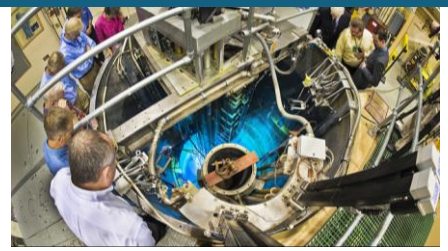
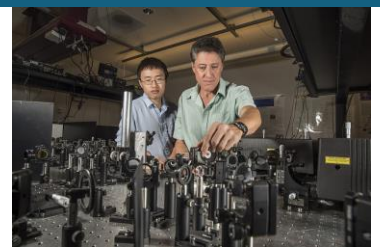
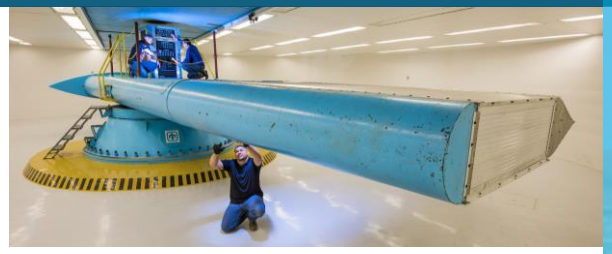
SAND2021-12256C

Sandia National Laboratories

Single-shot 2-D electron density measurement in a cathodic arc using laser-collision induced fluorescence data







Brian Z. Bentz, Kevin W. Hoyt, Daniel J. Scoglietti, and Edward V. Barnat

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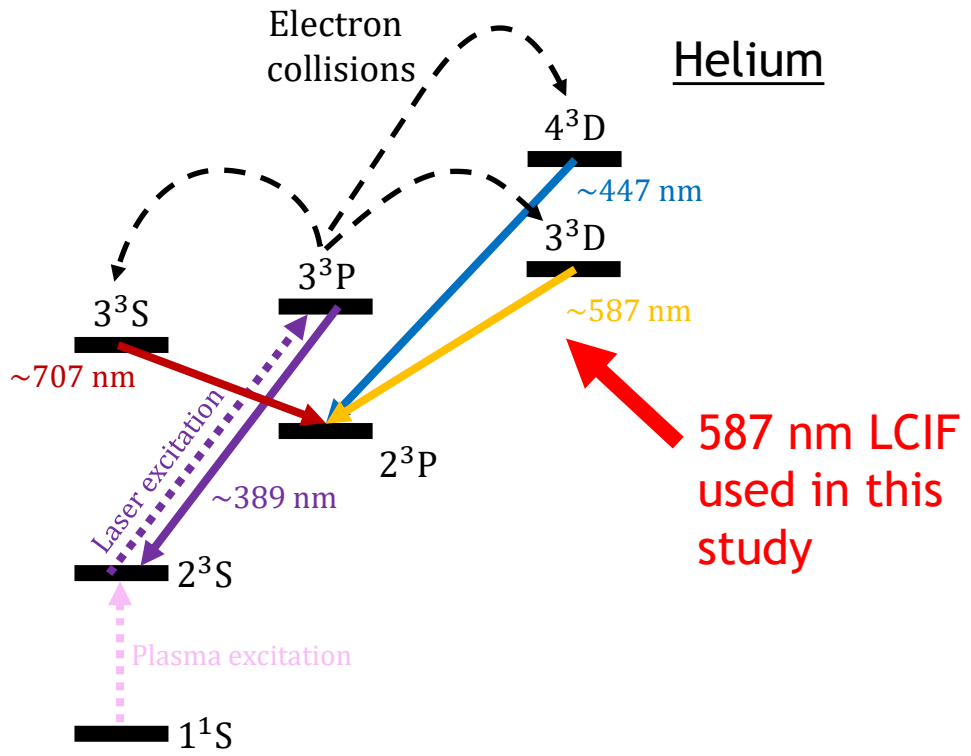
Laser-Collision Induced Fluorescence (LCIF)

- **Knowledge gap**: Understanding shot-to-shot variations in electron density (n_e) in cathodic arcs requires single-shot measurements
  - Ion source plasma repeatability is important for ion beam design
- LCIF diagnostic is non-invasive and can spatially resolve n_e [1,2]
  - Light emission depends on electron collisions
  - Helium acts as probing species
- Fast framing camera allows single-shot acquisition
  - Plasma emission and LCIF acquired in a single-shot
  - LCIF signal must be maximized
  - New model based interpretation required



[1] E. V. Barnat and K. Frederickson, *Plasma Sources Science and Technology* **19**(5), 055015 (2010)
[2] B. Scheiner, E. V. Barnat, S. D. Baalrud, M. M. Hopkins, and B. T. Yee, *Physics of Plasmas* **25**, (2018)

Collisional-Radiative Model (CRM)

Electronic Processes | Photonic Processes | Atomic Processes

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

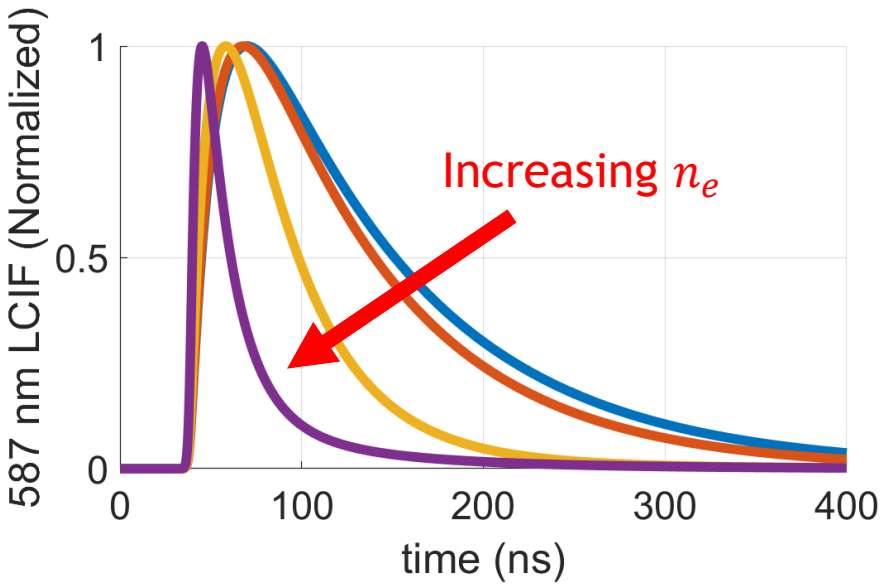
- N_x is the density of an atomic state, where $x = i, j, k$
- n_e is the electron density (e/cm^3)
- $K_{xy}^{a,e}$ is an atomic (a) or electron (e) mediated transition rate (cm^3/s)
- A_{xy} is the spontaneous emission rate (1/s)
- Three body interactions assumed negligible
- Assume atomic collisions are primarily with ground state
- Photons emitted $\sim A_{xy} \times N_x$

[1] E. V. Barnat and K. Frederickson, *Plasma Sources Science and Technology* **19**(5), 055015 (2010)
[2] Y. R. Ralchenko, R. K. Janev, T. Kato, D. V. Fursa, I. Bray, and F. J. De Heer, *Atomic Data and Nuclear Data Tables* **94**(4), 603 (2008)

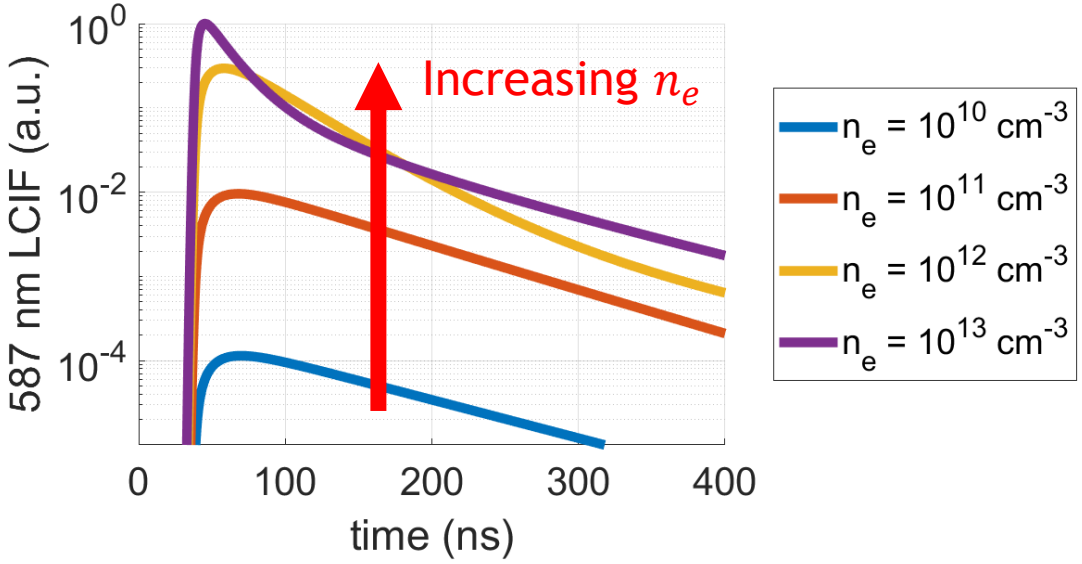
LCIF Temporal Response Calculated by CRM

- 587 nm LCIF lifetime and amplitude depend on n_e
  - Minimal dependence on T_e because 3^3P and 3^3D are close in energy
  - Higher signals when $n_e > 10^{12}$ cm^{-3}

LCIF lifetime decreases with n_e

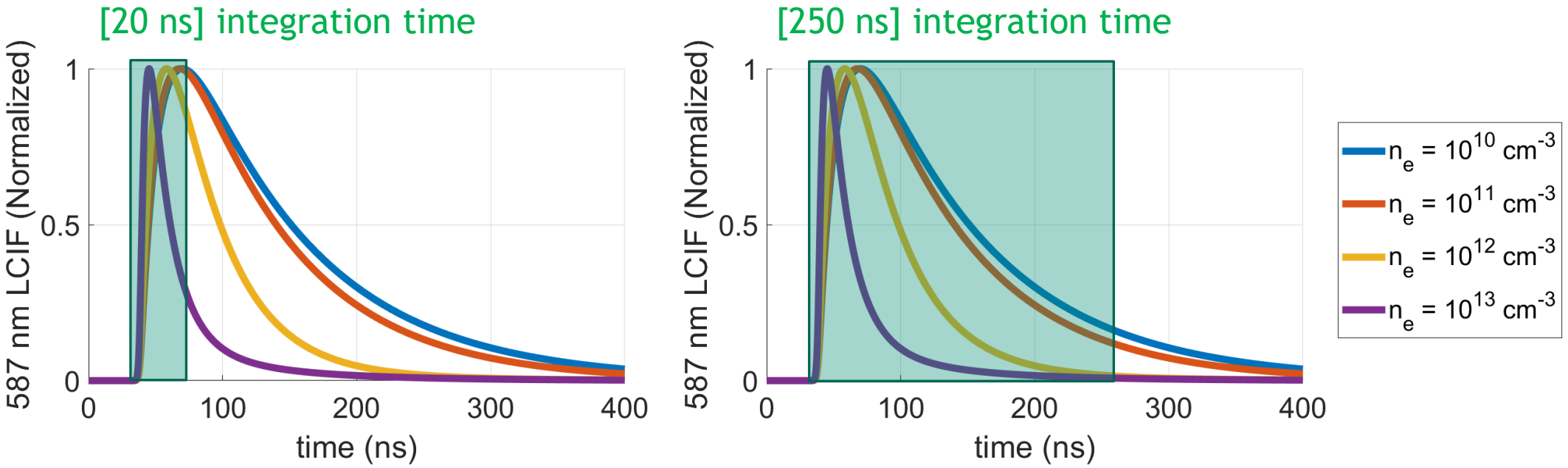


LCIF amplitude increases with n_e



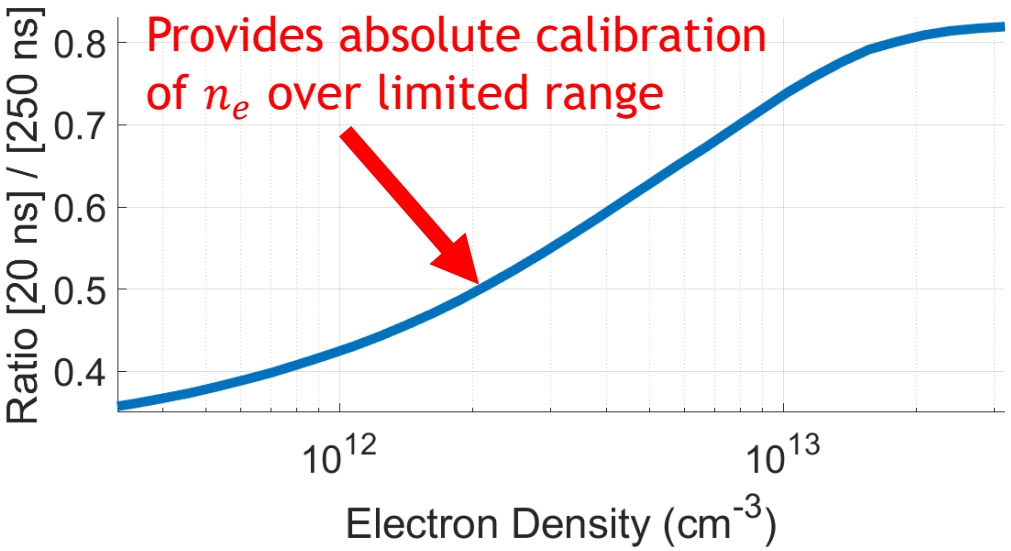
Time-integrated LCIF

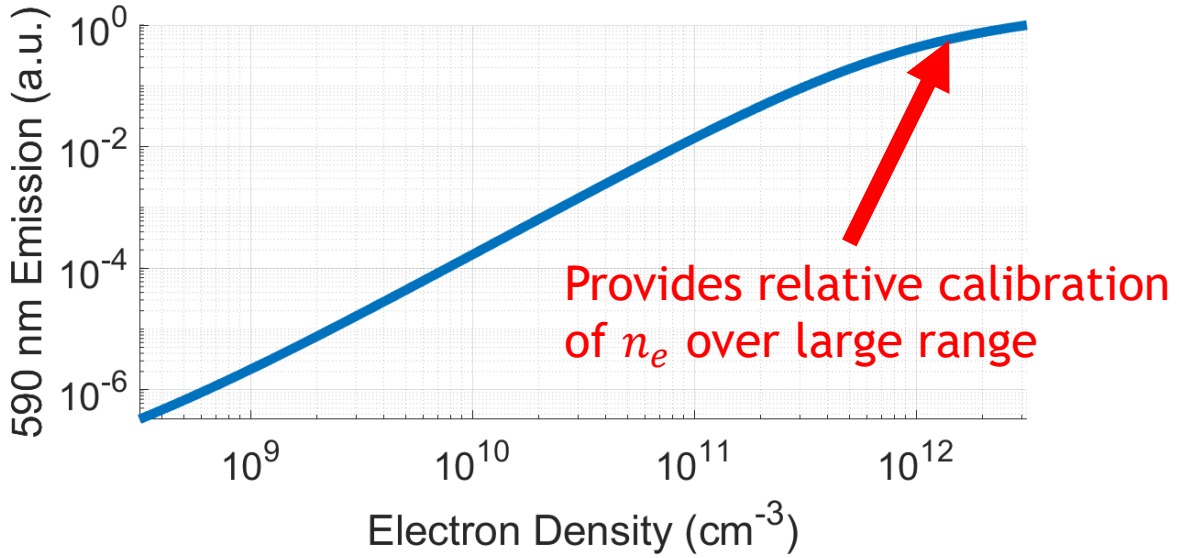
- Photodetectors temporally integrate LCIF emission
  - Higher signals require longer integration times
- Ratio of temporally integrated signals depends on n_e



Time-integrated LCIF

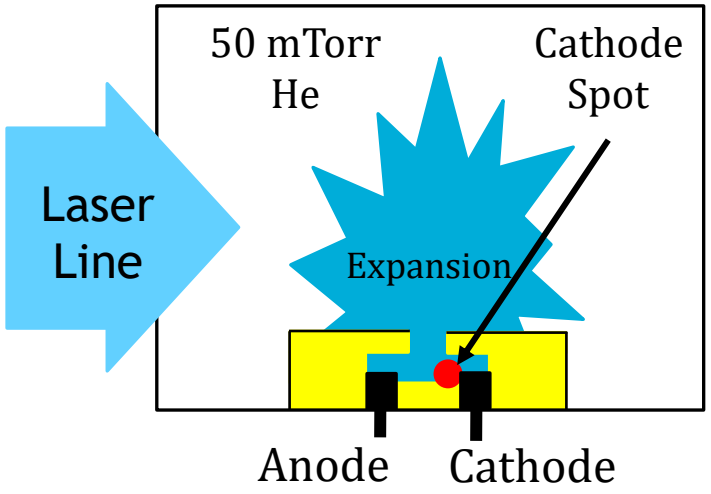
- Ratio of temporally integrated signals depends on n_e
  - Previously, ratios of signals from different species with one time window was used

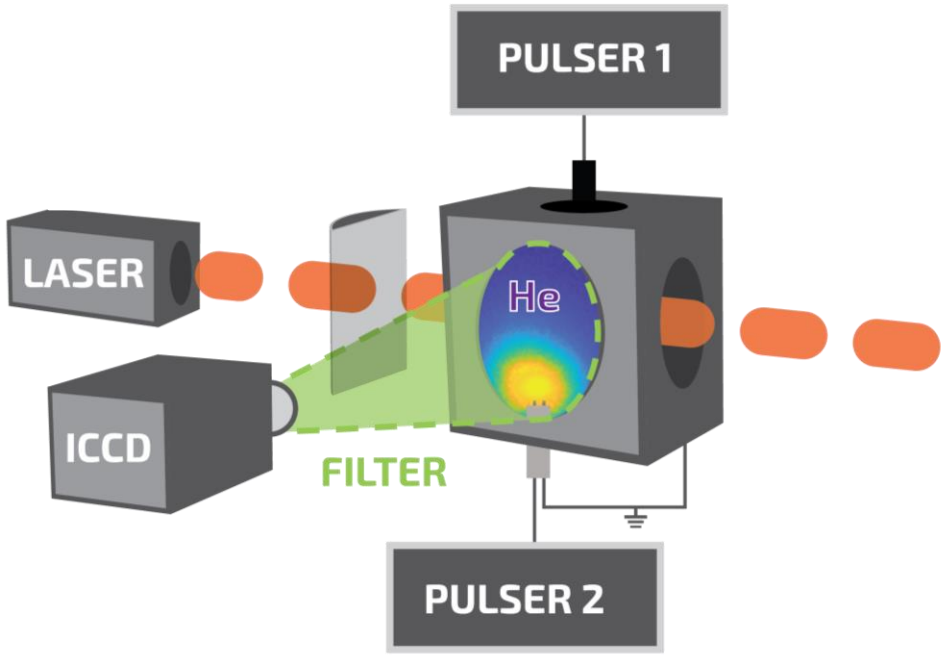




LCIF Experimental Setup to Study Cathode Arc Discharge

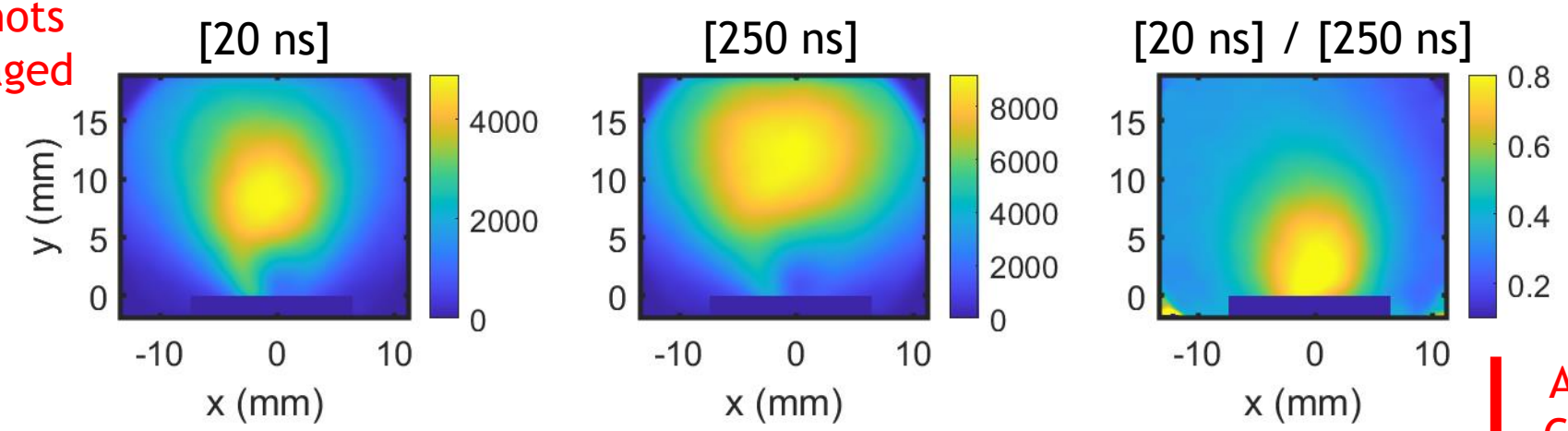
- Cylindrical lens forms light sheet for localized planar excitation
- LCIF temporal response measured by intensified cameras
  - Andor iSTAR (1 frame, 1 FPS): multi-shot acquisition
  - SIMX (8 frames, 1 Billion FPS): single-shot acquisition



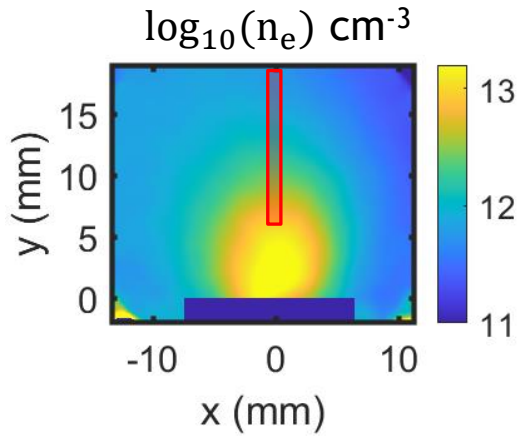


Testing Approach with multi-shot LCIF data (High SNR)

10 shots averaged



Apply CRM Calibration



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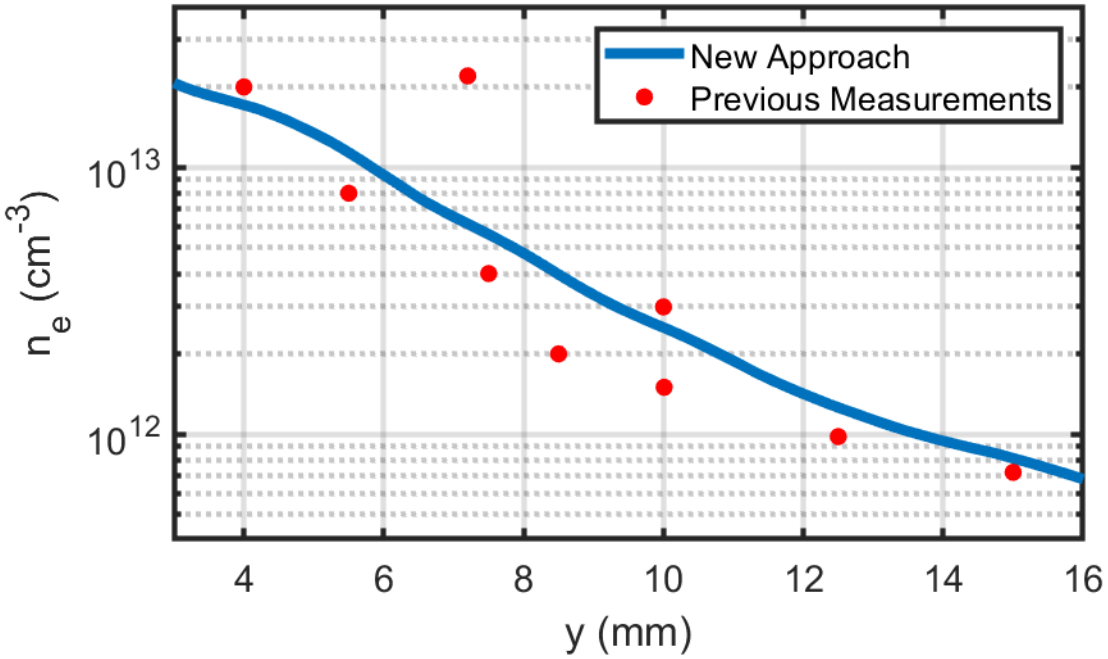
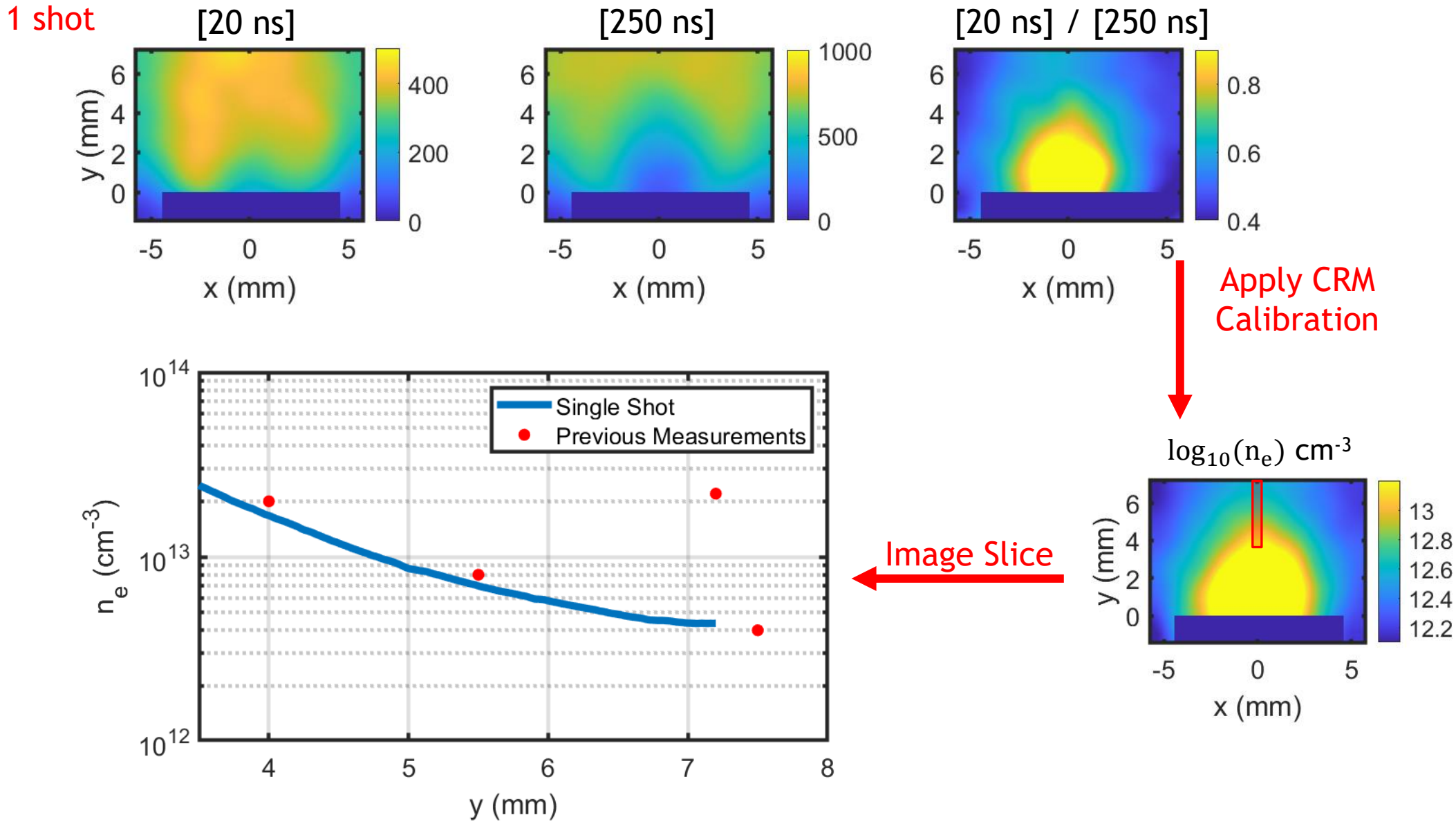
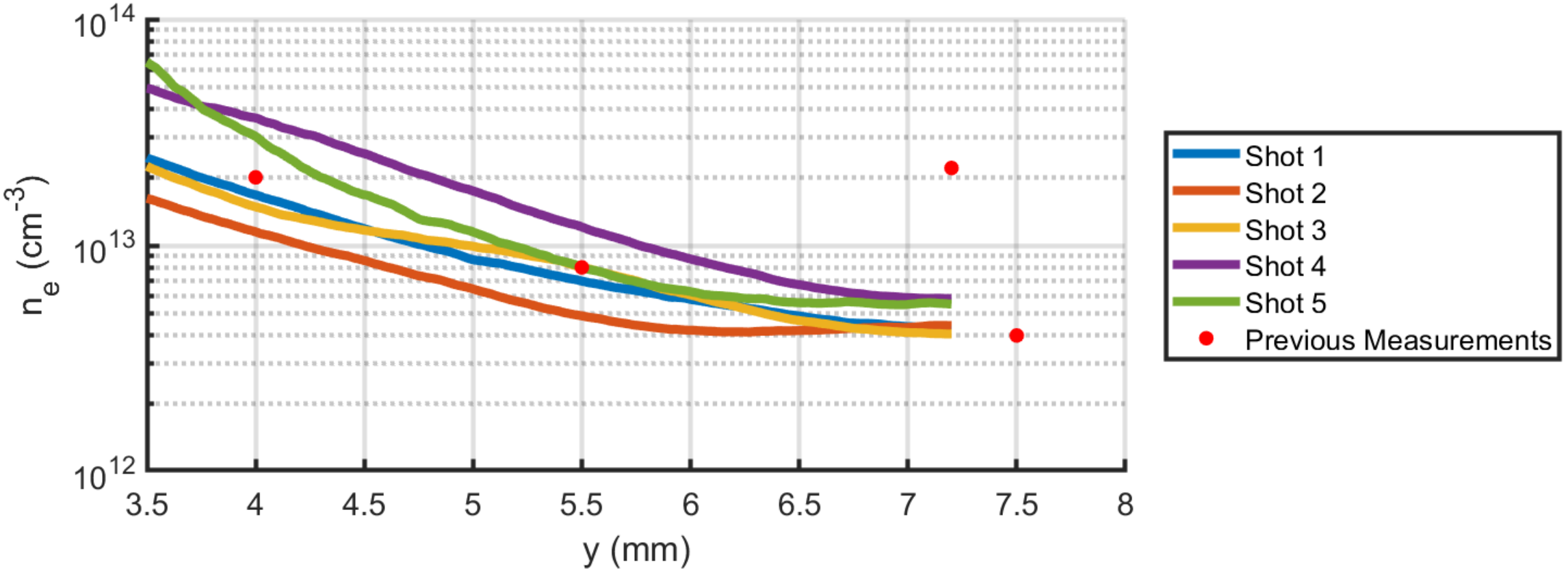


Single-shot LCIF (Low SNR)



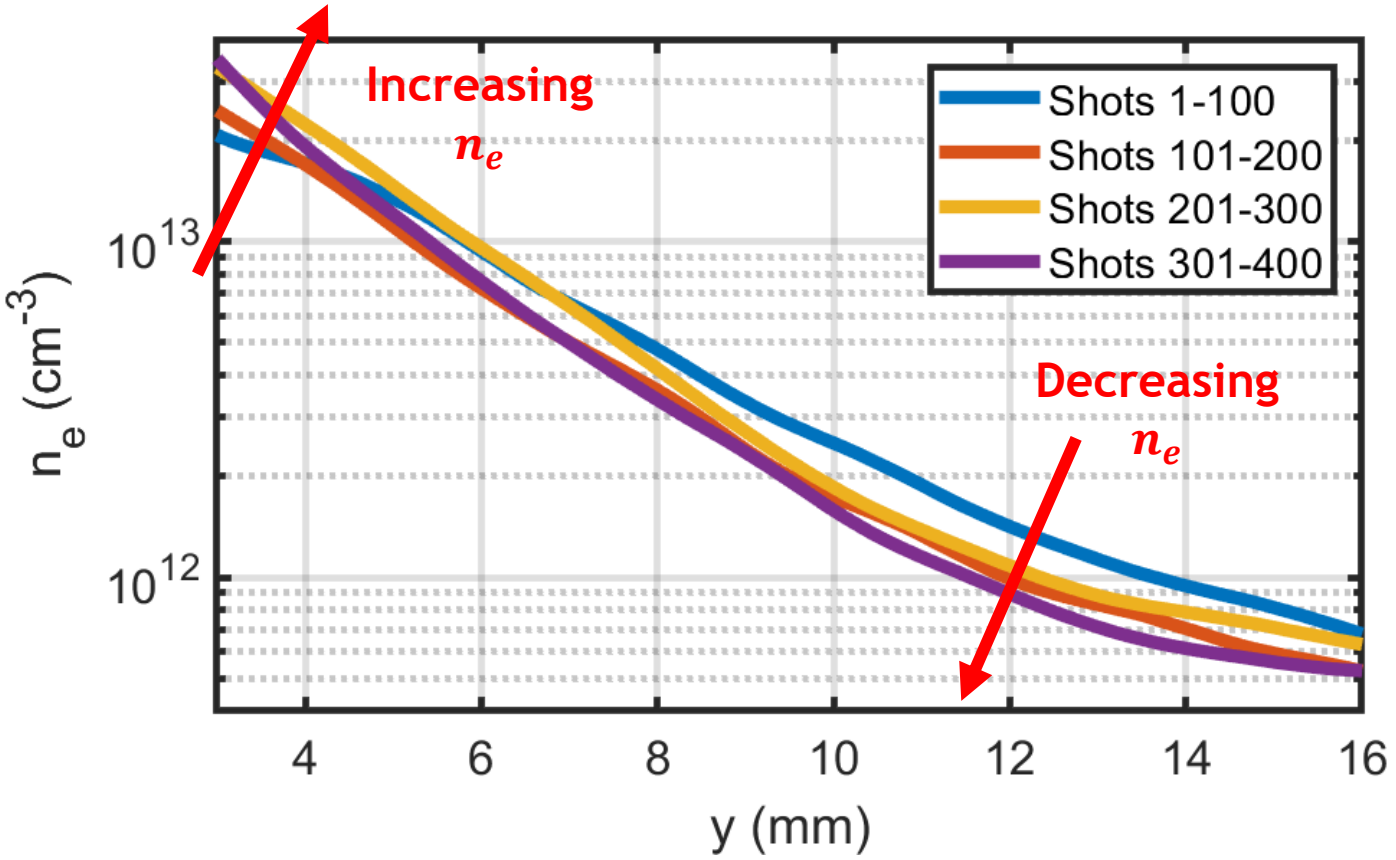
Shot-to-shot Variation

- n_e relative standard error is 31% (averaged over position)



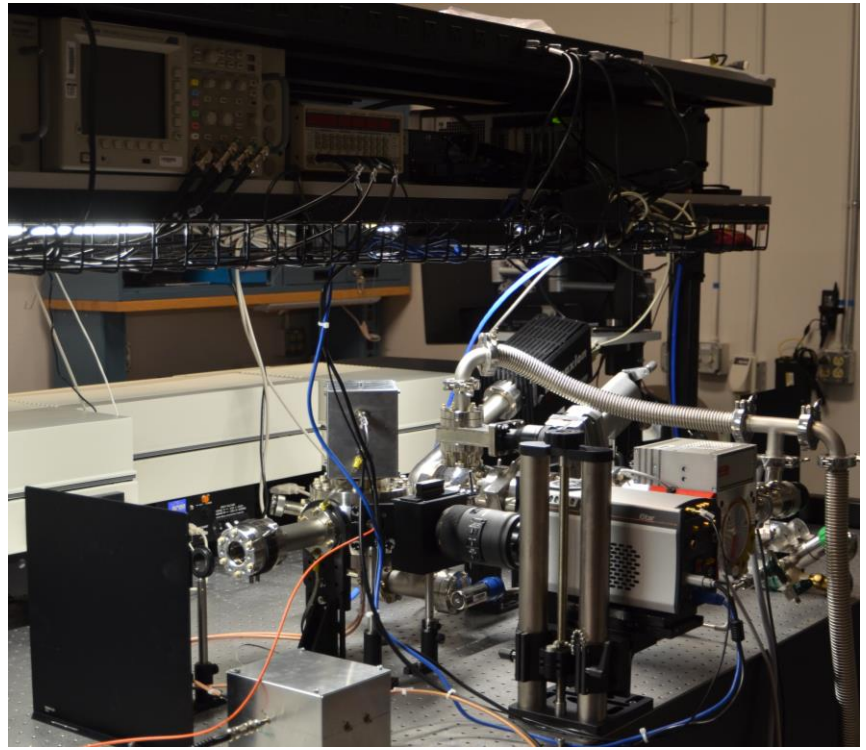
"Conditioning" effect

- A more repeatable operating mode is reached after the first 100 shots
  - Steady-state mean voltage increases ~50%, mean current decreases ~1%
- Suggests surfaces are conditioned or arc plasma constituents are changing



Conclusions

- Time-integrated 587 nm LCIF ratios allow absolute and relative calibration of measured data
- This approach is conducive to single-shot measurements of n_e with a fast framing camera
  - Requires signal maximization
- In the expansion region, n_e varies by ~31% shot to shot
- Conditioning the arc decreases mean n_e in the expansion region



Sandia Low-Temperature Plasma Research Facility (PRF)

- Propose a collaboration at: www.sandia.gov/prf
- Experimental Capabilities:
  - Femtosecond, picosecond, nanosecond and continuous lasers.
    - Diagnostics for measuring various neutral species densities (MBMS, LIF, PF-LIF), electric fields (LIF-Dip, EFISH), electron densities (LCIF), and temperatures (CARS).
  - High speed imaging.
  - Plasma generating capabilities from vacuum to atmospheric pressure.
- Computational Capabilities:
  - Massively parallel electrostatic particle-in-cell direct simulation Monte Carlo (PIC-DSMC).
  - 0D global modeling.
  - Electromagnetic, hybrid, and multiphase modeling capabilities.