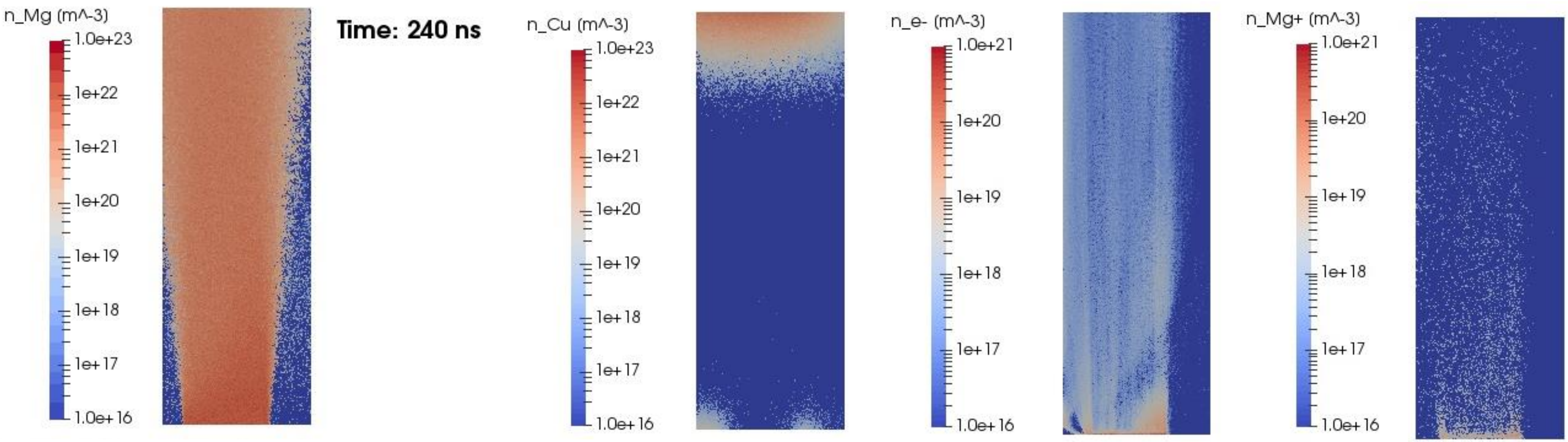

Model for Triggered Vacuum Switches

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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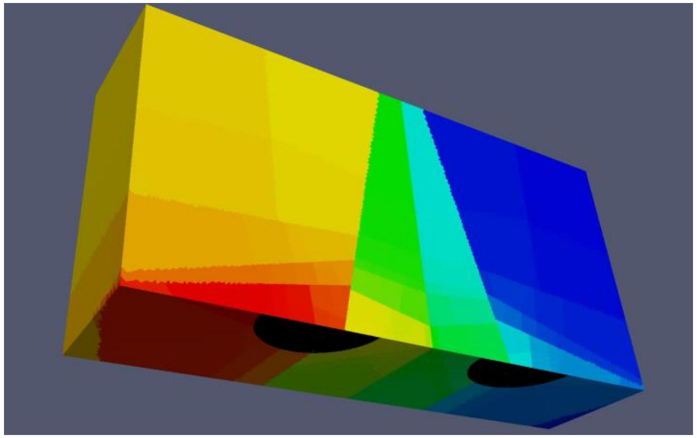
Introduction

- Triggered vacuum spark gaps (TVSGs) are useful as high voltage, high current switches
  - Fast, low variance switching time
  - Variable operating voltage
  - Limited shot life
- General TVSG operation
  - Electrodes separated by vacuum gap held at constant voltage drop
  - Trigger pulse heats a film & supplies material to the gap via vaporization
    - Vaccum $\longrightarrow$ Low pressure
  - The low pressure gap breaks down due to the voltage drop
- We desire a predictive model that captures the mean and variance in switching time and operating current from shot to shot

- Electrostatic PIC + DSMC
  - 1, 2, or 3D unstructured FEM (CAD-compatible)
  - Accounts for relative permittivity of materials
  - Can include time-varying magnetic field
- Massively parallel (scales up to ~50K procs)
  - Dynamic load balancing



Automatic Domain Decomposition

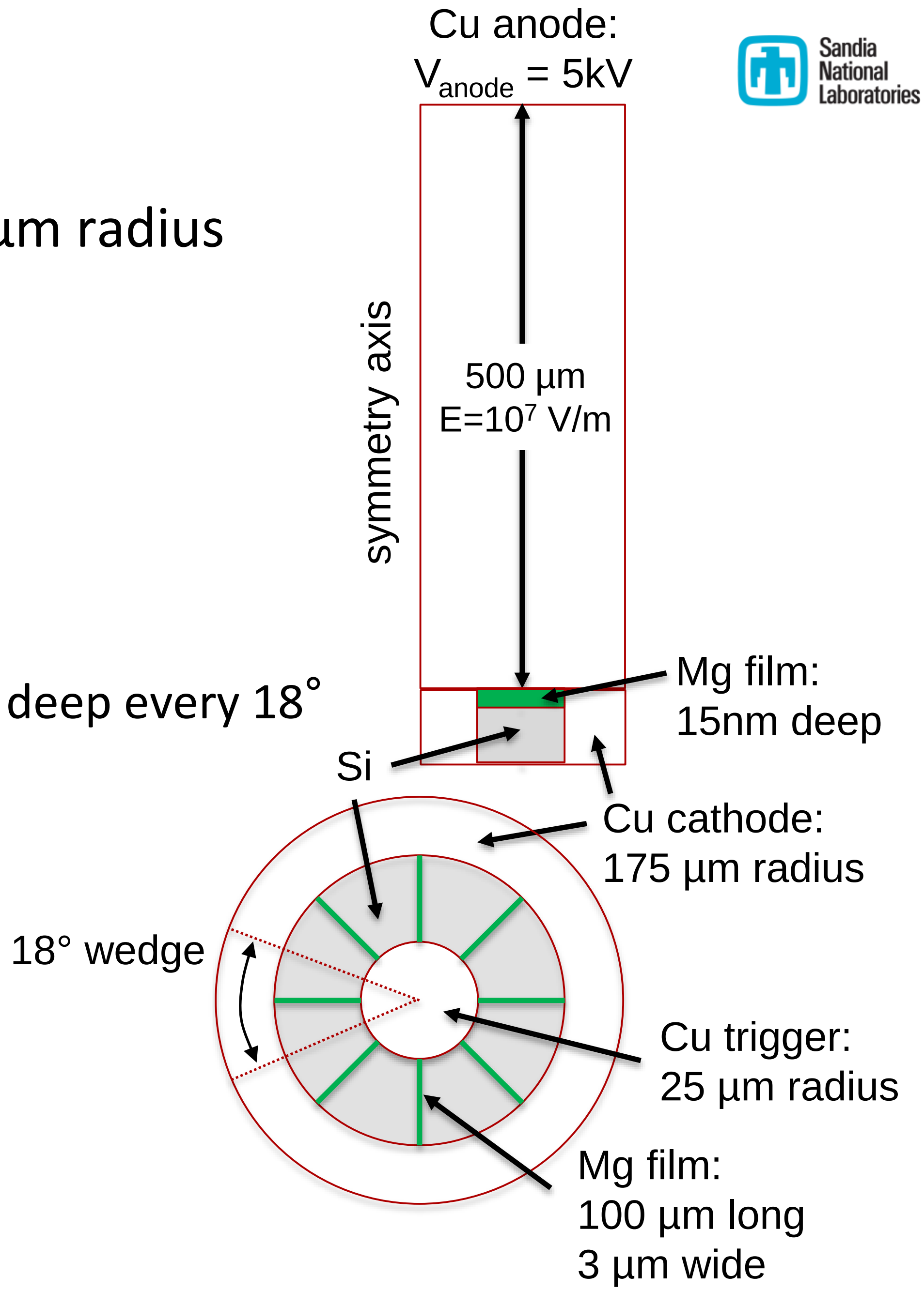
ALEPH
Advanced Plasma Transport & Kinetics

Sandia National Laboratories

- Surface physics models:
  - Fowler-Nordheim, thermionic, and Murphy-Good e^- emission models
  - Sputtering, surface charging, auger-neutralization, SEE, photoemission, sublimation/vaporization
  - Can use time-varying flux files (e.g., from data or pre-computed)
- Direct Simulation Monte Carlo Collision physics:
  - Simulate all species as simulation particles with variable particle weights
    - Can simulate evolution of neutral gas densities (important at low pressures)
  - Elastic, charge exchange, chemistry (dissociation, exchange, etc.), excited states (w/ radiative decay & self-absorption), ionization, Coulomb collisions (Nanbu)
- Simple RLC external circuit
- Future work: Fully couple Spice trigger circuit and thermal material supply model into Aleph

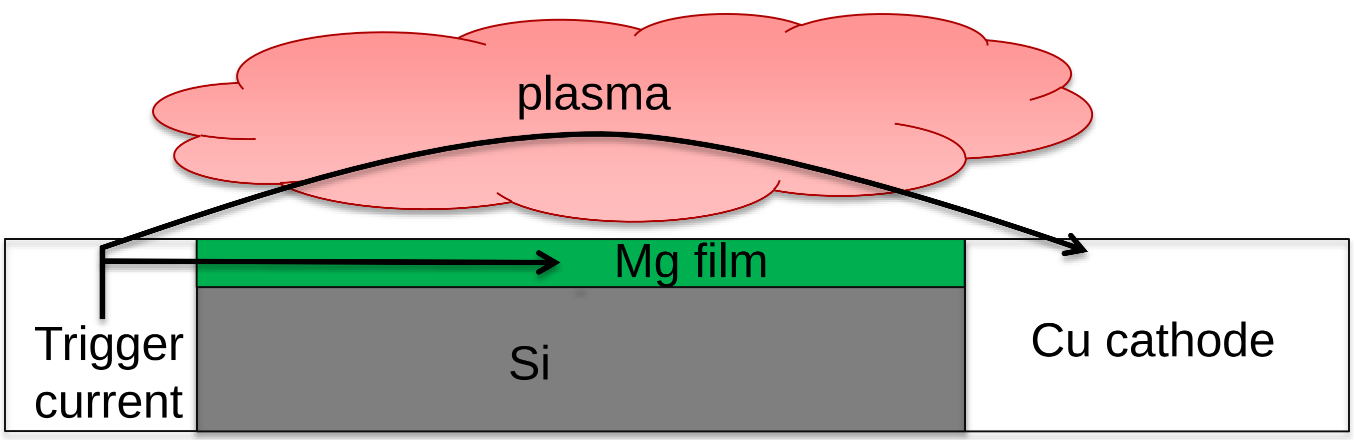
TVSG: Geometry

- 500 µm vacuum gap with 175 µm radius
- Inner ring
  - Cu trigger with 25 µm radius
- Middle ring
  - Si with 125 µm outer radius
  - Mg "wire": 3 µm wide × 15 nm deep every 18°
- Outer ring
  - Cu cathode
- If 100% of the Mg wires vaporize then $n_{Mg} \approx 10^{23}$ m^{-3}

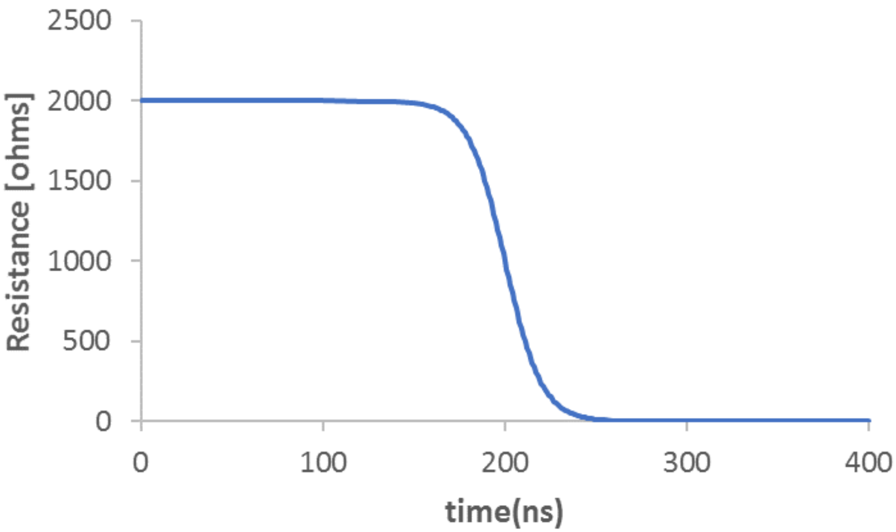


External Trigger Circuit

- Increasing the trigger input voltage leads to joule heating in the film and material emission
- Plasma forms over the film and provides an alternative conduction path that steals current from the film
- Film and plasma act like two varying resistors in parallel



External Trigger Circuit: Spice Model



ge

$R_i = 2000\Omega$; $R_f = 0.1\Omega$)

s

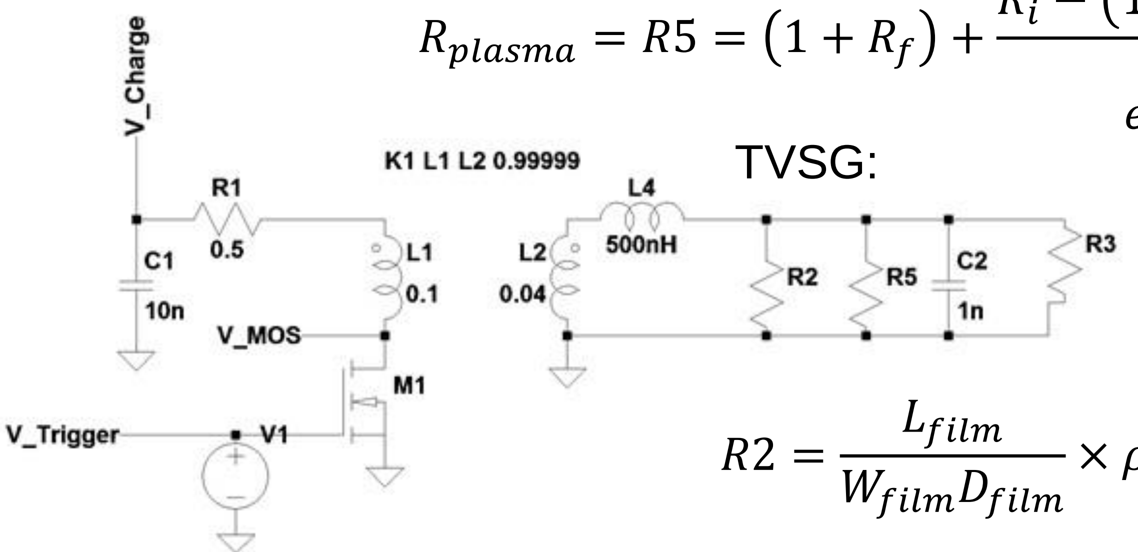
n delay time = 200ns

gh the R2 resistor

arallel Mg film “wire spokes”

$$R_{plasma} = R5 = (1 + R_f) + \frac{R_i - (1 + R_f) - e^{2(t - \tau_{collapse})/\tau_{form}}}{e^{2(t - \tau_{collapse})/\tau_{form}} + 1}$$

TVSG:



$$R3 = \frac{R2}{N_{wires} - 1}$$

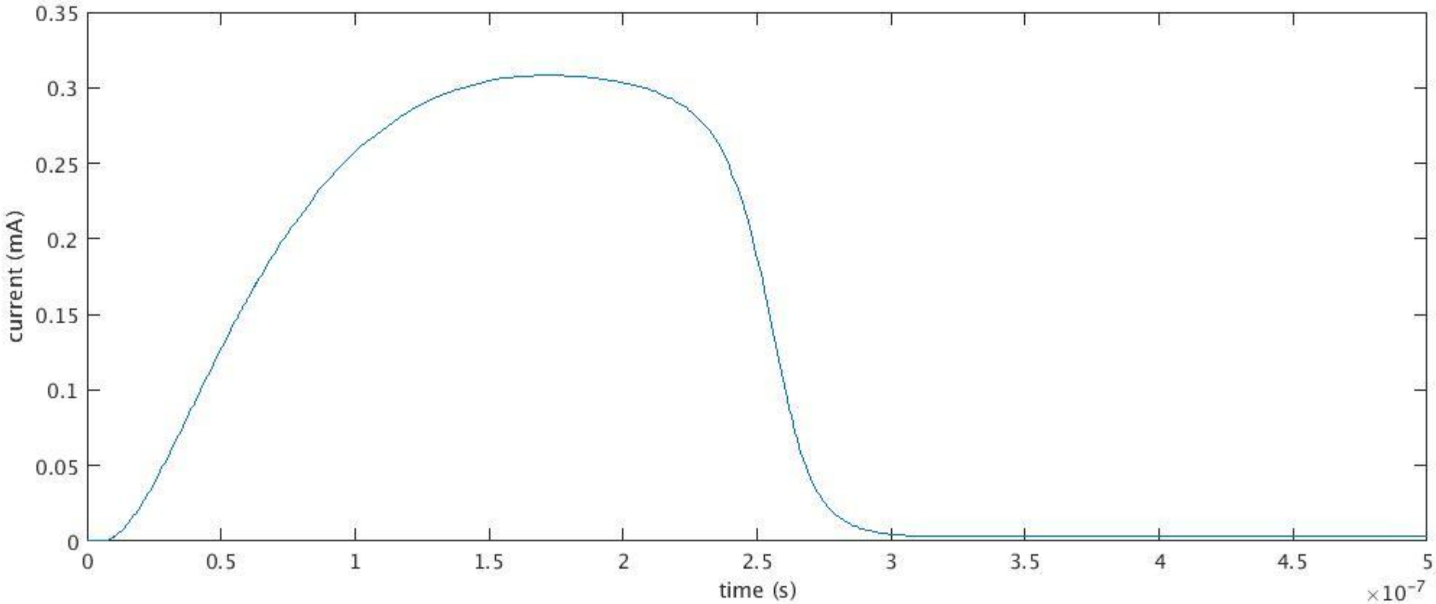
$$R2 = \frac{L_{film}}{W_{film} D_{film}} \times \rho_{film}(T_{flim})$$

External Trigger Circuit: Film Current

- Mg resistivity varies by >4x from 300K to T > 1200K during triggering:

$$\rho_{Mg}(T) \cong 0.143T + 2$$

- Until we couple the external circuit solve to the material supply and PIC simulation we use a constant value for Mg resistivity.
  - Use ρ_{Mg} (1000K) = 145 nΩ·m $\longrightarrow$ R2 = 322 Ω
- Film depth change negligible: triggering uses ~1% of total film mass



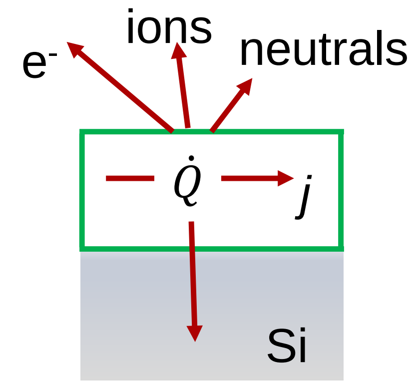
TVSG: 1D Thermal Model

- Solve 1D heat conduction equation in the film (assume κ=const)
  - Film is 3 μm wide vs. 15 nm deep

$$C_p \rho \frac{\partial T}{\partial t} - \kappa \frac{\partial^2 T}{\partial z^2} = \frac{j(t)^2}{\sigma_{film}}$$

$$T(t, z=0) = 300$$

$$\kappa \frac{\partial T}{\partial z}\Big|_{z=h} = q_i + q_n + q_e + q_{rad}$$

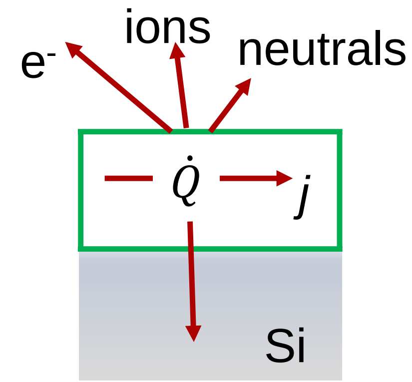


- q_{rad} :
  - Small compared to other terms → neglect from surface and plasma
- q_e :
  - Murphy-Good e⁻ emission (Benilov and Benilova, *J. Appl. Phys.* **114**, 2013)
  - Heating due to return e⁻ current assumed negligible (T_e < 100 eV)
    - Fully coupled Aleph model will naturally include this term
  - Ignore electron heating due to Nottingham effect – inversion temperature:

$$T^* = 5.67 \times 10^{-7} \frac{E}{\phi^{0.5}} t(y) \cong 74\text{K}$$

TVSG: 1D Thermal Model

- Solve 1D heat conduction equation in the film (assume κ=const)
  - Film is 3 µm wide vs. 15 nm deep



$$C_p \rho \frac{\partial T}{\partial t} - \kappa \frac{\partial^2 T}{\partial z^2} = \frac{j(t)^2}{\sigma_{film}}$$

$$T(t, z = 0) = 300$$

$$\kappa \frac{\partial T}{\partial z}|_{z=h} = q_i + q_n + q_e + q_{rad}$$

- q_n & q_i
  - Ion and neutral heating of film neglected
    - Model for *initiation* (breakdown time) of arc
    - Film area is relatively small thus assume most ions return to cathode/Si
    - Fully coupled Aleph model will include ion (and neutral) bombardment heating feedback
  - Assume evaporative cooling via Hertz-Knudsen vaporization to compute flux of film material into the vacuum
  - Specifics depend on sublimation vs. explosive emission models

TVSG: e^- Emission BC

- Use Murphy-Good emission (with "β"=25):

$$j_e(E,T,\zeta) = e\int_{-W_a}^{\infty} D(E,W)N(T,\zeta,W)dW$$

- Use computationally efficient approach of Benilov and Benilova, *J. Appl. Phys.* **114** (2013) to solve for current density:

$$j_e\left(T_{film}, E_w, \varphi\right) = \left(I_1 + gI_2\right)A_{em}{T_{film}}^2$$

  - I_1 and I_2 are numerically solved integrals; $g = \frac{1}{kT_w}\sqrt{\frac{e^3 E_w}{4\pi\varepsilon_0}}$

- We assume the electrons come off at the film wall temperature:

$$q_e = -\frac{j_e}{e}\left(2kT_{film} + \phi_s\right)$$

- Cu trigger and cathode emit using Fowler-Nordheim
- e^- emission space charge limited to Child-Langmuir limit

TVSG: Neutral/Ion Emission BC

- Compute fluxes from Hertz-Knudsen vaporization with Antoine vapor pressure for Mg (A=13.495, B=-7813, C=-0.8253):

$$\Gamma = \frac{P_{vap}}{\sqrt{2\pi mkT_{film}}}, \qquad log(P_{vap}) = A + \frac{B}{T_{film}} + Clog(T_{film})$$

- Questionable validity for $T_{film} > T_{boiling}$. However, energy deposited into the film via joule heating either heats the film (and increases material fluxes) or is conducted away (relatively small)
  - If $T_{film} > T_{boiling}$ and the physical flux rate should be larger than Hertz-Knudsen rate then the film temperature will increase until:

$$\Gamma_{real}(T_{film,real}) \approx \Gamma_{H-K}(T_{film,model})$$

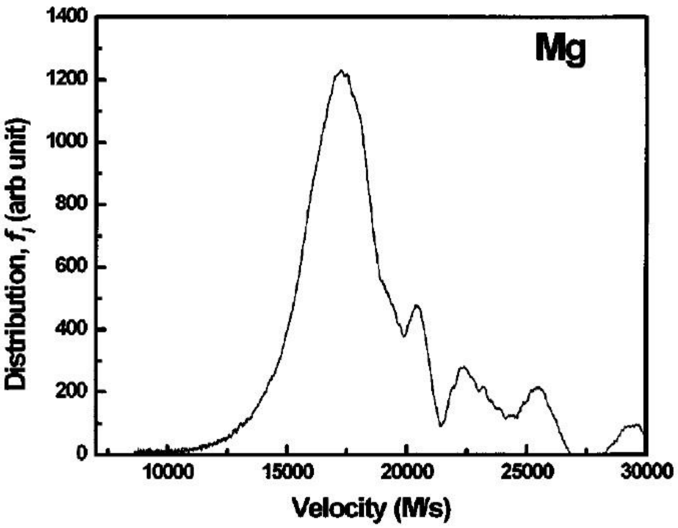
  - Because this requires heating the film further we still get the transient flux wrong as there is a lag (esp. near $T_{film}(t) \sim T_{boiling}$?)

TVSG: Neutral/Ion Emission BC

- 1D thermal model finds that the temperature at the film surface is less than the bulk film temperature
  - Possibility of phase transition to vapor under the surface in the bulk that leads to explosive emission once the pressure is high enough

- V_{Mg+} ~ 20 km/s (~50 eV) from prior vacuum arc data [1]

- Are the ions formed via ionization of neutrals and then expand at the ion sound speed or during an explosive phase change process in the film?
  - We will investigate with four approximate models



[1] Byon & Anders, *JAP* **93**, 1899 (2003)

TVSG: Neutral/Ion Emission BC

- We still need to know the energy carried away by each neutral/ion. Four models are examined:

- Sublimation (thermal bulk velocity away from film):

$$q_{neutral} = -\Gamma\left(2kT_{film} + E_{coh}\right)$$

- Fast Sublimation (~20km/s bulk velocity):

$$q_{neutral} = -\Gamma\left(2kT_{film} + E_{coh} + 0.5mv_{bulk}^2\right)$$

- Explosive Neutrals: (~20km/s bulk velocity when T_{film} > $T_{boiling}$):

$$q_{neutral} = \begin{cases} -\Gamma\left(2kT_{film} + E_{coh}\right), & T_{film} < T_{boiling} \\ -\Gamma\left(2kT_{film} + E_{coh} + 0.5mv_{bulk}^2\right), & T_{film} < T_{boiling} \end{cases}$$

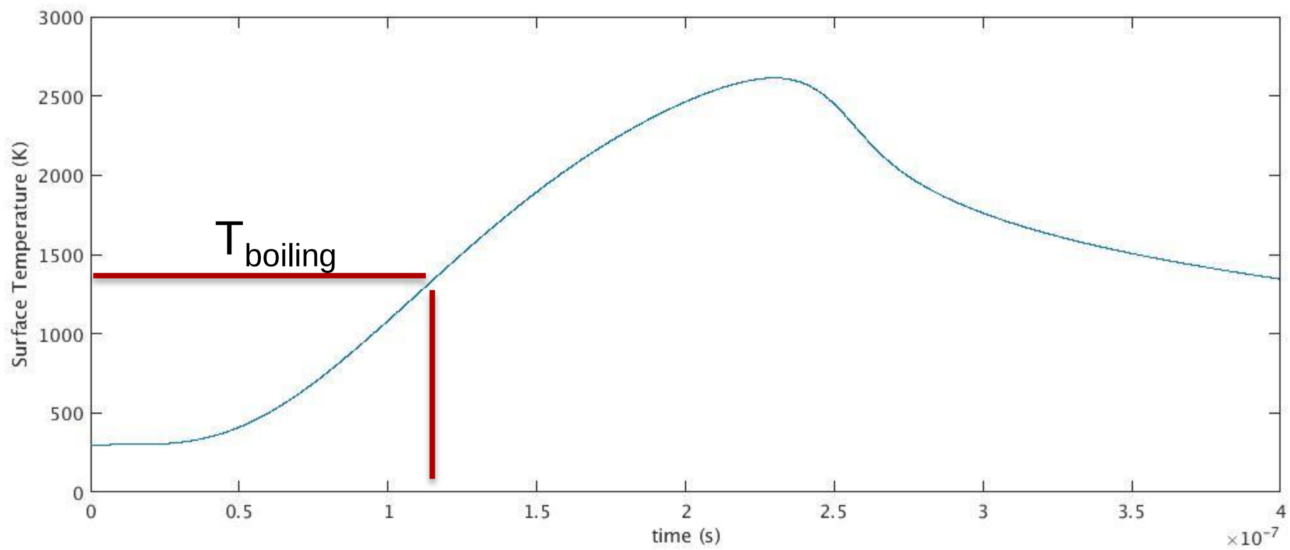
- Explosive Ions (ion emission when T_{film} > $T_{boiling}$):

$$q_{neutral} = -\Gamma\left(2kT_{film} + E_{coh}\right), \quad T_{film} < T_{boiling}$$

$$q_{ion} = -\Gamma\left(2kT_{film} + E_{iz} - \phi_S + E_{coh}\right), \quad T_{film} > T_{boiling}$$

TVSG: Surface Temperature

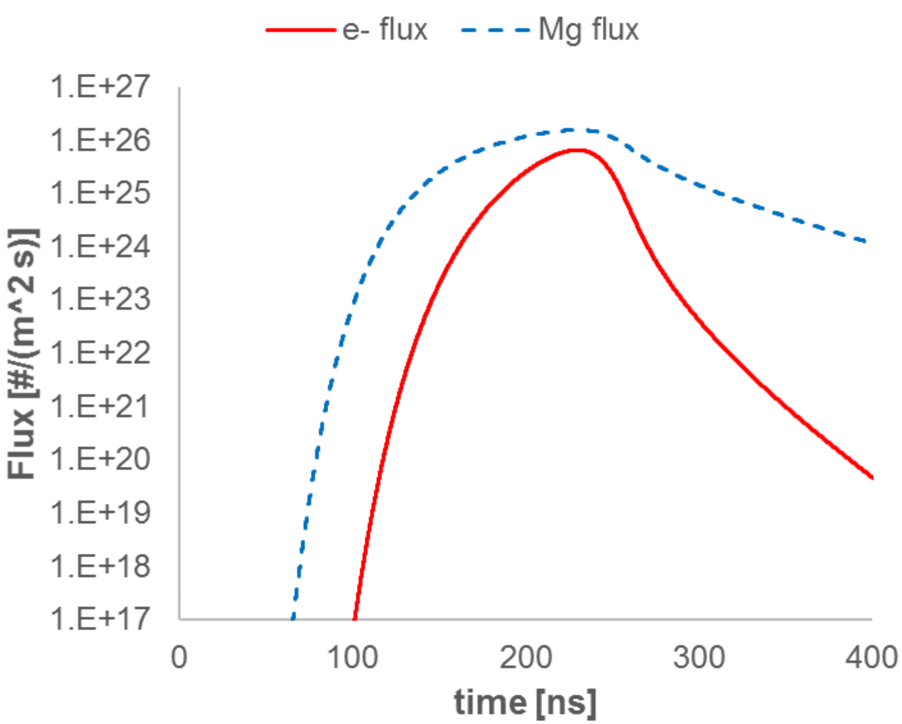
- Slight variations in surface temperature depending on neutral emission model
- Surface temperature > $T_{boiling}$ after ~115ns
  - If T_{film} held to less than $T_{boiling}$ (by adjusting the trigger circuit to obtain lower film current densities):
    - Not enough surface material/e^- are supplied → Gap does not break



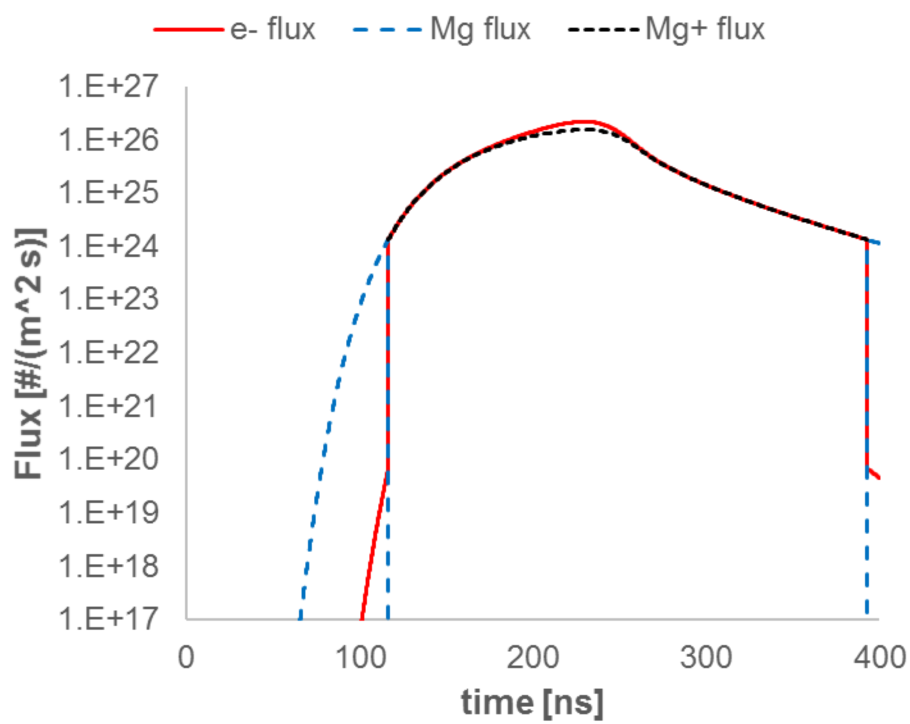
TVSG: Emission Fluxes

- Slight variation on total material emission based on emission model
- Total emitted material would fill gap to n ~ 10^{21} #/m^3
  - Paschen breakdown → no breakdown; would need ~10x more material
- Very little material emission until ~75ns → shift t_{sim} = 0 by 75ns

Neutral Sublimation:



Explosive Ion Emission:



TVSG: Plasma-Surface Interactions

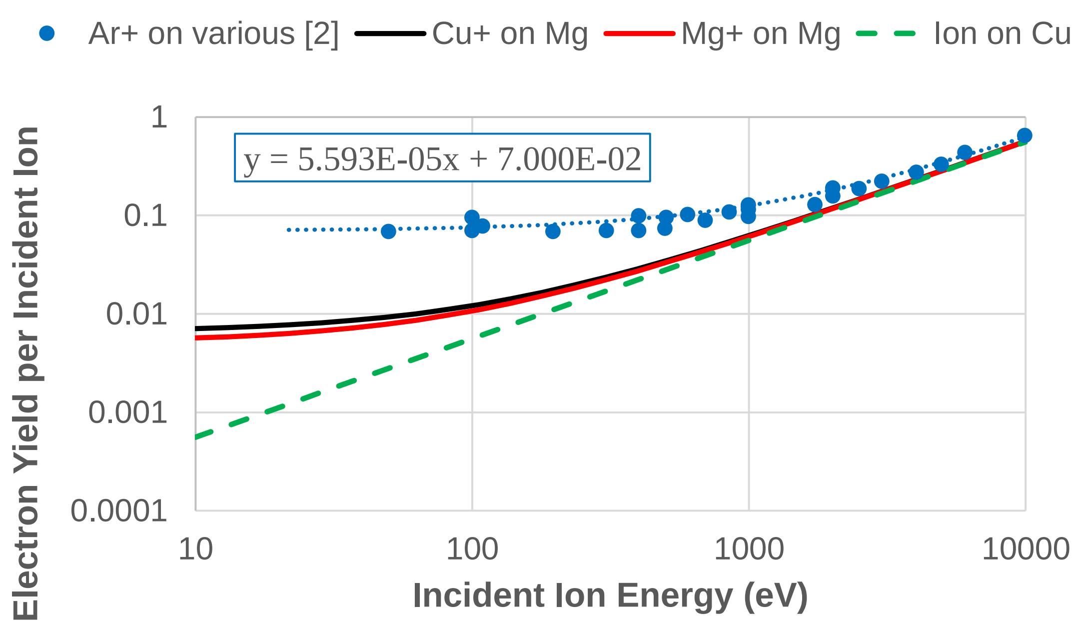
- Sputtering [1]:
  - Generalized equation based on impactor and target masses, impactor KE, and several fit parameters:

$$Y(E) = 0.042 \frac{Q(Z_T)\alpha^* \left(M_T/M_I\right)}{U_s} \frac{S_n(E)}{1 + \Gamma k_e \epsilon^{0.3}} \left[1 - \sqrt{\frac{E_{th}}{E}}\right]^s$$

- Ion-induced SEE:
  - Low energy limit [2]:

$$\gamma_{SEE} \approx 0.016(E_{IZ} - 2\phi)$$

  - High energy based on [3]
    - Fit Ar^+ yield data on diff. surfaces (~const ϕ)
    - Assume same high energy behavior for Cu^+ and Mg^+
  - SEE yield is very low



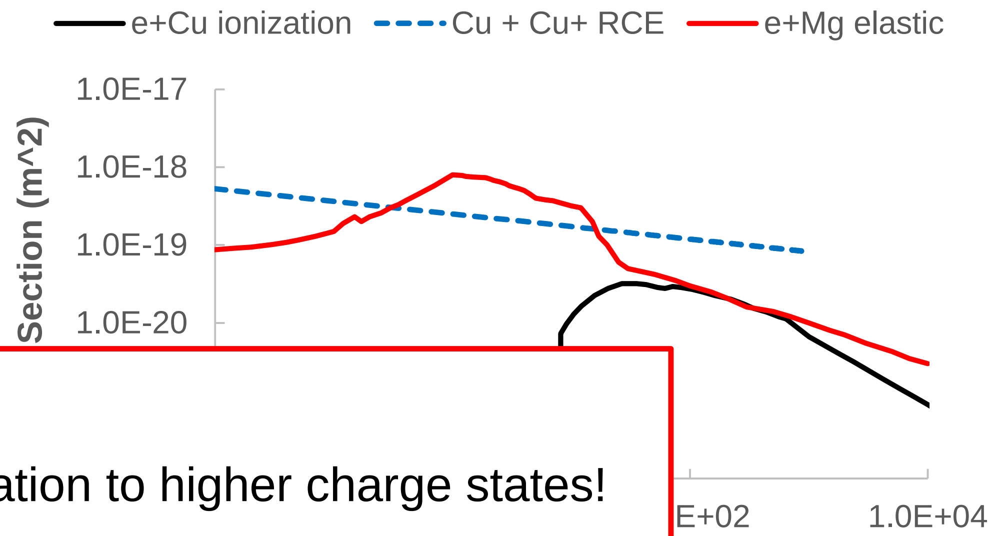
[1] Y. Yamamura and H. Tawara, *Atomic Data and Nuclear Data Tables* **62**, 149-253, (1996).

[2] Y. Raizer, *Gas Discharge Physics* (1991)

[3] A.V. Phelps and Z. Lj. Petrović, *PSST* **8,** R21, (1999). Figure 2

TVSG: Collisions

- e^- + Cu [1]
  - Elastic (isotropic scattering)
  - 4 excited states
  - Ionization to Cu^+
- e^- + Mg [2]
  - Elastic (
  - 2 excite
  - Ionizatio
- Neutral co
  - Cu + Cu
  - Mg + Mg^+ resonant charge exchange [4]
  - Cu + Cu^+ elastic isotropic scattering, VHS [5]
  - Cu + Mg, Mg + Mg, Mg + Mg^+ elastic isotropic scattering, VHS [5]



Currently lack ionization to higher charge states!

This could significantly impact ion-SEE yields

[1] SIGLO database, www.lxcat.net, retrieved on 9/30/2014

[2] Phelps database, www.lxcat.net, retrieved on 2/14/2017

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

[4] Smirnov, *Physica Scripta* **66**, 595-602 (2000).

[5] G. A. Bird, *Molecular Gas Dynamics and the Direct Simulation of Gas Flows* (1994).

Numerical Parameters

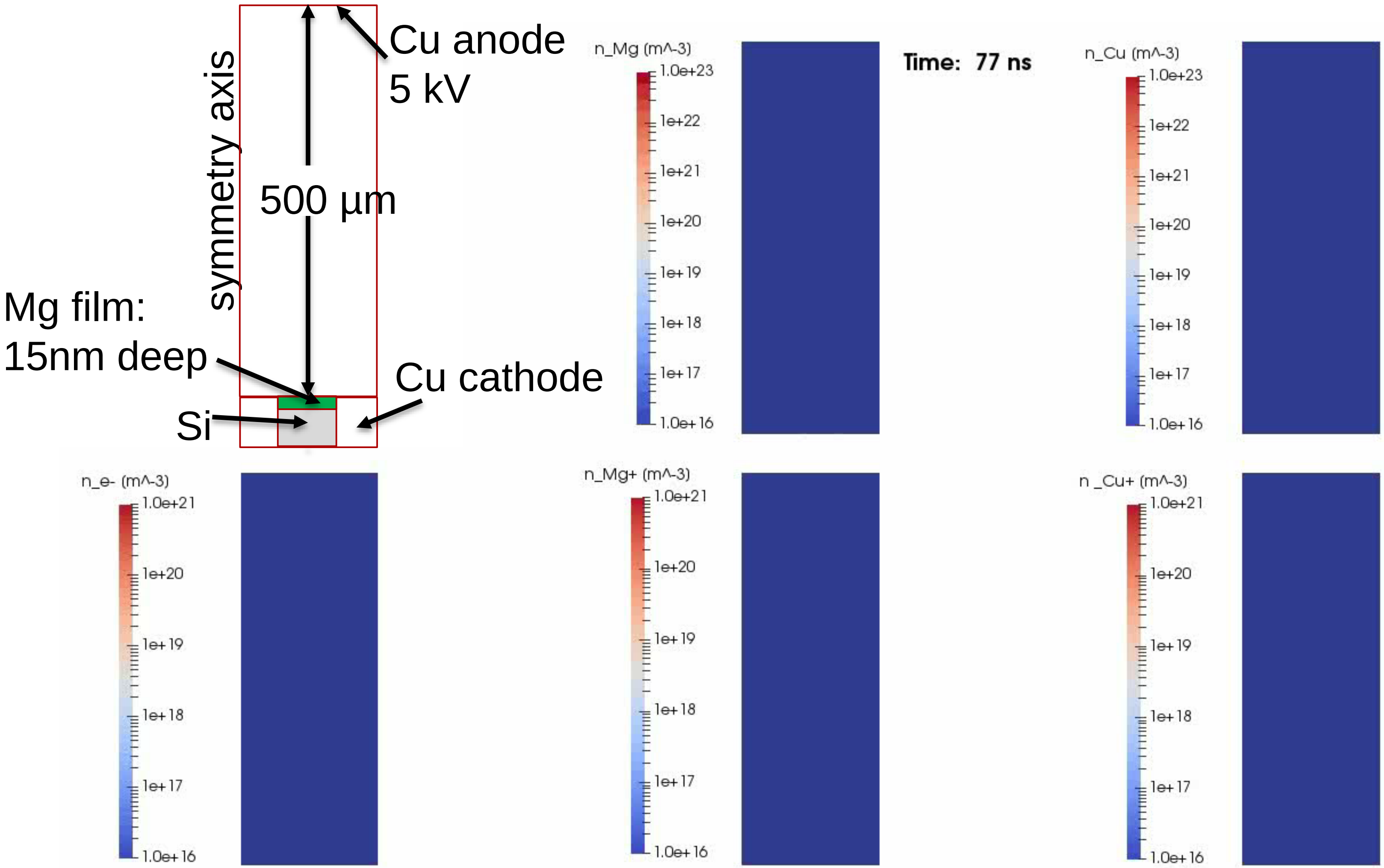
- Δx must resolve Debye length. Assume plasma density ≤ 10^{21} #/m^3 and T_e ≥ 10 eV ⟶ Δx = 2.35 μm near the film
  - Allow for mesh to grow slightly away from the film
  - ~10^6 elements

- Δt must resolve
  - Collision rate: Δ $= 10^{-12}$ s
  - Plasma frequen $^{-12}$ s
  - CFL: $\Delta t < \frac{\Delta x}{v_e} \sim \frac{10}{10^7} = 10^{-13}\ s$
  - We use $\Delta t = 2 \times 10^{-13}$ s
    - Acceptable error that a small fraction of electrons will violate CFL

Each simulation took
~1 day on 4096 cores

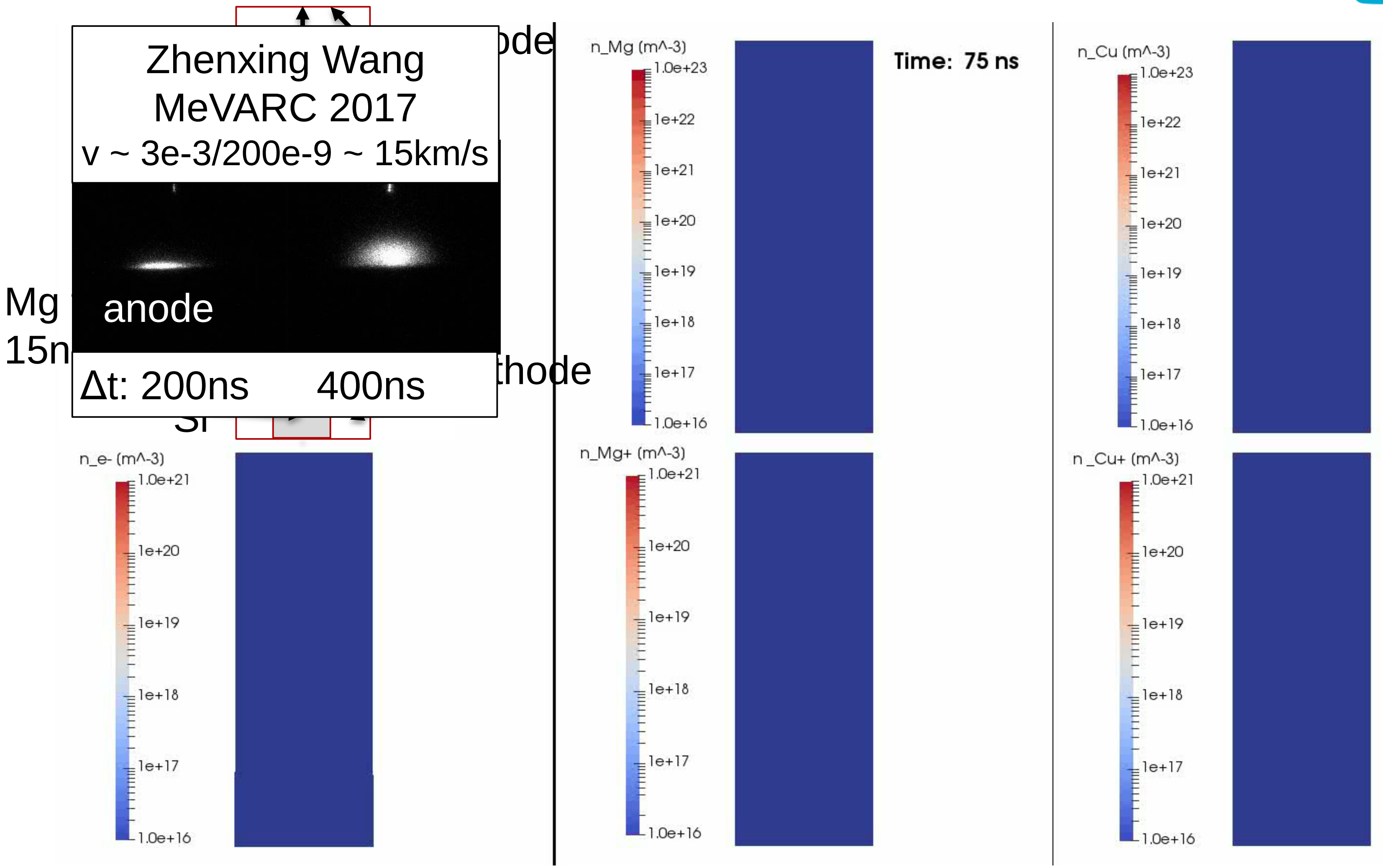
- Particle weights: Use particle merging to keep #/element ~ 100

Results: Neutral Sublimation



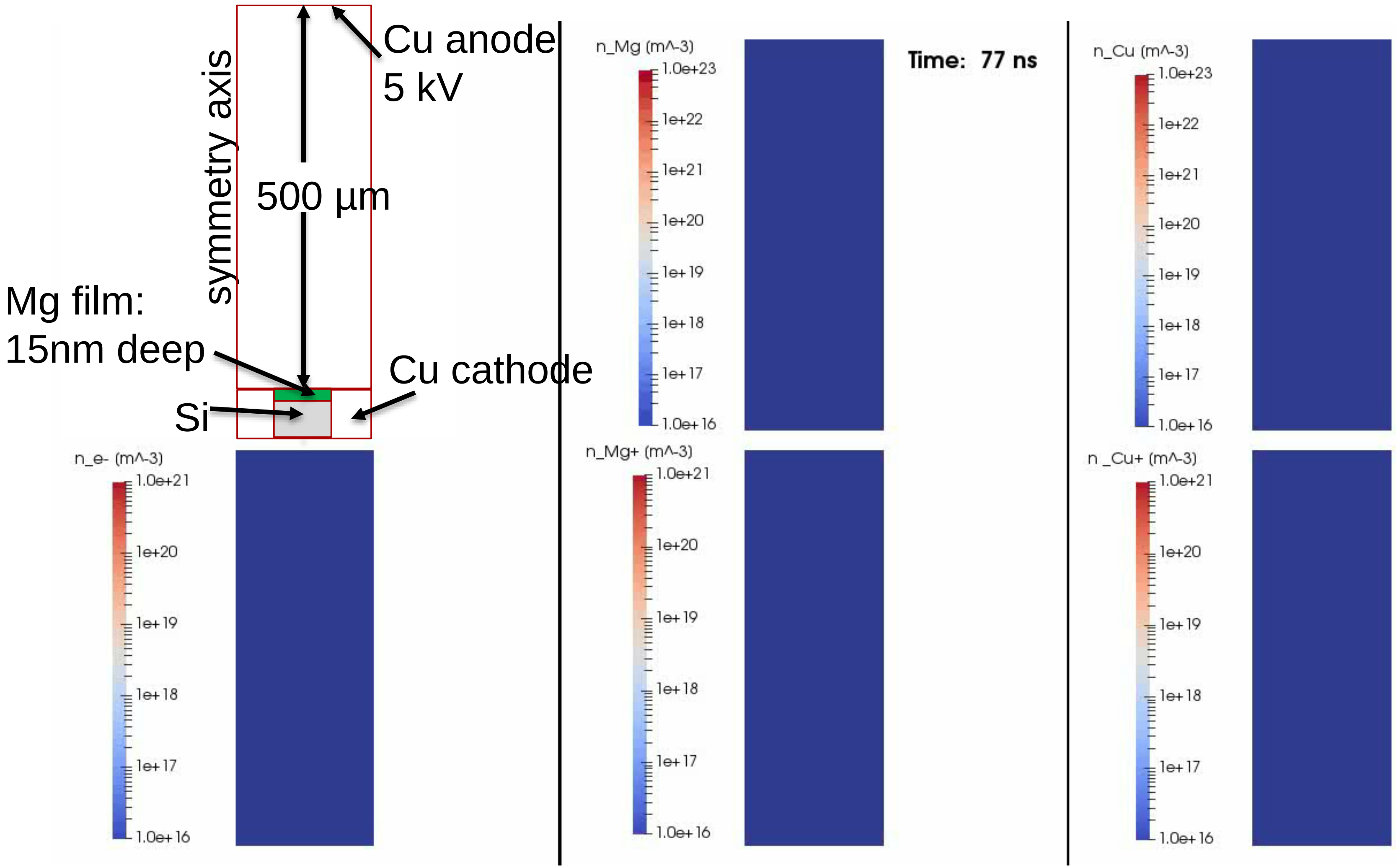
- Does not break down: sputtering doesn't increase density enough
- Plasma density ~10^{21}: and T_e ~5eV
  - Mesh is OK, but the gap 100nm breakdown
  - Plasma needs n_{gap} ~2×10^{23} m^{-3} with 1% SEE; 10% SEE yield needs n_{gap}~8×10^{22} m^{-3}

Results: Fast Neutrals



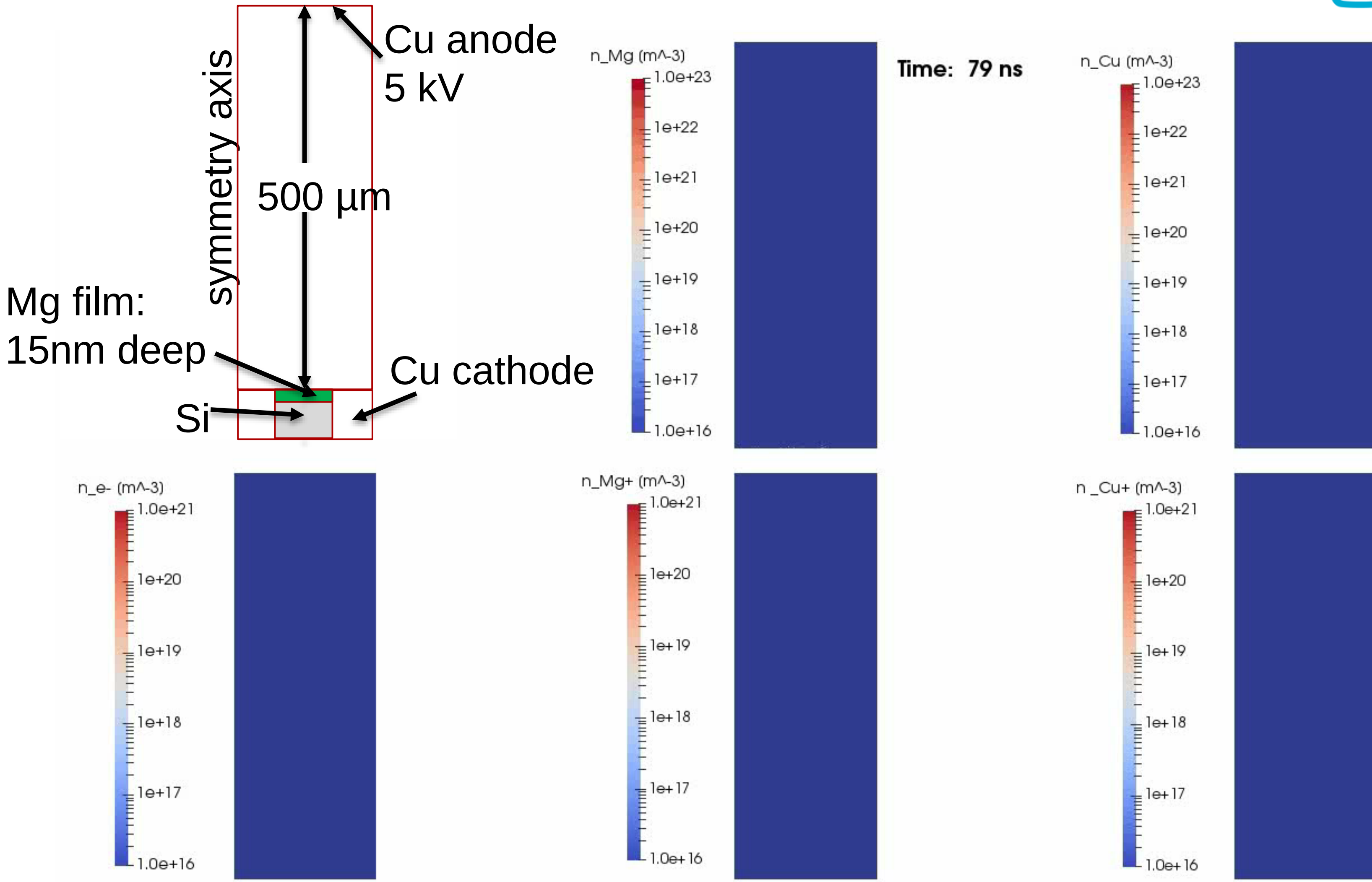
- Fast neutrals produced from cathode emission stream across gap and sputter significant anode electrode material *before* breakdown
  - We don’t expect early-time anode sputtering if we emit fast ions (~50eV)

Results: Explosive Neutrals



- Still have significant anode sputtering due to fast neutral collisions as “cloud” of sublimated (slow) film material is relatively collisionless

Results: Explosive Plasma



- Influx of quasi-neutral plasma near the cathode should exclude the applied field ⟶ mobile e^- charge separation drags ions to the anode
  - But this doesn't happen… why? Likely due to how Aleph handled the influx BC

Conclusions

- Developing model for Triggered Vacuum Spark Gaps. Includes:
  - External circuit with collapsing parallel plasma resistance to get film current
  - 1D joule heating model determines surface temperature
    - e^- flux based on Murphy-Good
    - Neutral flux based on sublimation
- Not surprisingly, ion-induced SEE yield matters for breakdown
  - Desirable to have film with high SEE yield on the cathode → $E_{iz,film} > \phi_{cathode}$
- If fast neutrals (~20 km/s) produced from cathode emission then significant anode electrode material can be sputtered *before* breakdown

- Future (potential) improvements:
  - Couple external circuit & material supply model to PIC-DSMC simulation
  - Better model for what happens when $T_{film} > T_{boiling}$
    - Species and velocity distribution?
  - Better cross section (e.g., Mg^{++}) and ion-induced SEE data