High-Speed Visualization of Spray Breakup and Velocity Estimation in a Rotating Detonation Combustor Using Laser Induced Fluorescence

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Motivation

Motivation:

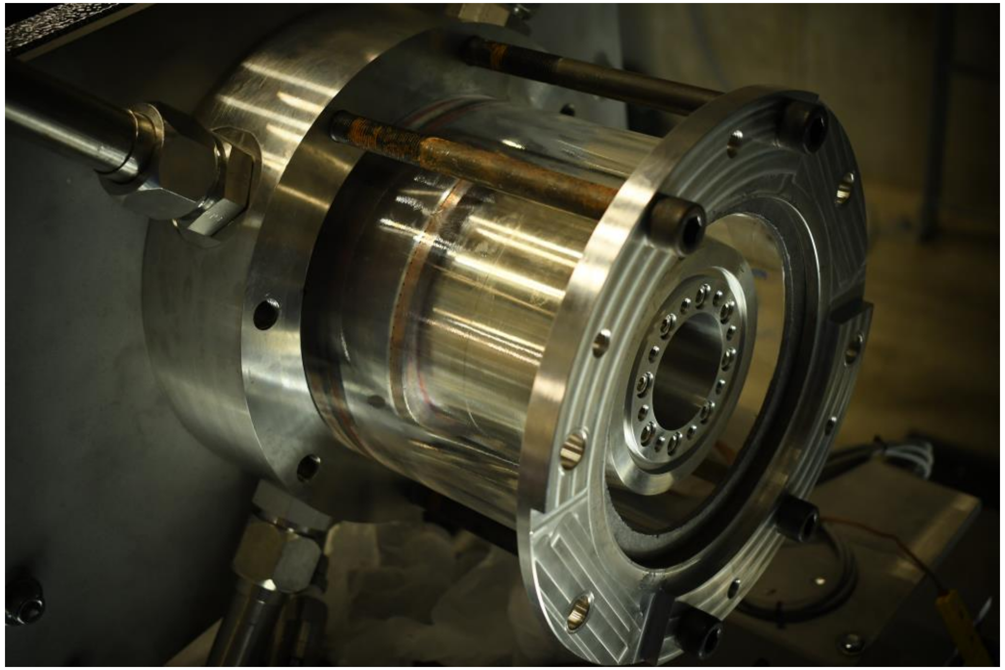
- Potential performance benefits of RDCs highly desired but many open questions remain; particularly for liquid fuel operation
- Quantifiable statistics regarding the recovery and refill process for liquid fuel injectors have not been previously reported
  - What are the driving factors?
  - How can a liquid fuel injector recover and promote sufficient mixing to support detonations in as little as 10s of μs?

Objective:

- Develop a test environment in an RDC where a **single liquid jet** can be studied
- **Directly visualize a liquid fuel spray** to study wave interaction and other dynamics
- Support model validation and generation

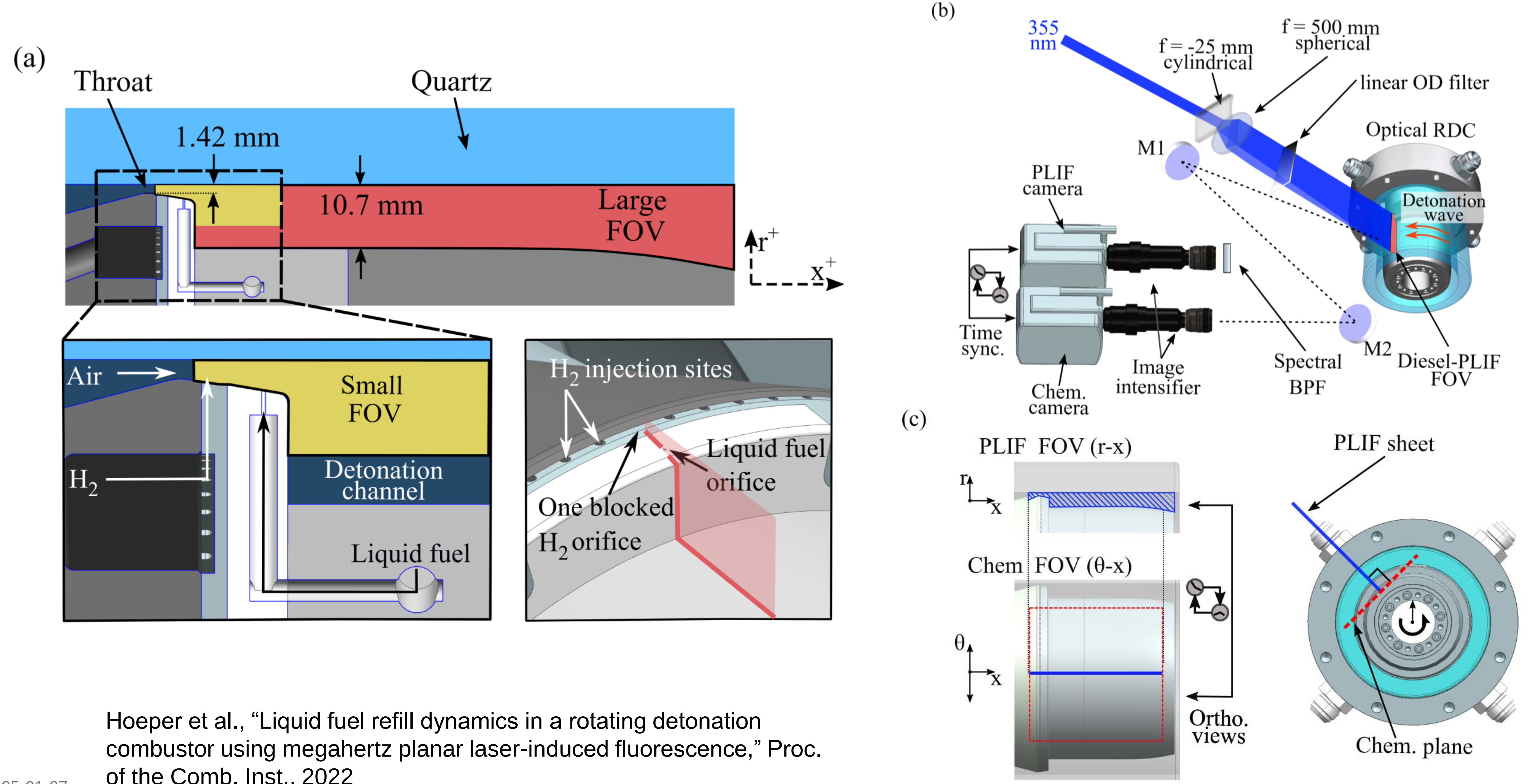
Test Platform Overview

- 125 mm nominal chamber diameter with optical access
- Operates with non-premixed Hydrogen/Air
  - Axial slot air injection
  - 100 hydrogen radial injection sites
- The RDC platform is well studied and characterized for a plethora of operating conditions
  - “Standard” test condition of 0.23 or 0.46 kg/s, $\Phi = 1$, and single wave operating mode at 4 kHz
- For this work, RDC acts as a detonation driver to investigate liquid fuel spray breakup



THOR with optical outer body installed

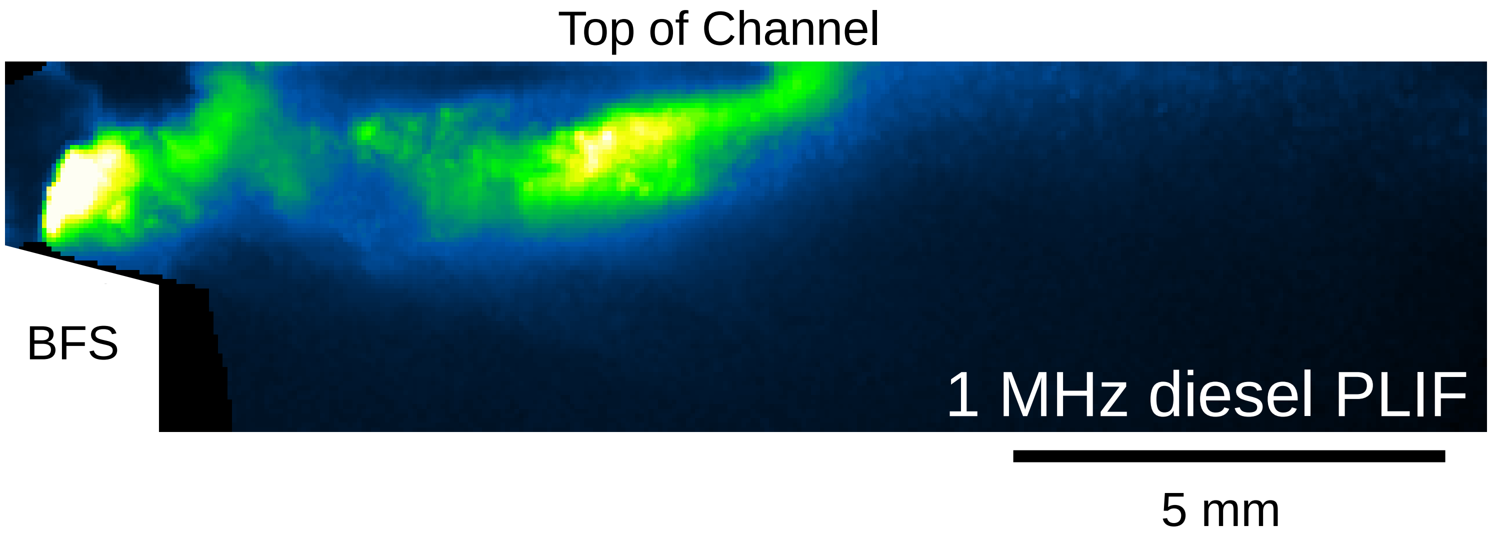
A Look at Prior PLIF Work

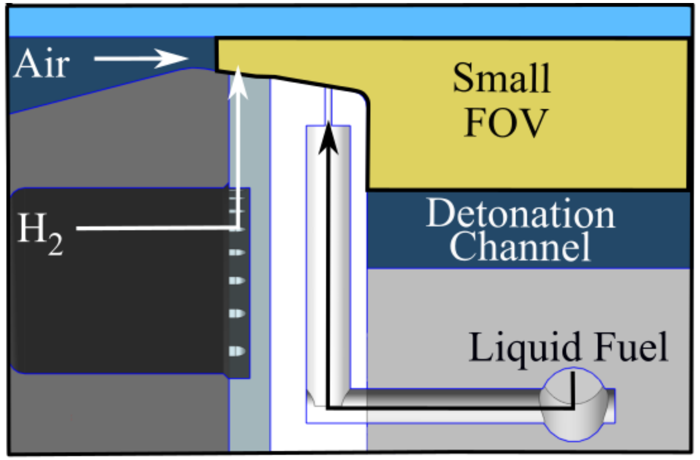


Hoeper et al., "Liquid fuel refill dynamics in a rotating detonation combustor using megahertz planar laser-induced fluorescence," Proc. of the Comb. Inst., 2022

A Look at Prior PLIF Work

- Example 1 MHz diesel PLIF data from previous work
- Imaging scheme is useful for monitoring near-field jet response in a spatio-temporal resolved manner
- Used to construct refill statistics across several conditions
- 430 µJ/pulse of 355 nm, 55 µm/pixel

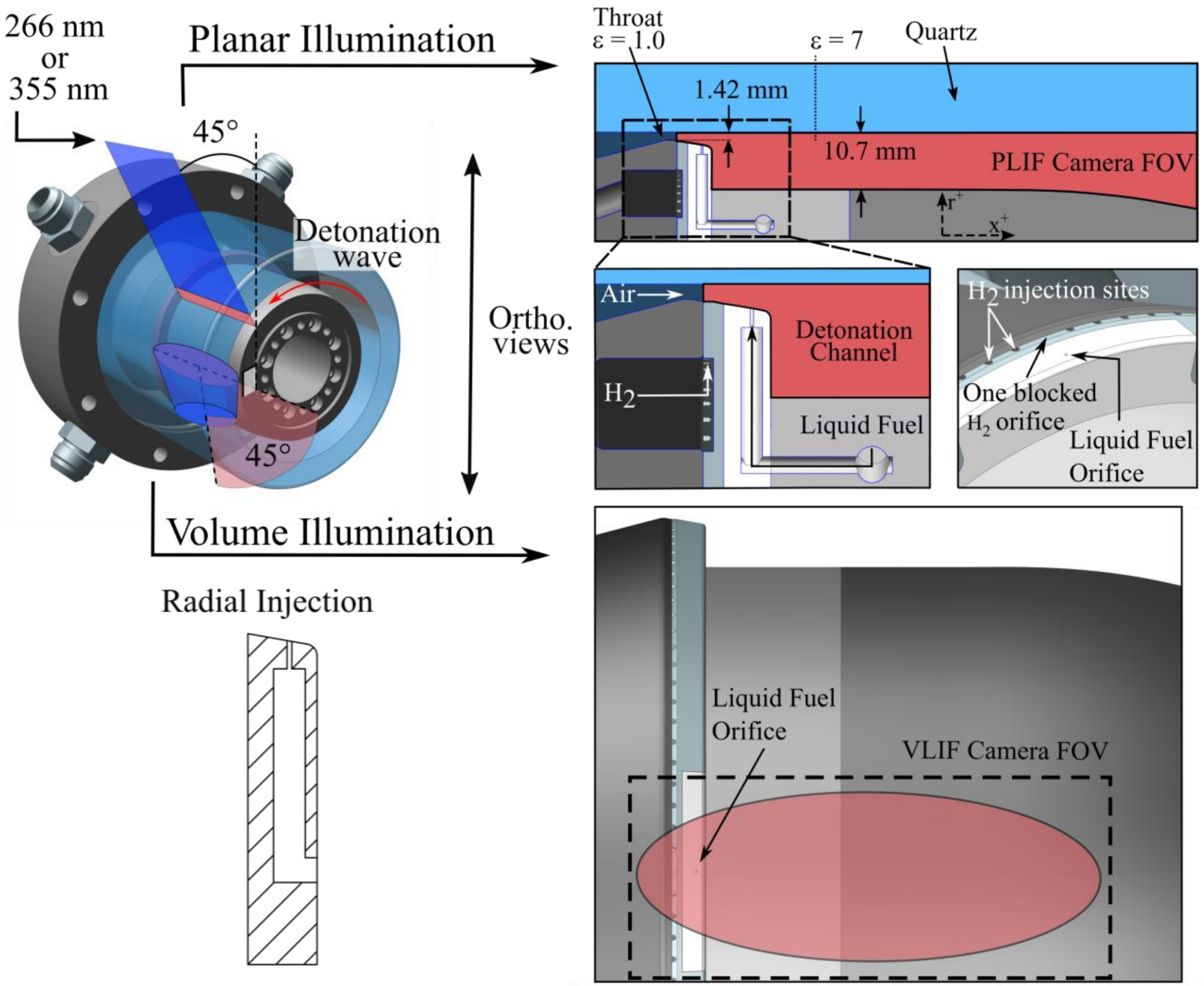




Volume Illumination Scheme (VLIF)

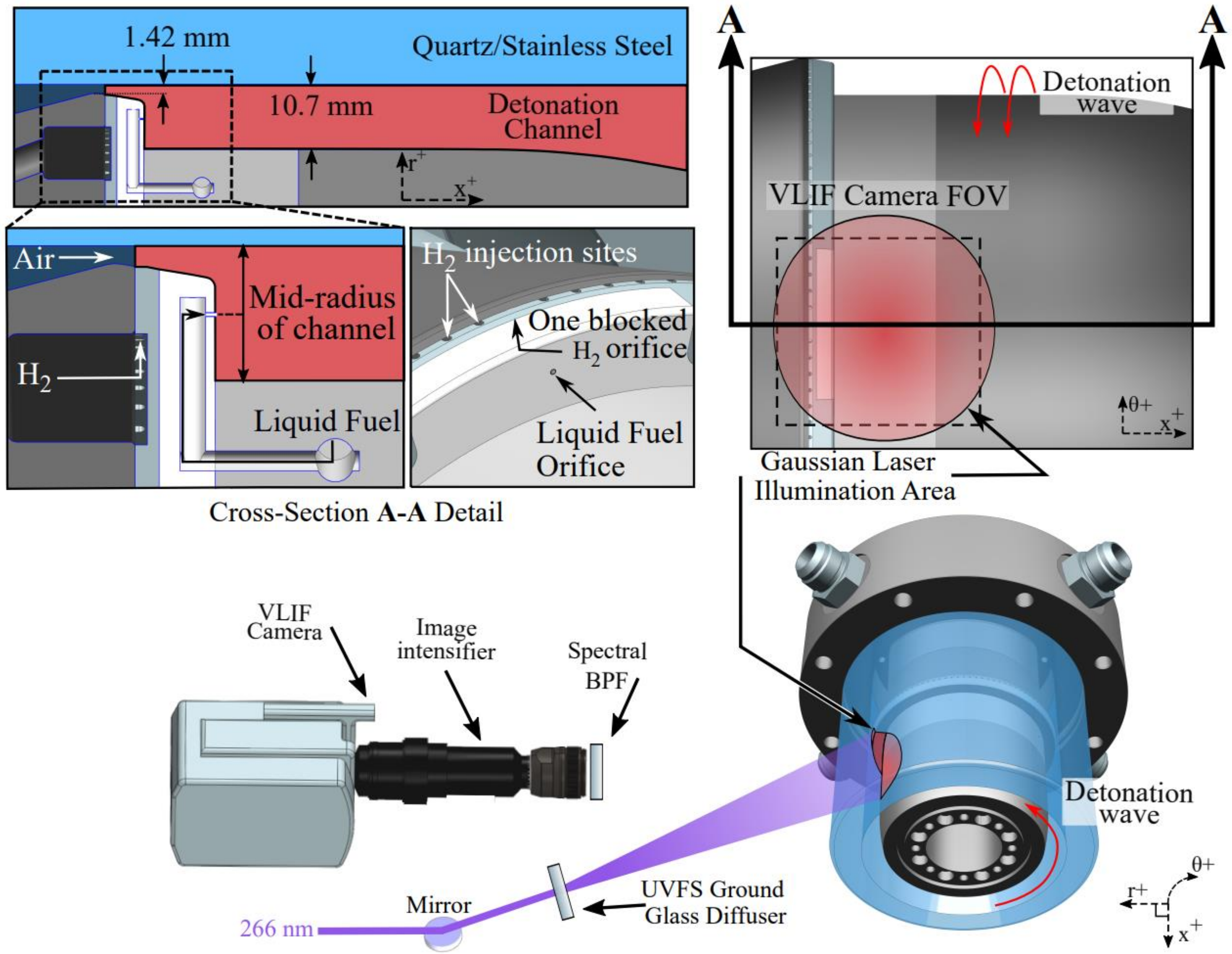
- The azimuthal spreading of the liquid fuel spray can not be captured with the PLIF setup
- In this case, the fuel spray was illuminated volumetrically to capture the axial-azimuthal directions
  - Radial direction information is lost
- The camera was position in a “top-down” view; looking at the PLIF sheet from the edge

20 mm

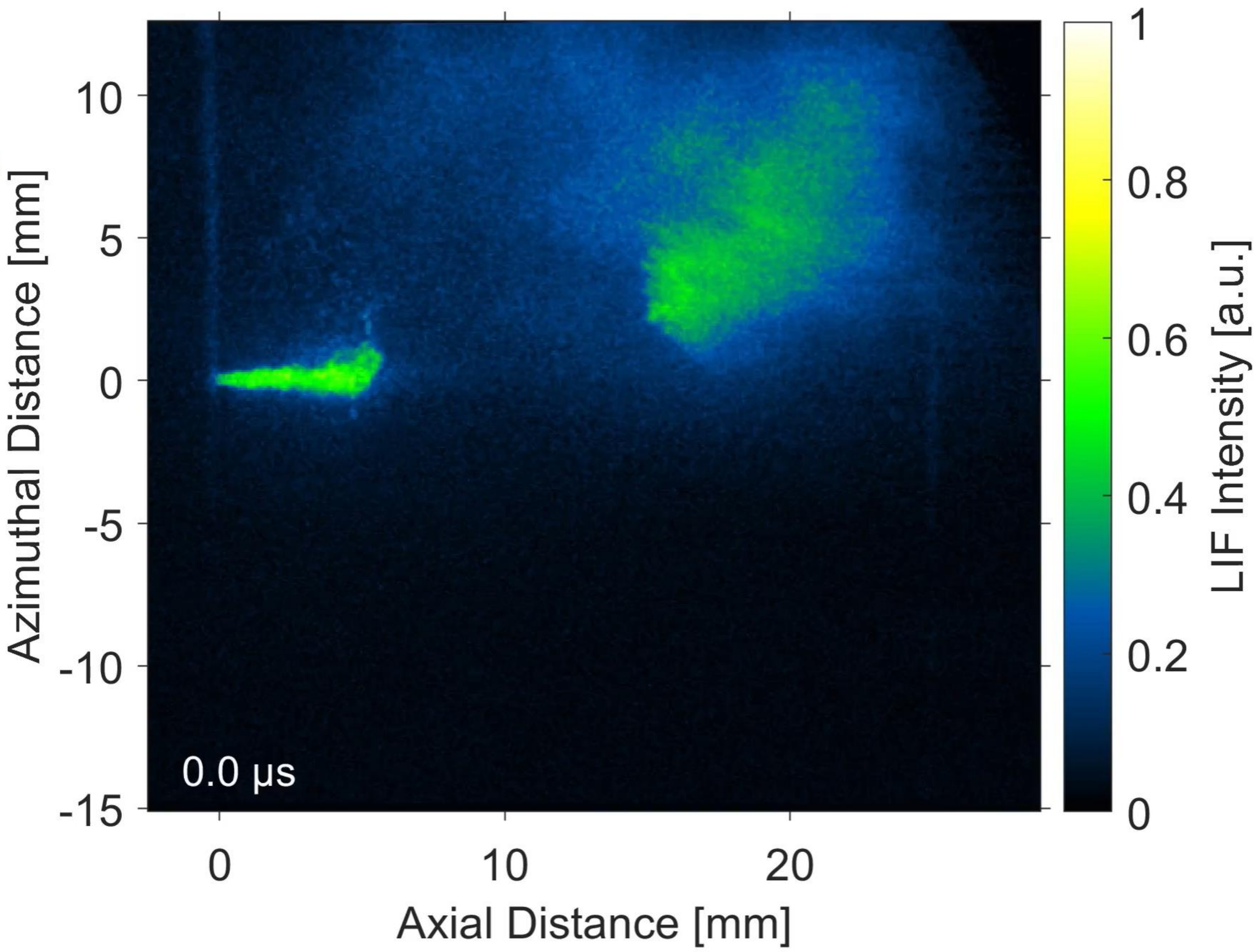


VLIF Sample Video Results

- 300 kHz Jet-A LIF, 10 ms burst length
- 300 µJ/pulse of 266 nm
- 68 µm/pixel

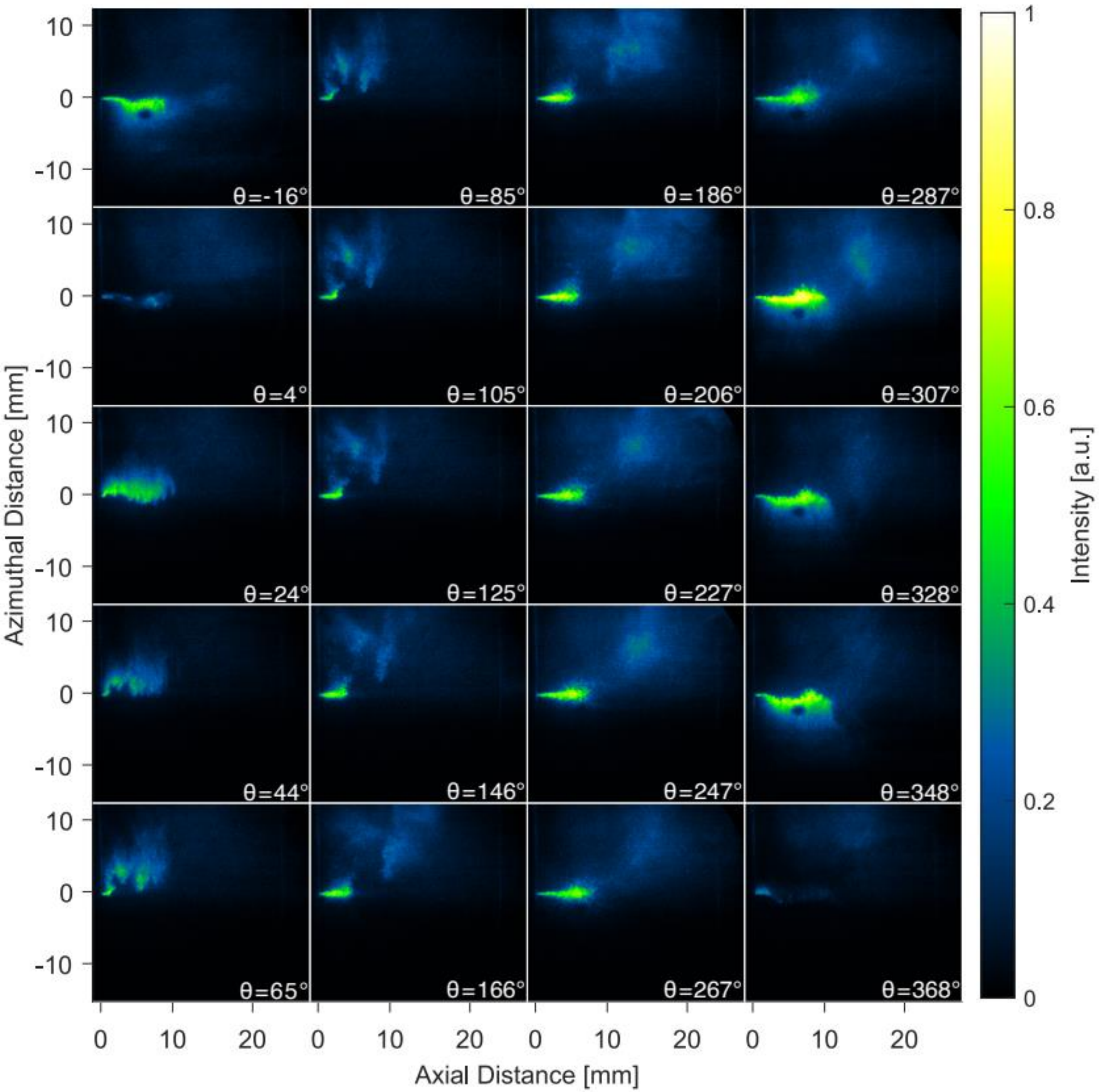


300 kHz Jet-A LIF

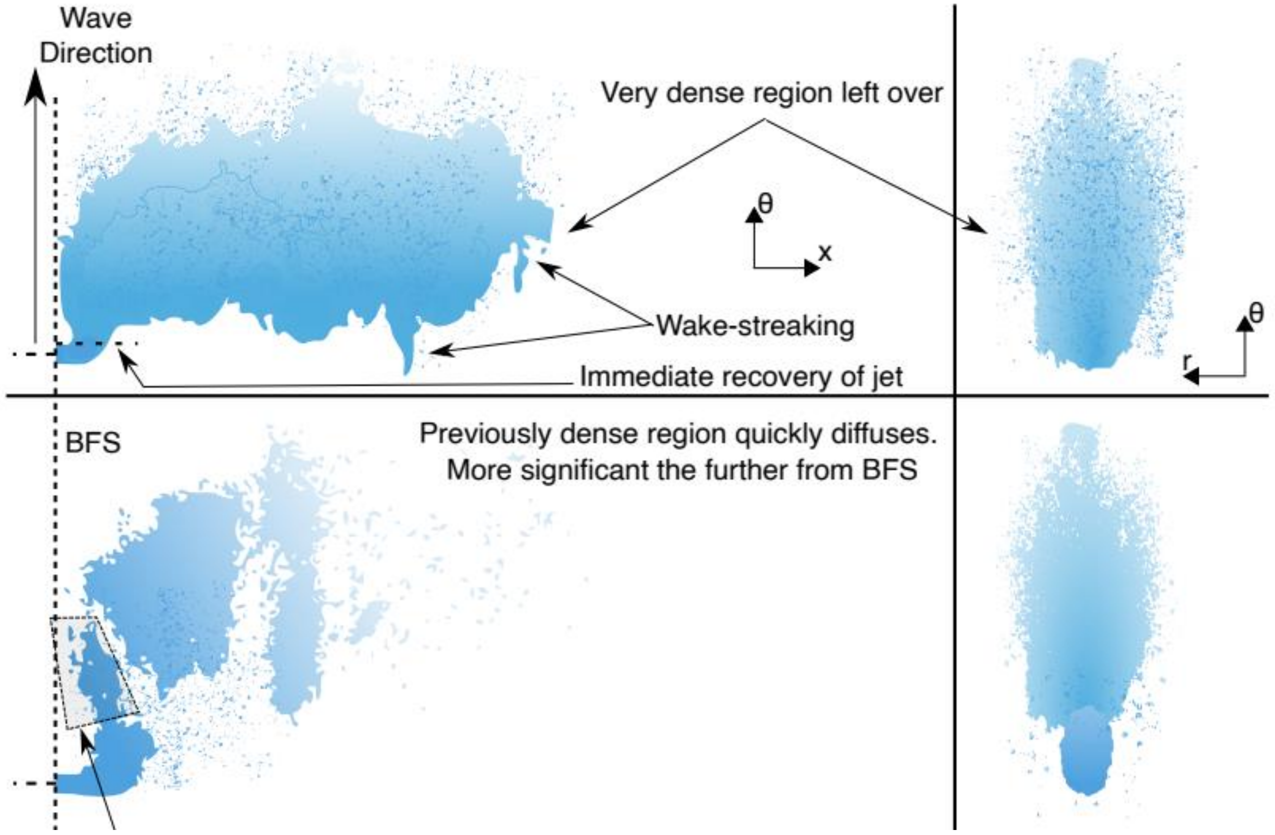


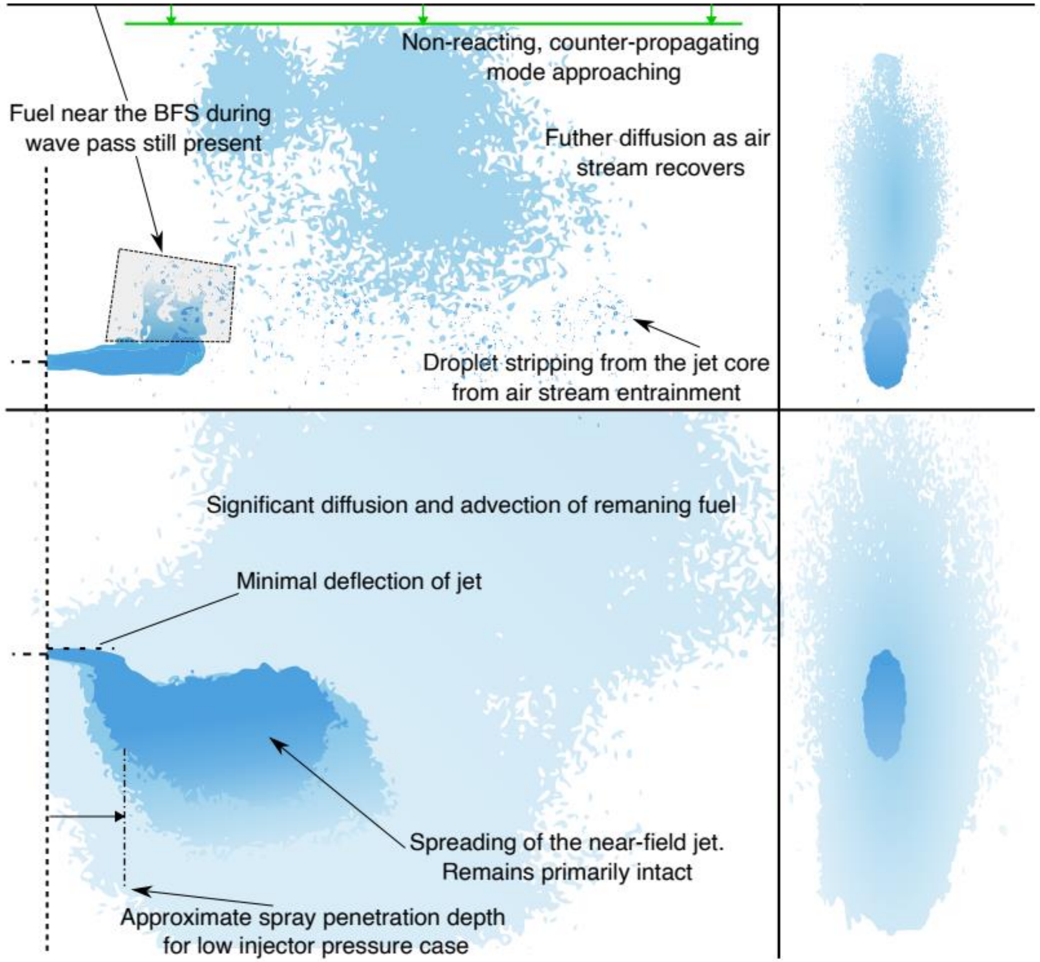
VLIF Sample Video Results

- Detonation wave passes between the $-16°$ and $4°$ frames
- Apparent loss of signal but returns within 6 µs
- After the wave pass, the jet core diffuses quickly
- Injector has no dwell period
- Before the detonation wave arrives, the spray is pushed in the opposite direction



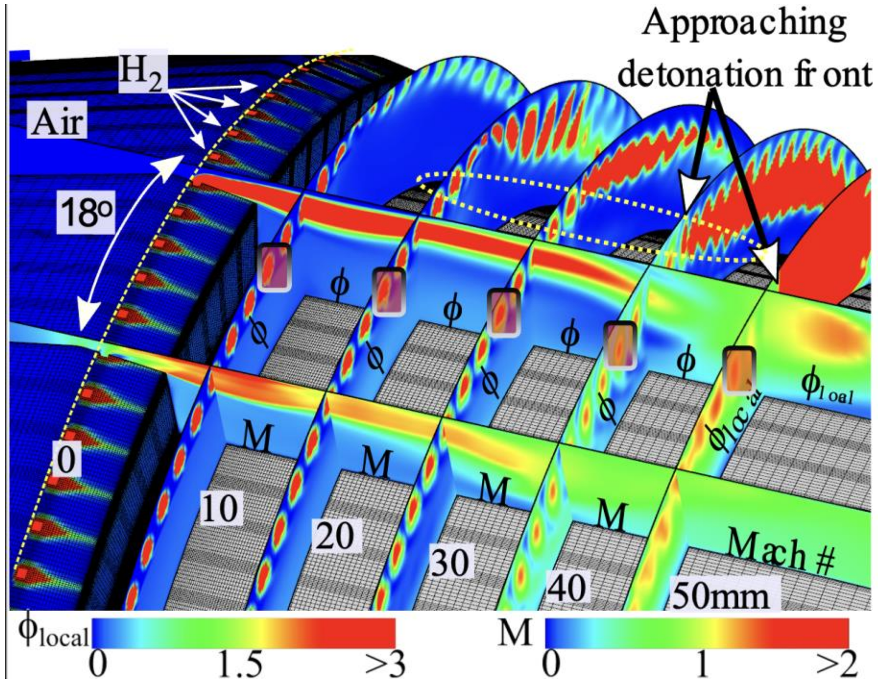
Major Stages of Spray Evolution





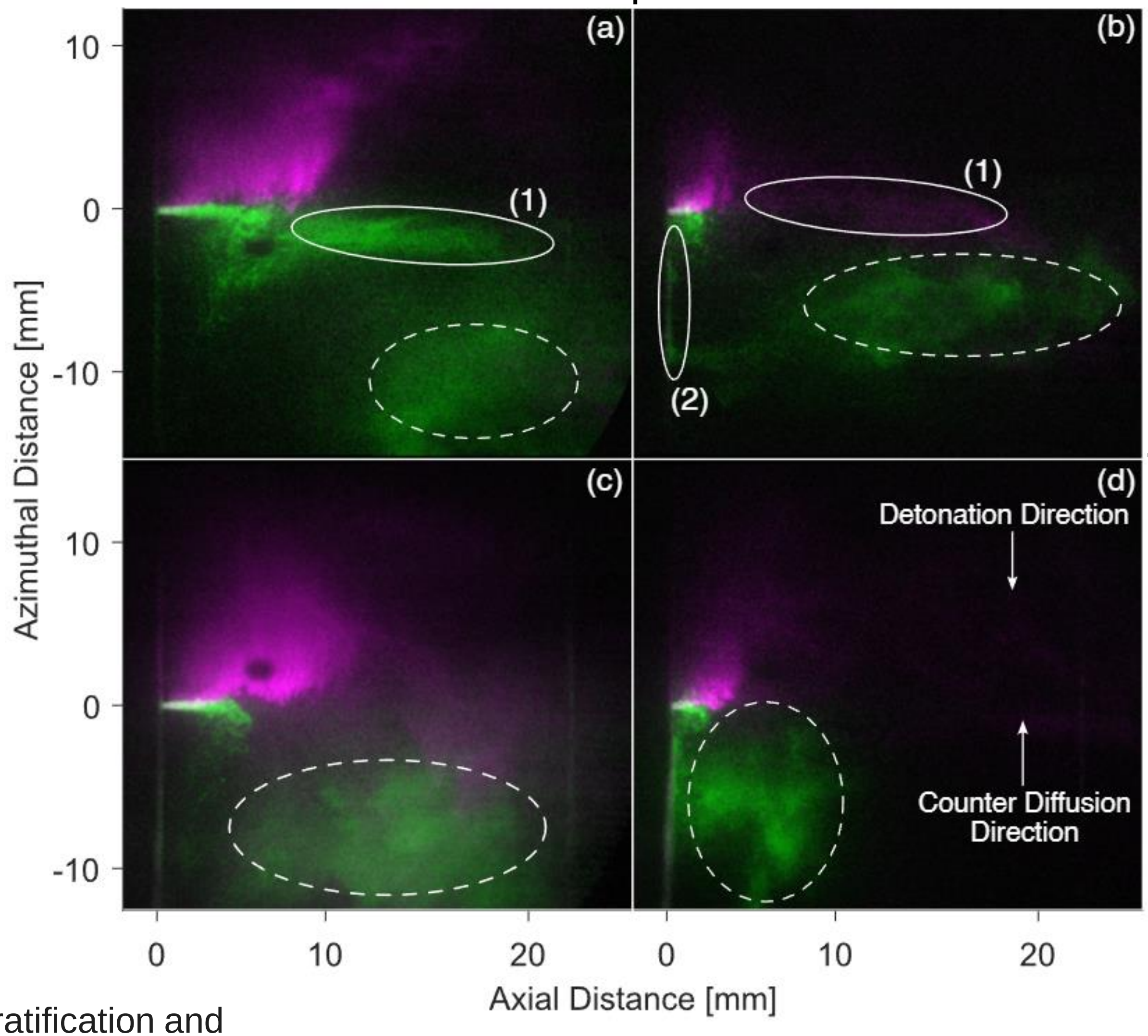
Comparison Between Chamber Conditions

- Regardless of condition, the major features and processes are always present
- More subtle features occur for different conditions



Athmanathan et al., On the effects of reactant stratification and wall curvature in non-premixed rotating detonation combustors, Combs. Flame. (2022)

9 bar inj. pressure | 2.7 bar inj. pressure

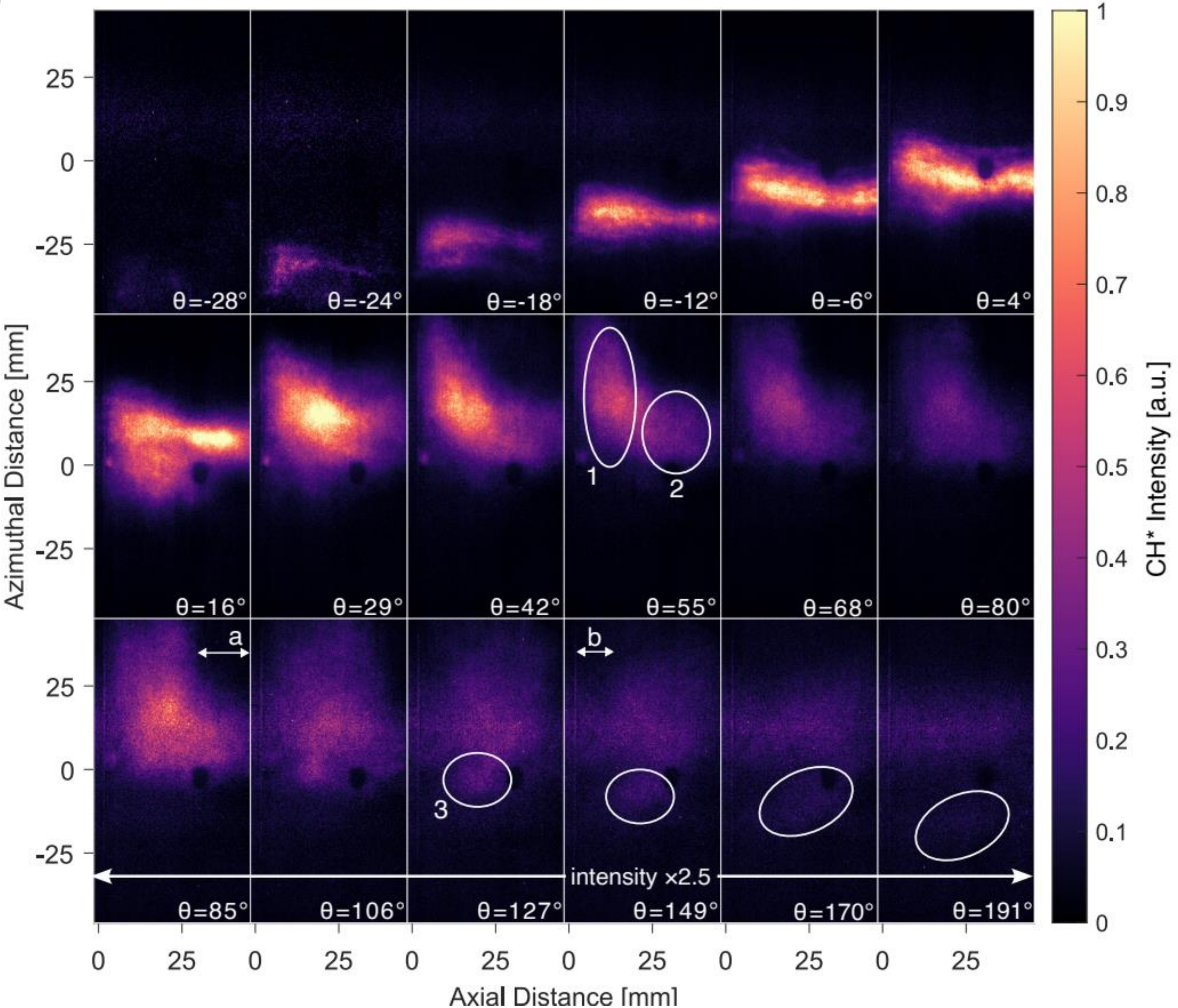


0.45 kg/s of air ($\sim$110 kg/m^2/s)

0.23 kg/s of air ($\sim$55 kg/m^2/s)

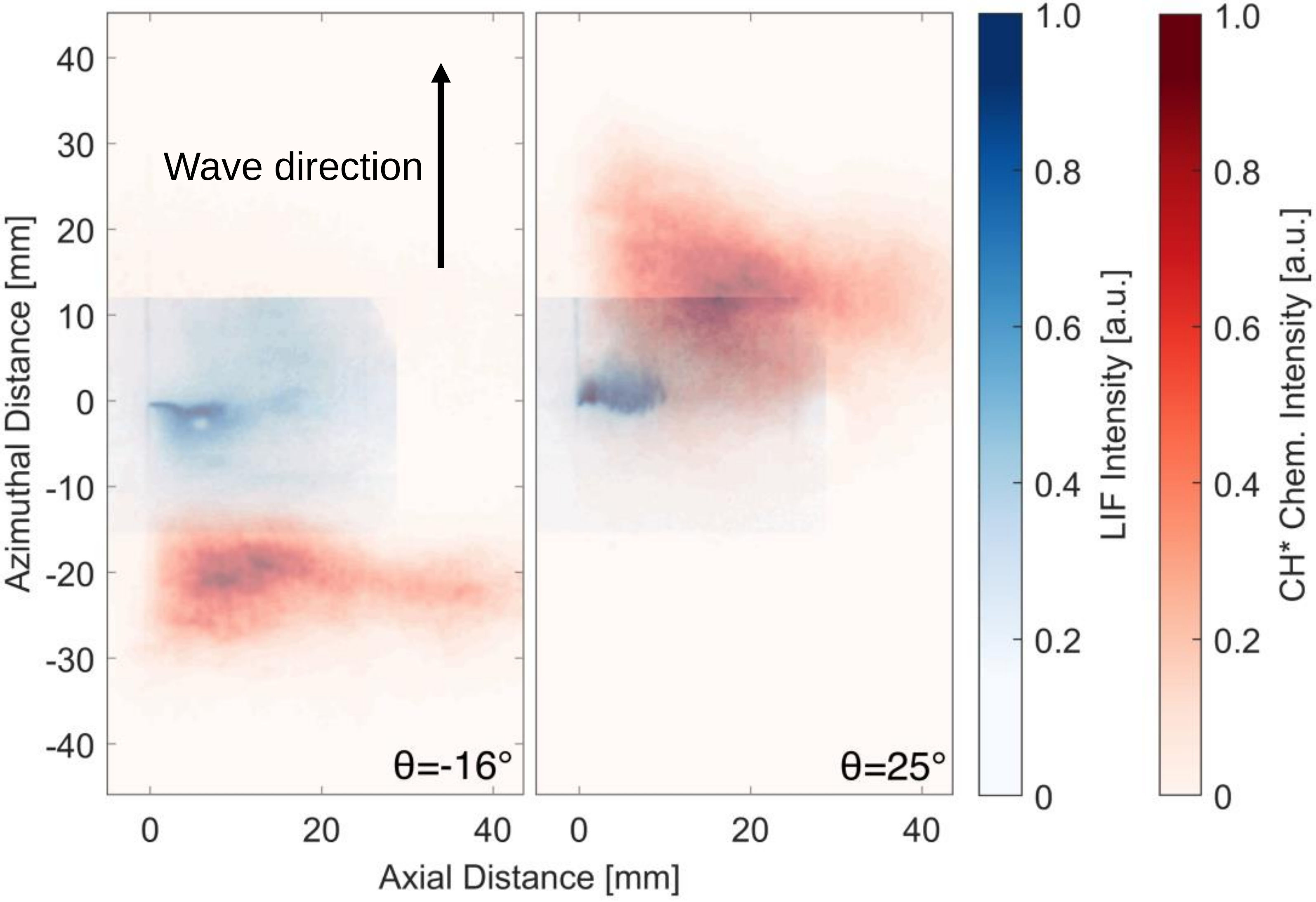
Chemiluminescence Imaging

- Filtered CH* chemiluminescence was also performed to support LIF data
- Field of view is slightly larger than the LIF frame
- Data was not taken simultaneously and so phase averaged results are used for comparison



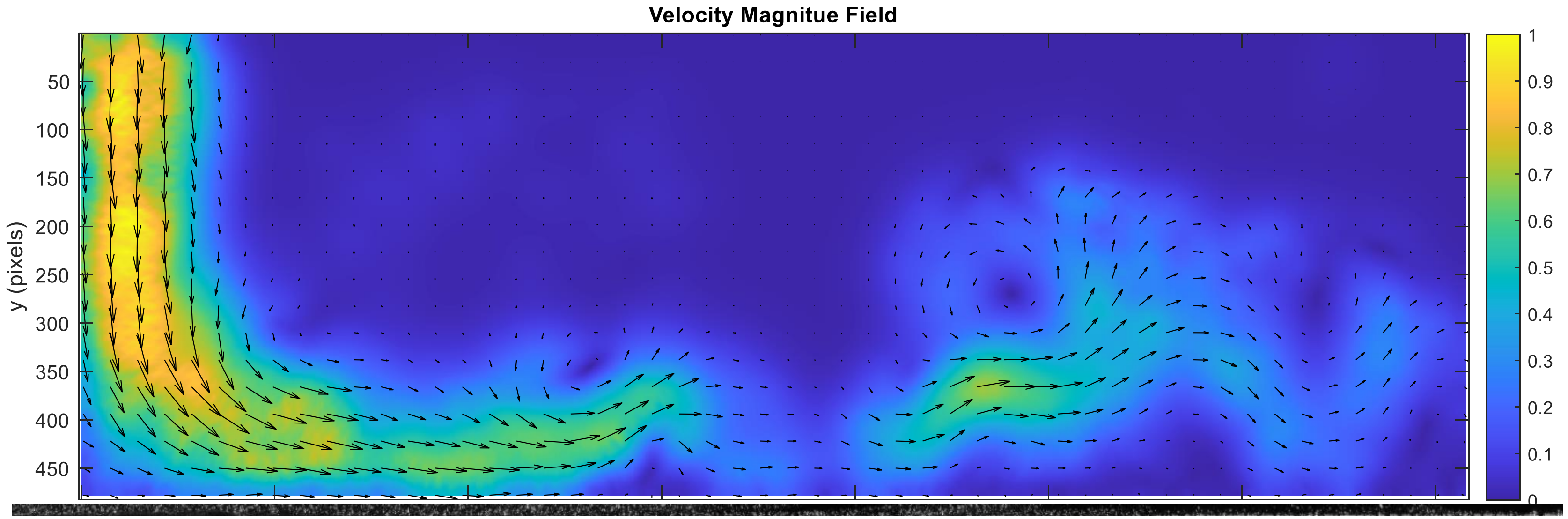
Jet-A LIF vs. CH* Images

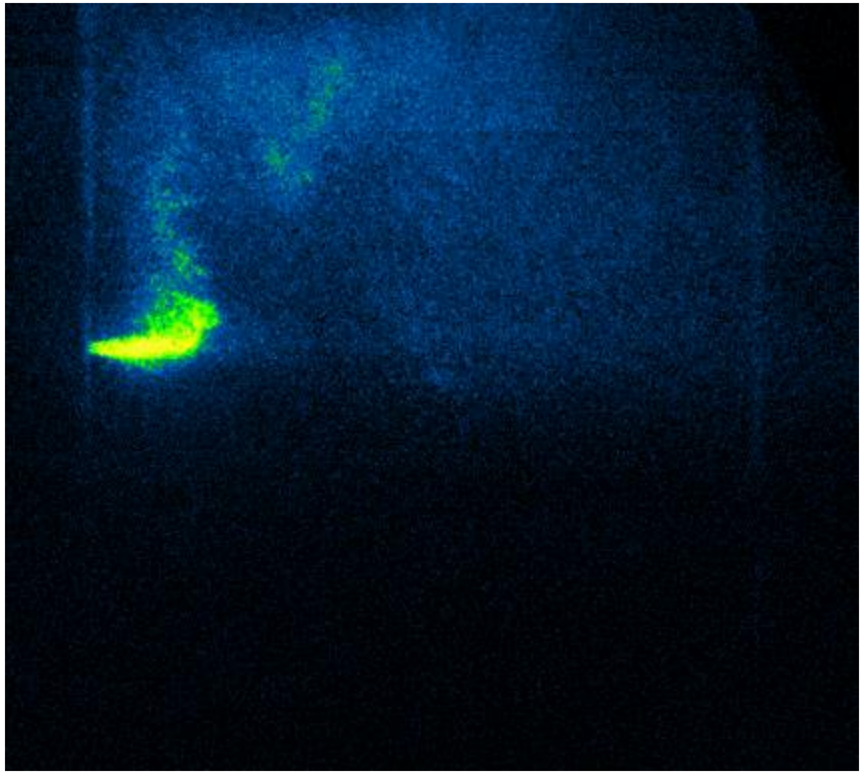
- CH* signal is present far away from the injection point. Much further than expected based on LIF images
- Other tests where the clocking between the camera and injection location was varied showed that CH* does not exist beyond the field of view shown
- Based on the phase angles and the time difference, Jet-A droplets or vapor would have to travel at 200 m/s



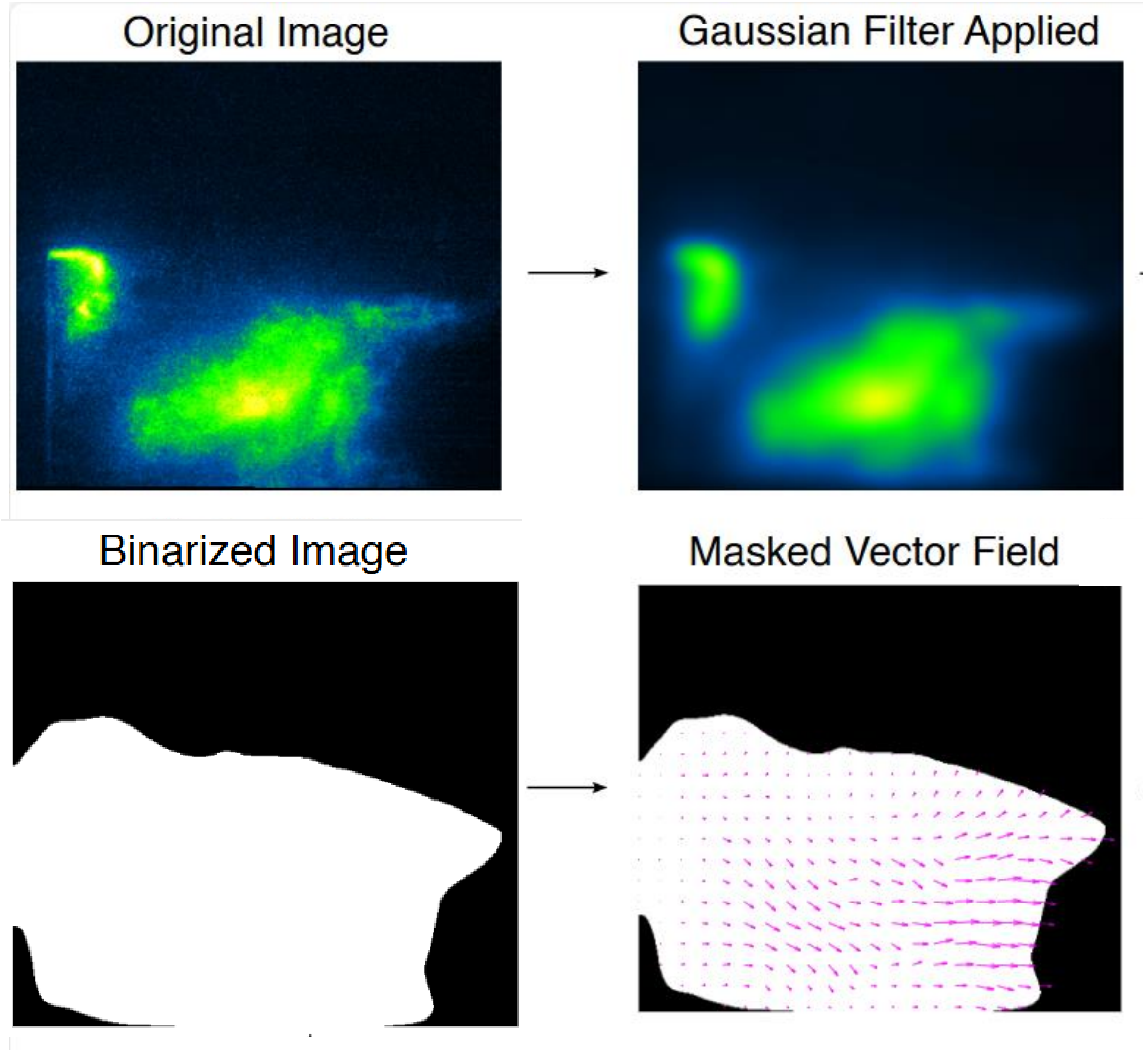
Velocity Estimation Through Optical Flow

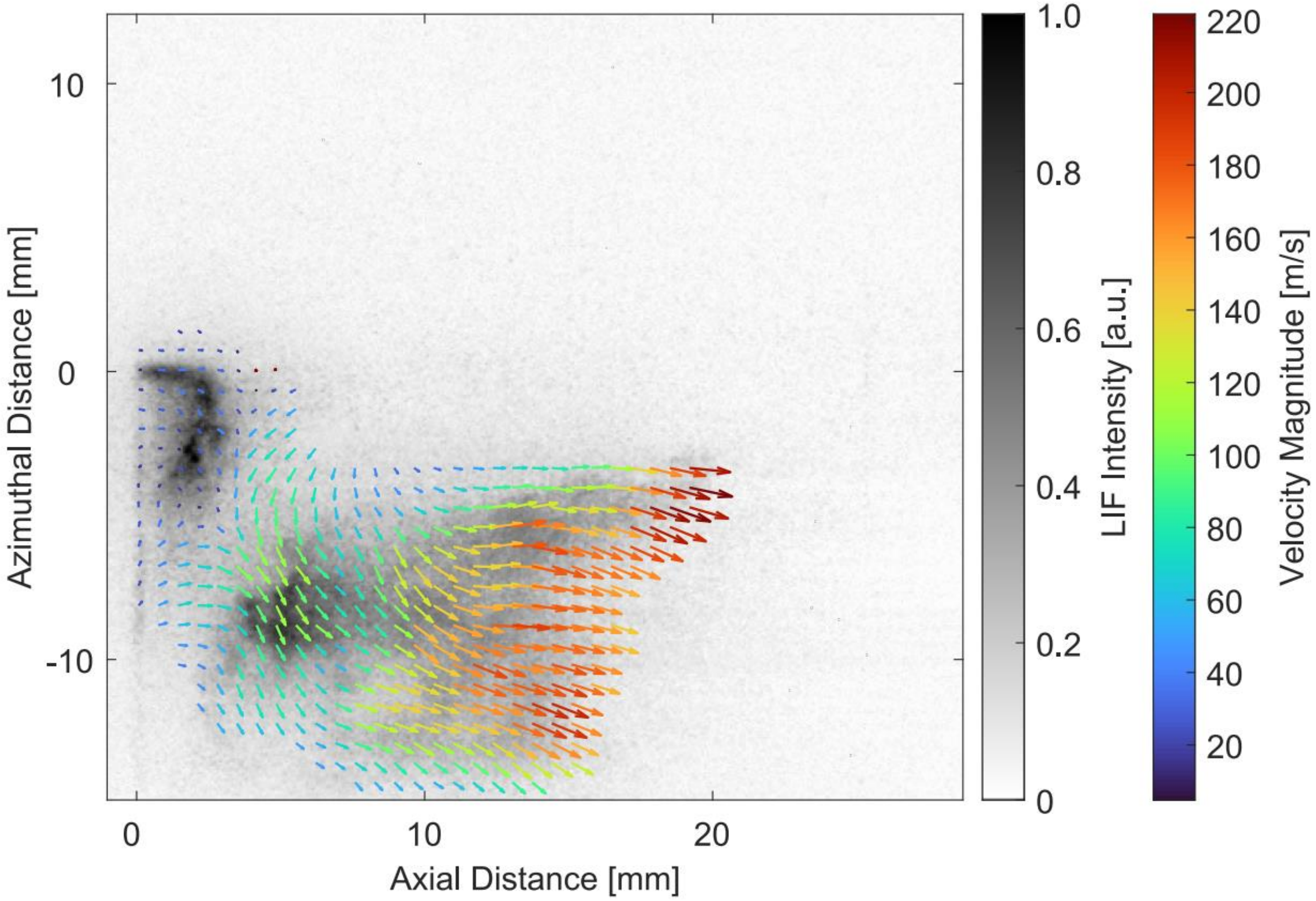
- Optical flow is an image analysis technique that can calculate velocity fields from a pair of images
- Due to the high temporal resolution in the LIF images, assuming the difference between two frames is small enough to be considered passive
- OpenOpticalFlow by Liu and Shen was used for computations. See Liu et al., OpenOpticalFlow, Journal of Research Software (2017)





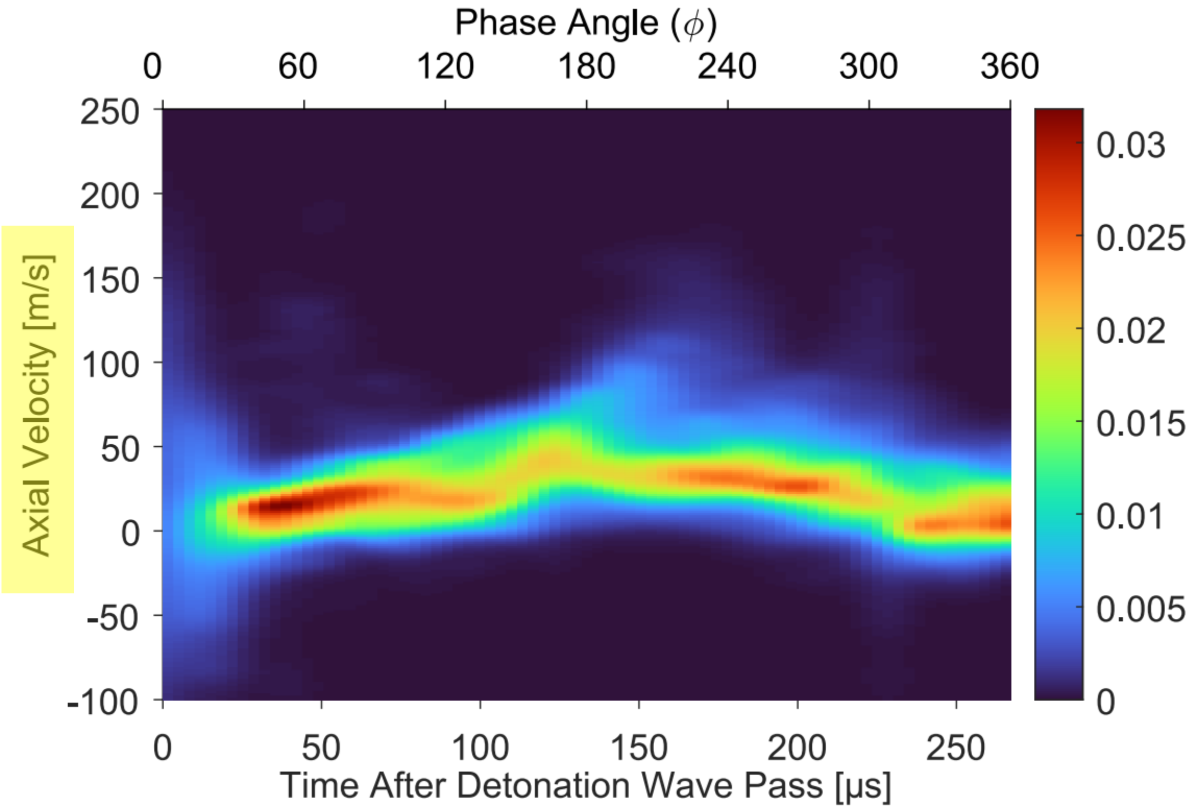
Velocity Estimation

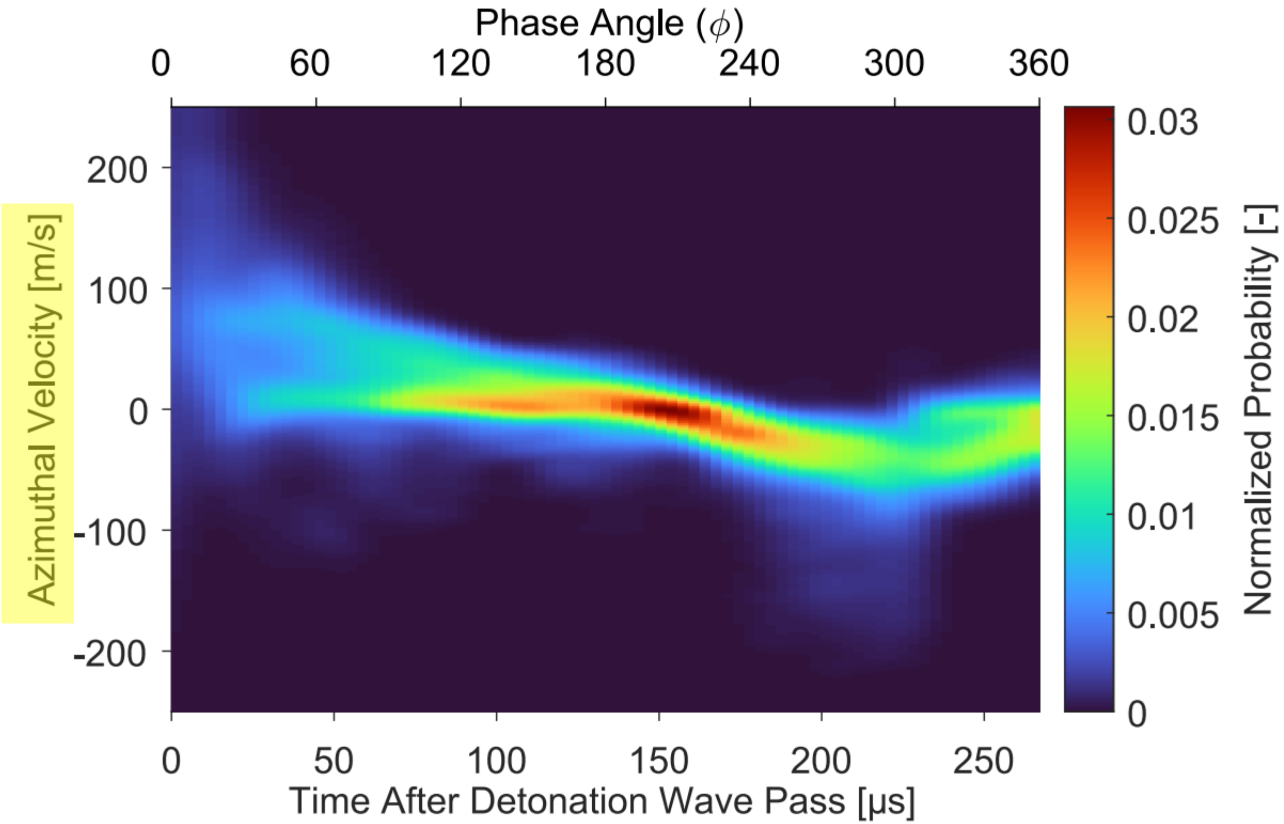




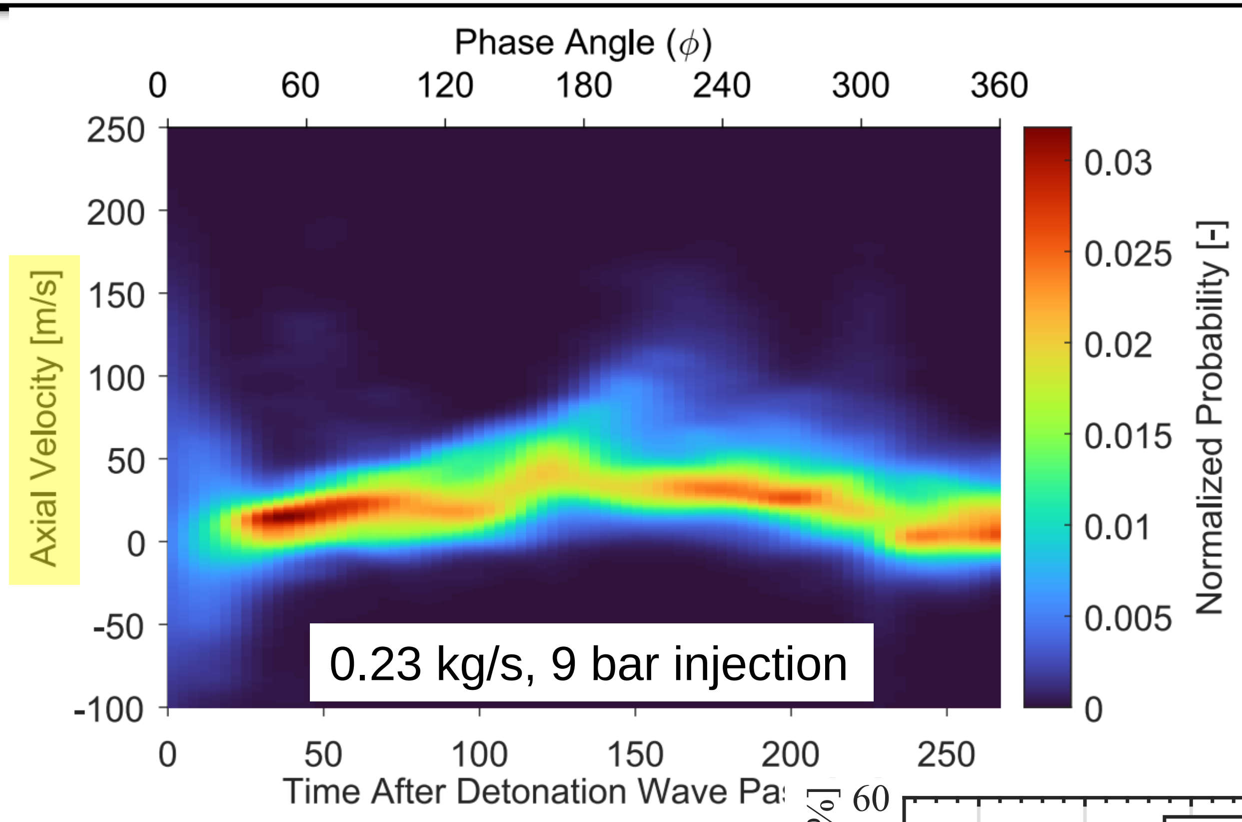
Velocity Estimation

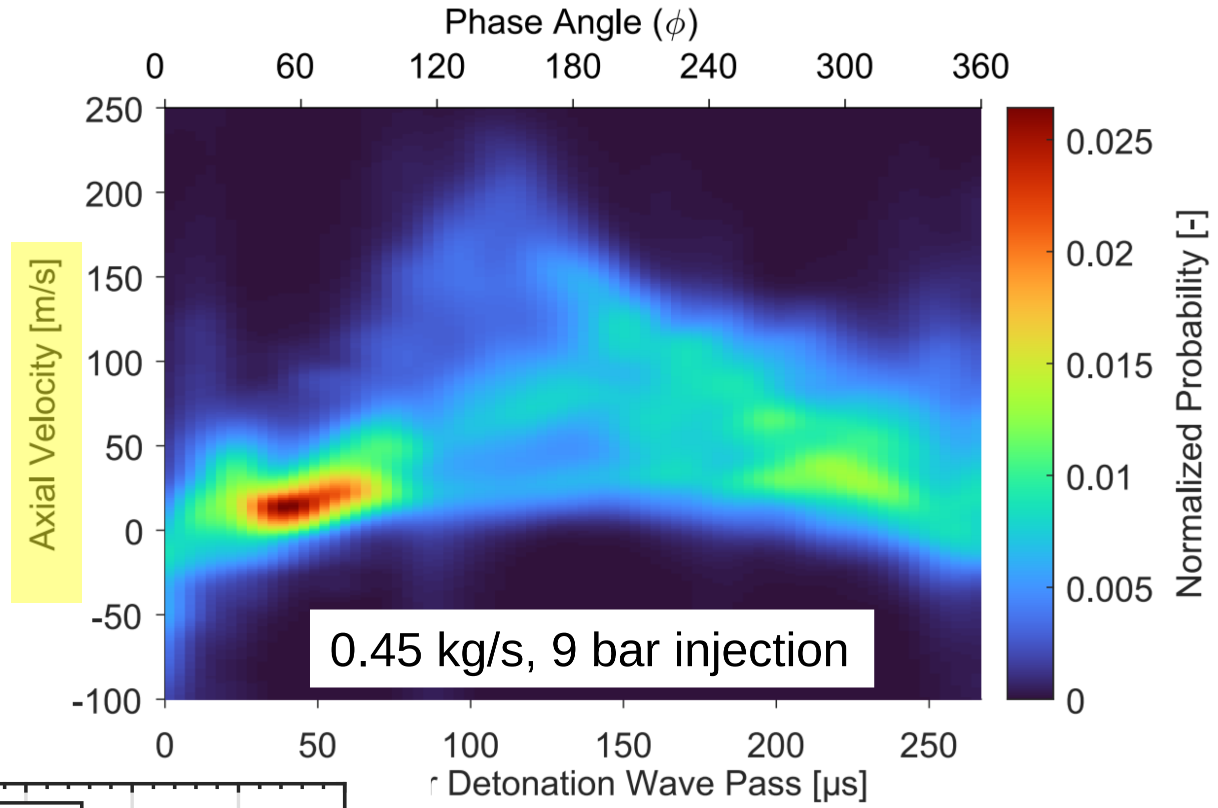
- Axial and azimuthal velocity components for the 0.23 kg/s, 9 bar injection case
- Optical flow suffers from noise so only 8 ms of the burst are used
- The first ~2 frames after the detonation wave pass typically have numerical instabilities
- The decrease in axial velocity is not a ‘deceleration’. Jet-A is leaving the field of view

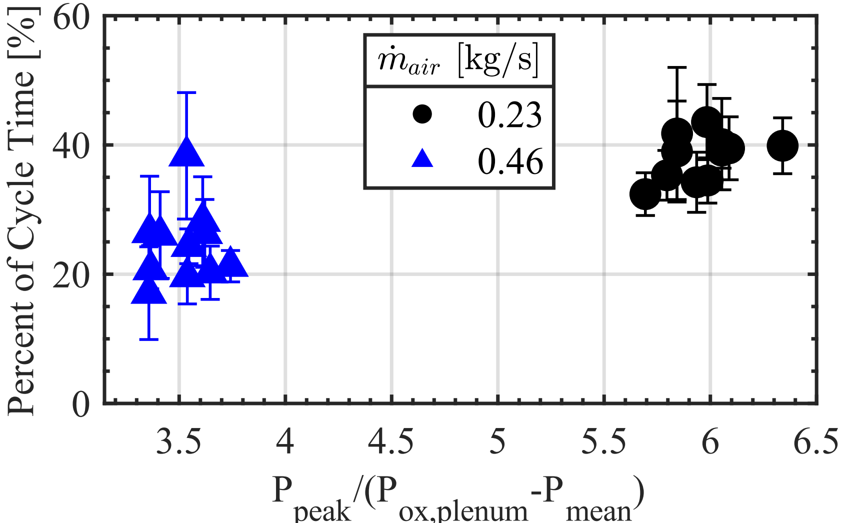




Velocity Estimation







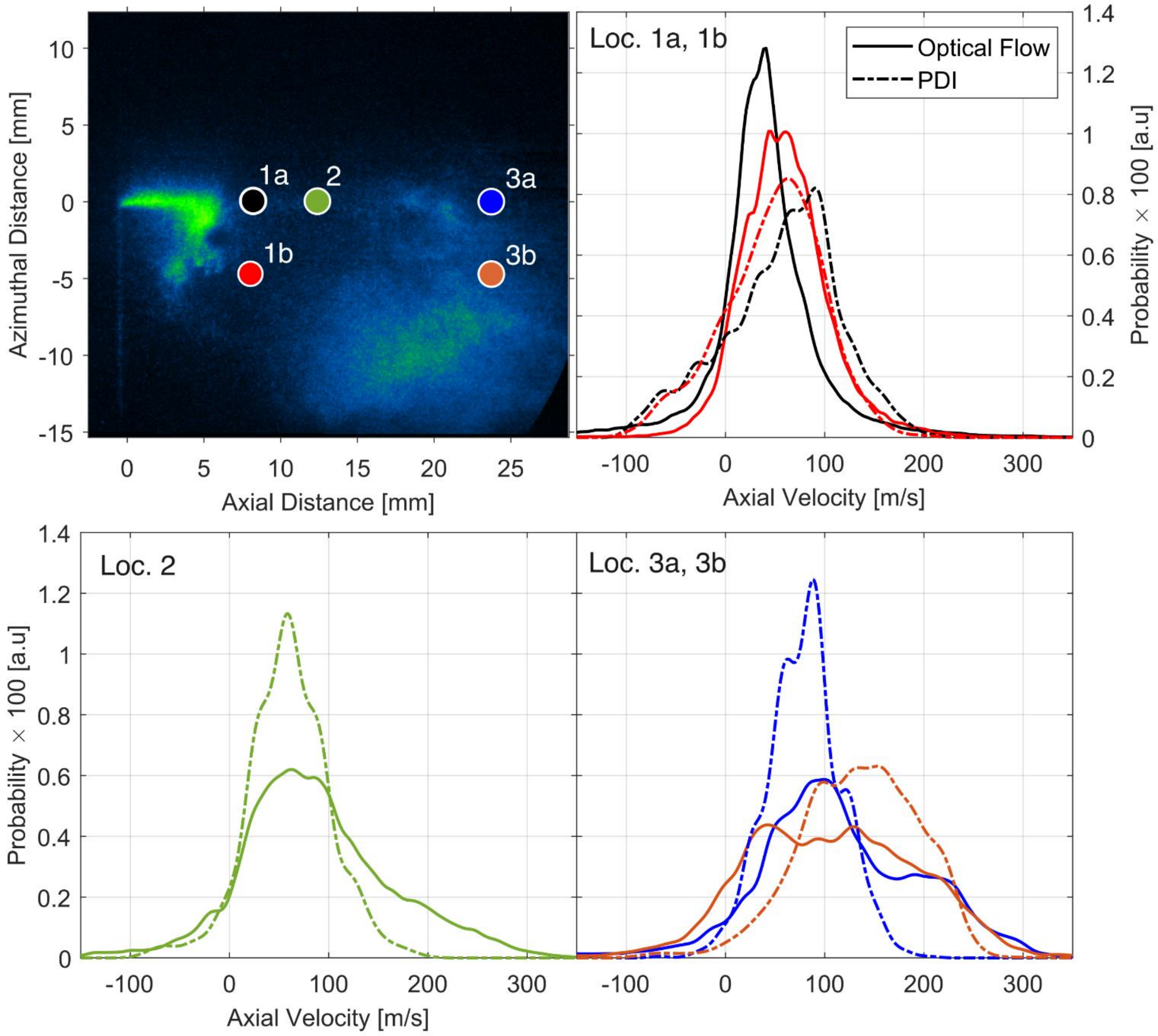
Comparison of PDI and Optical Flow

- Previous optical flow sampling was performed over the entire image
  - Here, each PDI probe location is compared to optical flow in a 1 × 1 mm box

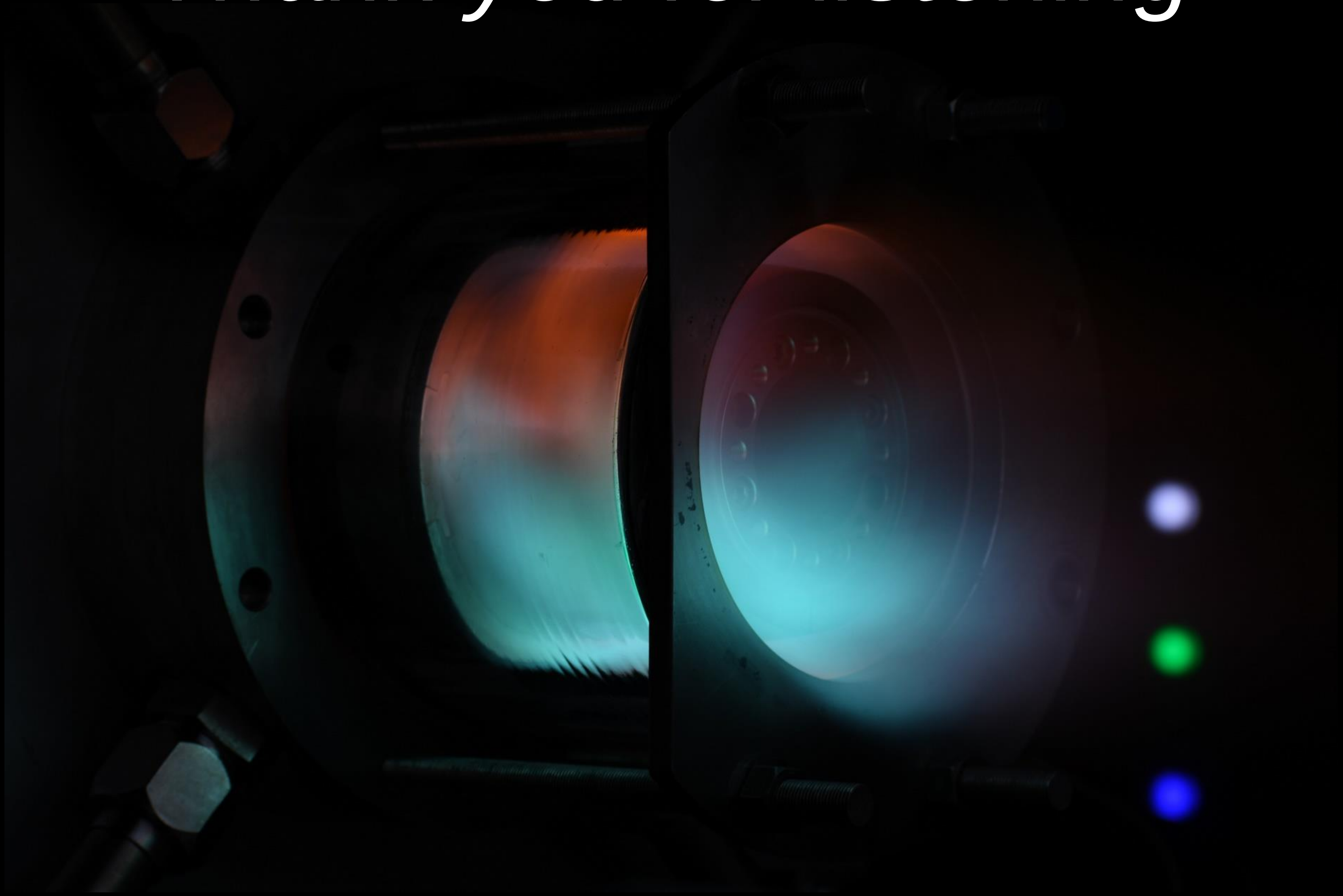
- Good agreement at location 1a and 1b
  - 1a PDI is likely dominated by post-detonation advection. Late in the cycle, 1a sees the jet core which is too dense

- Other locations have similar median velocities
  - Location 2 and 3a has longer tails for optical flow. LIF is likely detecting some level of vapor, and this is pushing the velocity range higher.

0.23 kg/s, 9 bar injection pressure

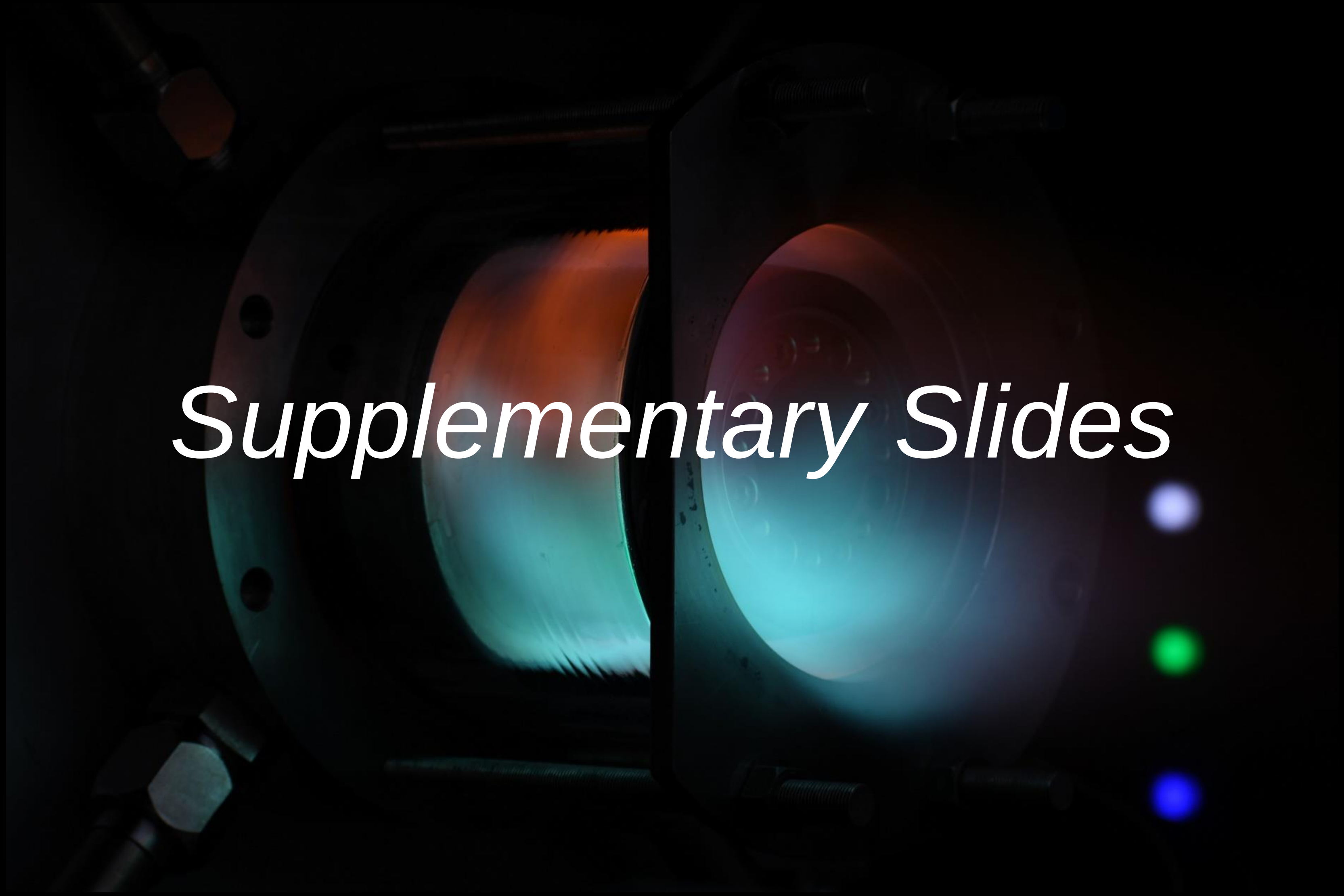


Thank you for listening



Questions?

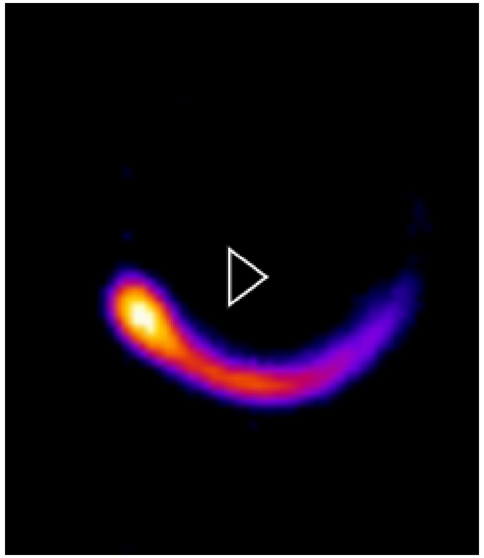
Supplementary Slides



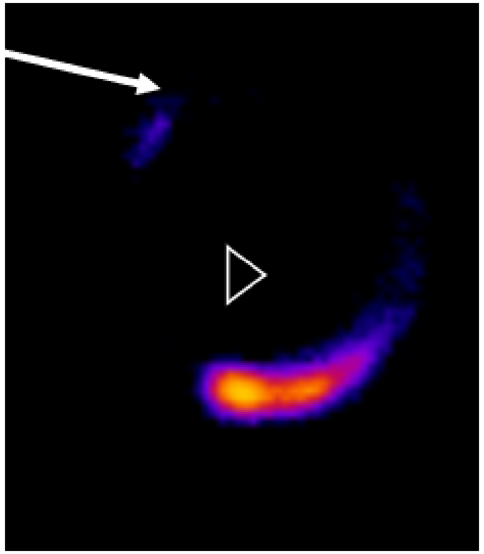
Aft-End Image Comparison

- Needed to verify no significant detonation wave perturbation from diesel spray
- Identical chamber conditions ($\dot{m}_{air}$=0.46 kg/s, $\Phi \sim 1$)
- Corroborated with high frequency pressure measurements

No Liquid Fuel

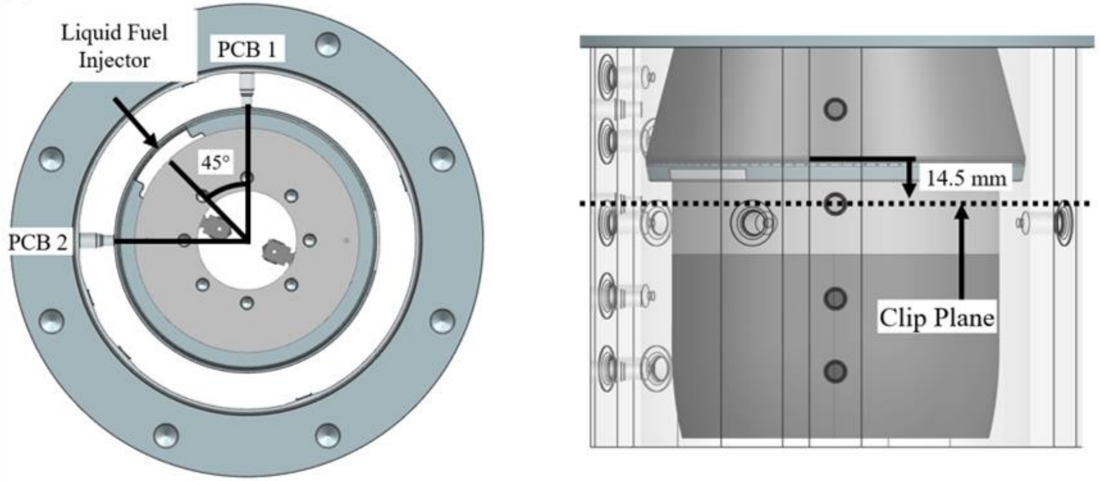


With Liquid Fuel

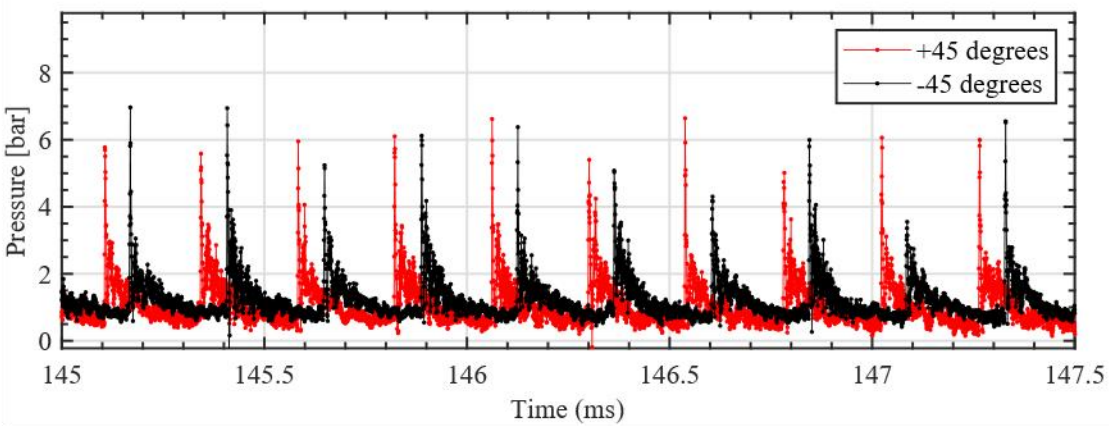


100 kHz Aft-End Chemiluminescence

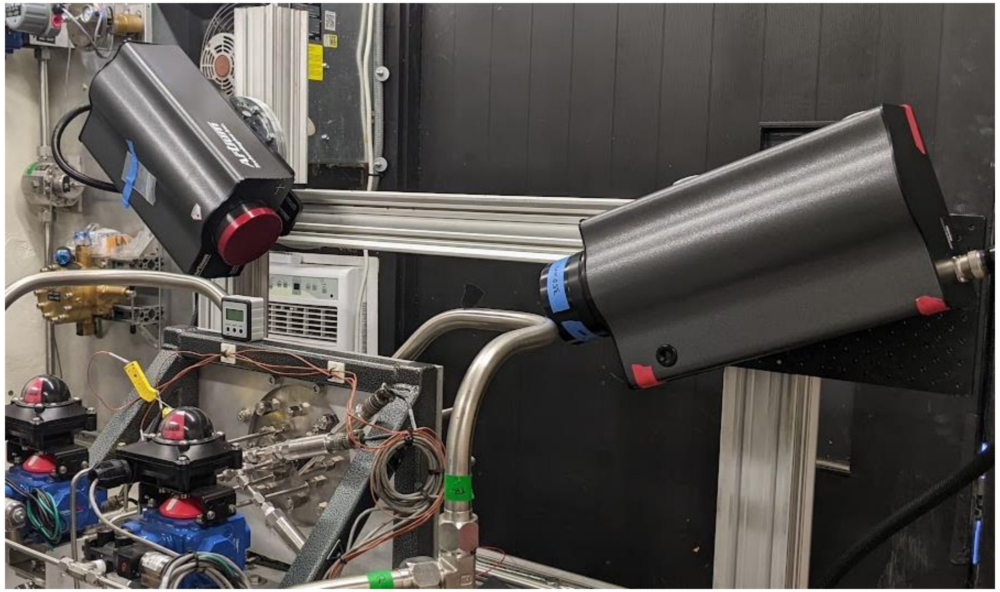
(b) PCB Arrangement

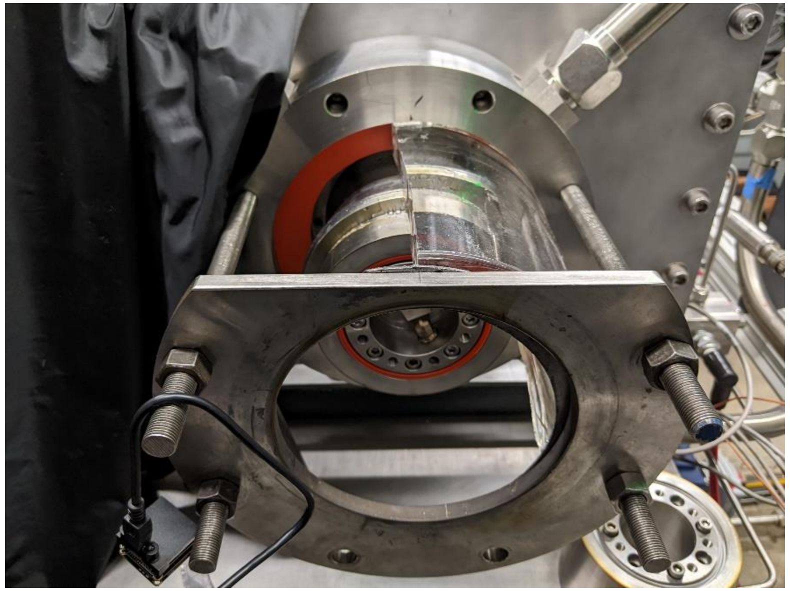


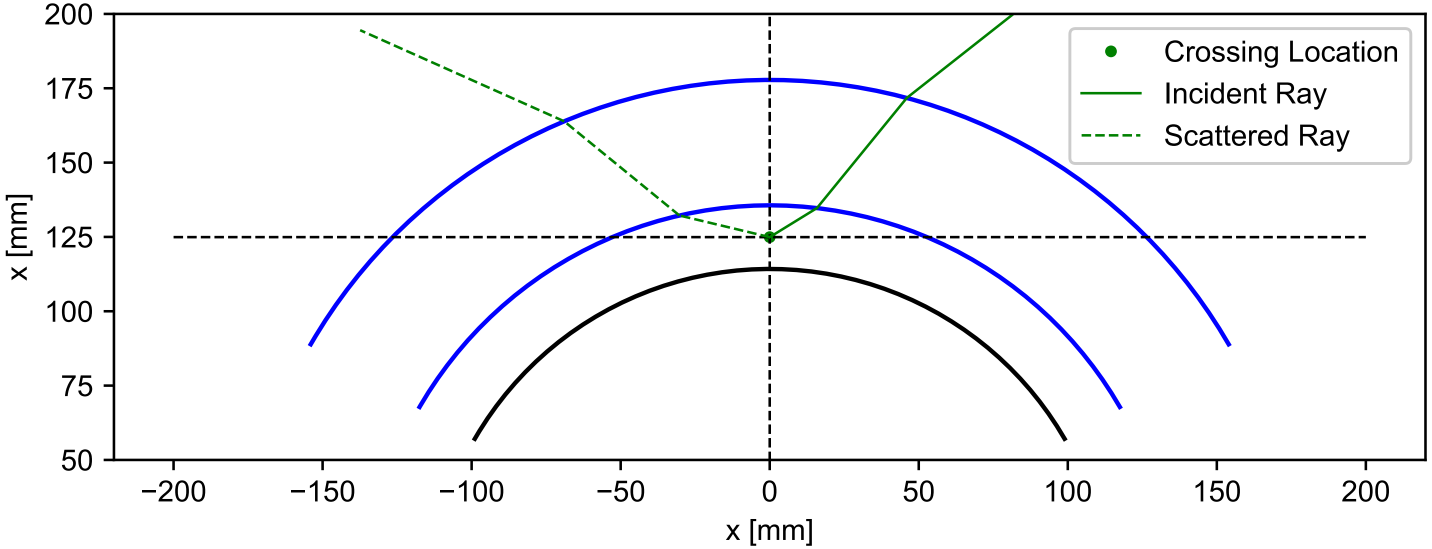
(c) PCB Profile

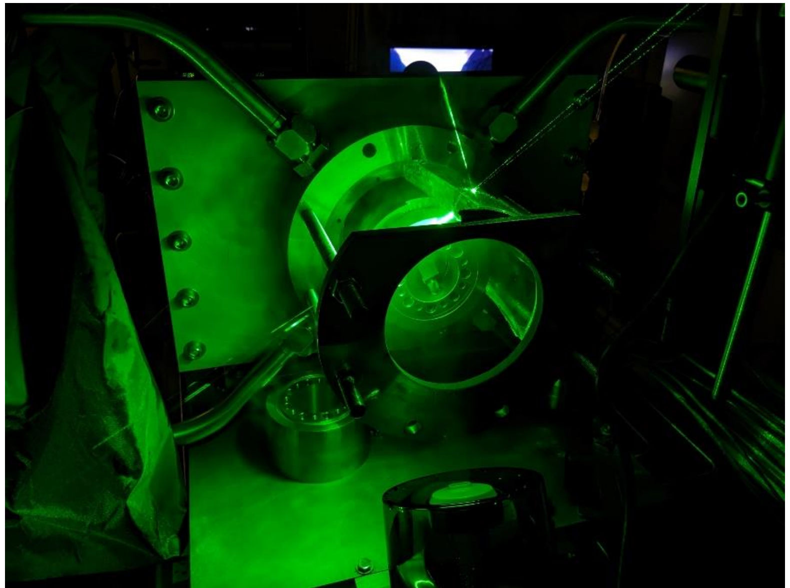


PDA During Hot Fire



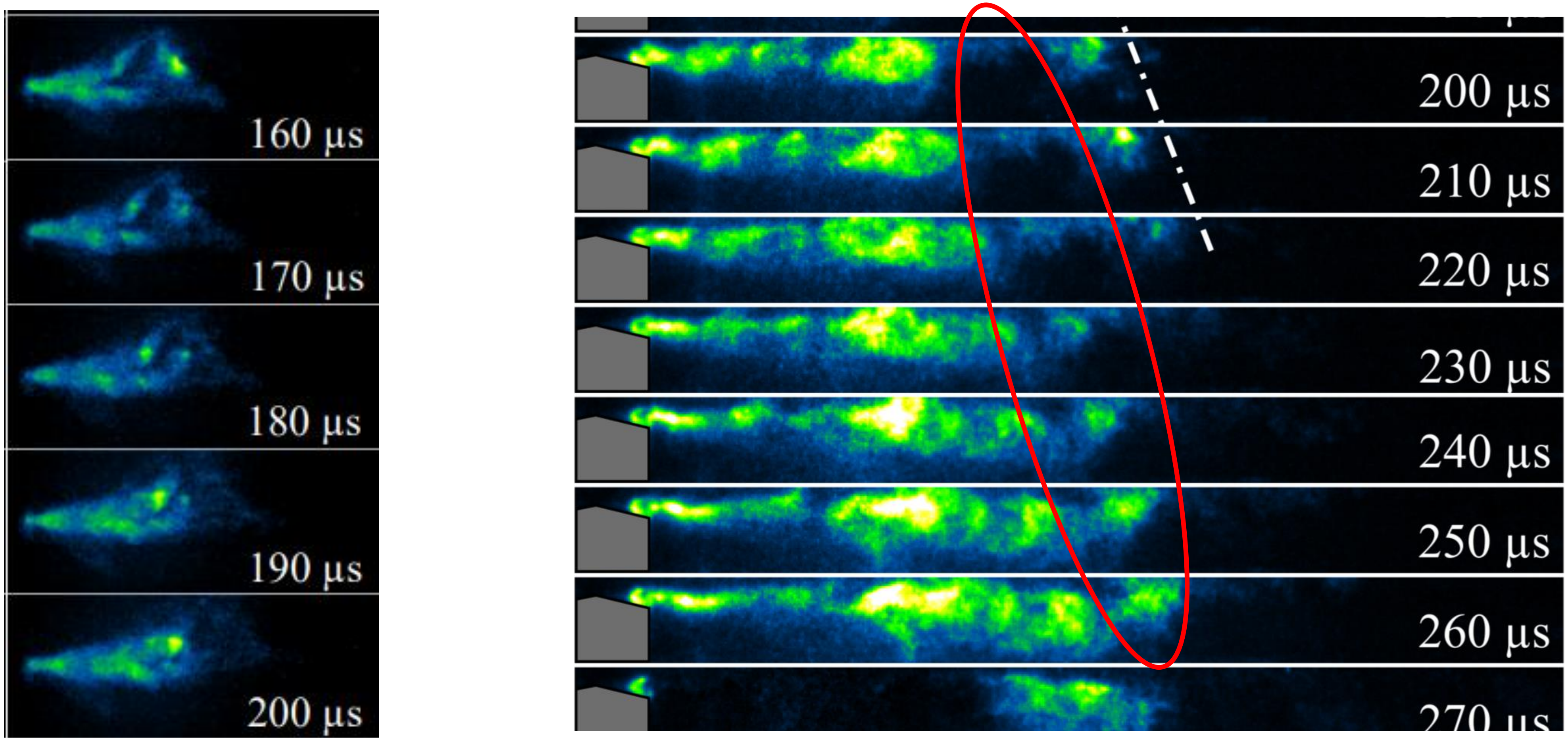






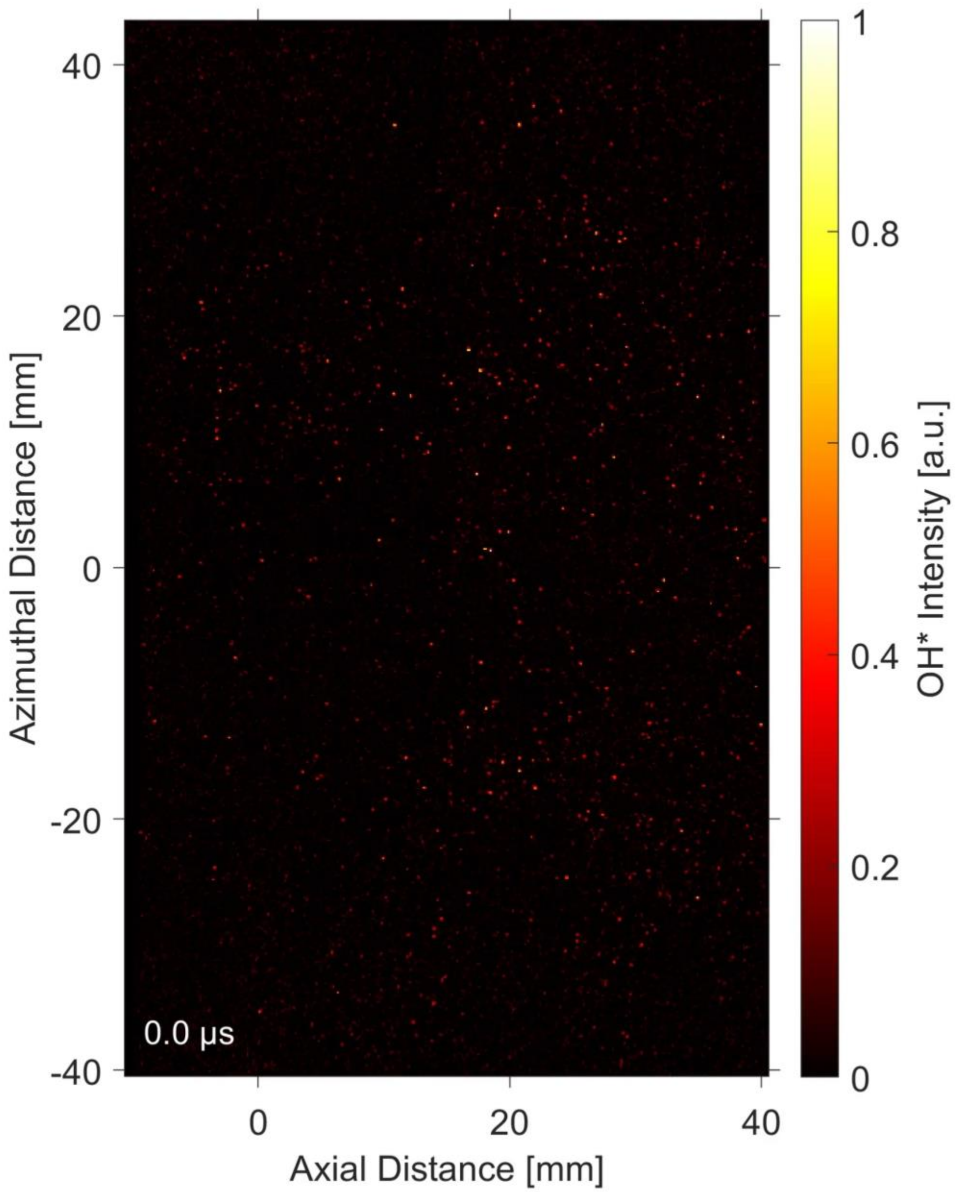
Volume Illumination Scheme (VLIF)

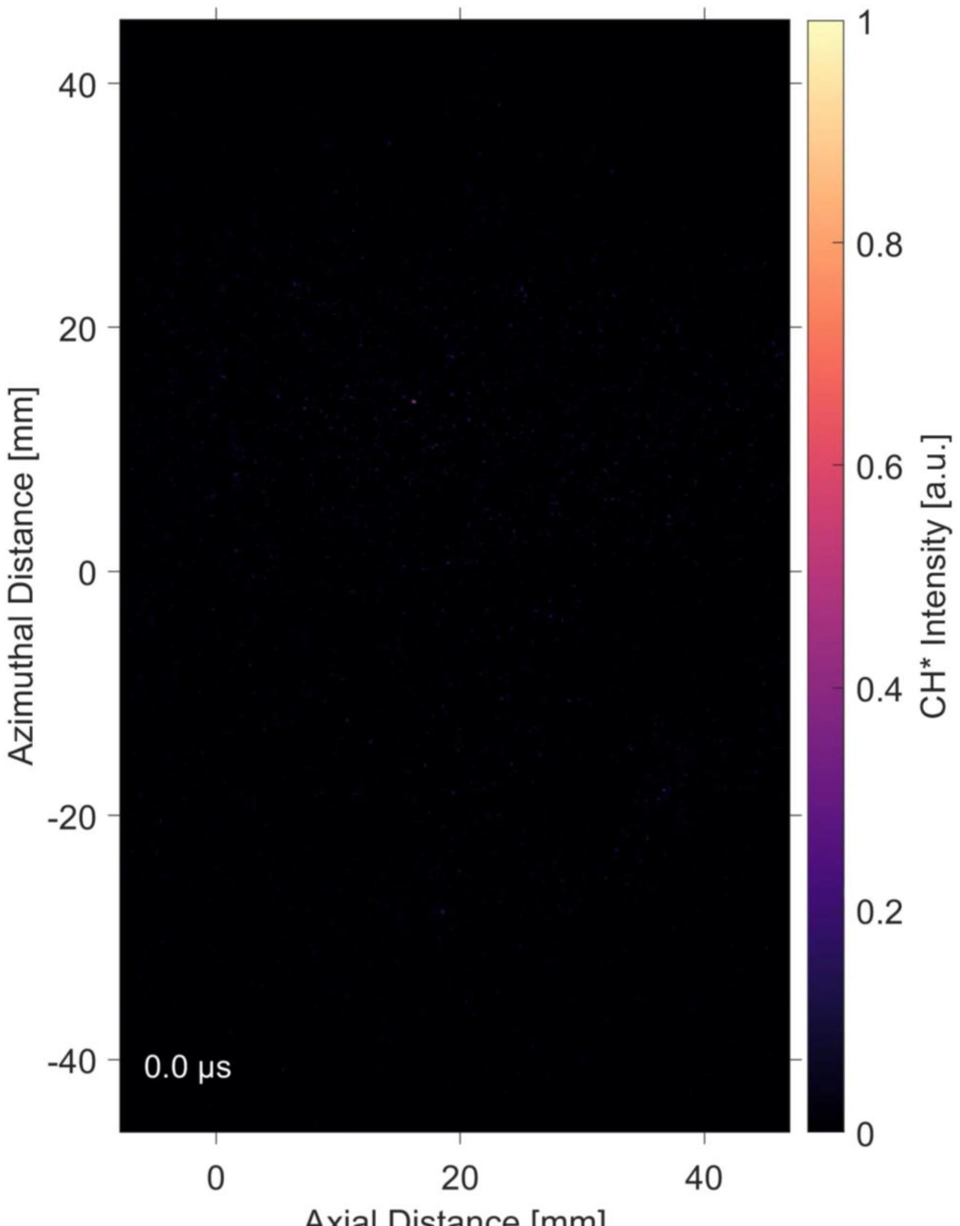
- Dynamic evolution of fuel spray from the PLIF data set proven to be “out of plane” motion of flow structures
- Key insight into fuel spreading as it refills channel and how it spreads post detonation



Chemiluminescence Imaging

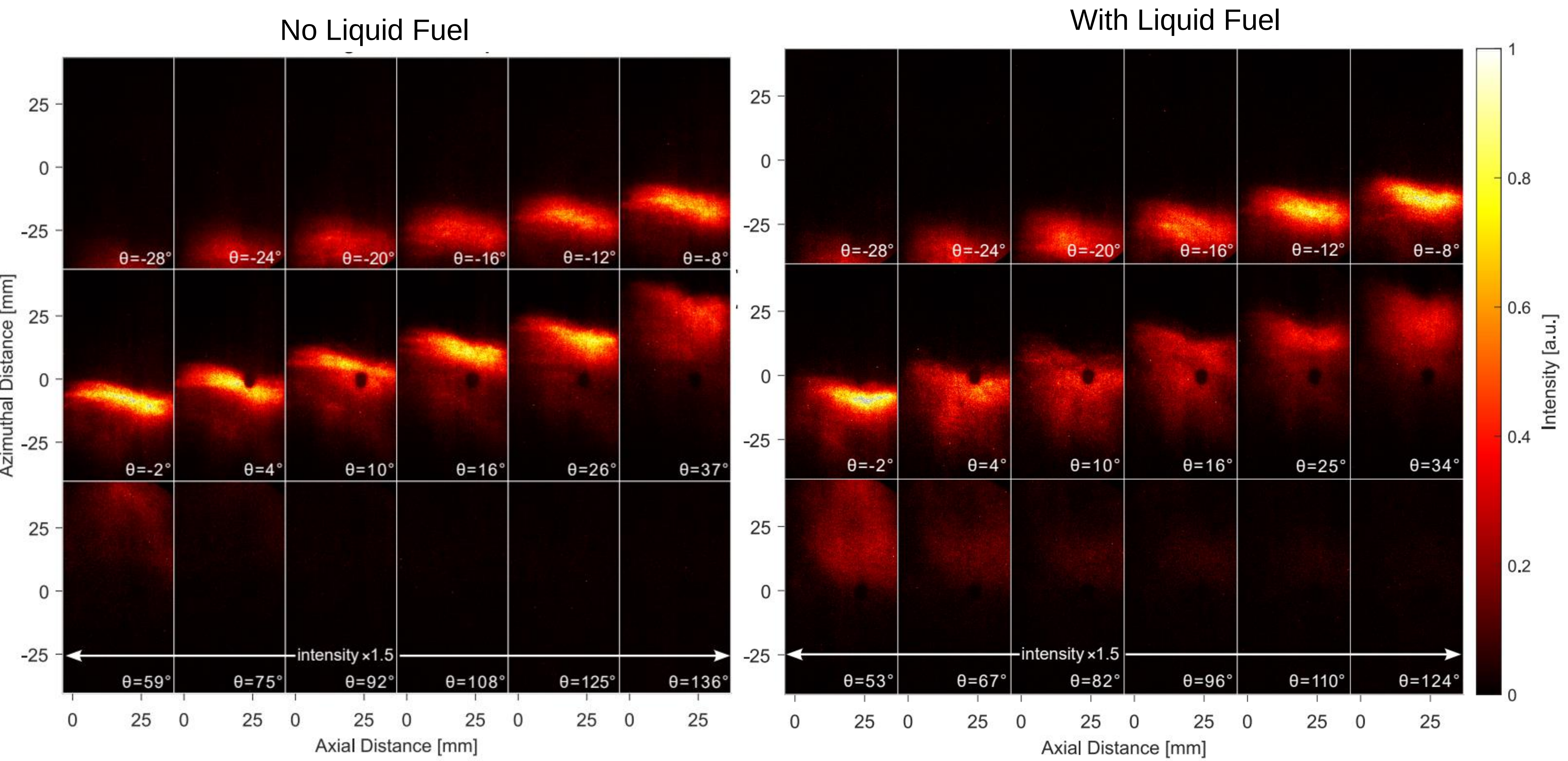
0.23 kg/s air with 9 bar injection pressure



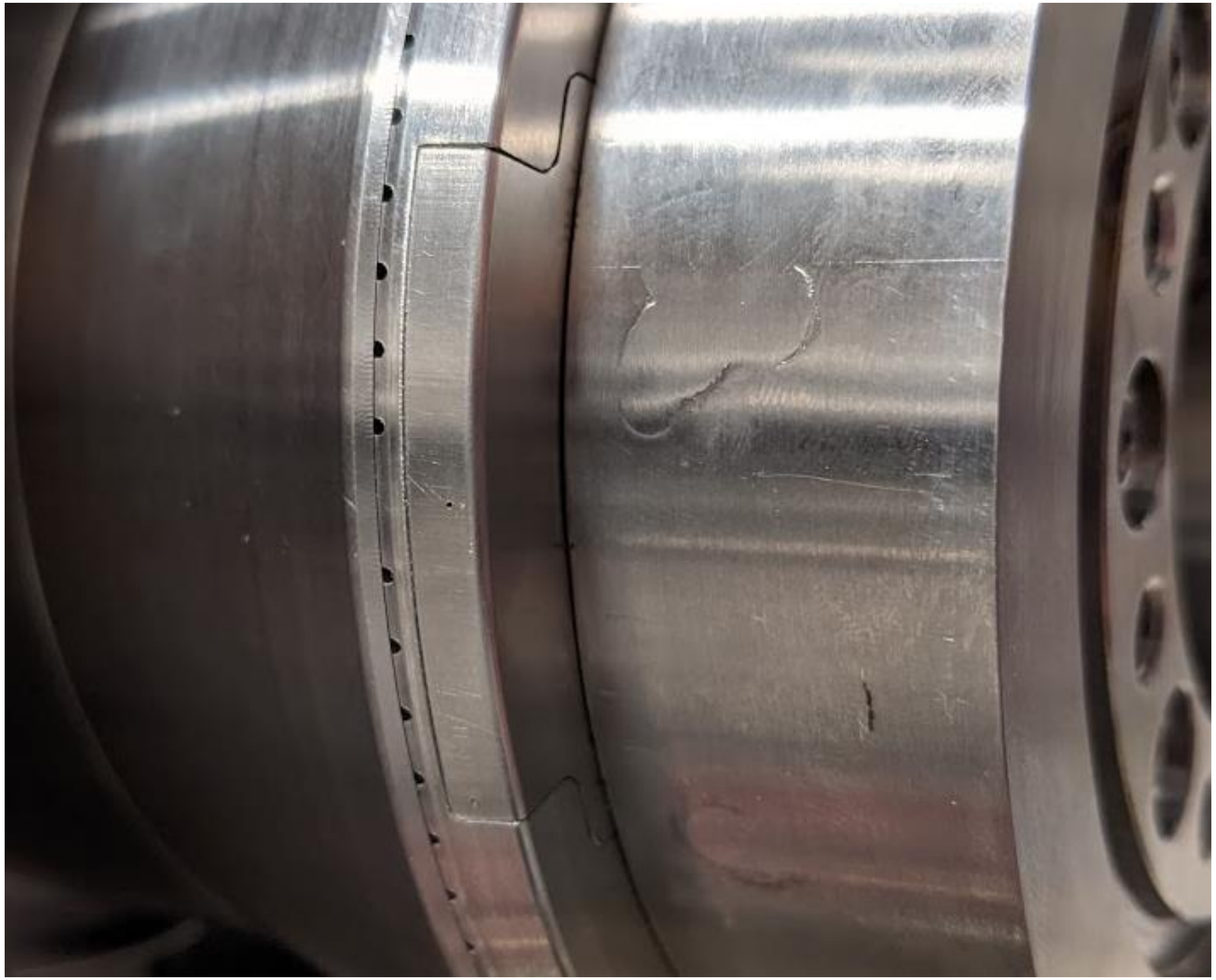


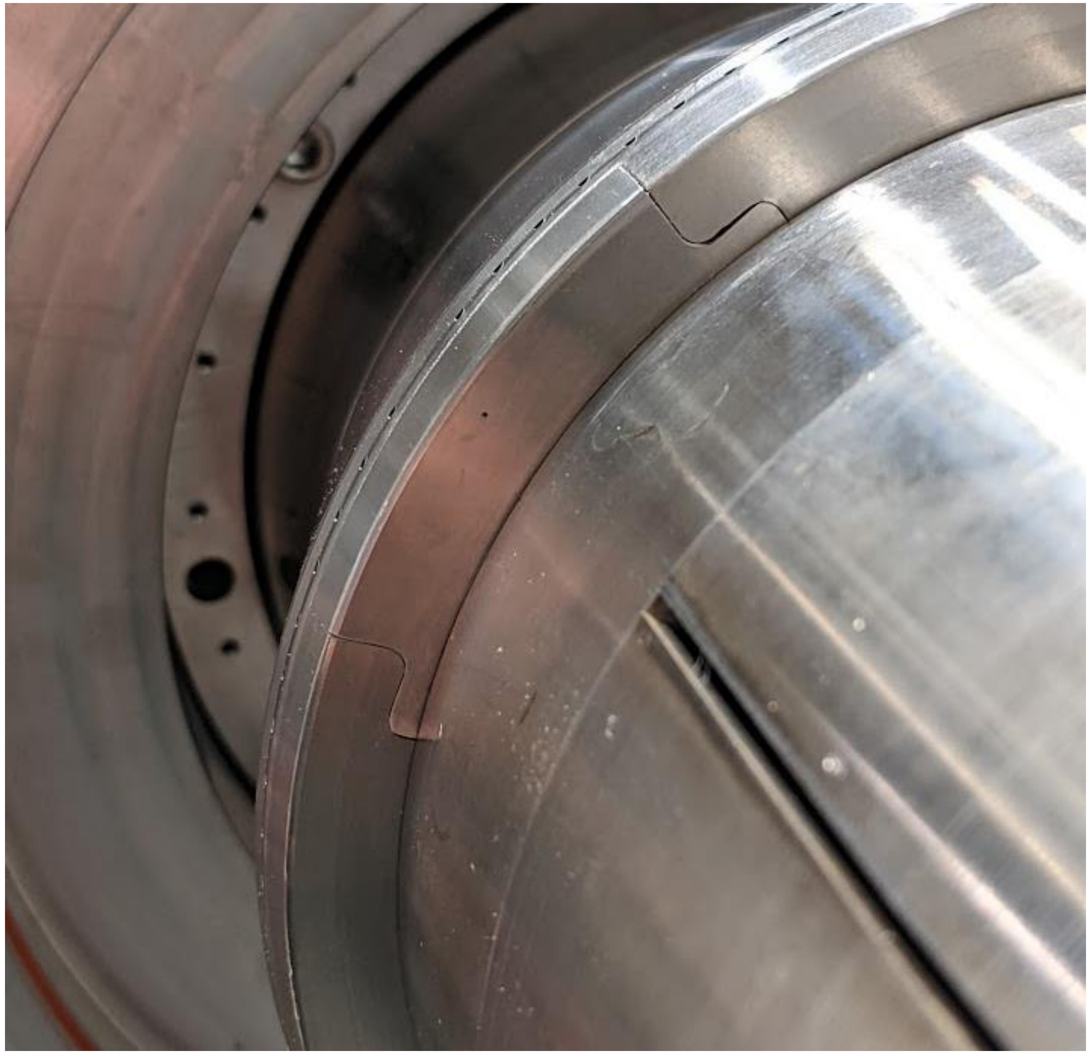
~120 μm/pixel

Chemiluminescence Imaging



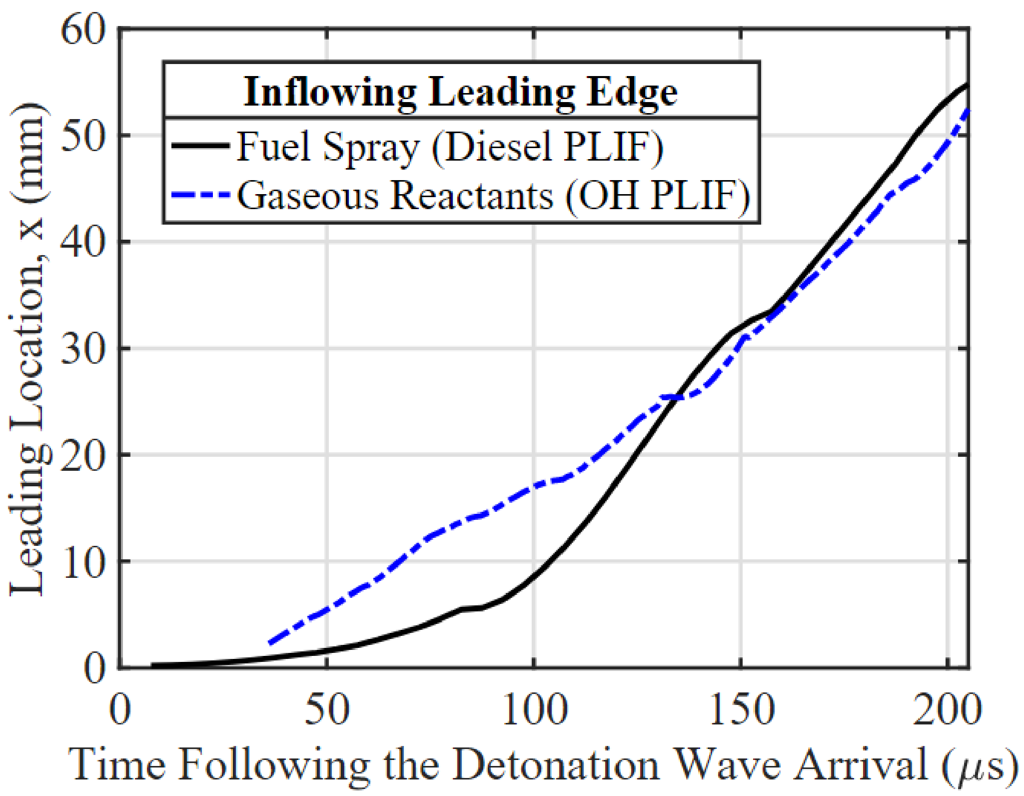
Liquid Fuel Hardware





Refill of Liquid Fuel vs OH PLIF

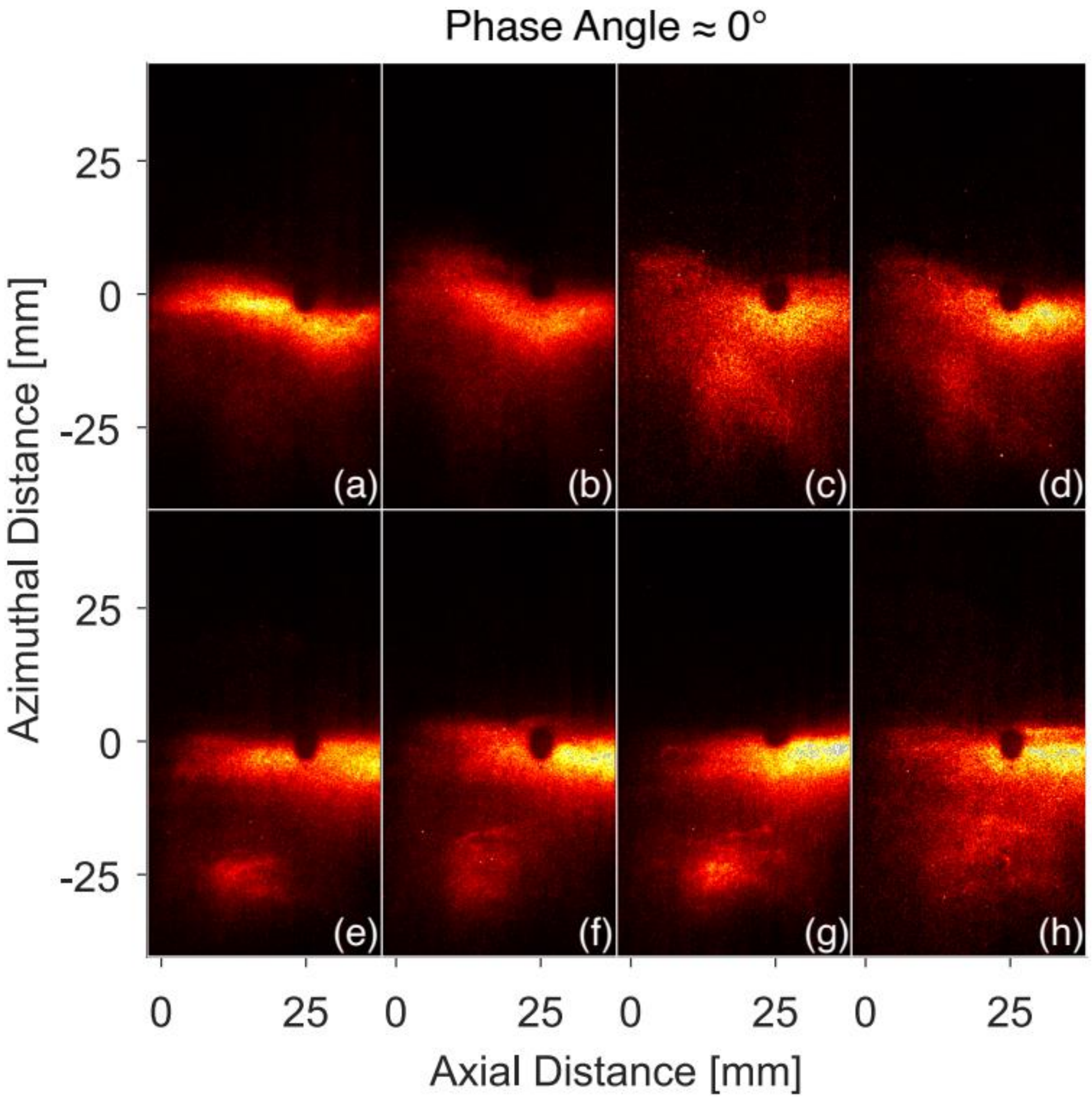
- A comparison between apparent leading edge (axial distance) of liquid fuel spray as it refills the channel and OH PLIF signal as fresh reactants enter the channel.



OH* For Different Conditions

(a) 0.5 lbm/s no liquid
(b) 0.5 lbm/s, low P
(c) 0.5 lbm/s, high P
(d) 0.5 lbm/s, high P

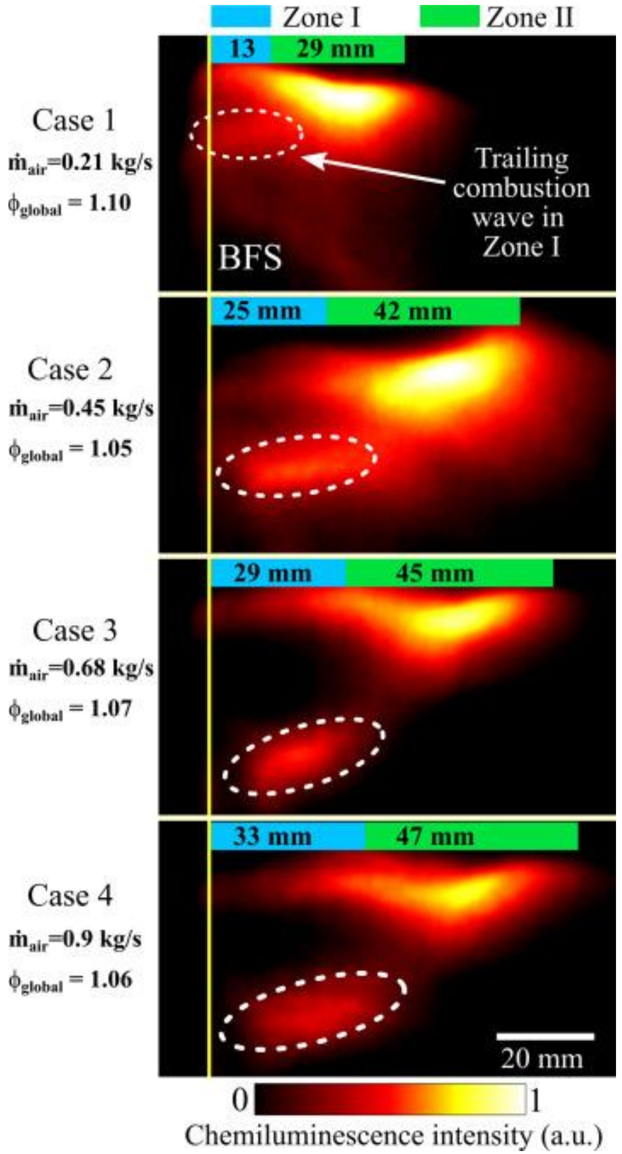
(e) 1.0 lbm/s, low P
(f) 1.0 lbm/s, high P
(g) 1.0 lbm/s, high P
(h)1.0 lbm/s, high P, phi 0.8

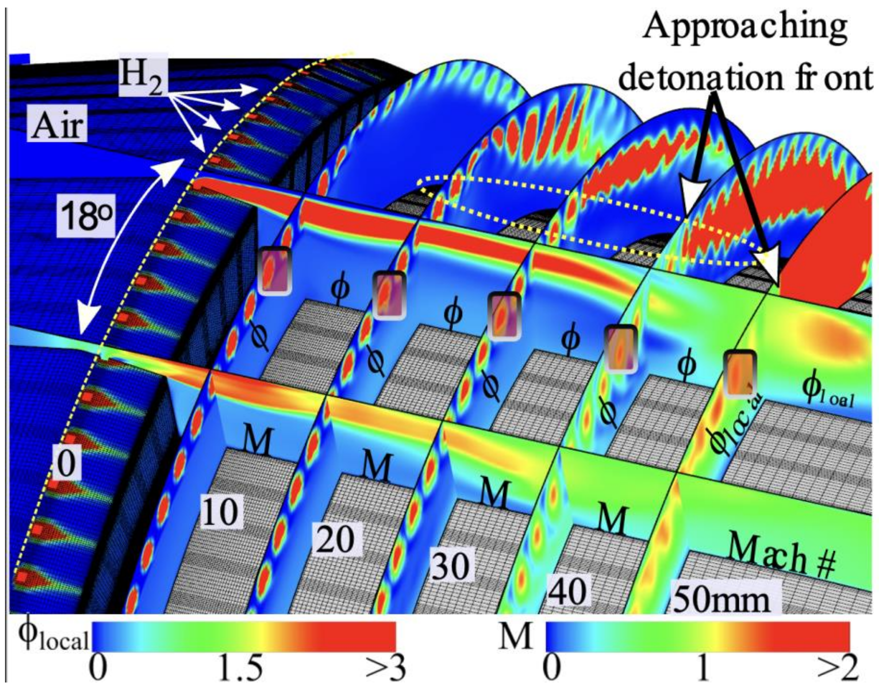


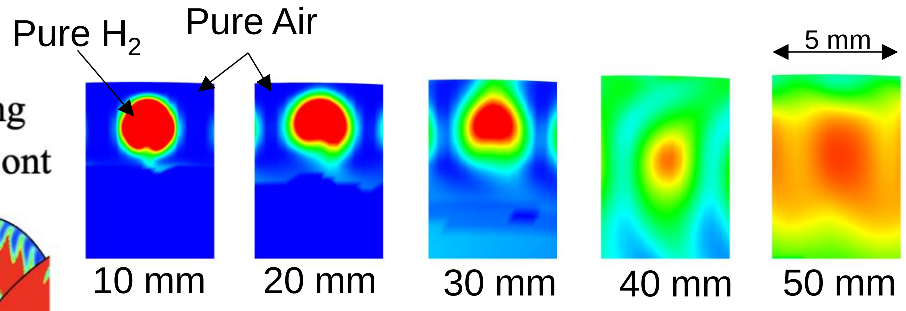
0.23 kg/s

0.46 kg/s

Numerical Simulations

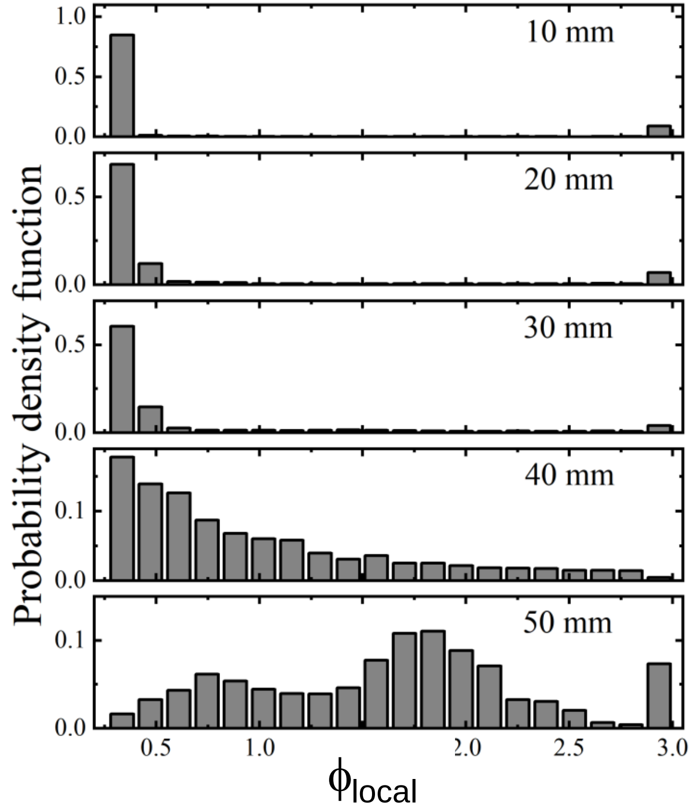






ϕ_{local} for a fully developed fuel jet

PDF of ϕ_{local} between 18° span



Athmanathan et al., On the effects of reactant stratification and wall curvature in non-premixed rotating detonation combustors, Combs. Flame. (2022)

OH PLIF Compared to URANS Simulation