

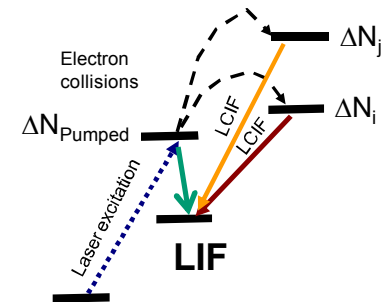
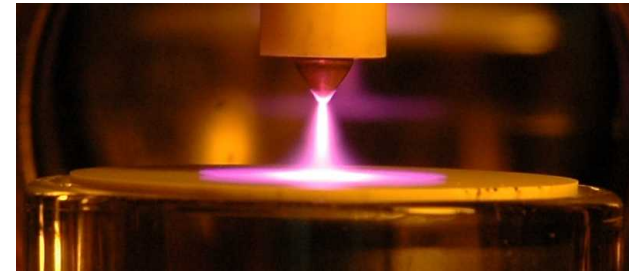
# Ultrafast Laser Diagnostics to Interrogate High Pressure, Highly Collisional Plasma Environments

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# INTRODUCTION AND MOTIVATION: CHALLENGES AND OBJECTIVES

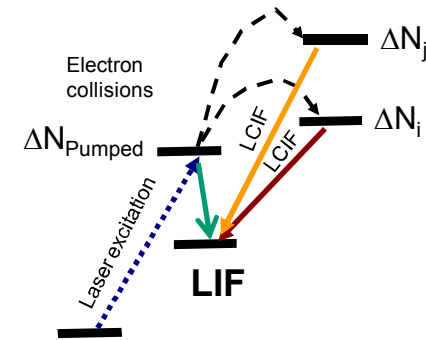
- High pressure ( $\sim 1$  ATM and beyond) plasma is challenging environment.
  - Higher densities.
  - Chemically complex environments
  - Smaller length scales.
  - Shorter lifetimes.
- Investigate diagnostics methods to access this challenging environment
  - Extend laser-collision induced fluorescence (LCIF) to atmospheric pressure helium discharge.
  - Examine suitability of ultrafast-short pulse lasers for use to these environments.



*Outline challenges and demonstrate implementation of LCIF to highly collisional environments.*

# OVERVIEW OF CHALLENGES OF EXTENDING LCIF TO HIGH PRESSURE

- Observed LCIF is superposition of several complex processes.
  - In general need a good model to describe the redistribution.



$$\frac{dN_j}{dt} = \underbrace{\left[ \sum_{i \neq j} K_{ij}^e N_i - \sum_{i \neq j} K_{ji}^e N_j \right] n_e}_{\text{"Electron mixing"}} + \underbrace{\sum_k \left[ \sum_{i \neq j} K_{ikj}^a N_i - \sum_{i \neq j} K_{jki}^a N_j \right] N_k}_{\text{"Neutral mixing"}} + \underbrace{\left[ \sum_{i > j} A_{ij} N_i - \sum_{i < j} A_{ji}^j N_j \right]}_{\text{"Photon mixing"}}$$



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

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

**Simplifications likely not to be so forthcoming at higher pressures**

# NEUTRAL INTERACTIONS KEY SOURCE OF INCREASED COMPLEXITY

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- Neutral-impact redistribution can play dominant role at higher pressures
  - More-types and evolving nature of neutrals (dimers).
  - “Book keeping” can require sophisticated models.
  - Uncertainties in species and cross-sections limit accuracy.

## Neutral mixing

$$\frac{dN_j}{dt} = \sum_k \left[ \sum_{i \neq j} K_{ikj}^a N_i - \sum_{i \neq j} K_{jki}^a N_j \right] N_k$$

## Bounds on detection

$$\frac{\Delta N_{Electrons}}{\Delta N_{Neutrals}} \sim \frac{K^e n_e}{K^N n_0} \sim 1$$
$$n_e \sim \frac{K^N}{K^e} n_0 \sim \frac{10^{-11}}{10^{-5}} n_0$$

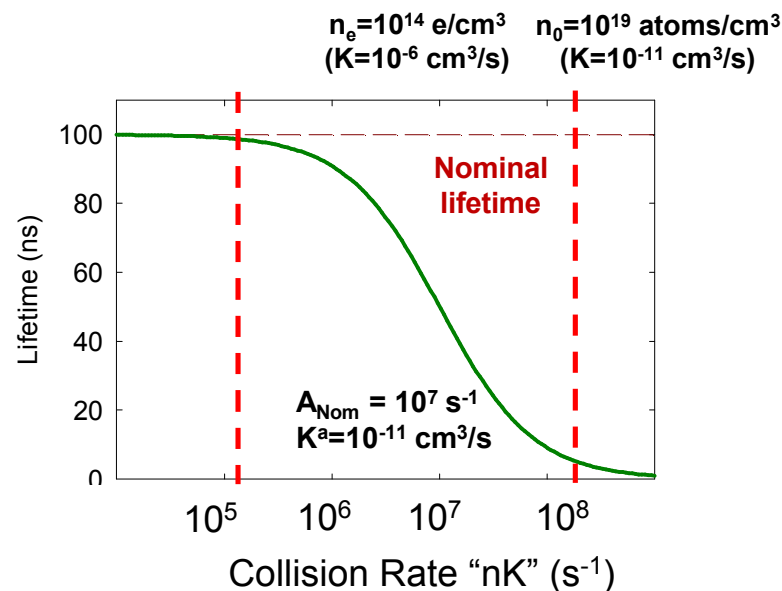
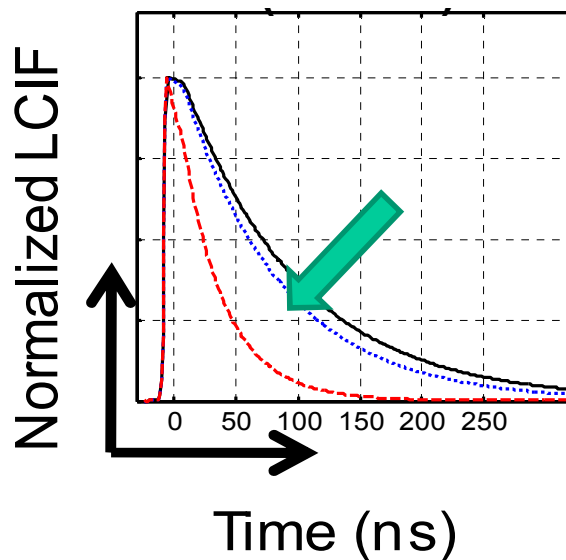
Limit  $\sim 10^{13}$  e/cm<sup>3</sup> at 1000 Torr

***Neutrals are anticipated place limits on lower bound of electron detection.***

# LIFETIMES OF EXCITED STATES BECOME VERY SHORT AT HIGHER DENSITIES

- Physics of electron-impact redistribution is not expected to change at higher pressures.
  - Sheer number of electrons increase probability of redistribution.
  - Effective Lifetimes become reduced because of redistribution.

$$\frac{dN_j}{dt} \sim \left[ \sum_{i \neq j} K_{ij}^e N_i \right] n_e$$

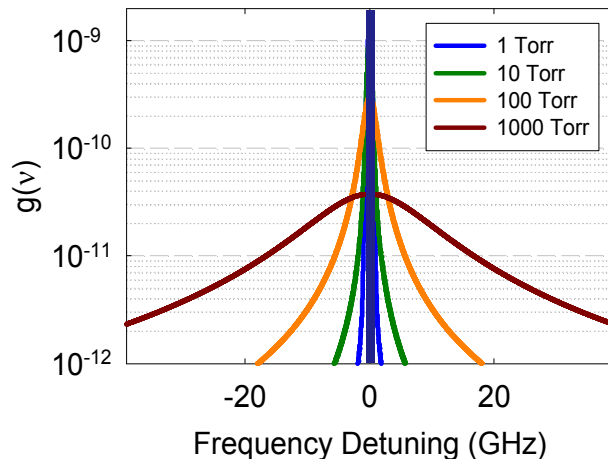


*Lifetime of excited states are quite short (~5 ns) at target conditions.*

# ULTRASHORT-PULSE LASER IS USED FOR INITIATION LCIF EVENT

- Ti:Sapphire, regenerative laser used to generate excitation pulse.
  - Tuned amplifier to 780 nm – doubled in BBO for ~ 390 nm.
  - ~ 100 fs pulse with 10 nm bandwidth (~ 100  $\text{cm}^{-1}$ ).
- Short-pulse laser well suited to interrogate short lifetimes (< 10 ns) and broad absorption profiles (~ 1 nm) associated with high pressure.
  - Still realize “step-like” populating process.
  - Sample most or all of the probed states.

## Anticipated absorption profiles



## Estimates of linewidths

ns laser ~ 0.5 GHz or 0.1  $\text{cm}^{-1}$

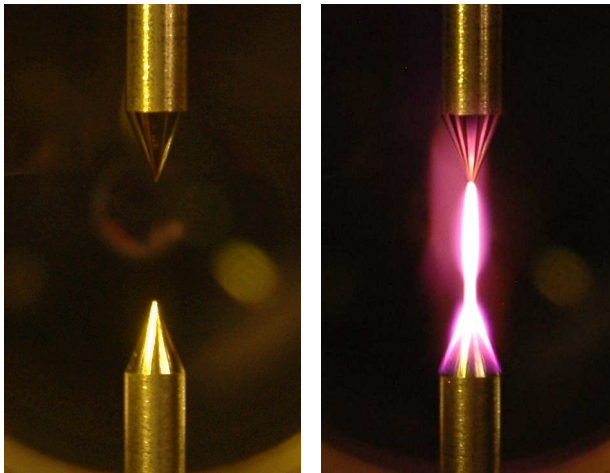
fs laser ~ 500 GHz or 100  $\text{cm}^{-1}$

Pressure Broadening ~ 0.01 GHz/Torr (He)

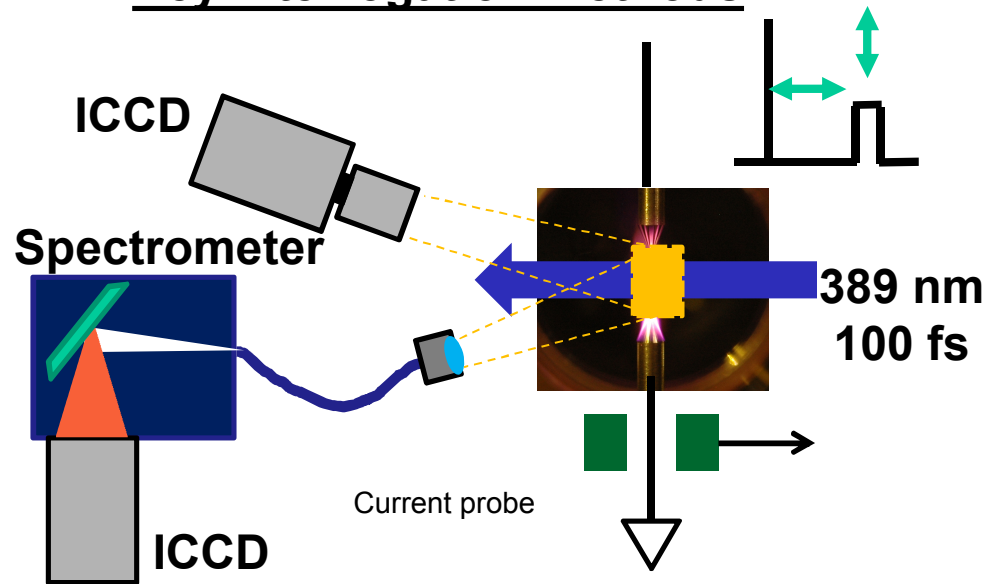
# KEY CHALLENGE: GENERATING AND MANIPULATING WELL CHARACTERIZED PLASMA

- Need plasma with well controlled  $n_e$ , E/N to calibrate LCIF.
  - Plasma generation in 640 Torr He.
  - Double pulse method to separate generation and interrogation.
  - Spectrometer to identify, camera to image.

## Discharge configuration



## Key interrogation methods

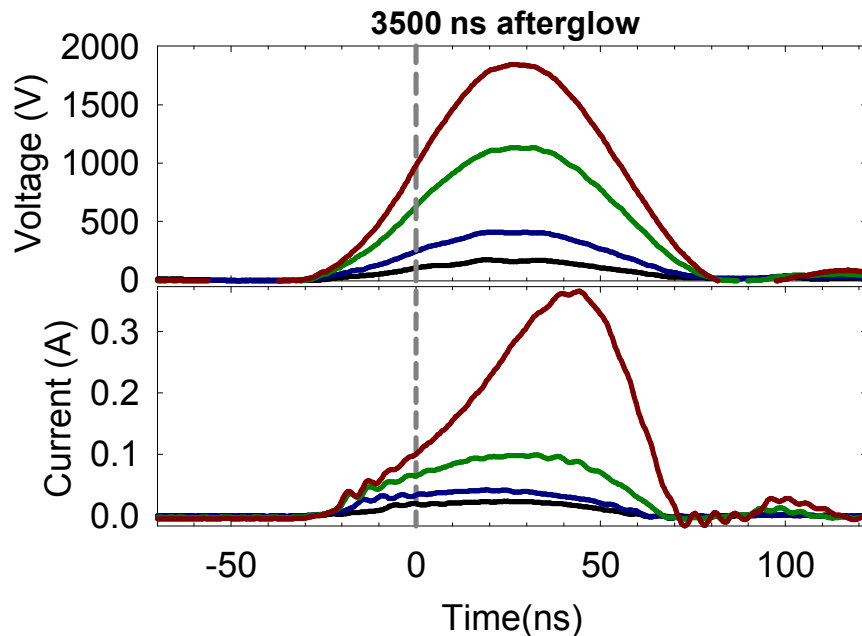


*Setup enables good access and control of the plasma for LCIF calibration.*

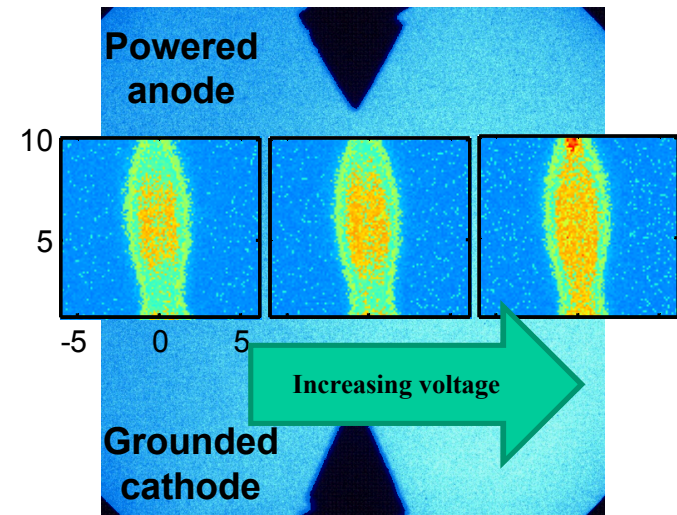
# DOUBLE PULSE PLASMA SEPERATES GENERATION FROM MANIPULATION

- Need plasma with well controlled  $n_e$ , E/N to calibrate LCIF.
  - First voltage pulse dictates plasma density and distribution.
  - Second pulse drives current through afterglow.

## Sample Response



## Observed Filament

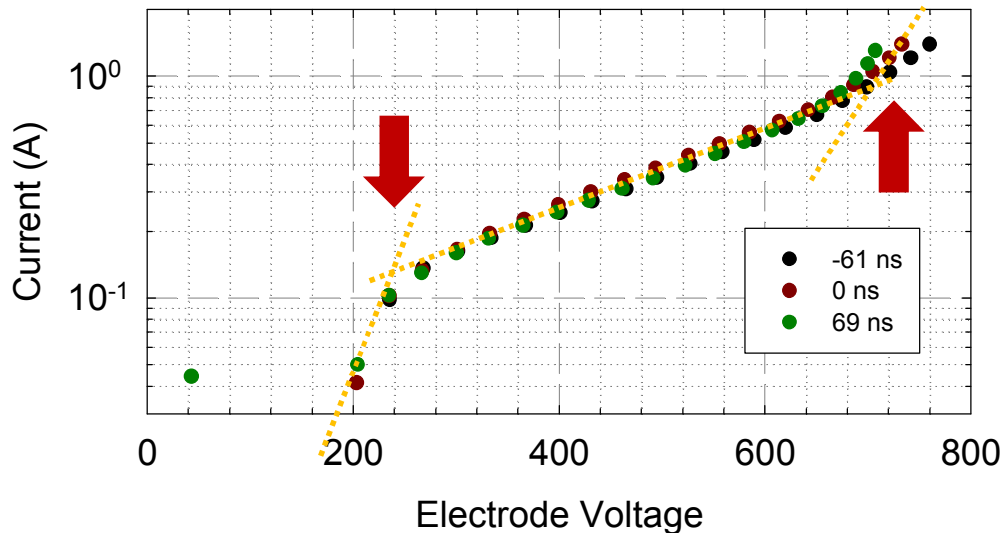


*Structure of the filament does not change significantly as it is "heated" – at least initially.*

# UTILIZE CURRENT-VOLTAGE TRENDS TO BOUND PLASMA PARAMETERS

- Published drift data (Phelps) is used to bound E/N with heating voltage.
  - Knees in current correspond to knees in drift velocities.
  - Electron density remains roughly constant at lower E/N values.

Extracted Current



Anticipated plasma parameters

$$n_e = \frac{m_e v_m N I}{e^2 N E A}$$

V	I	J	E/N	Vd	ne
V	A	A/cm <sup>2</sup>	Td	cm/s	e/cm <sup>3</sup>
225	0.1	3.18	0.1	1.50E+05	1.32E+14
700	0.6	19.10	5	1.00E+06	1.19E+14

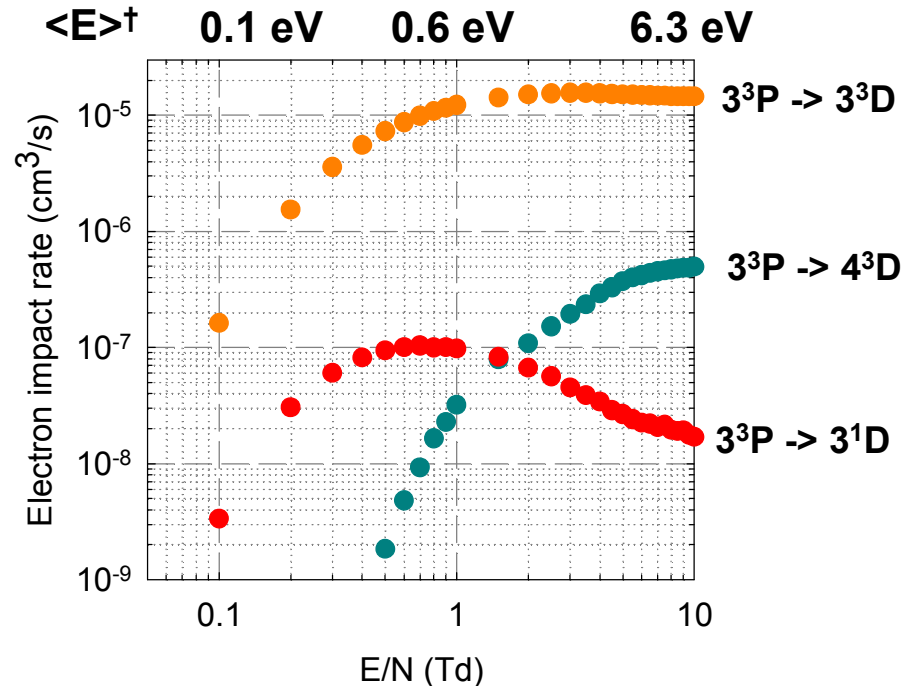
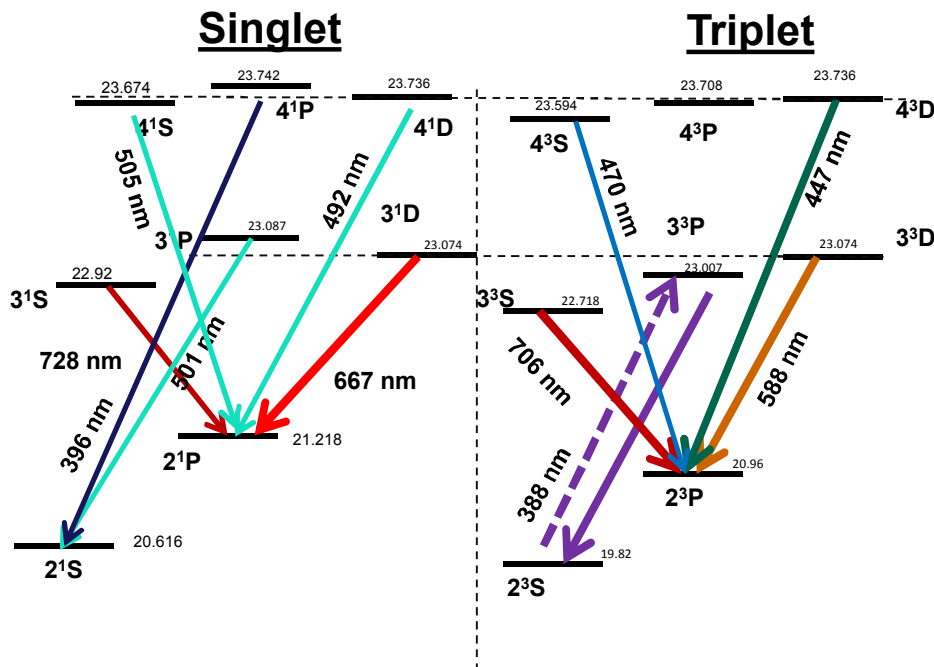
*Delay between first pulse and second pulse - Density*

*Magnitude of second voltage pulse – E/N*

# LCIF EVOLVES THROUGH SEVERAL SPECTROSCOPIC PATHWAYS

- Transitions from the laser excited  $3^3P$  state have different E/N scaling
  - Capitalize on unique characteristics to assess  $\langle E \rangle$  and E/N.

## Pathway and Rates

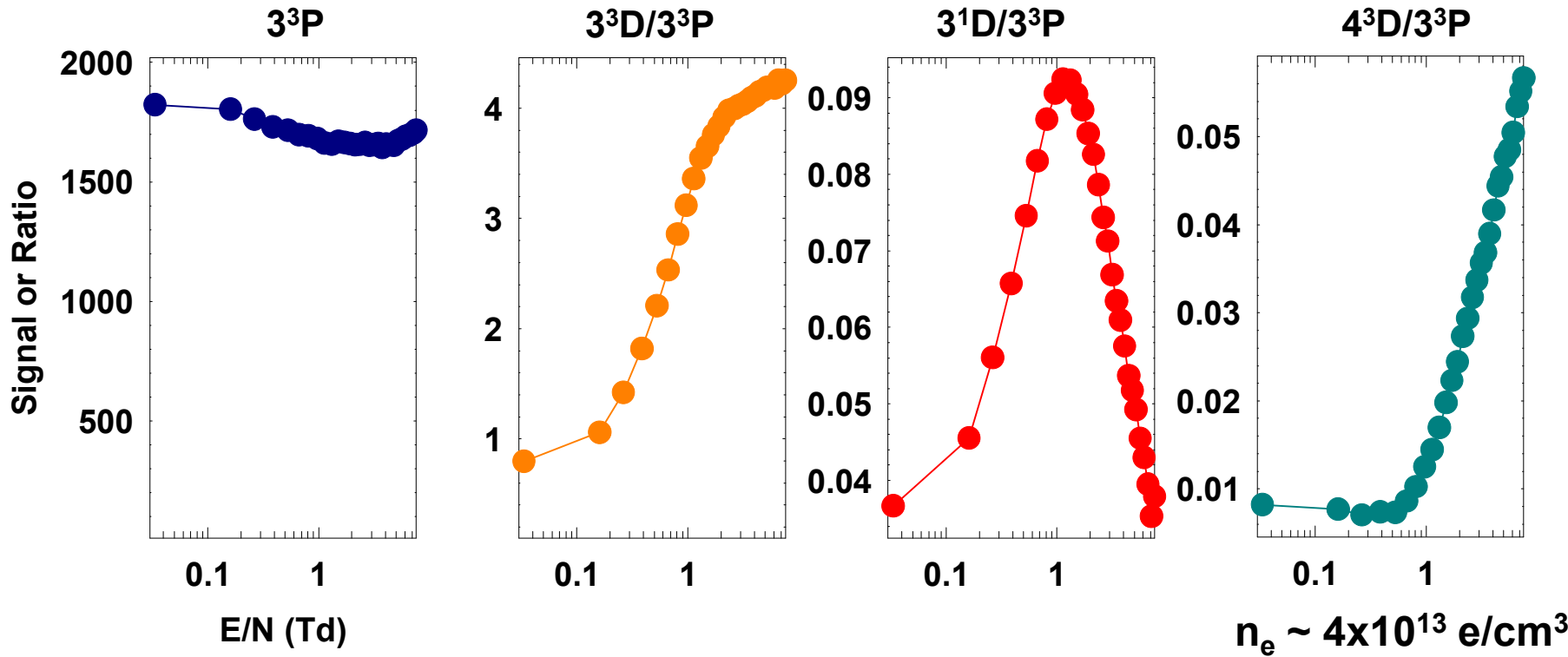


**Identify pathways that yield good signals and are “easy to” evaluate.**

# RATIO OF LCIF LINES ARE UTILIZED TO IDENTIFY SCALING TRENDS

- E/N is tuned and LCIF is measured early during applied pulse.
  - Ratio of LCIF to laser excited  $3^3\text{P}$  LIF is used to normalize signals.

## LCIF scaling with E/N



***Several LCIF transitions are observable!***

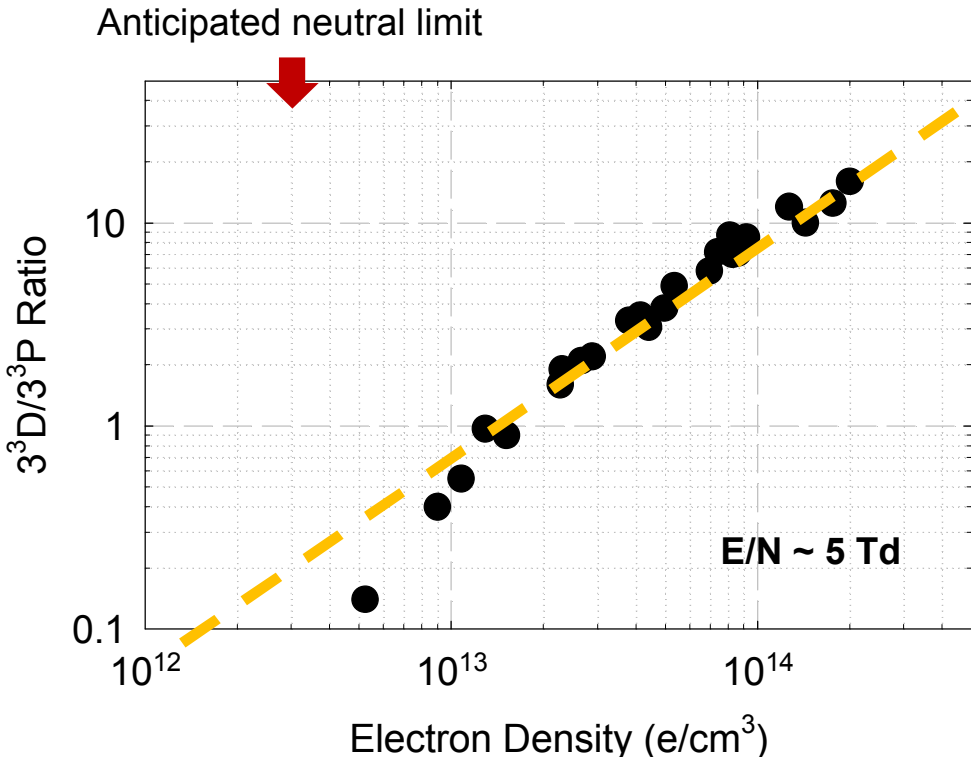
# RATIO OF LCIF LINES ARE UTILIZED TO IDENTIFY SCALING TRENDS

- Benchmark scaling of density dependence of 3<sup>3</sup>D LCIF.
  - Utilize the E/N invariance of 3<sup>3</sup>D LCIF above ~ 2 Td

## Simplified Scaling

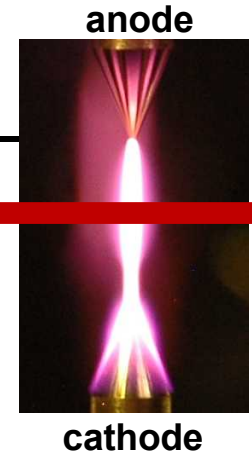
$$\Delta N_j \sim K_{ij}^e n_e \times \Delta N_i \times \Delta t$$

## Observed Scaling of LCIF

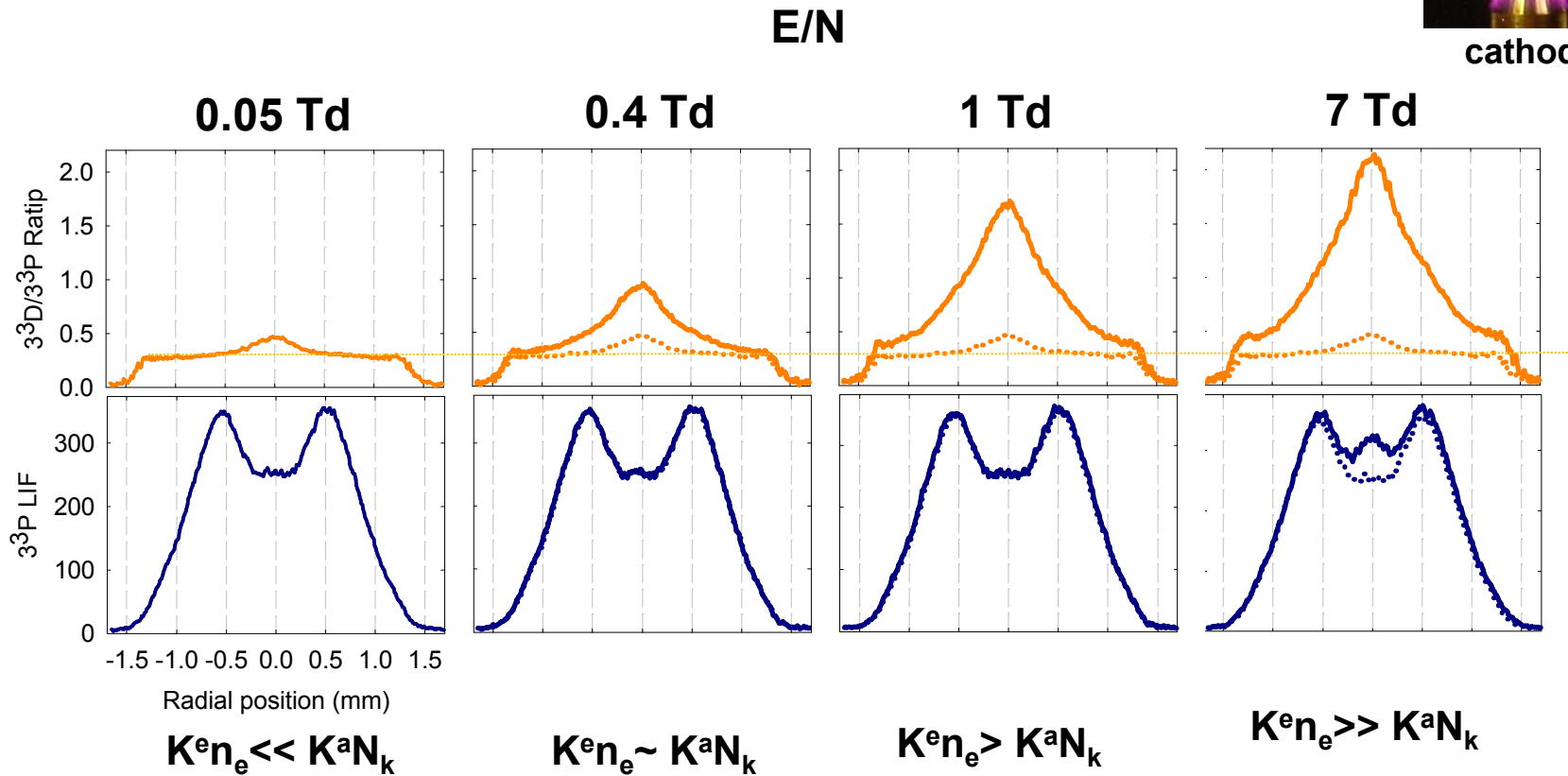


*LCIF from 3<sup>3</sup>D scales linearly with electron density*

# DEMONSTRATION OF SPATIAL RESOLUTION PROVIDED BY LCIF



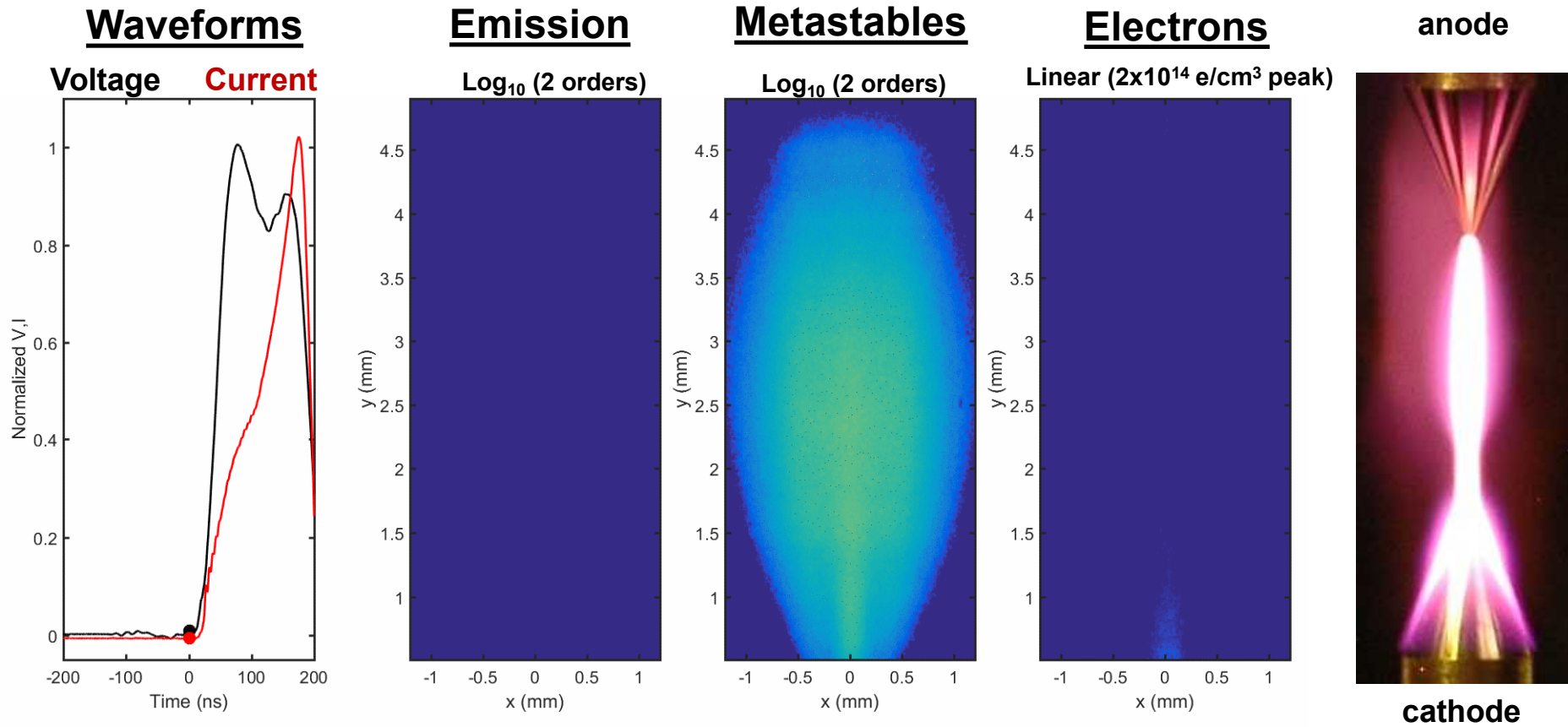
- Radial structure observed for various E/N.
  - Initial peak electron density of  $2 \times 10^{13}$  e/cm<sup>3</sup>.
  - Measured  $\sim 2$   $\mu$ s in afterglow of first voltage pulse.



*Observations consistent with initial assertions made*

# DEMONSTRATION OF SPATIAL AND TEMPORAL RESOLUTION PROVIDED BY LCIF

- Measured evolution of plasma formation during second pulse.
  - Initial peak electron density of  $2 \times 10^{13}$  e/cm<sup>3</sup> (2  $\mu$ s afterglow)

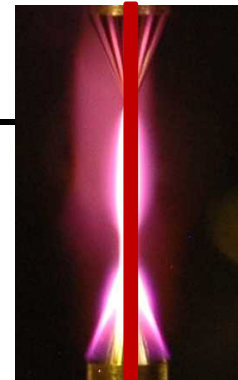


***LCIF provides two-dimensional plasma structure***

# UTILIZATION OF LCIF TO UNDERSTAND DISCHARGE EVOLUTION

anode

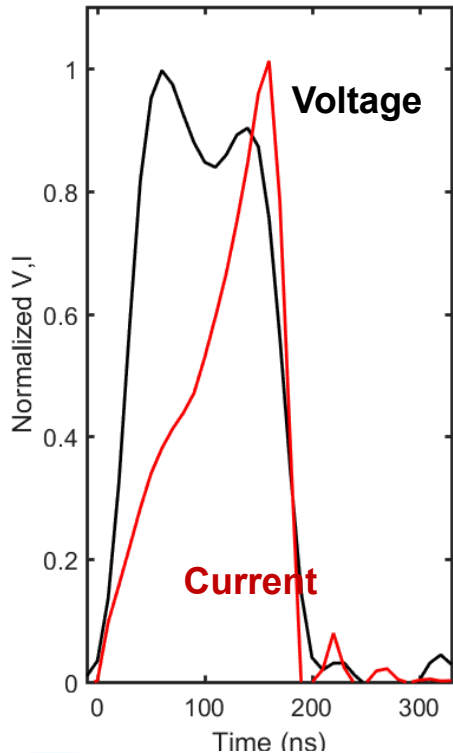
Averaged domain



cathode

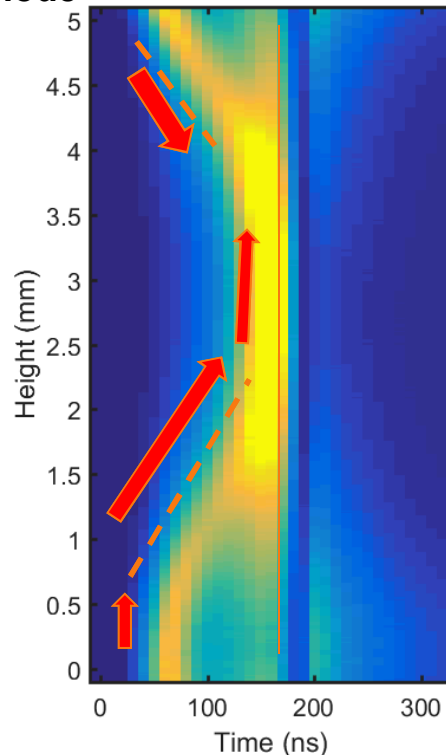
- Streak-like images of plasma initiation to examine dynamics of plasma formation.
  - Axial profiles at center of discharge.

## Waveforms

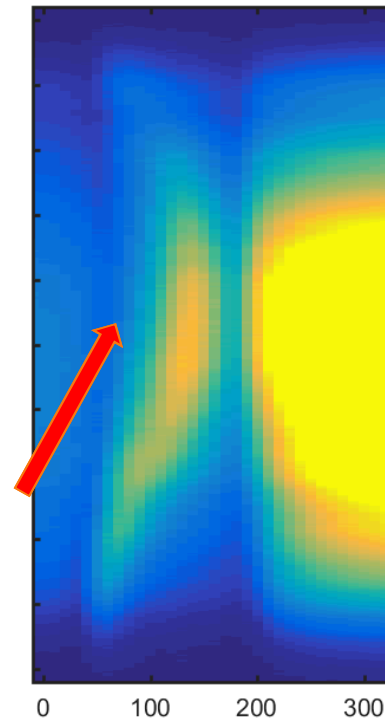


Powered anode

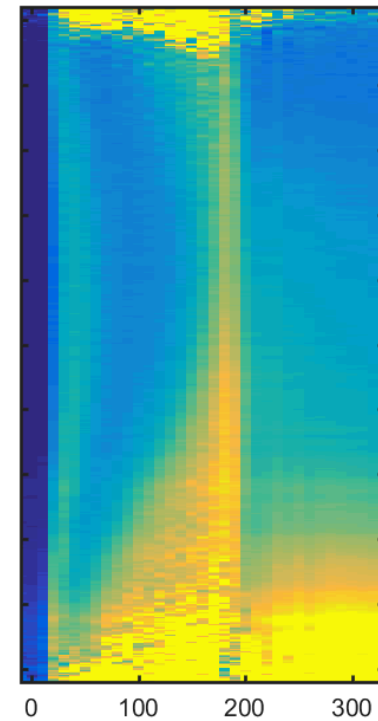
## Emission



## Metastables



## Electrons



Grounded cathode

*LCIF captures spatial and temporal evolution of plasma formation.*

# CONCLUSIONS

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- **Ultra-fast LCIF shows promise for interrogating high pressure plasma systems.**
  - **Outlined pitfalls that might be encountered at higher-pressure systems.**
  - **Can be extended to other systems of interest (Ar, N,...).**
- **Short-pulse lasers show promise for other measurements of interest.**
  - **Atomic species, collision rates and lifetimes..**

*Thank you for attention!*

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Energy Science*

*Contracts DE-SC0001939 and DE-AC04-94SL85000*



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Center for  
Predictive Control  
of Plasma Kinetics:  
Multi-Phase and  
Bounded Systems



**DOE Plasma Science Center**  
**Control of Plasma Kinetics**

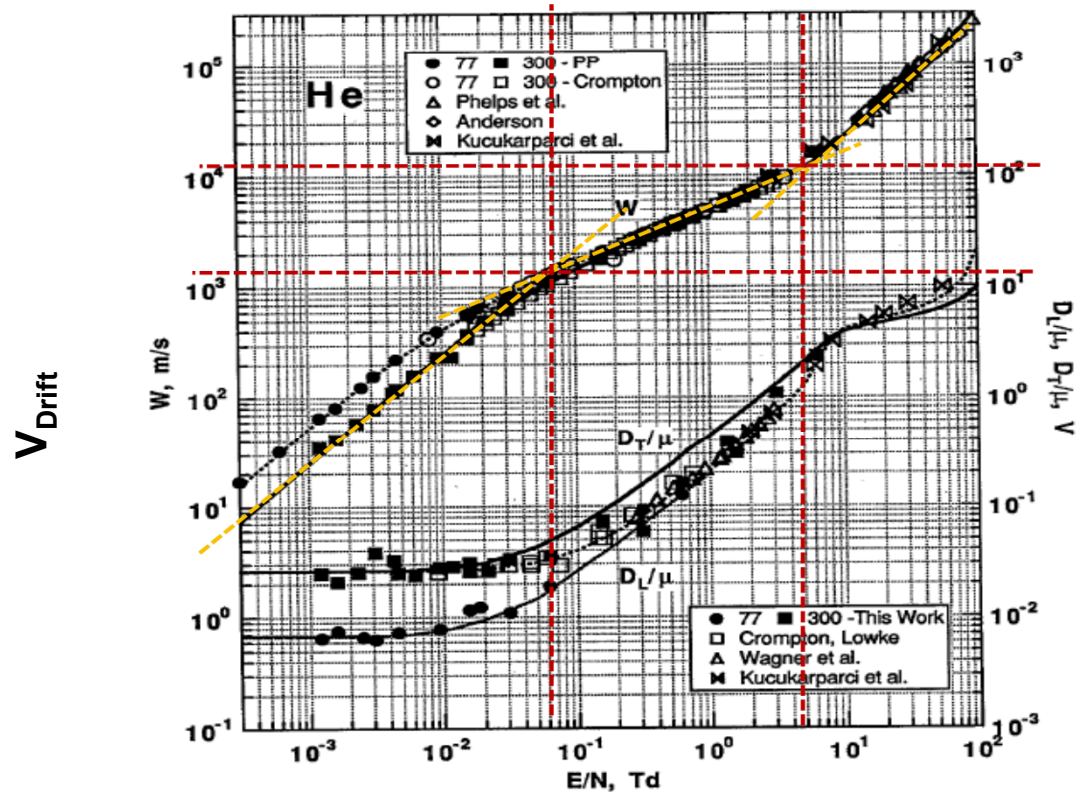
# AUXILARY SLIDES

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# UTILIZE CURRENT-VOLTAGE TRENDS TO BOUND PLASMA PARAMETERS

## Published drift data

J. Pack et al. JOAP, 71 (11) p5363, 1992



**First  $V_d$  Knee**

**$E/N \sim 0.08$  Td**

**$V_D \sim 10^5$  cm/s**

**Second  $V_d$  knee**

**$E/N \sim 5$  Td**

**$V_D \sim 10^6$  cm/s**

**E/N (Td)**