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Effect of close pilot spacing on combustion and emissions

Final report

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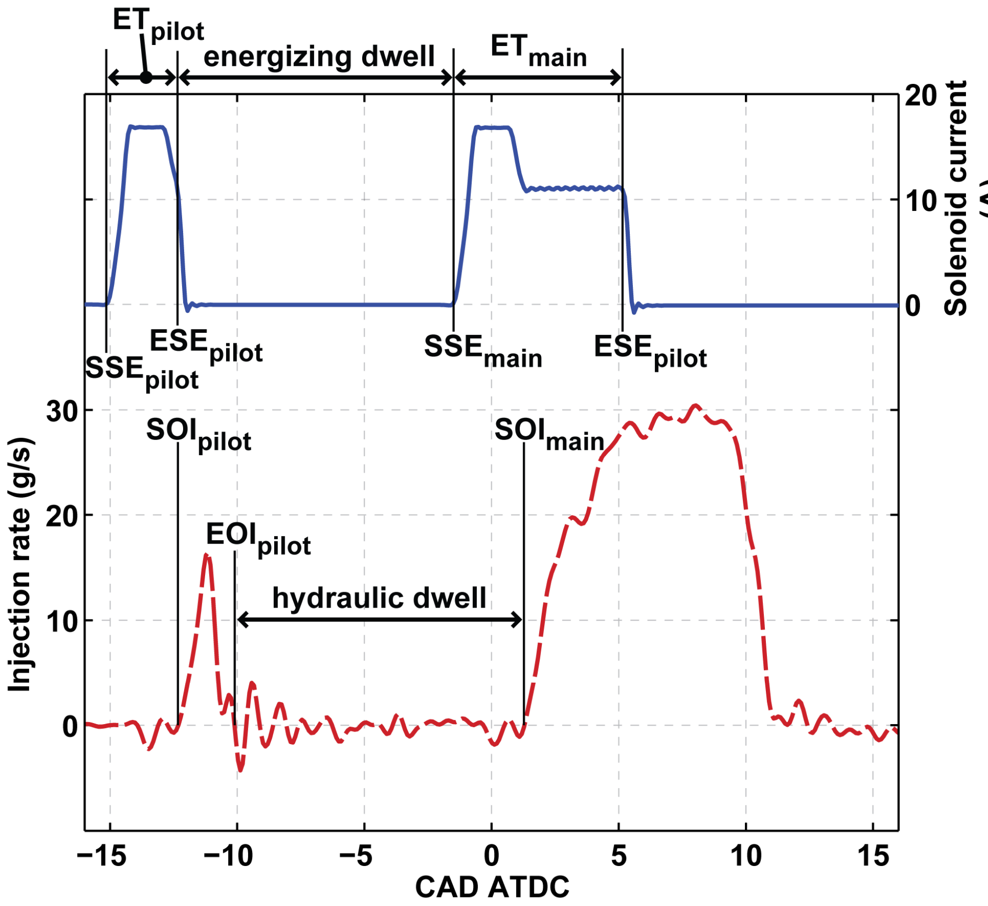
Outline

- Engine operation
  - Definition of terms
  - Pilot + main: dwell sweep
  - Far pilot + close pilot + main: single operating point
  - Experimental objectives
- Overview of engine configurations, experimental setups, data processing, and analysis techniques
- Results
  - Overall performance and emissions behavior (focus on smoke)
  - Ignition processes with a far pilot
  - The effect of dwell on main mixture ignition processes
  - Late cycle combustion and turbulent mixing
  - Adding a far pilot
- Summary; next steps

Definition of terms: solenoid energizing and fuel injection

- Solenoid energizing
  - ET: energizing time
  - SSE: start of solenoid energizing
  - ESE: end of solenoid energizing
  - DSE: duration of solenoid energizing; ESE - SSE
  - Energizing dwell: "dwell"
- Fuel injection
  - SOI: start of injection
  - EOI: end of injection
  - Hydraulic dwell



Operating points

- Part load, conventional combustion
- Fixed combustion phasing
- Pilot + main
  - Energizing dwell sweep
- Far pilot + close pilot + main
  - Single operating point
- TDC conditions adjusted to closely approximate conditions provided by GM

		Main	Pilot + main	Far pilot + close pilot + main
Eng. speed	[rpm]	1500		
$IMEP_g$	[bar]	9.0		
Rail pressure	[bar]	800		
$Q_{far\ pilot}$	[mg/str]	-	-	1.5
$Dwell_{far\text{-}near\ pilot}$	[us]	-	-	1200
$Q_{close\ pilot}$	[mg/str]	-	1.5	1.5
$Dwell_{close\ pilot\text{-}main}$	[us]	-	1200…*200*…600 600…*100*…200 200…*20*…80	90
Boost pressure	[kPa abs]	~150		
Intake temp.	[°C]	~80		
TDC temp.	[K]	~925		
EGR	[%]	~7 (10.3 accounting for residual fraction)		
$[O_2]$	[%]	19.73		
MFB50	[CAD]	~13		
Fuel	[-]	DPRF58 (CN 50.7) 58 vol% Heptamethylnonane 42 vol% n-Hexadecane		

Experimental objectives

- Pilot + main
  - What is the mechanism of combustion noise reduction by close-coupled pilots? (prior work; not covered in this presentation)
  - How does dwell impact ignition processes, combustion, and pollutant formation (especially PM)?

- Far pilot + close pilot + main
  - How does the addition of a second pilot change ignition, combustion, and pollutant formation?

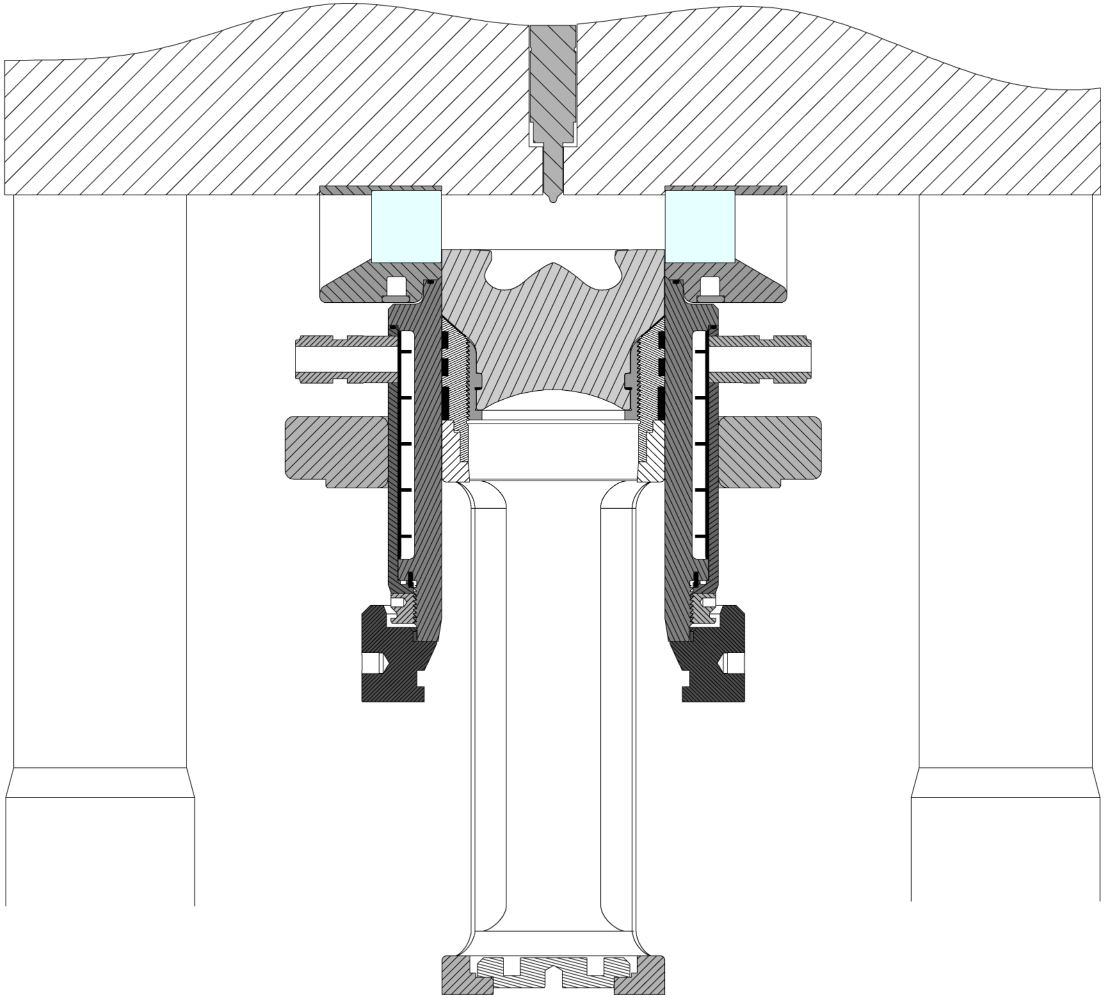
Experimental setup: engine configuration

Single-cylinder engine data

Bore x Stroke	82 mm x 90.4 mm
Compression ratio	16.7:1
Valves	4
Piston geometry	FP48_B2
Bowl:bore	45.28:82 (0.55)
Injector	Bosch CRI 2.16 Multijet 2
Holes x Ø	7 x 139 µm
Flow Number	440 cm^3/30s @100 bar
ks	1.5 / 86
Included angle	149°

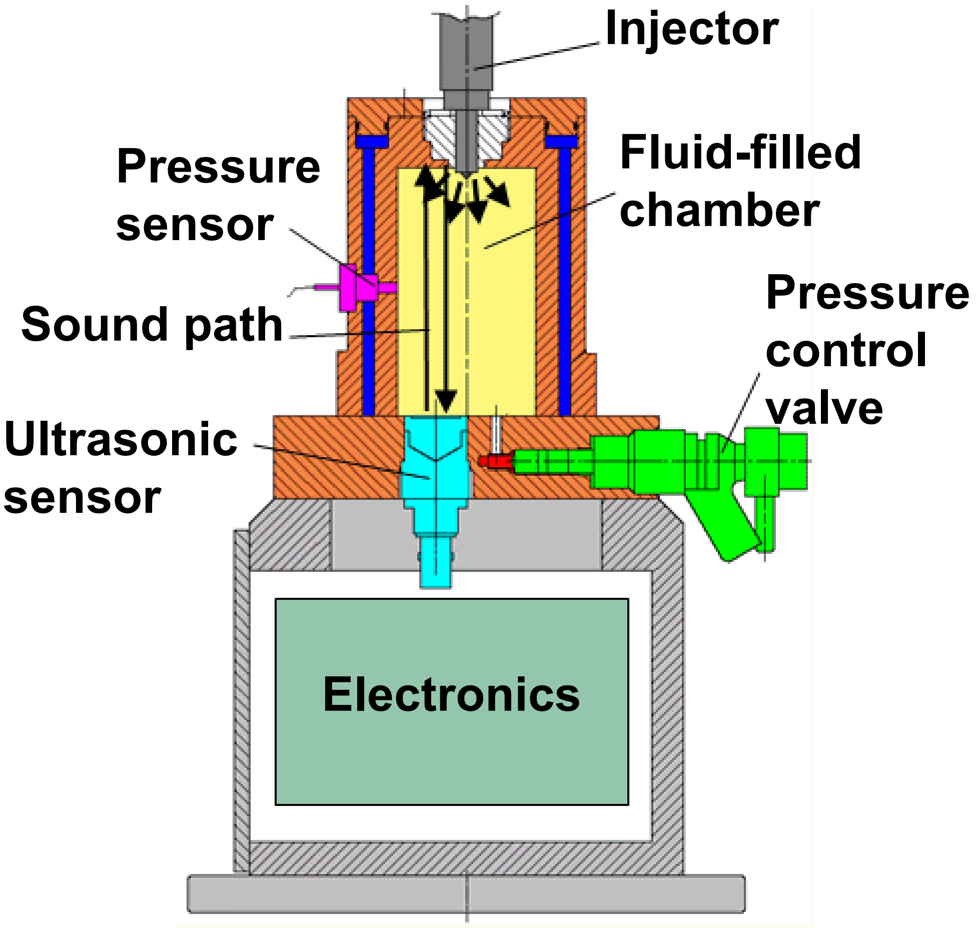
Pre-production solenoid injector

- Pressure-balanced pilot valve
- Fast acting → makes short hydraulic dwells possible



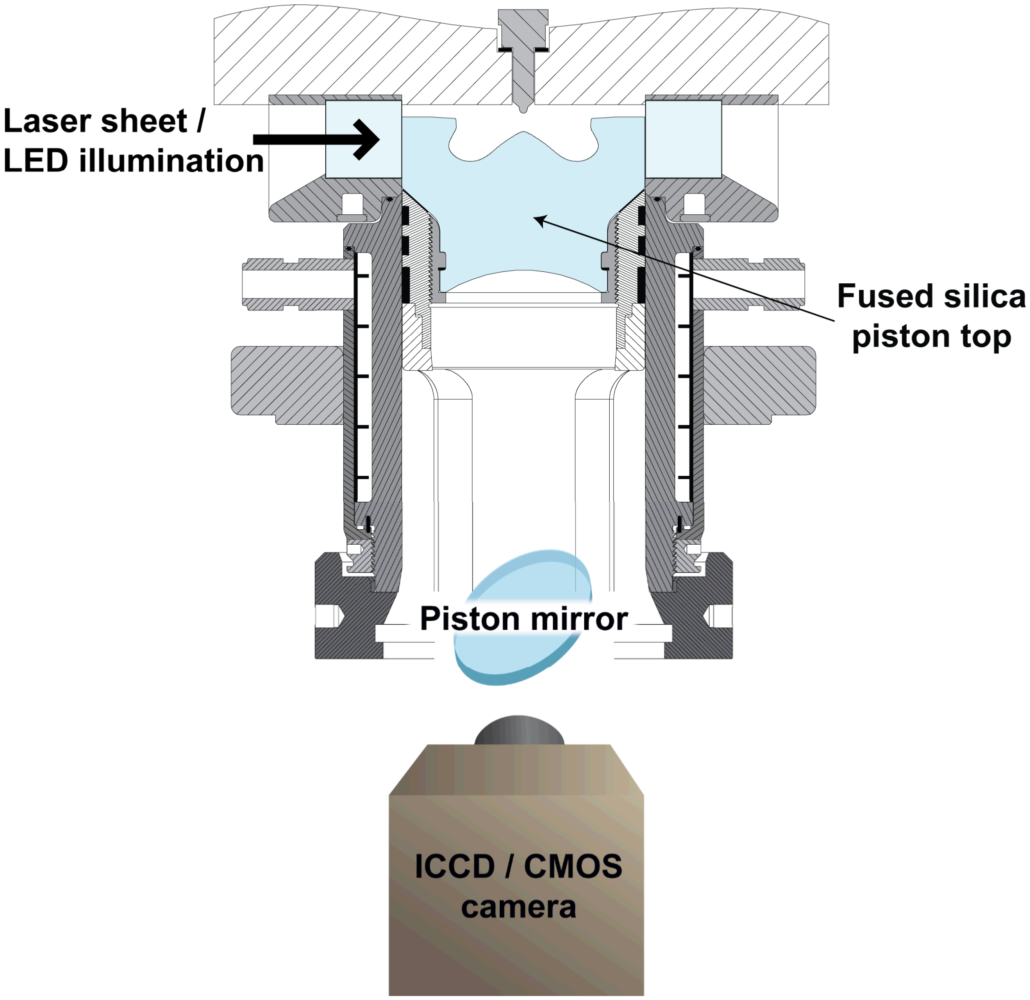
Experimental setup: Moehwald HDA

- Same fuel injection hardware as used in engine testing
- Same injection schedules as used in engine testing
- Chamber pressure corresponds to cylinder pressure at start of injection
- Measurement of chamber pressure and speed of sound of fuel in chamber
  - Fuel density and compressibility effects taken into account
- Derived fuel injection rates for each injection schedule



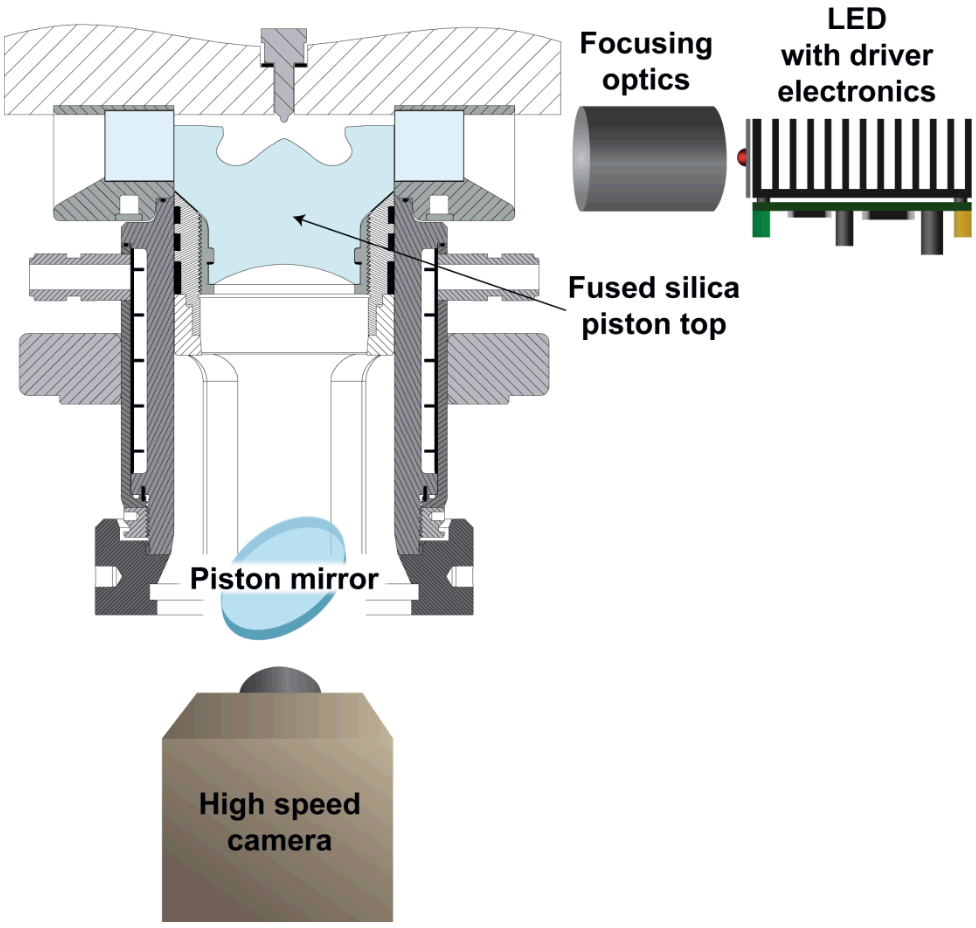
Experimental setup: optical engine

- Metal piston, skip-fired operation
  - Cylinder pressure & emissions
- Optical piston, motored (N_2) operation
  - High speed Mie scattering: liquid fuel penetration
  - Planar fuel tracer LIF: liquid and vapor fuel distributions
- Optical piston, skip-fired
  - High speed, simultaneous NL and OH* chemiluminescence imaging
    - Line-of-sight measurements
  - Ignition, inflammation, combustion processes; flame structure; flow during combustion



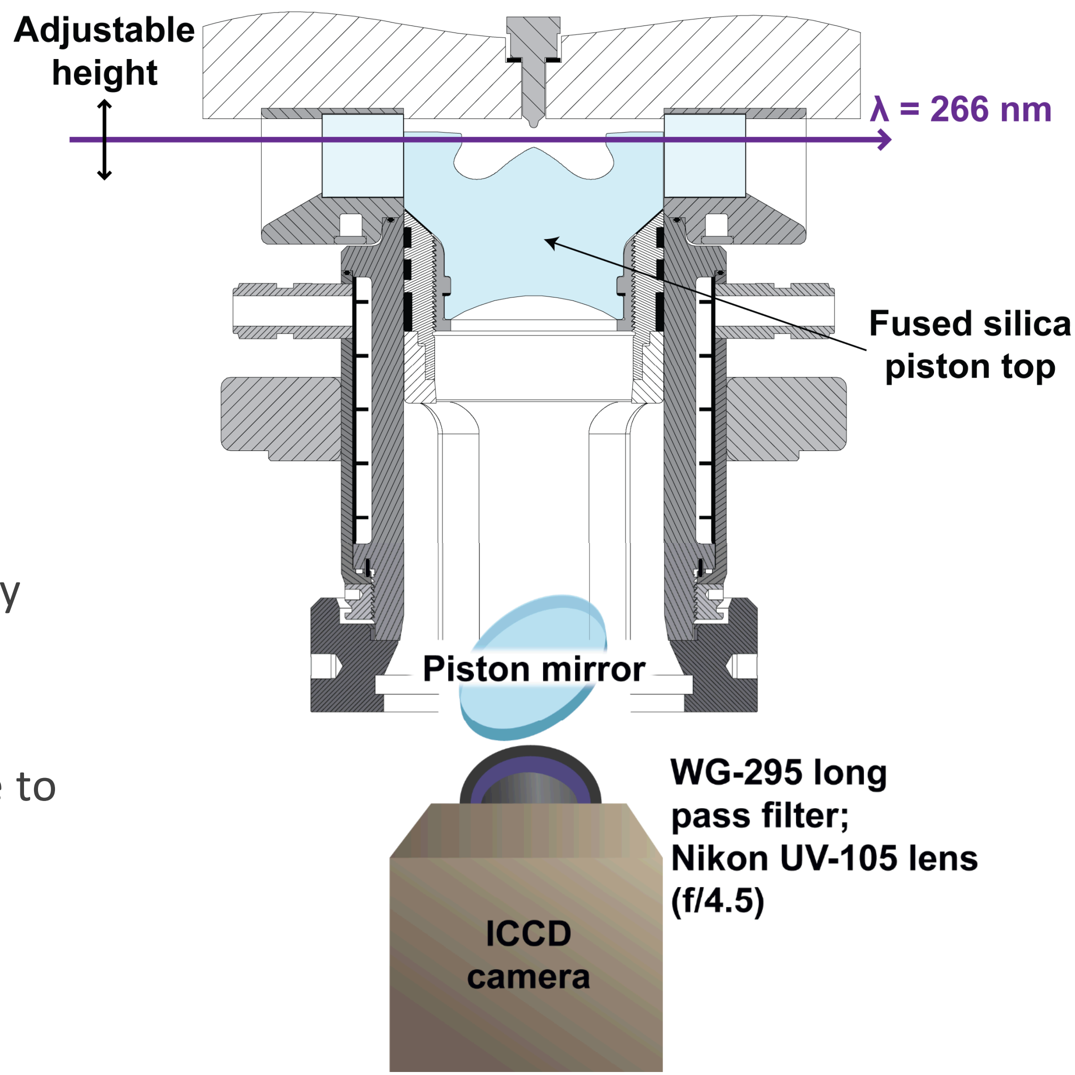
Experimental setup: high speed fuel injection imaging (motored)

- Elastic scattering: liquid fuel penetration
- Operating conditions
  - Injection schedules: 300, 140, 90 µs; single injection
- Side illumination
  - High-energy pulsed LED
  - Non-uniform illumination (but no evidence of signal degradation)
- Imaging through piston
  - Photron SA-X2 monochromatic CMOS
  - Enables view of injector tip
  - Imaging rate: 120 kfps
    - 0.075 CAD at 1500 rpm
  - Image size: 256x256 pixels



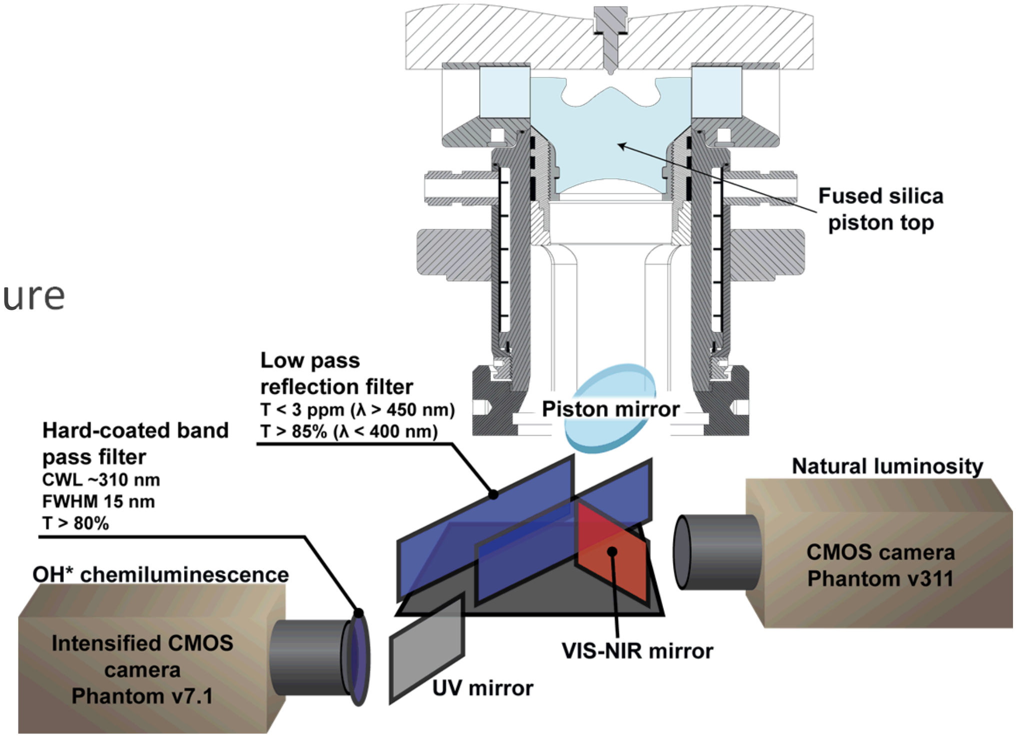
Experimental setup: PLIF imaging (motored)

- Spatially resolved, semi-quantitative measure of fuel concentrations
- Fuel doped with 0.5 wt% 1-methylnapthalene: fluorescent tracer with well-characterized photophysics
- Illumination source
  - Nd:YAG, 4^{th} harmonic (266 nm)
  - ~30 mJ / pulse (relative intensity measured for each shot)
  - Laser sheet thickness < 1 mm
  - Sheet positions defined relative to to piston geometry
    - Plane 1: squish region
    - Plane 2: upper bowl rim
    - Plane 3: deep in bowl



Experimental setup: high speed NL and OH* chemiluminescence imaging (fired)

- Natural luminosity (NL)
  - Primarily from broadband soot radiation, very strong function of temperature
- OH* chemiluminescence
  - $CH + O_2 \rightarrow OH^* + CO$
  - Spectral peak near 308 nm
  - Tells us about high-temperature ignition processes and flame structure
- ICMOS camera: Phantom V7.1
  - Sensitive to UV, visible, and NIR
  - Filtering needed to block vis-NIR, maximize transmission at 308 nm
- CMOS camera: Phantom V311
  - Sensitive to visible-NIR light rejected by the low pass filter
- Simultaneous imaging at 25 kfps
  - 0.36 CAD resolution at 1500 rpm



Analysis of raw exhaust emissions

- Exhaust emissions are measured in skip-fired operation at the end of each 3-minute measurement run with the metal piston
  - Engine operation has not reached steady-state; this is the best we can do
- Injected fuel mass is measured offline with the HDA
- Corrections
  - Analyzer drift / motored emissions levels are removed
  - Dilution correction to account for skip-fired operation
  - Dry emissions (CO, NOx) are corrected to account for residual vapor
- Emissions indices reported in [g/kgf]
- Paper blackening converted to FSN for skip-fired operation

Emissions measurement equipment

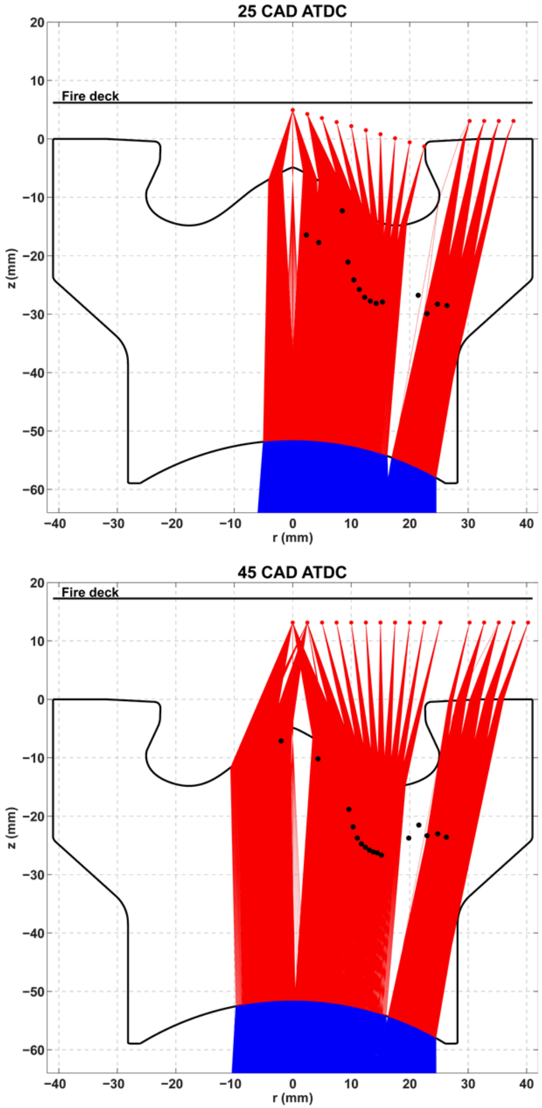
Exhaust Component	Analyzer
CO	CAI Model 300 Infrared Analyzer
UHC	CAI 600 Series FID
NOx	CAI 600 HCLD
FSN	AVL415S Smoke Meter

Cylinder pressure-based analyses: heat release analysis

- Cylinder pressure is low pass filtered (f_c = 4 kHz) before heat release analyses are performed
- Apparent heat release rate (AHRR) is computed in three stages
  - Takes variable mixture composition into account
  - Accounts for effects of fuel addition and temperature increase on specific heat ratio
  - Motored AHRR is subtracted from fired AHRR to remove anomalous behavior attributed to the optical engine configuration
- AHRR is computed for each of 50 fired cycles; the traces shown are ensemble averages unless otherwise noted

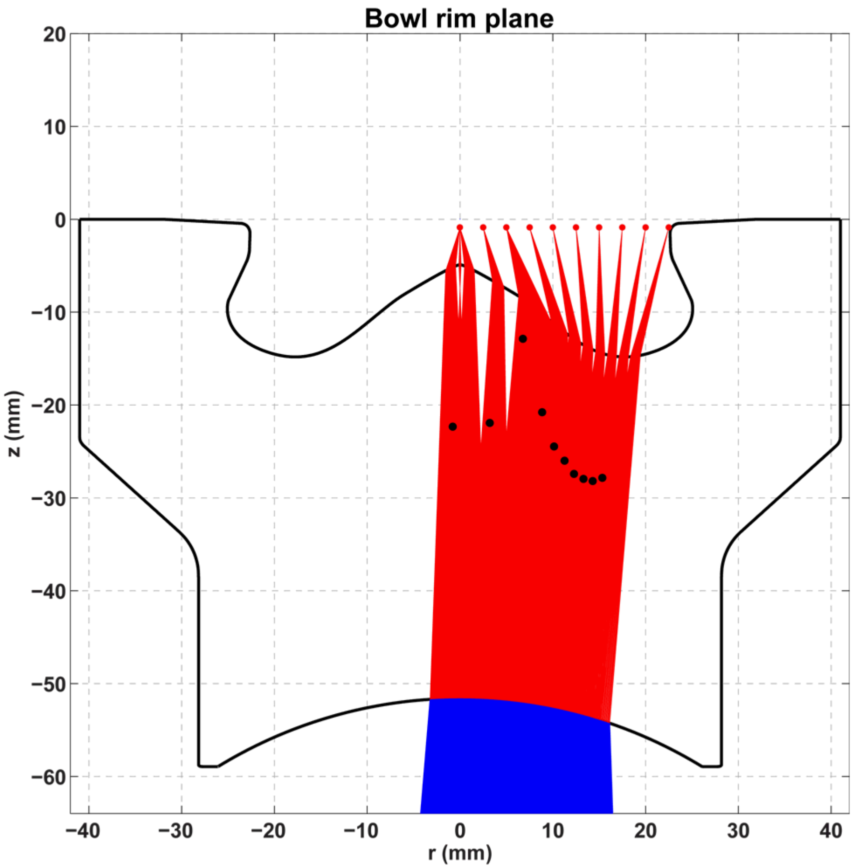
Analysis: automated image distortion correction (1/2)

- Image distortion arises from the complex piston geometry
  - Depends on crank angle, varies with radial and axial object position
- A ray-tracing based algorithm has been developed and is used extensively to distortion correct all optical data from the engine
- Natural luminosity and OH* chemiluminescence images
  - Distortion correction depends on crank angle
  - Before 28 CAD ATDC: along jet axes in the bowl, halfway between head and fire deck in squish region
  - After 28 CAD ATDC: along a plane 4 mm below the fire deck



Analysis: automated image distortion correction (2/2)

- PLIF imaging
  - Majority of data taken in Plane 2: bowl rim
  - Target is fixed in relation to the piston; moves relative to fire deck

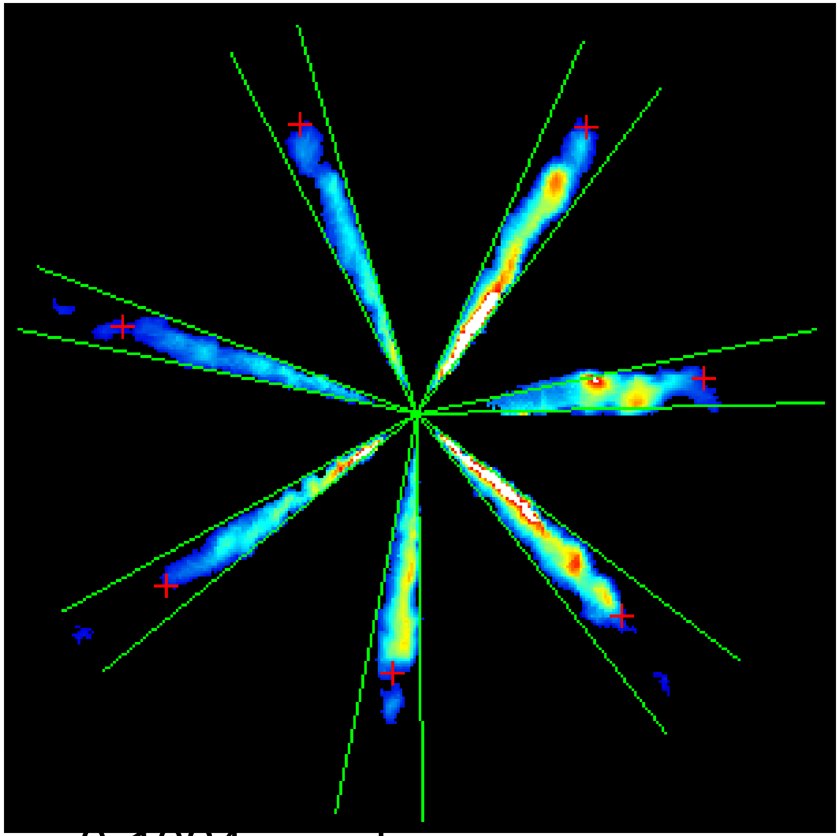


Analysis: processing fuel injection images

- Distortion correction is performed along the jet axis
- Background modeling and subtraction with approximate median method
- Quantitative data can be extracted from images
  - Penetration lengths and rates
  - Each jet is treated individually
  - 45 skip/fired cycles are analyzed for each operating point tested
- Calculation according to:

  Siebers, D.L., Naber, J.D., "Effects of Gas Density and Vaporization on Penetration and Dispersion of Diesel Sprays", SAE technical paper 960034, 1996.

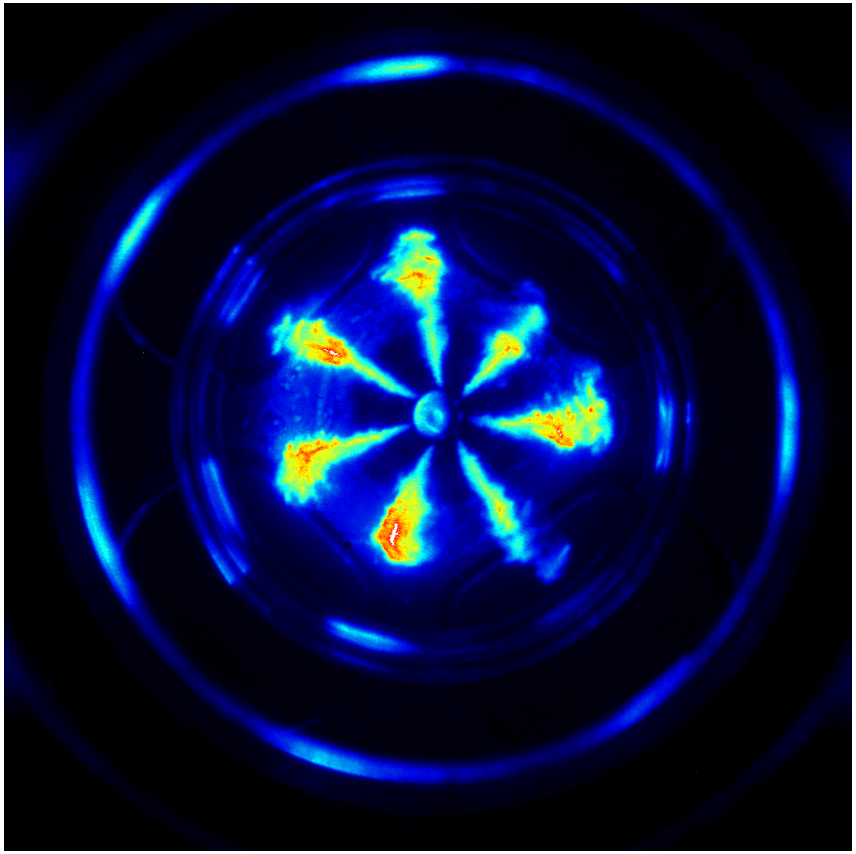
  - Intensity threshold: 3% of max intensity for each jet



0-1024 counts

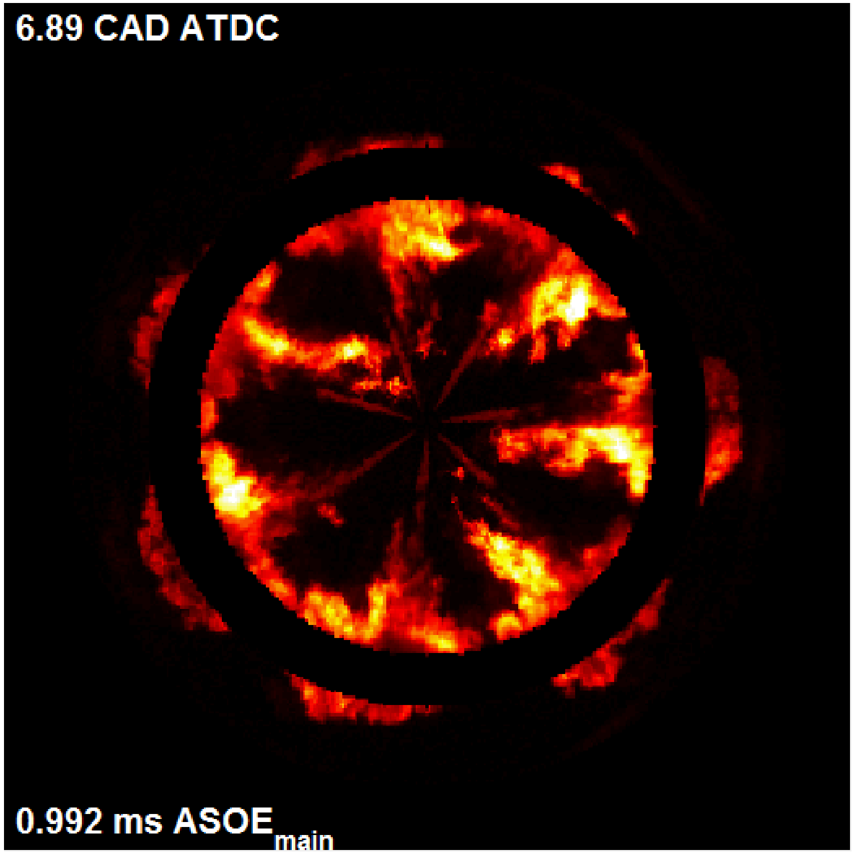
Analysis: fuel tracer PLIF

- The fluorescence intensity of 1-methylnaphthalene depends on concentration, temperature, pressure, and laser fluence
- Considerations:
  - Background intensity
  - Laser sheet fluence distribution (flat-field correction)
  - Shot-to-shot laser energy variation
  - Temperature change resulting from mixing (adiabatic, real-gas mixing model)
  - Temperature dependent absorption cross section and quantum yield
- Data taken for 50 consecutive skip-fired cycles at each imaged CA
- Result: fuel concentration (ϕ) distributions for various CAs



Analysis of high-speed natural luminosity (NL) data

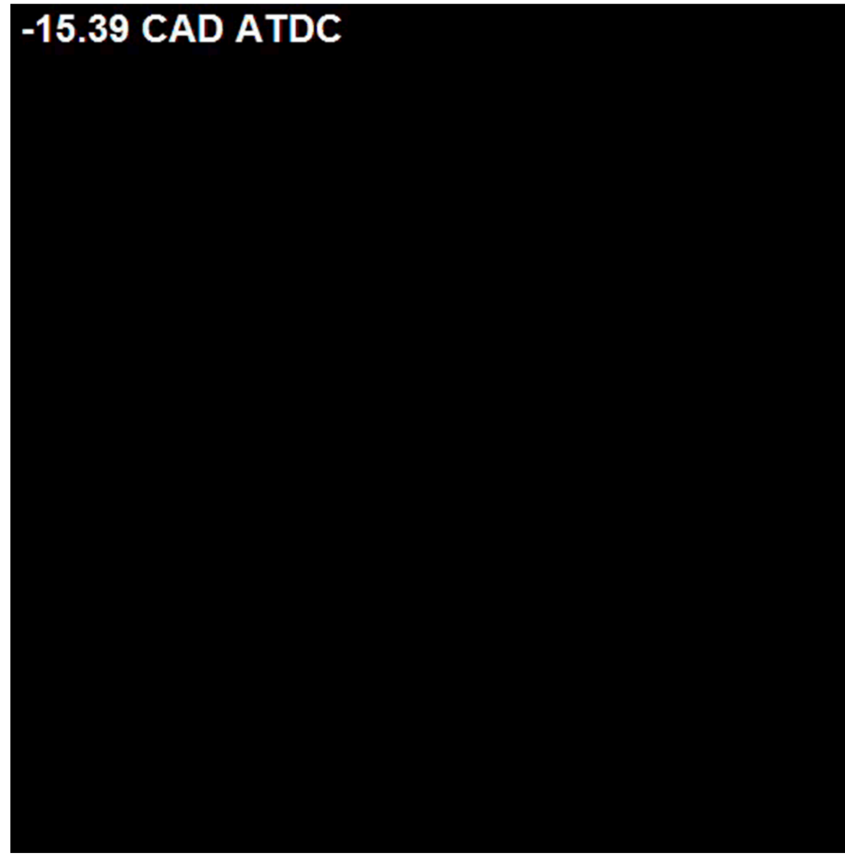
- The first five skip-fired cycles are taken from a run, and each operating point is run four times
  - Reduce effects of window fouling
  - 20 cycles for each operating point
- Images are thresholded and the pixels with detected NL are counted: A_{NL} (useful during early combustion)
- SINL: spatially integrated natural luminosity (sum of all pixels)
  - Region based: bowl and squish



Analysis of high-speed NL data: combustion image velocimetry (CIV)

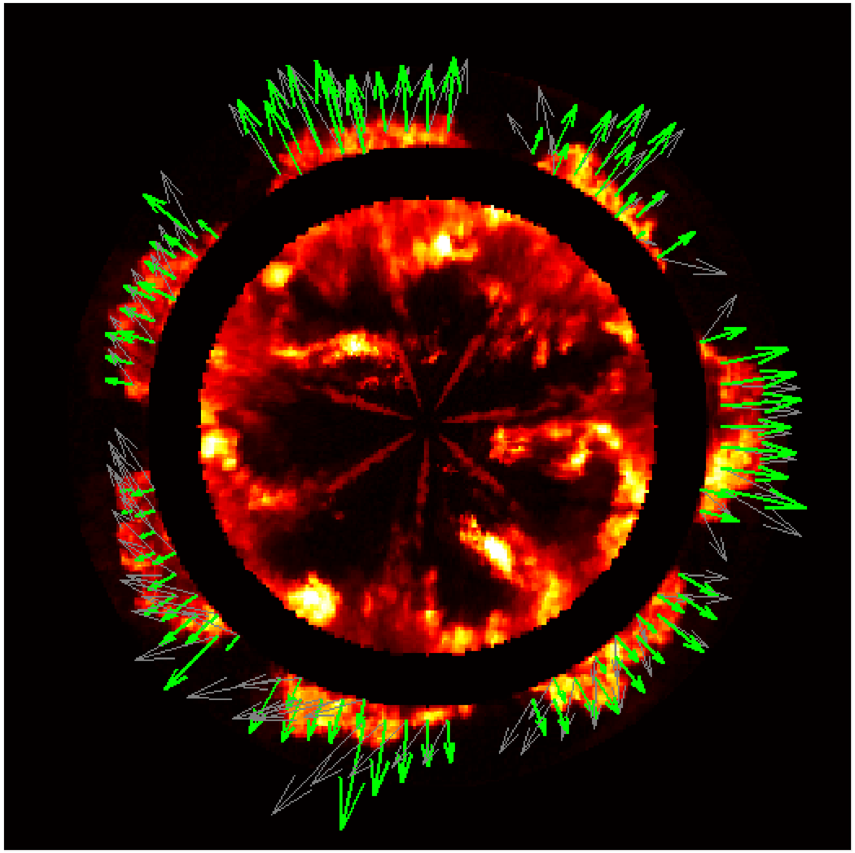
- Use NL image pairs with a cross-correlation routine (as in PIV)
- Vectors are only available where NL signal is present
- Computation for each of 20 skip-fired cycles; results are ensemble averaged
- This method is currently semi-quantitative and uncertainties / errors have not been analyzed
- The pseudo-velocity data are used to extract information about:
  - Flow into the squish region
  - Recirculation within the bowl

Single cycle, NL video



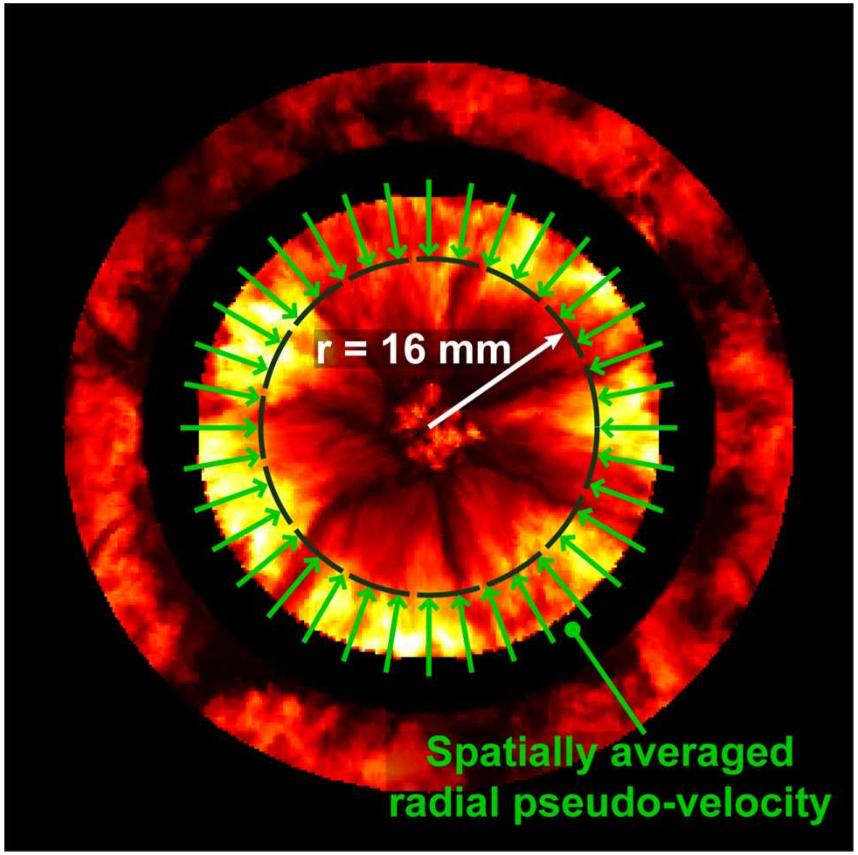
Analysis of high-speed NL data: characterizing squish flow

- For each single-cycle image, compute pseudo-velocity field
- Compute the radial component (shown in green) of each vector (gray) nearest the inner edge of the squish region
- The sum of the radial components gives a measure of the outward flux resulting from in-cylinder flows and combustion
- This flux is not weighted by the NL intensity
  - NL is likely not a reliable measure of relative soot concentration for these tests



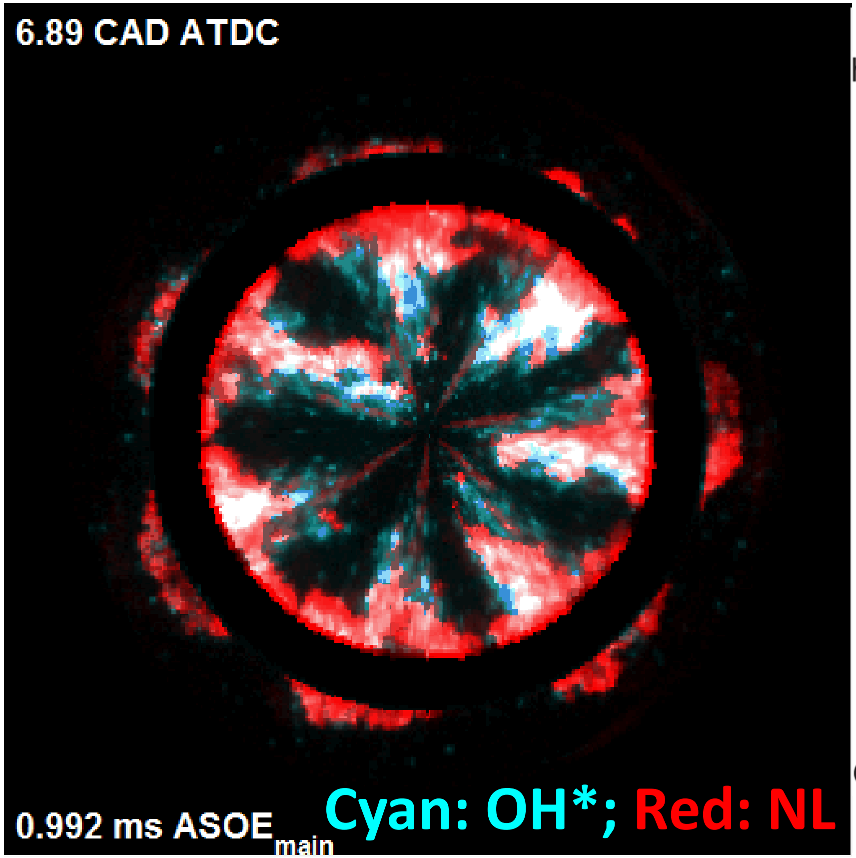
Analysis of high-speed NL data: characterizing recirculation in the bowl

- During combustion, the recirculating flow in the bowl has a strong radial component
  - CIV results can provide additional information about this behavior
- Radial pseudo-velocities are computed for an arbitrary radial location within the bowl
  - Interpolated and spatially averaged along a 32 mm circle
  - Bowl rim: d = 45 mm
- Ensemble average of 20 cycles is plotted against crank angle for a given dwell (later)



Analysis of high-speed OH* chemiluminescence data

- Image distortion correction is the same as for the NL images
- The OH* chemiluminescence signal is also highly temperature dependent
  - The meaning of the OH* intensity is not always clear
- Images are thresholded and the pixels with detected OH* are counted: A_{OH*}
  - The start of high temperature heat release corresponds to the initial rise of A_{OH*}
- OH* images are blended with NL images to show temporal and spatial relationships



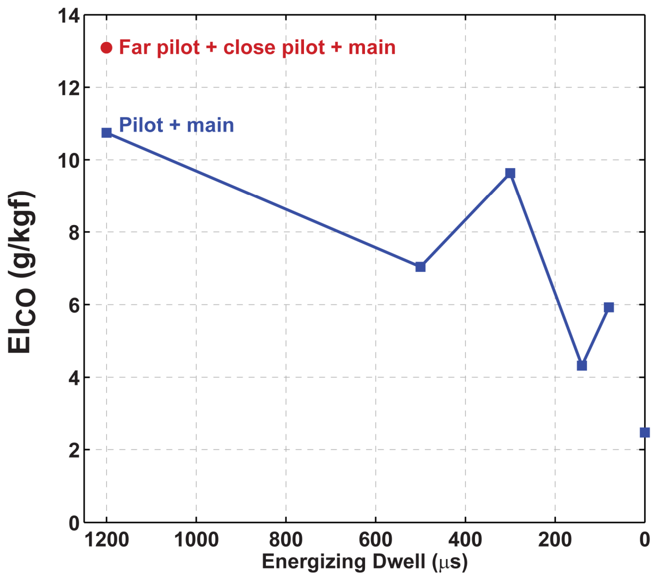
Results

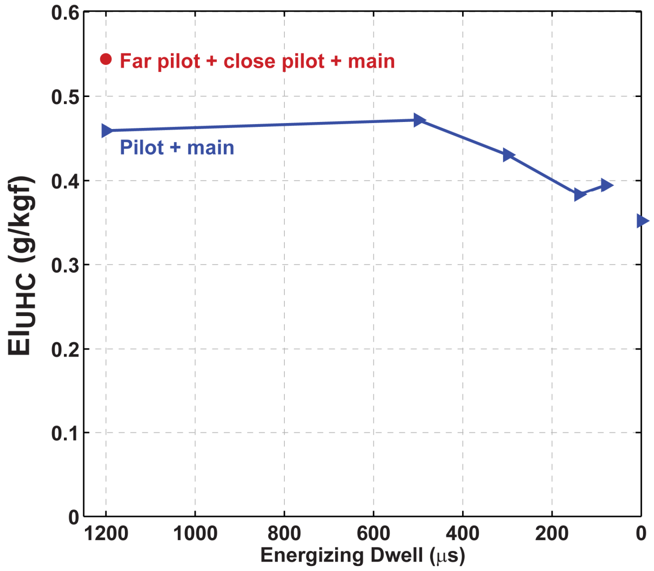
- Emissions trends
  - Pilot + main and far pilot + close pilot + main
- Pilot + main dwell sweep
  - Overall combustion, injection rates, ignition processes
  - Effect of dwell on ignition processes
  - Effects of dwell on late-stage combustion
- Far pilot + close pilot + main
  - Effect on injection rate, ignition processes, combustion

Results: CO and UHC emissions

- Pilot + main
  - CO emissions generally decrease for shorter energizing dwells
  - UHC emissions also decrease at shorter energizing dwells
  - Longer dwells may lead to overmixing and incomplete combustion

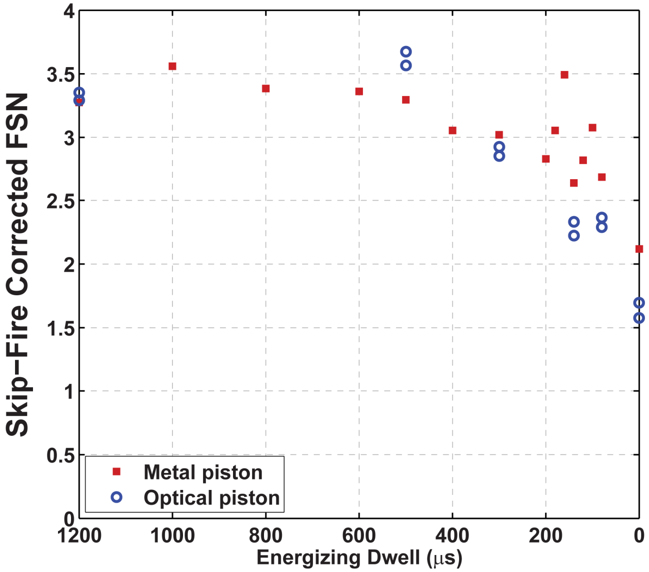
- Far pilot + close pilot + main:
  - CO and UHC emissions are higher than for the pilot + main strategy

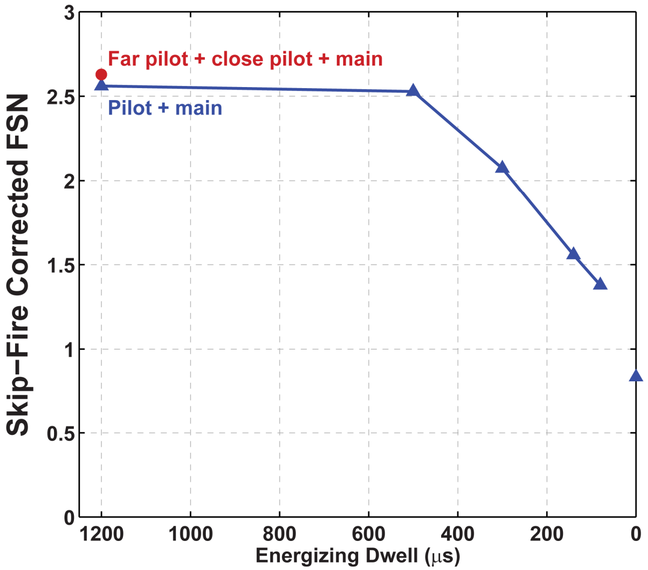




Results: soot emissions

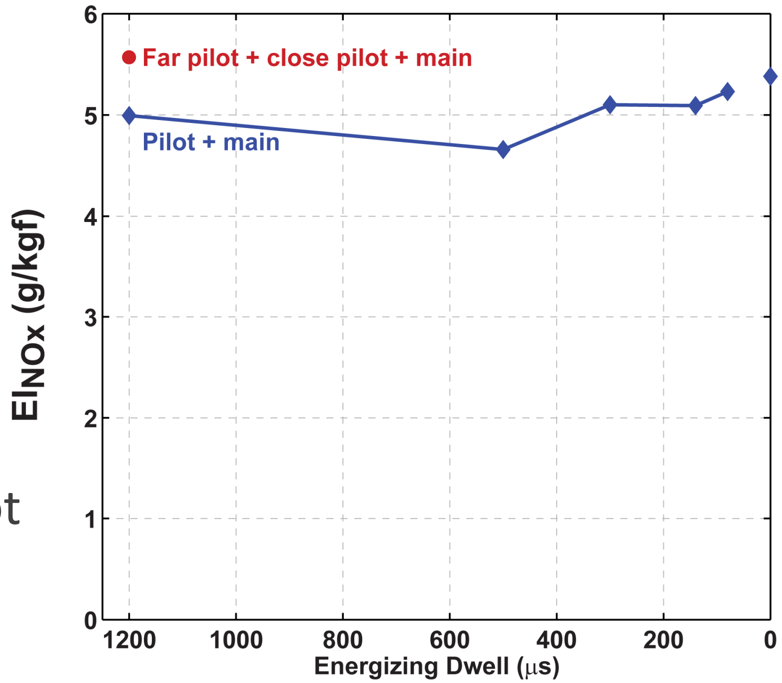
- Top plot: FSN for the pilot-main dwell sweep (metal vs. optical piston)
  - Good agreement between pistons
  - FSN generally decreases at shorter dwells
  - FSN may be very sensitive to dwell for energizing dwells below 200 µs
- Bottom plot: FSN comparison between pilot + main and far pilot + close pilot + main (metal piston)
  - Data taken 1.5 years after the data in the top plot shows a similar decrease in FSN at shorter dwells for the pilot + main case
  - Far pilot + close pilot + main: FSN comparable to single pilot + main with a long dwell





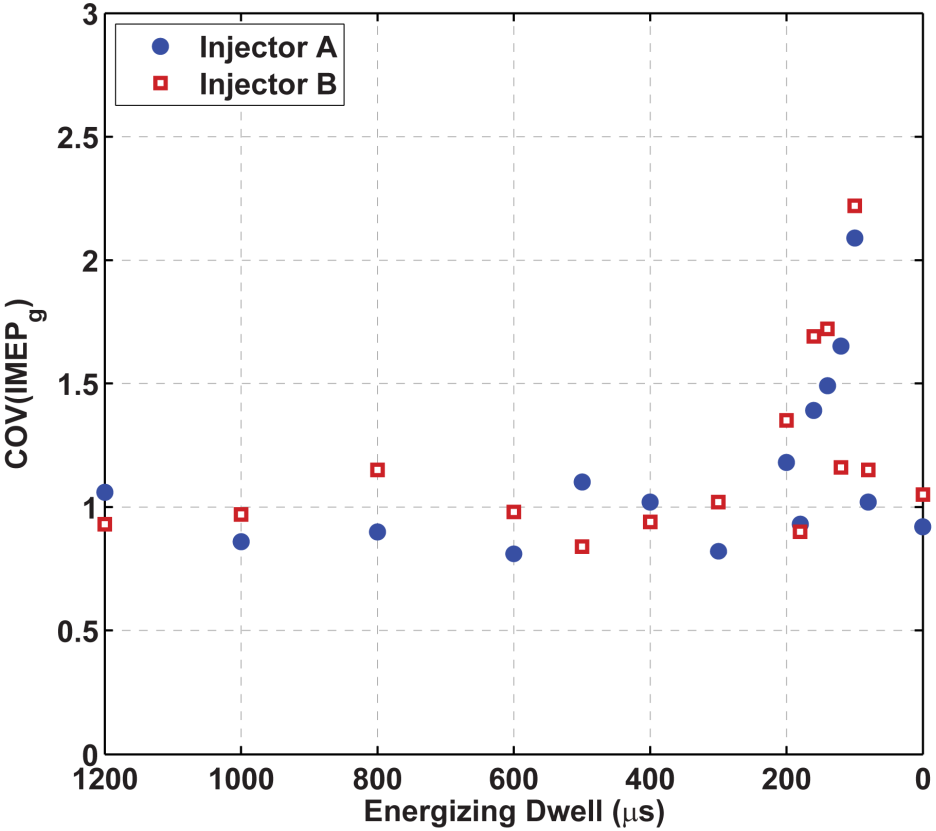
Results: NOx emissions

- Pilot + main
  - NOx emissions are not strongly affected by dwell; slightly lower than for the single injection
- Far pilot + close pilot + main
  - NOx emissions increase slightly above single injection value
- Summary of emissions data
  - Most significant trend: decrease in soot at shorter dwells for pilot + main strategy
  - Far pilot + close pilot + main: emissions slightly higher than long-dwell pilot + main case



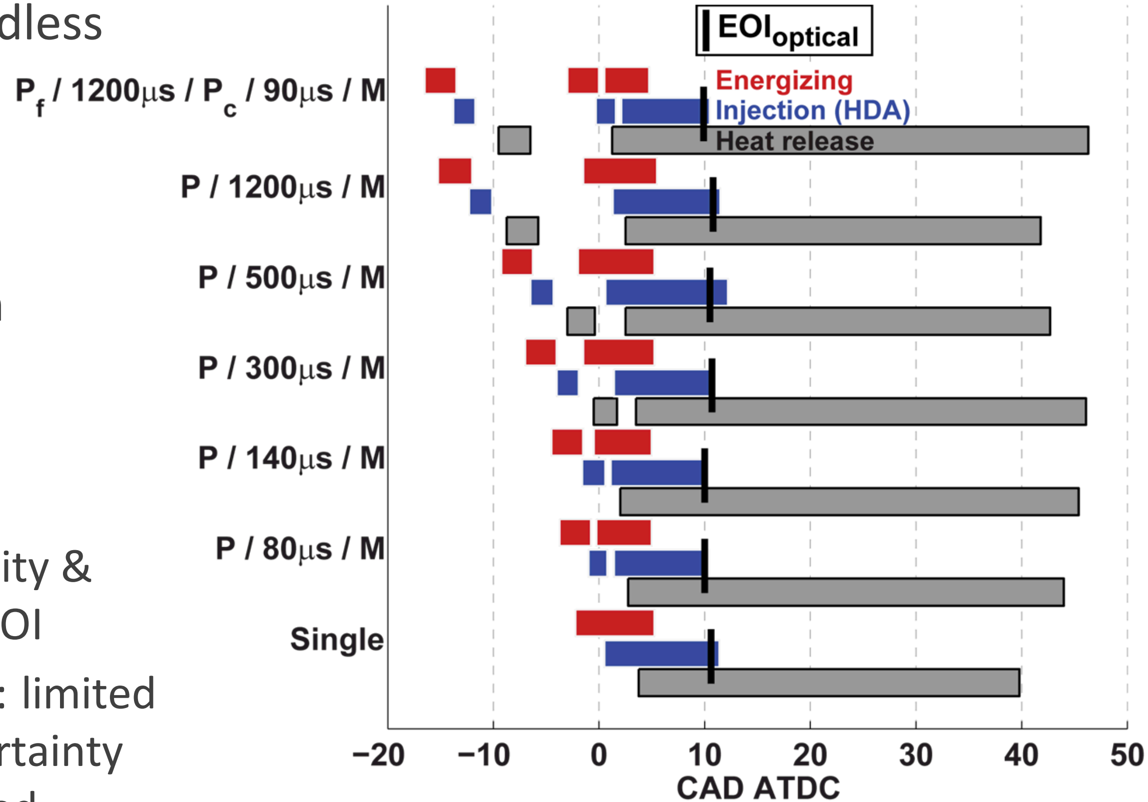
Results: COV(IMEP); P + M

- With far pilots, COV(IMEP) is very low (~1%)
- At the dwell for minimum noise of 140 µs, COV(IMEP) is near 1.5%
- COV(IMEP) peaks at a dwell of 100 µs just below 2.3%
- These data are taken in a skip-fired optical engine and may not be an accurate representation
- Planned testing at ORNL should demonstrate the variability over a wider range of operating conditions



Results: fuel injection summary

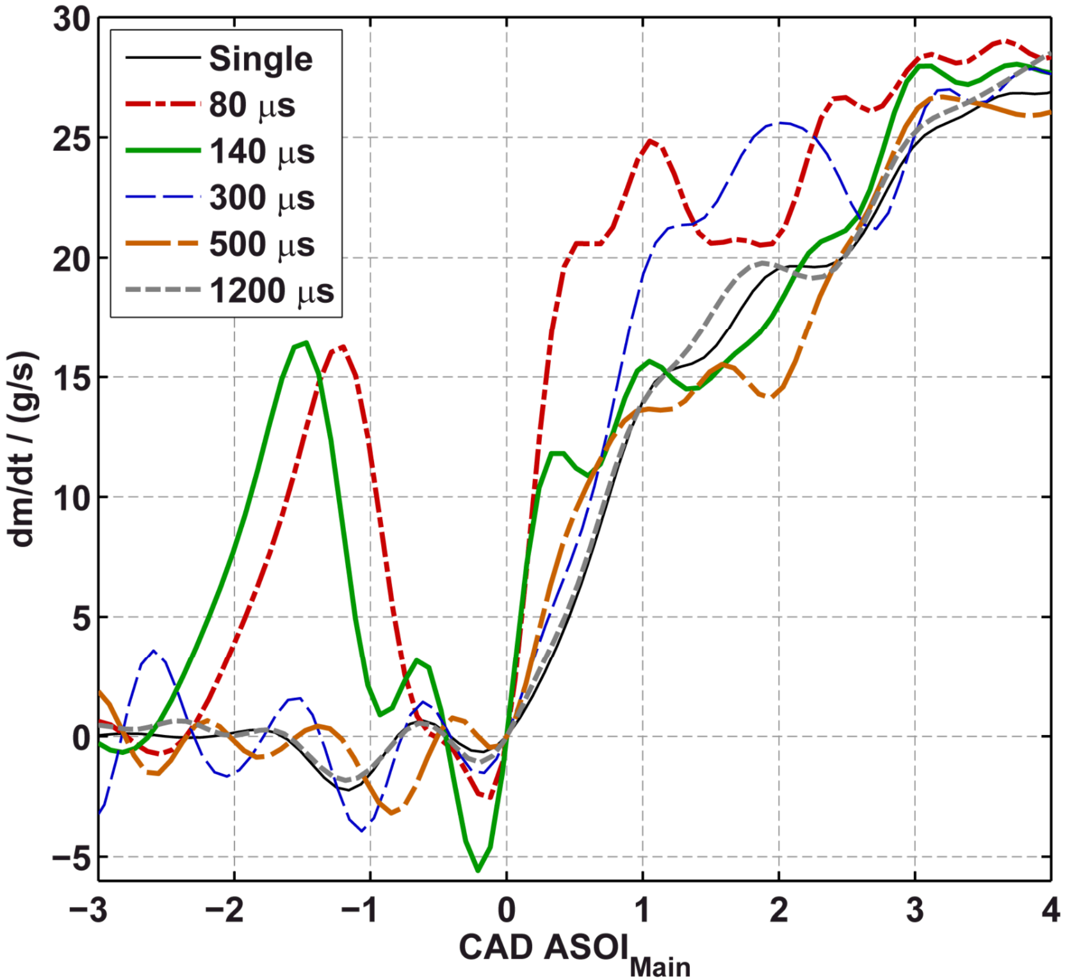
- Positive hydraulic dwell regardless of energizing dwell
- DSE_{main} decreases at shorter energizing dwells
- Relatively large uncertainty in estimating EOI
  - HDA: excessive pressure fluctuations near EOI
  - Optical: hole-to-hole variability & dribble – difficult to define EOI
  - Synchronization with engine: limited crank angle resolution, uncertainty in instantaneous engine speed



$EOI_{optical}$ is determined using a single jet that remains visible during natural luminosity imaging

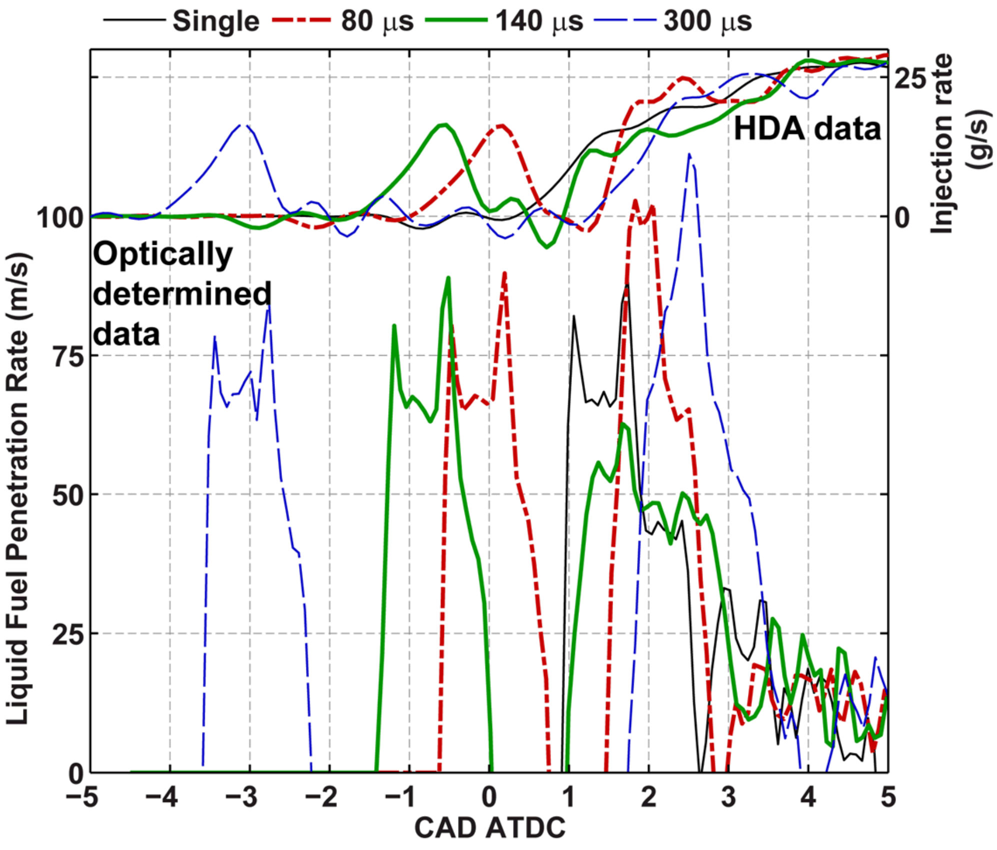
Results: fuel injection rates for P + M: beginning of the main injection

- Two injection events even for shortest dwells
- Changing dwell changes main injection rate shape
  - Dwell 1200 µs: main injection rate close to single injection rate
  - Dwell 80 µs: steepest injection rate increase
  - Dwell 140 µs: steep at first, less steep thereafter
- Optical experiments have provided evidence that similar main injection rate shaping occurs in the engine
  - SAE 2015-01-0796



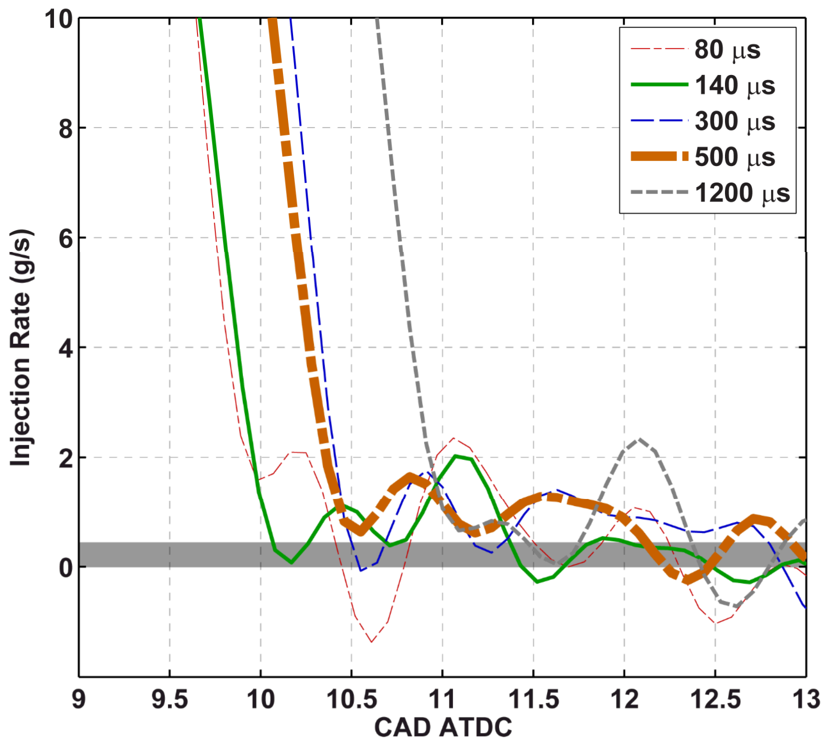
Results: fuel injection rates for P + M: rate shaping of the beginning of the main injection

- **Injection rate measurements:** shape of main injection rise rate is affected by hydrodynamics in the injector & high pressure fuel line as dwell changes: top plot →
- **Optical engine measurements:** a similar trend in main injection rate shaping is observed in the engine with high speed imaging: bottom plot →



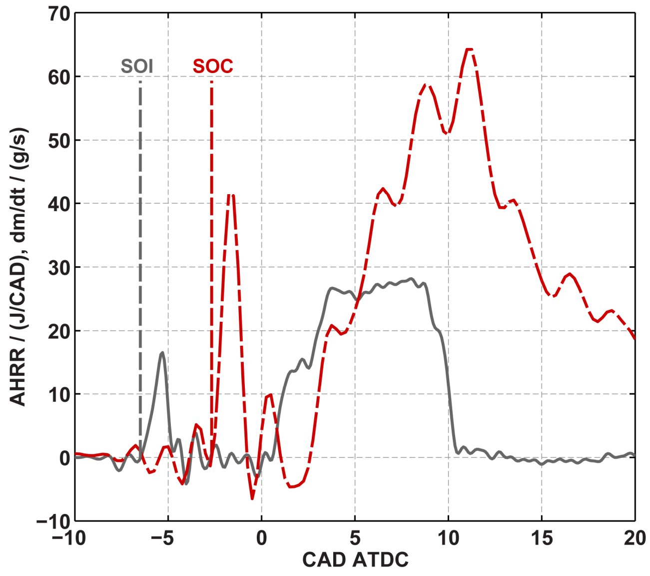
Results: fuel injection rates for P + M: end of injection behavior

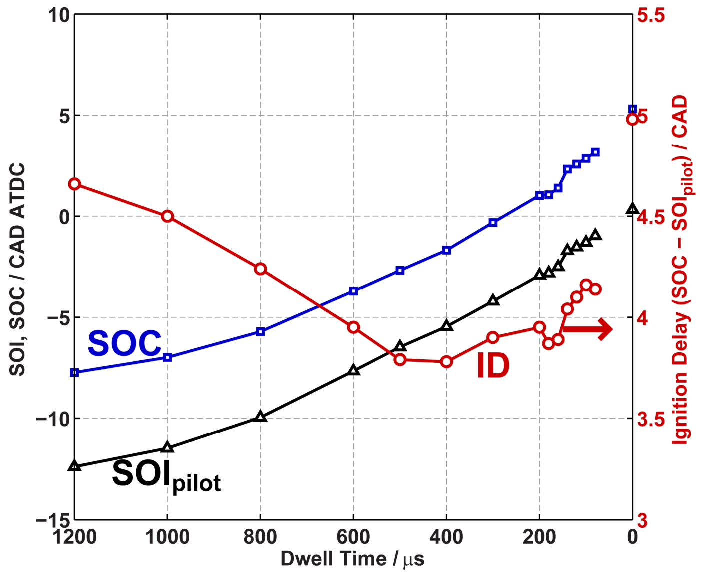
- End of injection (EOI) is defined for this data by the noise threshold determined before the start of injection
- Injection rate drops rapidly before EOI as the injector needle approaches the seat
- The injection rate may not drop monotonically to zero
  - Injector-rail hydrodynamics?
  - Needle bounce?
  - Dribble?
- The HDA data do not provide enough information to understand the behavior at EOI
- High speed imaging provides more insight (later)



Results: effect of dwell on (pilot) ignition delay

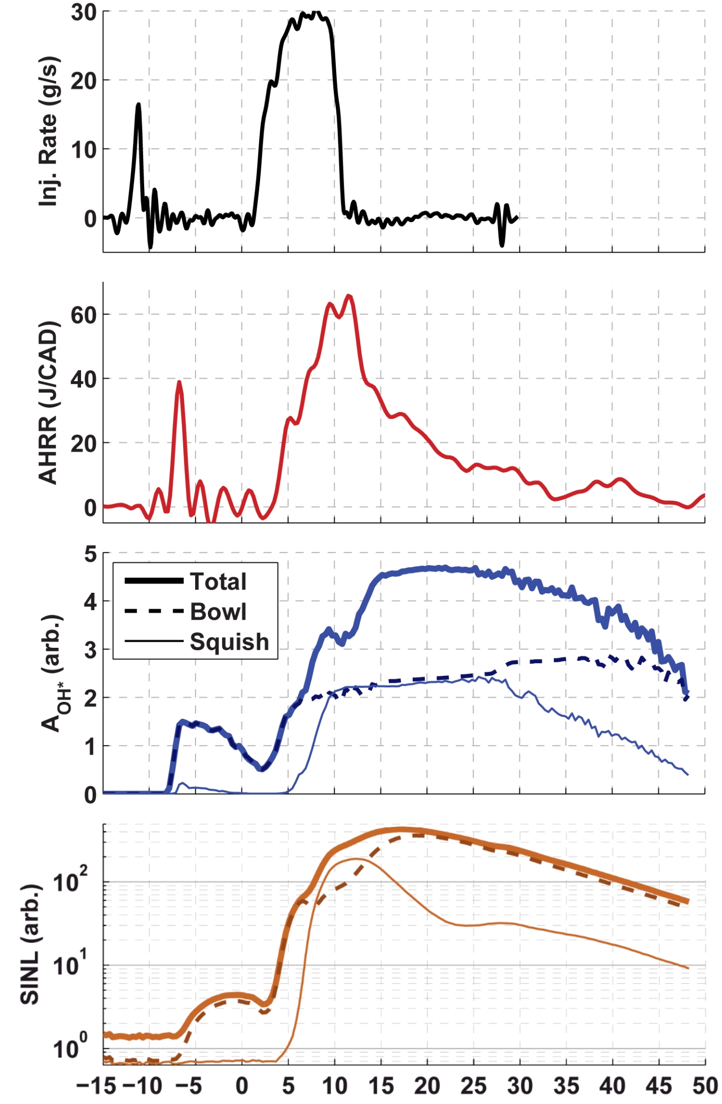
- Ignition delay: CAD between SOI_{pilot} and SOC
- Longer dwells
  - Pilot injected into cooler cylinder
  - Longer ignition delays
- Shorter dwells
  - Minimum ignition delay for a dwell of 400 µs
  - More rapid increase for dwells shorter than 180 µs
- Evidence of interaction between the pilot mixture field and the main injection





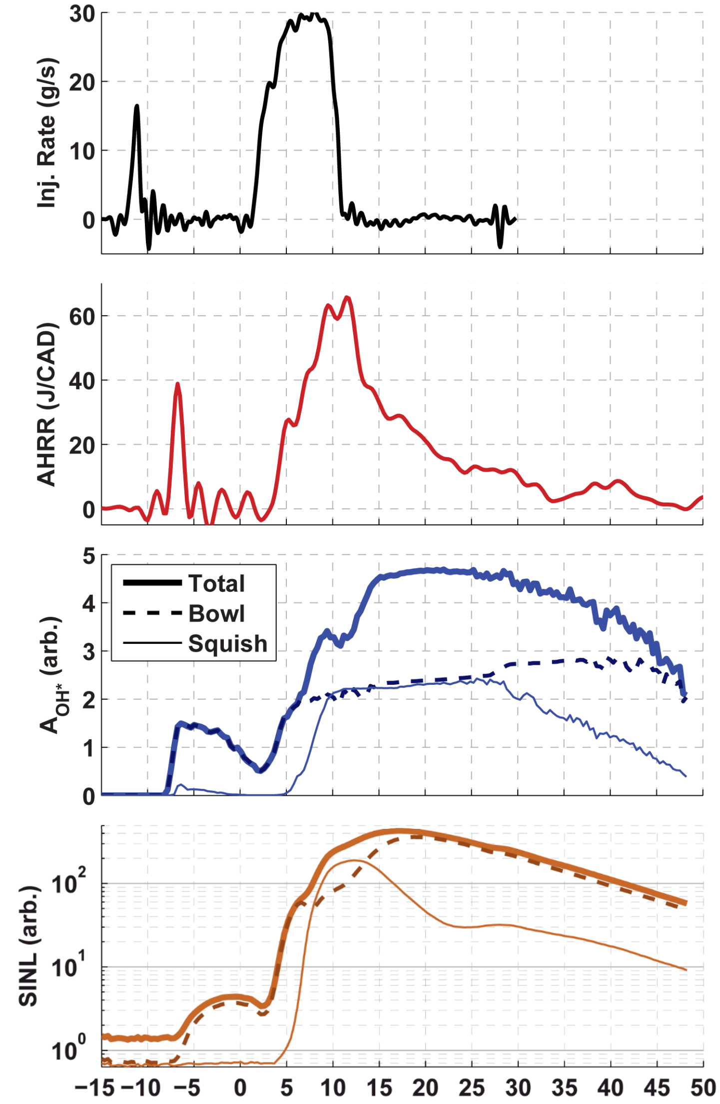
Results: P + M, 1200 μs dwell; fuel injection and combustion summarized

- Injection rate: measured offline with the HDA
  - 50 cycle ensemble average
- AHRR: computed for metal piston testing
  - 50 cycle ensemble average
- A_{OH*}: number of pixels with detectable OH* signal
  - 20 cycle ensemble average
  - Excellent indicator of SOC
- SINL: spatially integrated natural luminosity
  - Logarithmic scaling
  - 20 cycle ensemble average



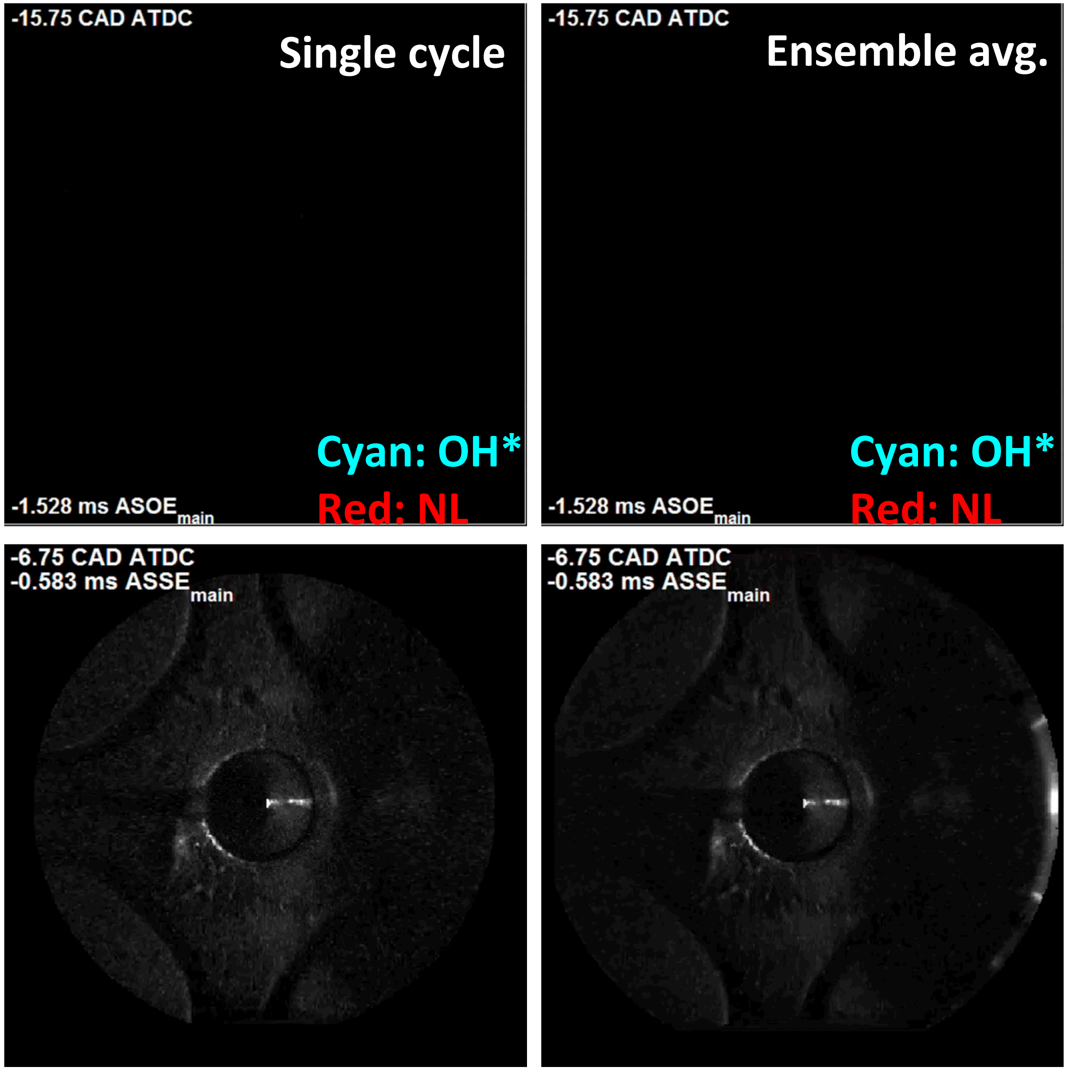
Results: P + M, 1200 µs dwell; fuel injection and combustion summarized

- Focus on AHRR behavior for this long dwell case:
  - High temperature pilot heat release finishes by ~5 CAD BTDC
  - Main injection starts shortly after TDC, after the premixed pilot heat release event has finished
  - Main heat release starts at approximately 3 CAD ATDC, shortly before the main injection rate reaches its peak



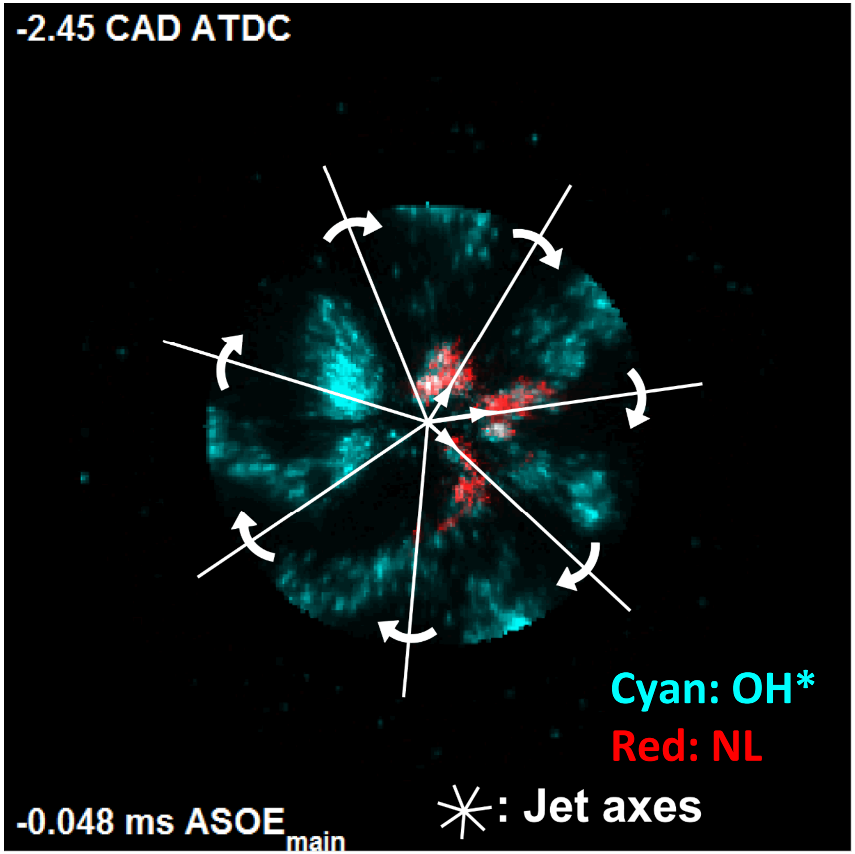
Results: P + M, 1200 μs dwell; how does the pilot burn?

- Combined OH*-NL imaging (top row)
  - Initially premixed, too lean to form soot; reaches the outer part of the bowl
  - Near end of pilot heat release (5 CAD BTDC), NL signal appears close to the injector
  - This behavior is highly repeatable (ens. avg. video)
- Liquid fuel imaging (300 μs dwell, bottom row)
  - End of injection and dribble behavior are highly repeatable
  - The jets with persistent fuel appear to be responsible for sooting pilot combustion



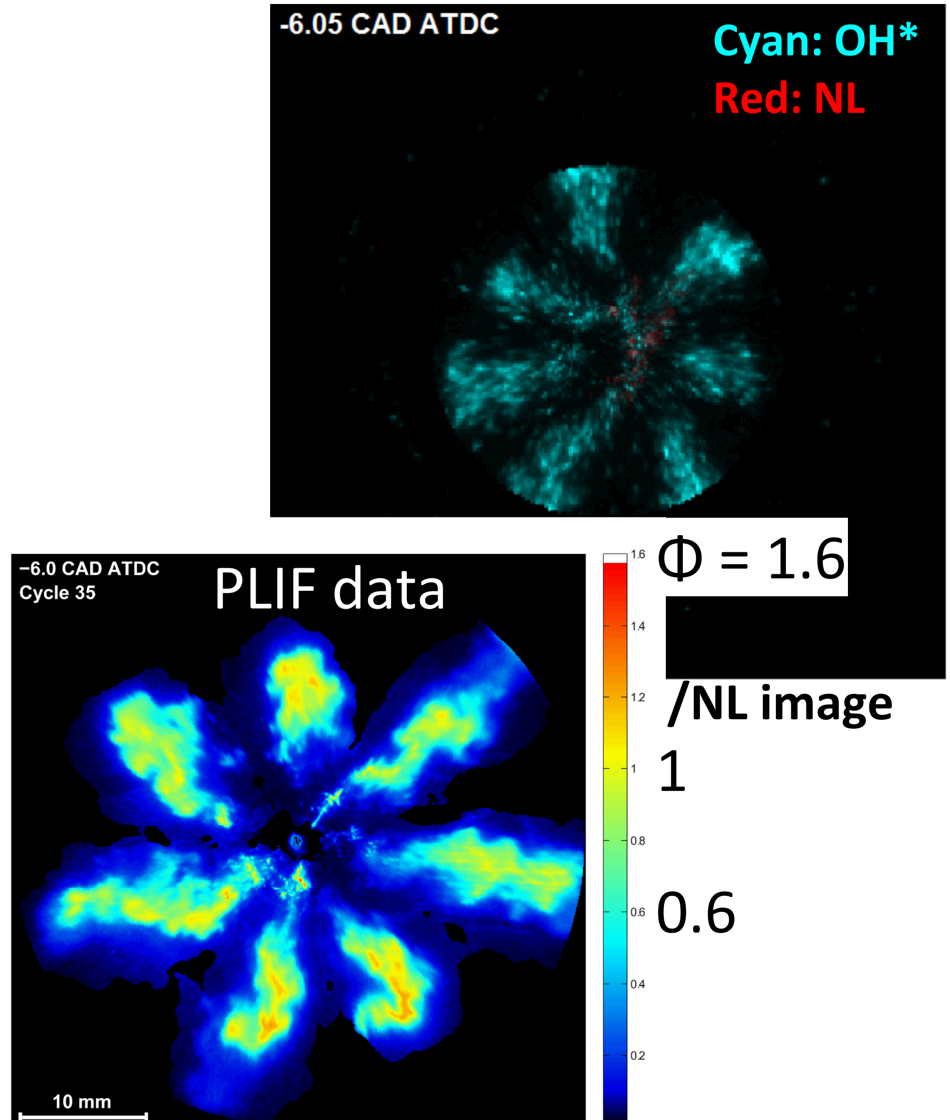
Results: P + M, 1200 μs dwell; pilot-swirl interaction

- Swirl transports the pilot mixture (clockwise) before and during its combustion
- Transport of the initial pilot mixture has taken place when the dribbled fuel begins to combust
- The rich combustion of fuel dribbled from a nozzle hole may be located near the pilot mixture from an adjacent hole



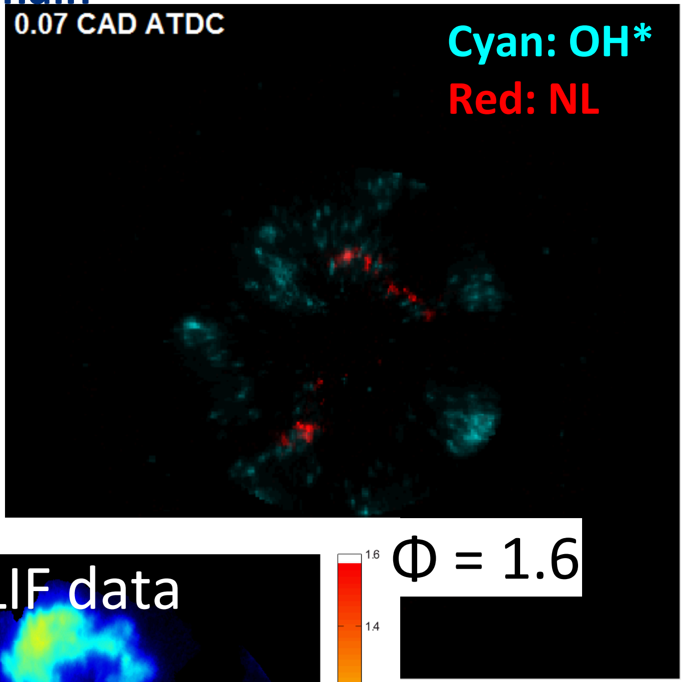
Results: P + M, 1200 μs dwell; pilot mixture combustion

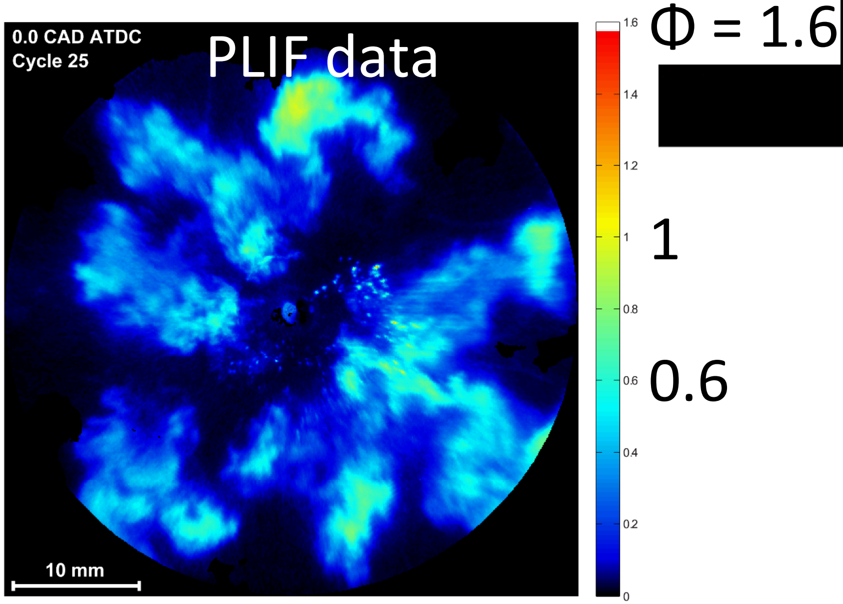
- Bulk of initial pilot combustion takes place without significant natural luminosity (ϕ < 2)
- PLIF images (taken in bowl rim plane) suggest that near-stoichiometric mixtures are found in large portions of the jets
- Dribbled fuel is associated with natural luminosity and sooting combustion
- We expect dribbled fuel to be extremely rich, but this is not always confirmed with PLIF
  - Out-of-plane and liquid-phase PLIF results are unreliable



Results: P + M, 1200 μs dwell; conditions shortly before SOI_{main} (TDC)

- Heat release is nearly finished
- Some reacting zones
  - Near outer regions of the bowl
    - OH* or HCO*?
  - Near the injector (NL)
- PLIF images (in motored operation) suggest that the pilot combustion products have mixed with fresh charge to some extent
- Dribbled fuel is still visible near the injector; some NL persists
- Pilot combustion products are likely cooled by mixing with fresh charge, but hot products of dribbled fuel combustion may still be near the injector

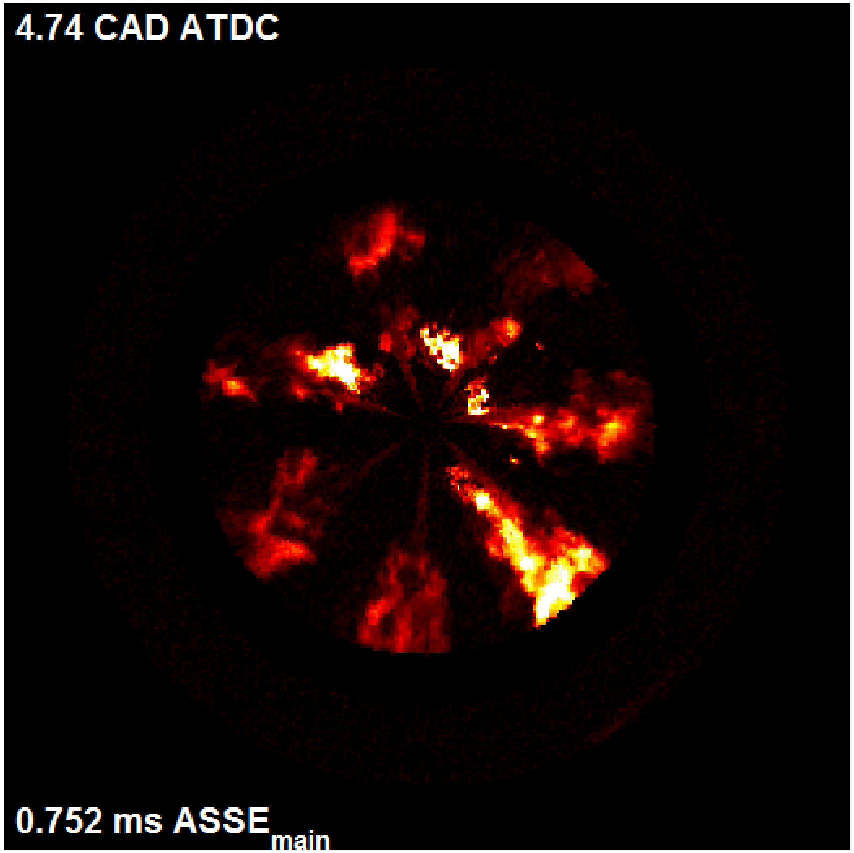




Results: P + M, 1200 μs dwell; inflammation of main injection (~0.75 – 7.25 CAD ATDC)

- The main mixture inflammation process varies from jet-to-jet and cycle-to-cycle
- Combined OH* and NL images provide insight into how the combustion of the main injection is initiated
- The following slides show the main injection inflammation process for a single cycle
  - First three slides: 3 different jets
  - Fourth slide: summary; all jets

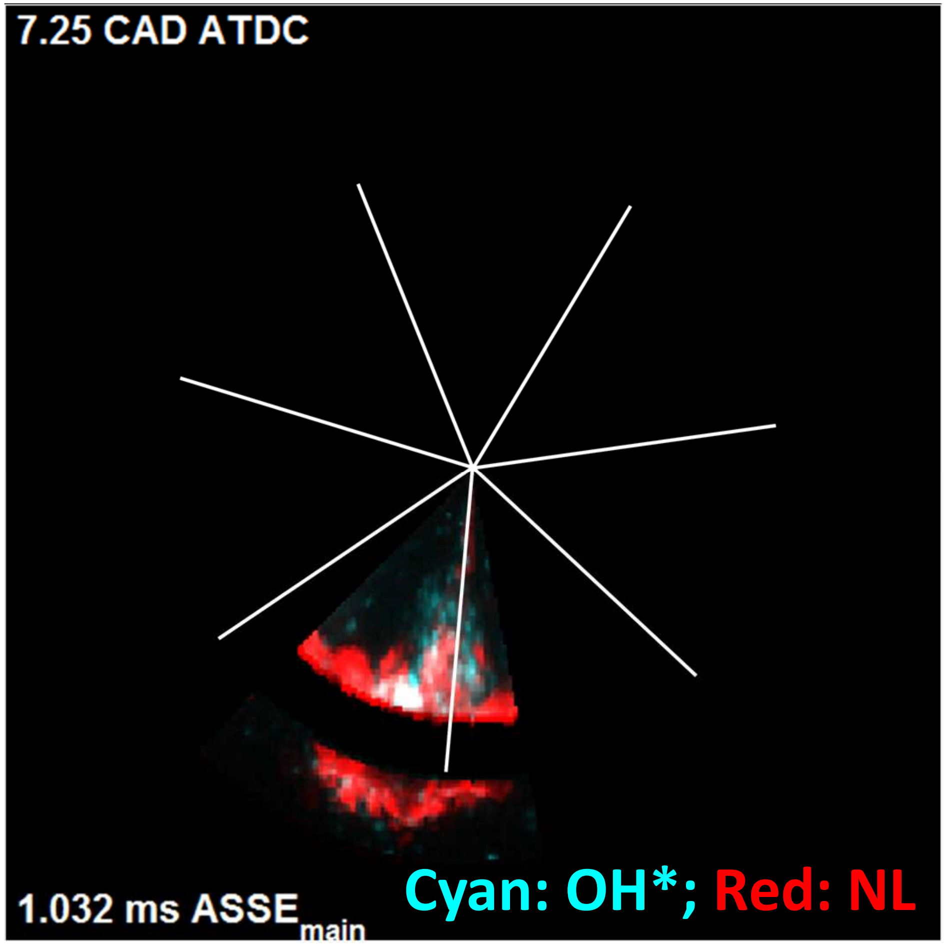
Single cycle NL image



Results: P + M, 1200 μs dwell; inflammation of main injection (~0.75 – 7.25 CAD ATDC)

- SOI_{main} (first frame): no large regions of active combustion
- Distributed ignition takes place in downstream region of the jet
- NL (soot) is first visible in the downstream portion of the jet approx. 1.5 CAD after ignition
- The flame structure takes shape very quickly and is stable
  - The relation between the OH and NL lift off lengths doesn't change significantly
- The main injection seems ignite with no direct interaction with the combusting pilot mixture field

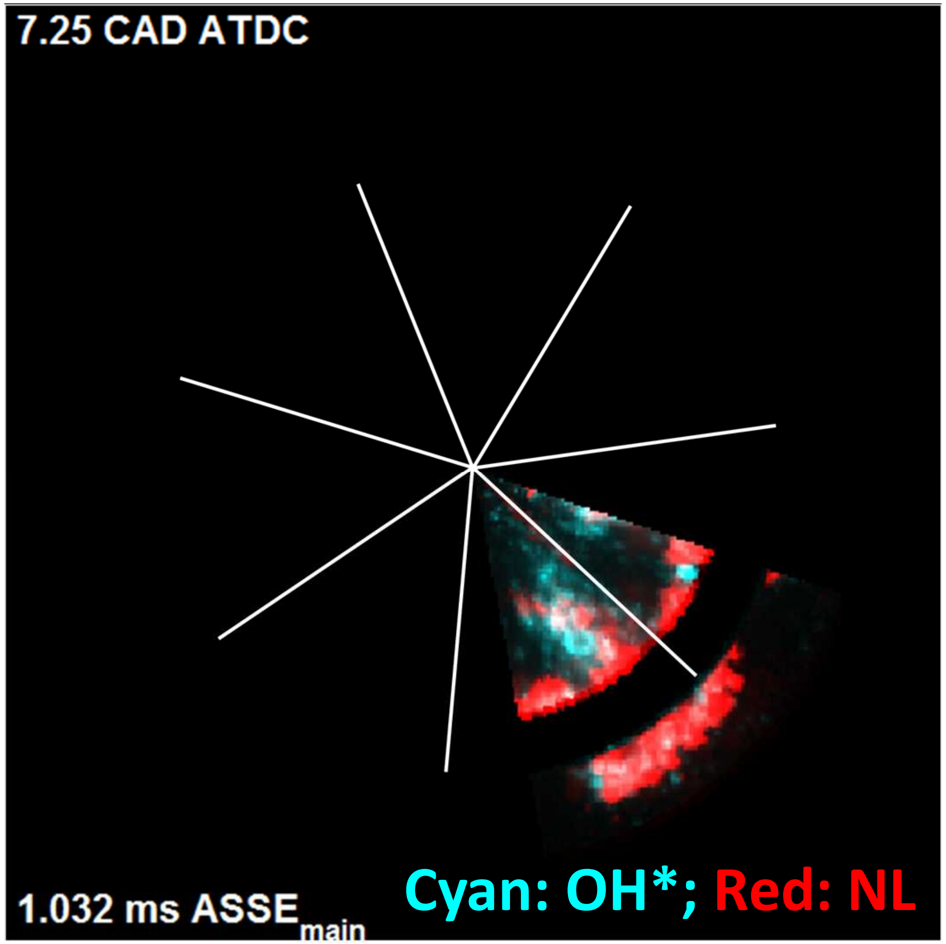
Single cycle, combined NL/OH* images



Results: P + M, 1200 μs dwell; inflammation of main injection (~0.75 – 7.25 CAD ATDC)

- SOI (first frame): pocket of sooty, active combustion located 5-10 mm from injector, downswirl
- Initial penetration (1.5-2.5 CAD ATDC): NL decreases and flame pocket moves towards injector
  - Evaporative cooling?
  - Consumption of soot due to air entrainment/turbulent mixing?
- Ignition occurs in downstream portion of jet, NL (soot) appear shortly thereafter
- Tail end of NL advances downstream towards the head
  - Enough air is entrained so that soot formation can be avoided until farther downstream

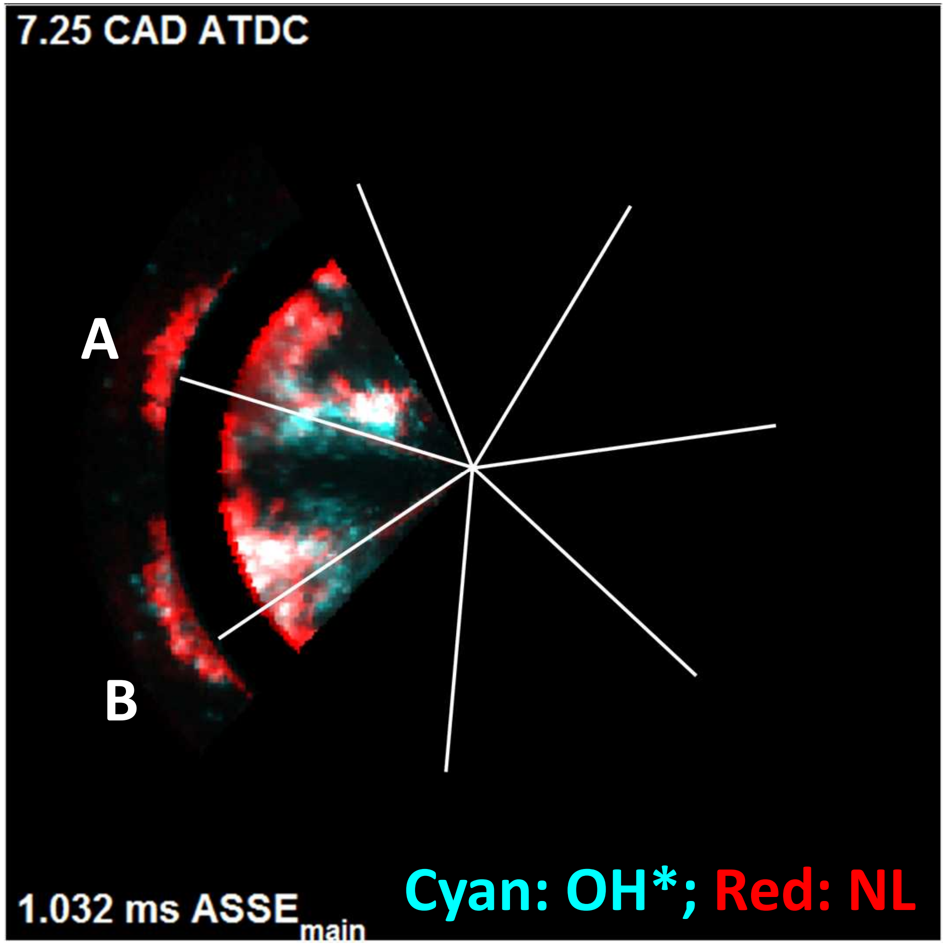
Single cycle, combined NL/OH* images



Results: P + M, 1200 μs dwell; inflammation of main injection (~0.75 – 7.25 CAD ATDC)

- SOI (first frame): pocket of active combustion (no NL) 9-15 mm from nozzle hole “A”. Combustion from jet “B” is still active and being carried downswirl.
- High temperature reactions (OH*) start within 1-2 mm of the nozzle hole, soot first forms upstream of existing combustion zone
- Active combustion region from jet B ignites a portion of jet “A”, both soot and OH* are formed
- The remaining portion of jet “A” ignites very rapidly (50-100 m/s)
  - Most likely not flame propagation
- Soot remains in upstream region of “A”

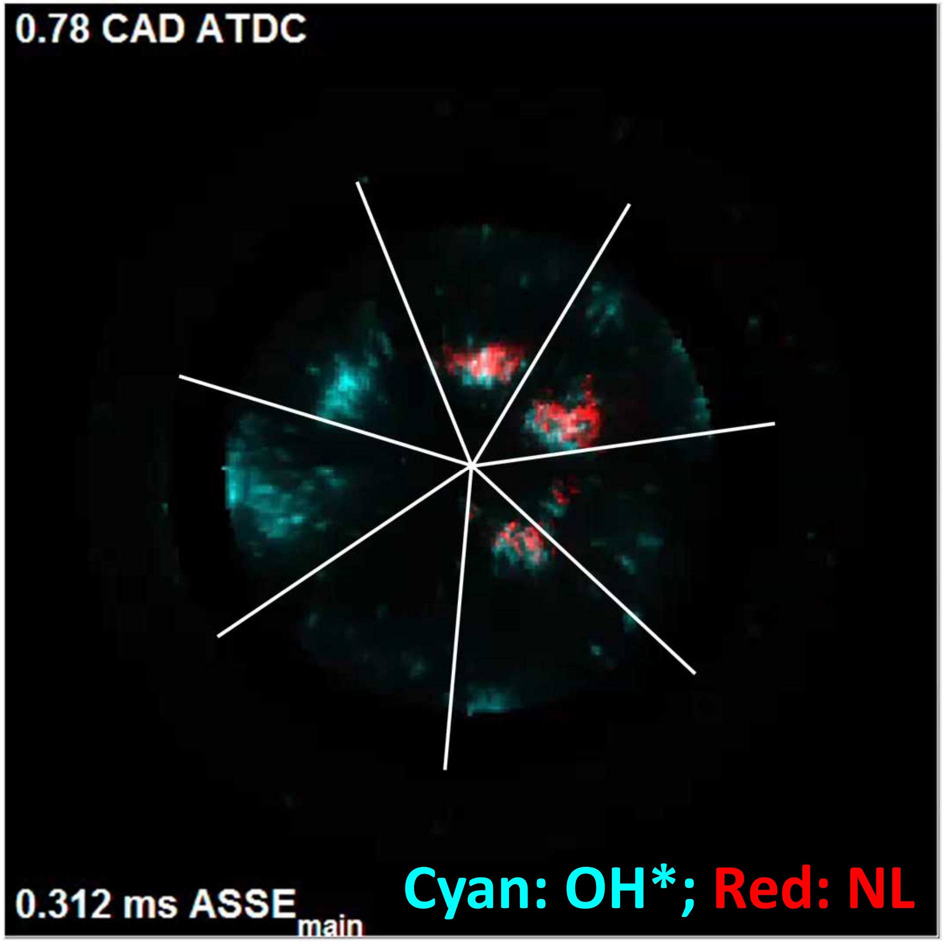
Single cycle, combined NL/OH* images



Results: P + M, 1200 μs dwell; inflammation of main injection (~0.75 – 7.25 CAD ATDC)

- The ignition of the main injection takes place in different ways for each jet and cycle, for example:
  - Autoignition in the absence of active combustion regions
  - Inflammation due to interaction of combusting dribbled fuel
  - Inflammation due to interaction with the combustion region of an adjacent jet
  - Autoignition triggered by combustion of a portion of the jet head
- Ignition of the main injection can take place by multiple mechanisms for even a single jet
  - Time of main ignition is nearly the same for all jets

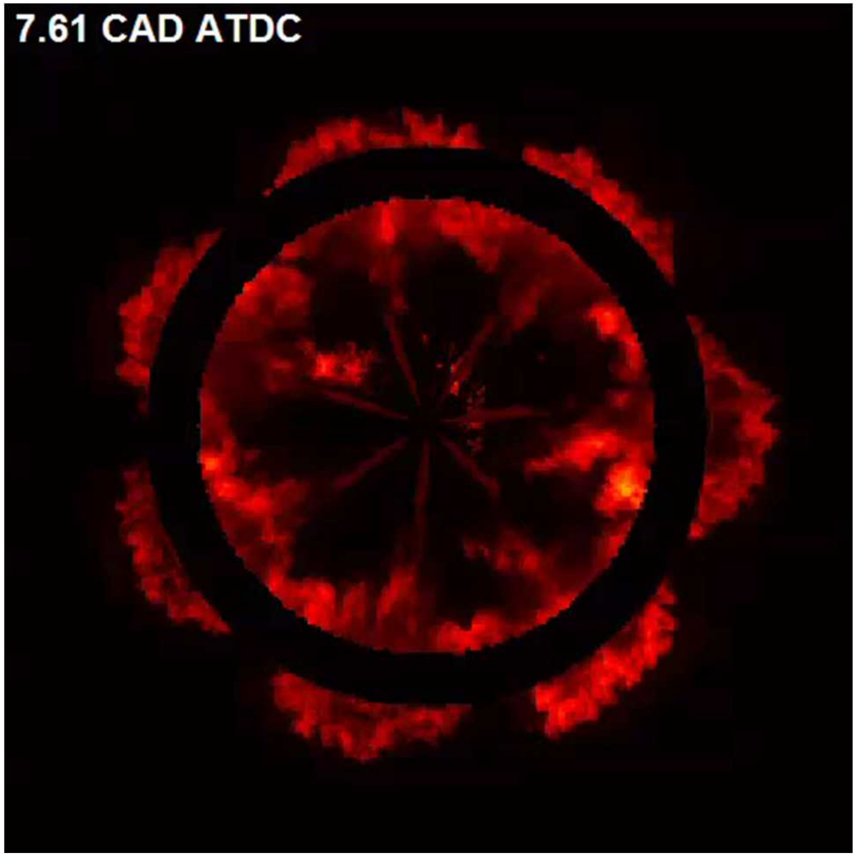
Single cycle, combined NL/OH* images



Results: P + M, 1200 μs dwell; main combustion (~7.5 – 1.5 CAD AEOI)

- Heads of injection jet split at the bowl rim
  - Portion directed into squish region: outward radial displacement
  - Portion directed down along the reentrant feature of the bowl and radially inward
  - NL intensity is lower in the bowl area; strong jet-bowl interactions may lead to decreased soot temperatures / NL signal near the surface
- EOI_{main} occurs as the recirculating jet heads approach the center
  - It appears that the fuel injected/dribbled at EOI_{main} forms a rich mixture and combusts in the center of the chamber

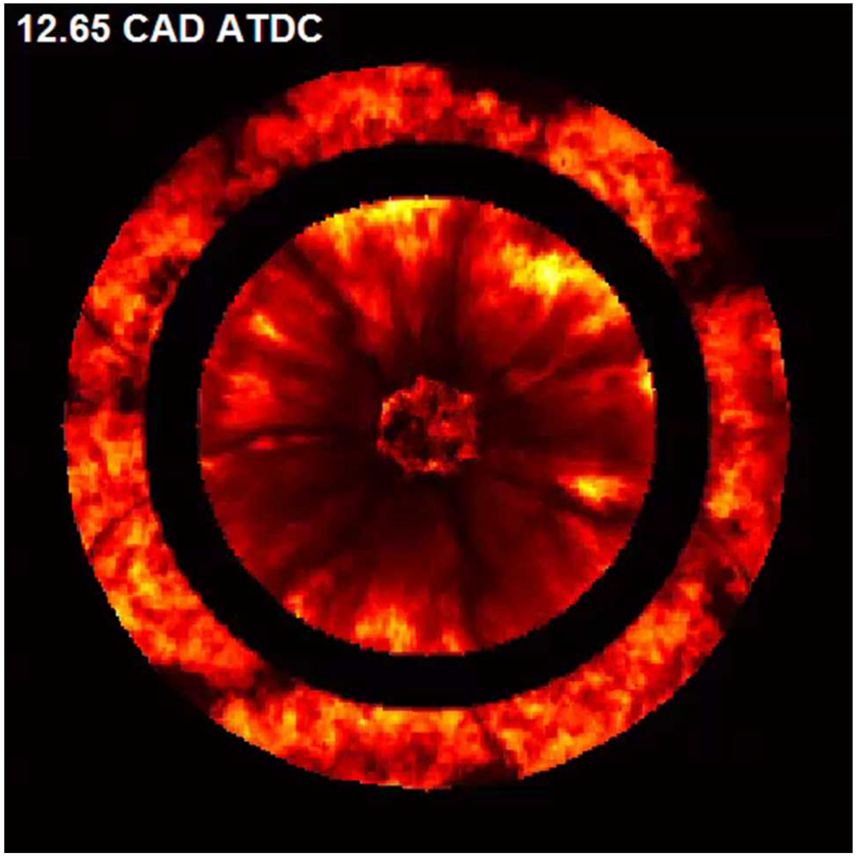
Single cycle, NL video



Results: P + M, 1200 μs dwell; main combustion (AEOI - …)

- Recirculation in the bowl slows after EOI_{main} (~10 CAD ATDC)
- NL intensities in the bowl increase after EOI_{main}
  - Brighter intensity regions are first found near the bowl rim and propagate inwards
  - This could indicate decreasing heat loss to piston bowl surfaces
- The NL in the squish region from the initial jet penetration fades away
- Second (bright) and third (faint) penetrations of NL signal into the squish region are observed
  - This appears to be the result of recirculation above the bowl / reverse squish flow

Single cycle, NL video



Recap: P+M, 1200 μs dwell; ignition processes

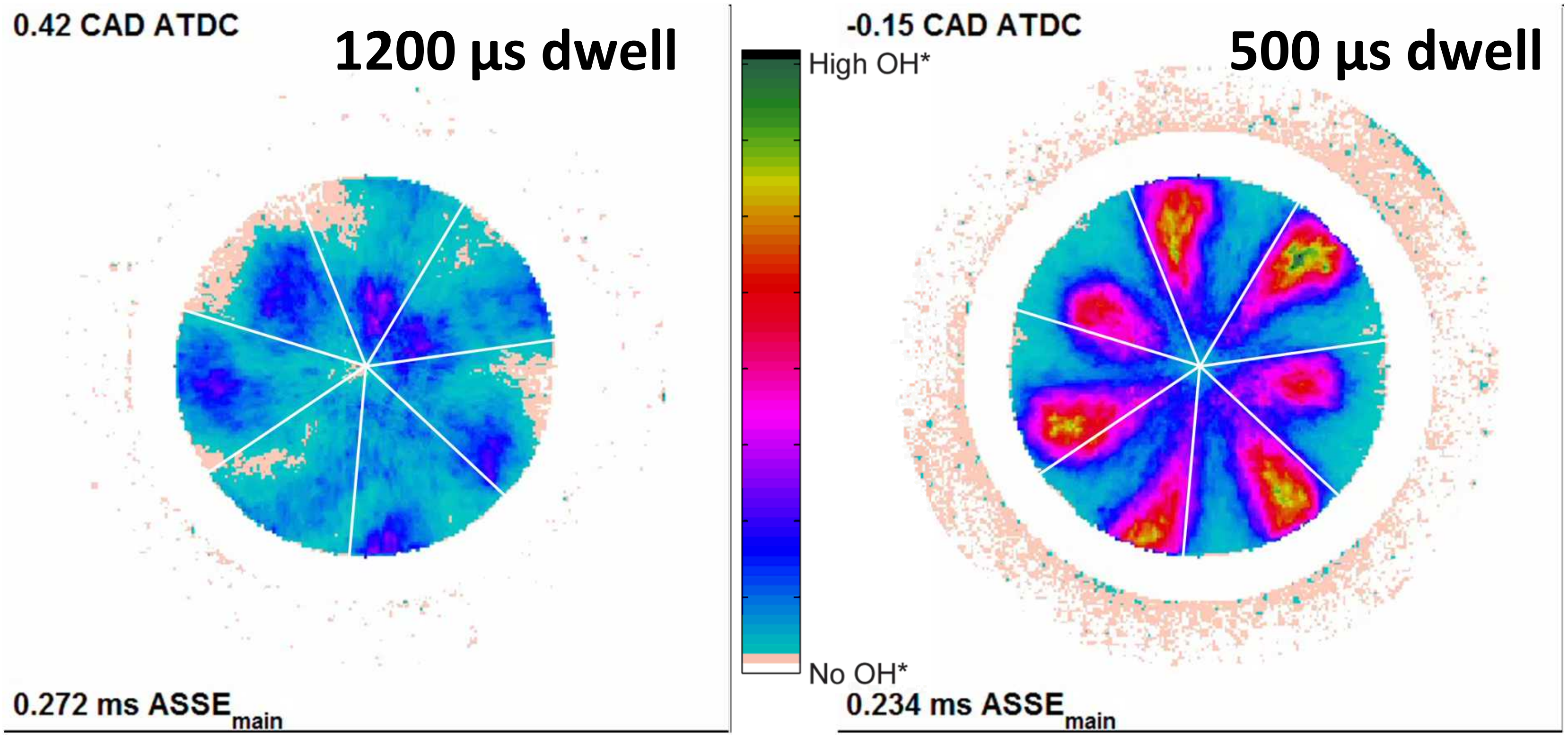
- Combustion of the pilot injection has two phases
  - First phase: autoignition of near-stoichiometric mixture, majority of total pilot heat release
  - Second phase: fuel injected/dribbled at the end of injection burns near the injector and forms soot
    - This effect may be exaggerated in the case of this pre-production injector
- Combustion of the main mixture in a given jet can be initiated by:
  - Pockets of active combustion remaining from the pilot:
    - With or without soot
    - From a neighboring jet or from the same jet
  - Autoignition in the absence of active combustion zones in the downstream region
  - Combinations of these
- Ignition occurs nearly simultaneously for all jets, but the initial flame structure varies considerably from jet-to-jet and cycle-to-cycle

Recap: P+M, 1200 μs dwell, main combustion

- Recirculation in the bowl
  - NL signals in the bowl are darker during the main injection, which may be the result of strong interactions between the combusting jets and the bowl surface
  - Heat loss (and potentially soot deposition) at the bowl surface may be highest during this phase of the cycle
- Propagation into squish region
  - Occurs at least twice during the main combustion
  - First occurrence: fuel split during main injection
  - Subsequent occurrences: result of recirculation above bowl rim, reverse squish flow
- How does dwell impact the ignition and combustion processes?
- Why do engine-out soot emissions tend to decrease with decreasing dwell?

Results: P+M, 500 vs. 1200 μs dwells; inflammation processes

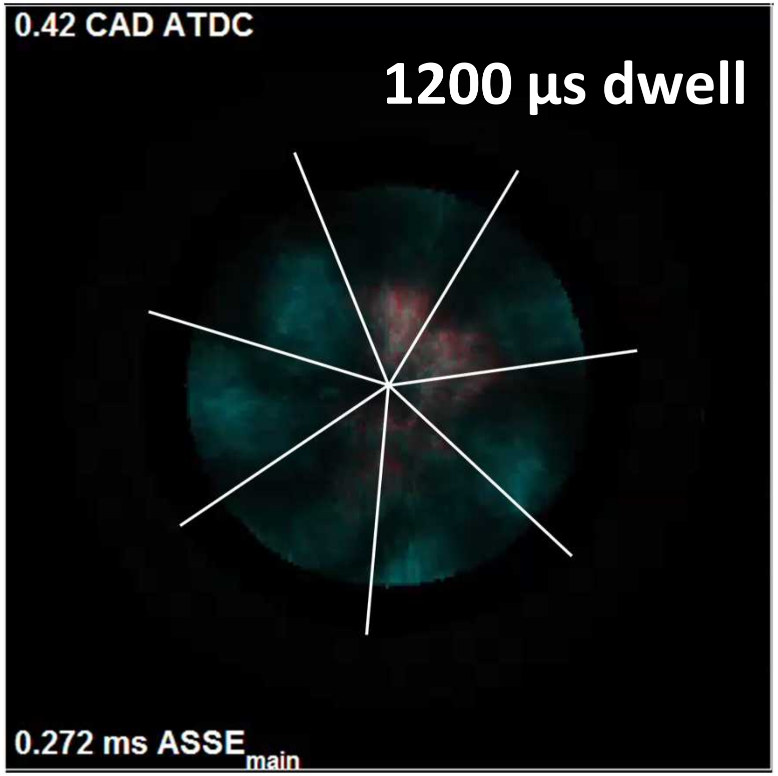
20-cycle ensemble-averaged OH* videos starting at SOI_{main}

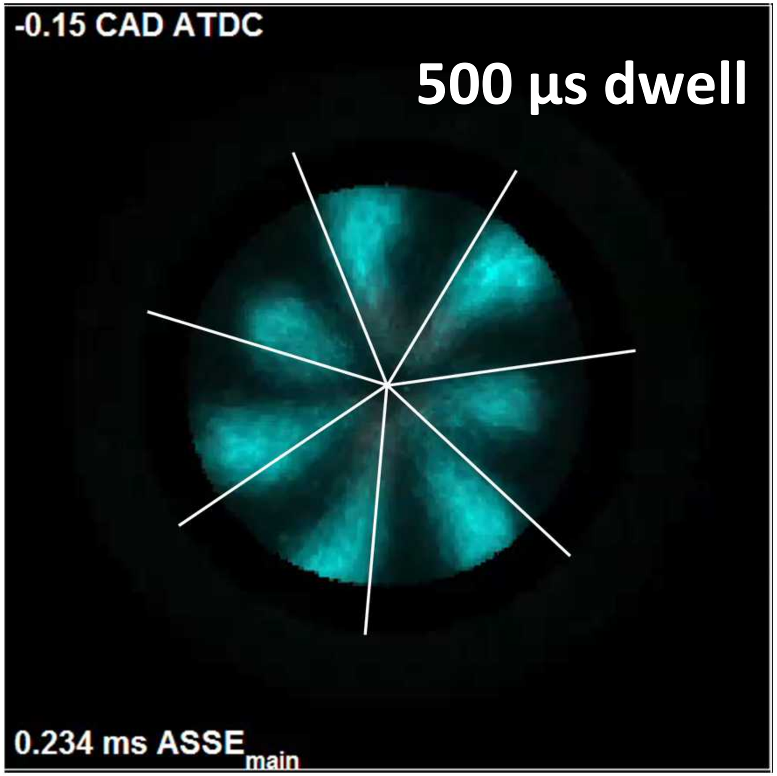


- 1200 μs dwell: pilot jet structure has dispersed; main fuel is injected into a more uniform mixture field that is still reacting
- 500 μs dwell: pilot jet structure is still intact; main injection interacts directly with high temperature reacting pilot jets

Results: P+M, 500 vs. 1200 µs dwells; inflammation processes

20-cycle ensemble-averaged combined NL/OH* videos starting at SOI_{main}





- 1200 µs dwell: main injection forms new jet structures
- 500 µs dwell: main injection jets quickly take on structure to replace the existing pilot jet structure
  - Higher NL signal in upstream portion of jets

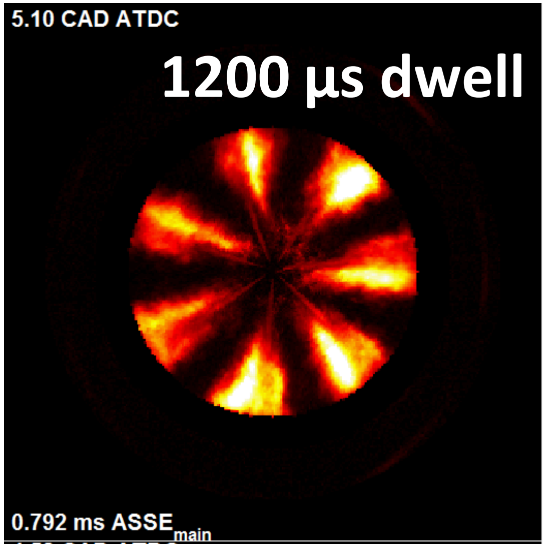
Results: P+M, 500 vs. 1200 μs dwells; inflammation processes

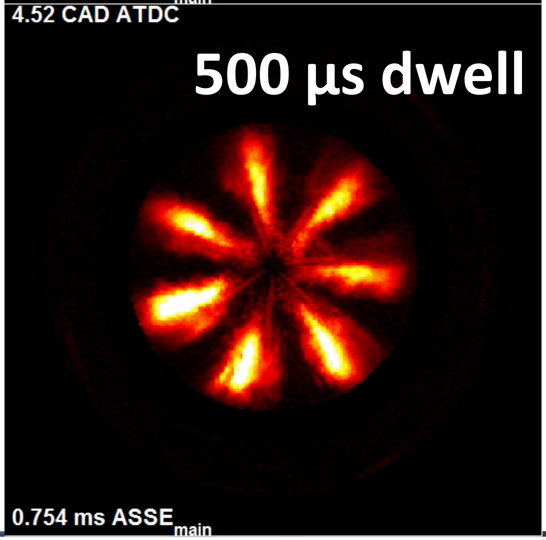
- 1200 μs dwell
  - Some reacting pilot mixture remains, but it does not resemble a jet structure
  - Main mixture forms a new jet structure
  - At time of main ignition, remaining pilot reaction zones are mostly associated with EOI behavior
  - Soot formation starts as close as 1-2 mm from the injector
- 500 μs dwell
  - Pilot jet flame structure is largely intact at SOI_{main}
  - Main mixture ignites and takes on a form similar to the existing pilot flames
    - Jet heads displaced by swirl
  - Some reacting pilot mixture remains at the downswirl periphery of jets
  - Soot formation starts as close as 1-2 mm from the injector

Results: P+M, 500 vs. 1200 μs dwells; early main combustion

- 500 μs dwell:
  - SOI_{main} occurs approximately 0.5 CAD earlier
  - Ignition delay is approximately 0.5 CAD shorter
  - Regions of high NL intensity tend to be located closer to the injector for each jet
- Soot formation seems to be located further upstream for the 500 μs dwell
- Does soot formation start sooner with the 500 μs dwell?
  - Look at A_{NL} (next slide)

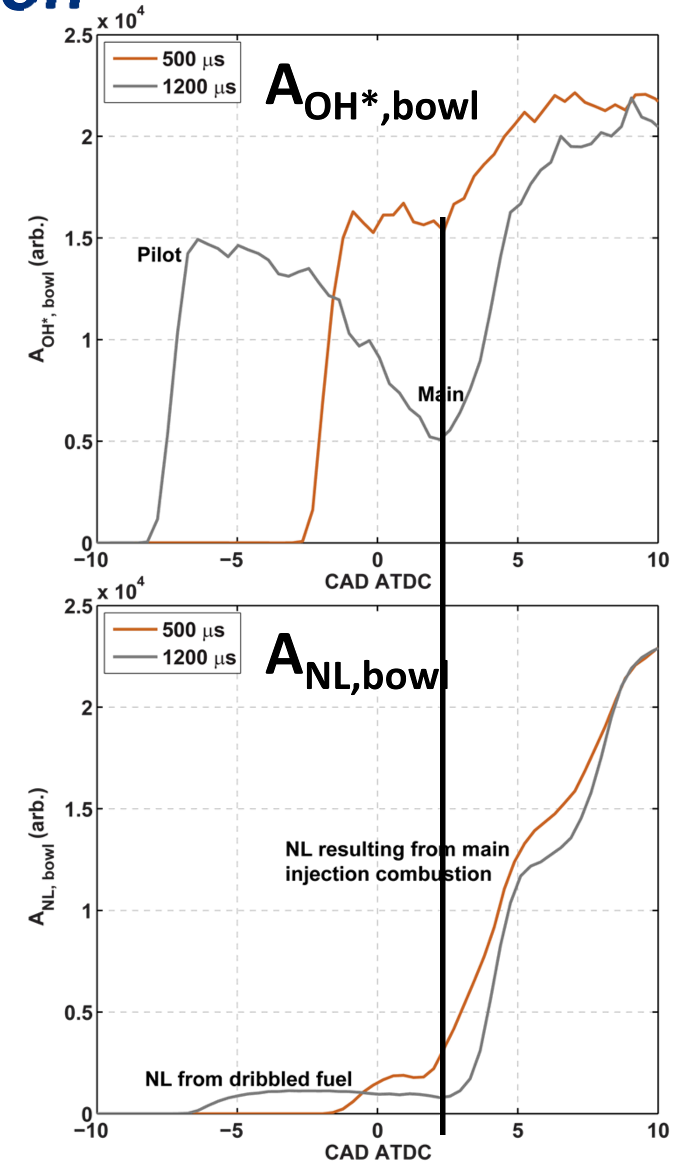
20-cycle ensemble-averaged NL images taken ~ 4.3 CAD $ASOI_{main}$





Results: P+M, 500 vs. 1200 μs dwells; early soot formation

- A_{OH*} begins increasing at the same time for each dwell after the start of main combustion, despite the earlier SOI_{main} for the 500 μs dwell
- 500 μs dwell: NL associated with fuel dribble is distributed over a larger area
- 500 μs dwell: A_{NL} increases earlier than for the 1200 μs dwell (relative to TDC and to SOI_{main})
- 500 μs dwell: soot formation begins in regions close to the injector before A_{OH*} starts increasing
- What do these differences suggest?

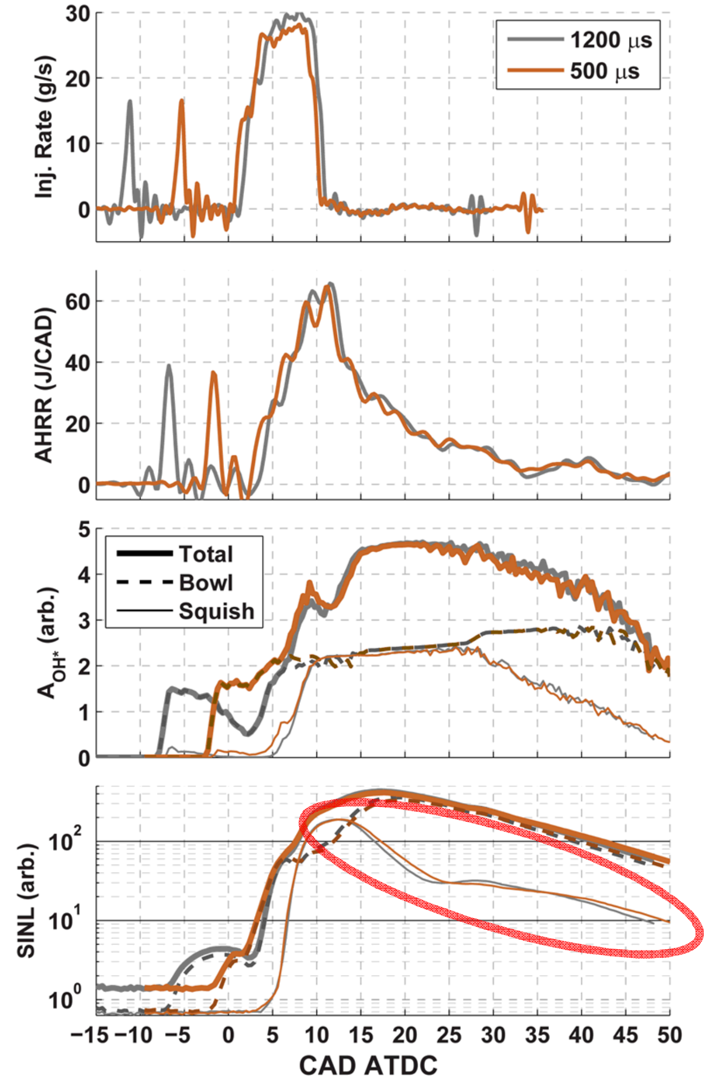


Recap: P+M, 500 vs. 1200 μs dwells; ignition processes and early combustion

- For the 1200 μs dwell, there is more time for the pilot mixture to react to completion and mix with cooler gases before the main injection starts
- For the 500 μs dwell, the main mixture interacts more directly with hot, reacting pilot mixture
  - The ignition delay for the 500 μs dwell is ~ 0.5 CAD shorter than for 1200 μs
  - During the initial phase of the main combustion, soot formation occurs earlier and regions of high NL intensities are located further upstream for the 500 μs dwell
  - These facts suggest that hotter temperatures near the upstream portion of the jets initiate main combustion and soot formation sooner for the 500 μs dwell case
- For 300 μs dwell, main injection ignition is similar to the 500 μs dwell case

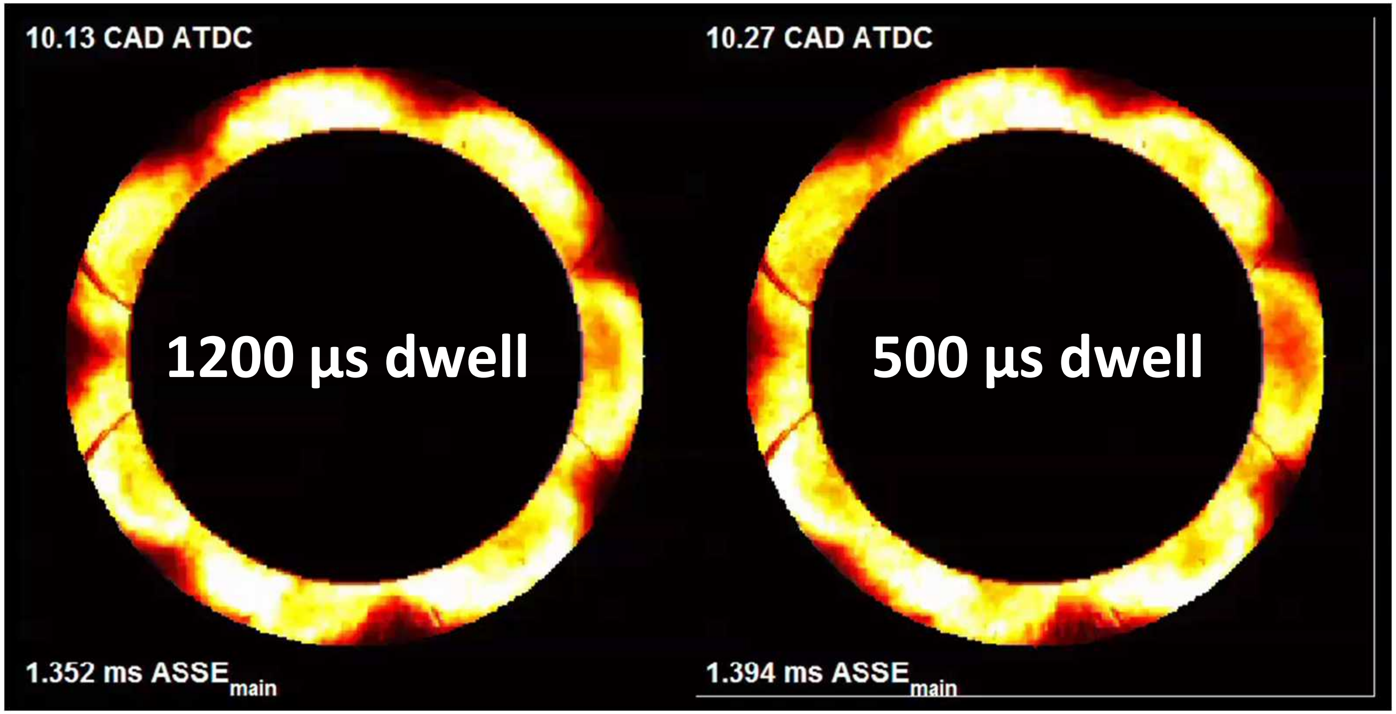
Results: P+M, 500 vs. 1200 µs dwells; main combustion

- OH* / NL behavior is similar for both dwells during the main combustion
  - FSN is also similar
- Some differences in SINL are observed in the squish region after 15 CAD ATDC
- SINL increases slightly after 25 CAD ATDC for the 1200 µs dwell
- What is happening in the squish region in the late stages of combustion?



Results: P+M, 500 vs. 1200 µs dwells; reverse squish flow

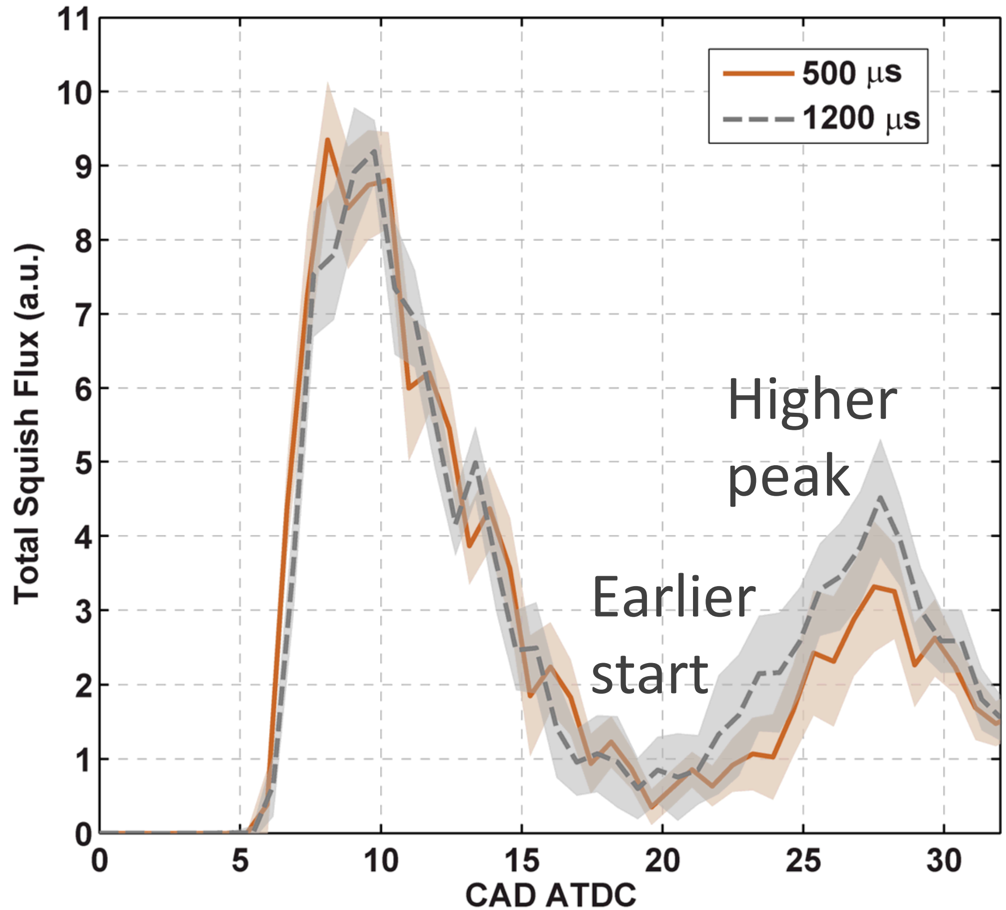
20-cycle ensemble-averaged NL videos starting near EOI_{main}



- 1200 µs dwell: second propagation into squish region starts earlier, even though the main injection starts later
- What can we learn from combustion image velocimetry analysis (squish flux)?

Results: P+M, 500 vs. 1200 μs dwells; reverse squish flow

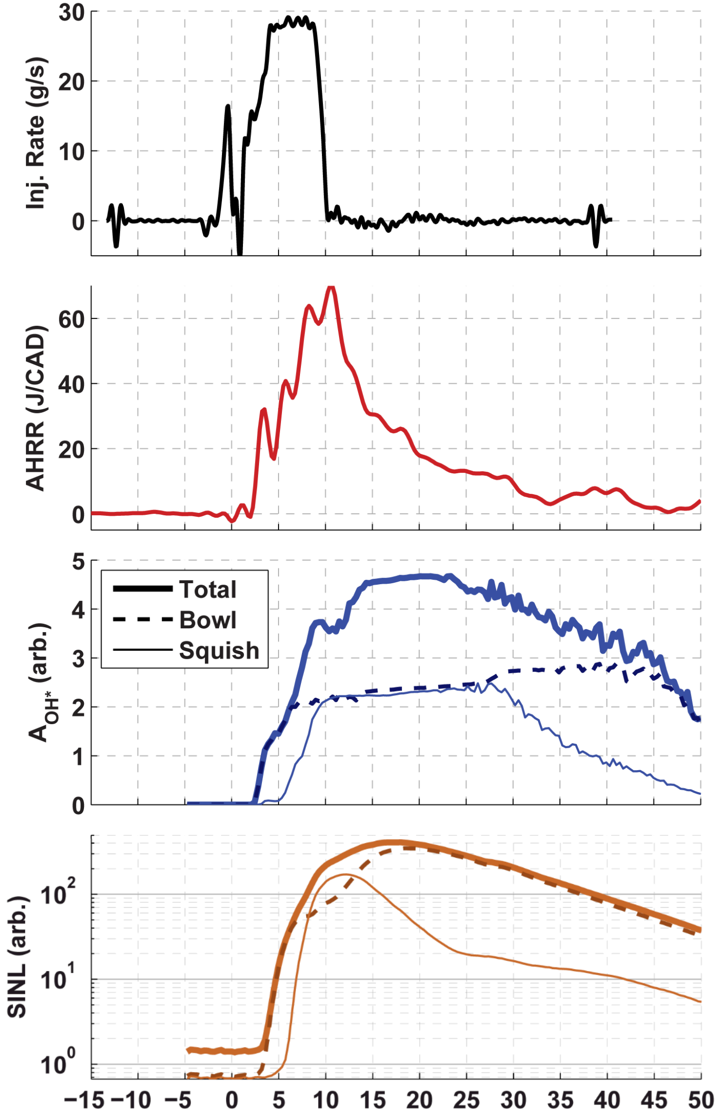
- On average, reverse squish flow starts earlier for the 1200 μs dwell case
- Squish flux seems to reach a higher maximum value for the 1200 μs dwell
  - This suggests slightly higher reverse squish flow velocities for the 1200 μs dwell
- Potential explanations
  - Higher rate of main injection, later EOI for 1200 μs dwell
  - Changes to the jet penetration / recirculating flow in the bowl resulting from the change in delay between the pilot and main injections
    - More on this coming up…



±σ scatter bands for 20 cycles of data

Results: P + M, 140 μs dwell; ignition process (~2.8 – 7.1 CAD ATDC)

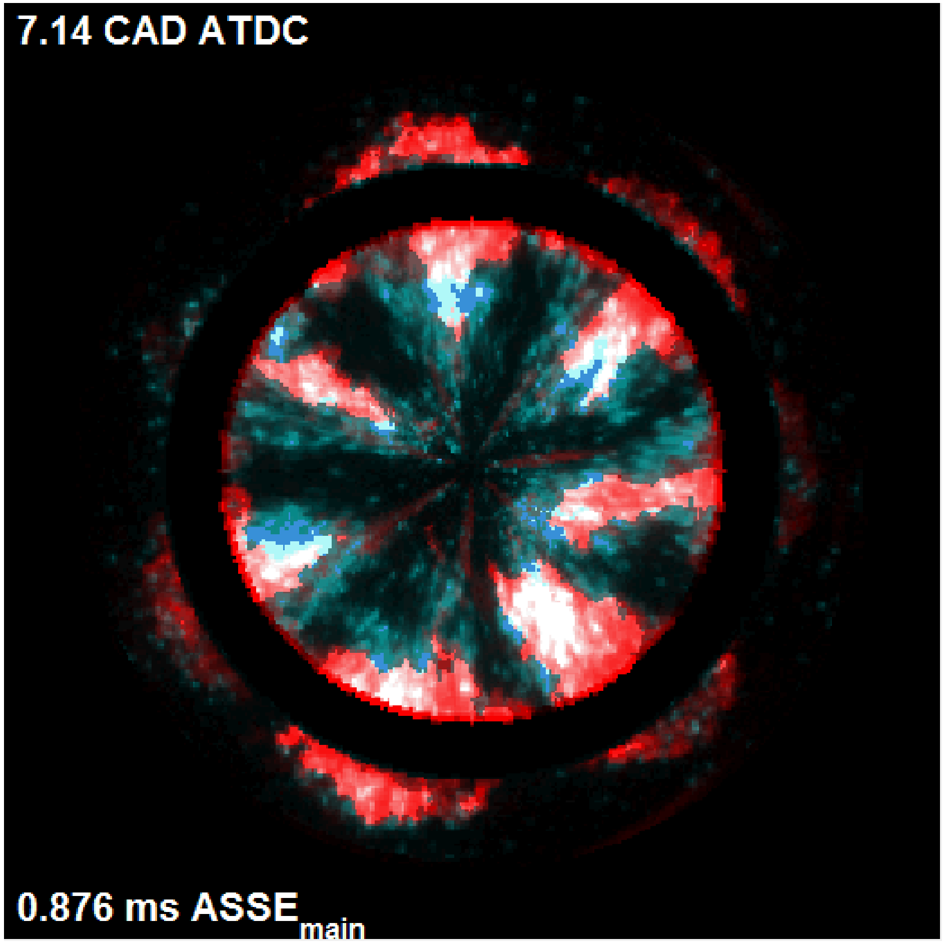
- High temperature heat release starts after SOI_{main}
- No clear separation between pilot and main heat release events
  - This is reflected in AHRR, A_{OH*}, and SINL data
  - This dwell is near the combustion noise minimum



Results: P+M, 140 μs dwell; inflammation processes

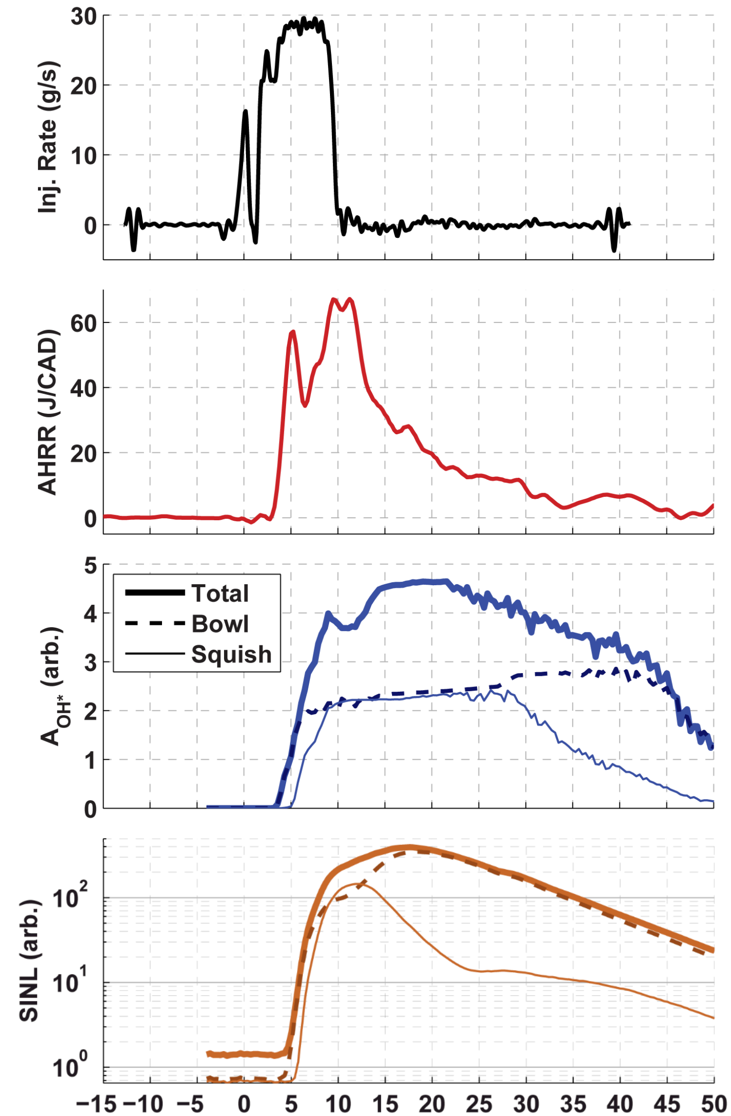
- First frame: start of high temperature reactions; after SOI_{main}
- Ignition process is somewhat similar to 500 and 300 μs cases
  - Main ignition occurs in in the reacting pilot jet mixture fields
- Significant transport of pilot jets by swirl has not occurred by the time of main ignition
- Soot is found throughout the jets and near the injector
- Combustion of dribbled pilot fuel is not typically observed

Single cycle, combined NL/OH* images



Results: P + M, 80 µs dwell; ignition process (~3.8 – 7.5 CAD ATDC)

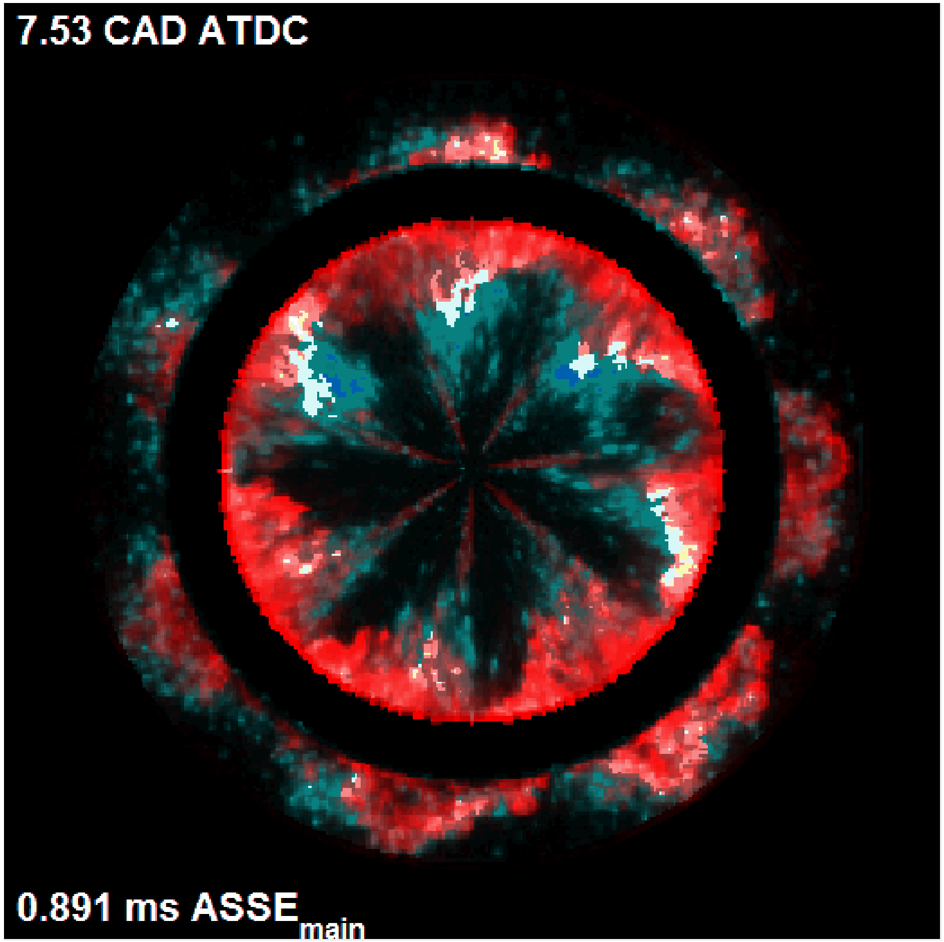
- High temperature heat release starts after SOI_{main}
- Initial premixed burn involves both pilot and main fuel
  - Peak premixed AHRR is too high for it to be attributed to the pilot alone
- A_{OH*} begins to rise 1 - 1.5 CAD before SINL



Results: P + M, 80 µs dwell; ignition process (~3.8 – 7.5 CAD ATDC)

- First OH* signal visible just after 3.8 CAD ATDC
- Autoignition sites distributed over downstream portion of jets
- Jets do not ignite simultaneously
- Bright NL signal is typically first observed in the heads of the jets near the bowl rim
  - For some jets, NL is first observed closer to the injector
  - Early soot formation is further downstream than for any other dwell
- No rich combustion of dribbled pilot fuel is observed

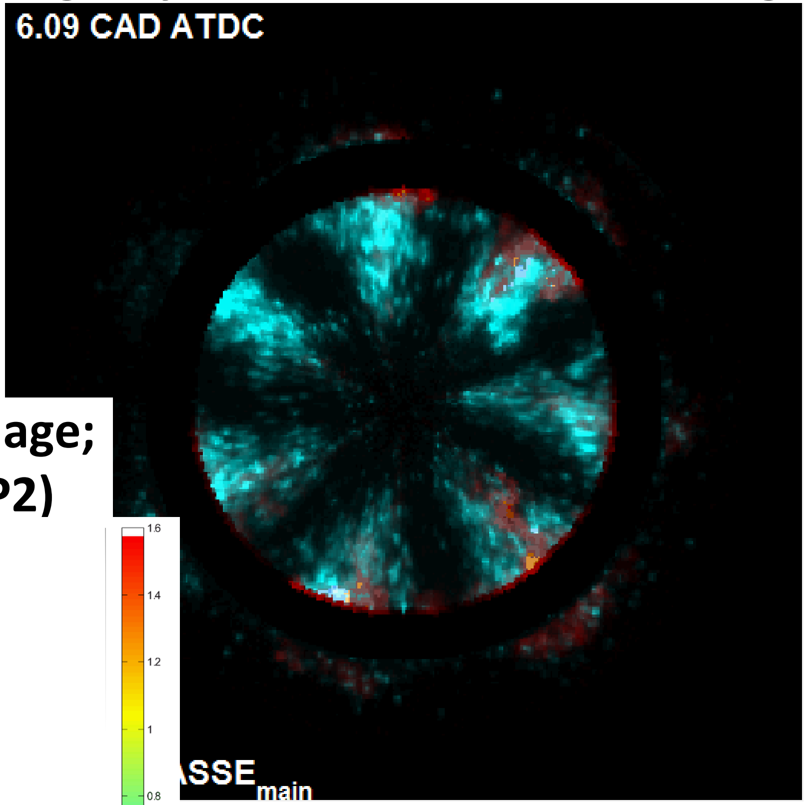
Single cycle, combined NL/OH* images



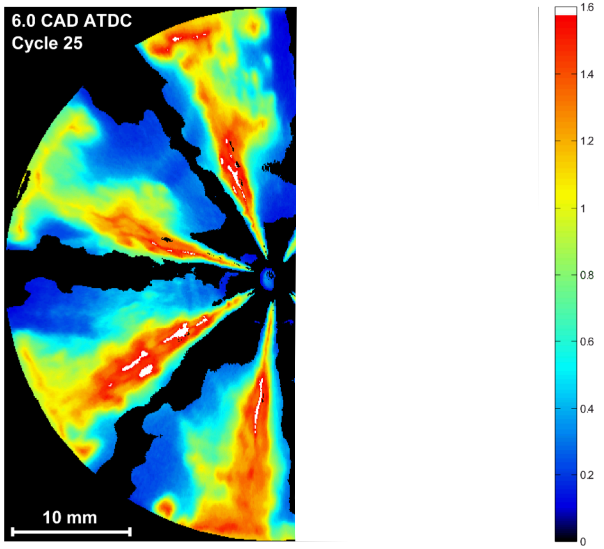
Results: P + M, 80 μs dwell; ignition process (~3.8 – 7.5 CAD ATDC)

- PLIF results show rich regions in the center of the spray and at the bowl rim (left side of PLIF image)
- OH* signal most likely originates in the outer portions of the jets
- NL signal is due to hot soot within the jet

Single cycle combined NL/OH* image



Single cycle PLIF image; bowl rim plane (P2)



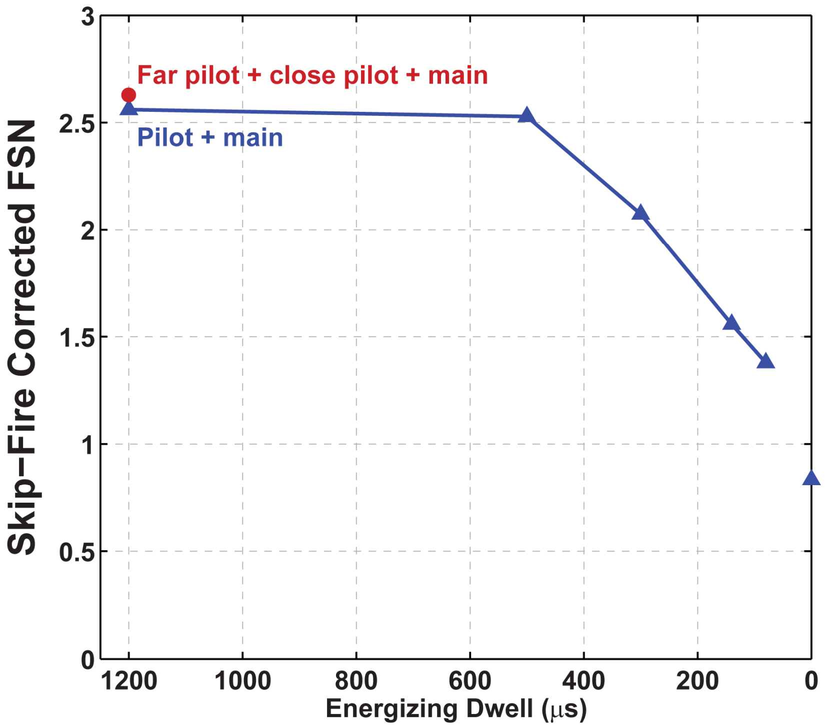
Results: P + M, 80 µs dwell; early soot formation processes

- Shortest dwell tested; no heating of cylinder contents by pilot heat release before main fuel injection starts
- No combustion of dribbled pilot fuel
- No entrainment of hot combustion products into main injection
- Pilot and main mixture appear to burn in the same space
- Apparent instantaneous lift-off lengths when the jets reach the bowl are longer than for the other dwells
  - Entrained gas is likely more oxygen-rich than for longer dwells
  - Early soot formation occurs farther downstream than for other dwells

Results: P+M; what is responsible for the FSN vs. dwell behavior?

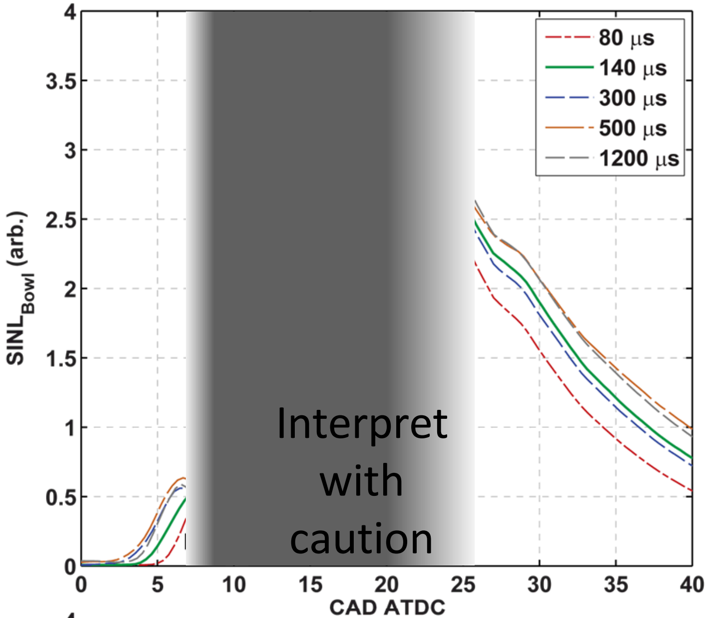
- Why do soot emissions decrease for dwells shorter than 500 μs?

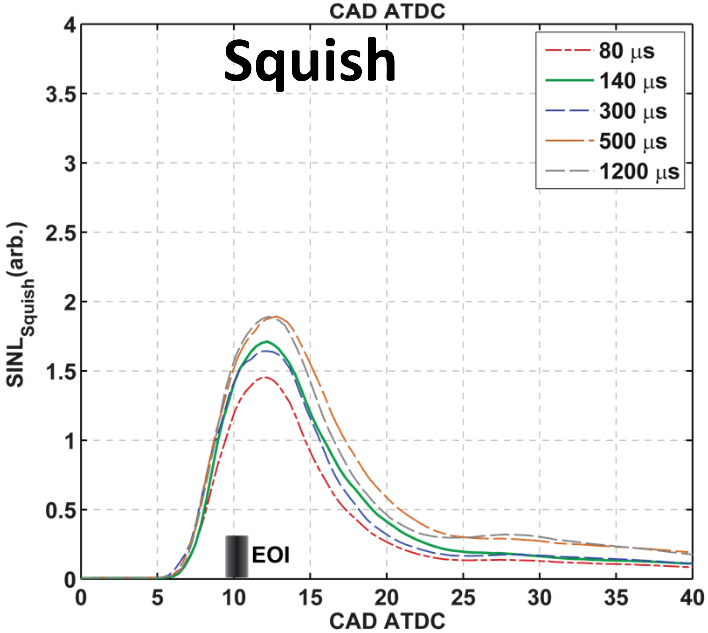
- What can we see in our optical measurement data that may help explain this?
  - Start with SINL in the bowl and squish regions



Results: P+M; SINL in the bowl / squish regions

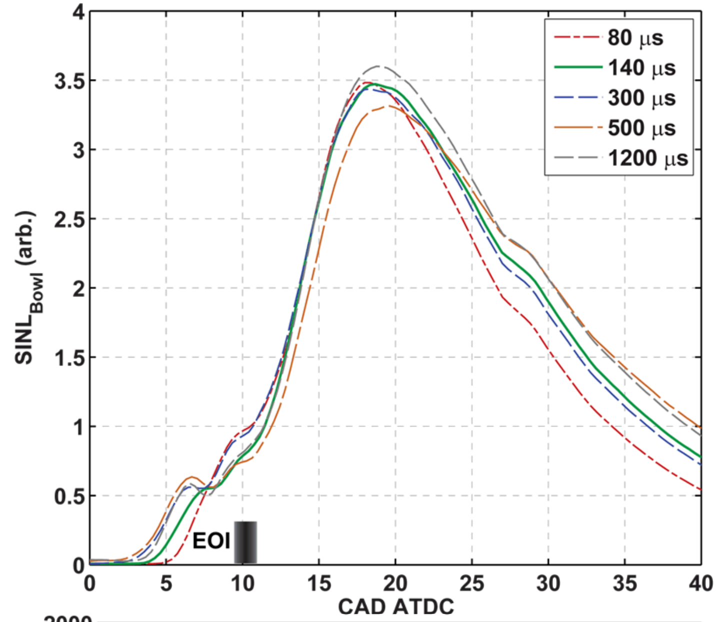
- SINL is not a good indicator of the total amount of soot present, particularly if the soot cloud is optically thick or interacts strongly with the bowl surface
  - i.e. in the bowl from ~5 CAD ATDC - ~25 CAD ATDC
- SINL begins to increase latest for the 80 µs dwell case
  - This is consistent with what we know about ignition and early stages of combustion for this dwell
- $SINL_{bowl}$ signals show some agreement with measured FSN trends in the late phase of the combustion
  - Most $SINL_{bowl}$ curves behave similarly until ~18 CAD ATDC
- $SINL_{squish}$ signals agree somewhat with measured FSN trends after EOI

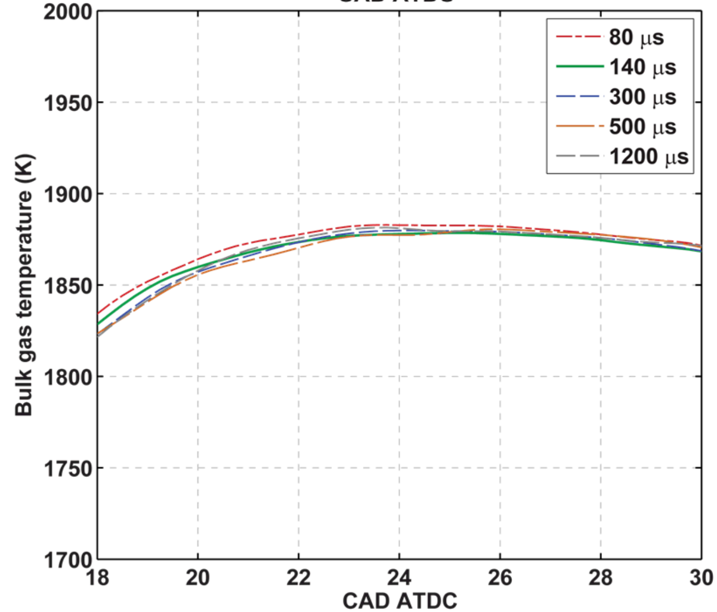




Results: P+M; SINL in the bowl

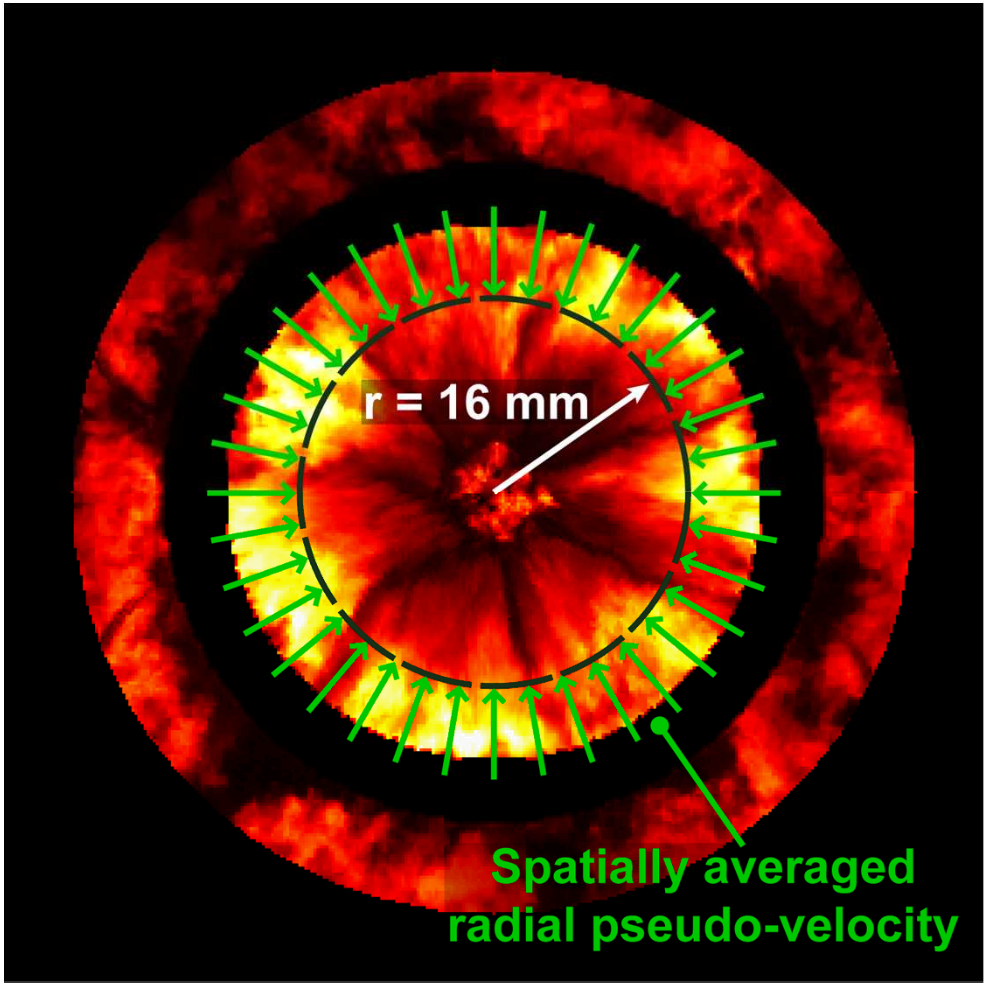
- Differences in SINL signals during the late phase of combustion
  - Seem to develop between ~18 CAD ATDC and ~30 CAD ATDC
- Late soot oxidation depends predominantly on:
  - Temperature
  - Reaction with OH / O_2
    - Mixing
- Large bulk gas temperature differences are not expected in this crank angle range for the different dwells (< 10 K)
- Do we see evidence of differences in mixing during this phase?
  - Look at recirculation within the bowl…





Results: P+M; recirculation within the bowl

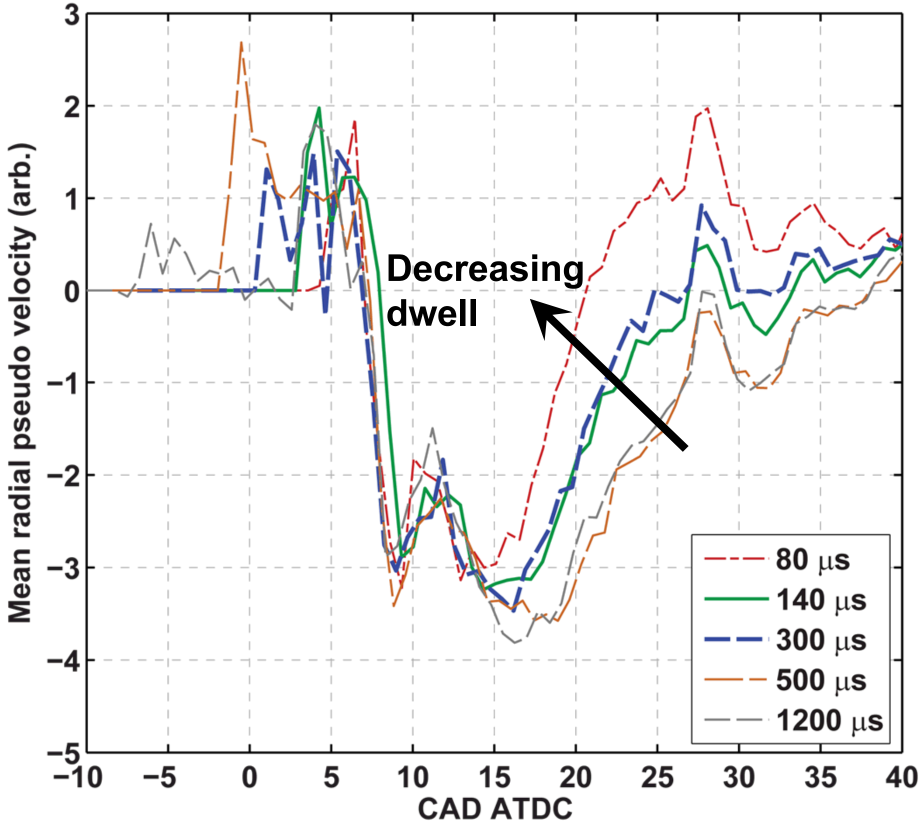
- Initial inward radial propagation
  - Small differences suggest that initial penetration of the jet heads is similar for all dwells
- Recirculation in the bowl
  - Significant differences suggest a changing turbulent breakdown process as dwell changes
- These are preliminary results
  - There are many unquantified potential error sources
  - These results do agree with what appears to be happening in NL videos
  - Analysis continues



20-cycle ensemble averaged data

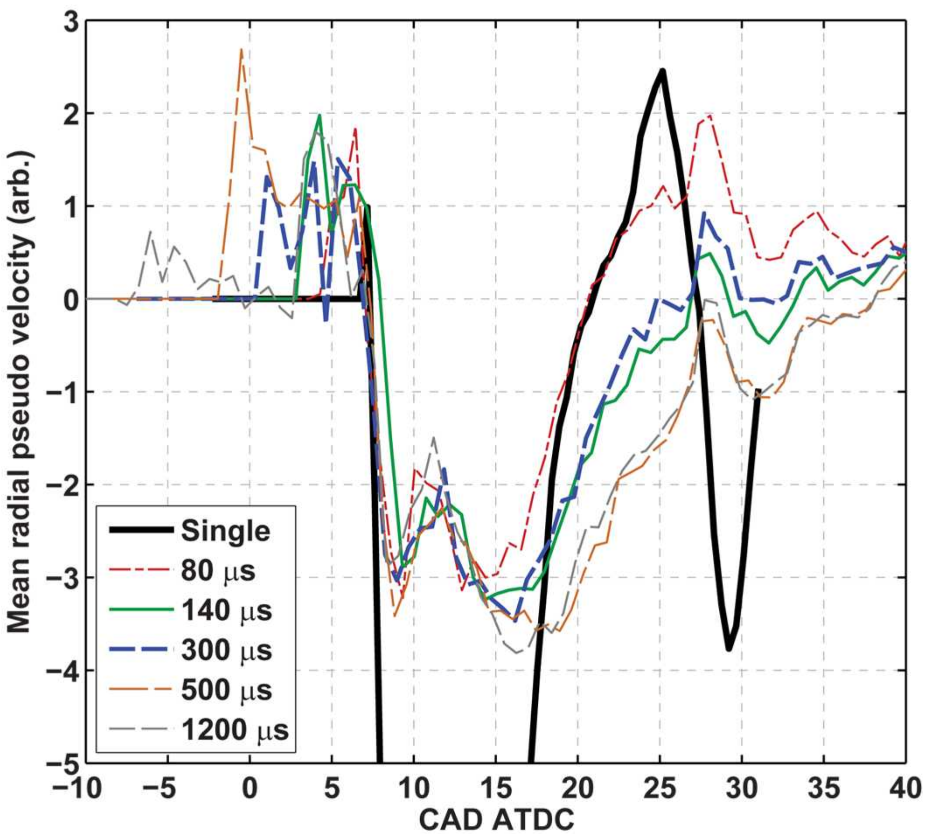
Results: P+M; possible differences in turbulent breakdown as dwell changes

- For shorter dwells, recirculation in the bowl is observed to stop sooner (zero-crossing)
- This implies turbulence levels may be higher for shorter dwells
- These higher turbulence levels at more advanced crank angles may help soot oxidation and contribute to lower soot emissions
  - Soot may be more likely to find oxygen/OH in a hotter environment
- The mechanism by which this possible difference in turbulence could occur is not understood



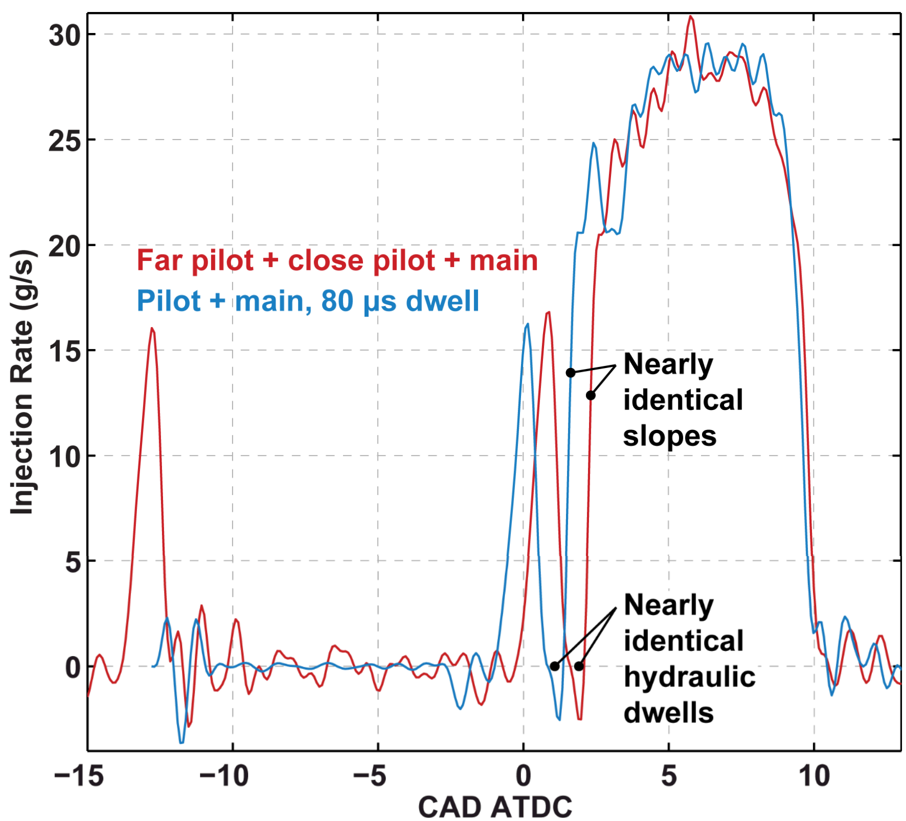
Results: P+M; recirculation in the bowl compared with a single injection

- For a single injection, recirculation within the bowl appears to reach a higher peak intensity
  - Further analysis is necessary to confirm this trend
- The single injection case behaves most similarly to the 80 μs dwell case
  - Radial velocity magnitudes begin to decrease shortly before 15 CAD ATDC
- Increasing dwell appears to delay the turbulent breakdown of recirculating flow in the bowl



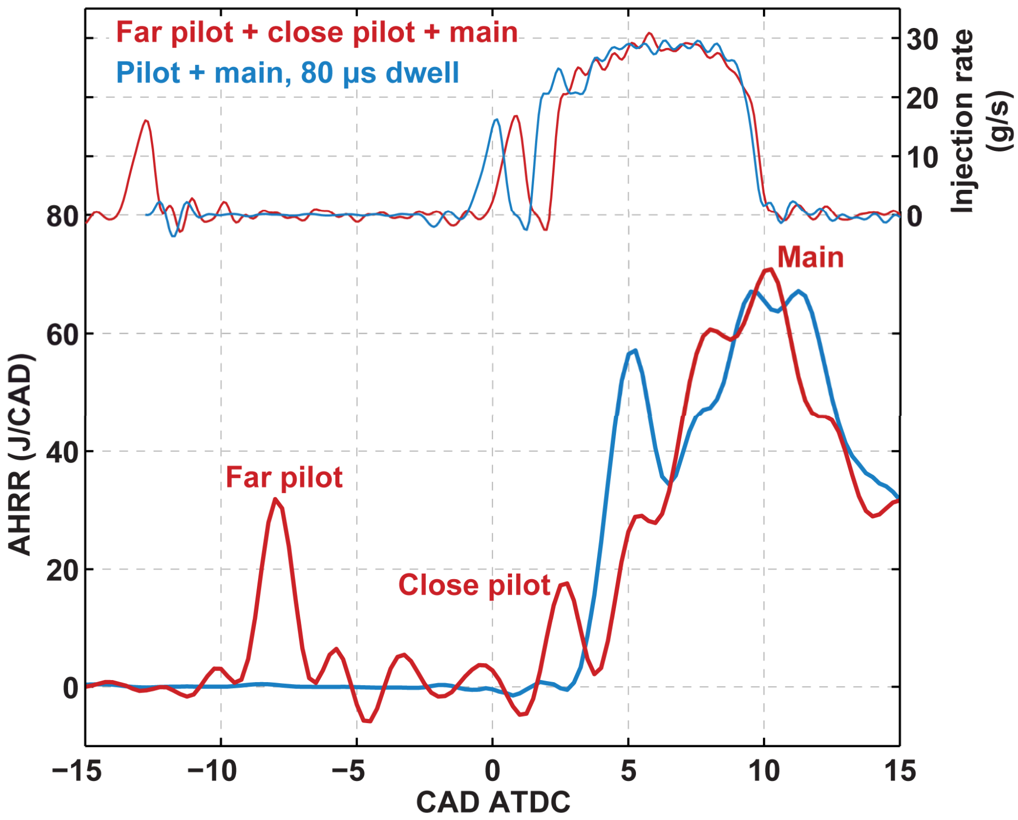
Results: fuel injection rate comparison: P + M vs. P_{far} + P_{close} + M

- Close pilot + main behaves as the pilot + main with an 80 (90) µs energizing dwell
  - Differences in injection rate traces for 80 and 90 µs energizing dwells are insignificant
  - Main injection rate shaping and close pilot – main hydraulic dwell is essentially unaffected by the far pilot
- Conclusion: main injection rate shaping due to hydrodynamics in the injector & fuel line is dominated by the close pilot



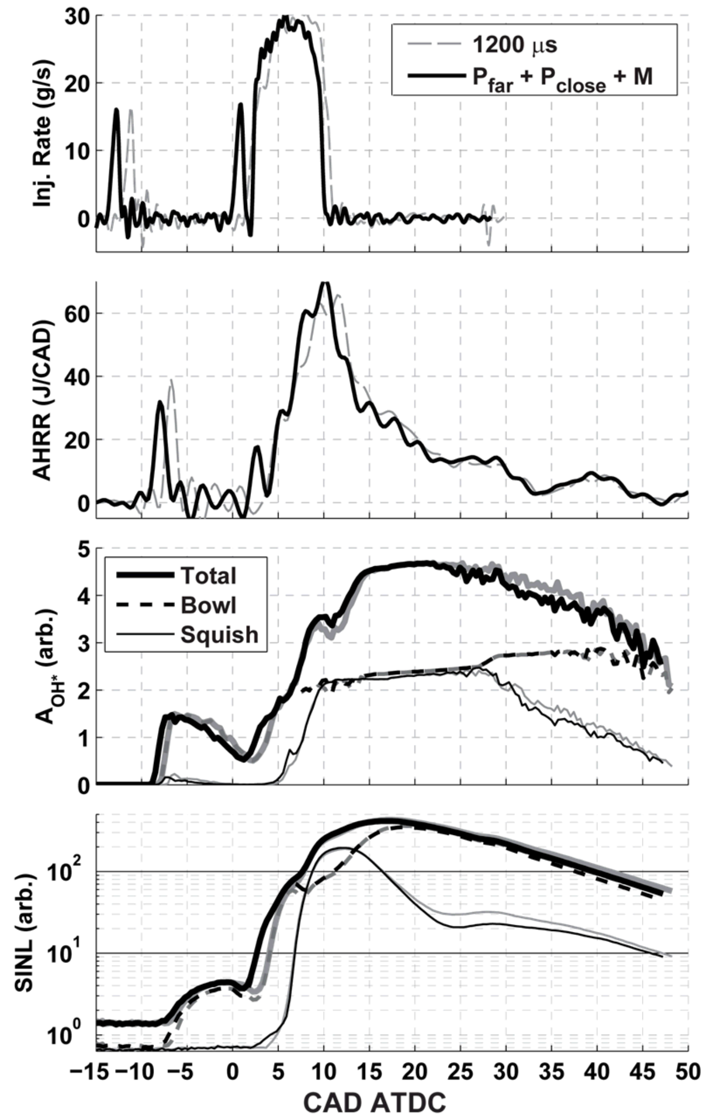
Results: heat release comparison: P + M vs. P_{far} + P_{close} + M

- P + M
  - Pilot and main heat release overlap; large amount of premixed heat release
- P_{far} + P_{close} + M
  - Far pilot decreases ignition delay of close pilot compared to single pilot case
  - Relatively low peak heat release rate for close pilot; possibly due to sensible enthalpy required to heat and vaporize main injection fuel



Results: P_{far} + P_{close} + M; comparison with P + M, 1200 µs dwell

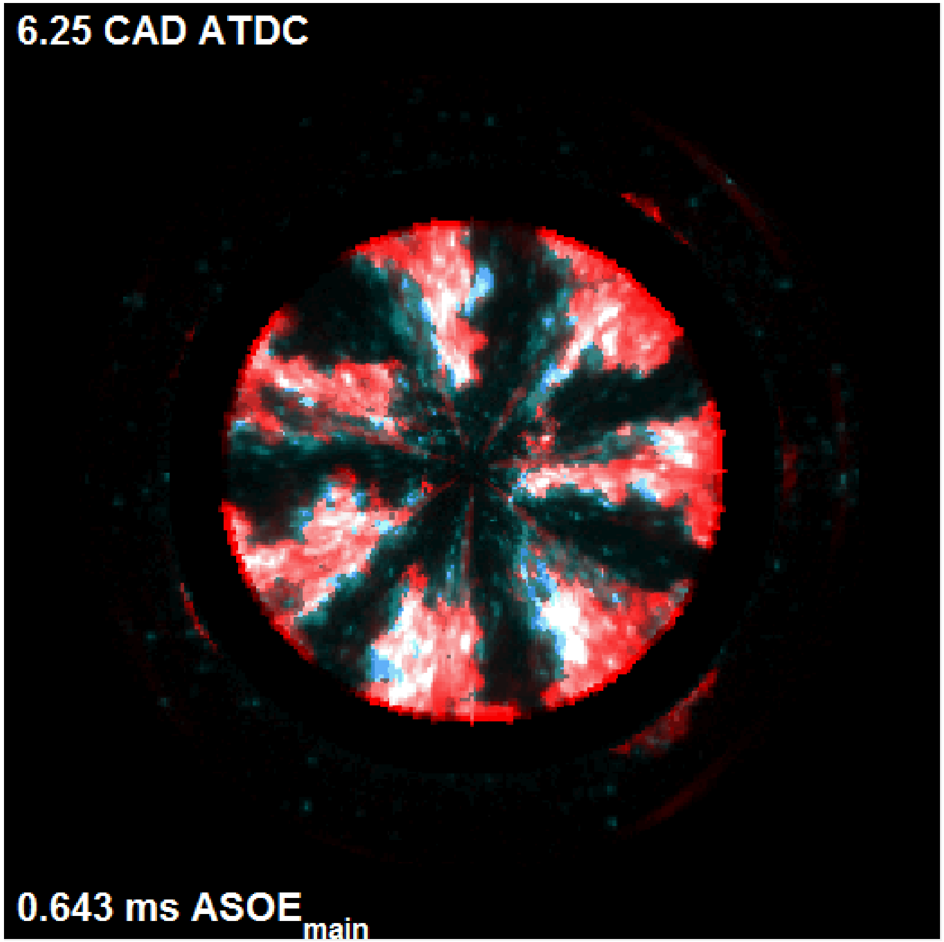
- AHRR
  - Primary difference is heat release from close pilot
  - Close pilot heat release starts ~0.5 CAD before SOI_{main}
- OH* appears to take up a slightly larger portion of the bowl at SOC_{main} for P_{far} + P_{close} + M
- More soot appears to form as a result of close pilot combustion (SINL signal)
- Differences in squish region during late phase of combustion



Results: P_{far} + P_{close} + M; ignition process (~1.5 – 6.25 CAD ATDC)

- First frame: start of close pilot heat release
  - Dribbled fuel and scattered pockets of OH* (HCO*?)
- Close pilot produces significant soot throughout the jets
- Close pilot jet penetration length reaches a quasi-steady value
- Main heat release starts before the main mixture has penetrated beyond the close pilot jets
- Continued penetration of the main mixture drives the further penetration of jets

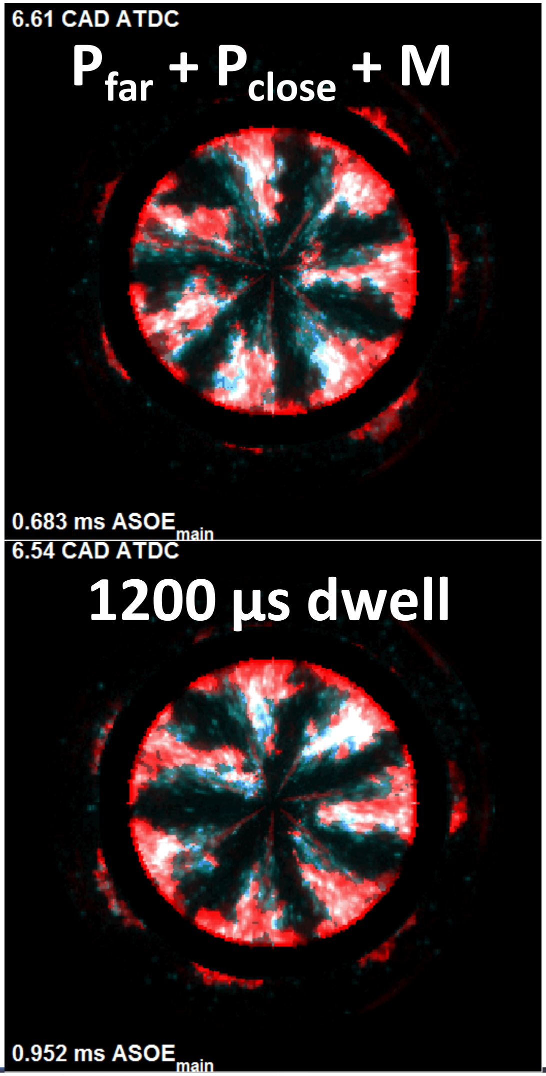
Single cycle, combined NL/OH* images



Results: P_{far} + P_{close} + M vs. 1200 μs; early combustion

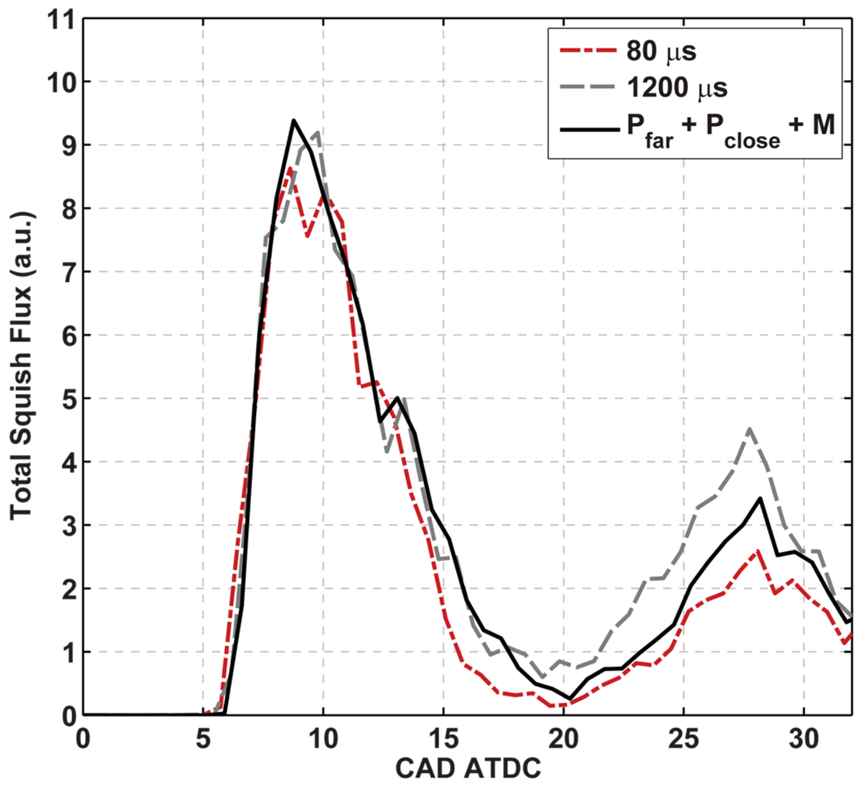
- Flame structure after main ignition is similar to 1200 μs dwell
- Soot is distributed over a slightly larger portion of the cylinder for the P_{far} + P_{close} + M case
- The close pilot appears to serve as an interruption in the main ignition process
- Close-pilot heat-release creates slightly hotter bulk gas temperatures during the early part of the main injection
- Flame structure during the early stage of main combustion does not appear to be strongly affected by the close pilot

Single cycle combined NL/OH* images taken shortly after initial squish penetration



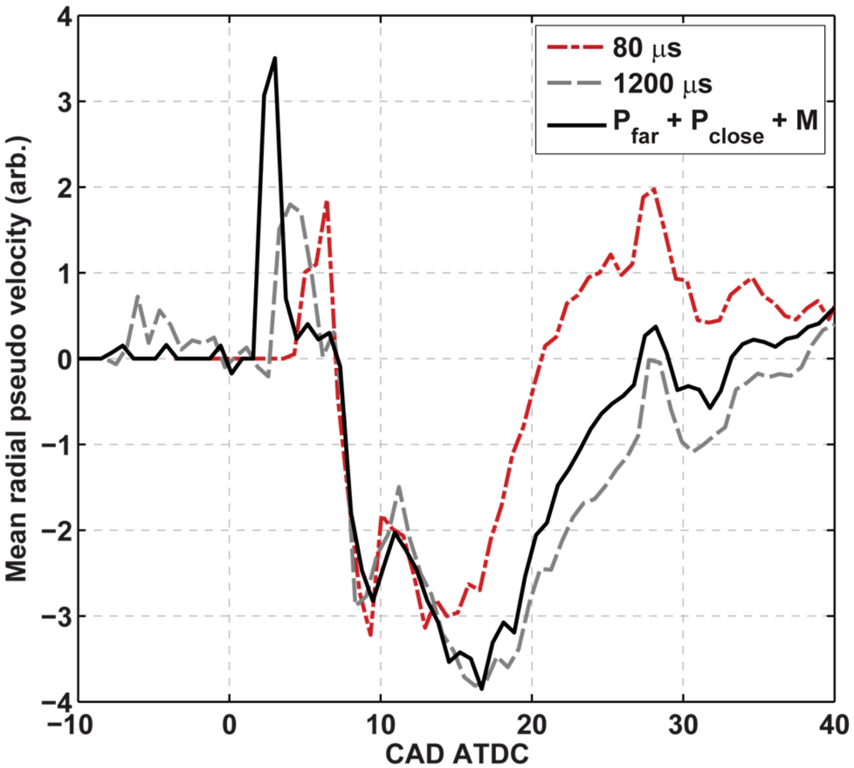
Results: P_{far} + P_{close} + M; reverse squish flow

- Initial flow into squish region is not changed by adding a close pilot
- Reverse squish flow
  - P_{far} + P_{close} + M initially behaves as the 80 µs dwell case
  - The reverse squish flow for P_{far} + P_{close} + M is similar to the 1200 µs case until ~18 CAD ATDC
  - After 18 CAD ATDC, the P_{far} + P_{close} + M case behaves more like the 80 µs dwell case than the 1200 µs dwell case



Results: $P_{far} + P_{close} + M$; recirculation in the bowl

- The presence of two pilots does affect recirculation in the bowl
- The effect seems to be smaller than the effect of changing dwell for a pilot-main strategy
- Slightly faster breakdown of recirculation for $P_{far} + P_{close} + M$
  - It may be expected that late-cycle oxidation is somewhat improved over the 1200 μs case
- A fundamental understanding of how the injection/combustion strategy affects in-cylinder flow is still lacking



Summary (1/3): Main mixture ignition processes

- Long dwell (1200 μs)
  - Pilot mixture reacts nearly to completion, mixes with cooler gases before SOI_{main}
  - Main injection is ignited by autoignition and/or inflammation by existing ignition sources (often from dribbled fuel or neighboring jets)
  - Initial soot formation sometimes takes place in upstream regions of jets, as well as in jet heads
- Intermediate dwells (500 μs, 300 μs, 140 μs)
  - The main mixture interacts more directly with hot, reacting pilot jets
  - Early soot formation is observed near the nozzle
  - The main jet structure replaces the pilot jet structure; increasing dwell gives the pilot jets more time to be transported by swirl
  - Flame structure resembles the long dwell case after the ignition process is complete
- Shortest dwell (80 μs)
  - Little to no interaction between pilot heat release and main injection
  - Initial soot formation is observed to occur only in jet heads

Summary (2/3): Late cycle flow and soot oxidation processes

- For dwells shorter than 500 μs, engine-out soot decreases
  - Differences in spatially integrated natural luminosity (SINL) seem to develop between 18 CAD ATDC and 30 CAD ATDC
  - Relative SINL magnitudes correspond roughly to engine-out soot behavior for the different dwells after 30 CAD ATDC

- Squish flow (reverse squish)
  - Squish flux is highest for the dwell of 1200 μs during the second propagation into the squish region
  - This suggests that flow patterns may be altered as a result of changing dwell

- Late cycle turbulence
  - The recirculating flow pattern in the bowl breaks down after EOI_{main}
  - This breakdown occurs as much as 5 CAD sooner for shorter dwells
  - If this breakdown is the result of turbulent mixing, then late cycle mixing and soot oxidation may be hindered for longer dwells

Summary (3/3): Adding a second pilot (P_{far} + P_{close} + M)

- Main injection rate shaping is dominated by the close pilot
- AHRR is similar to the 1200 µs dwell case except for a small contribution from the close pilot
- Initial soot formation appears to be increased by the addition of the close pilot, but flame structure does not appear to be significantly altered compared to the long and intermediate dwells with single pilots
  - More heating of the cylinder contents occurs as a result of the additional pilot
- The additional close pilot injection seems to decrease reverse squish flow compared to the 1200 µs dwell
- The breakdown of the recirculating flow in the bowl seems to be slightly enhanced by the addition of the close pilot (compared to the 1200 µs dwell)

Next steps

- CFD simulations
  - Is the breakdown of recirculating flow in the bowl captured in a simulation? What are the effects of changing dwell?
  - Can we explain the reverse squish flow behavior with simulation results?
- More careful approach to combustion image velocimetry processing (conclusions are not expected to change)
  - New ray tracing simulations based on assumptions about where the measured NL intensity originates
  - Recalibration and reprocessing of images to reduce uncertainties due to image distortion
  - More selective cross correlation procedures to improve confidence in the results
- Vertical plane PIV measurements (potentially)
  - Is combustion necessary to reproduce the flow structures associated with the recirculation breakdown?

Planned publications

- Ignition processes with pilot injections: one step towards a multiple injection spray combustion conceptual model
  - Journal, TBD

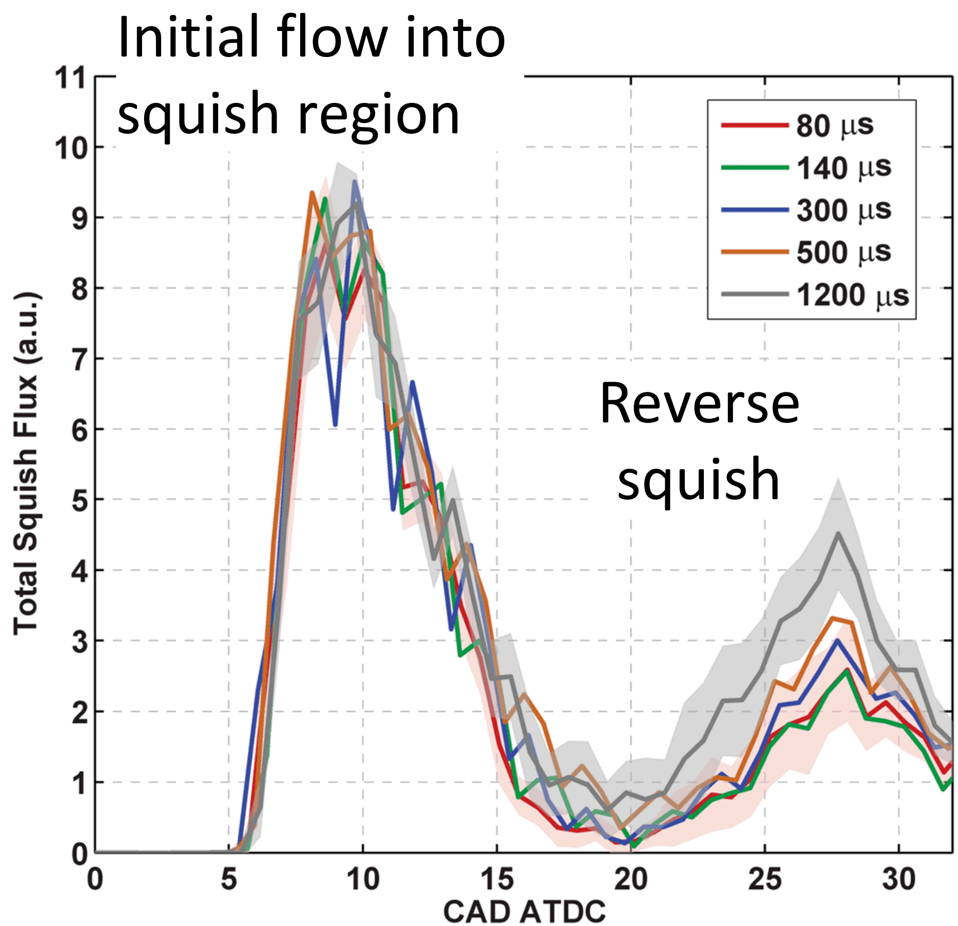
- Late cycle recirculation flow breakdown
  - IJER special edition

THANK YOU FOR YOUR ATTENTION!

Questions?

Results: Effect of dwell on total squish flux

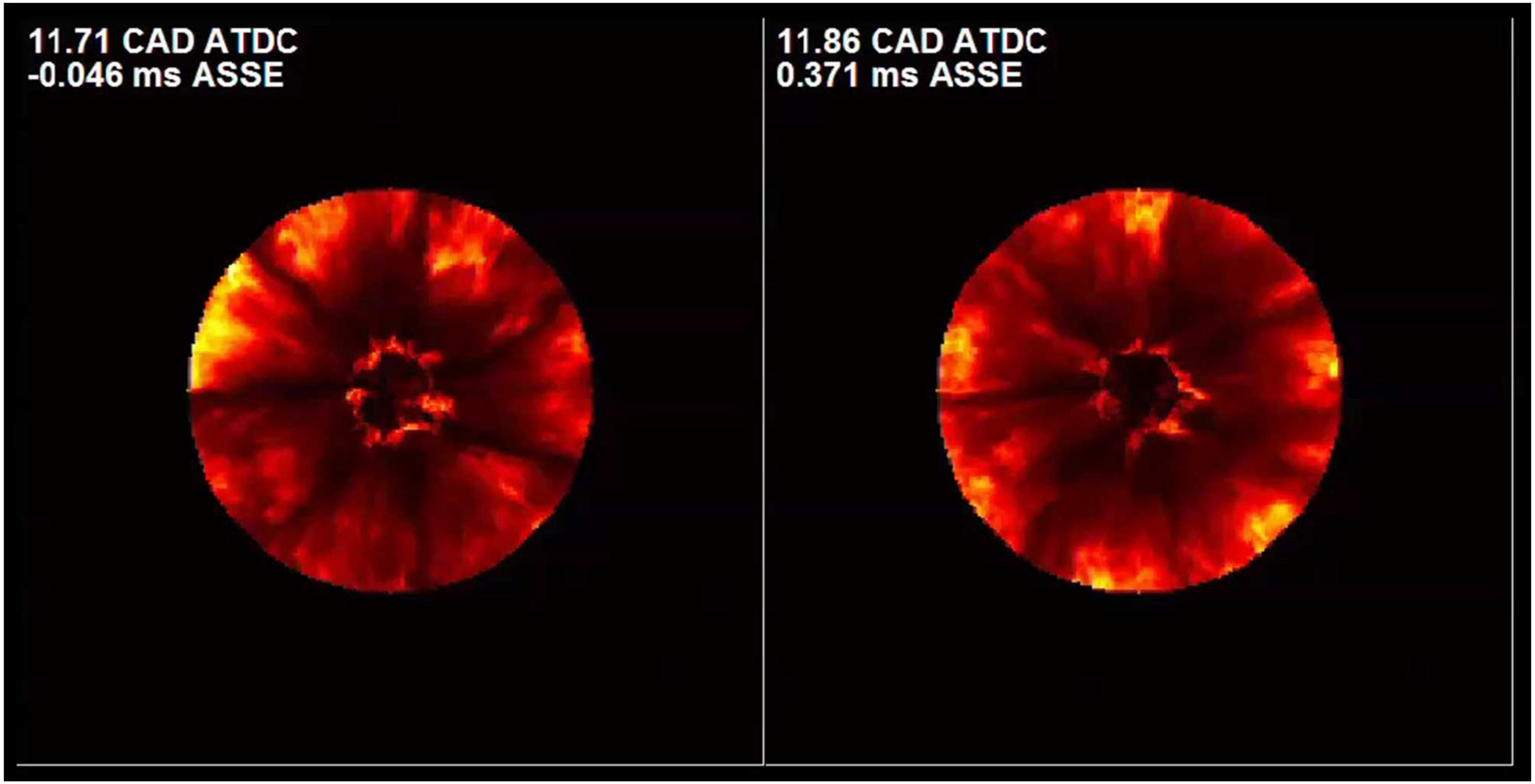
- No significant differences in initial flow into squish region
- For longer dwells (500 and 1200 μs), the reverse squish flow may be stronger than for shorter dwells
  - This may or not be related to the amount of soot ultimately carried into the squish region



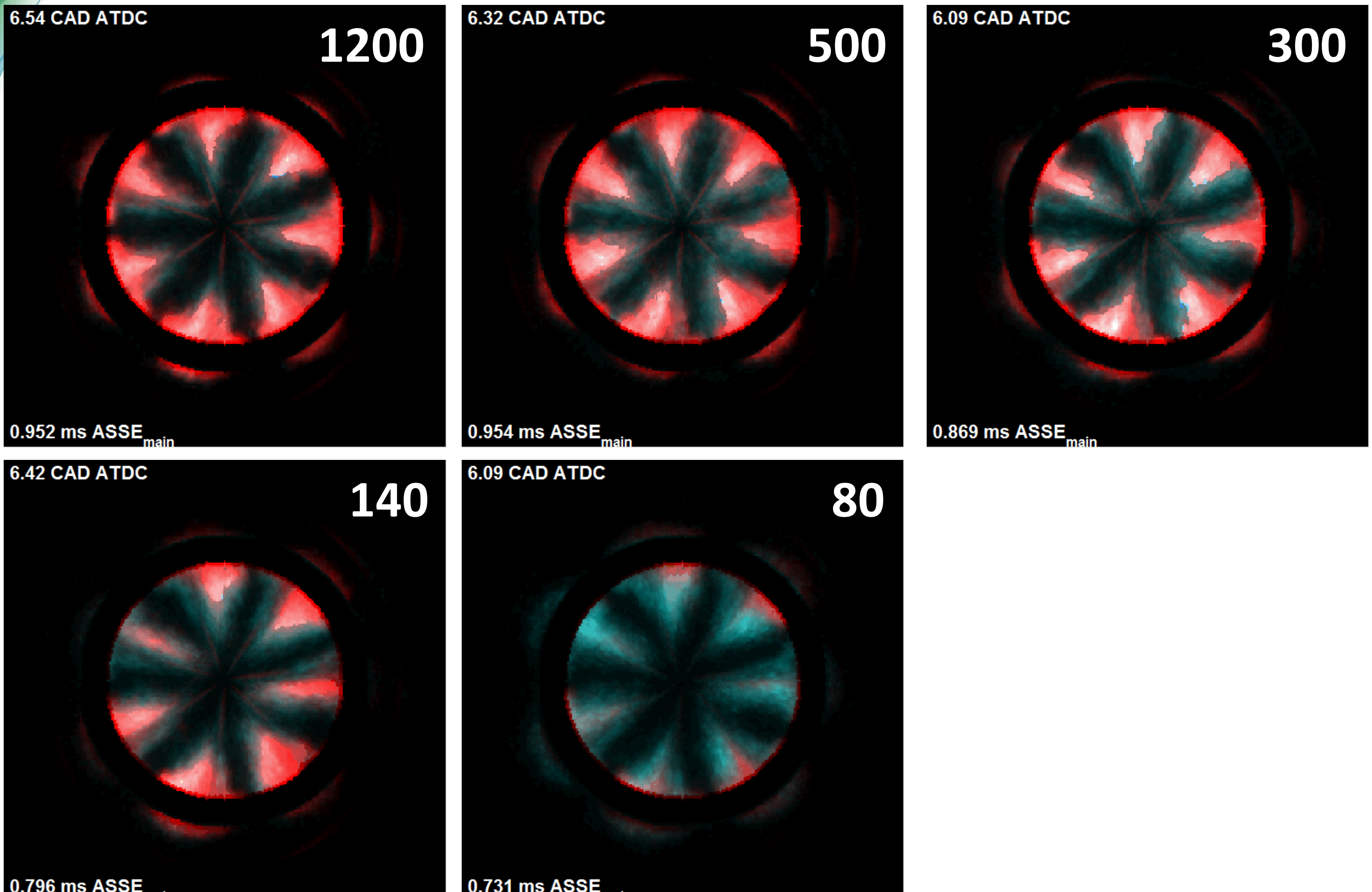
±σ Scatter bands for 1200 μs and 80 μs data

Results: recirculation within the bowl

500 µs dwell | **80 µs dwell**

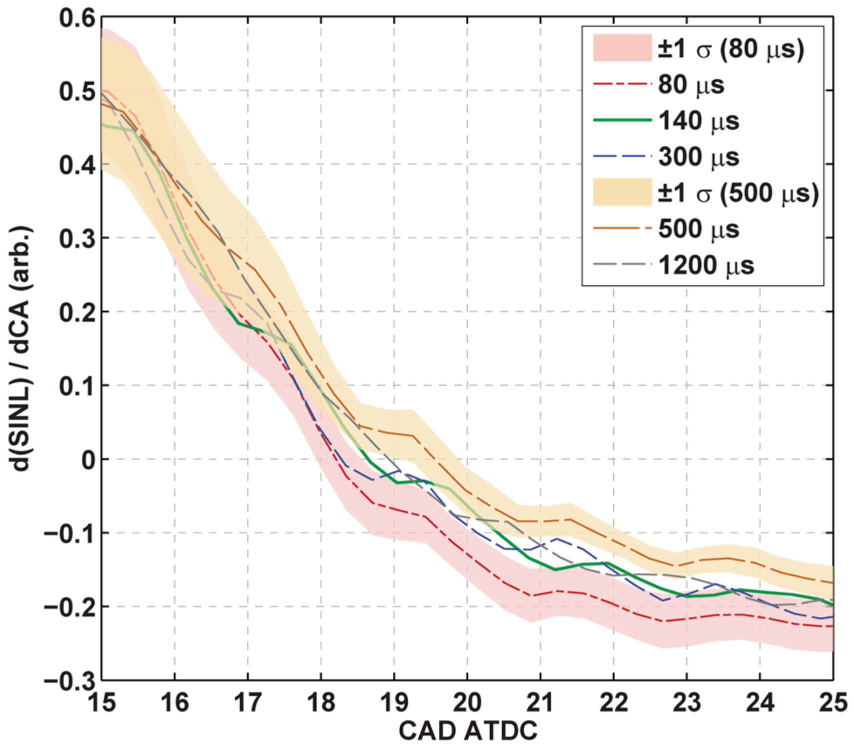


OH* / NL images during the early stage of squish region propagation



Results: P+M; derivative of SINL in the bowl after EOI_{main}

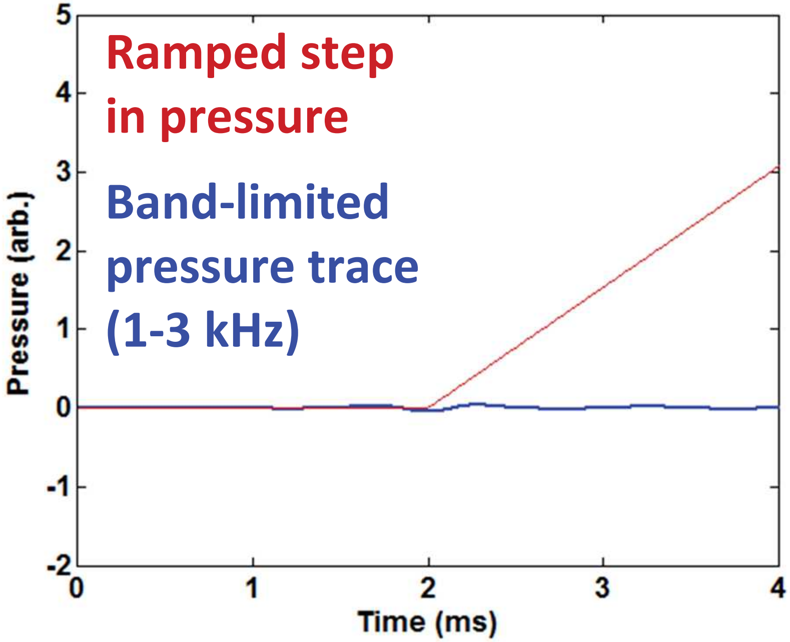
- Slope of SINL may provide some rough indication of how effectively soot is being consumed
- Differences are small except for dwells of 500 and 80 µs
- Do we see evidence in other optical data that could help explain this?



Results: combustion-noise reduction

- The effect of heat-release on cylinder pressure:
  - $dP = \frac{(\gamma - 1)dQ}{V} + \cdots$
- The contribution of a heat-release event of finite duration to the cylinder pressure trace can be approximated by a ramped step
- As the ramp becomes steeper, the harmonics associated with it become more intense
- As the duration of the ramp changes, the shape of the band-limited pressure trace changes
- The combination of ramp shape and duration determines noise reduction potential

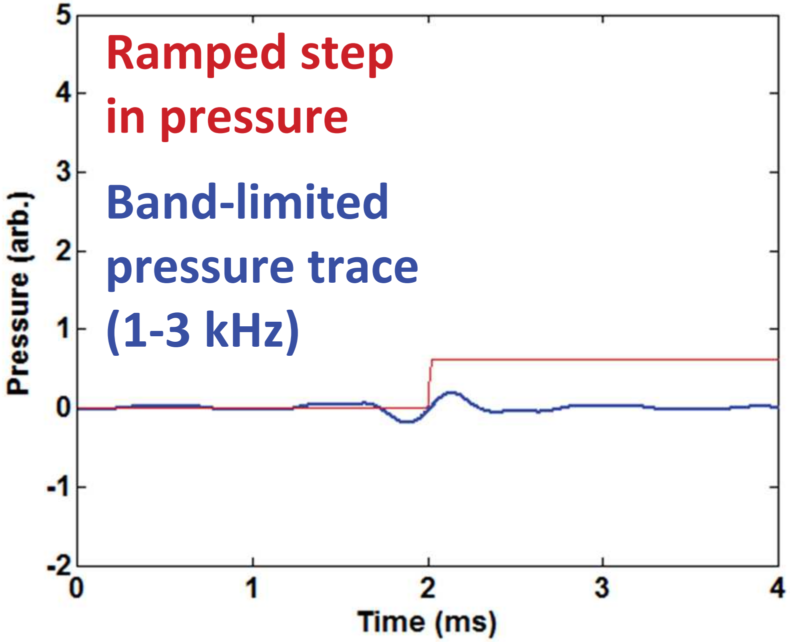
Constant ΔP, variable slope (dQ) and duration



Results: combustion-noise reduction

- The effect of heat-release on cylinder pressure:
  - $dP = \frac{(\gamma-1)dQ}{V} + \cdots$
- The contribution of a heat-release event of finite duration to the cylinder pressure trace can be approximated by a ramped step
- For a given ramp slope, the duration of the heat release event strongly affects the frequency content
- The start and end of heat release have a distinctive band-limited pressure signature

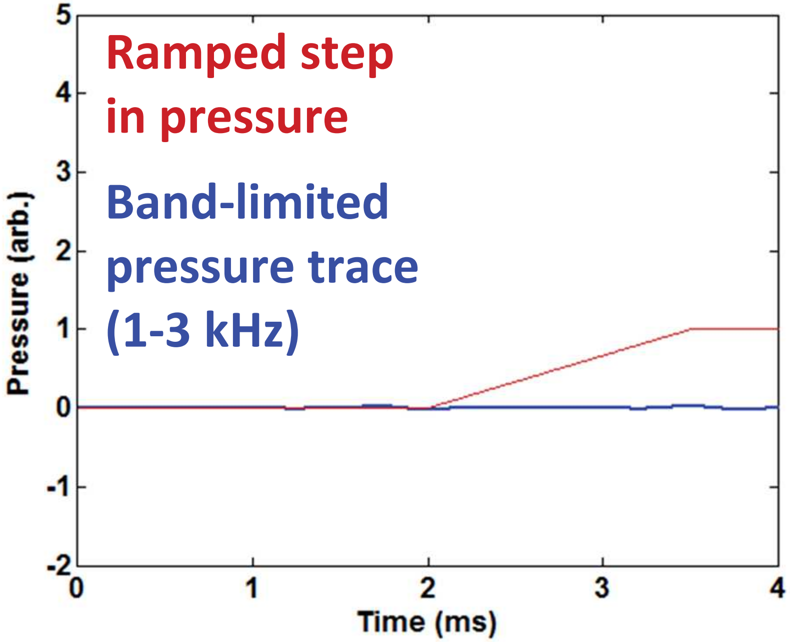
Constant slope (dQ), variable duration



Results: combustion-noise reduction

- The effect of heat-release on cylinder pressure:
  - $dP = \frac{(\gamma - 1)dQ}{V} + \cdots$
- The contribution of a heat-release event of finite duration to the cylinder pressure trace can be approximated by a ramped step
- For a given duration, the band-limited pressure signature increases in amplitude as slope increases

Constant duration, variable slope (dQ)



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

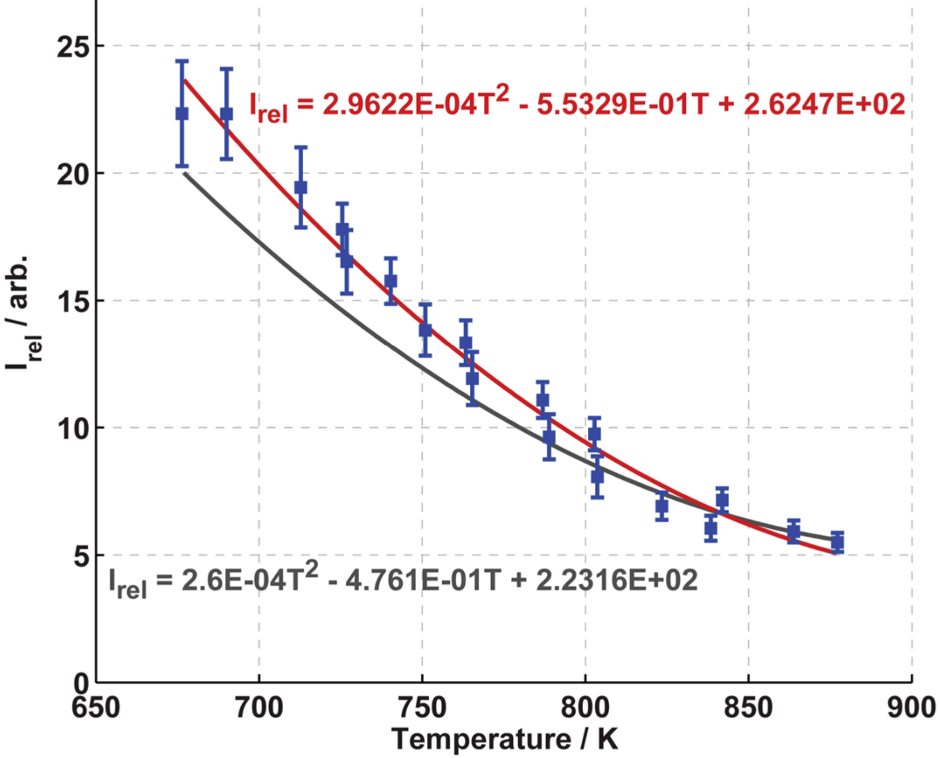
- Calibration with homogeneous mixture of known concentration ($\chi_{fuel,cal}$)
  - "Flat-field" correction

- $\sigma\eta(T)$ 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

Shown with 2σ-error bars



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

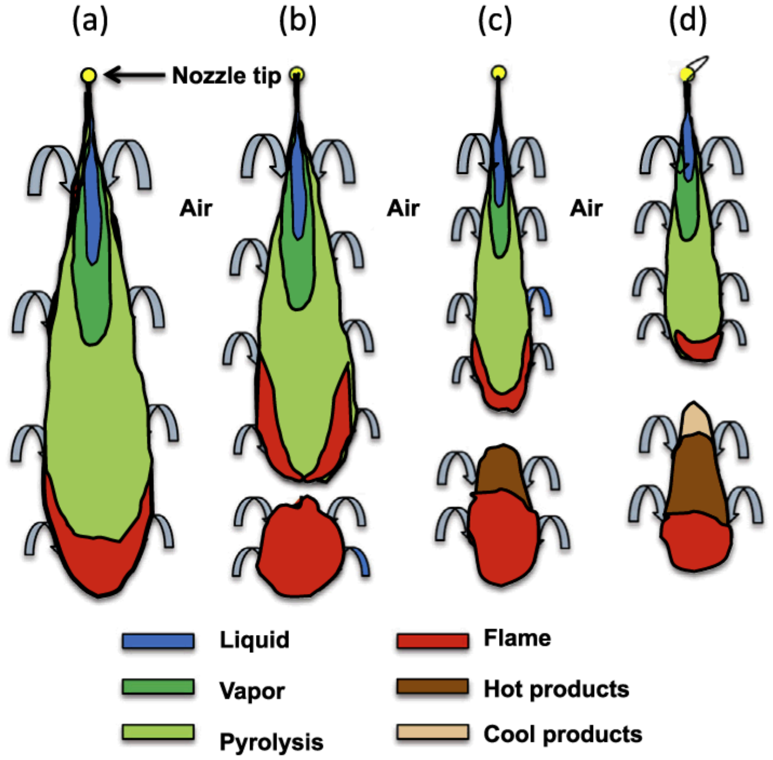


Fig. 7. Spray combustion interaction model for single and multiple-injection by varying dwell time; (a) single injection: (b) short DT: (c) medium DT: and (d) long DT.

Cylinder pressure-based analyses: combustion noise

- Measured cylinder pressure traces are filtered in the frequency domain:
  - Structural attenuation filter (acts as a low-pass filter)
  - A-weighted filter (frequencies near 1 kHz are emphasized)
- The filtered cylinder pressure spectrum is integrated
- The integrated value is normalized by the threshold of human hearing
  - Noise is reported in dBA
- For a given operating point, noise is computed for each of 50 skip-fired cycles; the average of these noise values is reported here

Details of combustion noise calculation are given in:

Shahlari, A., Hocking, C., Kurtz, E., and Ghandhi, J., "Comparison of Compression Ignition Engine Noise Metrics in Low-Temperature Combustion Regimes," SAE Int. J. Engines 6(1):541-552, 2013, doi:10.4271/2013-01-1659.