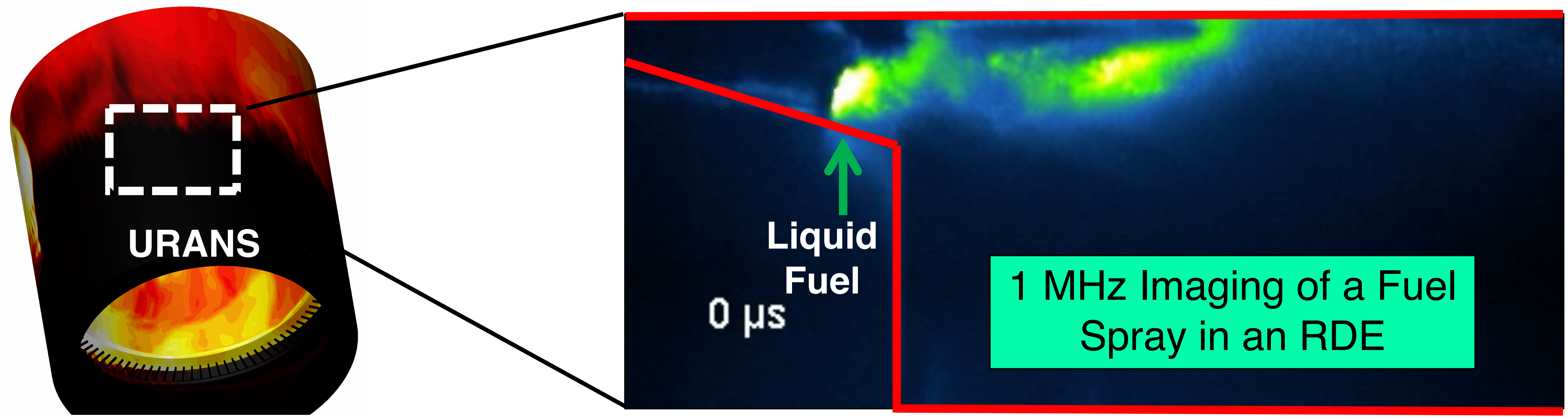
Time Resolved Visualization Of A Liquid Jet In An RDE Using MHz Rate Diesel PLIF



The Team

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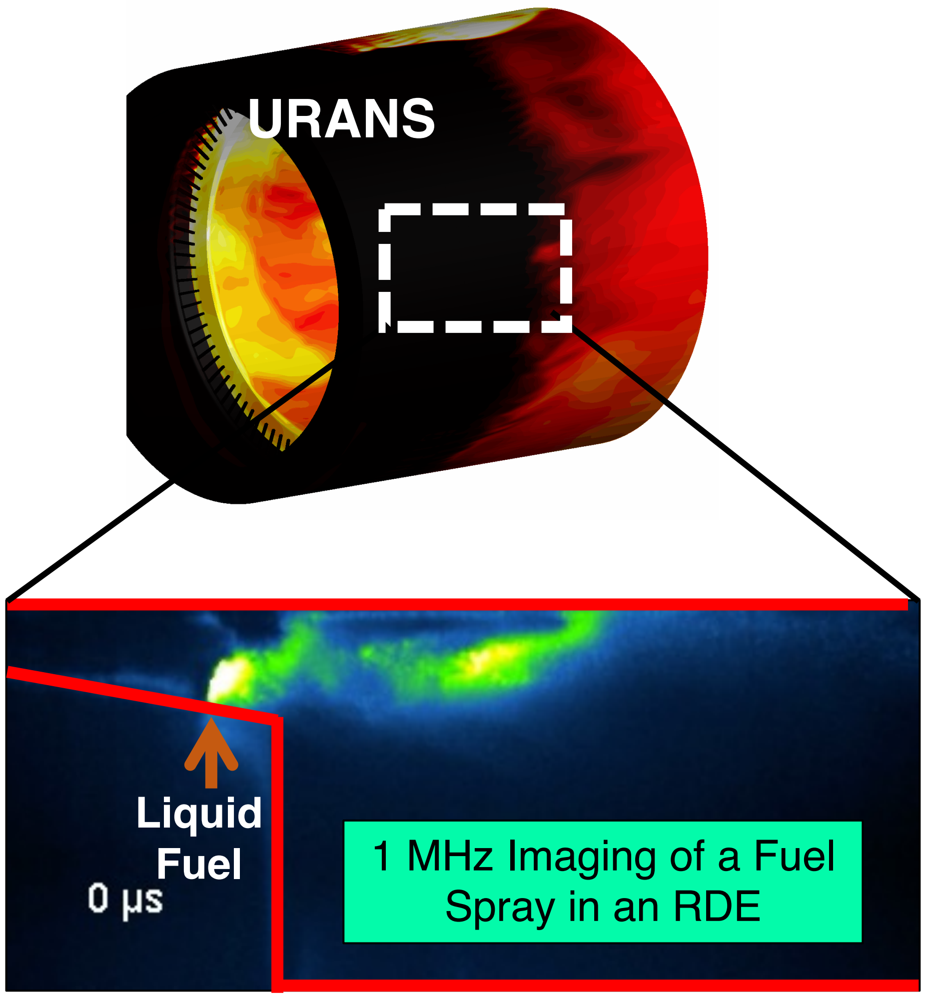
Overview

- ❑Motivation for RDE injector behavior studies
  - ❑Limited characterization of RDE processes
  - ❑Demonstrate advanced time-resolved imaging diagnostics for RDEs
  - ❑Leverage recent advancements in megahertz-rate, burst-mode-laser technology
  - ❑Investigate RDE mixing, fuel spray, and combustion behavior

- ❑Experiment
  - ❑Liquid fuel jet injection in an Annular RDE

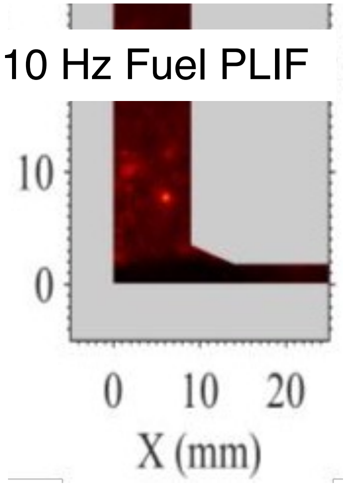


Motivation and Objectives

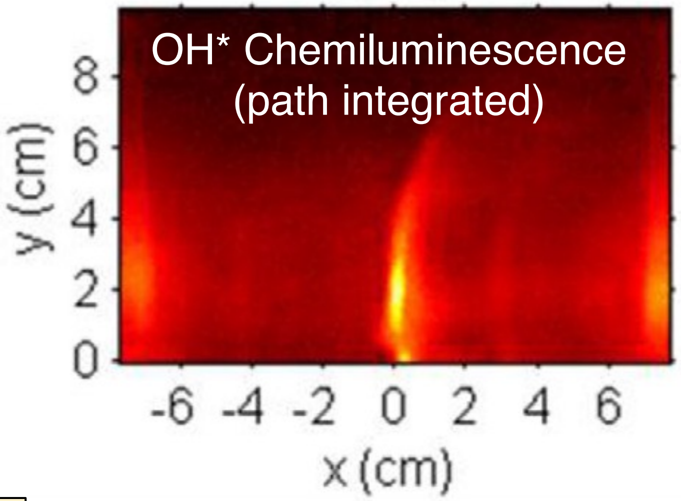
Motivation

- ❑ Mixing – what does it look like and how does it impact performance?
  - ❑ Non-premixed, stratification
  - ❑ Pre-wave and post-wave burning
  - ❑ Product mixing with reactants
- ❑ Injectors – Reverse flow. Ox/Fuel recovery times

AFRL RDE (2015)
Fuel turns off 22% of cycle



AFRL RDE (2017)
Pre and Post Wave Burning

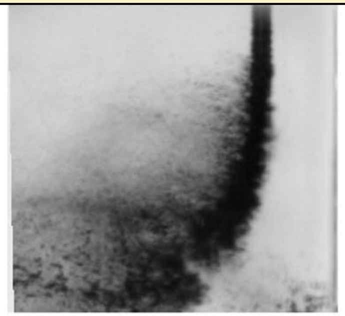


Objectives

❑ Transition/develop/evaluate 100 kHz – 1 MHz laser-based imaging measurements for mixing, behavior, and burning

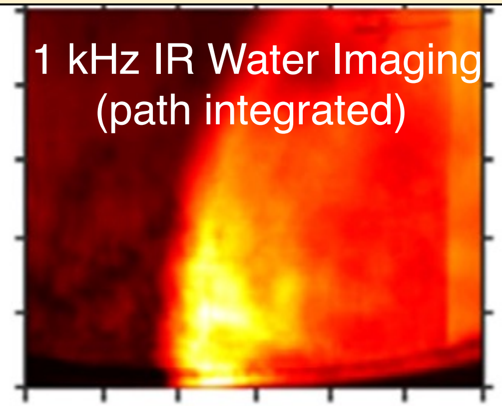
❑ Improve characterization of injector dynamics and mixing related processes, toward liquid RDEs

Heister (Purdue, 2019)
Long recovery time for liquid jets (longer than cycle times)



k) Full recovery (675 μs)

AFRL RDE (2019)
Structure of Combustion Products



Optically Accessible Annular RDC

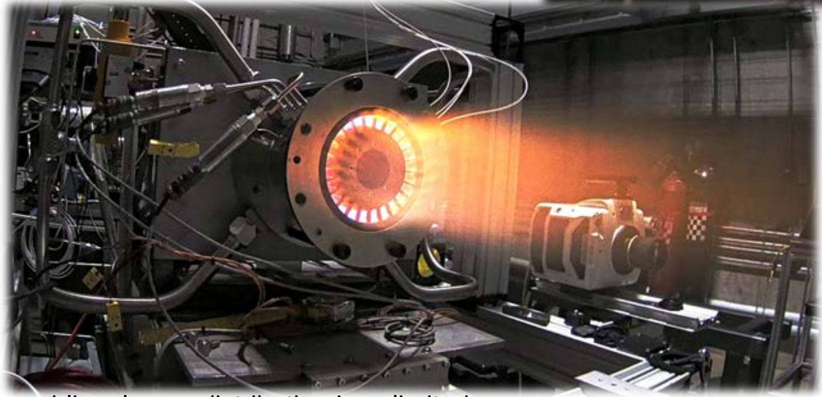
- ❑ **Turbine-integrated High-pressure Optical RDC (THOR) built in collaboration with Spectral Energies and Prof. Meyer, Prof. Paniagua and Prof. Braun.**

Why build another RDE?

- ❑ Experimental test bed to understand detonation physics from lab-scale to engine relevant testing
- ❑ Design Goals:
  - ❑ Canonical geometry and injector design
  - ❑ Relatively simple modeling effort
  - ❑ Maximum optical access (inlet plenum-exit)
  - ❑ Maximum modularity (Geometry, Fuels, Oxidizers)
  - ❑ Scalability for various TRL levels
  - ❑ **Concurrent URANS simulations** for understanding key flow physics
- ❑ **Non-premixed and premixed operation**
- ❑ Provide benchmark data for model evaluation
  - ❑ Currently 3 other groups simulating this RDE (NASA/PU/Argonne)
  - ❑ **Fluid geometry is open and available to community for testing.**
- ❑ **3+ years of continuous advancements in diagnostics and RDE physics understanding**

Optically accessible test rig

Premixed THOR (Meyer collaboration with Dan Paxson)

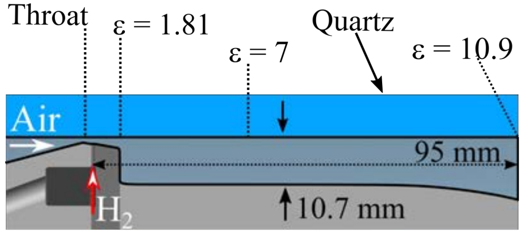


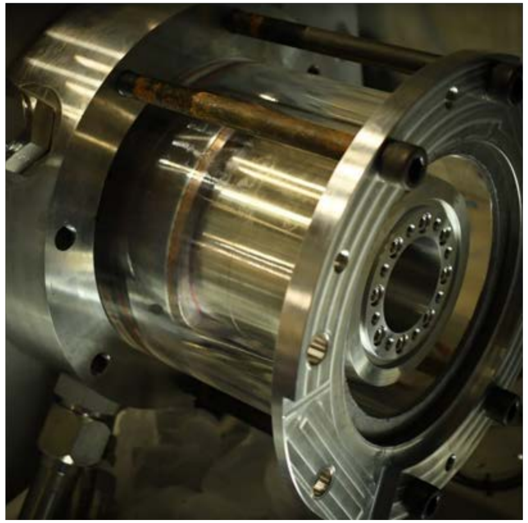
Turbine-integration efforts (Meyer/Paniagua collaboration with DOE UTSR)

THOR Overview

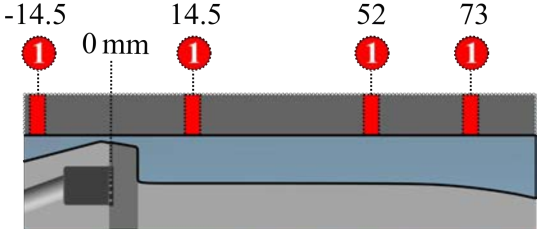
- Geometric Parameters
  - ID = 114 mm Length ~ 95 mm
  - 1.4 mm air slot for axial-air
  - JICF injection of hydrogen
  - 100 fuel injection holes
  - 10° expansion angle
- URANS simulation parameters (Metacomp CFD++ solver)
  - 45 million cells
  - Structured uniform grid
  - 1-step reaction model for H_2-air system (Frolov,2016)
  - Boundary layer mesh refinement
  - k-omega SST Turbulence model

Optical config.

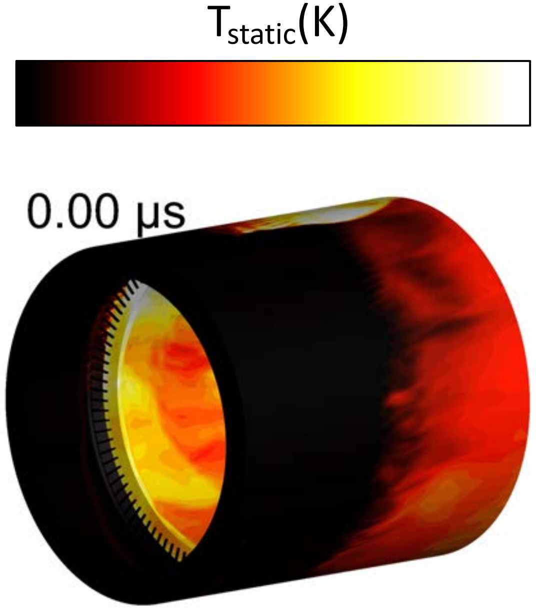




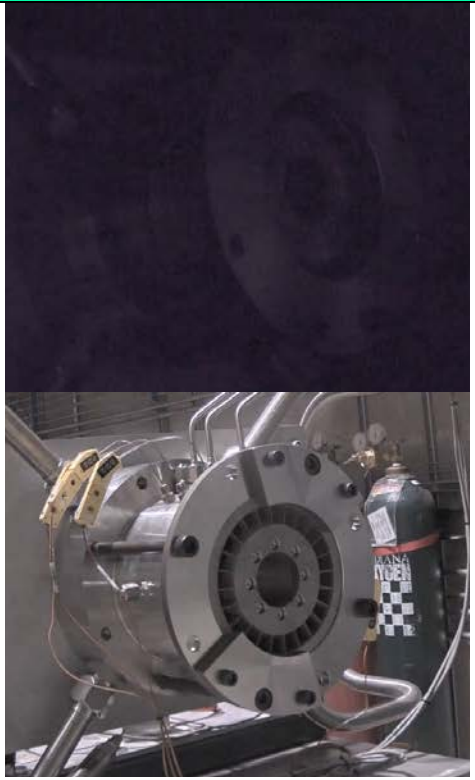
Instrumented config.



URANS (T_{static})



Low-speed video



Burst Mode Lasers for High-Speed Diagnostics for RDEs

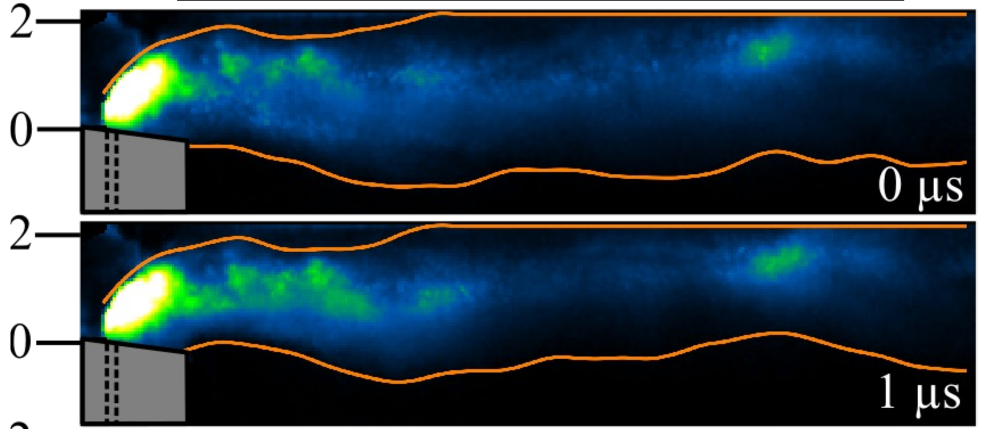
Transportable burst-mode laser system developed by Spectral Energies, LLC

Unique Features

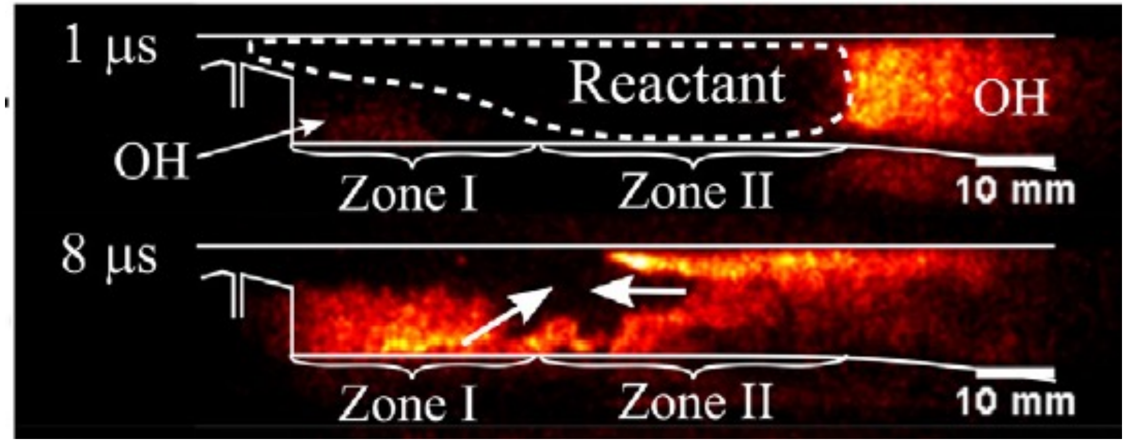
1. Versatile laser source
2. High power and high speed (MHz rates)
3. Adjustable repetition rate
4. Capabilities for multiple, simultaneous measurements
5. In-situ diagnostic tools

Measurements in RDEs

1 MHz Fuel-PLIF Imaging (Liquid Spray)



1 MHz OH-PLIF Imaging (Combustion)



THOR RDE Diagnostics Advancement Portfolio

Advanced Measurements in THOR

Current NASA Program
- MHz OH-PLIF
- MHz Liquid PLIF, Fuel PLIF and Mie Scattering
- MHz Seeded Tracer PLIF (NO, Dyes, etc.)

- Coherent anti-Stokes Raman Scattering
- Femtosecond Laser-Activation and Sensing of Hydroxyl (FLASH) velocimetry
- Background oriented Schlieren (BOS)

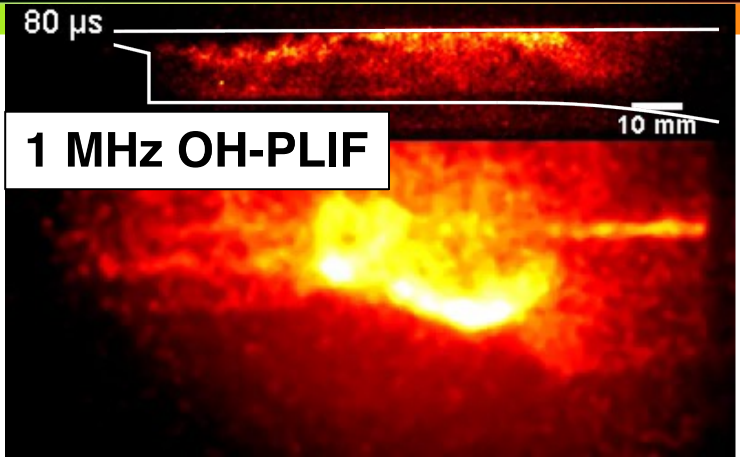
Detonation Structure and Evolution
- 3-D detonation structure
- Azimuthal reflected shock combustion
- Mixing effects on detonation structure

Liquid Injection
- Physics of liquid injection refill and recovery dynamics
- Liquid injector response

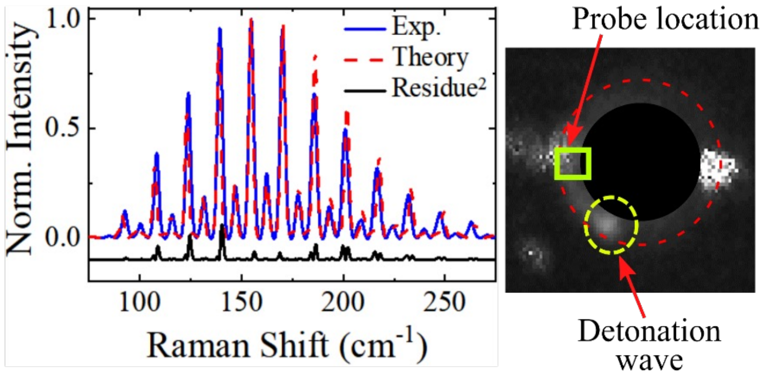
Mixing
- Fuel/Oxidizer mixing and distribution
- Trace gaseous flow paths
- Combustion products mixing

Quantitative Temperature and Species
- Feasibility of high precision exhaust thermometry
- Exhaust pattern factor

Flowfield velocity
- Tracer free velocity mapping at repetition rate up to 1 MHz



CARS Spectra fit for 2070 K



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Liquid Jet Physics in RDC Environment

Current state of the art

- **Full liquid injector based RDC** – lack of optical access
- **Simulations** challenging and cost prohibitive
- **Single-shot straight channel experiments don't inform inter-cyclic injector response**
- Additionally **curved wall physics** (e.g. ARSC) are **absent** in straight channel experiments

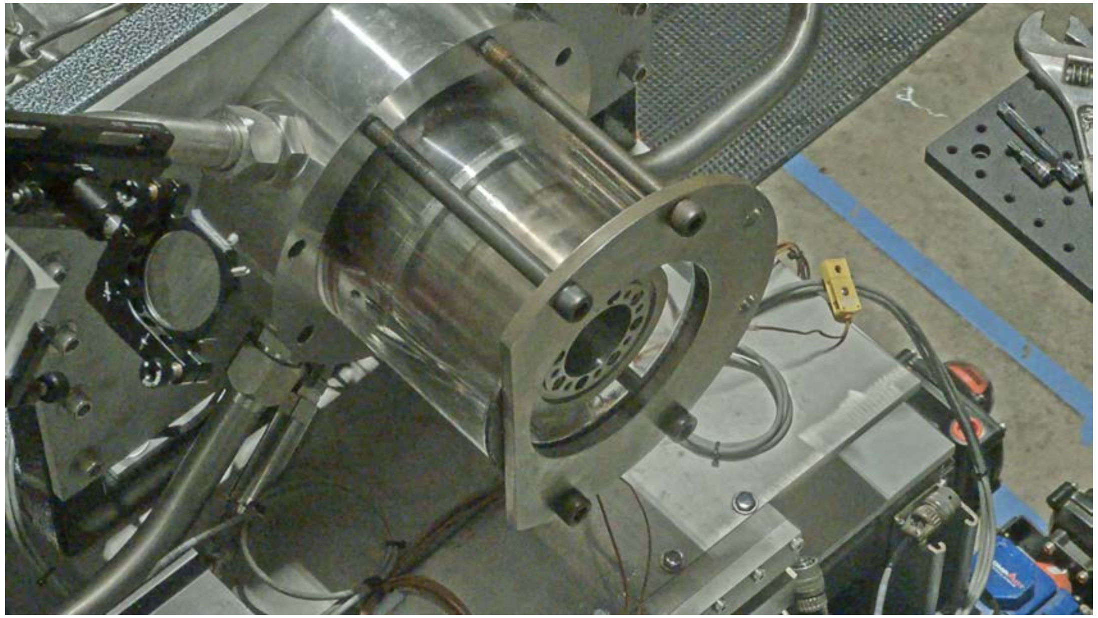
Approach Rationale

- Utilize THOR's optical access to inject liquid through a **'single-element'** injector and use the H_2/air detonations as a detonation driver.
- Minimize computational cost by having a small two-phase flow domain

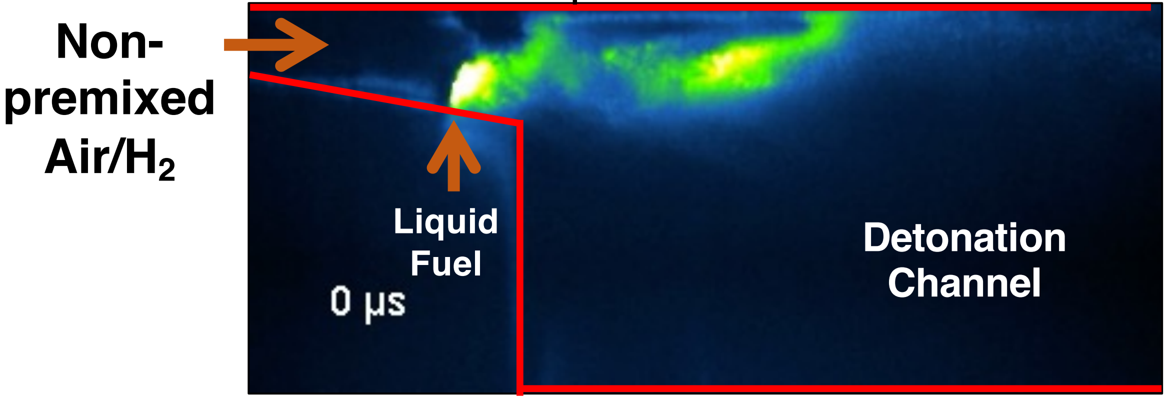
Goals

- Improve 'multi-cycle' injector response by injecting liquid into a continuous impulse of rotating H_2/air detonations
- Provide benchmark data for model validation
- Minimize impact of liquid fuel injector on detonation

Low speed video



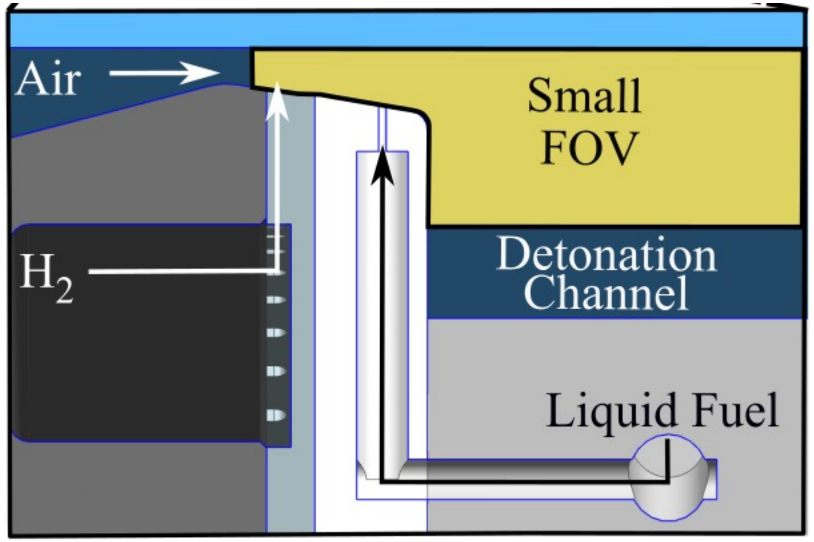
Sample MHz refill movie

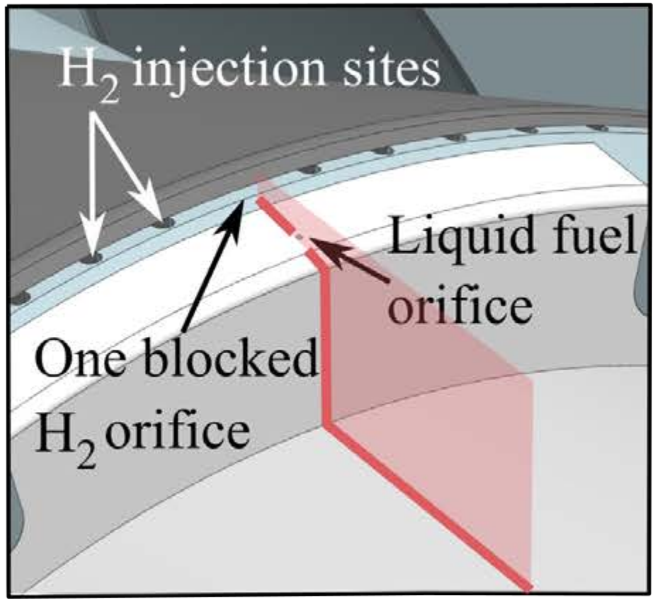


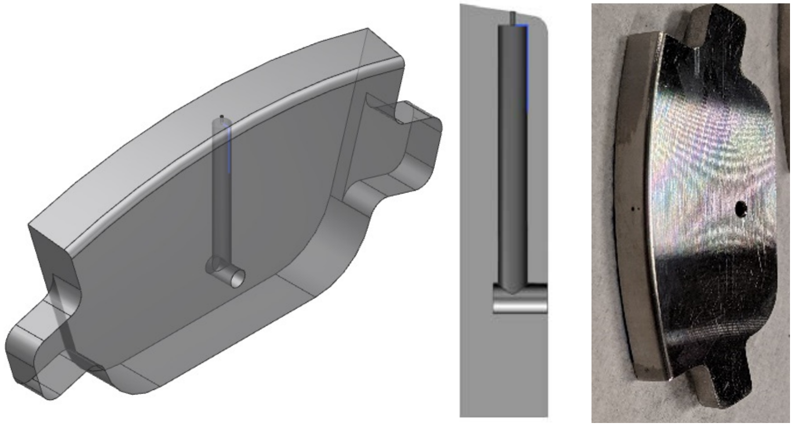
Experimental Setup

Experiment

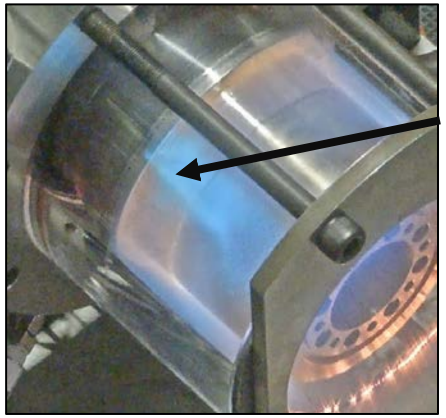
- THOR as a detonation driver
  - Air-H_2
- Replaced a H_2 injection orifice with a single liquid fuel jet
- Liquid fuel orifice diameter = 0.3 mm
  - Diesel flow rates between 0.2-1.5 g/s







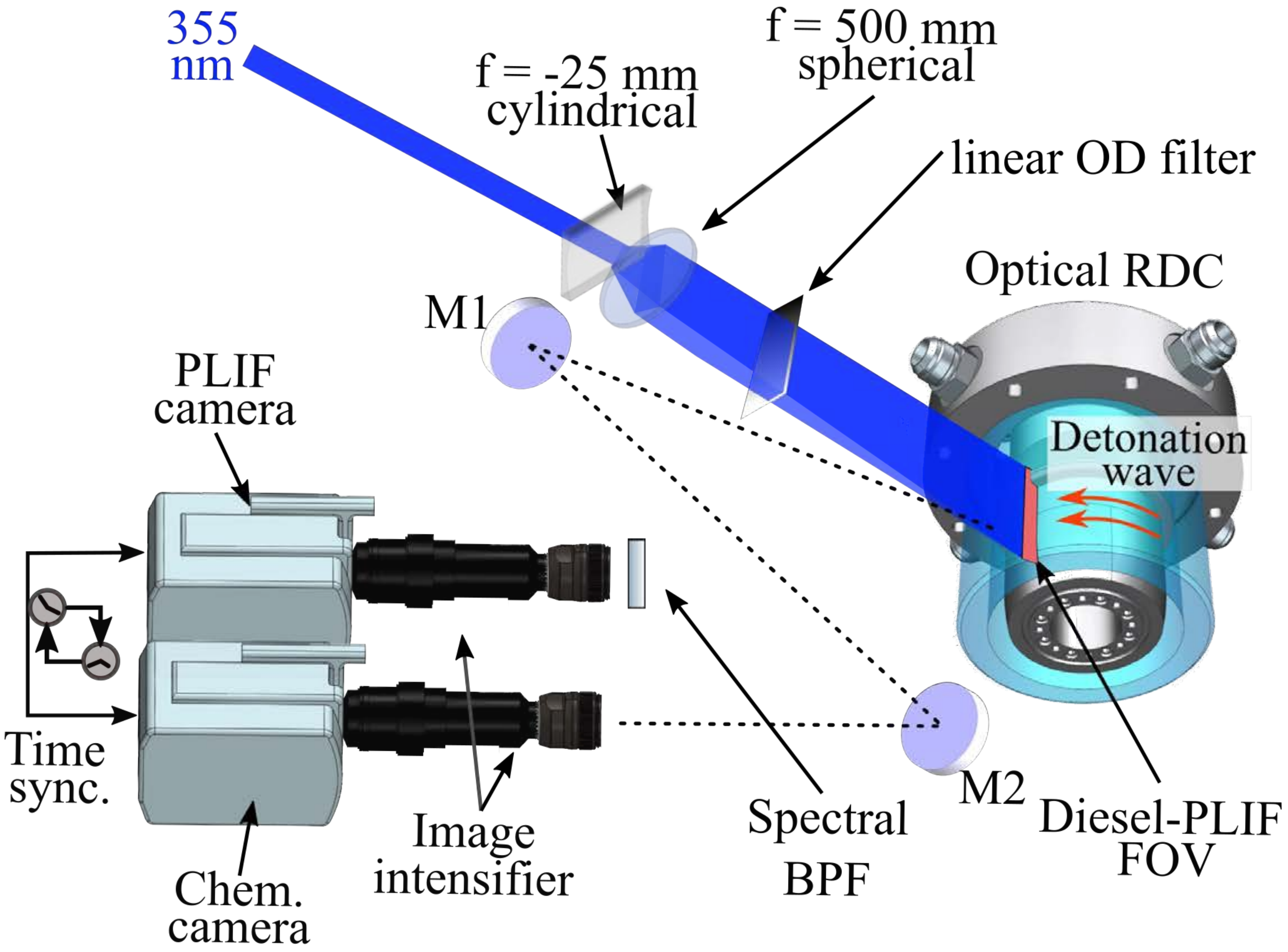
3D printed single element liquid injector



3D printed injector admitting diesel in RDE

Diagnostics

- A range of laser-based imaging diagnostics were initially explored, such as
  - 355-nm Fuel PLIF
  - NO-PLIF
  - Tracer PLIF
  - Mie Scattering
- 355-nm Fuel PLIF was chosen
  - High SNR
  - BML has suitable THG pulse energy
  - No need for added tracer
- 200 kHz – 1 MHz rep rates
- 10 ms BML duration
  - ~ 40 consecutive detonation periods are imaged per test



Test Matrix

Test Condition	Flow Rates			Equiv. Ratio [-]	Momentum Flux Ratio [-]	Liquid Fuel Inj. Pressure [bar]	Nom. Wave Speed [m/s]	Nom. Cycle Freq. [kHz]	Throat Mass Flux [kg/m²/s]
	Air [kg/s]	Hydrogen [kg/s]	Liquid Fuel [gr/s]						
1	0.46	0.012	0.91	~1	0.60	15.3	1560	3.9	750
2			0.64		0.29	8.0			
3			0.45		0.14	4.3			
4	0.23	0.006	0.63		0.51	7.6	1450	3.6	380
5			0.45		0.26	4.3			
6			0.34		0.15	2.6			

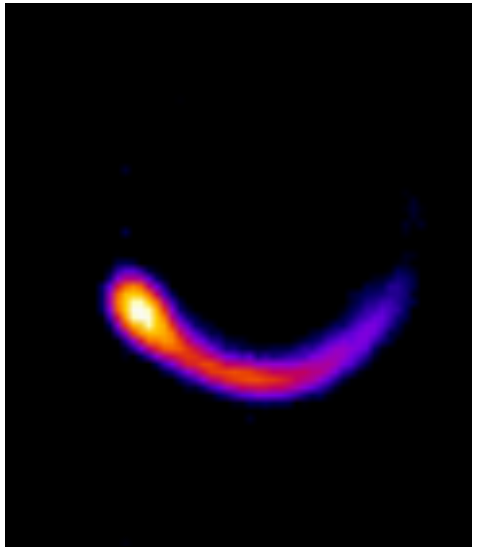
Varied chamber mass flux (low to high air injector stiffness)

Varied momentum flux ratio (liquid jet to air crossflow)

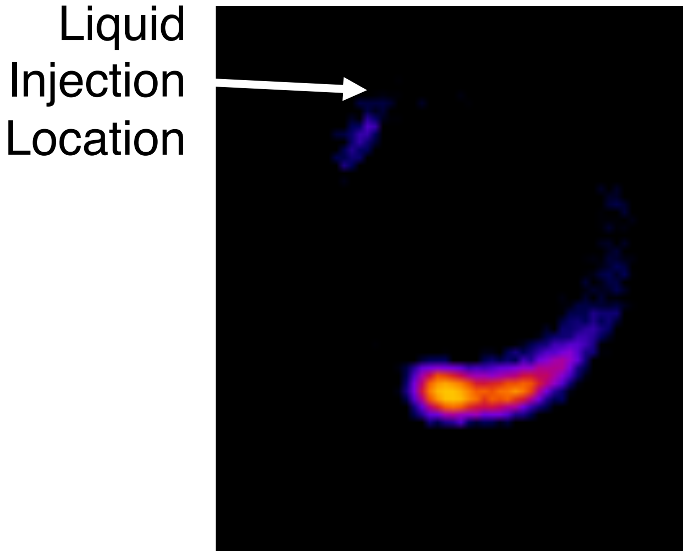
Aft-End Exhaust Imaging

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

No Liquid Fuel



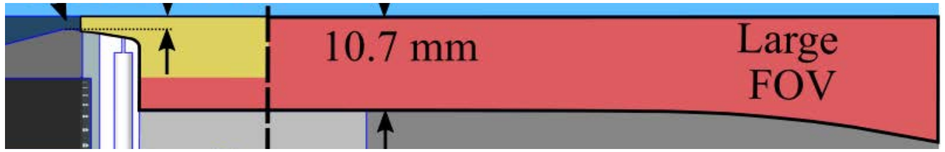
With Liquid Fuel

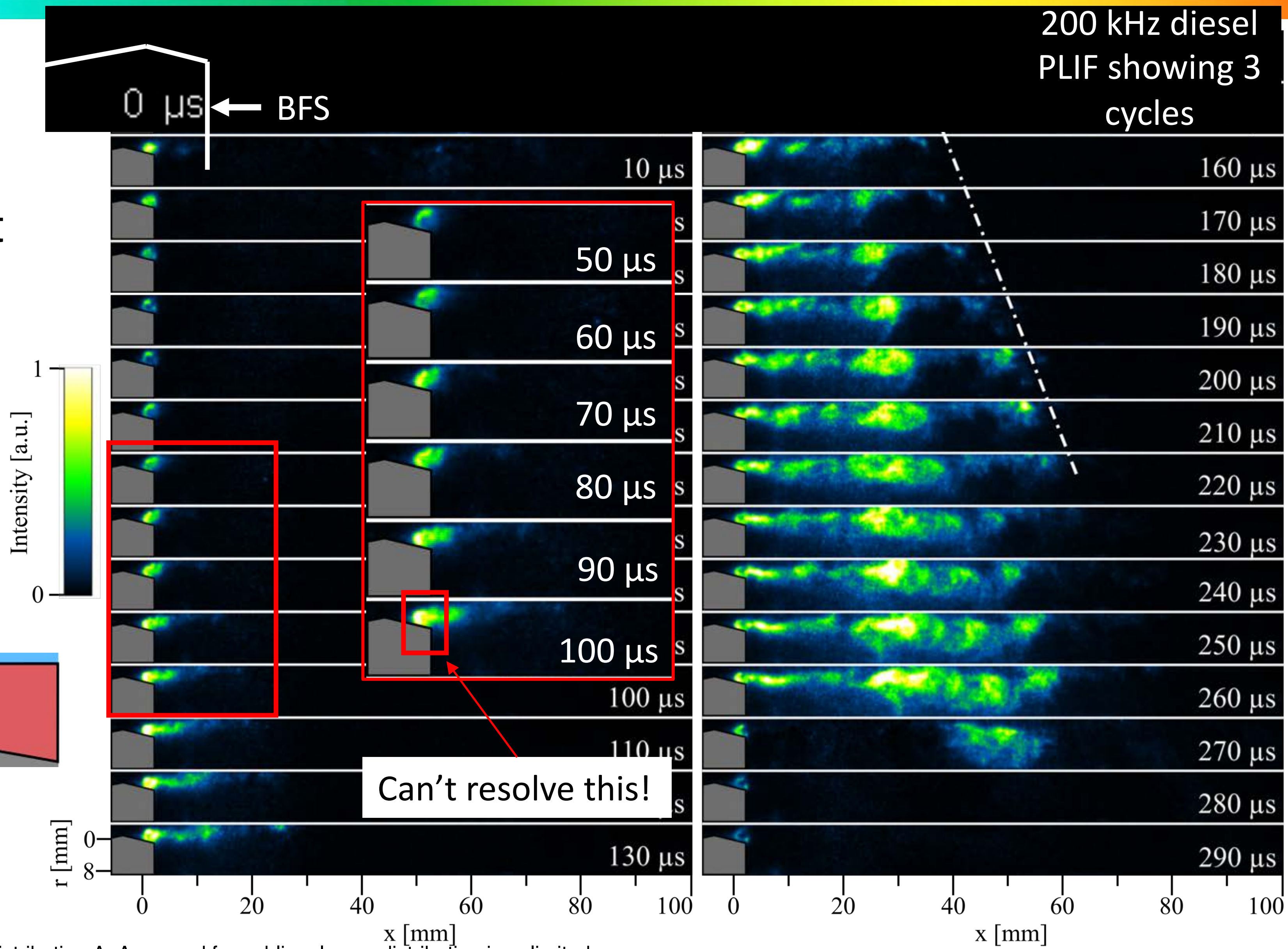


100 kHz Aft-End Chemiluminescence

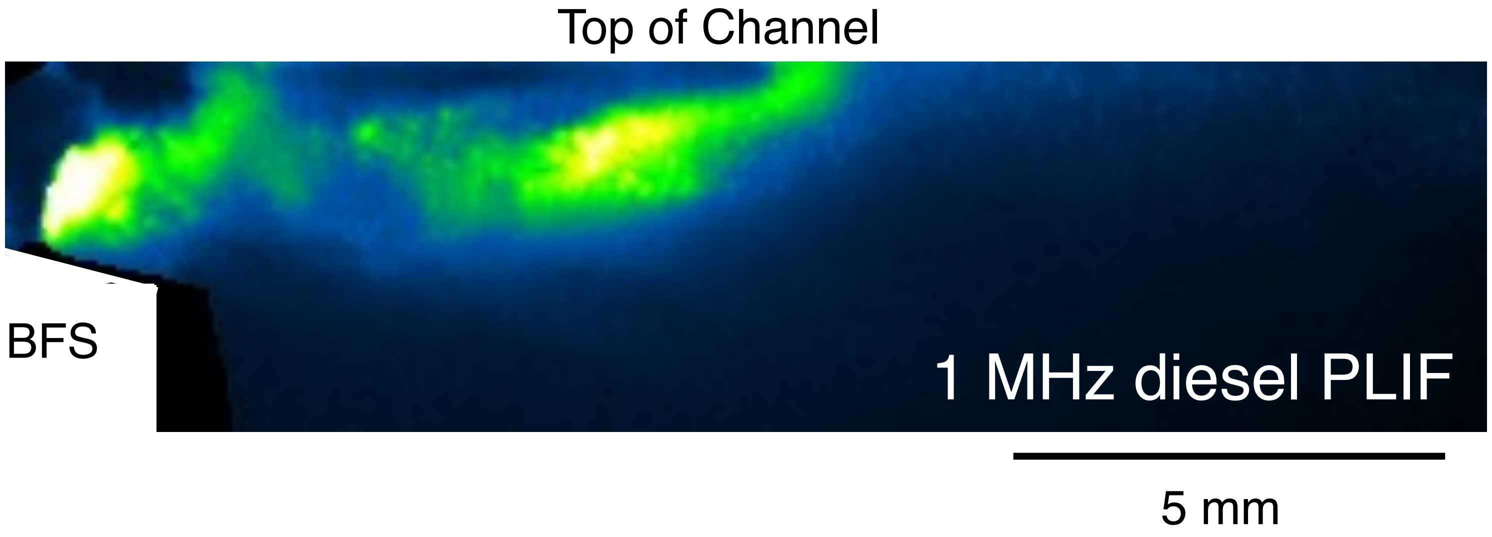
Liquid Fuel Spray - Detonation Interaction Large FOV

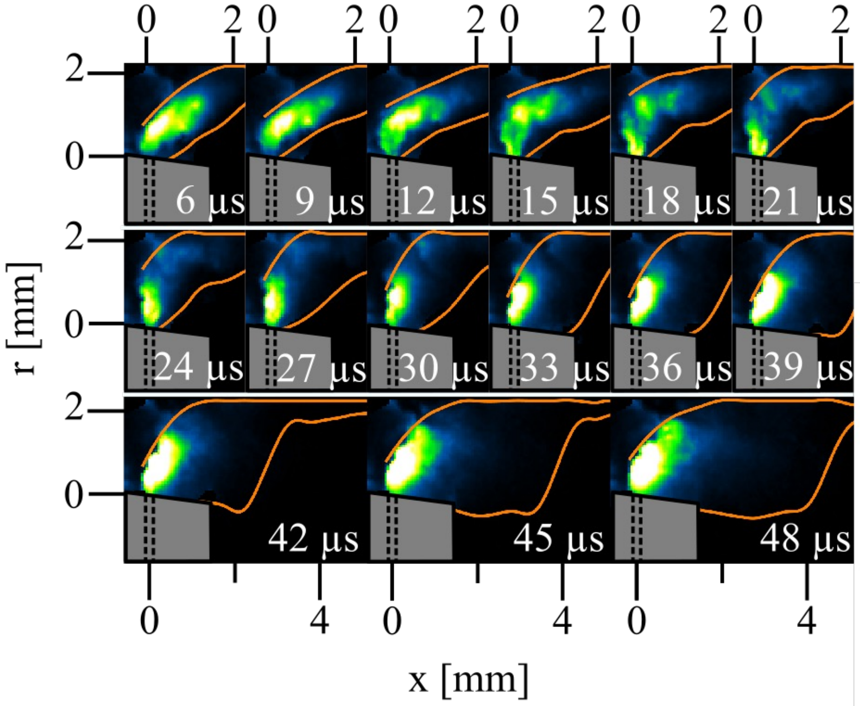
- There is a significant dwell period where diesel is not being issued into the channel
- Diesel injector element does not appear to turn off and recovers well within one detonation period
- This corresponds to Case 2 (0.46 kg/s and q=0.29)



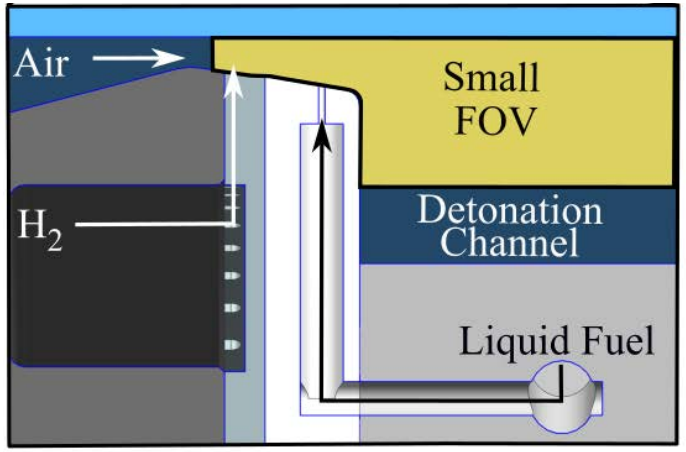


Liquid Fuel Spray - Detonation Interaction Small FOV





- Case 1 (0.46 kg/s and q=0.6)
- Previous data necessitated a test case that can monitor near-field jet response
- Liquid fuel is completely consumed or displaced from the channel within a few microseconds,
- No liquid fuel moves axially upstream after the detonation wave



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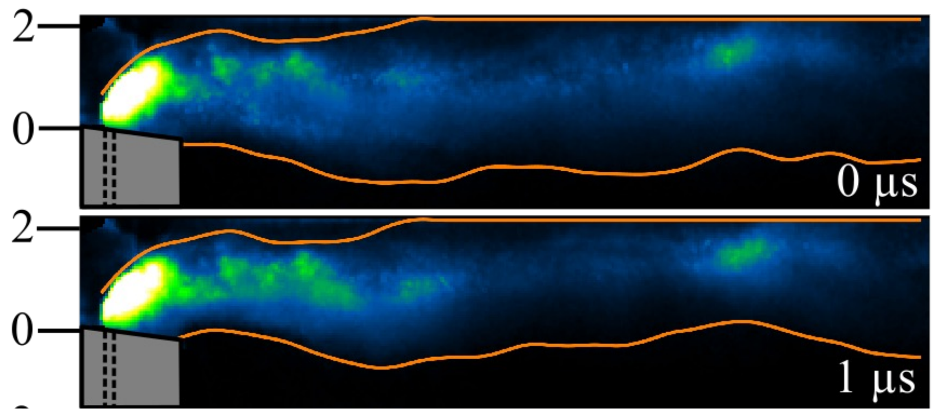
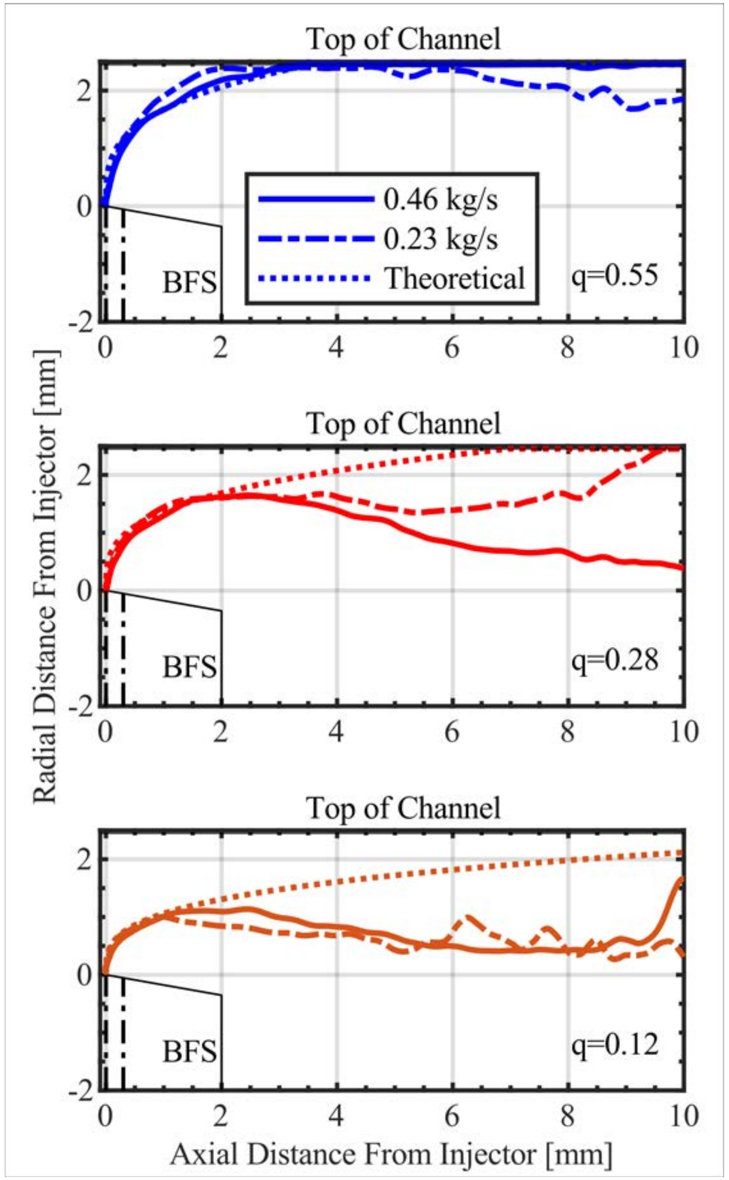
Fuel Spray Trajectory

- Leading edge of the fuel spray is tracked throughout the cycle



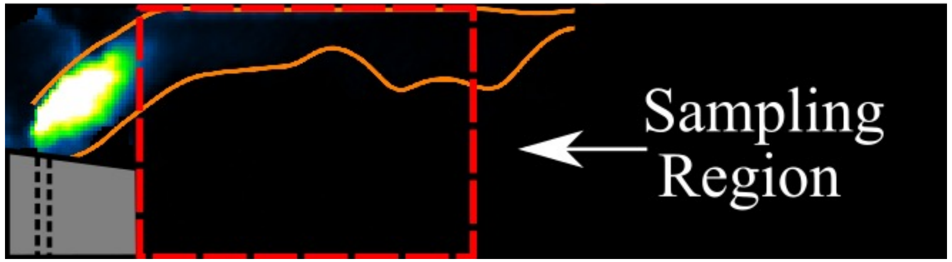
- Trajectories of the fuel spray immediately prior to the detonation wave arrival are averaged
- Trajectories are compared with an experimentally-derived steady flow model

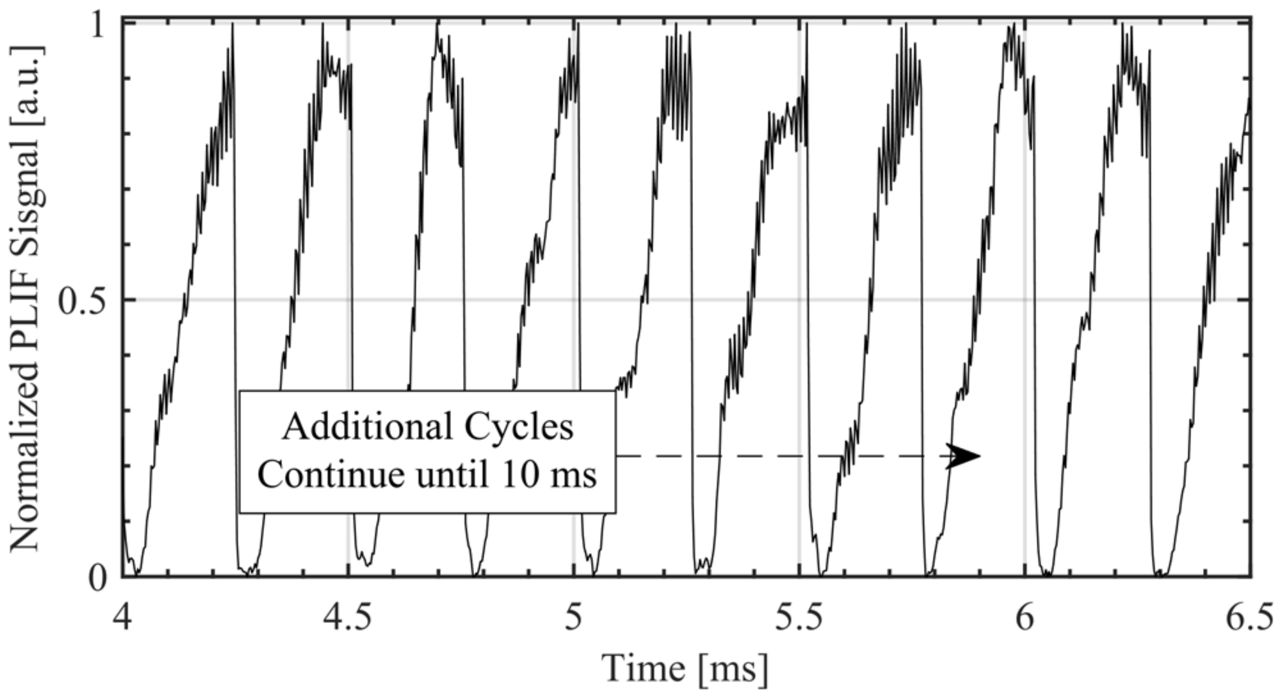
$$\frac{y}{d_j} = 4.73q^{0.3}\left(\frac{x}{d_j}\right)^{0.3}$$

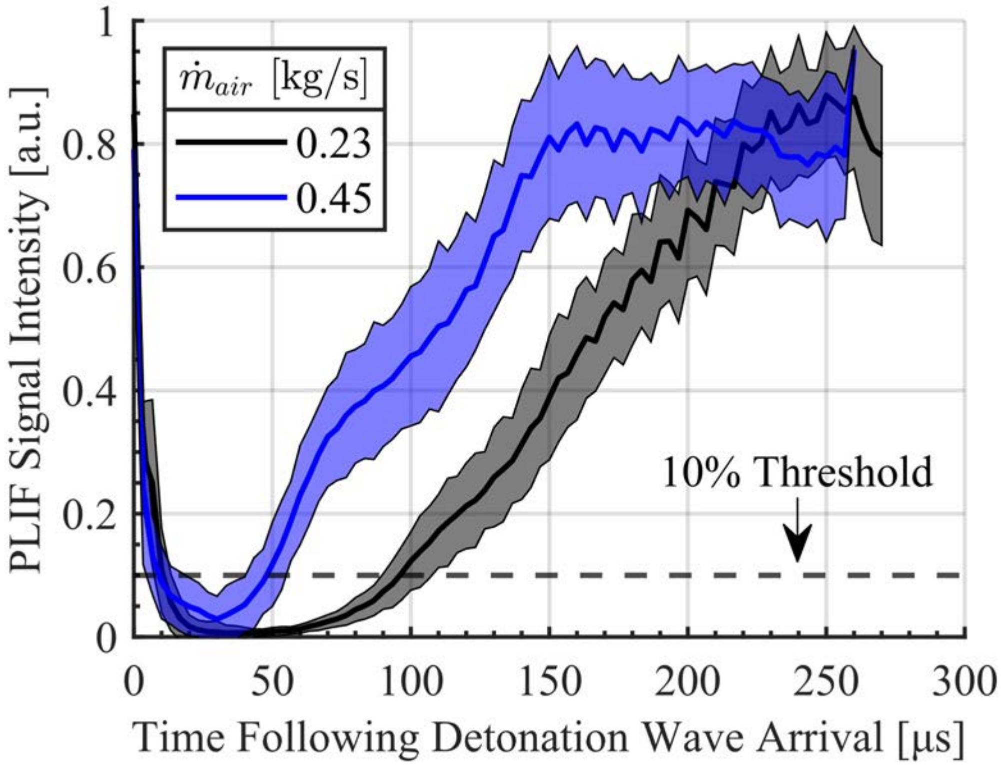


Fuel Spray Dwell Time Methodology

- Sampled PLIF signal immediately downstream of the BFS to monitor dwell time/refill dynamics
- Averaging 30-40 cycles per test to produce refill signal
- Characteristic refill time defined as point where intensity achieves 10%

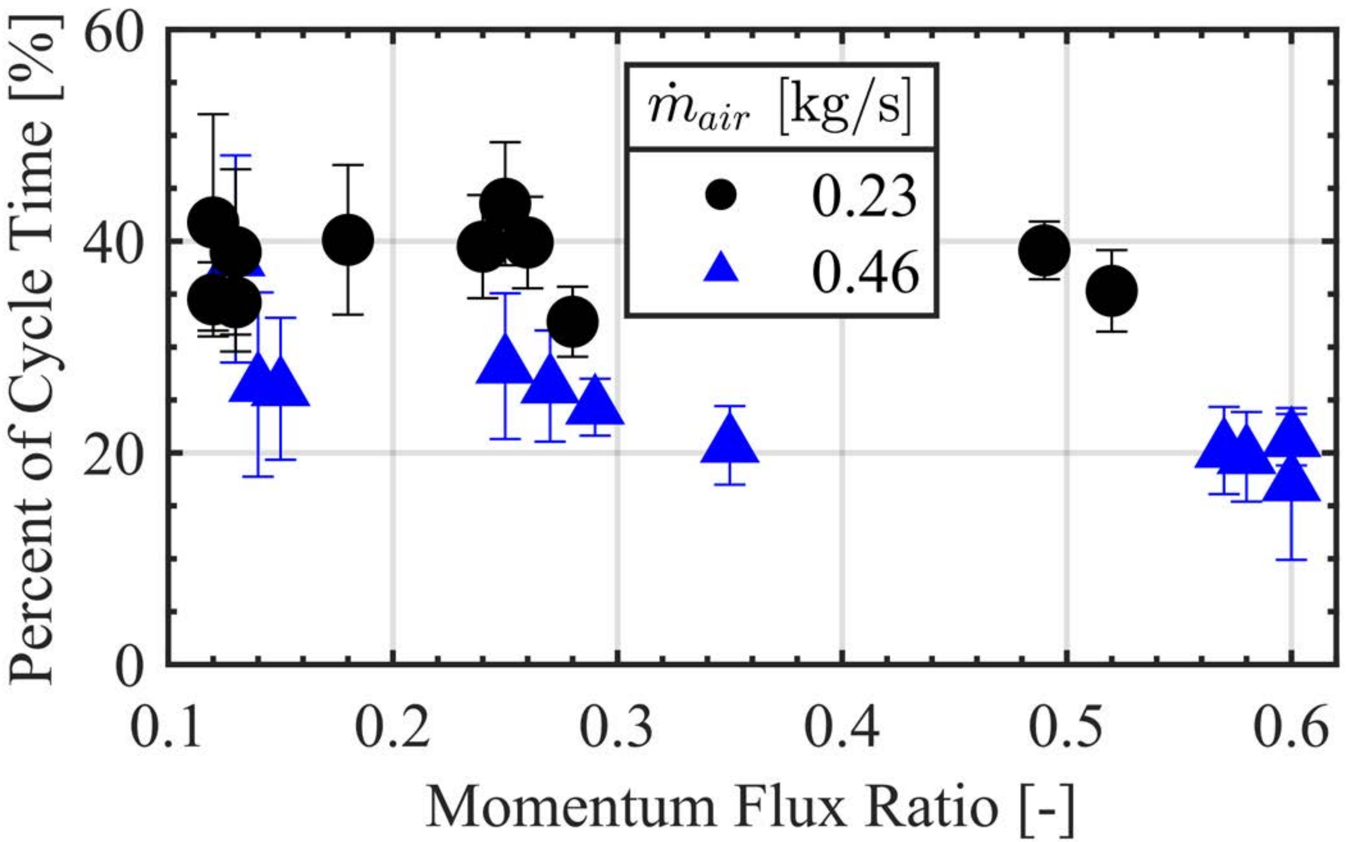






Fuel Spray Dwell Time Scaling

- A scaling is sought that captures the fuel spray dwell time in relation to other hypothesized parameters
- Lower air mass flow rate cases typically have longer fuel spray dwell times
- The fuel spray dwell time is observed to have a weak dependence on fuel spray to air crossflow momentum flux ratio

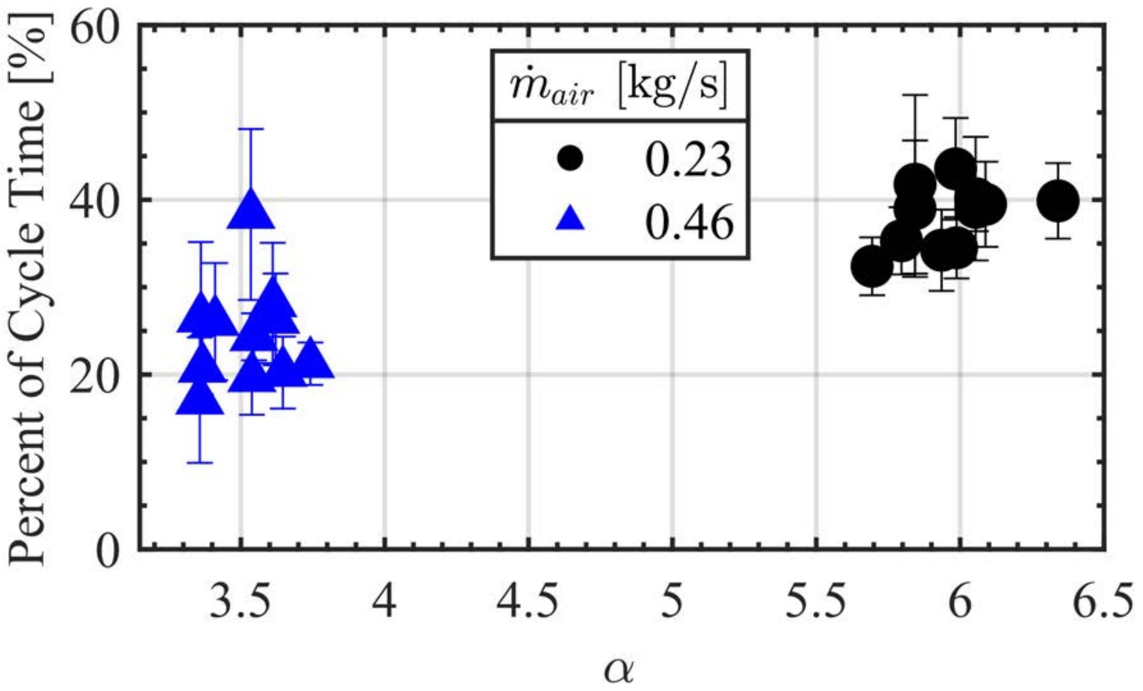


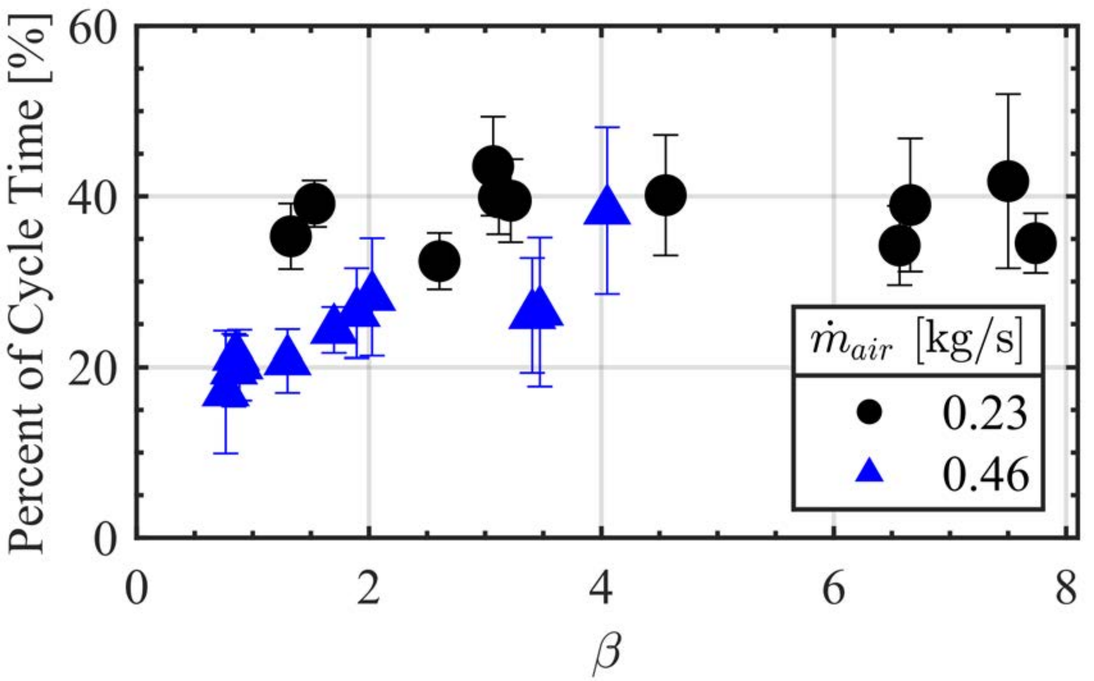
Fuel Spray Dwell Time Scaling

- As a jet in crossflow injection scheme, the fuel spray dwell time should display some dependency on the air injector recovery
- Fuel injector recovery scaling
  - Injector response $\sim f(P'_{det}, \nabla P_{inj}, \dots)$

$$\alpha = \frac{P'_{det}}{\nabla P_{AirInj.}} \qquad \beta = \frac{P'_{det}}{\nabla P_{LiqFuel}}$$

- Detonation impulse strength relative to injector pressure drops appears to influence liquid fuel refill time

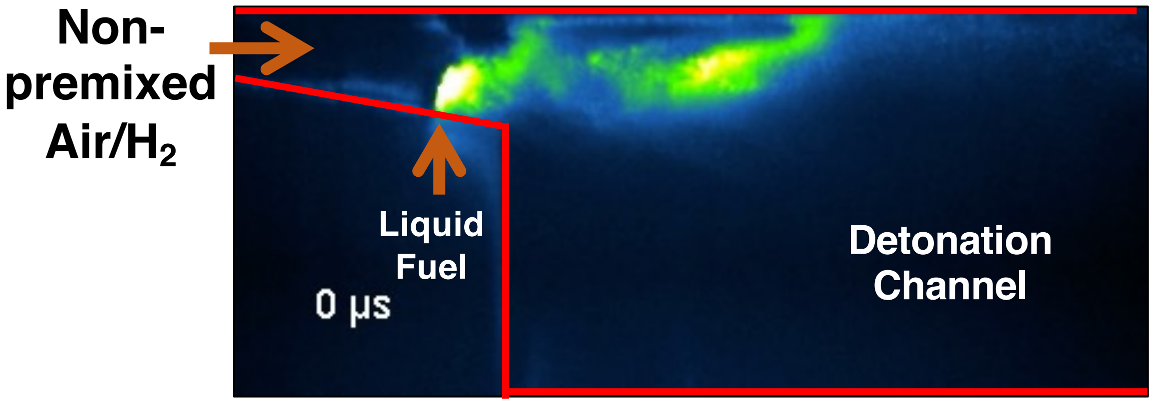




Summary

- A fuel spray has been directly visualized in an RDC with megahertz-rate liquid fuel PLIF imaging
  - Allowed direct visualization of unsteady liquid fuel injector dynamics
  - Quantified various time scales of the liquid fuel dwell time and refill process
- Fuel spray trajectory quantified and compared with a steady-state model
- Liquid fuel dwell time is observed to be ~20-40% of the detonation cycle period
  - No strong dependence on momentum flux ratio
  - Peak detonation pressures relative to air inlet plenum is a key factor

1 MHz Laser-Based Imaging of a Fuel Spray in an RDC



Acknowledgements

- This work was funded by NASA STTR Contract 80NSSC19C055

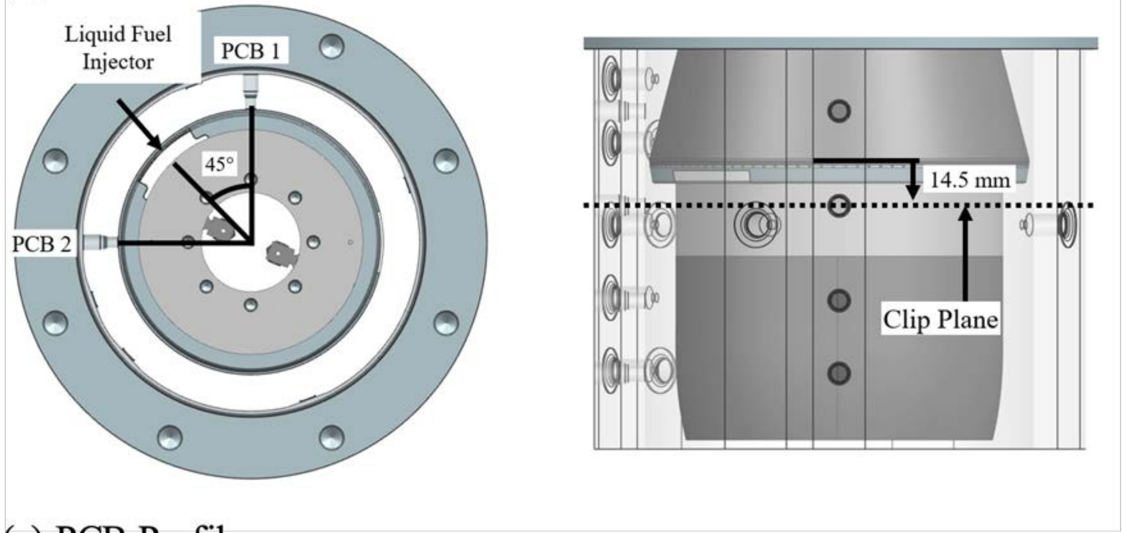
- Portions of the imaging equipment used in this work were funded by AFOSR Award No. FA955016-1-0315 (Dr. Martin Schmidt, Program Officer) and DTRA Award No. HDTRA1-17-1-0031 (Dr. Jeffery Davis, Program Manager)

- Matt Hoeper acknowledges partial support from NSTGRO Fellowship Program: No. 80NSSC21K129

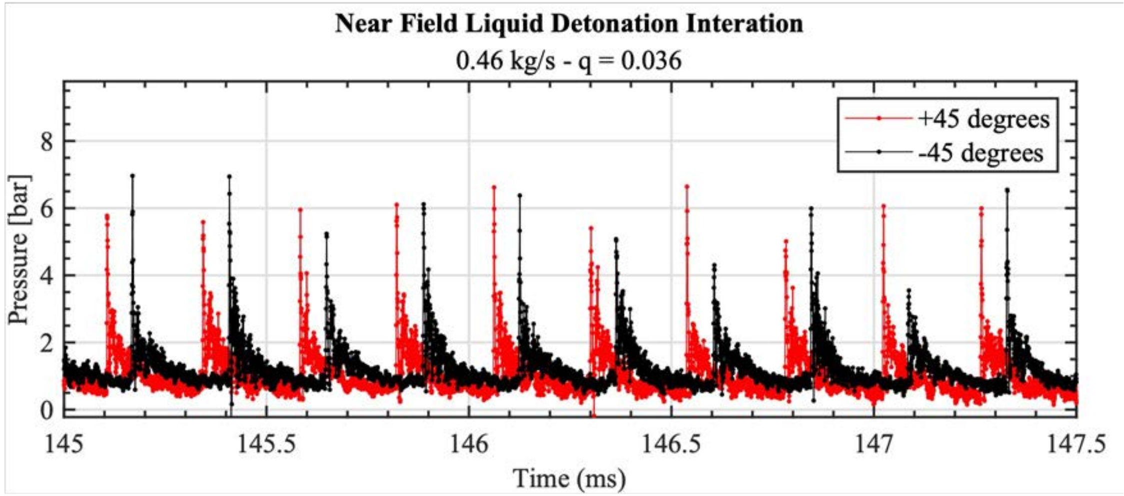
Appendix

- Presence of liquid fuel spray does not attenuate detonation wave propagation
- Azimuthally space measurements at 45° ahead and behind the liquid spray
- Obtain pressure measurements in the injection nearfield and far-field
  - Axially at 10 mm and 68 mm from injection point
- Instrumentation
  - PCB 113B21 (200 psi)
  - 2.5 MHz sampling (low pass filter at 200 kHz)
  - Captures ~ 300 ms of data (~ 1000 limit cycles)
  - Sampling area: ~5.6 mm diameter

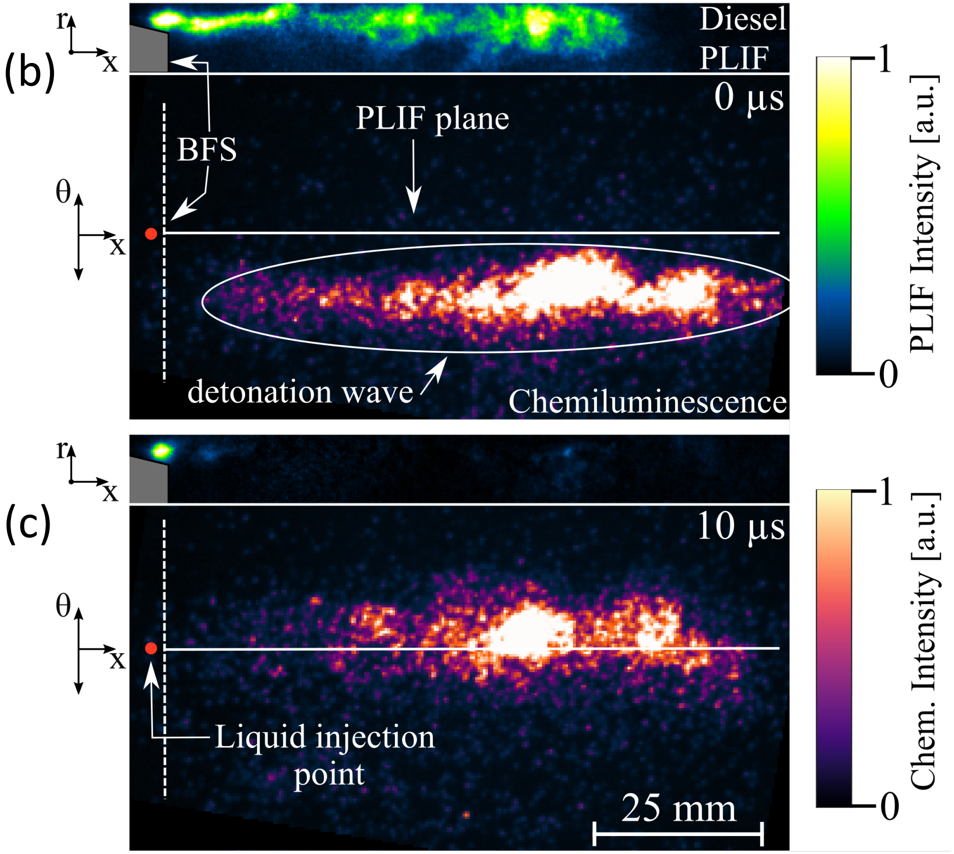
(b) PCB Arrangement

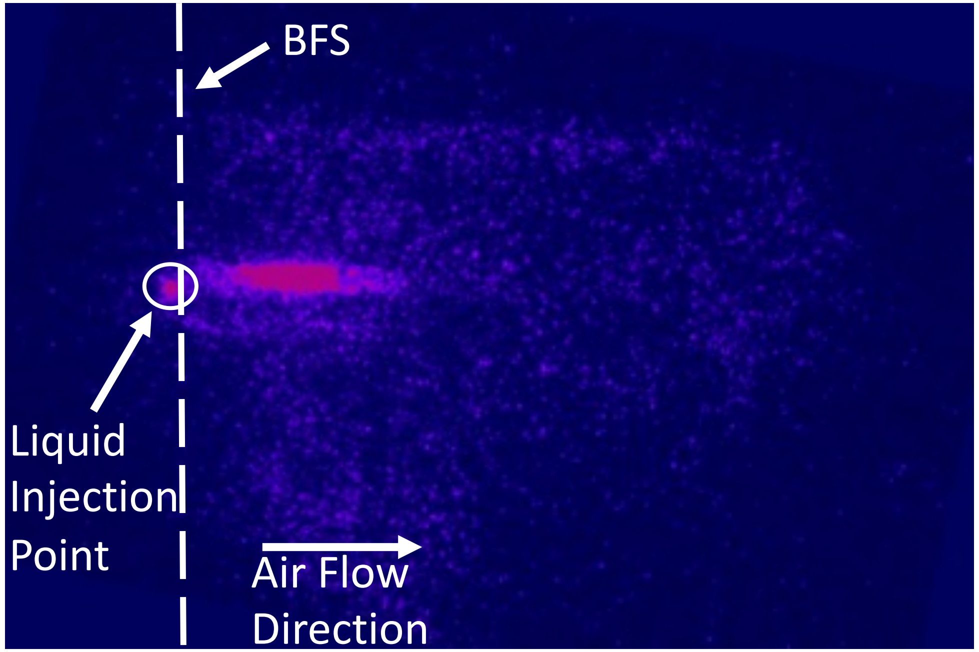


(c) PCB Profile



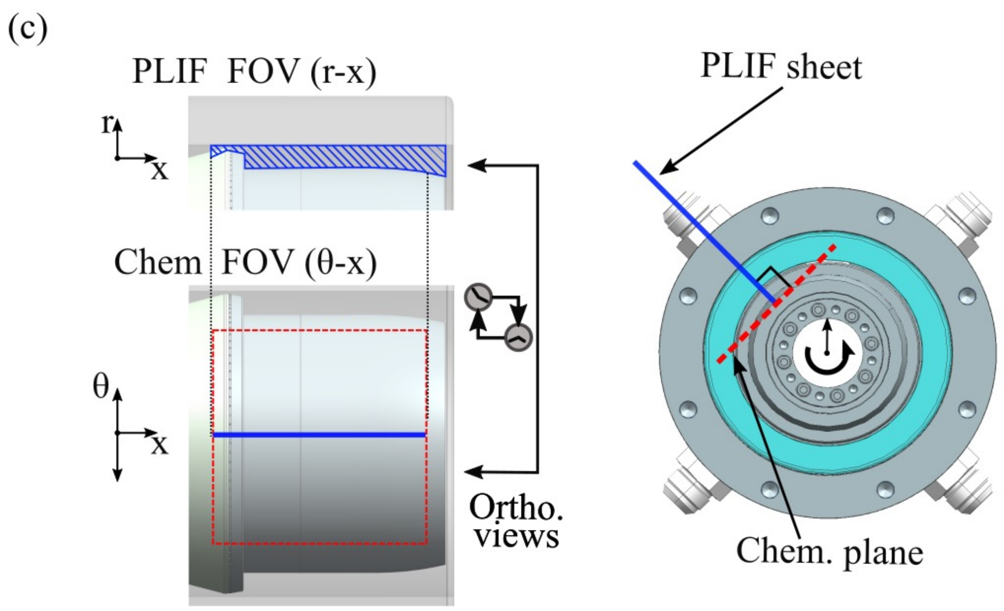
Chemiluminescence Quenching

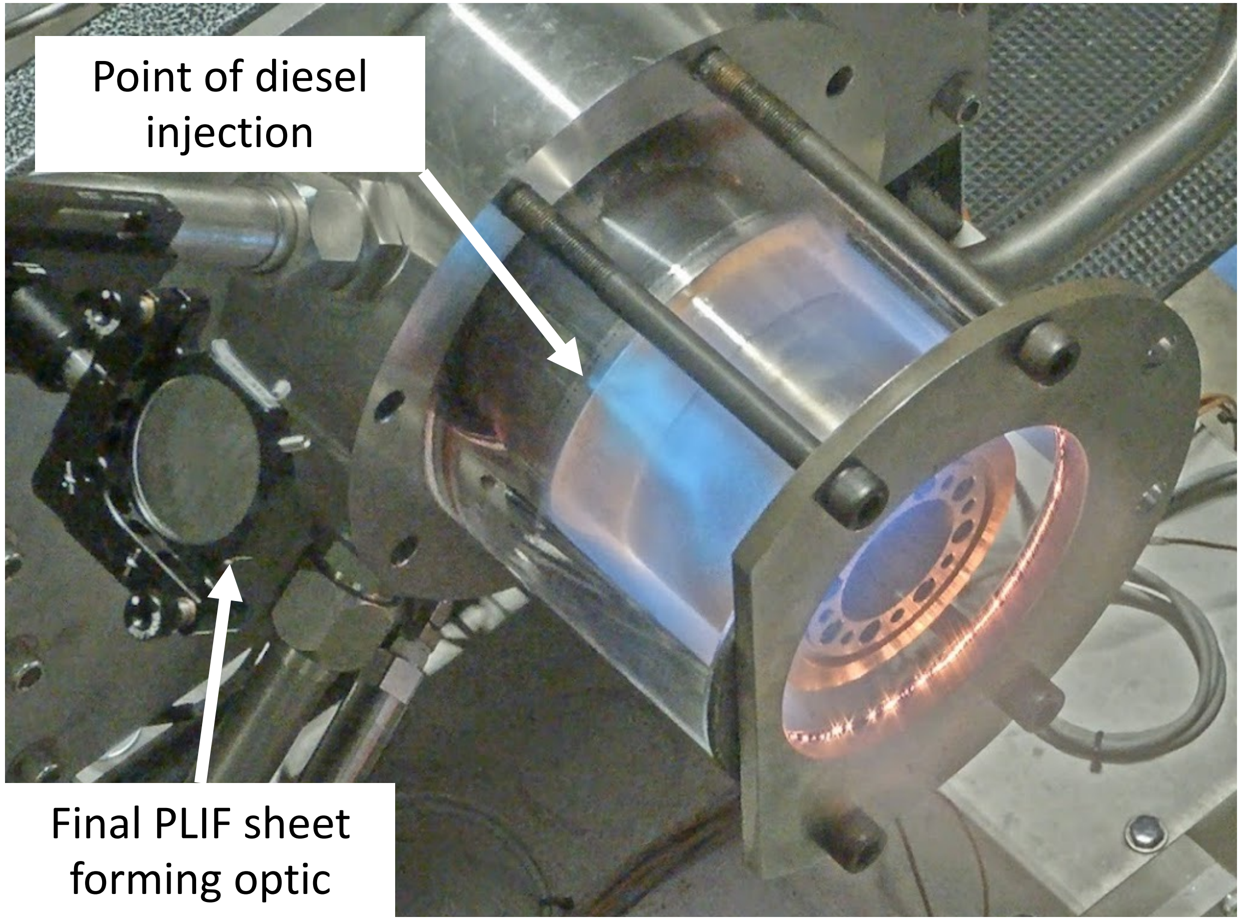




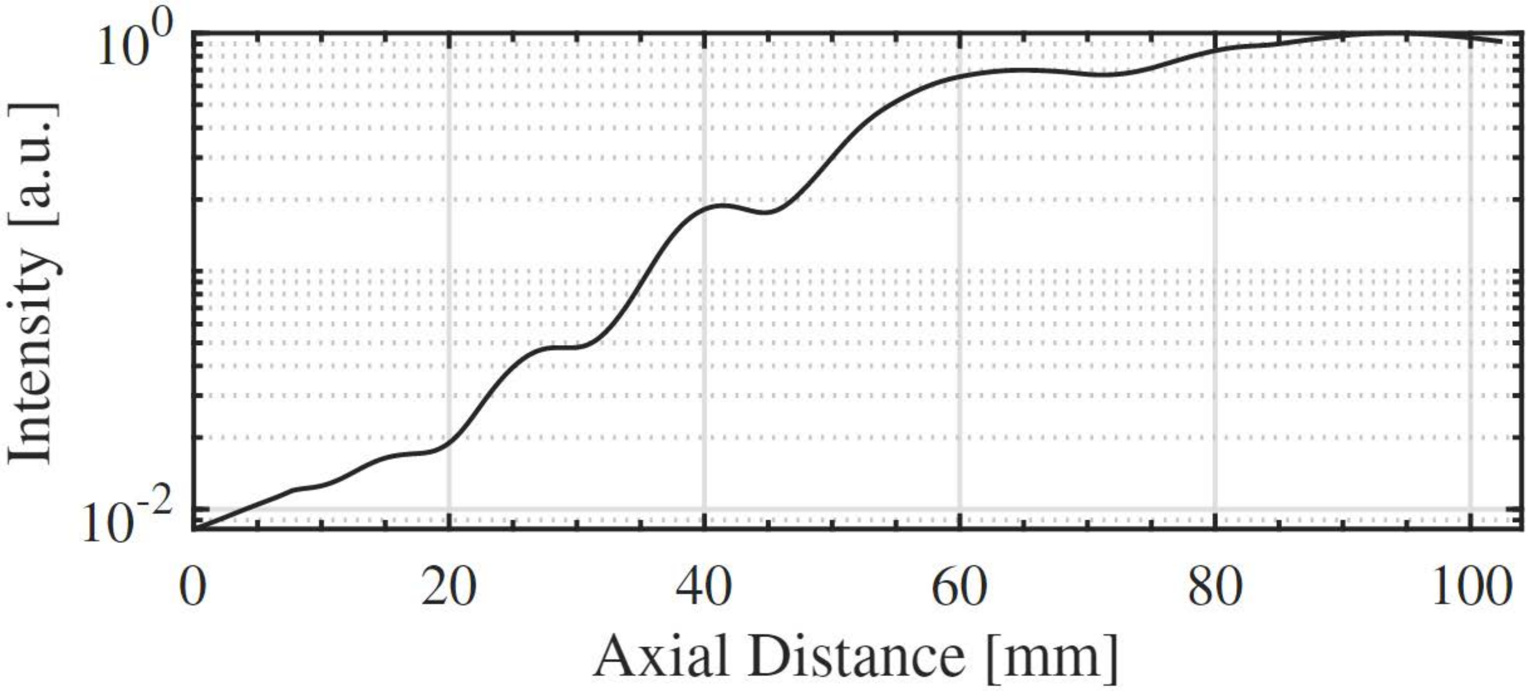
Example of broadband OH* chemiluminescence

Diesel Injection During Hot Fire



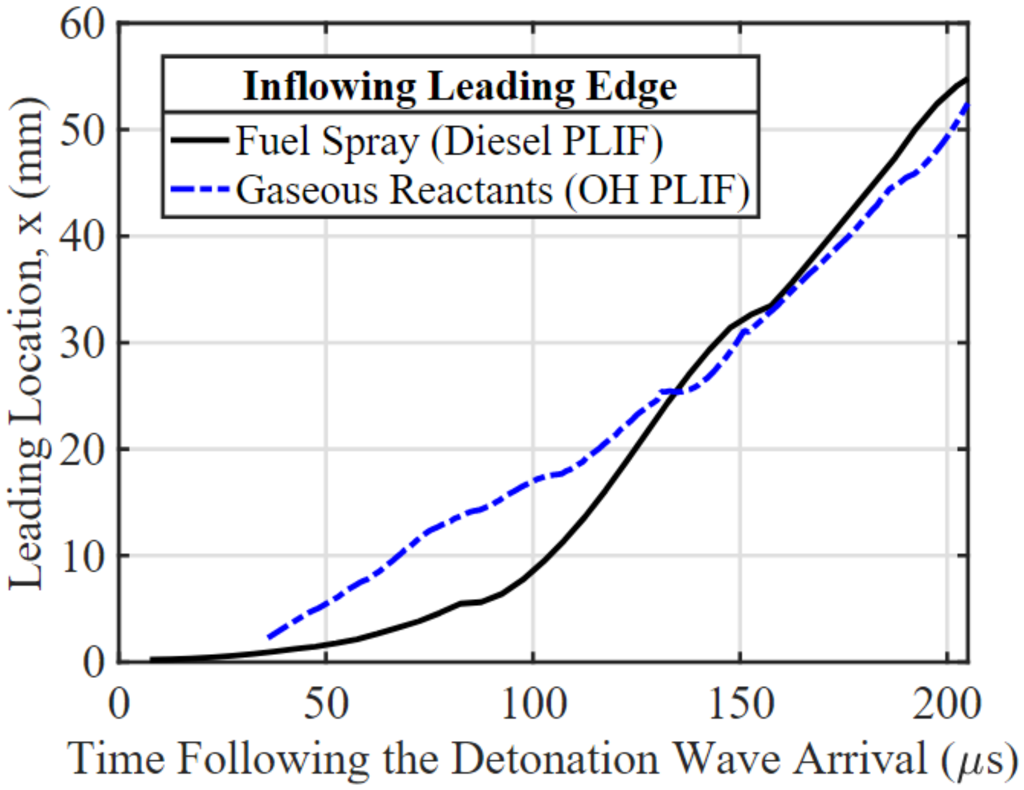


Typical Laser Sheet Intensity Profile



A typical laser sheet intensity profile for the large field of view cases.

Liquid Fuel Refill Comparison

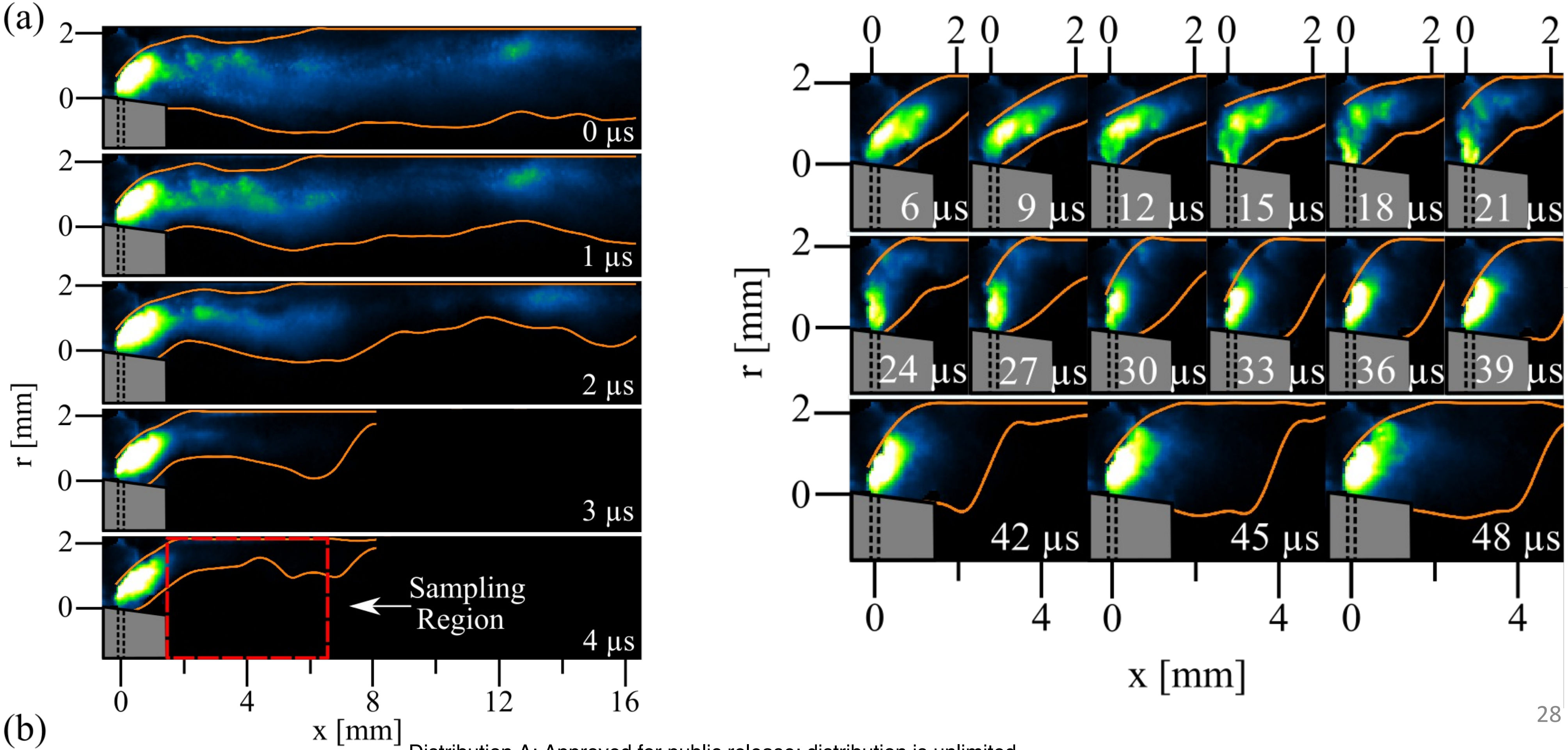


A comparison between apparent leading edge (axial distance) of liquid fuel spray as it refills the channel and OH PLIF signal as fresh reactants enter the channel.

Liquid Fuel Spray - Detonation Interaction Small FOV

- Liquid fuel is completely consumed or displaced from the channel within a few microseconds,
- No liquid fuel moves axially upstream after the detonation wave

(a)



(b)