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# Development and Application of Laser-Collision Induced Fluorescence for Studying Dynamic and Structured Plasmas

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# Acknowledgements to the many collaborators that made these efforts succeed

**Post-doctoral researchers:**
Kraig Frederickson (OSU) – Early development of LCIF
Brandon Weatherford (L3) – Application and development of LCIF
Ben Yee (SNL) and Ricky Tang (SNL) – Application and advancement of LCIF
Andy Fierro (SNL) – Kinetic simulations and radiation transport

**Visiting students:**
B. Schiner (U. Iowa) – Anodic interfaces
Aimee Hubble (U. Michigan -> Aerospace Corp.)– Magnetized interfaces

**Collaborators:**
Matt Hopkins (SNL) – Kinetic simulations
Scott Baalrud (U. Iowa) – Anode interface physics
John Foster (U. Michigan) – Plasma generation and plasma transport.
Vlaidimir Kolobov (CFDRC) – Physics of positive column discharges
Andy Xiong and  Mark Kushner (U. Michigan) – FIW simulations
Peter Bruggeman (U. Minnesota) – High pressure plasma physics

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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?**
  - Two-dimensional snap-shots of density provide insight into plasma physics.

- **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
    - Atmospheric pressure LCIF

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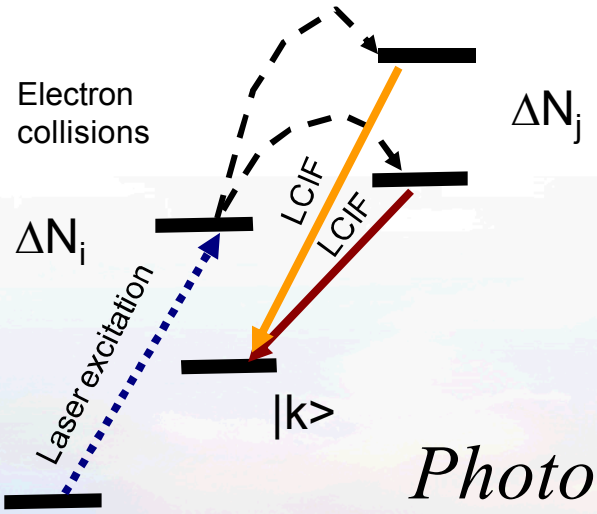
# LCIF is based on redistribution of excited state by plasma species (electrons)

- **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***

# 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

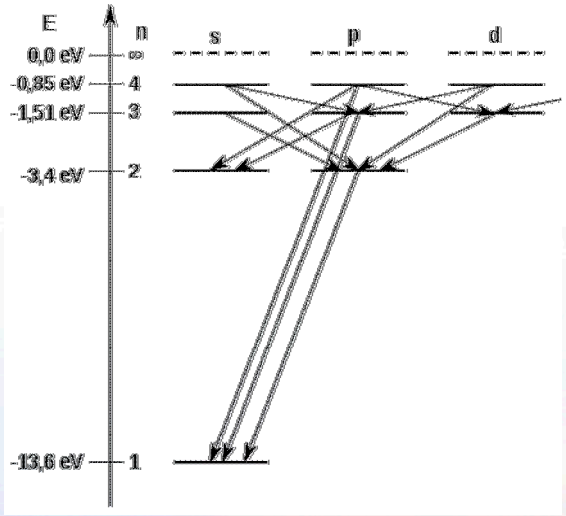
Excitation into and out of states

Redistribution

# Complexity of many atomic systems
# LCIF "challenging"

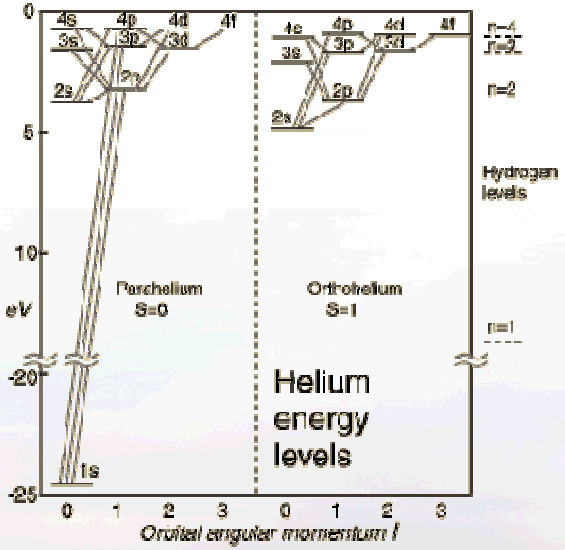
- **Atomic structure will govern which pathways are accessible for LCIF**
  - **Which states radiate, and are they uniquely detectable**

## Hydrogen



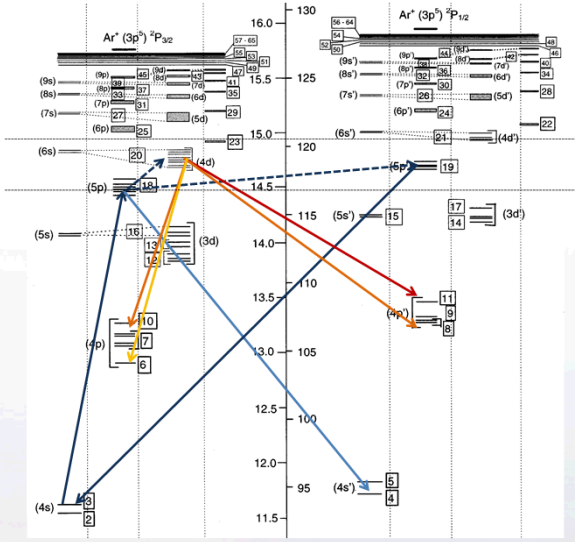

http://commons.wikimedia.org/wiki/File:Grotrian_H.svg

## 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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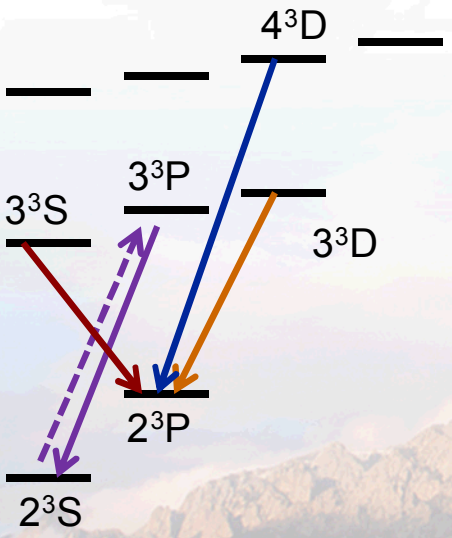
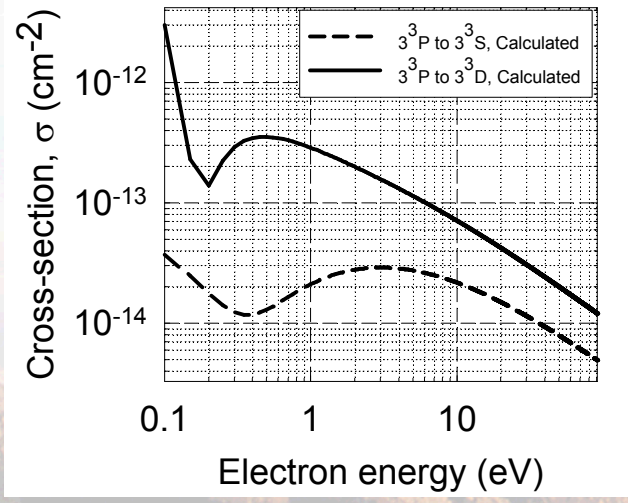
# Helium atom serves as target species for LCIF measurements

- **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]

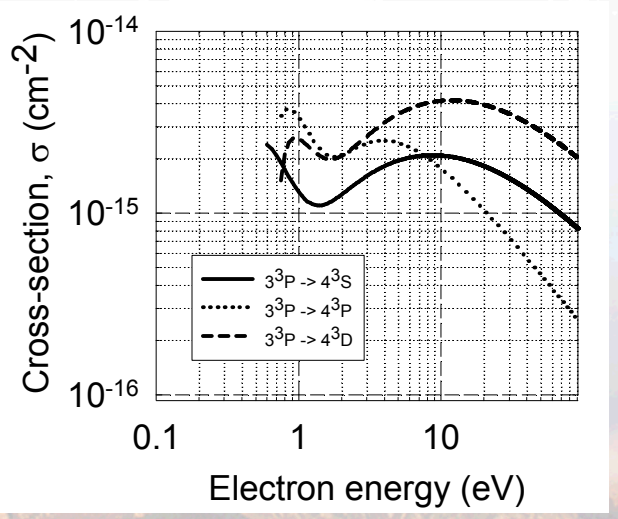
**Key transitions**




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




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




***Principles extend to other systems***

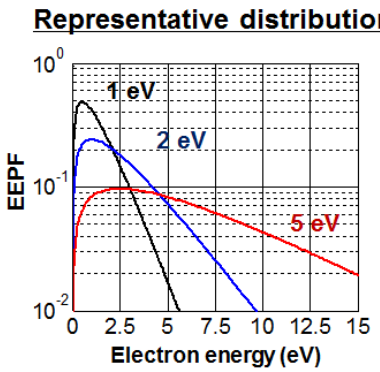


1: Yu. Ralchenko, R. K. Janev, T. Kato, D. V. Fursa, I. Bray, F. J. De Heer, Atomic Data and Nuclear Data Tables **94**, 603 (2008)

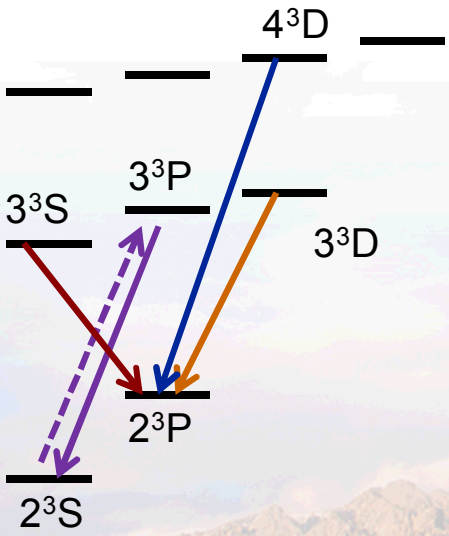
# Electron-induced collision rates are computed from cross-sections and electron distribution functions

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

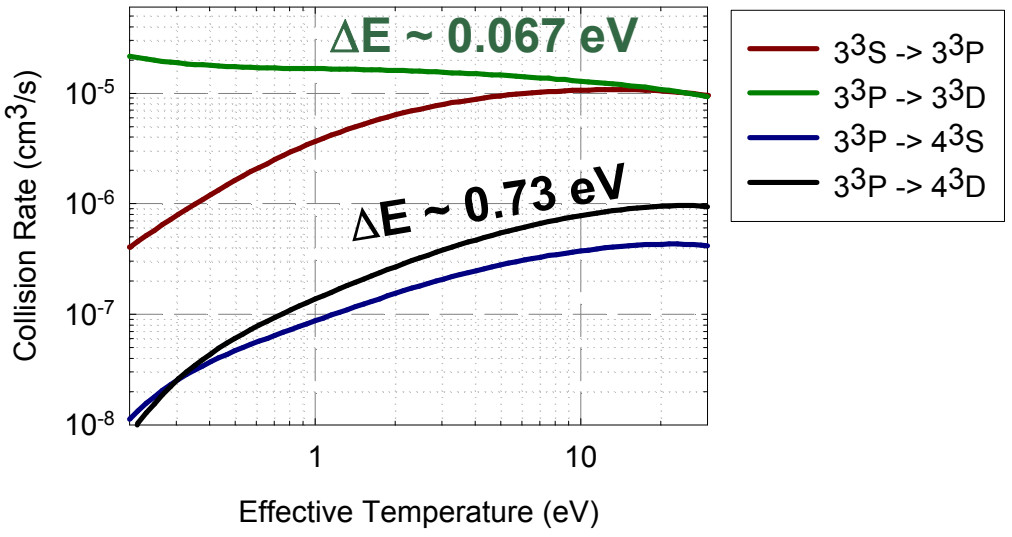
$$K_{ij}^{e} = \left\langle \sigma_{ij}(E) v_e(E) f(E) \right\rangle$$




## Key transitions



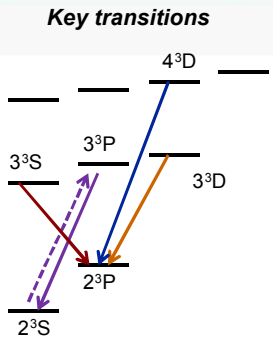

## Key Rates



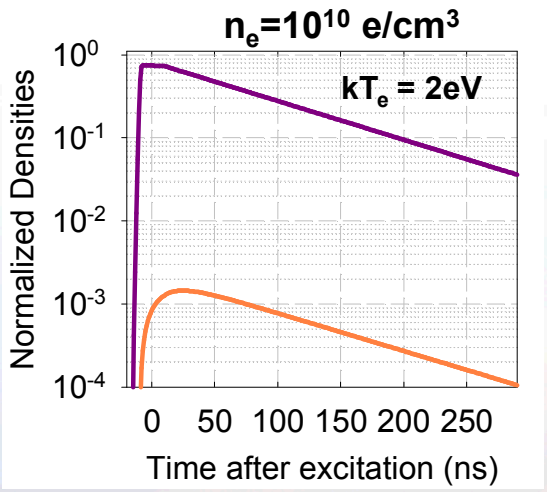

***Barrier between states plays key role in population transfer processes***

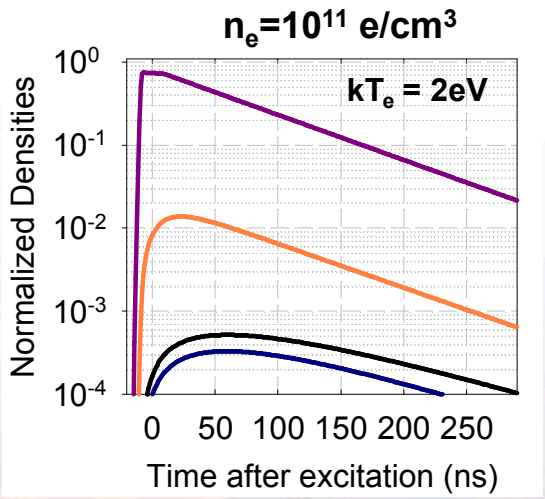
# Electron-induced collisions are observable in energetically "up hill" transitions

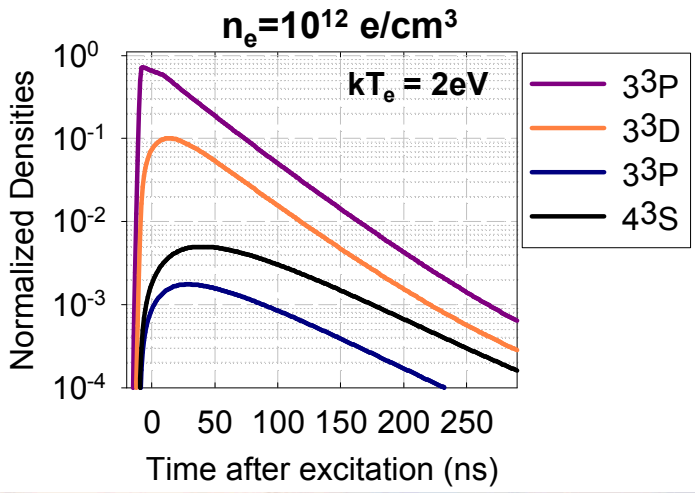
- **Solution of the CRM including both electrons and radiative decay.**
  - Electrons redistribute excited state to near by states
- **There are two key-observables obtained from these simulations**
  - Degree of re-distribution scales with collision rate ($n_e$, $T_e$)
  - Lifetime of excited states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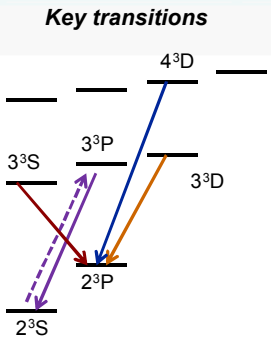


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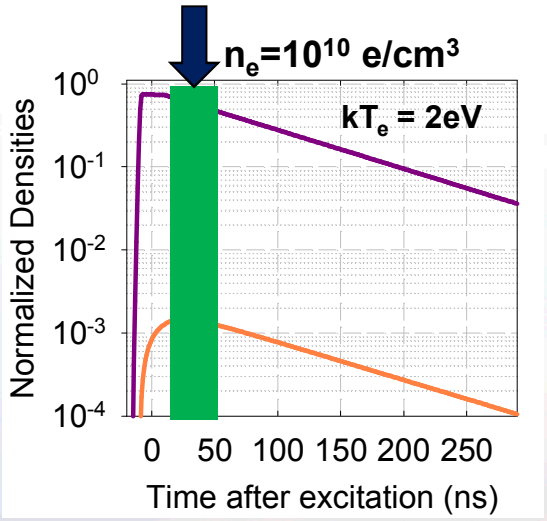
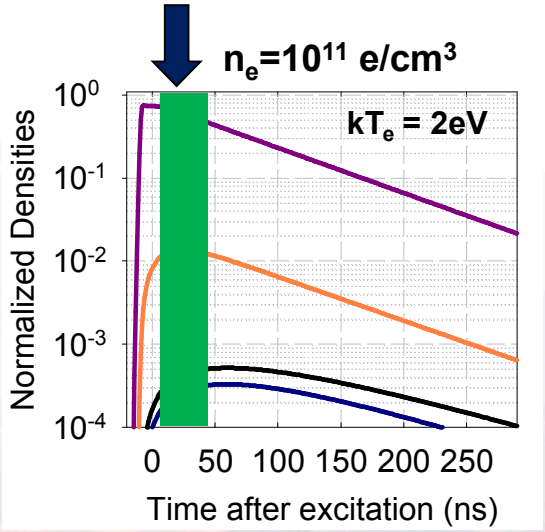
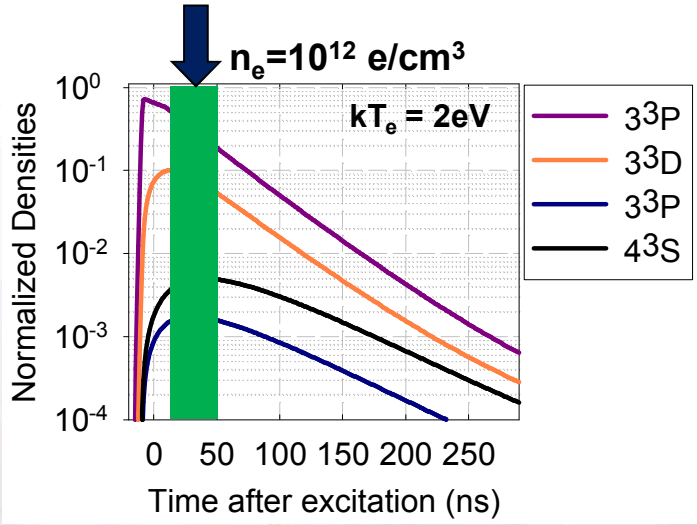



***Temporal integration of light detected serves to simplify LCIF implementation***

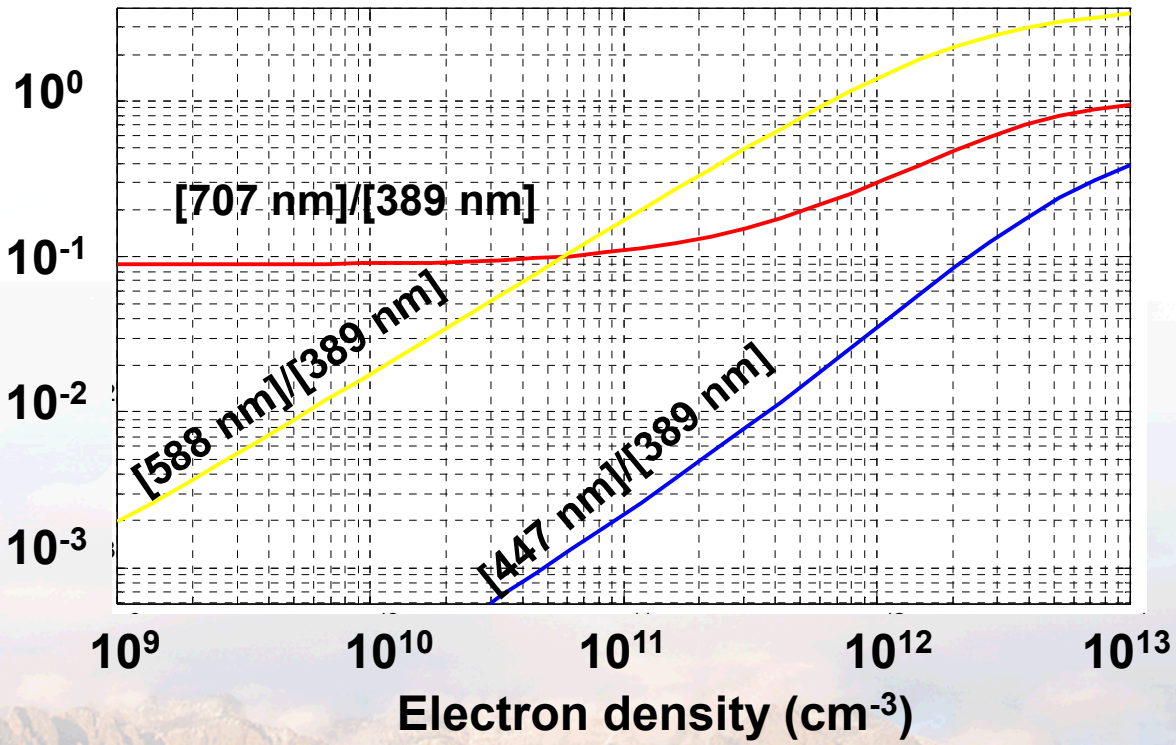
# Ratio of LCIF to LIF yields electron induced excitation rates

- **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 $T_e$***

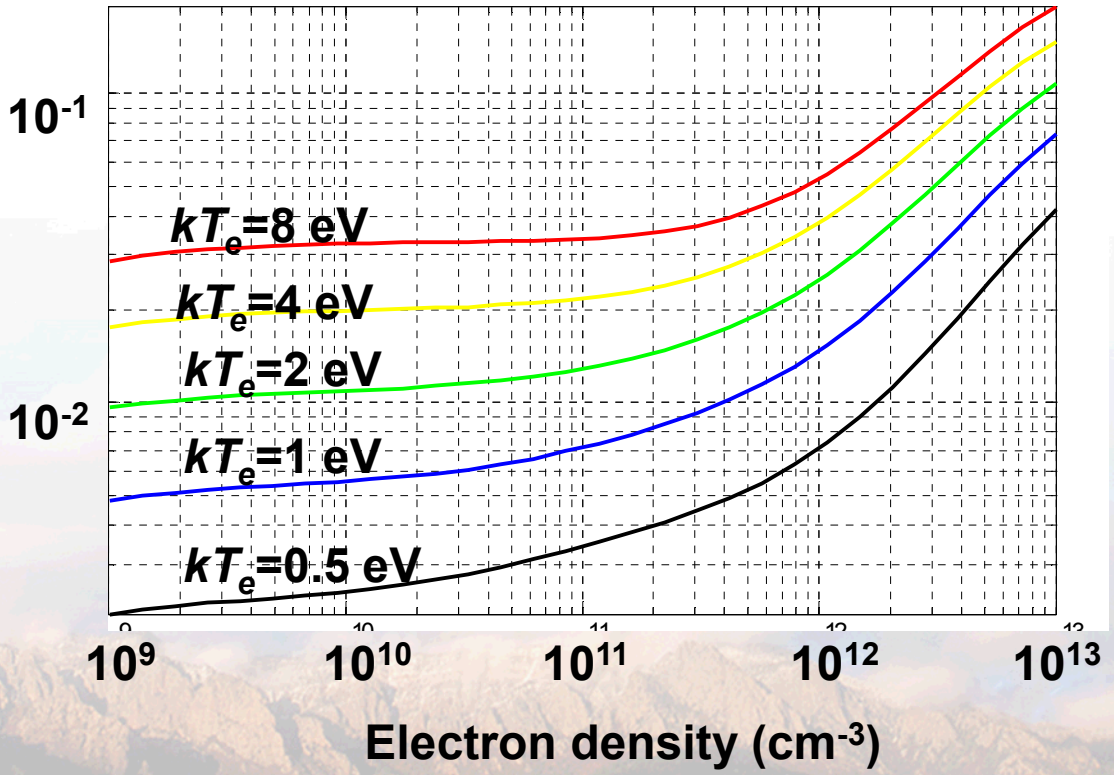
# Ratios of various LCIF lines can serve as a measure of effective temperature

- **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]**




E. V. Barnat and K. Frederickson, "Two-Dimensional Mapping of Electron Densities and Temperatures Using Laser-Collisional Fluorescence", Plasma Sources Sci. Technol. **19**, 055015 (2010).



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

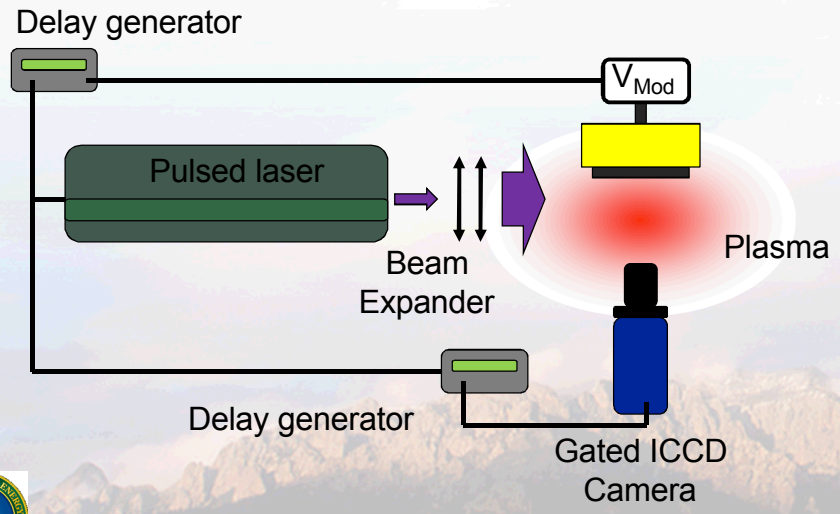
- **Motivation: What is the density? What is the temperature? Where and When?**
  - Two-dimensional snap-shots of density provide insight into plasma physics.

- **In this presentation**
  - Part I: Laser-collision induced fluorescence (LCIF) primer
    - Collisional-radiative model used to predict LCIF
    - Physics that governs LCIF
  - **Part II: Implement and benchmark technique**
    - **Experimental procedures**
    - **Demonstration of LCIF for various implementations**
  - Part III: Applications of LCIF:
    - Dynamic and structured plasmas
  - Part IV: Future directions and concluding comments
    - Atmospheric pressure LCIF

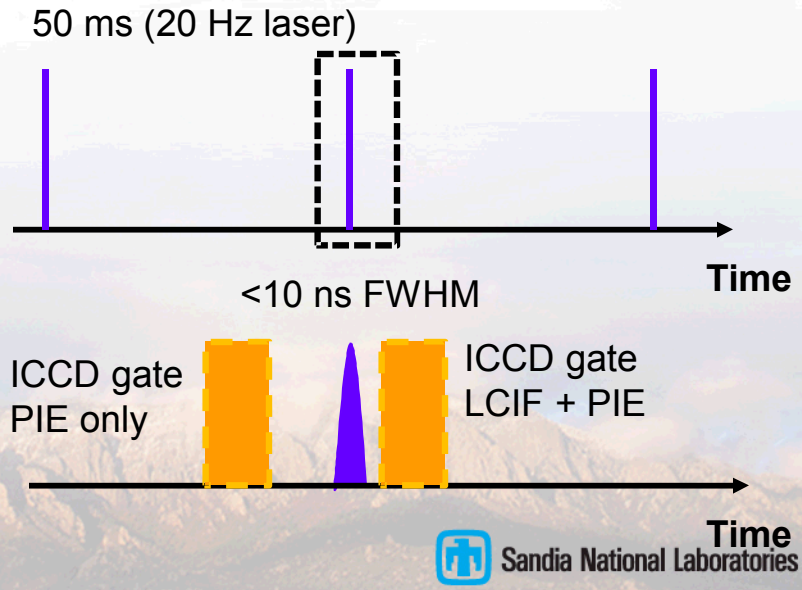
# Experimental implementation of the LCIF is realized

- **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 (~ 5 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**

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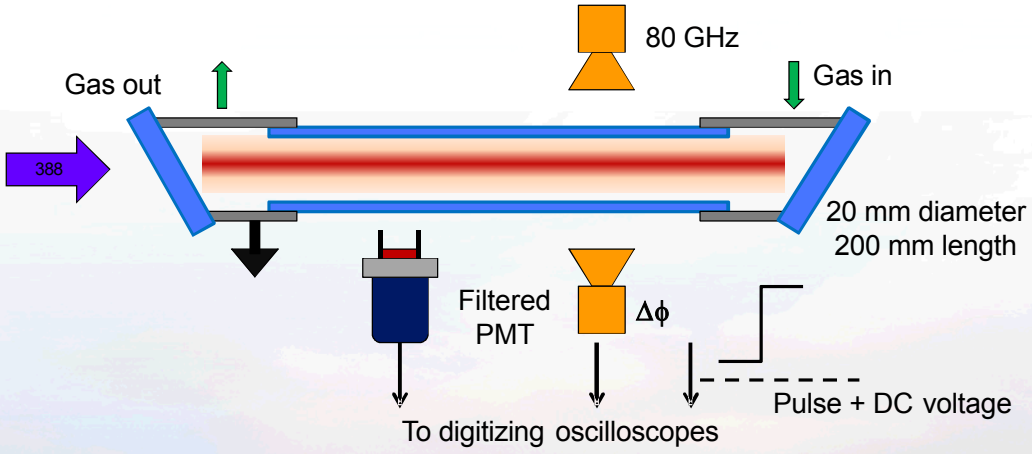
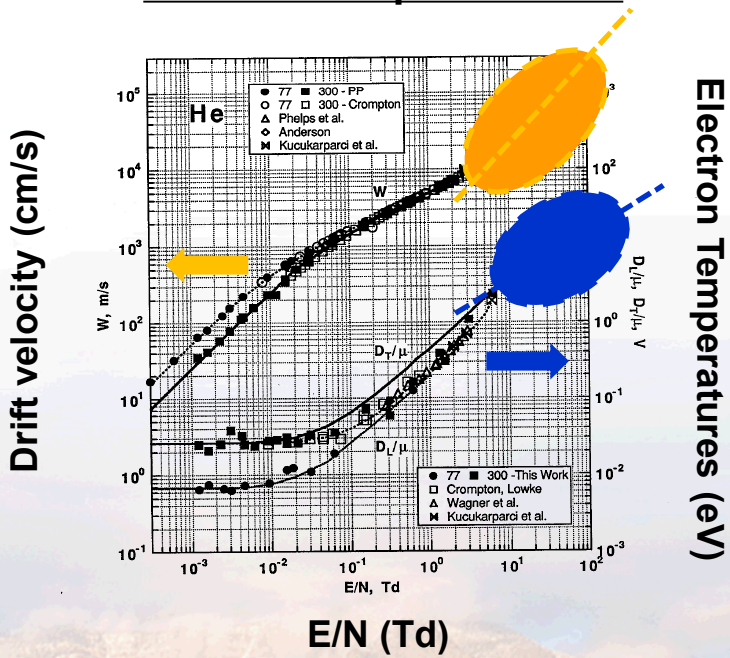
# Pulsed positive column is utilized to benchmark LCIF technique

- **Pulse discharge currents generate broad density range**
  - ~ 10 Microseconds, 80 GHz interferometer
- **Compute drift velocities and extract electron temperatures**
  - Use published drift parameters

**Positive column**




**Helium drift parameters**




***Positive column is a good vehicle to benchmark LCIF technique***

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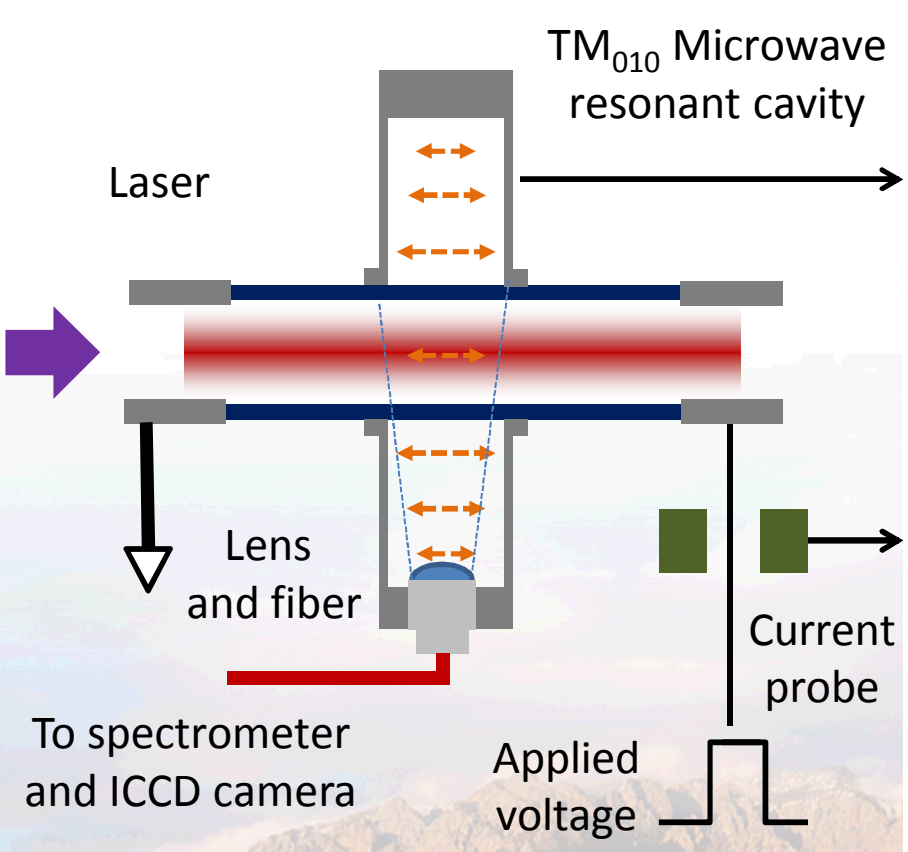
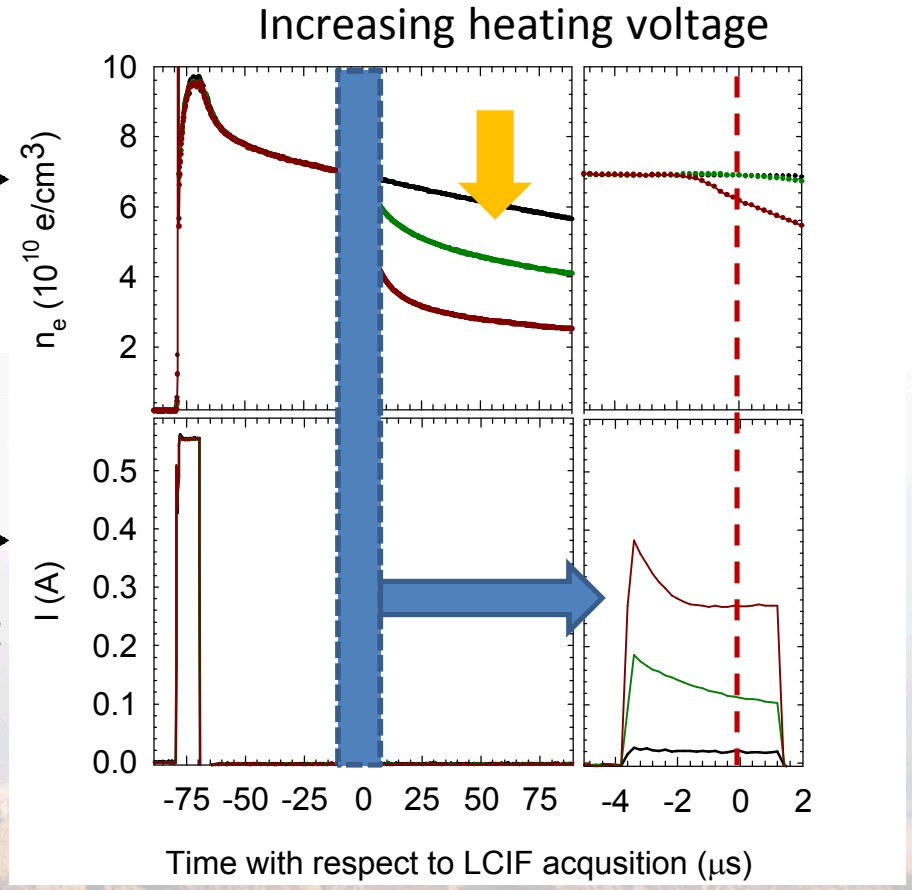
J. L. Pack, R. E. Voshall, A.V. Phelps and L. E. Kline, J. Appl. Phys. V71, p5363 (1992)

# (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"



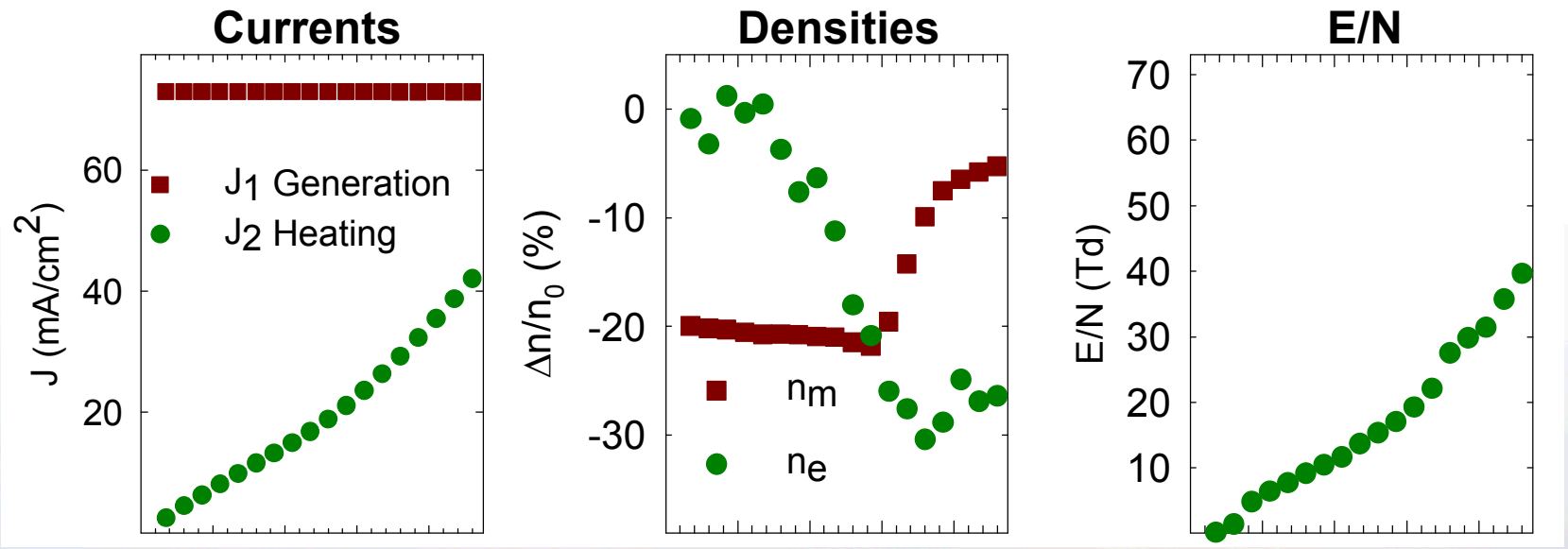



# E/N is manipulated with applied heating voltage

- **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



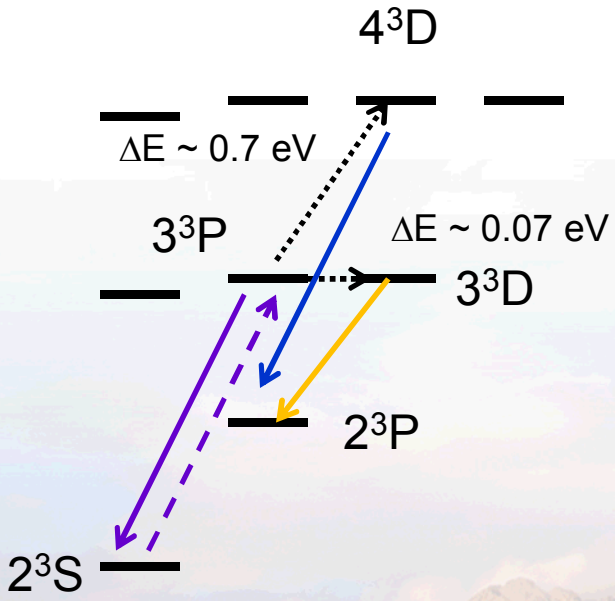

**Applied "heating" voltage**

***Good control over E/N with application of the second pulse***

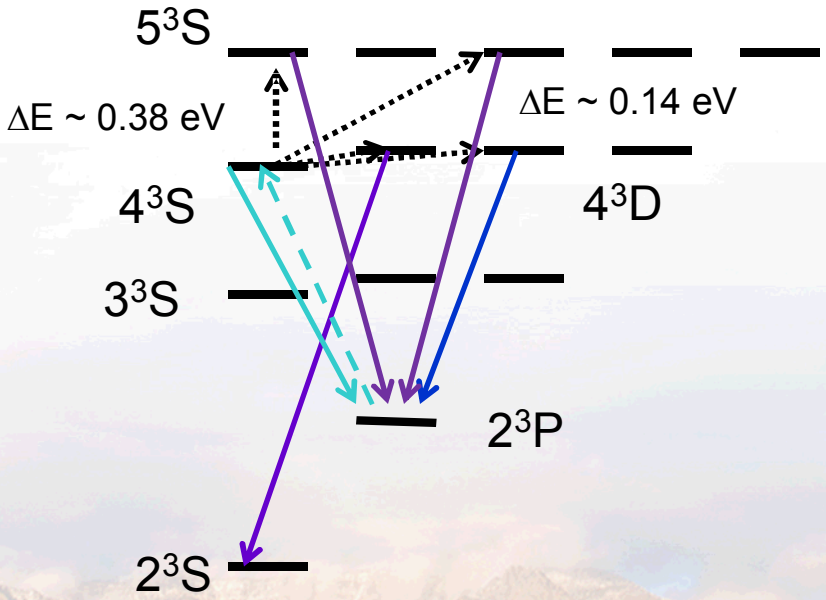
# Spectroscopic pathways interrogated for helium

- **Lower base density of $2^3P$ advantageous, but some tradeoffs**
  - Lose the nice "temperature free" $3^3P$ -> $3^3D$ transition
  - Spectrally dense - many transitions ~ 400 nm

**From $2^3S$**




**From $2^3P$**

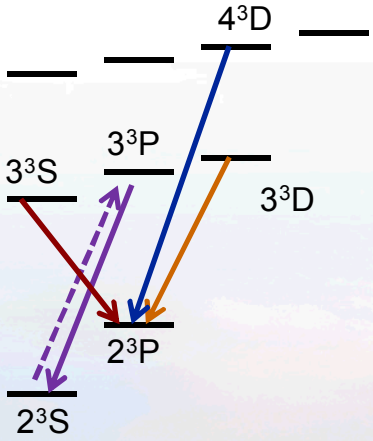



***Choice depends on optical thickness and density of probed state***

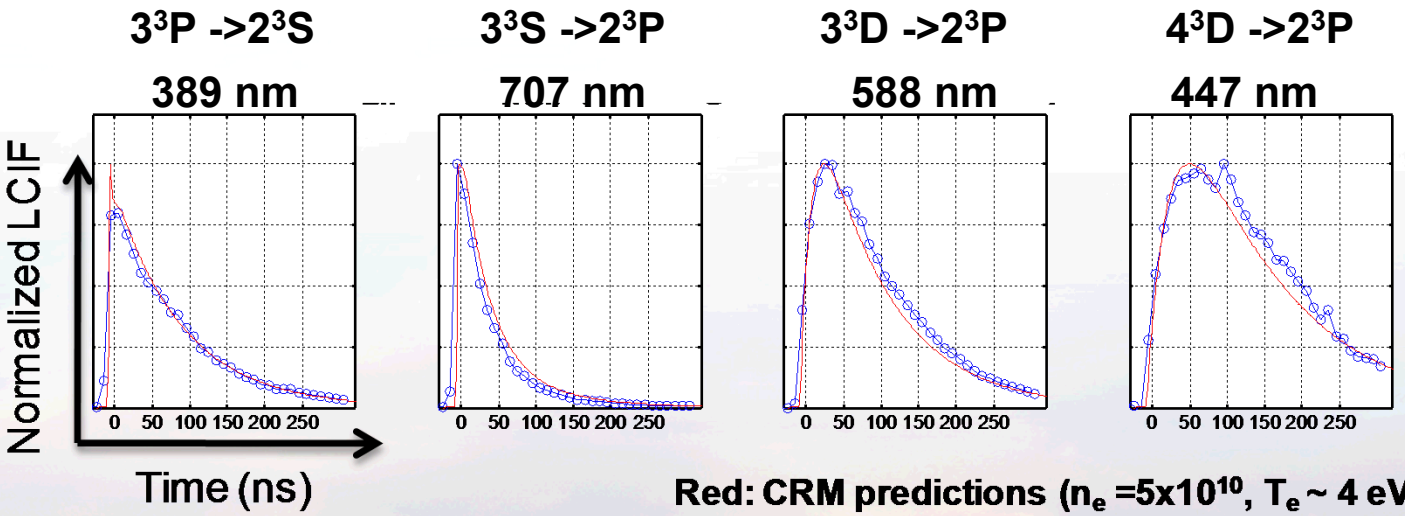
# First steps: Verify time resolved LCIF to test CRM

- **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**

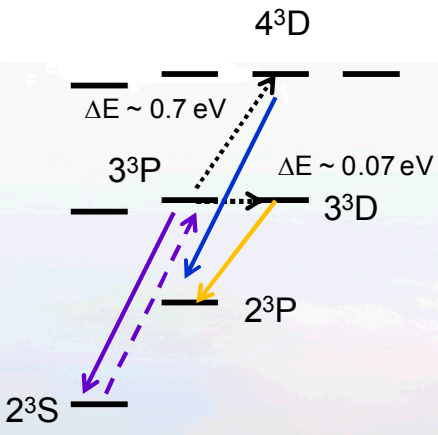



**Red: CRM predictions ($n_e$ =5x10$^{10}$, $T_e$ ~ 4 eV)**
**Blue: Measured LIF/LCIF**

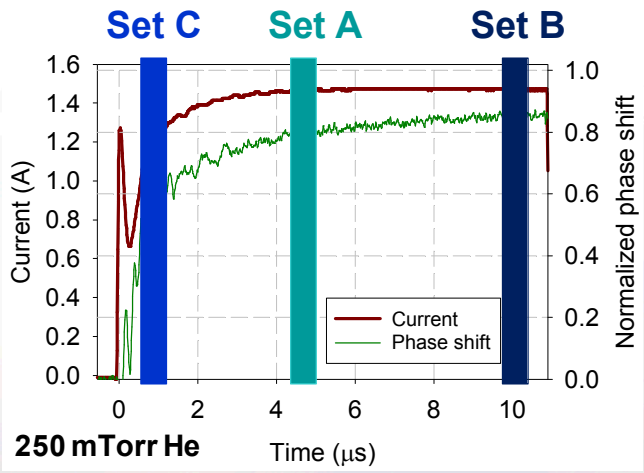
***Capturing time-resolved trends is key for benchmarking LCIF***

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

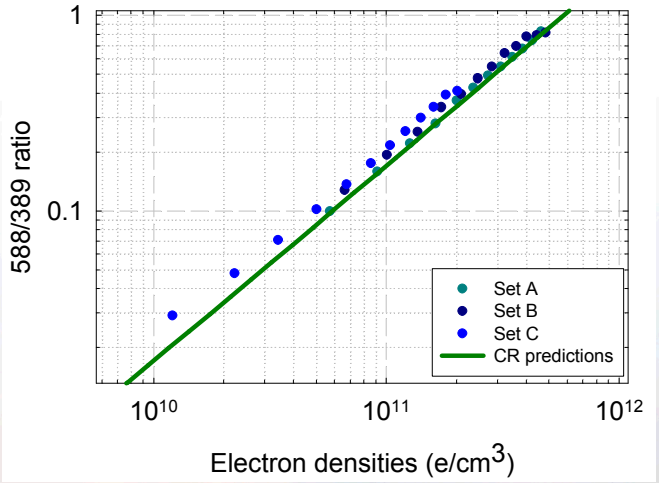
- **Better yet, measured ratios agree reasonably well with computed ratios**
  - Slightly higher, and some deviation at low density
- **Examined trends at different times during the current pulse**
  - Anticipate different temperatures as column is established




**Waveforms during excitation**



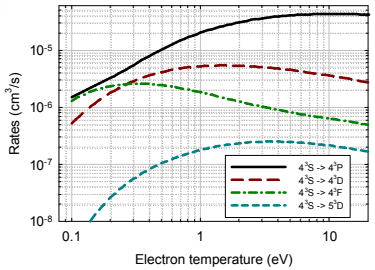

**Density dependent ratio trends**



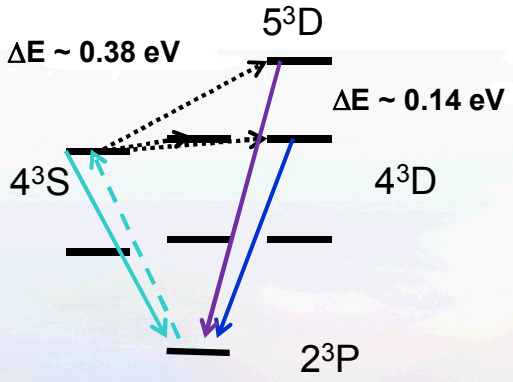

***Density measurements obtained at different times essentially overlay each other***

# $2^3P$ excitation pathway is also benchmarked

- **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[1]

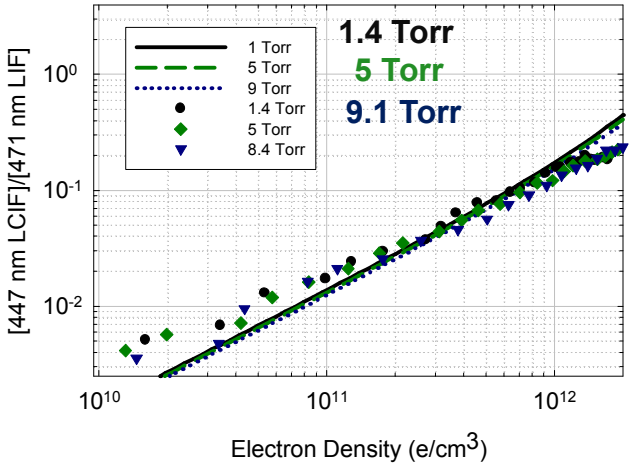



## Spectroscopic pathway

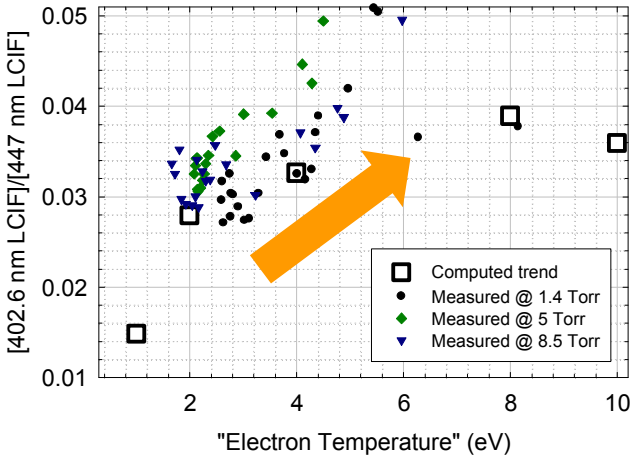



## Key Scaling Trends

### Electron density




### "Electron Temperature"




***Electron density trends gas pressure for modest pressures***

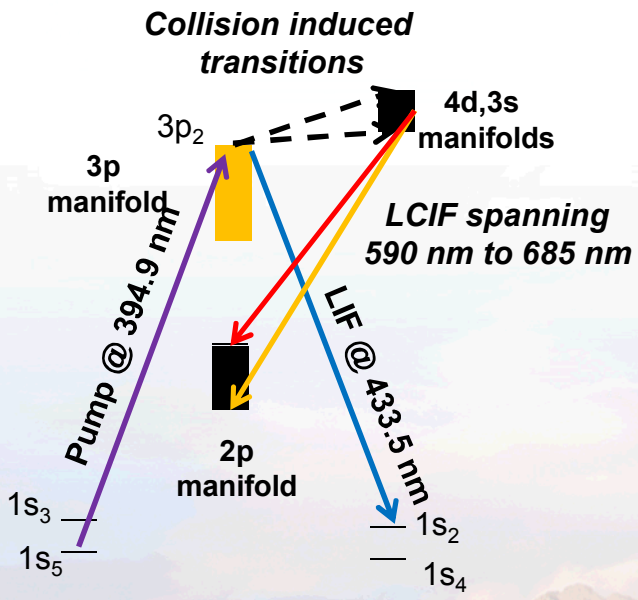


[1] Yu. Ralchenko, R. K. Janev, T. Kato, D. V. Fursa, I. Bray, F. J. De Heer, Atomic Data and Nuclear Data Tables **94**, 603 (2008).

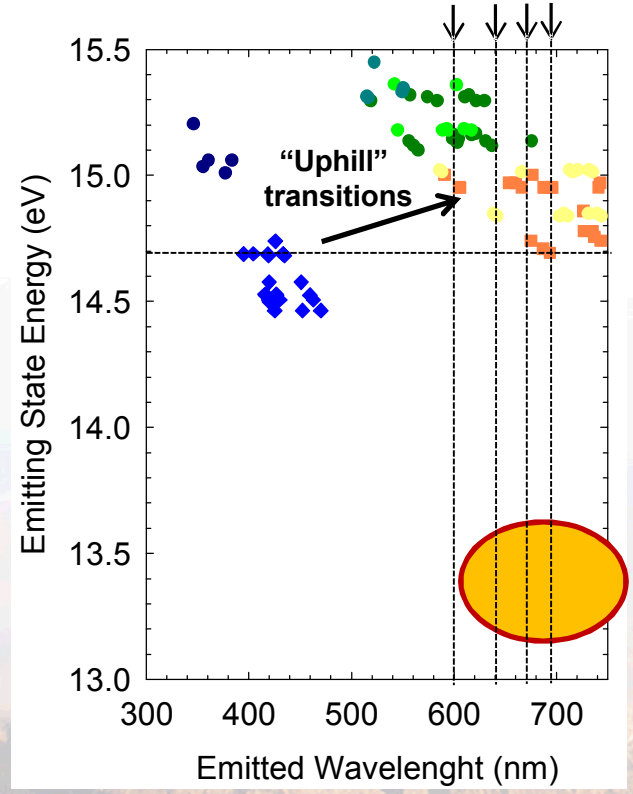
# Complexity of Argon manifold offers choice for LCIF implementation

- **Well-chosen excitation scheme is important for successful implementation**
  - **Excite the upper ($3p_2$) states and look for collisional coupling into higher (3s, 4d, 5d …) states.**

## Proposed pathway




## Target transitions




| Target transitions | Wavelength (nm) | A ($x10^6$ $s^{-1}$) | ΔE (eV) | |
|---|---|---|---|---|
| **$1s_5$ -> $3p_2$** | **394.9** | **0.46** | **0** | Pump |
| $3p_2$-> $1s_4$ | 404.6 | 0.04 | 0 | |
| $3p_2$-> $1s_3$ | 418.2 | 0.56 | 0 | Monitor |
| $3p_2$-> $1s_2$ | 433.5 | 0.39 | 0 | |
| **$4d_5$->$2p_{10}$** | **687.13** | **2.8** | **0.024** | LCIF |
| $4s_1'''$->$2p_7$ | 688.82 | 0.25 | 0.265 | |
| $4s_1''$->$2p_7$ | 687.96 | 0.18 | 0.268 | |
| **$4d_3$->$2p_{10}$** | **675.28** | **1.9** | **0.055** | |
| $4s_1'$->$2p_6$ | 676.66 | 0.4 | 0.316 | |
| **$3s_5$->$2p_{10}$** | **641.63** | **1.2** | **0.152** | |
| $3s_4$->$2p_{10}$ | 638.47 | 0.42 | 0.161 | |
| $3s_2$->$2p_8$ | 643.16 | 0.05 | 0.335 | |
| $5d_3$->$2p_6$ | 630.77 | 0.60 | 0.450 | |
| $5d_6$->$2p_7$ | 636.49 | 0.56 | 0.413 | |
| $5d_5$->$2p_6$ | 636.96 | 0.42 | 0.431 | |
| $3s_4$->$2p_{10}$ | 638.47 | 0.42 | 0.161 | |
| **$4s'_1$->$2p_{10}$** | **591.21** | **1.05** | **0.316** | |
| $3s_3$->$2p_{10}$ | 588.26 | 1.2 | 0.327 | |
| $3s_2$->$2p_{10}$ | 586.03 | 0.29 | 0.335 | |
| $4s_5$->$2p_9$ | 588.86 | 1.29 | 0.494 | |
| $4s_4$->$2p_8$ | 592.8812 | 1.10 | 0.498 | |
| $5s''_1$->$2p_6$ | 583.42 | 0.52 | 0.609 | |
| $4s_3$->$2p_4$ | 597.1601 | 1.10 | 0.671 | |

***Other excitation pathways also can be chosen***

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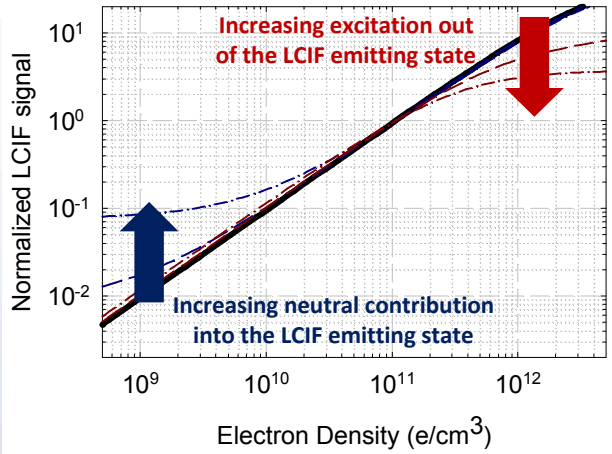
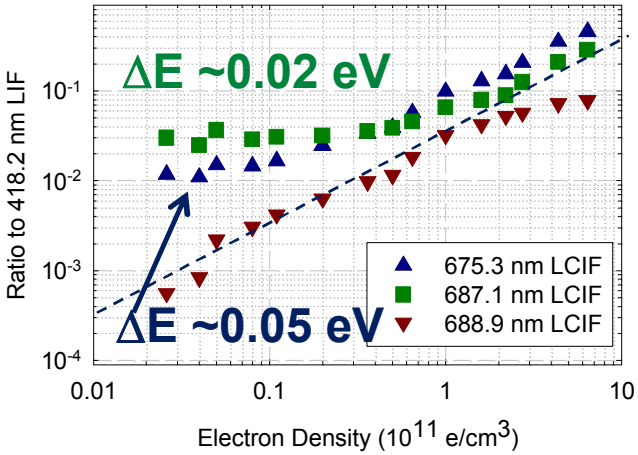
# Electron density scaling demonstrated for select transitions

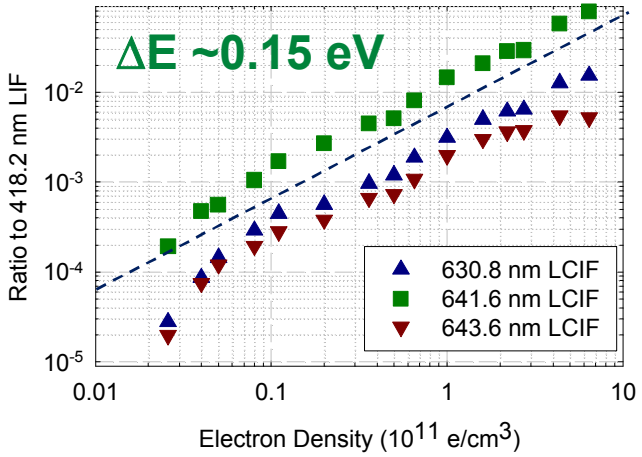
- Simple model is utilized to assess LCIF scaling.
  - Include neutral collisions and excitation into and out of target states.
- LCIF emanating form energetically uphill states is measured as a function of electron density.
  - Fixed E/N by tuning generating voltage pulse.

## Anticipated scaling




## Observed scaling




***Good linearity with electron density for higher lying states***

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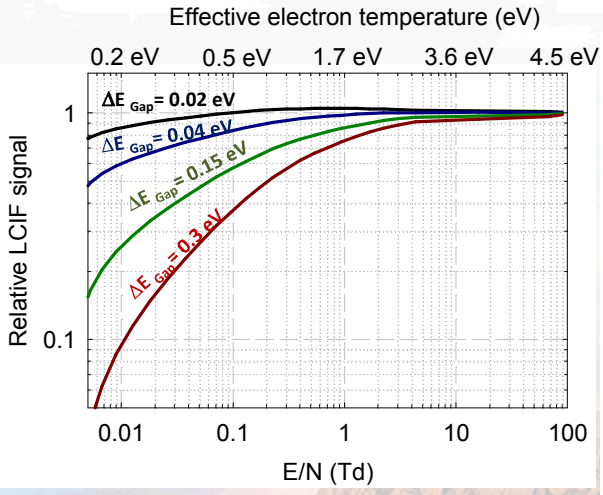
# E/N Scaling likewise demonstrated for select transitions

- **Cross-sections not well known, assume functional form**

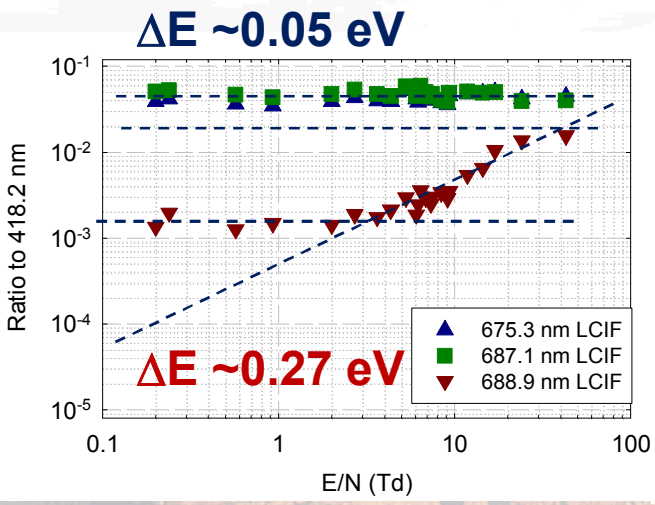
$$\sigma(E) = 4\pi a_0^2 \alpha \left(\frac{E}{\Delta E}\right)^n \left(\frac{E}{\Delta E} - 1\right) ln\left(1.25\beta \frac{E}{\Delta E}\right)$$

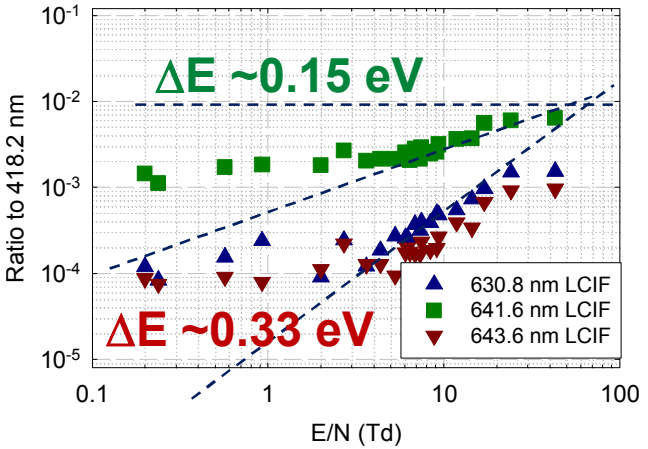
- **LCIF emanating form energetically uphill states is measured as a function of E/N at fixed density.**
  - **Residual E/N remaining due to ambipolar fields regulating losses.**

**Anticipated scaling**




**Observed scaling**




***Good range of transitions that demonstrate different E/N sensitivities***

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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?**
  - Two-dimensional snap-shots of density provide insight into plasma physics.

- **In this presentation**
  - **Part I: Laser-collision induced fluorescence (LCIF) primer**
    - **Collisional-radiative model used to predict LCIF**
    - **Physics that governs LCIF**
  - 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
    - Atmospheric pressure LCIF

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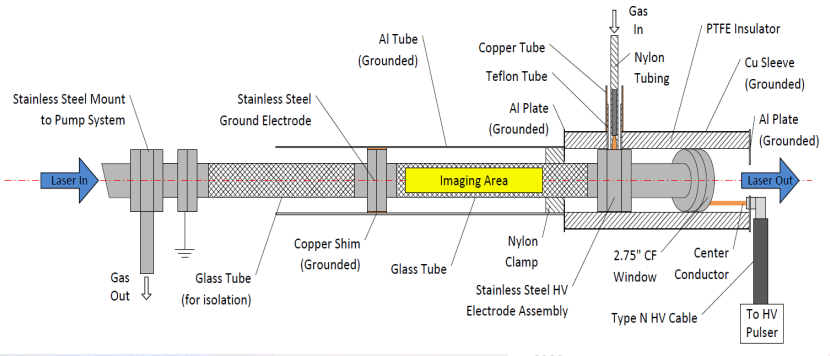
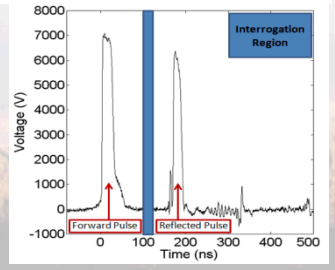
# Studies were performed to assess properties of FIW generated plasmas

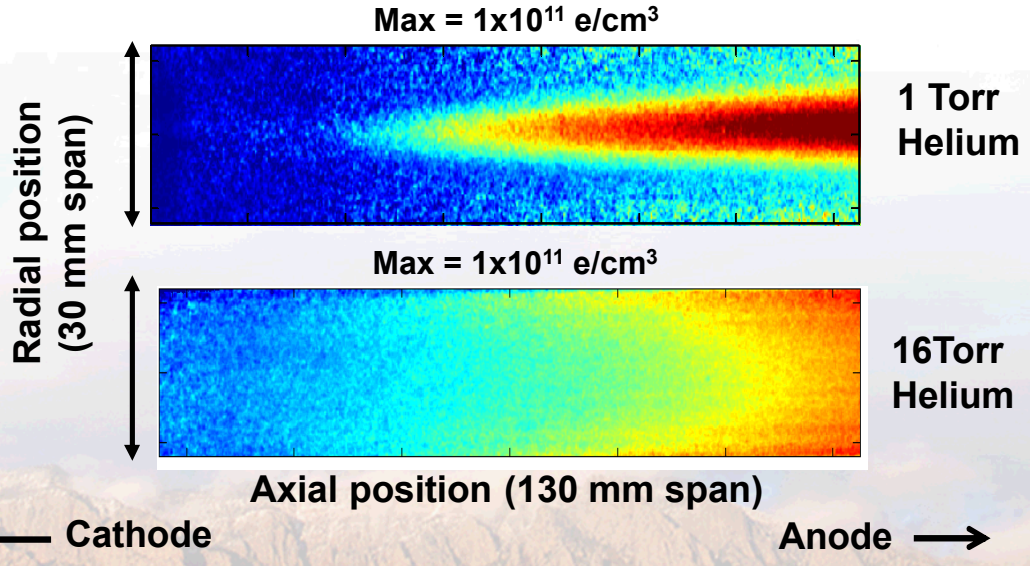
- **Fast-ionization waves (FIW) have been the subject of interest in the PSC.**
  - **High voltage (many kV), short pulse (10's ns) excitation.**
  - **Large E/N (100's Td) lead to efficient plasma formation.**
- **Earlier studies examined the plasma distribution immediately (~50 ns) after the FIW propagated. (B. Weatherford).**
  - **Laser (collision) induced fluorescence used to map plasma species.**

## Setup



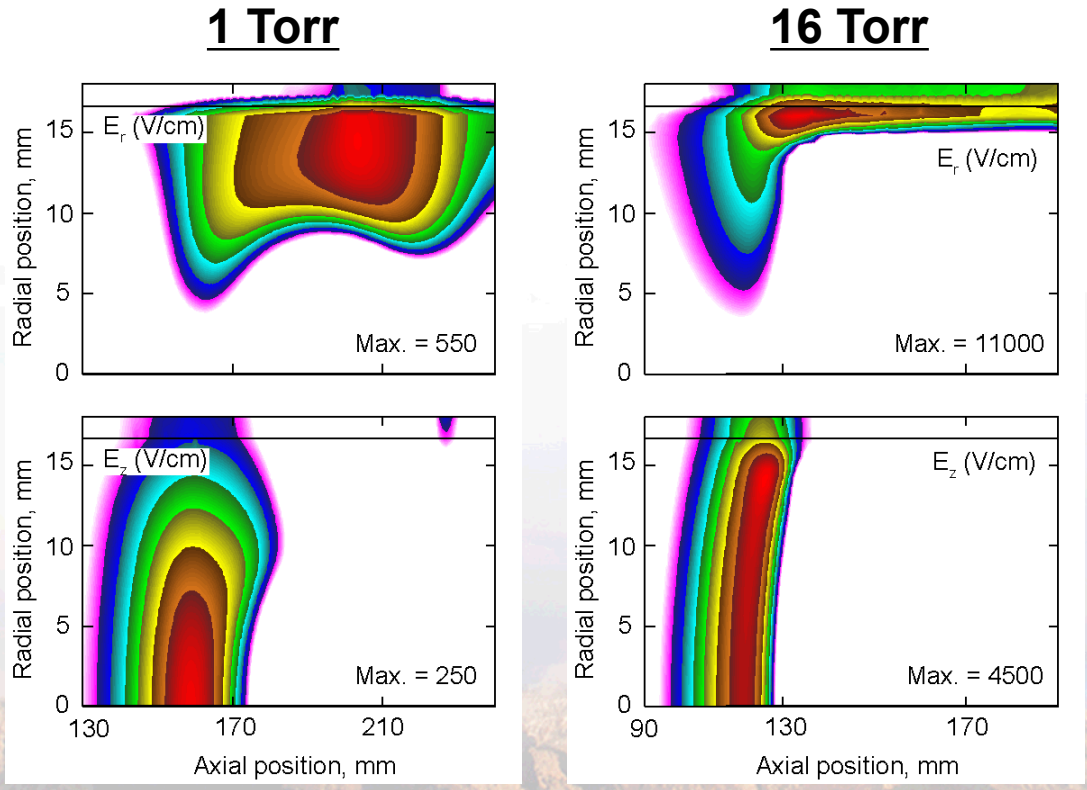




## Measured electron densities



# Changes in excitation are due to concentration of electric field

- **Electric fields are simulated to become stronger and more localized at higher pressures (A. Xiong, M. Kushner).**
  - **Energy deposition becomes more confined to the walls due to strong electric fields.**



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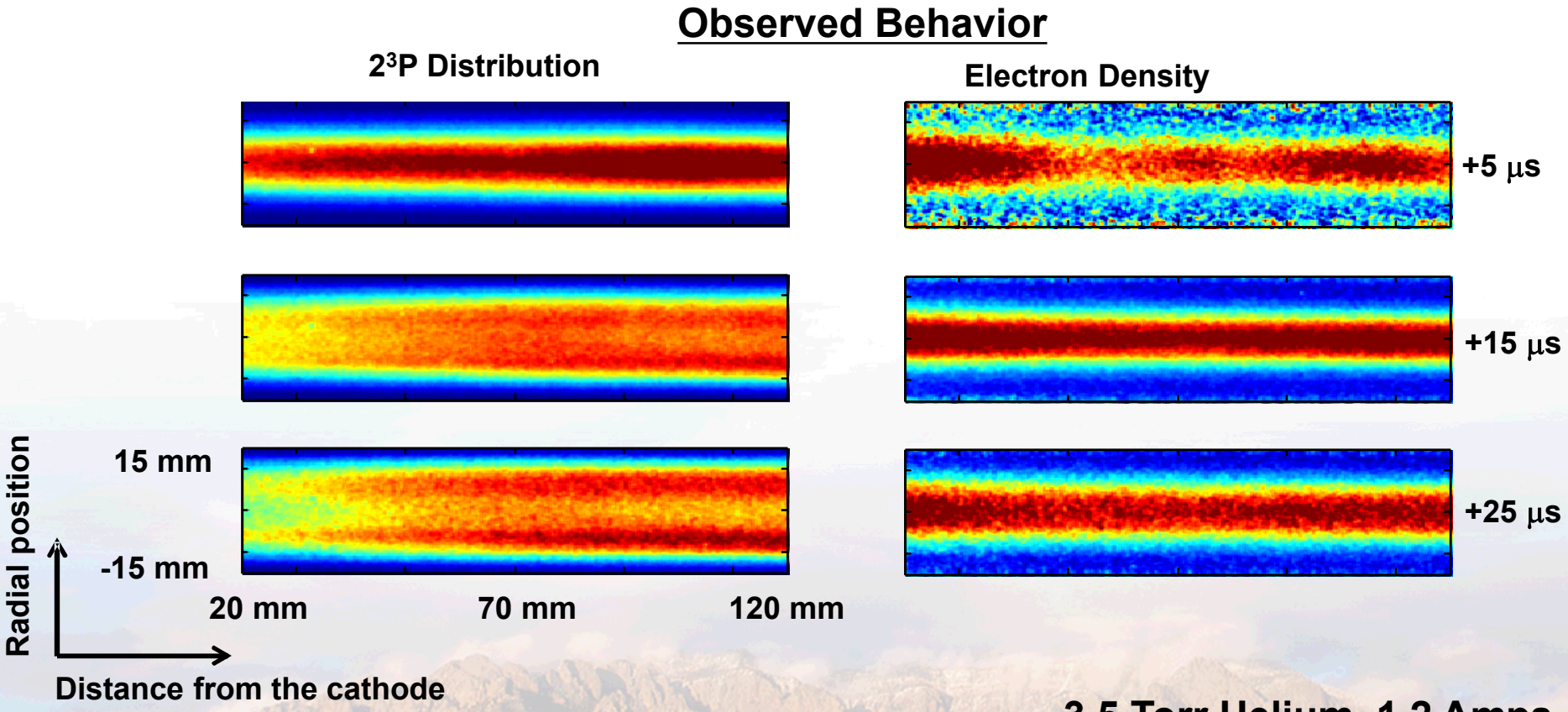
# “Unexpected” structure observed during calibration of the LCIF diagnostic

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




**3.5 Torr Helium, 1.2 Amps**

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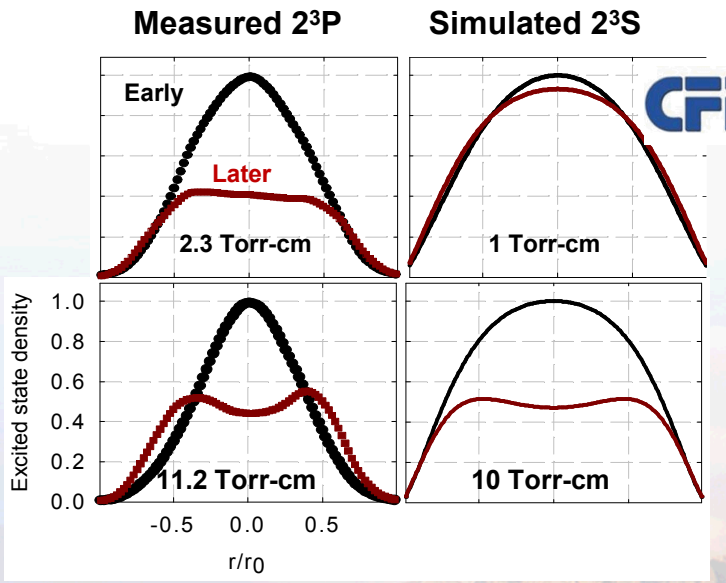
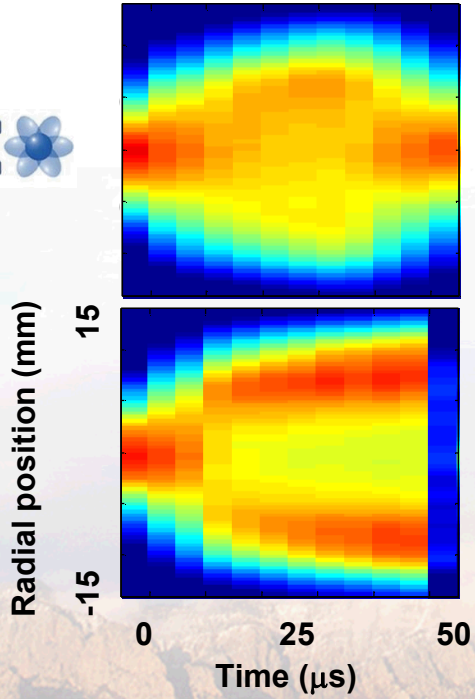
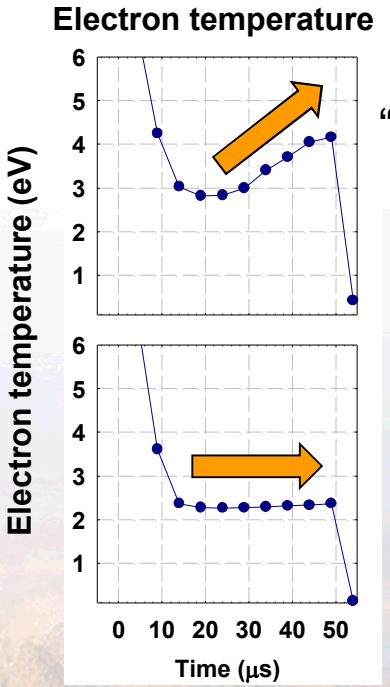
# Electron energies drive plasma structure

- Various processes were considered
  - Heating, constriction, non-linear or non-local kinetic processes
- Measurements and calculations were made to assess possibilities
  - Laser absorption to measure temperatures
  - 1D-Fluid based simulations with various “chemistries” (V. Kolobov)

## Spatial profiles




At lower pressures the both temperature and center-peaked structure are recovered; at higher pressures they are not

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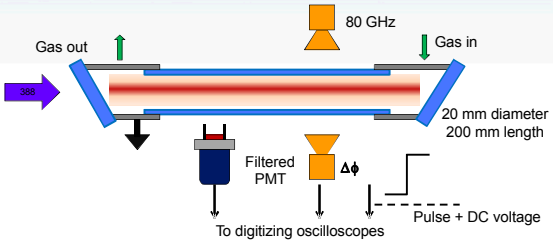
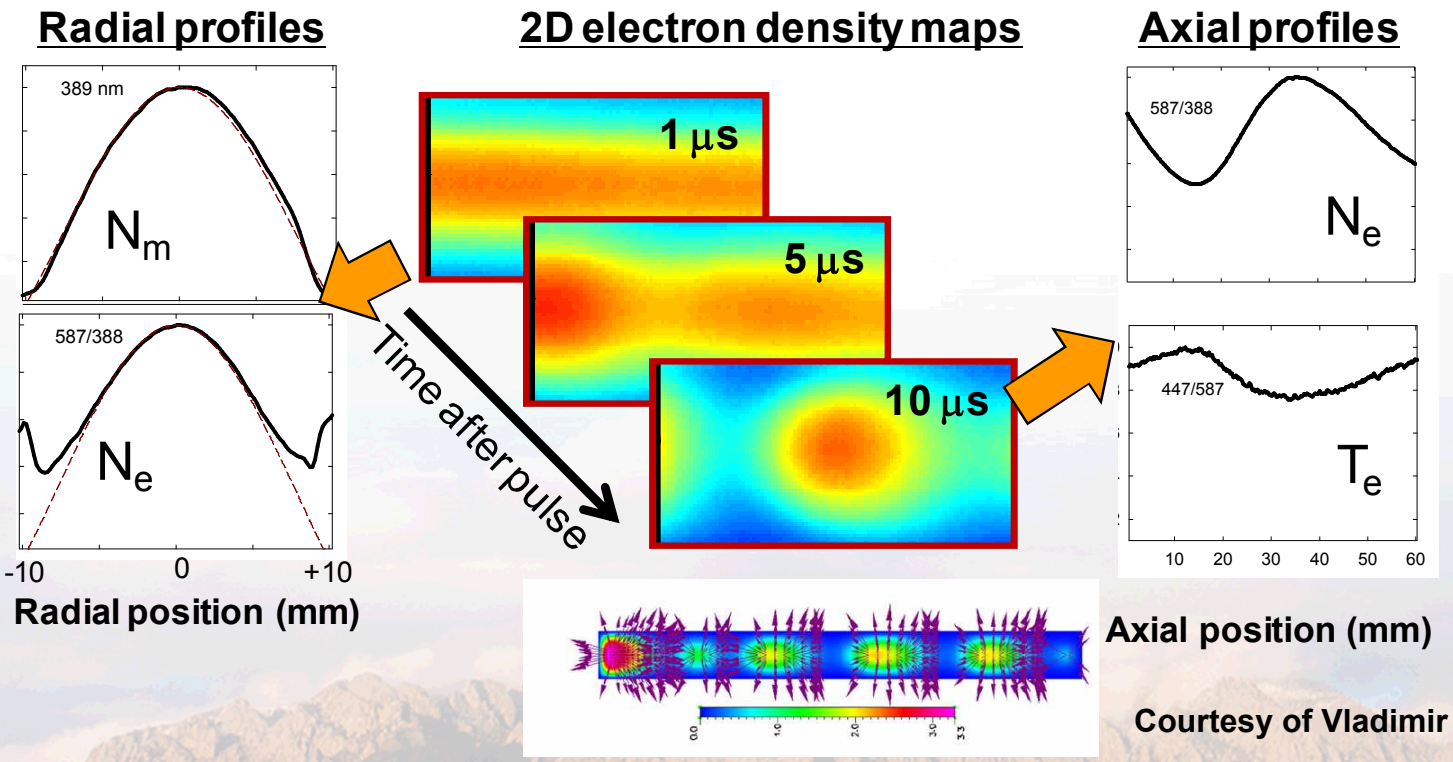
# LCIF is being used to study structure in a positive column

- **Positive column is "well understood" system**
  - Studied extensively, use it for calibration
- **Platform for fast ionization wave (FIW) studies**
  - Observations may warrant their own study




***Benchmark 2D simulations with measurements made by LCIF***



V. Kolobov, J. Phys. D: Appl. Phys. **39** (2006) R487

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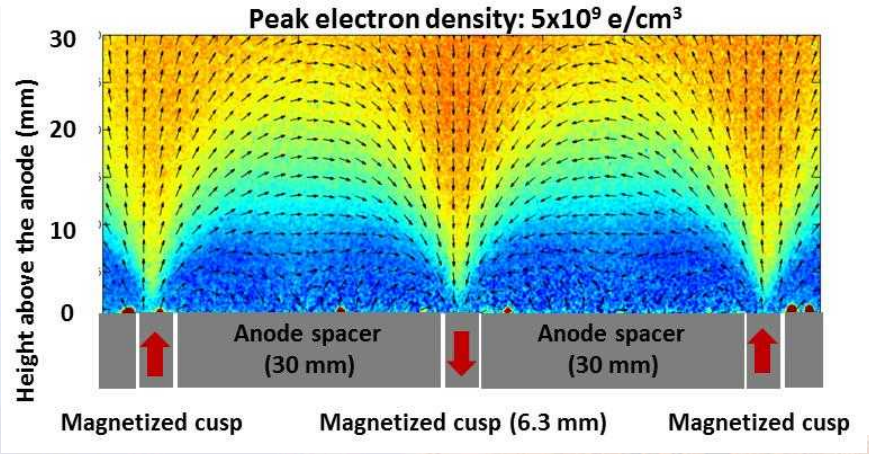
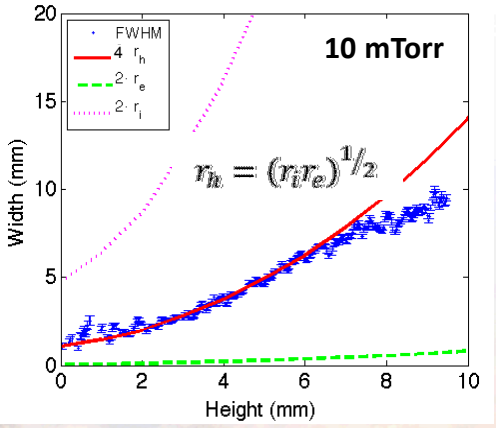
# LCIF method is utilized to look at transport in magnetized plasma

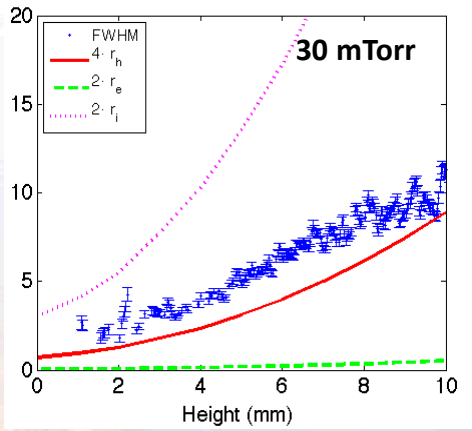
- **Plasma transport in magnetized plasma is important to understand but challenging to assess**
  - Magnetic configuration dictates particle balance in the plasma
- **Hosted Aimee Hubble (Ph.D. candidate w/ John Foster, U. Michigan) to address fundamental questions about electron loss**
  - Segmented,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

A. A. Hubble, E. V. Barnat, B. R. Weatherford and J. E. Foster, "The Electron Spatial Distribution and Leak Width in a Magnetic Cusp", Plasma Sources Sci. Technol. 23, 022001 (2014)

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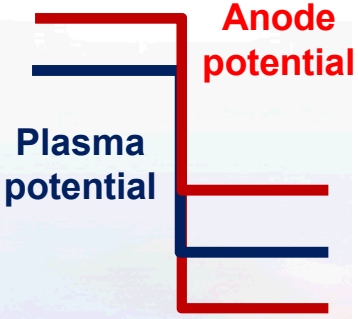
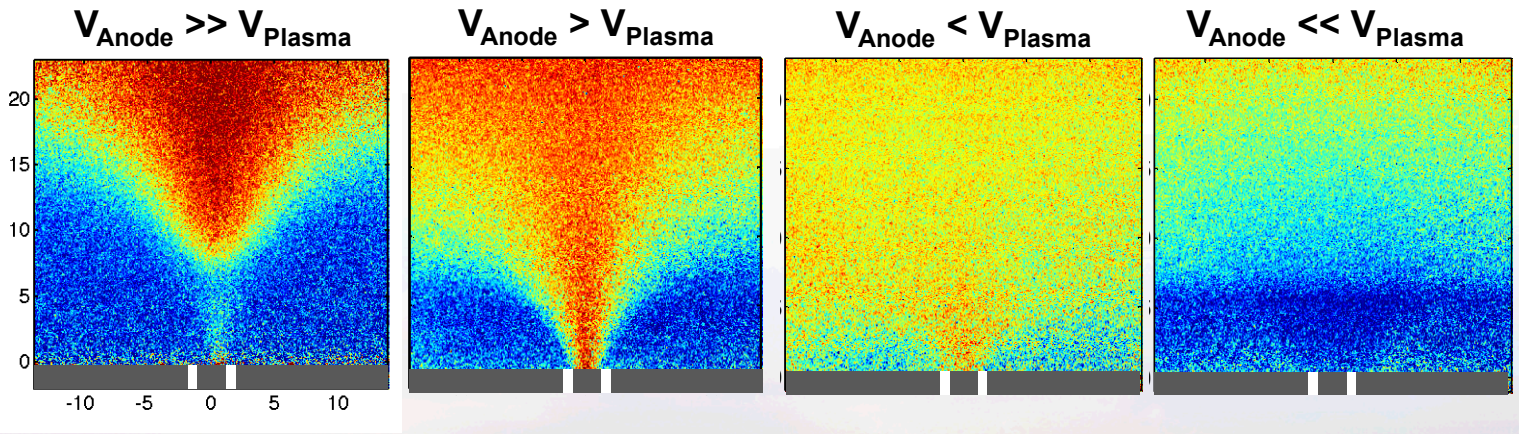
# Plasma transport is regulated by anode potential

- 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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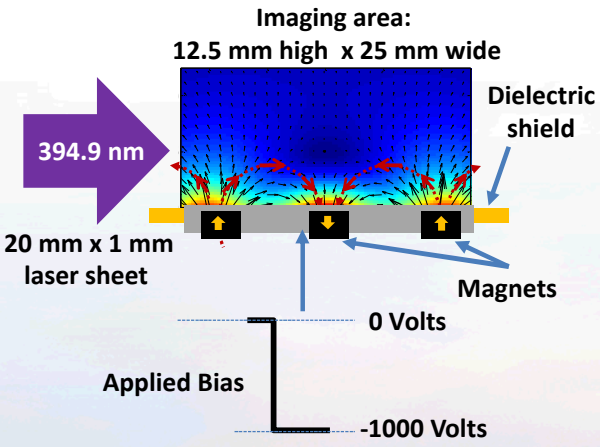
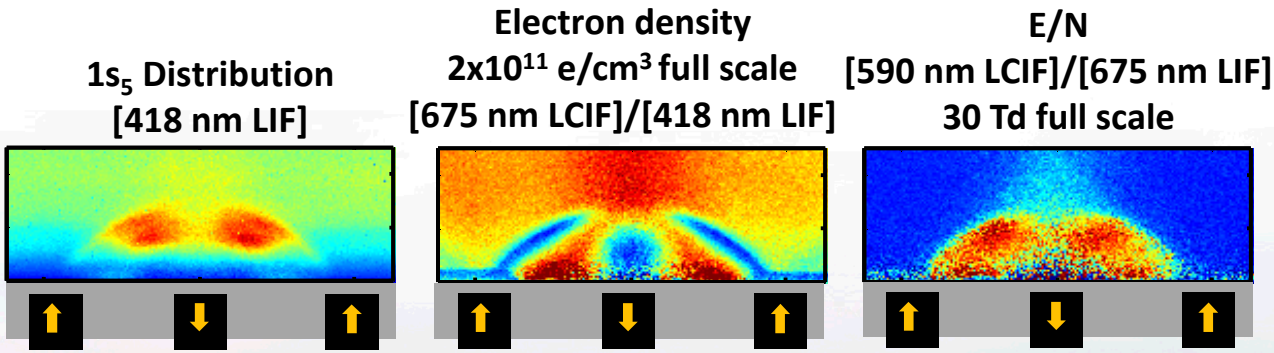
# Example of LCIF in argon environments

- Calibrated LCIF technique is applied to a transient magnetized discharge to demonstrate diagnostic capability.
  - 10 mTorr argon environment, - 1 kV pulse applied to 25 mm ϕ electrode
  - Measurements acquired 1 μs after pulse is applied

## Setup




## Observed plasma properties




***Interesting configuration that represents challenging plasma environment that is tough to access.***

E. V. Barnat and B. R. Weatherford, Plasma Sources Sci. Technol. **24,** 055024 (2015).

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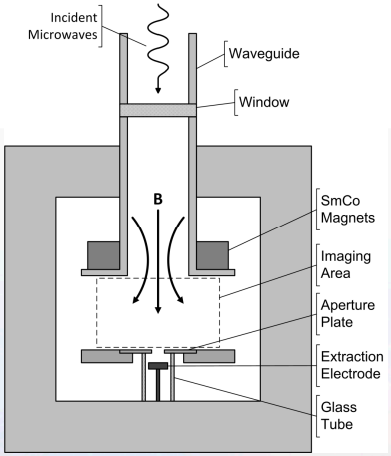
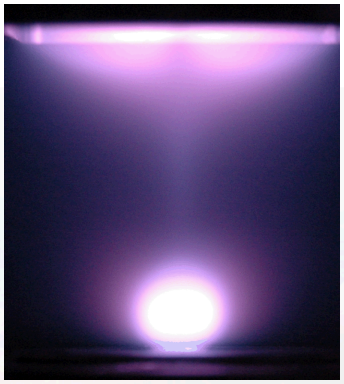
# Double layer more pronounced in ECR based plasma cathodes

- **NASA driven research interested in electron sources for propulsion**
  - Understand limitations on current extraction
- **Host Brandon Weatherford (U. Mich.) to implement LCIF**
  - Examine coupling of between plasma generation and electron extraction

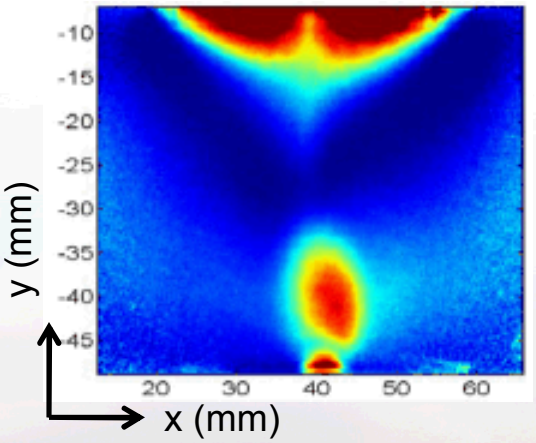
**Setup**



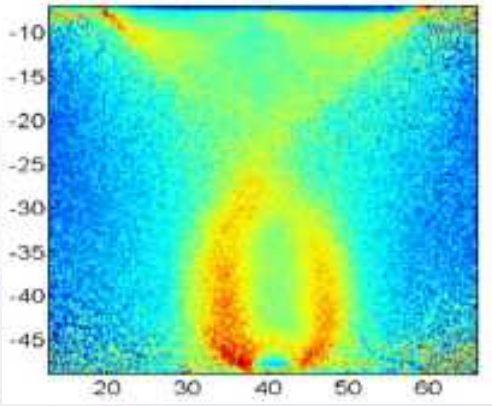

**"Full color" picture**



**Density**




**"Temperature"**



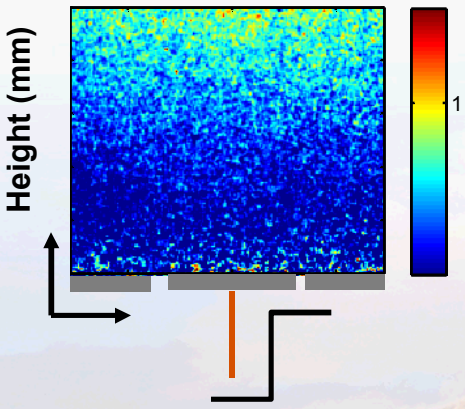

***Multi-structure plasma formed by electron-extracting electrode...***
***... quite difficult to probe with more conventional means!***

# LCIF is examining anode physics and spot dynamics

- **Recent studies have been focusing on anodic interfaces formed in plasma environments.**
  - **Rich set of physics that is uniquely different than cathodic interfaces.**
  - **Particularly difficult to access without perturbing the interface.**
- **Earlier efforts have focused on electron sheath and more recent efforts focused on spots**

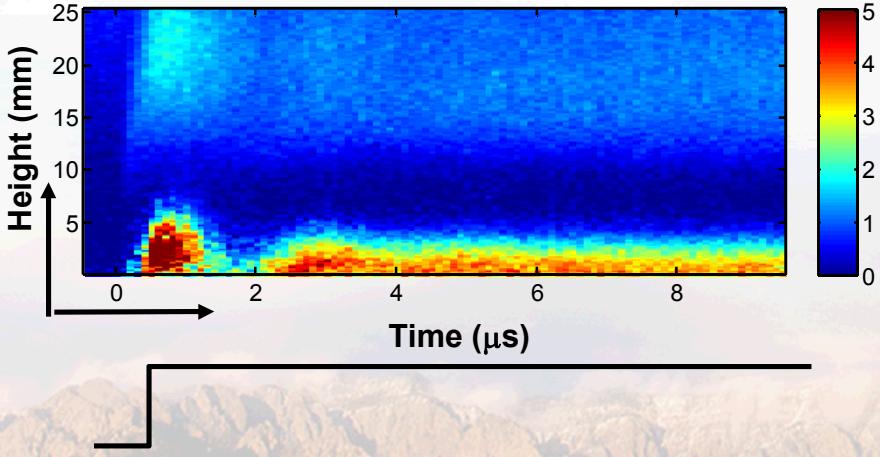
**Initial plasma state: Electron sheath**

$n_{e,\ Bulk} \sim 5 \times 10^8$ e/cm$^3$



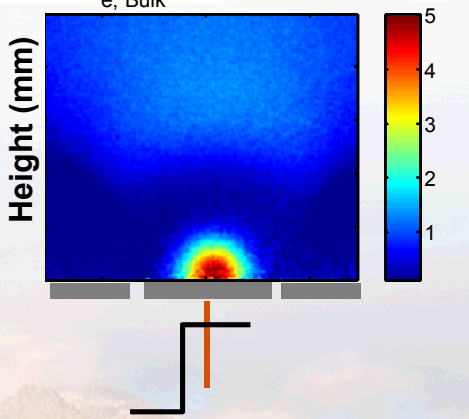

**25 mm x 25 mm**

**Induced transition**




**Final plasma state: Anode spot**

$n_{e,\ Bulk} \sim 1 \times 10^9$ e/cm$^3$




$n_{e,\ Spot} \sim 5 \times 10^9$ e/cm$^3$

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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?**
  - Two-dimensional snap-shots of density provide insight into plasma physics.

- **In this presentation**
  - **Part I: Laser-collision induced fluorescence (LCIF) primer**
    - **Collisional-radiative model used to predict LCIF**
    - **Physics that governs LCIF**
  - 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**
    - **Atmospheric pressure LCIF**

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# 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*

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# Thank you

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# References for rates and cross-sections

- **Superelastic**
  - Klein Rosseland
  - Sobelman

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


[1] C. F. Burrell and H.-J. Kunze, Phys. Rev. A **18**, 2081 (1978).
[1] P. Chall, E. K. Souw and J. Uhlenbusch. J. Quant. Spectrosc. Radiant. Transfer **34**, 309 (1985).
[1] G. Dilecce, P. F. Ambrico and S. De Benedictis, J. Phys. B: At. Mol. Opt. Phys. **28**, 209 (1994).
[1] R. Denkelmann, S.Maurmann, T. Lokajczyk, P. Drepper, and H. –J. Kunze, J. Phys. B: At. Mol. Opt. Phys. **32**, 4635 (1999).
[1] R. Denkelmann, S. Freund and S. Maurmann, Contrib. Plasma Phys. **40**, 91 (2000).
[1] K. Tsuchida, S. Miyake, K. Kadota and J. Fujita, Plasma Physics **25**, 991 (1983).
[1] B. Dubreuil and P. Prigent, J. Phys. B: At. Mol. Opt. Phys. **18**, 4597 (1985).
[1] E. A. Den Hartog, T. R. O'Brian and J. E. Lawler, Phys. Rev. Lett. **62**, 1500 (1989).
[1] K. Dzierzega, K. Musiol, E. C. Benck and J. R. Roberts, J. Appl. Phys. **80**, 3196 (1996).
[1] L. Maleki, B. J. Blasenheim, and G. R. Janik, J. Appl. Phys. **68**, 2661 (1990).
[1] R. S. Stewart, D. J. Smith, I. S. Borthwick and A. M. Paterson, Phys. Rev. E **62**, 2678 (2000).
[1] R. S. Stewart, D. J. Smith, J. Phys. D: Appl. Phys. **35**, 1777 (2002).
[1] A. Hidalgo, F. L Tabares and D. Tafalla, Plasma Phys. Control. Fusion **48**, 527 (2006).
[1] D. A. Shcheglov, S. I. Vetrov, I. V. Moskalenko, A. A. Skovoroda and D. A. Shuvaev, Plasma Phys. Rep. **32**, 119 (2006).
[1] M. Krychowiak, Ph Mertens, R. Konig, B. Schweer, S. Brezinsek, O. Schmitz, M. Brix, U. Samm and T. Klinger, Plasma Phys. Control. Fusion **50**, 65015 (2008).
[1] K. Takiyama, H. Sakai, M. Yamasaki, and T. Oda, Jpn. J. Appl. Phys. **33**, 5038 (1994).
[1] M. Watanabe, K. Takiyama, H. Toyota Jpn. J. Appl. Phys. **38**. 4380 (1999).
[1] G. Nersisyan, T. Morrow, and W. G. Graham, Appl. Phys. Lett. **85**, 1487 (2004)
[1] W. L Wiese, M. W. Smith, and B. M. Glennon, *Atomic Transition Probabilities **4/V1*** (Nat. Stand. Ref. Data. Ser., Nat. Bur. Stand. Washington DC, 1966).
[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).
[1] I.I. Sobelman, L. A. Vainshtein, and E. A. Yukov, *Excitation of Atoms and Broadening of Spectral Lines* (Springer, New York, 1981) p. 5.


$$K_{ij}^{e} = \left\langle \sigma_{ij} v_e \right\rangle = \left( \frac{m_e}{2\pi k T_e} \right)^{3/2} \int_0^{\infty} \sigma_{ij}(v) \exp\left( \frac{-m_e v^2}{2 k_B T_e} \right) 4\pi v^3 dv$$