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Tomographic Optical Imaging of a Pulsed Atmospheric Pressure Plasma Jet

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Plasma Complex Interfaces

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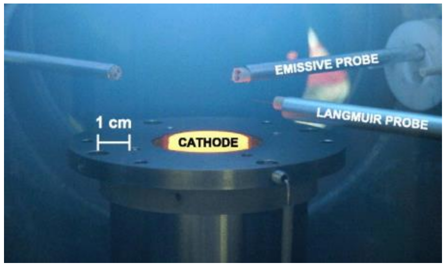
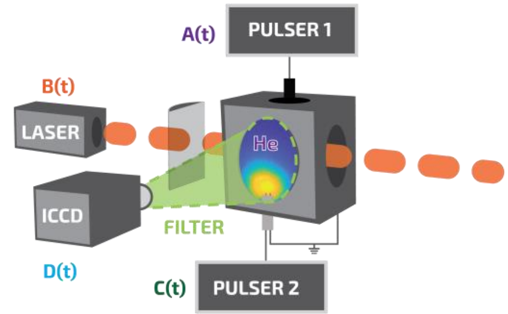
Background and Motivation

- **Widely used plasma diagnostics**



Electrical probe (Intrusive) [1]

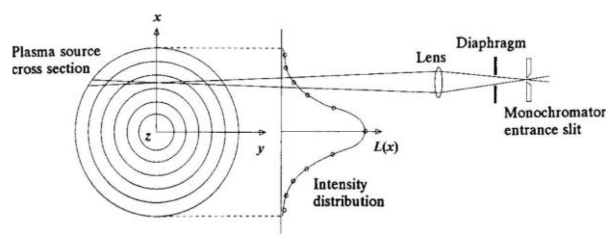


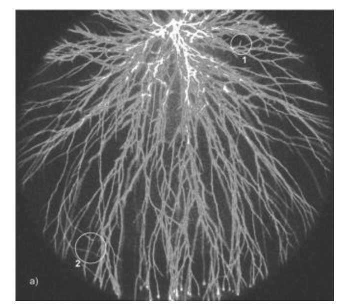
Optical diagnostics (Non-Intrusive)

- **Can observe plasma spatial distribution in 0, 1, or 2-D**
- **Abel inversion transform needed for 3D plasma distribution**

Based on assumption of axisymmetric distribution [2]

Not valid in many cases, especially for plasma with complex shapes [3]

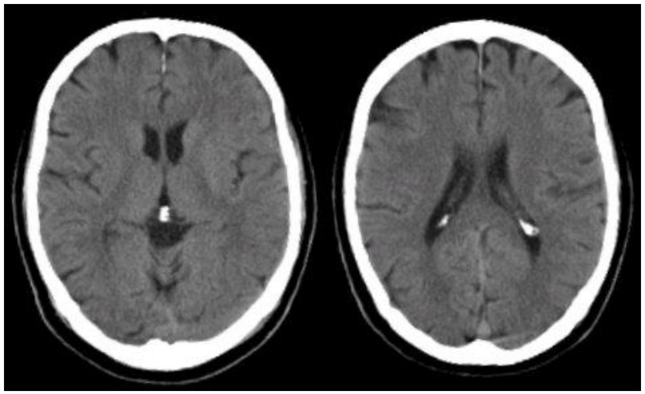




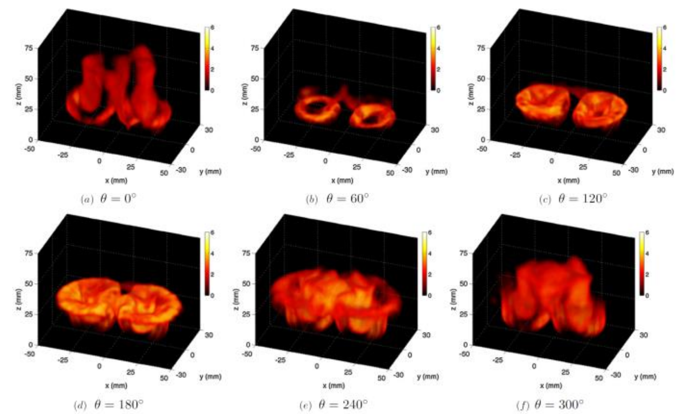
[1] J. P. Sheehan, E. V. Barnat, B. R. Weatherford, I. D. Kaganovich, and N. Hershkowitz, *Plasma Sources Sci. Technol.* **21**(1), 2014.
[2] J. R. Roberts, *J. Res. Natl. Inst.*, **100**(4), 1995.
[3] E. M. Veldhuizen, S. Nijdam, A. Luque, F. Brau, and U. Ebert, *EPJ Appl. Phys.* **47**(2), 2009.

Background and Motivation

- **Tomographic reconstruction**
  - **Recover 3D distribution using information from multiple projections**



Tomography in medicine [1]



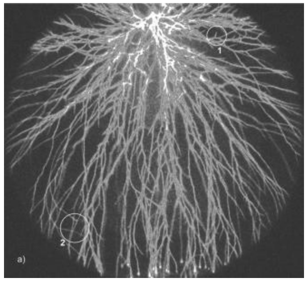
Tomography of turbulent flames [2]

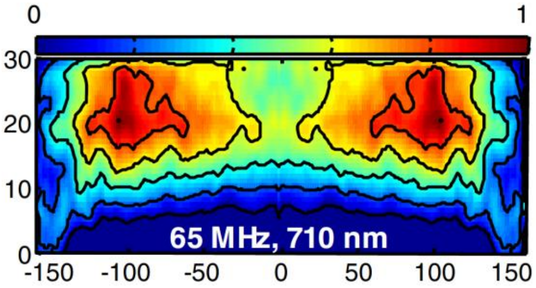
- **Compared with Abel inversion**
  - **Tomography reproduces plasmas without the axisymmetric assumption**
  - **Recovers the actual distribution of plasma with complex shape**

[1] T. M. Buzug, Springer Handbook of Medical Technology, *Springer*, 2011.
[2] N. A. Worth and J. R. Dawson, *Meas. Sci. Technol.* **24**(2), 2012.

Background and Motivation

- **Motivation and long-term goal of this work**
  - **Adapt tomographic capabilities to reveal volumetric information of plasmas with complex shapes**
  - **Surface ionization waves, streamers, anode spots, electromagnetic effects, arcs, cathode spots, etc.**





- **Optical tomography offers a promising avenue**
  - **High 3D spatial and temporal resolution**
  - **Can be combined with optical spectroscopy techniques**
  - **Can be single shot for investigating stochastic systems**

[1] E. M. Veldhuizen, S. Nijdam, A. Luque, F. Brau, and U. Ebert, *EPJ Appl. Phys.* **47**(2), 2009.

[2] R. L. Stenzel, C. Ionita, and R. Schrittwieser, *Plasma Sources Sci. Technol.* **17**(3), 2008.

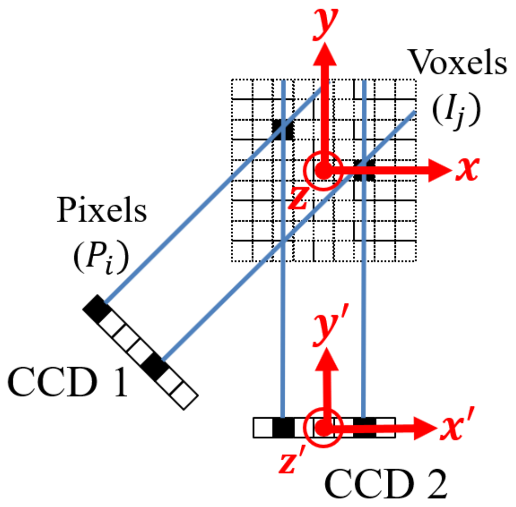
[3] E. V. Barnat, *Plasma Sources Sci. Technol.* **20**(5), 2011.

Optical Tomography Background Theory

- Camera pixels measure spatially integrated light intensity along their line of sight
- Each pixel intensity, P_i, is related to the intensity within a voxel, I_j, by

$$P_i = \sum_j W_{ij} I_j$$

- Where W_{ij} represents the contribution of the jth voxel to the $i$the pixel
- Tomography problem:
    - Estimate all I_j from known P_i and W_{ij}

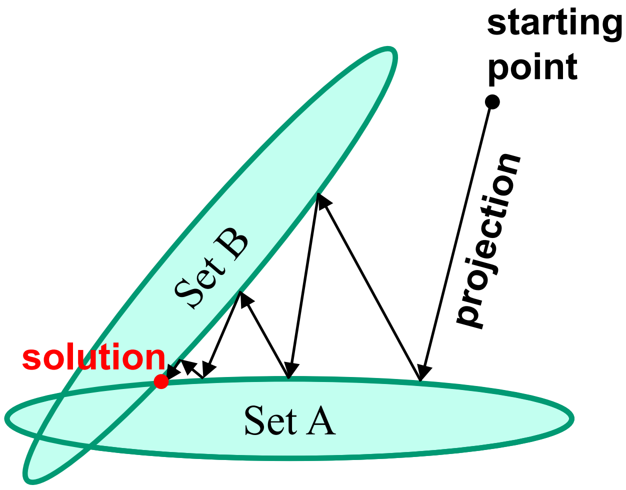


[1] C. Atkinson and J. Soria, *Exp. Fluids* **47**, 2009.

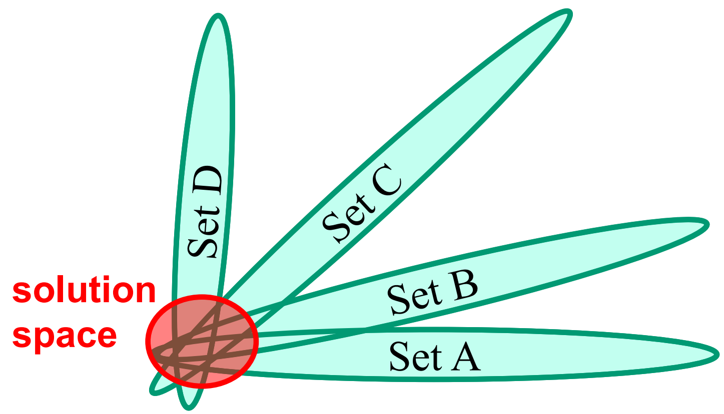
Tomographic Reconstruction Method

- **How do we estimate all I_j?**
- **Algebraic Reconstruction Techniques (ART) rely on projections onto convex sets**
- **At iteration k estimate $\hat{I}_j$ for known P_i and W_{ij}**

$$I_j^{k+1} = I_j^k \left(\frac{P_i}{\sum_j W_{ij} I_j^k} \right)^{\mu W_{ij}}$$



- **For tomography, convergence to a point in the solution space depends on**
  - **Number of pixels (Sets)**
  - **Number of angles/cameras**
  - **Signal-to-noise ratio (SNR)**
  - **Regularization factor (μ)**

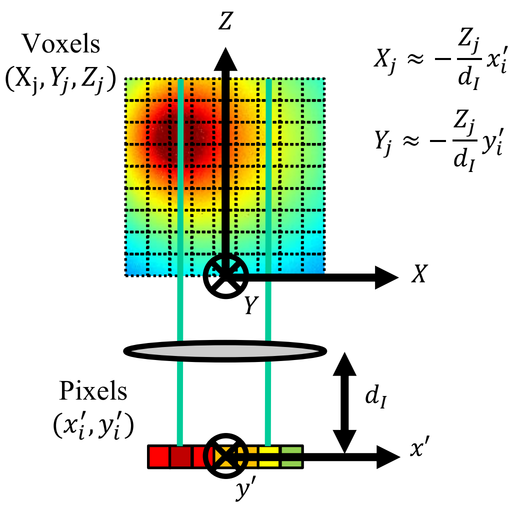


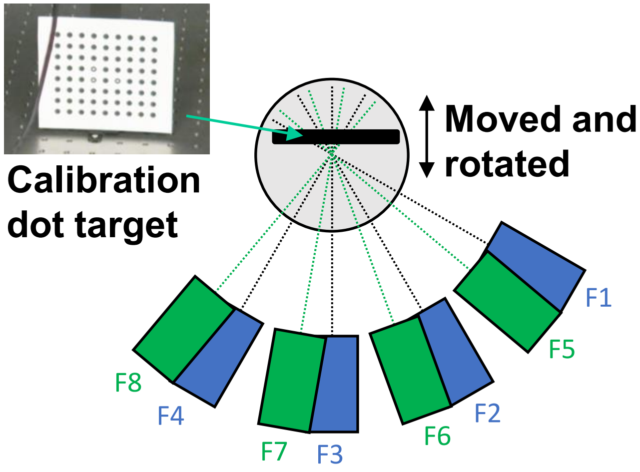
Camera Calibration

- **How do we construct W_{ij}, required for reconstruction?**
  - **Calibration targets provide empirical fit of mapping function F, used to construct W_{ij}**

$$(x_i', y_i') = \boldsymbol{F}(X_j, Y_j, Z_j)$$

- **Pinhole camera model provides functional form of $\boldsymbol{F}$**
- **Bottom line: Each camera is co-registered to the same voxel grid**

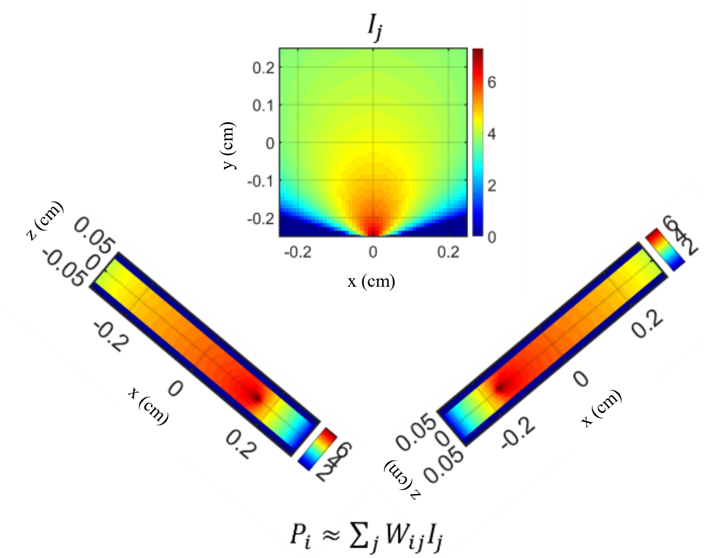




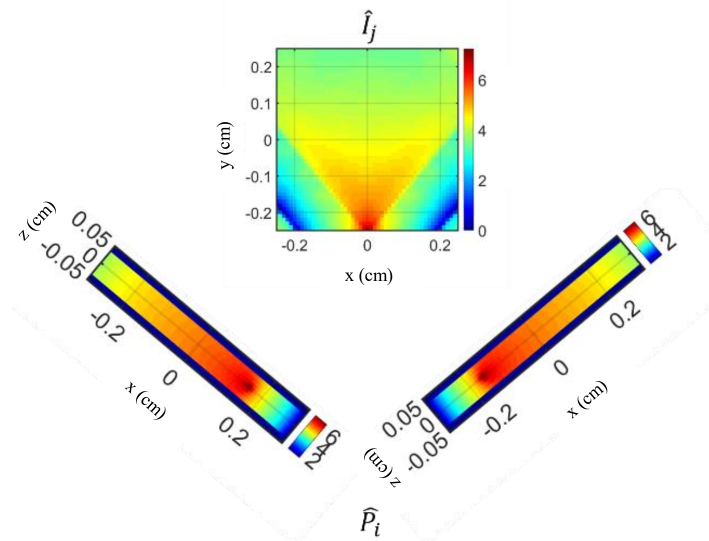
[1] S. M Soloff, R. J. Adrian, and Z-C. Liu, *Meas. Sci. Technol.* **8**(12), 1997.

Simulated Tomographic Reconstructions

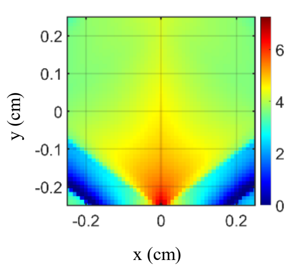
True 3D Test Image Slice



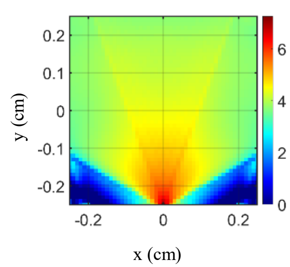
Reconstruction with 2 Angles



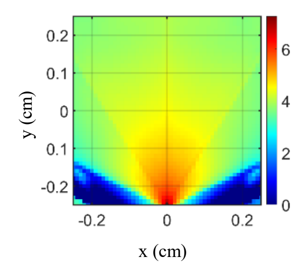
3 Angle Reconstruction



4 Angle Reconstruction



5 Angle Reconstruction

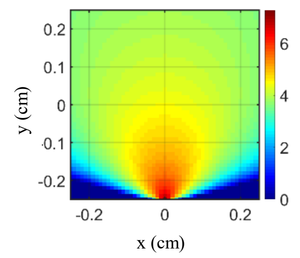


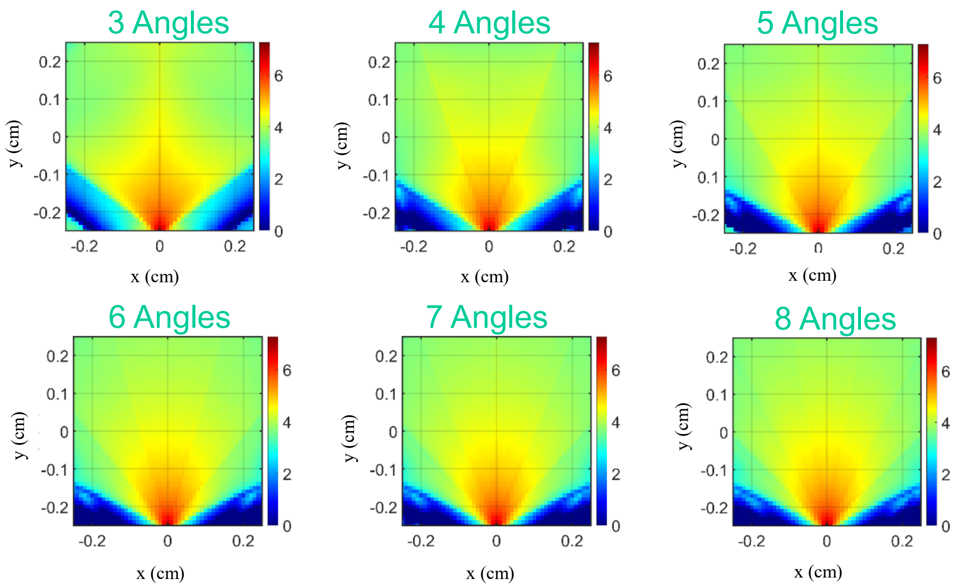
Quality Factors

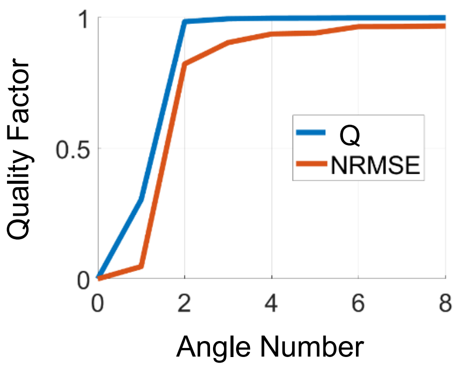
- **How do we evaluate requirements for a "good reconstruction?"**
- **Quality factors allow evaluation of simulated reconstructions**

$$Q = \frac{\sum_j I_j \hat{I}_j}{\sqrt{\sum_j I_j^2 \sum_j \hat{I}_j^{\,2}}} \qquad \mathrm{NRMSE} = 1 - \sqrt{\frac{\sum_j \left(\hat{I}_j - I_j\right)^2}{\sum_j I_j^2}}$$

True 3D Test Image Slice

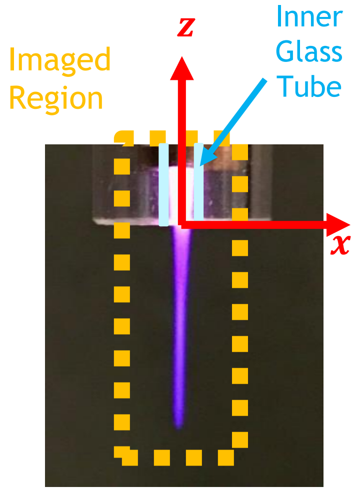






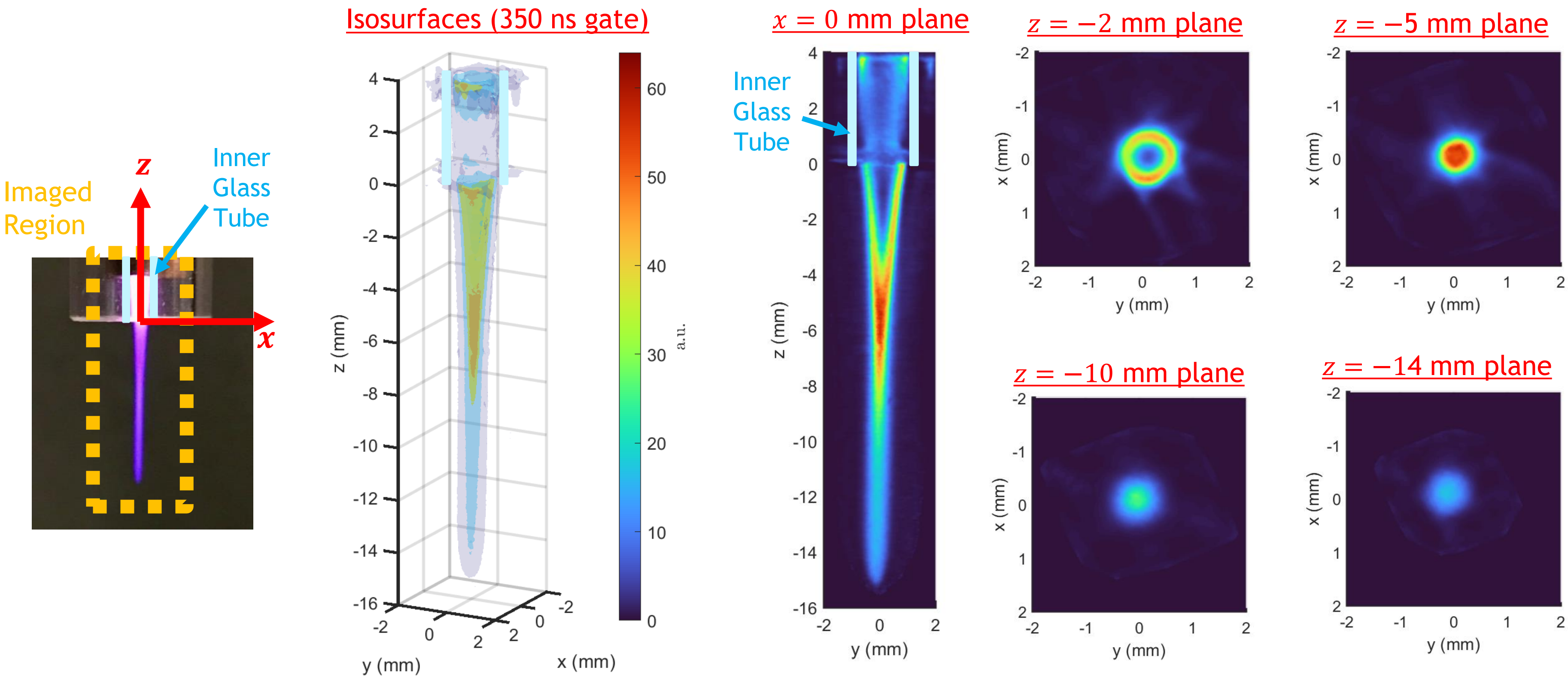
Tomography Experimental Setup

- **PICI Source: cylindrical plasma jet [1]**
  - **1 slm Helium**
  - **Pulsed DC: 4 kV, 10 kHz, 135 ns pulse width**
- **4 intensified cameras and eight viewing angles give 3D and temporal information**
  - **3D spatial resolution is 20 um**
  - **Temporal resolution is 5 ns**
- **Each tomographic reconstruction takes about 1 hour of computational time**

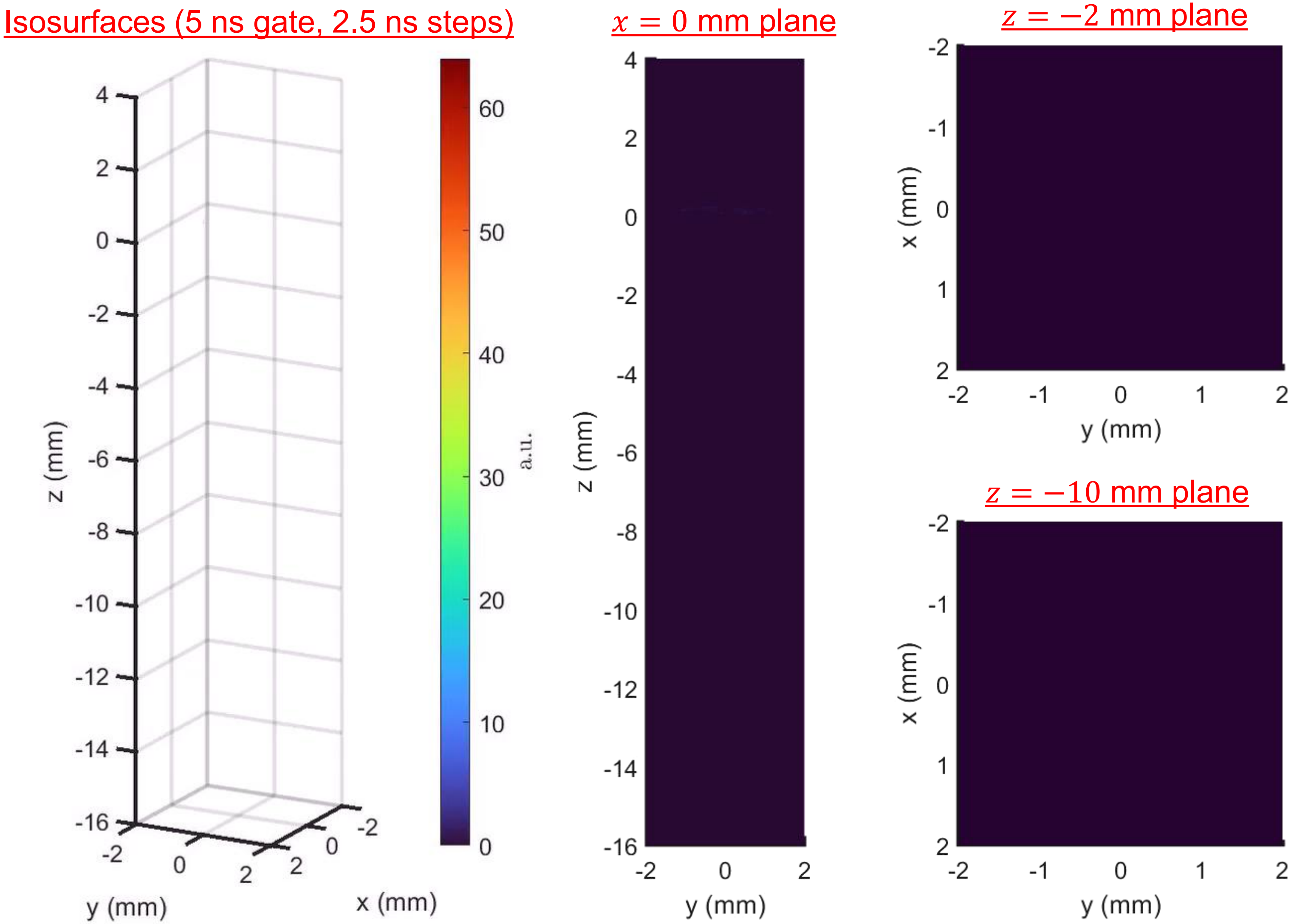


[1] M. Mirzaee, M. S. Simeni, and P. J. Bruggeman, *Phys. Plasmas*, **27**(12), 2020.

APPJ Tomographic Reconstructions



APPJ Tomographic Reconstructions



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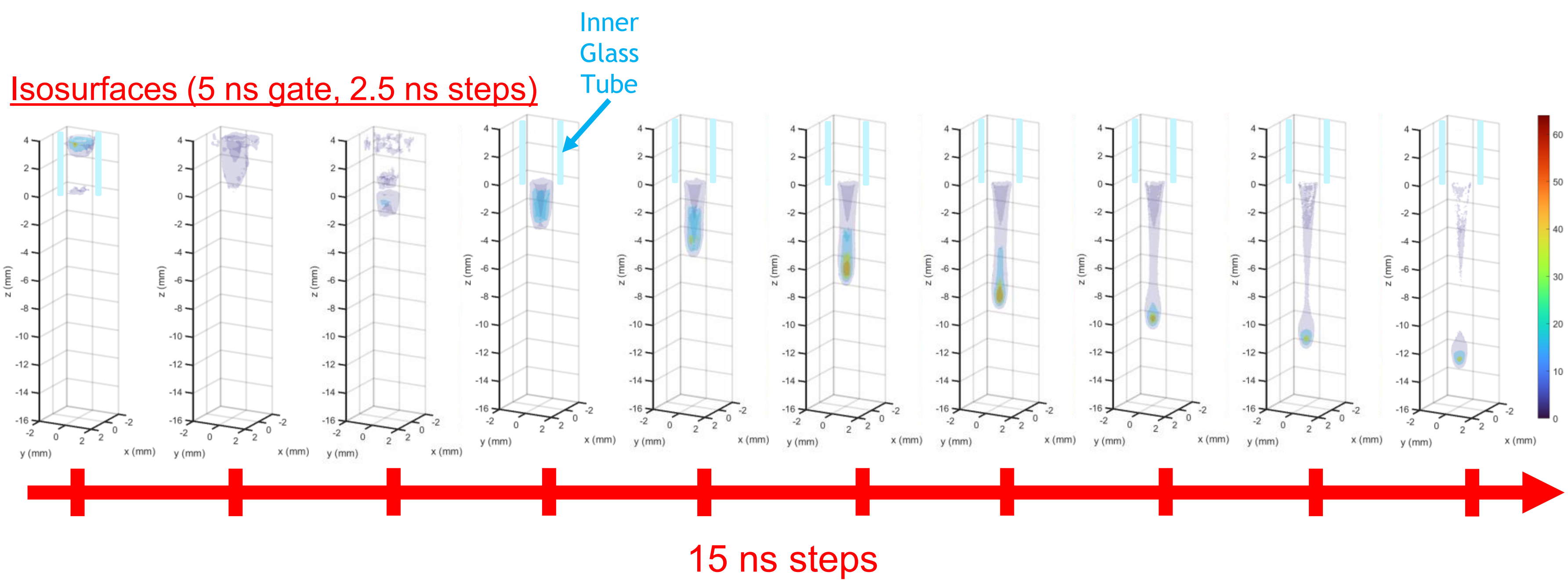
APPJ Tomographic Reconstructions

- **APPJ asymmetries revealed, Abel inversion is not strictly valid**
- **Calibration approach can correct for refraction by glass tube**
  - **Shows volumetric formation of the ionization wave as the surface charges**



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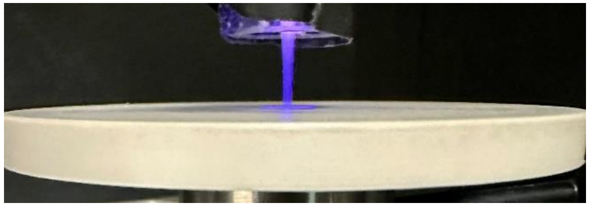
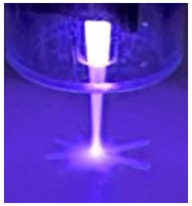
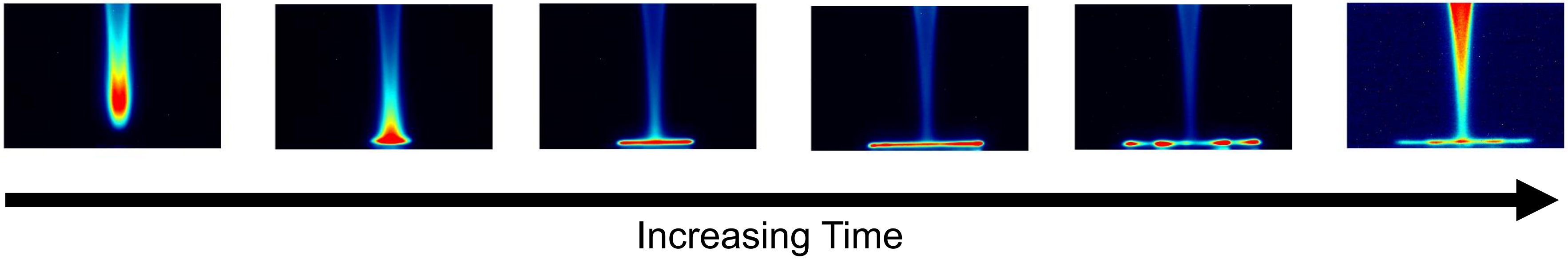
APPJ Incident on PEEK Surface

- Careful optical alignment required to minimize surface reflections in image
- Surface is 5 mm thick PEEK





- Spatial and temporal resolution are sufficient to observe ionization wave propagate across the surface
- Tomographic reconstructions are underway…



Conclusions and Future Work

- **Optical tomography is promising for investigation of volumetric phenomena in plasma systems**
  - **Capability is available to the community through the SPRF**
- **Diagnostic development next steps:**
  - **Improve specificity with bandpass filters and chemiluminescence**
  - **Make quantitative by combining with laser spectroscopy**
- **Scientific investigation next steps:**
  - **Volumetric interactions with complex surfaces**
  - **Electromagnetic effects in high frequency CCP**

Sandia Albuquerque
LTP postdoc position

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