Streamer Evolution Near a Dielectric Surface with Variable Permittivity

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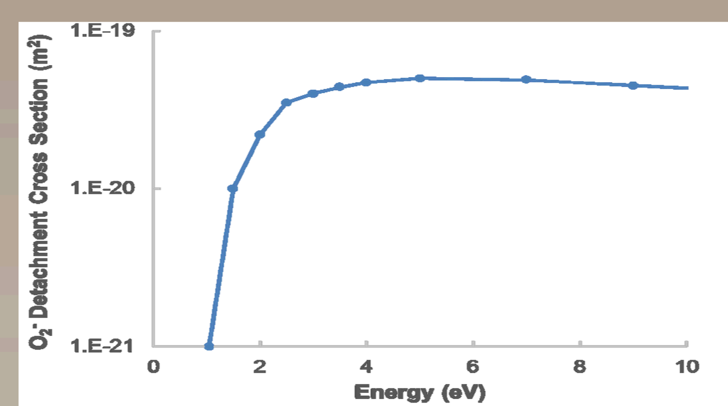
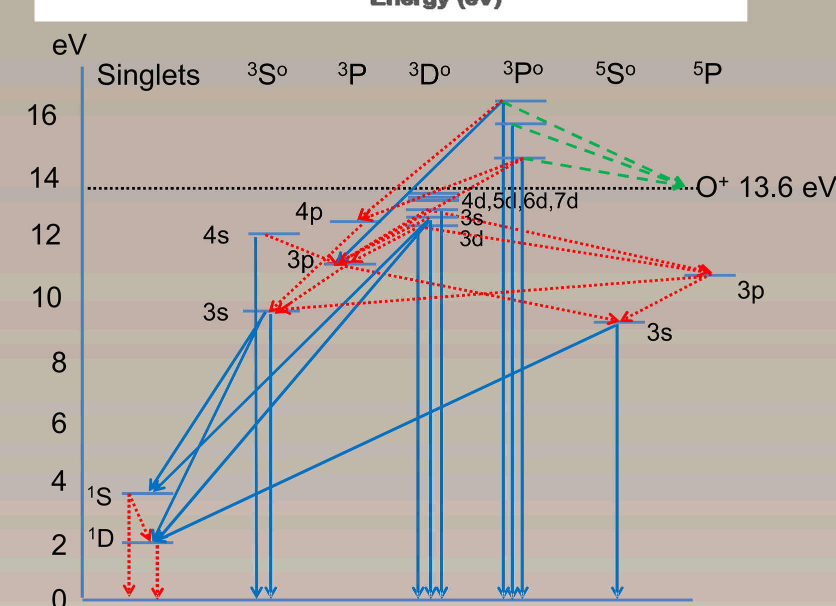
Abstract

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 10 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 near a dielectric surface of variable permittivity that spans the gap between electrodes. Initial results suggest that increasing the dielectric permittivity can significantly effect the streamer evolution along its surface due to the resulting *elevated* reduced electric field (E/n), with the functional dependence of E on ε_r described using charge image theory [4]. The strong relationship between E/n and Townsend's first ionization coefficient plays a decisive role in the 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 relative dielectric permittivity, ε_r, are modeled: ε_r = 1 and 100.



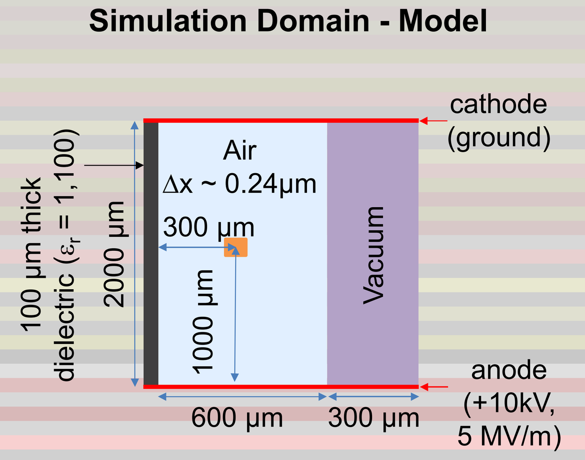


Modeled energy level and transition diagram for atomic O ($^3D^o$ transitions omitted for clarity). Solid blue lines represent radiative decay in which simulation photons are generated. Red dotted lines represent decay in which a simulation photon is not generated. Green dashed lines are auto-ionizing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

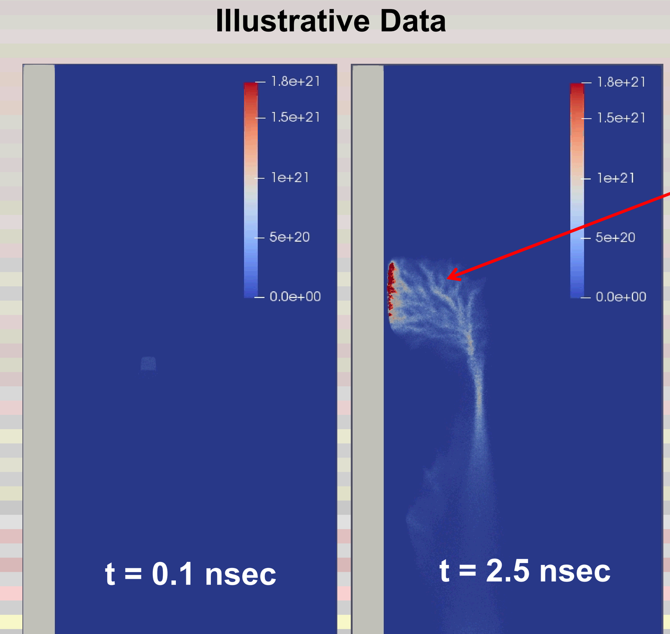
Initial Plasma Seed Model

- 2D simulation of a 760 Torr 2 mm air filled gap surrounded by vacuum, with a 100 μm thick TiO_2 (ε_r = 1 and 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 300 μm radially from dielectric surface and 1000 μm axially from bottom anode interface
  - An over-volted state (10 kV anode voltage, |E| = 5 MV/m) that allows for rapid evolution of the streamer

Simulation Domain - Model



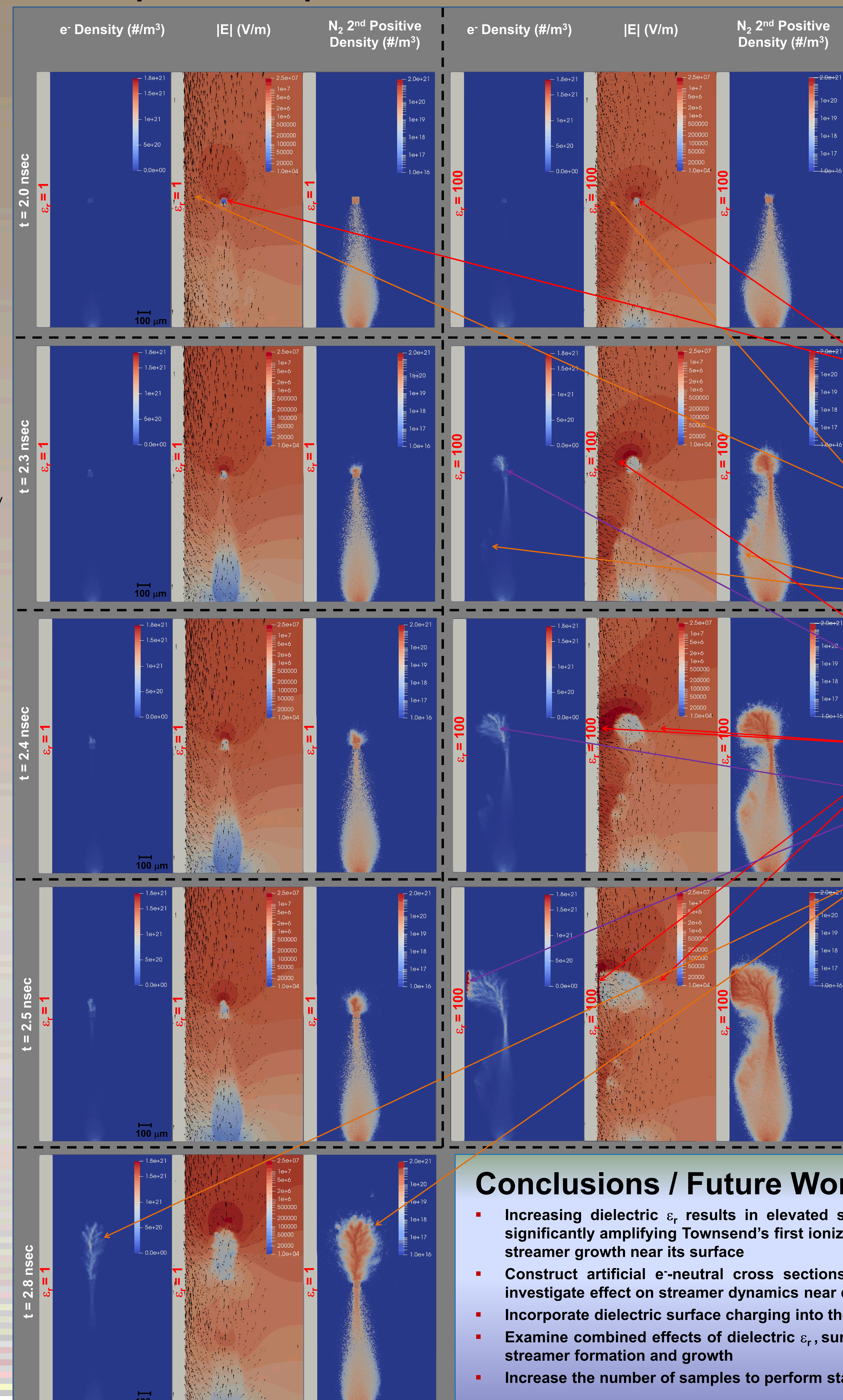
Illustrative Data



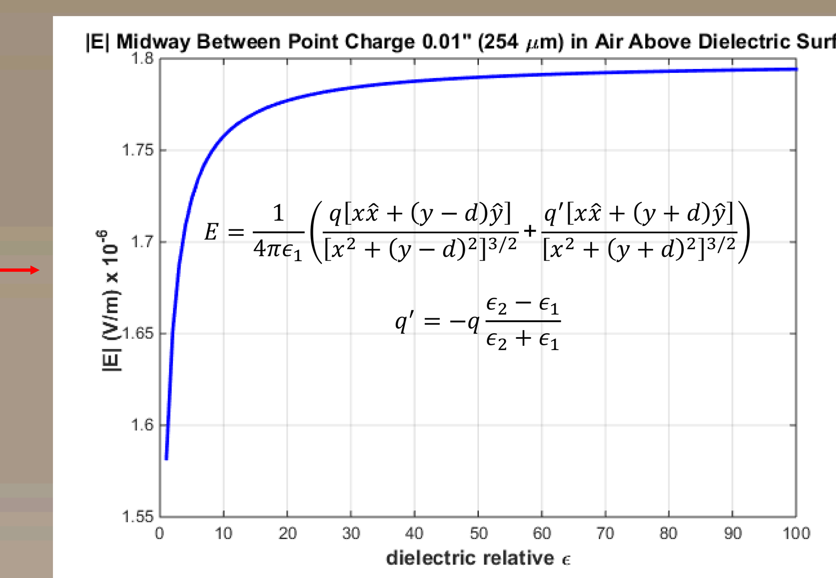
Plasma Parameters

λ_D (μm)	~0.1
λ_e (μm)	~0.37
λ_p (μm)	~33
f_{pe} (GHz)	~284
ν_{en} (THz)	~2.7

Temporal and Spatial Particle/Field Distributions



Results and Discussion



- Applying image charge theory, total E-field due to elementary point charge above a dielectric plane modeled as a super-positioning of fields from source and it's image within dielectric
  - Slope initially steep for extremely small differences in ε_r between air and dielectric, approaching 0 near ε_r =100
- Quasi-neutral plasma seed density results in E-field exclusion
- Black arrows overlaying |E| field plots represent direction of the local E-field, not vector field plots
- N_2 2^{nd} positive density (log scale) in regions of *apparently* negligible electron density (linear scale) are artifact of scaling
- At 2.0 ns, emergence of elevated E/n near dielectric (ε_r = 100) surface results in an increase in Townsend's first ionization coefficient, α = f(E/n), and the number of ionizing events
- At 2.3 ns the following are observed for the ε_r = 100 case :
  - Strong asymmetry in electron and N_2 2^{nd} positive densities due to photo-ionized electrons near dielectric surface having larger e^- - impact yields in the presence of elevated E/n; ionizing photons originating from seed plasma above
  - Increasing |E| near dielectric surface developing
  - Emerging streamer growing towards dielectric (ε_r = 100)
- At 2.4 and 2.5 ns, the following are observed:
  - Order of magnitude variation in |E| between dielectric surface and vacuum sides (ε_r = 100) result in ~ 5000x variation in α/p based on empirical data from Raizer [6]
  - Preferential growth of streamer towards dielectric surface due to significantly increased electron impact ionization yields of photo-ionized electrons returning to streamer
- At 2.8 ns, only data for ε_r = 1 case acquired, showing conventional cathode directed streamer

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] M. Zahn, "Electromagnetic Field Theory: A Problem Solving Approach", MIT Open Coarse Ware
[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] Y. P. Raizer, "Gas Discharge Physics", Springer-Verlag, 1991.

Conclusions / Future Work

- **Increasing dielectric ε_r results in elevated surface E/n in accordance with image charge theory, significantly amplifying Townsend's first ionization coefficient, α = f(E/n), and subsequently directing streamer growth near its surface**
- **Construct artificial e^--neutral cross sections such that α is (relatively) independent of E/n and investigate effect on streamer dynamics near dielectrics**
- **Incorporate dielectric surface charging into the current model**
- **Examine combined effects of dielectric ε_r, surface quantum yield, and placement of seed density on streamer formation and growth**
- **Increase the number of samples to perform statistical analysis**

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