Transient characteristics of a pulsed helium positive column as measured with laser-collision induced fluorescence

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Outline

- Extend laser-collision induced fluorescence diagnostic into higher pressure application space
  - Laser-collision induced fluorescence (LCIF) primer
  - Calibration of alternative spectroscopic pathways
- Application of LCIF to transient positive column
  - “Unexpected” non-monotonic radial distribution of $2^3\text{P}$ states
  - Predictive simulations that capture observations
- Conclusions and next steps
LCIF is based on redistribution of excited state by plasma electrons

- Laser excitation causes populates an intermediate state
  - Relaxation processes deplete excited state
- Portion of excited state population gets redistributed into "uphill" states
  - Driven by energetic species such as plasma electrons

\[ \Delta N_{i,j} \sim K_{i,j}^{e}(T_e) n_e \times \Delta N_{Pumped} \]

**Ratio**

\[ \frac{\Delta N_i}{\Delta N_{Pumped}} \sim K_i^{e}(T_e) n_e \]

\[ \frac{\Delta N_j}{\Delta N_i} \sim \frac{K_j^{e}(T_e)}{K_i^{e}(T_e)} \]

**LCIF looks for changes in emission of neighboring states after laser excitation**
Alternative spectroscopic pathways are investigated

- Atomic helium is utilized
  - Spectroscopically “simple”, “well known” rates
- Radiation trapping of LIF becomes problematic at higher pressures and for large volume plasmas
  - Degrades spatial resolution of the diagnostic technique

**Previous approach**

- $2^3S$ → $2^3P$
- $2^3P$ → $3^3P$
- $3^3P$ → $4^3D$
- $4^3D$ → $5^3S$

$\Delta E \sim 0.7 \text{ eV}$

$\Delta E \sim 0.07 \text{ eV}$

$\Delta E \sim 0.14 \text{ eV}$

$\Delta E \sim 0.38 \text{ eV}$

**New approach**

- $2^3S$ → $2^3P$
- $2^3P$ → $3^3D$
- $3^3D$ → $4^3D$
- $4^3D$ → $5^3S$

$\Delta E \sim 0.7 \text{ eV}$

$\Delta E \sim 0.14 \text{ eV}$

$\Delta E \sim 0.38 \text{ eV}$

Pumping less populated $2^3P$ state enables higher pressure interrogation
Pulsed positive column is utilized to benchmark LCIF technique

- Pulse discharge currents generate broad density range
  - ~ 50 Microseconds, 80 GHz interferometer
- Compute drift velocities and extract electron temperatures
  - Use measured currents, densities and published drift parameters

Positive column

Measured waveforms

Helium drift parameters

Observations made during calibration of the LCIF technique generated dialogue with collaborating institutions

Simple three state model predicts observed LCIF trends

- Utilize simple set of coupled equations to compute evolution of the system
  - Not self consistent, but sidesteps many unknowns
  - Rely on functional forms of excitation cross sections
- Ratios of emitted light are used to measure $n_e$ and $T_e$

## Key Scaling Trends

**Electron density**

- $n_e$ trends are independent of electron temperature and gas pressure

[Graph showing electron density trends over time and pressure]

**“Electron Temperature”**

- $T_e$ trends over different pressures

[Graph showing electron temperature over electron density and different pressures]

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“Unexpected” structure observed during calibration of the LCIF diagnostic

- Off-axis peak excitation is observed in $2^3P$ species
  - Electron densities remain peaked on-axis

**Observed Behavior**

<table>
<thead>
<tr>
<th>Distance from the cathode</th>
<th>Radial position</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 mm</td>
<td>-15 mm</td>
</tr>
<tr>
<td>70 mm</td>
<td>15 mm</td>
</tr>
<tr>
<td>120 mm</td>
<td>+15 mm</td>
</tr>
<tr>
<td>70 mm</td>
<td>+25 μs</td>
</tr>
</tbody>
</table>

- 3.5 Torr Helium, 1.2 Amps

Interesting profiles… so what is happening?
Various mechanisms might generate observed behavior

- Observations similar to phenomena reported in literature
  - Nonmonotonic excitation – non-local effects on EEDF (not for Helium)
  - Gas heating and possible constriction – rarefaction and or non-linear effects

- Difficult to extrapolate to experimental results
  - No direct one to one set of conditions between observed and reported behavior

"Paradoxical" Nonmonotonic excitation

Excited state density

R.R. Arslanbekov, V.I. Kolobov, E.A. Bogdanov and A.A. Kudryavtsev
APL 85, 3396 (2004)

Gas heating or constriction

Yu B Golubovskii, V. Nekuchaev, S. Gorchakov and D. Uhrlandt

Are these effects present in our experiment?
Predictive simulations guide understanding of the observed trends

- **Fluid based simulations emulate helium positive column**
  - Fluid plasma model (with Maxwellian and non-Maxwellian EEDF), gas heating, Poisson solver for radial electrostatic potential, self-consistent simulation of axial electric field
  - Different chemistry model(s) including stepwise ionization and collision-radiative effects
  - **Dynamic Regime** of discharge operation with strong oscillations of the axial electric field

- **Simulations capture qualitative behavior of the positive column**
  - Reasonable agreement in electron densities ($10^{12}$ e/cm$^3$), electron temperatures (2 eV) and E/N (≈ 5 Td)

**Gas heating does not appear to be significant contributor to observed behavior**
Fluid-based simulations predict non-monotonic profiles

- Structure of the transient column depends on operating conditions
  - Non-monotonic profiles are observed at higher pressures and higher currents

*Predicted non-monotonic behavior is not a kinetic effect*
Distribution of $2^3P$ tracks relaxation of global drift parameters

- **Competition between creation and depletion of the excited state**
  - Higher $E/N$, $T_e$ – Center peaked $2^3P$ distribution
  - Reduced $E/N$, $T_e$ – Non-monotonic or off axis $2^3P$ distribution

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**Global behavior**

1.7 Torr  
3.5 Torr

**Localized behavior**

1.7 Torr  
3.5 Torr

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Work in progress and continues to develop
Summary

- **LCIF extended to higher pressures by exciting from \(2^3P\)**
  - Avoid radiation trapping
  - Calibration shows good linearity over pressure range investigated

- **Unanticipated radial structure in laser-interrogated \(2^3P\) states**
  - Also observed in \(2^3S\) states (not discussed)
  - Predicted in fluid-based models

- **Behavior is thought to be correlated to E/N and electron temperature**
  - Recovery of profiles observed with higher E/N
  - Simulations indicate results are sensitive to plasma “chemistry” (not discussed)

- **Dynamic regime of discharge operation is favorable for controlling electron kinetics and reducing instabilities (constriction, striations)**

*This work was supported by the Department of Energy Office of Fusion Energy Science Contract DE-SC0001939*
Backup
Pump out of alternative helium states

- At higher pressures and densities, $2^3P$ state becomes adequately populated
  - Comparable oscillator strengths (into comparable levels)
  - Sufficiently lower population compared to $2^3S$

Scaling

$2^3S$ State:

$$n_{2(3)S} \sim \frac{K_{0->S}^e}{K_{S->P}^e} n_0 \sim 10^{-5} n_0$$

$2^3P$ State:

$$n_{2(3)P} \sim \frac{1}{A_{P->S}} \left[ K_{0->P}^e + K_{S->P}^e \right] n_0 n_e$$

Trends

"Not ok"

"ok"

Low $2^3P$ state densities should be high enough to pump but low enough not to trap
Helium becomes problematic at higher pressures and for mixed atmospheres

- Helium proved to be well suited for lower pressure and lower densities
  - Limited spectroscopic pathways
  - Well known cross-sections
  - Highly populated, long lived $2^3S$ metastable state

- As density increases and as composition changes
  - Radiation trapping/transport becomes problematic - limits spatial resolution
  - Collisional quenching with other species depletes metastable - limits signal

$$\tau \approx f_{nm} \lambda \left(\frac{MC^2}{kT_A}\right)^{1/2} N_A L \ll 1$$

<table>
<thead>
<tr>
<th>Transition</th>
<th>$f_{nm}$</th>
<th>$\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$3^3P \rightarrow 2^3S$</td>
<td>0.064</td>
<td>&gt;1</td>
</tr>
<tr>
<td>$4^3P \rightarrow 2^3S$</td>
<td>0.02</td>
<td>~1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Transition</th>
<th>$f_{nm}$</th>
<th>$\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2p_{10} \rightarrow 1s_5$</td>
<td>0.17</td>
<td>&gt;&gt;1</td>
</tr>
<tr>
<td>$3p_{10} \rightarrow 1s_5$</td>
<td>$9 \times 10^{-4}$</td>
<td>0.08</td>
</tr>
</tbody>
</table>

(Assuming $L=1$ cm and $N_A \sim 10^{13}$ absorbers/cm$^3$)

Low oscillator strengths and possibly lower densities make argon attractive
Experimental implementation of the LCIF is realized

- Nanosecond pulsed laser used for excitation
  - < 10 ns FWHM, ~ 0.02 cm\(^{-1}\) line width
- Timing of experiment controlled by delay generators
  - Move experiment and imaging with respect to firing of the laser
- Image LCIF with gated-intensified CCD
  - Narrow (~ 1 nm FWHM) interference filters centered on lines of interest
- Take two images per transition considered
  - Total emission and plasma induced emission (PIE) - subtract the two

**Optical setup**

**Timing sequence**

Need to make six (3 x 2) measurements to obtain \(n_e, kT_e\)
Global transient trends

1.72 Torr

3.5 Torr

7.011 Torr

Current (A)

E/N (Td)

Time (ms)

471 nm intensity

Plasma current

ne - mwave

ne - LCIF

kT_e (eV)

E/N

kT_e

Time (ms)

LCIF

PIE

ne (x10^{12} e/cm^3)