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SAND2018-12563C

3D STREAMER EVOLUTION IN AN AZIMUTHALLY SWEPT PIN-TO-PLANE WEDGE GEOMETRY USING A PIC-DSMC CODE

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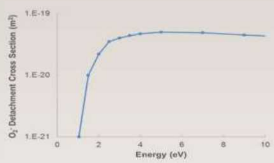
Abstract

Streamer evolution is modeled in 3D pin-to-plane geometries using an electrostatic particle-in-cell (PIC) code which simulates particle-particle collisions using the direct simulation Monte Carlo (DSMC) method. A 100 μm hemispherical anode held at 6kV DC lies 1.5 mm above a planar grounded cathode, over-volting the domain. A spherical 100 μm (radius) 1 eV plasma of density 10^{18} m^{-3} placed at the tip of the anode is used to seed the simulation domain in the presence of a 600 Torr 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]. A complete 3D volume is approximated as a wedge due to the sheer number of particles that must be tracked. We present preliminary findings that examine the temporal evolution of streamers in 3D wedge geometries where the azimuthal angle is swept in 15° increments from 15° to 45°. Initial results depict small differences in streamer propagation, branching, and velocity, as a function of wedge angle.

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 [4]
  - 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



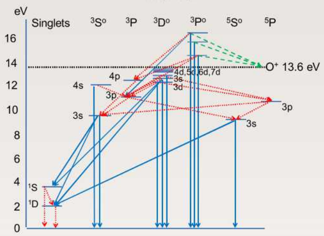
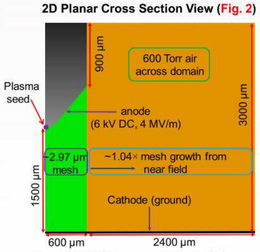


Fig. 1 Modeled energy level and transition diagram for atomic O ($^3D^o$ transitions omitted for clarity). Solid blue lines represent radiative decay in which simulation photons are generated. Red dotted lines represent decay in which a simulation photon is not generated. Green dashed lines are auto-ionizing states.

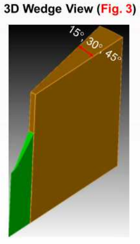
Geometry, Plasma Seed, and Mesh

- 3D wedge with azimuthal angle swept in 15° increments from 15° to 45° used to model a 1.5 mm air filled (600 Torr) pin-to-plane gap
- Initial seed plasma density modeled as the following:
  - $T_e = T_i$ = 11,605 K (1 eV) and n_e =10^{18} m^{-3}
  - 100 μm (radius) sphere located at tip of pin electrode (anode)
  - Initial electron and ion particle positions generated using random numbers, with two random seeds shown for the 3D wedge case
  - An over-volted state (6 kV anode voltage, |E| = 4 MV/m) that allows for rapid evolution of the streamer

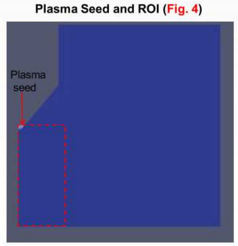
2D Planar Cross Section View (Fig. 2)



3D Wedge View (Fig. 3)



Plasma Seed and ROI (Fig. 4)



3D Temporal/Spatial n_e Distribution (#/m^3)

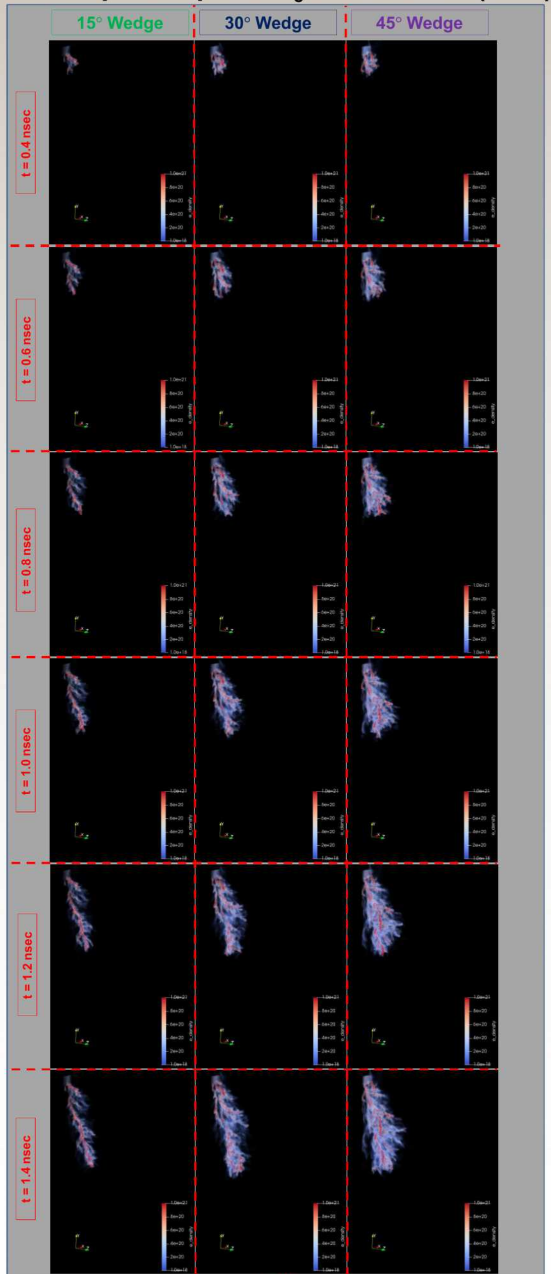
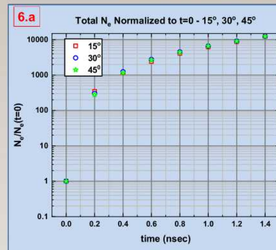


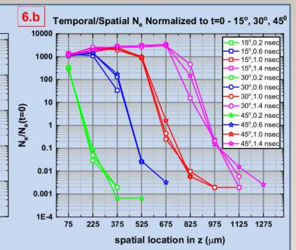
Fig. 5

Results and Discussion

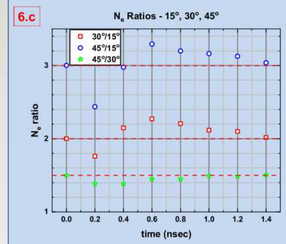
6.a



6.b



6.c



6.d

Δt (nsec)	15° (x10⁵)	30° (x10⁵)	45° (x10⁵)
0.2 – 0.6	5.83 m/s	7.15 m/s	7.27 m/s
0.6 – 1.0	5.93 m/s	4.75 m/s	4.75 m/s
1.0– 1.4	5.2 m/s	7.13 m/s	6.5 m/s

[a] Total number of *real* electrons, normalized to their respective values at time t=0, for 15°, 30°, and 45° wedges, as functions of time.

[b] *Real* N_e contained in 150 μm thick planar dz slabs, normalized to *total* N_e at t=0, as functions of time for 15°, 30°, and 45° wedges. Horizontal z-axis labels represent midpoint of each slab. 0 μm is tip of pin electrode and plasma seed at t=0.

[c] Ratios of total *real* N_e between 15°, 30°, and 45° degree wedges. Red lines represent numerical values of 45°/30° (1.5), 30°/15° (2), 45°/15° (3).

[d] Velocities calculated from 6.b at $N_e/N_e(t=0)$ = 100 over the 0.4 nsec intervals shown in column 1 for 15°, 30°, and 45° wedges.

- Figure 5 on the left depicts the 3D temporal and spatial evolution of cathode directed streamers for 15°, 30°, and 45° wedges using a spherical (r = 100 μm) plasma seed density of 1x10^{18} m^{-3} with location shown in Figure 2. Figure 6 above represents the analysis of this data.
- In Figure 6.a, the total number of real electrons as a function of time for 15°, 30°, and 45° wedges, when normalized to their respective values at time t=0, show that they are essentially independent of the wedge angle, as the data points lie approximately on top of one other.
- In Figure 6.b, the temporal and spatial distribution of the total number of real electrons contained in 150 μm thick dz slabs for 15°, 30°, and 45° wedges, when normalized to their respective values at time t=0, show that they are essentially independent of wedge angle.
- In Figure 6.c, the ratios of real electrons between 15°, 30°, and 45° wedges exhibit a transient response at early time that approach a steady state value near 1.4 nsec, aligning with the values of 1.5, 2, and 3 for ratios of 45°/30°, 30°/15°, and 45°/15°, respectively. Steady state values suggest that the fractional volume occupied by electrons scale with wedge angle. However, at some wedge angle Γ, exceeding 45°, the ratio of Γ/15° will be less than the volumetric steady state ratio. Data at early time, namely 0.2 nsec, suggest that the streamer is growing more slowly with increasing wedge angle, as there is a reduction (from t=0) of ~12% for 30° versus 15° and ~19% for 45° versus 15°. This is followed by an acceleration in growth, peaked at 0.6 nsec, and then subsequently damped, approaching steady state values (dotted red lines).
- The results in Figure 6.d, calculated from Figure 6.b at $N_e/N_e(t=0)$ = 100, indicate that the streamer velocity is only weakly dependent on the wedge angle.
- Collectively, the results from Figure 6 suggest that a higher fidelity analysis could potentially be conducted on the 15° wedge angle case, whereby the mesh is incrementally resolved with an edge length approaching the Debye length of ~0.2 μm. The caveat however to this approach may occur when the ratio of wedge angle Γ to 15° is less than the volumetric ratio.

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] 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.

Future Work

- **Increase wedge angle, Γ, to larger values until ratio of Γ/15° is less than volumetric ratio and investigate effects on streamer evolution**
- **Investigate temporal and spatial N_e distribution in vertical slabs of thickness, dr, in the radial direction for 15°, 30°, and 45° wedges.**
- **Resolve Debye length for 15° wedge angle case by decreasing cell edge length to ~0.2 μm and asses subsequent effect on numerical heating.**

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