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Two-Dimensional Profiles of Electron and Metastable Helium Production in Fast Ionization Wave Discharges of Positive Polarity

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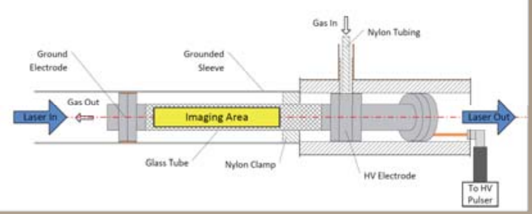
1. BACKGROUND

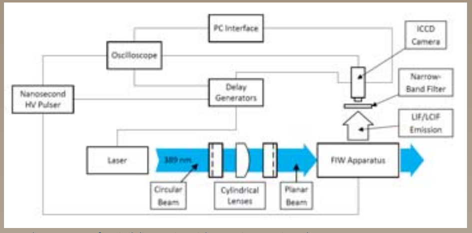
- Fast ionization waves (FIWs): high overvoltage with nanosecond duration → production of large-volume, high density plasma at higher pressures than in conventional low temperature discharges
- Possible applications for FIW discharges:
  - Plasma-assisted combustion [1]
  - High-pressure plasma chemistry
  - Pulsed UV light sources / laser pumping [2]
  - X-ray/runaway e⁻ generation at elevated pressure [3]
- Challenges with Fast Ionization Waves
  - Optimizing energy deposition and discharge uniformity
  - Predicting dependence of FIW parameters (density, EEDF, etc.) on controlled variables (pressure, bias, etc.)
  - Experimental benchmarking of numerical models
- Laser plasma diagnostics allow for spatially resolved measurements of FIW discharge properties on nanosecond timescales

2. EXPERIMENTAL SETUP

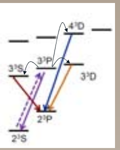


Schematic of Fast ionization wave discharge chamber.

- Setup Dimensions:
  - 3.3 cm ID x 25.4 cm long quartz
  - Coaxial shield: 7.3 cm ID
  - HV electrode inside Teflon sleeve within sheet metal shield
  - Imaged area: 20 - 140 mm from downstream ground electrode
- Discharge Properties
  - Helium feed gas
  - Variable pressure 1 - 20 Torr
  - Positive polarity, ~14 kV (open load) HV pulses
  - 20 ns duration, 3 ns rise time
  - 1 kHz pulse repetition rate



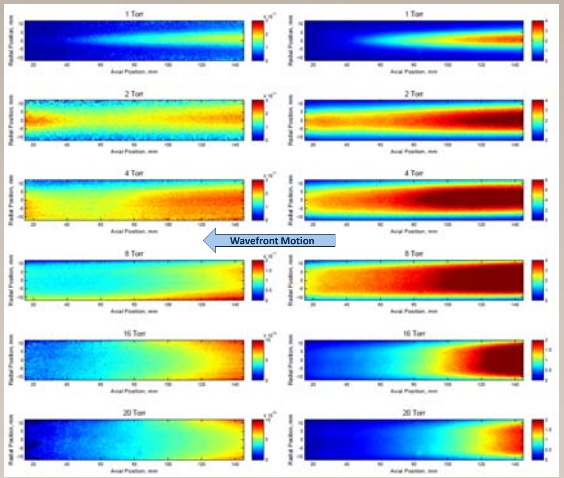
Above: Layout of optical diagnostics; Right: He LCIF pumping scheme



- Laser Collision-Induced Fluorescence (LCIF) [4]
  - For helium, 389 nm laser pumps 2^3S → 3^3P
  - Electron collisions with pumped atoms redistribute energy level populations
  - Ratio of 3^3D → 2^3P (588 nm) to 389 nm emission scales w/ absolute electron density
  - 389 nm LIF → relative metastable density

3. RESULTS

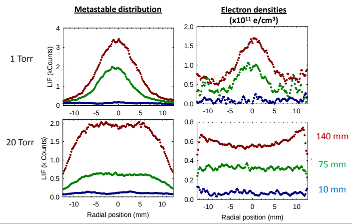
2-D LCIF Images – Electron and Metastable Densities



Left: Images of absolute electron density; Right: Relative metastable density. Images taken 100 ns after HV pulse

- Radial distribution of electron and metastable densities shows clear trend pressure increase: **transition from center-peaked to wall-peaked profiles**
- Maximum electron density achieved when profile approaches uniformity
- Discharge closes gap in high density, volume-filling cases

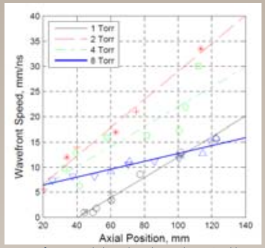
Radial Profiles



- Discrepancy in radial distributions of e- and metastables…
  - High energy e⁻ (several tens of eV)? Photoionization?

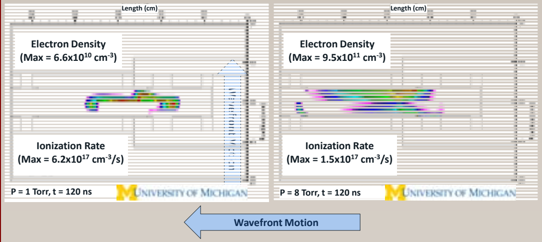
Wavefront Velocity

- Optical emission taken from 2 to 20 ns capture FIW motion
- Deceleration along gap at all pressures
- 1 Torr: Wave stalls before closing gap, as seen in images
- High wave velocities @ 2-4 Torr; near pressure regime with largest densities



Wavefront speed along the tube, as determined by 389 nm and 588 nm plasma-induced emission

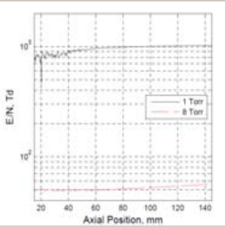
2-D Simulation Results



- FIW setup was modeled in 2-D with variable pressure (Xiong & Kushner)
- Model confirms trends in spatial profiles – center-to-wall transition
- In simulation, e⁻ & metastable profiles are **nearly identical** to each other
  - Resolving this difference → **New physical insights!**

Effective E/N Profiles

- No variation in LCIF images over40-100 ns
- Residual ionization << ionization in wavefront
- With estimates of initial n_e, change in n_e → ionization rate constant → effective E/N in wavefront
- E/N decreases along the discharge due to residual E-field behind wavefront



Estimated values of E/N in wavefront, on axis, determined from initial and final electron densities

4. SUMMARY / FUTURE WORK

- LCIF/LIF imaging has been demonstrated as a powerful technique for studying the production of electrons and metastable atoms in helium fast ionization waves
- Spatial uniformity of electron and metastable production in FIWs depends strongly on pressure, corresponding to trends in the peak values of electron / metastable density and FIW wavefront velocities.
- Profiles of metastable and electron densities suggest that the EEDF in the wavefront may include a large high-energy population, or that photoionization processes may play an important role.
- 2-D numerical models of FIW propagation confirm the transition in radial density profiles as pressure is varied. Further study of the difference between experiment and model regarding metastable production should yield new insights into FIW discharge physics.
- With estimates of initial electron densities, the decay of effective E/N in the wavefront can be calculated from the corresponding electron densities after the pulse.

- **Suggested future studies include:**
- Measurement of absolute metastable and excited state densities for independent calculation of effective E/N
- Use temperature-sensitive LCIF to estimate electron temperatures just after the passing of the FIW
- Dependence of FIW profiles on repetition rate, initial electron density, and electrode geometry
- LCIF/LIF imaging of single-shot FIW afterglow
- Experimental study of dielectric charging and photoionization effects on FIW properties.

5. REFERENCES / ACKNOWLEDGEMENTS

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