SAND2015-3063C

Development and Calibration of Electron Density Measurements Using Laser-Collision Induced Fluorescence

1st EPS Conference on Plasma Diagnostics

Frascati, Italy, April 14'th 2015

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

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LOCKHEED MARTIN

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Laser-collision induced fluorescence provides measure of electron density and "temperature"

- **Motivation: What is the density? What is the temperature? Where and When?**
  - More traditional probe 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**
  - Part I: Laser-collision induced fluorescence (LCIF) primer
    - Overview of the LCIF technique
    - Physics that governs LCIF and trends predicted by this physics
  - Part II: Implement and benchmark technique
    - Experimental setup
    - Time evolution of LCIF and time integrated LCIF
  - Part III: Applications of LCIF:
    - Dynamic and structured plasmas
  - Part IV: Future directions and concluding comments
    - Investigate argon
    - Proceed to higher pressures

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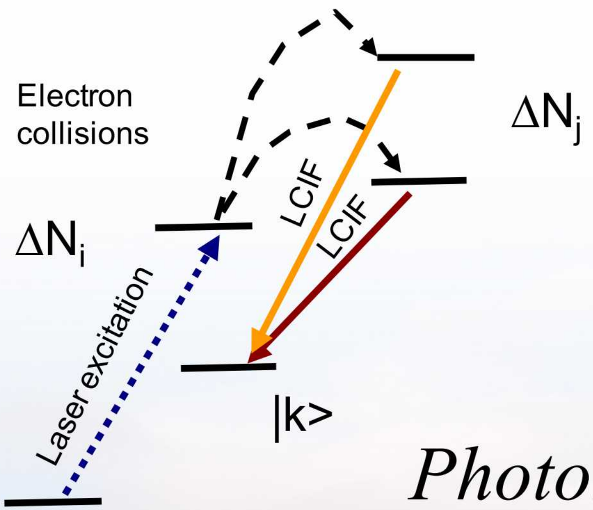
LCIF is based on redistribution of excited state by plasma species (electrons)

- **Pulsed laser excitation populates an intermediate state**
  - Relaxation processes deplete excited state
- **Portion of excited state population gets redistributed into "uphill" states**
  - Driven by interaction with energetic plasma species (electrons).



Electron- coupled interaction

$$\Delta N_j \sim K_{ij}^{e} n_e \times \Delta N_i \times \Delta t$$

Change in upper state due to excited state

$$Photons\ emitted \sim A_{jk} \times \Delta N_j \times \Delta t$$

Detected light

LCIF looks for changes in emission of neighboring states after laser excitation

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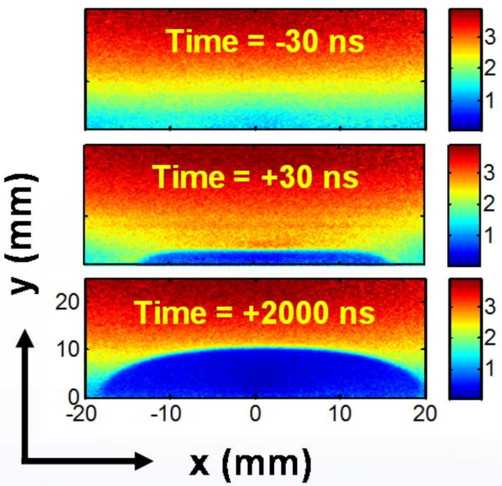
LCIF has been considered throughout the years

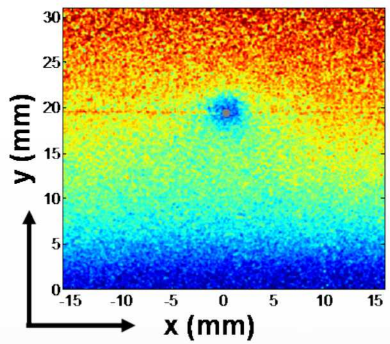
- **Laser-collision based techniques have been considered by many groups**
  - Burrell and Kunze - Collision rates (1978)
  - Tsuchida - First to use for density? (1983)
  - Den Hartog - 1D Sheath (1989)
  - Dzierzega - quasi 2D profiles GEC @ NIST (1996)
  - Stewart - CW LCIF (2002)
  - Nersisyan - He Metastable atmospheric plasma (2004)
  - Krychowiak - TEXTOR (2008)

Work performed at SNL builds on this work to construct temporal and spatial maps of densities and "temperatures"

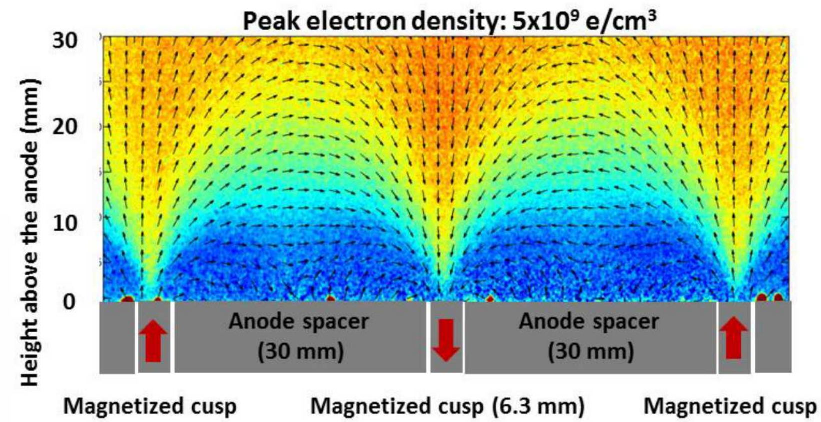
Work performed at SNL focused on 2D maps of electron densities and temperatures

Ion sheaths

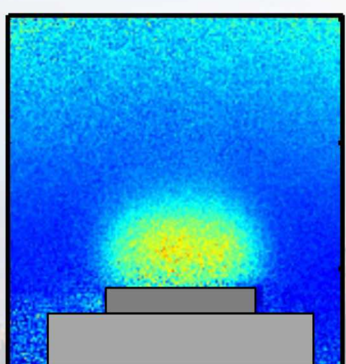


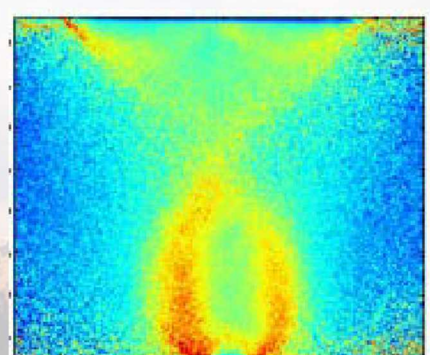


Magnetized plasmas

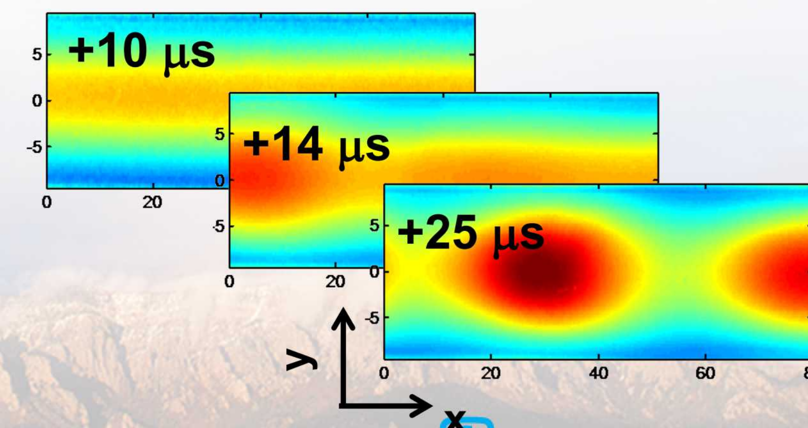


Double layers





Positive columns



Redistribution of laser excited states can be a complex process

- **A "good" model is required to predict transfer between levels.**
  - Employ a collisional-radiative model (CRM) to predict redistribution of
- **Sets of coupled equations scale with the number of states needed to be accounted for.**
  - Uncertainties will scale with the number of unknowns
  - Limit sets of interactions that are "most likely" going to impact system response

"Photon mixing" ***"Electron mixing"*** ***"Neutral mixing"***

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

Absorption and emission

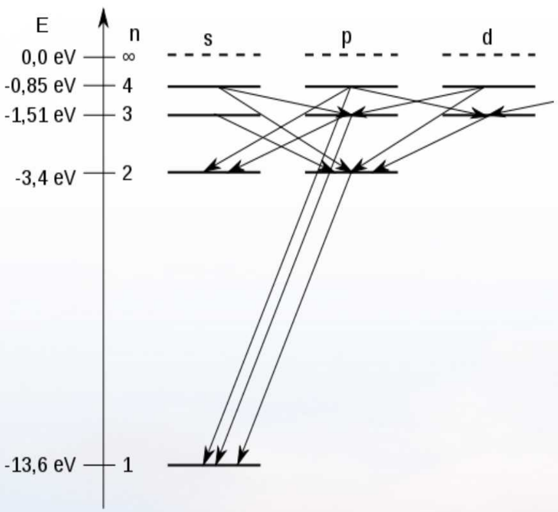
Excitation into and out of states

Redistribution

Complexity of many atomic systems LCIF "challenging"

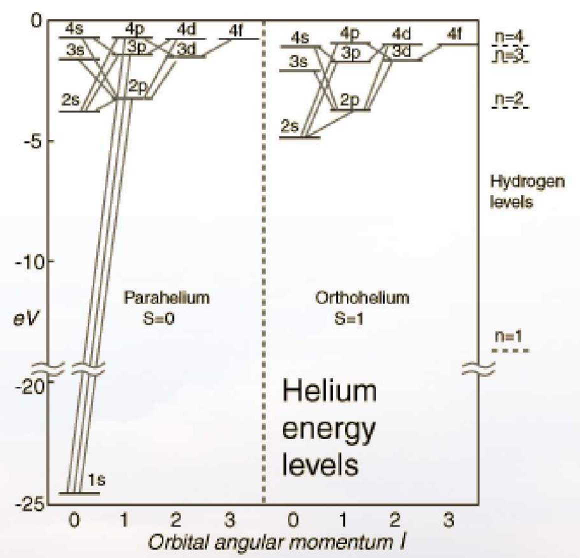
- **Atomic structure will govern which pathways are accessible for LCIF**
  - **Which states radiate, and are they uniquely detectable**

Hydrogen



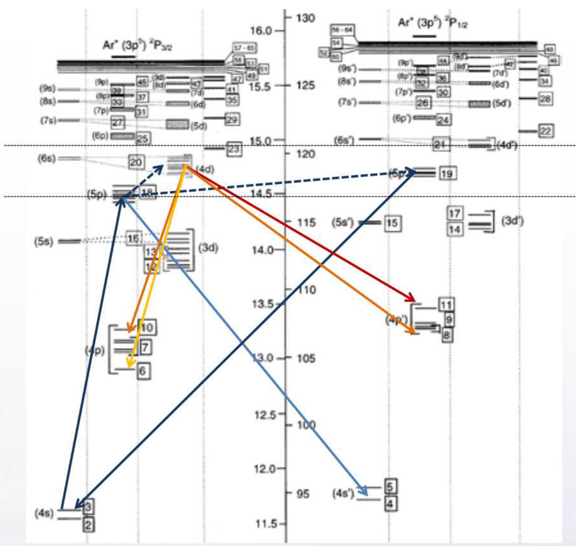
http://commons.wikimedia.org/wiki/File:Grotrian_H.svg

Helium



http://hyperphysics.phy-astr.gsu.edu/hbase/quantum/helium.html

Argon



Taken from Bogearts et. al, J. Appl. Phys. **84**, 121, 1998

The number of interactions that need to be accounted for scales with complexity of the system

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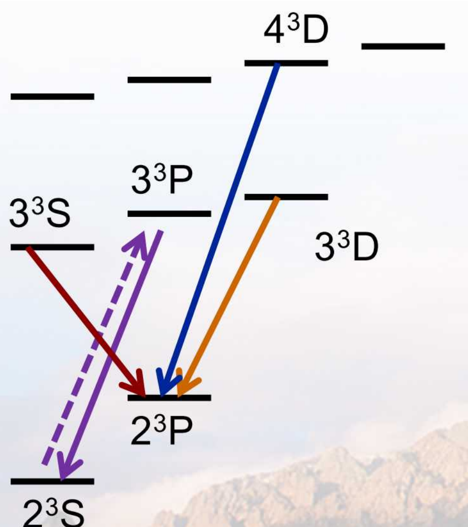
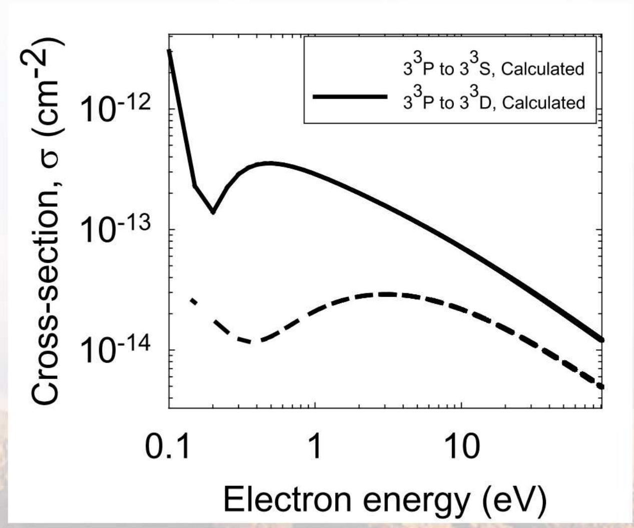
Helium atom serves as target species for LCIF measurements

- **Limited excitation/ de-excitation pathways.**
  - Hydrogen is simpler, but restricted pathways.
  - Neon, Argon, etc… more complex structure.
- **Cross-sections between states are well known.**
  - Inter-state transitions between high lying states are “known” for helium.
  - Utilize functionalized form of cross-sections compiled by Ralchenko[1]

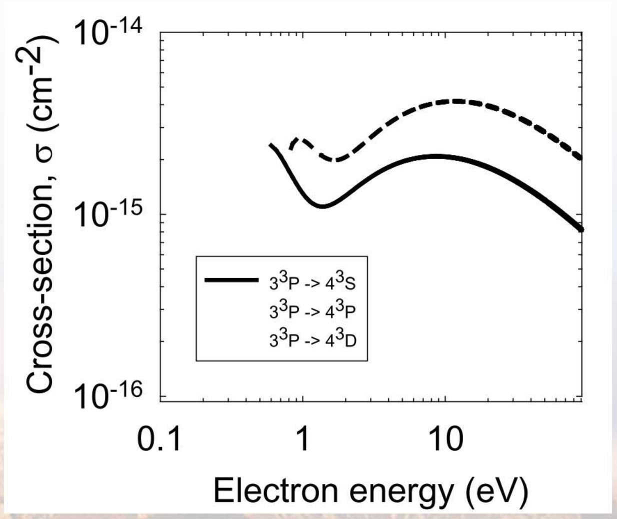
Key transitions



$3^3P \rightarrow 3^3S$, 3^3D



$3^3P \rightarrow 4^3S$, 4^3P, 4^3D



Principles extend to other systems

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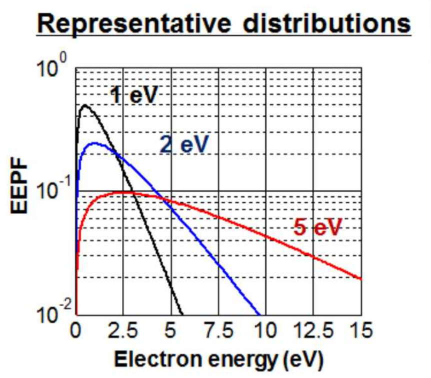
1: Yu. Ralchenko, R. K. Janev, T. Kato, D. V. Fursa, I. Bray, F. J. De Heer, Atomic Data and Nuclear Data Tables **94**, 603 (2008)

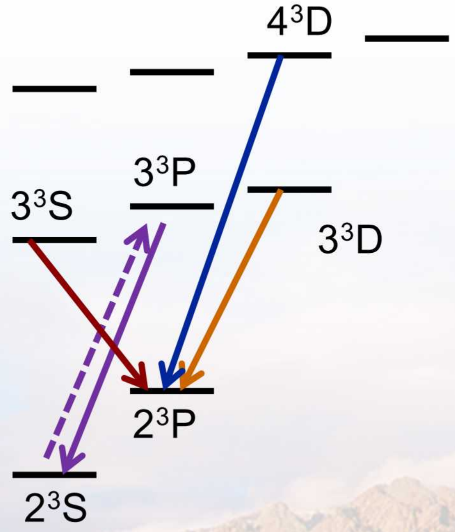
Electron-induced collision rates are computed from cross-sections and electron distribution functions

- **Functional dependence of collision rates are computed as a function of "effective" electron temperature**
  - Explicit dependence on EEPF will influence these curves

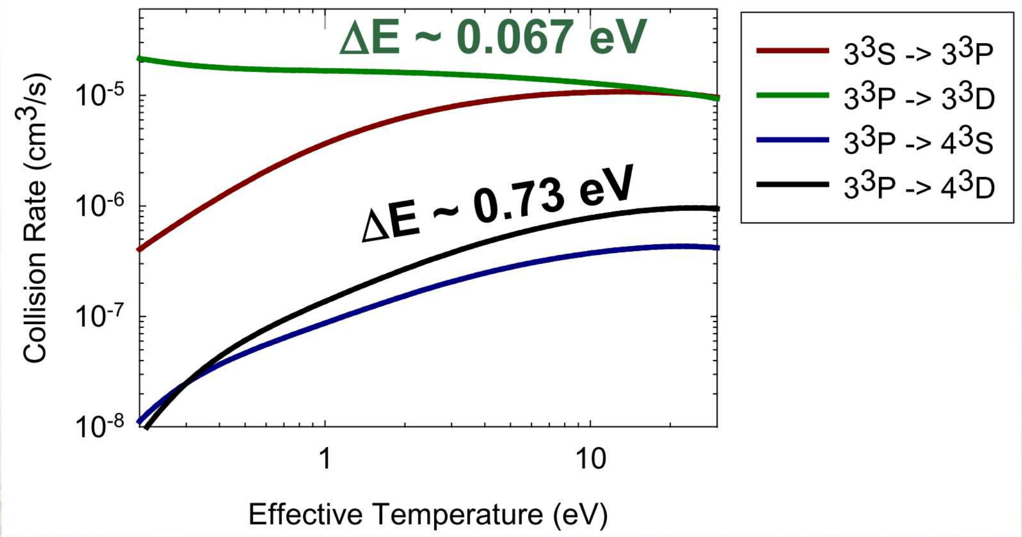
$$K_{ij}^{e} = \left\langle \sigma_{ij}(E) v_e(E) f(E) \right\rangle$$



Key transitions



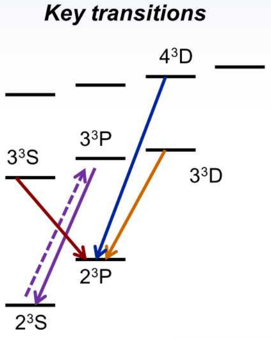
Key Rates



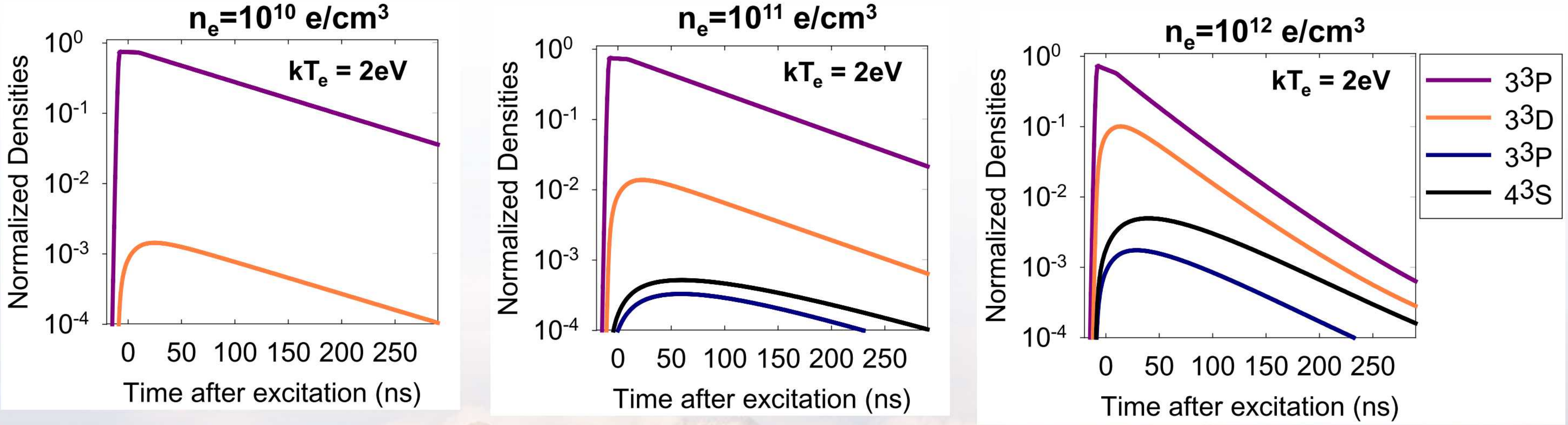
Barrier between states plays key role in population transfer processes

Electron-induced collisions are observable in energetically "up hill" transitions

- **Solution of the CRM including both electrons and radiative decay.**
  - Electrons redistribute excited state to near by states
- **There are two key-observables obtained from these simulations**
  - Degree of re-distribution scales with collision rate (n_e, T_e)
  - Lifetime of excited states become truncated at higher densities ($K \times n_e \sim A$)



Representative state populations after excitation



Temporal integration of light detected serves to simplify LCIF implementation

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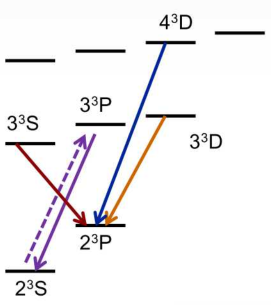
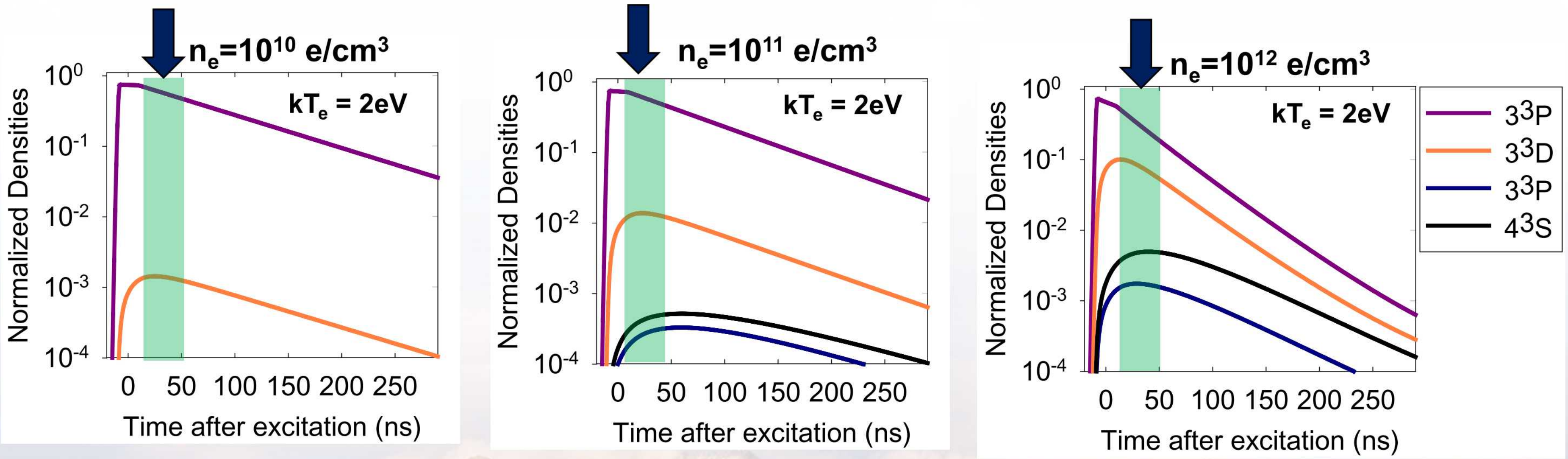


Representative state populations after excitation



Temporal integration of light detected serves to simplify LCIF implementation

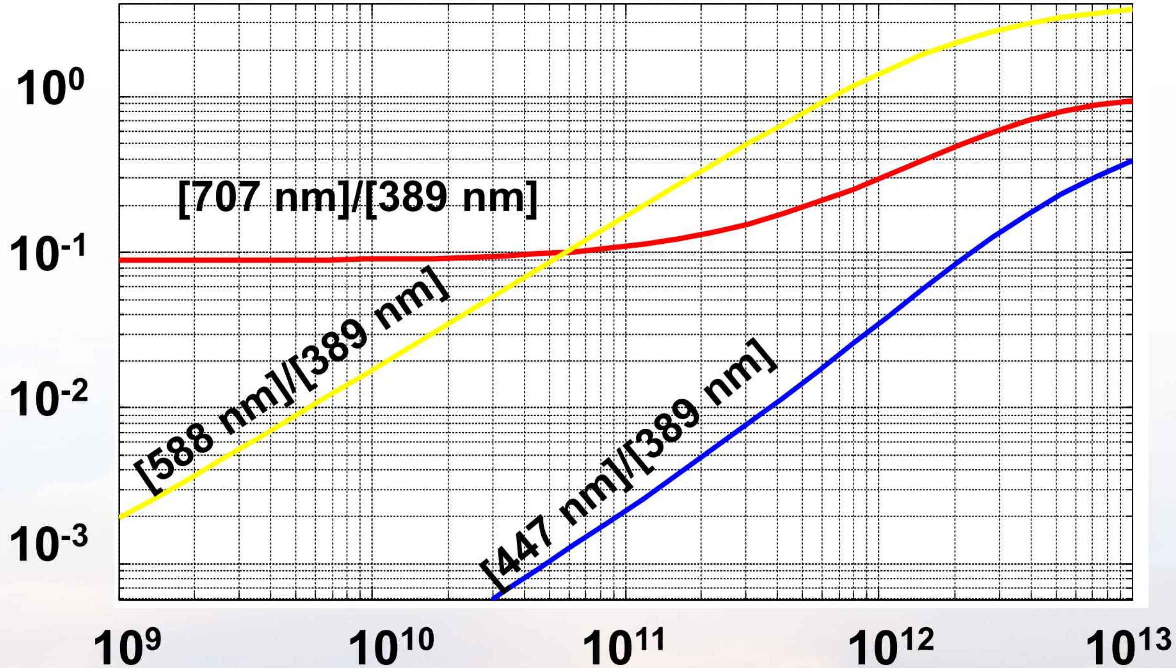
Ratio of LCIF to LIF yields electron induced excitation rates

- **Ratios constructed from LCIF and LIF from the laser excited state yields rates**
  - Eliminated dependence of exact knowledge of how much excited state was generated

Ratio between LCIF and LIF

$$\frac{\Delta N_j}{N_{3^3P}} \sim K^e_{3^3P->j} n_e \times \Delta t$$

Ratio of LCIF to 389 nm LIF



Provides a direct measure of n_e if K is independent of T_e

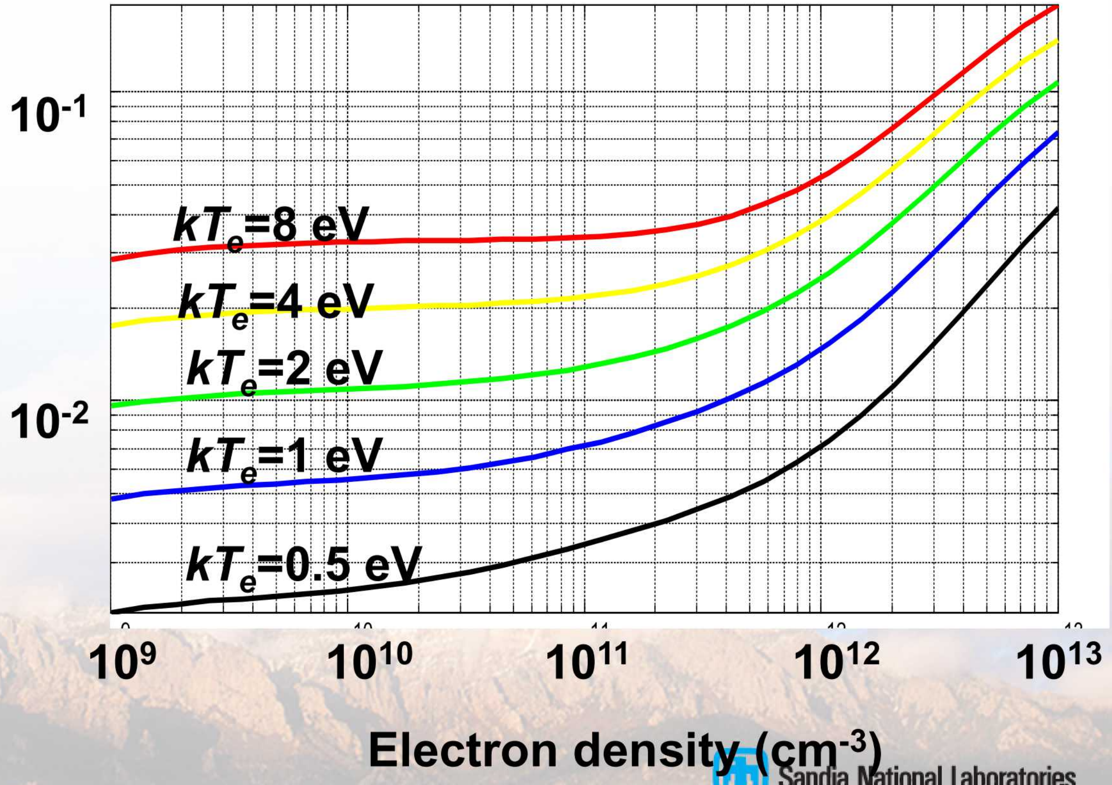
Ratios of various LCIF lines can serve as a measure of effective temperature

- **Ratios constructed from two LCIF measurements yields ratio of two rates**
  - Elimination of electron density dependence.

Ratio between two LCIF signals

$$\frac{\Delta N_j}{\Delta N_i} \sim \frac{K^e_{0j}}{K^e_{0i}}$$

Ratio [447 nm]/[588 nm]



Laser-collision induced fluorescence provides measure of electron density and "temperature"

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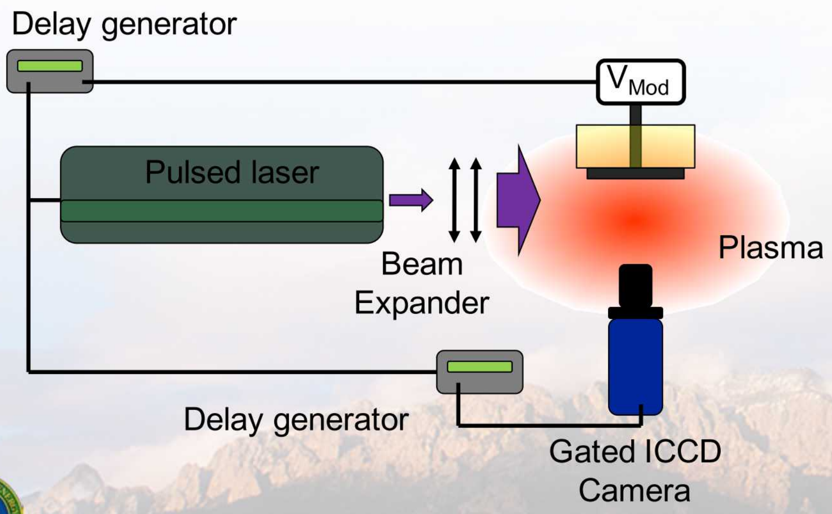
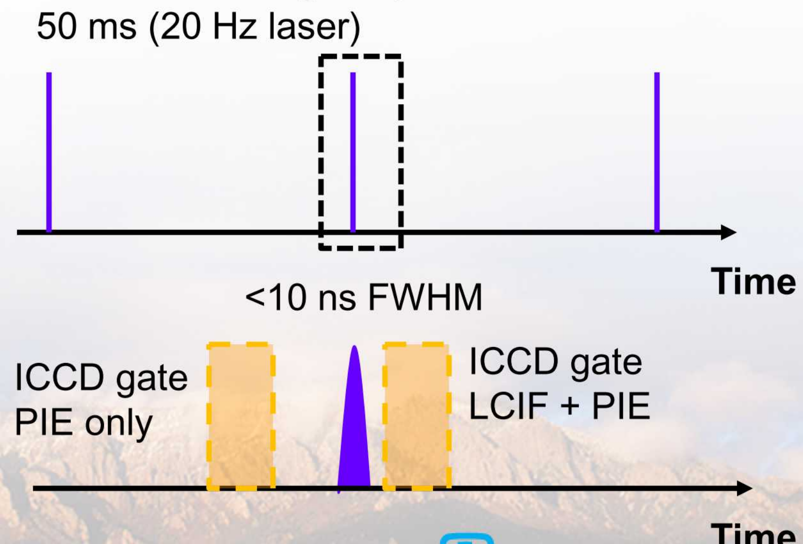
Experimental implementation of the LCIF is realized

- **Nanosecond pulsed laser used for excitation**
  - < 10 ns FWHM, < 0.1 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

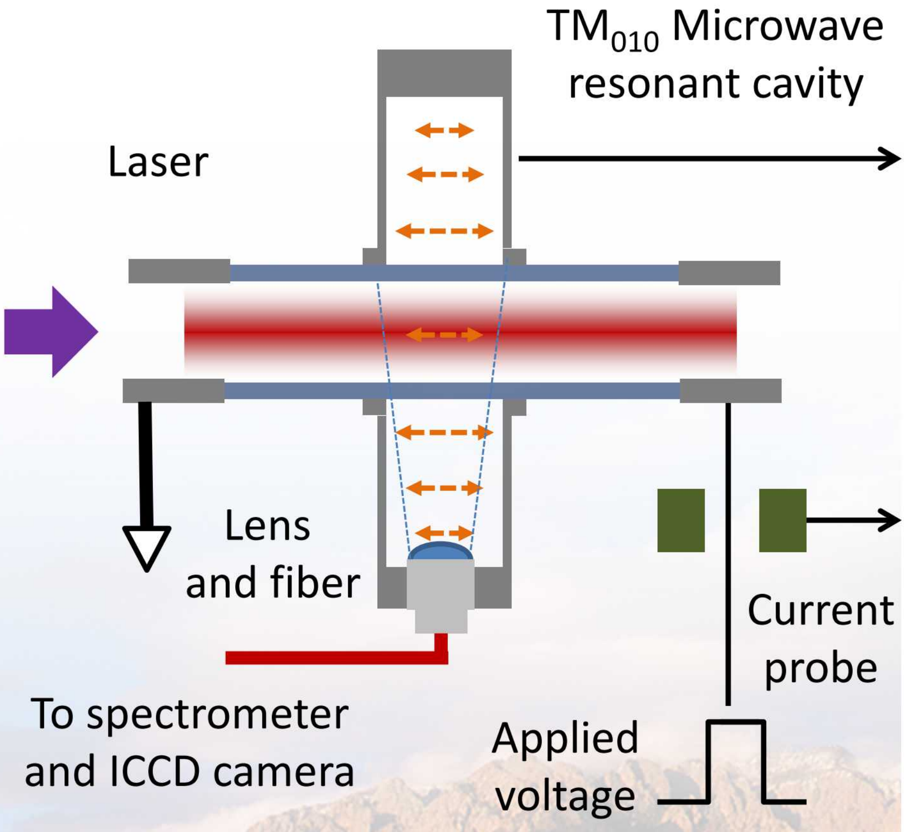


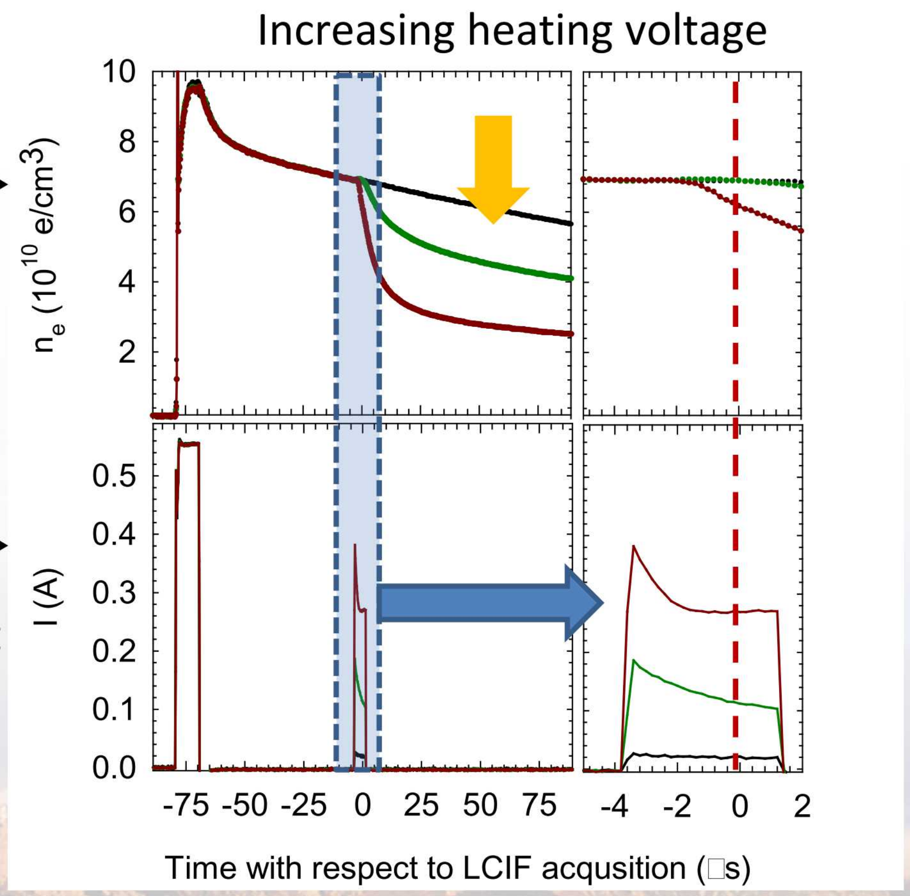
Timing sequence



(Double) Pulsed positive column is utilized to benchmark LCIF technique

- **Double pulse method controls plasma parameters (n_e, "T_e")**
  - First pulse generates plasma, second pulse "heats plasma"





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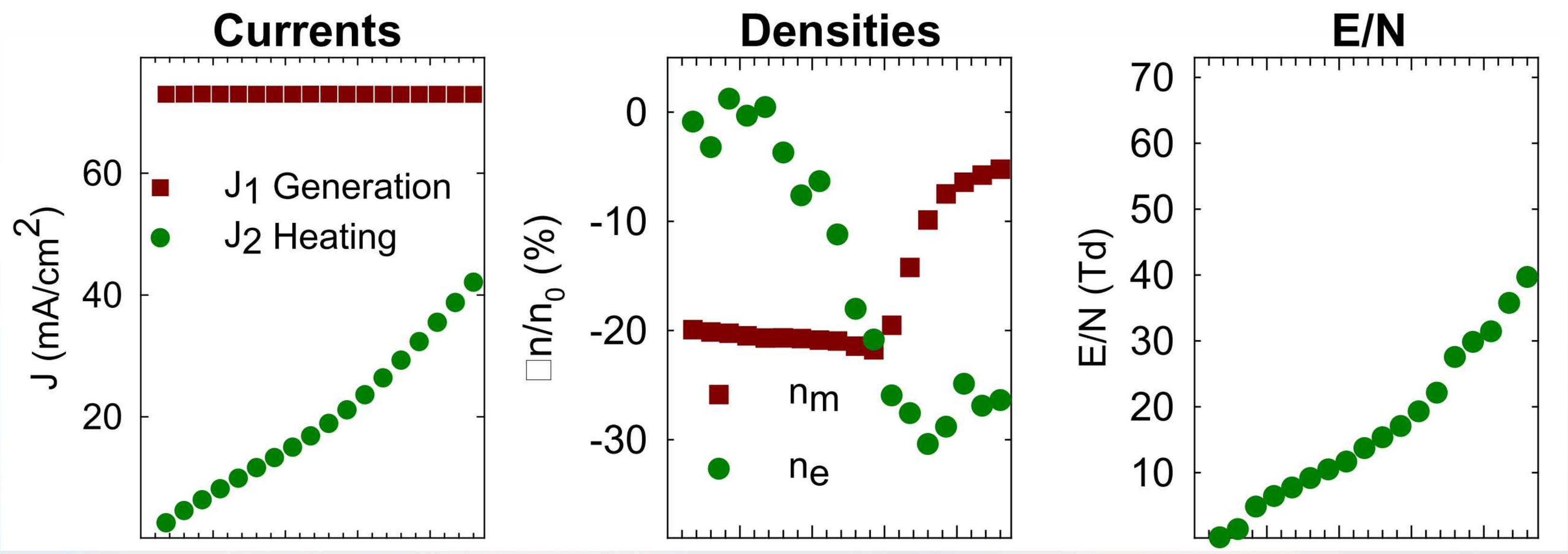
E/N is manipulated with applied heating voltage

- **Published drift parameters are utilized to correlate drift velocities to E/N**
  - Excitation and ionization compliments analysis.

Time averaged parameters

5 μs average, 10 μs after pulse is applied

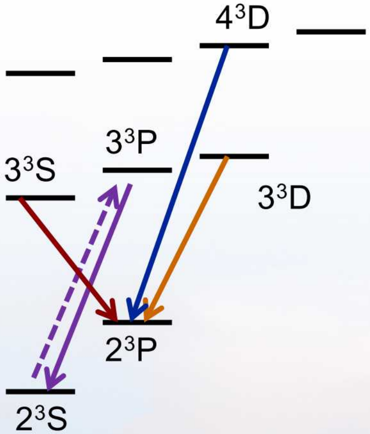


Applied "heating" voltage

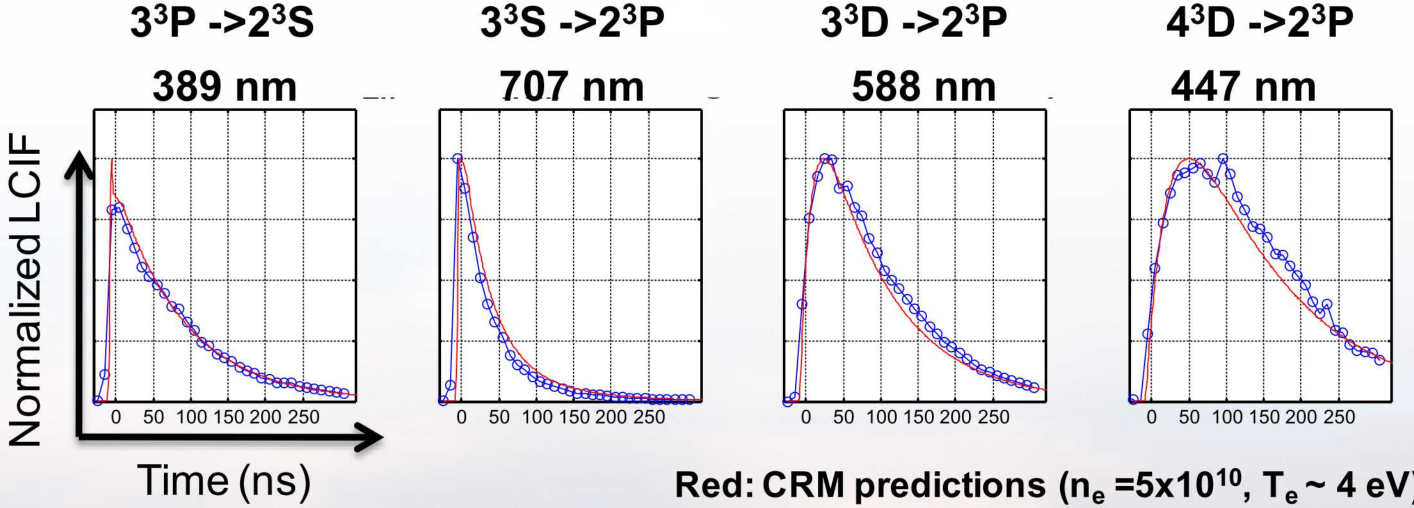
First steps: Verify time resolved LCIF to test CRM

- **Excite the 2^3S – 3^3P transition @ 389 nm**
  - Monitor LIF back to 2^3S
  - Monitor LCIF from 3^3D and 4^3D
- **Compare measured results to simulated results**

Key transitions



Representative results



Red: CRM predictions (n_e =5x10^{10}, T_e ~ 4 eV)
Blue: Measured LIF/LCIF

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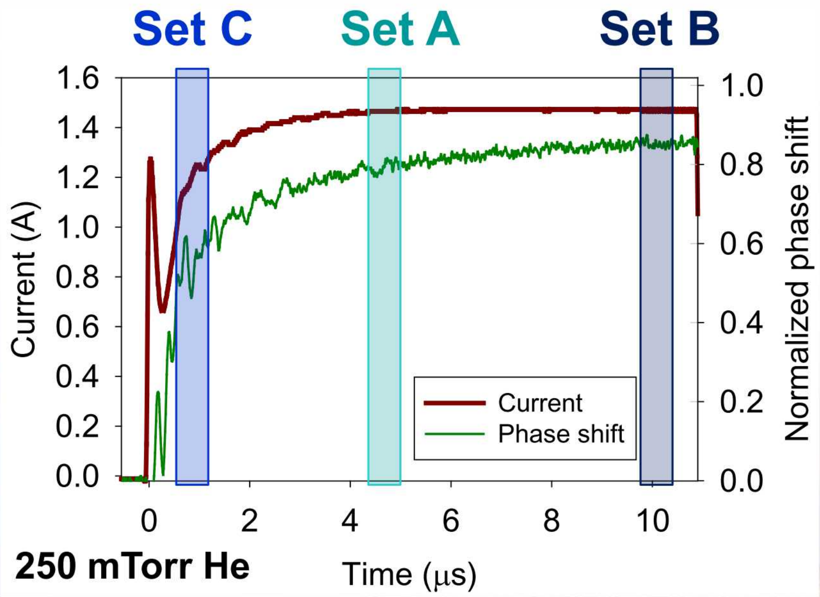
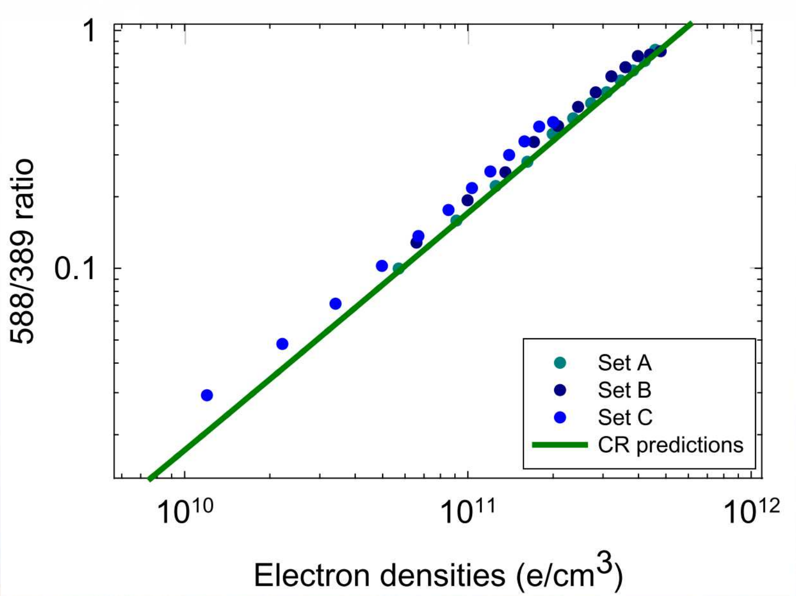
[588]/[389] ratio exhibits linearity over nearly two orders of magnitude

- **Better yet, measured ratios agree reasonably well with computed ratios**
  - Slightly higher, and some deviation at low density
- **Examined trends at different times during the current pulse**
  - Anticipate different temperatures as column is established

Waveforms during excitation



Density dependent ratio trends



Density measurements obtained at different times essentially overlay each other

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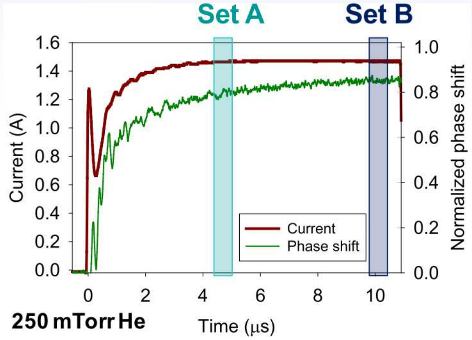
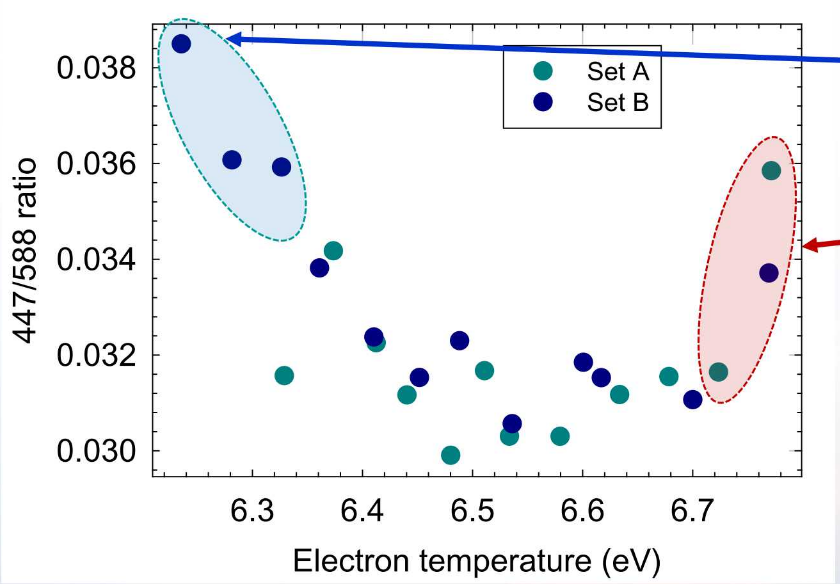
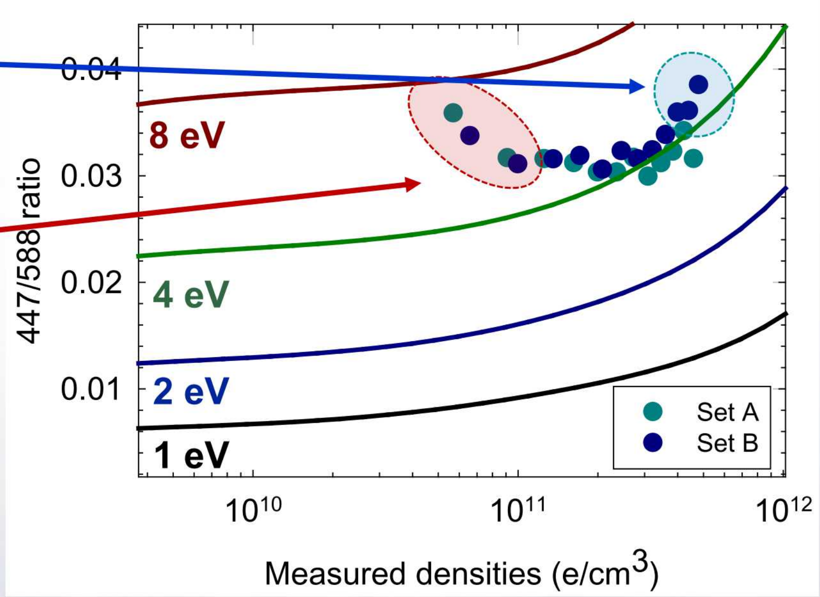
[447]/[588] ratio captures trends but misses absolutes

- **Anticipated T_e trends are observed**
  - High temperature at start, low temperatures later on
- **Measure T_e trends mimic computed trends**
  - Discrepancy in absolute values are apparent







Uncertainties in rates, EEDF and/or interpolation of T_e from drift parameters should impact absolute values

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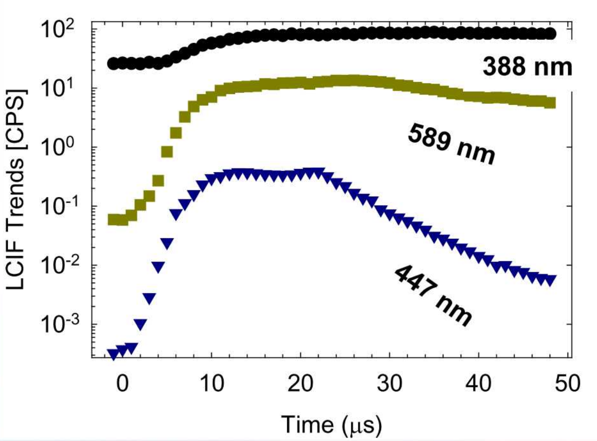
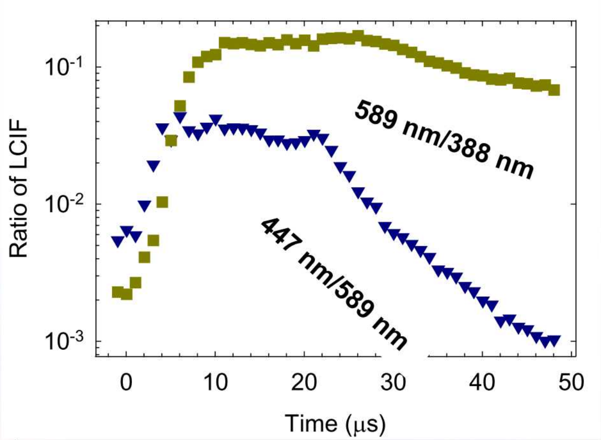
LCIF is utilized to study transient plasma

- **As a final benchmark, plasma generation and decay is observed with LCIF**
  - Produce broad array of n_e, T_e as functions of time

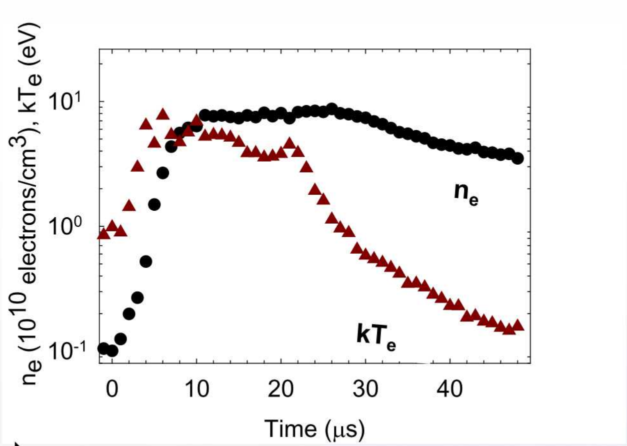
LCIF Trends



LCIF Ratios



Densities and temperatures



LCIF captures the evolution of transient plasma

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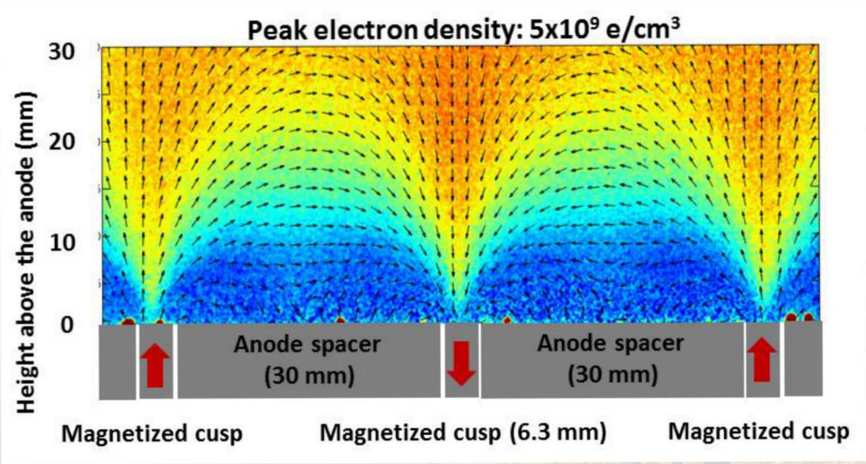
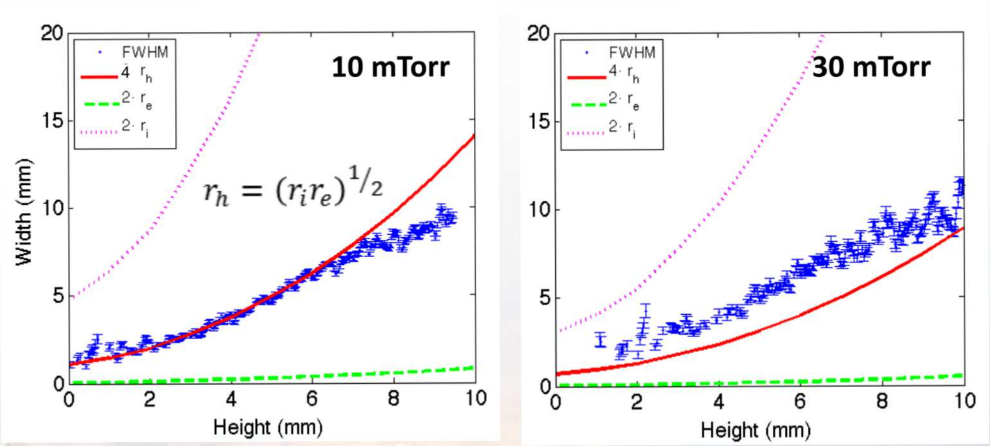
LCIF INTERROGATES MAGNITIZED PLASMA

- **Plasma transport in magnetized plasma is important to understand but challenging to assess**
  - Magnetic configuration dictates particle balance in the plasma
- **Hosted Aimee Hubble (Ph.D. candidate w/ John Foster, U. Michigan) to address fundamental questions about electron loss**
  - Segmented, magnetized anode to quantify plasma confinement
  - LCIF to interrogate electron densities and measure leakage widths

Measured electron densities



Electron leakage widths



- **Measured electron densities, temperatures and magnetic fields are used to compute leak widths**

LCIF provides non-invasive means of interrogating challenging plasma environments

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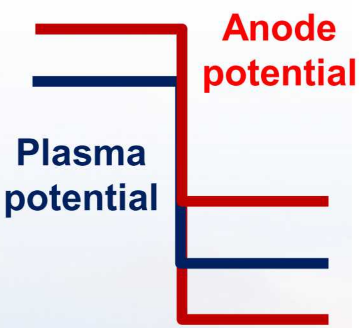
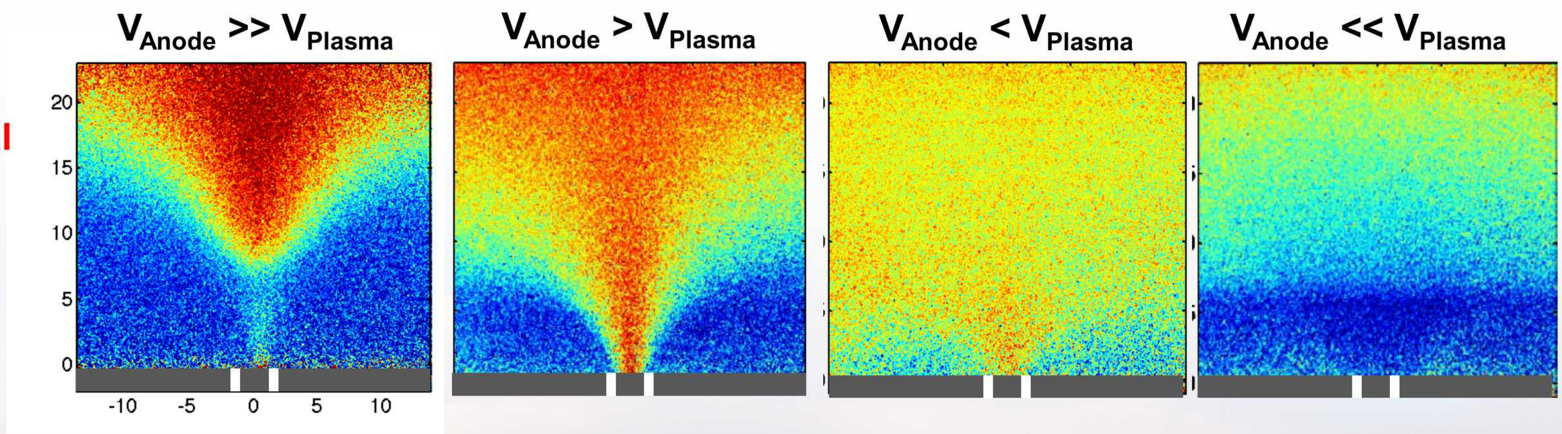
PLASMA TRANSPORT IS REGULATED BY THE ANODE POTENTIAL

- **Transient plasma enables access to different current collecting conditions**
  - **Dial in potential drop between the anode and plasma**
- **Confinement degrades as electrode potential approaches plasma potential**
  - **Ion flux carries electrons across the magnetic fields**

Anode drive



Measured electron densities



LCIF captures plasma flow to the electrode after polarity of the bias is reversed

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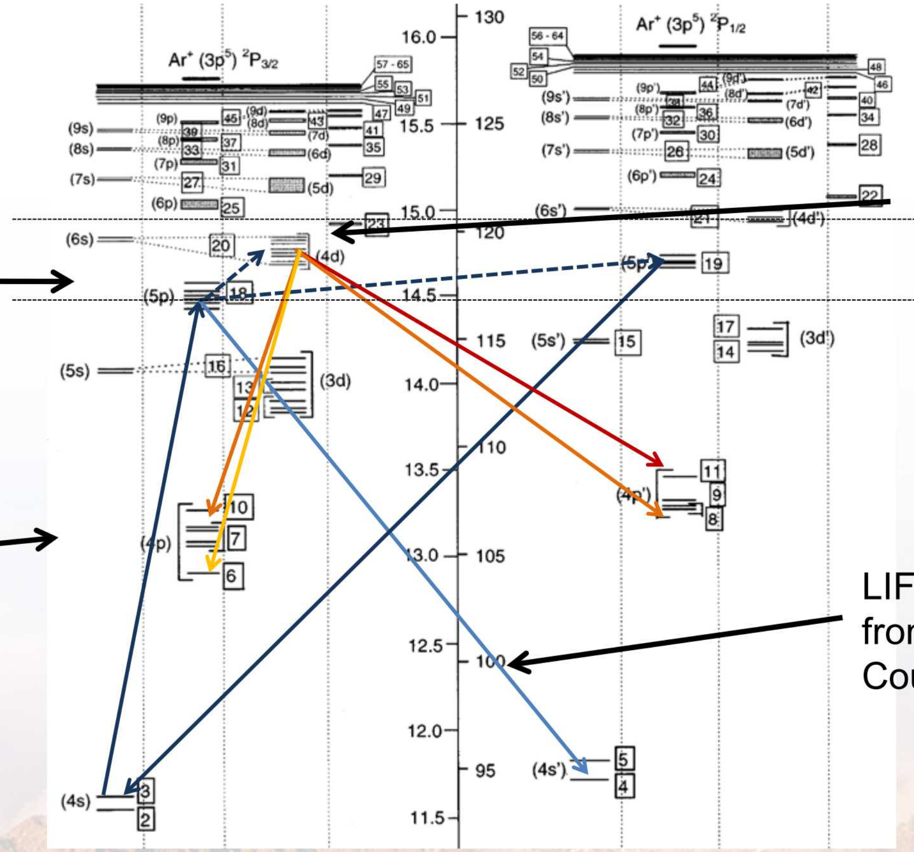
Complexity of many atomic systems makes LCIF "challenging"

- **Argon is a workhouse of low temperature plasma community**
  - **Complex atomic structure makes developmentt challenging**

Targeting lowest lying $3p_{10}$ state

Not pursuing radiation trapped 2p states



"Orange" LCIF from 4d states well separated from "red" lines emanating from 2p states

LIF at 470.2 is well isolated from other transitions Coupled to $1s_2$ state

Taken from Bogearts et. al, J. Appl. Phys. **84**, 121, 1998

Cross sections and rates not well known for electronic driven processes from 3p to higher states

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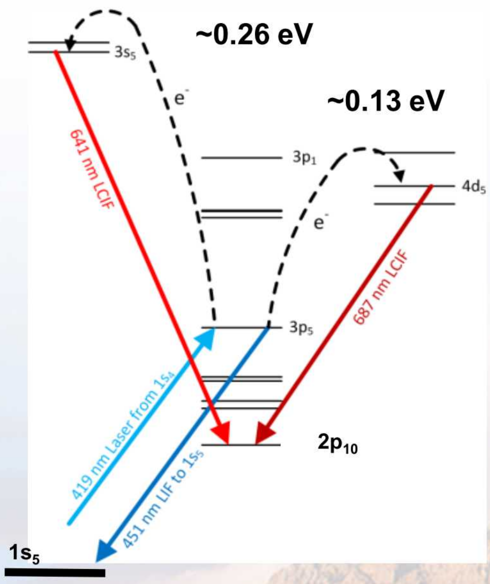
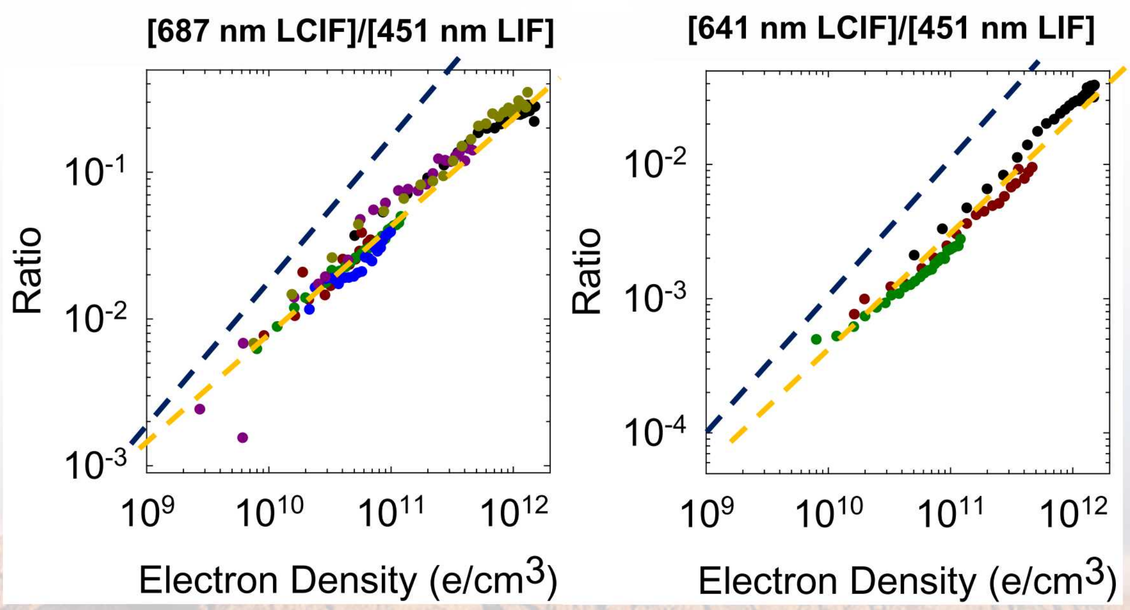
METHODS ARE BEING REFINED AND NEW DIAGNOSTICS ARE BEING IMPLEMENTED

- Argon laser collision induced fluorescence is being developed
  - Brandon Weatherford was developing (Hired to L3 Communications).
- Non-unity scaling with density have hindered completion.
  - Errors in density measurement, impact of electron temperature or spectral contamination are likely sources of scaling.

Excitation scheme



Argon LCIF



Concluding remarks and future directions

- **LCIF technique demonstrated in 2D**
  - Free of “line of sight” constraints
  - Good spatial resolution – limited by optical collection
  - Decent temporal resolution – limited by ICCD gate times & tolerable signals

- **Caution required for proper implementation of the technique**
  - Uncertainties about rates – Absolute bounds on measurements
  - Proper choice of model – Capture the required physics

- **Technique should be extendable over broad parameter space**
  - Higher pressures – neutral collisions
  - Smaller dimensions – scattering and access
  - Other atomic systems

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

Thank you

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References for rates and cross-sections

- **Superelastic**
  - Klein Rosseland
  - Sobelman

$$K_{ij}^{e}=\langle\sigma_{ij}v_{e}\rangle=\left(\frac{m_e}{2\pi kT_e}\right)^{3/2}\int_0^\infty \sigma_{ij}(v)\exp\left(\frac{-m_e v^2}{2k_BT_e}\right)4\pi v^2 dv\left[\frac{g_j}{g_i}\exp\left(\frac{(E_j-E_i)}{k_BT_e}\right)\right]$$

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