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PIC/DSMC Simulation of Radiation Transport Dynamics in Helium Gas Discharges

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Abstract

Largely absent from kinetic, low-temperature plasma simulations is the capability for simulating radiation transport. It is largely acknowledged that self-produced radiation from gas discharges may have an impact on plasma formation and there is a need to include this physics into modern simulation codes [1,2]. As such, there has been some effort in including photon dynamics into plasma simulations [3,4] although they are generally only applicable to a single gas mixture such as air or focus on a small subset of transitions. In this work, a thorough kinetic description of Helium [5] is included into a massively parallel Particle-in-Cell (PIC) utilizing Direction Simulation Monte Carlo (DSMC) for electron-neutral interactions. Additionally, a method for radiation transport is included that includes both natural and Doppler line broadening as well as self-absorption mechanisms. This method demonstrates the capability of modern PIC simulations to simulate temporally and spatially-resolved emission spectra and include energy-dependent photon dynamics such as photo-emission from the electrode surfaces.

Implementation

- Photons are modeled as discrete particles and are pushed independently through the simulation.
- The wavelength of each photon is chosen corresponding to a Voigt distribution.

(1) Determine if an excited particle radiates via the equation $R < 1 - e^{-\Delta t/\tau}$

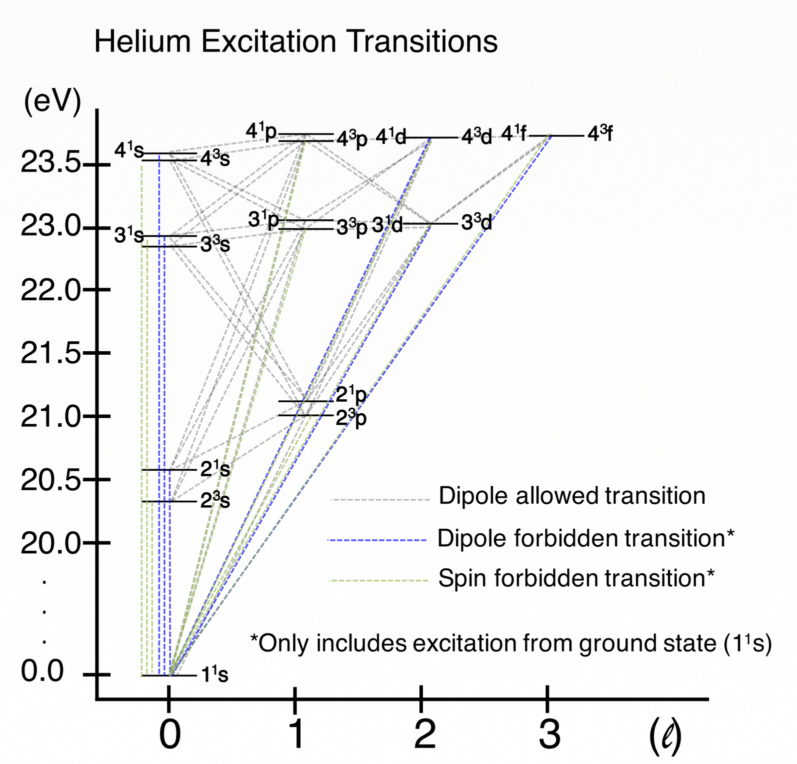
(2) Select wavelength to account for natural line broadening $\lambda_s = \tan((r-0.5)\pi)\Delta\lambda_L + \lambda_0$

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

(4) The final wavelength, accounting for Doppler line broadening, is selected by $\lambda_f = \dfrac{(c + \hat{\mathbf{v}}_{ph} \cdot \mathbf{v}_p)\lambda_s}{c}$

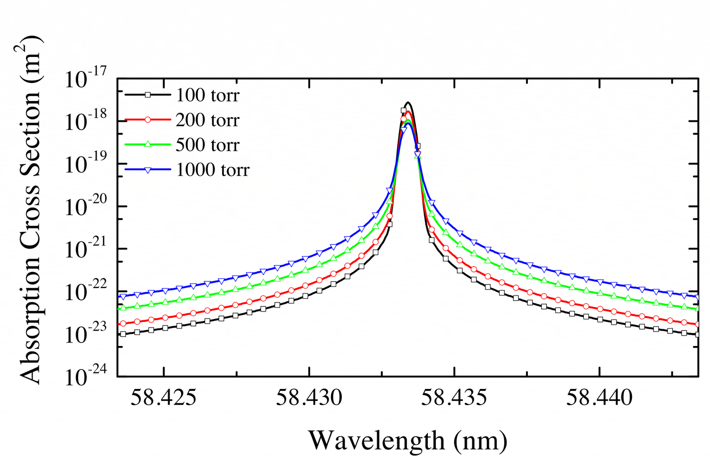
Simulation Setup

V_{anode} = Constant $V_{cathode}$ = 0



Excitation and de-excitation kinetic scheme.

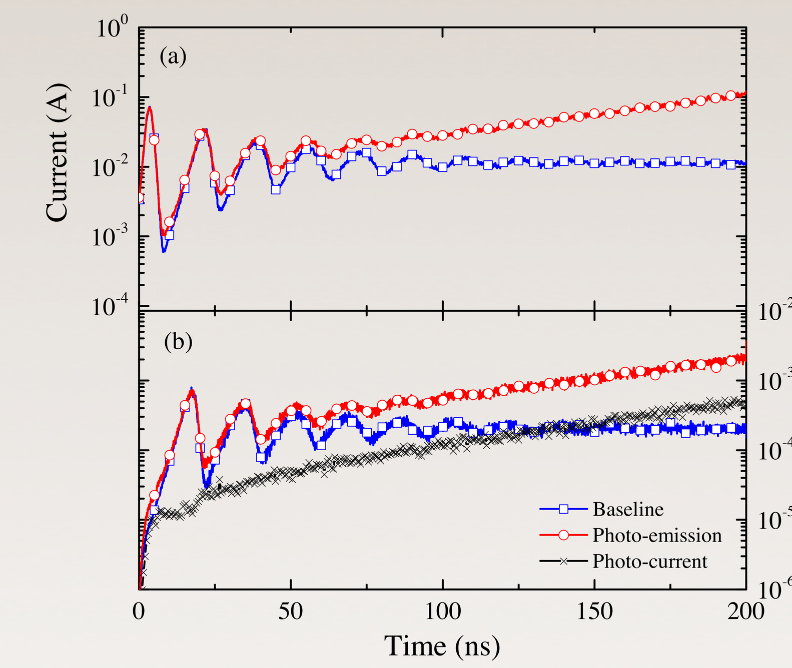
- Space charge effects are neglected to emulate a Townsend breakdown process.
- Photoemission from the cathode is included as an energy dependent quantum yield, approaching 0.1 for photons with λ < 100 nm.
- Broadening mechanisms include natural line broadening, Doppler line broadening, and pressure broadening.
- Kinetic scheme includes
  - 52 electron-impact excitation cross sections
  - 1 electron-impact ionization cross section
  - 1 electron-neutral elastic collision cross section
  - 42 de-excitation transitions and corresponding photons
  - 3 self absorption cross sections.



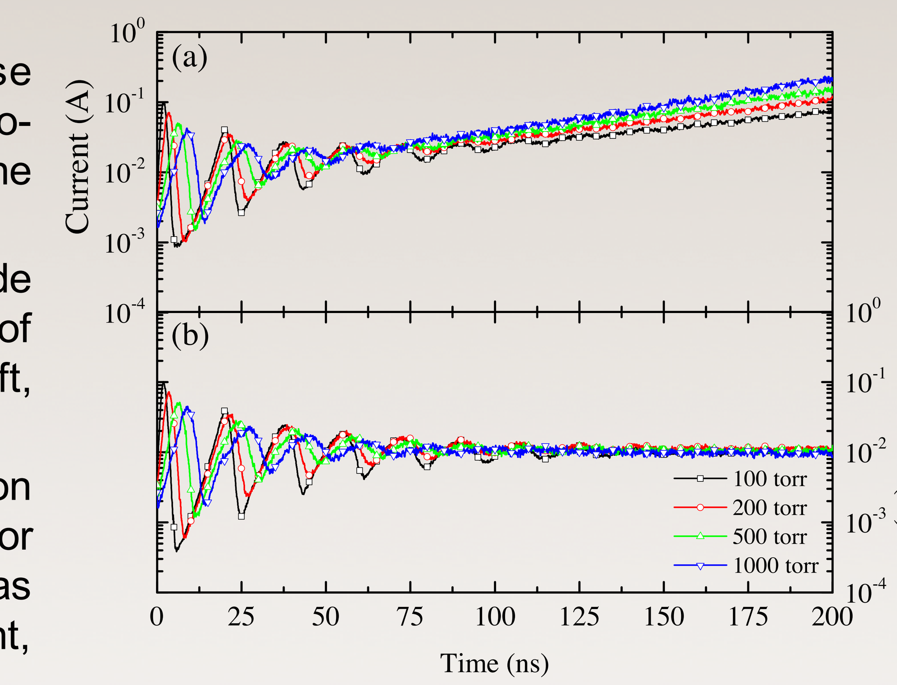
Example absorption cross section for the helium 1^1S to 2^1P transition as a function of wavelength and pressure.

$$\sigma(\lambda) = \frac{A_0 c^2 g(\lambda)}{8\pi \nu_0^2}$$

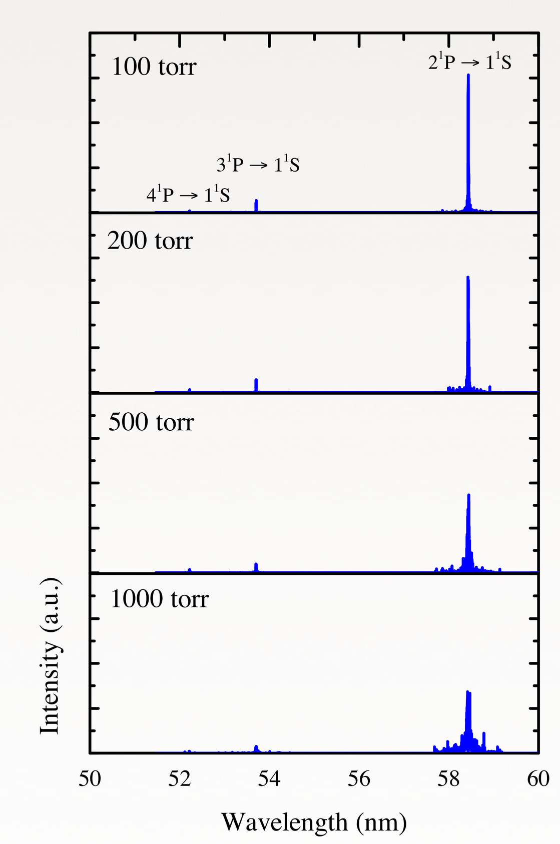
Simulation Results

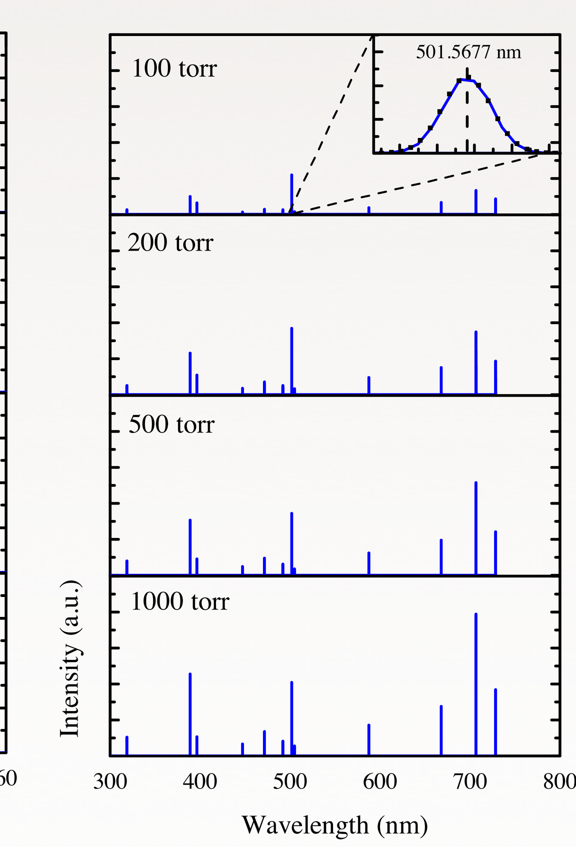


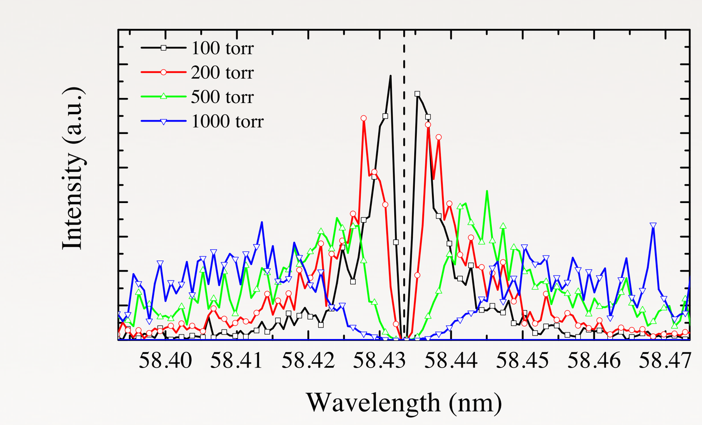
- 200 torr breakdown case demonstrates the effect of photo-emission on electron current into the anode (left, (a)).
- Photo-current from the cathode accounts for a significant portion of total current form the cathode (left, (b)).
- Photo-emission has an effect on electron current into the cathode for various pressures (right, (a)) as compared to the base case (right, (b)).

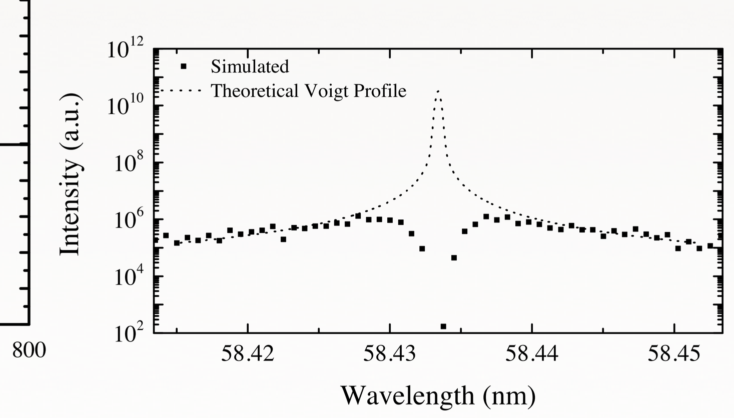


- Emission spectra shown are integrated at t = 50 ns to t = 60 ns and represent the spectra reaching the cathode.
- Inclusion of self-absorption shows strong absorption at line center.









Conclusions

- A discrete photon approach is used that enables photons to be created from excited states with a wavelength corresponding to a Voigt distribution.
- Simulations in one dimension demonstrate the method's ability to simulate emission spectra and show the effect of photo-emission on discharge currents.
- New models will look to investigate the effect of photo-ionization on streamer formation in atmospheric pressure air plasmas [2].

References

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