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Effect of Pilot Combustion on Main Mixture Ignition Processes in a Light-Duty Diesel Engine

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Recent experimental investigations have revealed much about ignition processes in diesel sprays in constant volume combustion chambers with single and double injection strategies, but further investigations are needed to provide an understanding of main mixture ignition processes with a pilot injection in a small-bore diesel engine. A simultaneous high-speed OH* chemiluminescence and natural luminosity (NL) imaging technique is developed and applied in light-duty optical diesel engine to investigate the pilot combustion and main ignition processes for a part-load operating point with conventional diesel combustion. The OH* chemiluminescence signal indicates the presence of high temperature combustion, whereas the NL signal appears in regions where sooty combustion takes place. Advanced image distortion corrections provide images that show the temporal and spatial behavior of the pilot combustion and main mixture ignition processes. The results demonstrate that the pilot combustion event takes place entirely within the piston bowl, and the initial phase of the pilot heat release takes place without soot formation. However, soot appears near the injector tip during the later stage of pilot heat release and is attributed to fuel injected or dribbled at the end of the pilot injection event. At the time of the start of main injection, isolated regions of reactive pilot mixture and isolated pockets of sooty combustion are observed throughout the piston bowl. The main mixture ignition process varies from jet-to-jet and cycle-to-cycle. High temperature reactions can be initiated in one or several locations throughout a given jet. The high temperature reactions for a particular jet may be influenced by nearby reactive pilot mixture that originates either from the given jet, the neighboring jet, or some combination of both. Future analyses will be focused on the effect of pilot-main dwell and on CFD simulation results.

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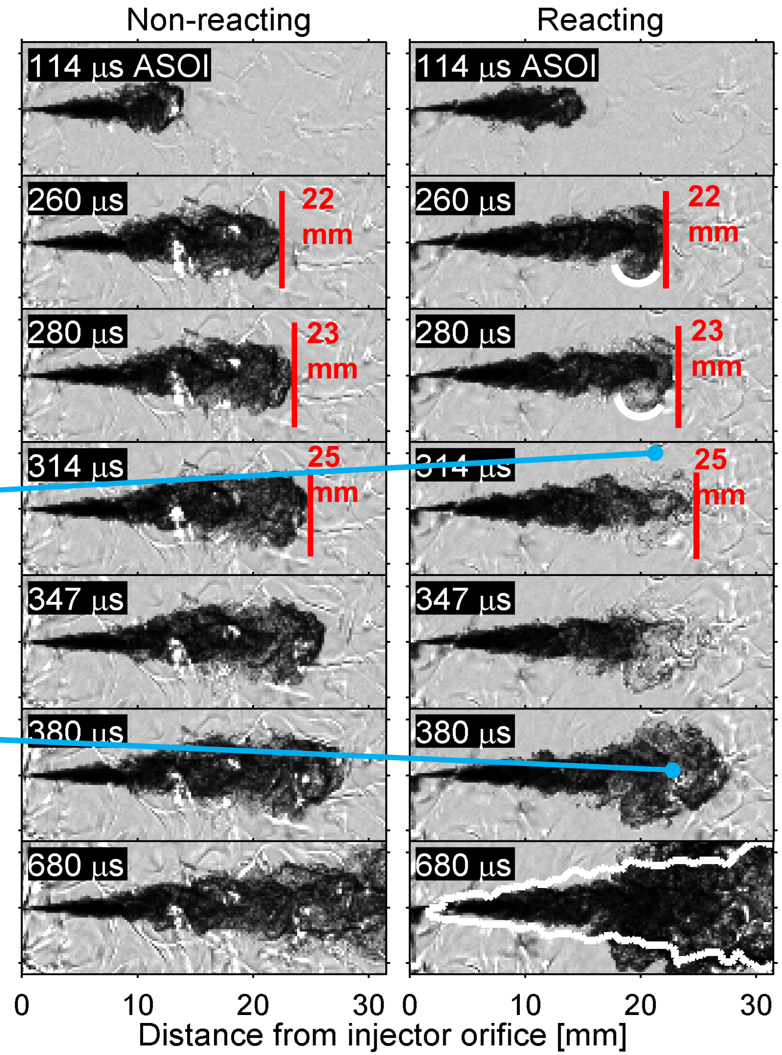
Introduction: ignition processes in diesel sprays (single injection)

- Recent experimental efforts have provided a better understanding of single injection ignition processes: Skeen, Manin, Pickett (SNL)
  - Low temperature reactions start in hot, lean regions near the jet periphery, then propagate through jet head
  - Shortly afterward, high temperature ignition occurs volumetrically throughout large portions of the jet head



Images courtesy of S. Skeen, J. Manin, and L. Pickett (Aug. 2014 AEC meeting)

Introduction: multiple injections in diesel engines

- Multiple injections can help optimize tradeoffs between emissions, efficiency, noise, and exhaust aftertreatment systems
  - Post injections to reduce engine-out soot
    - Experiments in low-swirl HD diesel engine: O'Connor and Musculus (SNL)
    - Accompanying computational studies: Hessel, Yue, Reitz (UW-M)
  - Close-coupled pilot injections as a means to reduce combustion noise
    - Experiments in LD, swirl-supported diesel engine; theoretical analysis (Busch, SNL)
- Focus of this work: main mixture ignition processes with a single pilot injection
  - Conventional combustion
    - Relatively high oxygen concentration (compared to LTC)
    - Low degree of premixing for the main injection
  - Objectives: improved understanding of ignition processes in light-duty, swirl supported diesel engines; guidance of simulation efforts to improve predictive capabilities

Ignition processes in piloted diesel jets – some open questions for engine operation

- Where does the pilot combustion take place, and what is the state of the cylinder contents at the start of the main injection?
- How does the pilot influence / enhance main mixture ignition?
  - Thermal influence – local or global
  - Source of radicals
  - What is the role of cool flame chemistry?
- How do operating parameters impact main mixture ignition?
  - Pilot timing and mass
  - Injection pressure
  - Injector design
- How is main mixture formation and ignition in an engine different than in an injection chamber?
  - Slipstream effect
  - Interaction with combustion chamber geometry
  - Bulk flow structures / turbulence
- Can main ignition processes be accurately simulated?

Outline

- State of knowledge – ignition processes in piloted diesel sprays
- Experimental setup
  - Light duty optical Diesel engine
  - High speed simultaneous OH* and NL imaging setup
  - Engine operation
- Data processing
  - Image distortion correction
  - Image registration
- Results
  - Pilot combustion
  - Main ignition
- Summary and conclusions
- Future work

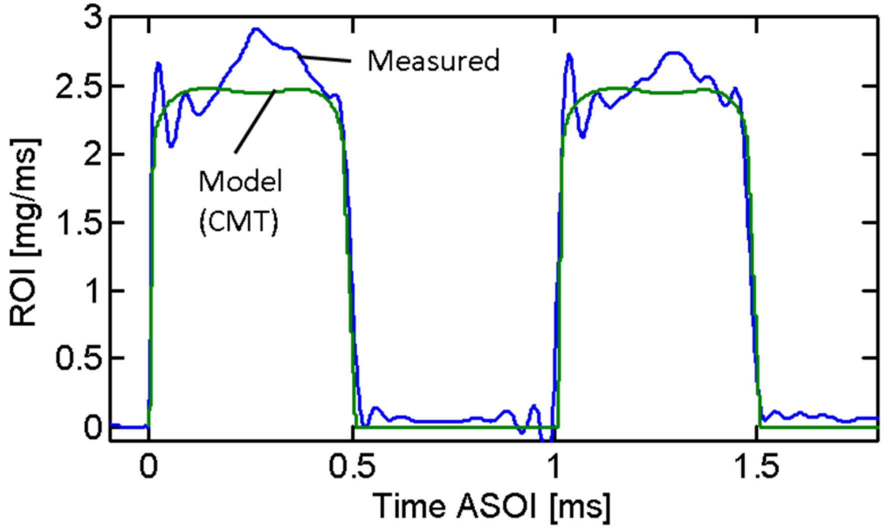
Double-pulse injection – mixture formation and combustion

- Bruneaux and Maligne (IFP) studied double pulse injections in a quiescent injection chamber with a single-hole injector[1]
  - Two energizing dwells studied: 875 µs and 400 µs
- "Slipstreaming" observed for the shorter dwell case; second injection into hot combustion products from first injection may decrease mixing rates and reduce the benefits of this interaction
- Timing and location of combustion of the first injection determines the environment into which the second injection is injected
  - Short dwell: second injection entrains some air since first combustion is still progressing downstream; hot gases in tail of first injection decrease ignition delay of second injection
  - Long dwell: first injection combustion recession takes place; second injection entrains hot first-stage ignition products from first injection; ignition delay is very short and lift-off length decreases; soot forms rapidly and in higher concentrations

[1] Bruneaux, G. and Maligne, D., "Study of the Mixing and Combustion Processes of Consecutive Short Double Diesel Injections," *SAE Int. J. Engines* 2(1):1151-1169, 2009, doi:10.4271/2009-01-1352.

ECN: double injection with spray A - experimental conditions

- Previous work focused on a single n-dodecane injection at Spray A conditions (900 K, 22.8 kg/m^3, 15% O_2)
- Engine Combustion Network (ECN) has proposed two multiple-injection scenarios as parametric variations on Spray A
  - **0.5 ms / 0.5 ms (dwell) / 0.5 ms**
  - 0.3 ms / 0.5 ms (dwell) / 1.3 ms
- CMT Model Parameters
  - d = 0.0908 mm
  - ρ_{fuel} = 698 kg/m3
  - C_d = 0.888
  - ROI available on ECN website

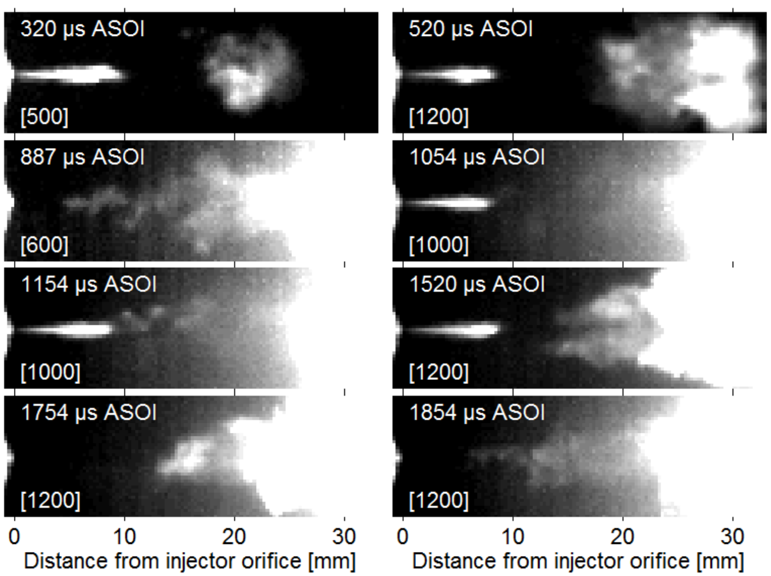


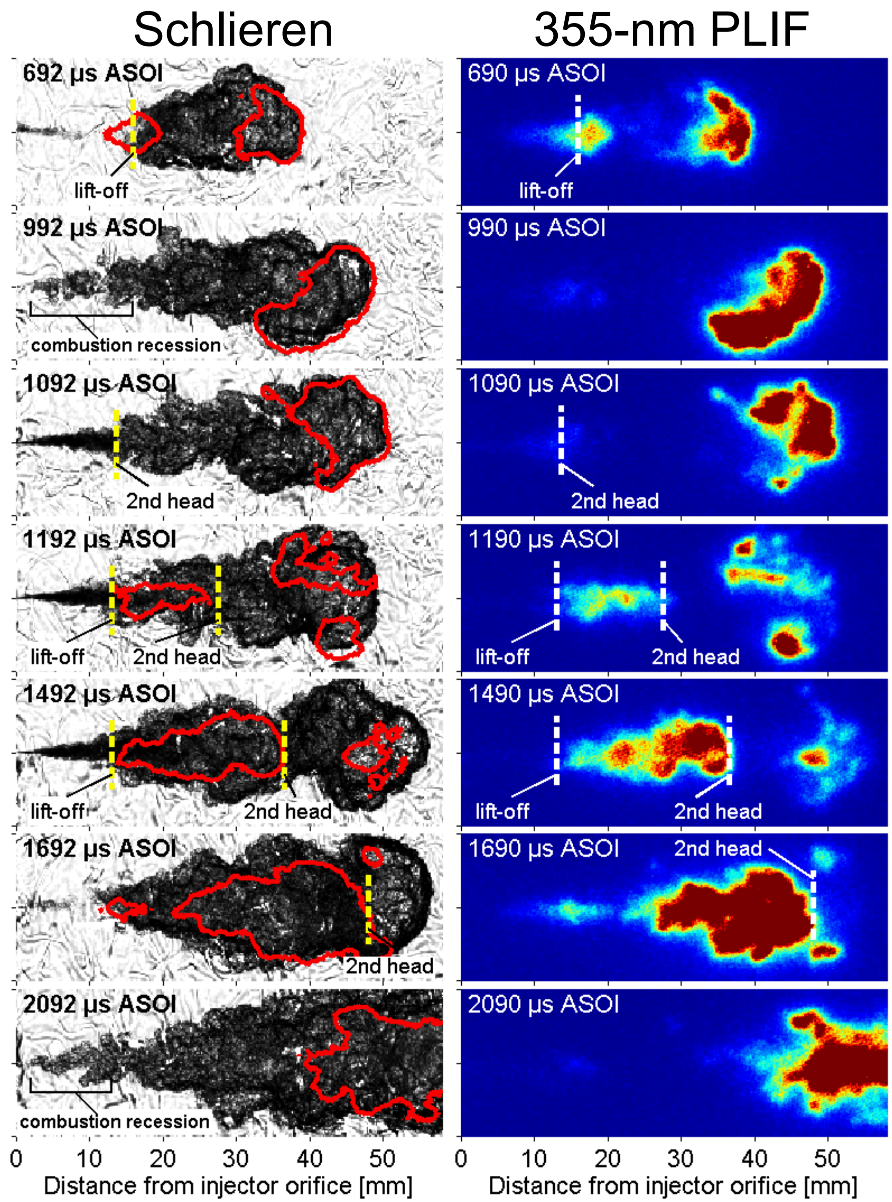
- Three ambient temperature conditions at 22.8 kg/m^3 and 15% O_2 using n-dodecane injected at 1500 bar
  - 900 K
  - 800 K
  - 750 K

Slide courtesy of S. Skeen, J. Manin, and L. Pickett (Feb. 2015 AEC meeting)

ECN: ignition of 2nd injection with spray A (900 K)

- At Spray A conditions first- and second-stage ignition occur in the near injector region after the end of injection "combustion recession"
- Second injection penetrates into high-temperature products, including radical species (OH, O, H)
- Lower density enhances "slipstream effect"
- Narrower spreading angle for 2nd
- Earlier ignition, earlier (and more) PAH and soot formation





See also: Skeen, S., Manin, J., and Pickett, L., "Visualization of Ignition Processes in High-Pressure Sprays with Multiple Injections of n-Dodecane," *SAE Int. J. Engines* 8(2):696-715, 2015, doi:10.4271/2015-01-0799.

Conceptual model for a single diesel jet with a pilot injection

- Pilot-main interaction mechanism proposed by Cung et al. in 2015[2]
  - Interaction between combustion of pilot and ignition/combustion of main mixture depends on pilot-main dwell
  - The burning pilot mixture heats the main mixture, but can also deprive it of oxygen
- For "medium" pilot-main dwell, the main injection penetrates towards a pocket of hot, burning pilot mixture
  - Heating by the pilot causes the main mixture to burn intensely at the front (tip and surrounding portions) of the jet
- At longer dwells, pilot combustion is largely complete by the time of main injection, and pilot combustion products have mixed with cooler air
  - Heating of the main mixture is more gradual → smaller temperature gradients in the spray

[2] Cung, K., Moiz, A., Johnson, J., Lee, S.-Y., Kweon, C.-B., Montanaro, A., "Spray–combustion interaction mechanism of multiple-injection under diesel engine conditions," Proc Combust Inst, Vol. 35, Nr. 3, 2015, pp 3061-3068, http://dx.doi.org/10.1016/j.proci.2014.07.054.

Recap: ignition processes in diesel jets in injection chambers

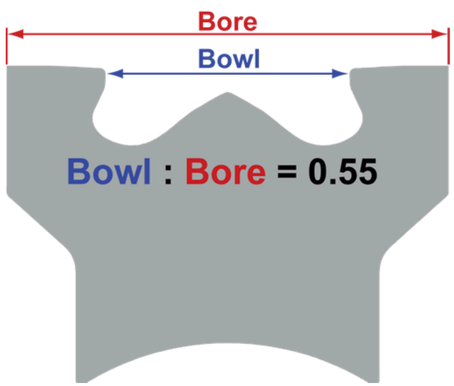
- Single injection ignition (main-only)
  - Low temperature ignition in periphery of jet head
  - High temperature ignition distributed throughout jet
- Main ignition with a single pilot injection
  - Timing, location, and extent of pilot combustion determine what the main injection entrains and/or interacts with
  - The pilot injection can be a source of heat and intermediate species that act to enhance ignition of the main mixture
- What is different in a light-duty engine?
  - Multihole injector
  - Strong interactions between sprays and combustion chamber geometry
  - Turbulent in-cylinder flow field: swirl, squish-swirl, and jet-swirl interactions

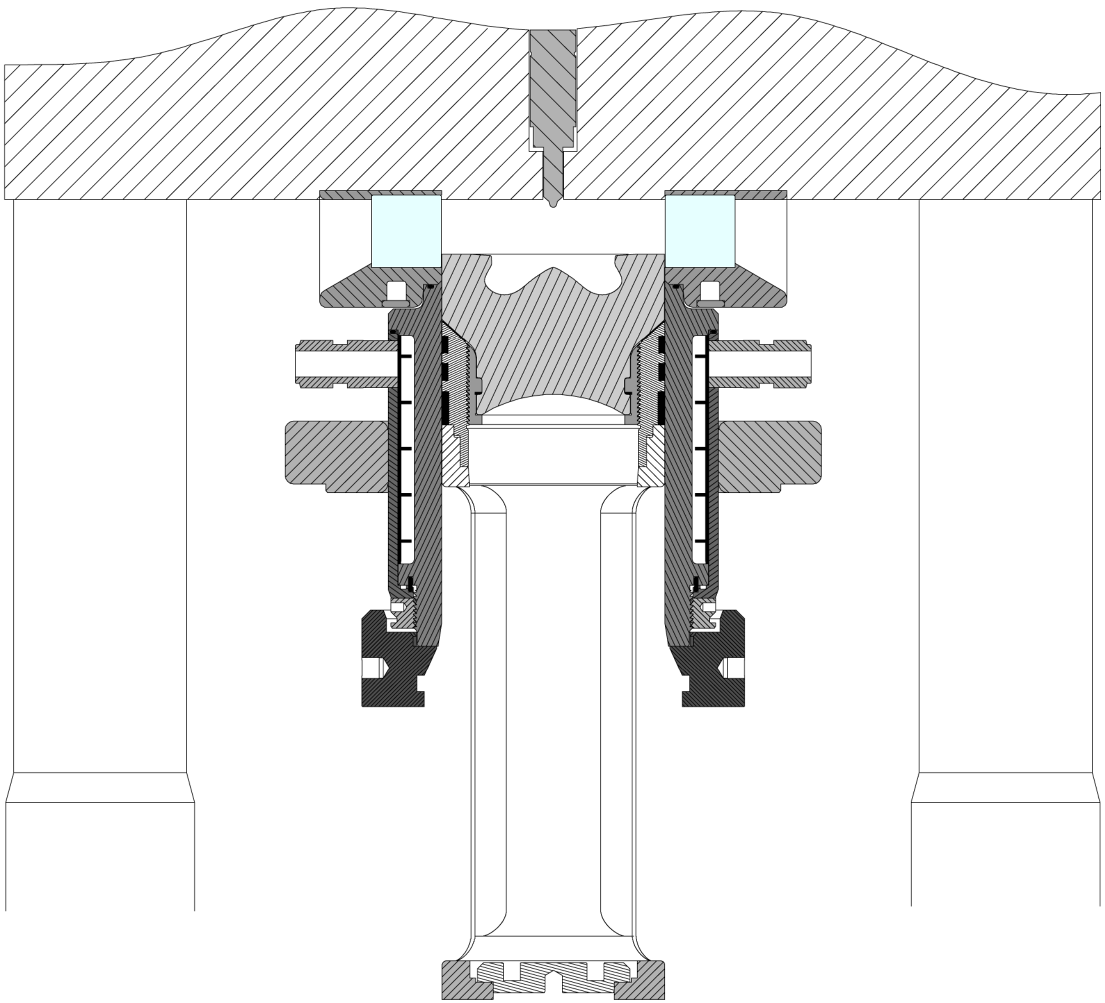
Experimental setup: engine configuration

Single-cylinder engine data

Bore x Stroke	82 mm x 90.4 mm
Compression ratio	16.7:1
Valves	4
Injector	Fast-acting solenoid valve
Holes x Ø	7 x 139 µm
ks	1.5 / 86
Included angle	149°

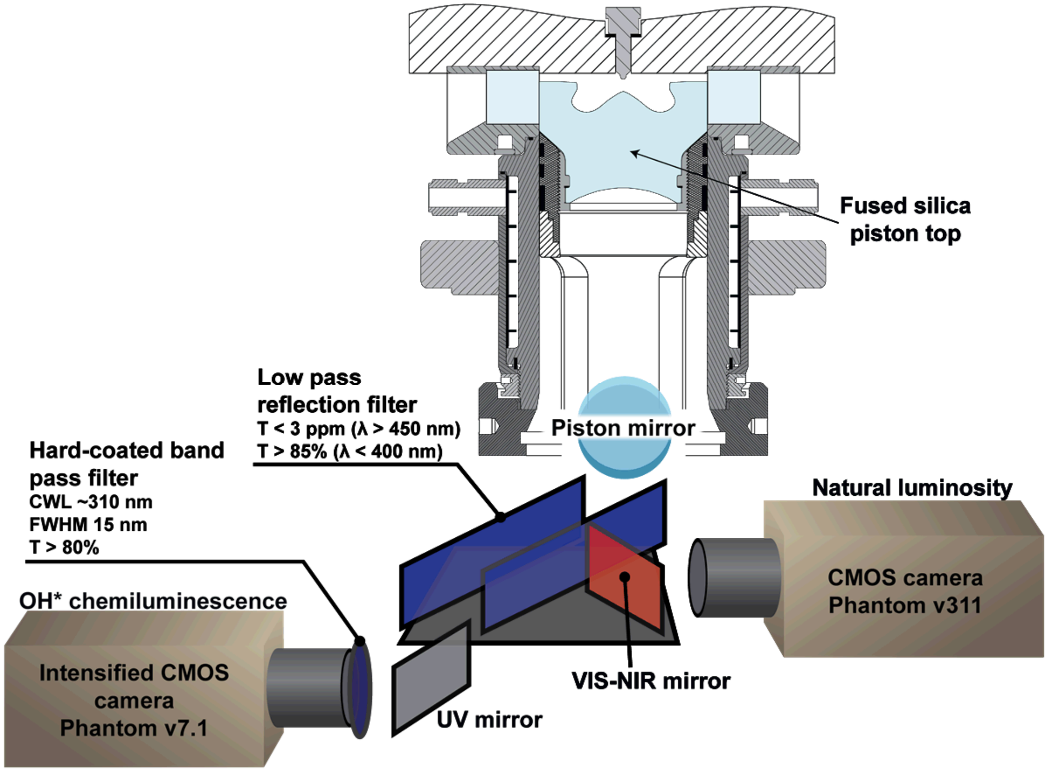
Bowl : bore ratio





Experimental setup: high speed NL and OH* chemiluminescence imaging

- Natural luminosity (NL)
  - Primarily broadband radiation from soot; very strong function of temperature
  - NL indicates rich, hot combustion
- OH* chemiluminescence
  - $CH + O_2 \rightarrow OH^* + CO$
  - Spectral peak near 308 nm
  - Information about high-temperature ignition processes and flame structure
- Simultaneous high-speed imaging: 25,000 kHz
  - 0.36 CAD resolution at 1500 rpm



Engine operation

- Part load, conventional combustion
  - Relatively long pilot-main dwell; slipstream effect not expected based on injection chamber results[1]
- Main injection duration adjusted to achieve desired load
- Skip-fired operation
- Images taken during the first five skip-fired cycles of four different runs
  - Reduce impact of piston sooting
  - 20 cycles of time-resolved images

	Main Only	Pilot - Main
Eng. speed	1500 rpm	
$IMEP_g$	9.0 bar	
Rail pressure	800 bar	
m_{pilot}	-	1.5 mg/str
m_{pilot} / m_{main}	0	~6%
Dwell	-	1200 μs
P_{intake}	150 kPa abs	
T_{intake}	353 K	
T_{TDC}	925 K (estimated)	
TDC density	~21.8 kg/m^3	
EGR	~7% (10.3% accounting for residual fraction)	
$[O_2]_{intake}$	19.73%	
MFB50	~13 CAD ATDC	
Fuel	DPRF58 (CN 50.7) 58 vol% Heptamethylnonane 42 vol% n-Hexadecane	

[1] Bruneaux, G. and Maligne, D., "Study of the Mixing and Combustion Processes of Consecutive Short Double Diesel Injections," *SAE Int. J. Engines* 2(1):1151-1169, 2009, doi:10.4271/2009-01-1352.

Image distortion correction

- Image distortion arises from the complex piston geometry
  - Depends on crank angle, varies with radial and axial object position
- A ray-tracing based algorithm is used to distortion correct both the NL and the OH* images
  - Algorithm requires *a priori* knowledge of signal origins
- Assumed signal origins:
  - Along jet axes in the bowl
  - Halfway between head and fire deck in squish region

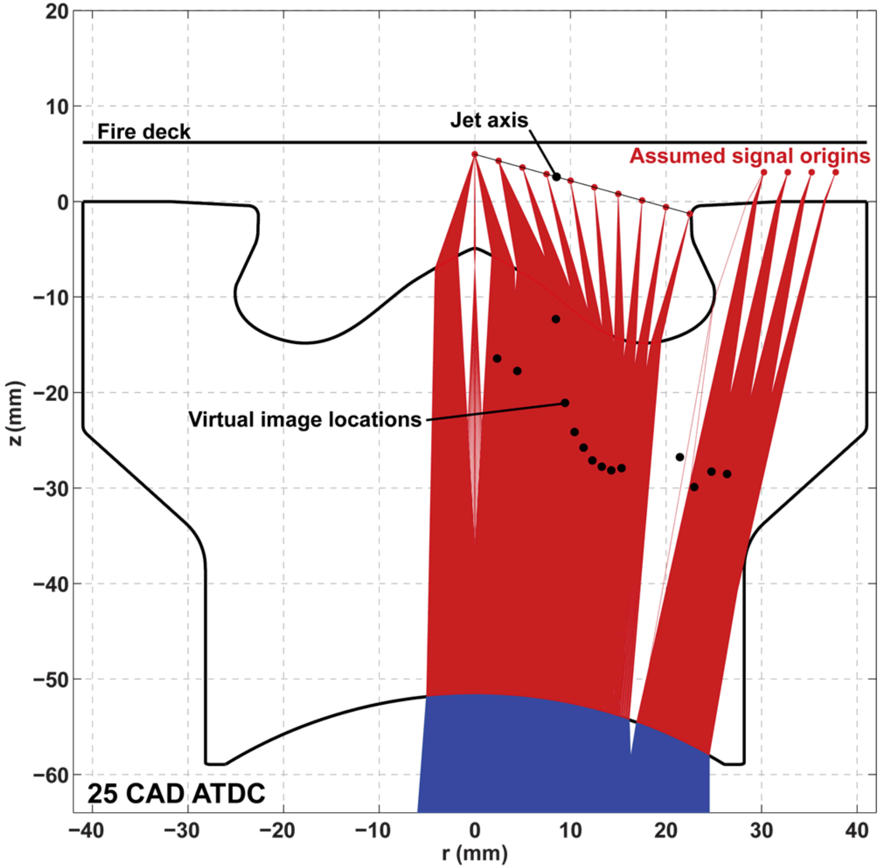
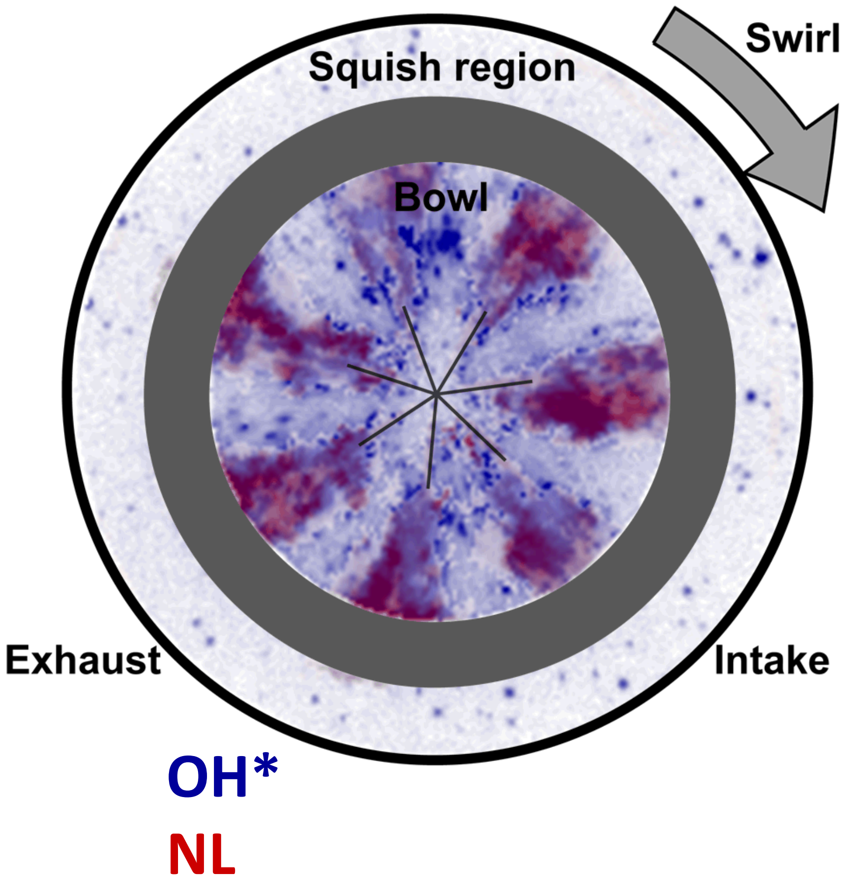


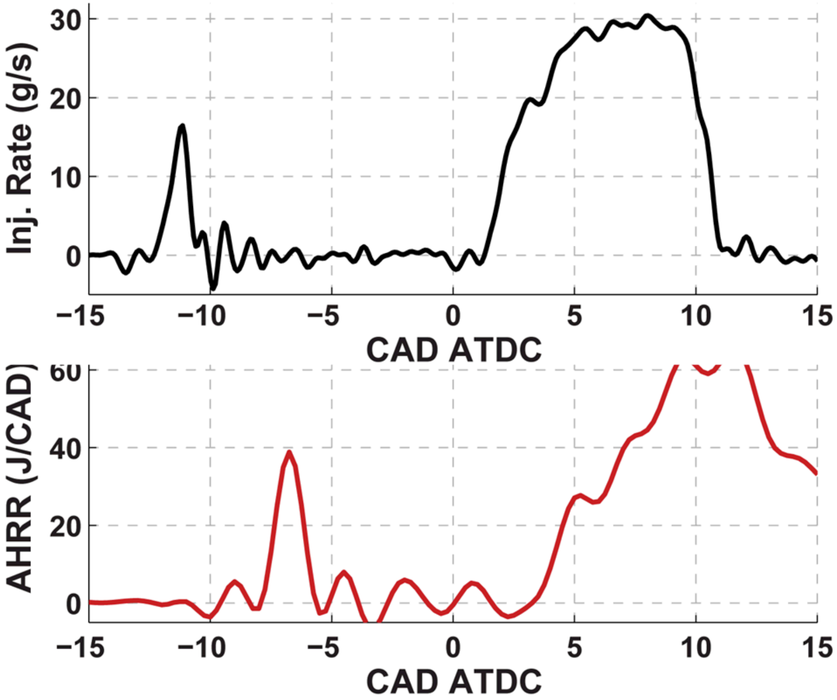
Image registration: OH* and NL Images

- OH* image: intensity scaled to emphasize location of detected OH* signal; shown with blue false-color
- NL image: scaled to increase visibility of lower intensity range; shown with red false-color
- OH* image serves as background; NL image is overlaid with 50% transparency
- Image intensities are not a quantitative measure of concentration or temperature
  - These images tell us when and where high-temperature and/or sooting combustion is taking place



Results: summary of fuel injection and AHRR

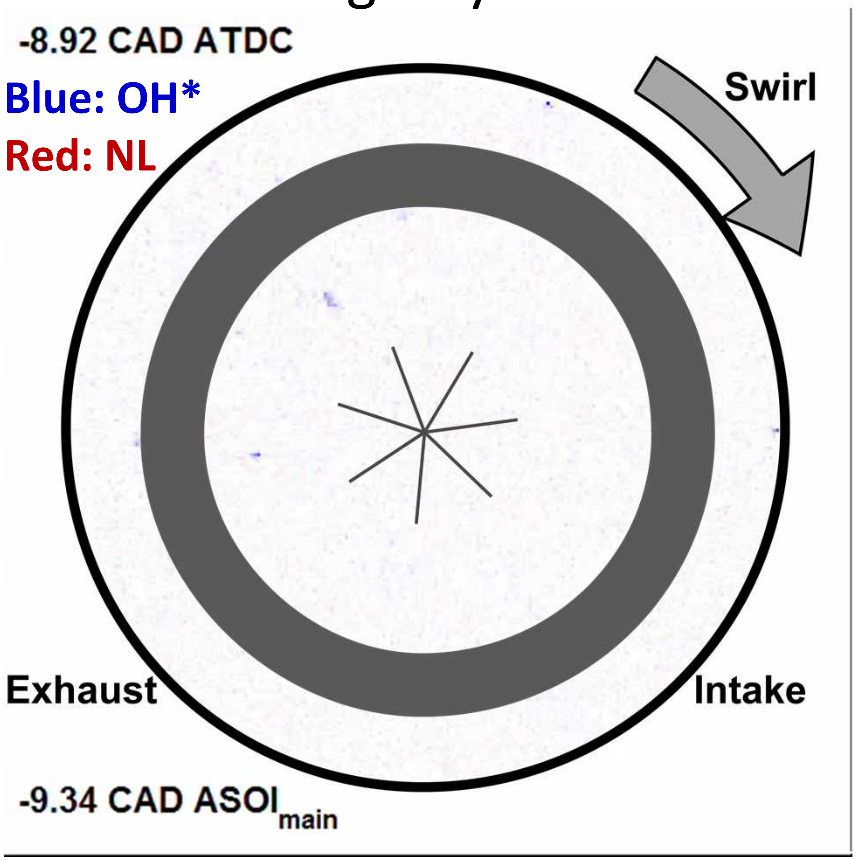
- Fuel injection
  - Pilot injection starts near 12 CAD BTDC, ends near 10 CAD BTDC
  - Main injection starts just after 1.25 CAD ATDC
- AHRR
  - High temperature pilot heat release starts near 8 CAD BTDC, finishes before 5 CAD BTDC
  - Main heat release starts at approximately 3 CAD ATDC
    - During initial ramp-up of main injection



Pilot combustion overview

- Pilot combustion is contained within the bowl
  - Combustion occurs close (< 10 mm) to the injector
- Initial reactions take place without NL emissions
  - Suggests that pilot fuel is well-mixed ($\phi < 2$)
- NL appears starting at maximum $AHRR_{pilot}$ (~6.8 CAD BTDC)
  - NL signal does not penetrate far into the cylinder
- Regions of OH* and NL persist after the end of pilot heat release and are visible at SOI_{main}

Single cycle

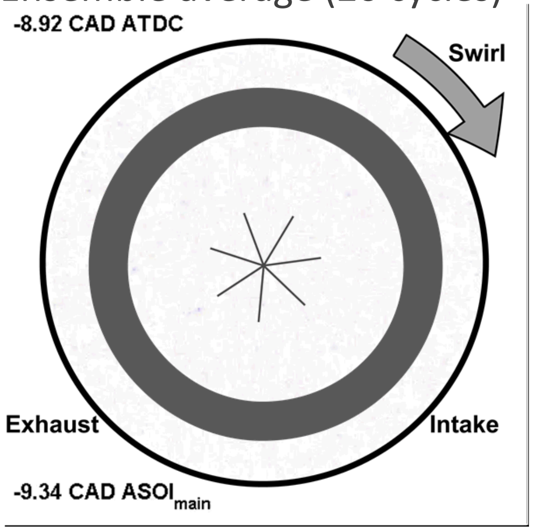


Rich, sooty portions of the pilot combustion are attributed to dribbled fuel

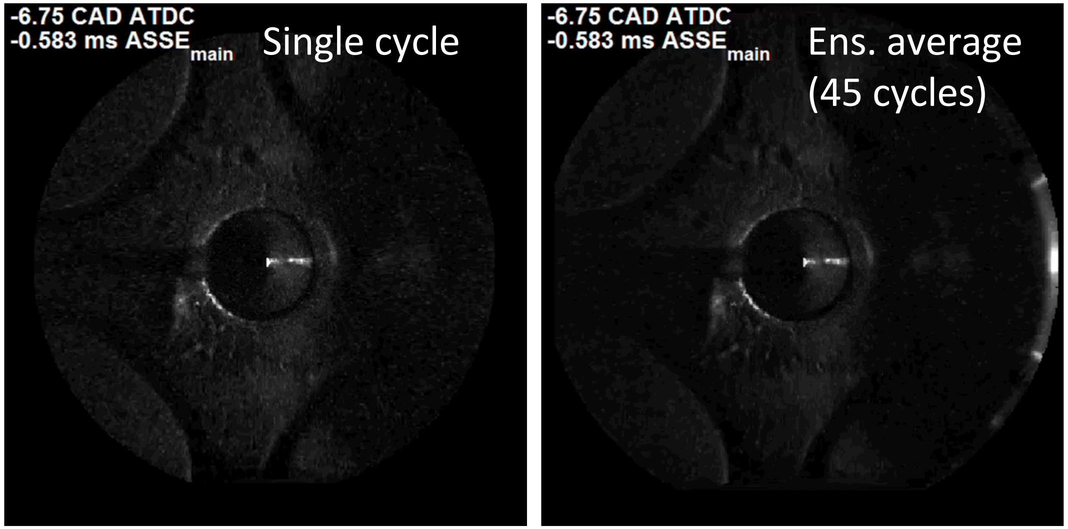
- Combined OH*-NL imaging (fired operation)
  - Similar NL behavior is observed in every cycle
  - Uneven distribution; NL first visible near peak of pilot HR

Blue: OH*
Red: NL

Ensemble average (20 cycles)



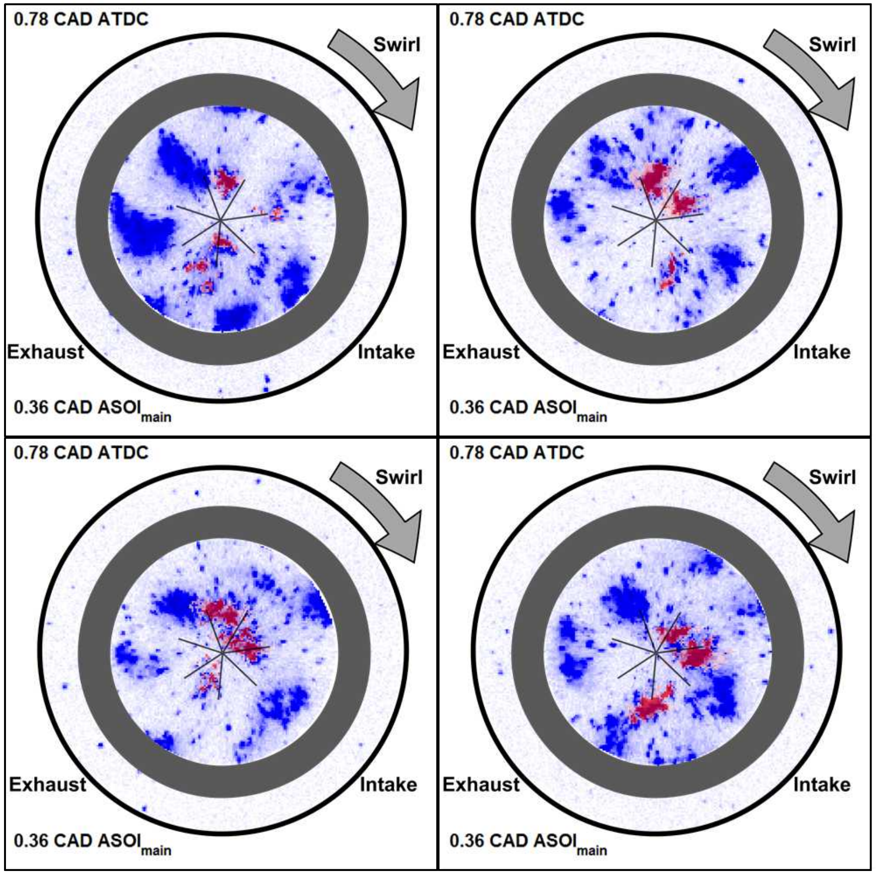
- Liquid fuel imaging (motored operation)
  - End of injection and dribble behavior are highly repeatable
  - There appears to be some correlation between jets with persistent liquid fuel and the appearance of NL during pilot combustion



What is the state of the cylinder contents at SOI_{main}?

- Pilot heat release event has finished, but both OH* and NL signals are observed
- Some mixing has taken place:
  - Transport by swirling flow
  - Turbulent diffusion
- Active radicals and combustion products are unevenly distributed
- Temperature field is likely inhomogeneous
- How does the main mixture ignite in this environment?

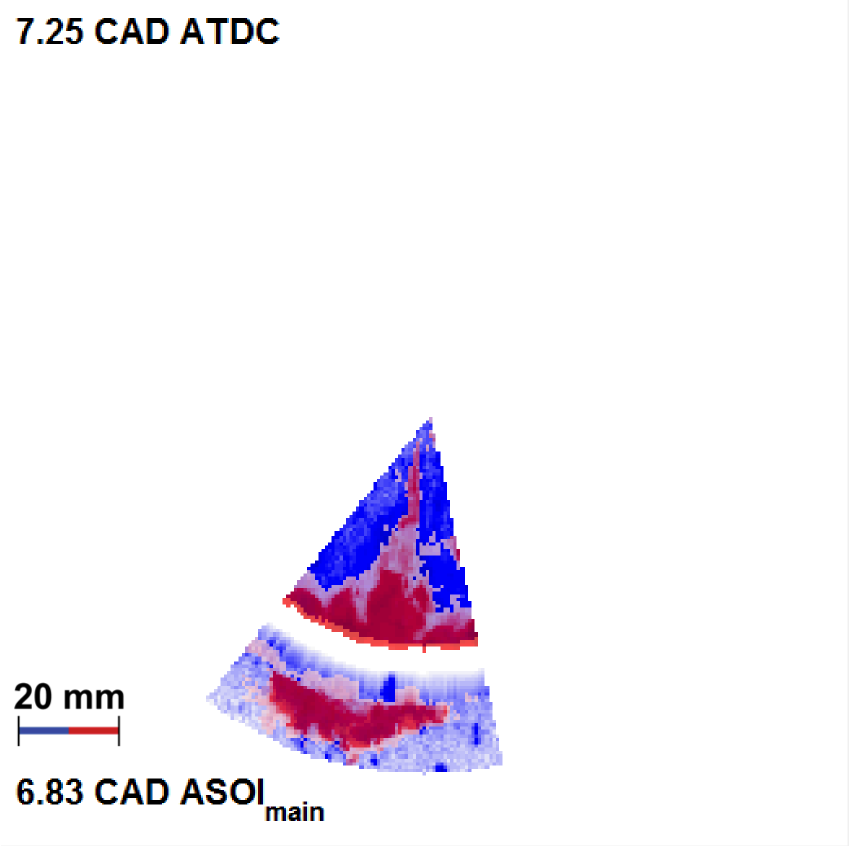
Images taken at SOI_{main}



Blue: OH*; Red: NL

Main ignition process for a single jet (1)

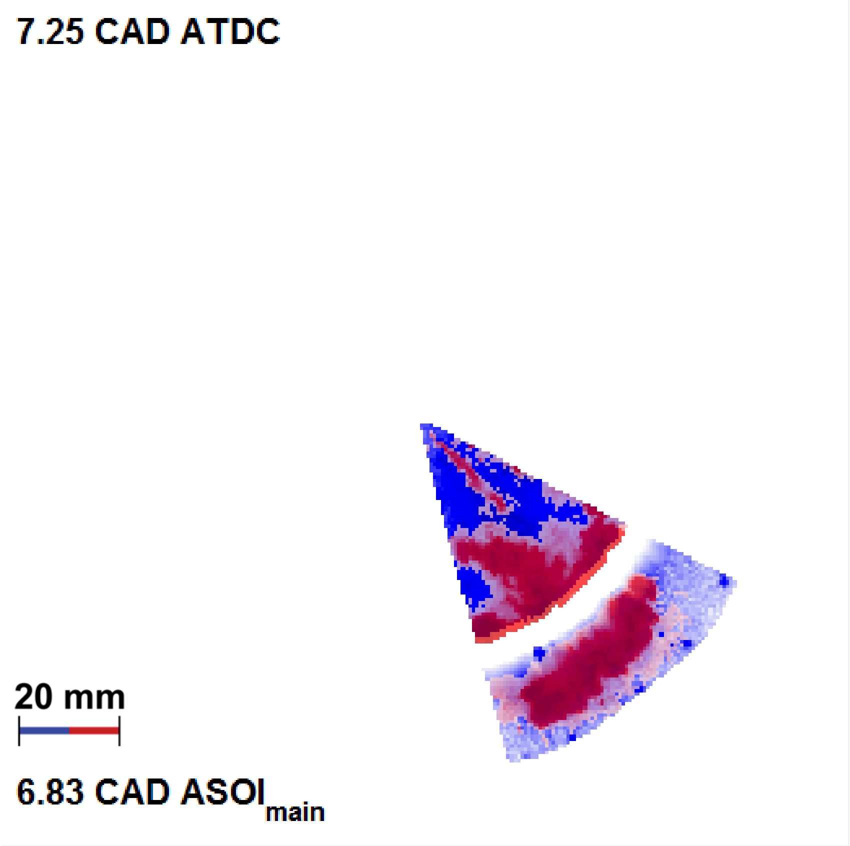
- SOImain: reactive pilot mixture deep in bowl, near injector tip
- OH* signaling the start of high temperature heat release first appears in multiple locations
- Ignition locations may be influenced by reactive pilot mixture (deep in bowl) or dribbled fuel (right side)
- Soot appears in head of jet as the jet takes on its familiar structure



Blue: OH*; Red: NL

Main ignition process for a single jet (2)

- SOI_{main}: NL and OH* near injector – rich combustion of dribbled fuel
- First OH* attributed to main mixture appears immediately downstream of dribbled fuel combustion, signal progresses downstream
- Soot is found throughout the jet in the early stage of ignition
  - Similar findings in [1]
  - Region of sooty combustion shifts downstream
- Jet structure develops; head of jet tangentially displaced by swirl

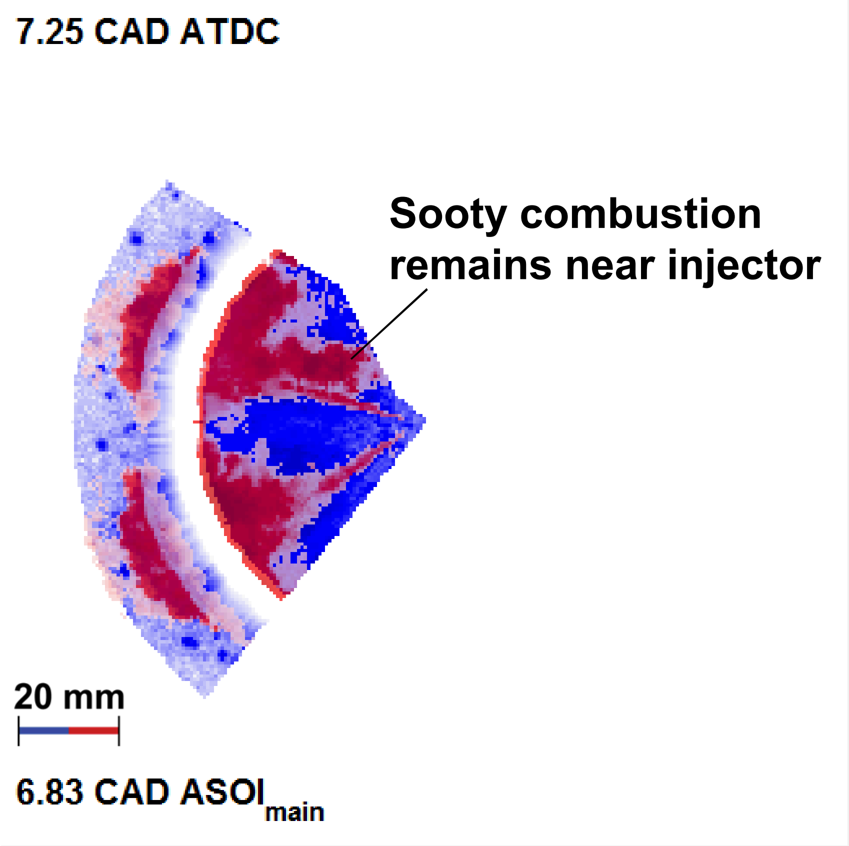


Blue: OH*; Red: NL

[1] Bruneaux, G. and Maligne, D., "Study of the Mixing and Combustion Processes of Consecutive Short Double Diesel Injections," *SAE Int. J. Engines* 2(1):1151-1169, 2009, doi:10.4271/2009-01-1352.

Main ignition process for a single jet (3)

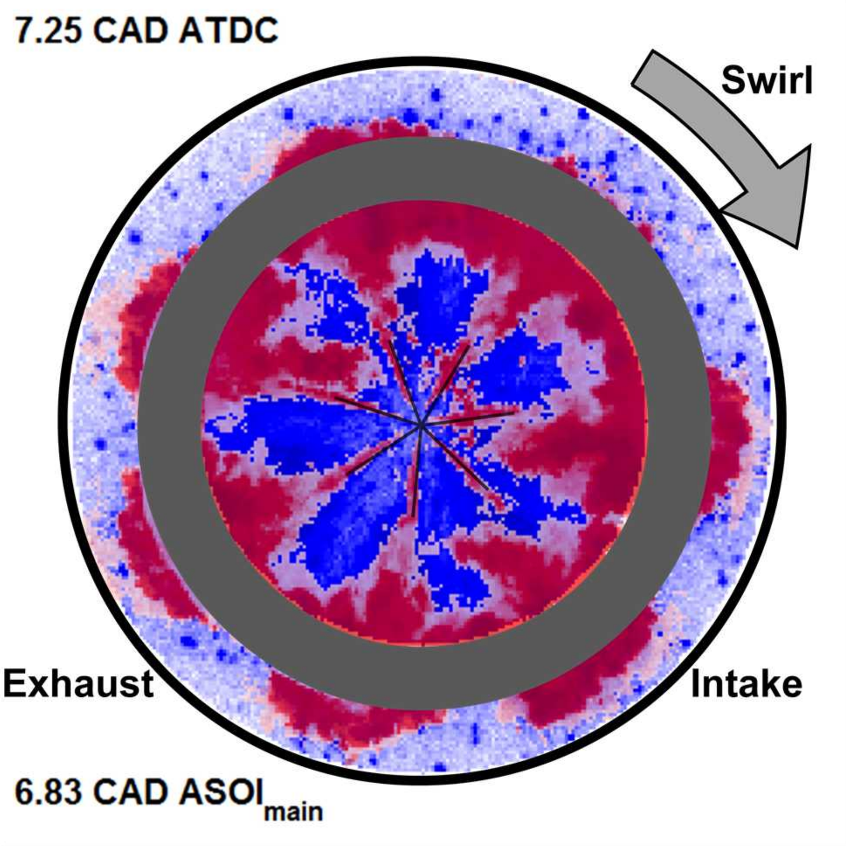
- SOI_{main}: reacting pilot mixture from jet of interest and from its neighboring jet
- Initial high temperature reactions take place several millimeters from the injector tip
  - NL is observed very near the injector tip shortly thereafter
- Isolated region of sooty combustion appears in jet head
  - Evidence of local ignition by interaction with the neighboring jet
- High temperature reactions quickly appear in remainder of jet
- Rich, sooty combustion remains near the injector



Blue: OH*; Red: NL

Main ignition process with a single pilot injection

- The processes shown in the last three slides happen within one and the same cycle
- The main ignition process varies from jet-to-jet and cycle-to-cycle
- High temperature main ignition:
  - May begin at one or multiple locations within a jet
  - Influenced locally by pockets of reacting pilot/dribbled fuel
  - Can be influenced by reacting pilot mixture from the "up-swirl neighbor"
- Soot may initially form very near the injector
  - The location of initial soot formation may move downstream as the jet structure develops



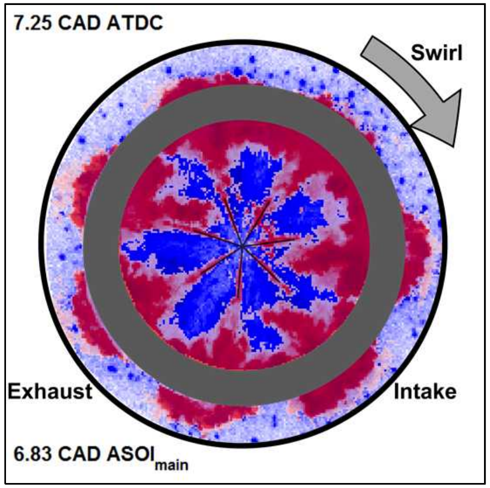
Blue: OH*; Red: NL

Spray flame structure

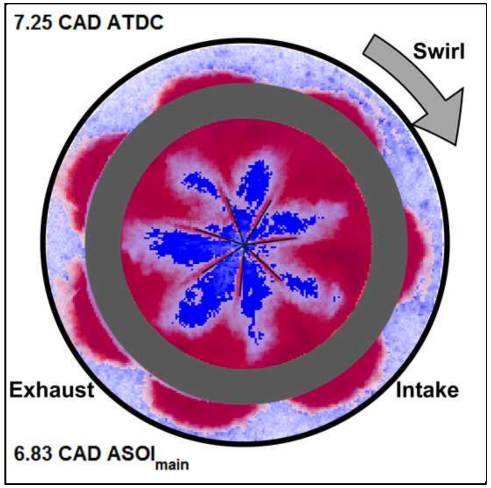
- Swirl displaces the jet structure tangentially
  - The amount of tangential displacement is different for each jet
- Trends in overall jet structure are generally repeatable from cycle-to-cycle
- Possible causes of jet-to-jet variability
  - Injector nozzle geometry (effect on jet spreading angle, air entrainment)
  - In-cylinder flow asymmetry

Blue: OH*
Red: NL

Single cycle

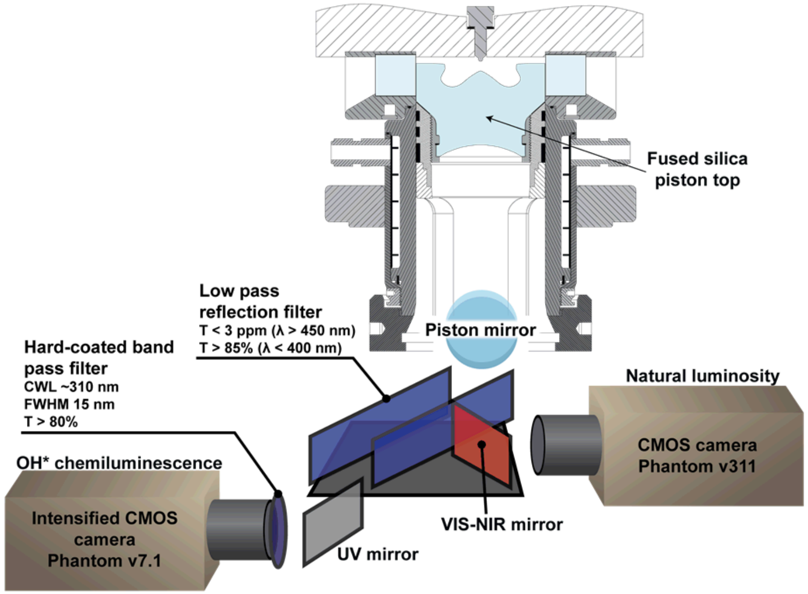


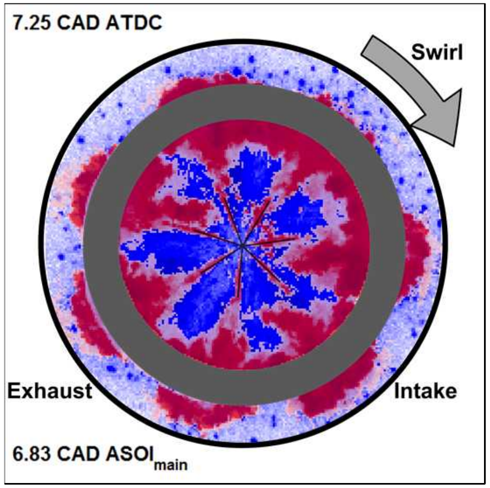
Ensemble average (20 cyc.)



Summary

- Simultaneous high-speed OH* chemiluminescence and NL imaging
  - Combined with advanced image processing techniques
  - Provides temporally and spatially resolved information about ignition processes and flame structure evolution
- Study of main mixture ignition processes with a pilot injection in a light-duty optical diesel engine
- Measurement results provide insight into complex main mixture ignition processes
  - Data will be used to evaluate CFD simulation capabilities and drive advanced modeling efforts





Conclusions

- Pilot combustion
  - Confined to the piston bowl
  - Flames associated with high temperature heat release are lean enough to avoid soot formation, but sooty combustion appears to be linked to end of injection / dribble behavior
  - Pockets of reactive pilot mixture and/or soot persist until after SOI_{main}
- Main ignition process
  - High temperature reactions can be initiated in multiple locations within a jet
  - Reacting pilot mixture from an individual jet or from its neighbor may act as local ignition sources
  - Ignition processes vary from jet-to-jet and cycle-to-cycle, but the jet structure, once established, appears to be generally repeatable from cycle-to-cycle

Future work

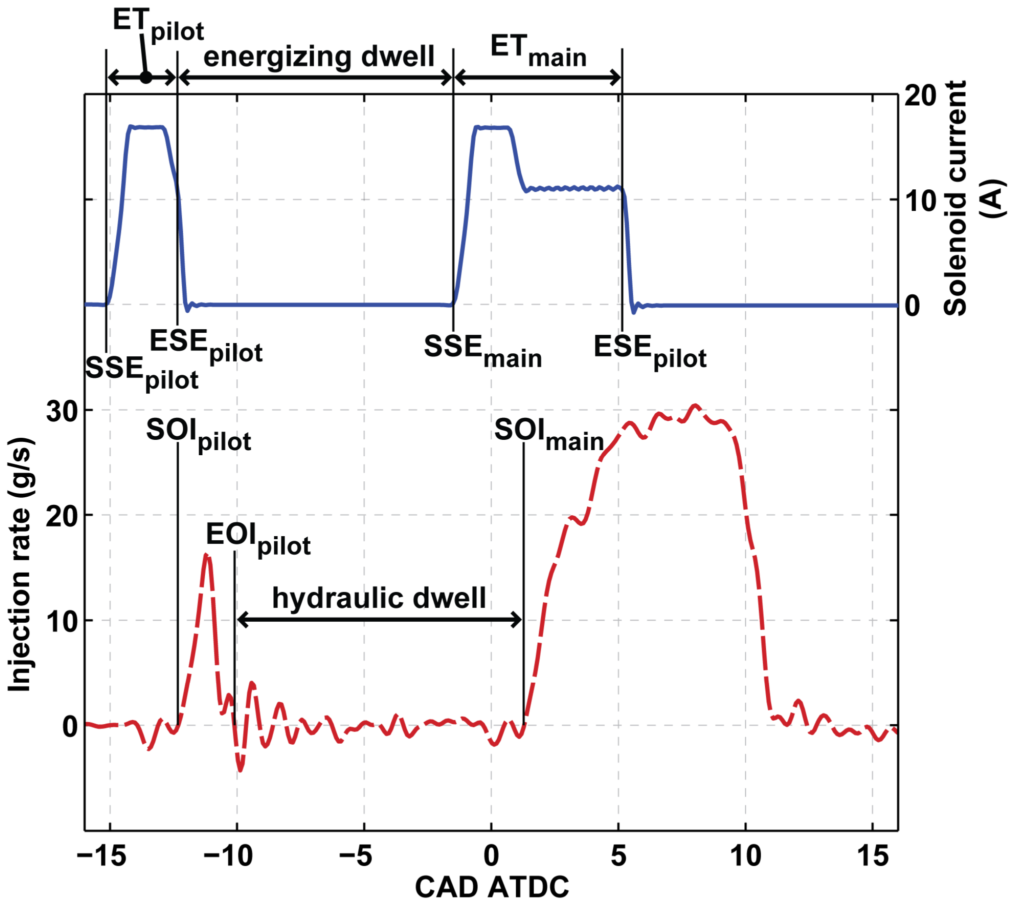
- Next steps
  - Effect of pilot-main dwell on main ignition processes
  - Evaluation of CFD simulation capabilities to model ignition processes; identify needs for further optical research if needed
  - Interactions between pilot injection and in-cylinder flow structures
  - Influence of pilot-main dwell on soot emissions
- Open questions
  - What role do cool-flame reactions play when reactive pilot mixture influences the main ignition process?
  - How does pilot quantity impact the main mixture ignition process?
  - How can nozzle geometry affect the pilot combustion and main mixture ignition processes?
  - Influence of other operating parameters (injection pressure, swirl ratio, engine speed, etc.)

THANK YOU FOR YOUR ATTENTION!

Questions?

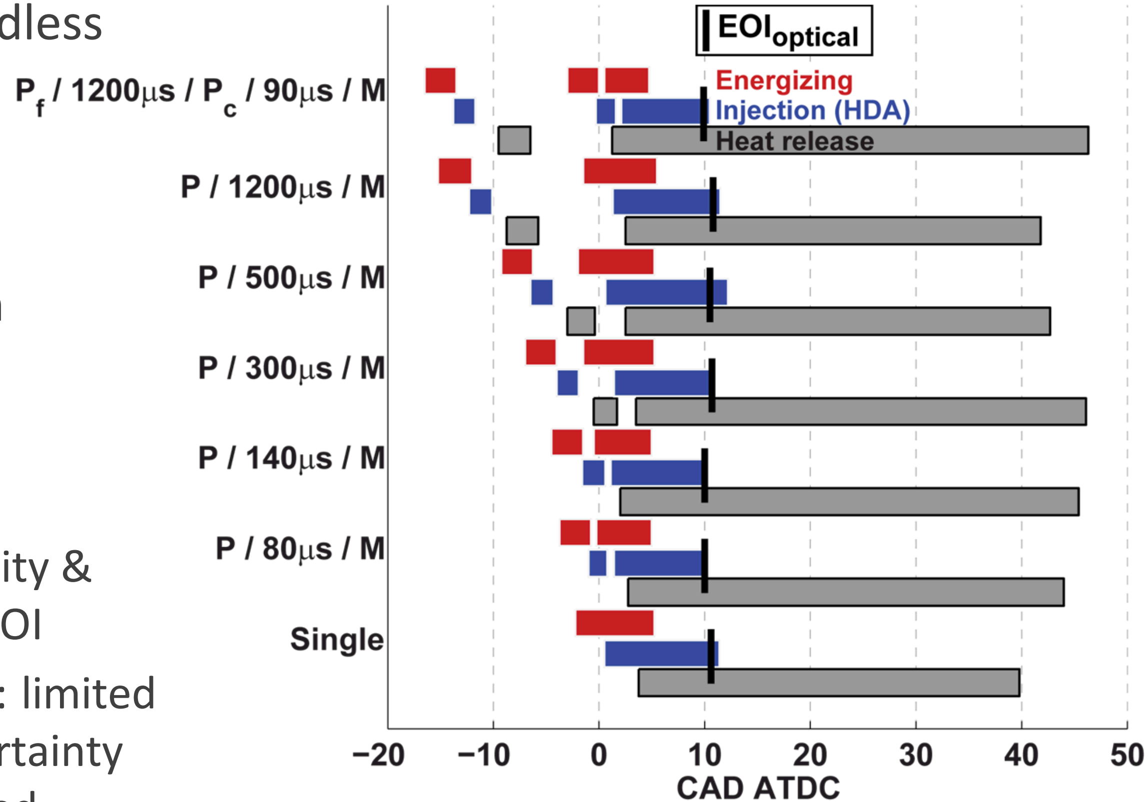
Definition of terms: solenoid energizing and fuel injection

- 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



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