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COMBUSTION RESEARCH FACILITY

A Conceptual Model for Low-Temperature Diesel Combustion

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Sponsor: **U.S. DOE Office of Vehicle Technologies**
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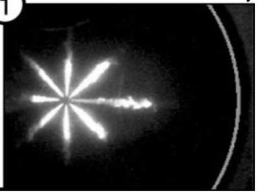
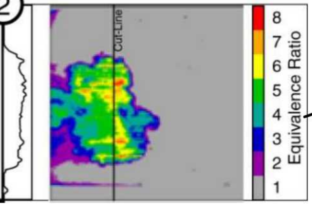
Dec's conventional diesel conceptual model describes short-ID mixing & combustion

O_2 = 21% (no EGR)
SOI = 10 BTDC
P_{inj} = 1000 Bar

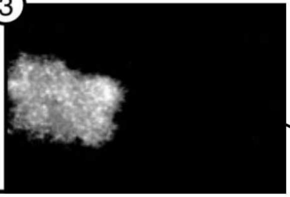
1 Mie Scatter: Liquid Fuel
After penetrating approx. 25 mm, the hot, entrained gases completely vaporize the liquid fuel.



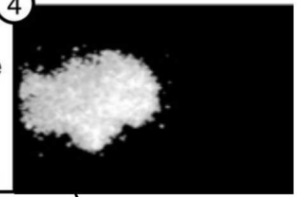
2 Rayleigh Scatter: Vapor Fuel
The vaporized fuel-air mixture downstream of the liquid is relatively uniform and fuel-rich (Φ = 2-4).



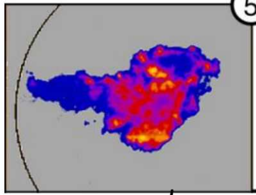
3 Chemiluminescence: Ignition
Spontaneous ignition reactions occur in the hot mixture of fuel and air throughout the leading portions of the jet.



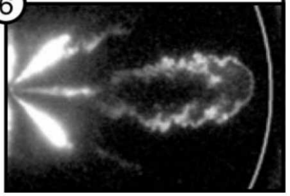
4 PAH PLIF: Soot Precursors
As hot ignition reactions increase the temperature in the jet, fuel fragments are formed into chemical building blocks for soot.



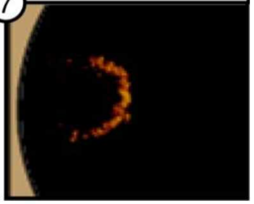
5 LII: Soot Concentration
Shortly after the premixed fuel burns, soot is formed in the hot, fuel-rich region throughout the jet cross-section.

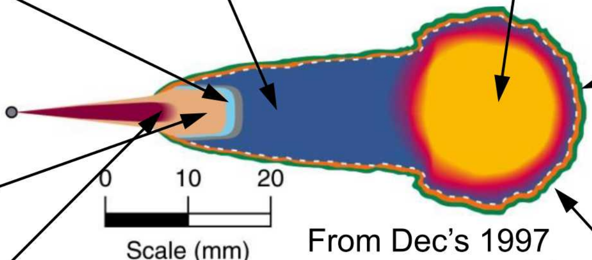


6 OH PLIF: Diffusion Flame
Shortly after the premixed fuel burns, a thin diffusion flame forms on the jet periphery, surrounding the interior soot cloud.

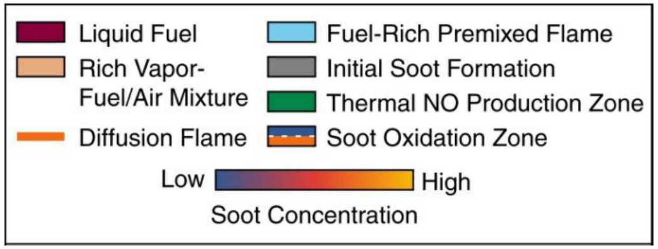


7 NO PLIF: Thermal NO
NO forms on the periphery of the jet in the hot diffusion-flame products.



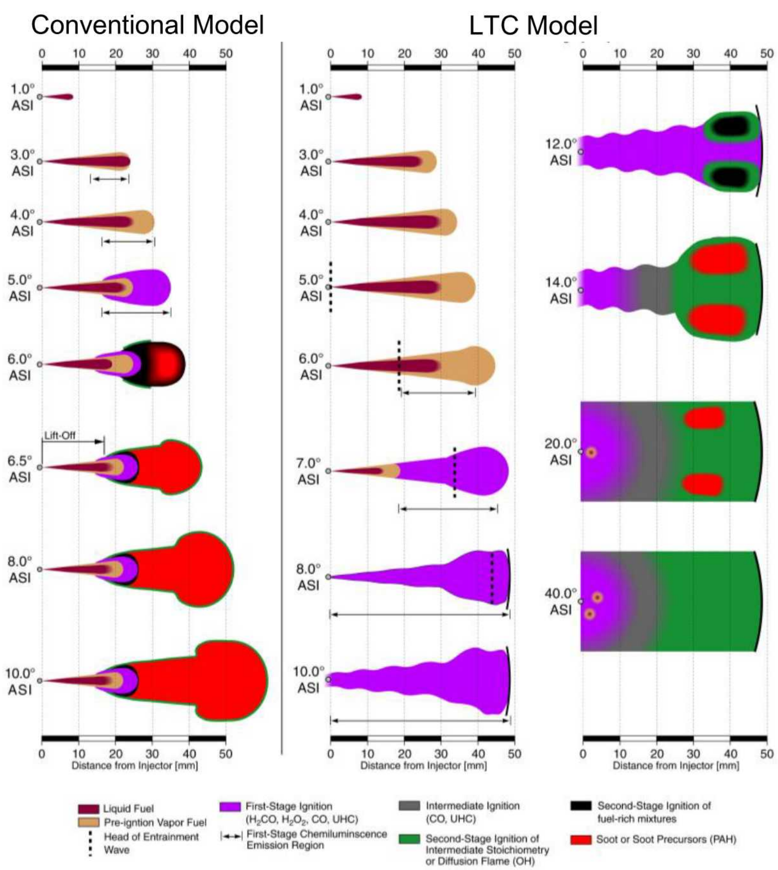


From Dec's 1997 conceptual model (SAE 970873).



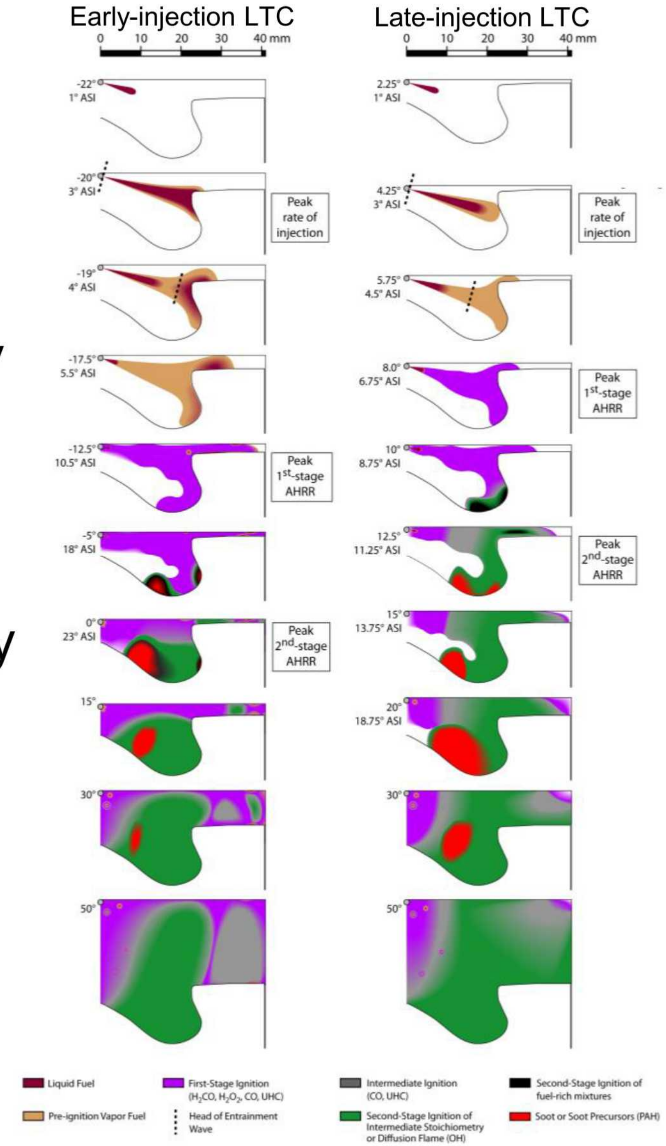
LTC conceptual model describes long-ID mixing & combustion for both heavy- and light-duty

- Team effort with Lyle Pickett and Paul Miles
- Conceptual models for partially premixed low-temperature diesel combustion," M.P.B. Musculus, P.C. Miles, and L.M. Pickett, Progress in Energy & Combustion Science 39(2):246-283, 2013



light-duty →

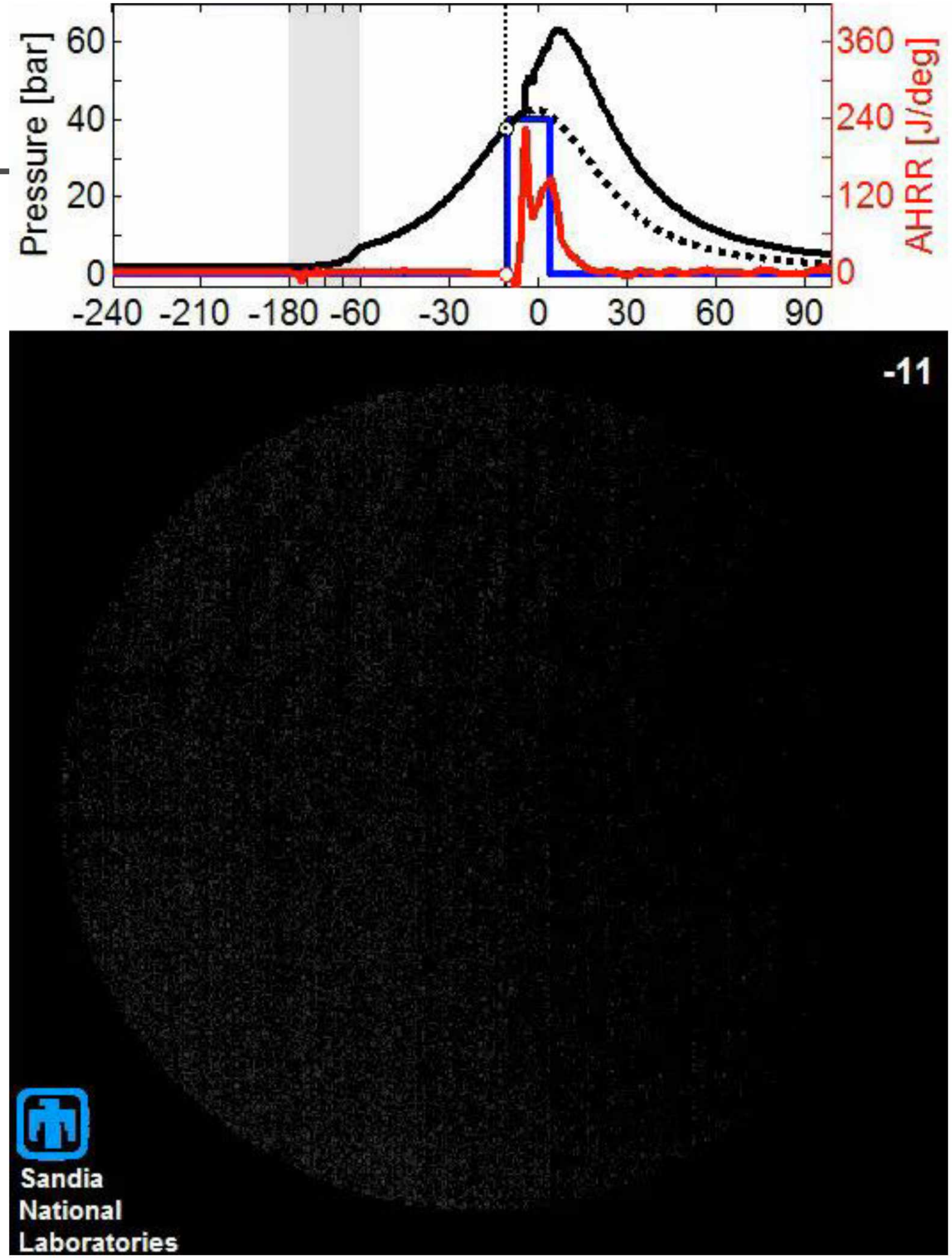
heavy-duty ←



Conventional Diesel Combustion

- n-Heptane fuel, so spray is short
- Low camera gain – bright soot
- Late soot at center: injector dribble

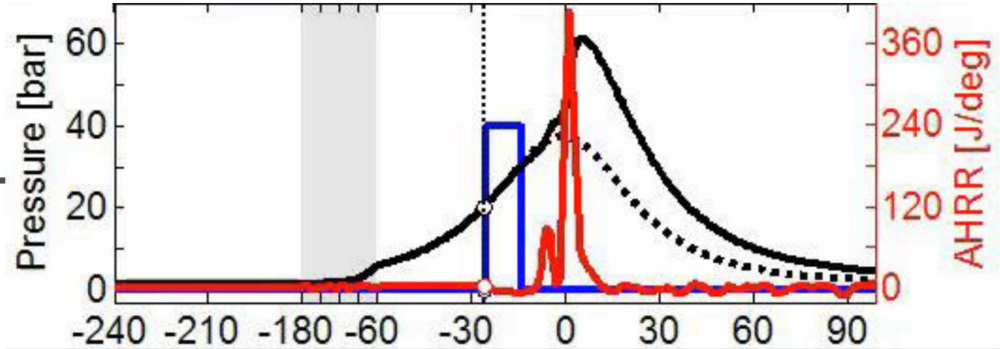
Fuel	n-heptane
Intake	21% O_2
Load	4.6 bar IMEP
Intake T	153 C
Intake P	1.80 bar
CR SOI	10º BTDC
Speed	1200 rpm
Engine r_C	10.75
Window	100 mm diam
Framing	7200 fps
Gain	1
Filter	500 nm SWP

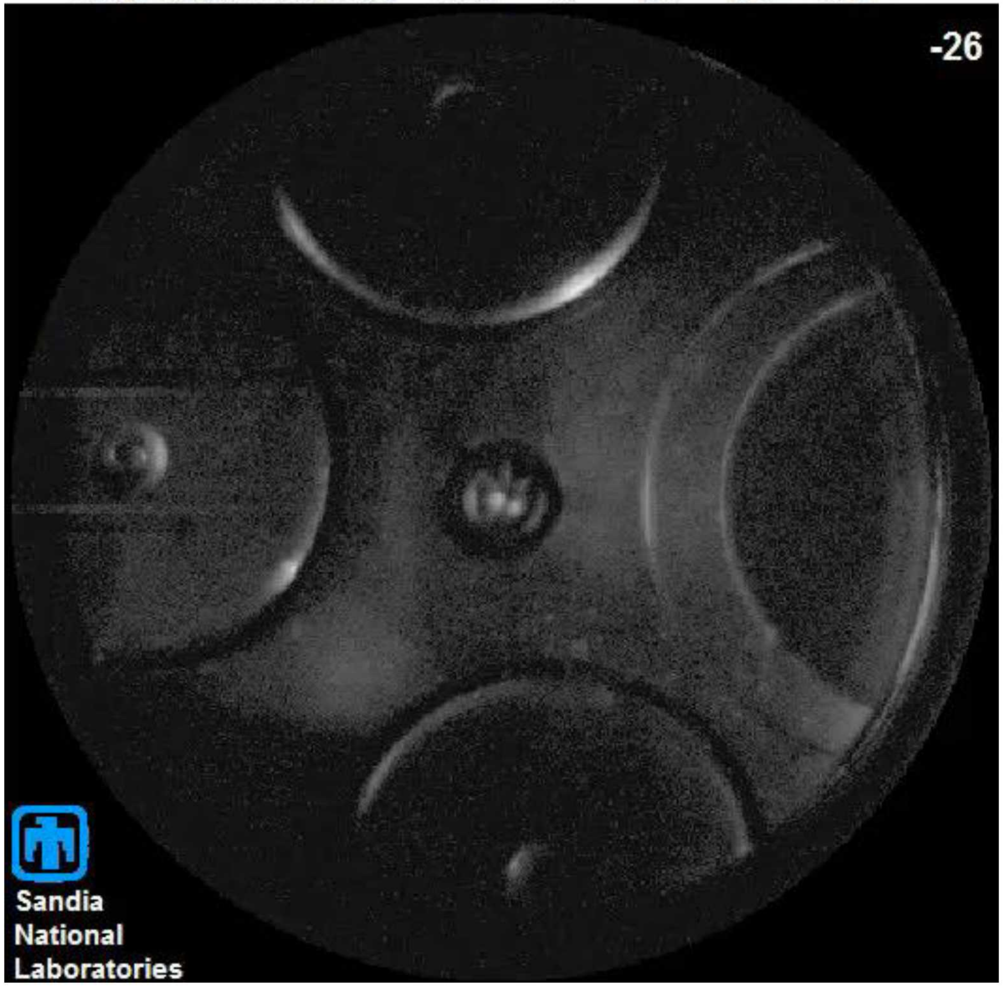


LTC: Early-Injection PCCI

- n-Heptane fuel, so spray is short
- High gain: very little soot, cool flame
- No combustion at center: UHCs

Fuel	n-heptane
Intake	~~21%~~ **13%** O_2 (EGR)
Load	4.5 bar IMEP
Intake T	~~153 C~~ **30 C**
Intake P	~~1.8~~ **1.5** bar
SOI	~~10º~~ **25º** BTDC
Speed	1200 rpm
Engine r_C	10.75
Window	100 mm diam
Framing	7200 fps
Gain	~~1~~ **500**
Filter	500 nm SWP

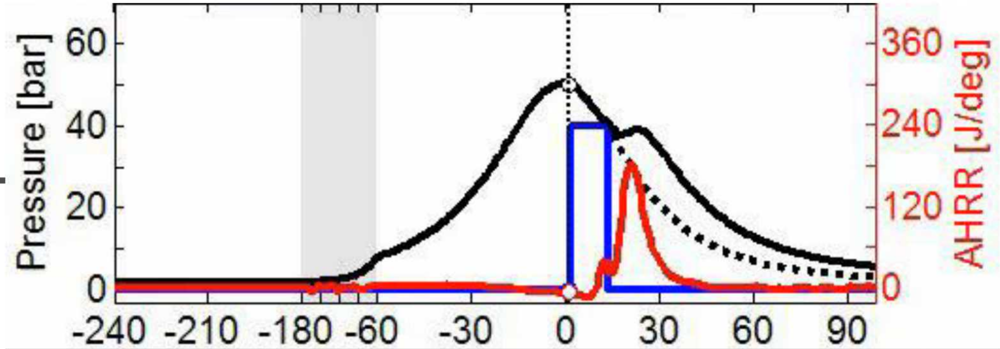




LTC: Late-Injection PCCI (MK)

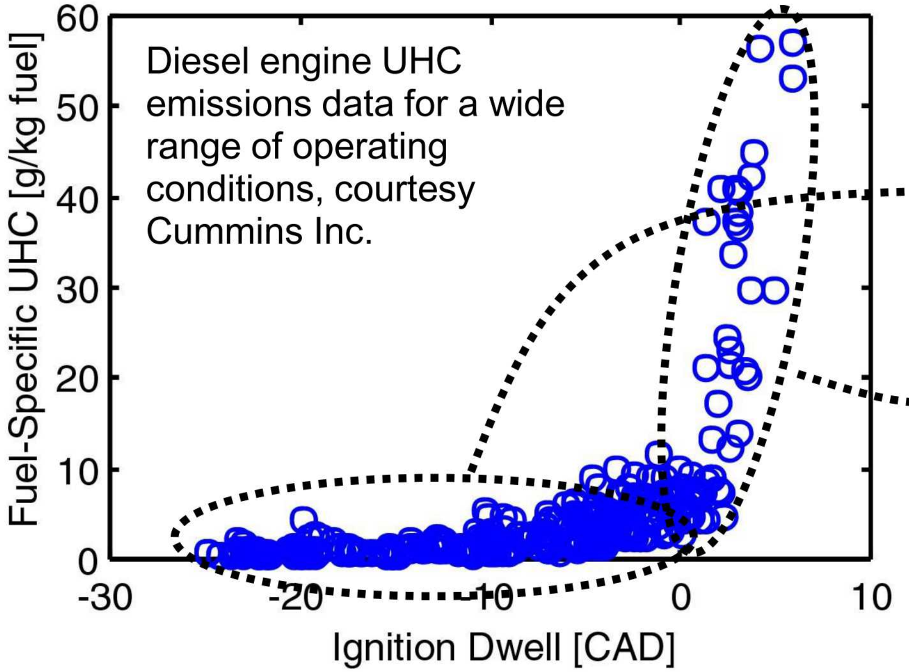
- Near-TDC inj.: shorter spray & ID
- High gain: very little soot, cool flame
- No combustion at center: UHCs

Fuel	n-heptane
Intake	~~21%~~ **13%** O_2 (EGR)
Load	4 bar IMEP
Intake T	~~153 C~~ ~~30 C~~ **50 C**
Intake P	~~1.8~~ ~~1.5~~ **2.0** bar
SOI	~~-10º~~ ~~-25º~~ **3º ATDC**
Speed	1200 rpm
Engine r_C	10.75
Window	100 mm diam
Framing	7200 fps
Gain	~~1~~ **500**
Filter	500 nm SWP



LTC: Increased premixing and high EGR reduced PM & NOx, but other problems arose, including UHC

- Many potential sources may contribute to UHC emissions (wall wetting, crevices, etc.)
- Some UHC emissions increase rapidly when ignition occurs after end of injection



"Ignition Dwell" ≡ Time from end of injection to start of combustion

↳ **Most conventional diesel combustion conditions have negative ignition dwell and low UHC emissions**

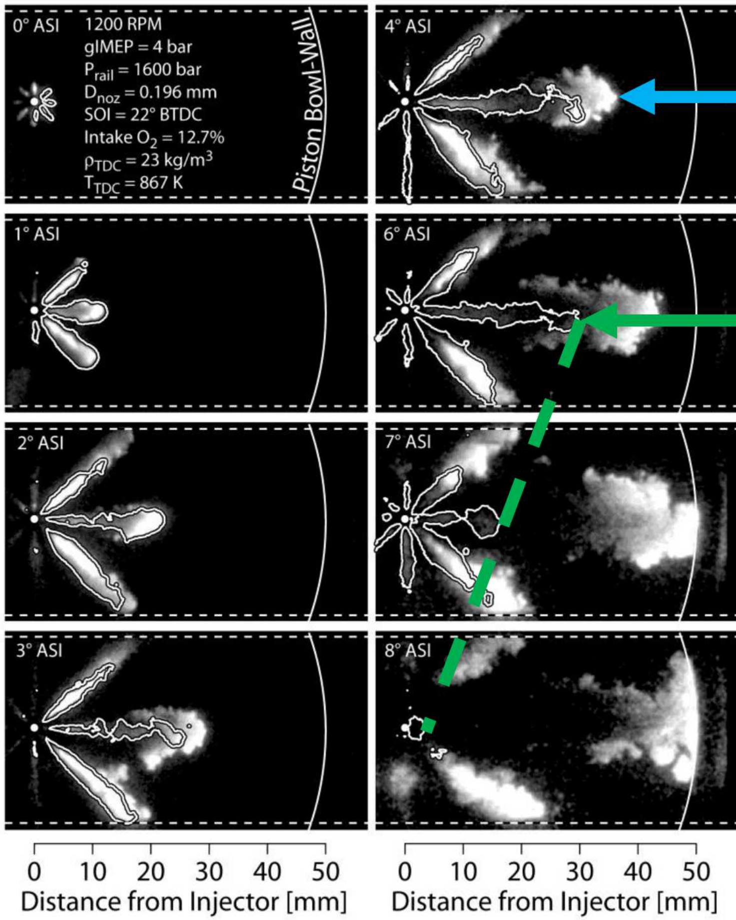
↳ Many LTC (PPCI, HCCI, MK, etc.) and some low-load diesel conditions have positive ignition dwell, and high UHC emissions

"Hockey Stick": When ignition is delayed just a few crank angle degrees (<1 ms) after the end of injection, UHC emissions increase by an order of magnitude.

What is causing <u>this source</u> of UHC emissions?

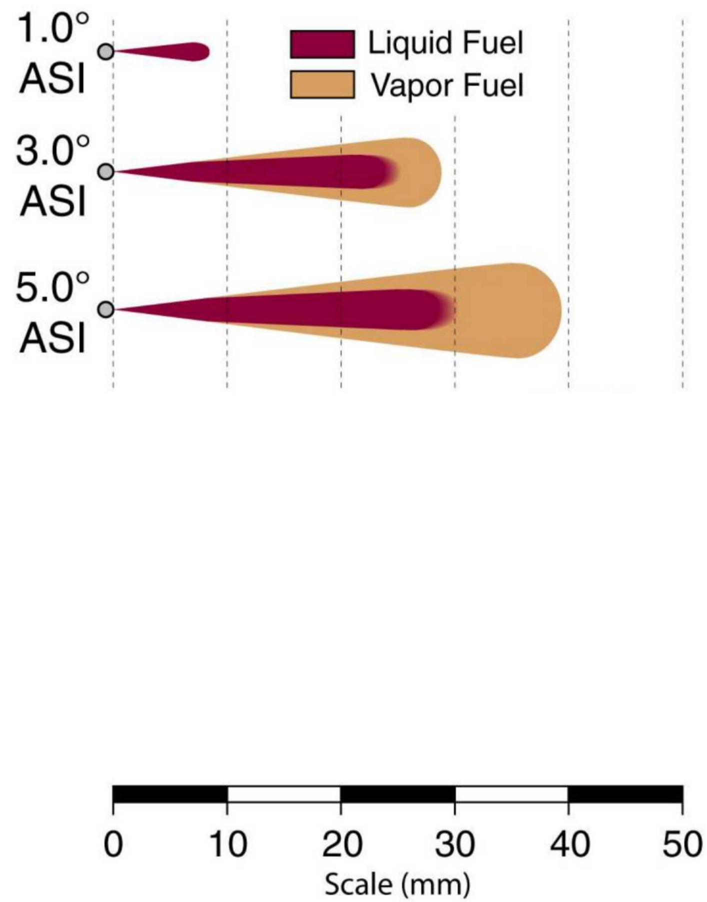
LTC spray penetrates more quickly + longer liquid; liquid recedes after EOI, but before SOC

- Injection into lower density: faster spray penetration, longer liquid length
- Liquid recedes at/after EOI, but before SOC (not vaporized by combust.)
  - If vaporization is still mixing-limited, implies **increased mixing after EOI**

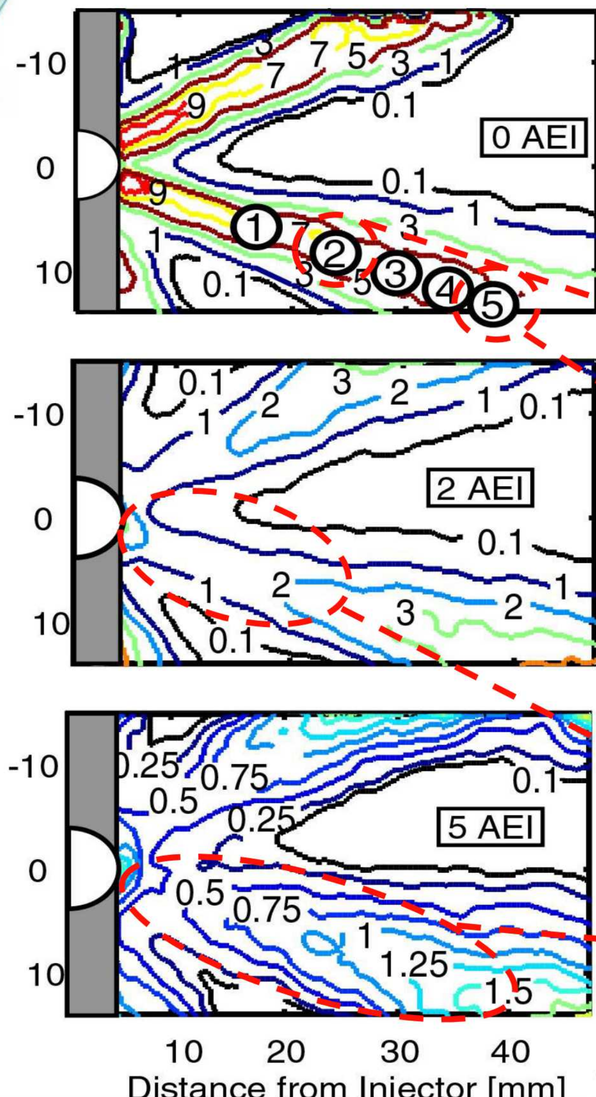


Grayscale: Leading edge of vapor fuel

Contours: Outline of liquid fuel



Fuel-tracer fluorescence shows near-injector mixtures rapidly become fuel-lean after EOI



- At end of injection (0 AEI), mixtures are richer near injector (ϕ ~ 9) and leaner downstream
- In the quasi-steady jet, from a Lagrangian perspective (moving with jet fluid at penetration rate):
  - After 2º crank angle, 25 mm penetration to ϕ = 5 to 7
  - After 5º crank angle, 45 mm penetration to ϕ = 3 to 5
- After end of injection, mixtures near injector are much leaner than expected for downstream transport in a steady jet
  - At 2º AEI, within 25 mm penetration, ϕ = 1 to 3
  - At 5º AEI, within 45 mm penetration, ϕ = 0.5 - 1.5

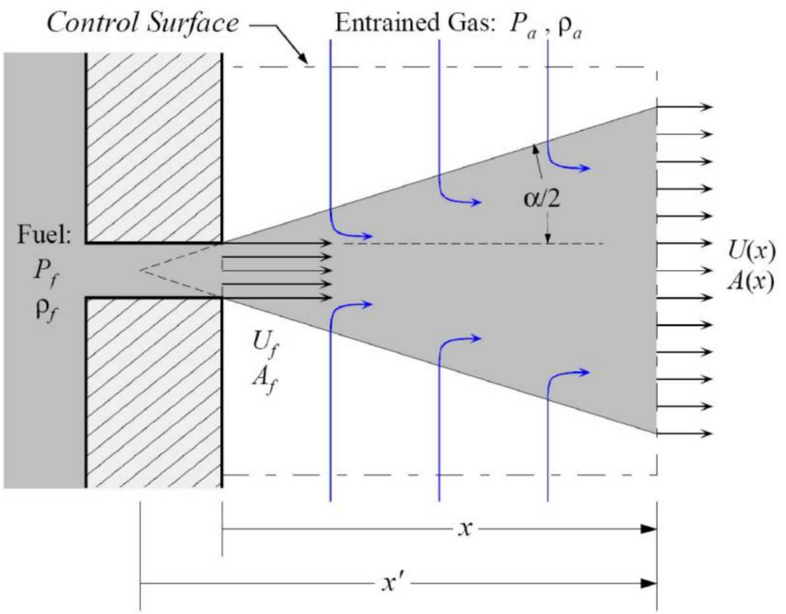
(SAE 2007-01-0907, Musculus et al.)

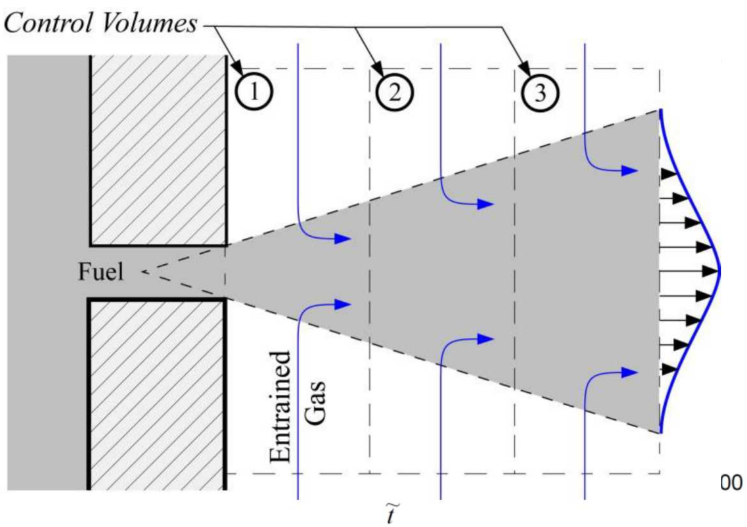
Analytical control-volume analysis for steady jets predicts richest mixtures near injector (liquid)

- In 1996, Naber and Siebers used control-volume analysis to predict diesel jet penetration and mixing (SAE 960034)
- Some assumptions:
  - –Non-vaporizing, isothermal
  - –Injection rate and ambient are steady
  - –Uniform velocity and ϕ profiles
  - –Constant spreading angle (adjusted)
  - –Fuel velocity = entrained gas velocity
- Apply conservation of mass and momentum to derive analytical penetration & ϕ solution:

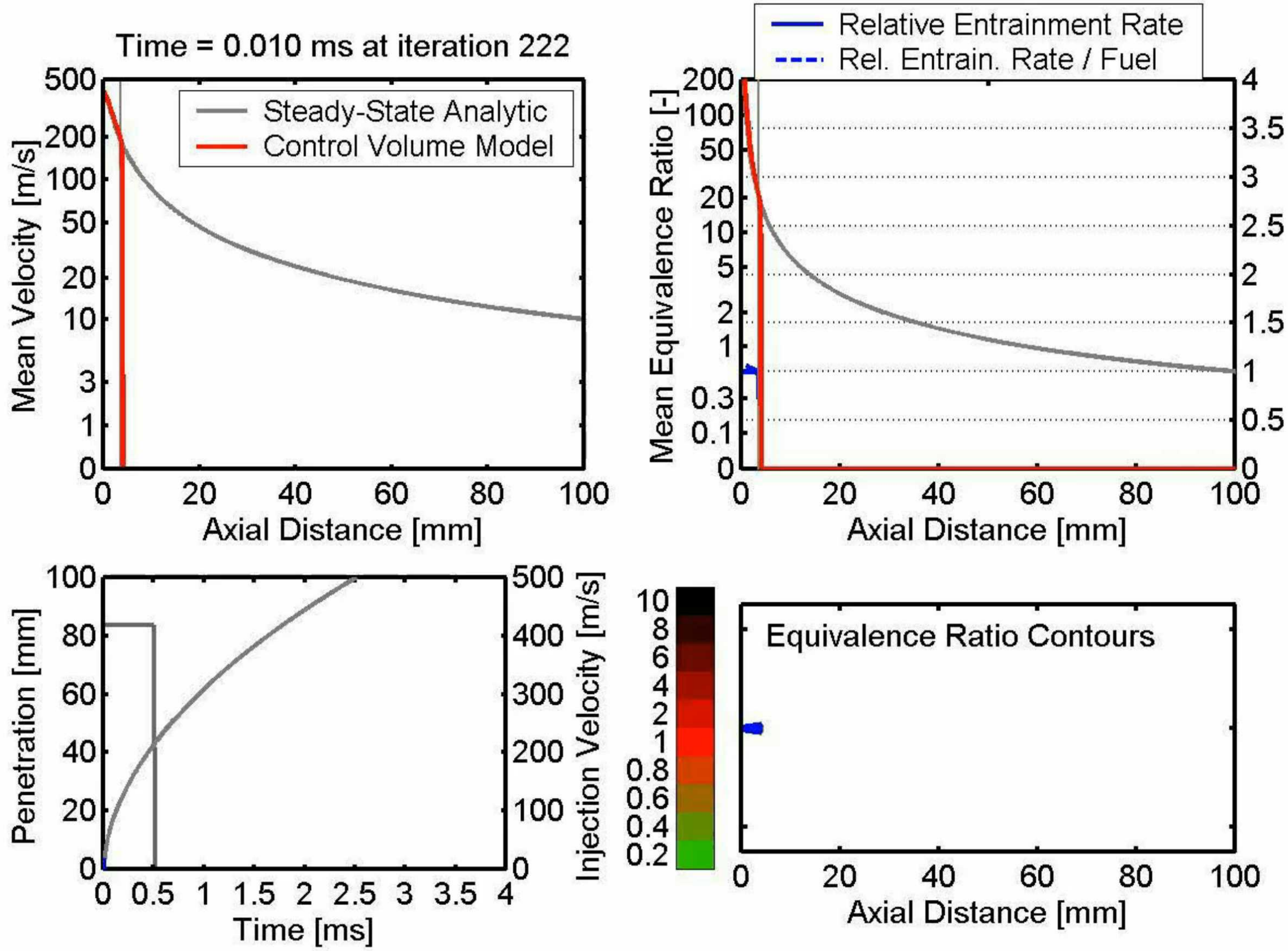
$$\phi(\tilde{x}) = \frac{30}{\sqrt{1+16\tilde{x}^2} - 1}$$

- Excellent prediction of experimental penetration, equivalence ratio, liquid length
  - ↳ **But, richest mixtures are near injector, which is inconsistent with LTC liquid vaporization after EOI**
  - ↳ **Re-derive 1-d discrete/analytical model for transient jets**





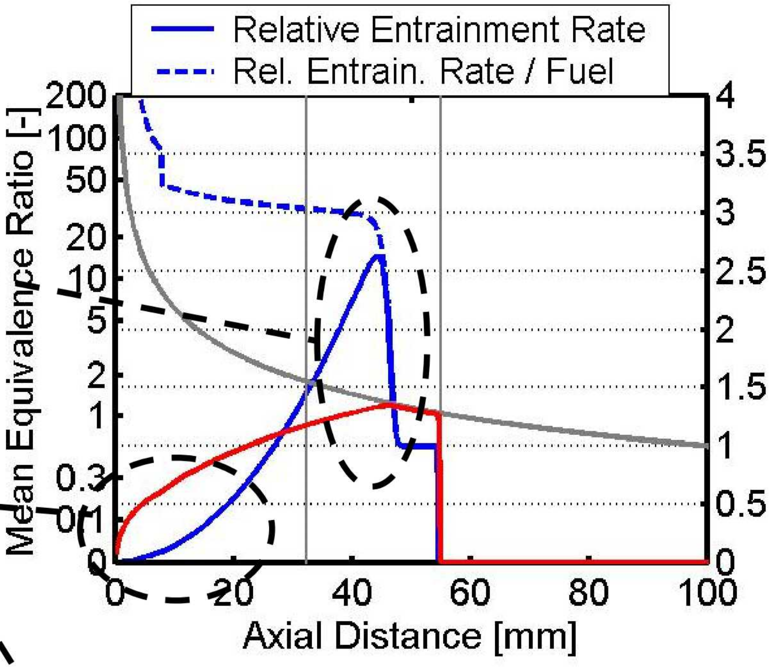
1-D jet model predicts lean mixtures near injector after EOI due to "wave" of increased entrainment

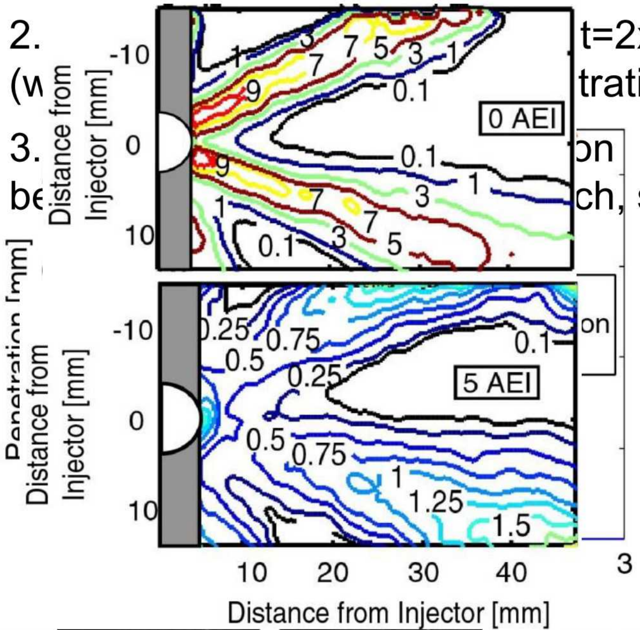


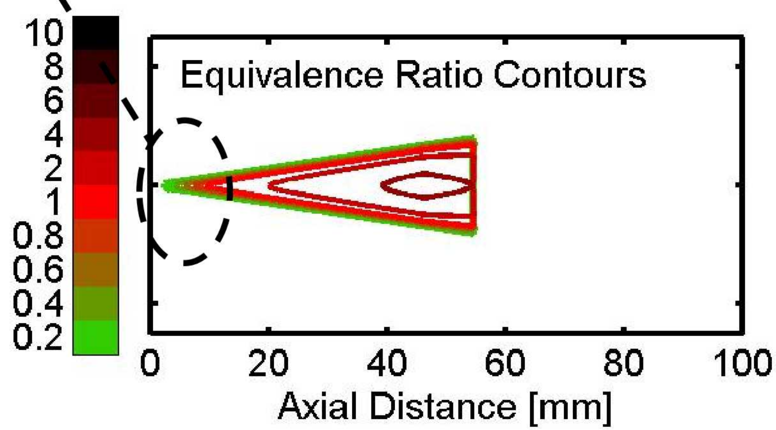
The entrainment wave action is consistent with several observations in diesel jets

1-D Diesel Jet Control-Volume Model

- Solves conservation of mass and momentum for 1-D control volume array
- Prediction: An “entrainment wave” travels downstream after EOI, with higher mixing
  - Entrainment wave is not an input, but an <u>output</u> of the model (cons. of mass)
  - 1. Explains rapid leaning of mixtures near injector that contribute to exhaust UHC
  - 2. ... t=2xDOI (w... tration)
  - 3. ... on be... ch, split)







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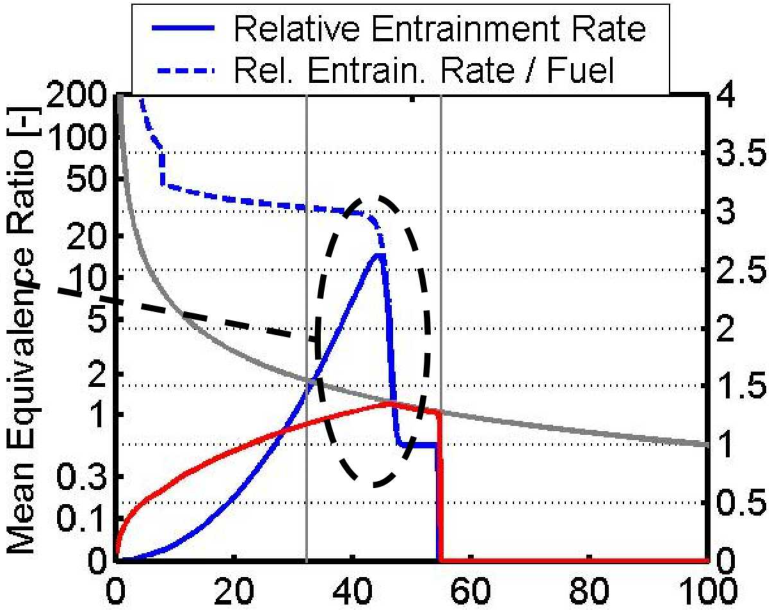
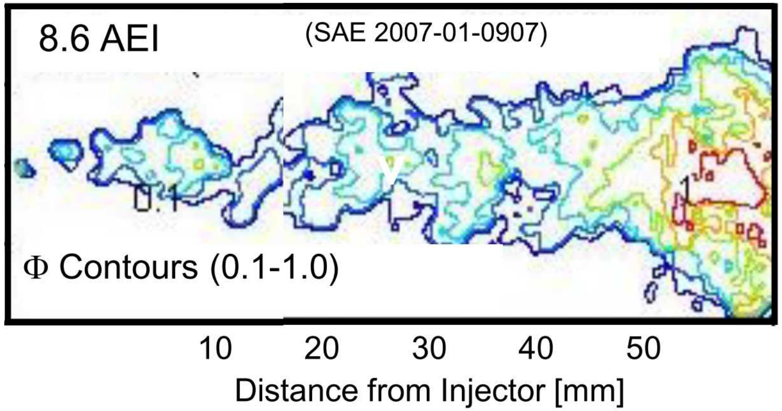
1-D Diesel Jet Control-Volume Model

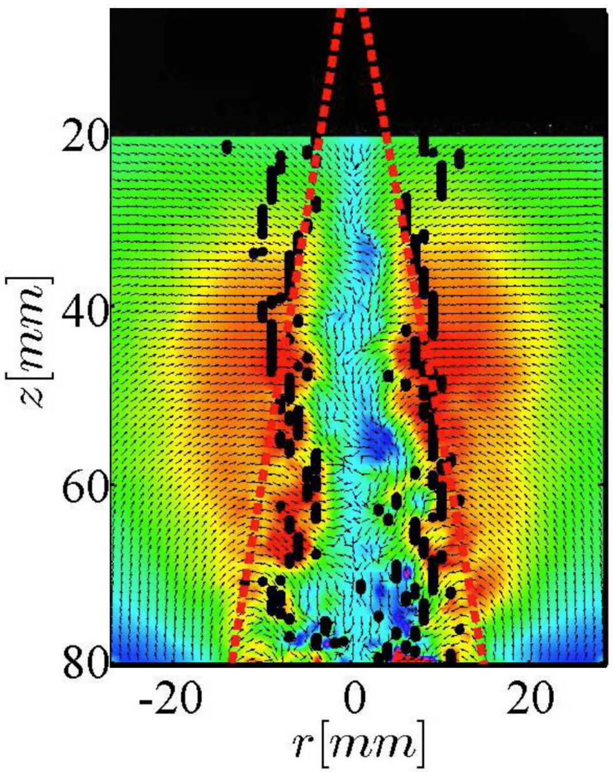
- Solves conservation of mass and momentum for 1-D control volume array
- Prediction: An "entrainment wave" travels downstream after EOI, with higher mixing
  - Entrainment wave is not an input, but an output of the model (cons. of mass)
  - 1. Explains rapid leaning of mixtures near injector that contribute to exhaust UHC
  - 2. Explains penetration "kink" at t=2xDOI (wave propagates at 2x jet penetration)
  - 3. Explains liquid-fuel vaporization behavior after EOI (retreat, detach, split)
  - 4. Explains rapid oxidation of soot in the upstream jet after the end of injection
  - 5. Explains lack of soot formation in upstream jet with long ignition dwell
  - 6. Explains stagnant region near injector after end of injection

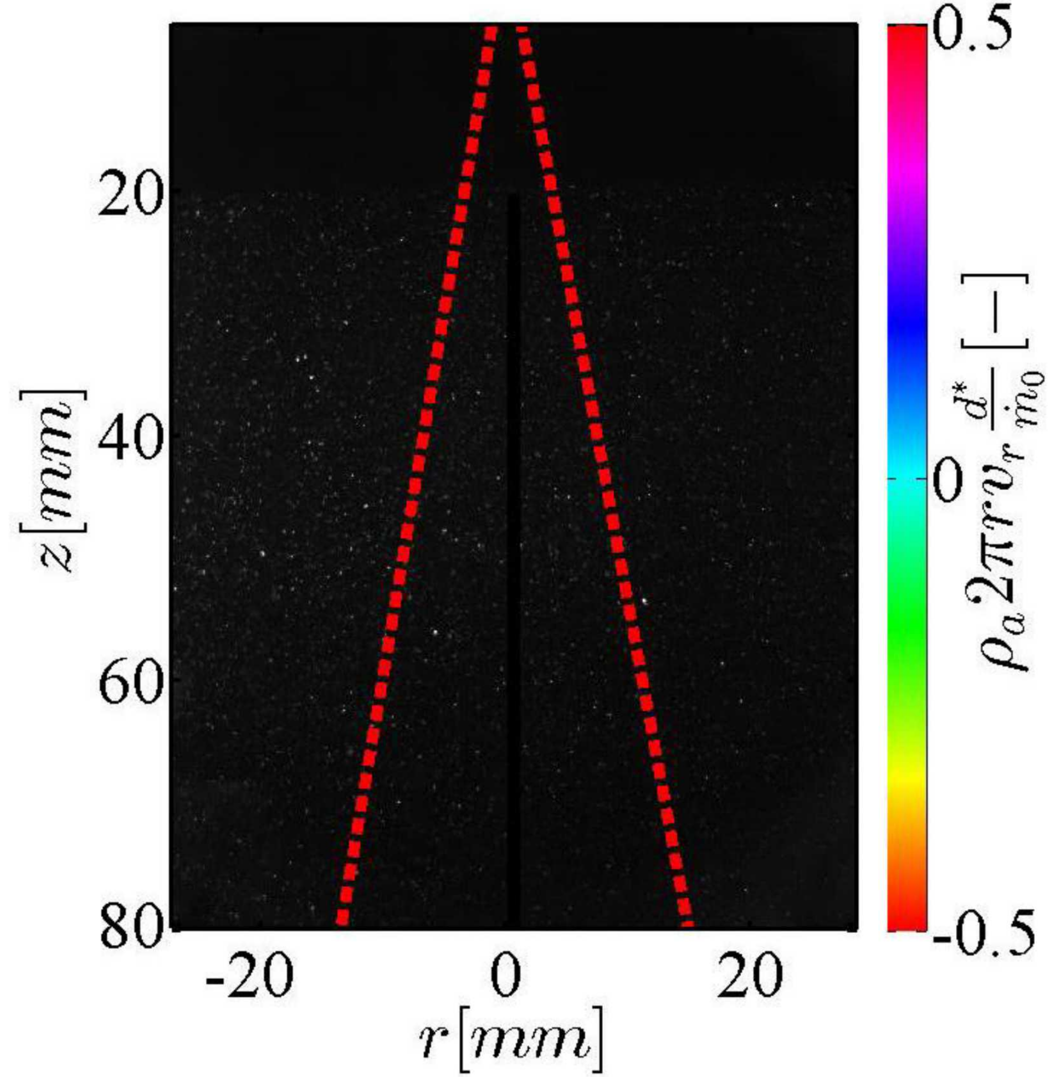




PIV measurements at IFPEN (via ECN) confirm wave of increased entrainment after EOI

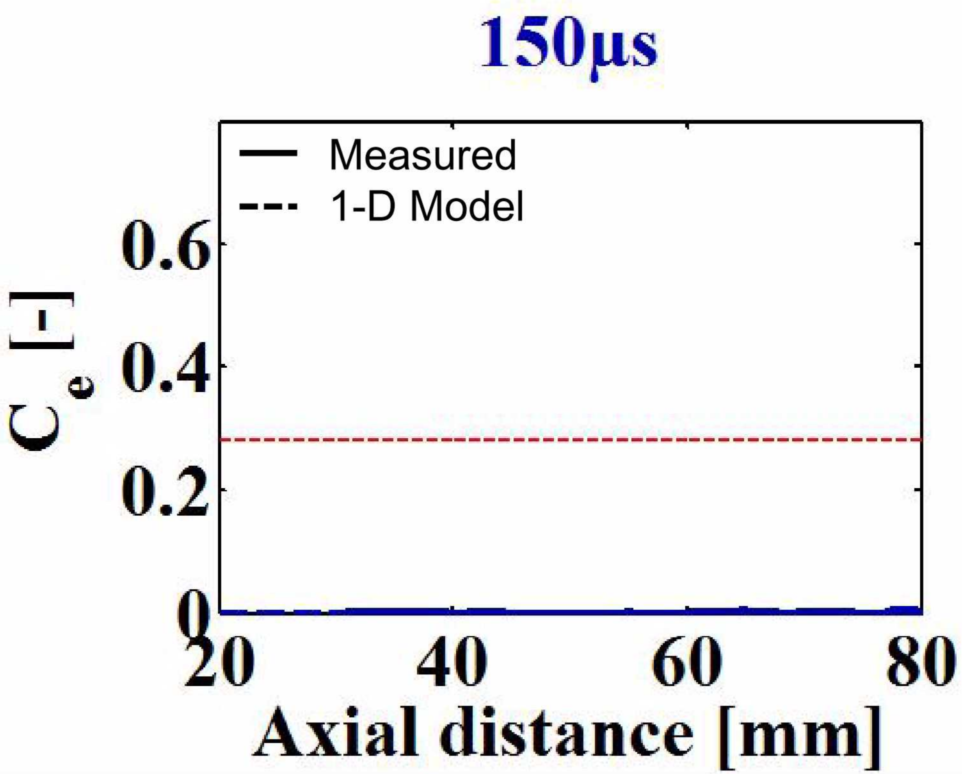
- Contours: non-dimensional entrainment flux from PIV
- Early, quasi-steady jet w/ constant entrainment (positive entrainment flux) / After EOI, entrainment temporarily increases (yellow/red)

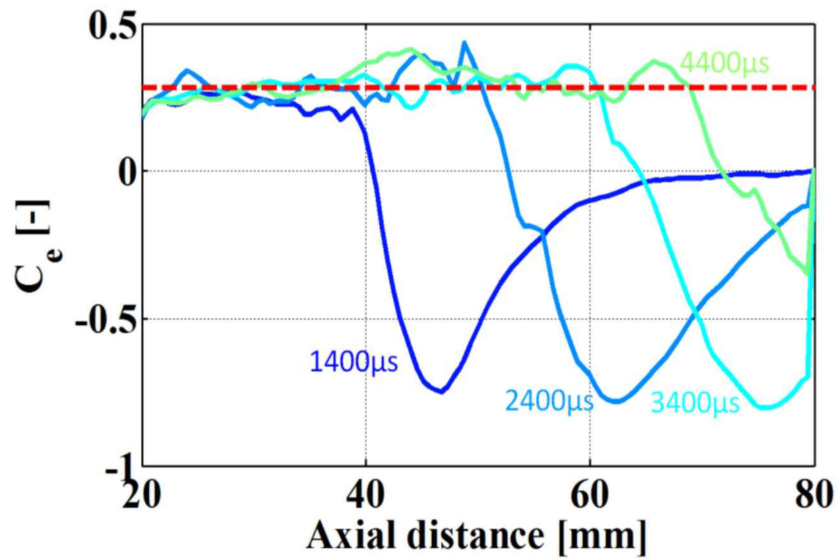


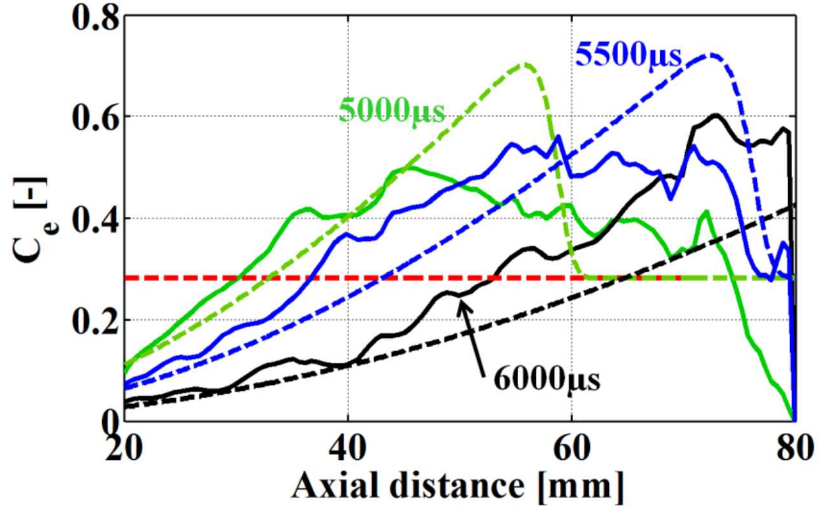


* "An improved entrainment rate measurement method for transient jets from 10kHz particle image velocimetry," WE Eagle, MPB Musculus, L-MC Malbec, G Bruneaux, Atomization and Sprays 27(6):531-37 (2016)

Measured entrainment coefficient (C_e) from PIV data agrees surprisingly well with simple 1-d model



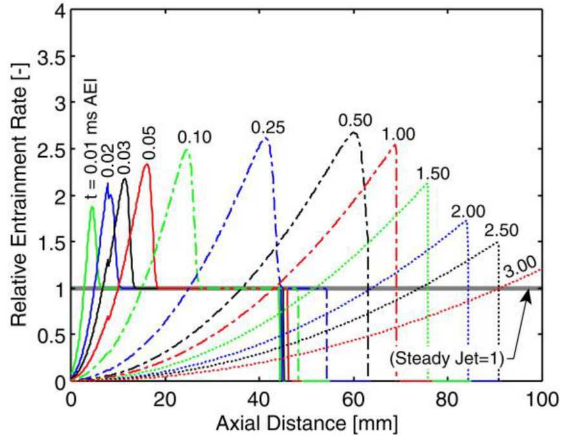




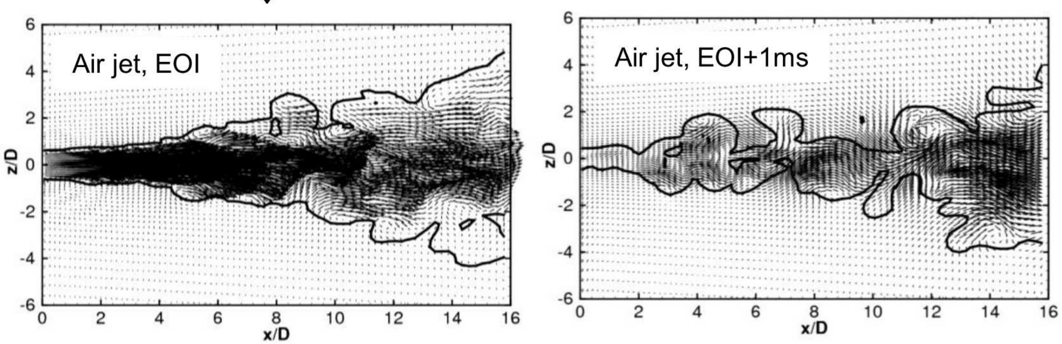
1-D analytic, KIVA RANS, and Sandia LES models predict wave of increased entrainment after EOI

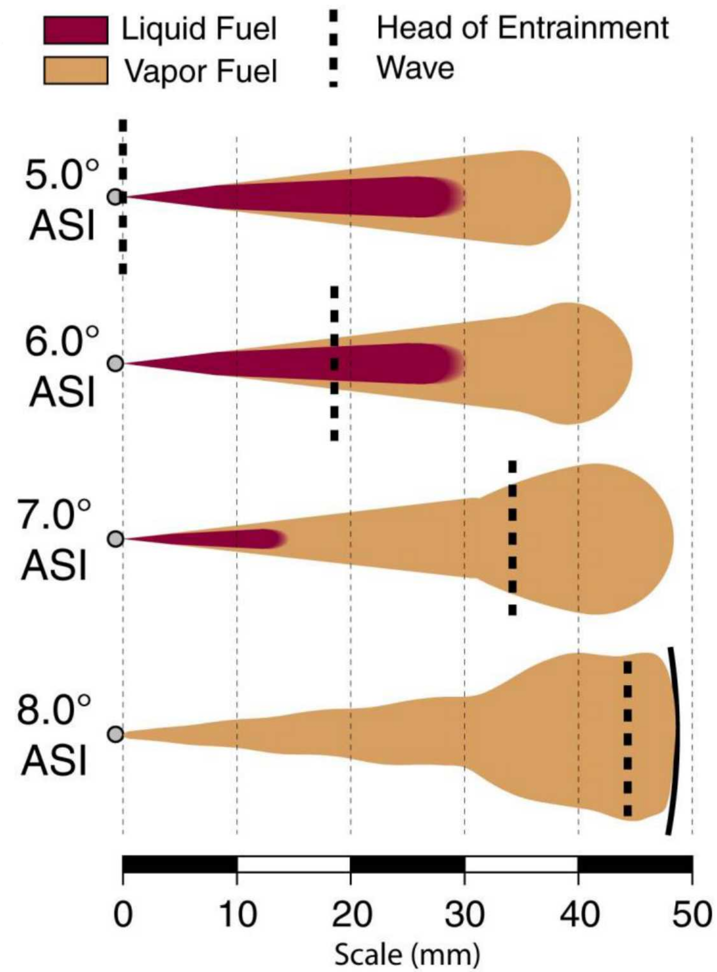
- Reduction in upstream jet velocity draws in more entrainment, which reduces velocity further, driving more entrainment, etc.
- LES (Oefelein, Hu): EOI ramp-down causes large flow structures to separate rather than collide; ambient fluid is entrained into gaps

1-D model →



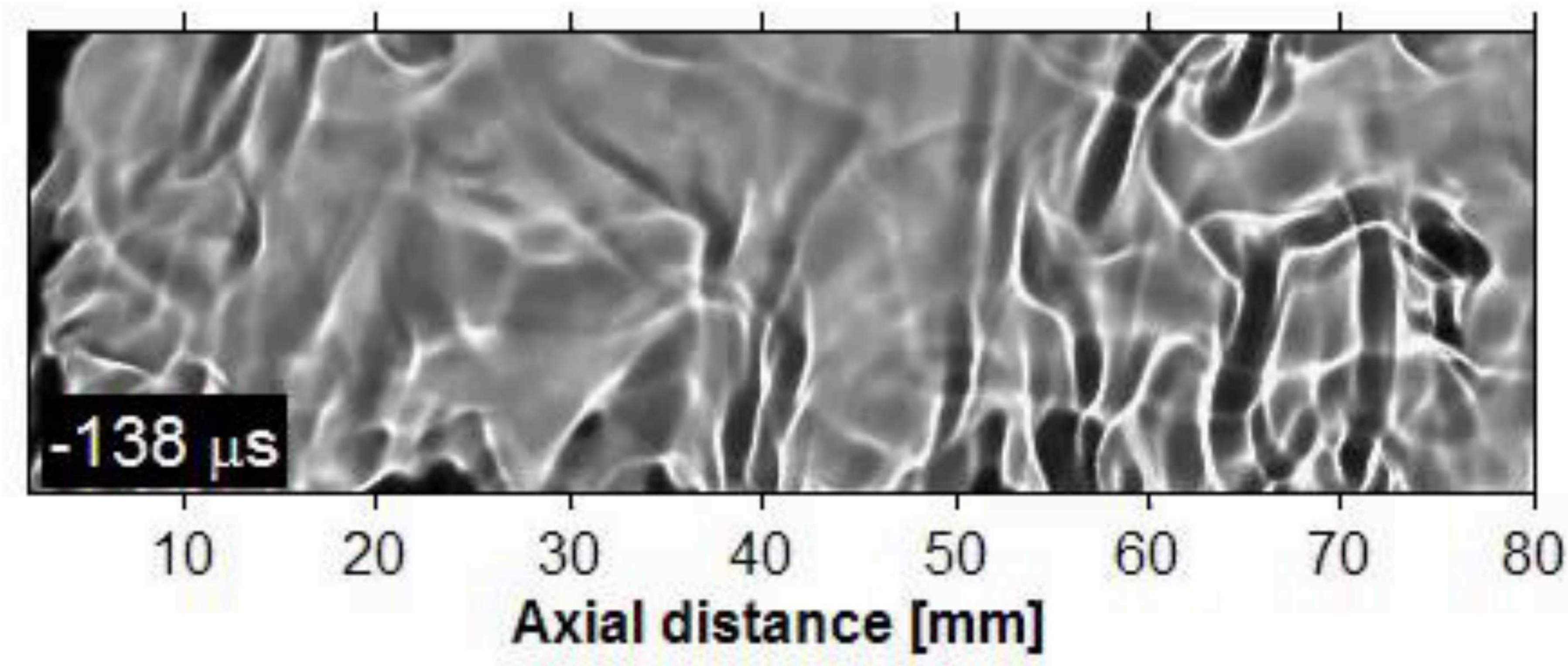
LES model
↓





Experiments show significant near-injector structural changes after EOI

- Models and experiments: Upstream velocities decrease significantly after EOI, downstream velocities remain higher until entrainment wave
- LES and experiments: Jet is tightly confined during injection, but large, slow-moving near-injector structures emerge after EOI



Diesel Shadowgraph (Lyle Pickett and coworkers, available at www.sandia.gov/ecn/)

LES air-jet model shows fluid-mechanical changes in jet structure and entrainment increase after EOI

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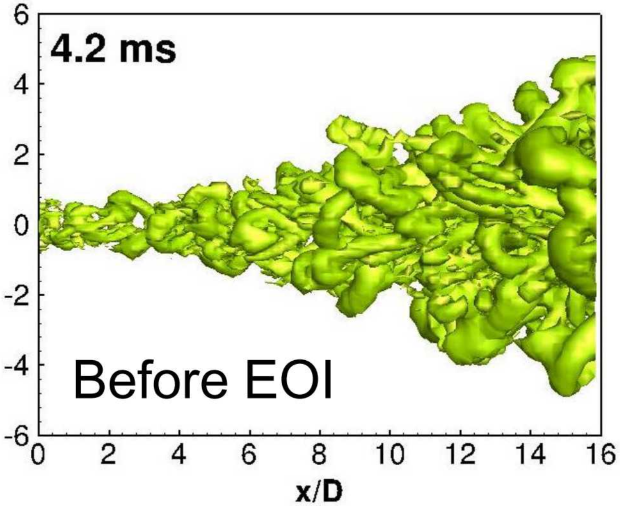
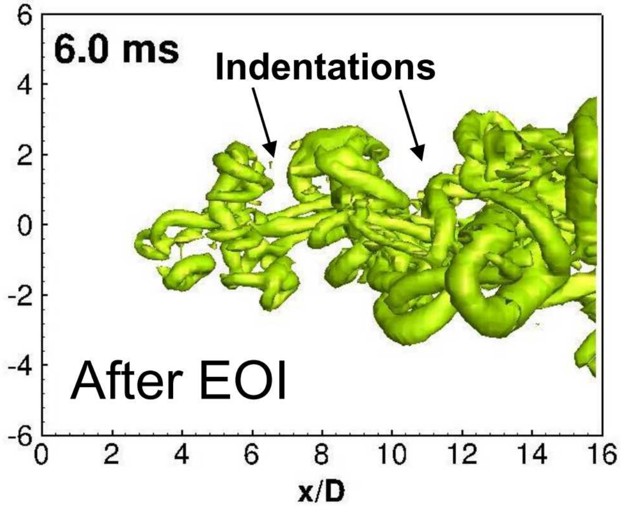
LES λ_2 visualization shows ambient engulfment between separating large-scale structures after EOI





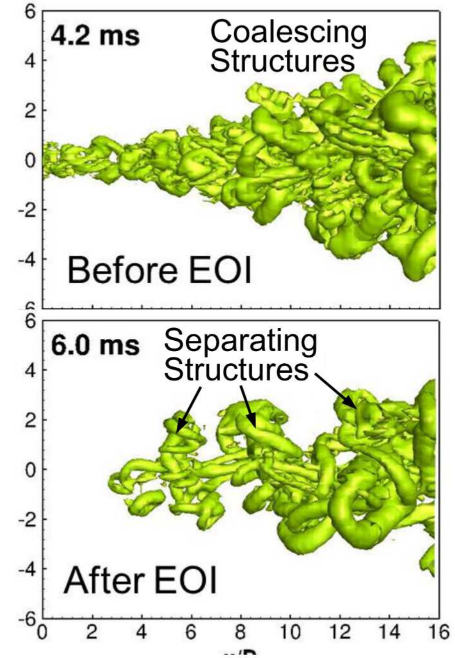
- $\lambda_2 \equiv$ 2nd-largest eigenvalue of $S^2 + \Omega^2$ (S and Ω $\equiv$ symmetric and anti-symmetric parts of ∇V)
- Vortex cores have $\lambda_2<0$, so $\lambda_2=0$ marks vortex core boundary, where azimuthal velocity is max.
- After EOI, vorticity, breakdown and turnover rates ↓, so large structure growth ↑
- Axial velocity inversion separates large structures, inhibiting coalescence
- Ambient fluid entrains into indentations between large structures (not apparent in RANS)
- Small-scale dynamics (scalar dissipation) decrease: not responsible for ↑ entrainment

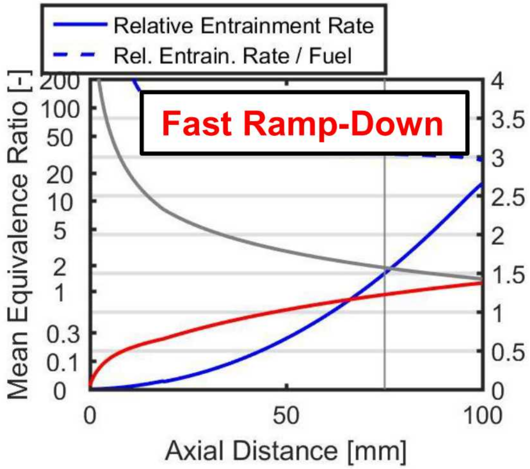
LES predictions imply that boundary conditions (rate-shaping), which affect large-scale structures can be tailored to achieve a desired mixing state

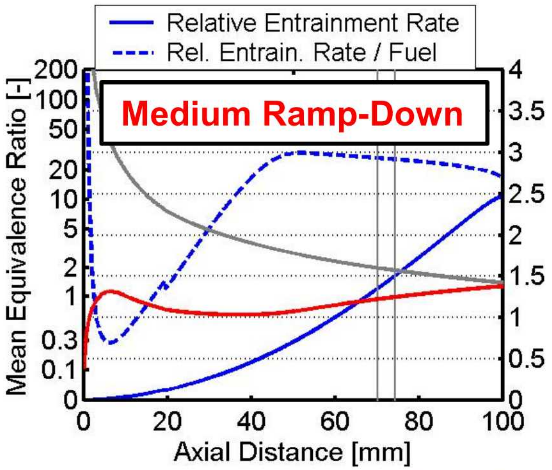
Existence of large-scale structures in end-of-injection entrainment: another “knob” to control mixing

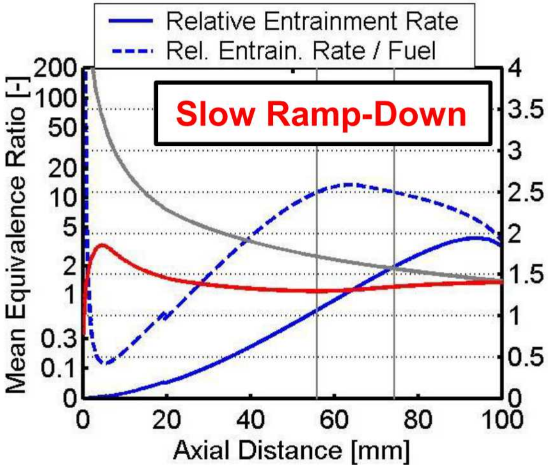
Fuel-air mixing depends on fluid mechanics over a wide range of turbulent structures

- Small scale turbulence results from natural turbulence cascade from larger structures, and control is limited
- Large-scale turbulence depends on boundary conditions, and thus offers possibilities for control
  - Injection ramp-down rate
  - Number of ends of injections (multiple injections)

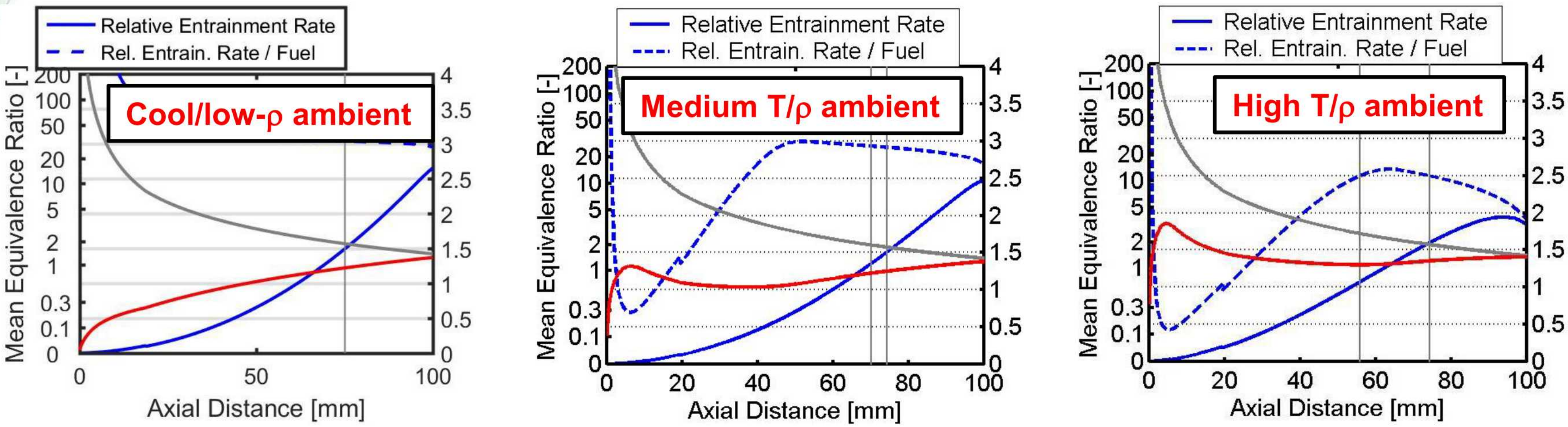


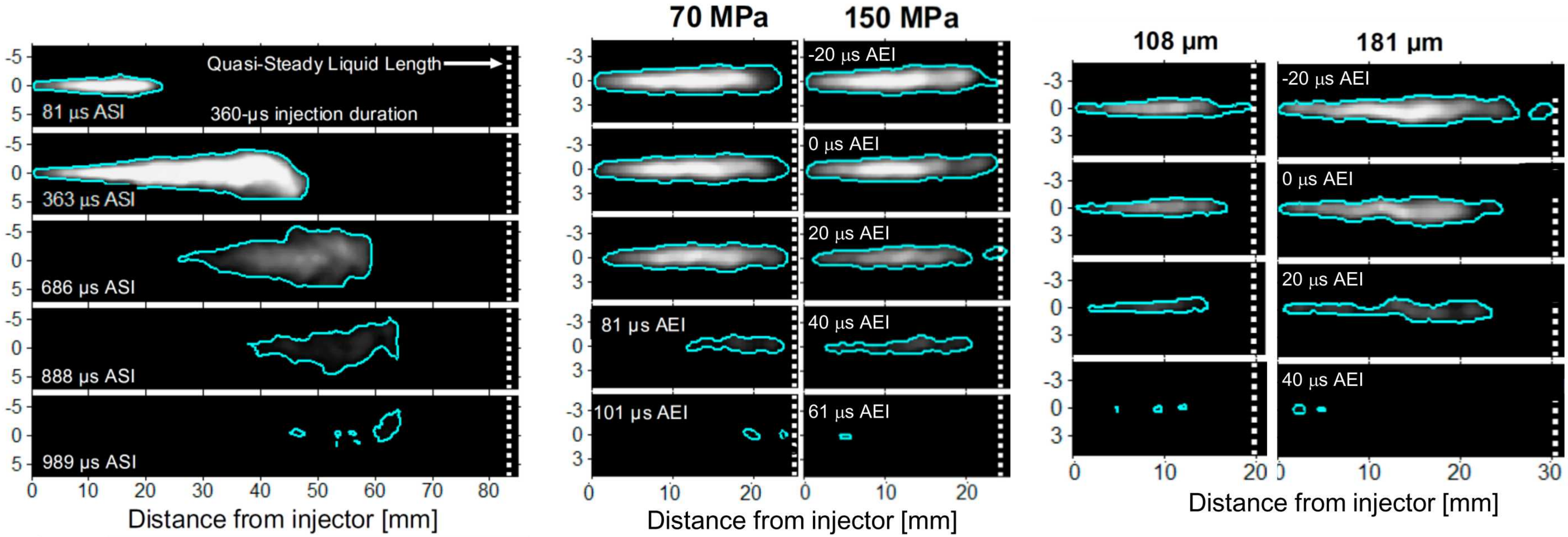






Varying ambient conditions, injection duration, and orifice size creates effects analogous to rate shaping

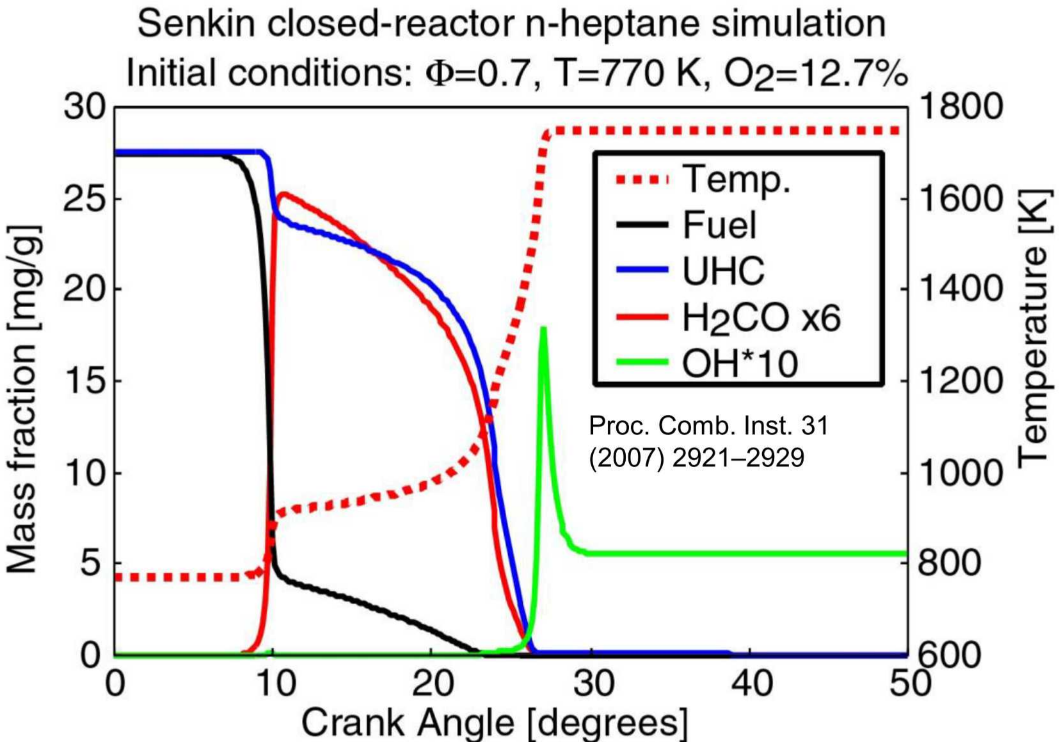




* SAE 2009-01-1356, "Influence of diesel injection parameters on end-of-injection liquid length recession, Kook S, Pickett LM, Musculus MPB

Formaldehyde is a naturally occurring tracer for UHC between 1st and 2nd stages of ignition

Closed-reactor CHEMKIN simulation of n-heptane ignition using the LLNL detailed mechanism (Combust. Flame 114:149-177, 1998)



First-Stage (10 CAD):

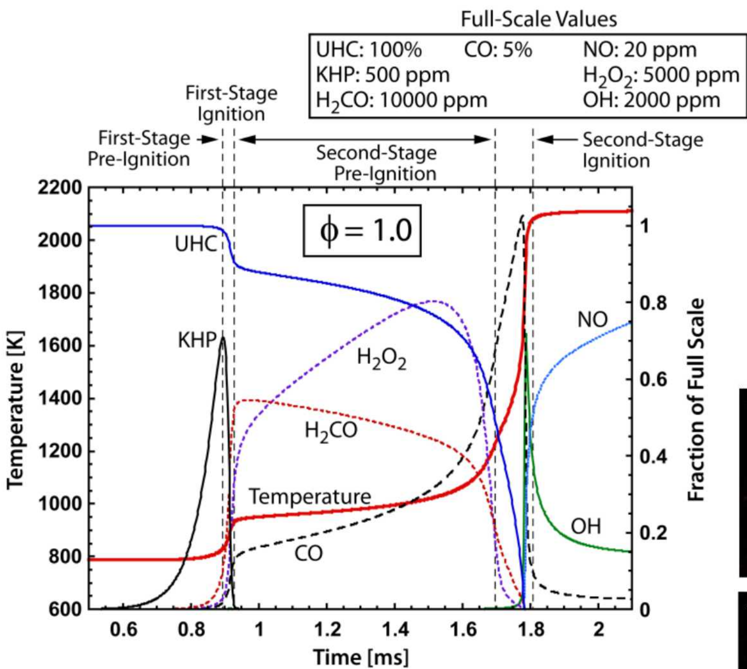
- Much of the **parent fuel molecule (black)** reacts, and a "soup" of **UHCs (blue)** is formed
- **For these lean mixtures, Formaldehyde (H_2CO, red) can track the soup of UHC (blue)**

Second-Stage (25 CAD):

- Nearly all **UHC** and **H_2CO** consumed
- **Appearance of OH (green) marks hot ignition and consumption of UHC**

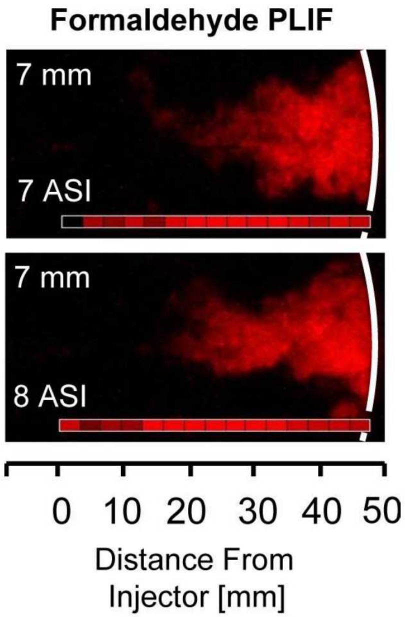
First-stage ignition in downstream vapor fuel, partially burned fuel (UHC, CO) throughout jet

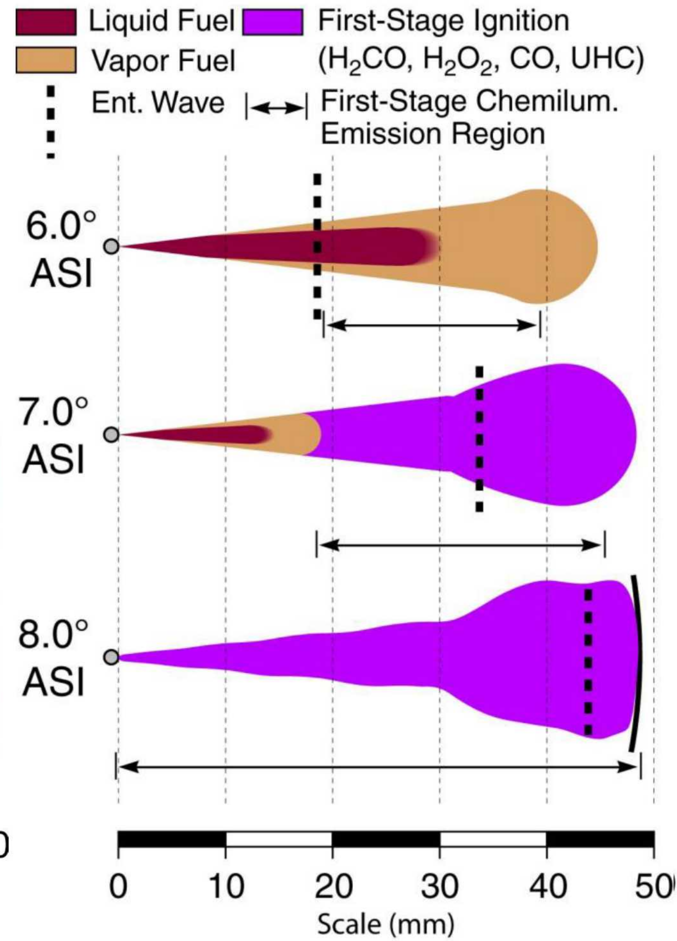
- LLNL chemical kinetics model: formaldehyde at 1st-stage ignition
- Experiments: Formaldehyde fluorescence at 1st stage, throughout jet



← Model

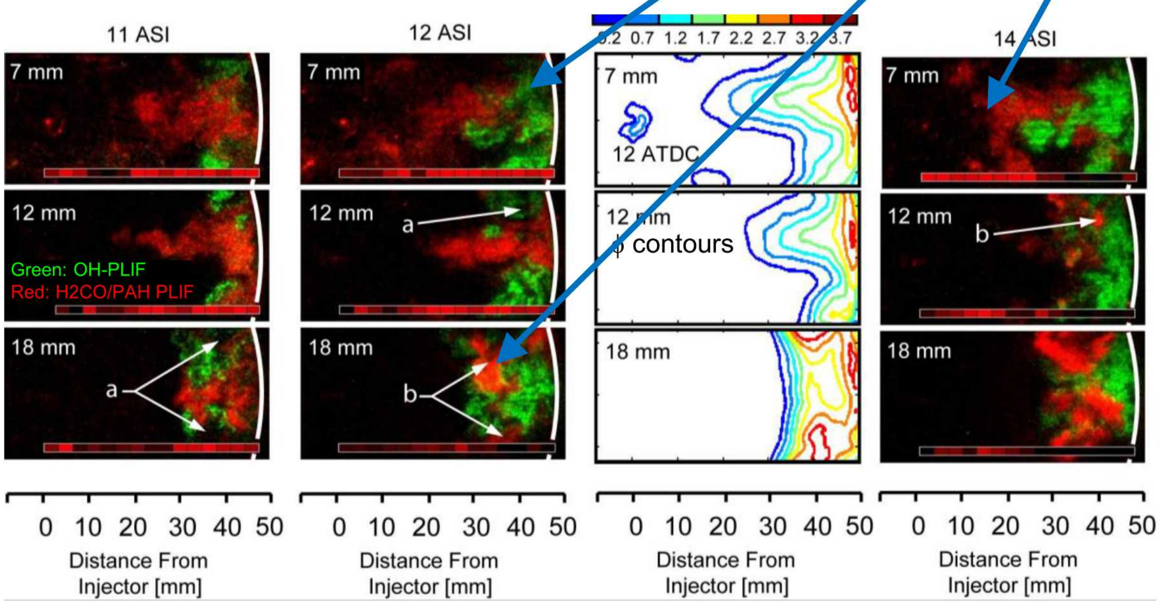
Experiment →

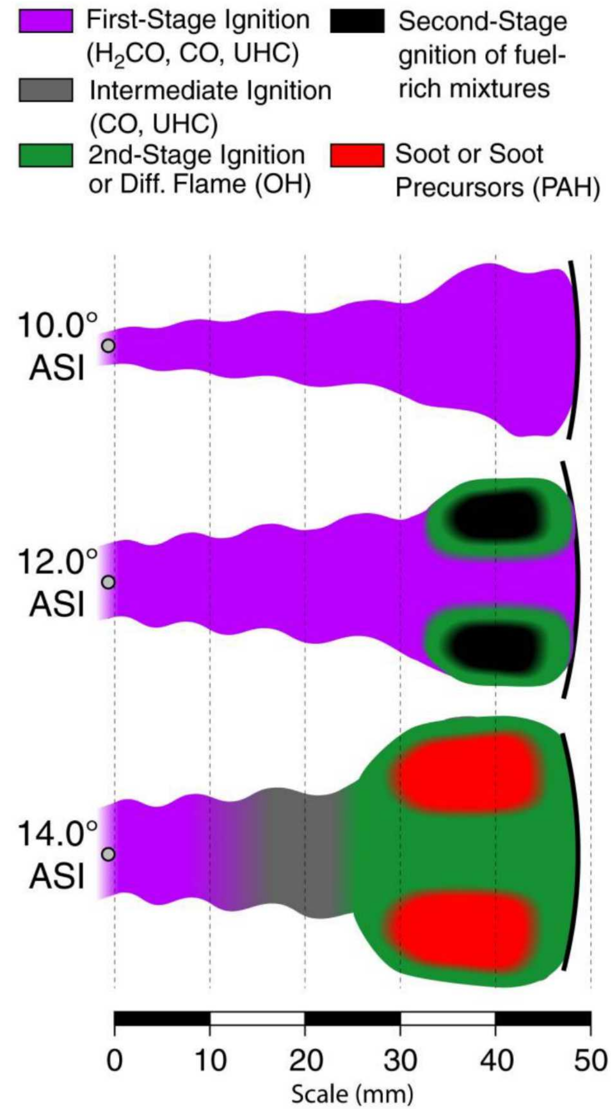




Second-stage ignition downstream where ϕ~1, followed by soot in rich pockets at head of jet

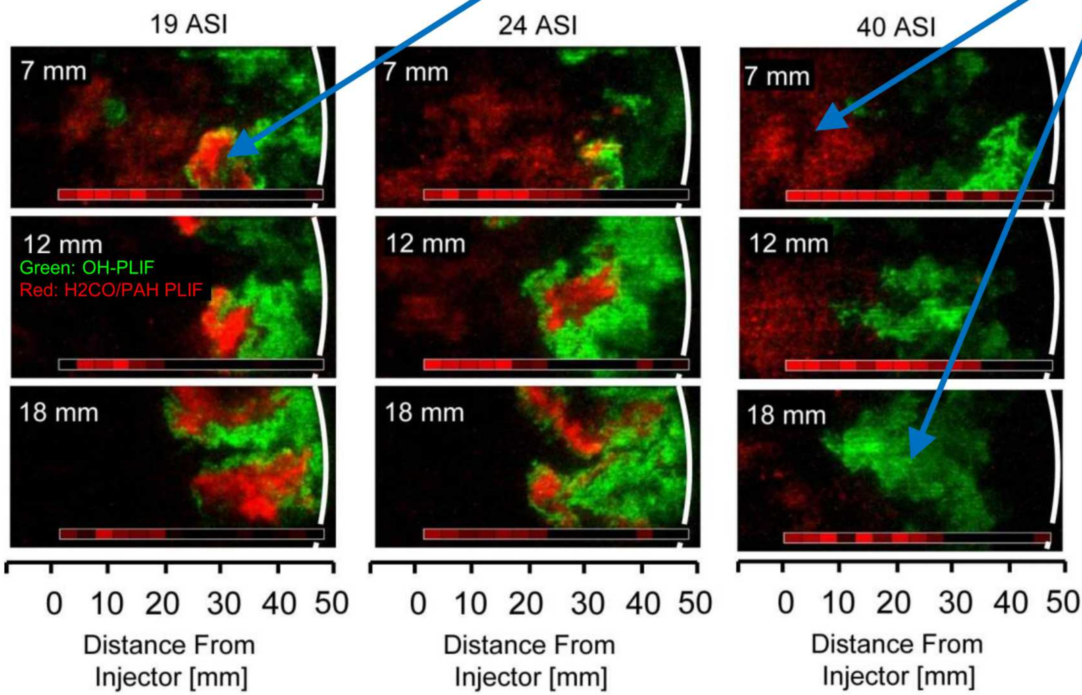
- Simultaneous PLIF of OH (green) and formaldehyde/PAH (red) show 2nd-stage ignition across most of downstream ϕ~1 jet
- Soot and PAH form in ϕ>2 pockets
- In lean upstream regions, experiments and LLNL kinetics simulations show partially burned fuel (CO, UHC, formaldehyde)

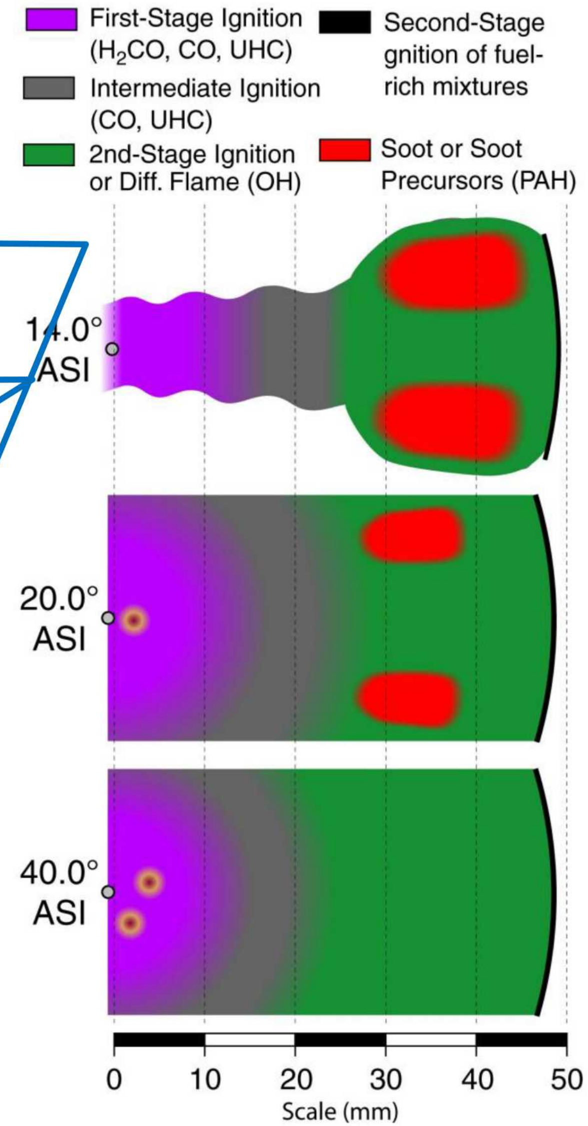




Late cycle: soot pockets largely oxidize, formaldehyde, CO, UHC remain upstream

- Late in cycle, simultaneous PLIF of OH (green) and formaldehyde/PAH/soot LII (red) show soot pockets surrounded OH
- Soot pockets are mostly oxidized by 40º ASI
- Partially burned fuel (CO, UHC, formaldehyde) remain late in cycle



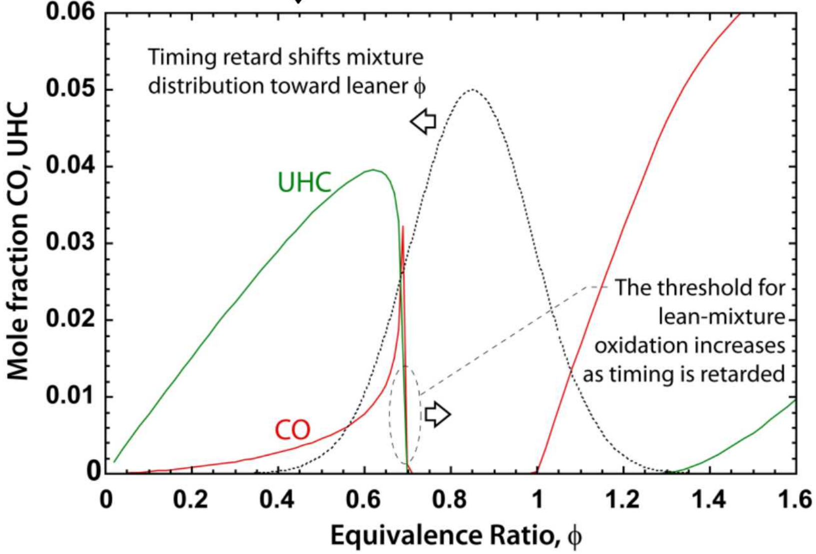


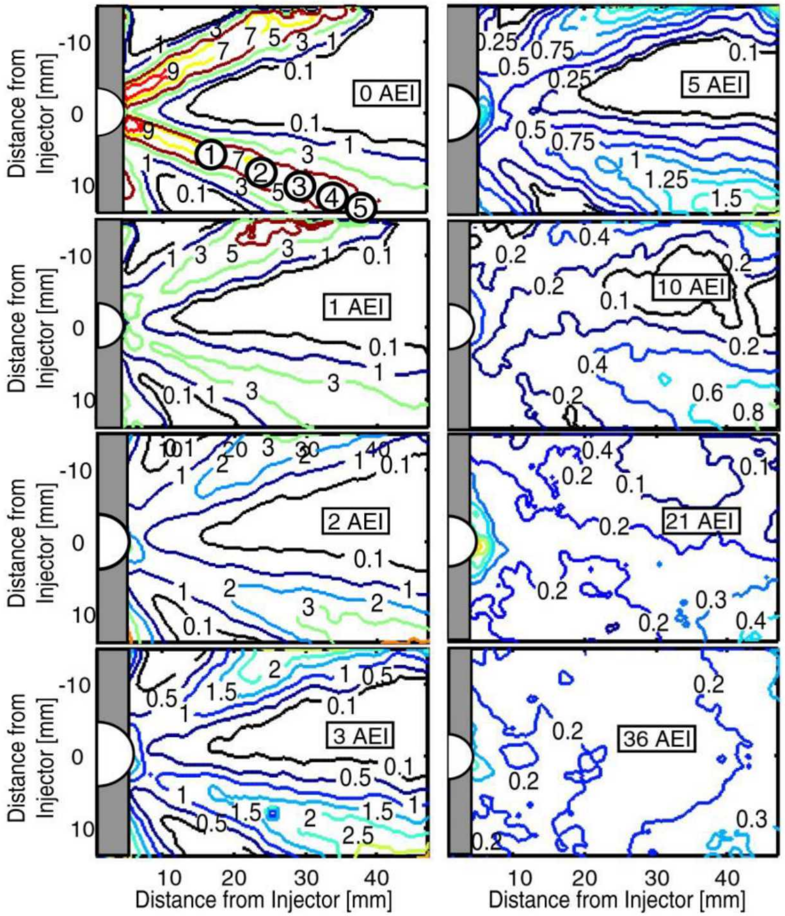
Experiments show over-lean regions near injector, where kinetics models predict partial combustion

- Experiments: vapor-fuel tracer-PLIF shows lean mixtures near injector where combustion-PLIF shows late-cycle formaldehyde and CO
- LLNL kinetics models: Lean mixtures have long dwell between first- and second-stage ignition, with UHC and CO persisting to exhaust

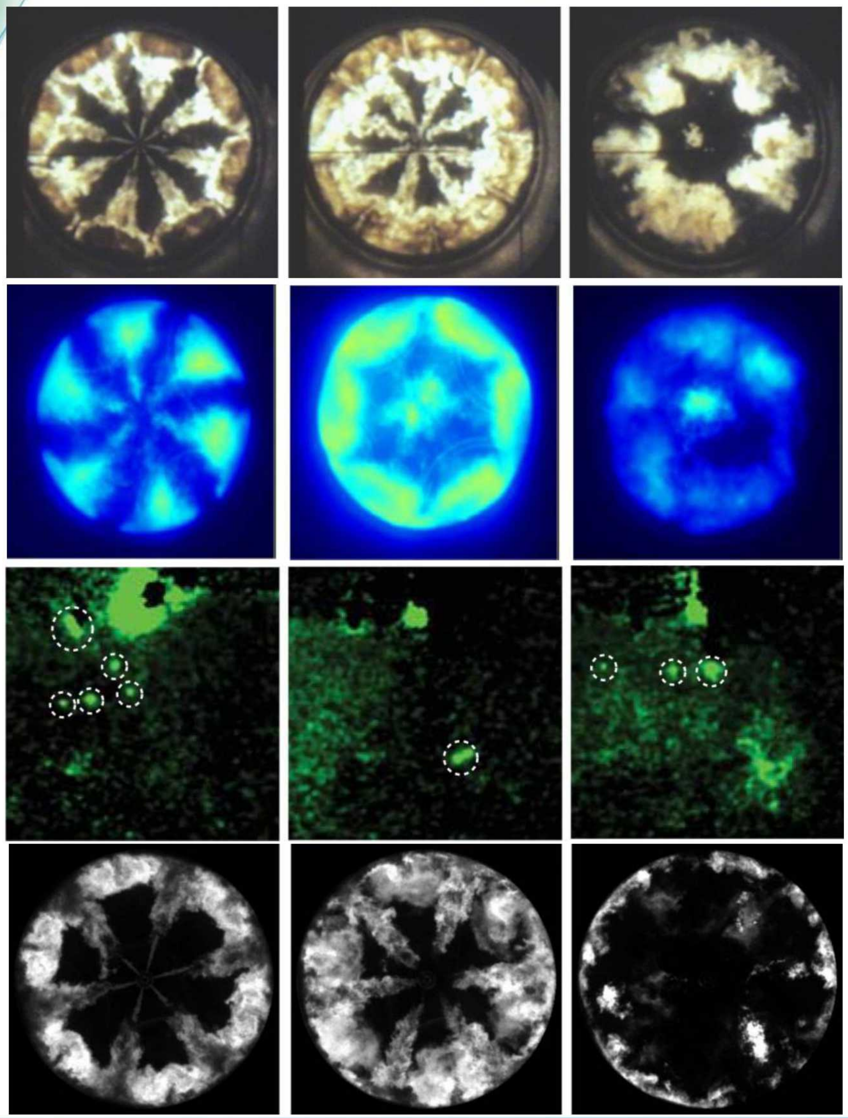
Kinetics Model ↓

ϕ from experiment →





Injector dribble is not universal in the literature, but it is not uncommon either



SAE 930971 (Dec, Sandia)

- Heavy-duty, diesel reference fuel
- Cam-driven, mini-sac injector
- Late soot at center

SAE 2005-01-3845 (Taschek et al., Aachen)

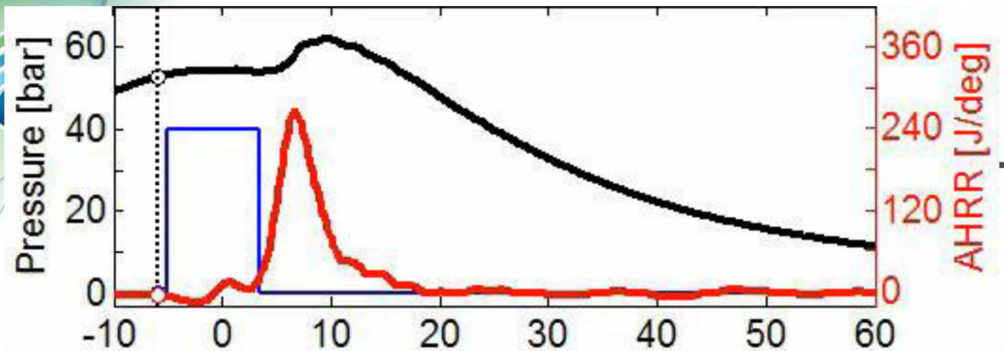
- Light-duty, diesel fuel
- Common-rail, mini-sac injector
- Conceptual model: Inj. sac vapor → soot

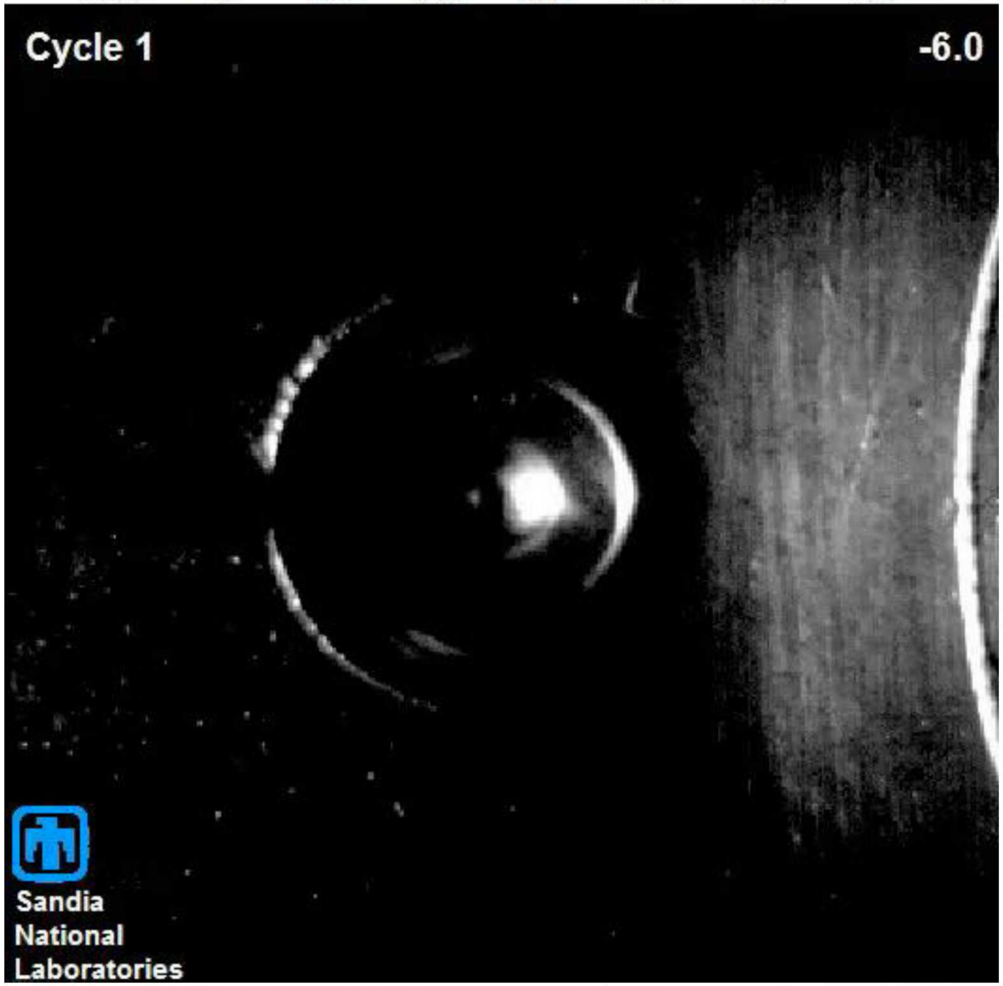
SAE 2009-01-1446 (Ekoto et al., Sandia)

- Light-duty, diesel fuel
- Common-rail, mini-sac injector
- Side-view PLIF, bright fuel droplets late

SAE 2001-01-2004 (Mueller et al., Sandia)

- Heavy-duty, diesel reference fuel
- HEUI, VCO injector
- No late soot at center (but sometimes yes)





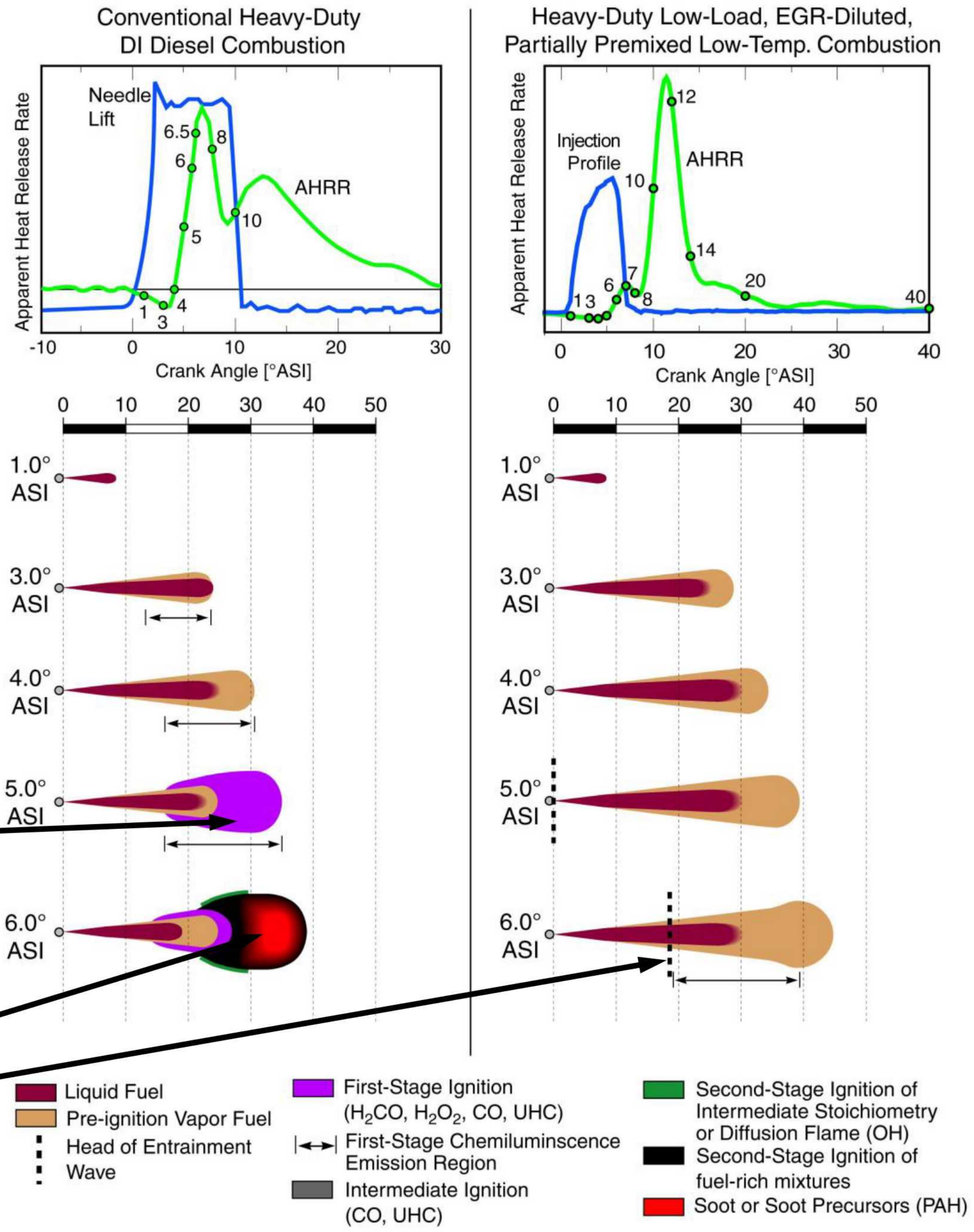
LTC PCCI: Injector Dribble

- Diesel PRF (realistic boiling pt)
- Droplets emerge from different holes each cycle
- "Sparkling" could be flash-boiling events or tumbling ligaments

Fuel	Diesel PRF CN42.5
Intake	13% O_2
Load	3 bar IMEP
Intake T	78 C
Intake P	2.14 bar
CR SOI	-5° ATDC
Speed	1200 rpm
Engine r_C	10.75
View	35 mm square
Framing	14400 fps
Filter	None

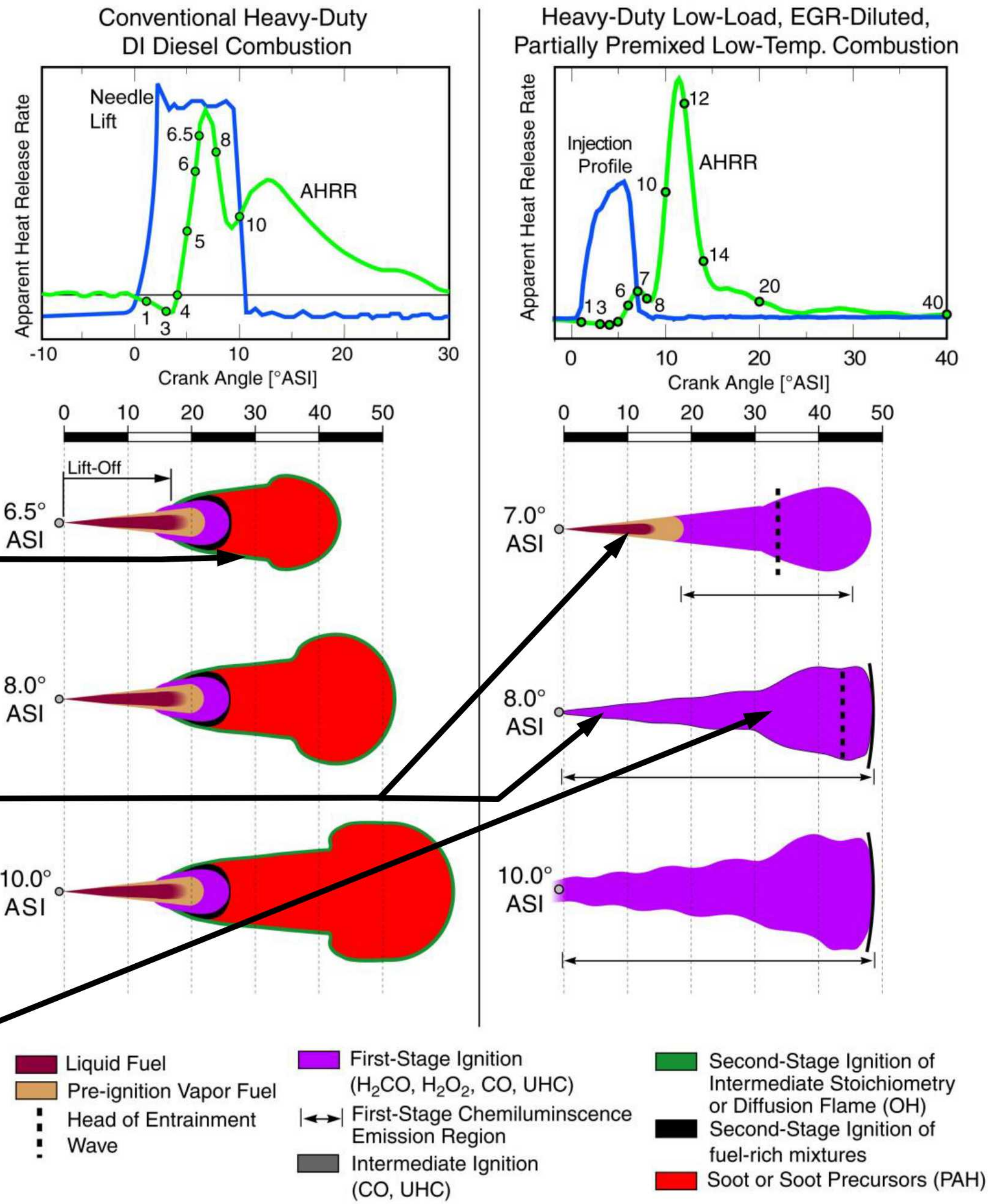
HD Conv. vs. LTC: 0-6 ºASI

- Early penetration and vaporization are similar for conventional and LTC
  - Liquid fuel penetration is longer for early-injection LTC (cooler, lower density ambient)
- First-stage ignition occurs sooner for conventional diesel, during injection, in the downstream jet
- Conventional second-stage ignition in rich mixtures yields early soot formation
- As LTC injection ends, entrainment is temporarily boosted in traveling wave



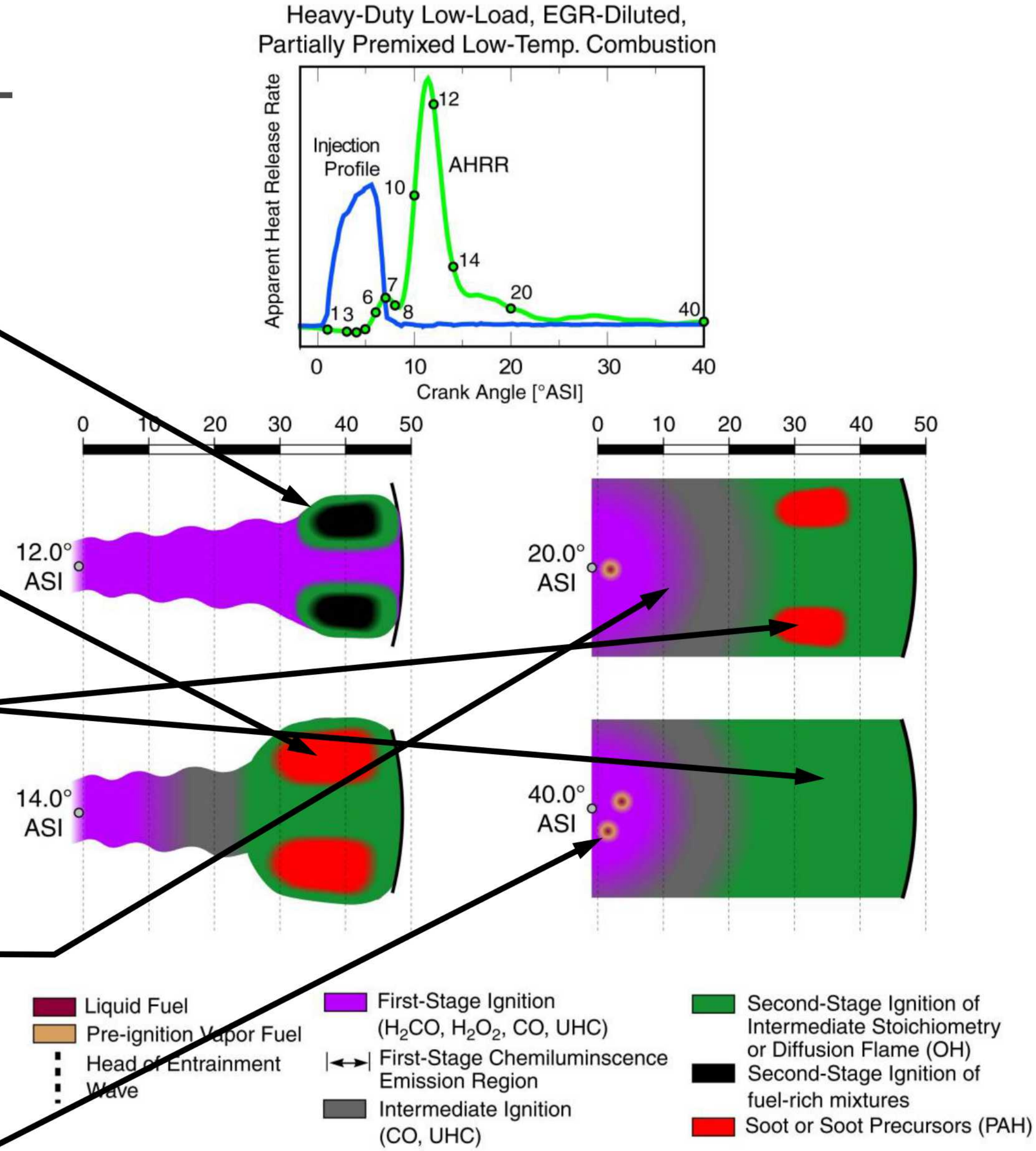
HD Conv. vs. LTC: 6-10 ºASI

- Conventional diesel jet enters “quasi-steady” period, characterized by fuel-rich, soot-filled interior surrounded by diffusion flame
- Increased entrainment after end of injection causes liquid-length recession in LTC jet
- First-stage ignition occurs throughout most of LTC jet, from lean upstream mixtures to richer downstream mixtures.



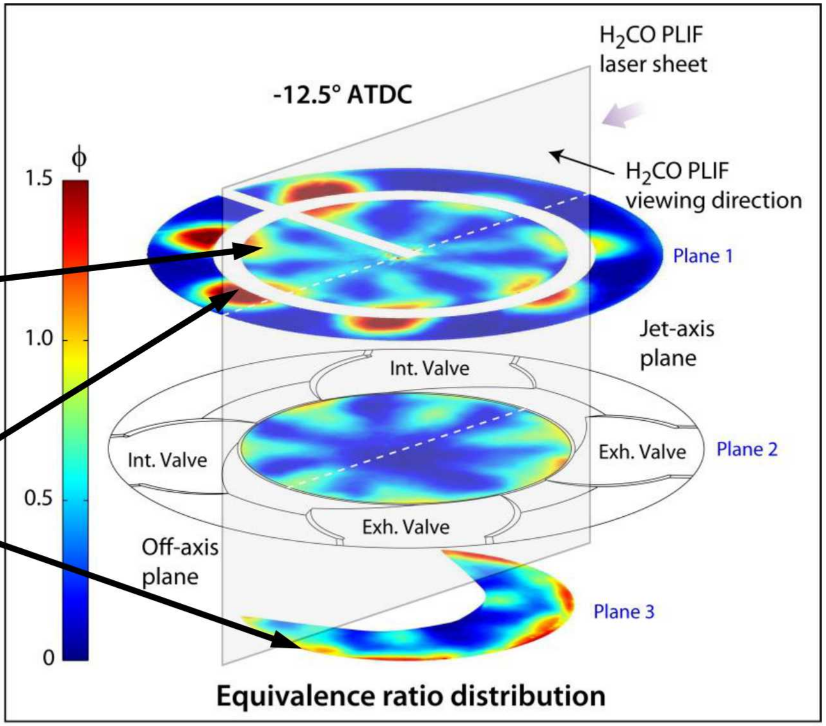
HD LTC: 10-40 ºASI

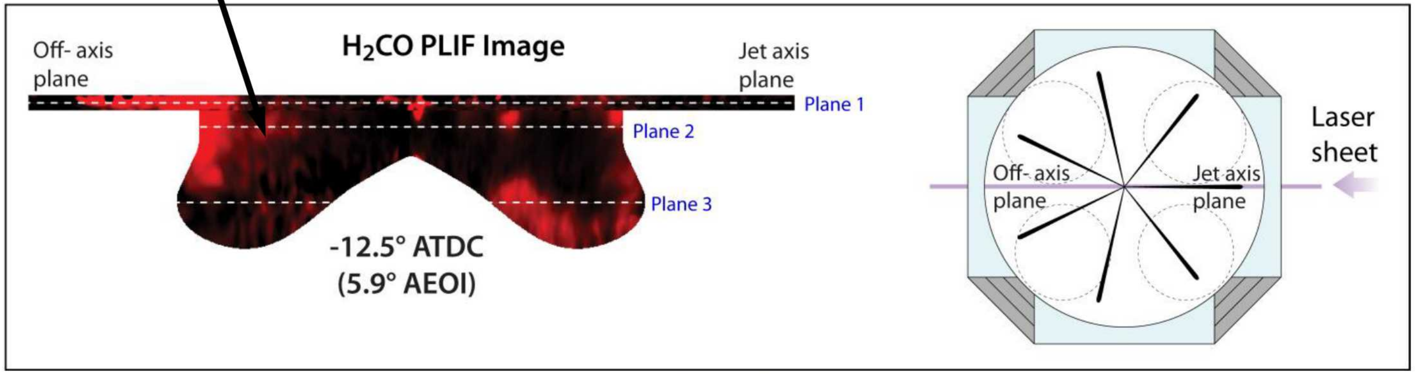
- Second-stage ignition occurs after the end of injection, in the downstream jet
- At “threshold-sooting” conditions, soot forms in fuel-rich pockets near the piston bowl-wall
- Late in the cycle, most bulk soot oxidizes
- Fuel-lean upstream regions do not achieve second-stage ignition, and contribute to UHC and CO emissions
- Injector “dribble” deposits fuel-rich droplets within fuel-lean field near injector



Light Duty: Swirl transports mixtures away from jet axes, first-stage ignition throughout jet

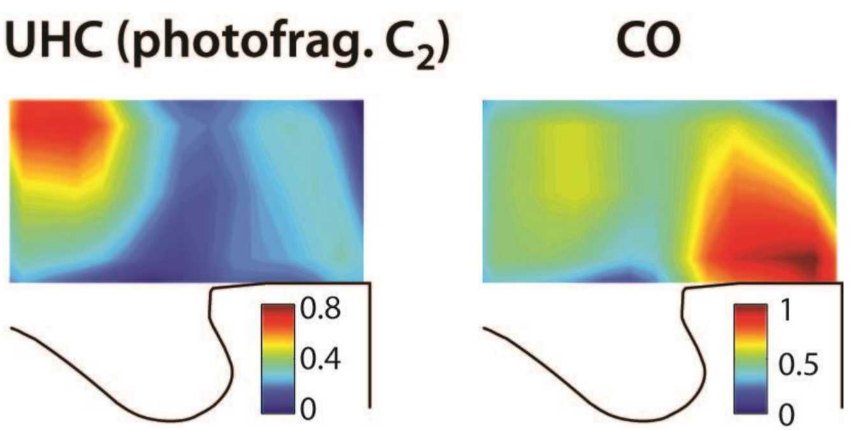
- For light-duty, swirl transports mixtures off the jet axes
- Like heavy-duty, light-duty jet is lean upstream and fuel-rich close to bowl
- Piston bowl contour redirects jet, with rich mixtures at lip and in piston bowl
- First-stage ignition (H_2CO PLIF) occurs nearly simultaneously throughout jet

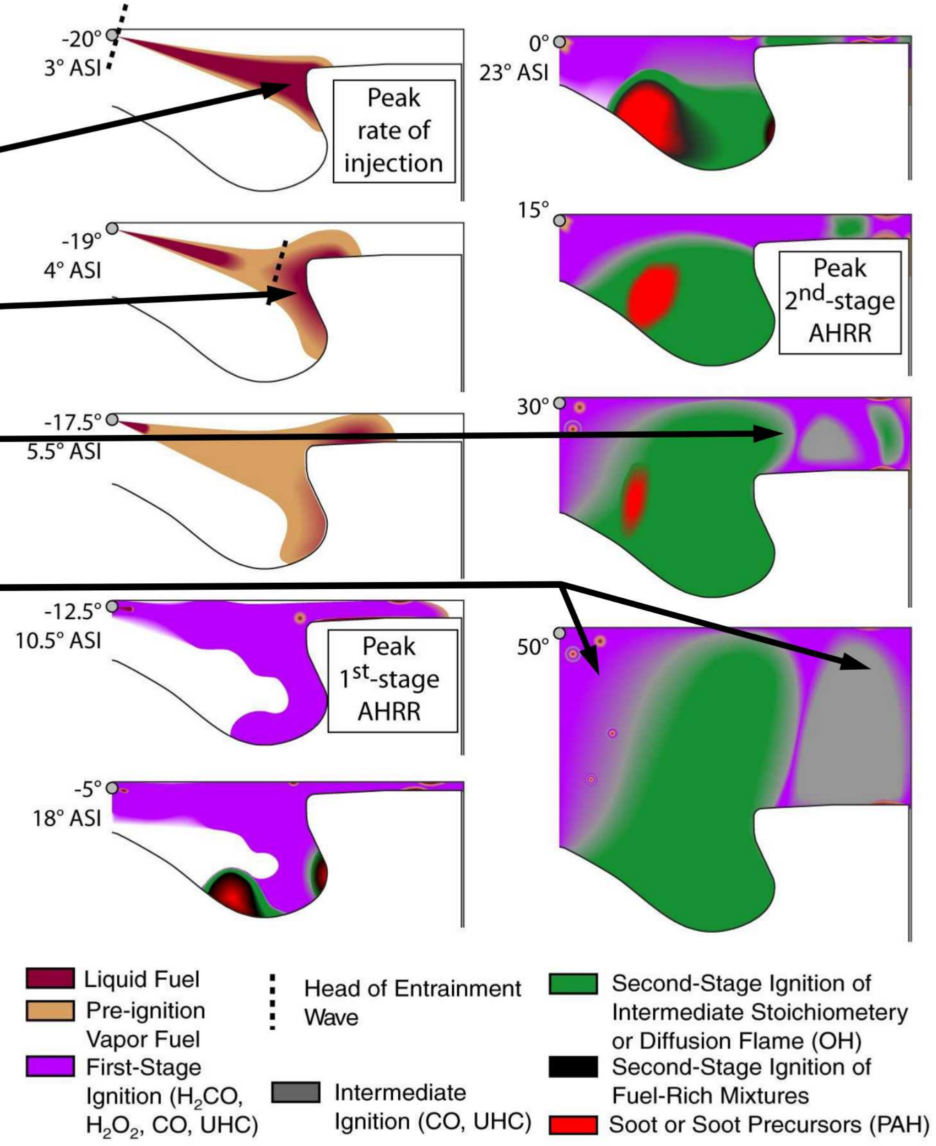




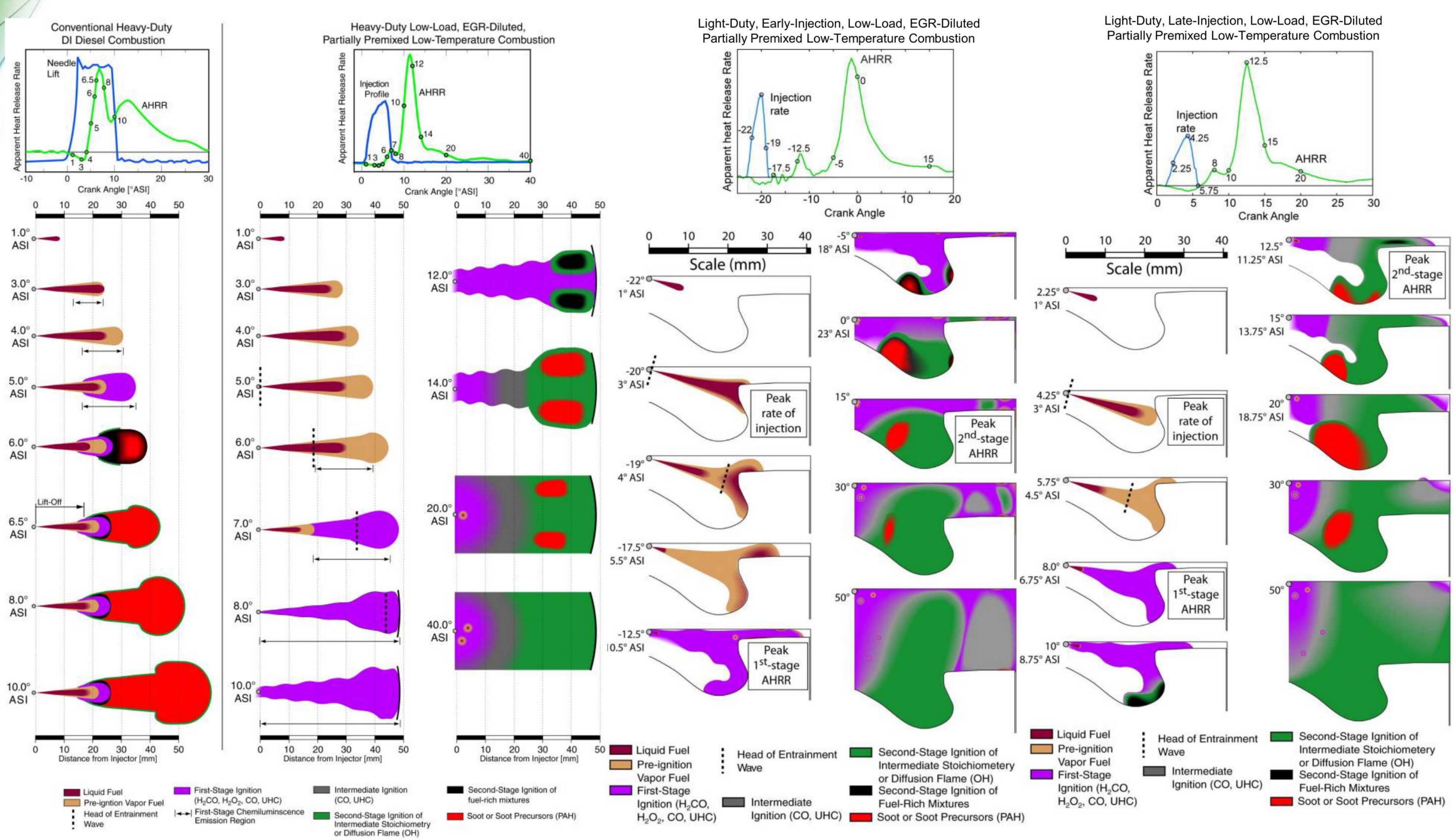
Light Duty: Interaction with piston bowl and reverse squish play more prominent role

- In light-duty engines, liquid fuel impinges on piston, especially for early injection
- Jet is split by lip of piston bowl, with rich mixtures mostly in bowl
- Reverse-squish pulls lean near-injector mixtures into squish.
- Incomplete combustion + late film vaporization → CO, UHC





Review article summarizes heavy- and light-duty low-load EGR-diluted partially premixed LTC



"Conceptual models for partially premixed low-temperature diesel combustion," M.P.B. Musculus, P.C. Miles, and L.M. Pickett, Progress in Energy & Combustion Science 39(2):246-283, 2013

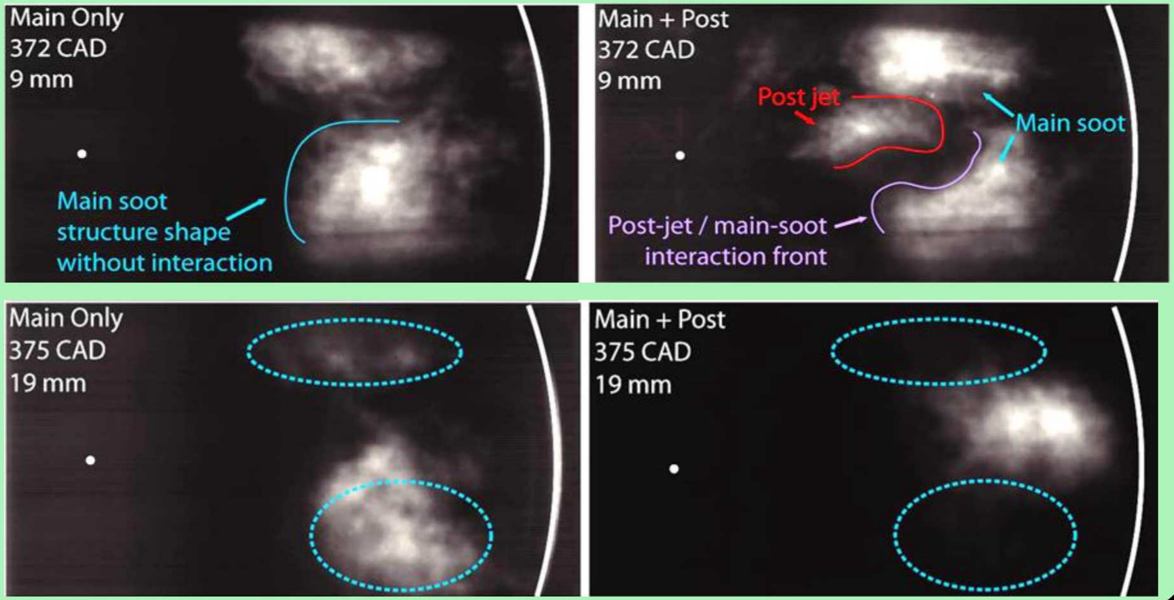
Multiple injections shift noise/emissions/efficiency tradeoffs, but in-cylinder mechanisms are unclear

- Both heavy- and light-duty engine/vehicle manufacturers use multiple-injection strategies to reduce noise, emissions, and fuel consumption
- For both conventional and low-temperature diesel combustion, the state of knowledge and modeling tools for multiple injections are far less advanced than for single-injection strategies
- Recent work on this project is filling some knowledge gaps

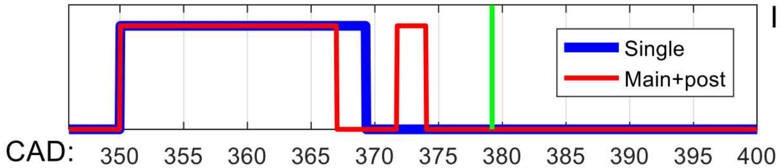
2014 AMR: Soot PLII is first in-cylinder evidence of post-jet interacting with main-injection soot

- Second injection alters the shape of the first-injection soot cloud and late cycle first-injection soot decreases, but why?

1. Enhanced oxidation?
2. Disrupted formation?
3. Displacement?



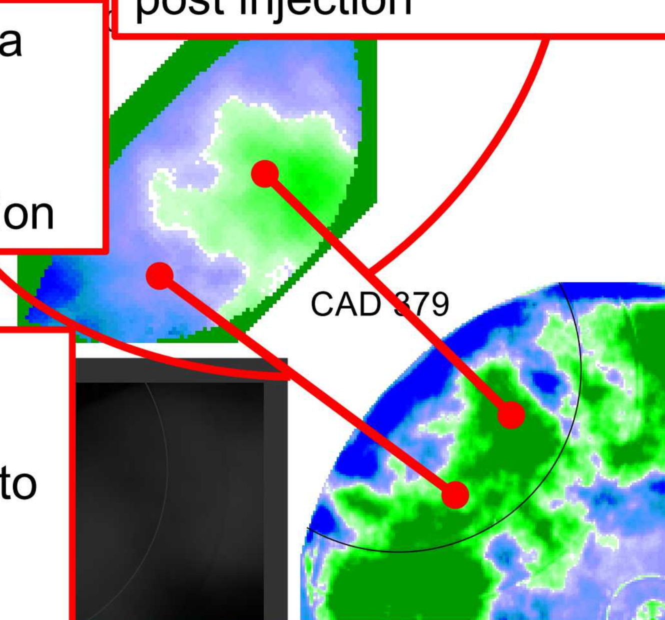
2017 AMR: KL & luminosity show increased T with second-injection + 2013 OH = (1) enhanced oxidation



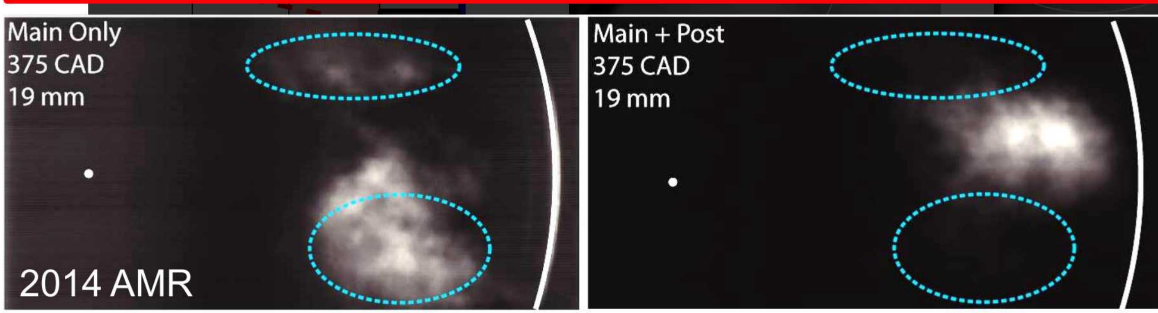
Within the post-jet, KL (f_vL) and NL both increase with post injection

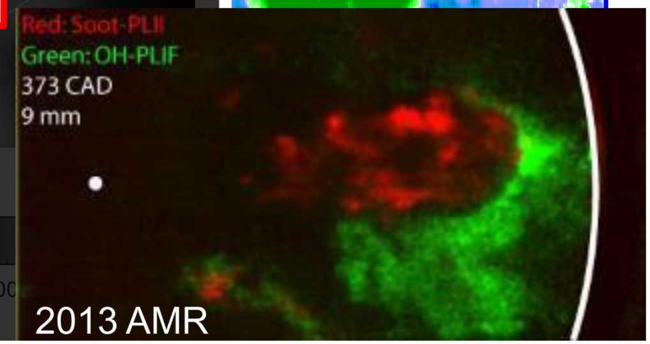
To the side of the post-jet, KL (f_vL) decreases with a post injection, while NL increases.

→ If NL = f(f_vL,T), then the post injection must increase T locally, which should aid soot oxidation



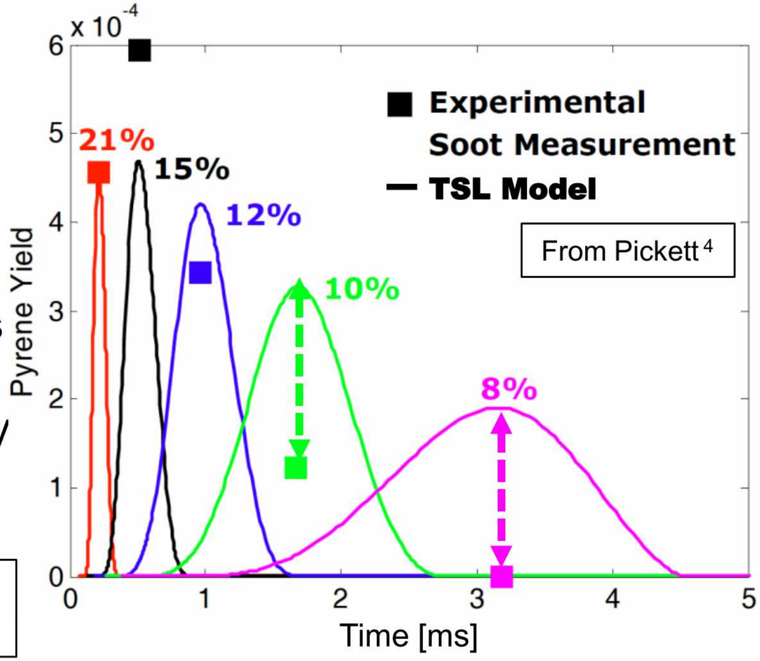
Consistent with previous soot PLII (2014 AMR) showing decreased soot to side of post-jet within laser sheet, and increased OH PLIF signal (green) to side of sooty jet (red). OH is a strong soot oxidizer typically formed in high-temperature regions.





Second-injection (2) disrupting soot formation can be observed at threshold-sooting LTC conditions

- In addition to oxidation, 2015 AMR models predict (2) disrupted soot formation
- We can measure soot, but discerning formation vs oxidation is difficult
- PAH & soot formation are strongly dependent on temperature[1], so (2) disrupted formation may be more evident at LTC conditions
- Also provides opportunity for much-needed improvements to PAH/soot models, especially at LTC conditions
  - "… **[PAH] formation pathways [are] fraught with uncertainties.**"[2]
  - "The measured temperature … where PAHs appear first was … **higher than temperatures predicted by a soot model**."[3]
  - Soot models can reproduce O_2 trends, but they significantly over-predict soot/PAH at LTC conditions.[4,5]

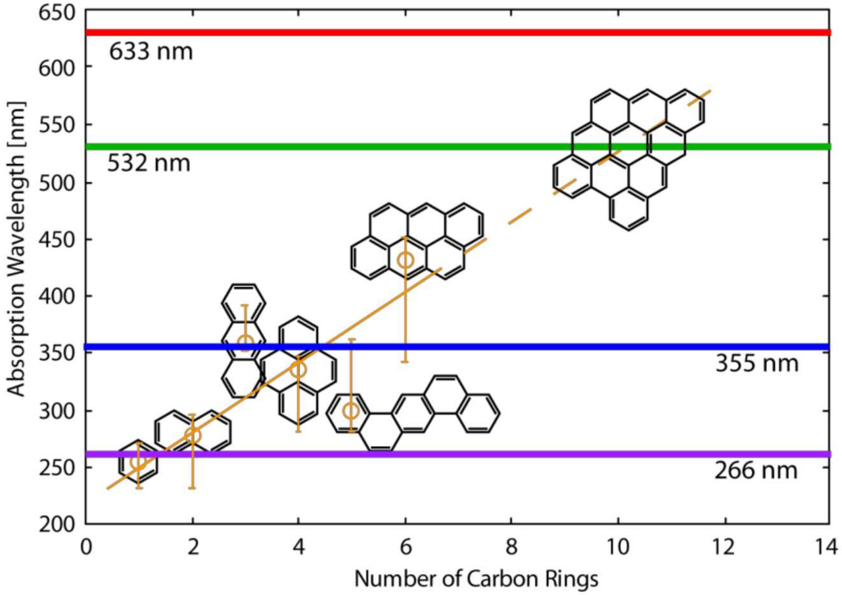


[1] Ciajolo et al, Proc. Comb. Inst. 26: 2327-2333 (1996)
[2] Violi et al, osti.gov/servlets/purl/1351404 (2017)
[3] Kamimoto et al., Int. J. Engine Res. 18(5-6):397–399 (2017)
[4] Pickett, DOE AMR (2006)
[5] Vishwanathan & Reitz, Fuel 139:757-770 (2015)

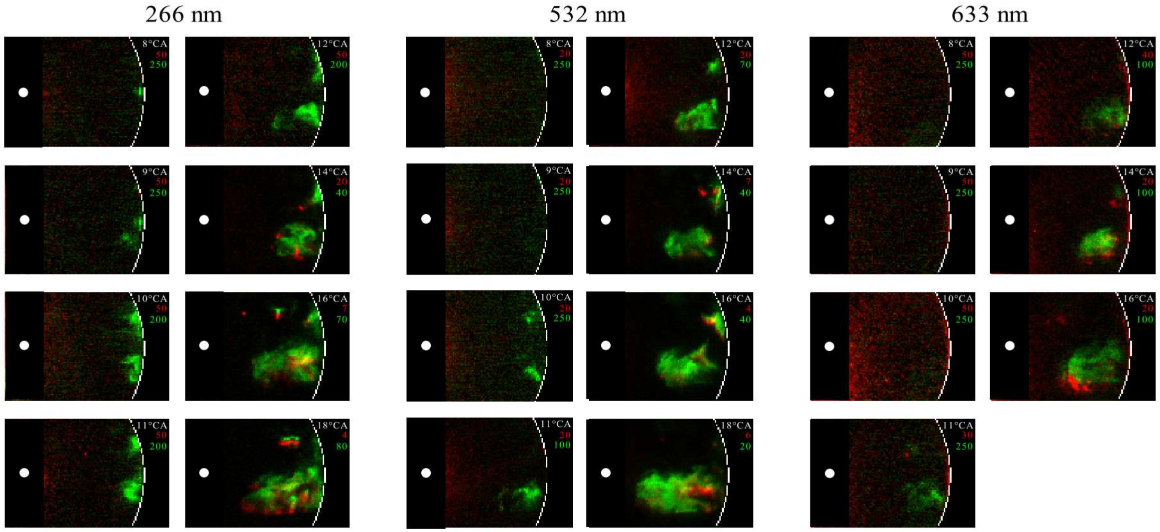
Joint DOE/NSF project with UW aims to improve PAH and soot modeling from conventional diesel to LTC conditions

2014 AMR: Multi-wavelength LIF at 1 LTC condition shows PAH & soot growth for model improvement

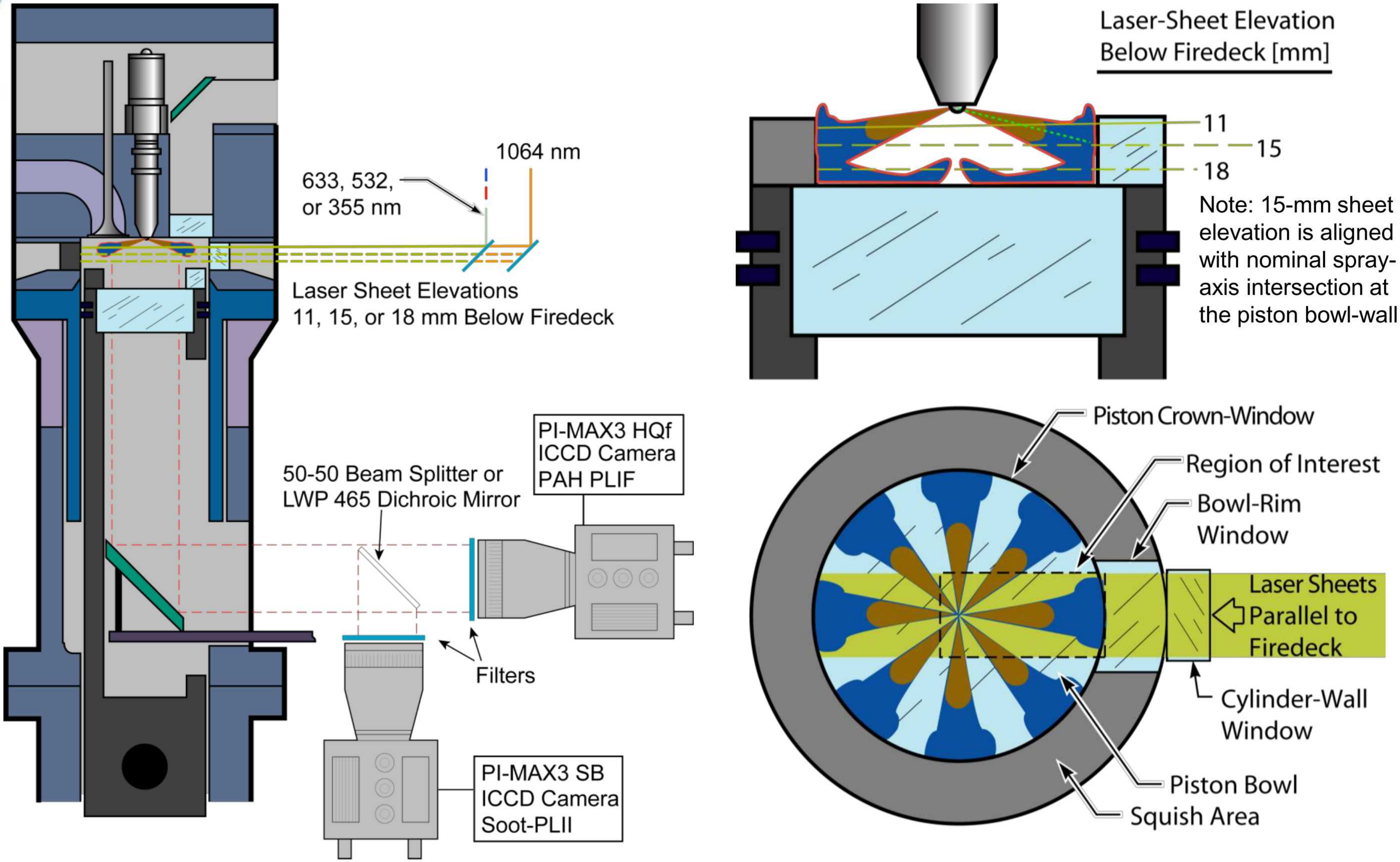
- As poly-aromatic hydrocarbons (PAH) soot precursors grow and accumulate more carbon/aromatic rings, their absorption spectra shift to longer wavelengths
- Laser-induced fluorescence (LIF) using different excitation (laser) wavelengths (266, 355, 532, 633 nm) can probe growth of PAH
- Combined with laser-induced incandescence using IR laser (1064nm), can also probe soot



- 2014 AMR: PAH LIF (green) at 3 laser wavelengths shows LTC PAH growth and conversion to soot (red)
- 2014 dataset is limited to single injection, PAH inception only, and one laser sheet elevation

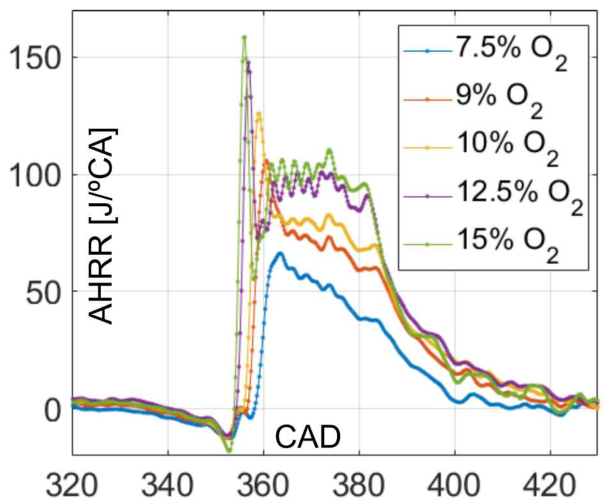


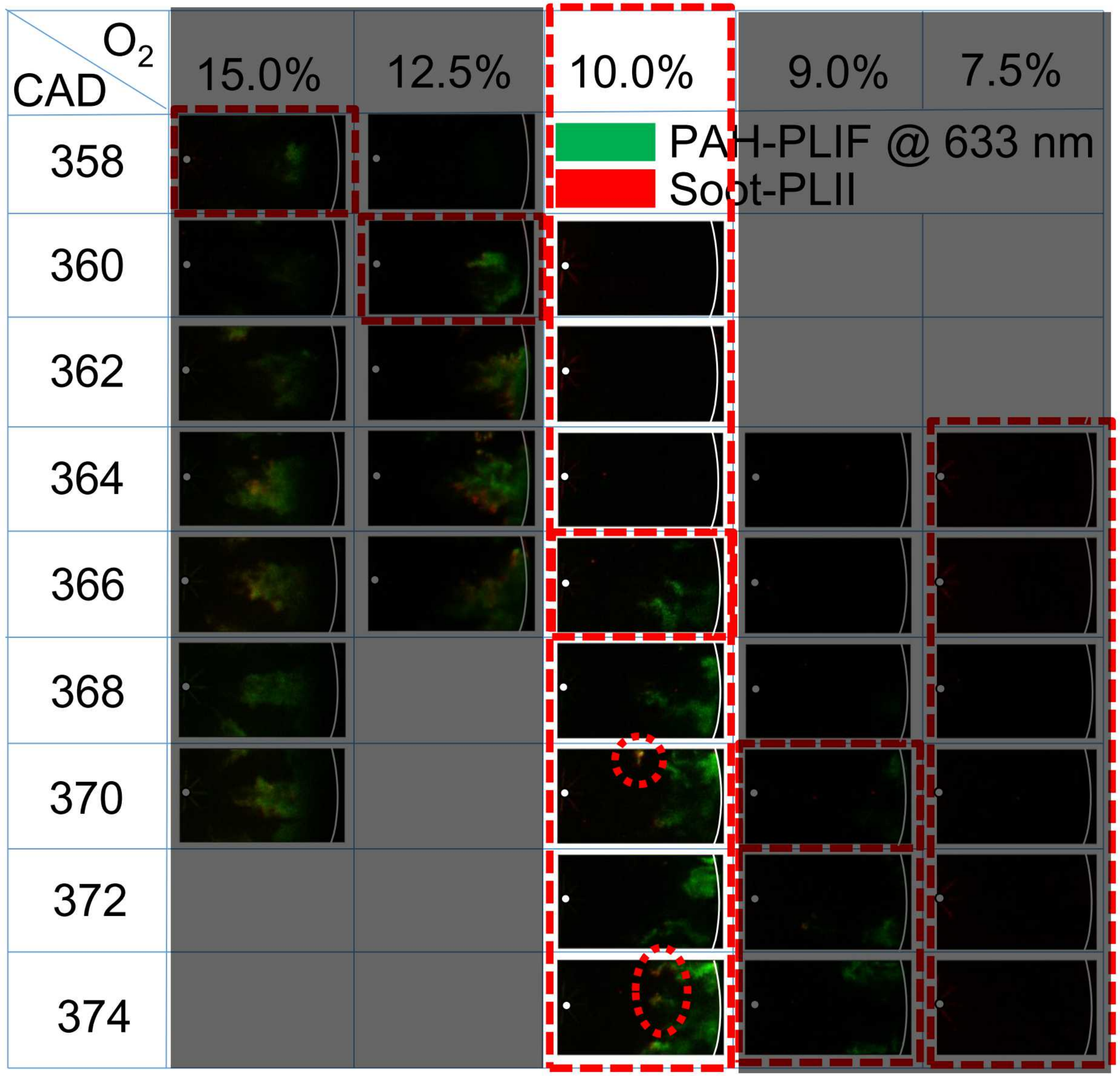
Planar PAH LIF and soot-LII at three slices through 3-D multi-injection and bowl-wall interactions



Single injections: N_2 dilution retards PAH/soot; Use 10% O_2 (threshold soot) for multi-inj. study

- Large **PAH** inception from 358 CAD for 15% O_2 to 370 CAD for 9% O_2
- 7.5% O_2 condition has no **PAH** or **soot**
- 9% O_2 condition has **PAH** but no **soot**
- 10% O_2 condition has **PAH** & borderline **soot;**
  - **Use 10% O_2 for multiple injection experiments**

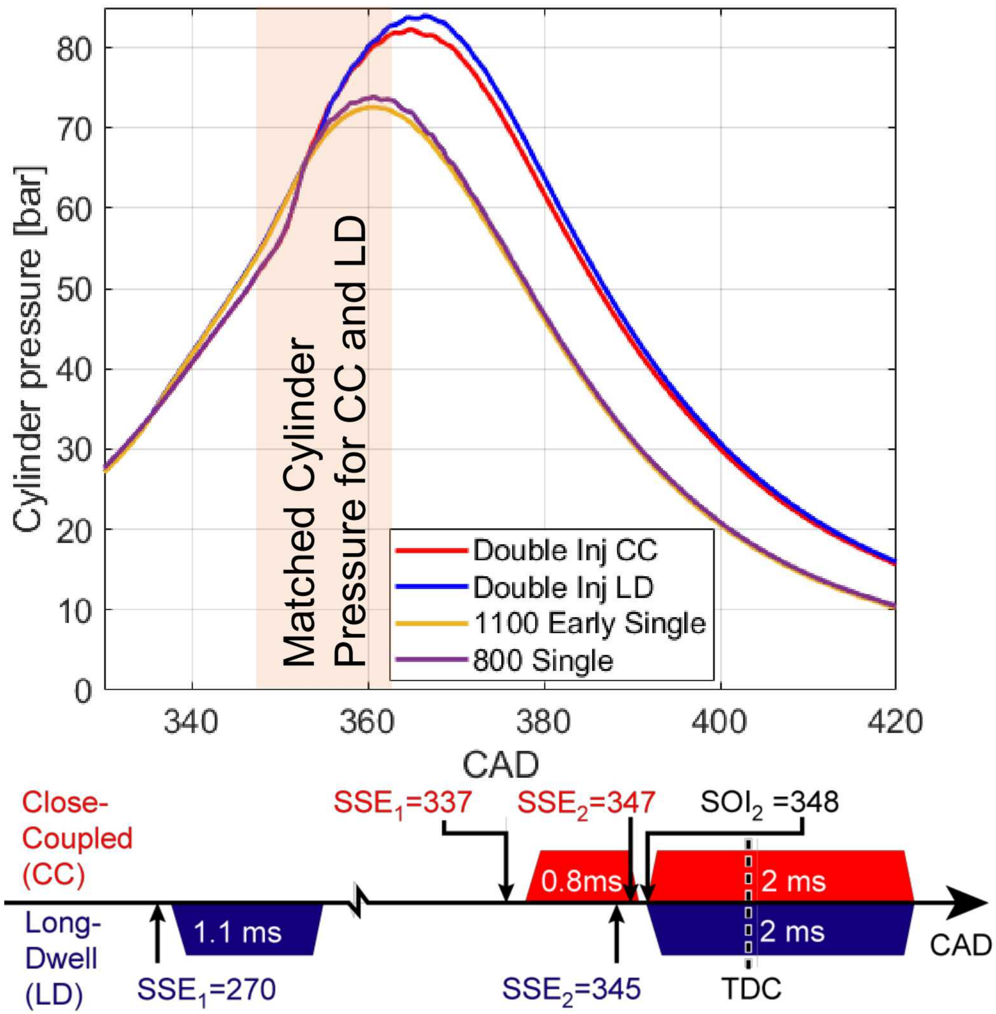




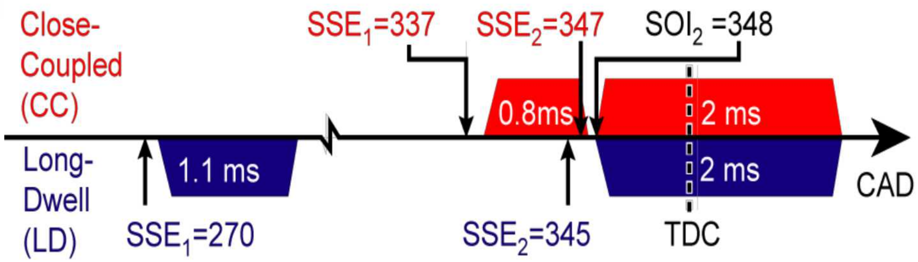
Use short- and long-dwell multiple injections at same cylinder pressure to probe jet-jet interactions

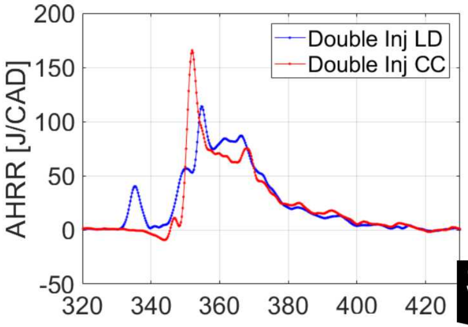
Two multiple-injection schedules tested:

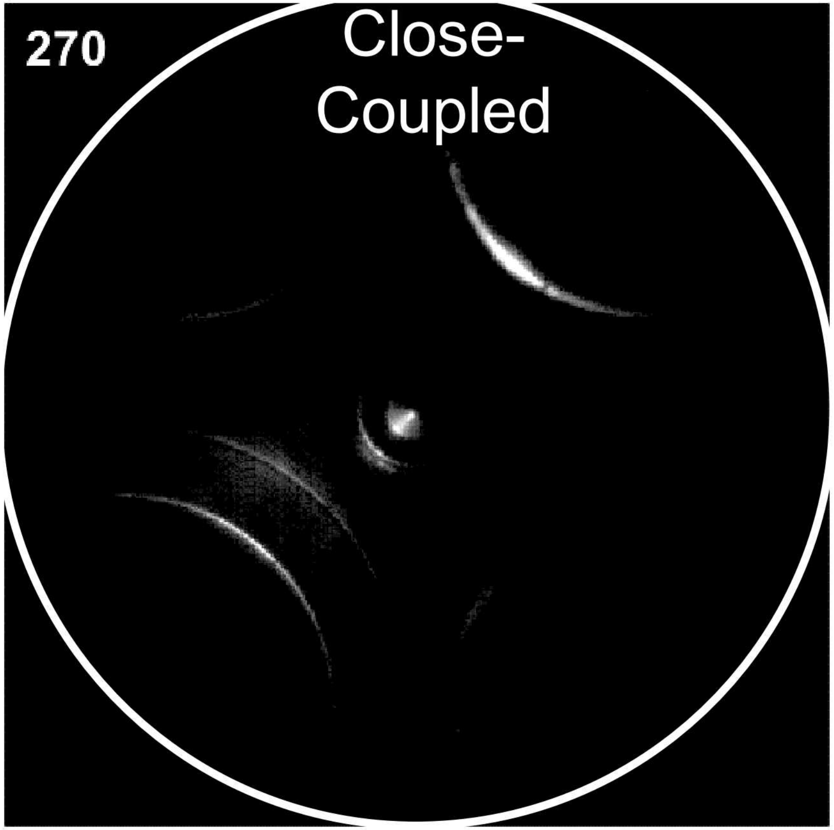
- Close-coupled (CC) condition with short dwell has second injection penetrating into residual jet / turbulence
- Long-dwell (LD) condition has second injection penetrating into more uniform mixture with less residual jet / turbulence
  - Adjust first-injection duration to match cylinder pressure, and hence compressed gas temperature, in CAD range of PAH inception

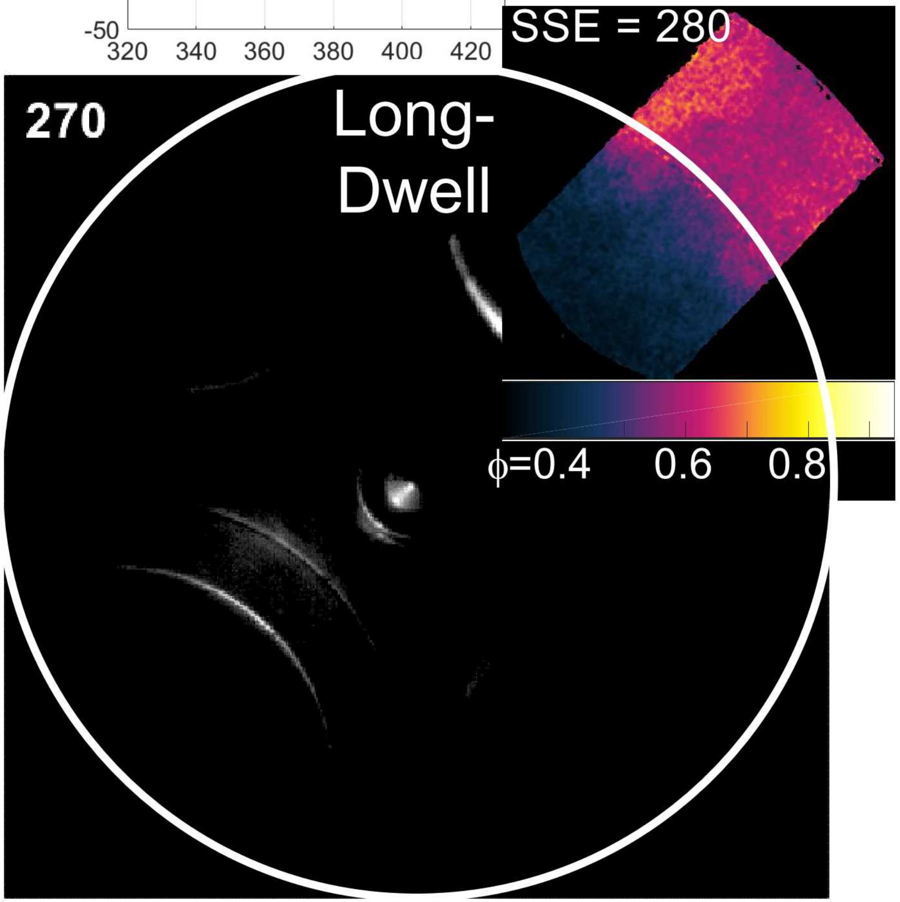


Use short- and long-dwell multiple injections at same cylinder pressure to probe jet-jet interactions



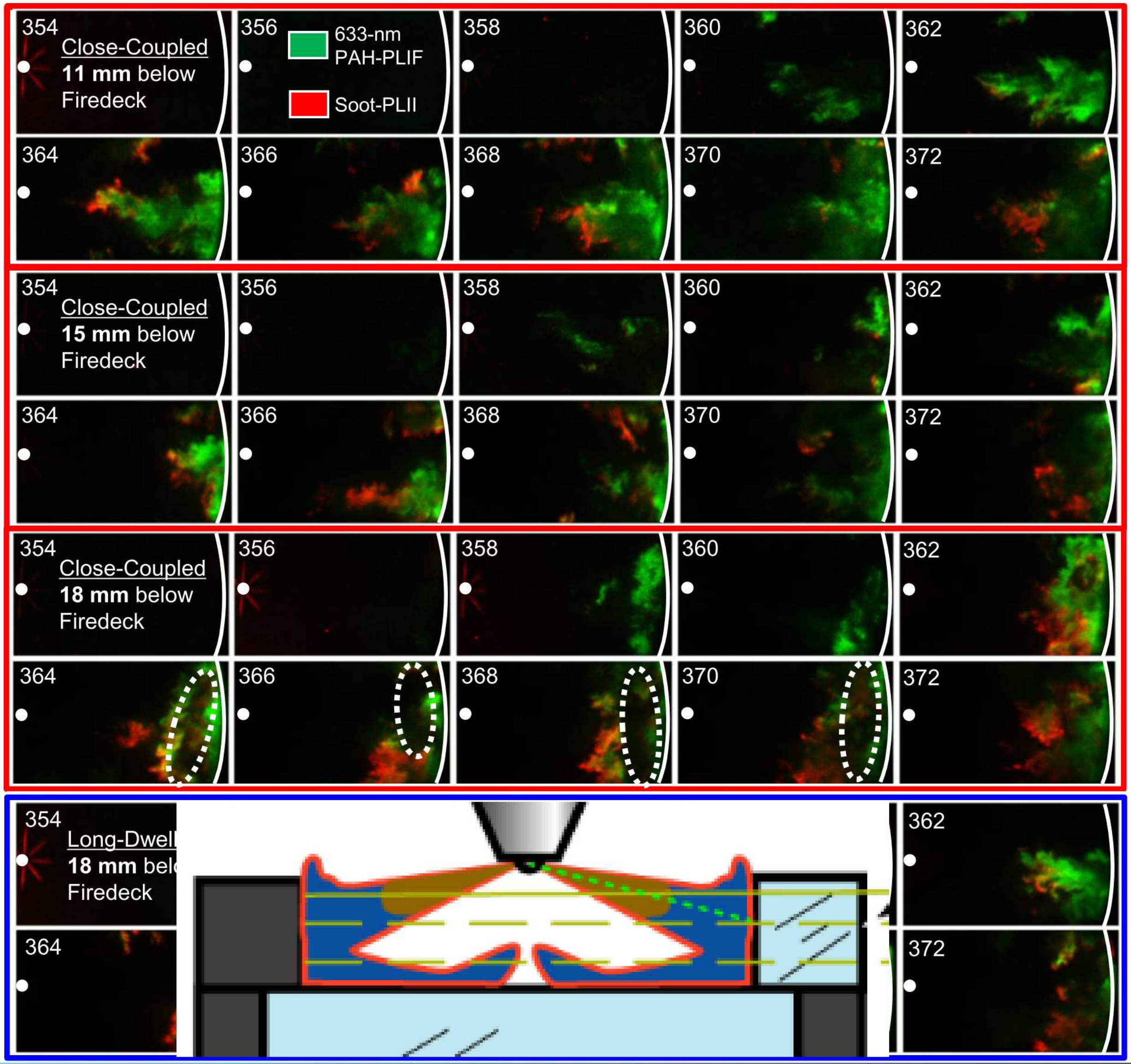






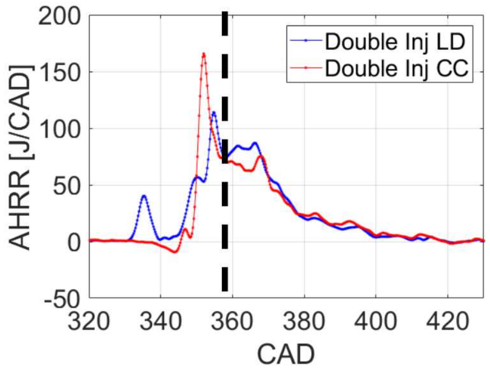
Large PAHs fill downstream jet and is consumed when soot appears, at jet periphery/diffusion-flame

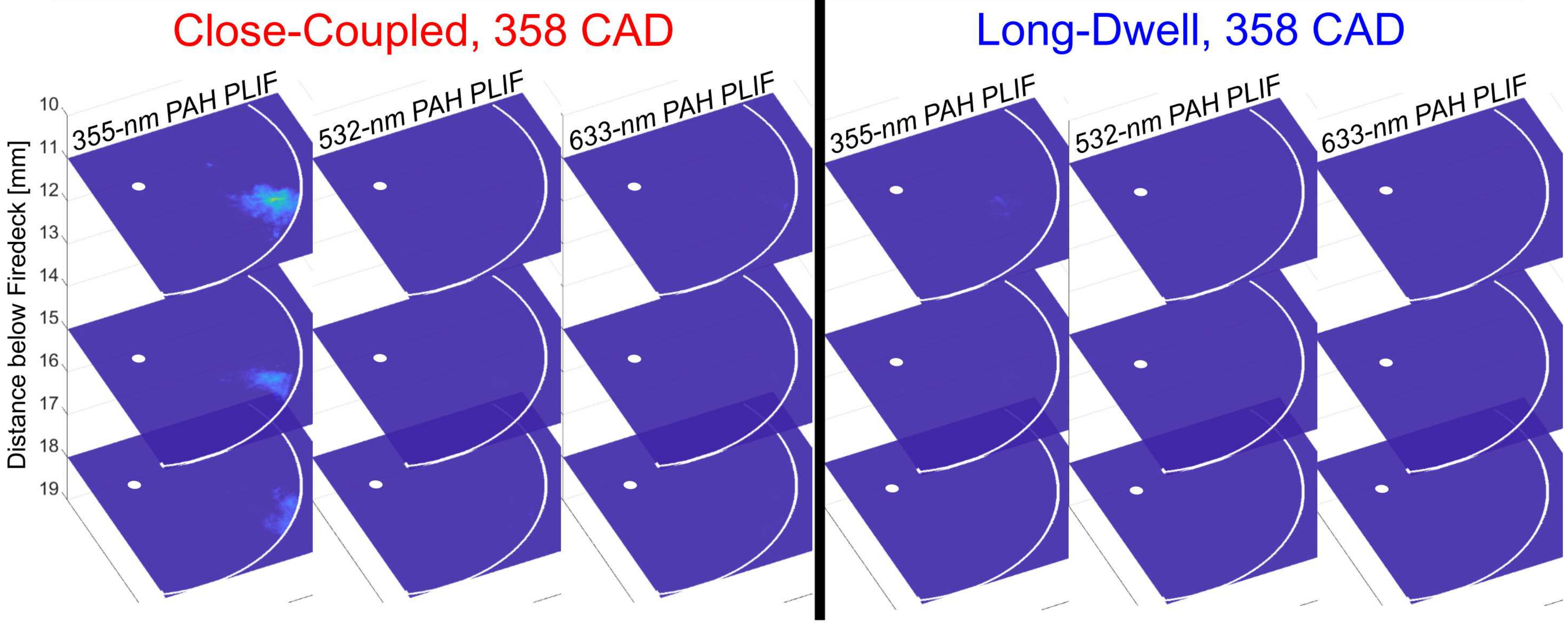
- Large **PAH** fill down-stream jet to bowl wall
- **Soot** appears later, upstream, near jet periphery, little overlap (**yellow**) with **PAH**
  - T high enough for soot only at diffusion flame?
  - All PAH consumed when soot forms?
- At lowest elevation, gap regularly appears
  - Could be due to **(3) displacement** by second injection, or jet-wall interactions at laser sheet
  - Gap does not appear for long-dwell injection: Residual jet may be factor in PAH/soot distribution



Small PAH appear first and earlier for close-coupled injections, suggesting interaction with residual jet

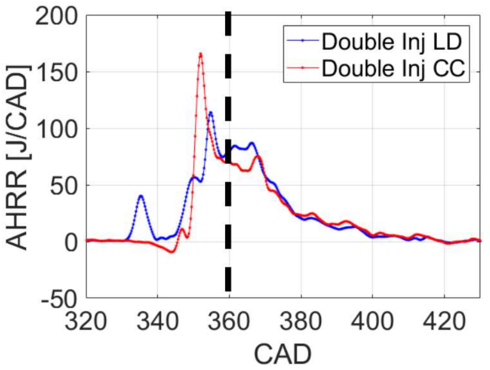
- In ensemble-averaged CC images, small PAH (355-nm PLIF) appear before large PAH (532- or 633-nm PLIF)
- PAH appear later for **LD** than **CC**, even though early cylinder pressure is matched and **LD** ignites earlier
  - Suggests important interaction with residual jet (e.g., locally hotter/richer residual gas, turbulence)

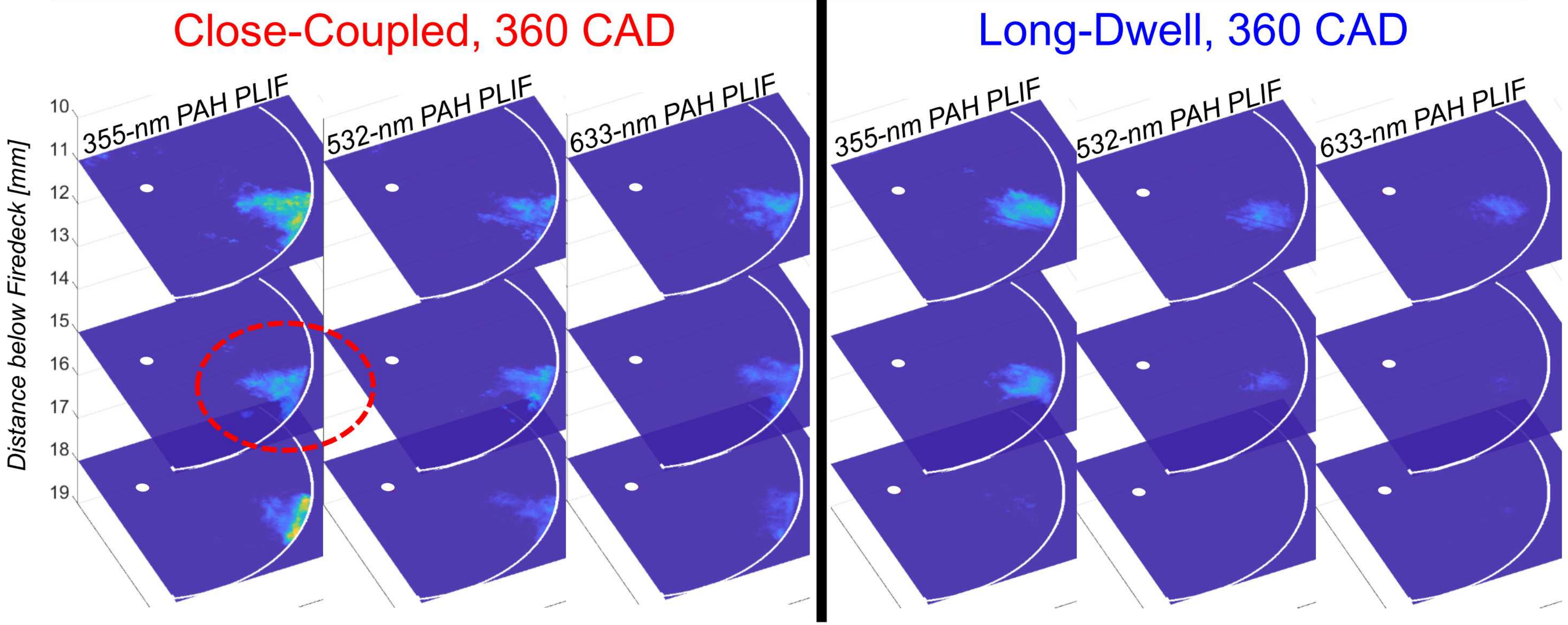




Larger PAH quickly appear near the bowl wall; much stronger PAH-PLIF in bottom of bowl for CC than LD

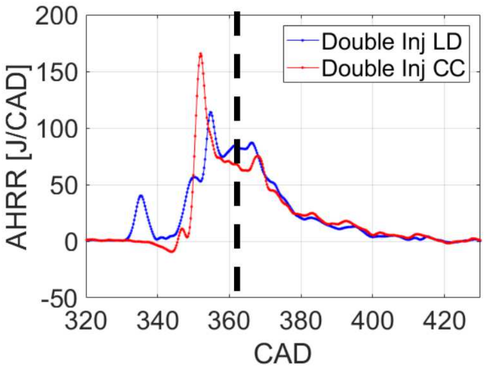
- 2 ºCA later in the ensemble-averaged images, larger PAH (532- or 633-nm PLIF) fill the jet to the bowl wall
- Both small and large PAH continue to lag for the long-dwell condition, especially at low sheet heights
  - Shorter dwell condition has stronger small-PAH signal (355-nm PLIF) in bottom (and top) planes ("hollow" middle)

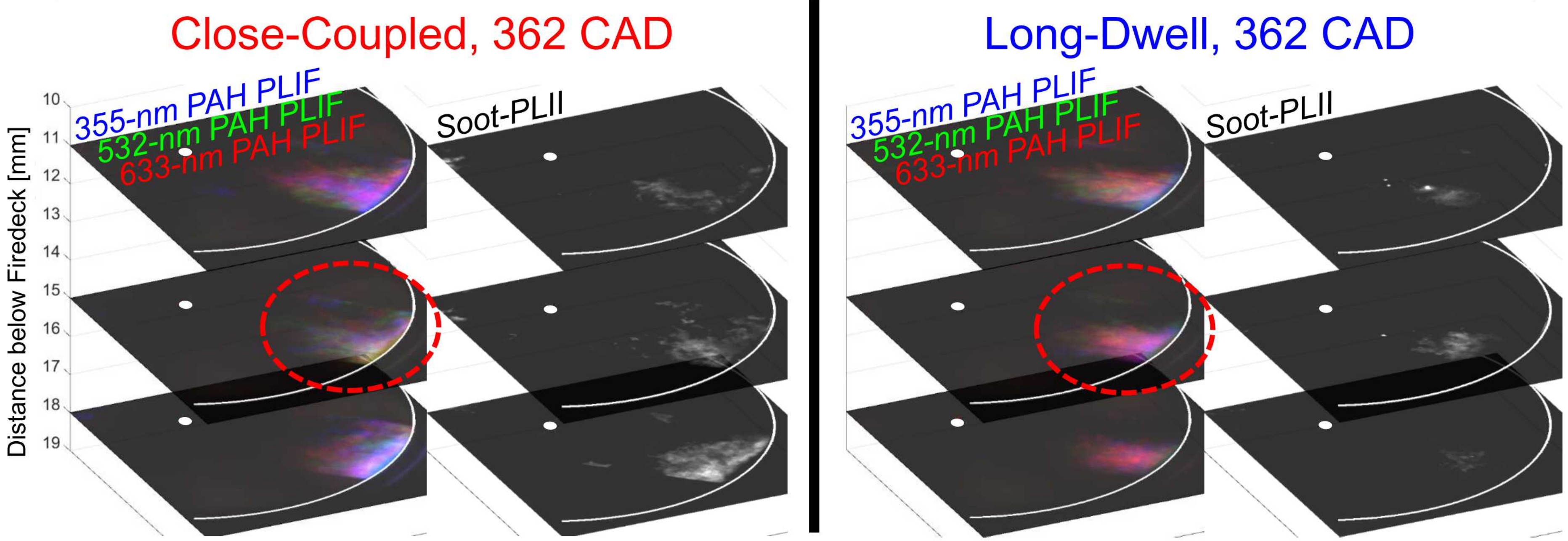




Structural differences in PAH and LII in the three sheets for CC and LD jets persist later into cycle

- Tri-color RGB images show overlay of ensemble-averaged 355-nm, 532-nm, and 633-nm PAH PLIF
  - 355+532 nm, 532+633 nm, 355+633 nm, 355+532+633 nm
- 2 ºCA later, weaker PAH-PLIF & soot-PLII emission persists in the center of the CC jet, while the LD jet is more uniform or even stronger in middle sheet
  - In addition to real physical differences in CC and LD jets, may be optical artifact (e.g., signal trapping, laser attenuation)





Swirl brings separated ensemble-averaged adjacent jet into field of view for LD injection, but not for CC

- 4 ºCA later, the weak swirl flow (0.5 swirl number) transports an adjacent jet into the field of view for the **LD** condition, but not for the **CC** condition
  - Such a separate and distinct shape in ensemble-averaged images indicates a repeatable occurrence (both PAH & soot)
- Suggests that jet-jet interactions along the bowl wall for CC create a more uniform mixture in the downstream jet, even though first LD injection is more mixed