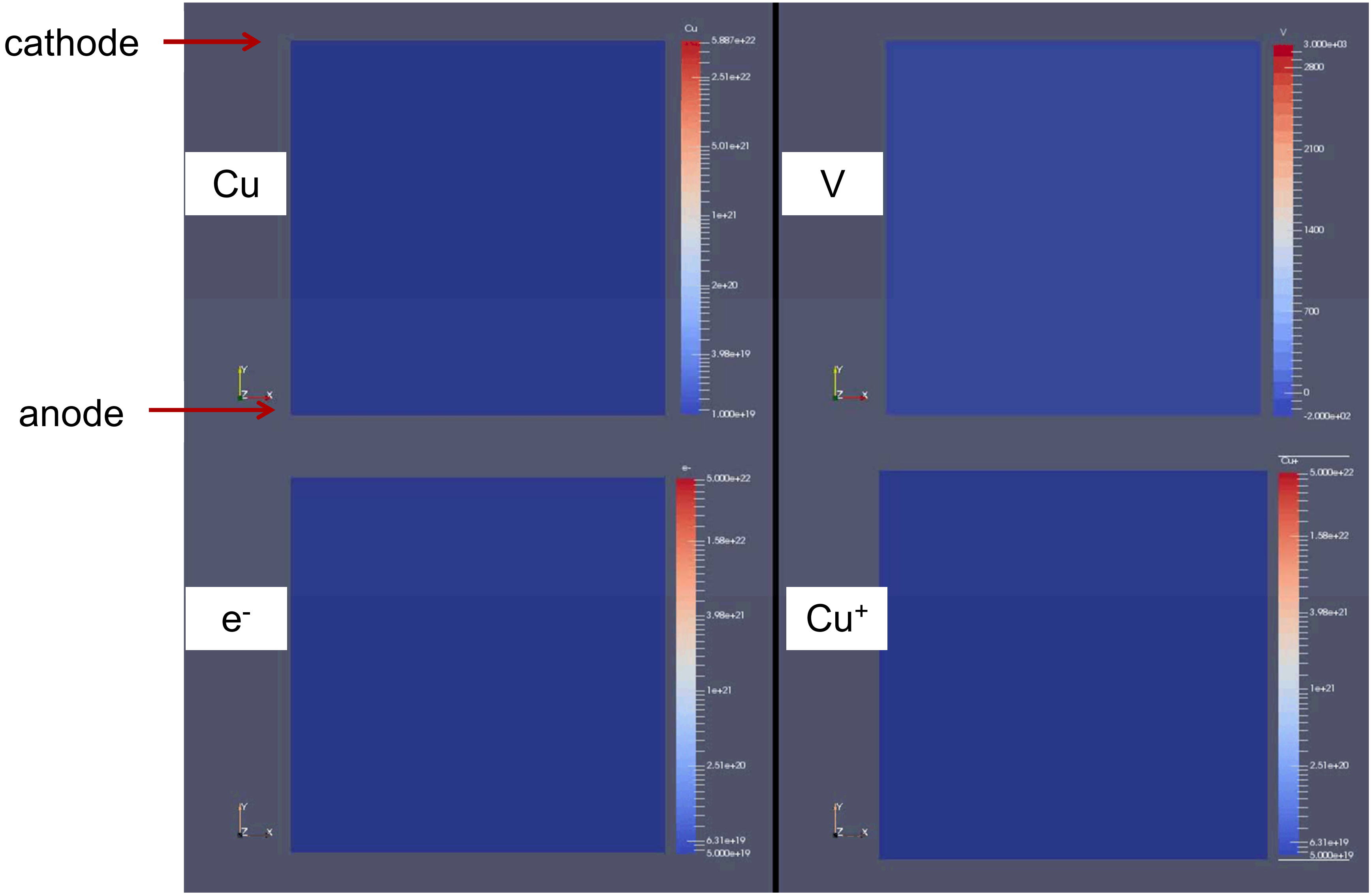


Simulation Results, Case 2

- Again, 2D effects lead to a faster breakdown time



Simulation Results, Case 2



Conclusions

- For this model, the outflux BC has little effect on time to breakdown
- 2D effects decrease time to breakdown, even though the total injection rate of neutrals is held constant
- Decreased breakdown time cannot be explained alone by the higher density (changing E/n and α_{iz})

Thank you

- Questions?

Email: stamoor@sandia.gov

Particle Interactions

- Cu + Cu, elastic collisions [1]
- Cu + $Cu^+ \longrightarrow Cu^+$ + Cu, charge exchange [1]
- e^- + Cu, elastic isotropic scattering [2]
- e^- + Cu, excitation (x 4) [2]
- e^- + Cu $\longrightarrow e^-$ + Cu^+ + e^-, ionization [2]
- Cu + Cu+, elastic isotropic scattering, VHS cross section [3]

[1] A. Aubreton and M. F. Elchinger, J. Phys. D: Appl. Phys. 36(15), 1798-1805 (2003).

[2] SIGLO database, www.lxcat.net, retrieved on September 30, 2014

[3] G. A. Bird, Molecular Gas Dynamics and the Direct Simulation of Gas Flows, Oxford University Press, Oxford, UK (1994).

Sputtering and Secondary Electron Emission

When a particle hits a copper surface:

- $Cu \rightarrow Cu + e^-$, sputtering [1-2]
- $Cu^+ \rightarrow Cu + e^-$, sputtering [1-2]
- $e^- \rightarrow e^-$, secondary electron emission [3]

[1] "Energy Dependence of Ion-induced Sputtering Yields From Monatomic Solids at Normal Incidence," Y. Yamamura and H. Tawara, Atomic Data and Nuclear Data Tables V 62, p 149-253, (1996).

[2] "Cold-cathode discharges and breakdown in argon: surface and gas phase production of secondary electrons", 1999 Plasma Sources Sci. Technol. 8 R21, Figure 2

[3] "A New Examination of Secondary Electron Yield Data," Y. Lin and D.C. Joy, Surface and Interface Analysis, V 37, p 895, (2005)