SAND2015-0007PE

Effect of close pilot spacing on combustion and emissions

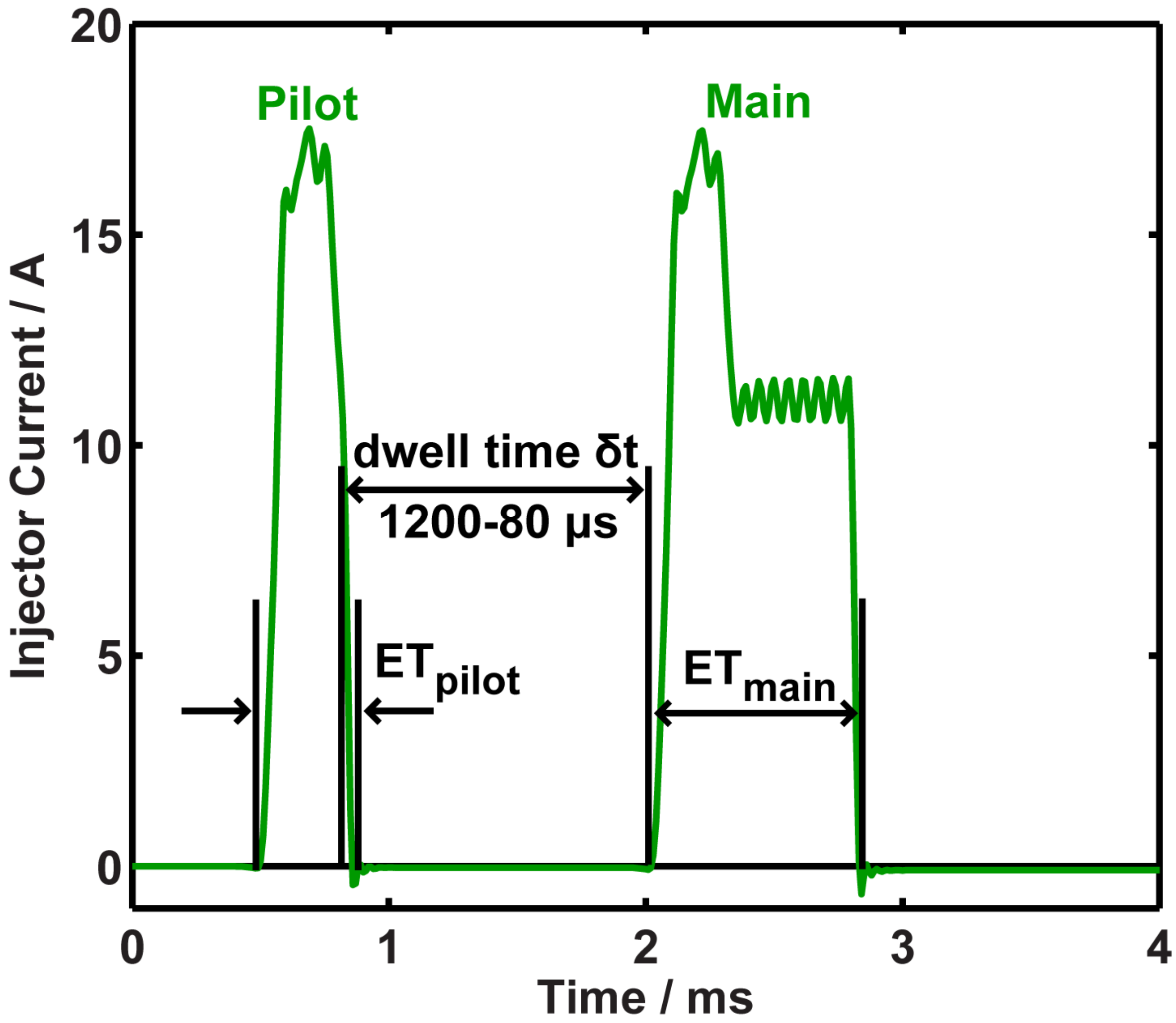
Steve Busch, Kan Zha, Cheolwoong Park, Paul Miles
Sandia National Laboratories

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000

Outline

- Review: operating point with pilot-main injection strategy
- Review: combustion noise reduction mechanism
- Mixture formation and combustion processes with multiple injections
- Current experimental results: first look
  - Fuel tracer PLIF
    - (Semi)quantitative, spatially resolved measurement of fuel concentrations
    - Motored (air replaced by N_2) operation: no combustion
  - High speed natural luminosity imaging
    - Initial scoping study – how many cycles can we see? When and where can combustion luminosity be seen, and how does dwell impact this?
- Implications for combustion and pollutant formation
- Open questions and next steps

Review: pilot + main injection strategy

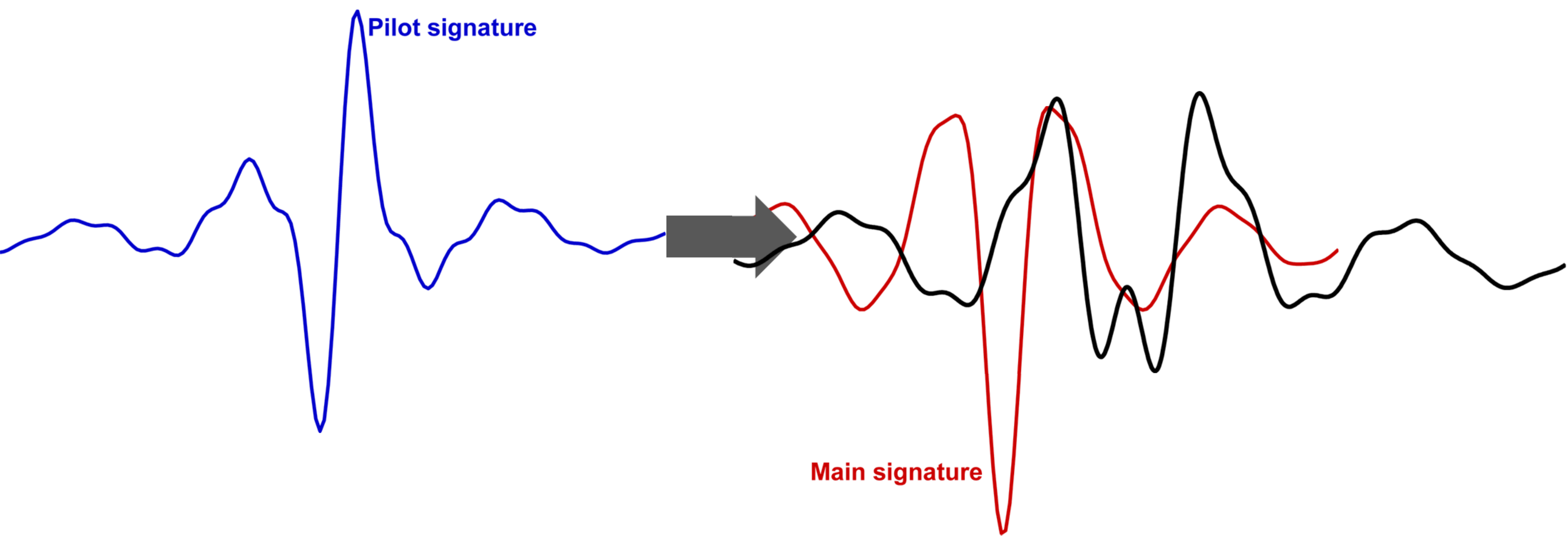


Review: combustion noise reduction mechanism with close-coupled pilots

- Problem has been reduced to a zero-dimensional phenomenon
- Investigation continues: wavelet analyses, band pass filtering
  - Noise reduction trend also occurs with top hat heat release profiles and a constant volume, adiabatic, constant gamma model: $dP \propto dQ$
- Frequency band responsible for noise reduction: ~1-3 kHz
- Pilot and main heat release events each have a distinct "pressure signature" in this frequency band
  - These pressure signatures can be obtained analytically for top-hat heat release profiles and constant volume
- Temporal overlap of pilot and main heat release results in a pressure waveform with reduced amplitudes in the critical frequency band
- Destructive interference in pressure-time history (not due to traveling waves or acoustics)
- Publication to come (IJER?)

Review: combustion noise reduction mechanism with close-coupled pilots

- Pressure signature from pilot + pressure signature from main → waveform of reduced amplitude



Existing conceptual models for spray combustion ignition with multiple injections

- Short dwell (b)
  - Long main injection vapor penetration
  - Main injection mixture ignites around edges
    - O2 has been consumed by the pilot in the center
- Medium dwell (c)
  - Well-established pilot combustion heats main mixture over a larger area
  - Main mixture burns at front and around the head
- Long dwell (d)
  - Pilot combustion nearly complete
  - More gradual and even heating of main injection mixture field

From: K. Cung et al. / Proceedings of the Combustion Institute 35 (2015) 3061–3068

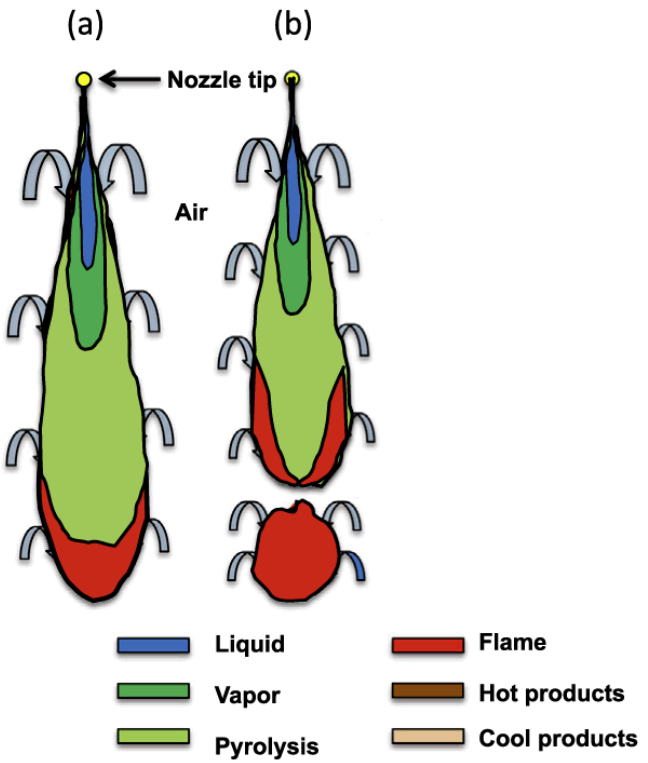


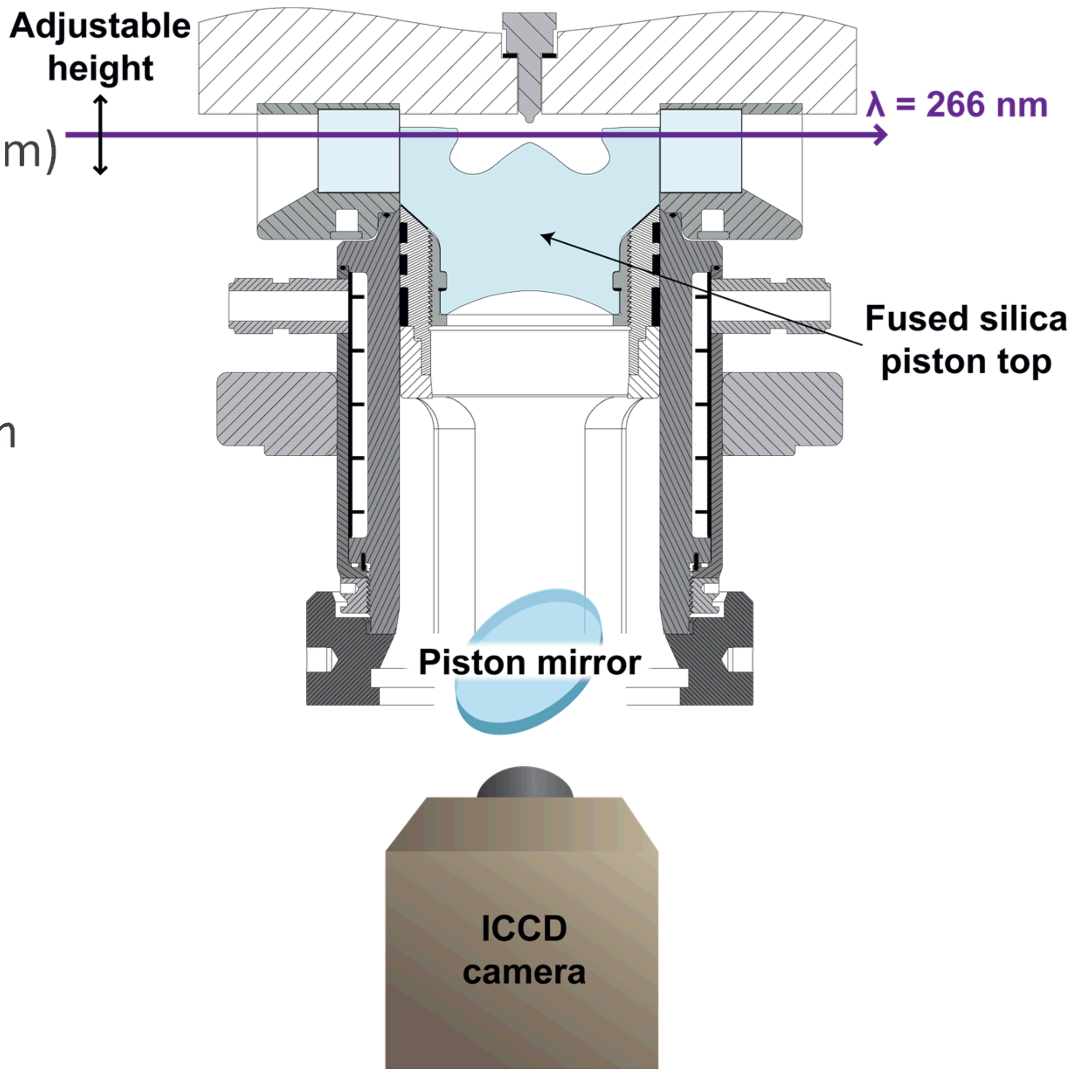
Fig. 7. Spray combustion interaction model for single and multiple-injection by varying dwell time; (a) single injection: (b) short DT: (c) medium DT: and (d) long DT.

Fuel tracer PLIF

- Experimental goals:
  - Spatially resolved, quantitative measure of fuel concentrations (Φ)
  - Measurements at multiple crank angles and for various dwells
  - Improved understanding of how changing dwell impacts mixture formation processes
- Methodology
  - Planar laser induced fluorescence (PLIF) of DPRF58 doped with 1-methylnapthalene
  - Imaging with ICCD camera
  - Calibration for temperature dependence of fluorescence signal
  - Iterative, pixel-by-pixel calculation of fuel-air equivalence ratio
  - Analysis of individual and ensemble averaged images

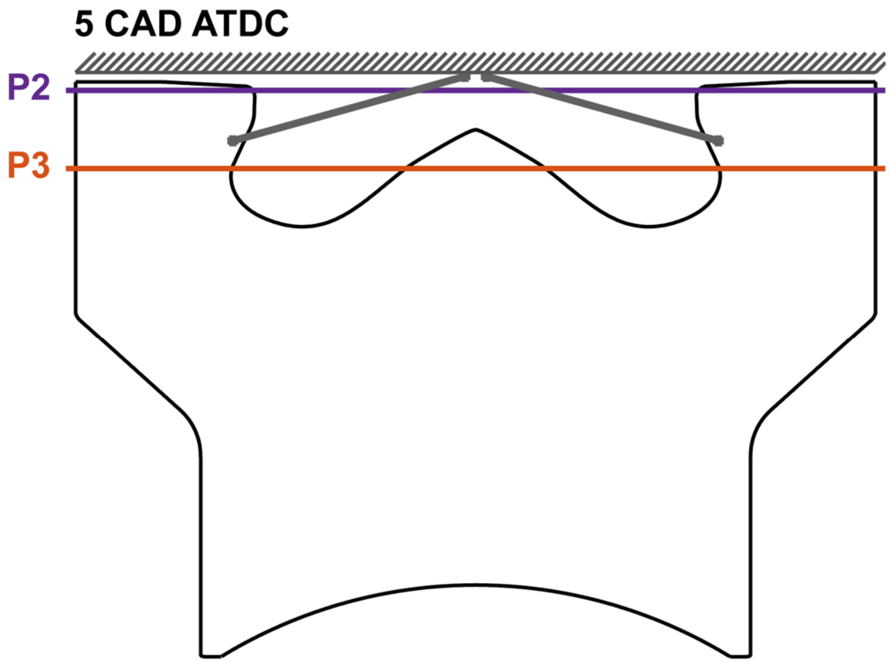
PLIF setup: laser and camera configuration

- Illumination source
  - Nd:YAG, 4th harmonic (266 nm)
  - ~30 mJ / pulse (relative intensity measured for each shot)
  - Laser sheet thickness < 1 mm
  - Sheet positions defined relative to piston geometry
    - P2: upper bowl rim
    - P3: deep in bowl
- Imaging
  - WG-295 long pass filter
  - Nikon UV-105 lens (f/4.5)
  - PI-MAX 4 ICCD camera



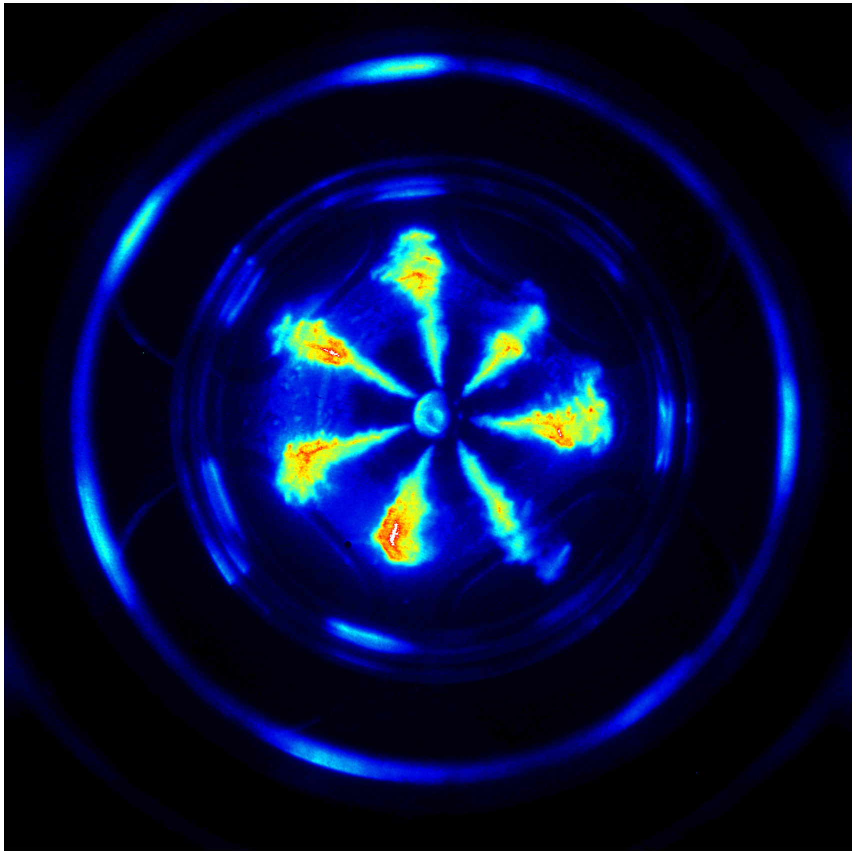
PLIF setup: laser plane locations

- Plane 2 (P2)
  - Empirically determined
  - At rim of bowl where laser sheet passes through with minimal deflection
- Plane 3 (P3)
  - Deep within bowl
  - Position estimated within ~0.15 mm of Sahoo’s P3
- P2 and P3 move with the piston as crank angle changes
  - For this work, positions change by at most 1 mm



PLIF: data collection and processing

- Three sets of images for a given crank angle, plane, and operating point (51 images per set)
  - Background (no fuel injection)
  - Flat-field (8 injections in intake stroke)
  - Fuel injection image (desired operating point)
- 9:15 measurement schedule to maintain temperatures and pressures
- Distortion correction according to established ray-tracing routine

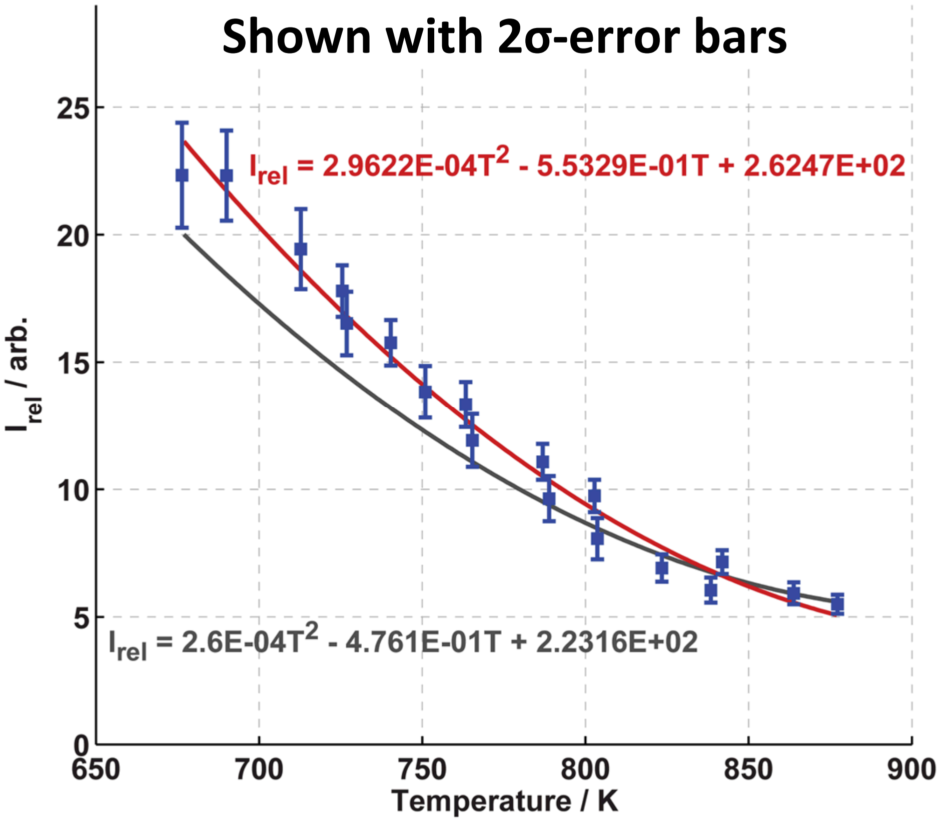


PLIF: computation of fuel concentrations

- $\chi_{fuel,d} = \chi_{fuel,cal} \frac{S_d}{S_{cal}} \frac{E_{cal}}{E_d} \frac{T_d}{T_{cal}} \frac{P_{cal}}{P_d} \frac{\sigma\eta(T_{cal})}{\sigma\eta(T_d)}$
  - S : background-subtracted, distortion-corrected image intensity
  - E : measured laser pulse energy
  - T : bulk gas temperature from GT-Power model
  - P : cylinder pressure from GT-Power model
  - $\sigma\eta$: product of absorption cross section and quantum yield; function of temperature alone
- Calibration with homogeneous mixture of known concentration ($\chi_{fuel,cal}$)
  - "Flat-field" correction
- $\sigma\eta(T)$ is determined with separate measurements and analyses

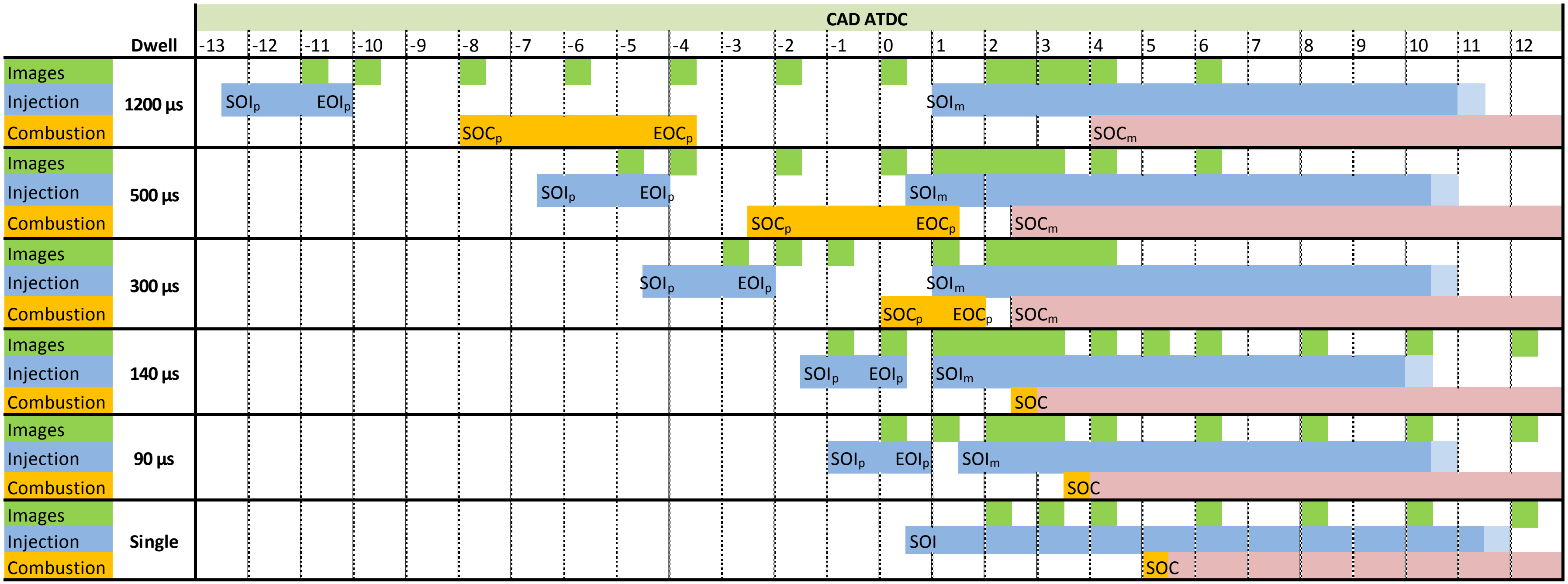
PLIF temperature calibration

- $\sigma\eta(T)$ determined from flat-field images taken at various crank angles and for various intake temperatures
- Upper limit of possible flat-field fuel concentrations limited by wall-wetting
  - $\phi_{ff} \approx 0.3$
- Comparison with previous temperature calibration
  - Coefficients between 14-18% higher than previously determined values
  - The arbitrary normalization of the calibration curve is responsible for the majority of this discrepancy
- Future plans include expanded calibration dataset



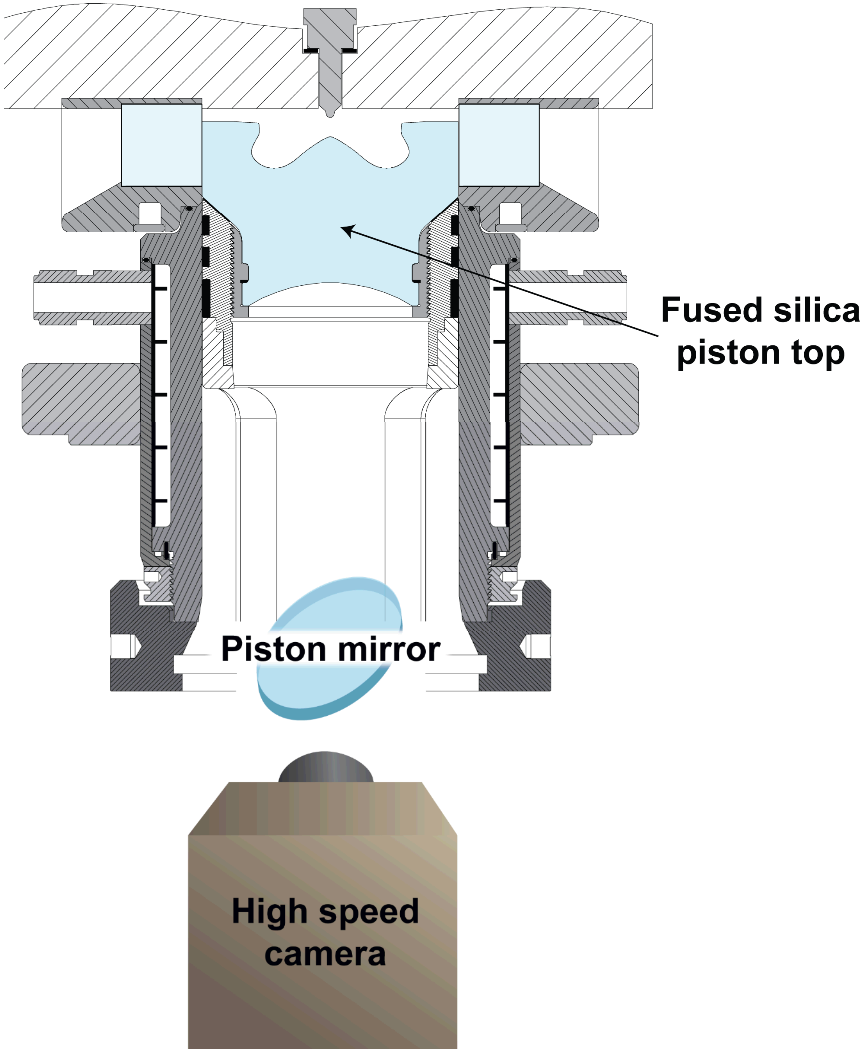
PLIF: crank angles imaged

- Image sets taken over range starting during pilot injection, ending during main combustion
- Over 6000 result images generated
  - Today only d1200, d300, d90, P2
- Particular interest in images taken at
  - SOC_p, SOC_m (determined from AHRR data), SOI_m (HDA)

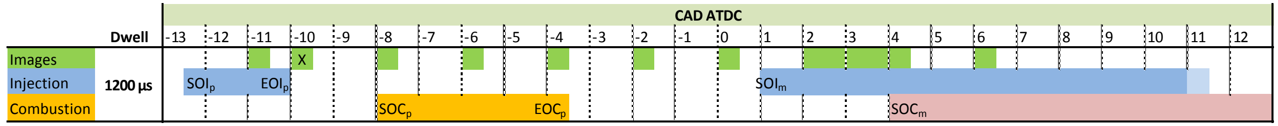


High speed natural luminosity imaging

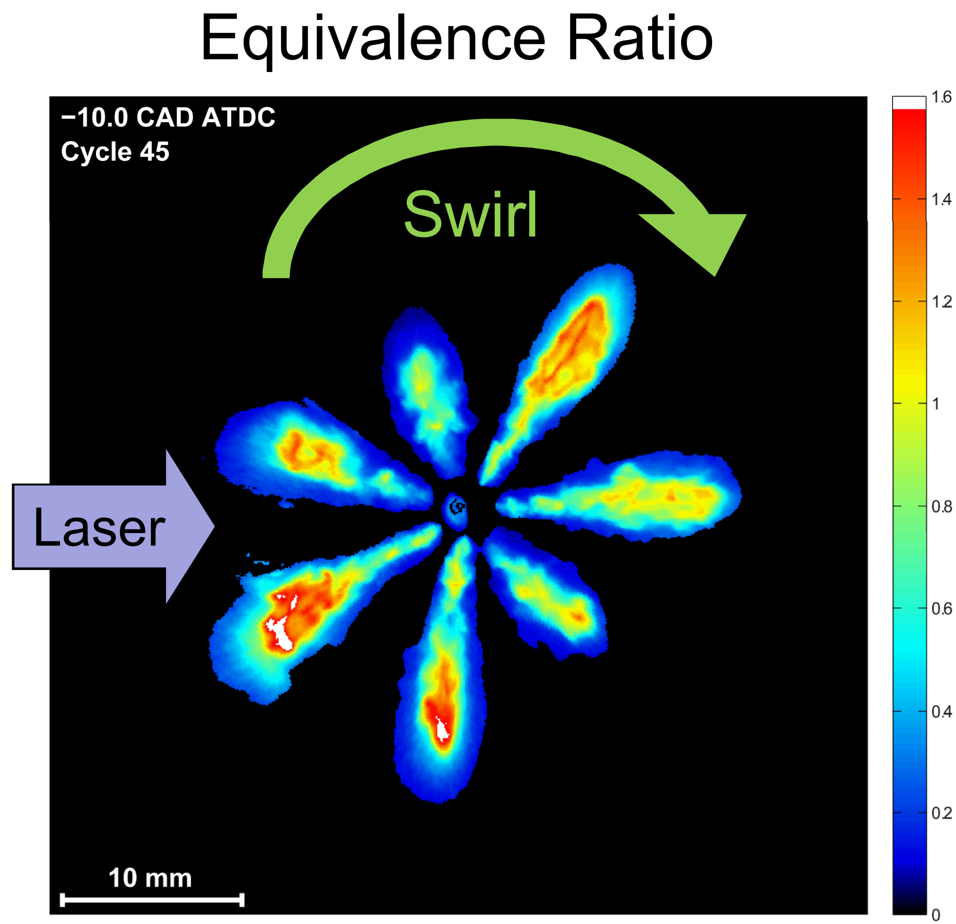
- Camera: Vision Research Phantom v311
  - Frame rate: 40 kHz
  - Exposure duration: 3 µs
  - Lens aperture: ~f/11 (optimized for viewing soot)
- Sequence of 320 images per cycle (span of 72 CAD)
- Sequences triggered on SOE_p of first 50 fired cycles
- Window sooting occurs during every cycle
  - First five cycles are used for analysis



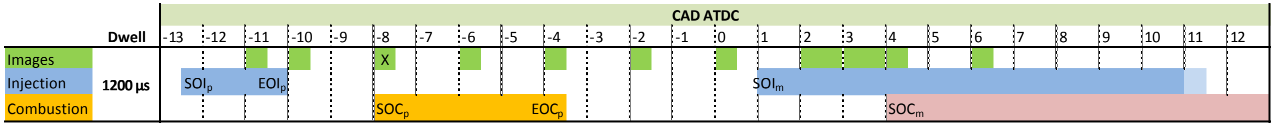
PLIF results: 1200 μs dwell



- Equivalence ratio distribution at EOI$_p$ (10 CAD BTDC)
- Background removed in areas with low standard deviations over 50 cycles
  - Mixture fields are almost always contained within the shapes shown
- Equivalence ratios near center not reliable
  - Scattering of laser and fluorescence signal by liquid
- Absorption and beam steering of laser sheet may decrease equivalence ratios on right side of images

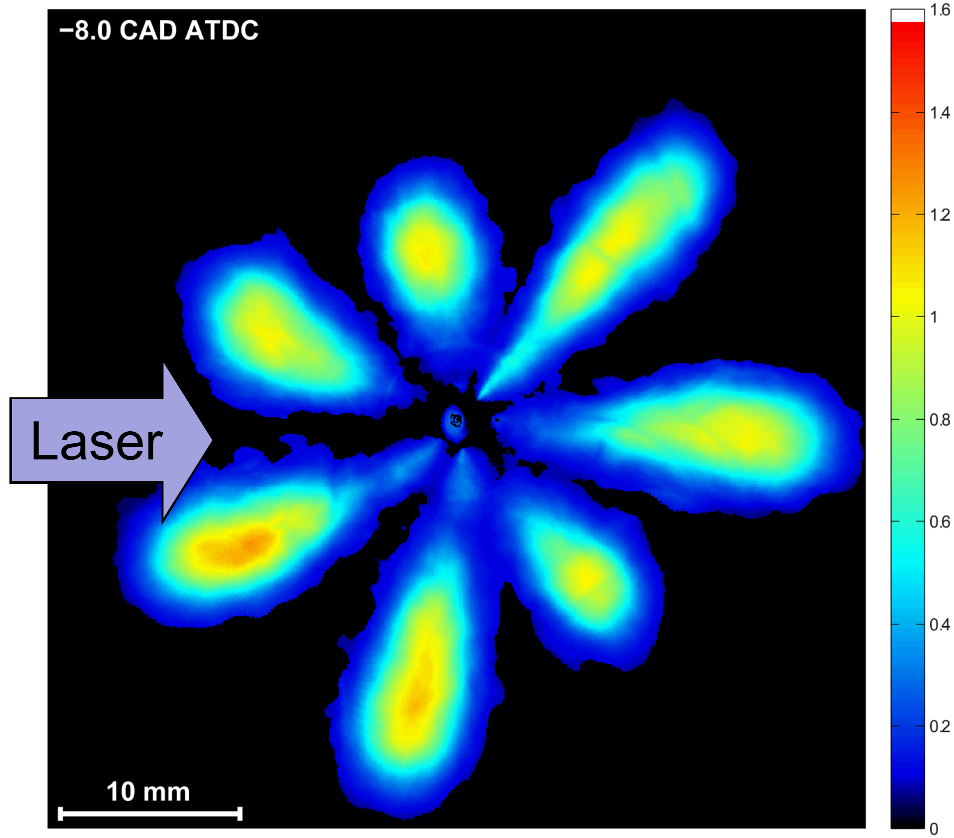


PLIF results: 1200 µs dwell



- Equivalence ratio distribution at SOC$_p$ (8 CAD BTDC)
- Shortest ignition delays expected for near-stoichiometric mixtures
  - Such mixtures do exist at this CA
  - Autoignition in these mixtures is most likely where scalar dissipation rates (mixture fraction gradients) and strain rates are minimized
  - Gradients have decreased since EOI$_p$
  - Pilot soot not expected
- Ensemble average images indicate equivalence ratios that are lower than in individual cycles
  - Cycle-to-cycle variability makes it necessary to look at individual cycles
  - Image masks provide information from all cycles

Equivalence Ratio



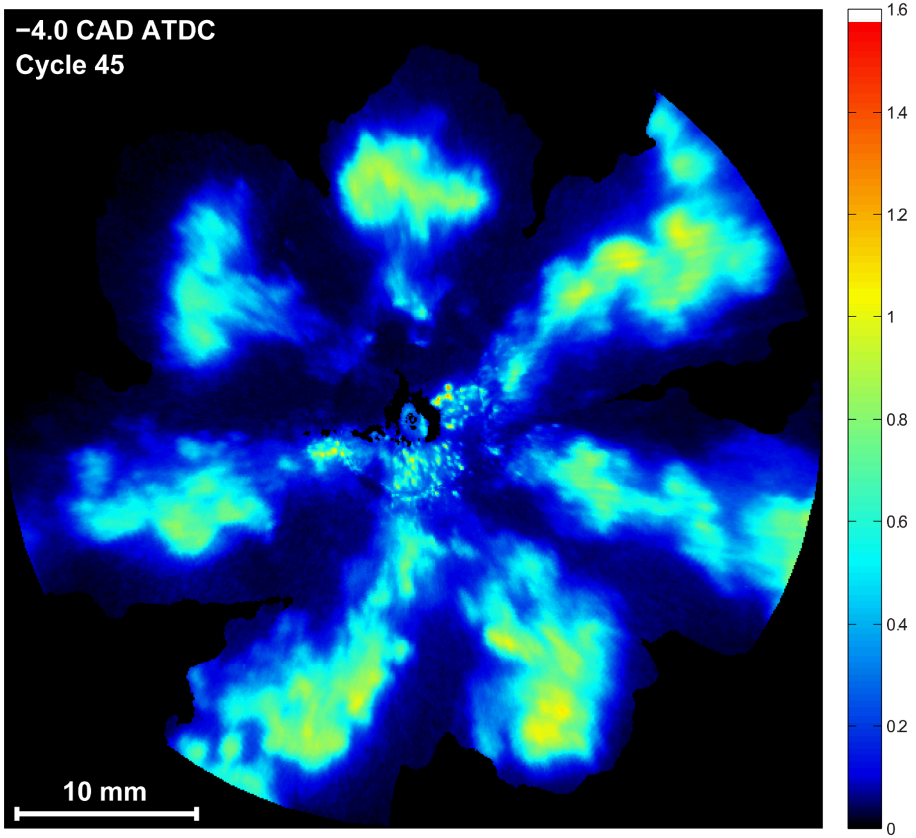
PLIF results: 1200 μs dwell

CAD ATDC

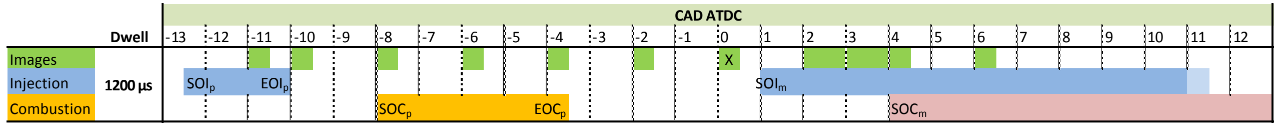
	Dwell	-13	-12	-11	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8	9	10	11	12
Images											X																
Injection	1200 μs	SOI_p		EOI_p												SOI_m											
Combustion							SOC_p				EOC_p								SOC_m								

- Equivalence ratio distribution at EOC_p (4 CAD BTDC)
- Transport of mixture fields by swirl is evident
- Larger cycle-to-cycle variations
  - Mixture fields may be found over a large region of the bowl
- Fuel dribble from injector is consistent with high speed elastic scattering imaging results
- Equivalence ratios shown are misleading – majority of pilot heat release is finished
  - Locations of mixture fields provide some indication of state of combustion products

Equivalence Ratio

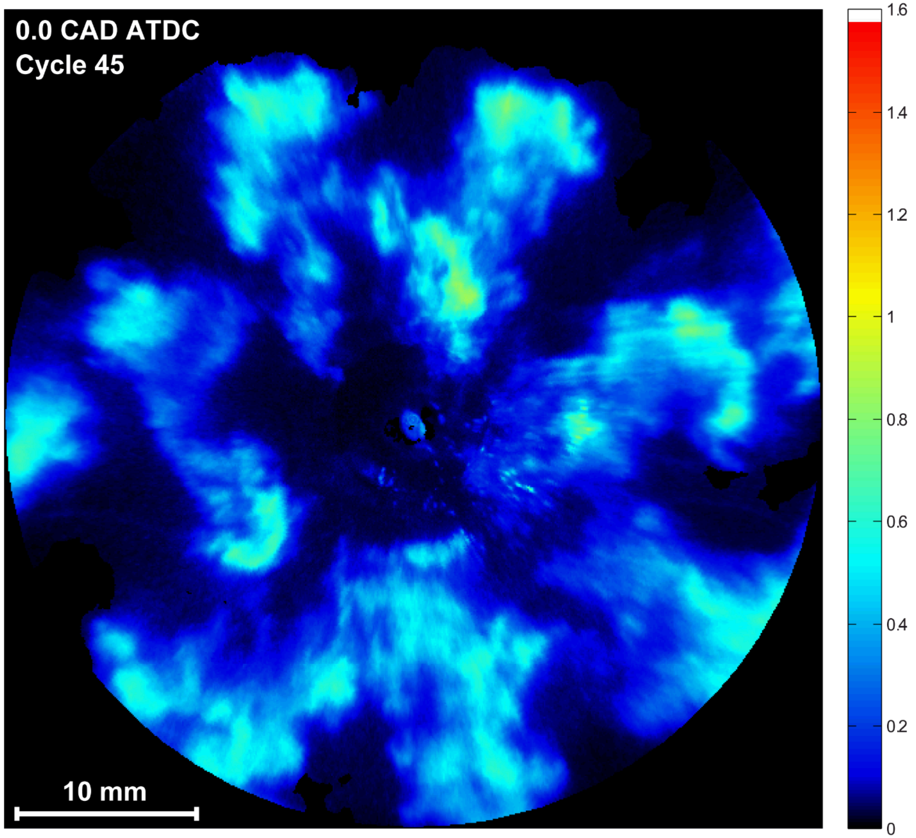


PLIF results: 1200 μs dwell

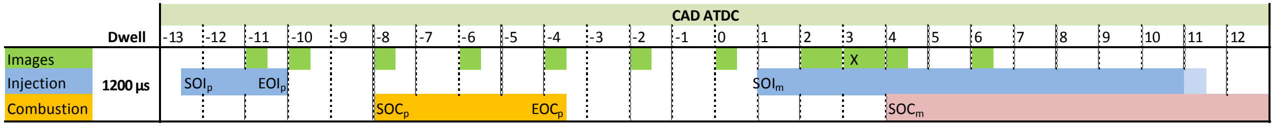


- Equivalence ratio distribution just before SOI_m (TDC)
- Pilot jet structure hardly identifiable
- Large cycle-to-cycle variations
  - Mixture (combustion products) often found near injector
- Fuel dribbled from injector is still visible in some cycles

Equivalence Ratio

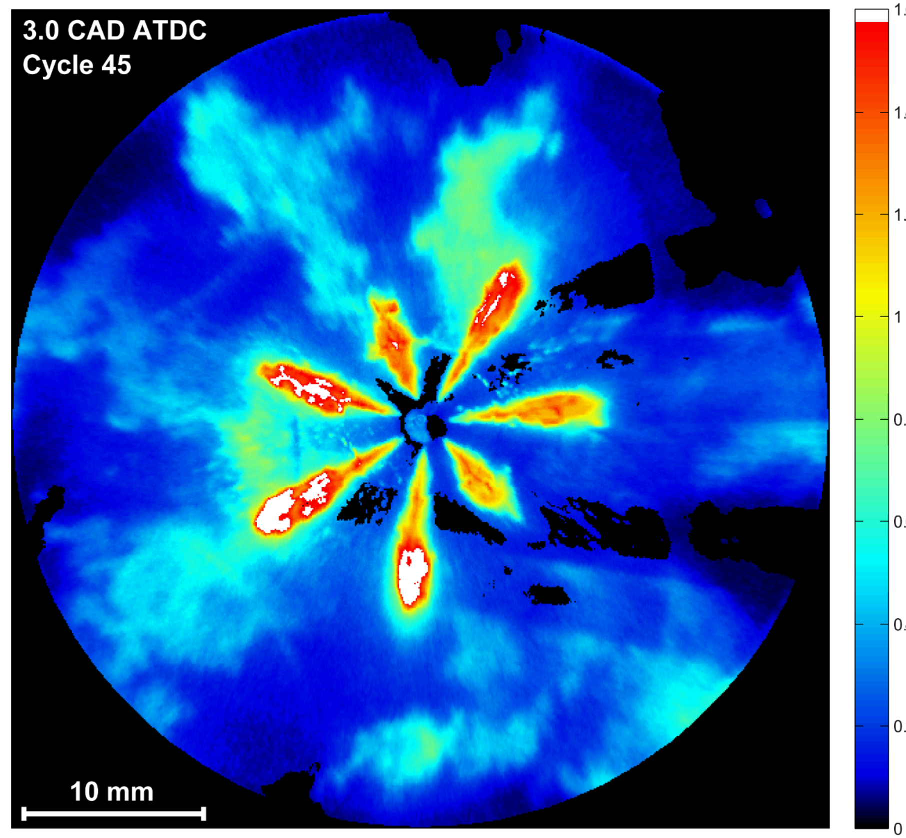


PLIF results: 1200 µs dwell



- Equivalence ratio distribution after SOI$_m$ (3 CAD ATDC)
- Fuel is being injected into a partially premixed fuel-air mixture
  - Not an accurate representation of real conditions
  - More likely: fuel injected into partially mixed combustion products
- Combustion products are likely distributed throughout the bowl
- Evidence of dribbled fuel droplets near the injector
  - Low velocities and mixing rates
- How do natural luminosity images reflect what's been shown for this dwell?

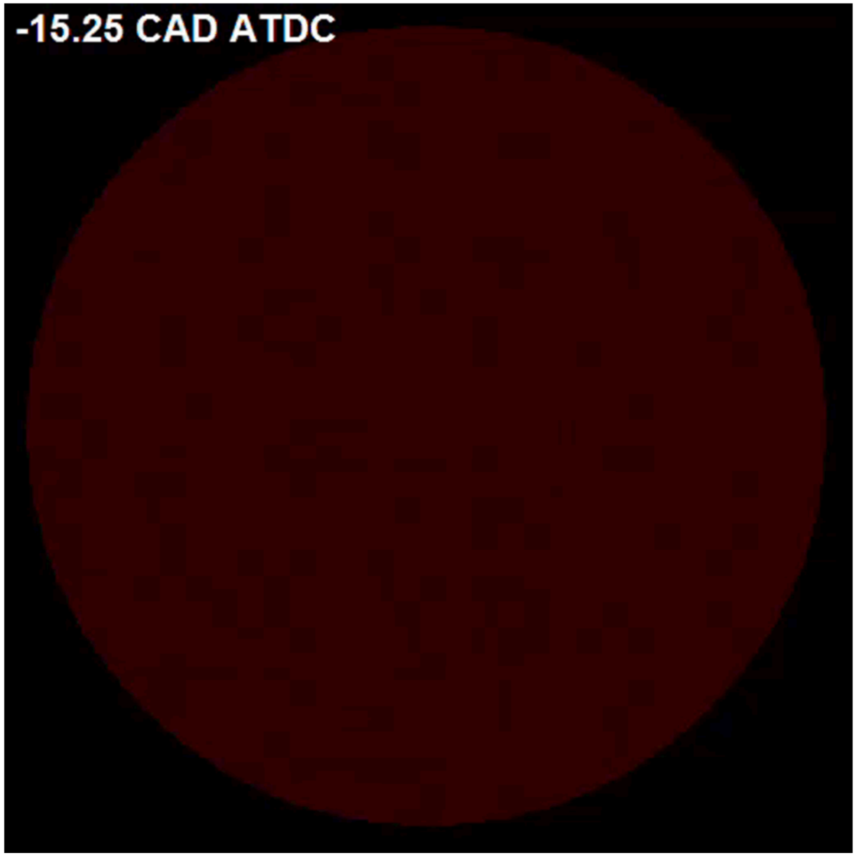
Equivalence Ratio



High speed natural luminosity: 1200 µs dwell

- Some luminosity during pilot combustion in each cycle
  - Unevenly distributed and long lived; seems to be soot
- PLIF results did not suggest that soot would form
  - Soot wasn't expected based on peak equivalence ratios at SOC_p of ~1.5
  - Rich mixtures may be found in other parts of the cylinder
  - Uncertainties in measurement and data processing procedures
  - Requires further investigation

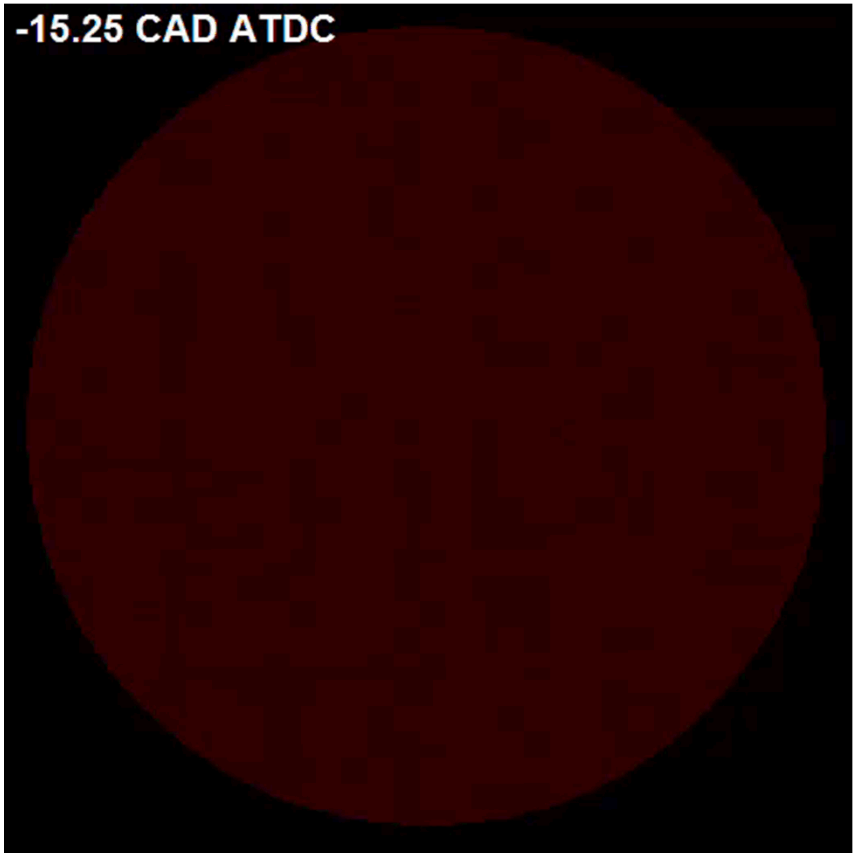
Second fired cycle



High speed natural luminosity: 1200 µs dwell

- Pilot soot is slowly carried by swirl, pulled inward between jets as main injection starts, mostly consumed during main injection
- More soot forms around main injection jets, but it is consumed as the luminosity in the head of the jet increases
- Soot luminosity is observed in the heads of the jets (downswirl side)
  - It grows in intensity and moves inward towards the center
  - Soot luminosity reaches center of chamber as injection ends
- Soot luminosity penetrates into the squish region twice

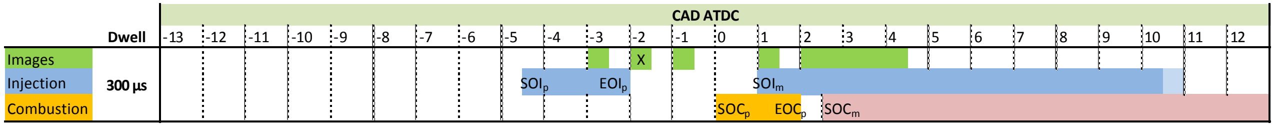
Third fired cycle



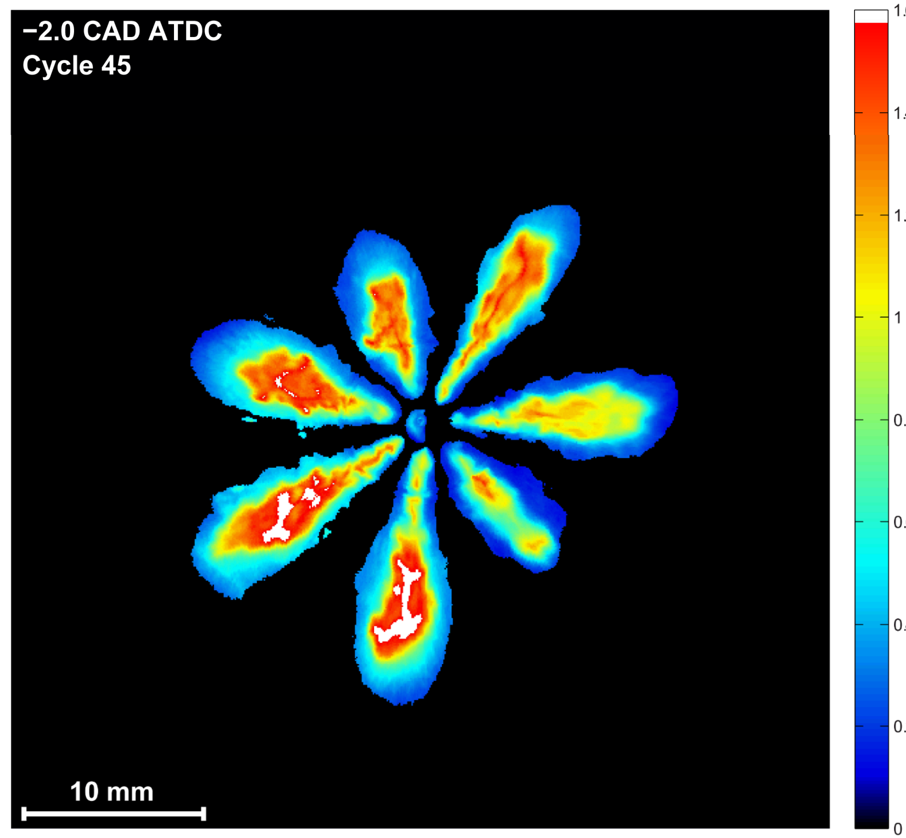
Recap: dwell 1200 μs

- Pilot heat release finishes before main injection starts
- Pilot combustion products have time to mix with air and cool
- Soot forms near the injector as the pilot mixture burns
  - Is carried by entrainment flow towards the center of the chamber as main injection commences
  - Is consumed during main injection and ensuing main combustion
- Regions of high soot luminosity form in jet heads
  - Penetration into squish region
  - Regression toward center of chamber
  - Soot moves from bowl outwards to squish region on two occasions

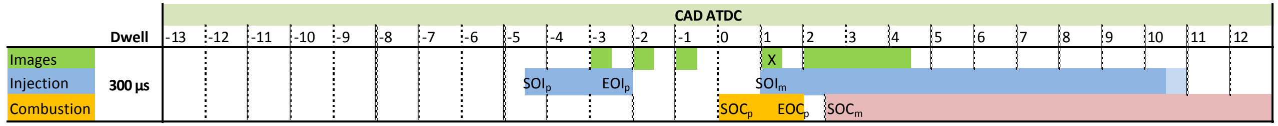
PLIF results: 300 µs dwell



- Equivalence ratio distribution at EOI$_p$ (2 CAD BTDC)
- Penetration lengths tend to be slightly less than for the 1200 µs dwell case
  - Higher charge density near TDC
- Slightly richer conditions compared to 1200 µs dwell

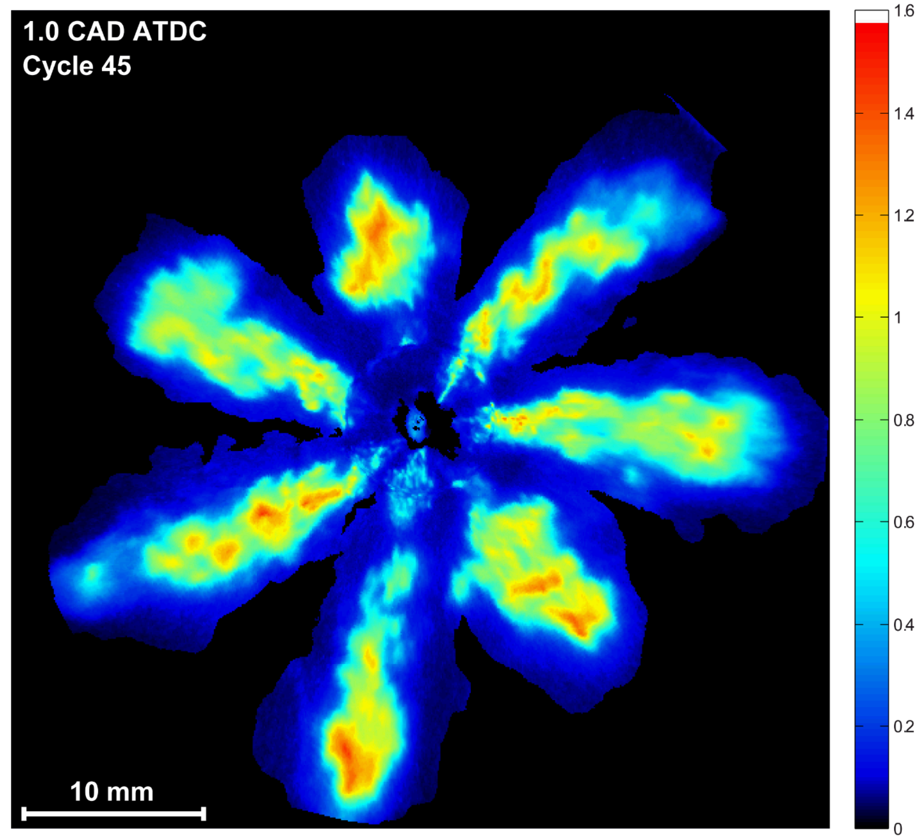


PLIF results: 300 µs dwell

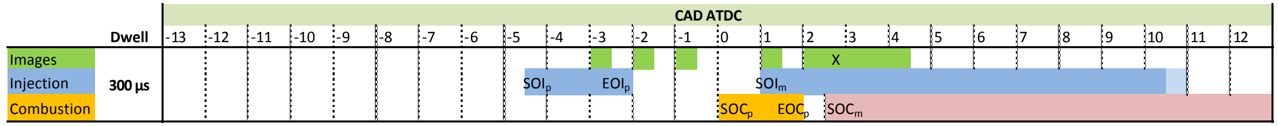


- Equivalence ratio distribution shortly before SOI_m and during pilot combustion (1 CAD ATDC)
- Stream of fuel observed for some jets
  - Consistent with dribble seen in elastic scattering imaging
- Slight displacement of mixture fields due to swirl motion
- Pilot jet structure still identifiable

Equivalence Ratio

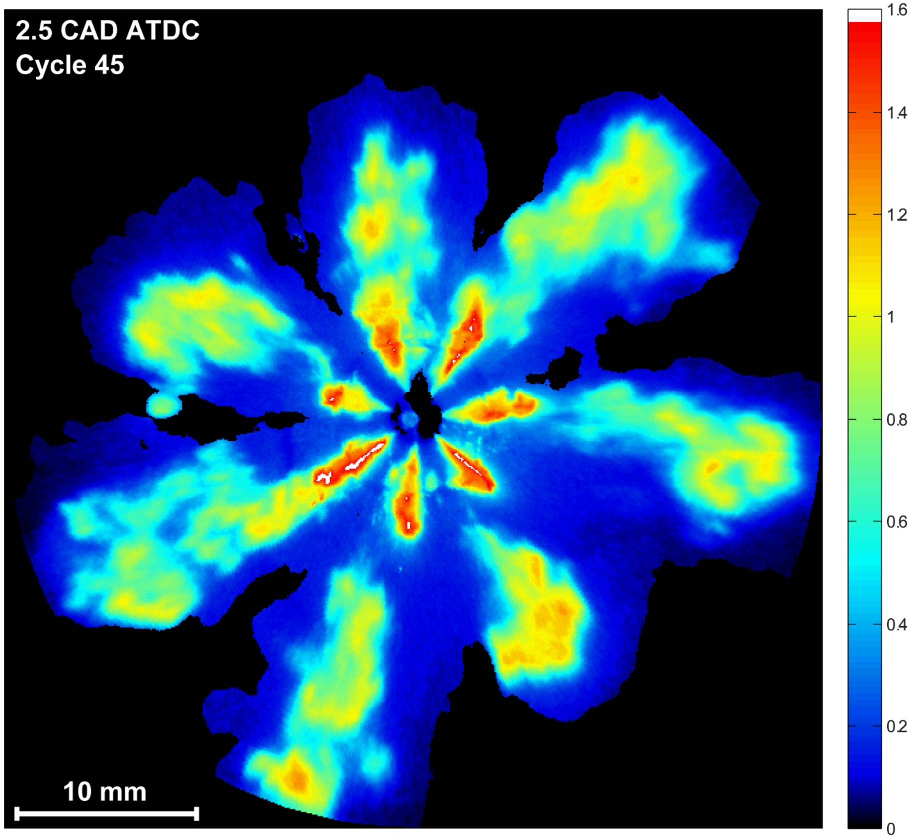


PLIF results: 300 μs dwell

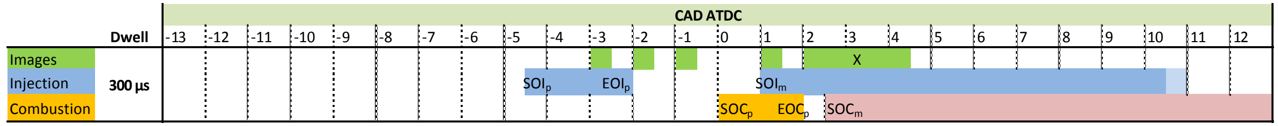


- Equivalence ratio distribution after SOI_m and EOC_p, but near SOC_m (2.5 CAD ATDC)
- Main fuel likely injected into hot combustion products that have been slightly displaced in the downswirl direction
  - Some separation between main injection jet head and pilot mixture field may be present at this crank angle
- Coexistence of dribbled fuel and main injection
  - Much richer upstream conditions
  - Fuel may be injected next to burning soot

Equivalence Ratio

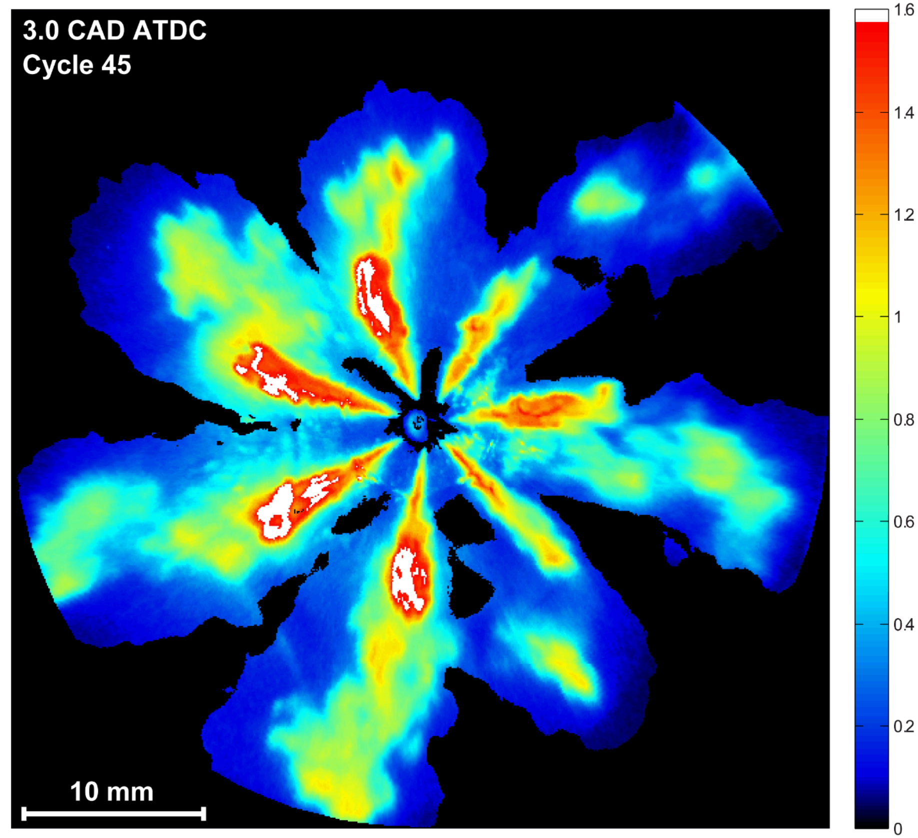


PLIF results: 300 μs dwell



- Equivalence ratio distribution after SOC_m (3 CAD ATDC)
- Fairly compact main injection mixture field
- Steep concentration gradients in a compact main injection field

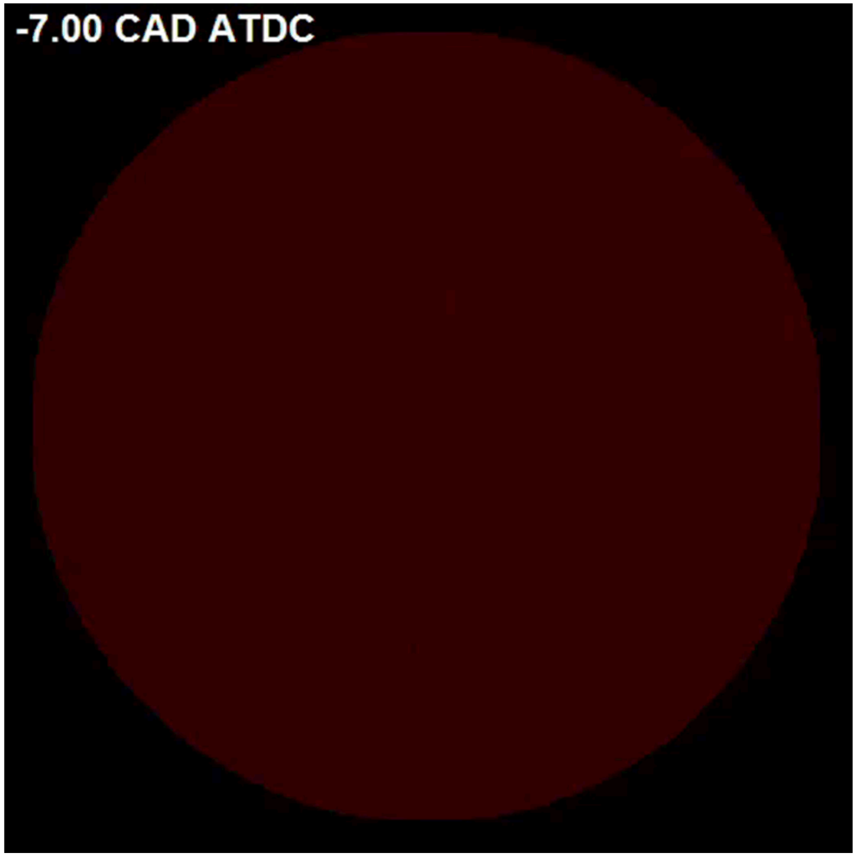
Equivalence Ratio



High speed natural luminosity: 300 μs dwell

- Soot formed in pilot mixture is almost immediately affected by the main injection
  - Entrainment flow carries soot radially inward
- Similar progression of luminosity distribution to 1200 μs case
  - Soot is initially formed upstream and downswirl but is consumed as combustion progresses
  - High luminosities first appear in the heads of jet, but then the sooting region expands inwards and into the squish region
  - Soot enters the squish region twice

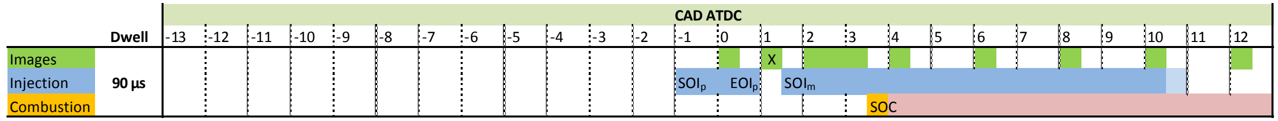
Second fired cycle



Recap: dwell 300 μs

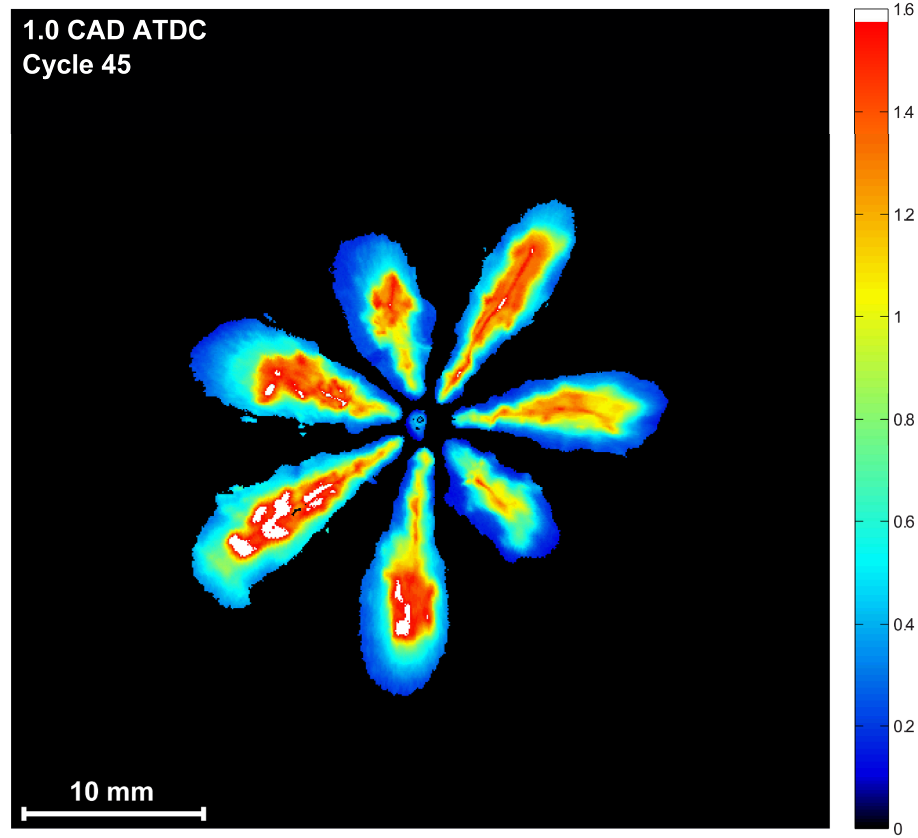
- Pilot heat release starts before SOI_m and finishes after SOI_m
- Products of pilot combustion have little time to mix and cool before the main injection and combustion events
- The main injection fuel is likely injected into hot combustion products that have been transported slightly by in-cylinder swirl
- The development of soot luminosity distributions is similar to the dwell of 1200 μs

PLIF results: 90 µs dwell

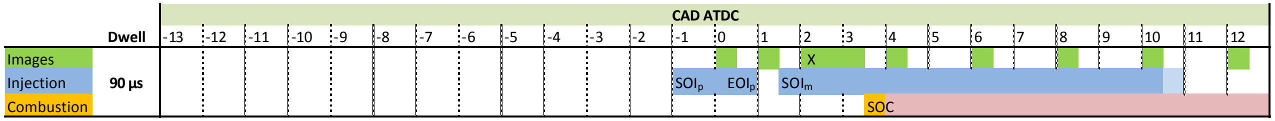


- Equivalence ratio distribution at EOI$_p$ and just before SOI$_m$ (1 CAD ATDC)
- Comparable images to 300 µs dwell

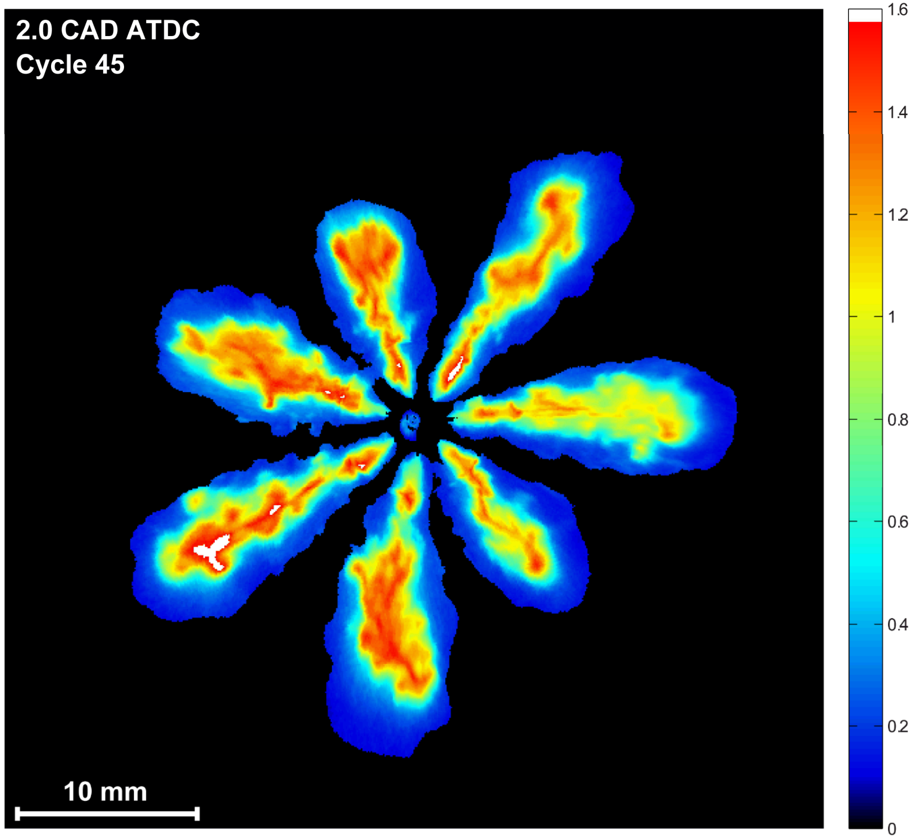
Equivalence Ratio



PLIF results: 90 μs dwell



Equivalence Ratio



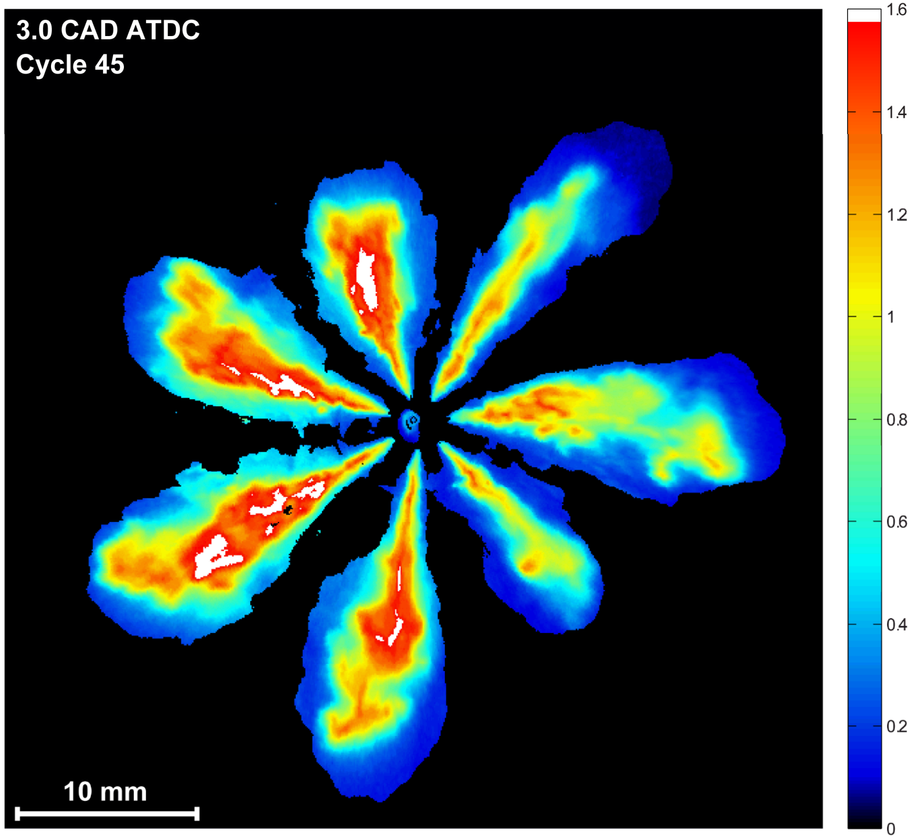
- Equivalence ratio distribution just after SOI_m but before SOC (2 CAD ATDC)
- Very little time for swirl to transport pilot mixture
- Difficult to distinguish between pilot and main mixture fields
- Main injection fuel is interacting very directly with pilot mixture fields

PLIF results: 90 µs dwell

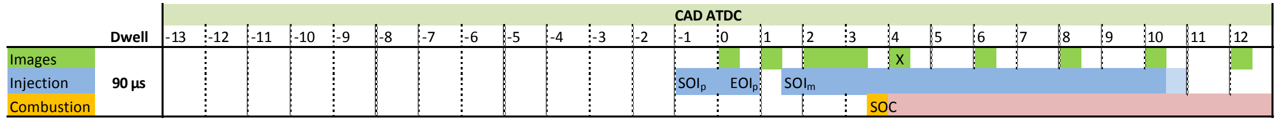
		CAD ATDC																									
	Dwell	-13	-12	-11	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8	9	10	11	12
Images																		X									
Injection	90 µs													SOI_p	EOI_p	SOI_m											
Combustion																		SOC									

- Equivalence ratio distribution just before SOC (3 CAD ATDC)
- Very difficult to distinguish between pilot and main mixture fields
- Some influence of swirl flow is seen at the heads of the jets

Equivalence Ratio

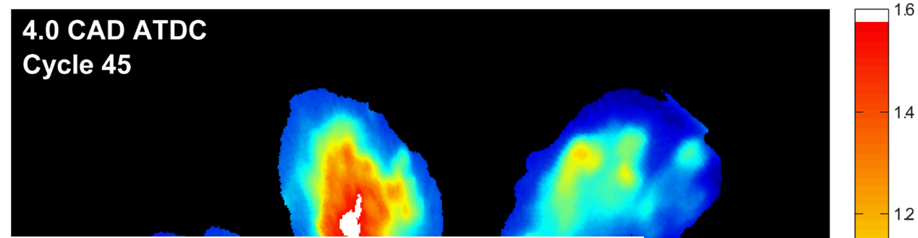


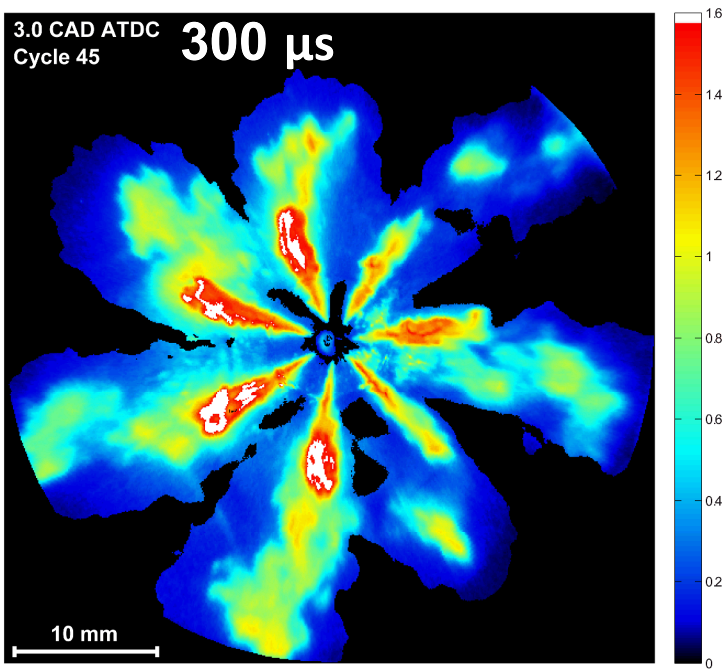
PLIF results: 90 μs dwell

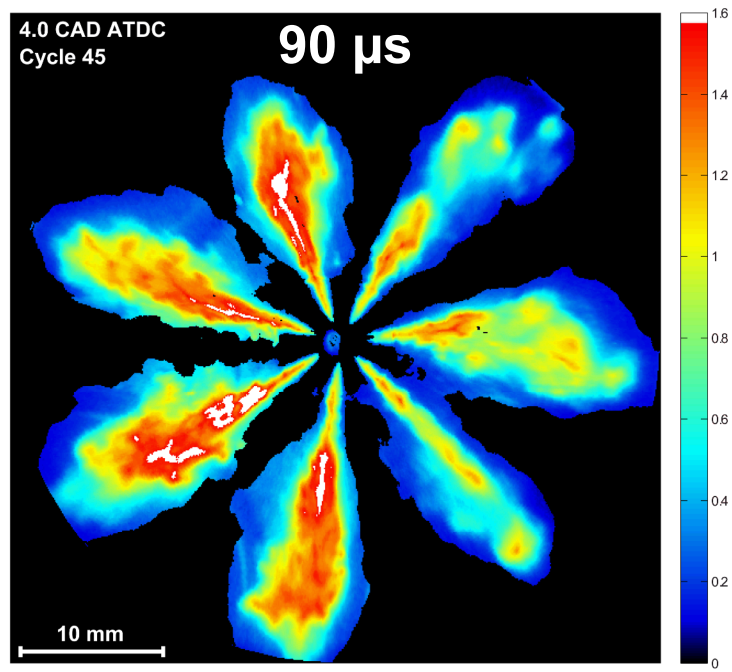


- Equivalence ratio distribution just after SOC (4 CAD ATDC)
- Rich mixtures appear over a larger area of the cylinder than at SOC$_m$ for a dwell of 300 μs after the start of combustion

Equivalence Ratio



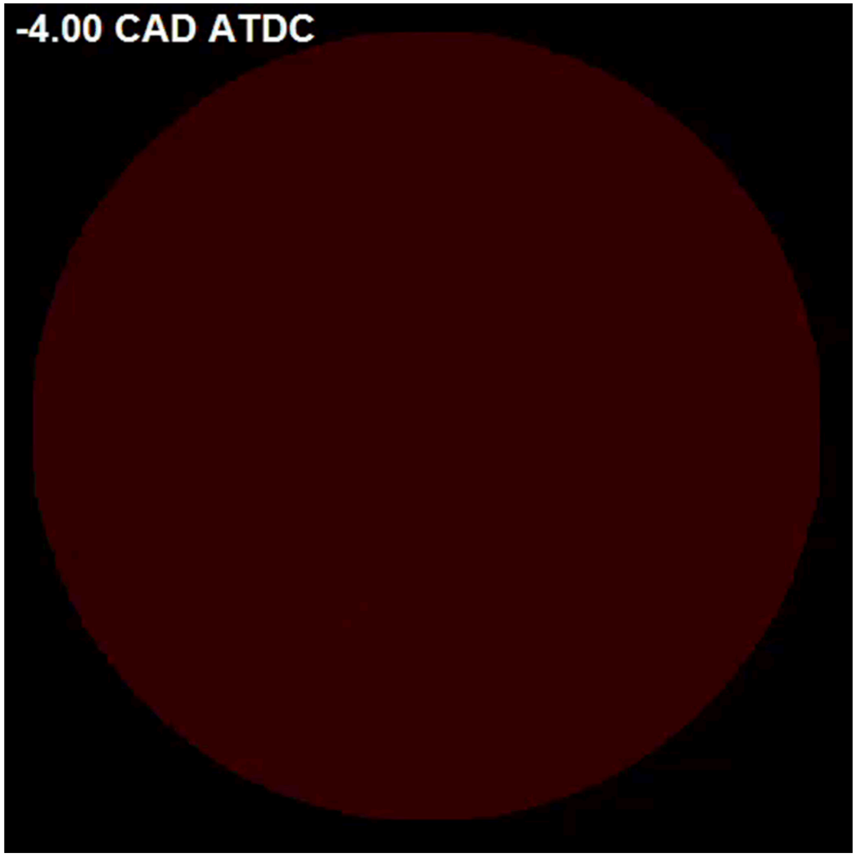




High speed natural luminosity: 90 μs dwell

- Initial combustion luminosity occurs in downstream, downswirl portions of jets
- Similar progression of luminosity distribution towards center
  - Motion of coherent structures suggests convection plays a role in this
  - Convection due to recirculation flow pattern in bowl?
- Soot enters the squish region twice

Third fired cycle



Recap: dwell 90 μs

- Main injection fuel interacts directly with the pilot mixture field
- Minimal mixing and swirl-assisted transport of pilot mixture field before onset of combustion
- Just after combustion starts, rich mixture is present in a large region of the cylinder
- No interaction between products of pilot combustion and main injection

Summary after initial review of data

- **PLIF:** As dwell decreases, the main injection likely interacts with cooled, mixed combustion products, then hot, less mixed combustion products, then directly with the pilot mixture field

- **Natural luminosity imaging:** if the pilot combustion occurs before the main injection, it will form soot that interacts with the main injection. Soot formed during the early part of the combustion near the center of the chamber is typically consumed before the high intensity regions at the heads of the jets are pushed into the center of the chamber.

Some open questions

- How and where does combustion of the main injection mixture field get started? How does the dwell impact this?
- The initial phases of combustion look quite different for the various dwells. How does this affect the total amount of soot formed / oxidized / emitted?
- Adding a pilot injection essentially doubles soot emissions. What do we see in the images that explains this?
- What causes the strong inward radial motion during the main combustion event?
  - Convection?
  - Shortening of lift-off lengths?
  - Optical distortion?
- How well can these phenomena be reproduced with CFD tools?

Next Steps

- Continued analysis of PLIF and combustion luminosity results
  - More direct comparison with conceptual models in the literature
  - Thorough comparison with single injection results
  - Publication(s)
- CFD simulations at UW
- Chemiluminescence imaging to provide insight about ignition/inflammation processes (potential mid-term project)
- Two pilot injections (potential mid to far-term project)