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Surface photon flux dynamics during breakdown initiation

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Introduction

Breakdown initiation relies on feedback from surface processes. Even in streamers, a sustained discharge is only possible with surface feedback. In Paschen's theory, surface effects are accounted for in the secondary electron emission coefficient, γ. This term encompasses many processes (Phelps, 1999), including those due to ions, electrons, photons, and excited states. Each of these processes depend upon the potential or kinetic energy of the incident particle, its angle of incidence, and many other factors. The properties of the particles incident on the surface are a function of the plasma properties and vice versa.

In this work, we describe initial efforts to assess the dynamics of the particles and photons incident on a surface using kinetic models and *in situ* measurements. These predictions will feed into a larger body of work intended to further extend our understanding of how surface effects impact breakdown.

Aleph: PIC-DSMC Simulation Capability

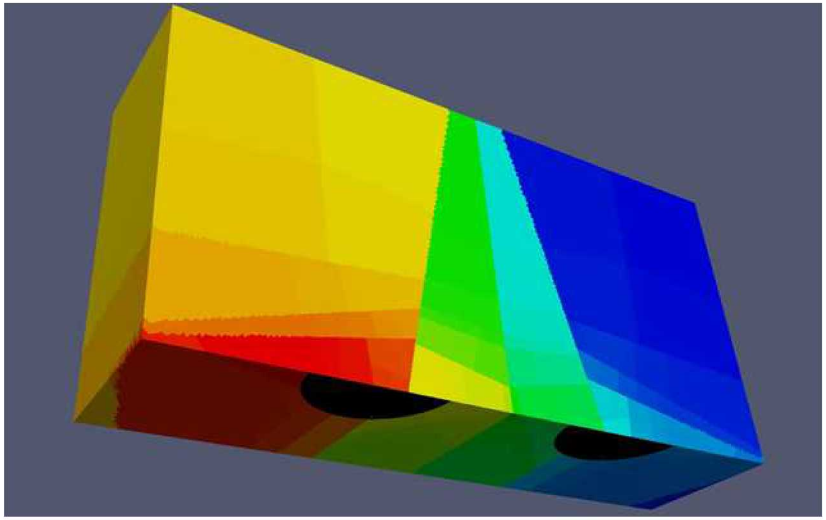


Figure 1 Illustration of dynamic load balancing capabilities of Aleph.

- 0, 1, 2, or 3D Cartesian
- Unstructured FEM (compatible with CAD)
- Massively parallel
- Hybrid PIC + DSMC (PIC-MCC)
- Electrostatics
- Fixed B field
- Solid conduction
- Advanced surface (electrode) models
- Photon transport, photoemission, photoionization
- Advanced particle weighting methods
- Dual mesh (Particle and Electrostatics/Output)
- Dynamic load balancing (tricky)
- Restart (with all particles)
- Agile software infrastructure for extending BCs, post-processed quantities, etc.
- Currently utilizing up to 64K processors (>1B elements, >1B particles)
- e- approximations (quasi-neutral ambipolar, Boltzmann)
- Collisions, charge exchange, chemistry, excited states, ionization

Discharge Conditions

- Background Gas: helium, 50 Torr
- Gap: 1.0 cm
- Applied Potential: 1 – 2 kV
- External ballast resister, 1 kOhm
- Cathode
  - 1" diameter wafer
  - PVD-deposited Pt
- Anode
  - Polished stainless steel
  - 0.25" radius hemisphere

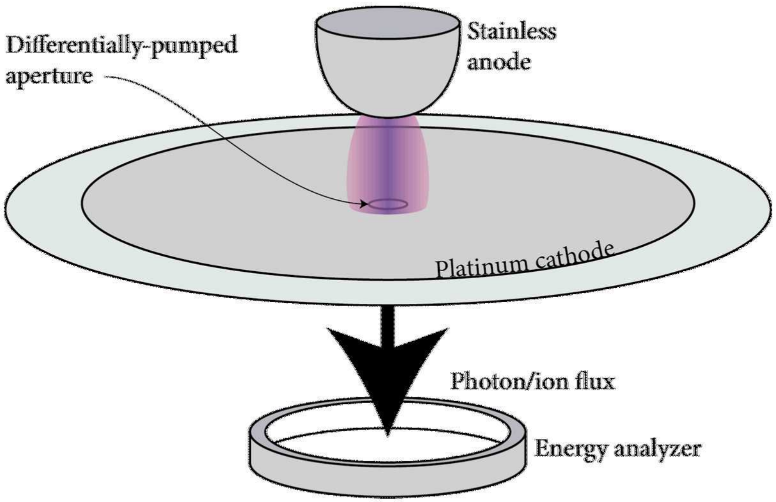


Figure 2 Conceptual depiction of the discharge geometry and the scenario modeled using Aleph.

Model Description

- Regularly spaced 1D mesh, dx ~ 2.5 um
- Time step of 4 fs
  - Resolves photon transit time across cells
- Dynamic reweight with ~100 electrons per cell
- Secondary electron emission models with fixed γ for ions and photons
- Constant electron flux from electrode (UV lamp illumination)
- External *RC* circuit model

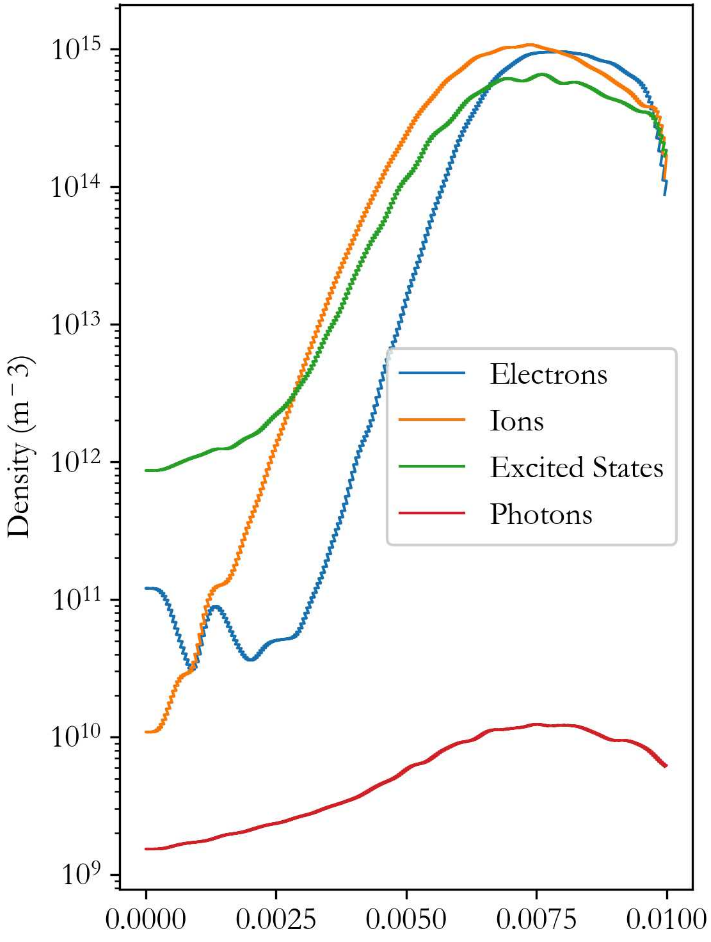


Figure 3 Discharge properties after 40 ns from a breakdown simulation in Aleph at 2 kV.

Particle Interactions

- Elastic collisions
- Ionization and 2^1P excitation (Ralchenko, 2008)
  - Primary source of high energy photons
  - Other resonance radiation or ion lines may contribute
  - Non-trapped radiation may cause emission from materials with lower work functions
- Helium resonant charge exchange (Smirnov, 2001)
- Kinetic radiation transport (Fierro, 2017)
  - Includes self-absorption

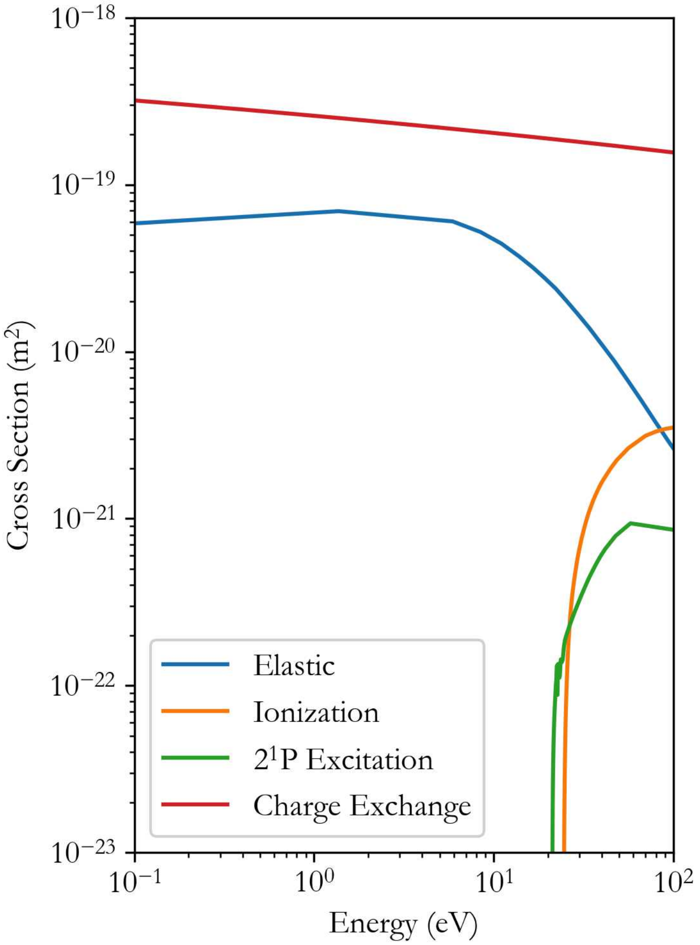


Figure 4 Plot of relevant cross sections used in simulations of breakdown dynamics.

Current Waveforms

- 1 – 2 kV in 100 V increments
- Two-capacitor system
  - Power supply (behind ballast), 50 μF
  - Cable (directly attached), 40 pF
- Initial peak caused by fast ionization
  - Limited by cable capacitance
- Collapse due to overdriven gap

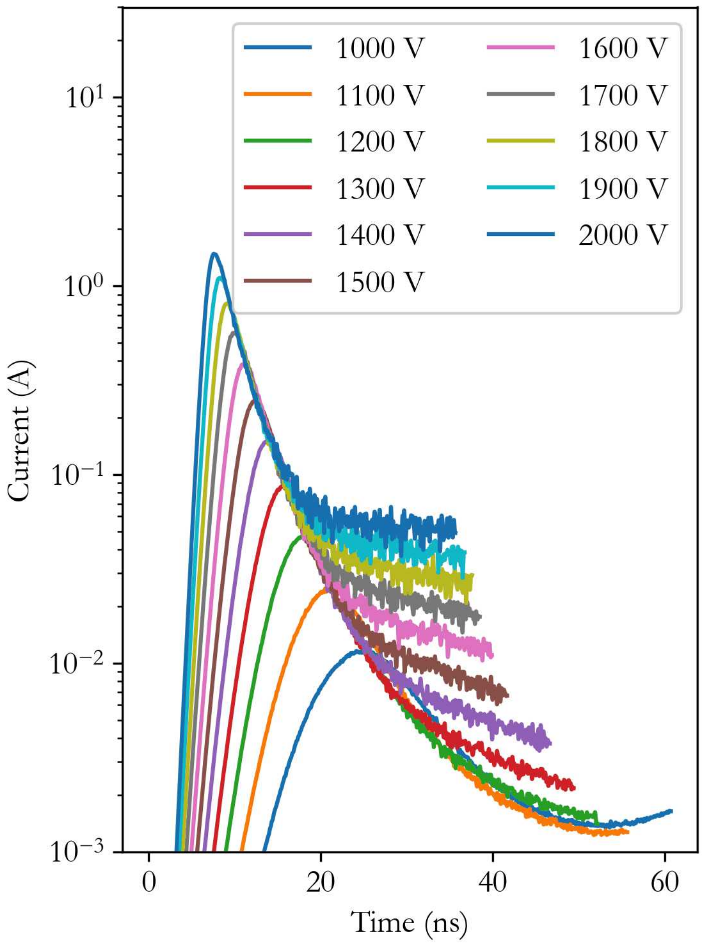


Figure 5 Calculated current during breakdown initiation for a range of applied voltages.

Cathode Photon Flux

- Photon flux to cathode tracked over time
- Strong trapping smooths out current dynamics
- Linear scaling of steady state VUV production with applied potential, despite ballast
- Variable delay in onset due to excited state production rate

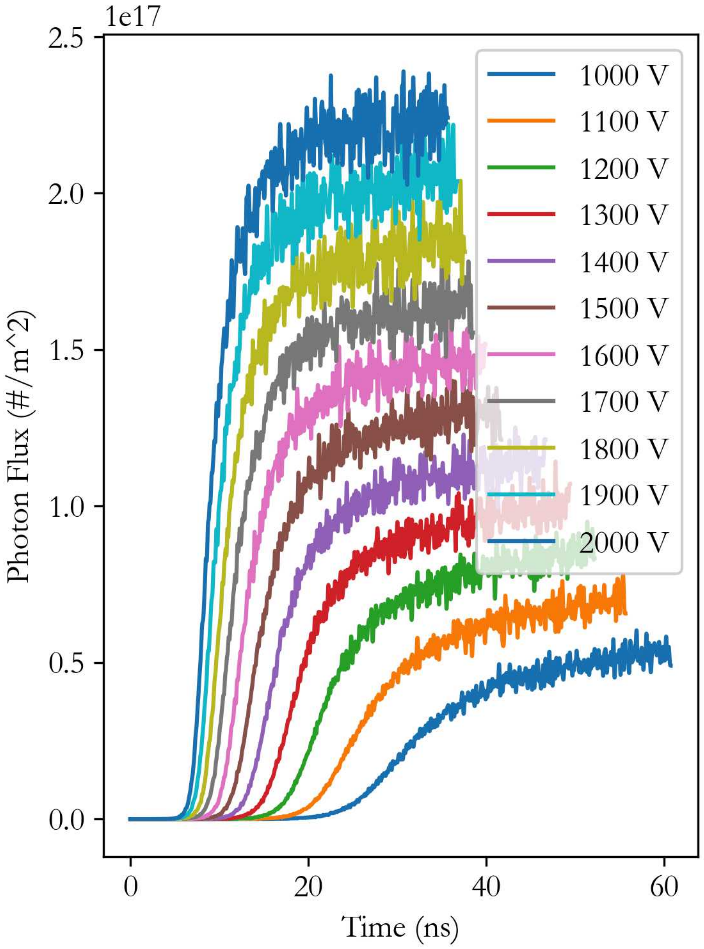
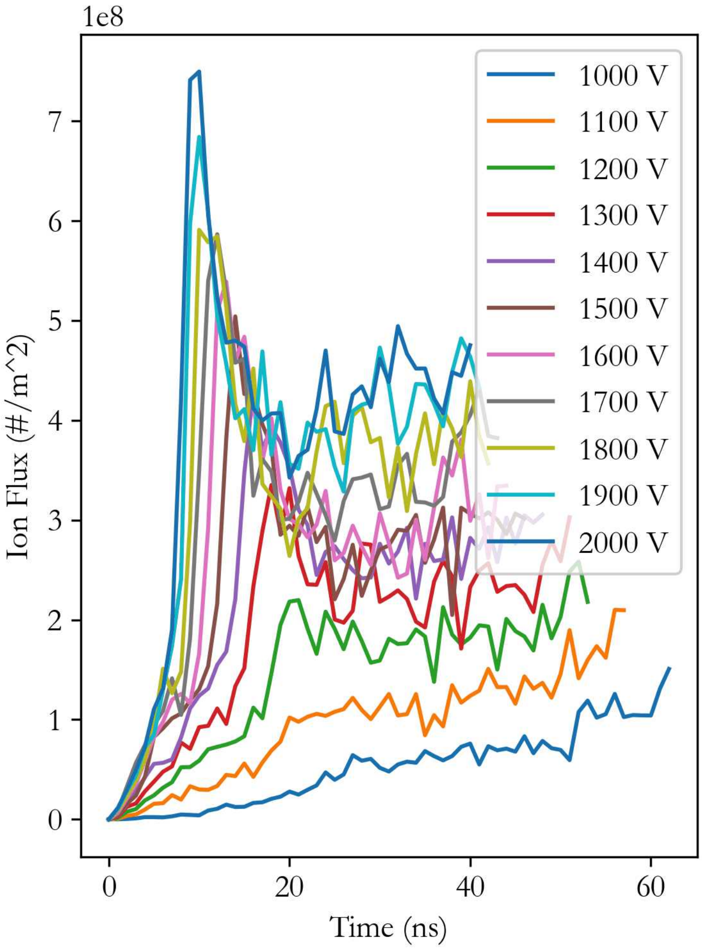


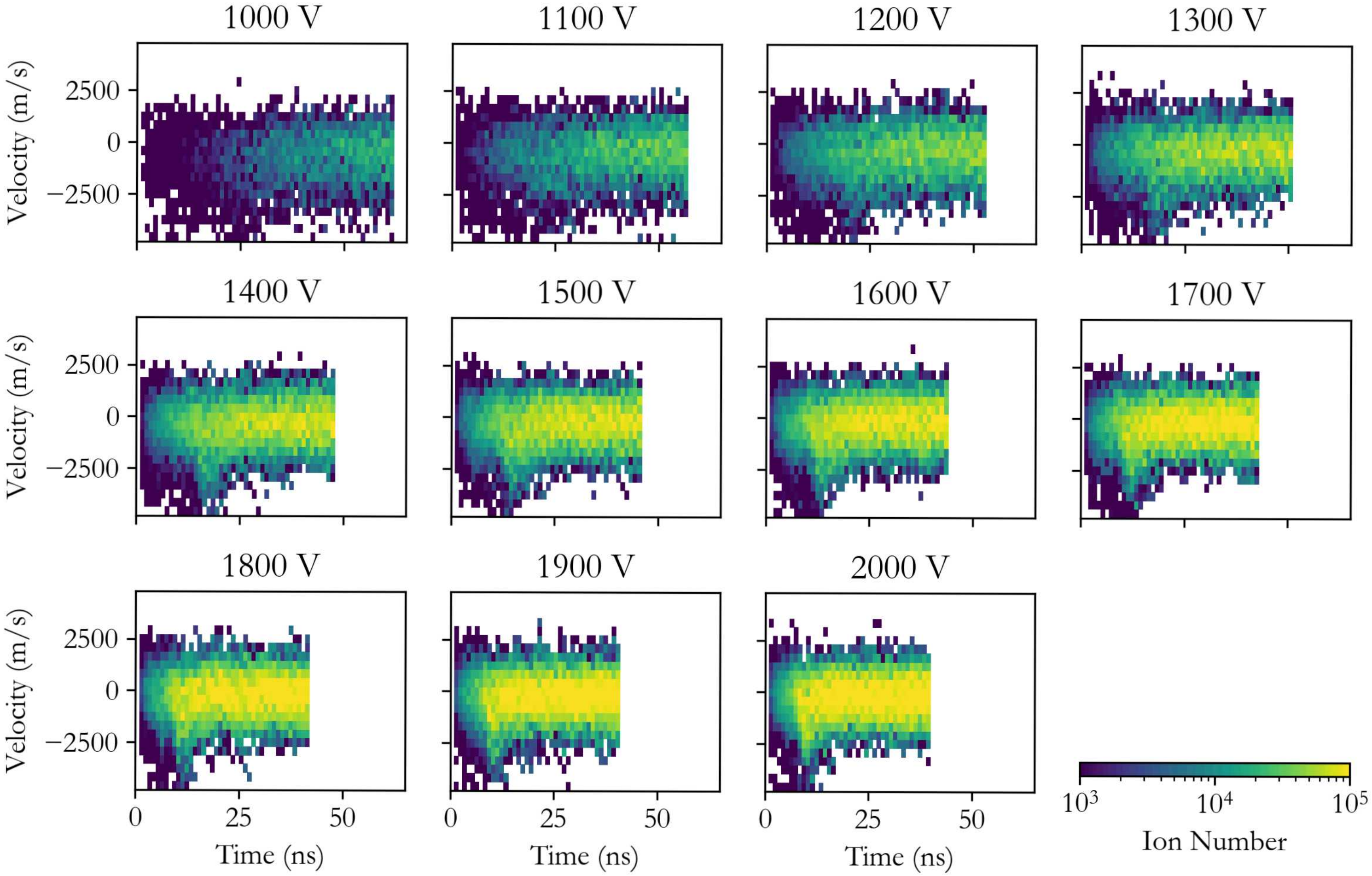
Figure 6 VUV photon flux to the cathode surface during breakdown initiation for a number of applied voltages.

Cathode Ion Flux

- Ion flux impacted by potential inversion
- Variable secondary contribution from ions
- Overall flux significantly lower than VUV photons
- Roughly linear scaling with potential



Ion Velocity Distributions



Necessity for differential pumping

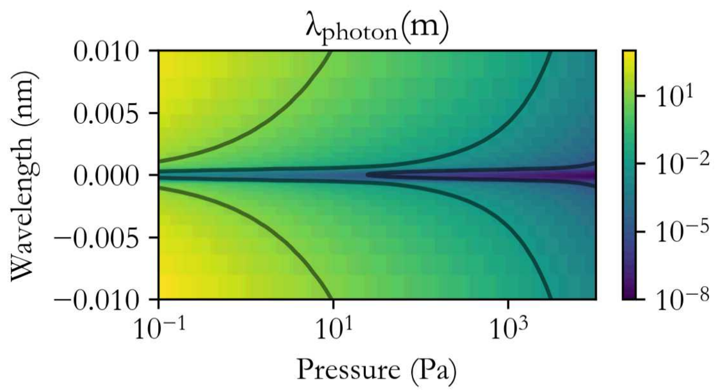


Figure 6 Mean free path of resonance radiation for different pressures and wavelengths.

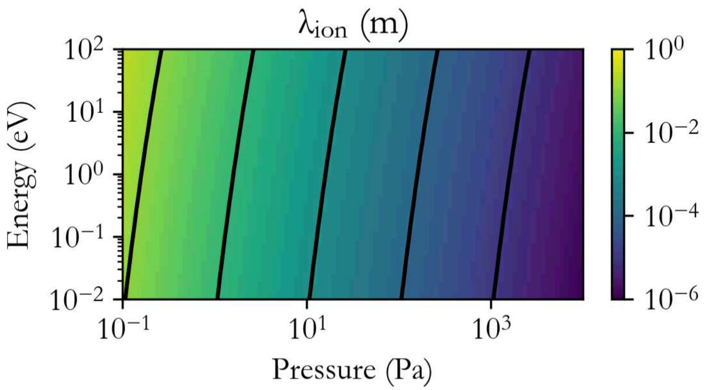


Figure 7 Mean free path of ions for different energies and different background pressures.

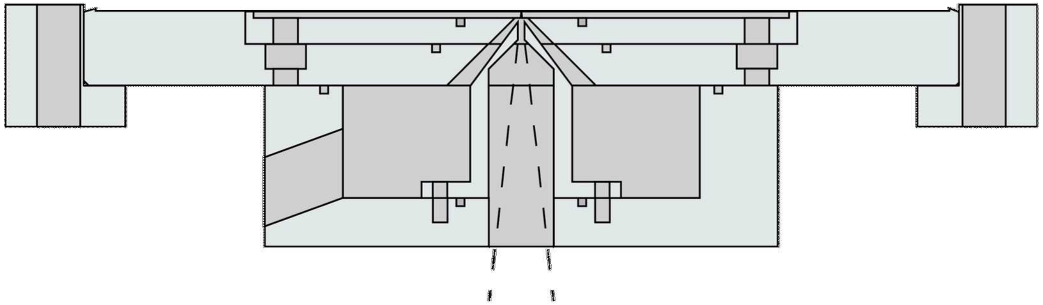
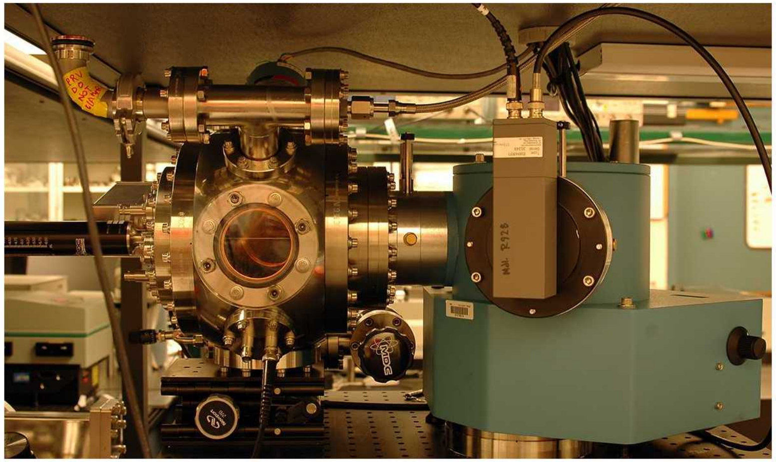
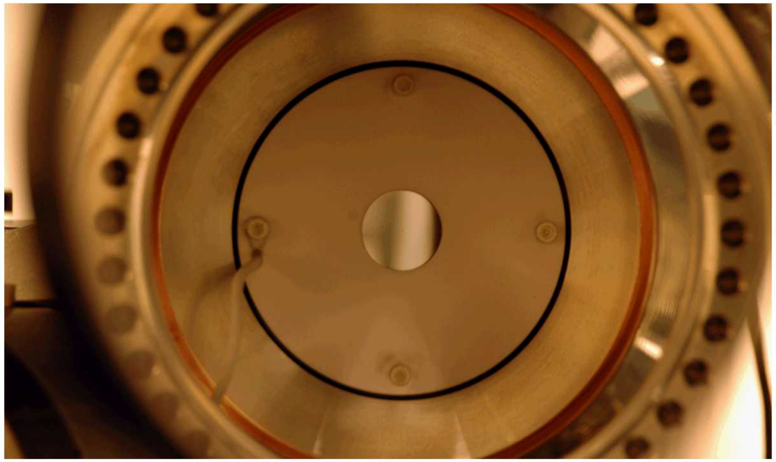


Figure 8 Two-stage differential pumping apparatus designed for coupling to VUV spectrometer and ion energy analyzer.

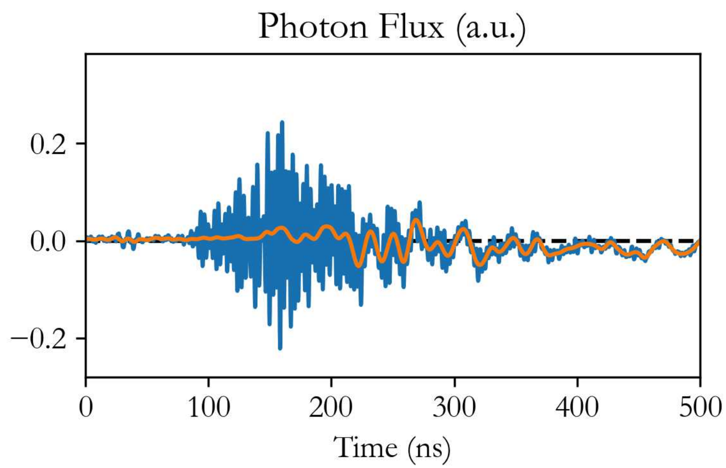
Experimental Setup

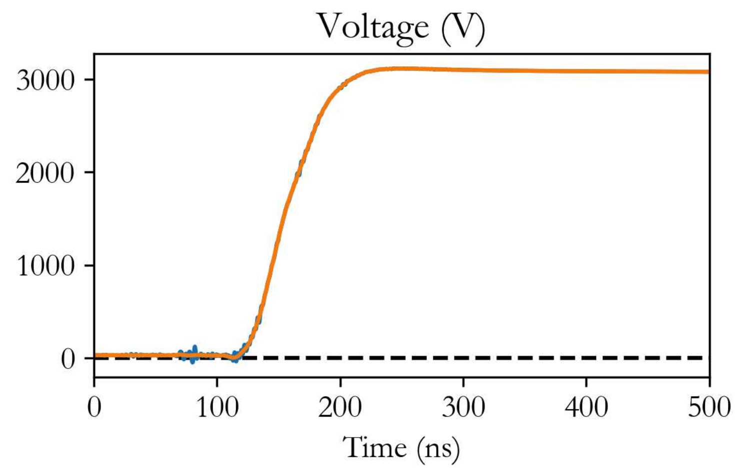
- Platinum-coated Si cathode
- 100 μm diameter aperture
- McPherson 234/302 vacuum spectrometer
  - 2,400 g/mm platinum grating
  - PMT detector with phosphor
- UV photodiode used for triggering breakdown
- DEI PVX-4140 high voltage switch
- Isolated ground return for current sensing

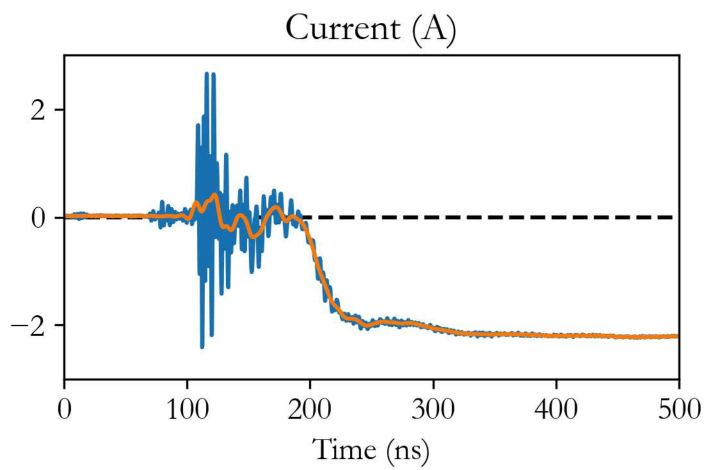


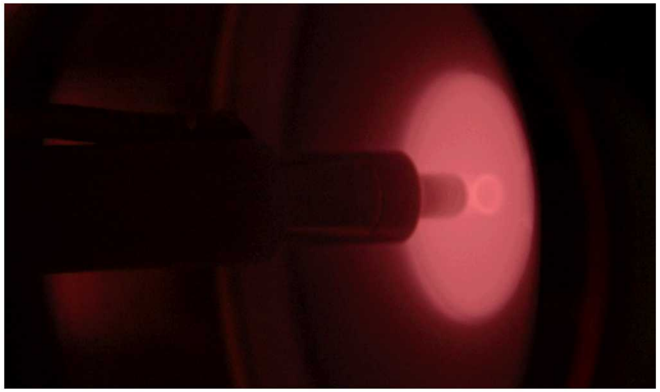


Experimental Waveforms









Conclusions and Future Work

- Use recent algorithmic advances in photon transport (Roberds, GT1.00078)
- Assess effects of additional plasma chemistry
- Improve differential pumping system
  - Higher operating pressures
  - Reduced photon diffusion in spectrometer
- Measure dynamic line shape profile of VUV photons for Doppler shift effects
- Improve "1D-ness" of system
- Incorporate ion energy measurements
- Examine effect of changing cathode materials
- Expand measurement parameter space

Citations

- Smirnov, Boris M. "Atomic structure and the resonant charge exchange process." *Physics-Uspekhi* 44.3 (2001): 221.
- Ralchenko, Yu, et al. "Electron-impact excitation and ionization cross sections for ground state and excited helium atoms." *Atomic Data and Nuclear Data Tables* 94.4 (2008): 603-622.
- Fierro, Andrew, et al. "Radiation transport in kinetic simulations and the influence of photoemission on electron current in self-sustaining discharges." *Journal of Physics D: Applied Physics* 50.6 (2017): 065202.
- Phelps, A. V., and Z. Lj Petrovic. "Cold-cathode discharges and breakdown in argon: surface and gas phase production of secondary electrons." *Plasma Sources Science and Technology* 8.3 (1999): R21.