SAND2014-4413C

Characterization of dynamic and structured plasma using laser-collision induced fluorescence

2014 IEEE ICOPS/Beams

May 27, Washington D.C.

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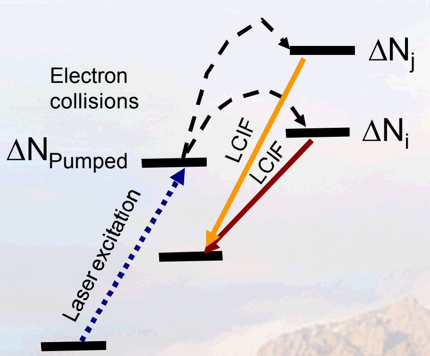
This work was supported by the Department of Energy Office of Fusion Energy Science Contract DE-SC0001939

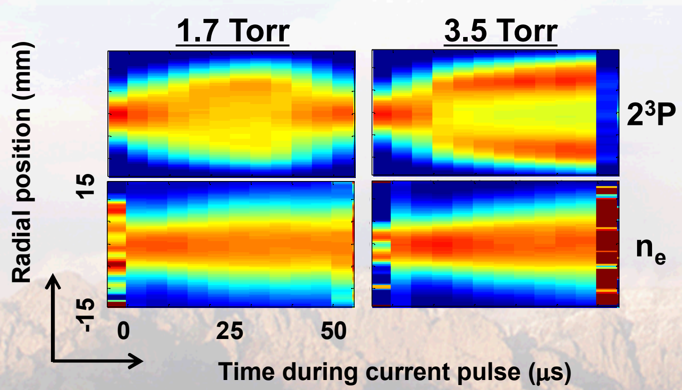
Outline

- **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 2^3P states
  - Transport in magnetized plasma
- **Conclusions and next steps**

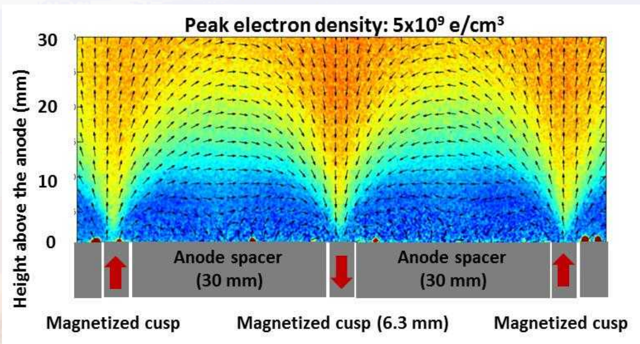
LCIF Diagnostic



Transient positive column

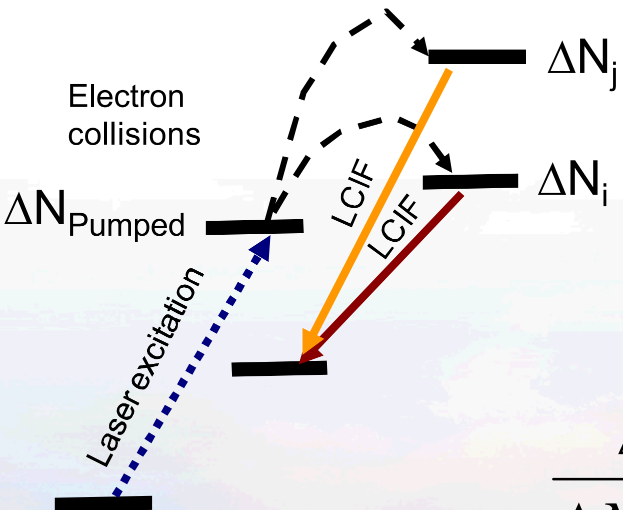


Magnetized plasma



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



Change in upper state due to excited state

Electron- coupled interaction

$$\Delta N_{i,j} \sim K^{e}_{i,j}(T_e)n_e \times \Delta N_{Pumped}$$

Ratio

Ratio

$$\frac{\Delta N_i}{\Delta N_{Pumped}} \sim K^{e}_{i}(T_e)n_e$$

$$\frac{\Delta N_j}{\Delta N_i} \sim \frac{K^{e}_{j}(T_e)}{K^{e}_{i}(T_e)}$$

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

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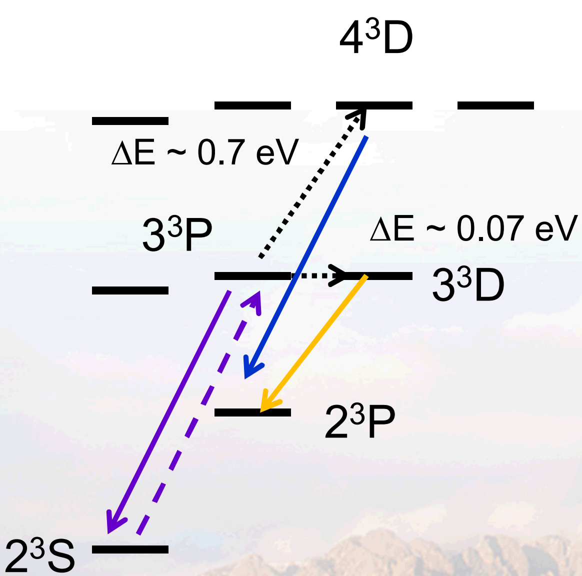
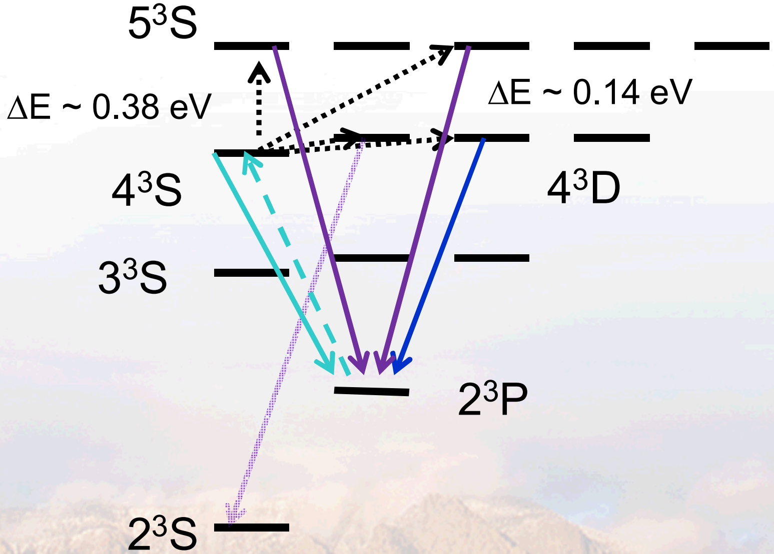
Alternative spectroscopic pathways are investigated

- **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

Excitation from 2^3S



Excitation from 2^3P



Pumping less populated 2^3P state enables higher pressure interrogation

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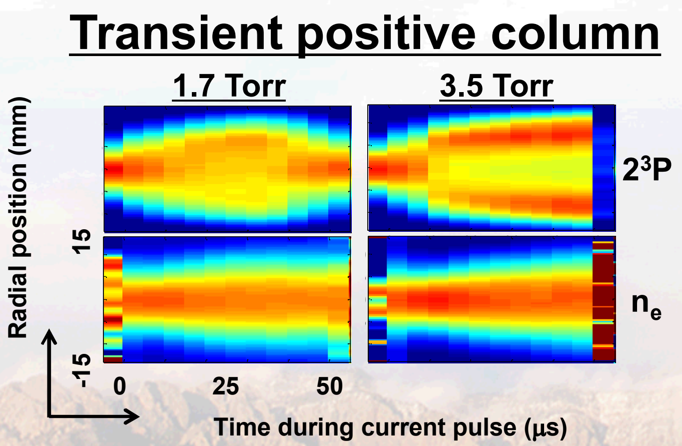
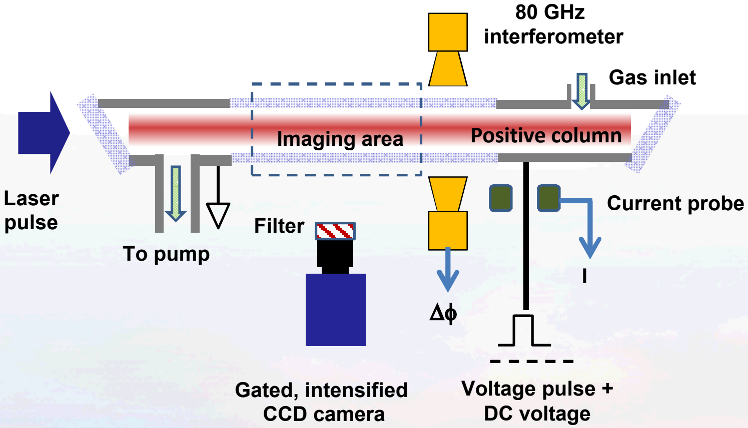


E. V. Barnat and V. I. Kolobov, "*Nonmonotonic Radial Distribution of Excited Atoms in a Positive Column of Pulsed Direct Current Discharges in Helium*", Appl. Phys. Lett. **102**, 034104 (2013).

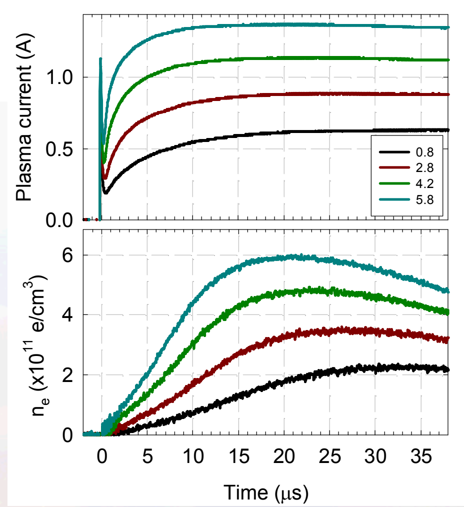
Pulsed positive column is utilized to benchmark LCIF technique

- **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

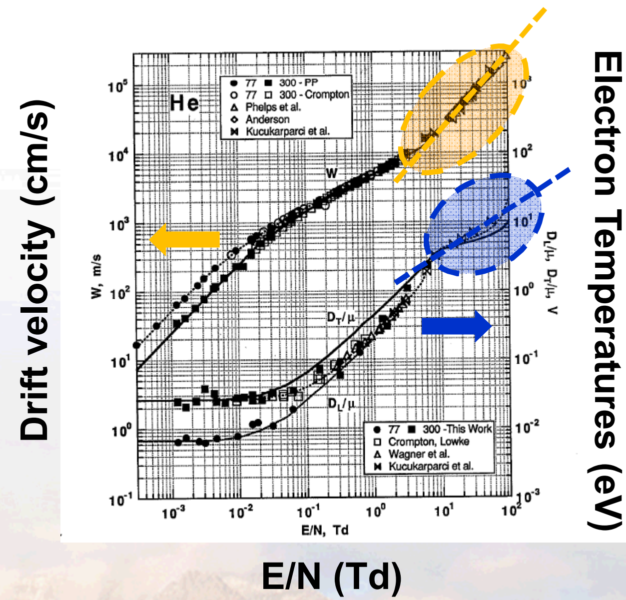
Positive column



Measured waveforms



Helium drift parameters



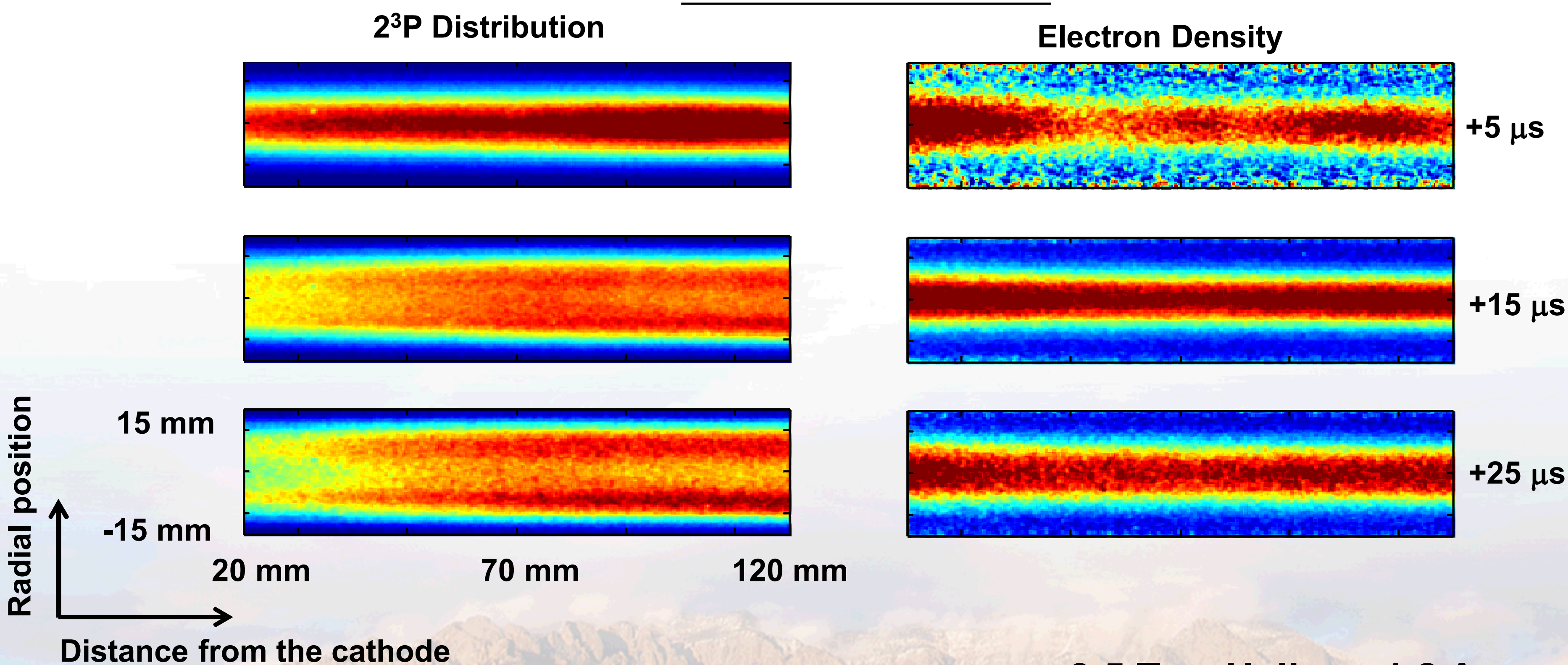
Observations made during calibration of the LCIF technique generated dialogue with collaborating institutions

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

"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

<u>Observed Behavior</u>



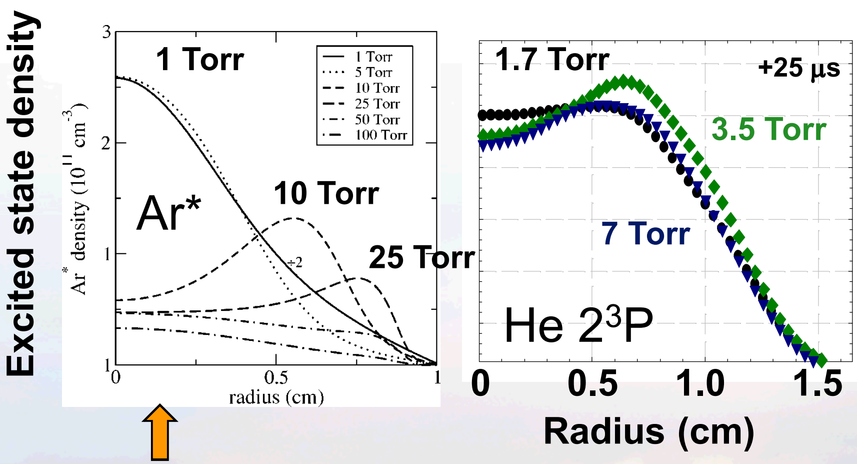
3.5 Torr Helium, 1.2 Amps

Interesting profiles… so what is happening?

Various mechanisms might generate observed behavior

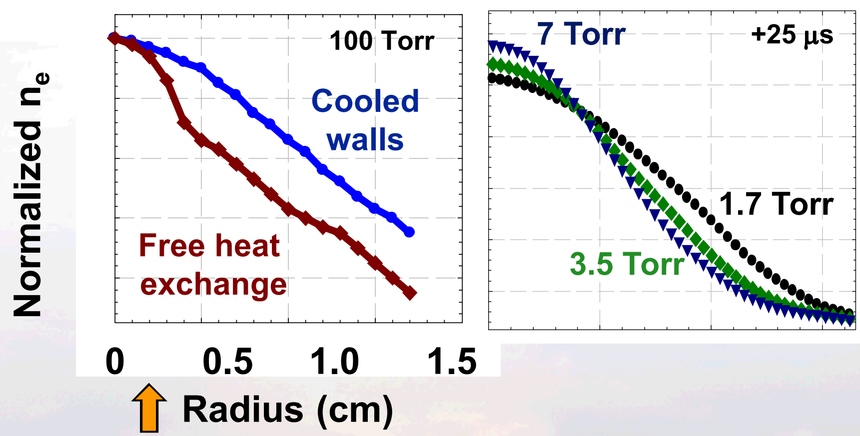
- **Observations similar to phenomena reported in literature**
  - Nonmonotonic excitation – non-local effects on EEDF (not for Helium)
  - Gas heating and possible constriction – rarefaction and or non-linear effects
- **Difficult to extrapolate to experimental results**
  - No direct one to one set of conditions between observed and reported behavior

"Paradoxical" Nonmonotonic excitation



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, Plasma Source Sci. Technol. **20**, 053002 (2011)

Are these effects present in our experiment?

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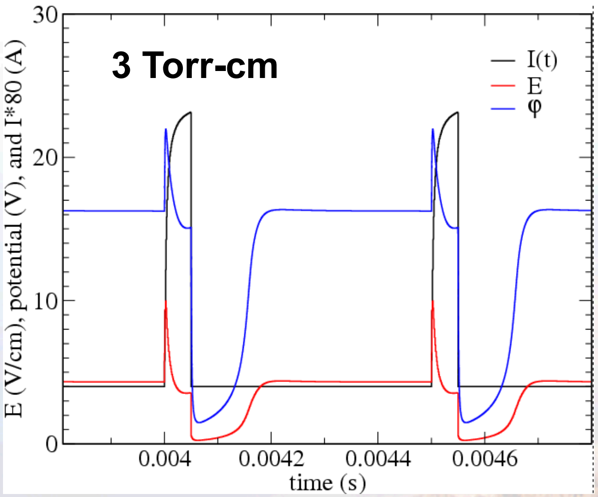
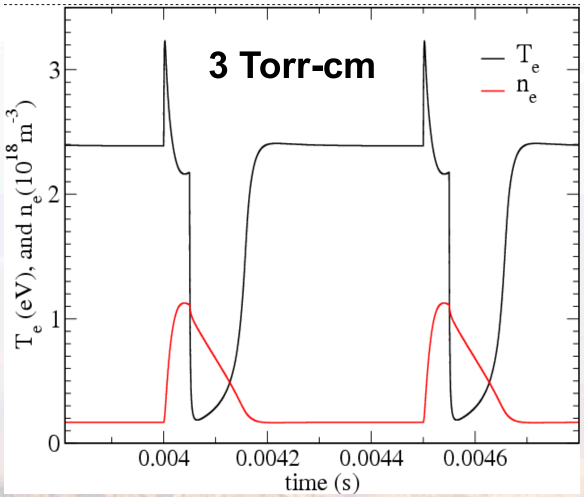
Predictive simulations guide understanding of the observed trends

- **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)

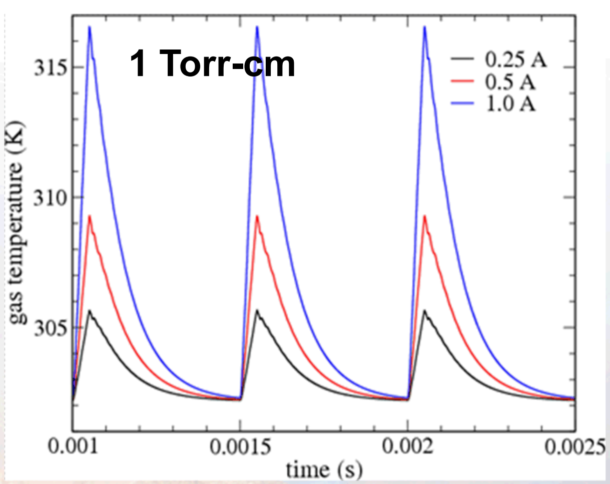
Currents and fields



Densities and temperatures



Gas temperatures



Gas heating does not appear to be significant contributor to observed behavior

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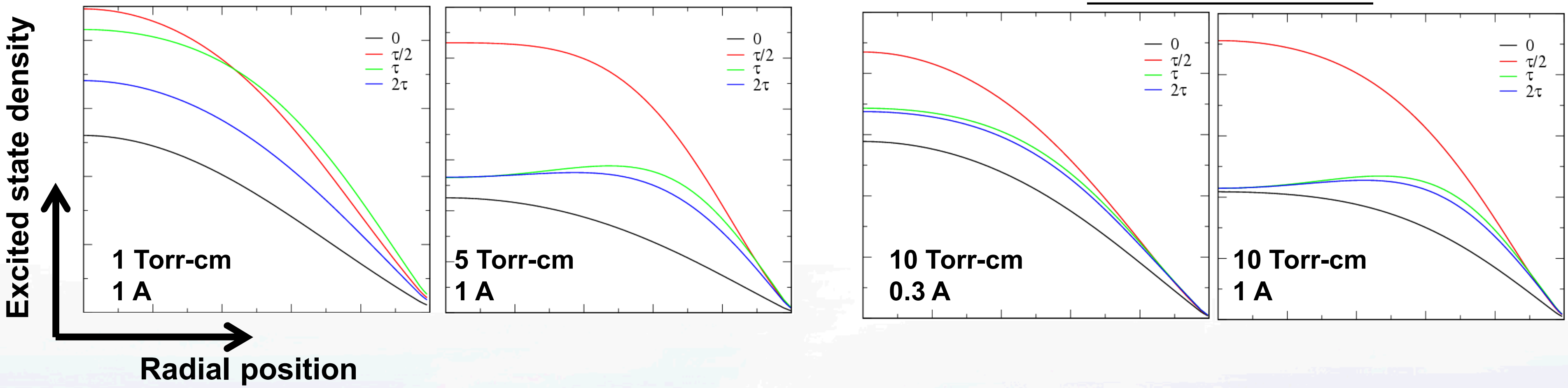
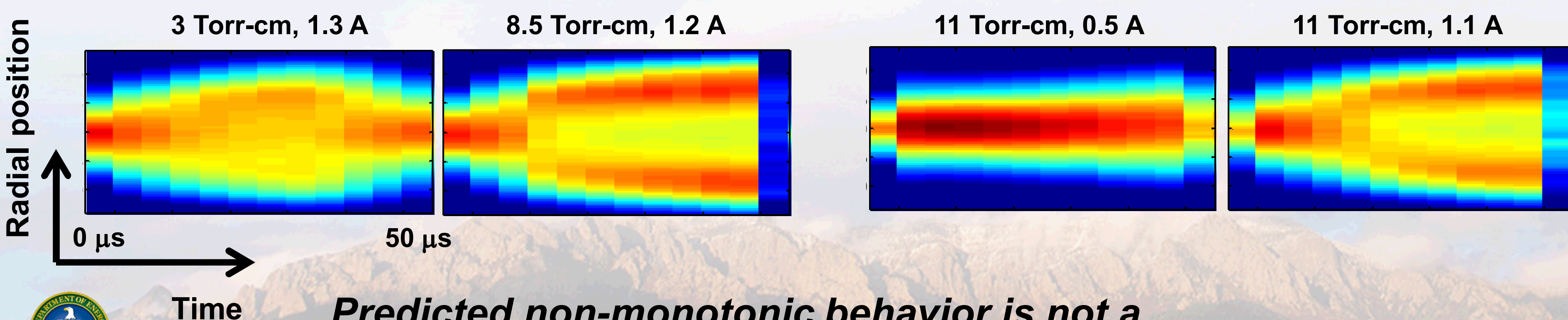
Fluid-based simulations predict non-monotonic profiles

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

Pressure trends **Current trends**



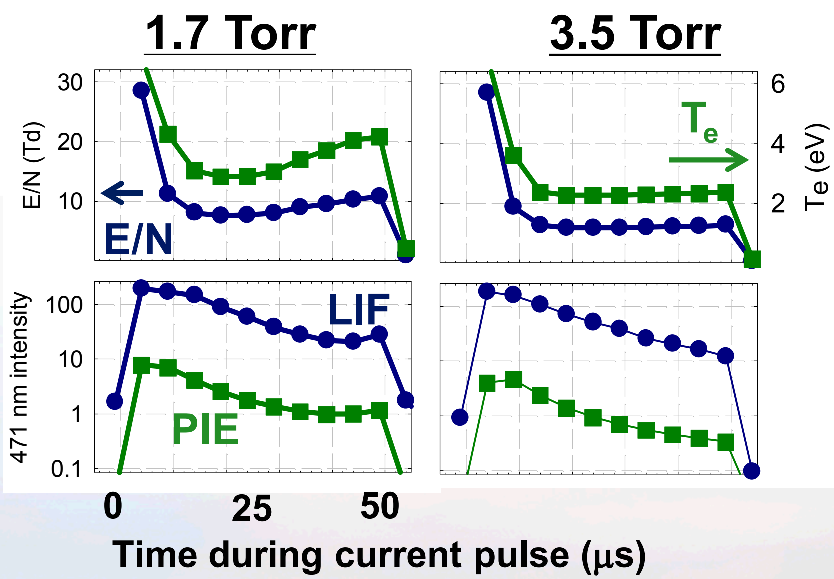


Predicted non-monotonic behavior is not a kinetic effect

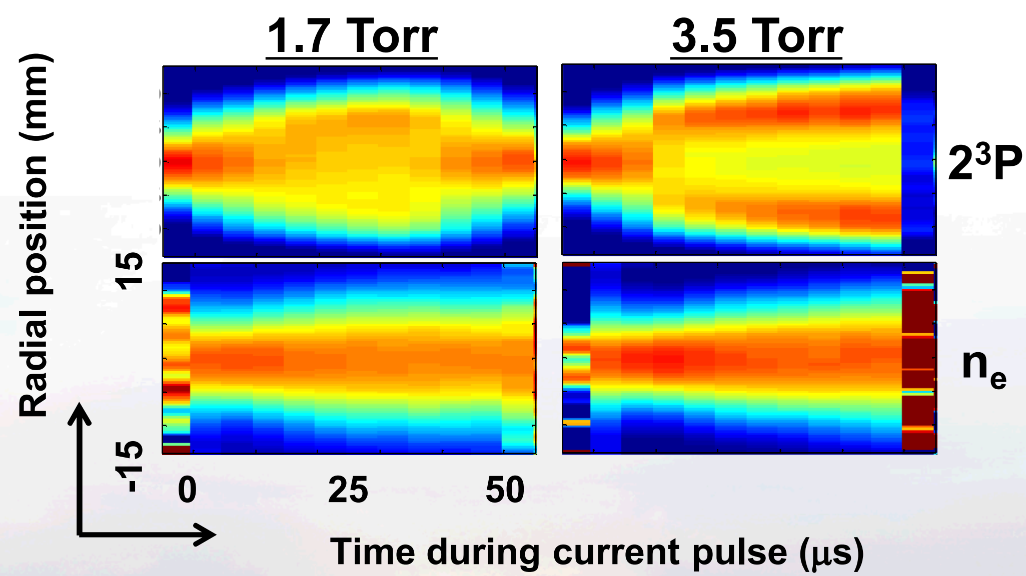
Distribution of 2^3P tracks relaxation of global drift parameters

- **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

Global behavior



Localized behavior



Tuning E/N facilitates "dialing" of plasma chemistry

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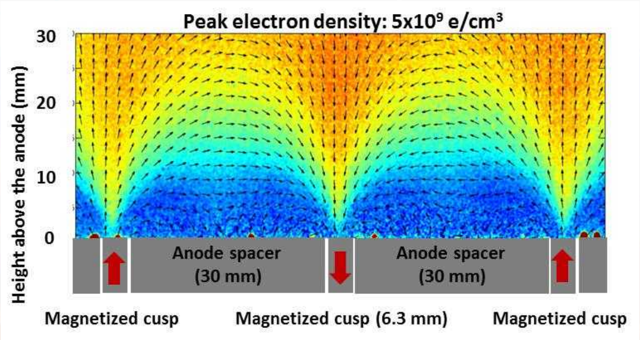
Magnetized plasma



A. A. Hubble, E. V. Barnat, B. R. Weatherford and J. E. Foster, "*Plasma Leak Measurements in a Magnetic Multi-Cusp Anode*", Plasma Sources Sci. Technol. **23**, 022001 (2014)

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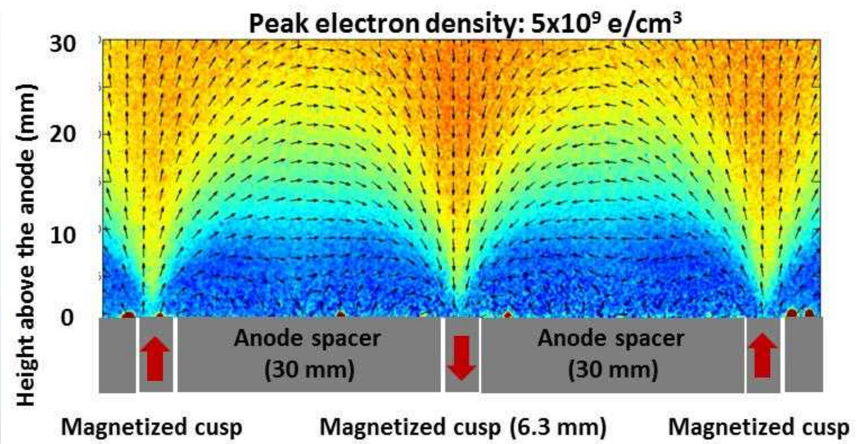
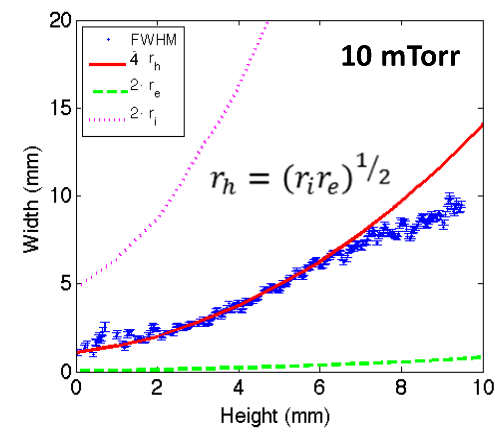
LASER DIAGNOSTICS DEVELOPED IN PSC INTERROGATES MAGNITIZED PLASMA

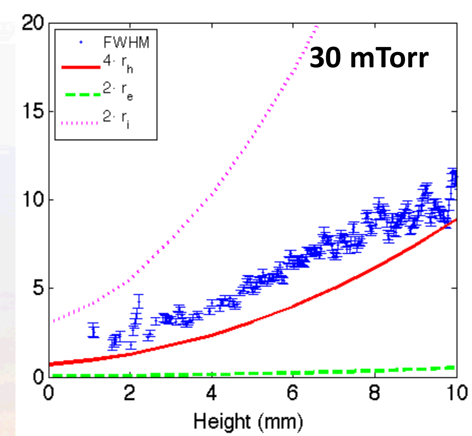
- **Plasma transport in magnetized plasma is important to understand but challenging to assess**
  - **Magnetic configuration dictates particle balance in the plasma**
- **Hosted Aimee Hubble (Ph.D. candidate w/ John Foster, U. Michigan) to address fundamental questions about electron loss**
  - **Segmented,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

Measured electron densities



Electron leakage widths



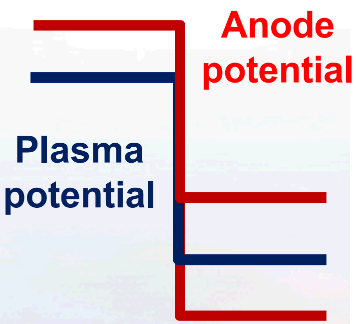


- **Measured electron densities, temperatures and magnetic fields are used to compute leak widths**

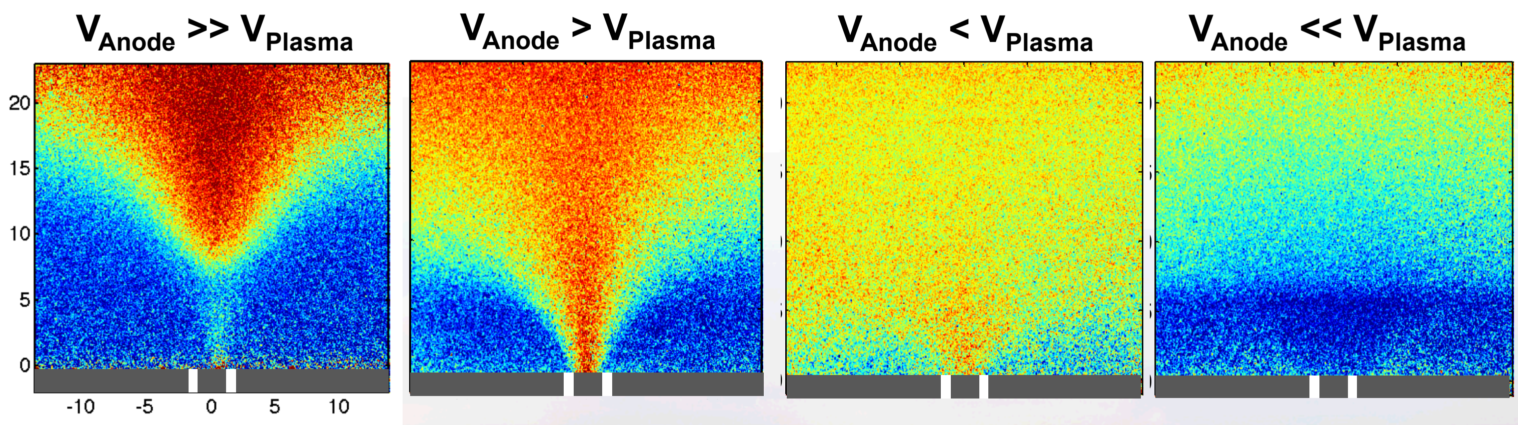
PLASMA TRANSPORT IS REGULATED BY THE ANODE POTENTIAL

- 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



- We intend to use these observations to foster new collaborations and efforts

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)
  - Discharge structure is correlated to changes to E/N (Creation and depletion)
- **Electron leakage width is assessed with LCIF**
  - Electron loss scales with the hybrid radius
  - Sheath structure is controlled with post-discharge bias

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

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