Study of a low-pressure high voltage switch triggered by laser-surface interaction

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Principal of Operation

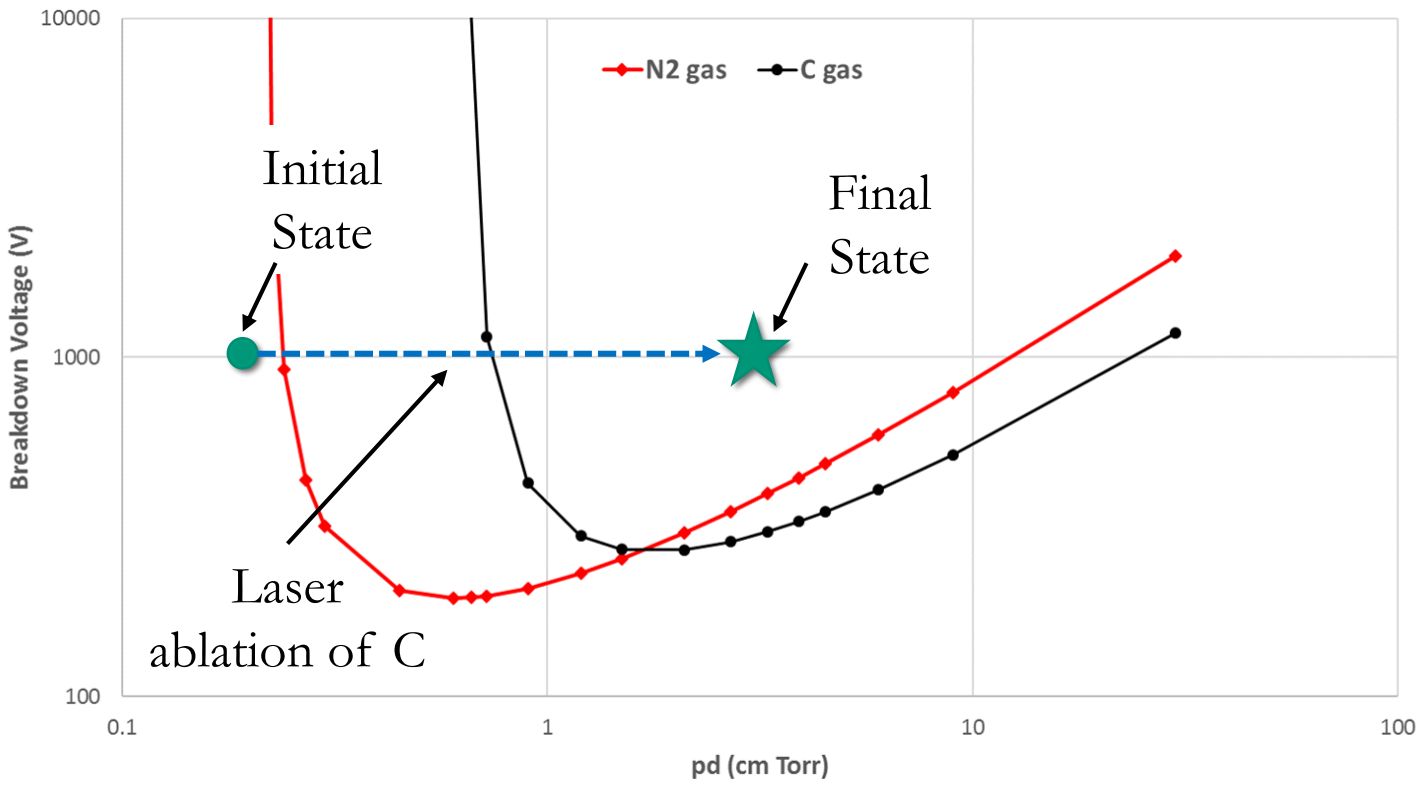
Start with an initial density of gas, in this case N_2.

- Operate on the left side of the Paschen curve – High voltage, no breakdown operation

Injection of material into the electrically stressed gap increases the pressure

- Move the right hand side of the Paschen curve where a conducting channel is formed

Currently unclear: the interplay between the two neutral species. The "mixed" Paschen curve.

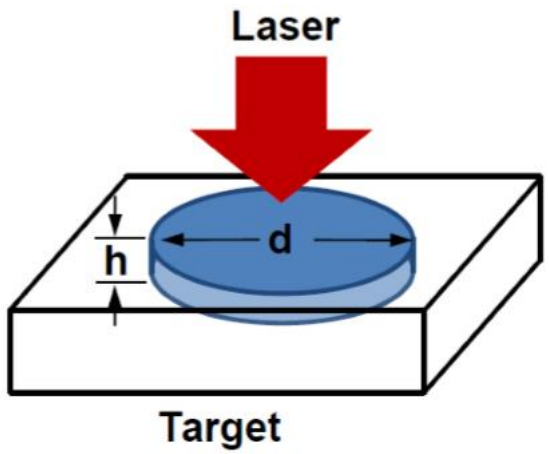


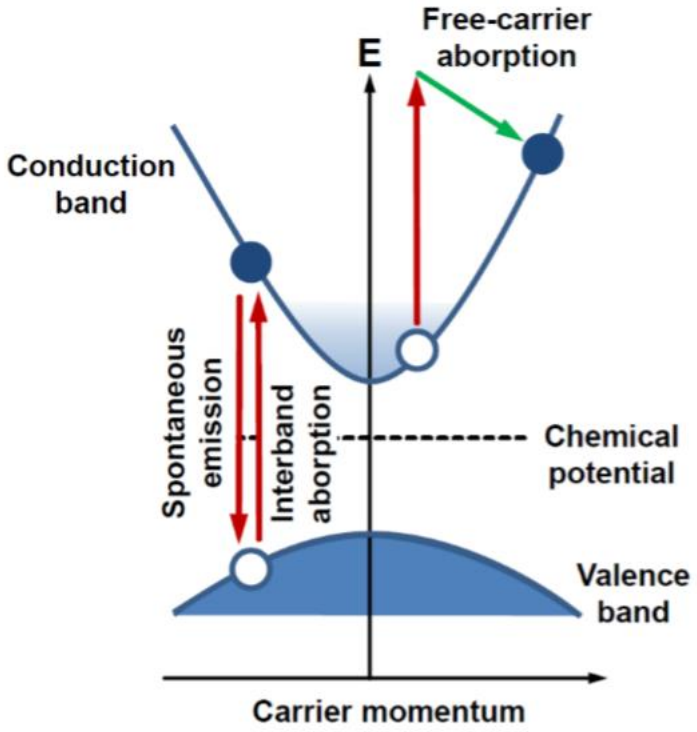
Simulated pure nitrogen and carbon Paschen curves

Laser-Surface Model

Model the material ablation due to laser heating of the solid by tracking dynamics of electron and hole populations in momentum resolved conduction- and valence-band states.

- Include optical transitions: absorption, emission, and free-carrier absorption
- Include carrier-carrier and carrier-phonon scattering
- Scattering results in lattice heating and target material ablation





2D Simulation Model

Utilize a 2D simulation model with hemispherical electrodes, radius of 10 mm.

Initial low pressure (1 torr) background gas of N_2

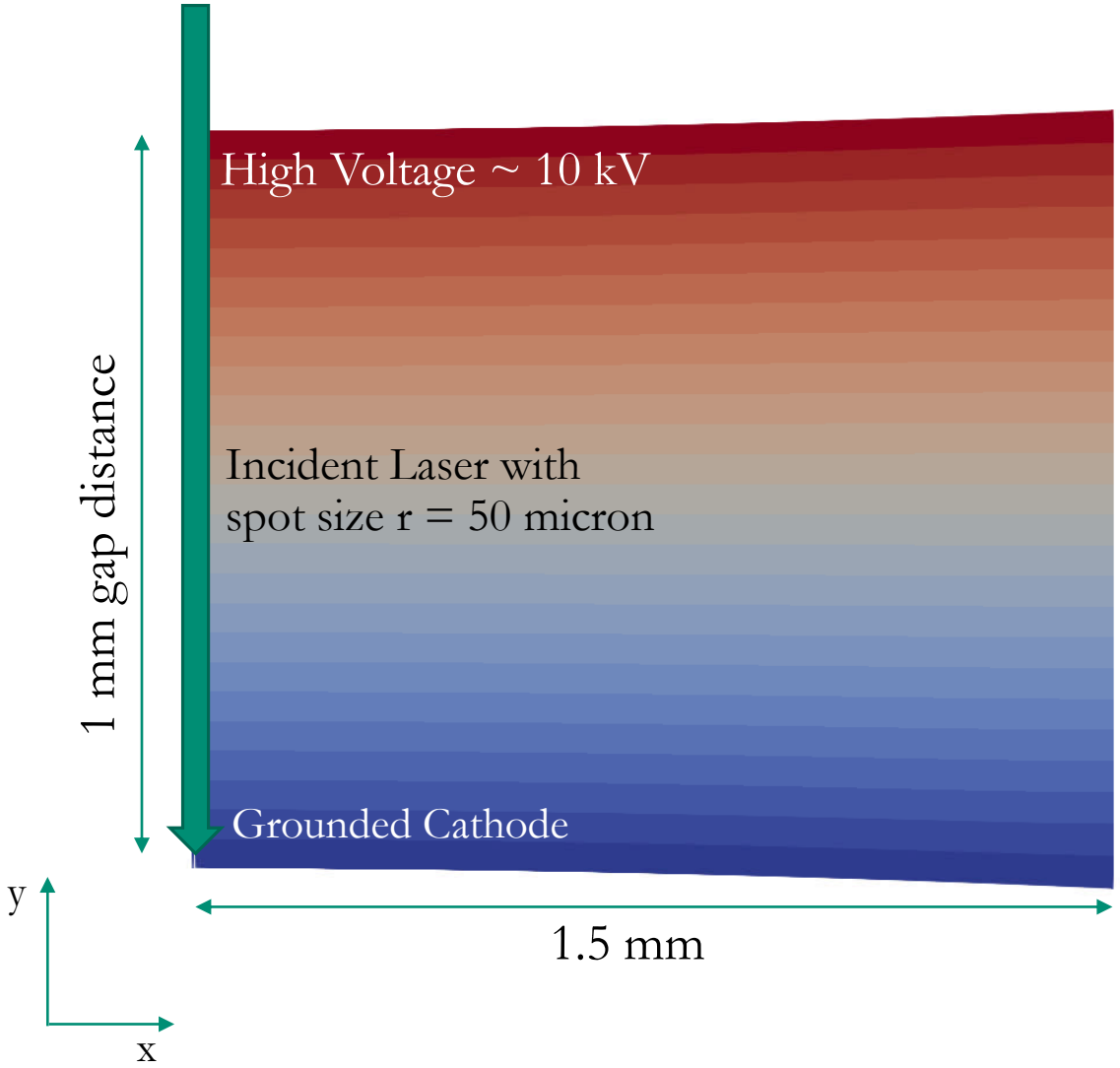
Laser is incident upon a Carbon target material

- Cathode also serves as source of new electrons via secondary electron emission due to ion impact

Mesh resolution of approximately dx = 250 nm on axis

No laser-gas interaction

Limitation: The species injection model is only dependent on the laser influx and not coupled to the transient plasma model. Thus, there is no feedback between injection fluxes and the developing plasma.



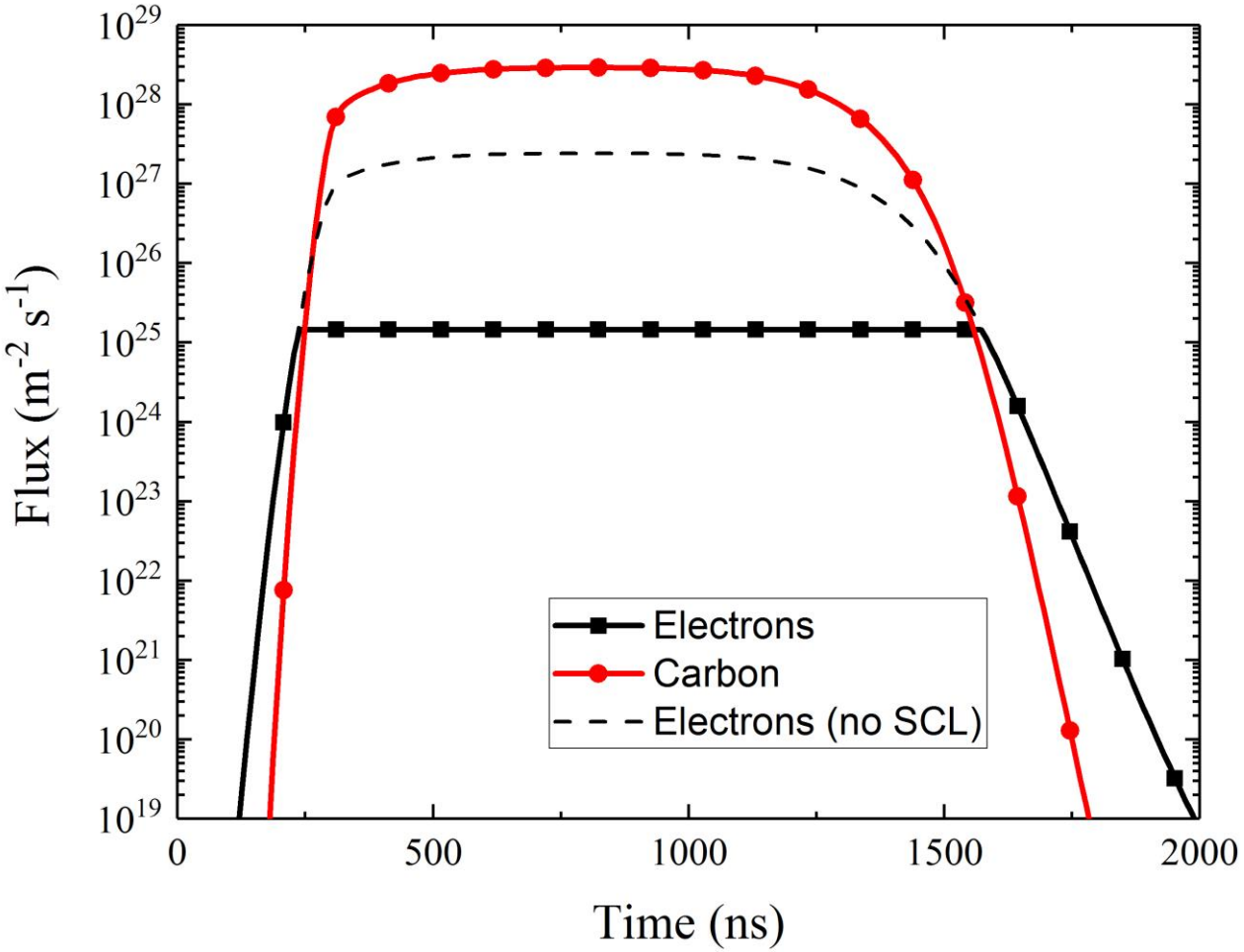
Injection Fluxes

Laser parameters

- 500 mW – peak power (60 MW/m^2)
- 1064 nm, monochromatic
- ~1 microsecond FWHM

Laser injection model and plasma model are decoupled leading to very large electron fluxes above the space charge limit.

- At the applied voltage (10 kV) and gap distance (1mm), limit is approximately 10^{25} m^{-2} s^{-1}.
- Enforce the SCL limit at this flux.



Chemistry Set

Electron-neutral collisions (elastic, inelastic, ionization)

- e- + N_2 → products
- e- + N → products
- e- + C → products

Ion-neutral charge exchange

- $N_2 + N_2^+ \rightarrow N_2^+ + N_2$

Heavy-body reactions

- N_2 + C
- $N_2 + C^+$
- N_2^+ + C

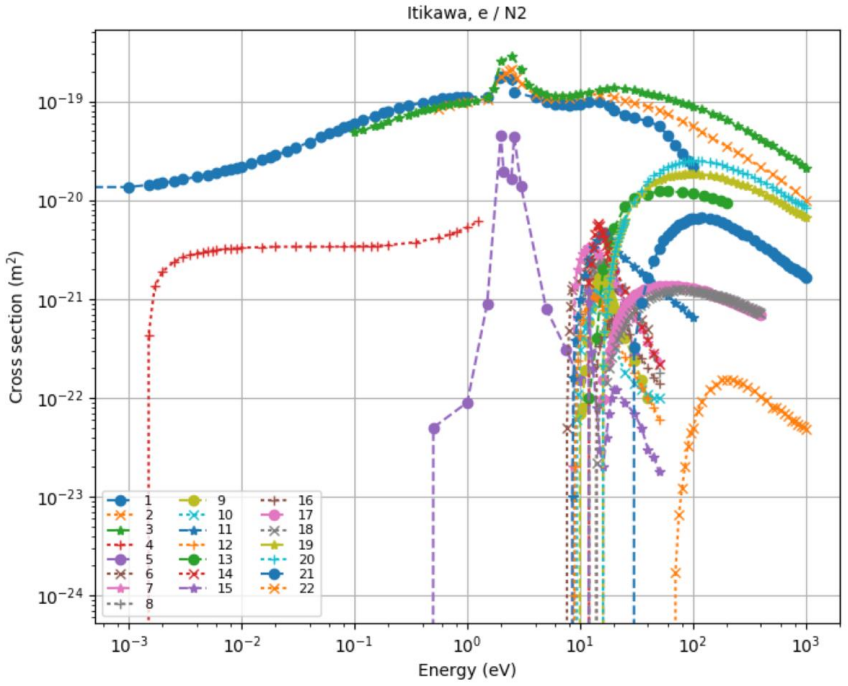
Spontaneous Emission

- $N_2^* \rightarrow N_2$ + photon

Total of about 150 reactions

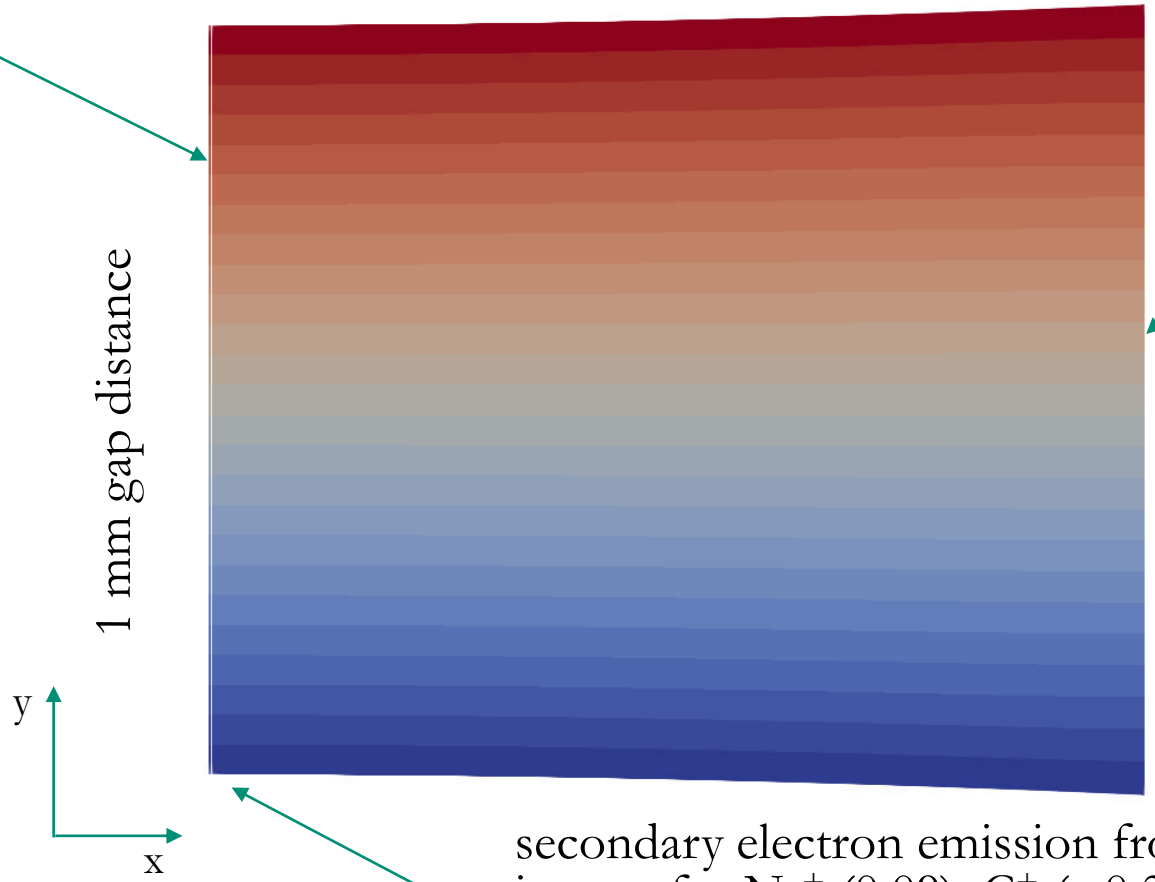
Species	Product	E (eV)
C	**C***	**1.26**
C	**C***	**2.68**
N_2	A $^3\Sigma_u^+$, v=0-4	6.17
N_2	A $^3\Sigma_u^+$, v=5-9	7.00
N_2	B $^3\Pi_g$	7.35
N_2	W $^3\Delta_u$	7.36
N_2	A $^3\Sigma_u^+$, v=10-v_{max}	7.80
N_2	B' $^3\Sigma_u^-$	8.16
N_2	a' $^1\Sigma_u^-$	8.40
N_2	a $^1\Pi_g$	8.55
N_2	w $^1\Delta_u$	8.89
C	**C^+**	**10.60**
N_2	C $^3\Pi_u$	11.03
N_2	E $^3\Sigma_g^+$	11.88
N_2	a'' $^1\Sigma_g^+$	12.26
N_2	b $^1\Pi_u$	12.50
N_2	c'$_4$ $^1\Sigma_u^+$	12.85
N_2	b' $^1\Sigma_u^+$	12.94

Itikawa dataset from LxCAT.net



Particle Boundary Conditions

reflection for all particle types on axis.



outflow boundary for all particle types

secondary electron emission from ion impact for N_2^+ (0.09), C^+ (~0.3), N^+ (0.07)

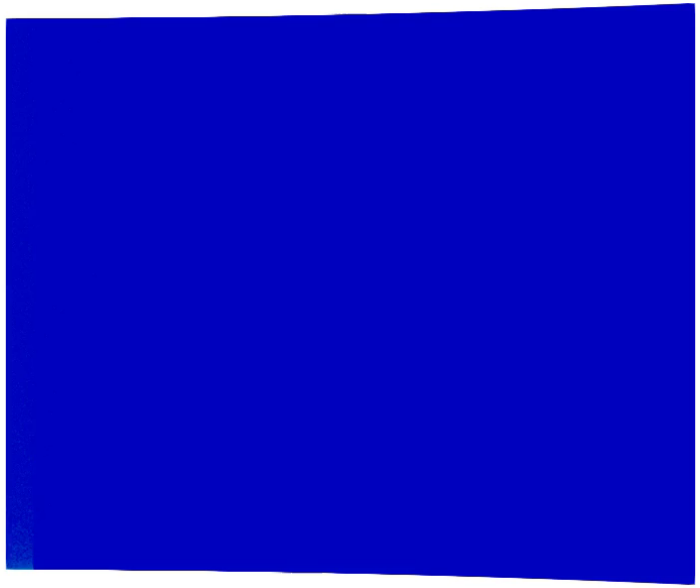
Sputtering of C for C and C+ impact

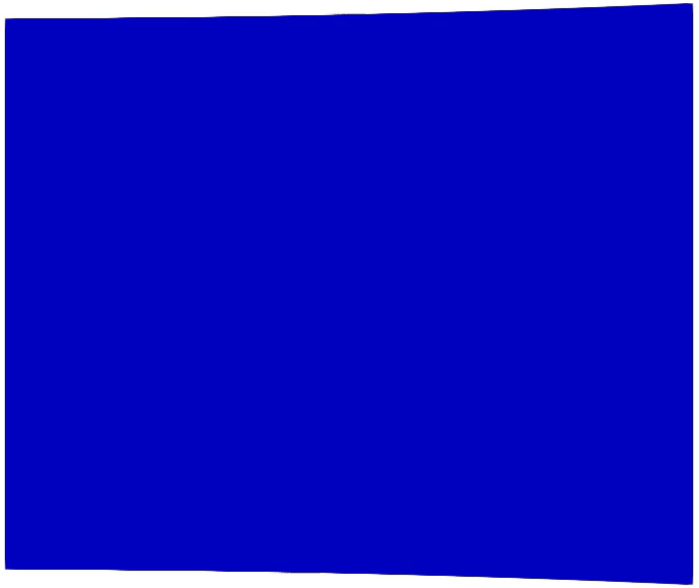
Temporal Electron and Carbon Density

Time: 125.00 ns

Electron density

$10^{12} – 10^{20}$ m^{-3}





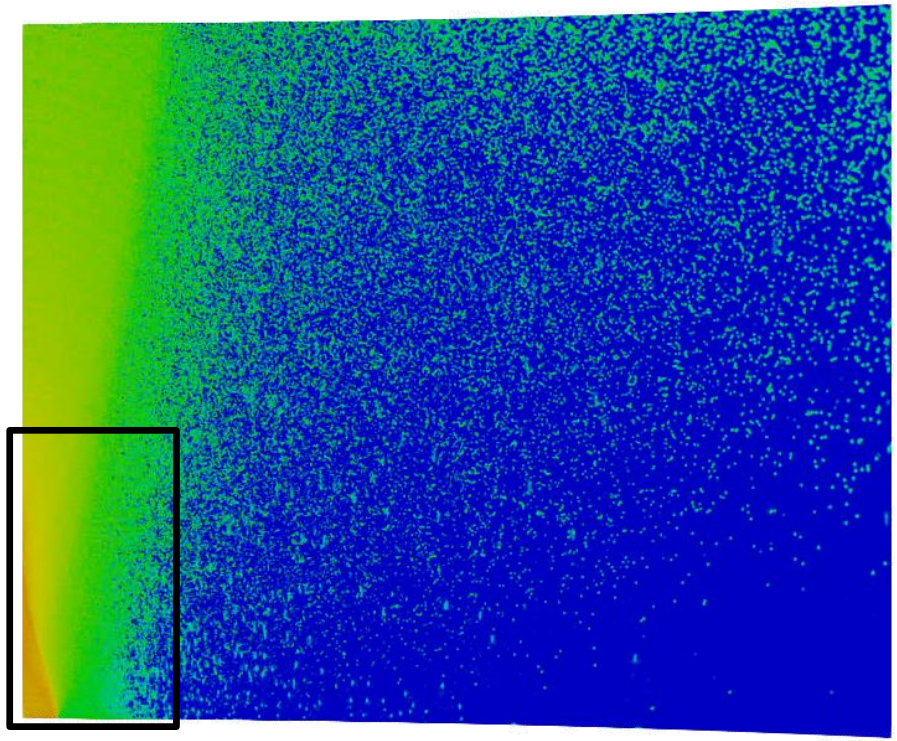
Carbon density

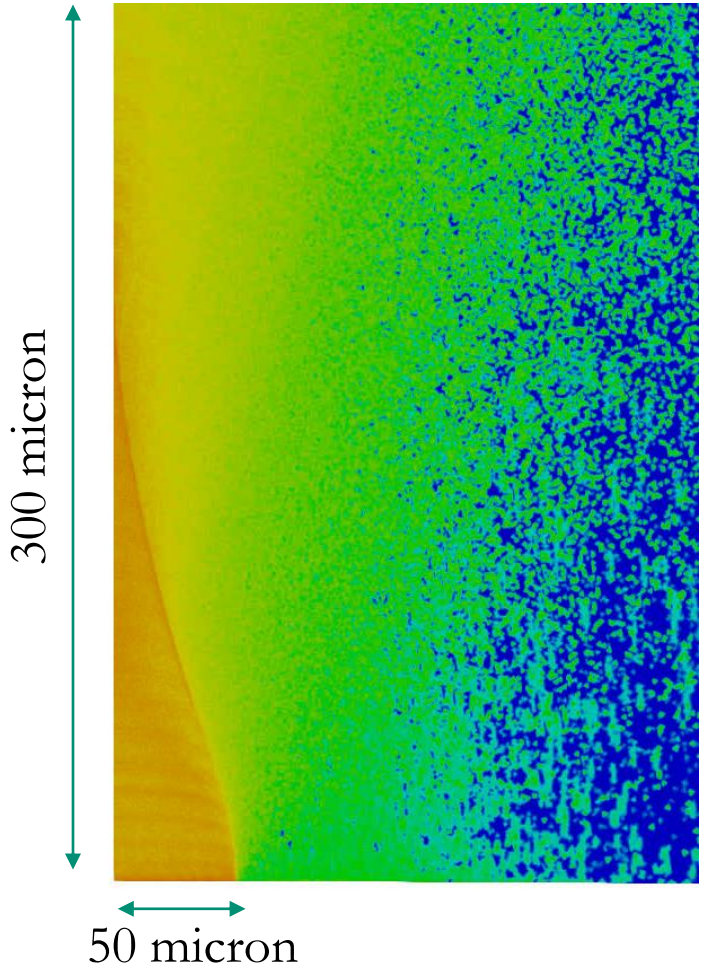
$10^{14} – 10^{22}$ m^{-3}

Electron Funneling Effect

Electron Density

t = 300 ns

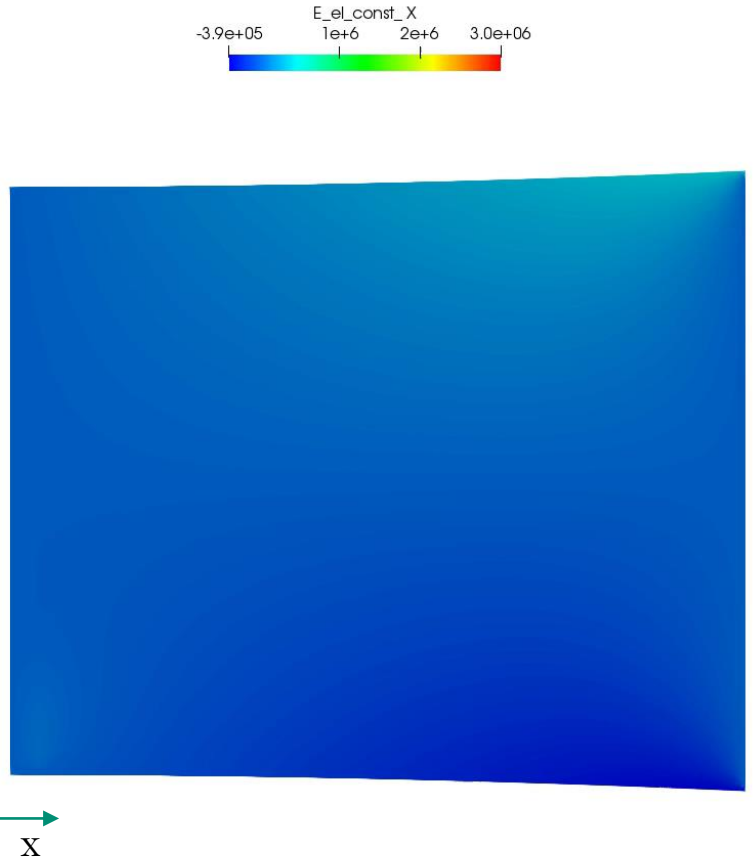




A funneling effect of electrons begins to appear as the electron density is increasing on-axis.

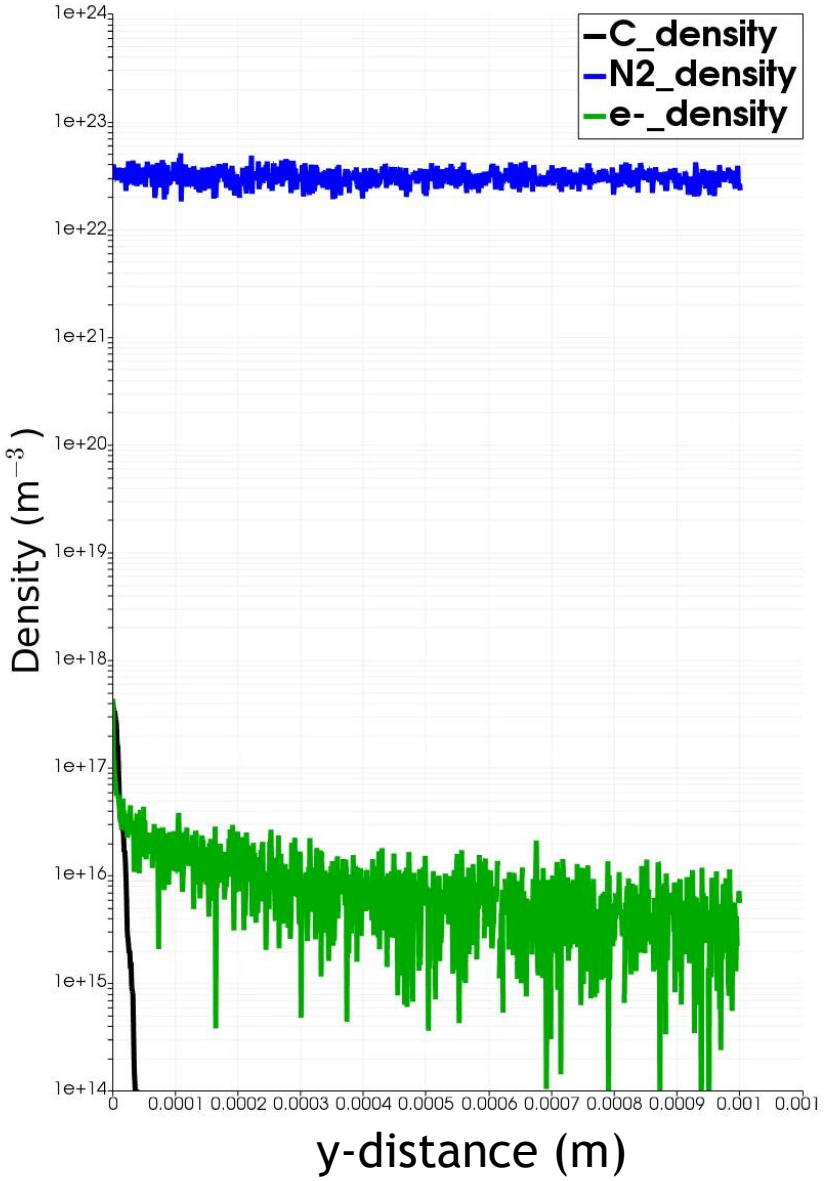
Electron Funneling Effect

Time: 195.25 ns



Electric Field in X-direction,

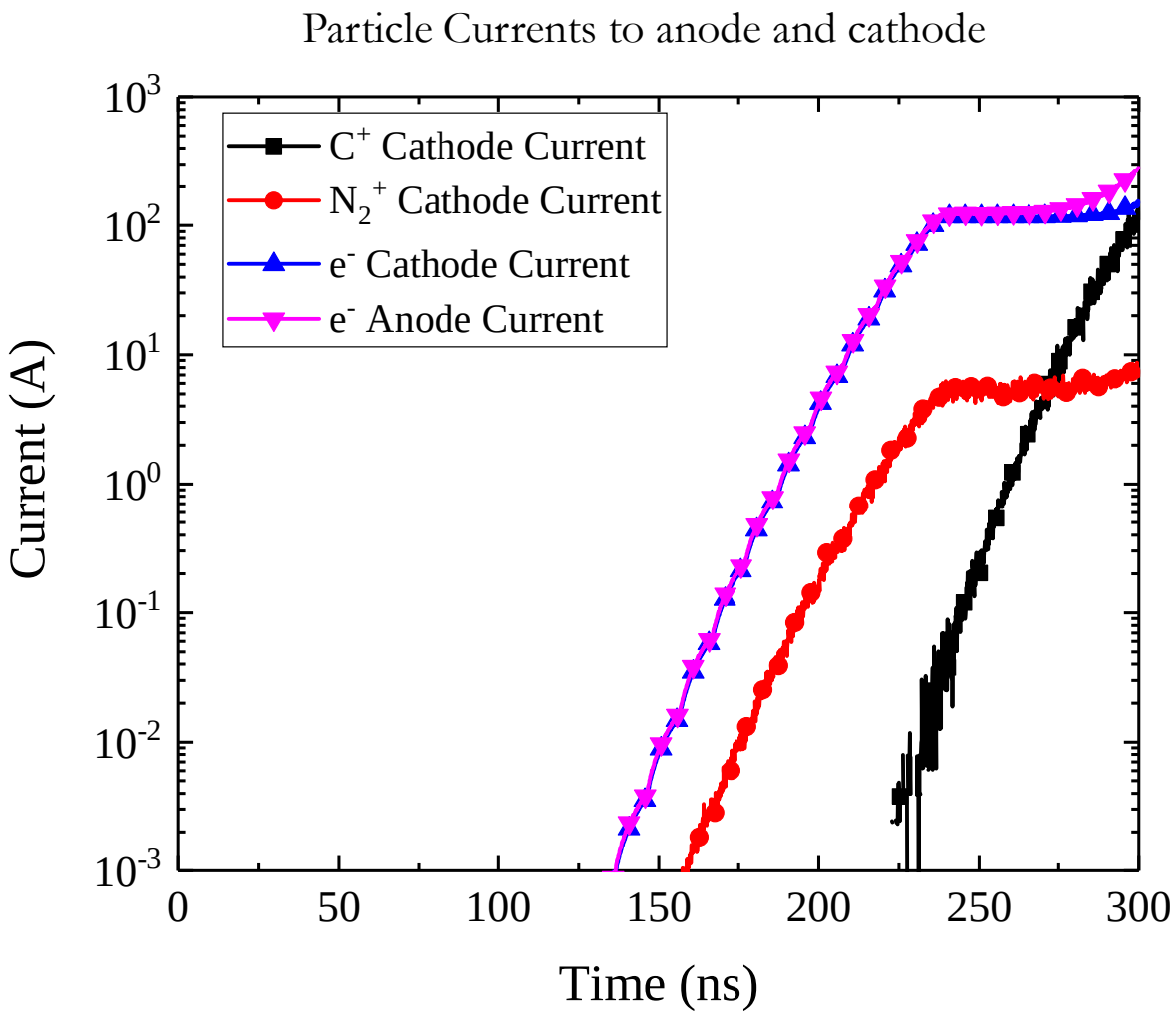
Red = positive (electrons move towards center axis)

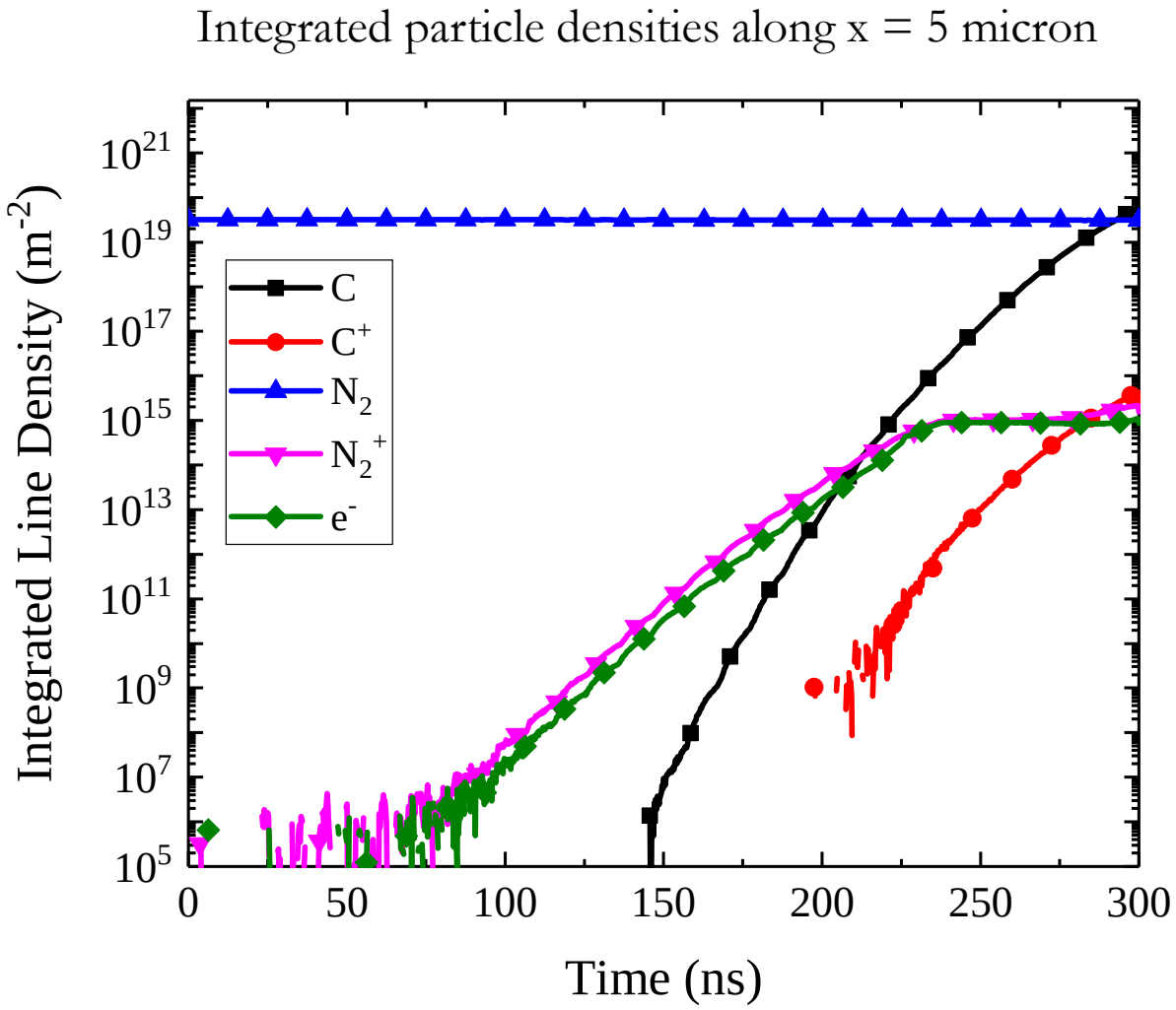


Line densities at x = 5 micron

DSMC needed to model the shock formation

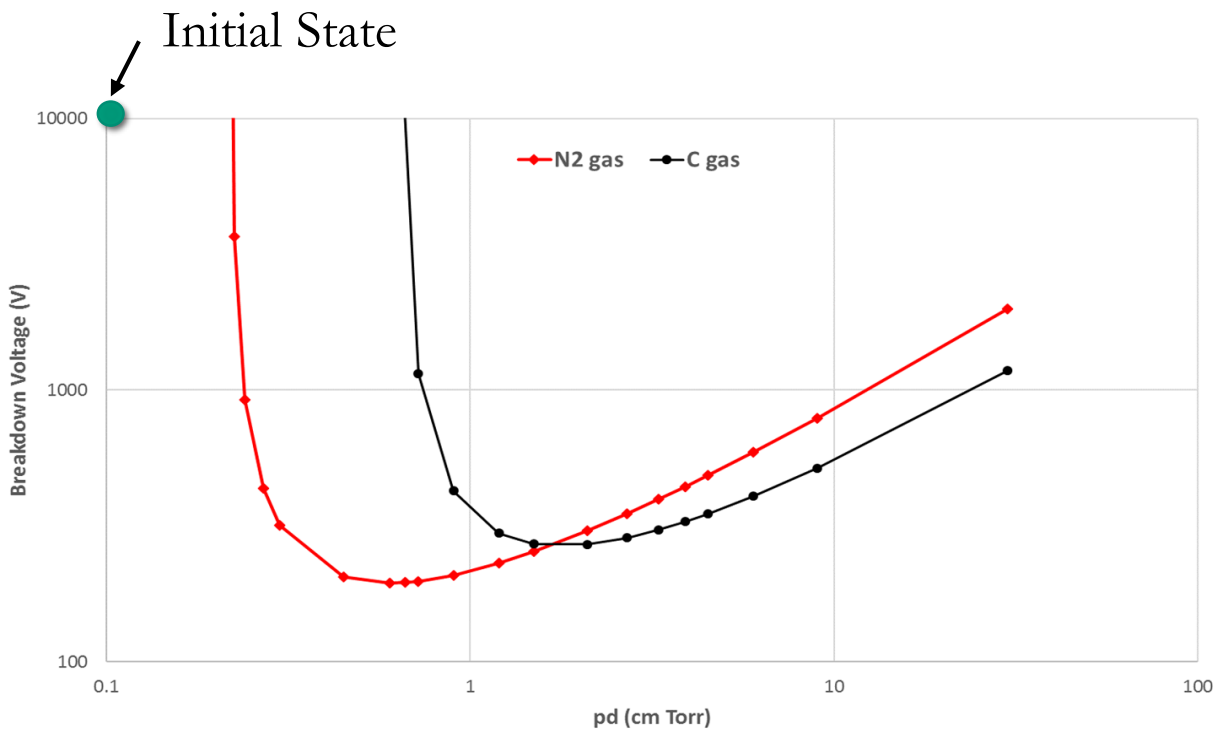
Cathode and Anode Currents





Where did we end up

10 kV and a gap distance of 1 mm yields a *pd* of 0.1 cm-torr



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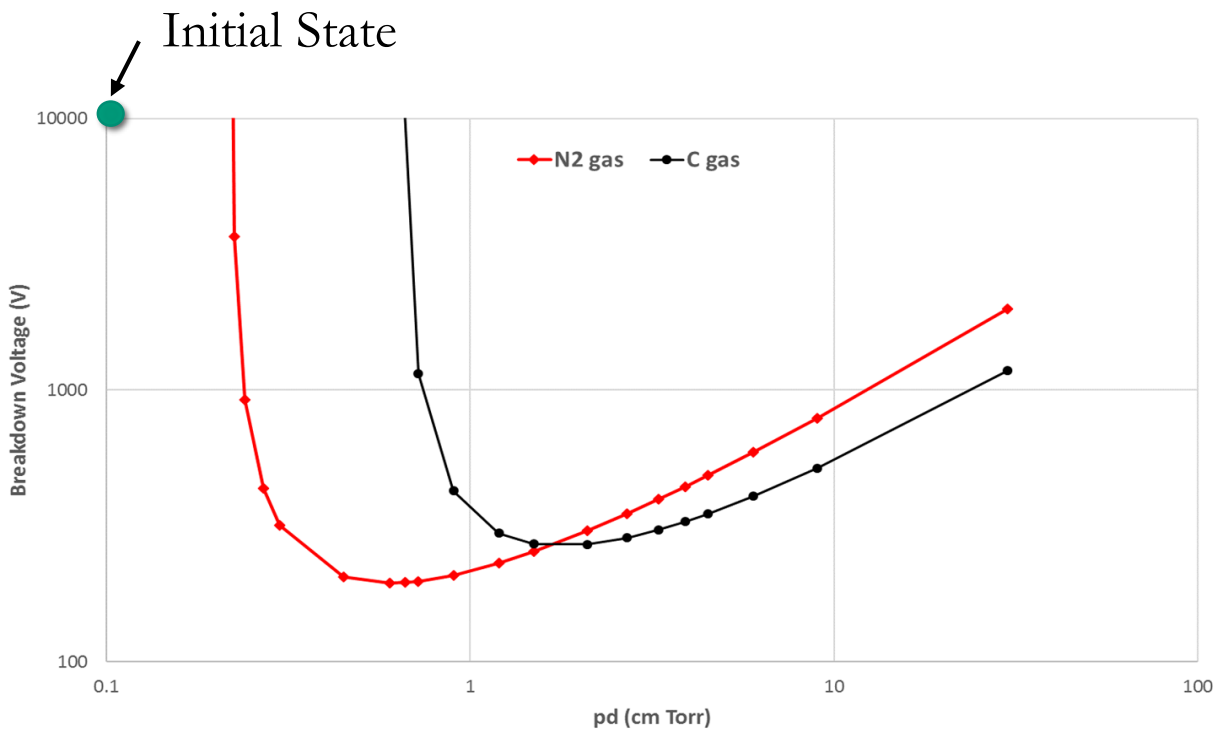
What is the *pd* when breakdown starts occurring?



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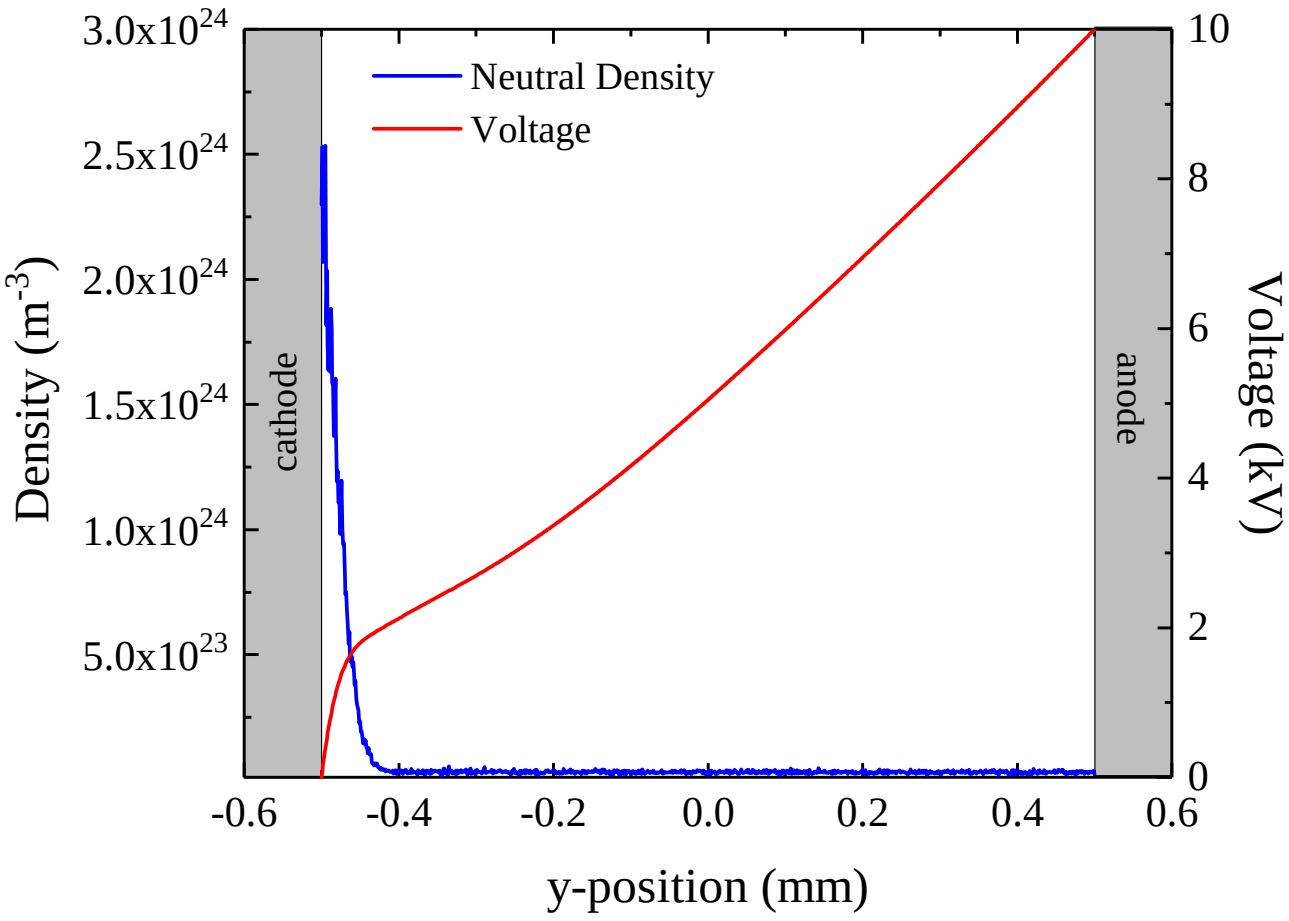
Line out of Neutral Density and Voltage along x = 5 micron, t = 300 ns



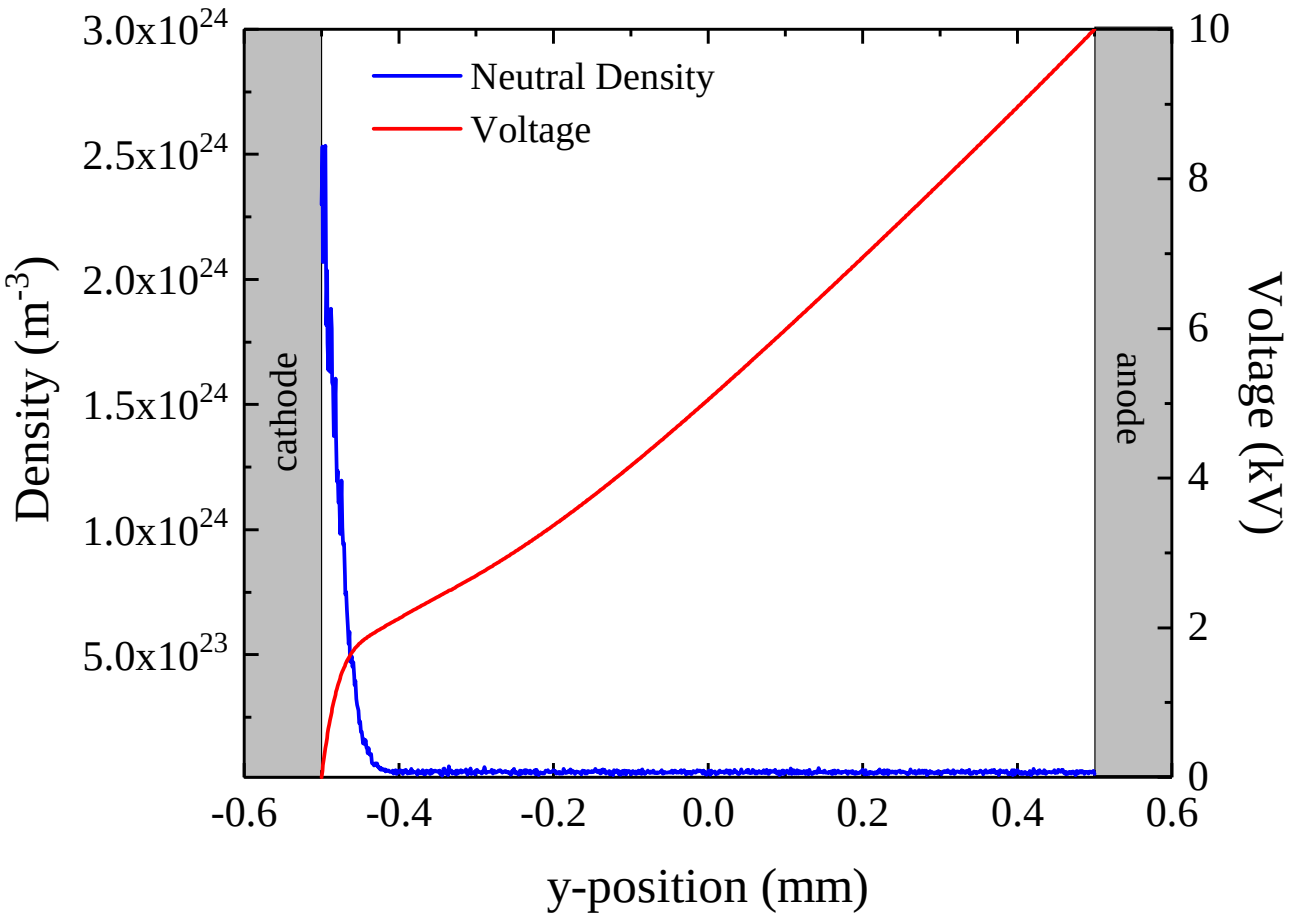
Where did we end up

10 kV and a gap distance of 1 mm yields a *pd* of 0.1 cm-torr

What is the *pd* when breakdown starts occurring?

Take the average of the density from -0.5 mm to -0.42 mm, distance of 80 micron. ~1.3 x 10^{24} m^{-3}

Line out of Neutral Density and Voltage along x = 5 micron, t = 300 ns



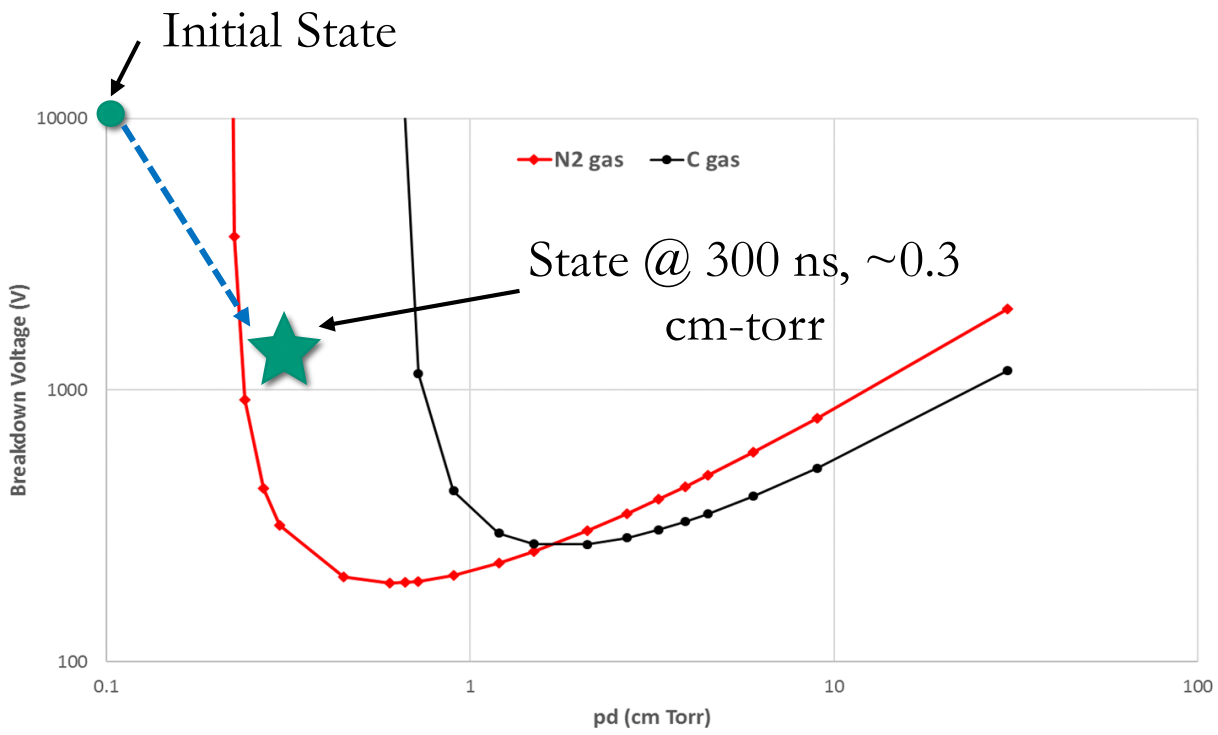
Where did we end up

10 kV and a gap distance of 1 mm yields a *pd* of 0.1 cm-torr

What is the *pd* when breakdown starts occurring?

Previous analysis yields a *pd* of approximately 0.3 cm-torr @ ~1500 V.

However, most of the neutral species is Carbon, which according to our curve should not break down.



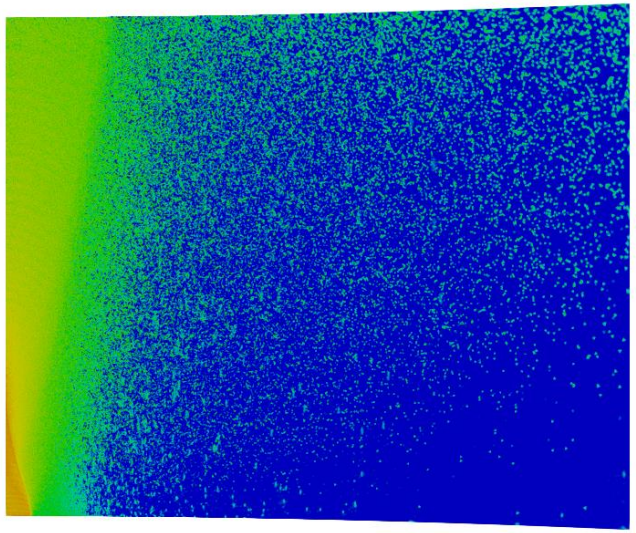
Simulated pure nitrogen and carbon Paschen curves

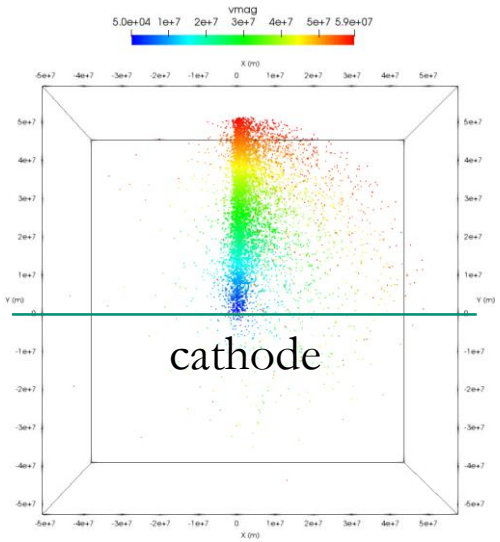
Conclusions

Developed a laser-surface interaction model that is used as input to a plasma transient simulation. Future work will include coupling between the two such that the results are self-consistent.

Have shown with modeling that laser injection of electrons and neutrals leads to increase in plasma densities although it still seems that the switch is below the breakdown threshold.

Electron Density @ t = 300 ns





EVDF showing the electron injection beam @ t = 120 ns

An electron funneling effect towards the center of the simulation was observed and attributed to an increase in electric field as the x-coordinate increases.