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Characterizing Ignition and Sooting Behavior in High-Pressure Sprays with Multiple Injections of n-dodecane

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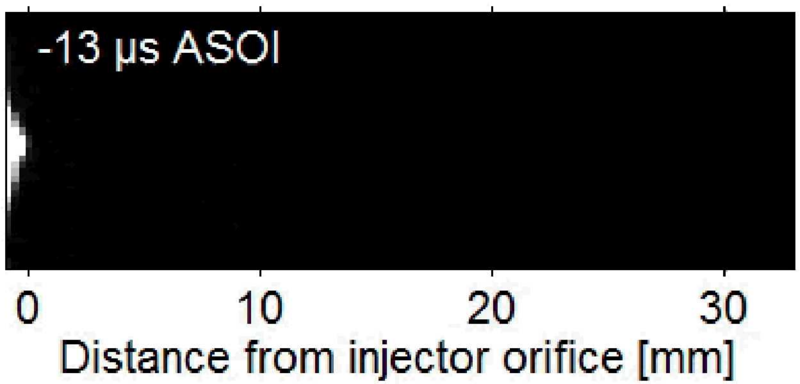
Outline

- Background and Motivation
- Experimental Methods & Conditions
- Results
  - Unique ignition characteristics of Spray A
  - Typical pressure traces
  - Address 900-K, 800-K, and 750-K cases independently (brief discussion about existing chemical models)
- Summary/Conclusions

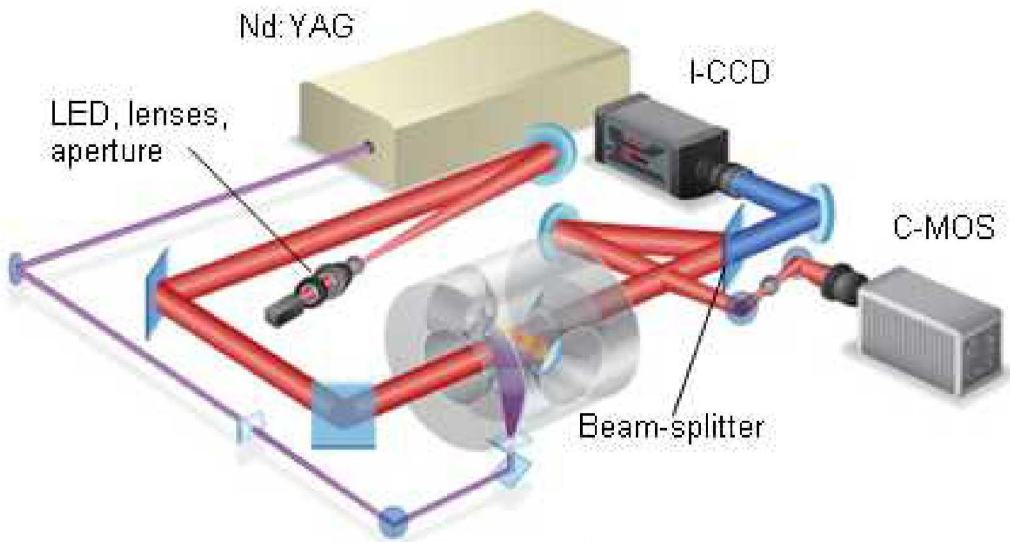


Background and Motivation

- **Multiple injection** strategies are now commonly used in direct-injection CI engines (reduce emissions and noise and optimize fuel economy)
- **Pre- and pilot-injections** can reduce NOx, CO, UHC and noise but may lead to increased soot, which can be addressed with a **post-injection**
- **Multiple injections** can be tailored to **reduce heat loss**
- Optimization of **multiple injection** strategies for **low-temperature Combustion (LTC)** necessary
  - High EGR, low CR, alternative fuels
- **ROI profile** needs special attention
  - Shortened injection duration, dwell time, hydraulic pressure waves modify injection profiles
  - Throttling during opening and closing reduces mass injected relative to single injection
- Fundamental studies have been performed to characterize the velocity, mixing, and combustion of subsequent injections
  - “slipstream” and enhanced mixing (turbulence)
  - Dwell impacts combustion of second injection
- What are the possible **states of the ambient as second injection penetrates? How might this influence ignition and soot formation?**
  - (1) non-reacted mixture
  - (2) first-stage ignition products
  - (3) second-stage (high-T) combustion products without soot
  - (4) second-stage (high-T) combustion products with soot

High-speed schlieren imaging and single-shot CH_2O PLIF for ignition characteristics in a split injection scenario

- High-pressure, high-temperature pre-burn spray vessel capable of reaching the thermodynamic conditions of modern compression ignition engines
- Large optical windows offer multiple simultaneous views of the event



- Single-hole Bosch fuel injector from family of ECN injectors (s/n #370)
  - Injection pressure: 150 MPa
  - Fuel: n-dodecane ($C_{12}H_{26}$)
- High-speed pressure transducers (speed of sound corrected ID and AHRR)
- High-speed (150 kHz) schlieren imaging
  - Cool flame (low-temperature ignition)
  - High-temperature ignition
  - Vapor penetration
- Single-shot formaldehyde (and PAH) PLIF with 355-nm (100-mJ/pulse) excitation
  - Select timings for multiple identical injection events

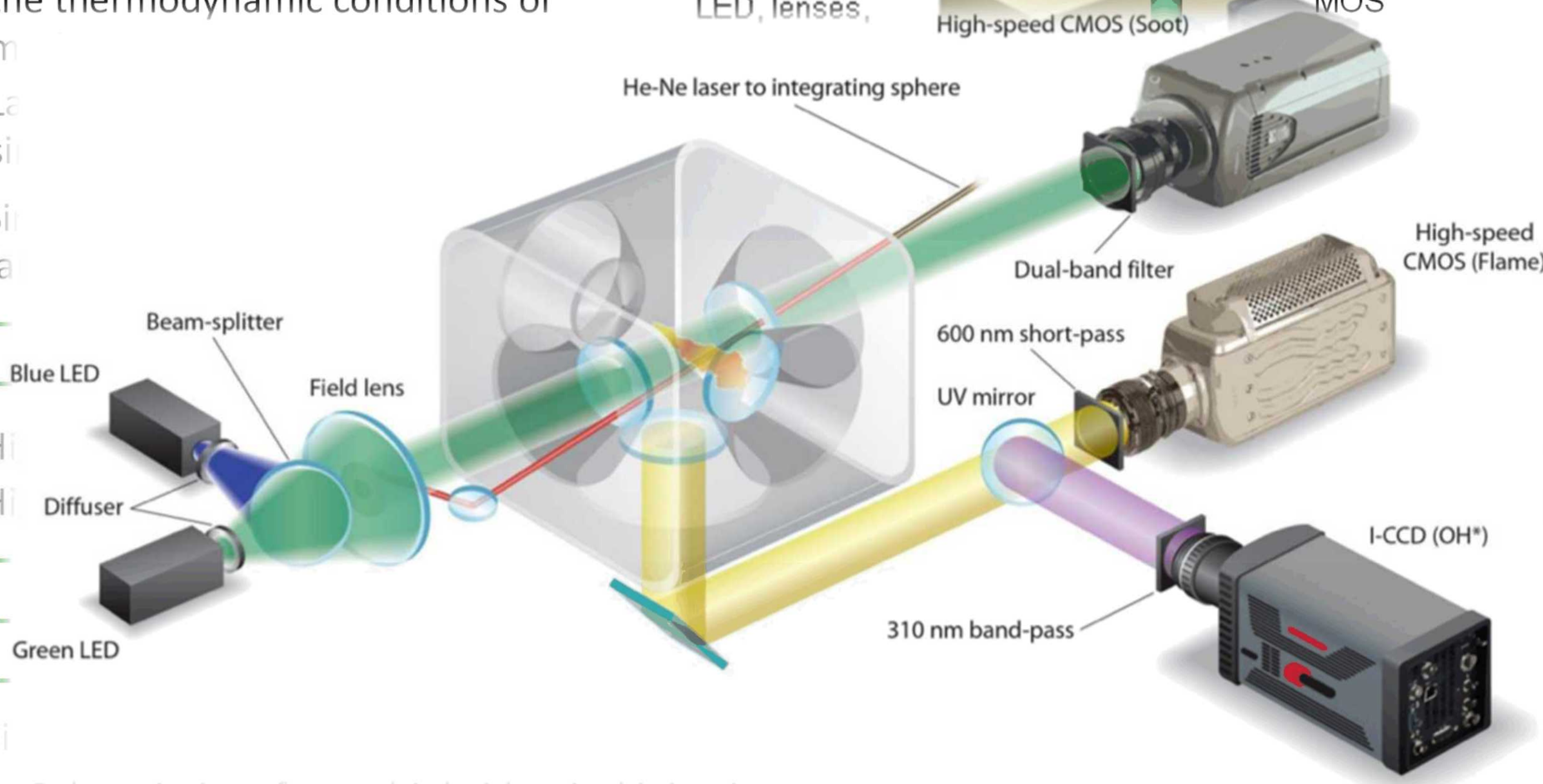
High-speed soot extinction imaging coupled with high-speed chemiluminescence and schlieren

- High-pressure, high-temperature pre-burn spray vessel capable of reaching the thermodynamic conditions of m

Nd:YAG

LED, lenses,

C-MOS



sight

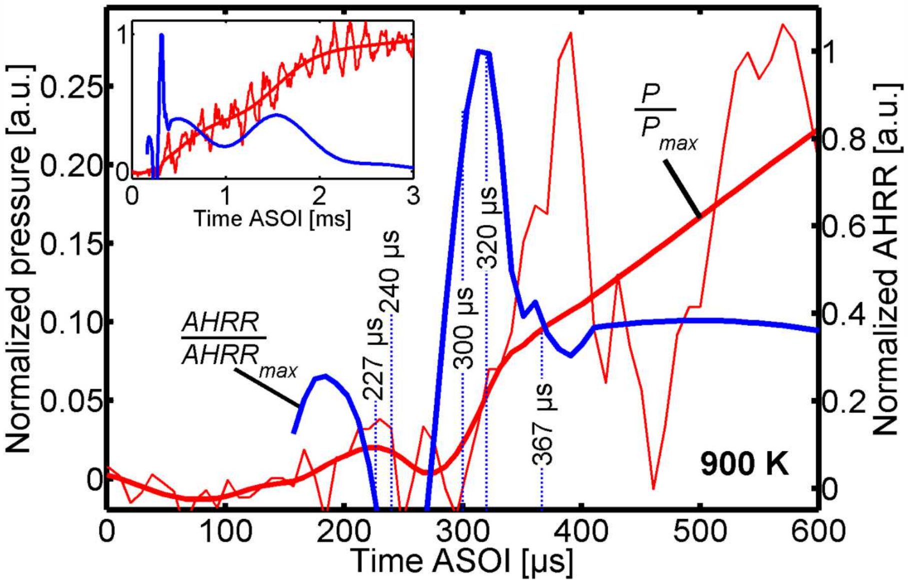
aging

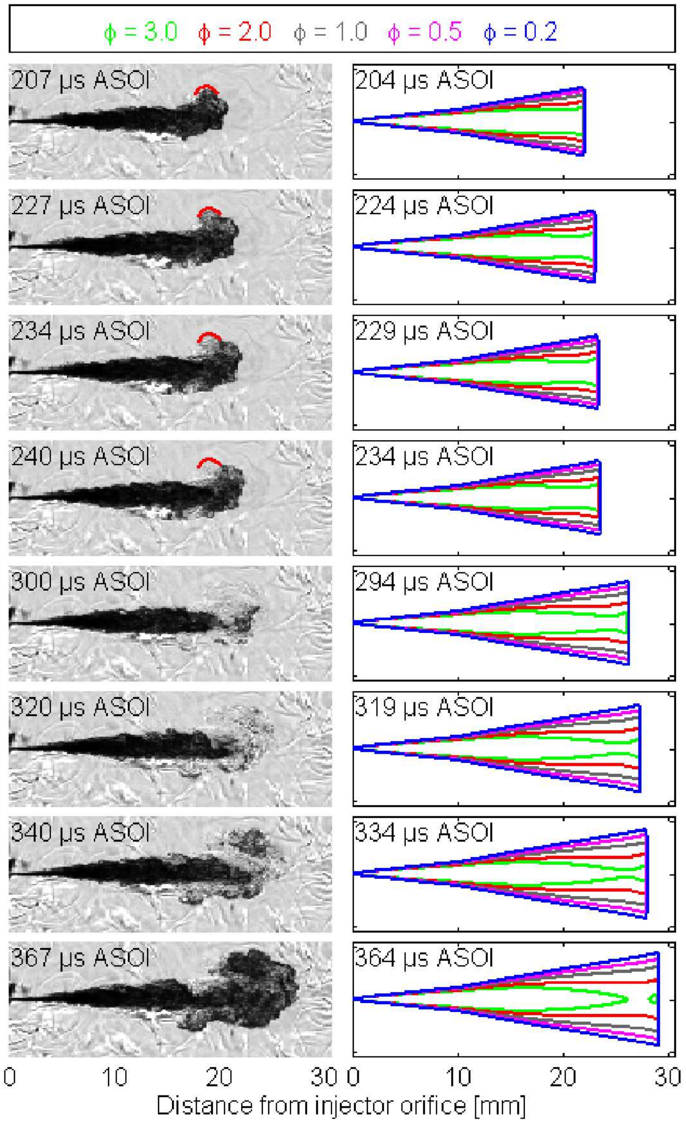
– Select timings for multiple identical injection events

- High-speed chemiluminescence imaging (600 nm SP filter) for ignition delay, quasi-steady lift-off length
- High-speed extinction imaging for optical thickness (soot mass); time- and ensemble averaged for tomographic reconstruction and SVF (f_v)

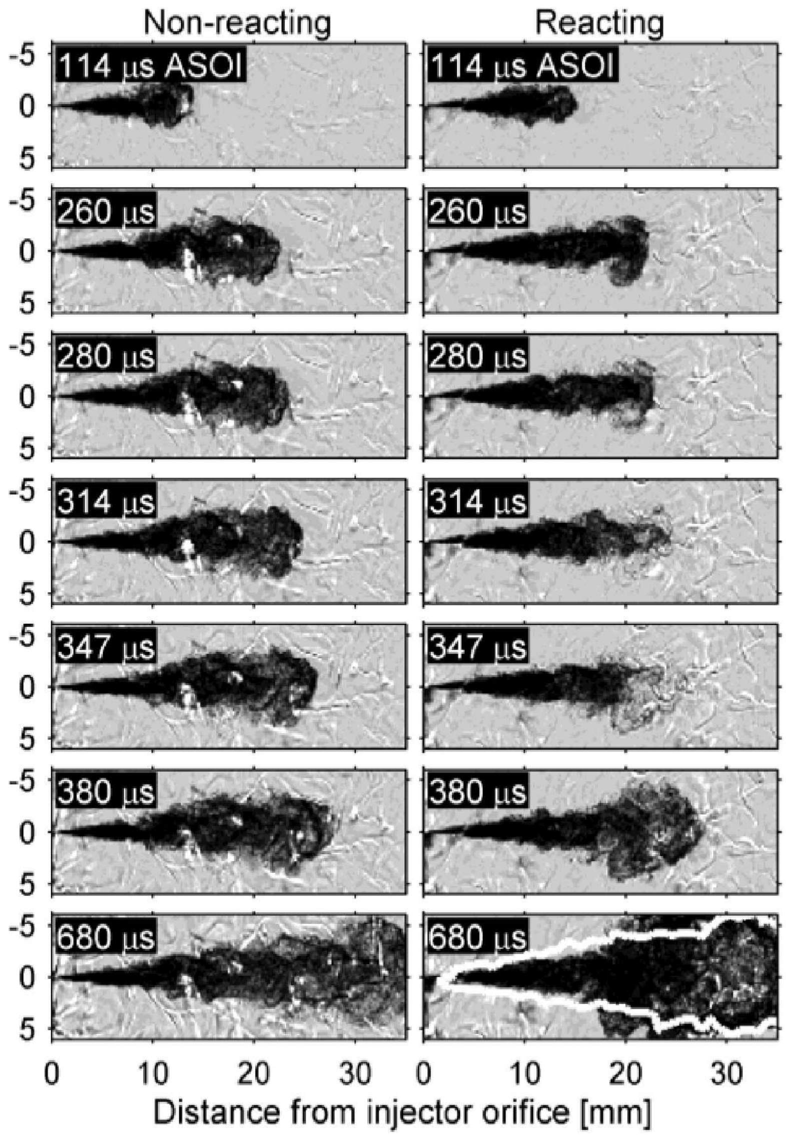
High-speed schlieren imaging demonstrates that first-stage ignition occurs in the radial periphery of the spray head for the Spray A condition

- Pressure transducer captures first-stage (cool-flame) heat release
- Pressure rises above noise near 220 μs ASOI
- Peak AHRR (filter dependent) just prior to 2nd stage ignition as observed in schlieren
- **More evidence of cool-flame initiating in radial periphery (large-scale organization)**

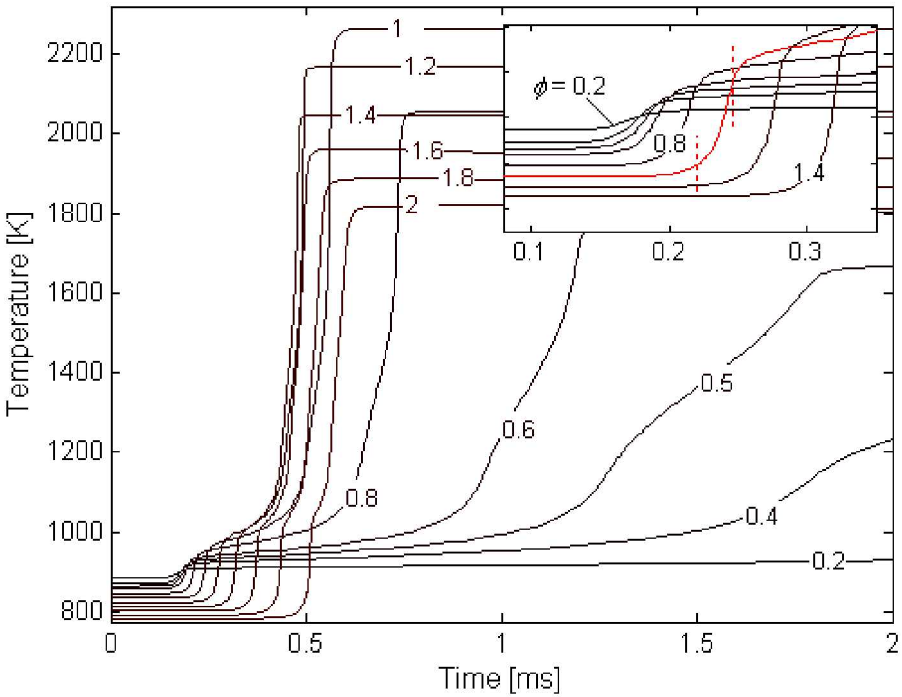




High-speed schlieren imaging demonstrates that first-stage ignition occurs in the radial periphery of the spray head for the Spray A condition



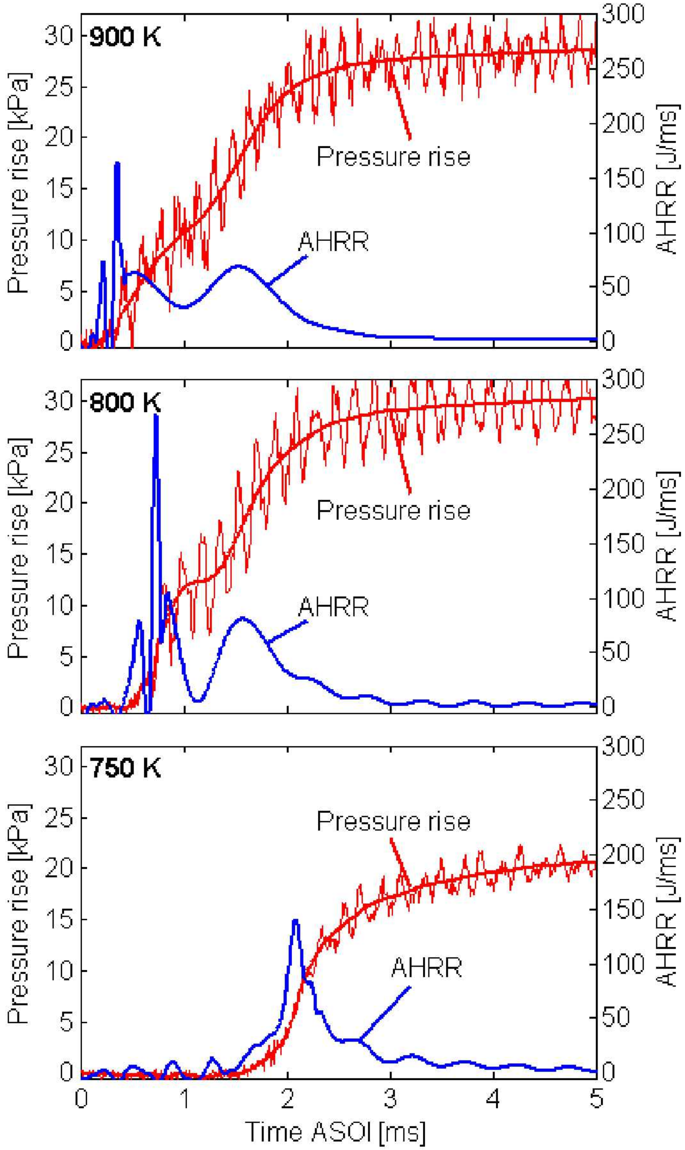
- Radial periphery is more fuel lean and therefore higher temperature (based on adiabatic mixing assumption).
- Closed homogeneous reactor simulations indicate leaner regions ignite first.



Skeen et al. *Proc. Comb. Inst.* 35 (3), 2015

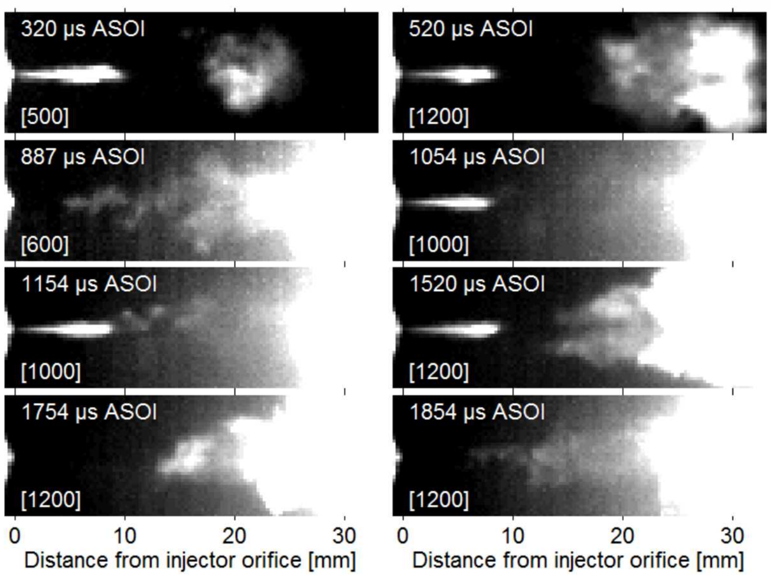
Three distinct regimes for split injection ignition depending on ambient temperature

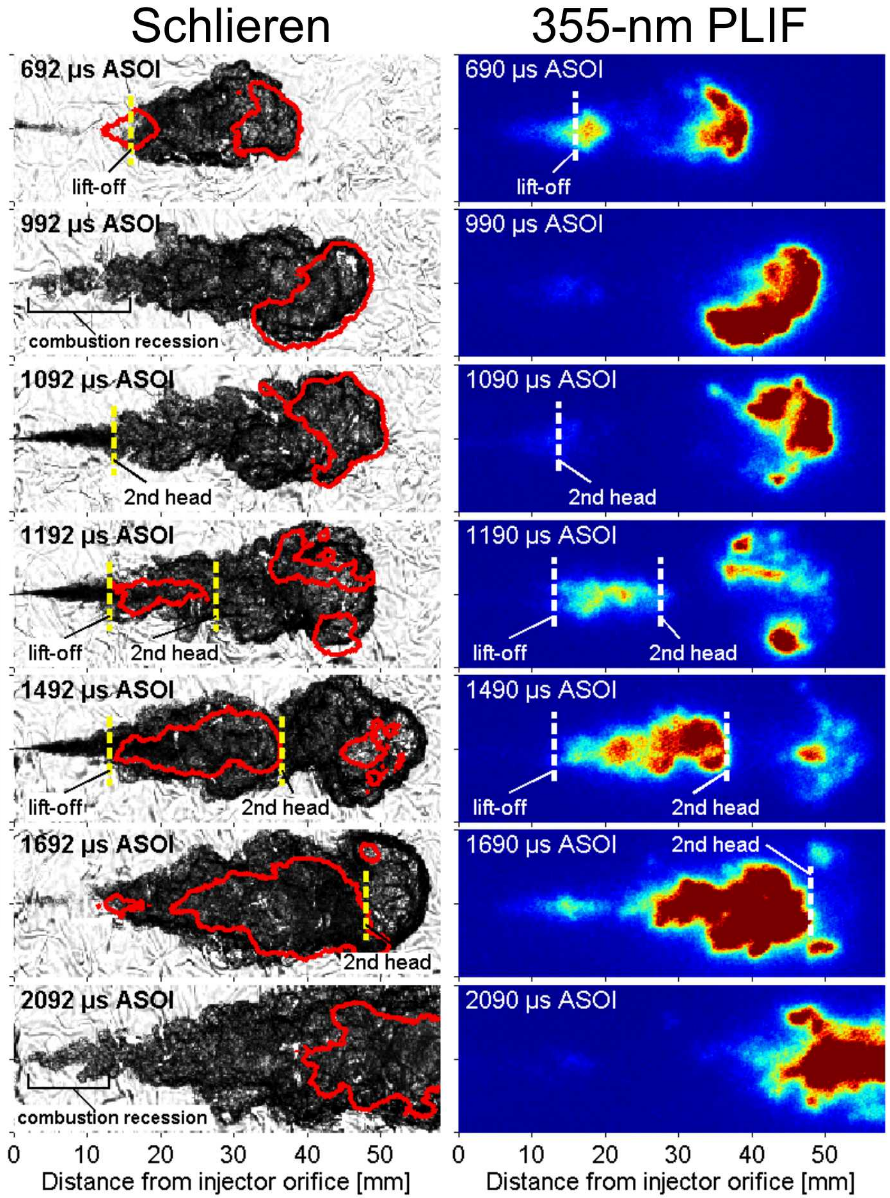
- 900 K ambient
  - Combustion recession leaves high-temperature products (potentially including radical species) near injector
  - 2nd injection ignites near the liquid length
- 800 K ambient
  - No combustion recession; however, cool-flame (1st stage) products remain resulting in earlier ignition of 2nd injection
  - 800 K consistently shows largest peak AHRR (larger volume of combustible charge)
- 750 K ambient
  - Two injections are rarely distinguishable in AHRR
  - Second injection undergoes high-temperature ignition prior to first injection



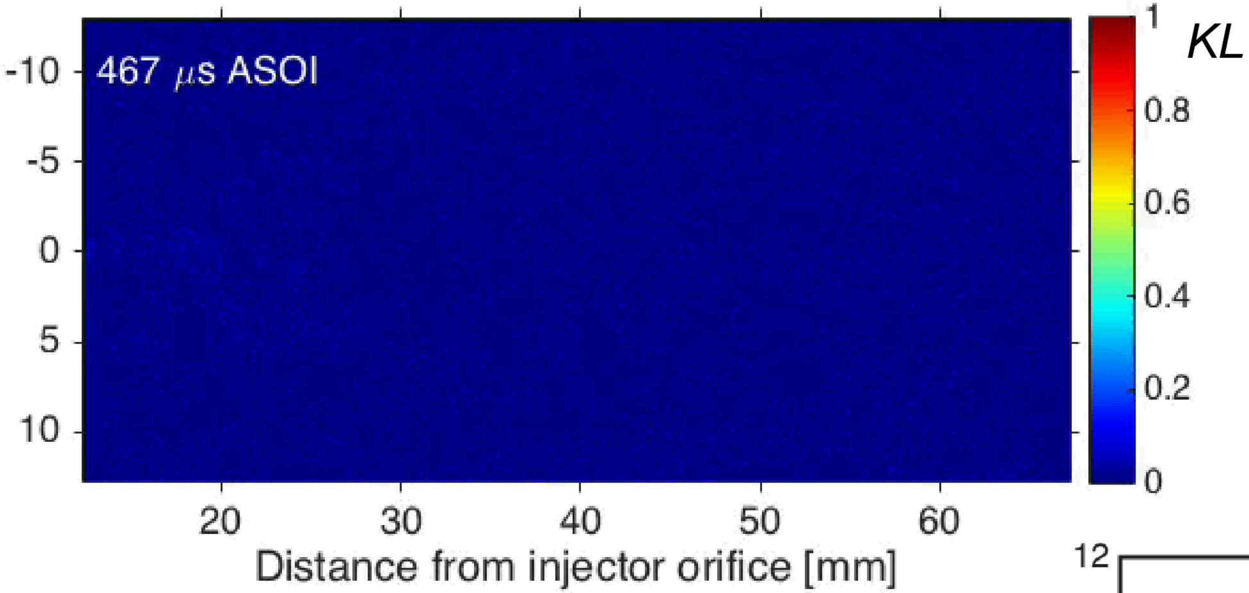
900 K End of 1st, Ignition of 2nd Injection

- 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

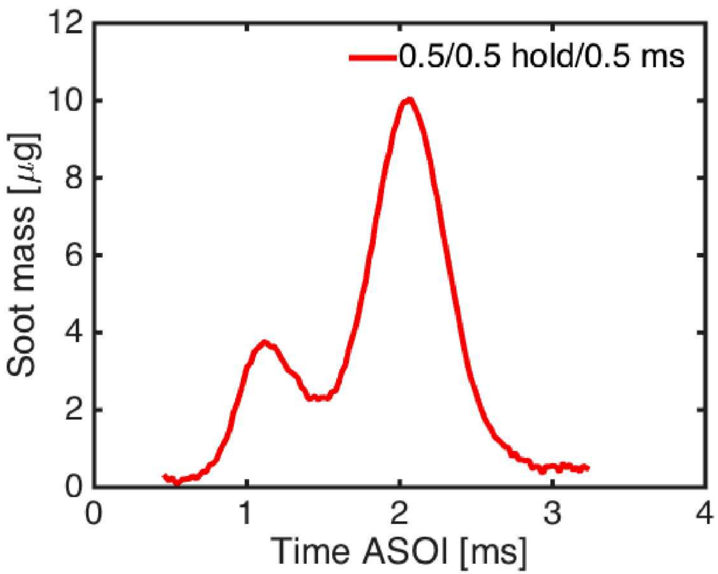




Split injection case: Soot mass more than doubles in second injection

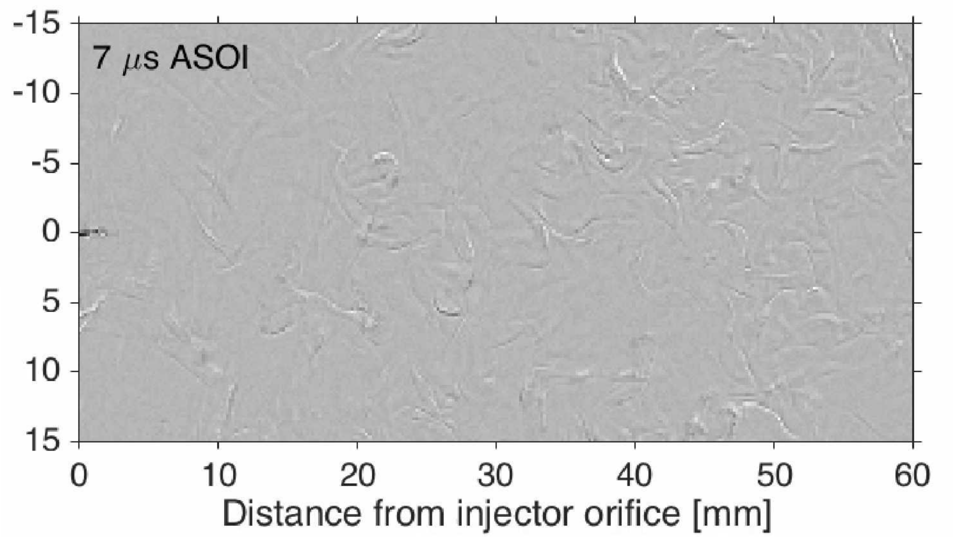


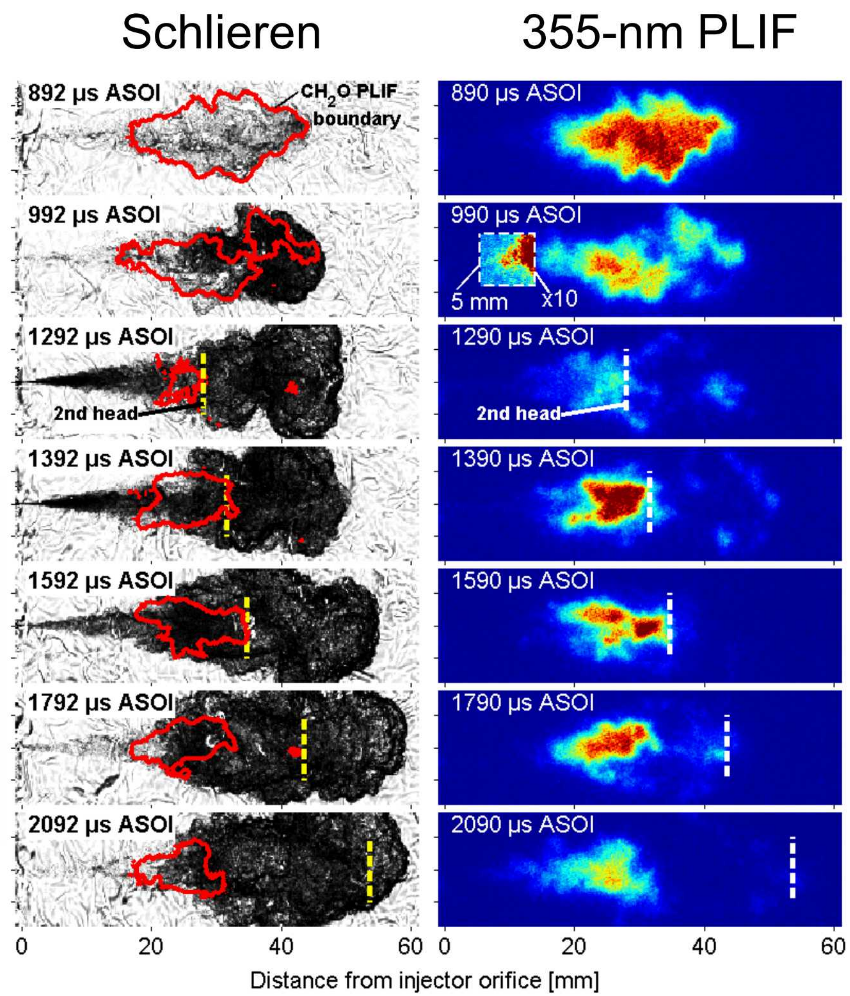
- Early ignition near liquid length results in more fuel-rich conditions locally and therefore greater soot formation in second injection.



800 K End of 1st, Ignition of 2nd Injection

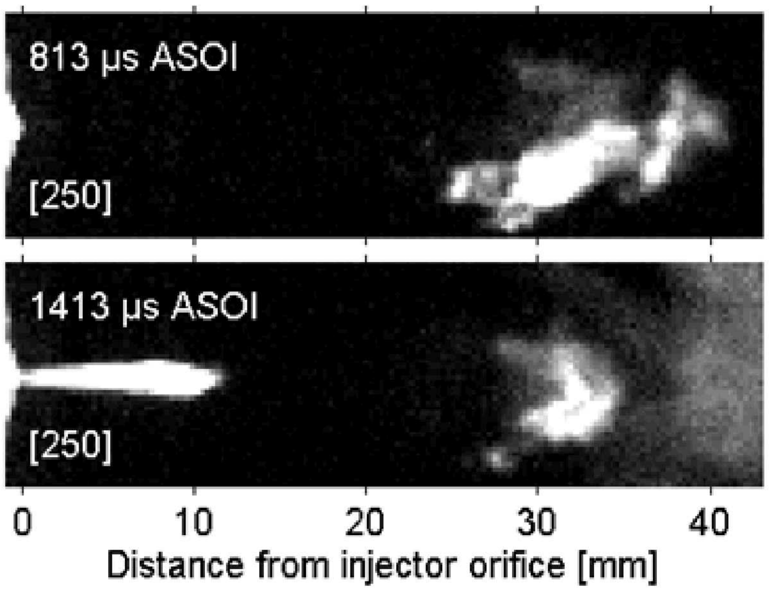
- Softening of schlieren over large region corresponds to large region of 355-nm PLIF
- After end of first injection, CH_2O PLIF observed above background as close as 5-mm from injector tip
- No combustion recession
- PLIF shows narrower spreading angle for 2nd injection
- Still observe earlier ignition for second injection





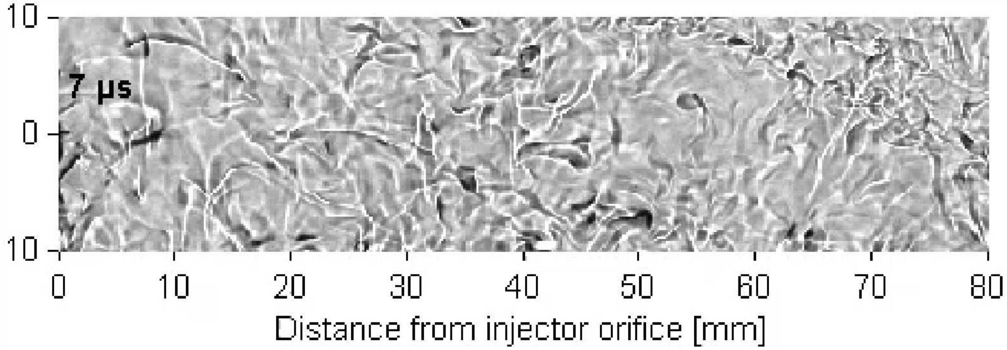
800 K End of 1st, Ignition of 2nd Injection

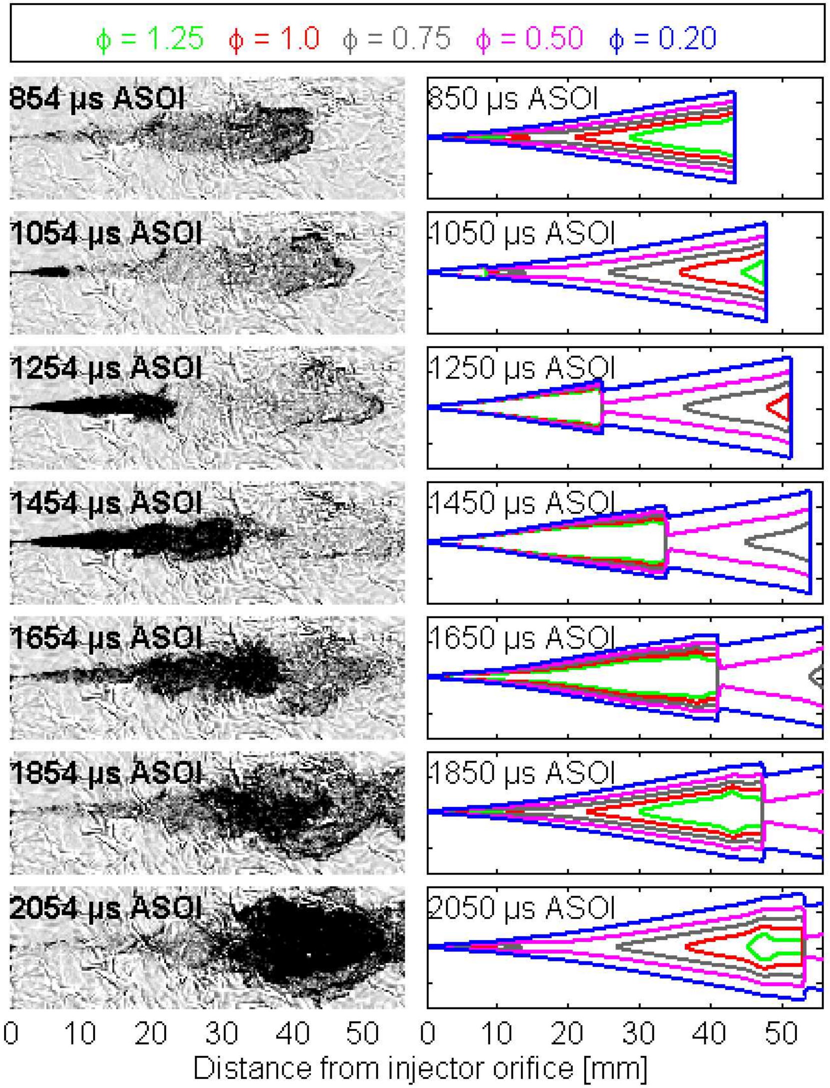
- CHR simulation at near-nozzle EOI conditions
  - From Musculus model, cross-sectional average equivalence ratio at liquid length just prior to second injection
  - Φ=0.3 and 782 K from adiabatic mixing
- Cool-flame temperature in CHR of 870 K
- Cool-flame products
  - Considered species > 500 ppm after cool-flame temperature rise
  - CH_2O, C_2H_4, C_3H_6, 2-propenal, formic acid, and H_2O_2
  - H_2O_2 is an ignition enhancer!
- Increased temperature alone reduced ignition delay by 60%
- Addition of 1000 ppm of hydrogen peroxide reduced ignition delay by more than 50%
- Formaldehyde acts as an inert



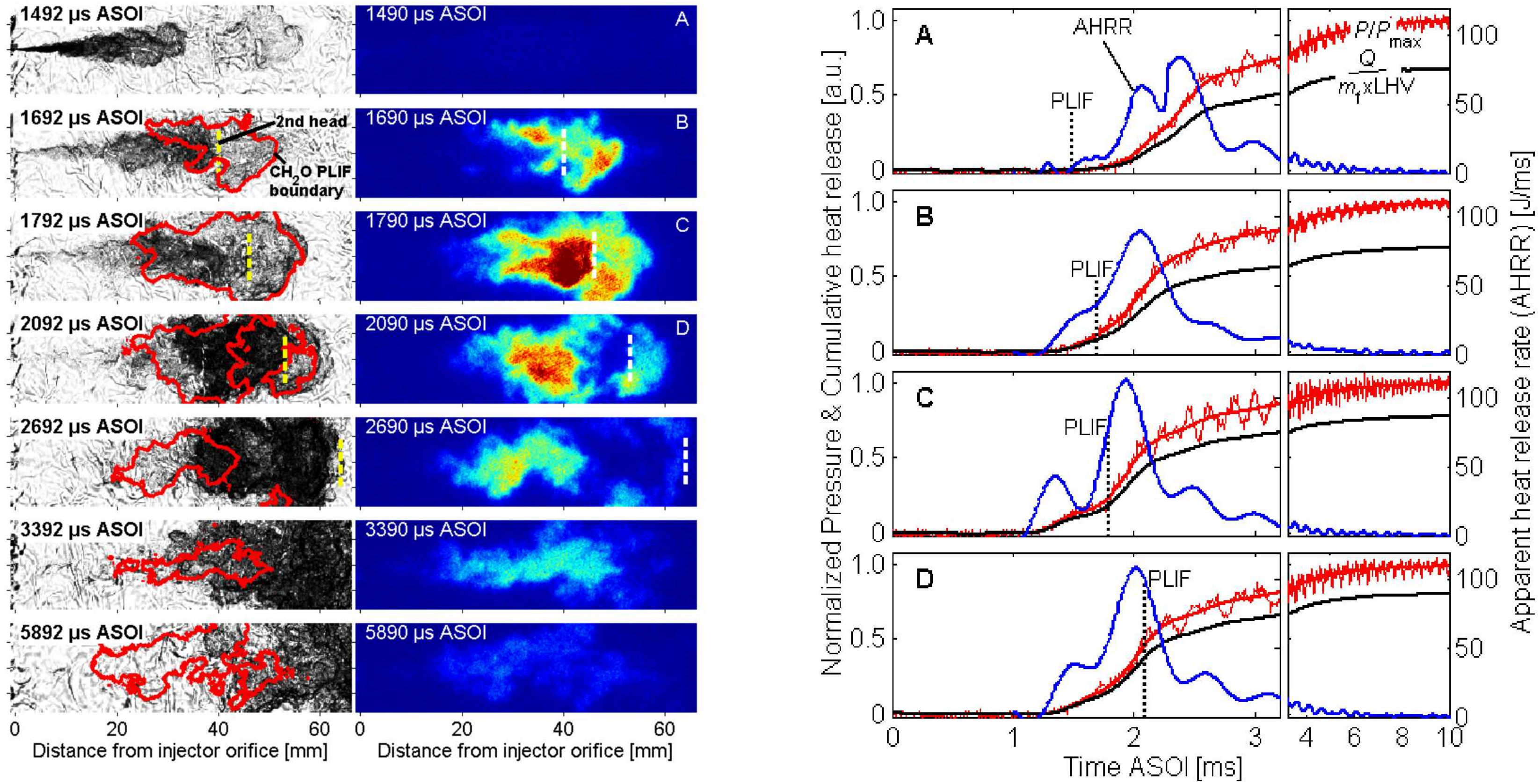
750 K: Ignition of First Injection

- At 750 K, no sudden softening of schlieren effect is observed
- Transparent schlieren image due to mixing, not chemistry
- Cool-flame causes schlieren to darken
- 2nd injection appears to enable ignition of over-mixed 1st injection





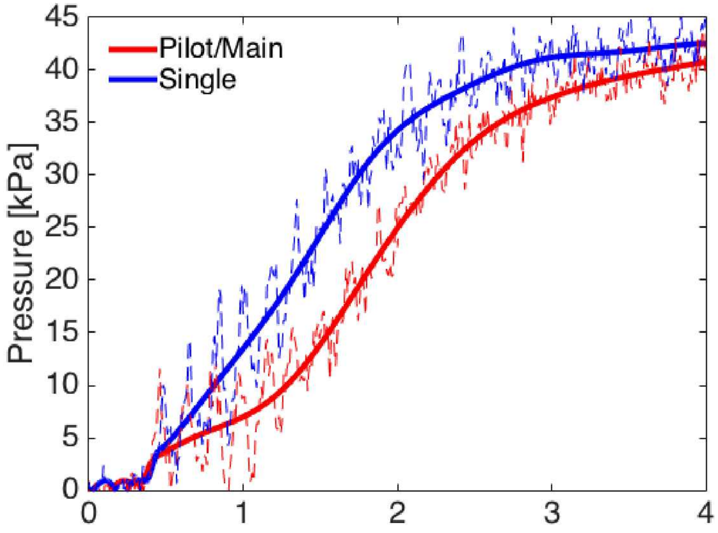
750 K End of 1st, Ignition of 2nd Injection

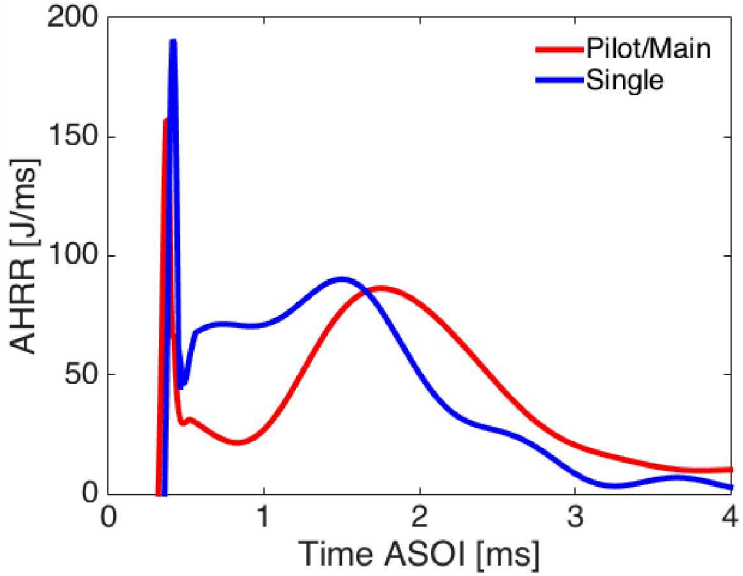


- Pressure trace + 355-nm PLIF provide proof that cool-flame has not begun
- Still observe narrower spreading angle for 2nd injection
- 2nd stage ignition begins "upstream" of 2nd head
- Is the first injection still influencing earlier ignition of second injection? Possibly.
  - CHR simulation suggests that that hydroperoxy radical (HO_2) forms closely in time with decomposition of parent fuel

Pressure and AHRR data show features making for an interesting comparison of soot formation

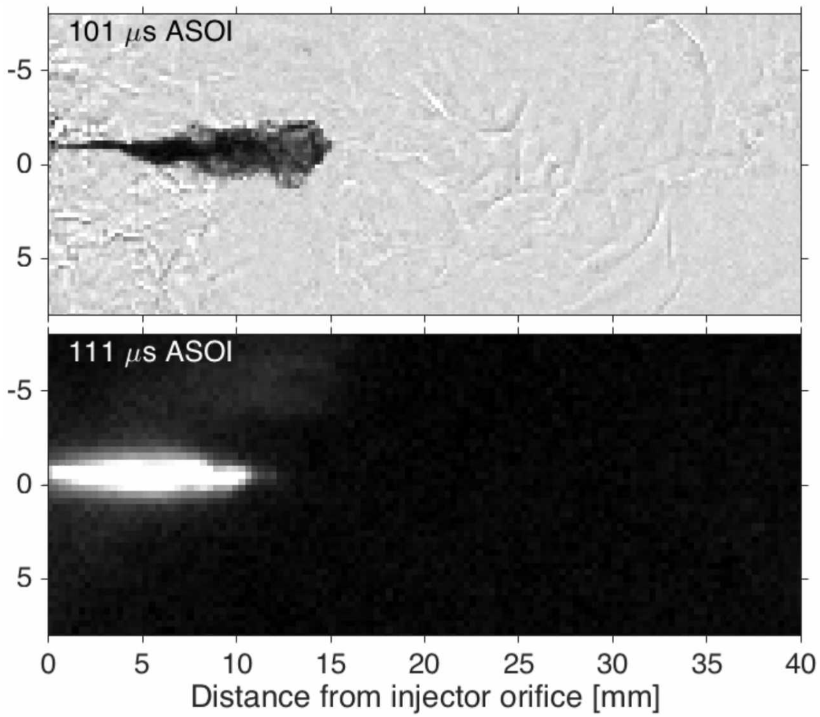
- Comparing 1.5 ms Single injection with Pilot/Main (0.3/0.5 dwell/1.2 ms) injection
  - High-temperature ignition delay of first injection for Pilot/Main case equivalent to Single injection case
  - Peak in AHRR slightly delayed for Pilot/Main
  - Peak pressure slightly lower for Pilot/Main (injector throttling/dynamics reduces fuel mass injected)



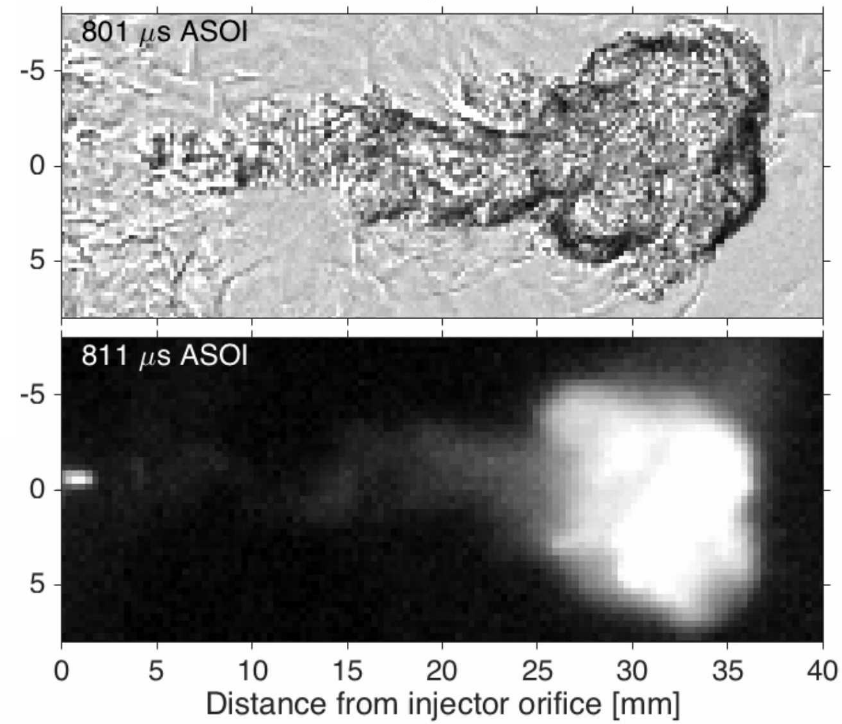


High-temperature ignition occurs earlier for 2nd injection due to residual temperature and products

1st Injection



2nd Injection



- Transparent schlieren observed at radial periphery representing first-stage ignition
- First luminosity observed (near 25 mm, 411 μs) when schlieren begins to darken for first injection
- 2nd injection ignites near liquid length (12-15 mm, 211 μs) resulting in more fuel-rich conditions during high-temperature combustion

Optical thickness (KL) is proportional to soot mass integrated over the path length

Mie Theory: $$KL = \int \frac{k_e}{\lambda} f_v \, dL$$

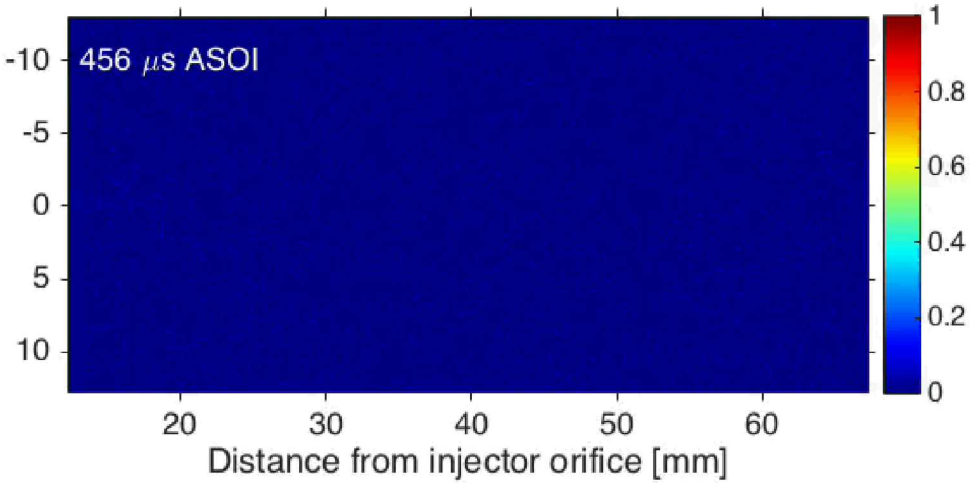
KL from Beer-Lambert Law: $$KL = -\ln\left(\frac{I}{I_0}\right)$$

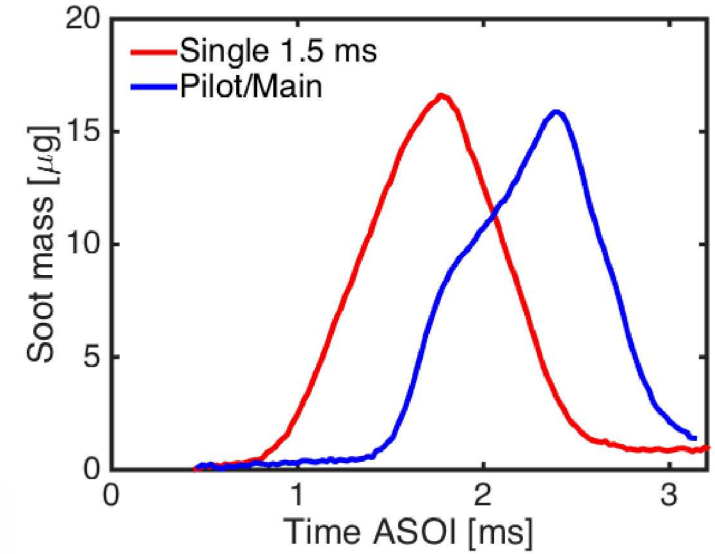
Assume k_e and soot density are constant

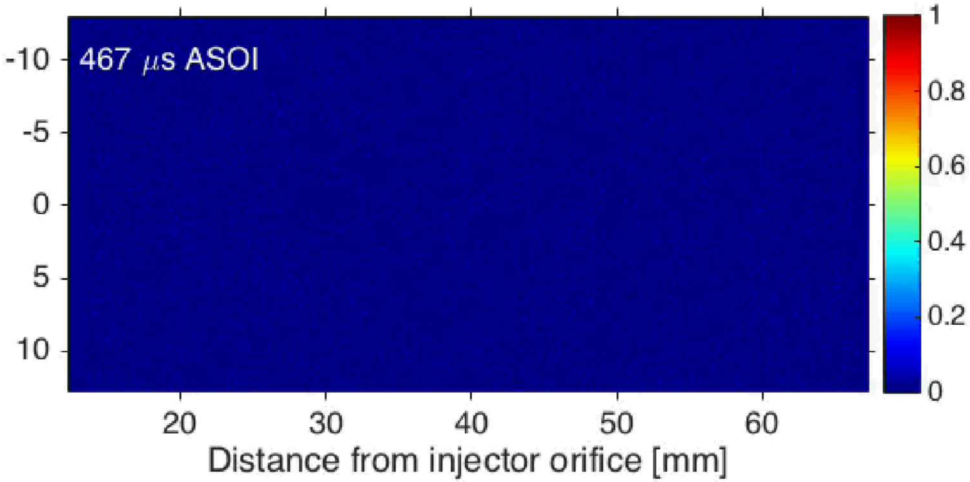
$$\frac{KL}{k_e}\lambda\rho_{soot} = \rho_{soot}\int f_v \, dL = m_{soot}\left[\frac{g}{m^2}\right]$$

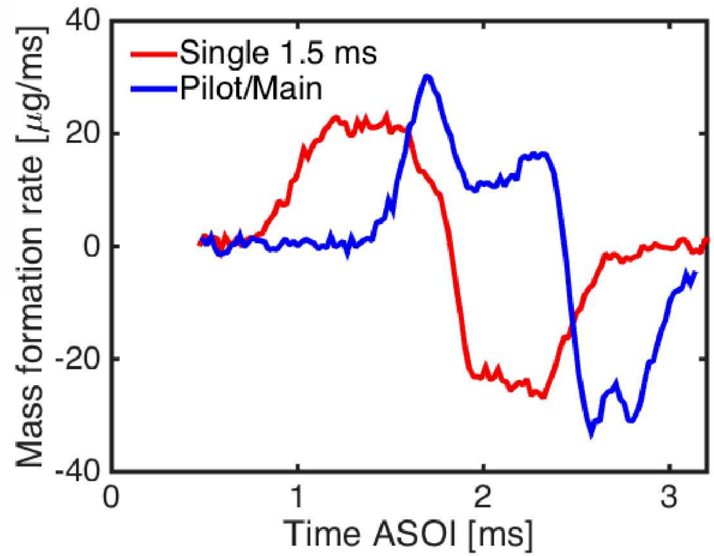
Multiplying by pixel area from image scaling yields mass through chosen cross-section

Peak soot mass similar within FOV for single and pilot/main injection cases but formation rates differ



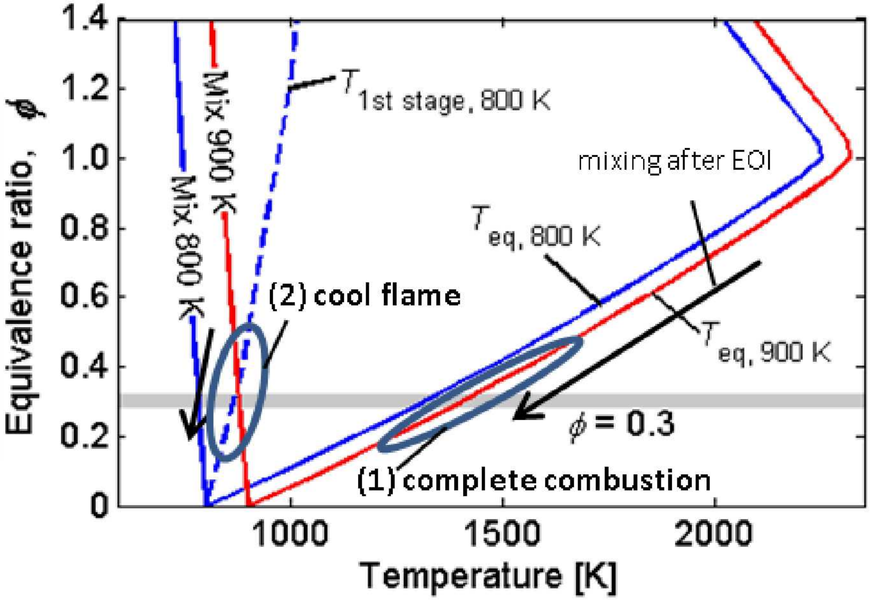






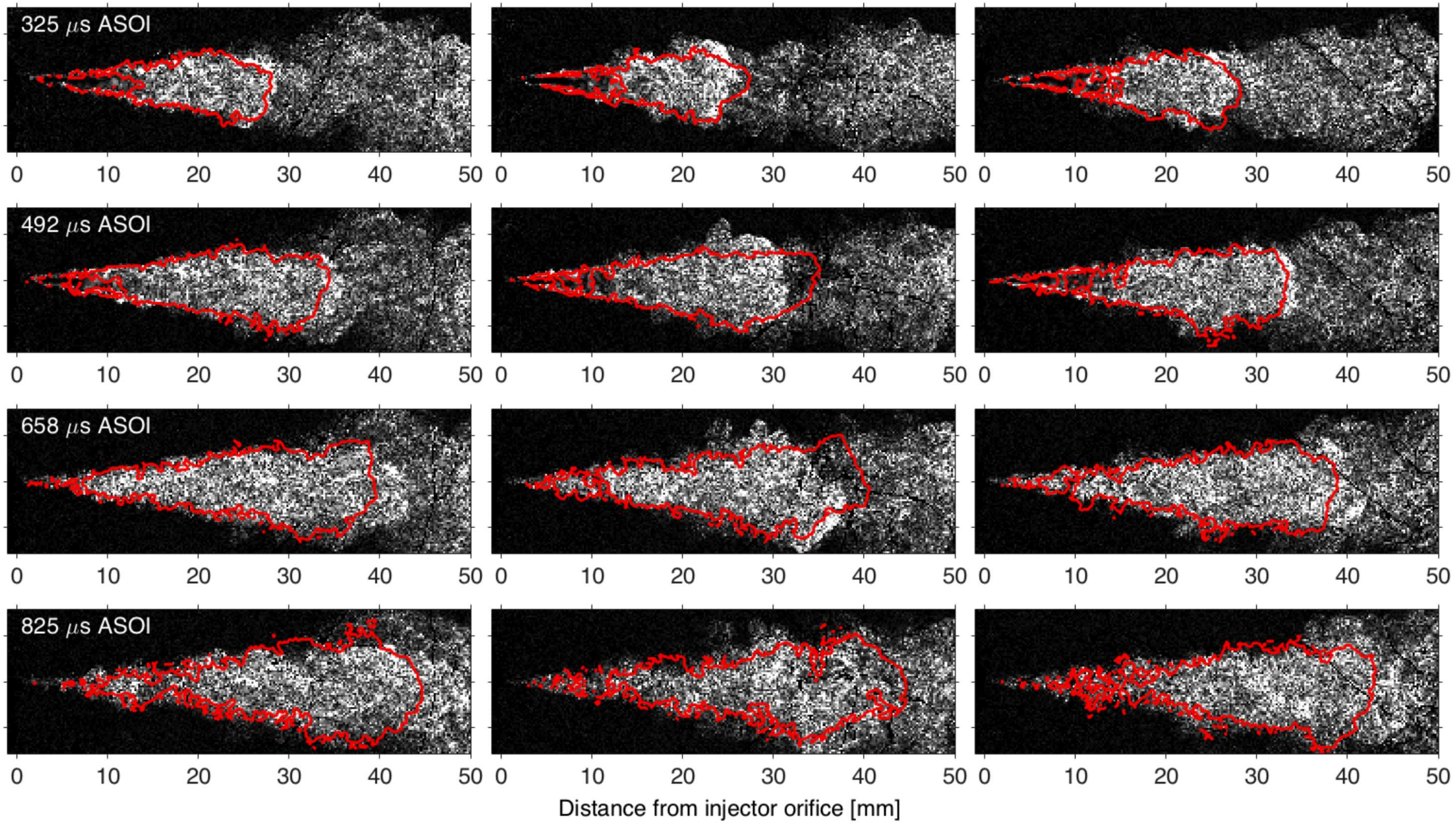
Summary

- Additional evidence of first-stage ignition in the radial periphery of the spray, upstream of the spray head at Spray A condition
- Softening of schlieren effect through entire line of sight occurs on a chemical time scale (as determined by CHR) providing evidence of large-scale organization
- Initial ambient temperature clearly influences the state of the near-nozzle charge into which the second injection penetrates
- If combustion recession occurs, high temperature (>1200 K) and radical species can initiate combustion of the second injection near the liquid length resulting in a shorter ignition delay and increased PAH/soot formation
- At lower temperatures combustion recession may not occur, but cool-flame products such as formaldehyde along with a modest temperature increase can still reduce the ignition delay
- When ambient temperatures are too low, the first injection can become over-mixed (too fuel lean) and may not undergo second-stage ignition
- The second injection may still benefit from radical species formed during the initial parent fuel decomposition

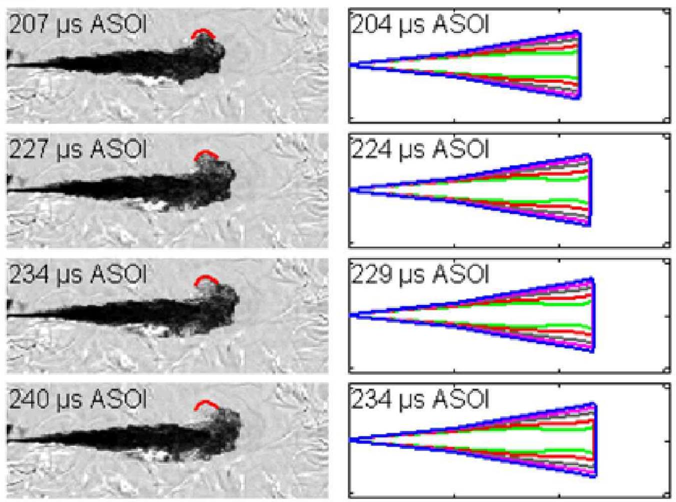


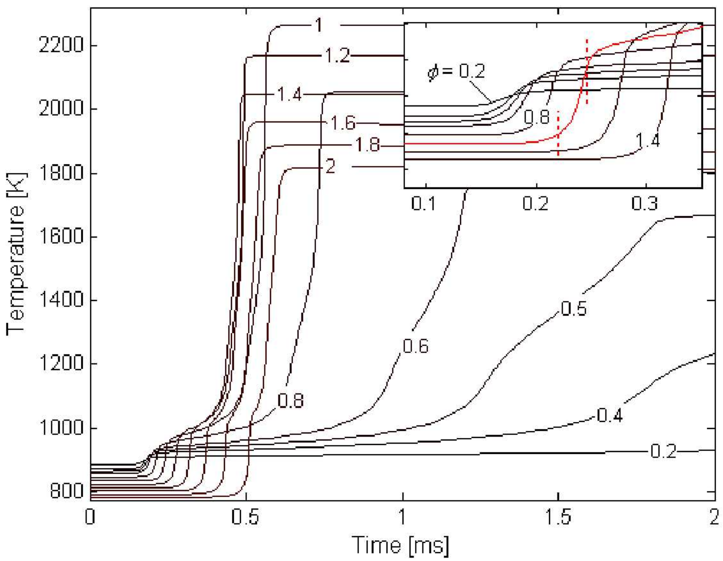
- The second injection also "enriches" the first and may ignite simultaneously or even earlier than the first injection

For Split Injection second injection does not always benefit from slipstream in non-reacting spray

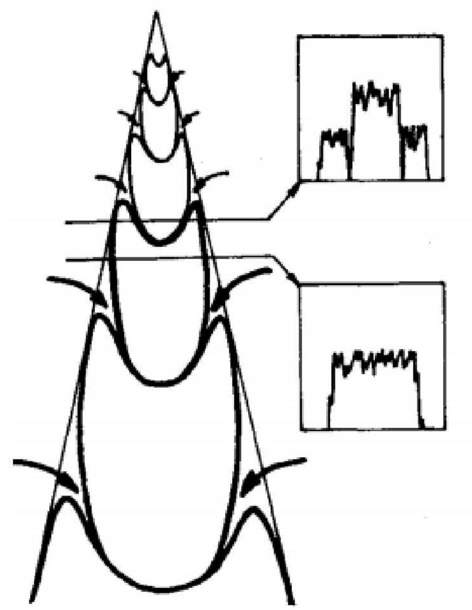


Large-scale Organization?

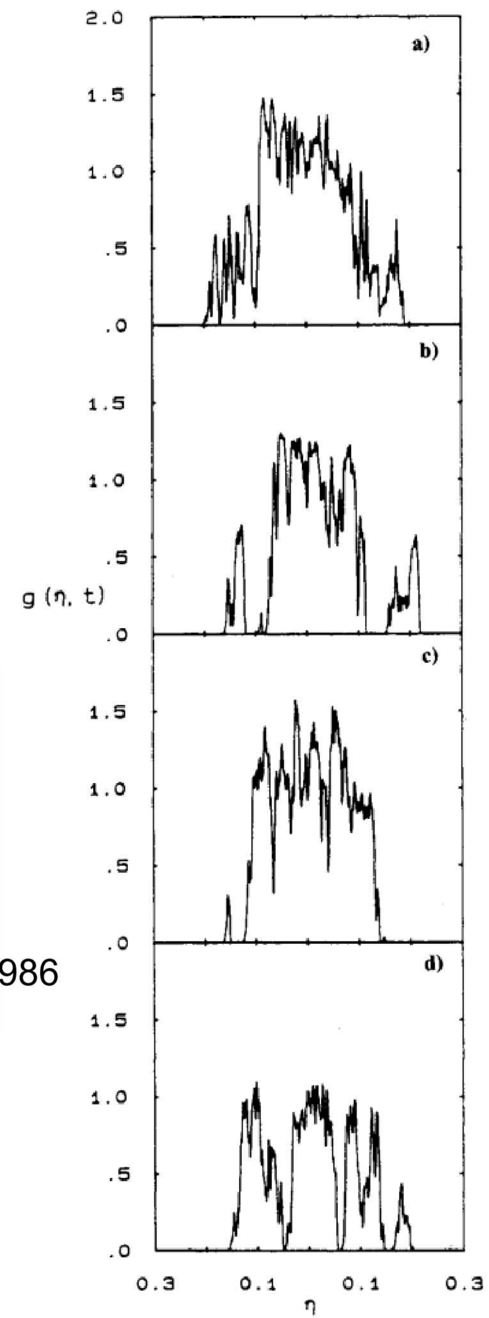




Closed homogeneous reactor (CHR) model with detailed 2-methylalkanes chemistry (Sarathy et al. *C&F* 2011)

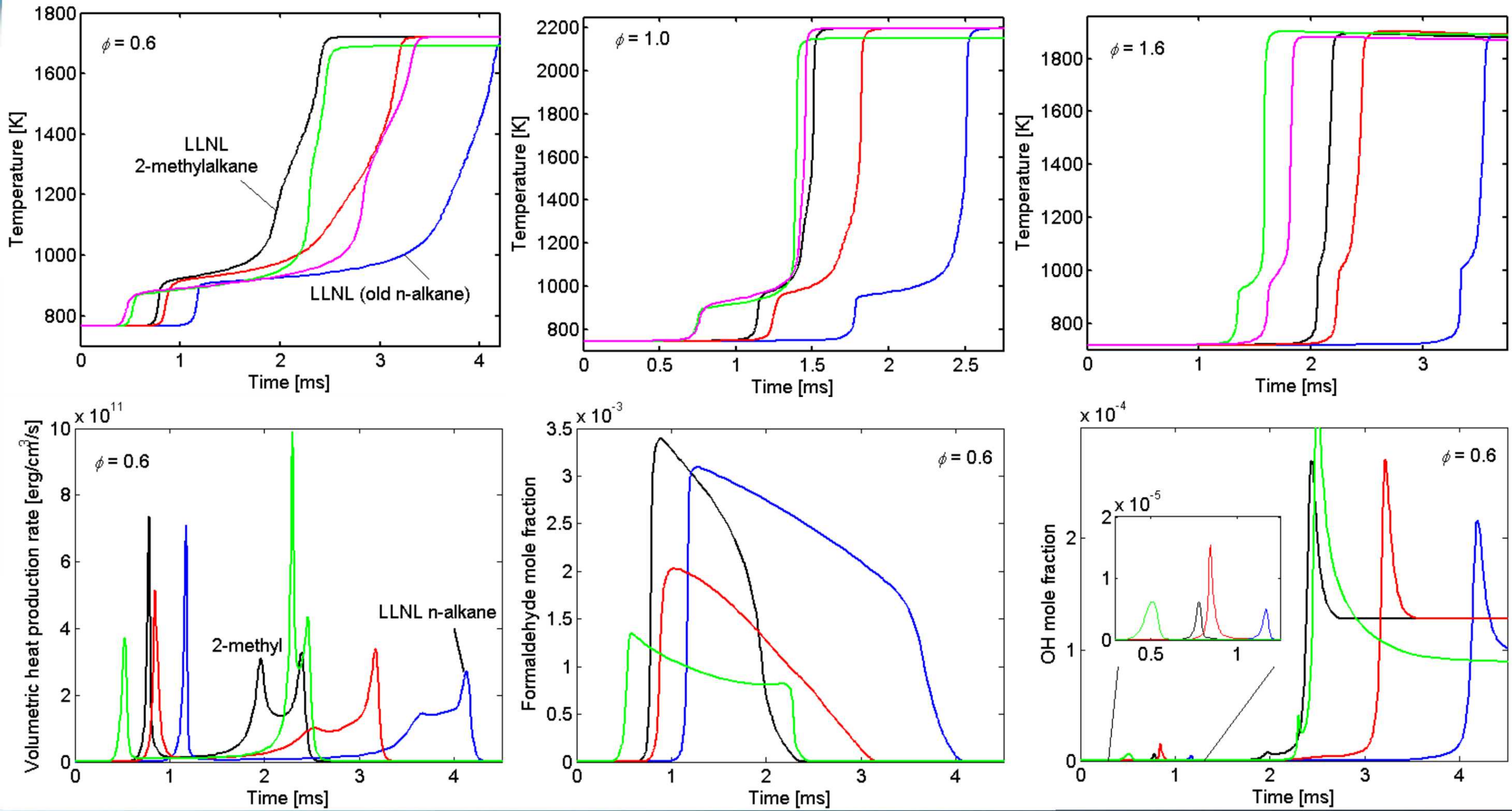


Dahm and Dimotakis
AIAA Journal 25(9) 1986



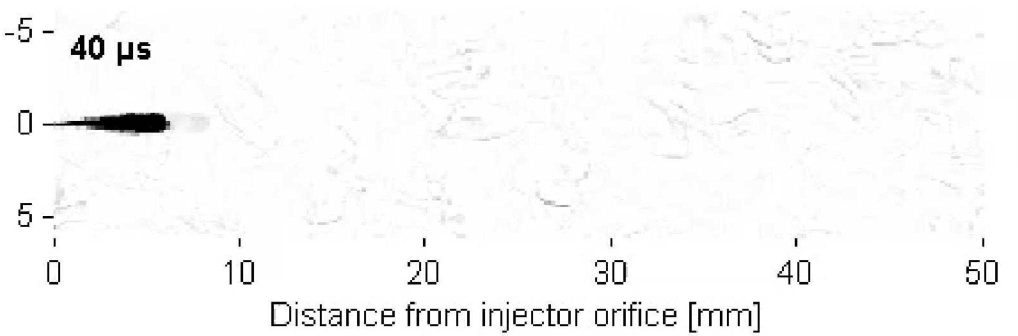
Mechanism Evaluation

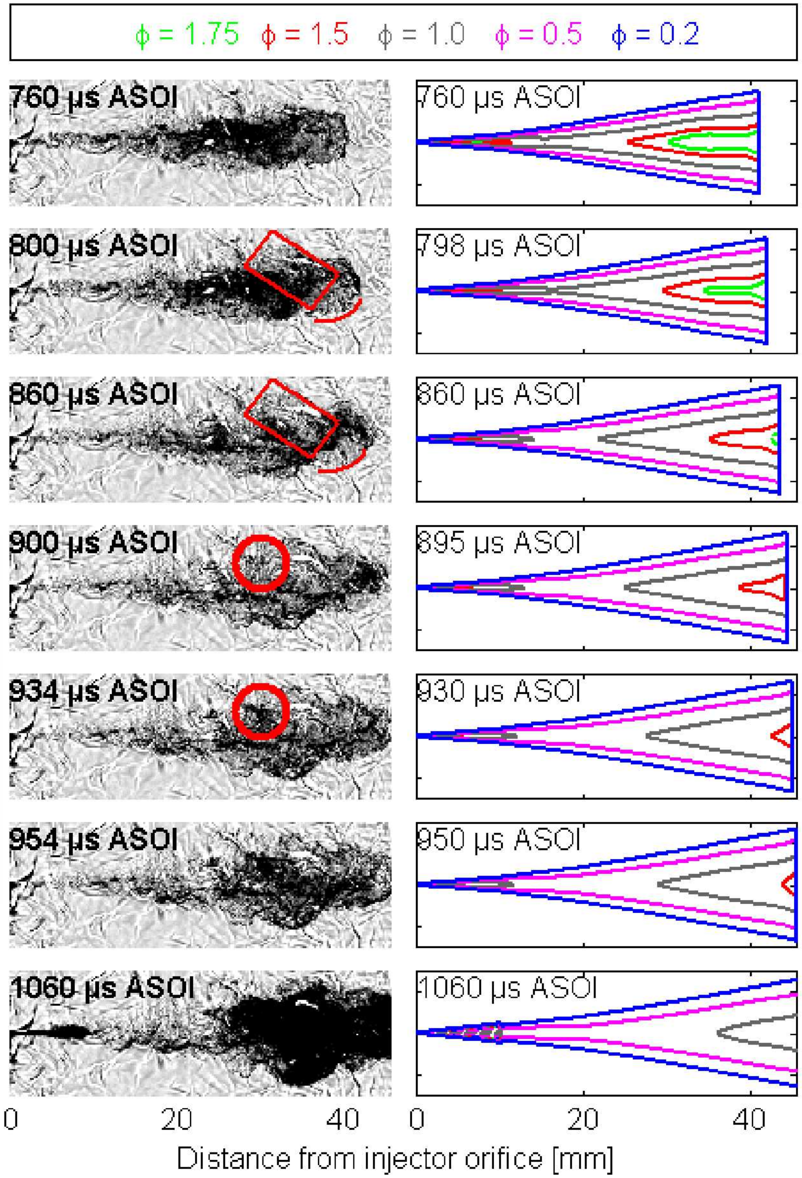
- Changing trends with equivalence ratio (one with different temperature!)
- Differences in heat production rate profiles, CH_2O consumption…
- **Not shown: Major differences with pressure variation!**



800 K: Ignition of First Injection

- Softening of schlieren during cool-flame not as easily distinguished at 800 K
- Longer ignition delay and more mixing leads to softer density gradients before reactions begin
- More fuel-lean (or less fuel-rich) conditions at time of ignition





Results: Non-Reacting Penetration

- In this single realization, the initial penetration of second injection appears somewhat faster, but then slightly lags behind first injection
- Second injection can benefit from “slipstream” after reaching 30 mm as shown here, but this is not always the case. Most of momentum has dissipated.
- Try to get Mark’s model working??? What’s wrong?