Time resolved evolution of transient plasmas as measured with laser-collision induced fluorescence

2010 GEC-ICRP, Paris, France
Edward V. Barnat and Kraig Frederickson
Sandia National Laboratories
Albuquerque, N.M.

This work was supported by the Department of Energy Office of Fusion Energy Science
Contract DE-SC0001939

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.
LCIF provides 2D snapshots of plasma density and temperature

- **Motivation:** What is the density? What is the temperature? Where and When?
  - Electrical probe based techniques may couple and perturb
  - Optically passive techniques are line-of-sight limited
  - Optically active-techniques such as Thomson scattering pose their own set of challenges

- **In this presentation**
  - Laser-collision induced fluorescence (LCIF) primer
    - Describe LCIF technique and application to triplet manifold of Helium
    - Experimental implementation of LCIF
  - Applications of LCIF
    - Pulsed plasmas
    - Transient anodic plasma structure
    - Ion sheath expansion and collapse
  - Future directions and concluding thoughts
LCIF technique relies on redistribution of excited states by (electron) collisions

- This is LCIF
  - Electrons redistribute laser-excited population
  - Monitor changes in emission from coupled states
- Employ a collisional-radiative model (CRM) to predict redistribution
  - Utilize limited basis of states to reduce number of equations
  - Helium, 15 states (ground + 14 triplet states)

\[ \frac{dN_j}{dt} = \sum_{i \neq j} K^e_{ij} N_i - \sum_{i \neq j} K^e_{ji} N_j n_e + \sum_{i > j} A_{ij} N_i - \sum_{i < j} A^l_{ji} N_j + \sum_k \left[ \sum_{i \neq j} K^a_{ikj} N_i - \sum_{i \neq j} K^a_{jki} N_j \right] N_k \]

- Electron density and electron temperature appear in first term
  - Temperature dependence introduced via \( K^e_{ij} t \)
    \[ K^e_{ij} = \langle \sigma_{ij} v_e \rangle = \left( \frac{m_e}{2\pi k T_e} \right)^{\frac{3}{2}} \int_0^\infty \sigma_{ij}(v) \exp \left( -\frac{m_e v^2}{2k_B T_e} \right) 4\pi v^2 dv \]
- Technique has been employed for over 30 years

We extend the technique for use in two-dimensions and obtain time resolved information
Ratios of intensity are utilized for determining $n_e$, $kT_e$

- **Utilizing ratio of intensities**
  - Eliminate problems associated with absolute calibration
  
  \[ \Delta N_j \sim K_{0j}^e n_e \times N_0 \times \Delta t \quad \Rightarrow \quad \frac{\Delta N_j}{N_0} \sim K_{0j}^e n_e \times \Delta t \]

- **Capitalize on weak $kT_e$ dependence of $3^3P \rightarrow 3^3D$**
  - Ratio of 588 nm to 389 nm yields $n_e$;
  - Ratio of 447 nm to 588 nm yields $kT_e$

- Only need to make three measurements to obtain $n_e$, $kT_e$
Experimental implementation of the LCIF is realized

- Nanosecond pulsed laser used for excitation
  - < 10 ns FWHM @ 20 Hz
- 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

Observer sequence

Optical setup

Timing sequence

Need to make six (3 x 2) measurements to obtain $n_e$, $kT_e$
Experiment designed for flexibility

- Time modulated rf plasma
  - Generate metastable "seed" to prepare for transient measurements
- Segmented electrodes
  - Positive and or negative polarity pulses
- Computer controlled delays
  - Time step across event of interest

Setup

Timing sequence

Examine phenomena on different spatial and temporal scales
Plasma generated by time modulated anode tests
LCIF technique

- Challenging plasma system
  - Dynamic plasma potential
- Examine time evolution of transient plasma
  - RF afterglow, 50 mTorr He
  - Positive pulse bias (~ 1 kV) applied to planar electrode

Setup and behavior

Viewing area

Two dimensional images vary by orders of magnitude in intensity
LCIF data analyzed with CRM predictions to yield $n_e$, $kT_e$

- Trends analyzed with CR model
  - Produce $n_e$, $T_e$ as functions of time

Densities and temperatures vary by orders of magnitude; rates demonstrate different time scales
Transient structure of plasma observed after pulse excitation

- Closer analysis of initial plasma distribution
  - Use smaller (25 mm) diameter electrode, 100 mTorr afterglow

Initial plasma distribution is unstable
Higher energy electrons observed around edge of anode plasma

- Temperature measurements made for +900 ns case
  - Challenging measurement because of low level signals

Electron Densities

Electron Temperatures

Electrons energized by localized electric fields supporting double layer

LCIF captures 2D-sheath formation

- Examine evolution and structure of ion sheath
  - -1 kV, 1 μs bias applied to inner electrode, 5 μs after + pulse ends
  - 20 ns snapshots of LCIF

Transient sheath dynamics captured by LCIF
Concluding remarks and future directions

- **LCIF technique demonstrated in 2D**
  - Good spatial resolution – limited by optical collection
  - Decent temporal resolution – limited by ICCD gate times & tolerable signals

- **Technique should be extendable over broad parameter space**
  - Higher pressures – neutral collisions
  - Other atomic systems - Argon

- **Looking into**
  - ECR based plasma systems (B. Weatherford and J Foster, U. Michigan)
  - Rare gas/Hydrogen mixtures (A. El Saghir and S. Shannon, NC State)
  - Fast Ionization wave (W. Lempert and I. Adamovich, Ohio State)
Helium atom serves as target species for LCIF measurements

- Employ Helium to start with
  - "Simple system" with "better known" rates
- Utilize functionalized form of cross-sections compiled by Ralchenko\(^1\)
  - Integrate to get rates, compare to measured rates\(^2,3\)

Key transitions

**Computed and measured excitation rates in Helium**


Accuracy of \(n_e, T_e\) depend on knowledge of \(K_{ij}(kT_e)\)
CRM predicts evolution of various Helium states after laser excitation

- Computed evolution of LCIF
  - After laser excitation of $3^3P$ from $2^3S$
- Temporal evolution may serve as "fingerprint" of electron interaction
  - Below $n_e \sim 10^{11}$ absolute intensities are needed
  - Analyze shape of decay above $n_e \sim 10^{11}$ electrons/cm$^3$

*Computed temporal evolution*

\[
\begin{align*}
3^3P & \rightarrow 2^3S \\
& (389 \text{ nm}) \\
3^3S & \rightarrow 2^3P \\
& (707 \text{ nm}) \\
3^3D & \rightarrow 2^3P \\
& (588 \text{ nm}) \\
4^3D & \rightarrow 2^3P \\
& (447 \text{ nm})
\end{align*}
\]

- $n_e = 10^{10}$ e/cm$^3$
- $n_e = 10^{11}$ e/cm$^3$
- $n_e = 10^{12}$ e/cm$^3$

Need at least two time-resolved profiles to uniquely obtain $n_e, kT_e$
References for rates and cross-sections

- **Superelastic**
  - Klein Rosseland
  - Sobelman

\[ K_{ij}^e = \left\langle \sigma_{ij} v_e \right\rangle = \left( \frac{m_e}{2 \pi k T_e} \right)^{\frac{3}{2}} \int_0^\infty \sigma_{ij}(v) \exp\left( \frac{-m_e v^2}{2 k_b T_e} \right) 4\pi v^2 dv \left[ \frac{g_j}{g_i} \exp\left( \frac{E_j - E_i}{k_b T_e} \right) \right] \]