SAND2017-6791D

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Developing a kinetic approach to radiation transport and its interaction in He/N_2 ionization waves

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Implementation and Simple Example

(1) An excited particle radiates via the equation

$$R < 1 - e^{-\Delta t/\tau}$$

(2) Account for natural line broadening

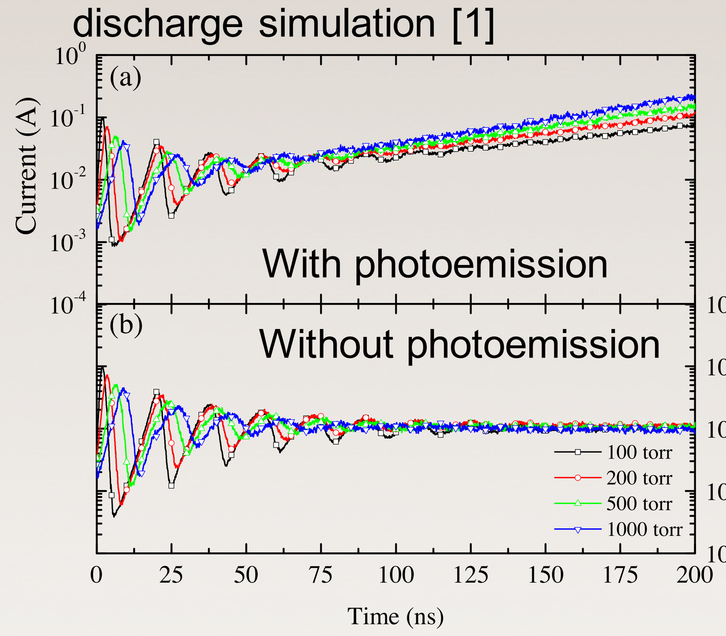
$$\lambda_s = \tan((r - 0.5)\pi)\Delta\lambda_L + \lambda_0$$

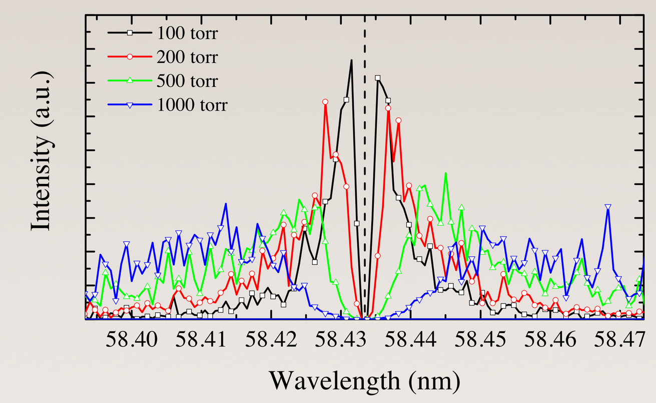
(3) Determine the vector for photon propagation (chosen isotropically), $\mathbf{v}_{ph}$ and the vector of the emitting particle, $\mathbf{v}_p$.

(4) Account for Doppler line broadening

$$\lambda_f = \frac{(c + \hat{\mathbf{v}}_{ph} \cdot \mathbf{v}_p)\lambda_s}{c}$$

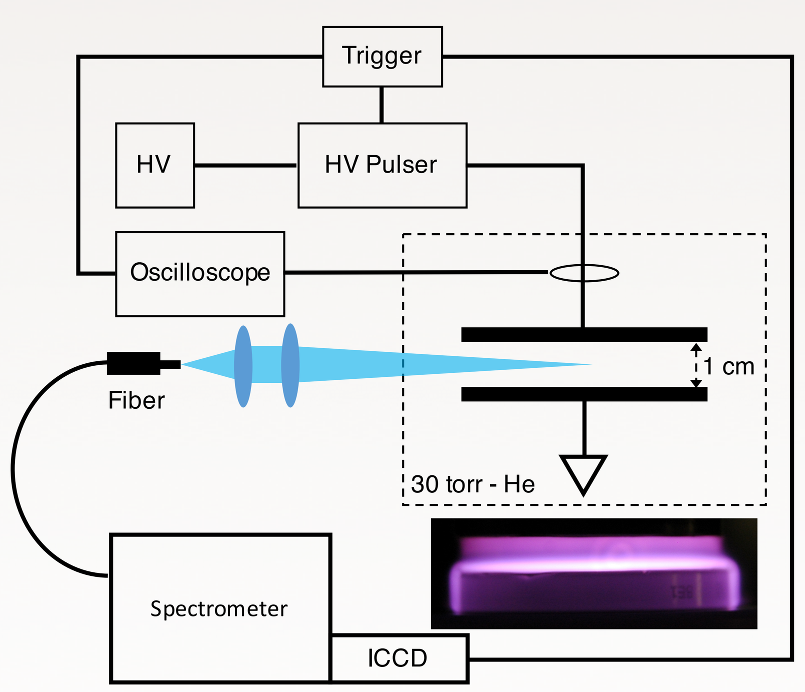
Anode current for a 1D Townsend discharge simulation [1]



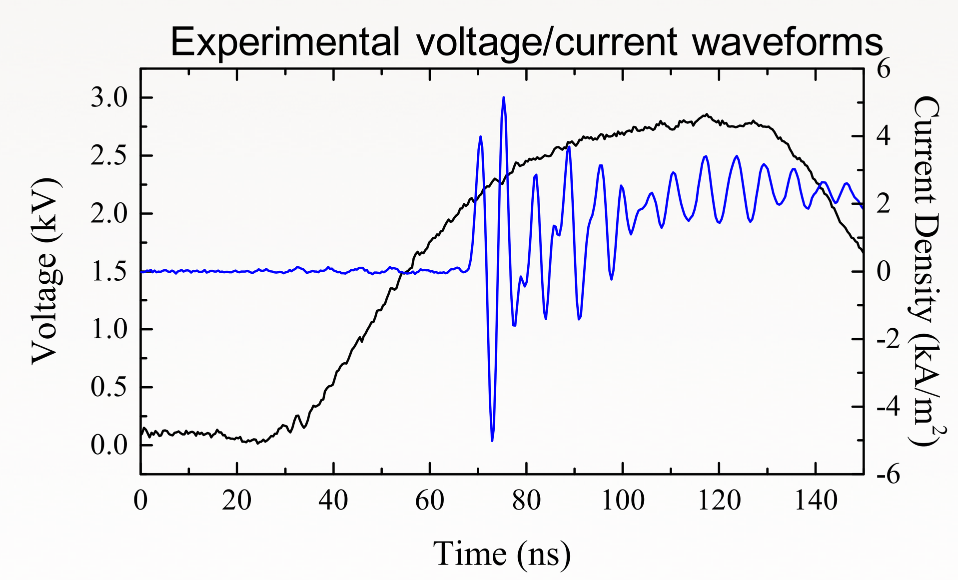


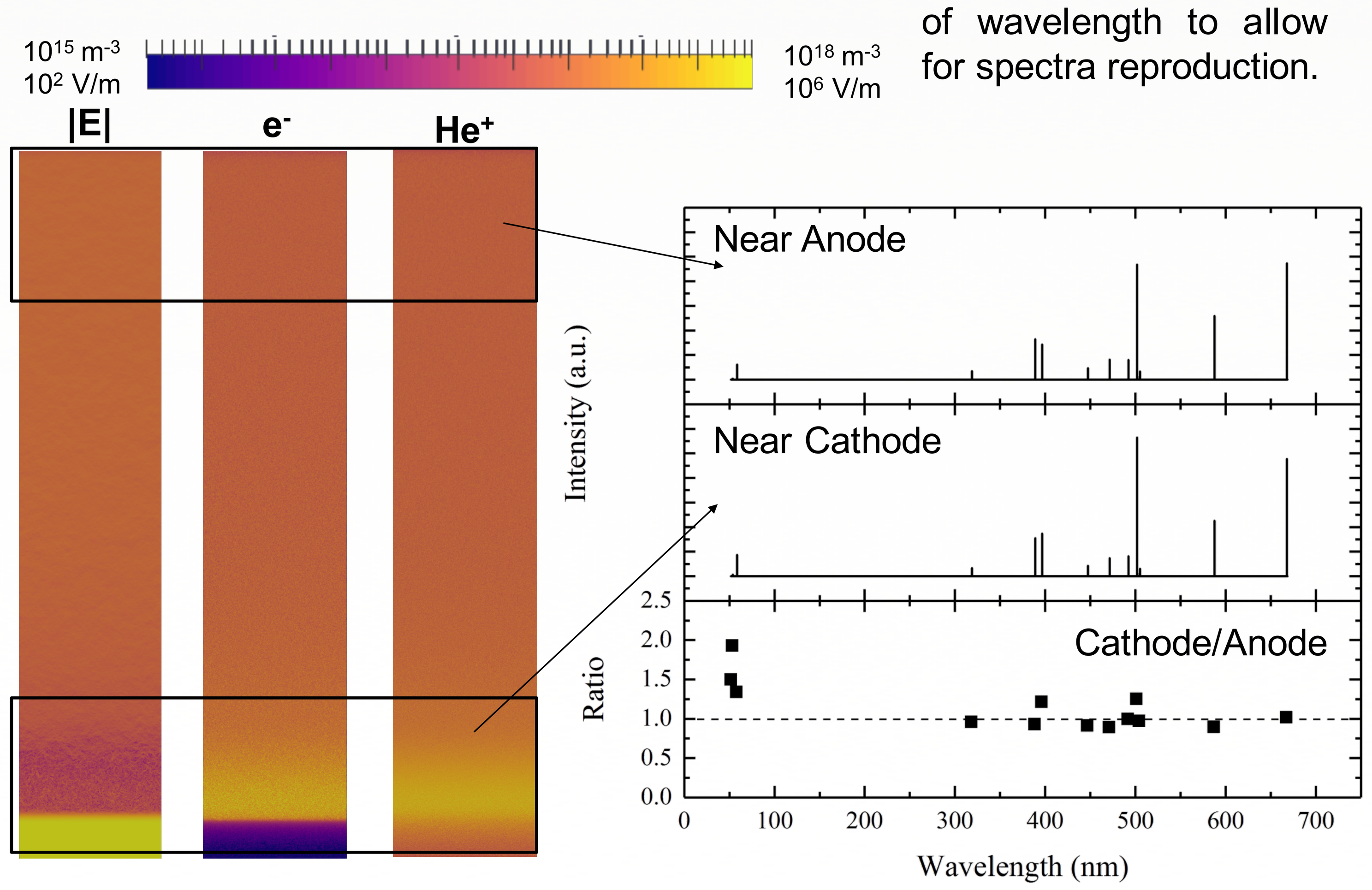
Spectrum of the 58.4334 nm $2^1P \rightarrow 1^1S$ reaching the cathode at different pressures. Self-absorption at line center is evident and the profile becomes broader in the wings as pressure is increased.

Towards Validation with OES

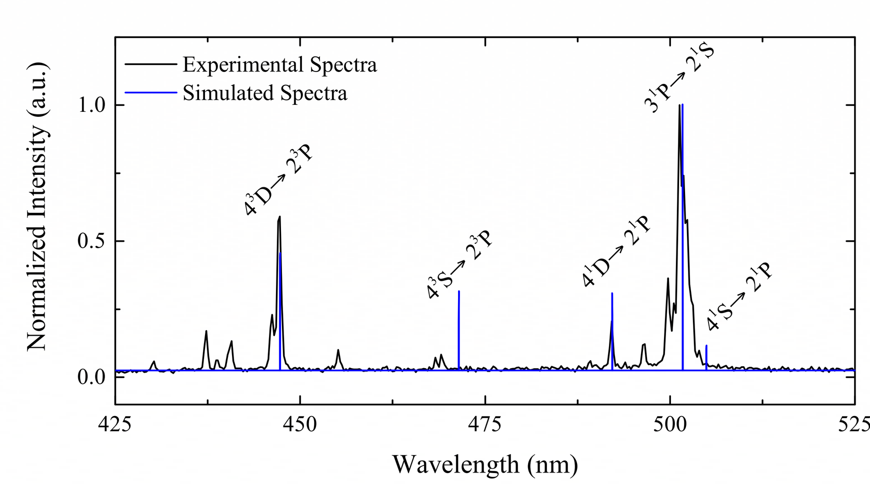


- A simple experiment was constructed to allow for optical access and obtain time-resolved optical emission spectroscopy.
- A background gas of helium at a pressure of 30 torr yielded a relatively uniform plasma formation between parallel plates.
- For comparison, a Helium 2D simulation was built using the experimentally applied voltage waveform as the electrostatic boundary condition.
- Photons in the simulation volume are integrated as a function of wavelength to allow for spectra reproduction.

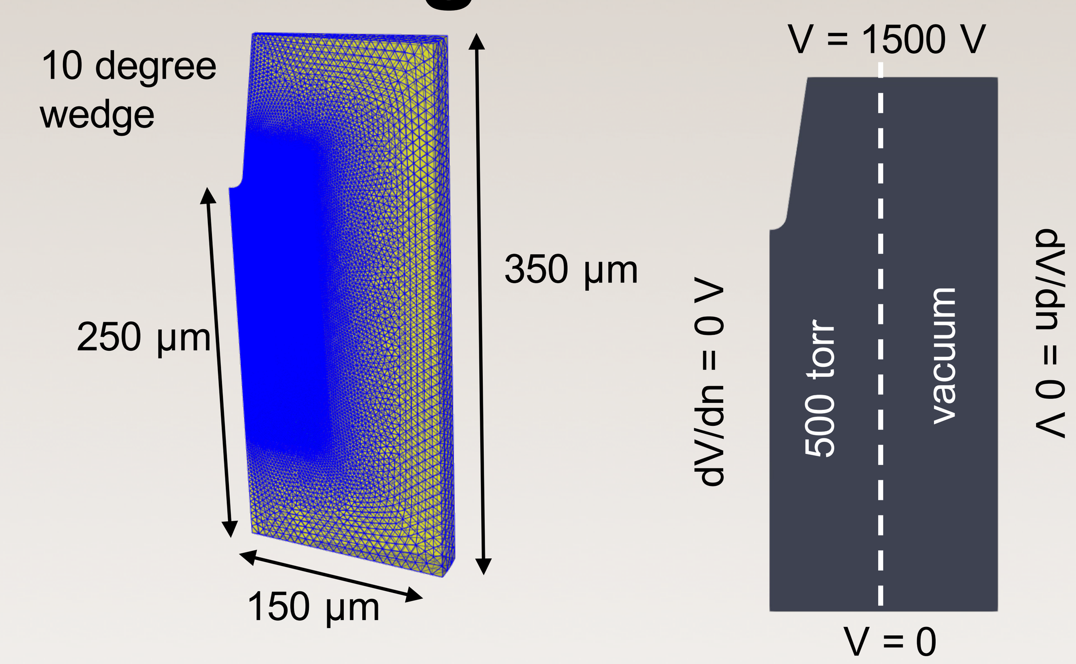




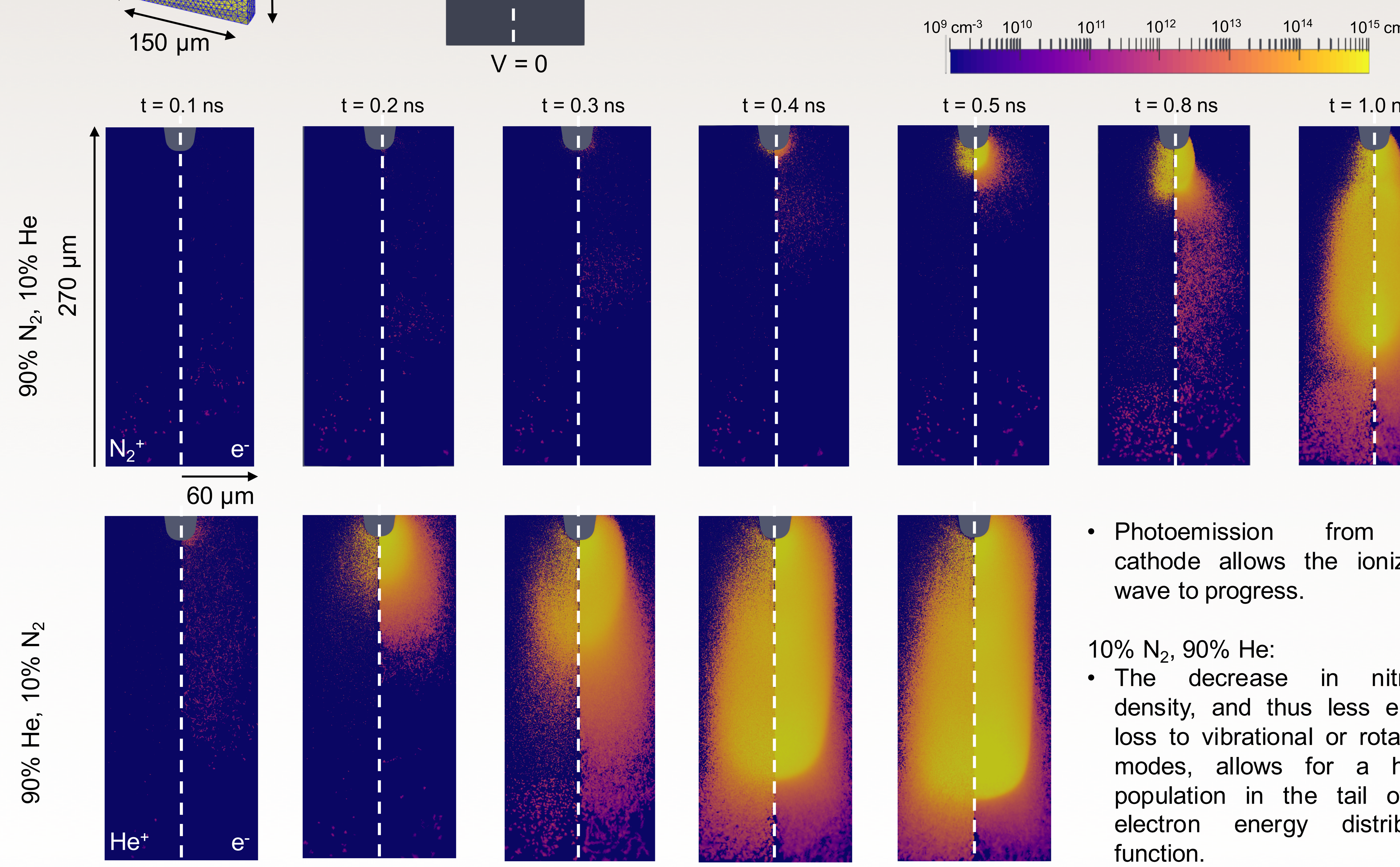
- Data comparison between the simulation and experiment show good agreement for the range between 425 nm and 525 nm.
- Nominal helium transitions appear with most disagreement occurring for the $4^3S \rightarrow 2^3P$ transition.



3D Wedge Simulation



Parameter	Spatial or Time Scale
Debye Length - λ_D	~150 nm
Electron Mean Free Path - λ_{mfp}	~200 nm
Photon Mean Free Path - γ_{mfp}	~25 µm
Inverse plasma frequency - $(\omega_{pe})^{-1}$	~1 x 10^{-13} s
Inverse collision frequency - $(\nu_c)^{-1}$	~300 x 10^{-12} s
Electron CFL @ 5 x 10^6 m/s	~1 x 10^{-13} s
Photon CFL	1-2 x 10^{-15} s



- Photoemission from the cathode allows the ionization wave to progress.

10% N_2, 90% He:

- The decrease in nitrogen density, and thus less energy loss to vibrational or rotational modes, allows for a higher population in the tail of the electron energy distribution function.

Conclusions

Only a small angle wedge is used for the 3D simulation here. Fully 3D computations for a full 360 degree model will require on the order of tens of billions of grid elements. Additionally, fully resolving near atmospheric pressure discharges where charged particle densities are expected to become greater than 10^{13}-10^{14} cm^{-3} in gap sizes greater than several millimeters is a long-term goal but far off with current computational methods and hardware. Current estimates for this type of simulation would require roughly millions of processors and many Petabytes of memory which current hardware is only beginning to approach. Solutions to alleviate this could be the use of adaptive mesh refinement, implicit schemes, or hybrid (fluid/kinetic) methods.

References

[1] A. Fierro, C. Moore, B. Scheiner, B. Yee, M. Hopkins, "Radiation Transport in Kinetic Simulations and the Influence of Photo-emission on Electron Current in Self-Sustaining Discharges," Journal of Physics D: Applied Physics, vol. 50, 065202, 2017.

[2] A. Fierro, J. Stephens, S. Beeson, J. Dickens, A. Neuber, "Discrete Photon Implementation for Plasma Simulations," Physics of Plasmas, 23, 013506, 2016.

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