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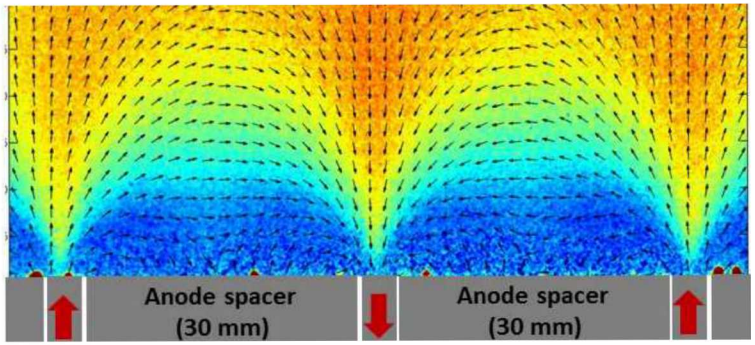

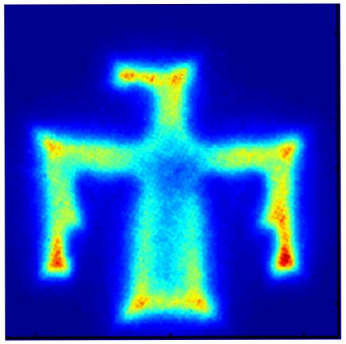

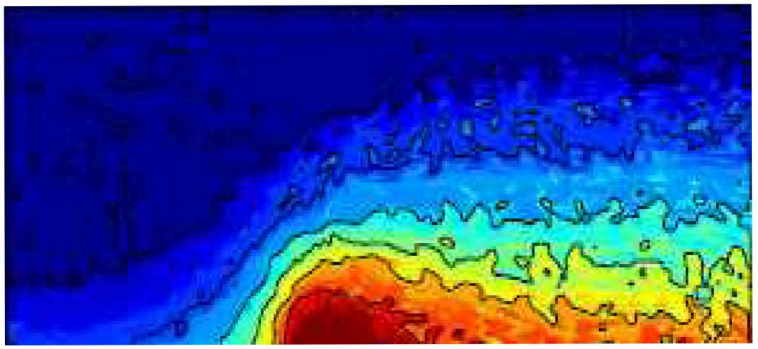

Developing the Plasma Physicists Toolbox: The Good, the Bad and the Ugly

Ed Barnat

Gordon Research Conference:
Plasma Processing Science

August 8, 2018

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Role of Diagnostics in Plasma Science

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- Often diagnostics are a “means to an end”.
  - Provide answers to outstanding questions we have about a given plasma.
- Diagnostics provide physical data or information regarding what is happening in and around a plasma environment.
  - Spatial, temporal evolution of electrons ions, neutrals, photons, fields…
  - Close “knowledge gaps” associated with plasma physics (rates, lifetimes).
- Particularly effective when used to test model or simulations.
  - Diagnostics usually provide limited information (Cant measure everything).
  - Target key quantities of interest (QOI) to provide confidence in predictions.

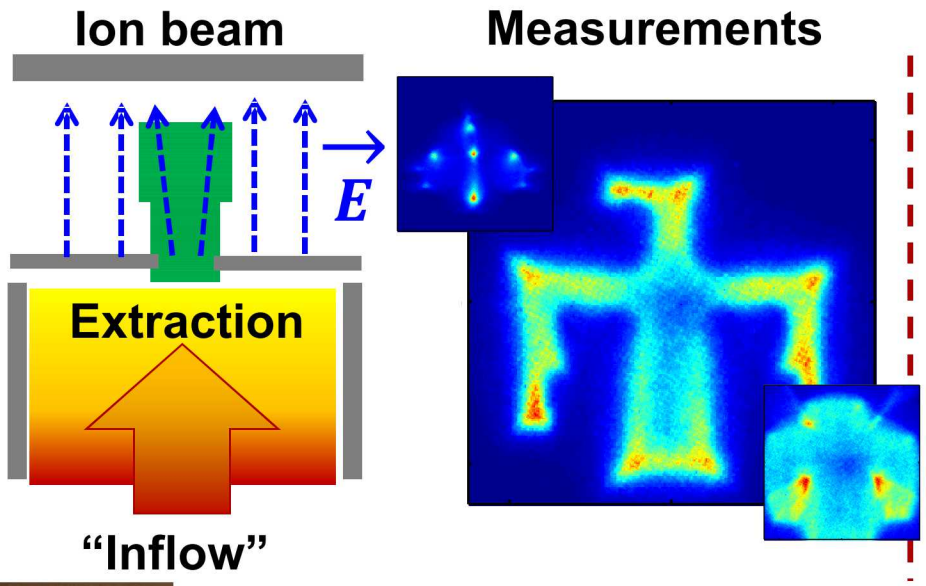
Key point #1: Diagnostics are necessary for testing our understanding of plasma physics phenomenon.

As practitioners our job is to identify and appropriately employ the appropriate diagnostic to measure the value of interest.

Sandia Loves Developing Code

- Verification and validation (V&V) is the metric for code acceptance.
  - Solving equations correctly, Solving the right equations.
- Measurements are performed to validate codes.
  - My job is to build the right setup and employ the right diagnostic.

Validation of ion extraction from a dynamic plasma



We rely heavily on developing and deploying the appropriate "tool box" of diagnostics to provide solutions for our "customers"

Plasmas Are Like Children: "No Two Are The Same"

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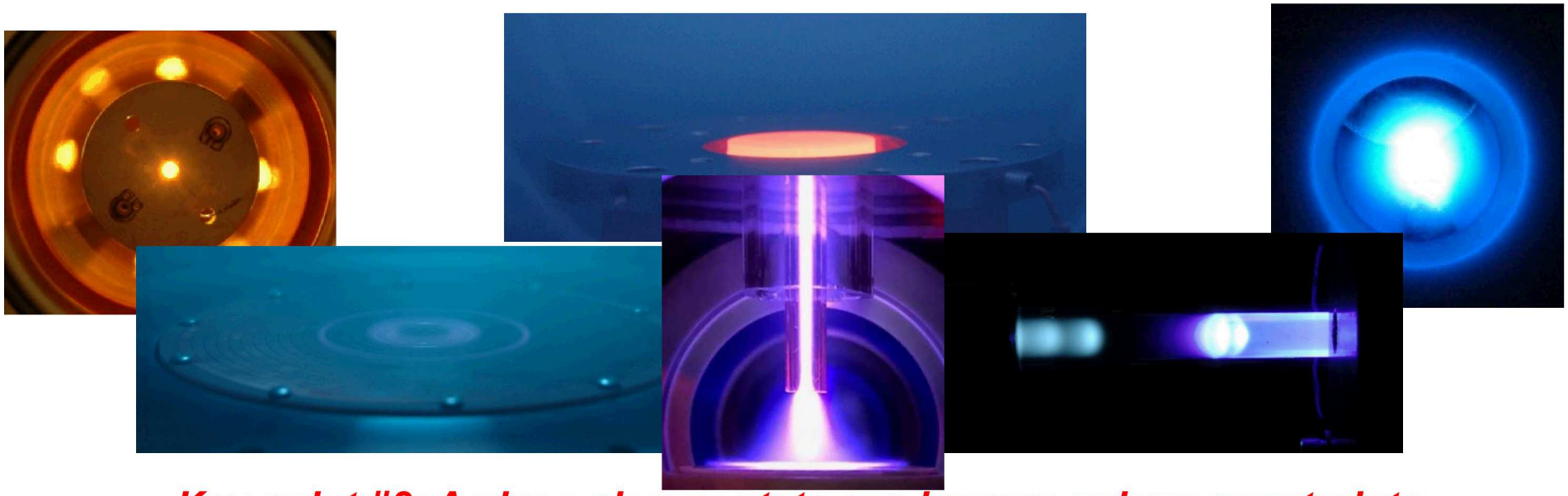
- Broad range of configurations, composition, density and timescales really pose a challenge to the plasma community.



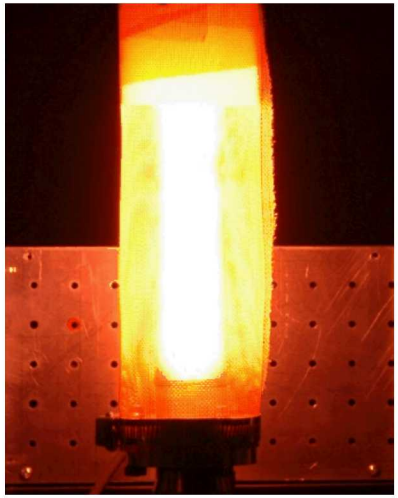
Key point #2: A given plasma state can impose unique constraints on applicable range of a given diagnostic.

The devil is in the details..
In general need to know what you are getting into before jumping in…
"Good, the bad and the ugly" of sides of diagnostics manifest

When Things Are "Good"

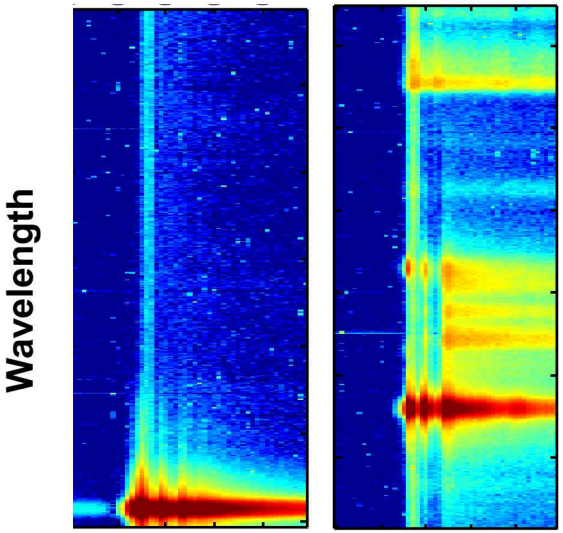
- Some diagnostics provide clean-cut measurements.
  - Easy to implement, plenty of signal and non perturbing.
  - Measurements can be taken at or very near face value.
  - Sometimes a simple calibration can be used to extract info of interest.

Plasma Glow



Spectrometer

Spectrum

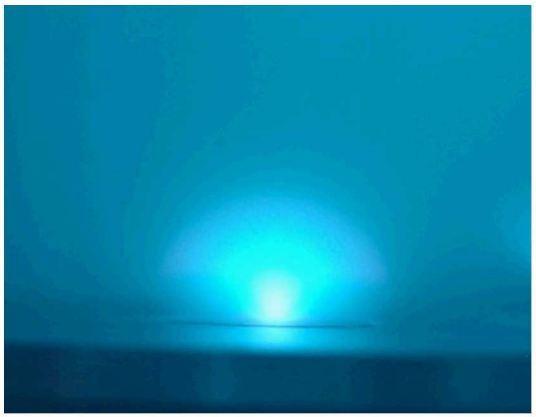


This is a great place to be!
Results abound and understanding can be achieved.
This may be relatively small/limited set of cases.

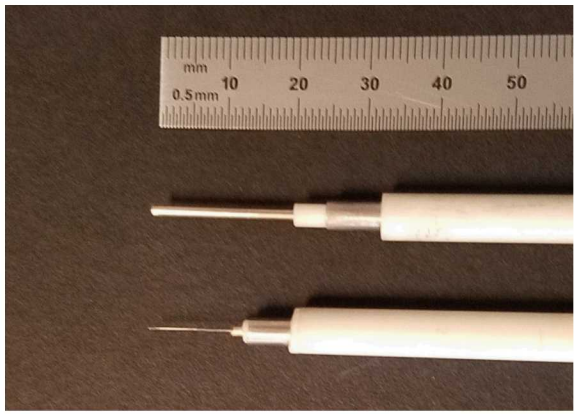
When Things Are "Bad"

- "The Bad": Some diagnostics are a poor match to targeted plasma.
  - Most if not all diagnostics have limitations and range of validity.
  - Diagnostics can perturb the plasma.
  - Even if applicable , conditions are such that signals are just too weak or the environment is too hostile.

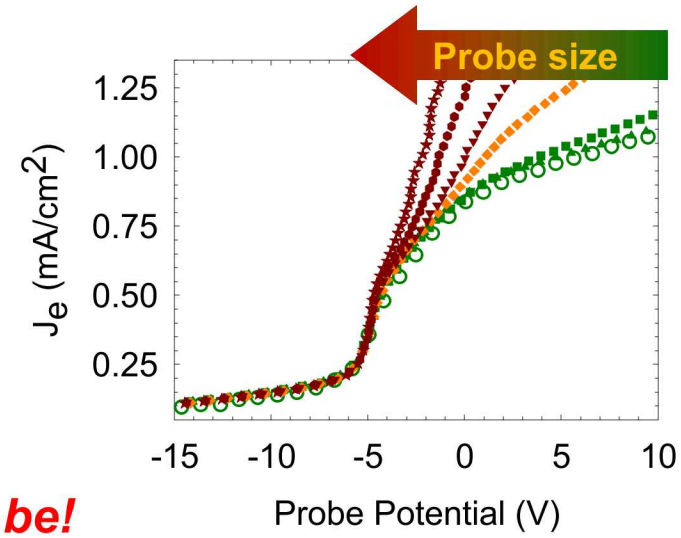
Anode Spot



Langmuir Probe



Extracted Current



This is not a good place to be!

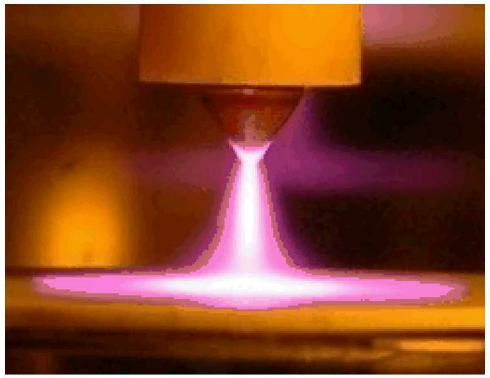
No one wants to sink days, weeks, months…into effort that doesn't pan out!!

It's not that the diagnostic is bad, but perhaps the choice of diagnostic

When Things Get "Ugly"

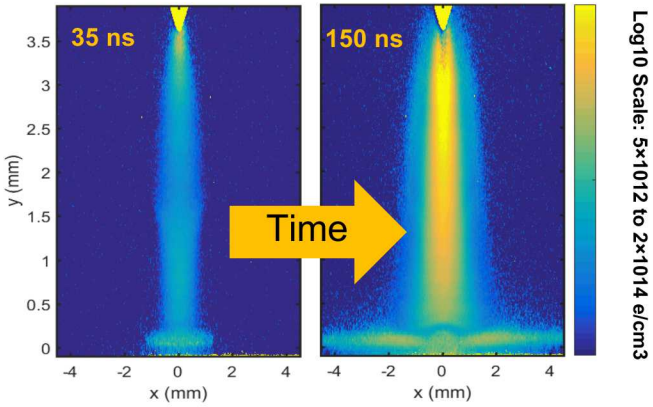
- "The "Ugly": Interpretations of results are not straightforward.
  - Measurements don't directly correlate to desired quantities of interest.
    - Usually revert to a model of varying complexity to describe results.
    - Accuracy of analysis depends on fidelity of the models.
  - Plasma state demonstrates odd and unexpected behavior.
    - Confusion about fidelity of the diagnostic.

640 Torr He Plasma



Ultrafast Lasers

Electron Densities?

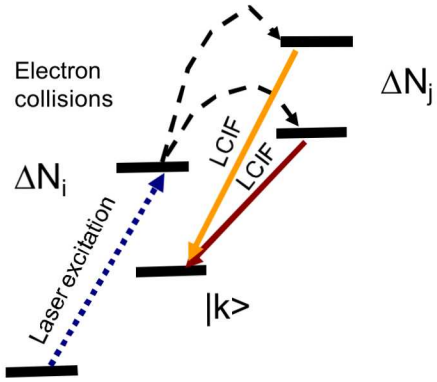


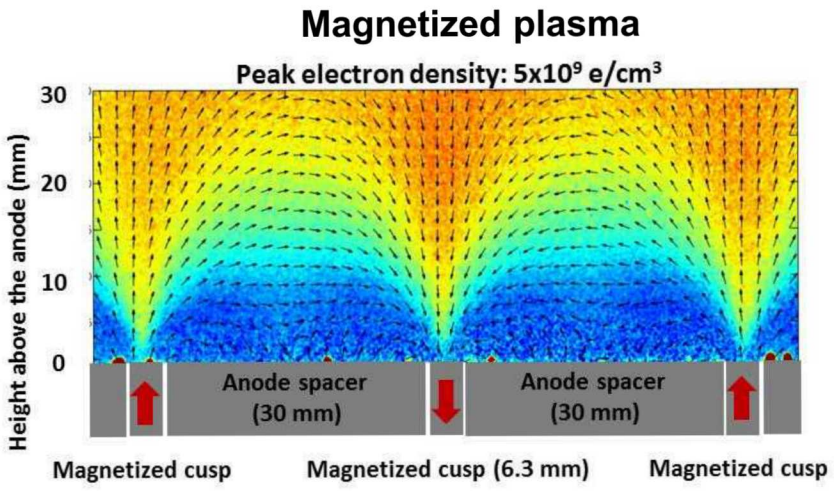
Many diagnostics live here…
Mix of risk, challenge and reward…
particularly when extension of a diagnostic to a given plasma is needed

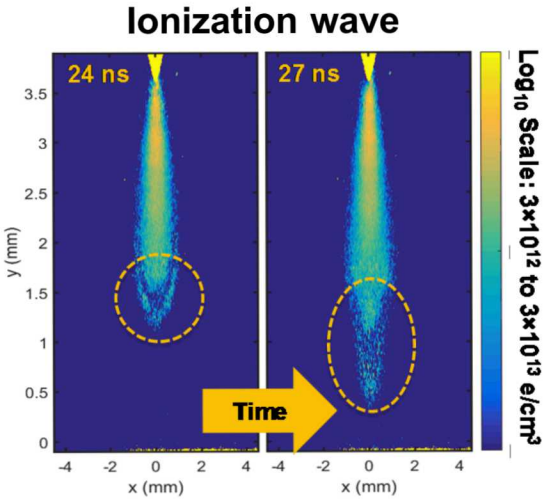
When Things Get "Interesting"

- Diagnostics often become an "end unto themselves"
  - What needs to be done to match the diagnostic to the plasma?
  - What sets of physics can I employ? What else has been done? Are new enabling technologies available?

Laser Collision Induced Fluorescence





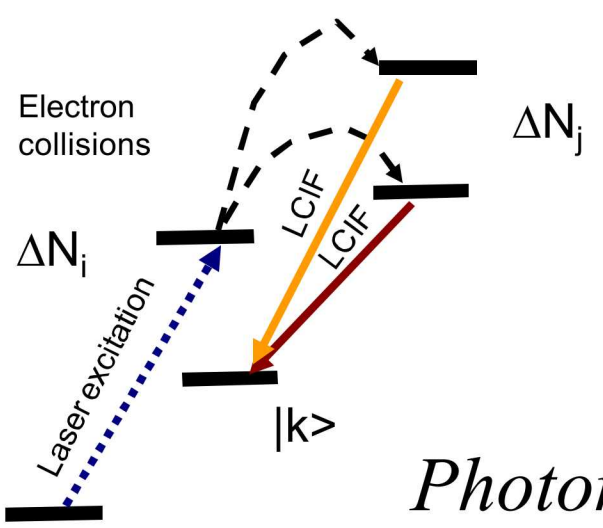


Key point #3: Modifications and adaptations to diagnostics are often required for successful matching of the diagnostics to the plasma of interest.

This can be an "interesting" place to be!

Early Days: Diagnostic Development

- Laser-Collision Induced Fluorescence (LCIF) is used to assess electron densities and "temperatures" (E/N)
  - "up-hill" redistribution of laser excited states by energetic collisions.
  - Higher jumps correspond to more energetic impacts.



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

"Simple" concept that could be really useful!
What can go wrong??

Extending Collision-induced Fluorescence Based Methods

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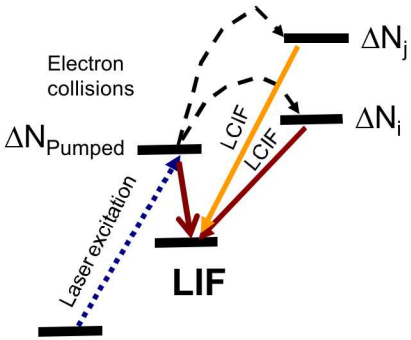
- Laser-collision based techniques have been considered by many groups
  - Burrell and Kunze - Collision rates (1978)
  - Tsuchida - First to use for density? (1983)
  - Den Hartog - 1D Sheath (1989)
  - **Dzierzega - quasi 2D profiles GEC @ NIST (1996)**
  - **Stewart - CW LCIF (2002)**
  - Nersisyan - He Metastable atmospheric plasma (2004)
  - Krychowiak - TEXTOR (2008)
  - Kraig Frederickson and I started in 2009

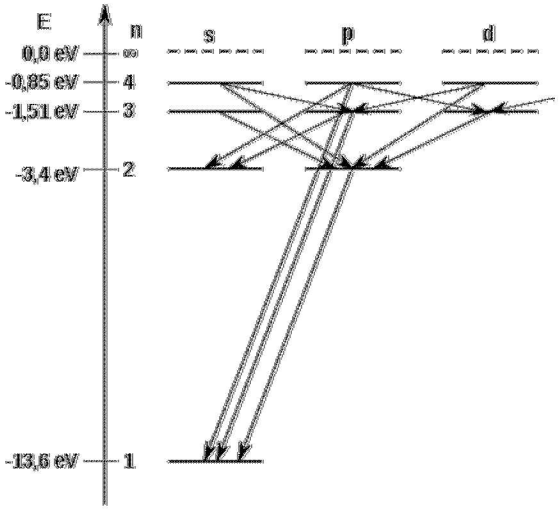
Our efforts focused on developing the method to…
provide high spatial (<< mm) and temporal (<10 ns) resolution …
afforded by fast lasers and image intensifying cameras

Things Can Get Ugly with LCIF

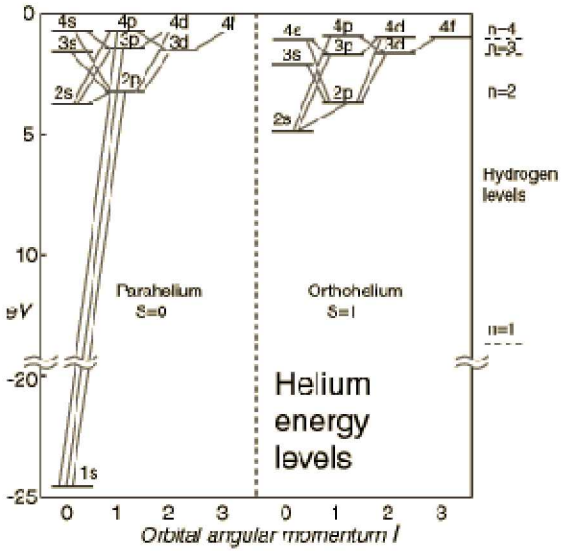
- Choosing the right system to interrogate is essential
  - Laser accessible states
  - Transitions amenable to plasma conditions
  - Unique spectral signatures..



Hydrogen

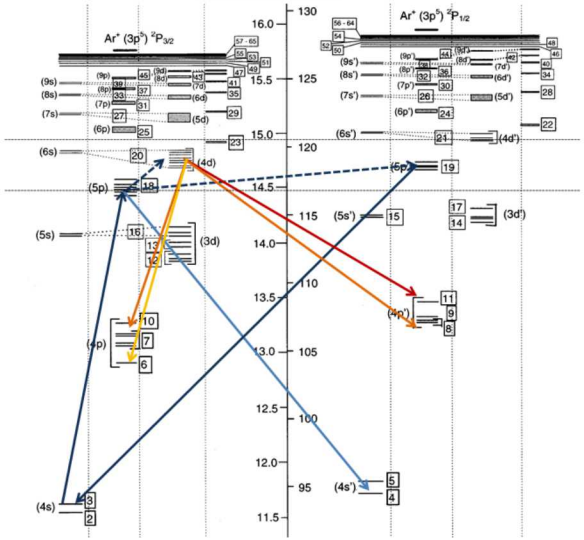


Helium



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

Argon

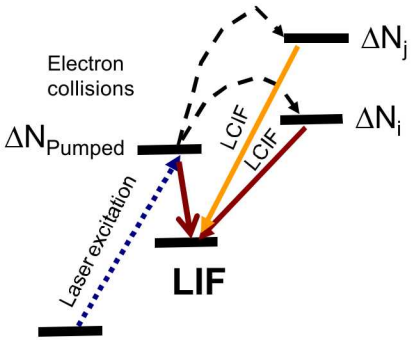


Taken from Bogearts et. al, J. Appl. Phys. **84**, 121, 1998

In principle can be extended to any atomic or molecular system… observing these guidelines

Things Can Get Ugly with LCIF

- A good model is used to describe the redistribution
  - Interstate transitions should be known
  - Mixing species should be minimum or at least known
  - Photon transport gets complicated



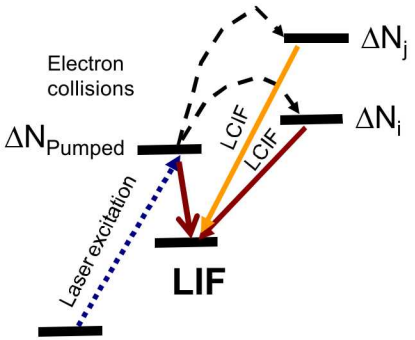
"Electron mixing" ***"Neutral mixing"*** ***"Photon mixing"***

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

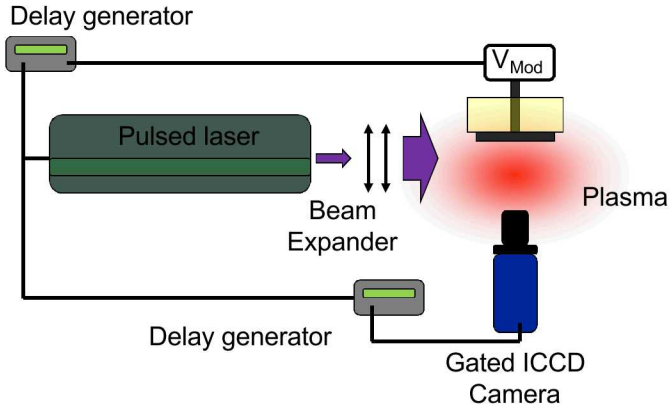
Uncertainties in any of the input can really limit or constrain interpretation of observed LCIF

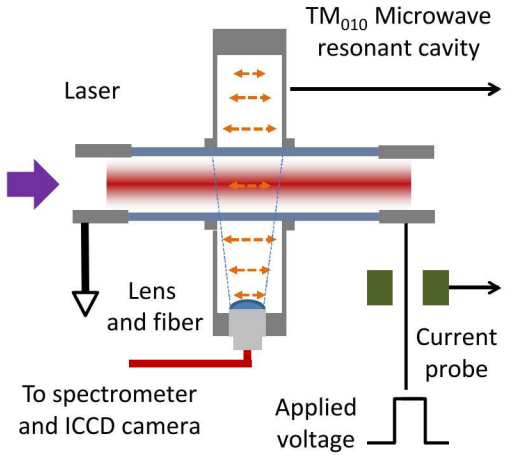
Things Can Get Ugly with LCIF

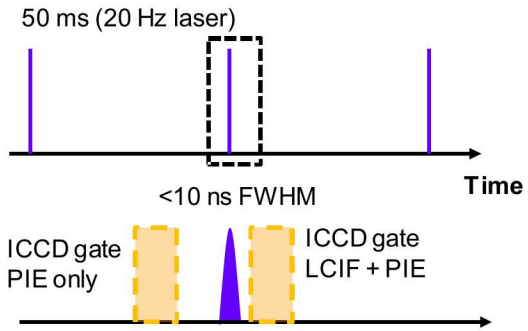
- A really good setup is needed to make LCIF work
  - Having the right stuff to get the job done.
  - Appropriate method for calibrating the signals.
  - Developing the infrastructure to extract signal from noise.



Experimental setup and benchmarking



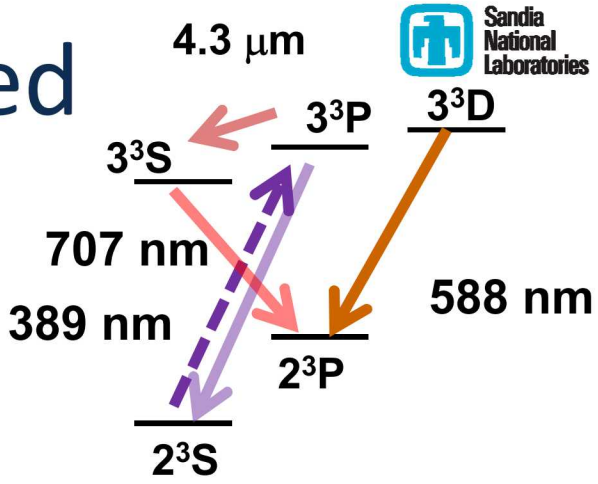




Non-trivial setup that is a pretty equipment and infrastructure intensive endeavor

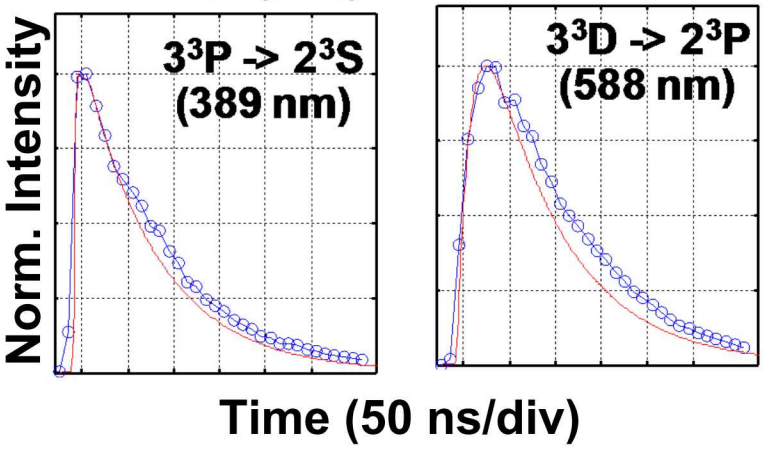
Despite All That We Proceeded

- We ran the model and built the experiment.
  - Started with simplified triplet system of Helium



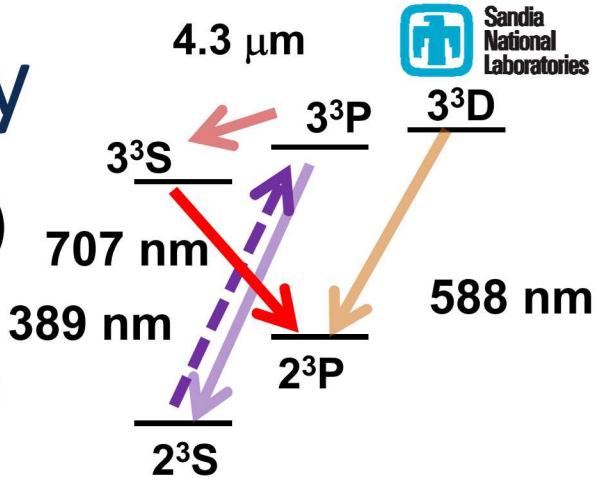
Time Resolved LIF and LCIF trends

Predicted (Red)
Observed (Blue)



Things look good! I think we nailed it!

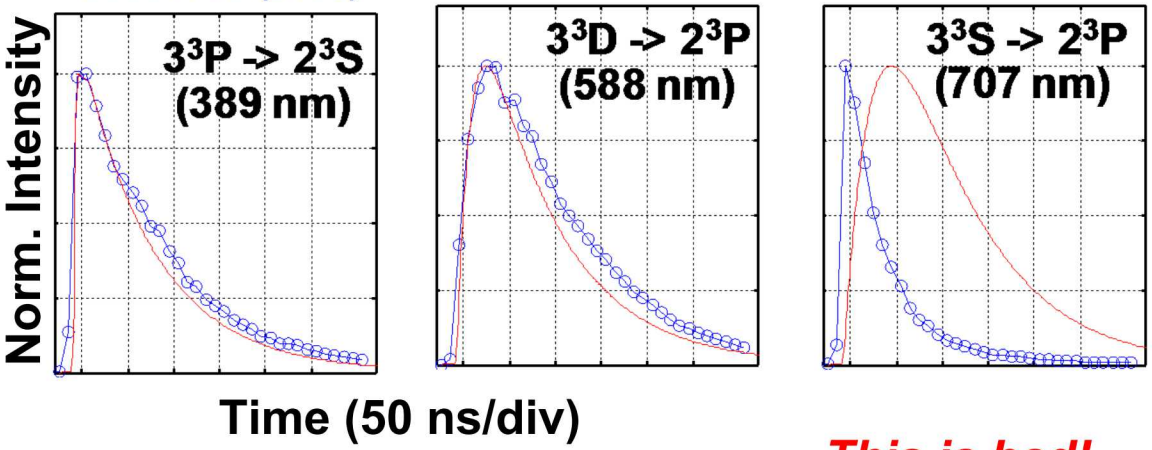
But That Wasn't the Full Story



- We started off on the wrong path (~ one year)
  - Using 3^3S as a surrogate for the 3^3P
  - We really wanted to avoid using resonant radiation
  - Model said is was ok to do!

Time Resolved LIF and LCIF trends

Predicted (Red)
Observed (Blue)

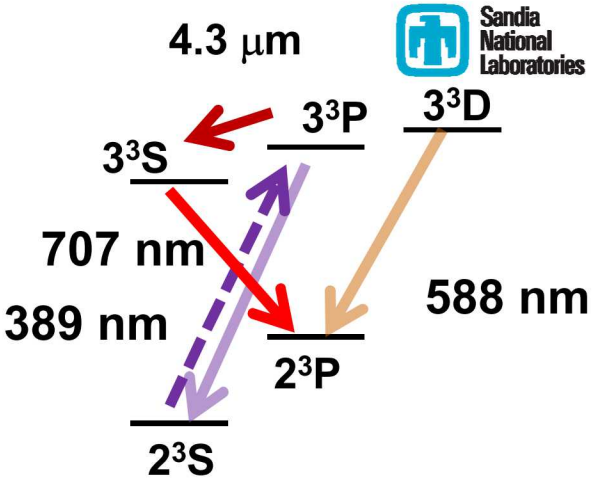


This is bad!

The model and measurement totally do not agree

Additional Physics is Needed

- Considerable head scratching to understand
  - Wrong input, higher rates,… missing physics?
  - Model now indicates density dependence… not an optimal place to be.



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Spontaneous Emission

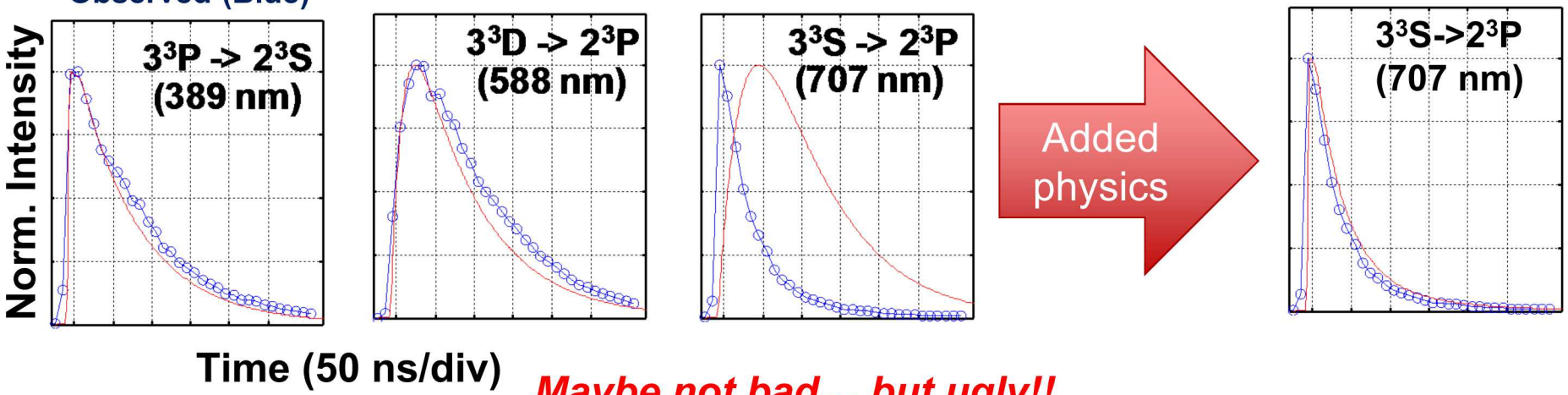
Stimulated emission & absorption

$$\frac{dN_S}{dt} = AN_P + A\left(\frac{\lambda^2}{8\pi}\right)g(\nu)\left(N_P - \frac{g_2}{g_1}N_S\right)\frac{I}{h\upsilon}$$

Time Resolved LIF and LCIF trends

Predicted (Red)

Observed (Blue)

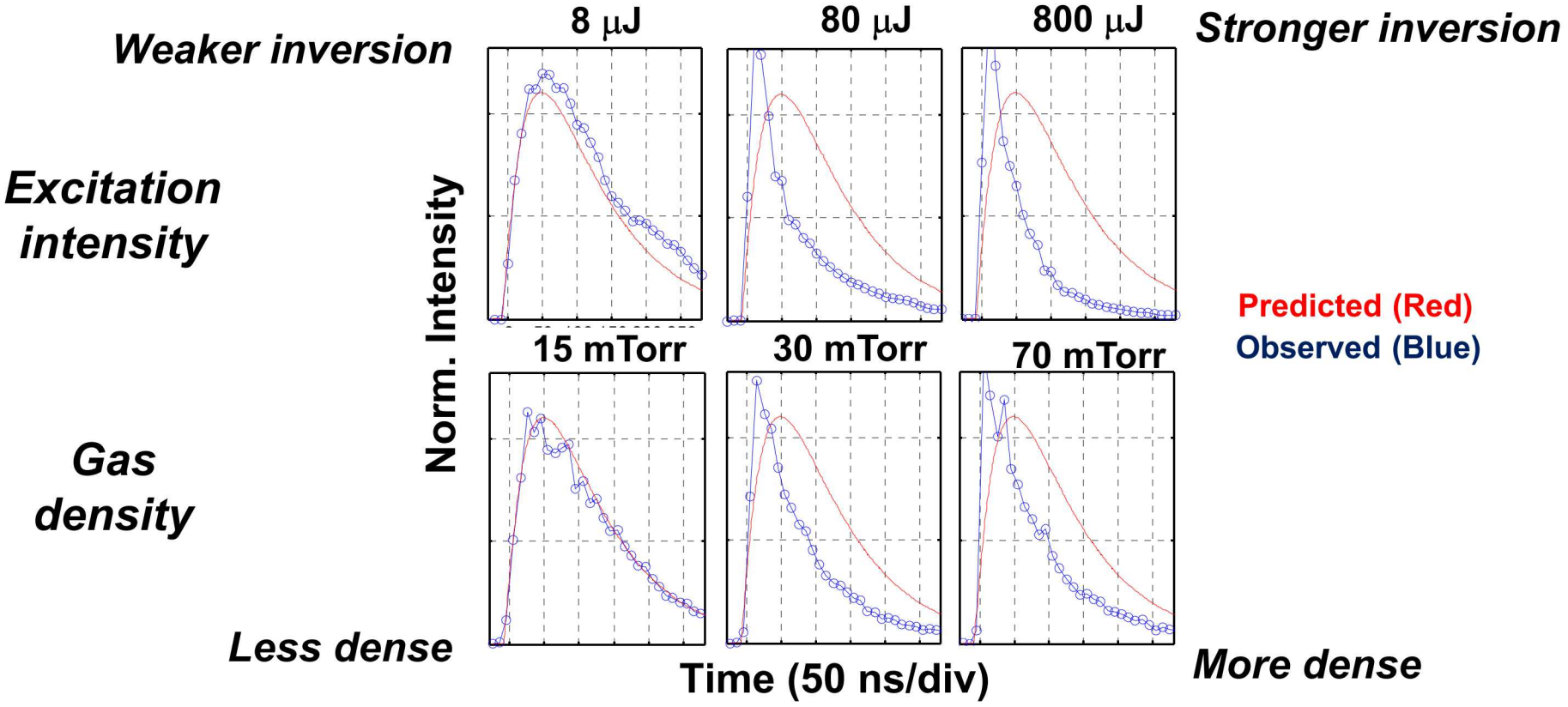


Maybe not bad… but ugly!!

Results now depend on plasma conditions and magnitude of the inversion

We Can Test This Physics

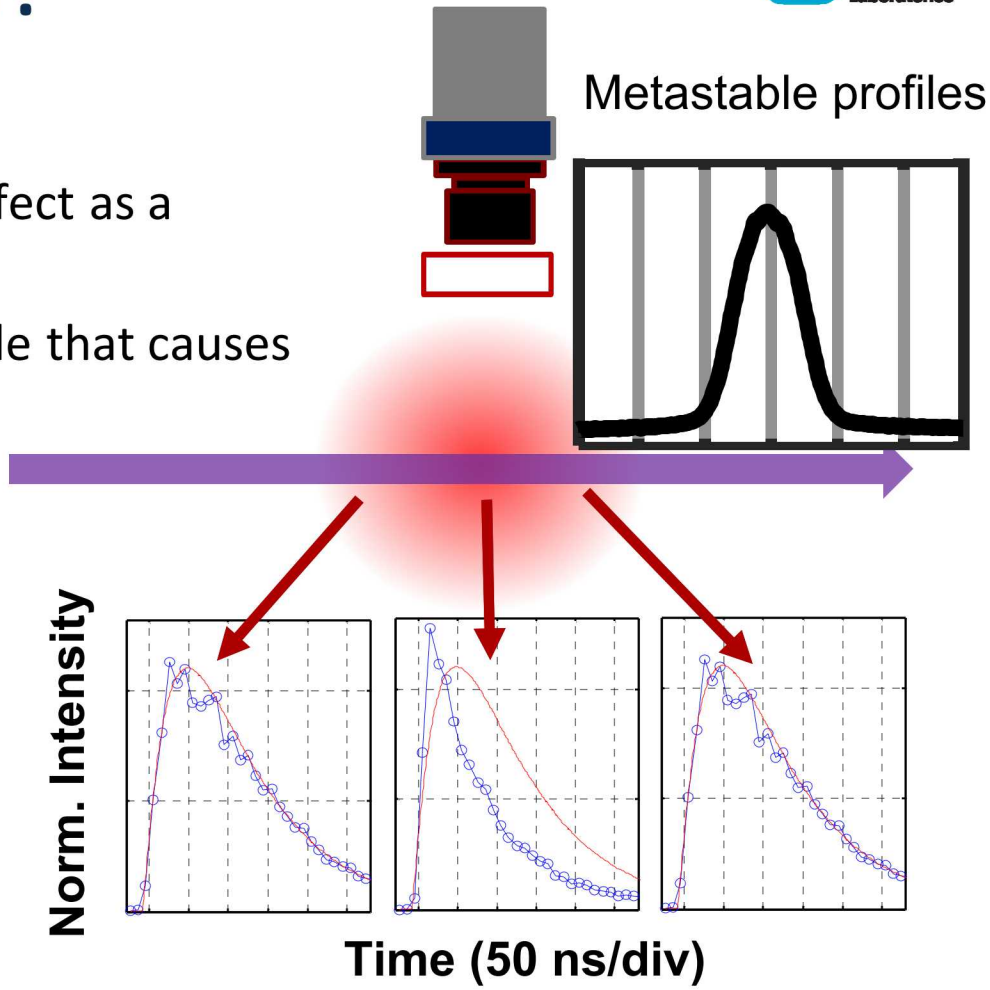
- This transition from weak to strong radiative coupling is observed in simple experiments



Coupling from 3^3P to 3^3S does not "significantly" impact other LCIF trends. Things maybe got back to good.

Is This Physics Useful?

- Can we use this ugliness??
  - Is there a clever way to use this effect as a measure of metastable densities?
  - Is there some density of metastable that causes change in radiative coupling?



Spontaneous Emission

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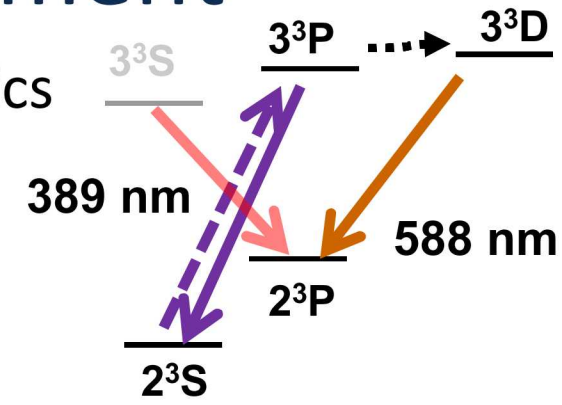
It's an idea.. Likely not good… probably bad..
Probably with some other more reasonable solution
But… there may be an application space where this physics is useful!

Latter Days: Diagnostic Deployment

- New challenges await when deploying diagnostics
  - Focus on 3^3P to 3^3D coupling



Collisional Contribution to the 3^3D state

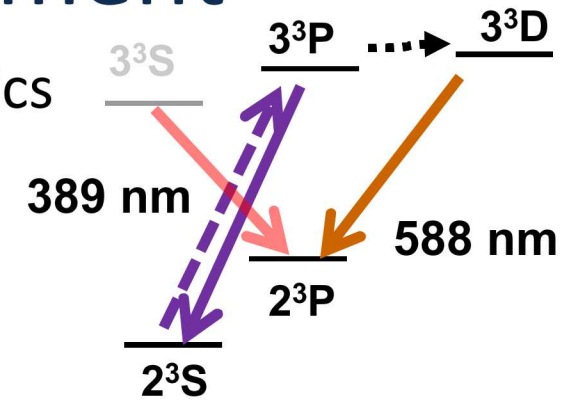
$$N_{3^3D} = \{K^{e}_{P\rightarrow D}(Te)n_e + K^{n}_{P\rightarrow D}(T_g)N_0\}N_{3^3P}\Delta t$$

Electronic *Neutral*

Diagnostic deployment can also present unique sets of challenges where ….

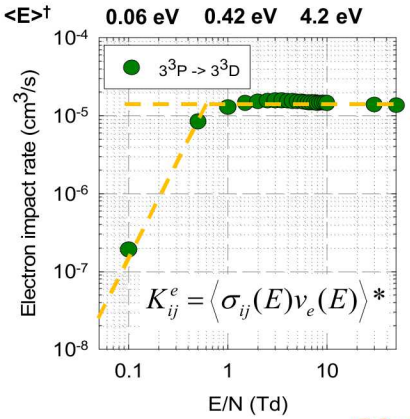
Latter Days: Diagnostic Deployment

- New challenges await when deploying diagnostics
  - Focus on 3^3P to 3^3D coupling

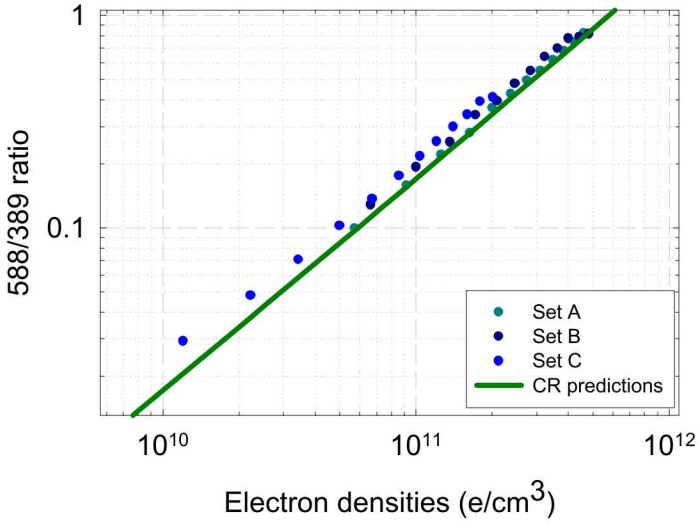


Anticipated and Measured LCIF Scaling

(After neutral component subtraction)



$$\frac{N_{3^3D}}{N_{3^3P}} = K^e_{P\to D}(Te) n_e \Delta t$$

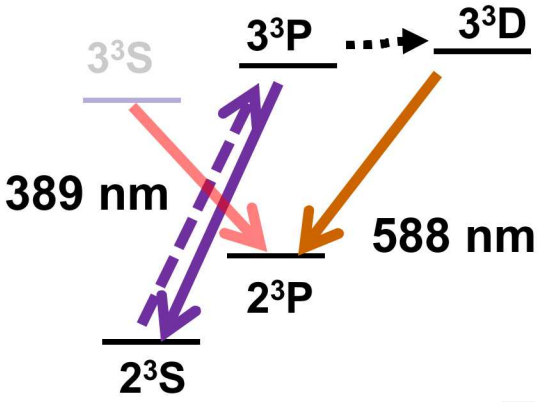


What luck!

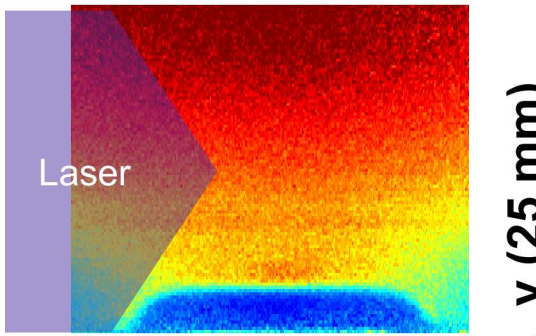
Near linear dependence of LCIF on electron density!!

Ion Sheaths Were Studied First

- Ion sheaths are studied to benchmark LCIF
  - Anticipate electron free region in the sheath
  - Provide a measure of neutral component contribution to LCIF



Setup



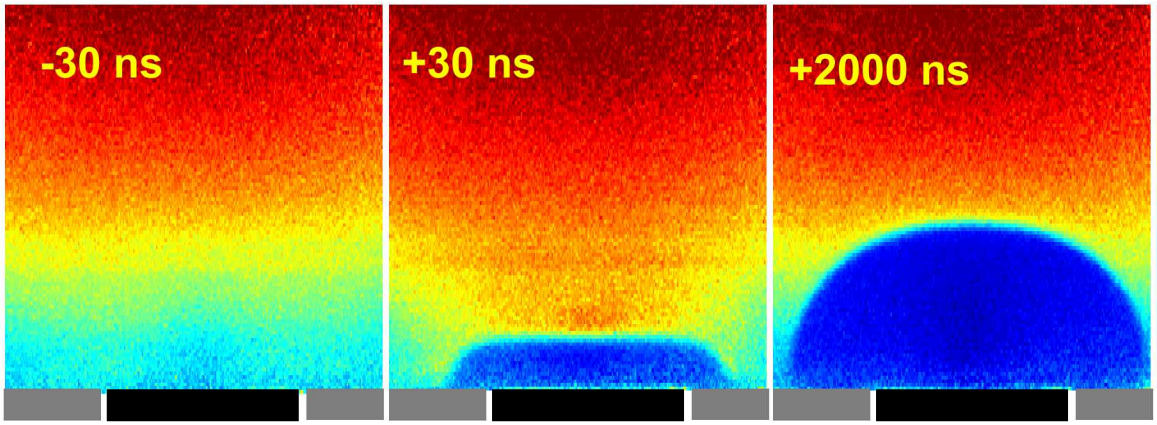
Electrode Guard ring

Bias

0 V

-1000 V

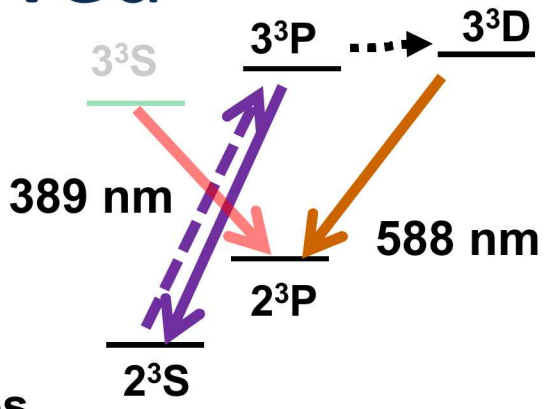
2D Profiles



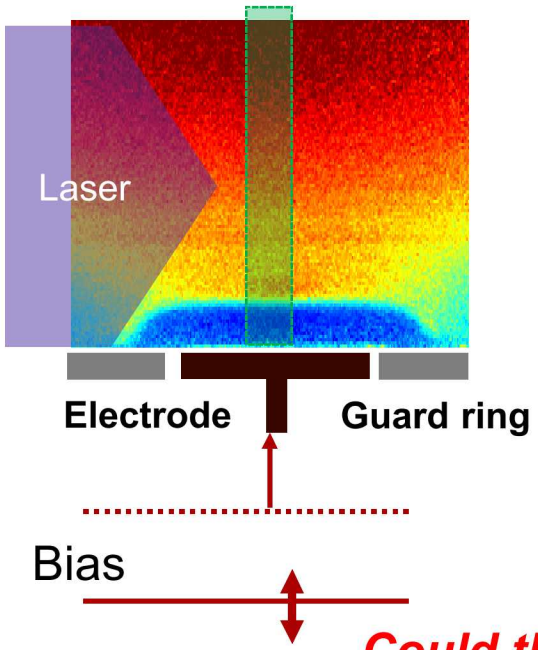
The ion sheath is a great test case to showcase LCIF!

“Anomalous” LCIF Signal Observed

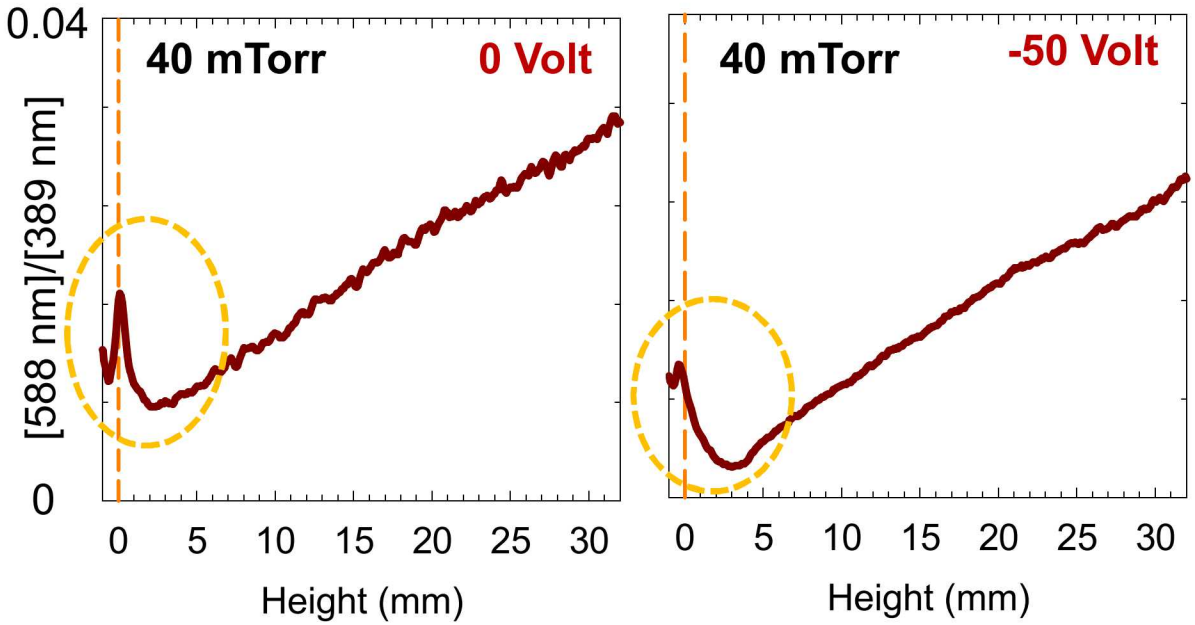
- Large LCIF signals are present near the surface
  - Counter to anticipated electron densities.



Setup



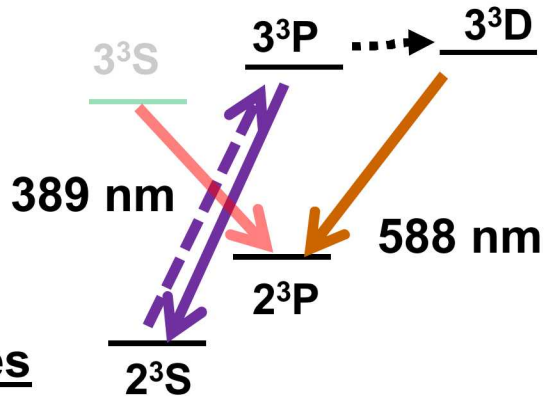
On-axis profiles



Could this be evidence of secondary electrons streaming from the surface??

The Signal is Electric Field

- Large LCIF signals persists and are unchanged after pulse is applied
  - Square wave voltage pulse sweeps electrons away
  - Strong electric fields at surface region.



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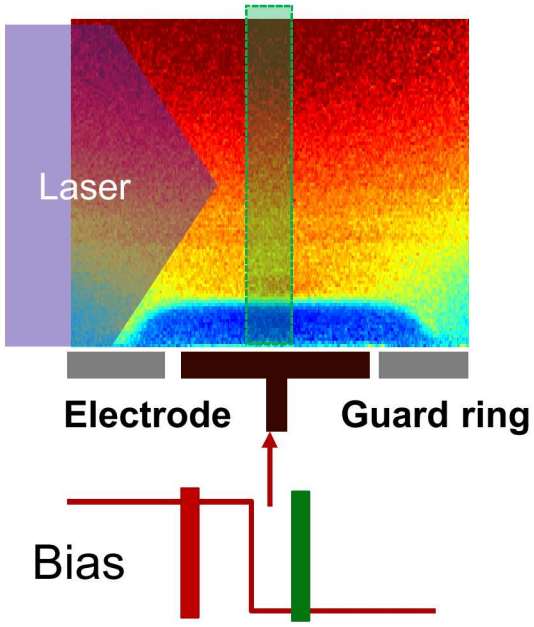
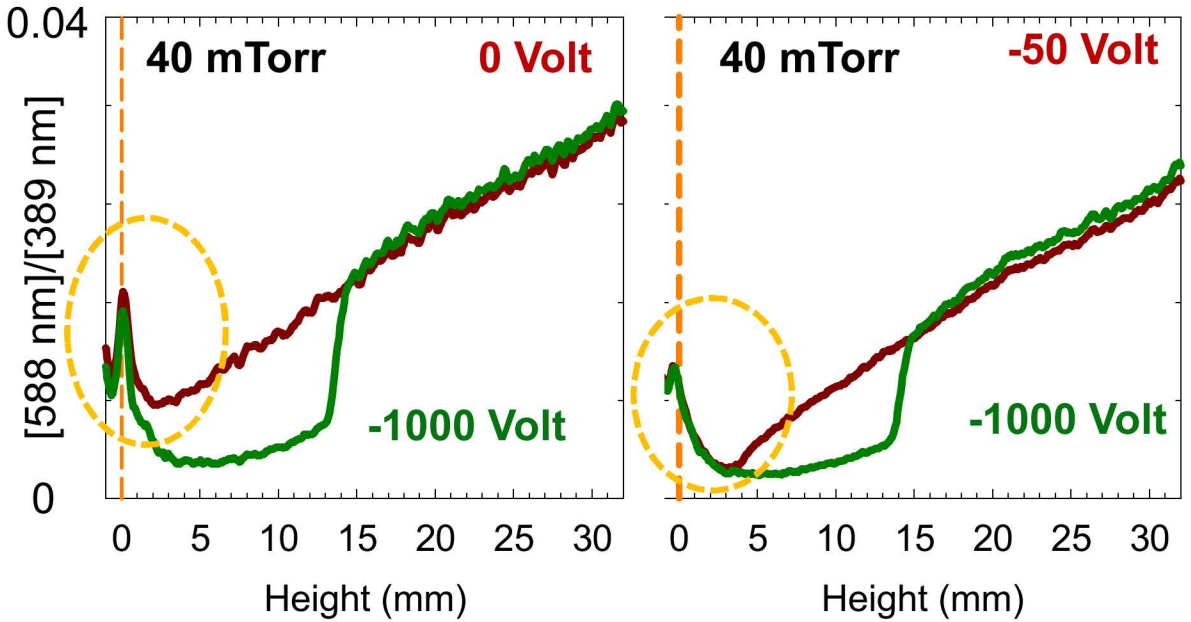


On-axis profiles

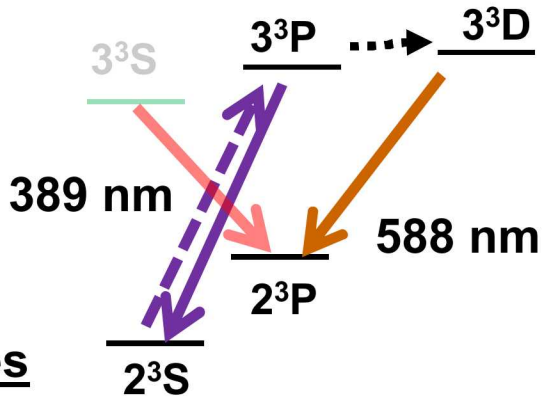


It seems probable that this is not an electron induced process!

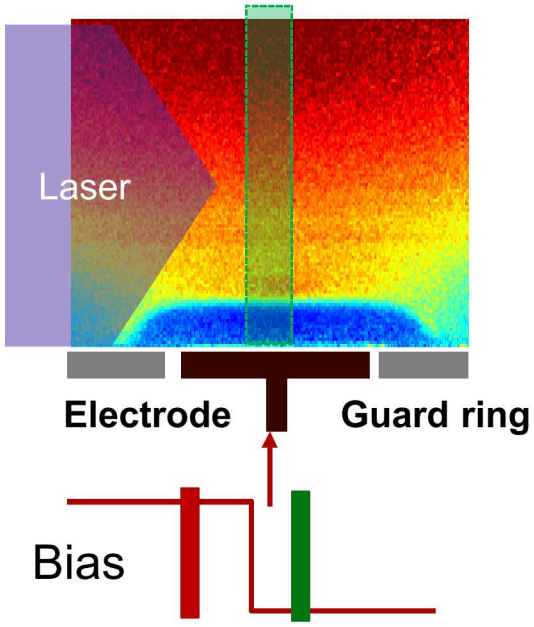
The Signal Depends on Pressure

- Gas density impacts surface LCIF

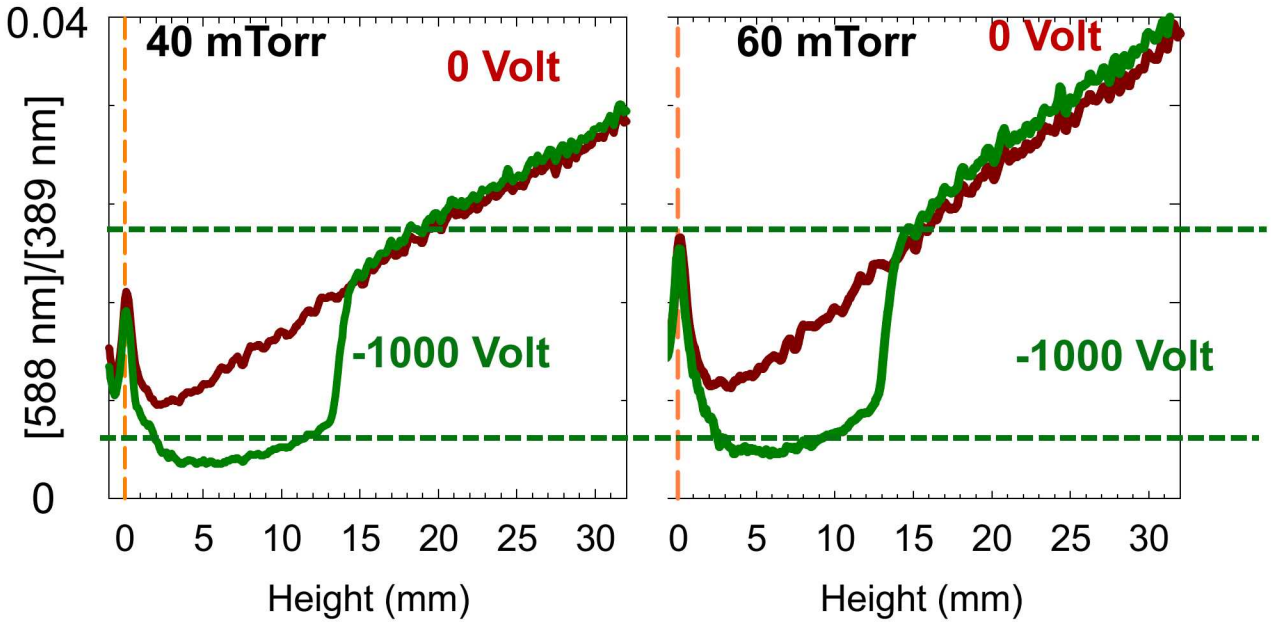
$$\frac{N_{3^3D}}{N_{3^3P}} \sim K^n_{P\to D}(T_g) N_0 \Delta t$$



Setup



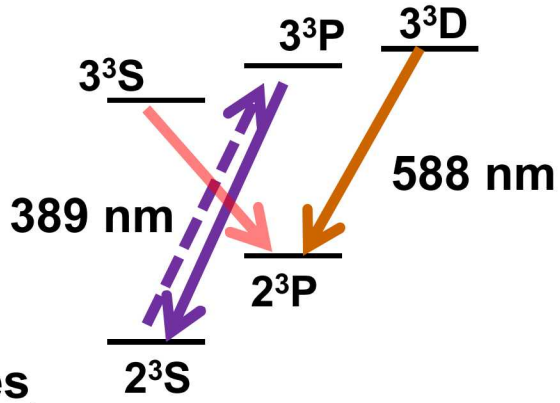
On-axis profiles



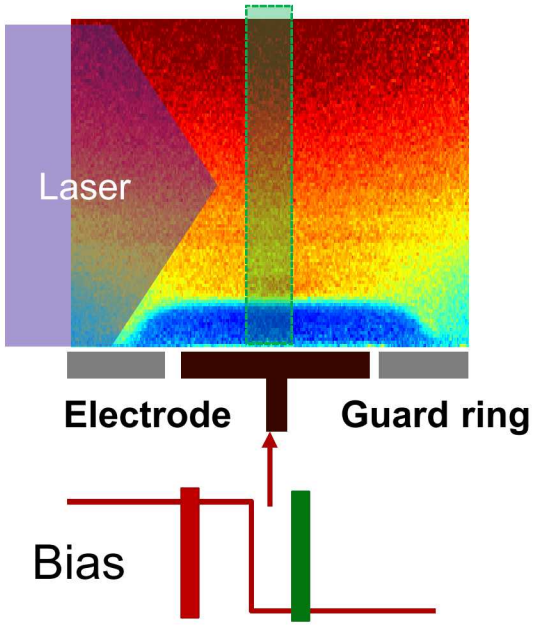
What is happening at the surface?
Is there an increase in neutral density or temperature??

Signal Can be Extracted

- A correction factor can be constructed to extract out the “offending” signal
  - As long as sheath is pushed far enough…

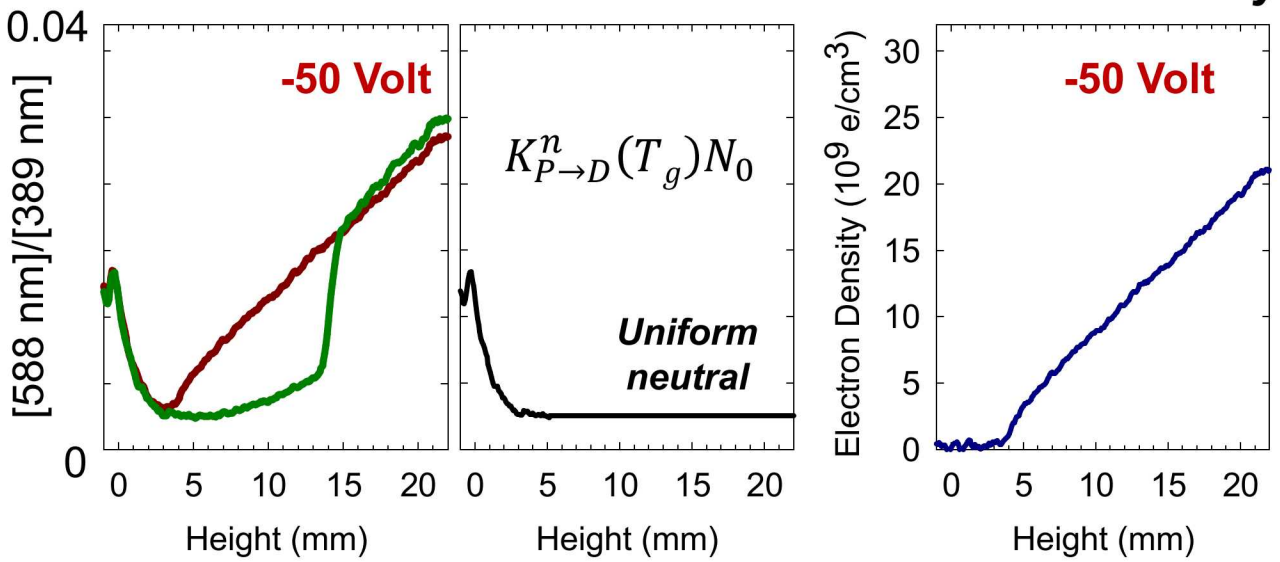


Setup



On-axis profiles

Measured – Correction = Electron Density

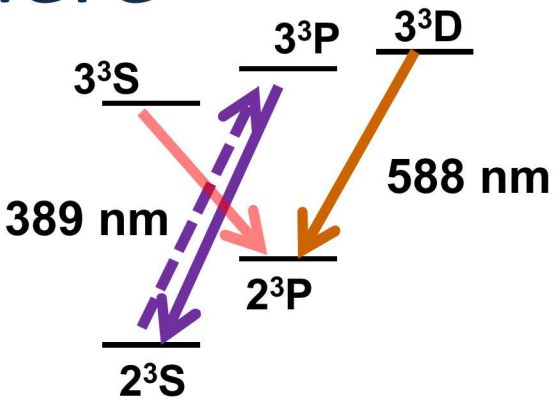


Not a solution but a band-aide!

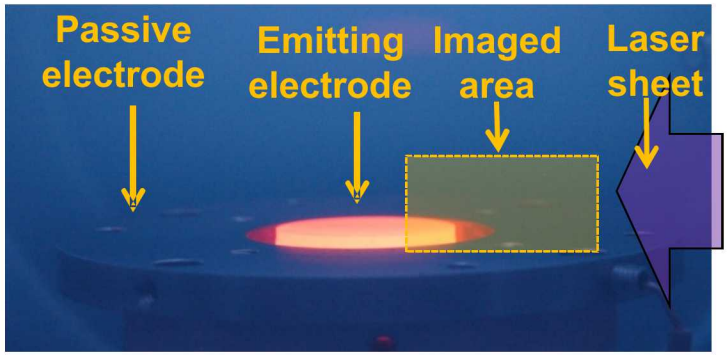
On the other hand… does this point to interesting surface physics??

Similar Signal Observed Elsewhere

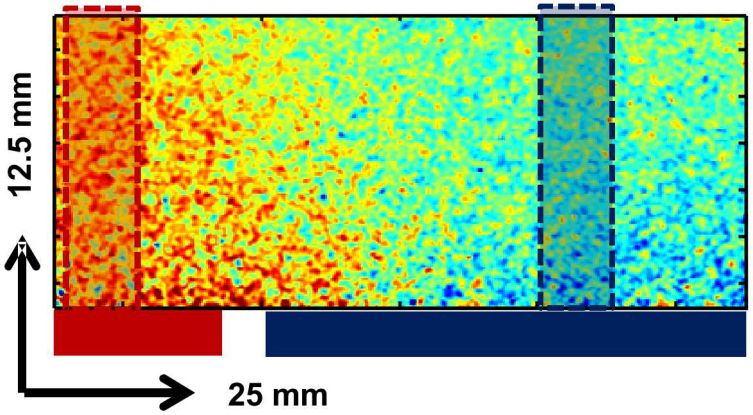
- LCIF was utilized to probe plasma above heated thermionic emitter
  - Looking to quantify electron emission
  - LCIF structure persisted even as bias is varied



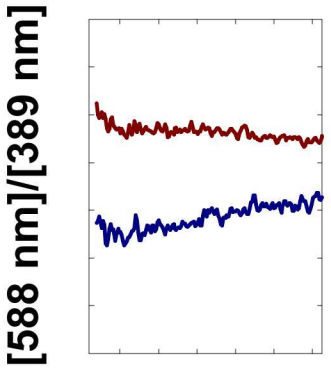
Setup in 20 mTorr He



2D Profile of LCIF



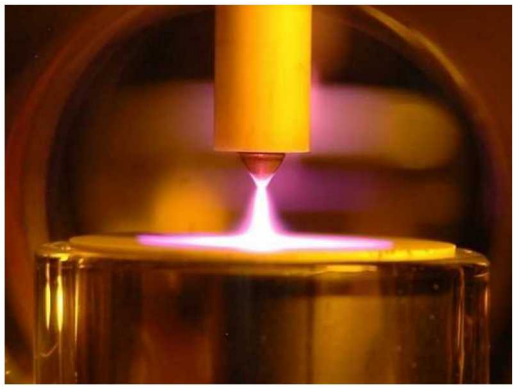
On-axis profiles



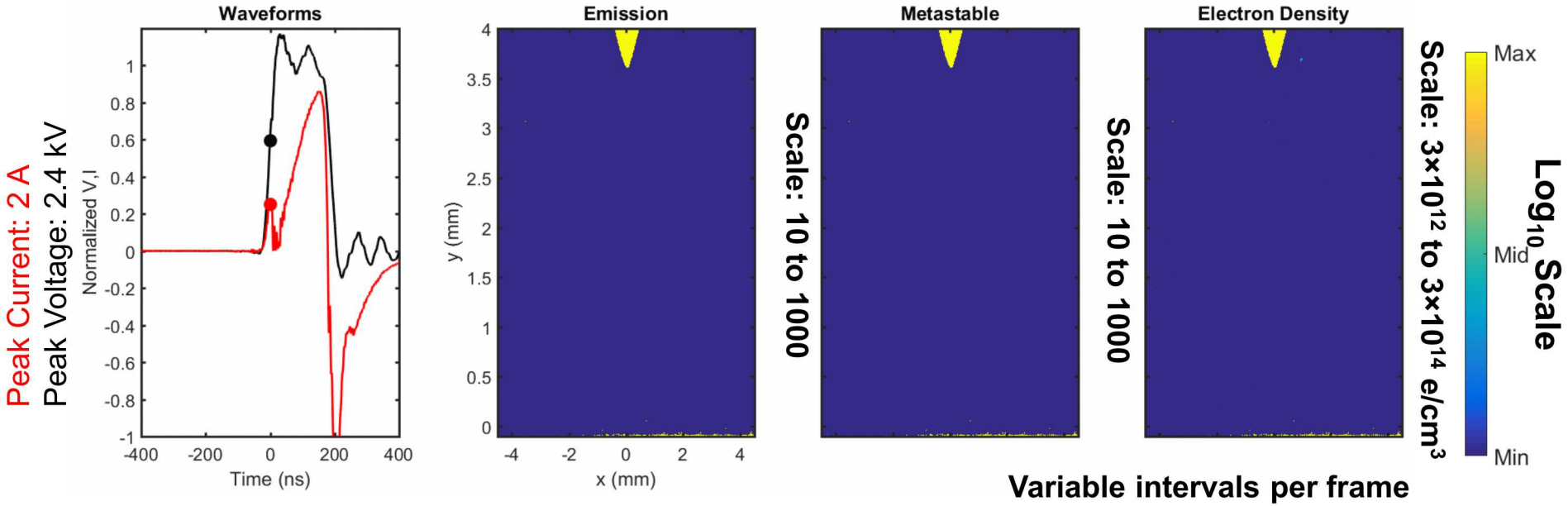
Increase gas temperature proposed as change in LCIF signals..
Could a setup like this be used to assess temperatures??

A Final Example is Offered

- Recent efforts have been focused on extending LCIF to (near) atmospheric pressure environments



Entire Discharge Event

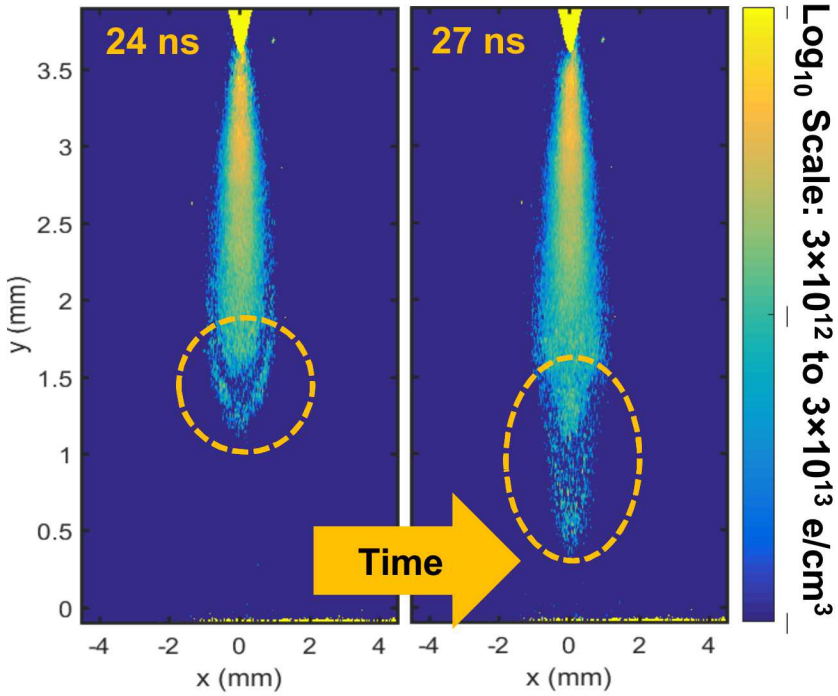


Considerable challenges to realize this…
…but successful… mostly!

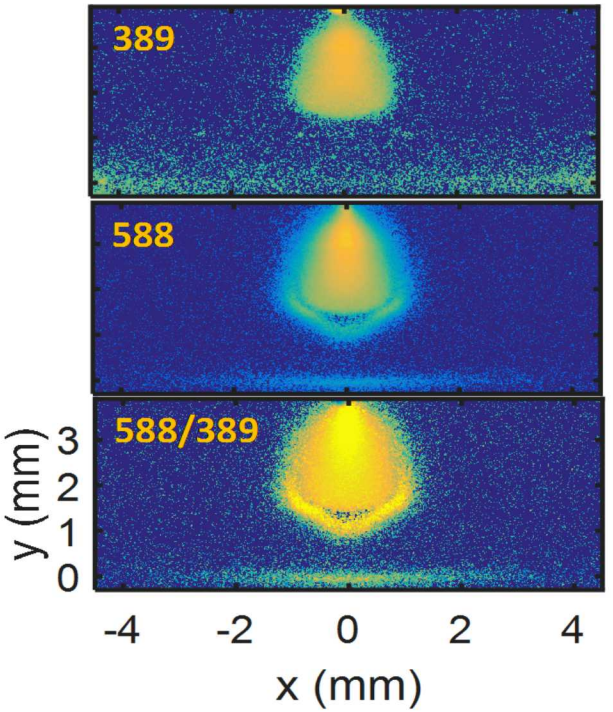
Leading Edge Signal Observed

- Another "Amorously" odd manifestation of LCIF!
  - Electron density should be low.. to non-existent
  - Gas heating not likely, to occur on these time scales
  - Excitation rates drop at extreme E/N

2D Profile



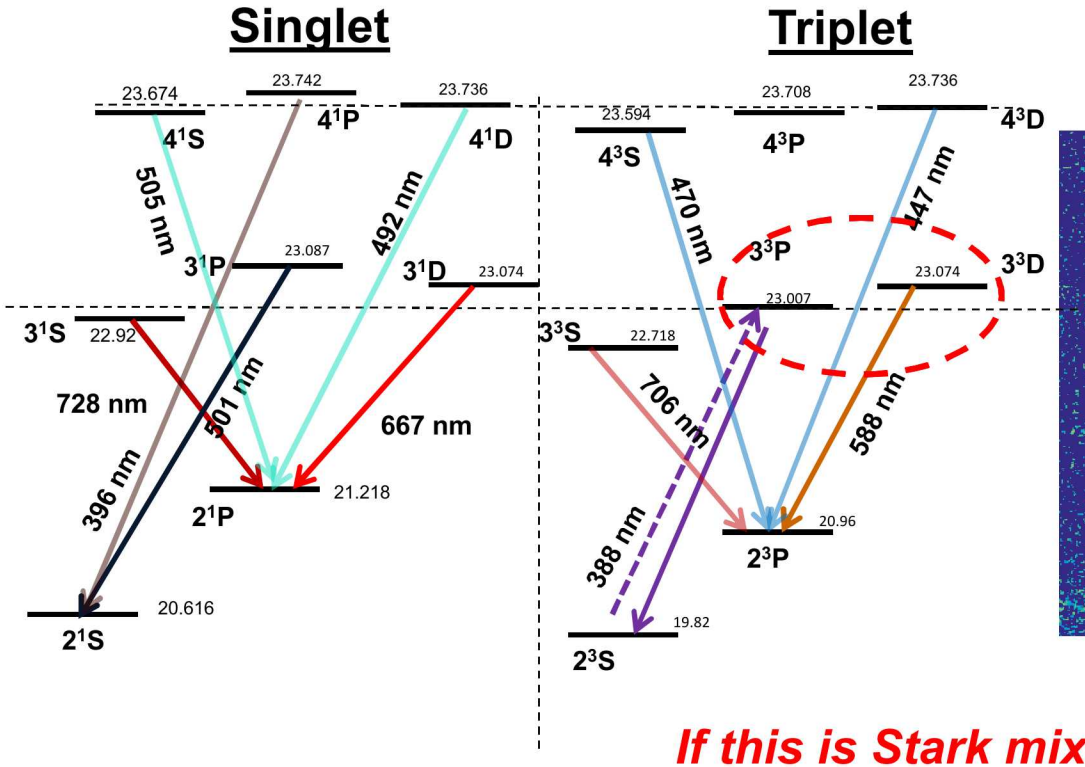
Raw Signals

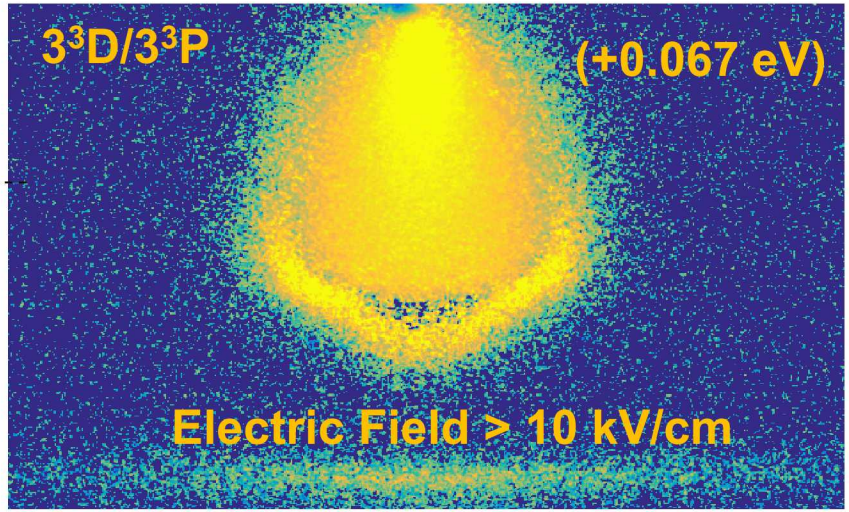


What other physics may be at play here??

Stark Mixing May Be the Cause

- Electric fields at leading edge can exceed 10 kV/cm.
  - Estimates of Stark shifting suggest energy levels do not change significantly.
  - Unclear if mixing between 3^3P into other states is probably at these fields.





If this is Stark mixing….

Is this a new way to assess electric fields???

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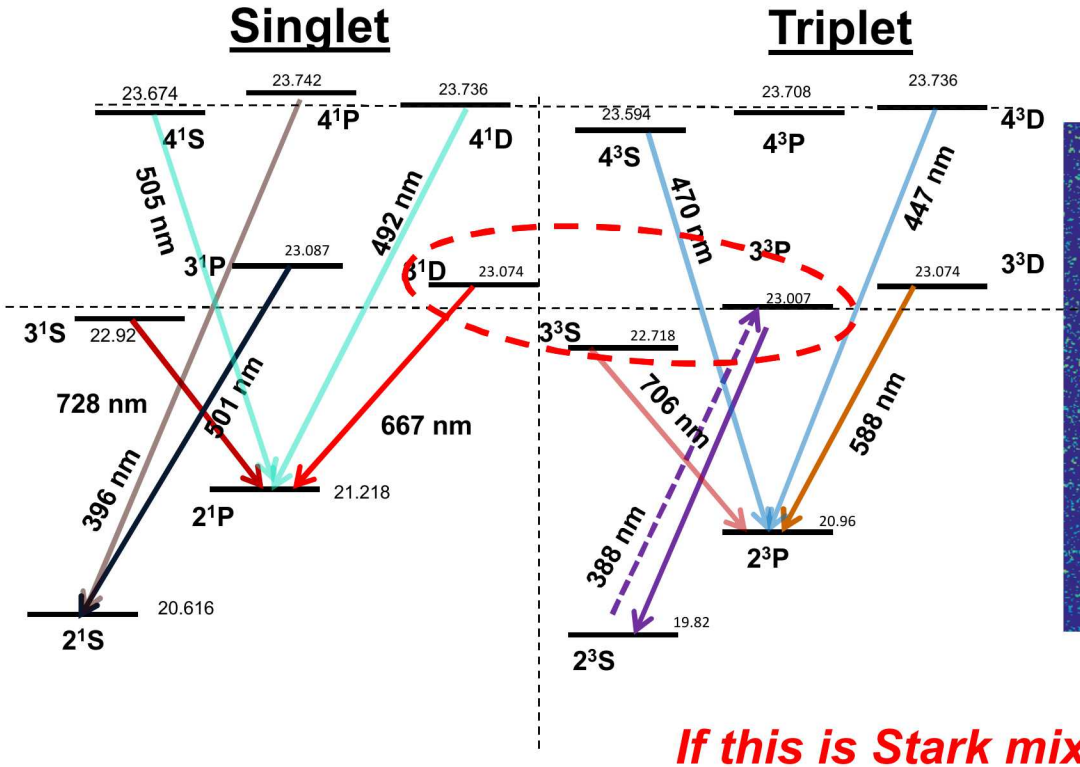

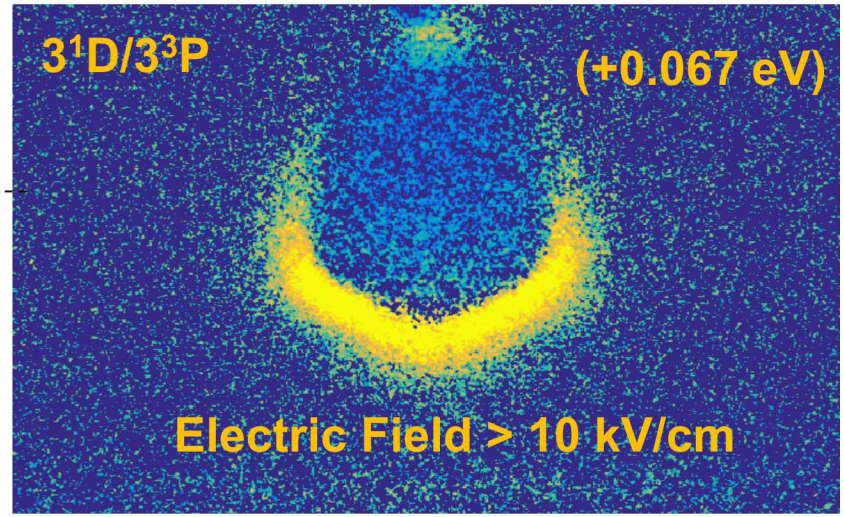

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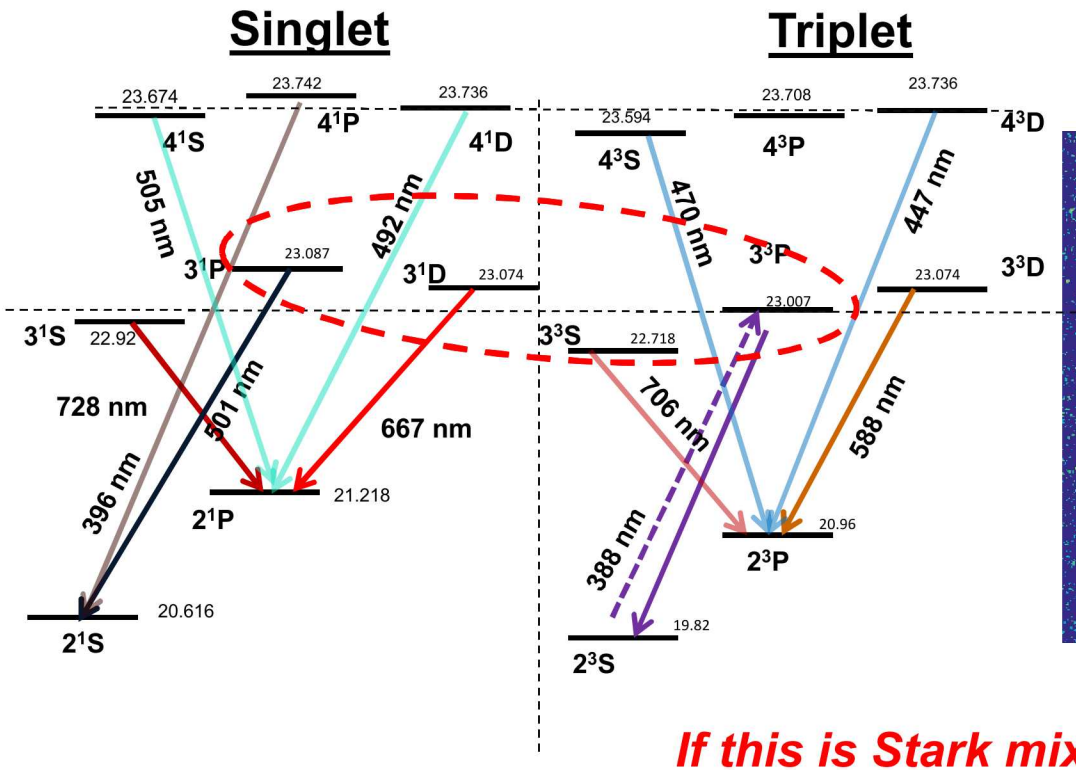
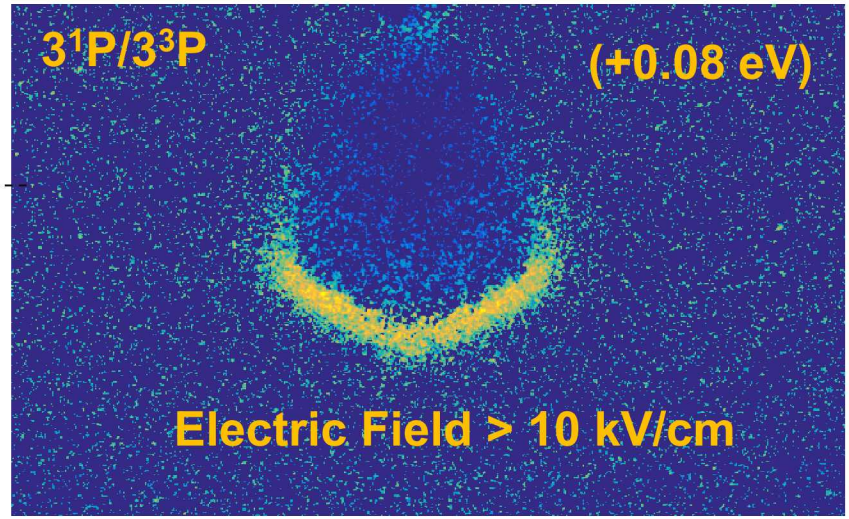




If this is Stark mixing….
Is this a new way to assess electric fields???

Conclusions

- What are diagnostics good for?
  - Means to an End
    - Validation example
  - But not always
- Outline challenges associated with diagnostics
  - "Children"
  - I want to have fun with this
  - I want to tell interesting stories that highlight the challenges and rewards associated with diagnostic developments

Most often it is our job to match the right tool for the right job…
Kind of need to know what you are getting into before jumping in..
"Good, the bad and the ugly of diagnostics manifest"

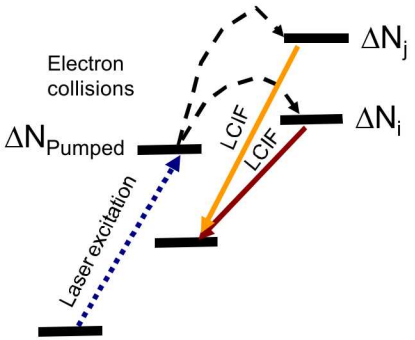
Auxilliary Info

- What are diagnostics good for?
  - Means to an End
    - Validation example
  - But not always
- Outline challenges associated with diagnostics
  - "Children"
  - I want to have fun with this
  - I want to tell interesting stories that highlight the challenges and rewards associated with diagnostic developments

Most often it is our job to match the right tool for the right job…
Kind of need to know what you are getting into before jumping in..
"Good, the bad and the ugly of diagnostics manifest"

Imaging is Central Extension to LCIF

- Narrow band interference filters are critical component of setup
  - Isolates key LIF or LCIF signals from other emission
  - Enables two-dimensional realization of technique



Setup

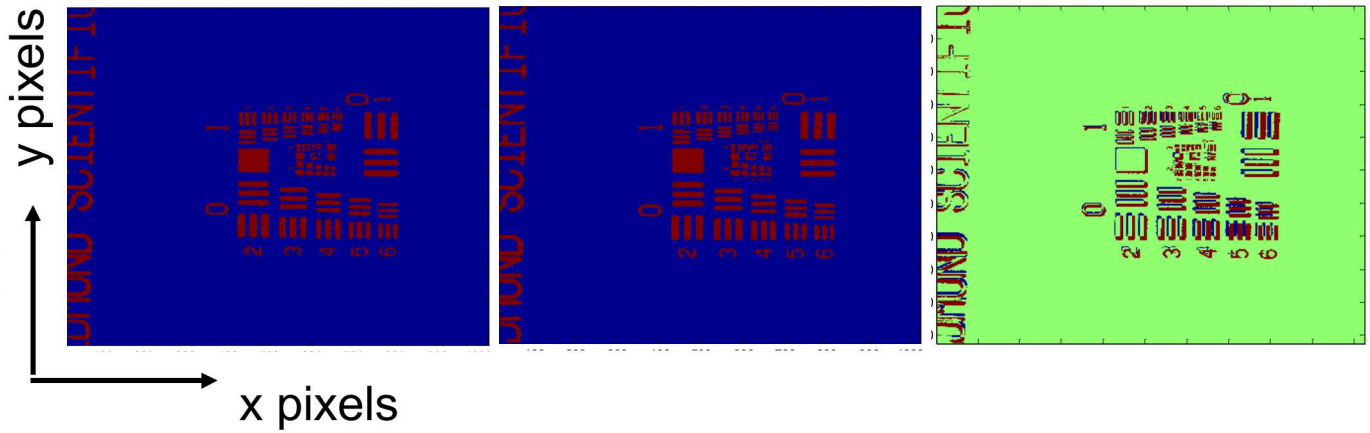
Target reticle

Narrowband filters

ICCD camera

390 nm image **590 nm image** **Difference**

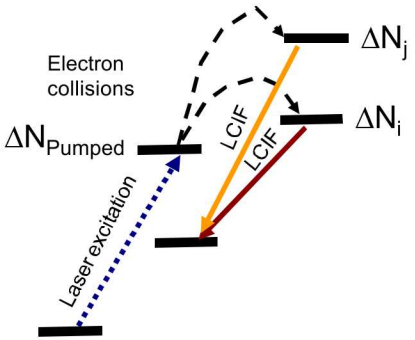
1024x1024 pixel images



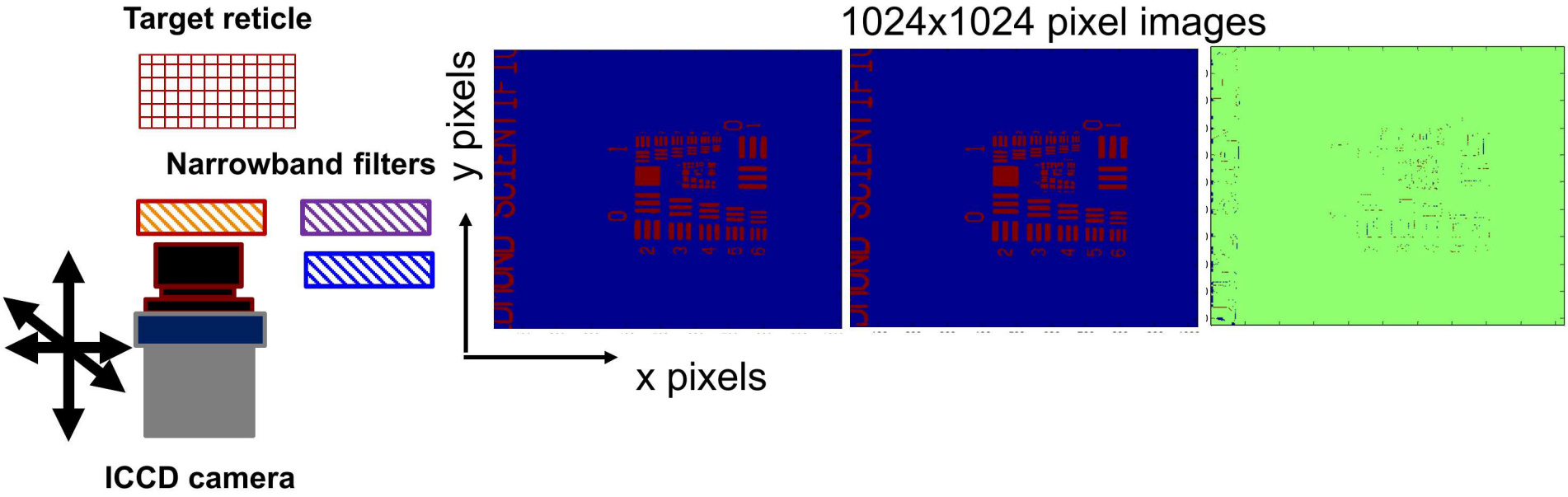
Images are not well aligned… off by several pixels in both directions

Imaging is Central Extension to LCIF

- Add 3-axis stage for sub-mm translation of ICCD
  - Correct for small displacements in image due to interference filters
  - Translate camera for every filter used



Setup **390 nm image** **590 nm image** **Difference**

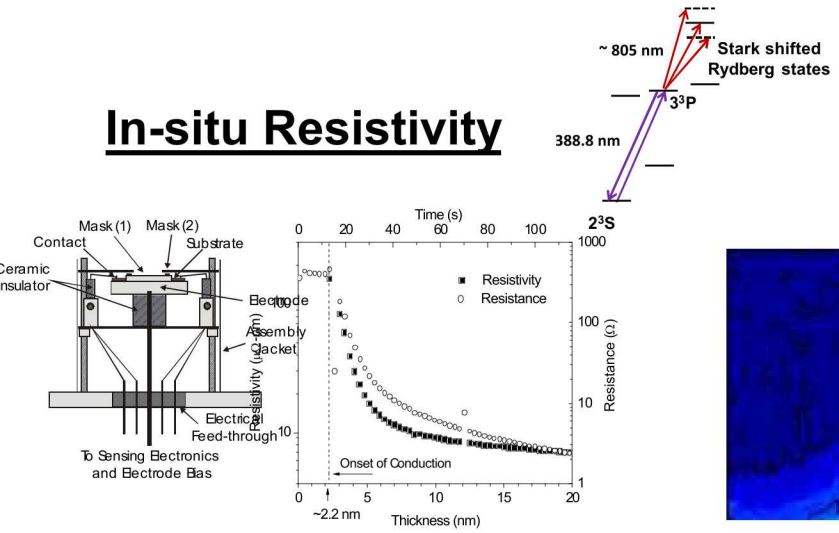


Pixels become important when studying very high gradient regions (interfaces, arcs, …)

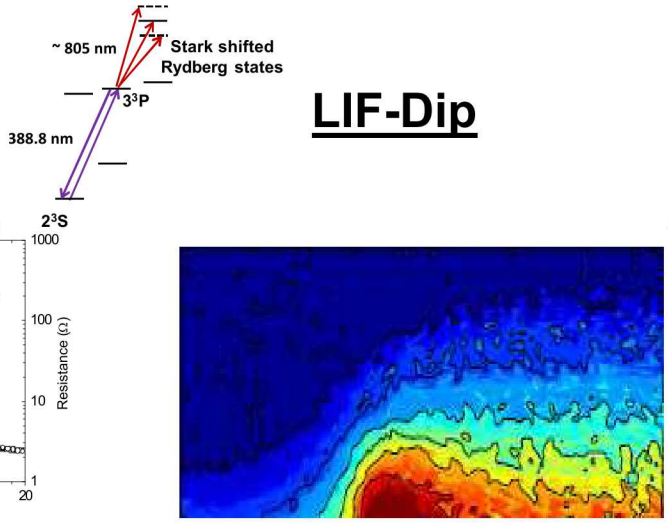
Diagnostic Development: "End Unto Themselves"

- There is a point where new ground is discovered
  - Does something exist to measure what I need?

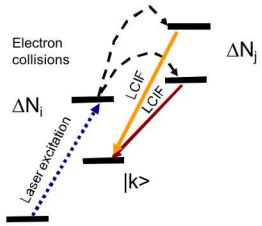
In-situ Resistivity

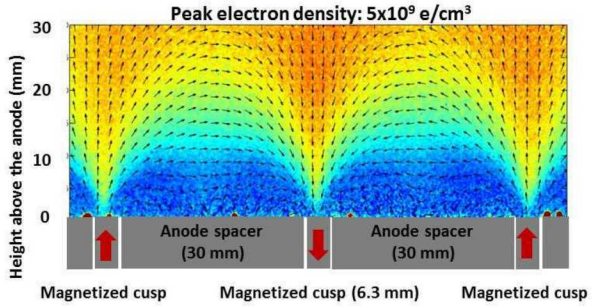


LIF-Dip



LCIF

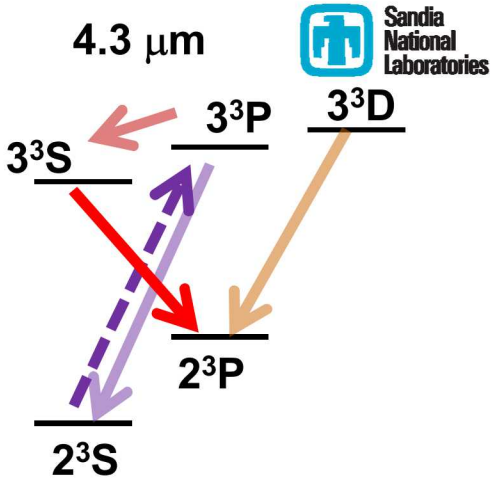




I have been involved in developing and deploying diagnostics for 18+ years…
This is a particularly rewarding experience for me

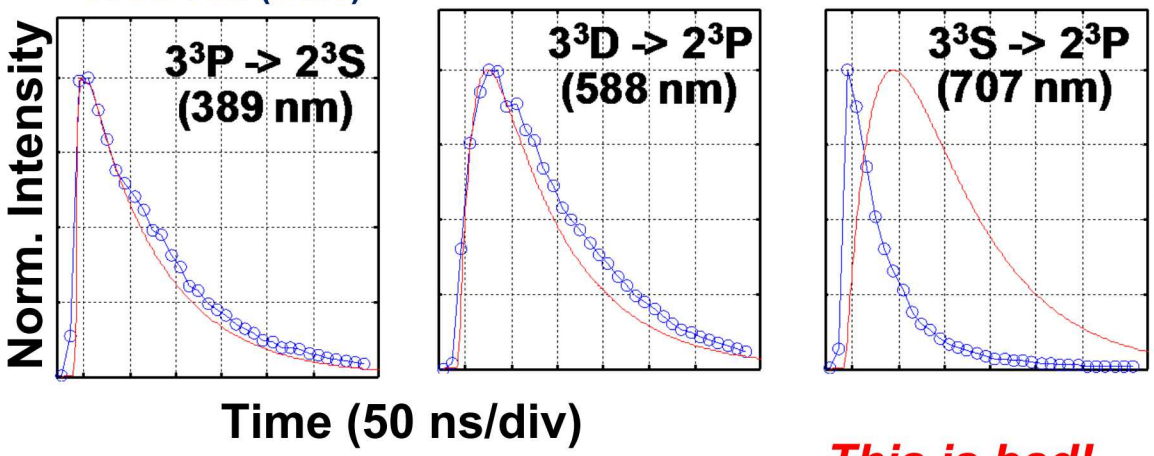
But That Wasn't the Full Story

- We started off on the wrong path (~ one year)
  - Using 3^3S as a surrogate for the 3^3P
  - We really wanted to avoid using resonant radiation
  - Model said is was ok to do!

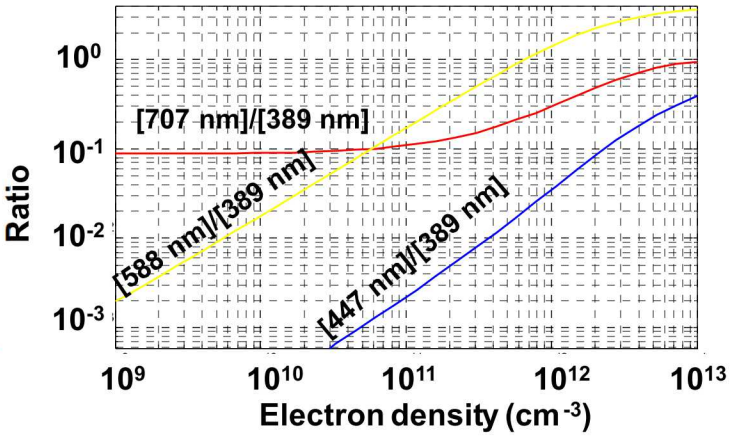


Time Resolved LIF and LCIF trends

Predicted (Red)
Observed (Blue)



Predicted scaling

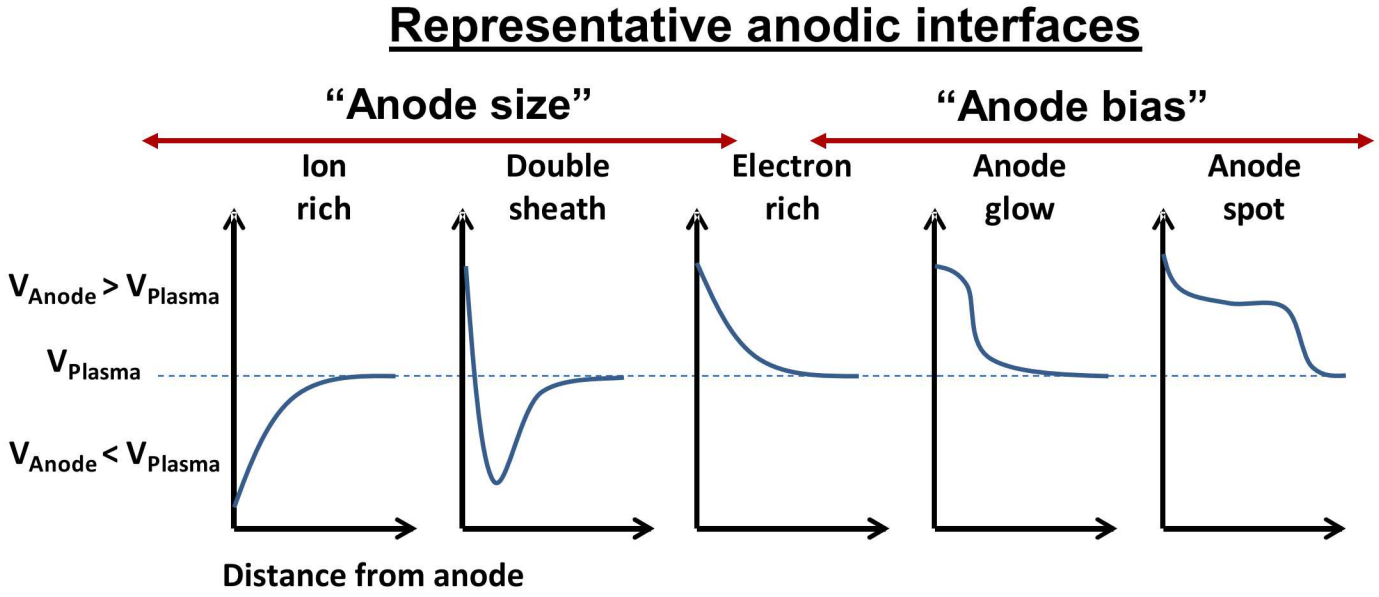


This is bad!

The model and measurement totally do not agree

We Used LCIF to Study Anodic Interfaces

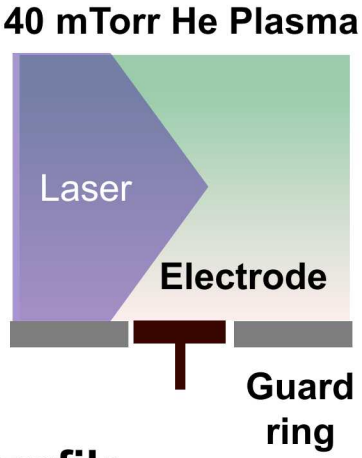
- Basic GPS program to study the scaling and the structure of anode interface and anode spot formation.
  - Ben Yee and Matt Hopkins (SNL), Scott Baalrud and Brett Scheiner (U. Iowa).
- Utilize LCIF to interrogate



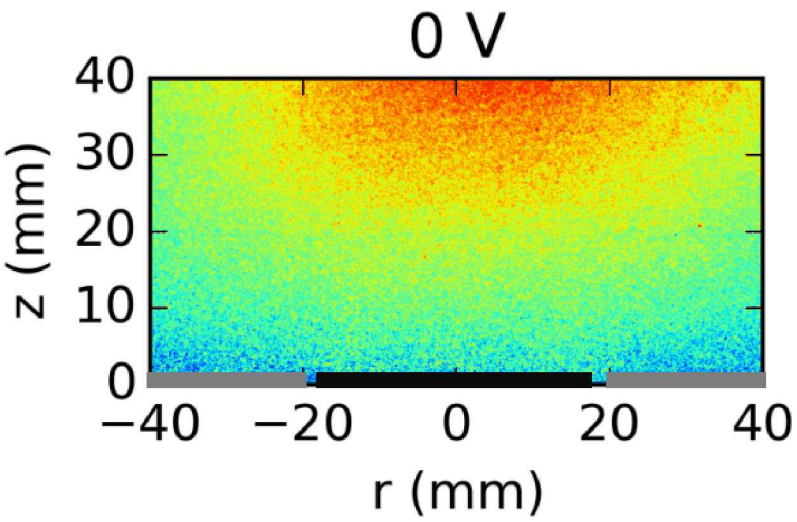
Anodic structures are anticipated to have many configurations.. which are challenging to interrogate.

LCIF Interrogated Unbiased Interface

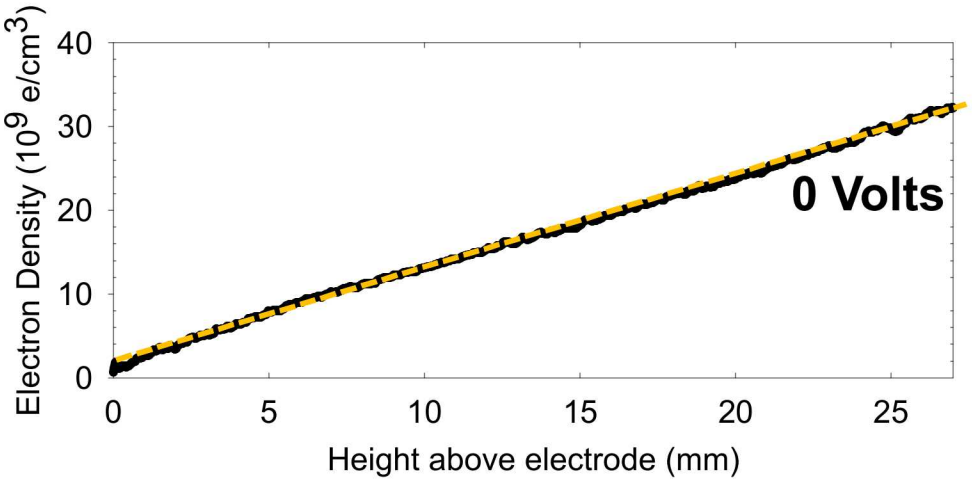
- Measured plasma structure to grounded electrode
  - Uninteresting test case to baseline comparisons.



2D Image



On-axis profile

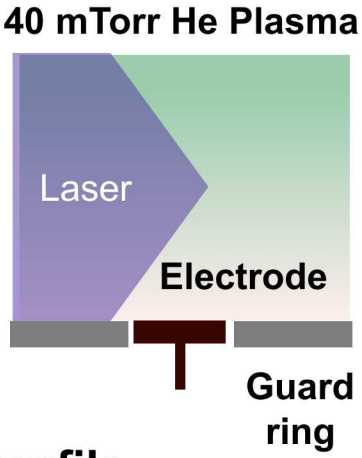


Plasma has uniform gradient…
…nothing to see here

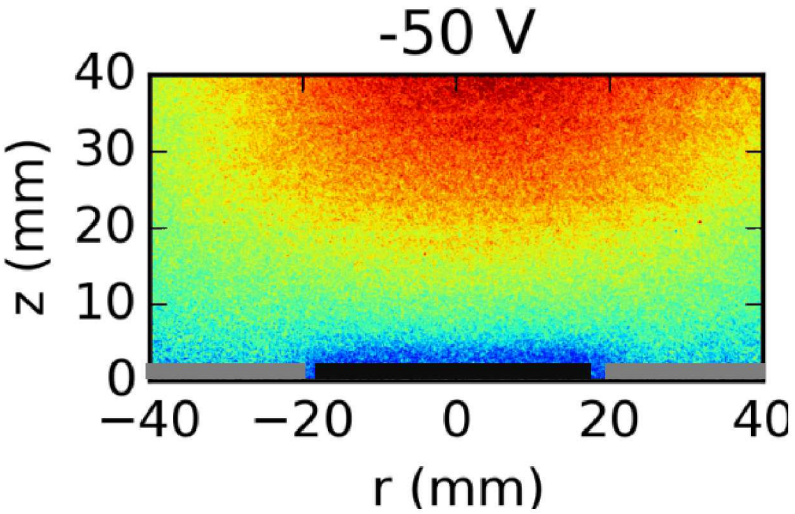
B. T. Yee et al., Plasma Sources Sci. Technol. AA, XYZ (201Q)

LCIF Interrogated Cathode Interface

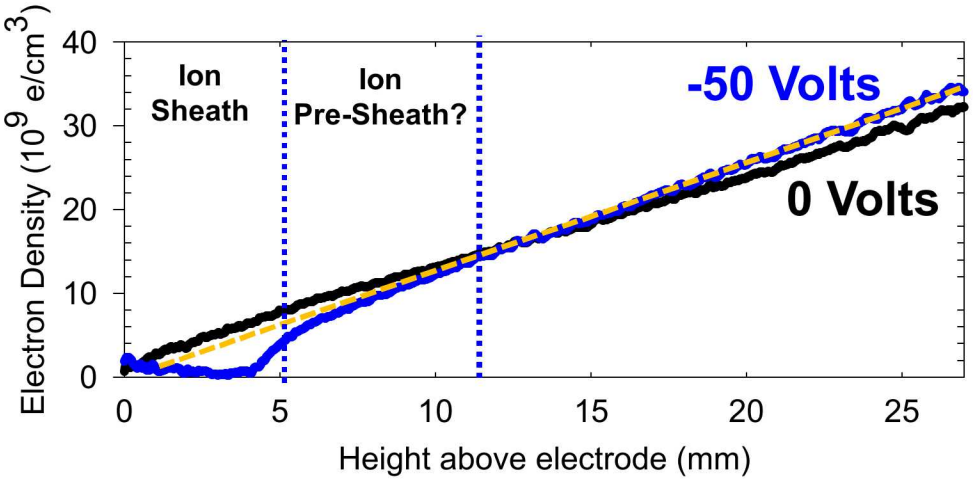
- Applied -50 volts to electrode to form an ion sheath
  - Examine structure for a “known” case.
  - Observe electron free sheath and perhaps electron-depleted presheath.



2D Image



On-axis profile

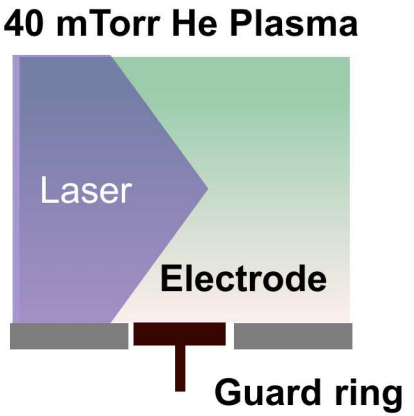


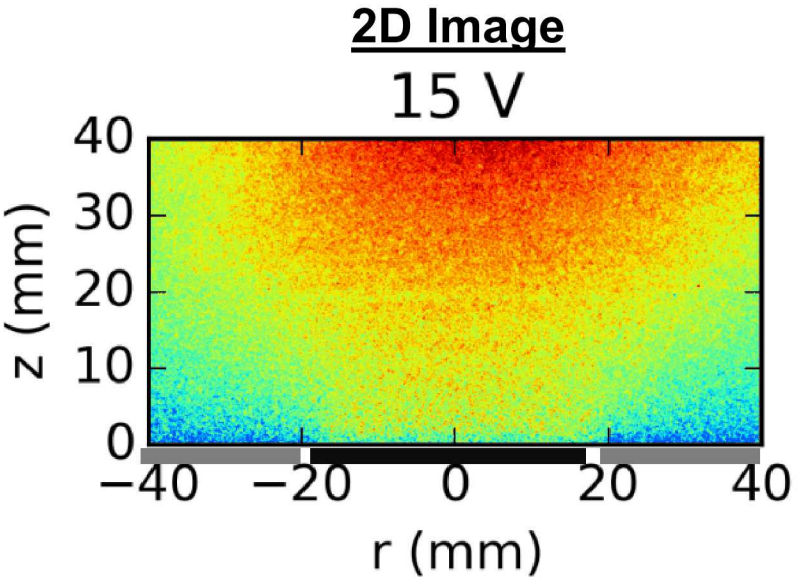
Cathodic interface is interesting… but basically anticipated.

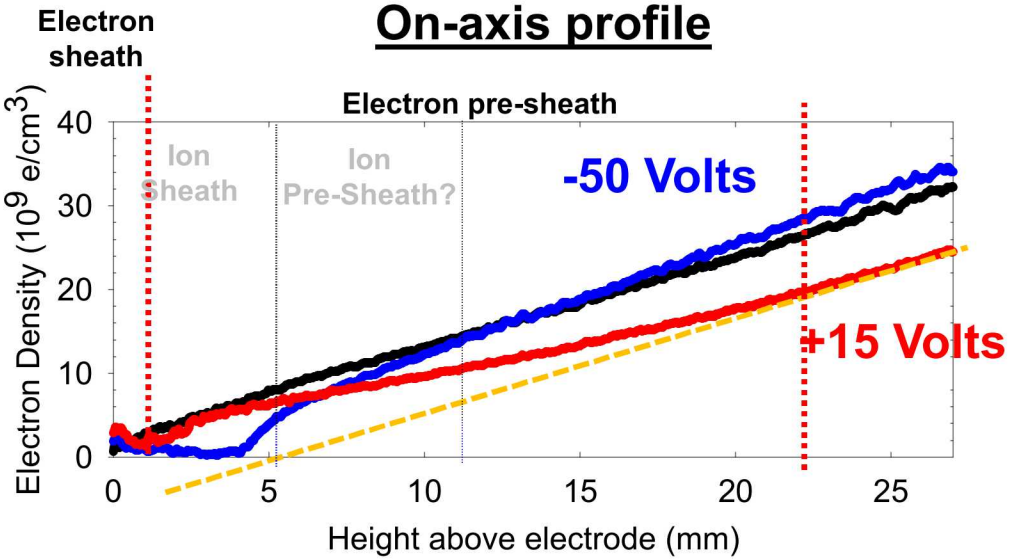
B. T. Yee et al., Plasma Sources Sci. Technol. AA, XYZ (201Q)

LCIF Interrogated Anode Interface

- Initial observations of electron rich interfaces were "confusing".
  - Odd structure observed in anodic state.







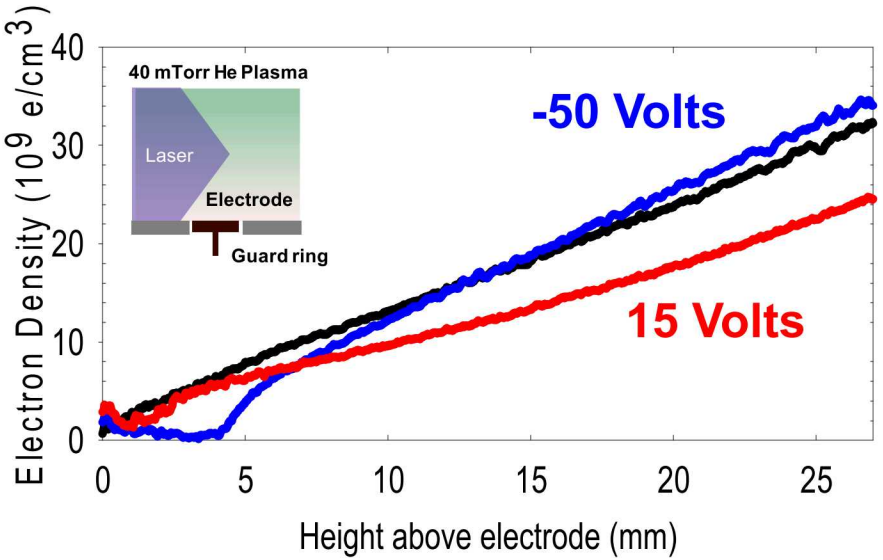
Anodic interface seems to have far reaching extent into the plasma... why does the electron density have that funky structure… could we believe the results??

B. T. Yee et al., Plasma Sources Sci. Technol. AA, XYZ (201Q)

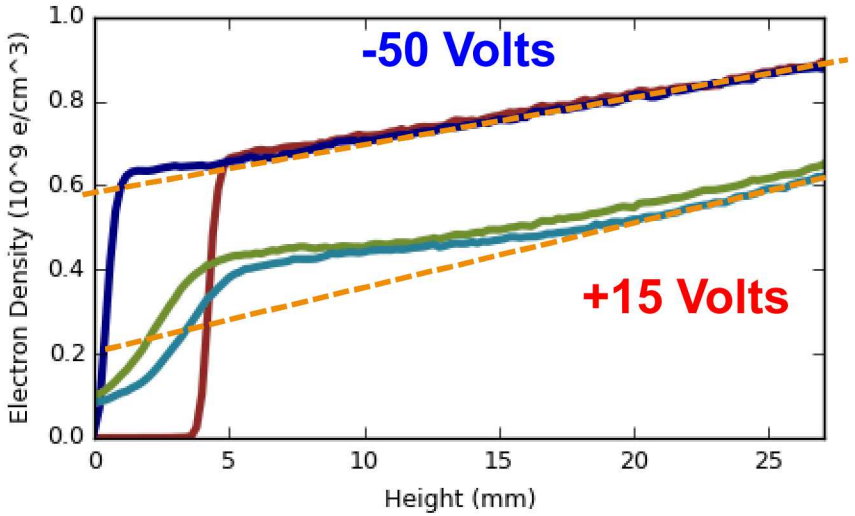
We Used LCIF to Study: Anodic Interfaces

- Considerable effort went into vetting the measurements.
  - We wanted to make sure something was “wrong”.
  - After some time, ran simulations to see if this was “real physics”.

Experiment



Simulation



Simulations had similar characteristic that measurements had shown!
We were observing interesting physics!!

Observations led to new insight

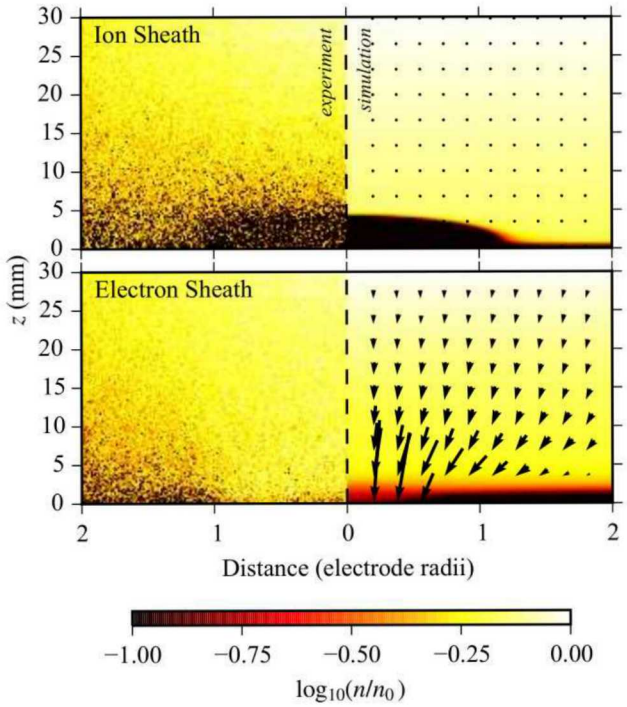
- After vetting LCIF,

Static Sheaths

Modified Flow Fields

Dynamic Spots

measured **simulated**



Much of this was initially unintended and could have been easily overlooked

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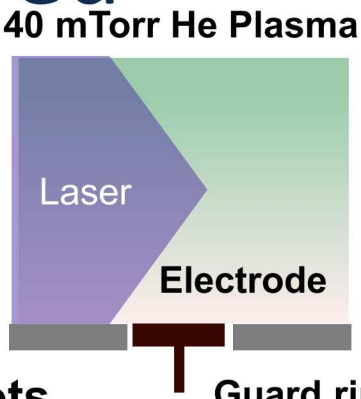
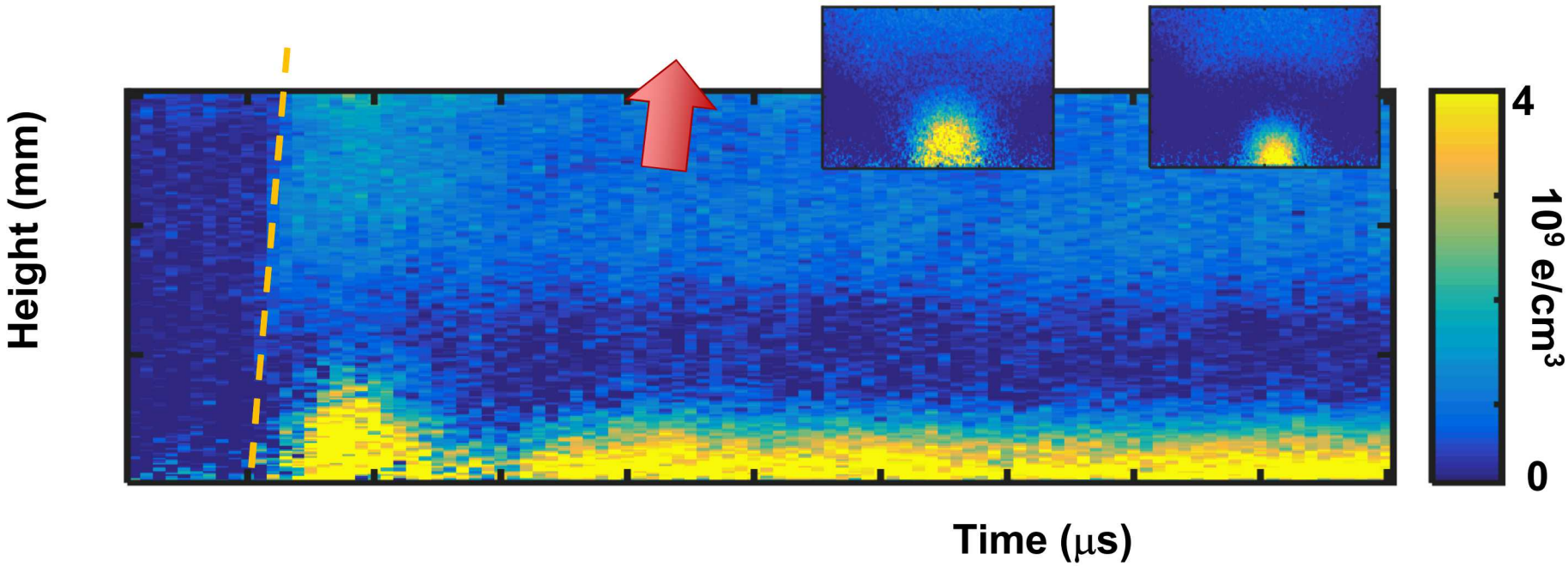
Phases of Anodic Interfaces Explored

- After vetting LCIF,
  - We were sure that something was “wrong”.
  - After some time, ran simulations to see if this was “real physics”



Dynamic Spots



Considerable ground covered with LCIF!

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