Interrogating vacuum arc physics with advanced diagnostic methods

Presentation to:

3rd International Workshop on Mechanisms of Vacuum Arcs (MeVArc 2012)

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Ed Barnat

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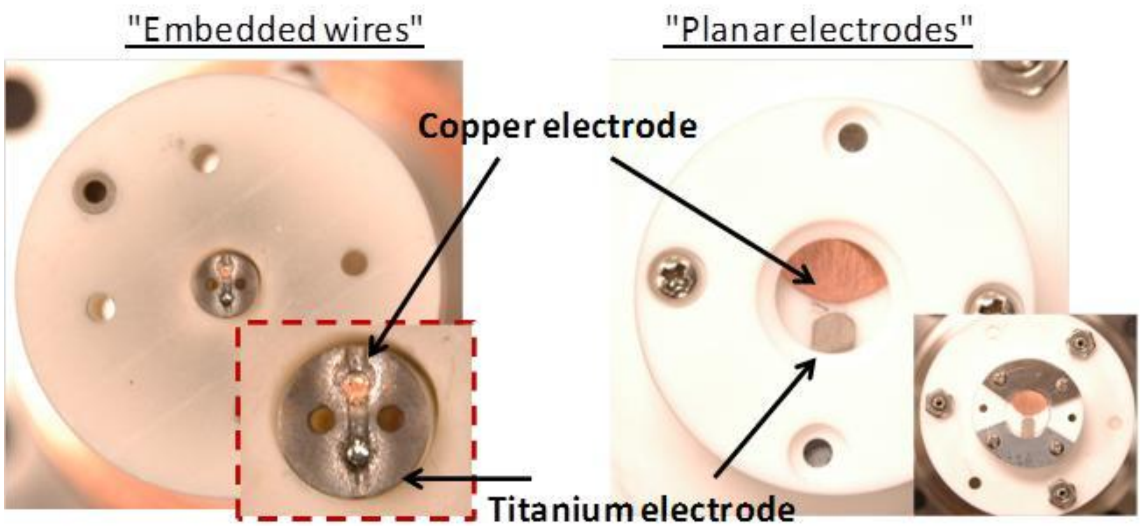
Vacuum arcs represent challenging environments both computationally and experimentally

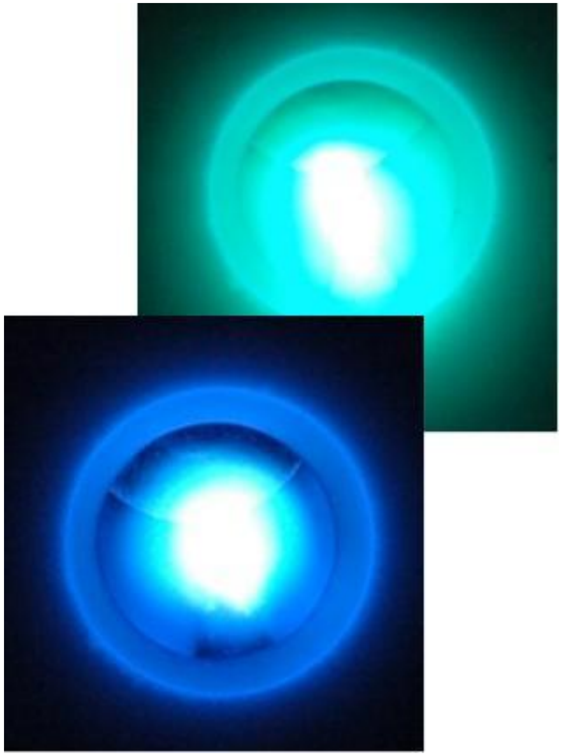
- For us, the arc is a “good thing”
  - We use it to generate high density plasma
- Our main challenge is to have a reliable, reproducible arc
  - Do the same thing over and over
- Central questions include
  - What is present in the arc?
  - When is it generated?
  - Where is it generated from?
  - What are these species properties?
  - How does the output change with operation
- Answers to these questions help us understand
  - Phenomena of arc generation and maintenance
  - Plasma transport from the source

Our progression has been from “far” to the “near”

Introduction to the types of arcs we are considering

- Experiments need to be flexible and versatile
  - Test predictive capabilities of code
  - Target desired physics
  - Overcome intrinsic headaches associated with arcs
- Co-planar two electrode metal arcs embedded in ceramic sleeves
  - Various configurations and compositions
  - Mostly vacuum, but not always





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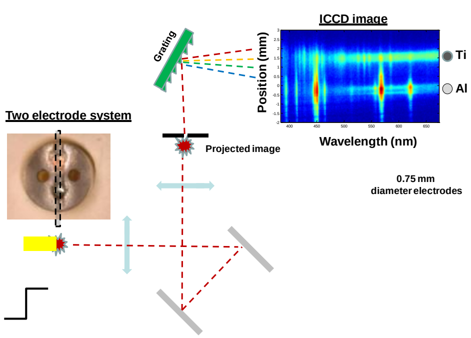
A wide range of diagnostic techniques are needed to study arc physics

- A wide range of techniques can be utilized to probe aspects of plasma generated in an arc
  - Our challenge is to match the right tool to the right job
- Tools can consist of
  - "Global" current and voltage
  - Semi-localized optical emission and ion beam spectroscopies
  - Localized laser induced fluorescence, absorption and or scattering

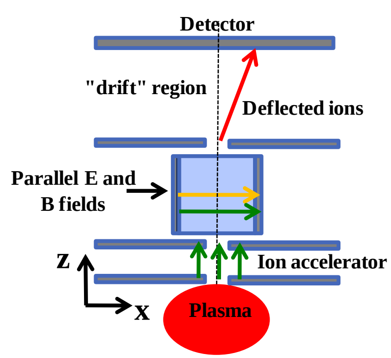
Optcial diagnostics

“Near the source”



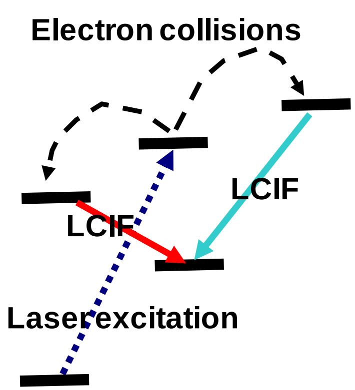
Ion-based diagnostics

“Downstream”



Laser spectroscopy

“Bridge the gap”



Emphasis is placed on laser based diagnostics

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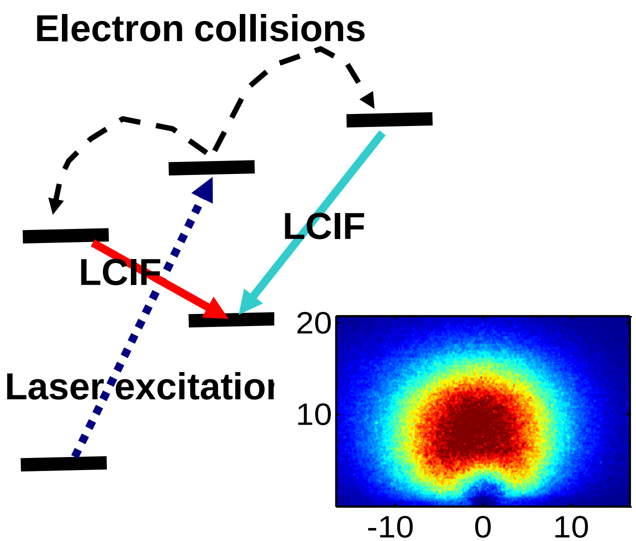
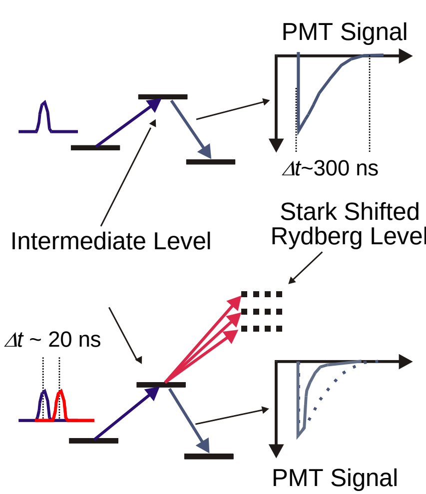
Laser based diagnostics facilitate measurements of the arc environment

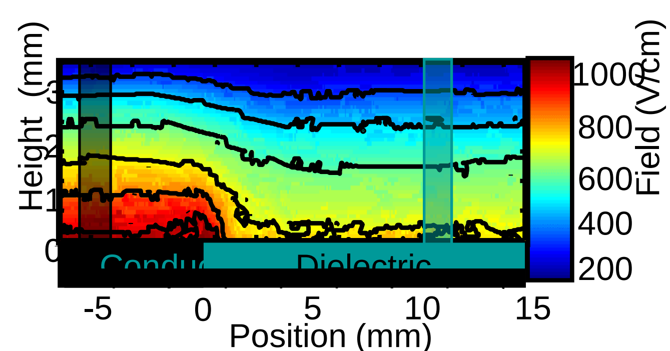
- Laser diagnostics offer good spatial and temporal resolution
  - Region of interrogation limited to where the beam is
  - Temporal resolution governed atomic response
- “Minor” perturbations to the plasma
  - Some redistribution of excited states, possibly some ionization
- Diagnostics based on laser-induced fluorescence (LIF)
  - Laser collision induced fluorescence (LCIF) for electron densities
  - LIF-Dip for electric fields

LCIF



LIF-Dip





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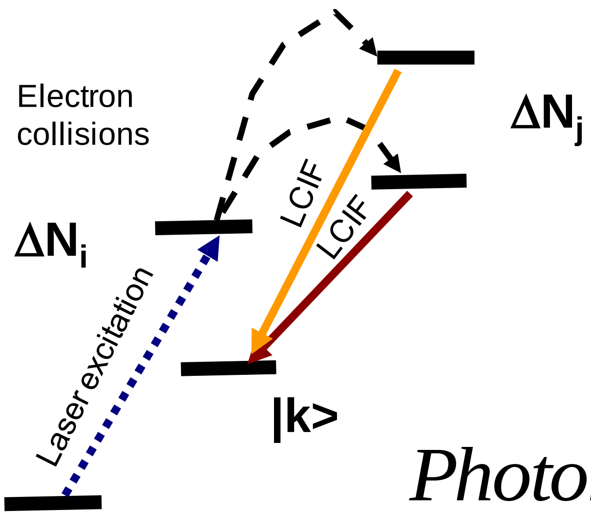
LCIF is based on redistribution of excited state by plasma electrons

- Laser excitation populates an intermediate state
  - Relaxation processes deplete the 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 "uphill" states after laser excitation

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Redistribution after laser excitation is complex

- A "good" model is required to predict transfer between levels
  - Employ a collisional-radiative model (CRM) to predict redistribution

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

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

- Electron density and electron temperature appear in first term
  - Temperature dependence introduced via K^e_{ij}

Electron-temperature dependent rates

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

Distribution function used for describing electron velocities

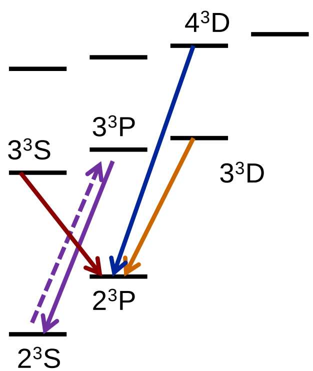
$$f(v) \sim e^{\left(\frac{1}{2} m v\right)^{x} / kT}$$

Approach is applicable to various atomic and molecular systems of interest

Helium atom serves as target species for LCIF measurements

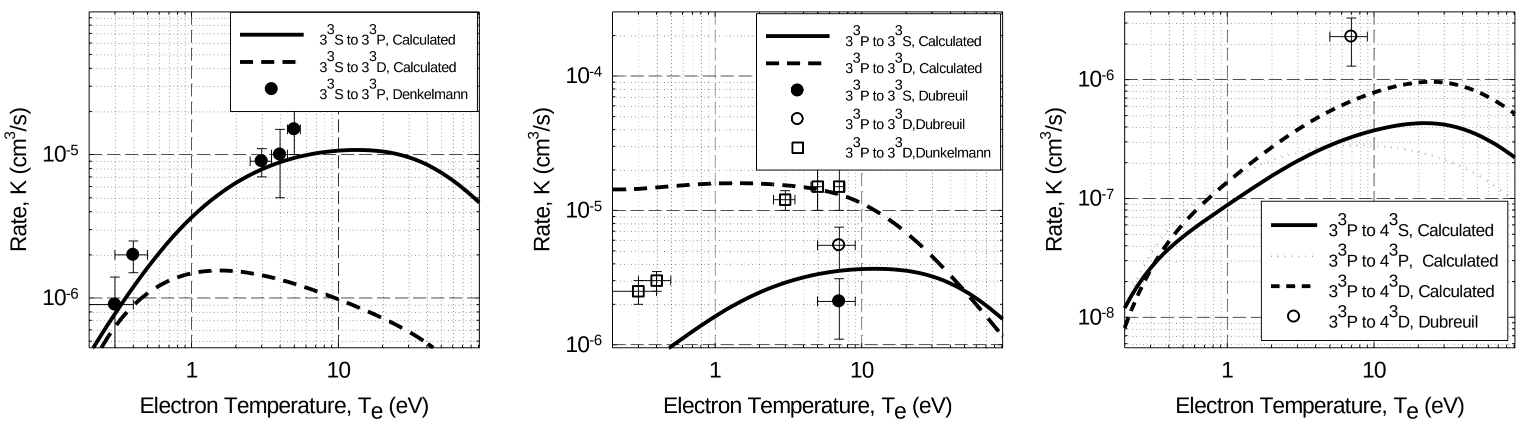
- Employ Helium to start with - considering argon
  - "Simple system" with "better known" rates
- Utilize functionalized form of cross-sections compiled by Ralchenko[1]
  - Integrate to get rates, compare to measured rates [2,3]

Key transitions



Computed and measured excitation rates in Helium

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



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)

2: R. Denkelmann, S.Maurmann, T. Lokajczyk, P. Drepper, and H. –J. Kunze, J. Phys. B: At. Mol. Opt. Phys. 32, 4635 (1999). R. Denkelmann, S. Freund and S. Maurmann, Contrib. Plasma Phys. 40, 91 (2000).

3: B. Dubreuil and P. Prigent, J. Phys. B: At. Mol. Opt. Phys. 18, 4597 (1985).

Accuracy of n_e, T_e depend on knowledge of $K_{ij}(kT_e)$

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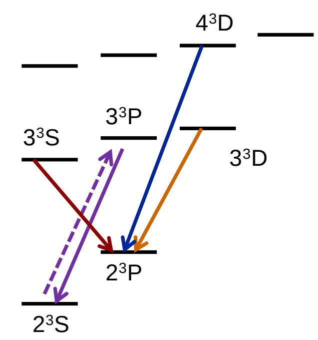
CRM predicts evolution of various helium states after laser excitation

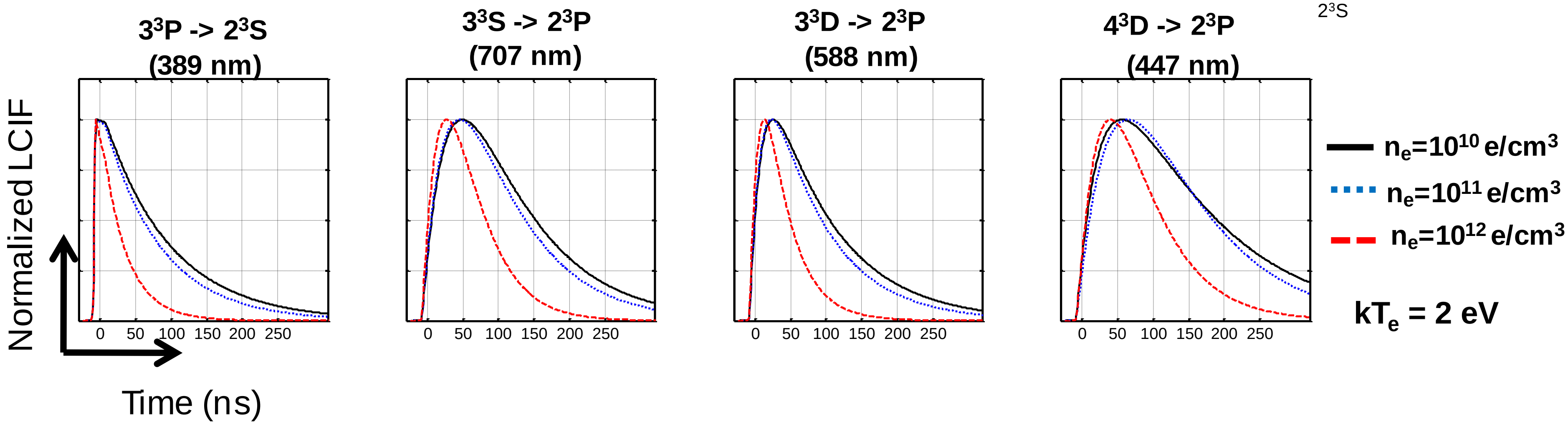
- Temporal evolution serves as a partial "fingerprint" of electron interaction
  - Analyze shape of decay above $n_e \sim 10^{11}$ electrons/cm^3
  - Below $n_e \sim 10^{11}$ absolute intensities are needed

Key transitions



$$K^{e}_{ij} n_e \sim A_{ij} \Rightarrow \mathbf{10^{-5} \times 10^{11} \sim 10^{7}}$$

Computed temporal evolution



Need at least two time-resolved profiles to uniquely obtain n_e, kT_e

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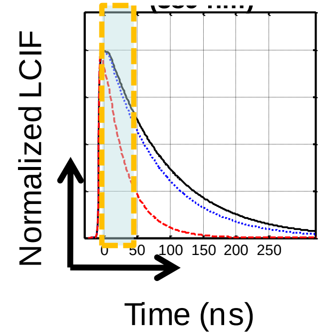
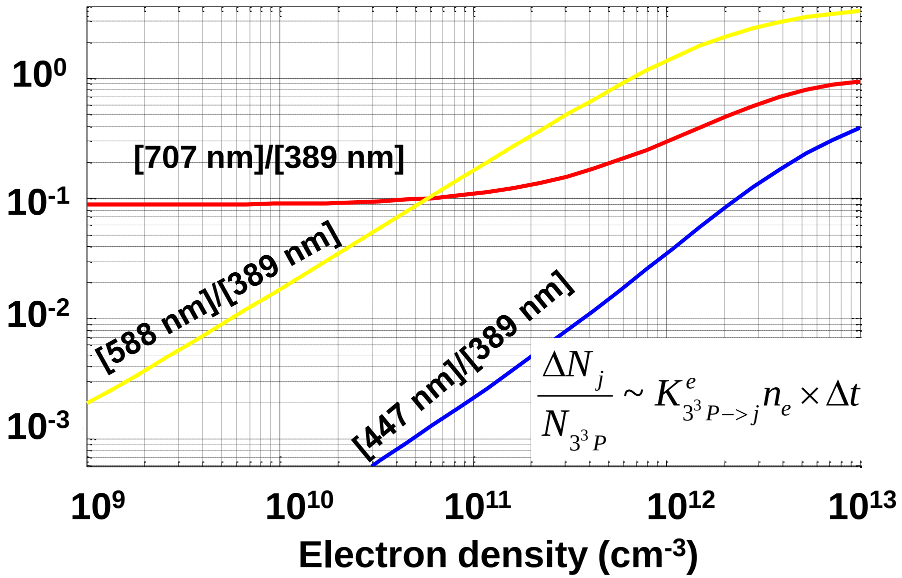
Trends can be extracted to bypass the need for resolving LCIF evolution

- Examine ratios of time integrated LCIF
  - Eliminates need for absolute calibrations
  - Still need relative efficiencies of imaging system
- Capitalize on "kT_e independent" coupling of 3^3P to 3^3D
  - Ratio of 588 nm to 389 nm yields n_e
  - Density + Ratio of 447nm to 588 nm yields kT_e

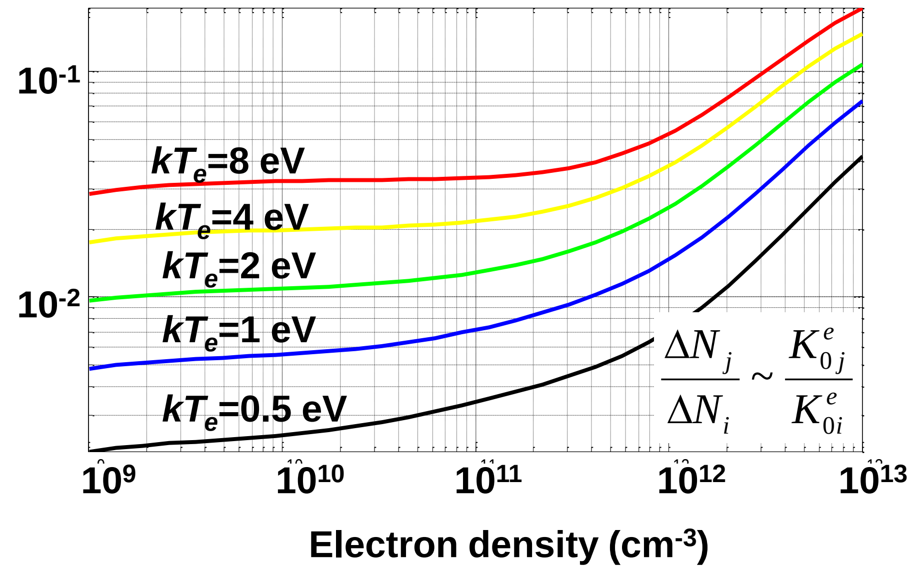
Window of integration



Ratio to 389 nm



Ratio [447 nm]/[588 nm]



Only need to make three measurements to obtain n_e, kT_e

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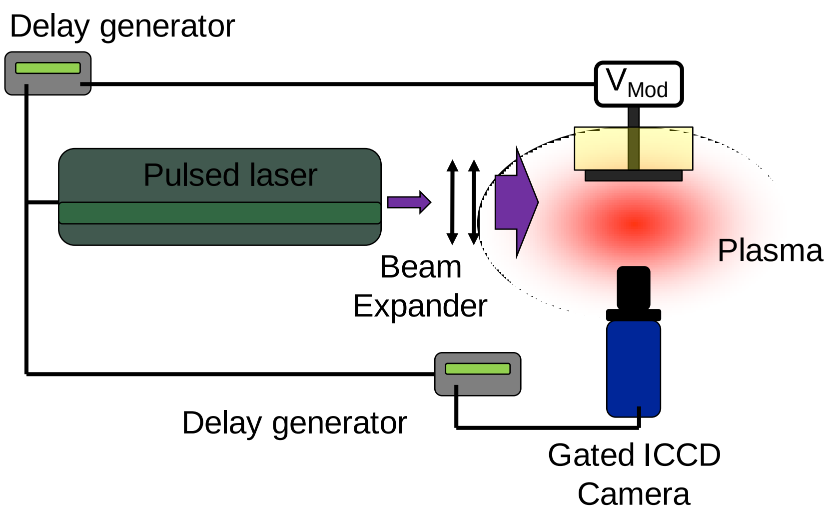
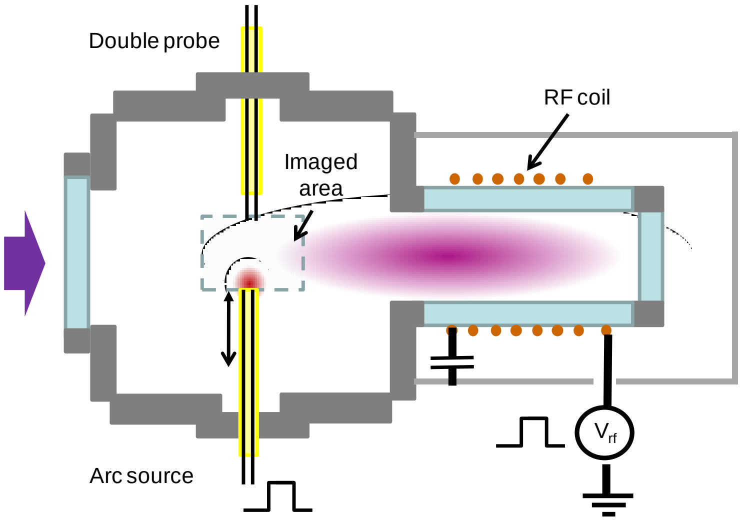
Experimental implementation of the LCIF technique is realized

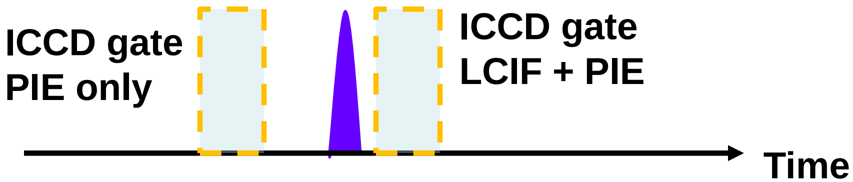
- Desirable to develop technique over broad range of densities (and temperatures)
  - Expanding arc in helium aftergolw
  - Arc moves on translatable stage
  - Double probe to measure ion/electron densities

Optical setup



Vacuum system





Now need six measurements (3x2) n_e, kT_e

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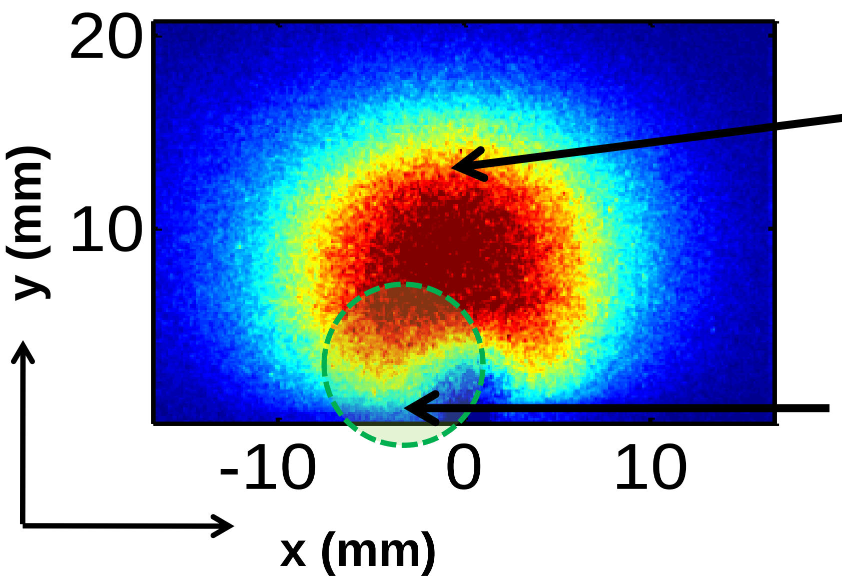
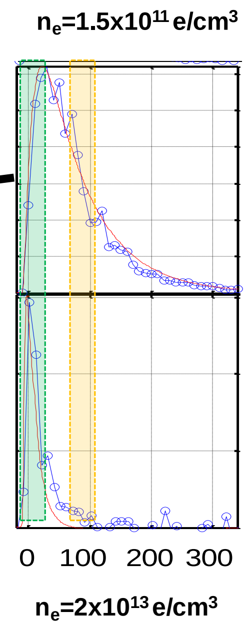
LCIF works quite well over broad density range

- Technique can measure densities from <10^{8} to >10^{12} e/cm3
  - Demonstrates good spatial resolution (< 1 mm)

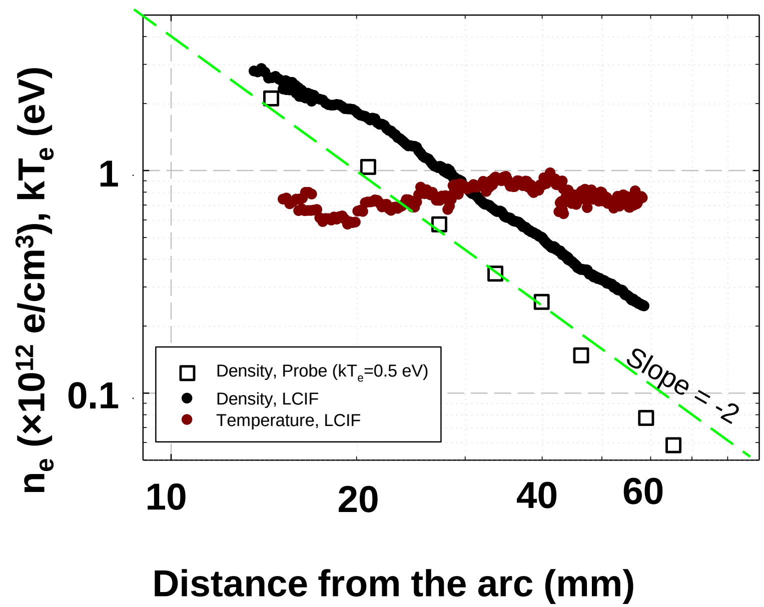
Measured profile



Temporal signature



Comparison to double probe



Higher densities (>10^{13}) can be measured but time resolution is needed

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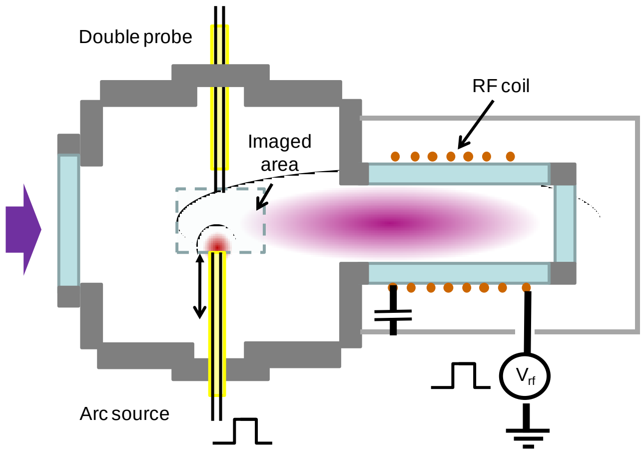
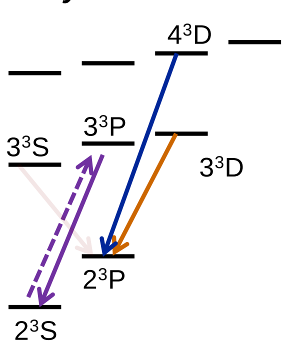
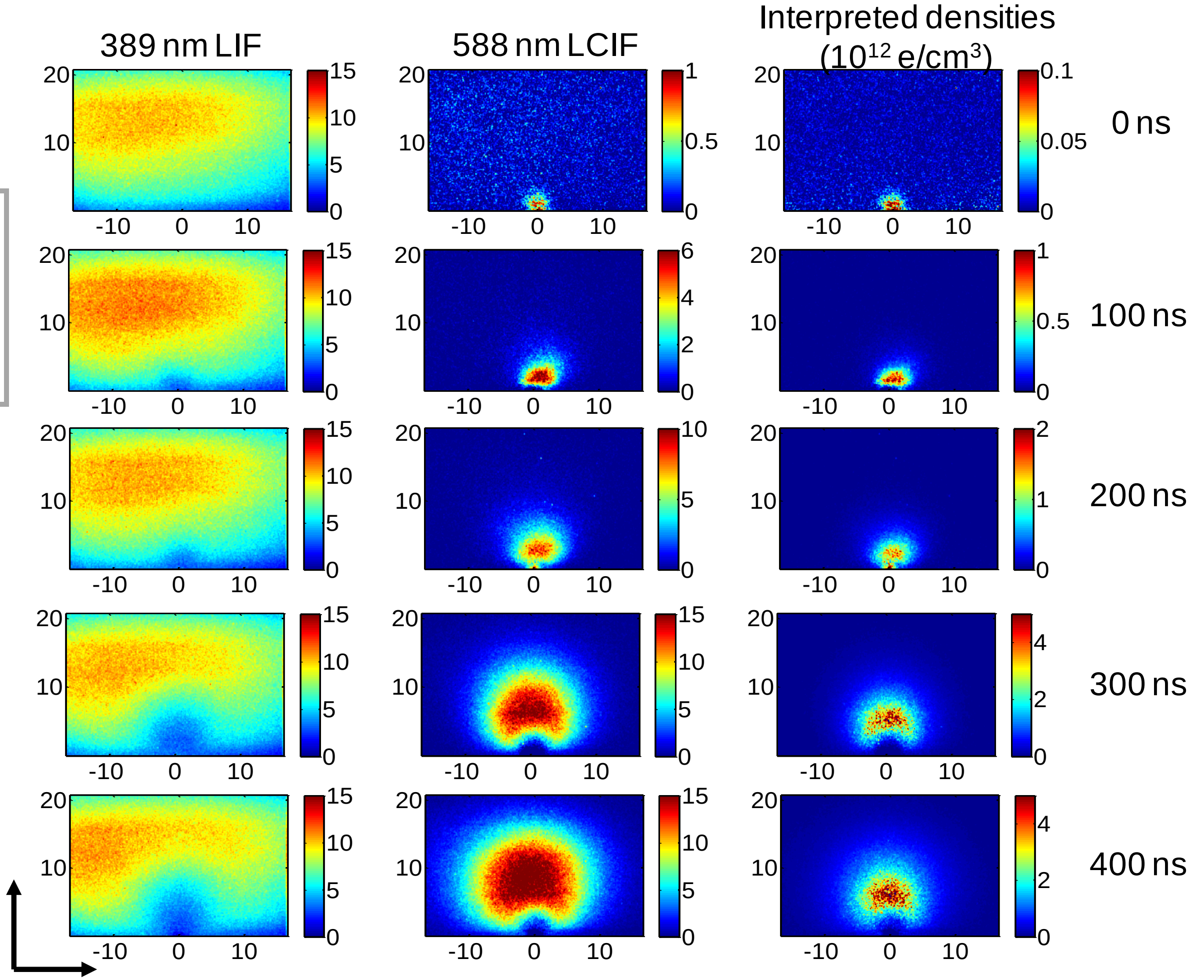
LCIF captures transient phenomenon

- **Examine generation of arc**
  - Low pressure (30 mTorr) helium after glow
  - Time steps of 100 ns, 50 ns gates







Spatial-temporal maps of arc expansion are illustrated with LCIF

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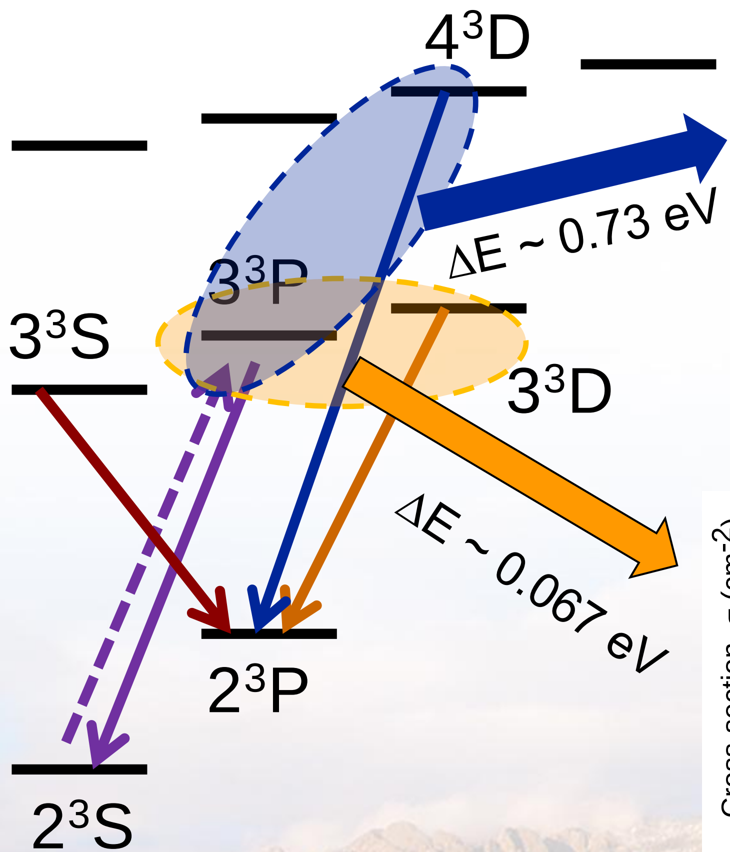
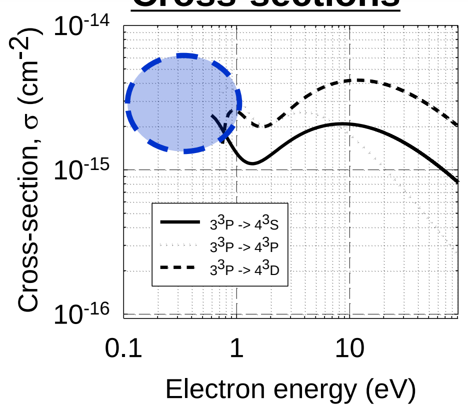
Monitoring higher levels gives measure of "electron temperature"

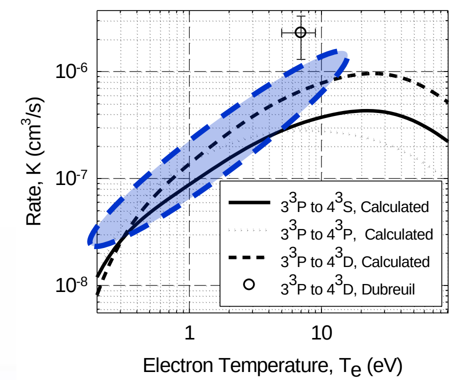


$3^3P \rightarrow 4^3D$

Cross-sections

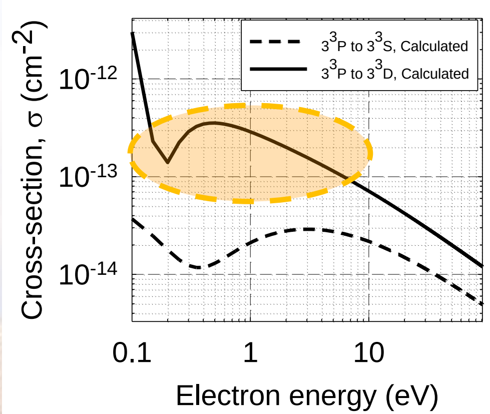


Rates

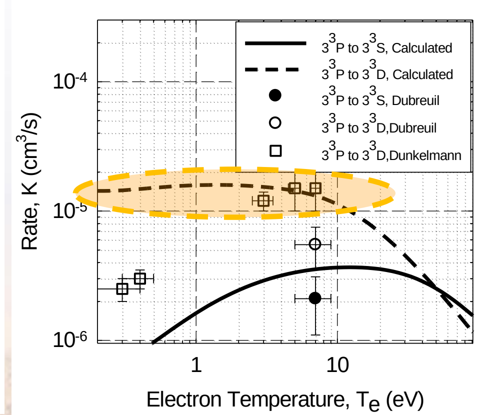


$3^3P \rightarrow 3^3D$

Cross-sections



Rates



This is a work in progress and quite sensitive to functional forms of rates

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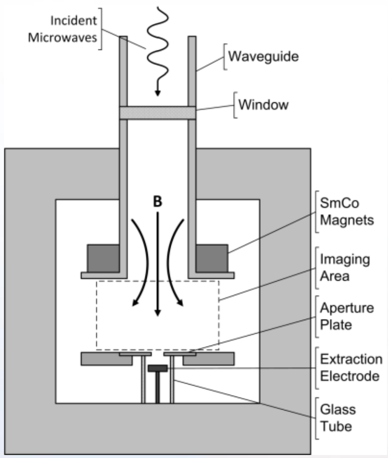
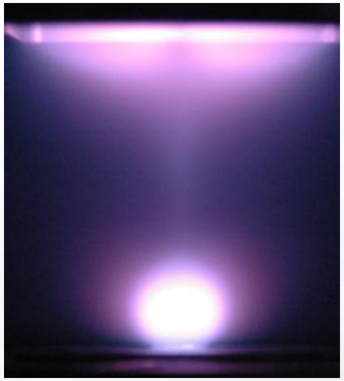
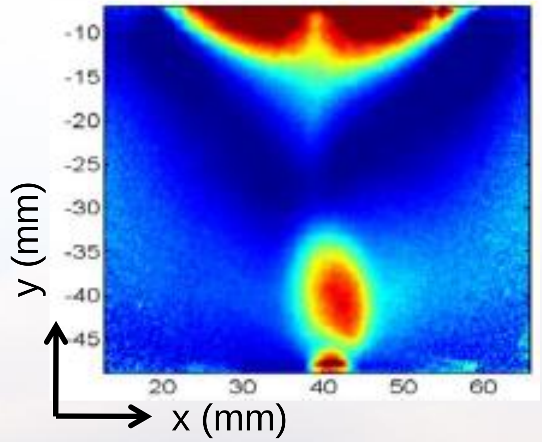
Yu. Ralchenko, R. K. Janev, T. Kato, D. V. Fursa, I. Bray, F. J. De Heer, Atomic Data and Nuclear Data Tables **94**, 603 (2008)

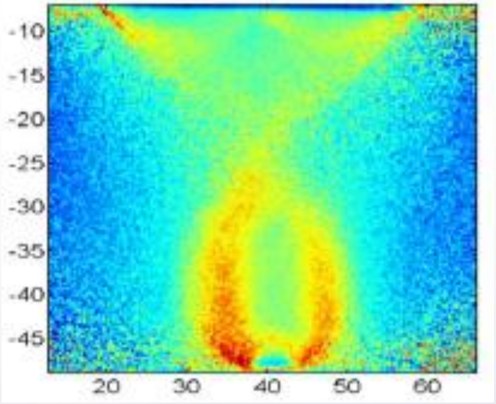
"Temperature" measurements have been illustrated in other plasma systems

- Electron temperature concept has been employed in other plasma systems
  - ECR generated plasma cathode experiments
  - NASA driven research interested in electron sources for ion propulsion neutralization









Regions of adjacent plasmas are mediated by electric fields that induce higher electron temperatures

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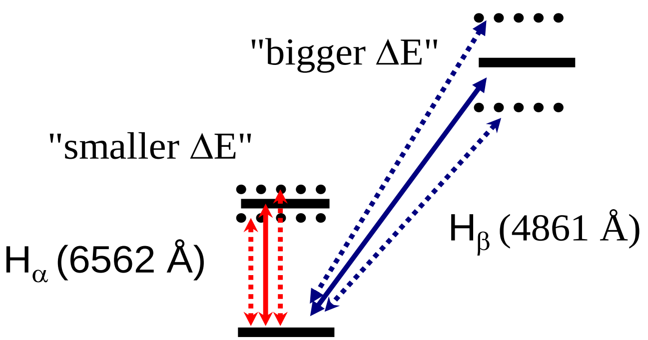
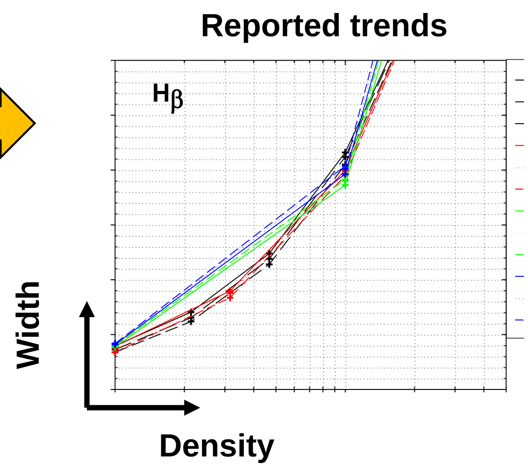
Stark broadening is used to target higher densities

- Electrons and ions "perturb" atomic orbitals
  - Degree of interaction ~ n_e and T_e
- Measured profiles are convolution
  - Stark, Van der Waals, Doppler and Instrument
- Fit profiles to obtain n_e,

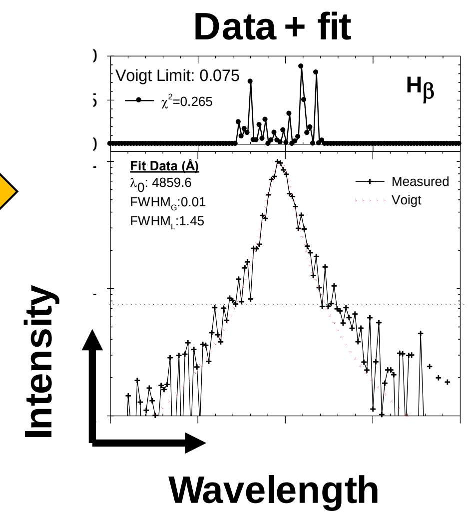
Concept



Scaling trends



Representitive results



Hydrogen emission is typically used but other species exhibit Stark broadening

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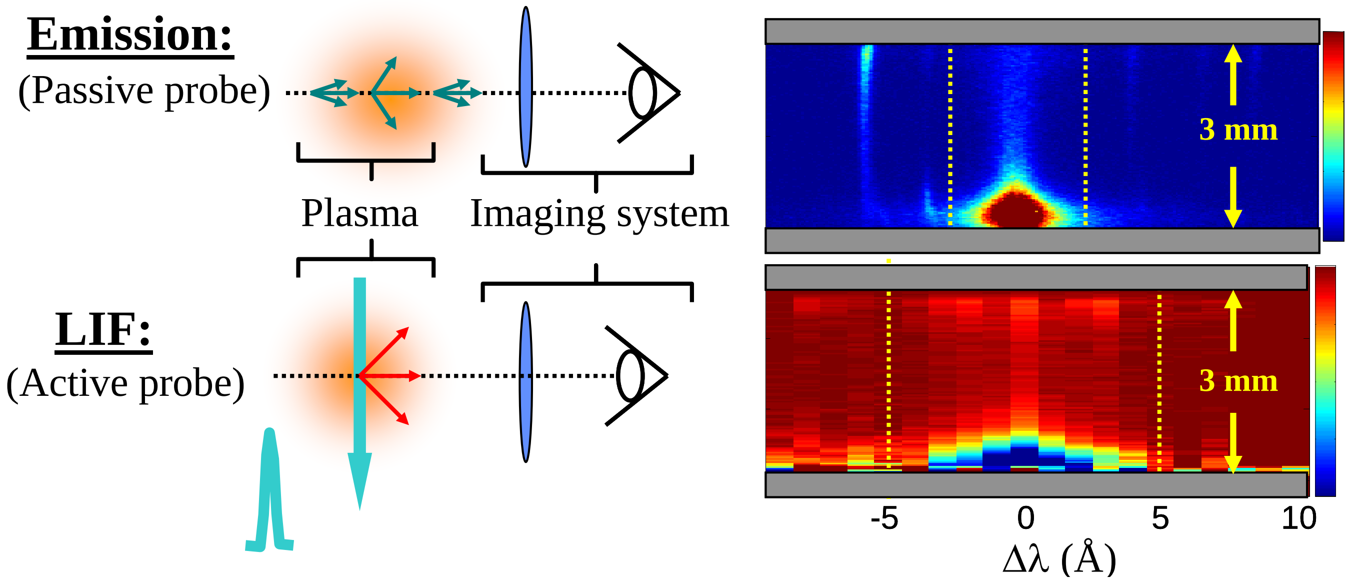
Both passive and active interrogation are being considered

- Nanosecond pulsed laser excitation is more difficult, but……
  - Overcomes "line of sight" convolution
  - Better spectral resolution (~ pm) than spectrometers (~10 pm)
  - Can provide 2d spatial maps

<u>Comparison of the two techniques</u>



Active interrogation provides more accurate measure of line broadening and is free of spectral contamination

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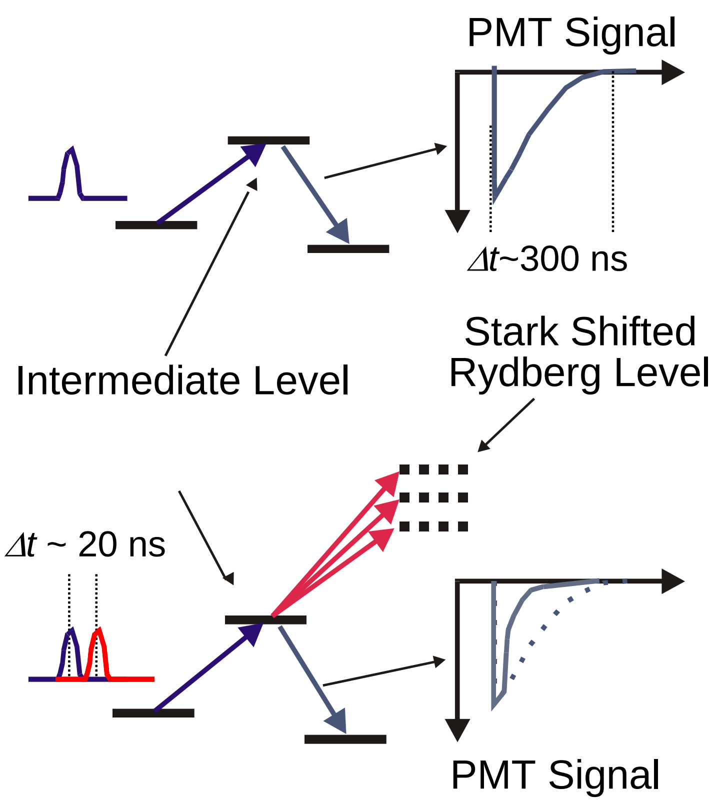
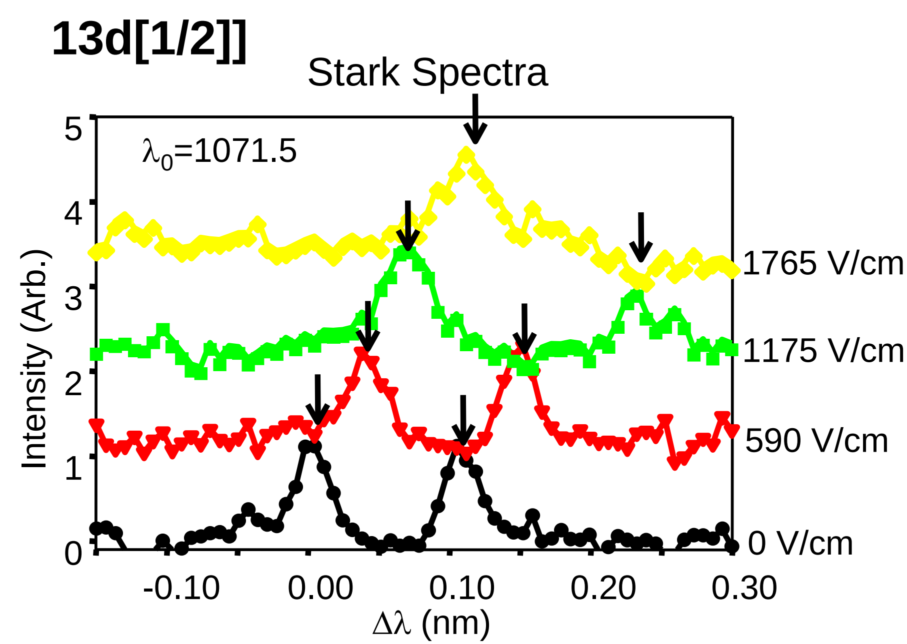
LIF-dip technique detects Stark-shifted states of probed atoms

- Fluorescence dip spectroscopy is a two laser technique
  - Probe Stark-shifted Rydberg states
- Transition to the Rydberg level is monitored by a “dip” in the fluorescence from the intermediate state





Electric field sensitivity is determined by Rydberg level probed

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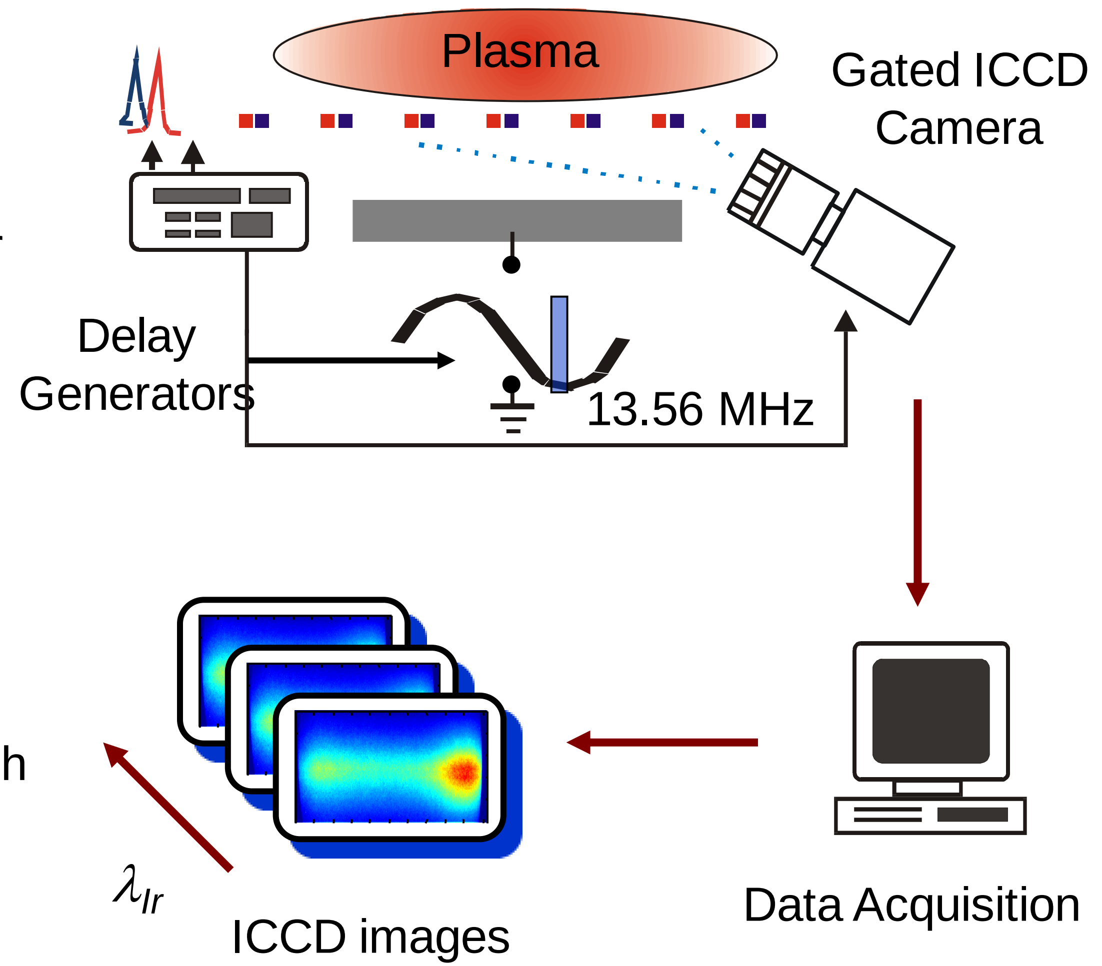
Typical 2D LCIF-dip experimental arrangement

- Firing of lasers synched to rf phase.
  - 13 MHz rf, 20 Hz lasers
  - Time resolved rf voltages
- Gate ICCD after firing of the lasers
  - 2D snapshot of LIF
  - Accumulate for ~ 100's of laser shots
- Repeat as probe laser is incrementally stepped
  - Typically 30 discrete steps
- Post process to determine electric fields
  - Plot LIF vs. wavelength for each pixel
  - Assign electric field, create 2D map



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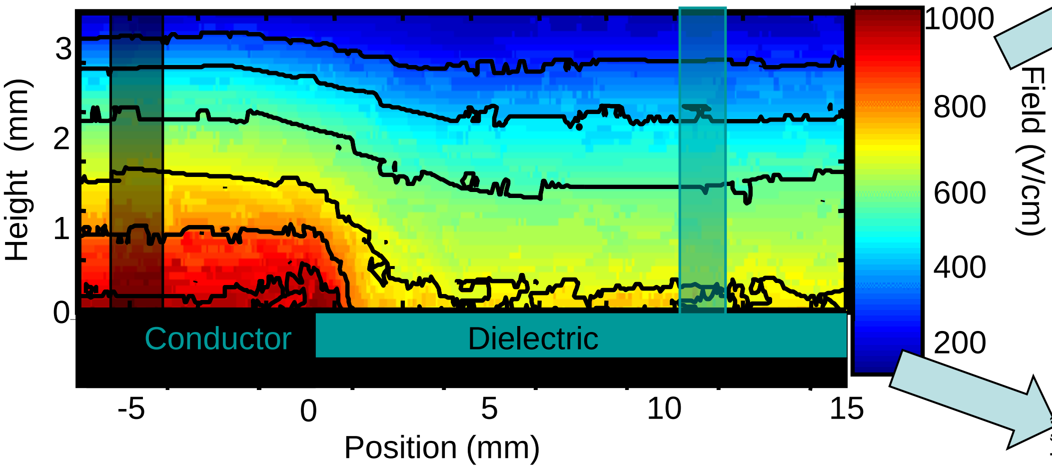
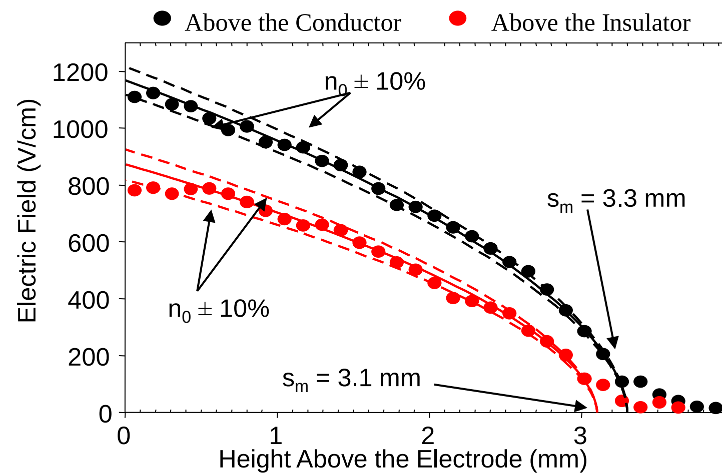
LIF-Dip technique has been used to study boundaries in rf plasma systems

- Representative “toy” problem that looks at “edge effects”
  - Non-uniformities in fields, and energy

Spatial distribution of electric fields

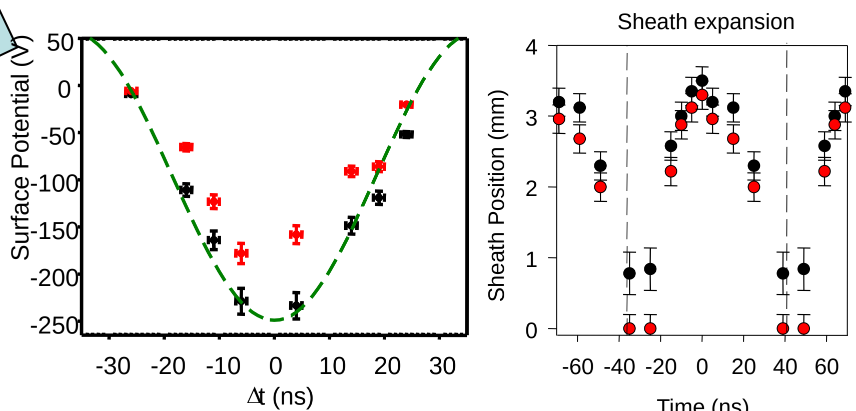


Spatial structure of the sheath



[1] M. A. Lieberman, IEEE Trans. Plasma Sci. V17, 338 (1989)

Temporal evolution of the sheath



This technique is not utilized in arc studies…..

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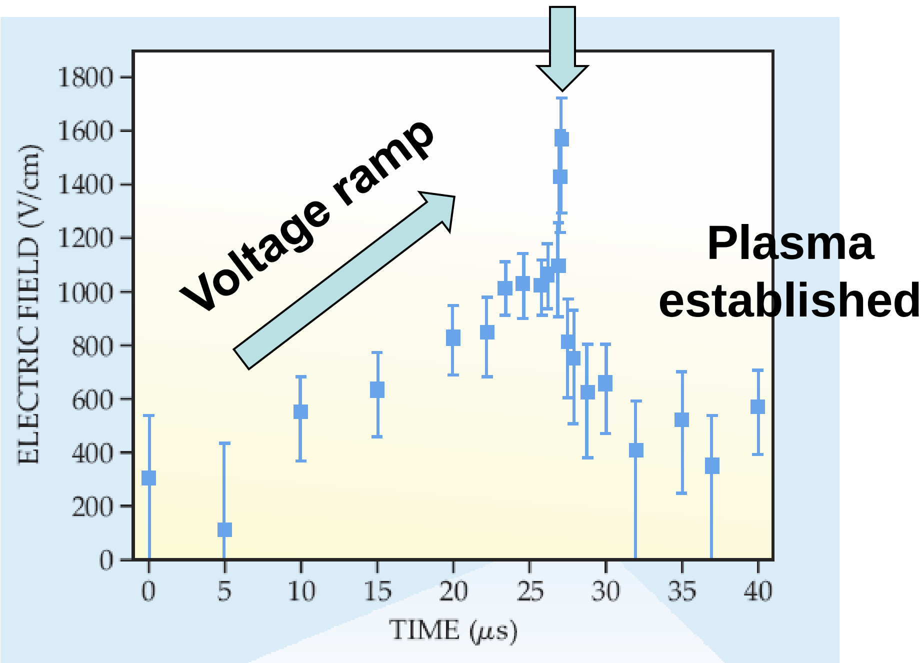
LIF-Dip spectroscopy has been utilized to measure plasma formation between gap

- Eindhoven studies captured the cover of Physics Today (May, 2007)
  - Gerrit Krosen, Erik Wagenaars and Mark Bowden
- Utilized two-photon absorption from Xe ground state
  - Pre-plasma formation

Plasma formation



Physics Today, 60(5) May 2007, page 19

Could this idea be applied to a (vacuum) arc breakdown?

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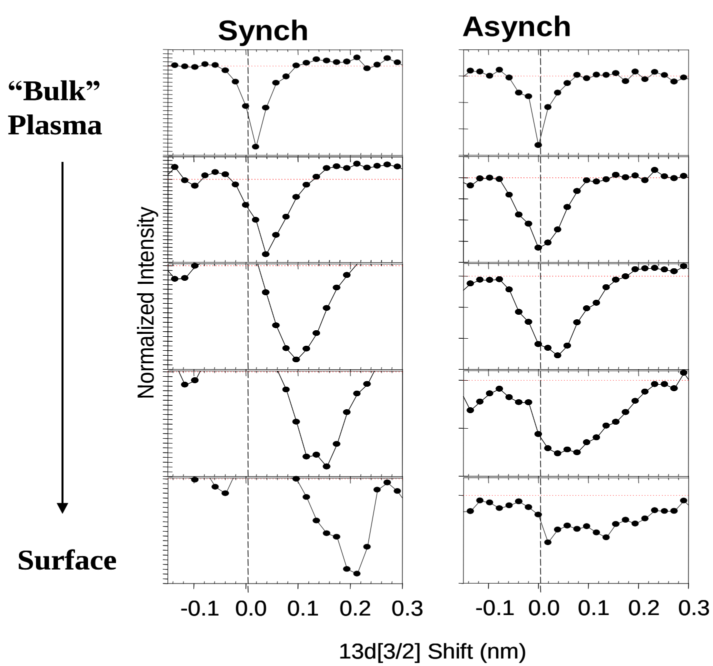
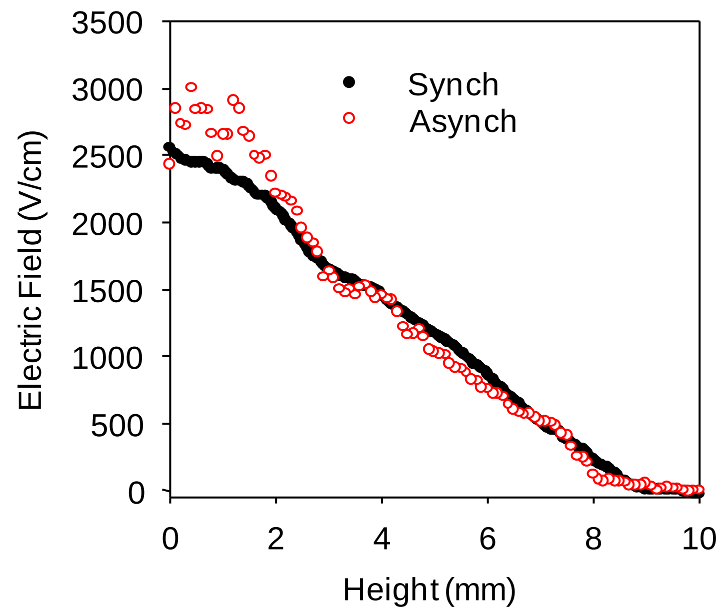
For fast phenomenon, time-resolved (field) measurements becomes challenging

- (at least) Two key challenges need to be overcome
  - Stuff to excite from and resolution of fast phenomena
- Similar to earlier studies on high frequency (>100 MHz) rf plasmas
  - Free run rf, no phase reference
  - Measure total broadened LIF-dip profile

Test technique: 13.56 MHz





There may be ways to side-step limitations to extract useful information

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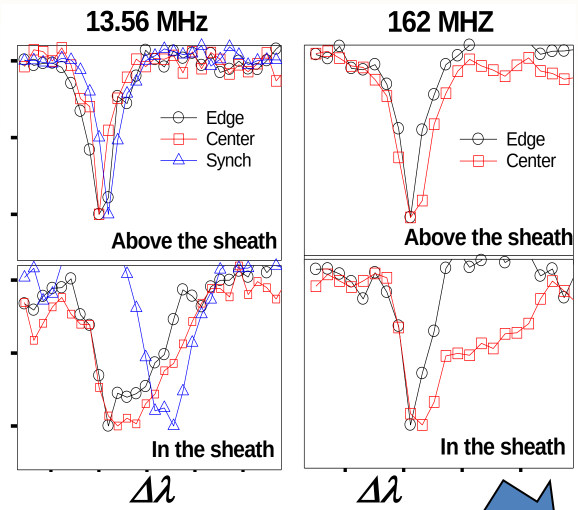
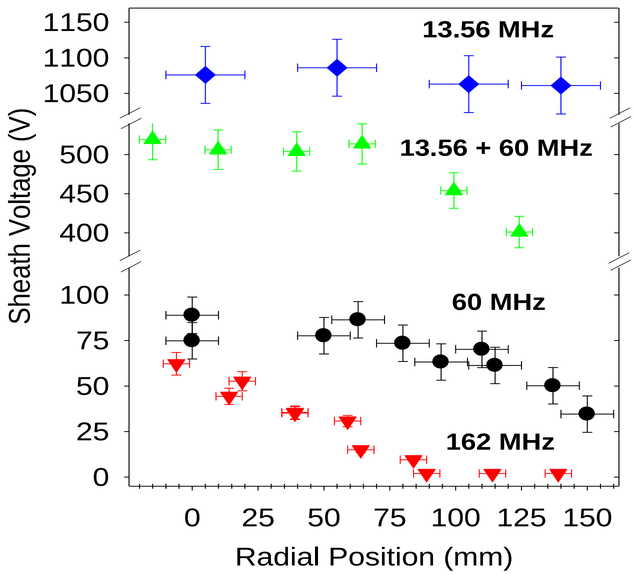
Proof of principle demonstrated in high frequency plasma reactor

LIF-dip profiles

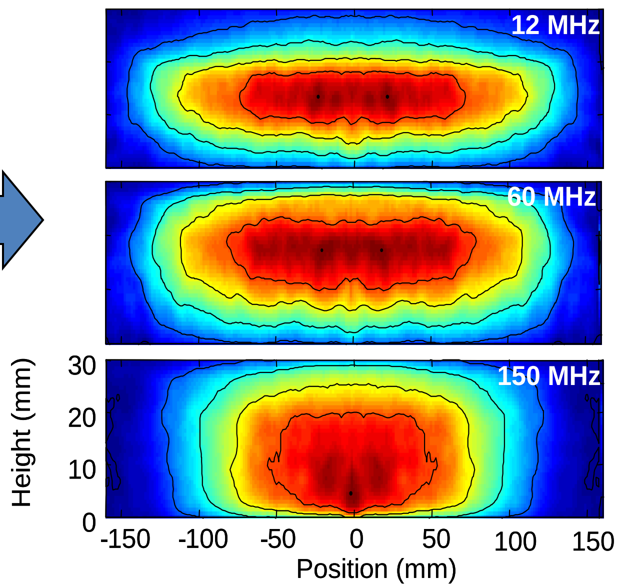


- **Apply technique to plasma generated at higher frequencies**
  - **Measure across wafer, determine peak fields**
  - **Integrate fields, calculate sheath voltage**

Peak sheath voltages



Plasma induced emission



May be able to determine bounds on transient phenomena using approaches like this

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Concluding thoughts and future directions

- The arc represents a challenging environment to both experimentalist as well as modelers
  - Spatial scales, temporal scales and gradients all add to these challenges
  - Randomness, stochastic nature of these devices add additional challenge

- “Plasmas or arcs are like children, no two are alike”
  - Clearly application governs ones concerns
  - It is important to look for similarities to gain understanding

- “New” approaches and clever uses of “older” approaches need to be employed to gain access to these phenomena
  - Keep looking for that clever idea that might be useful for addressing some of these questions

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