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PIC-DSMC numerical grid heating in collisional plasmas: Application to streamer discharge simulations

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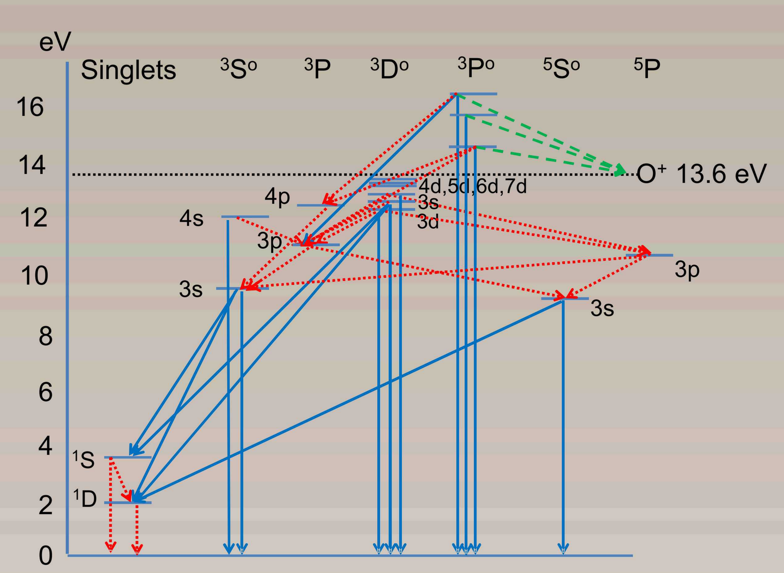
Abstract

Numerical heating due to the mesh size being larger than the Debye length is well understood for collisionless PIC simulations [1]. However, the importance of grid heating in collisional, partially ionized plasmas such as streamer discharges is less understood. In these plasma regimes the artificial numerical heating of the plasma can, at least theoretically, be mitigated by collisional energy transfer to the dense background gas. Elastic energy transfer is inefficient and electron energy transferred into electronic excitation and ionization will likely lead to significant error in streamer evolution. In the present work we investigate how numerical heating in collisional plasmas affect the evolution of a 2D streamer.

Electron-air interactions

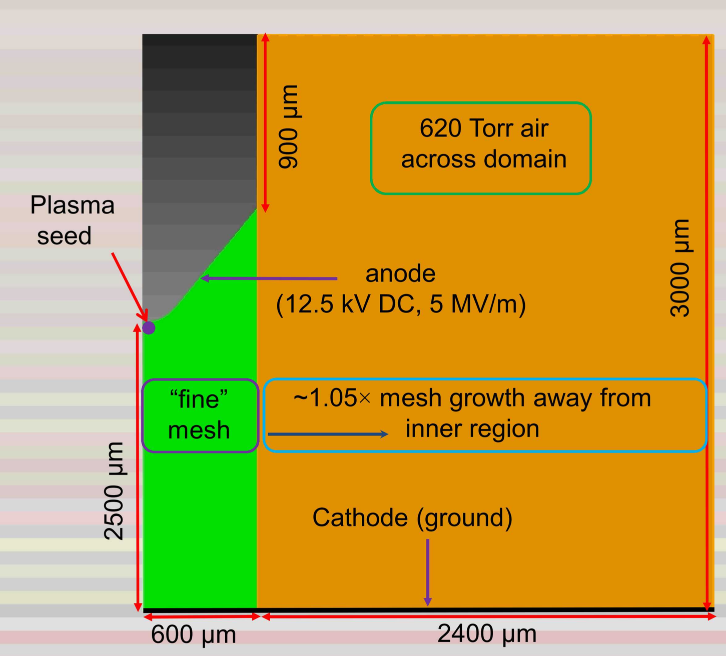
- Details can be found in [2]
- e-neutral interactions included for N_2, O_2, N, O and metastable states. Use anisotropic scattering model for all electron-neutral collisions.
  - Elastic
  - Ionization: Single (ground and metastable states), double, and dissociative
  - Attachment (3-body and Dissociative)
  - Vibrational and rotational excitation
  - Electronic excitation
- Includes e-N_2^+ and e-O_2^+ dissociative recombination and O_2^- + M detachment
- 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



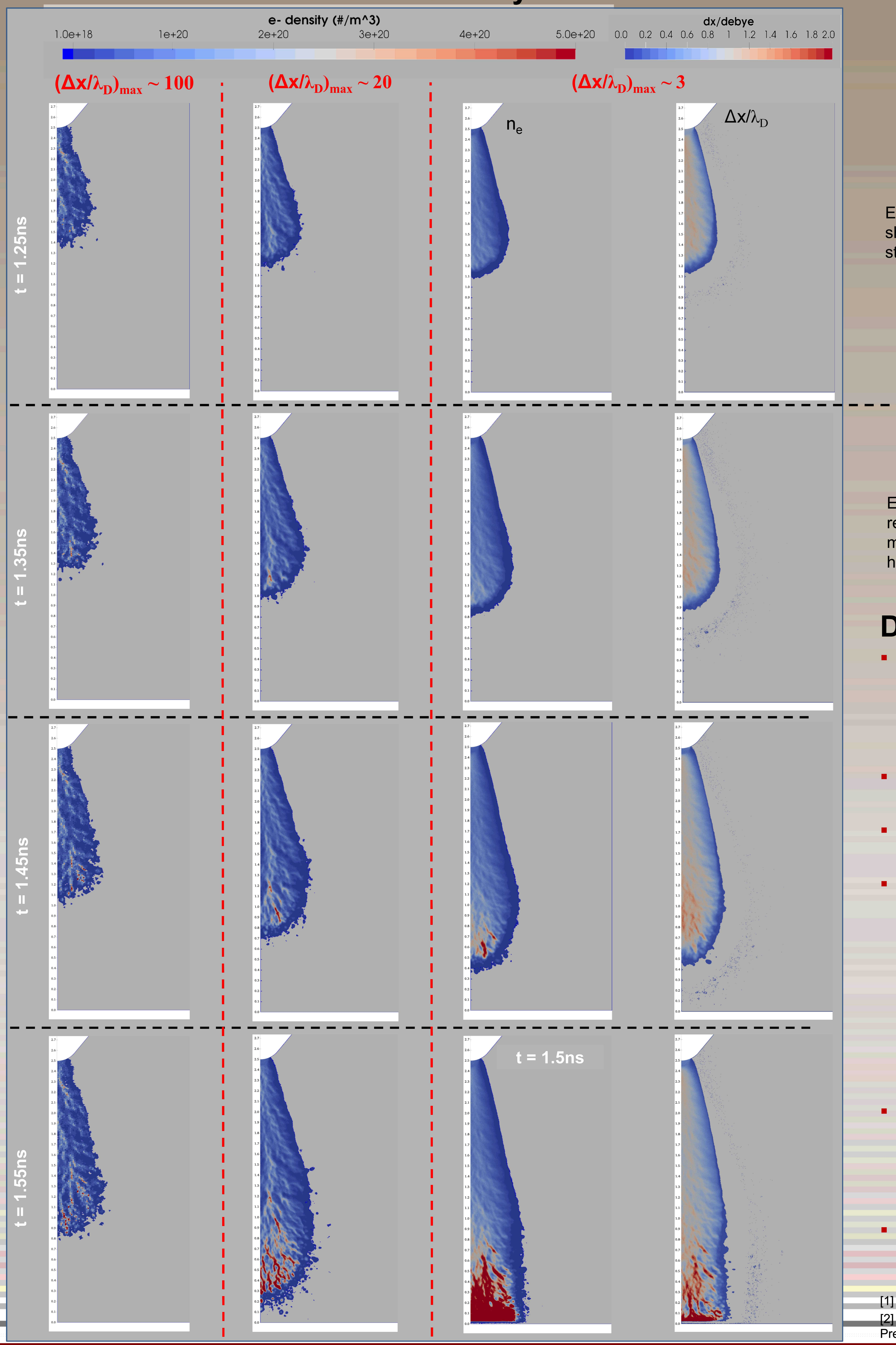
Modeled energy level and transition diagram for atomic O ($^3D^o$ transitions omitted for clarity). Solid blue lines represent radiative decay in which simulation photons are generated. Red dotted lines represent decay in which a simulation photon is not generated. Green dashed lines are auto-ionizing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

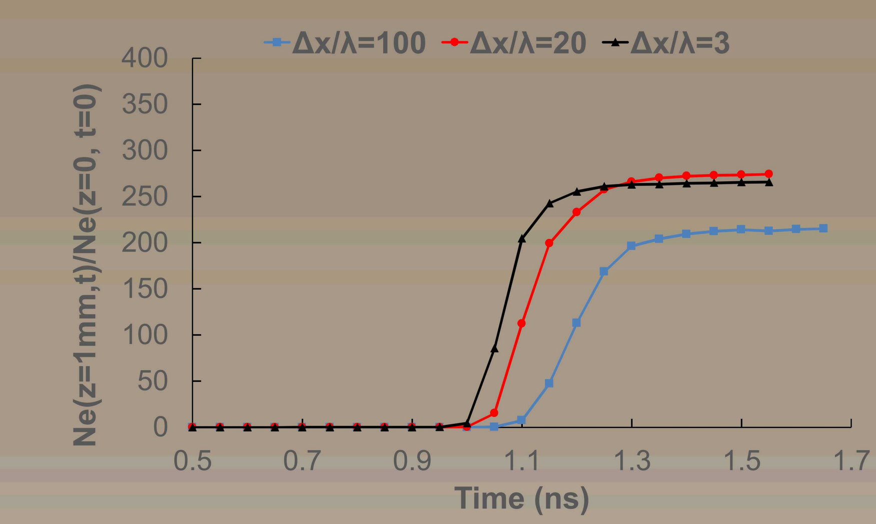
Geometry, Plasma Seed, and Mesh

- 2D "knife-edge"-to-plane with a 2.5mm air filled (620 Torr) gap
  - Use constant "fine" mesh in inner region where streamer is expected to grow.
  - Inner region "fine" mesh sizes based on estimate for Debye length, λ_D=0.16μm (n_e=10^{21} #/m³ and T_e = 0.5 eV)
  - Chose inner-region $\Delta x/\lambda_D$ = {100, 20, 3}
- Initialize seed plasma near the anode knife-edge:
  - T_e = T_i = 11,605 K (1 eV) and n_e =10^{18} m^{-3}
  - 100 μm (radius) sphere located at tip of the anode knife-edge
  - Apply 12.5 kV anode voltage (sufficiently over-volted to allow rapid streamer evolution)

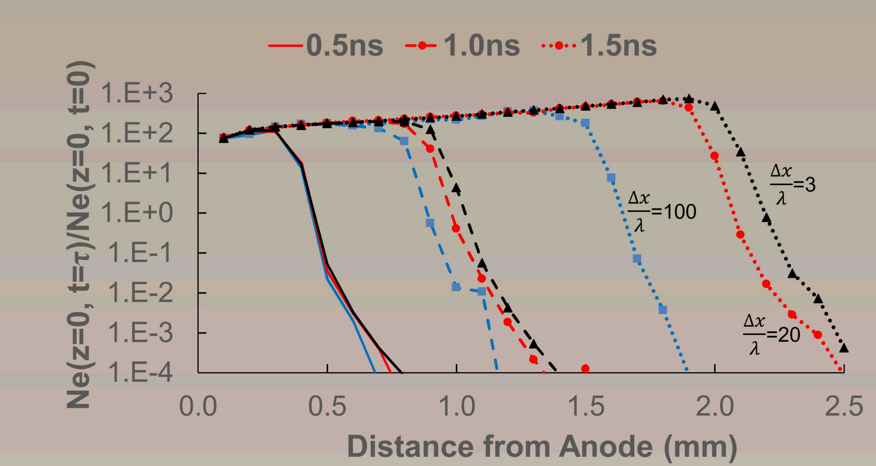


Evolution of electron density vs. mesh size





Electron density at z=1mm (normalized by the seed density) shows that the more resolved meshes reach a higher quasi-steady state electron density after the streamer head has passed.



Electron density versus distance from the anode at three representative times normalized by the seed density. For each mesh the streamer propagation starts at nearly the same time; however, the streamer velocity is larger with smaller elements.

Discussion

- Unresolved mesh sizes greater than λ_D result in substantive changes in (2D) streamer evolution. The results shown are a representative subset of multiple runs with different RNG seeds. Depending on the quantity of interest this numerical error may or may not be important.
- More resolved meshes result in increased e⁻ density in the streamer channel in "steady state"
- Streamer velocity seems to increase with smaller elements that better resolving the Debye length.
- Both the increased streamer velocity and higher e-density imply a higher net ionization rate, α,and thus E/n, for the more resolved mesh. However, near the streamer tip, electric field gradients on the scale of the streamer radius are reasonably resolved (10's-1000's of elements) for all mesh sizes. Therefore the difference in evolution does not appear to be driven by error in the large-scale electric field around the streamer tip. Instead it is likely the error in resolving the small-scale density features and the resultant smoothing of the field in the coarser meshes
- Needs further study to determine whether the numerical error is driven by heating in the streamer channel (where the Debye length is smallest) or the avalanche region upstream of the streamer tip (where field gradients are largest and fine-scale features first appear)
- We have yet to show convergence! Must run at several smaller mesh sizes with $\Delta x/\lambda_D < 1$

[1] C.K. Birdsall and A.B. Langdon, Plasma Physics via Computer Simulation (2005).

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

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