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Streamer Formation Near a Dielectric Surface with Variable Quantum Efficiency

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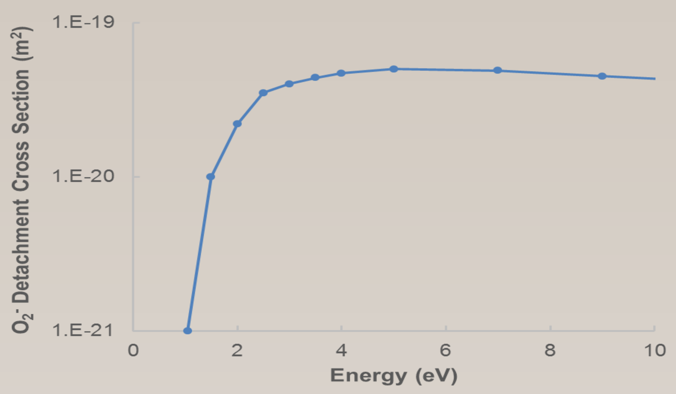
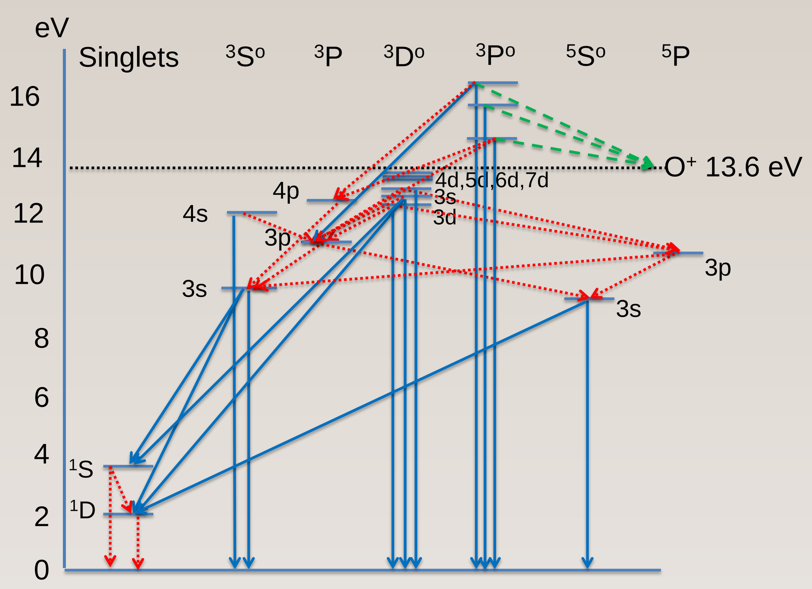
Abstract

Streamer formation near a dielectric surface is modeled using an electrostatic particle-in-cell (PIC) code which simulates particle-particle collisions using the direct simulation Monte Carlo (DSMC) method. The domain is over-volted and the anode potential is held at 8 kV DC. A 1 eV 50 µm x 50 µm initial plasma density of 10^{20} m^{-3} is used to seed the simulation domain in the presence of an atmospheric neutral background gas mixture. The air chemistry model [1] includes standard Townsend breakdown mechanisms (electron-neutral elastic, excitation, ionization, attachment, and detachment collision chemistry and secondary electron emission) as well as streamer mechanisms (photoionization and ion-neutral collisions) via tracking excited state neutrals which can then either quench via collisions or spontaneously emit a photon based on transition-specific Einstein-A coefficients [2, 3]. The current simulation is a preliminary study of streamer formation at early times both in the absence and presence of secondary electron emission due to photon bombardment at a nearby dielectric surface that spans the gap between electrodes. Initial results suggest that photoemission can significantly effect the streamer evolution along the dielectric and that *elevated* reduced electric field (E/n) near the dielectric surface plays a decisive role in the initial streamer profile and preferred path of propagation.

Air and Dielectric Model

- Details can be found in [1]
- Assume N_2 and O_2 are dominant species for heavy-heavy interactions. Model dry air and neglect N–N, N – O, and O – O interactions.
  - Include elastic (VHS), charge exchange, and quenching heavy-heavy interactions
- Include e-N_2^+ and e-O_2^+ dissociative recombination
- Include O_2^- + M detachment via cross section [5]
  - Self-consistently leads to higher detachment rate in high-field regions
- e-neutral interactions included for N_2, O_2, N, O and metastable states. Use anisotropic scattering model for all electron-neutral collisions.
  - Elastic
  - Ionization: Single (ground and metastable states), double, and dissociative
  - Attachment (3-body and Dissociative)
  - Vibrational and rotational excitation
  - Electronic excitation
- Excited states have probability to radiate a photon based on transition-specific Einstein-A coefficients, quench via collision (assumed P_{quench} = ½) with background neutrals, or, in some cases, auto-dissociate or auto-ionize with state-specific rate
- Photons are modeled as discrete particles that move and stochastically collide through a simulation timestep just like all other particles
- Field solve accounts for relative permittivity
- Two cases of secondary electron emission from the dielectric surface are modeled due to photon bombardment: 0.0 and a constant energy independent value of 0.1



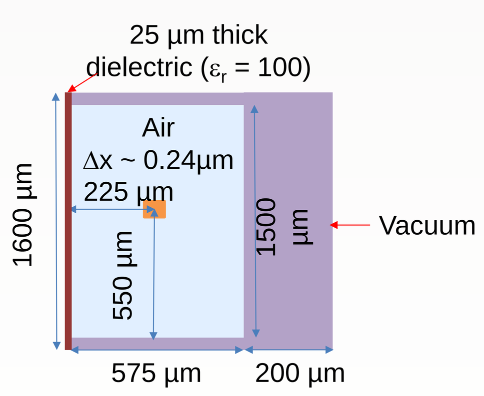


Modeled energy level and transition diagram for atomic O ($^3D^o$ transitions omitted for clarity). Solid blue lines represent radiative decay in which simulation photons are generated. Red dotted lines represent decay in which a simulation photon is not generated. Green dashed lines are auto-ionizing states.

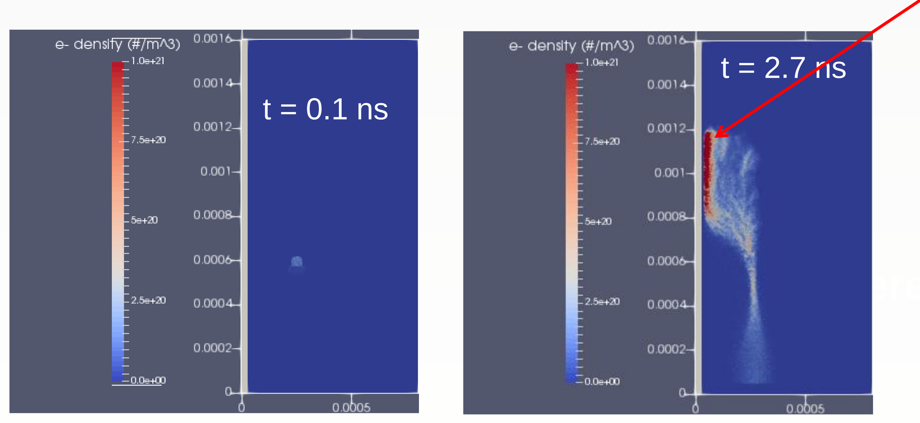
Initial Plasma Seed Model

- 2D simulation of a 760 Torr 1.5 mm air filled gap surrounded by vacuum, with a 25 µm thick TiO_2 (ε_r = 100) cylinder between electrodes
- Initial seed plasma density modeled as the following:
  - $T_e = T_i$ = 11,600 K and n_e =10^{20} m^{-3}
  - 50 µm^2 square centered at 225 µm radially from dielectric surface and 550 µm axially from bottom vacuum interface
  - An over-volted state (8 kV anode voltage) that allows for rapid evolution of the streamer

Simulation Domain - Model



Full Simulation Domain – Illustrative Data

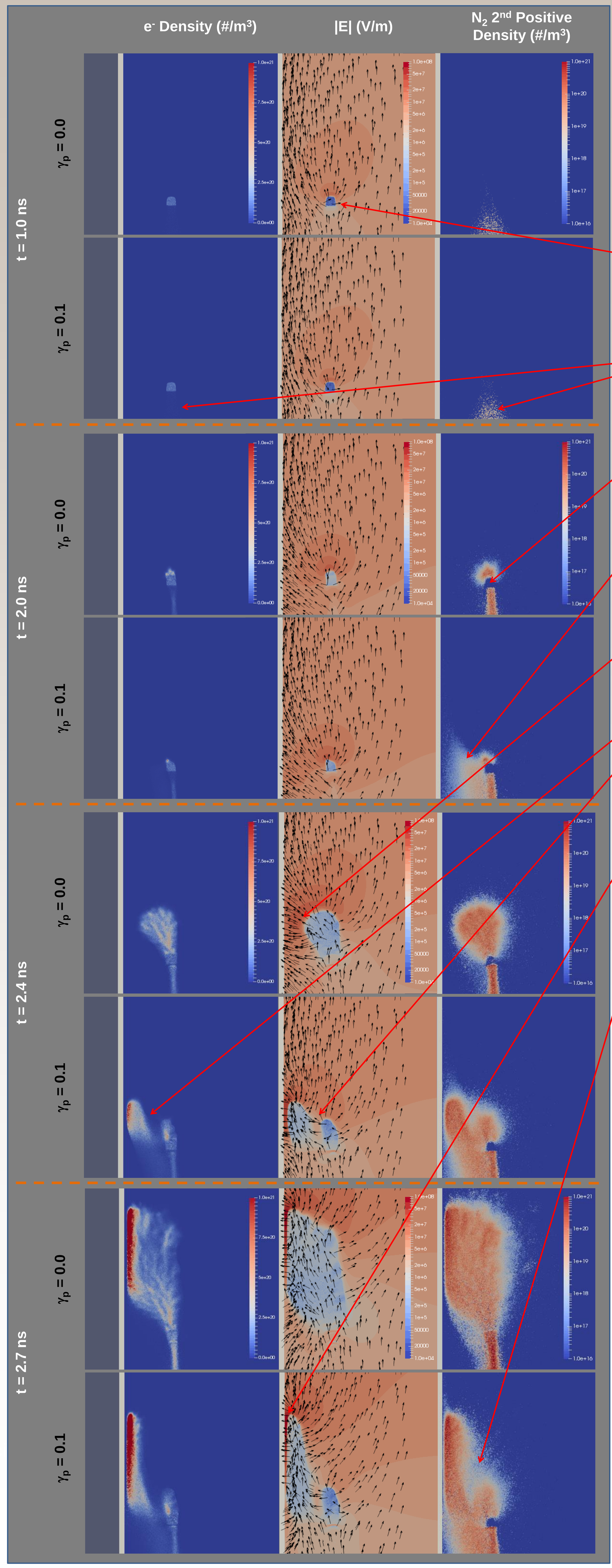


γ_p = 0.0 cases shown

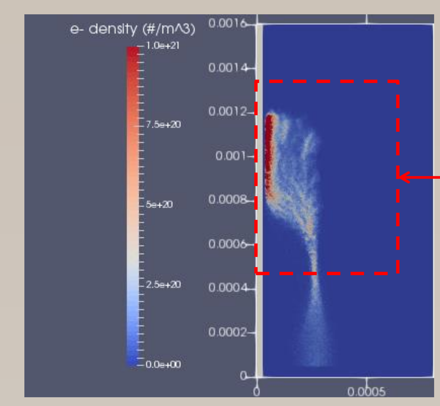
Plasma Parameters

λ_D (µm)	~0.1
λ_e (µm)	~0.37
λ_p (µm)	~33
f_{pe} (GHz)	~90
ν_{en} (THz)	~2.7

Time Evolution – Particle/Field Distributions



Results and Discussion



Zoomed region in time evolution of particle densities and field distributions (on left)

- 8 kV DC anode voltage (bottom electrode)
- A quasi-neutral plasma seed density results in E-field exclusion within this region
- Black arrows overlaying |E| field plots represent direction of the local E-field – they are not vector field plots
- The N_2 2nd positive density (on a log scale) in regions of *apparently* negligible electron density (on a linear scale) is simply an artifact of scaling
- With the exception of the 0.0 quantum yield case at 2.7 ns, the N_2 2nd positive density remains essentially zero at the location of the original plasma seed density
- At 2 ns, an increase in the N_2 2nd positive density emerges near the surface of the dielectric for the 0.1 quantum yield condition, as a result of photoemitted electrons streaming back to the now ion-rich initial seed plasma region
- At 2.4 ns, various interesting phenomena begin to take form:
  - electrons approaching the dielectric see an elevated E/n near its surface, resulting in an increase in Townsend's first ionization coefficient, α = f(E/n), and the number of ionizing events, even in the absence of surface quantum yield
  - The elevated surface E/n near the tip of the streamer *attracts* a larger density of electrons, expanding the E-field exclusion region
  - An apparent splitting of the E-field exclusion region occurs in the quantum yield case, resulting in two distinct cathode directed streamers – one growing from the original plasma seed due to elevated near surface E/n (0.0 photon yield), and the other from increased electron and photoionization events (0.1 photon yield)
- At 2.7 ns, the following are observed:
  - The E-field exclusion region for the zero quantum yield case has grown considerably
  - The streamer near the dielectric surface is expanding at a faster rate than the initial plasma seeded streamer due to the significantly larger E-field at the streamer head
  - The N_2 2nd positive density exhibits two distinctly disproportionate branches in sync with streamer growth

Conclusions / Future Work

- Increased E/n near dielectric results in amplification of Townsend's first ionization coefficient, α = f(E/n), preferentially directing streamer growth near surface even under conditions of zero quantum yield
- Competing processes may be occurring in the presence of photon emission from the dielectric, as the streamer near the dielectric appears to be starving growth of the initial plasma seeded streamer
- Place seed plasma density at varying distances from the dielectric surface to investigate the effect on streamer formation and growth
- Examine the influence of varying magnitudes of quantum yield on streamer formation and growth
- Increase the number of samples to perform statistical analysis

References

[1] C. Moore *et al.*, "Development of Kinetic PIC-DSMC Model for Breakdown in the Presence of a Dielectric", ICOPS, Banff, 2016

[2] C. Moore *et al.*, "Development and Validation of PIC/DSMC Air Breakdown Model in the Presence of Dielectric Particles," Pulsed Power Conference, Austin, TX, 2015.

[3] A. Fierro *et al.*, "Discrete Photon Implementation for Plasma Simulations," Physics of Plasma, 23, 013506, 2016.

[4] H. Hjalmarson *et al.*, "Calculations of Photoemission from Rutile," APS Meeting, San Antonio, TX, 2015.

[5] A. Ponomarev and N. Aleksandrov, "Monte Carlo simulation of electron detachment properties for O_2^- ions in oxygen and oxygen:nitrogen mixtures," PSST **24**, 035001, 2015.

[6] S. Feathers, A. Fierro, S. Beeson, J. Stephens, A. Neuber, "Fundamental investigation of microsecond breakdown near a high permittivity dielectric," IEEE International Pulsed Power Conference, Austin, TX, 2015.

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