Engine Combustion Network

Topic 1.2: Near field fuel structure and coupled nozzle flow and spray simulations

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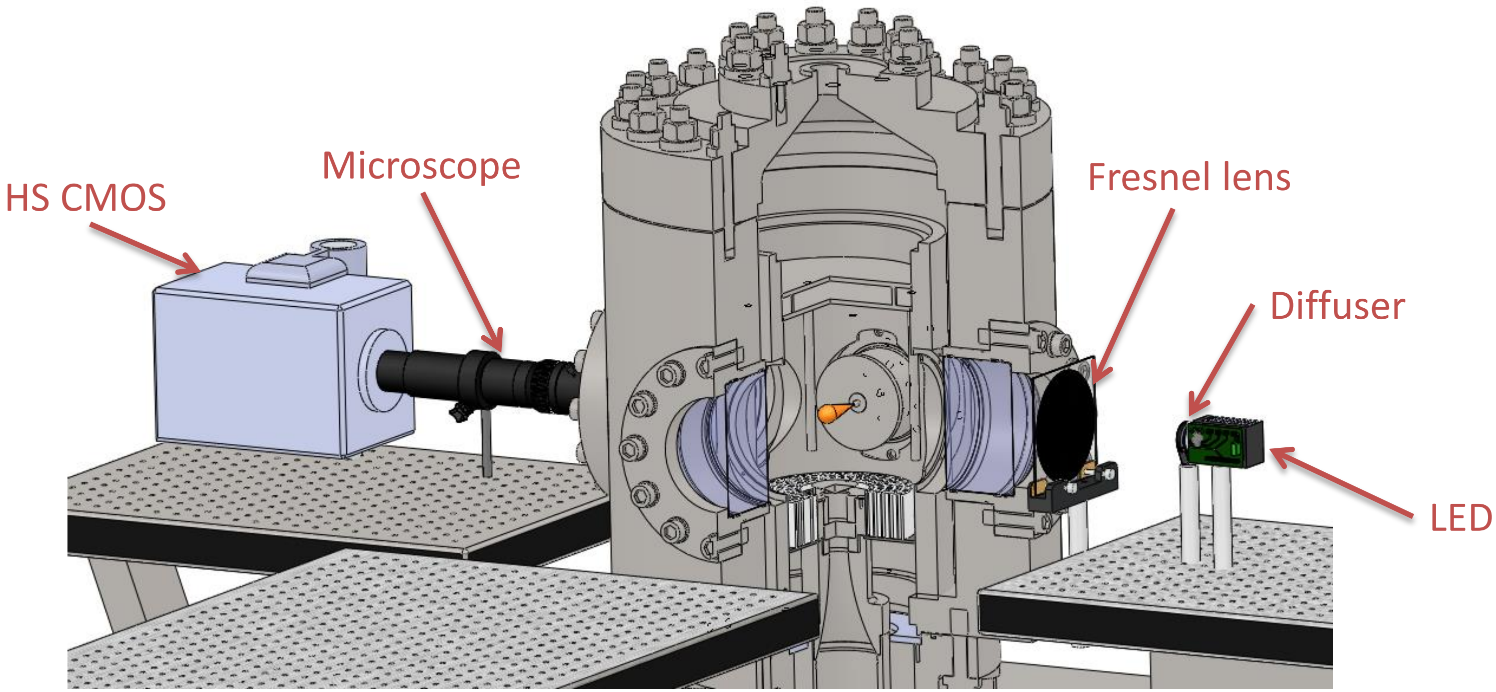
Overview

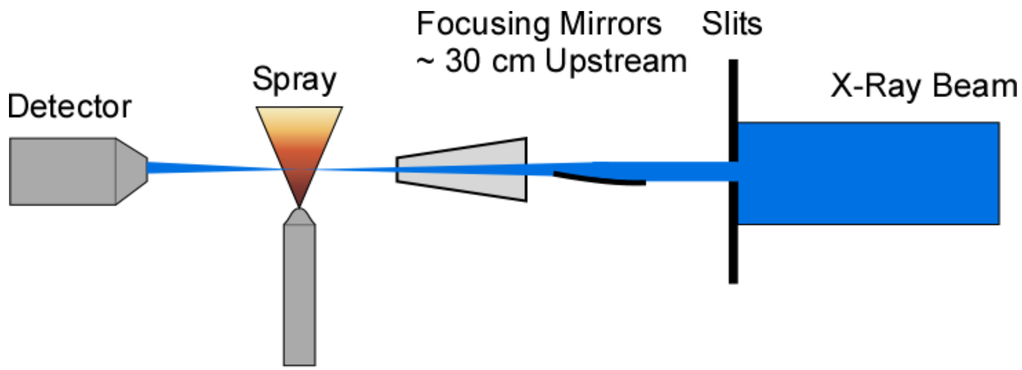
- Measurement techniques
- New Spray A measurements
- Spray B measurements: comparison to Spray A
- Nozzle Ageing
- Experimental conclusions and future directions

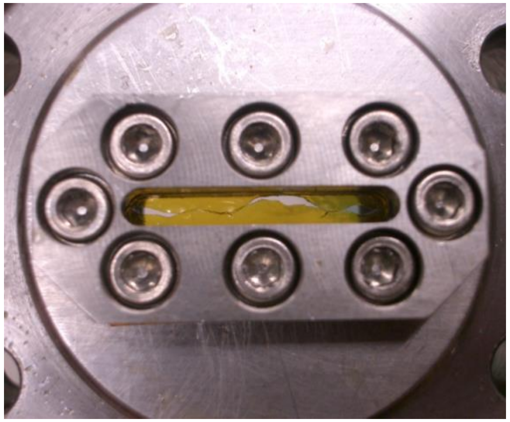
Long-distance microscopy setup (CMT)

- High-speed CMOS equipped with a long-distance microscope lens
- Image resolution varied between 7.8 and 16.9 µm per pixel
- High-speed imaging (up to 263 kHz) to describe each individual event
- High power <50 ns LED pulse duration to freeze the flow
- Combination of engineered diffuser and Fresnel lens to deliver a diffused and powerful illumination



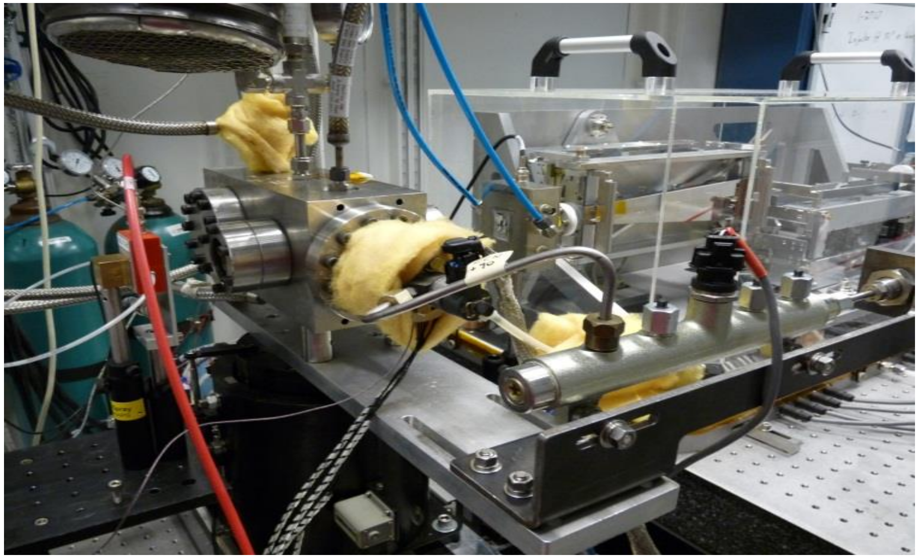
X-Ray Radiography Measurements





22 mm

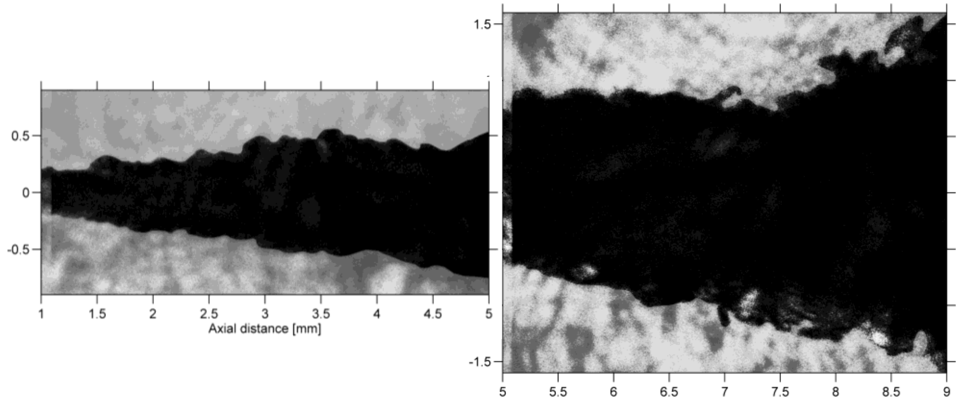
$$I = I_0 e^{-\mu M}$$



- Focus Size: 5 x 6 µm FWHM
- Time Step: 270 kHz
- Photon Energy: 8 keV
- Windows: 50 - 125 µm Polyimide
- Room Temperature

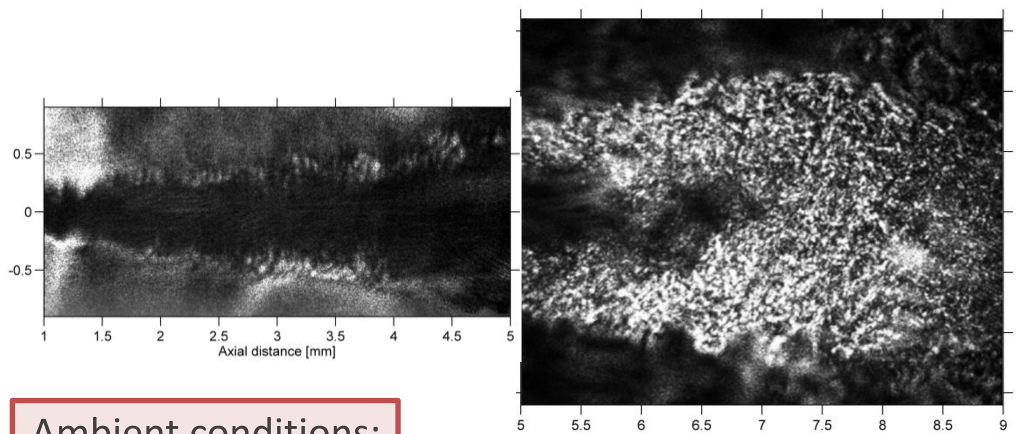
New Spray A Results

Ballistic Imaging of Spray A: 210677



Ambient conditions:
440 K – 22.8 kg/m^3

- Still shots of ballistic images in the near-field show a liquid core structure with sharp liquid/gas interface, ligaments and some voids inside the core structure

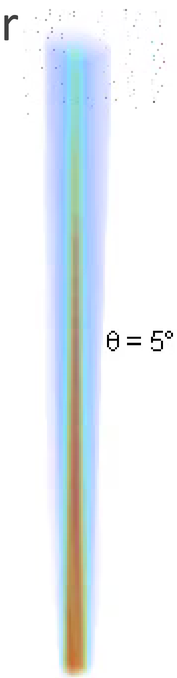


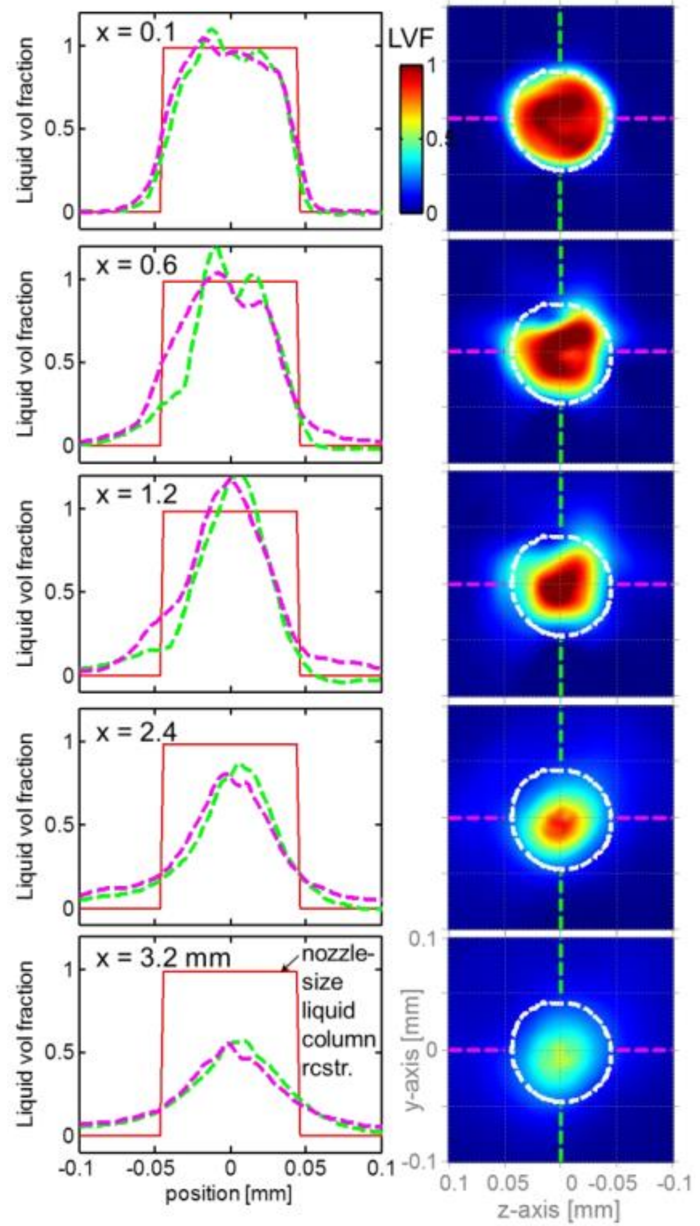
Ambient conditions:
900 K – 22.8 kg/m^3

- No sharp interface between liquid and gas
  - ➡ Interface thickening
  - ➡ Diffusive mixing
- Cellular structure around high density “liquid” core

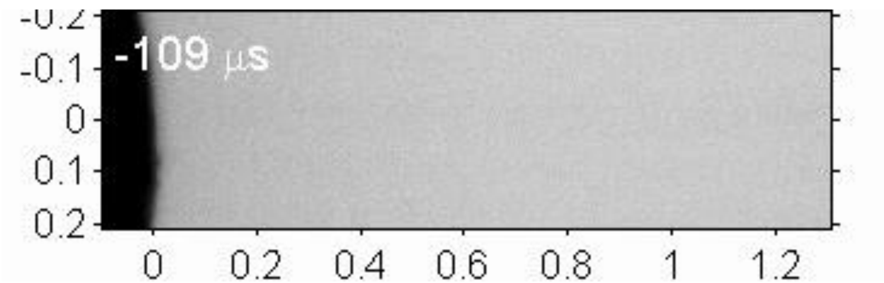
3-D tomography reconstruction

- Tomographic reconstruction of radiography data has been performed at different axial measurement locations
- Accurate knowledge about spray centerline location is required to obtain sound results from a physical perspective
- Results show pure liquid at the center of the spray (LVF = 1) immediately downstream of the orifice
- The 3D reconstruction reveals an intact liquid core that penetrates to approximately 3 mm



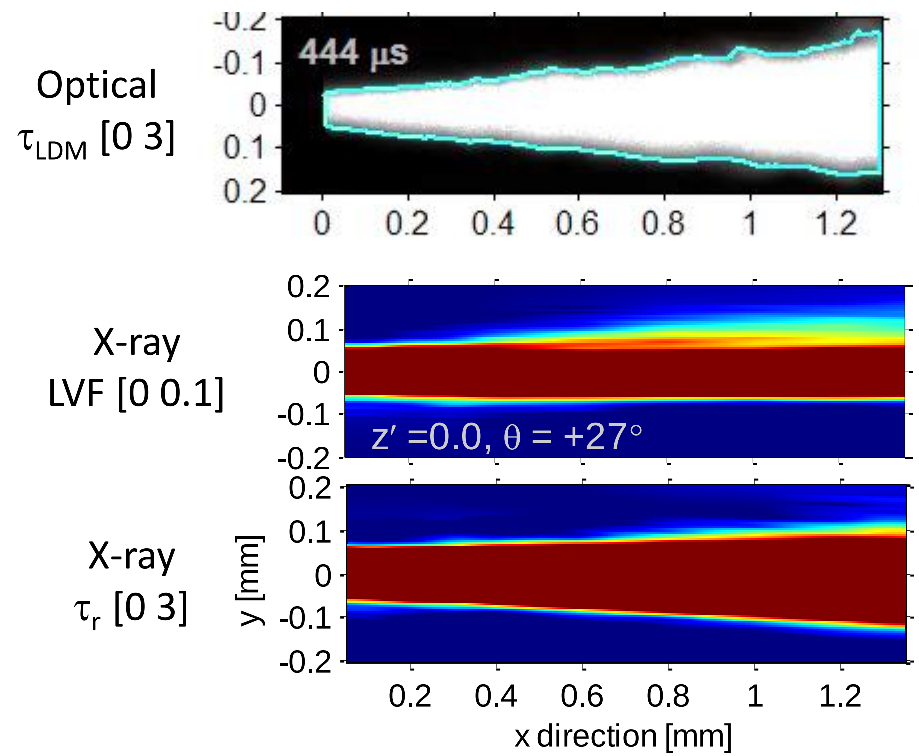


Edge detection sensitivity and quantification



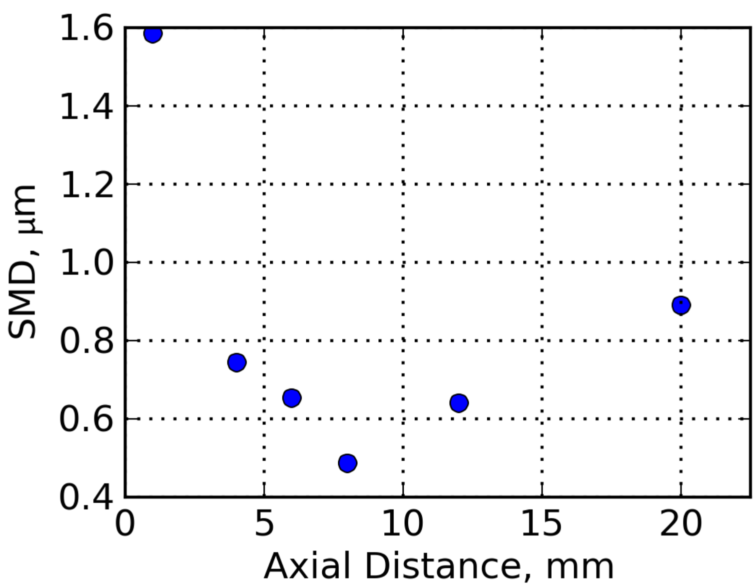
- Assuming an average droplet diameter of 2 µm, Mie-scatter theory reveals that $\tau = 1$ corresponds to a projected mass below 1 µg/mm^2 (LVF ≈ 1 %)
- These results emphasize the complementary nature of the optical and x-ray techniques
- It is recommended that edge detection of sprays be processed at an optical depth of 1

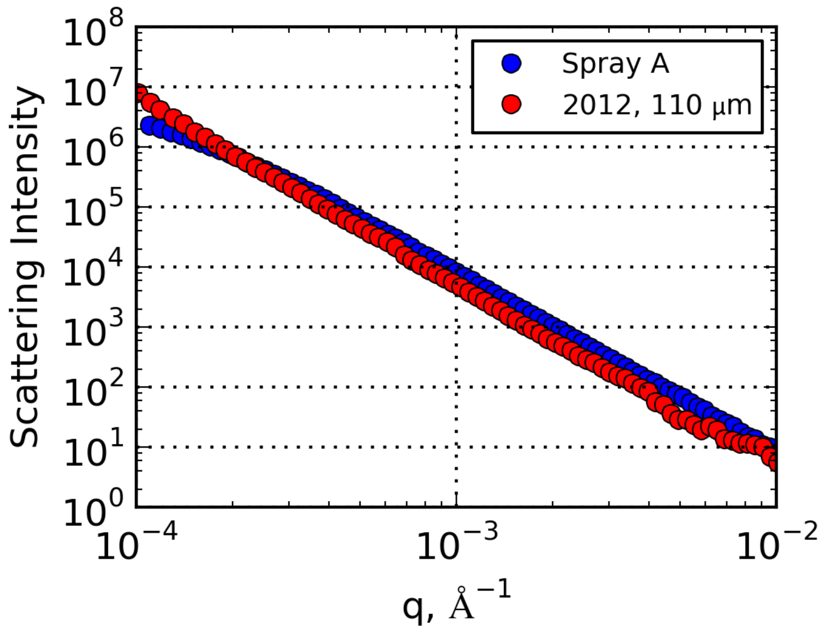
- The spray measured with optical diagnostic appears wider than that with x-ray radiography at first sight
- Further analysis reveals that the spray edge is at low LVF, near the detectible limit of the x-ray measurements



Ultra-small angle x-ray scattering measurements

- Use ultra-small angle x-ray scattering (USAXS) to probe average droplet size
  - Measure surface area
  - Combine with radiography to measure SMD: surface area/volume
- Accuracy of the measurements is +/- 20% at each measurement location
- The measurements for this particular injector (Spray A) provide much smaller droplets than previous USAXS measurements (~ 4 µm): fuel properties?
  - Cavitation?
  - Fuel properties

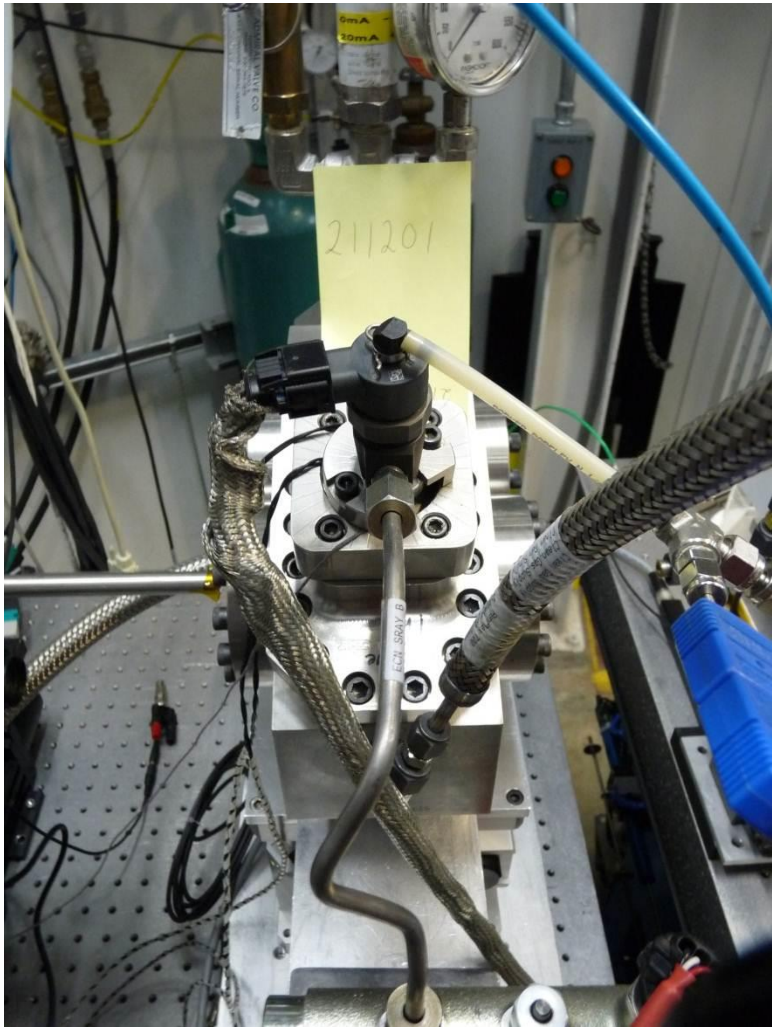




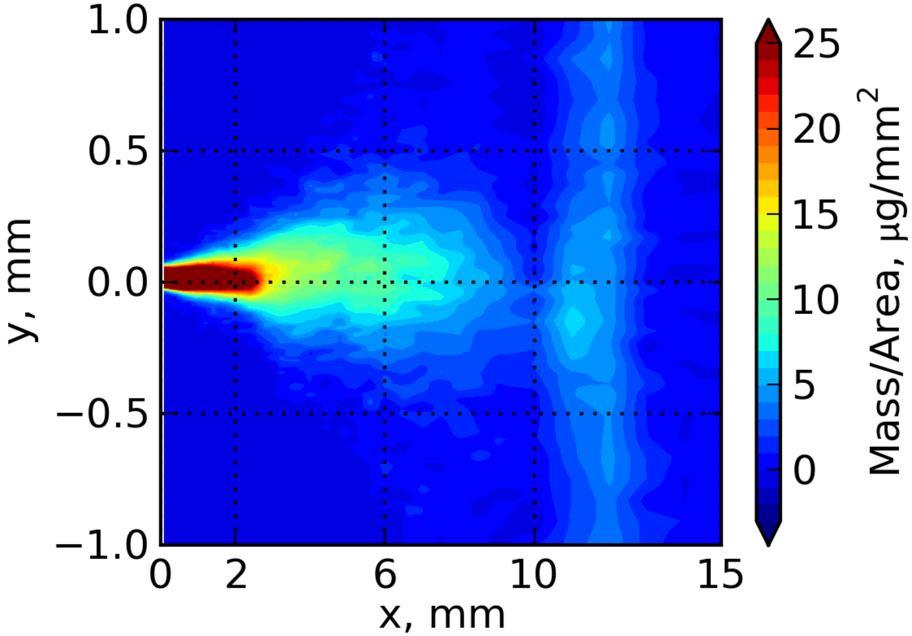
Comparison
Spray A vs. Spray B

X-Ray Radiography Measurements

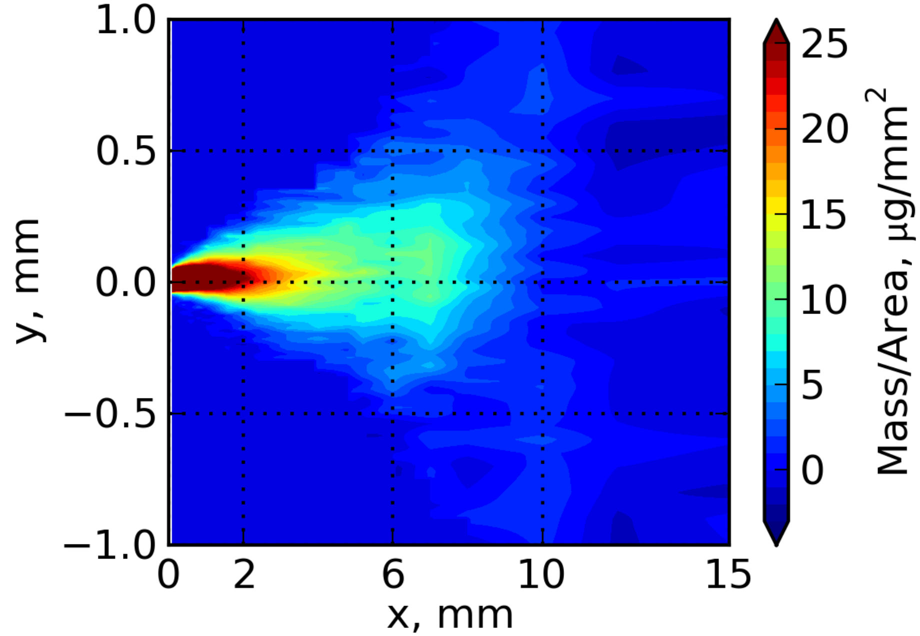
- X-ray radiography performed on injectors 210679, 211199, November-December 2013
- Problems with Spray B data: measure 211200 and 211201 February 2014
- Differences between Spray A and Spray B
  - Injection rate from 3 Hz (Spray A) to 1 Hz (Spray B)
  - Larger windows (3 x 22 mm Spray A, 12 x 30 mm Spray B)
  - Higher gas flowrate Spray B (8 L/min vs. 4 L/min Spray A)
  - Screens in chamber to cut down on overspray, stray droplets for Spray B
  - Fuel absorption coefficient 8% higher than in initial tests in 2011



2D Mass Distribution, 0° View, 40 µs After SOI



Spray A

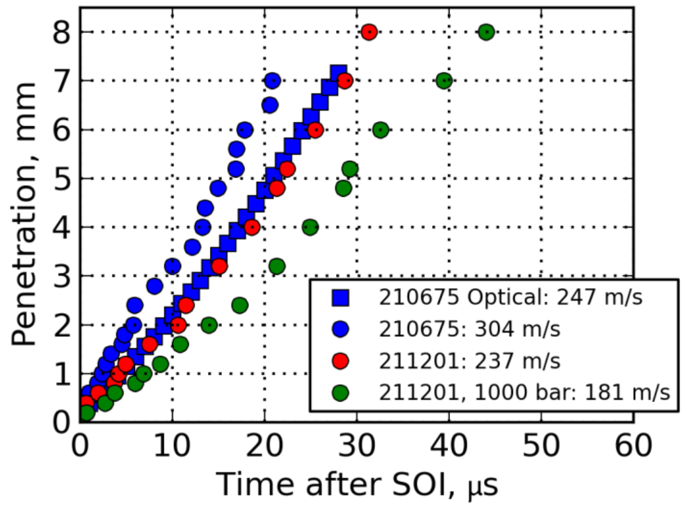


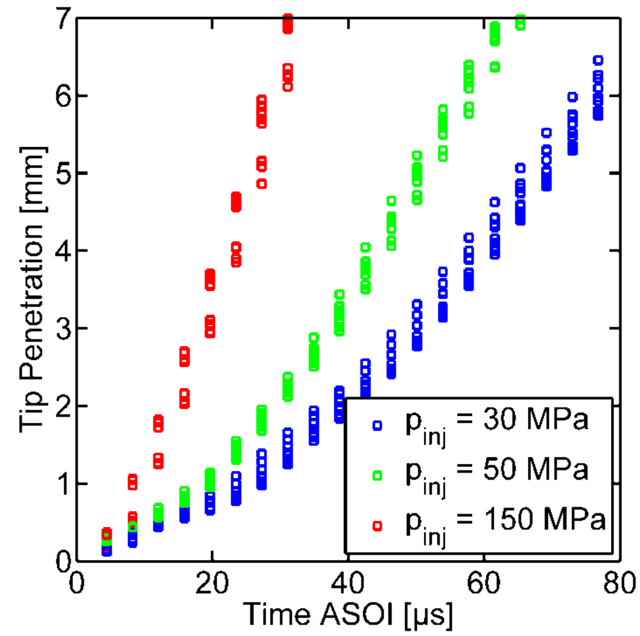
Spray B

- Little or no evidence of shock formed by Spray B, in stark contrast to Spray A
- Direct consequence of slower penetration speed: subsonic, rather than supersonic

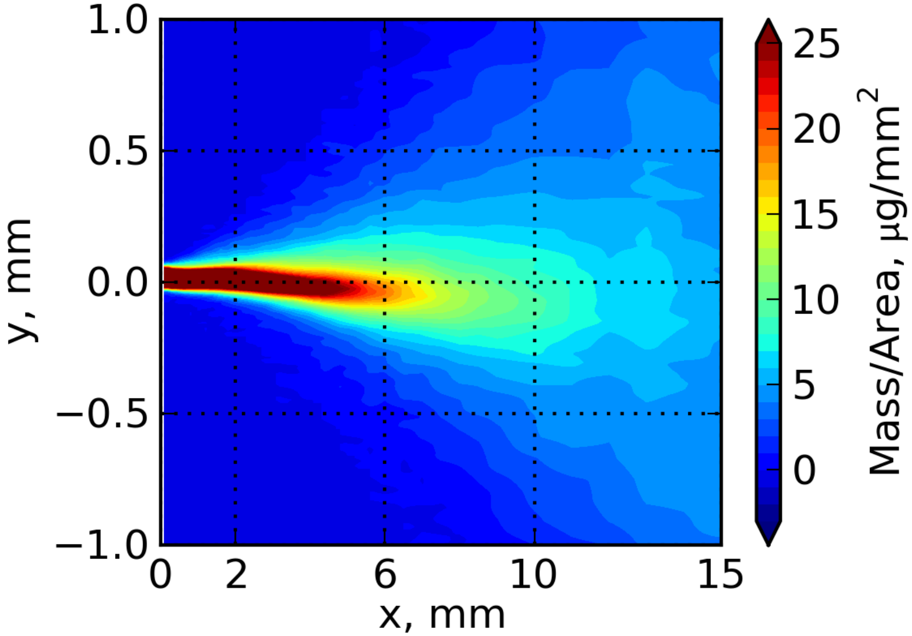
Initial Spray Penetration

- Penetration measured with x-ray radiography: threshold at 25% of peak TIM at each x position
- Penetration is significantly faster for Spray A than Spray B
  - Lower sac pressure due to throttling at needle seat
  - Less shock formation
  - Slower ROI Spray B vs. Spray A
- 1000 bar: 193 m/s if speed dependent on $P^{1/2}$
- Lag commanded to actual SOI similar for Spray A and Spray B
- Microscopy penetration slower
  - Higher ambient T and P than radiography
  - Thermal boundary layer?
  - Injector repetition rate?

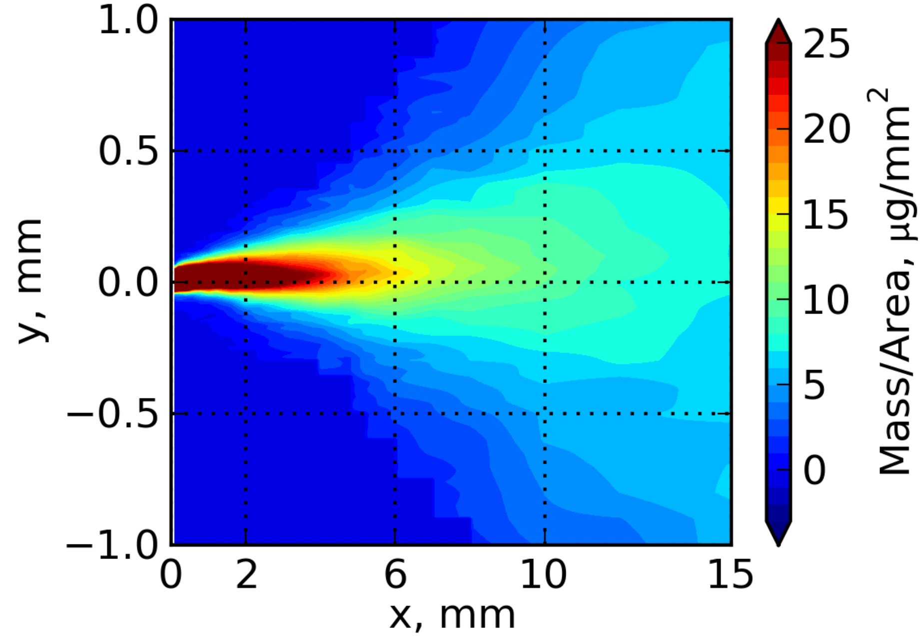




2D Mass Distribution, 0° View, 0.7 ms After SOI



Spray A



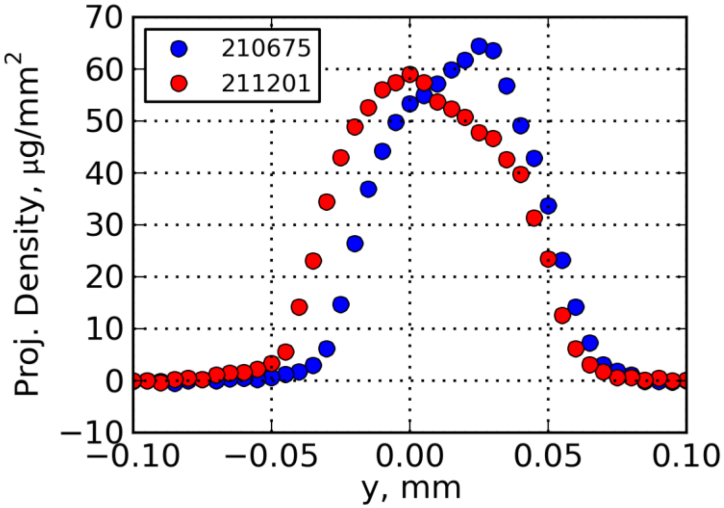
Spray B

- Data averaged over 37 µs of time
- Overall spray shape similar between two sprays
- Spray B wider, but less dense along spray axis x = 2 – 6 mm
- Spray B more dense for x > 10 mm, but this is transient. Density lower at later times

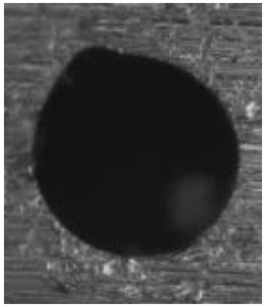
Transverse Mass Distribution

- Cross-sections through spray at t = 0.5 ms after SOI
- Average over 25 time steps (92 μs)
- Near nozzle exit, Spray B a bit wider than Spray A: supports larger nozzle size
  - Extra width on +y side due to hole asymmetry?
  - Both Spray A and Spray B skewed, even at nozzle exit
- As x increases, Spray B tends to be wider, but with lower peak
- More Gaussian shape: less evidence of core-sheath structure

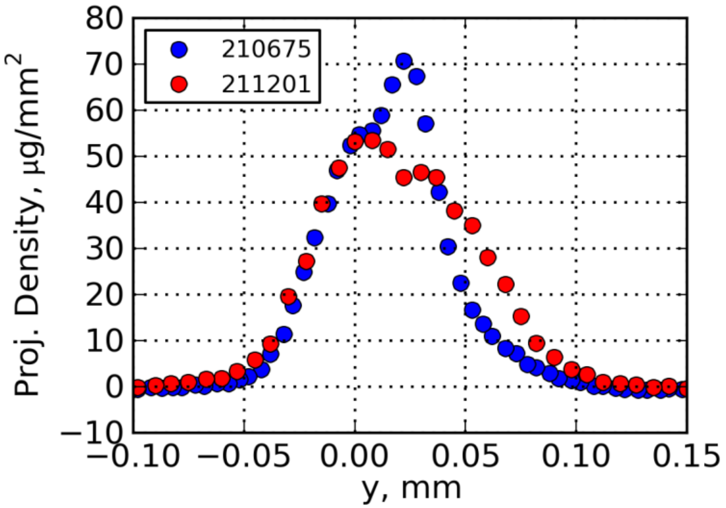
x = 0.1 mm



Fuel Inlet



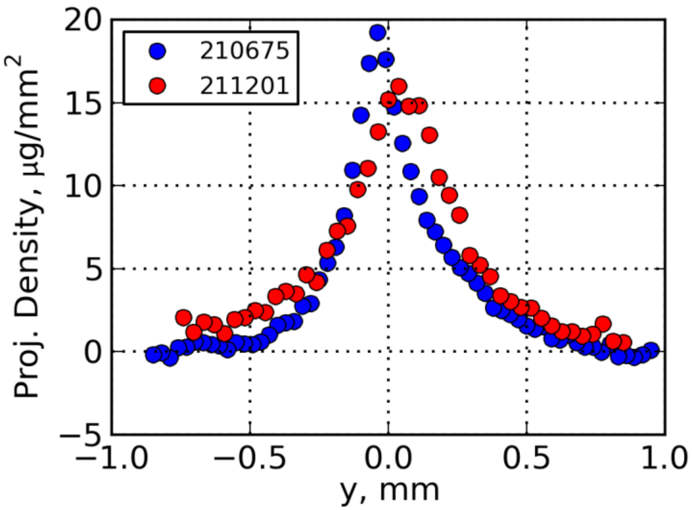
Injector Tip



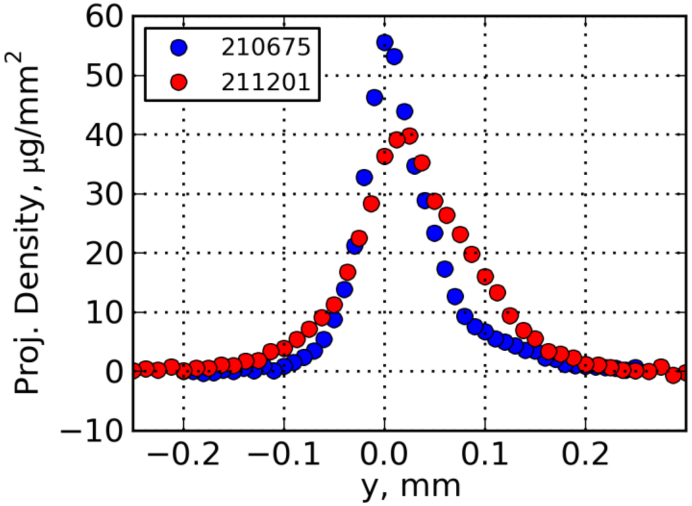
x = 0.6 mm

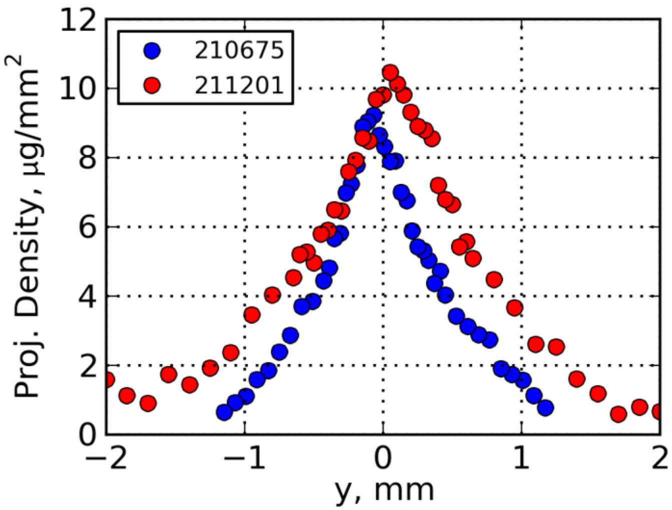
Transverse Mass Distribution

x = 6.0 mm



x = 2.0 mm

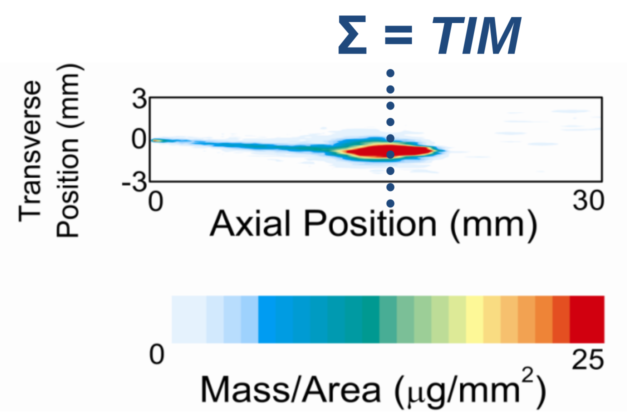


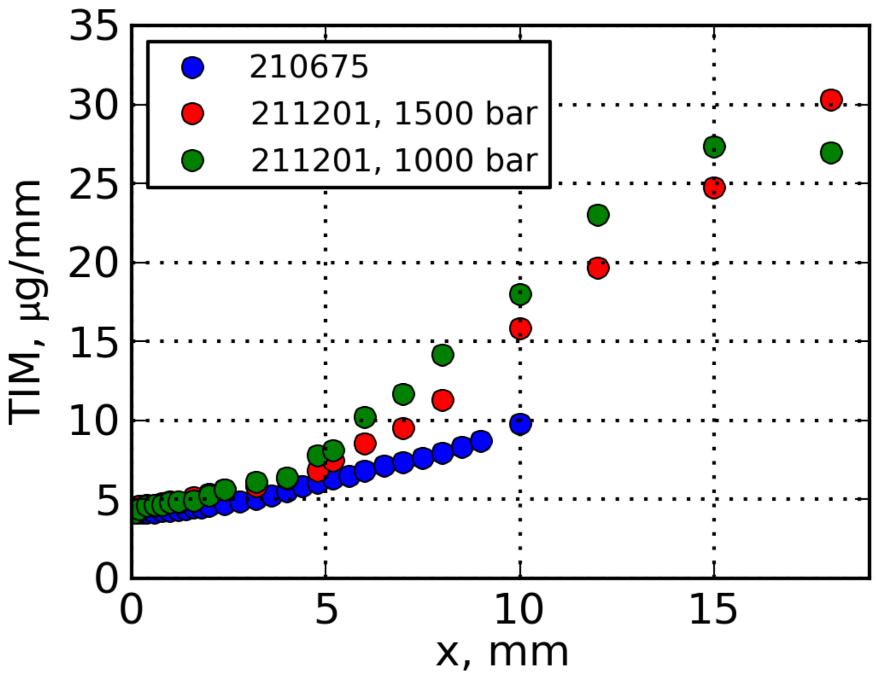


x = 10 mm

Axial Mass Distribution: TIM at 0.7 ms ASOI

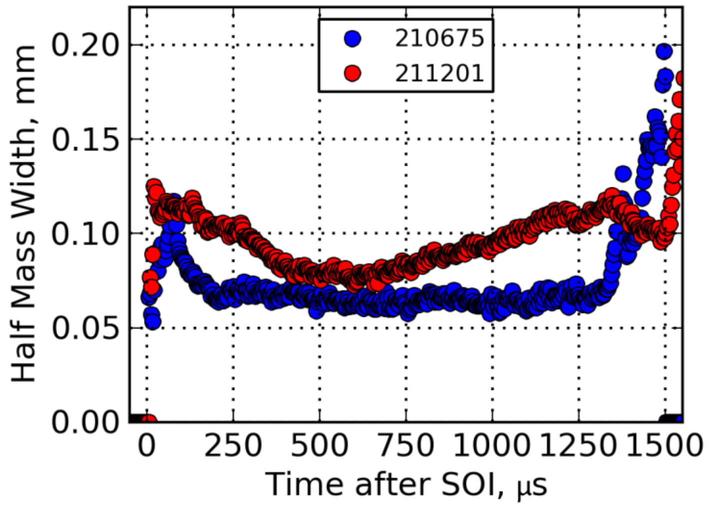
- Initial TIM is about 10% higher for 201 injector than 675
  - Consistent with larger hole diameter
  - 93.8 µm vs. 89.4 µm = 10% more area
  - Error bars < 0.1 µg/mm near nozzle
- Spray A and Spray B follow similar trends for x < 5 mm.
- Farther downstream, TIM higher for Spray B than Spray A, 1000 bar vs. 1500 bar rail pressure
  - Stronger mixing with ambient?
  - Sac pressure different Spray A vs. Spray B?
- Points with x > 10 mm are somewhat suspect
  - Very low spray density
  - Background corrections for radiography less certain here



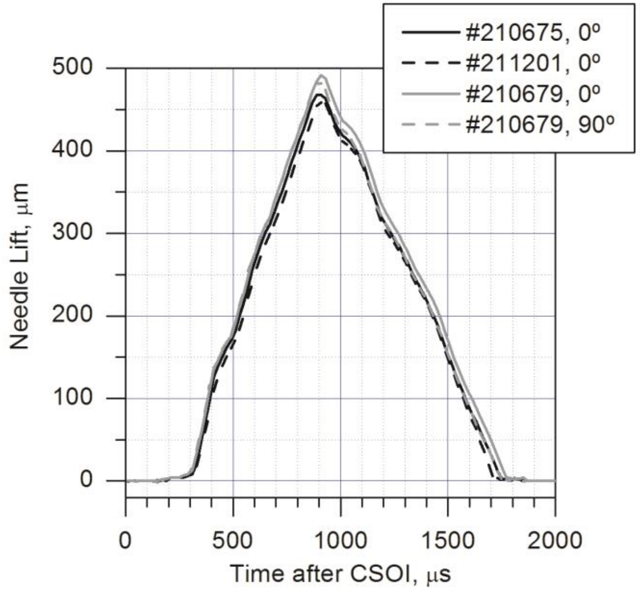


Spray Dynamics: Width vs. Time

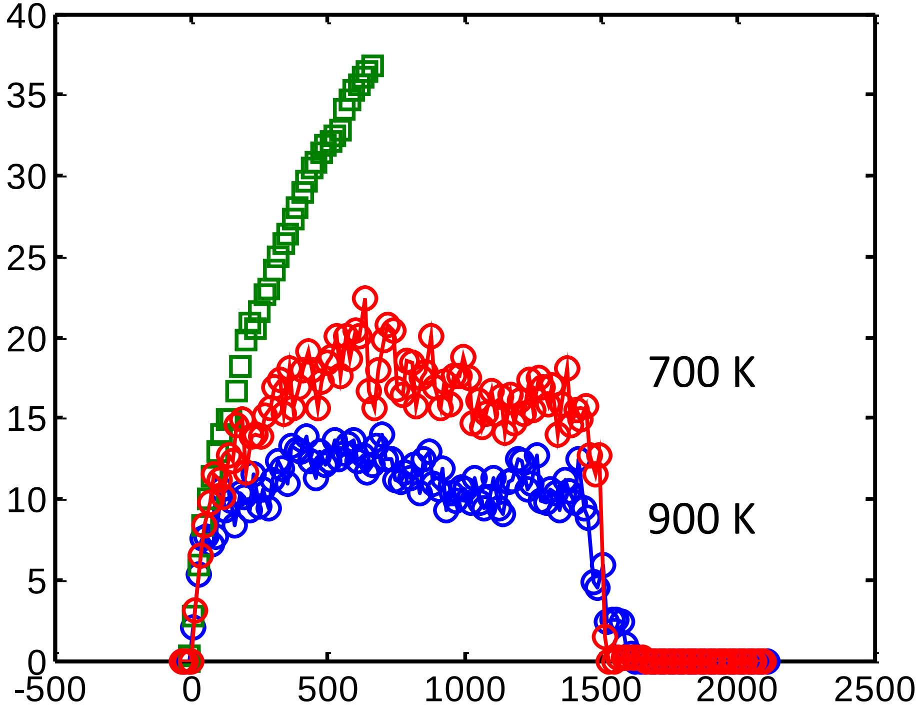
- Measure spray width vs. time
  - Width that contains half of mass
  - Less noisy than FWHM
- Spray B is far more dynamic than Spray A: never really steady-state
- At x = 2 mm, width starts increasing roughly when needle starts to close
- For most points, Spray B wider than Spray A
- With similar TIM and wider spray, lower peak density in plume



x = 2.0 mm

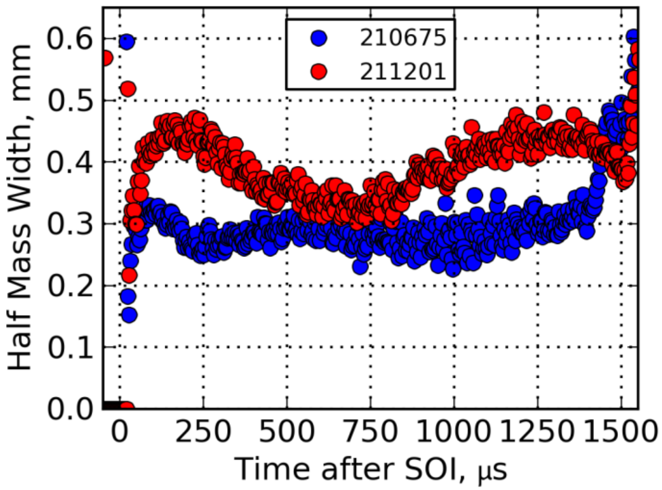


Spray Dynamics: Width vs. Time

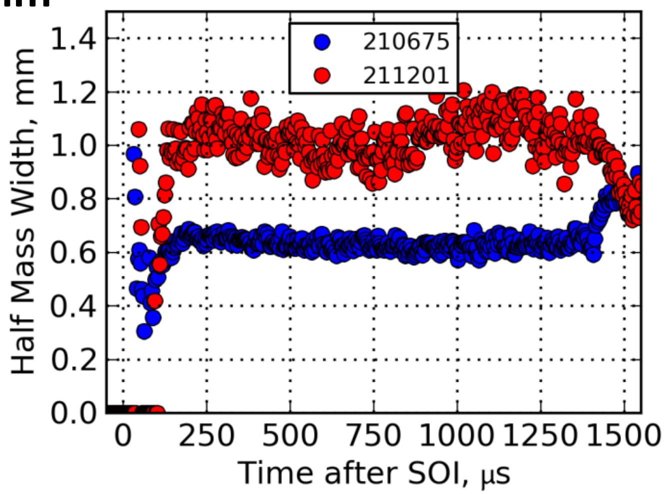


Sandia Penetration Measurements
Vapor (Green), Liquid (Red and Blue)
Diffuse Back Illumination
211200, x = 3.5 mm

x = 6.0 mm



x = 10.0 mm



Argonne Radiography
Width Containing Half of Mass
Injector 211201

Spray Dynamics: Optical Measurements

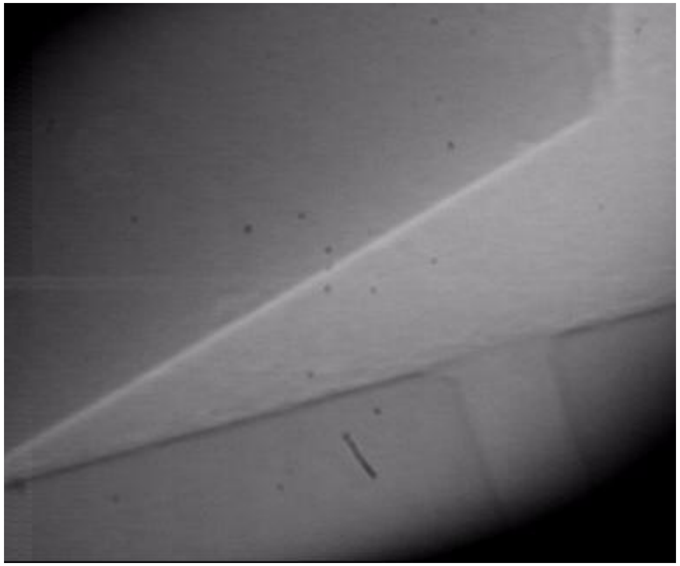
- Imaging of Spray B, nozzle 211201
- 440 K ambient T, 22.8 kg/m^3 ambient density
- Images by Yongjin Jung, KAIST at Sandia

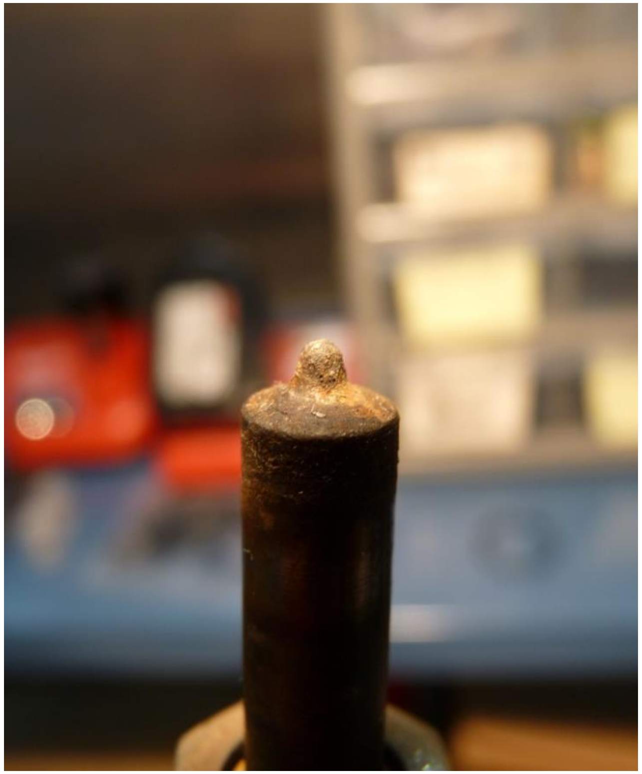
Spray Dynamics Movie

Injector Ageing

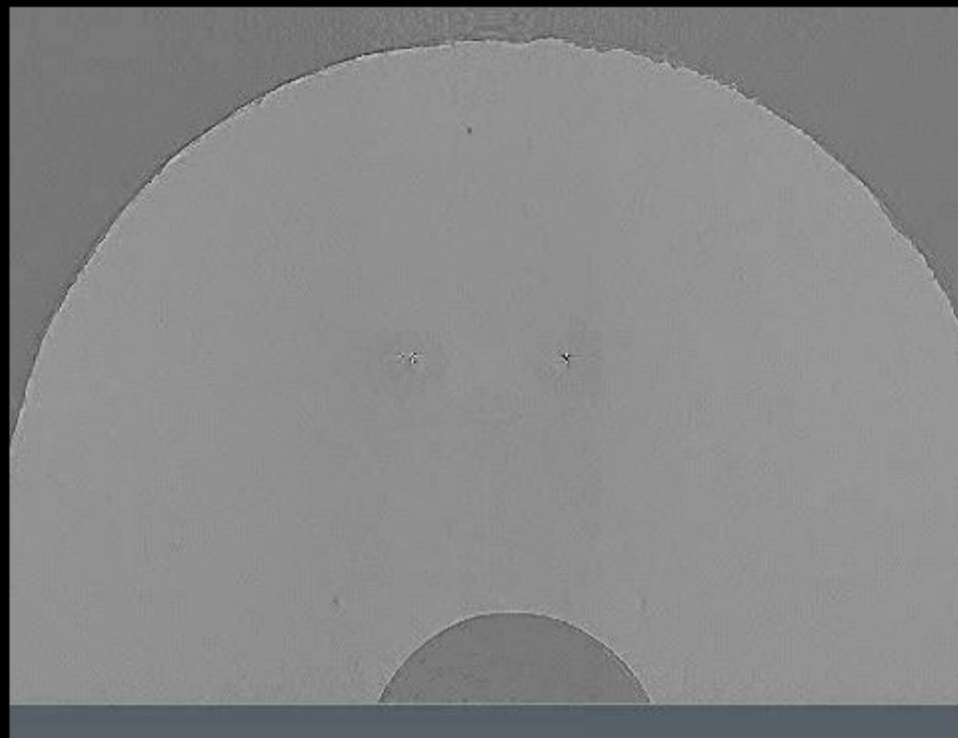
Injector ageing and damage

- More than half the injectors of the ECN (Spray A or B) have suffered corrosion
- This is a significant impediment to cross-comparisons of different measurement techniques

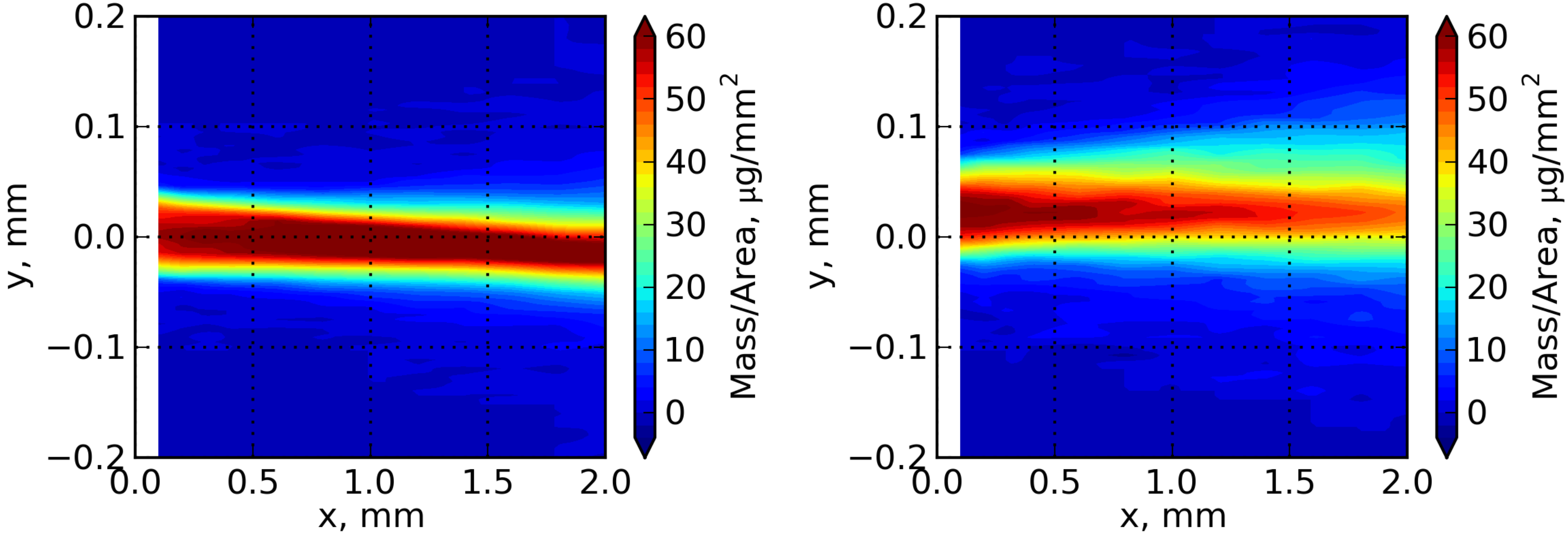




211196



2D Mass Distribution, 0° View, 0.7 ms After SOI

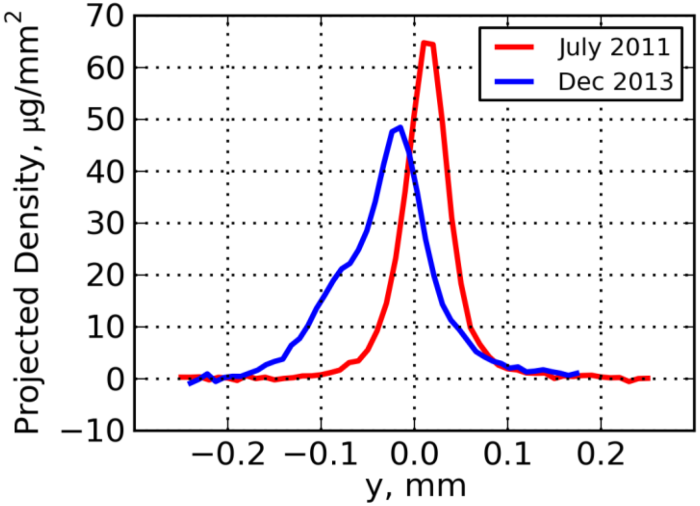


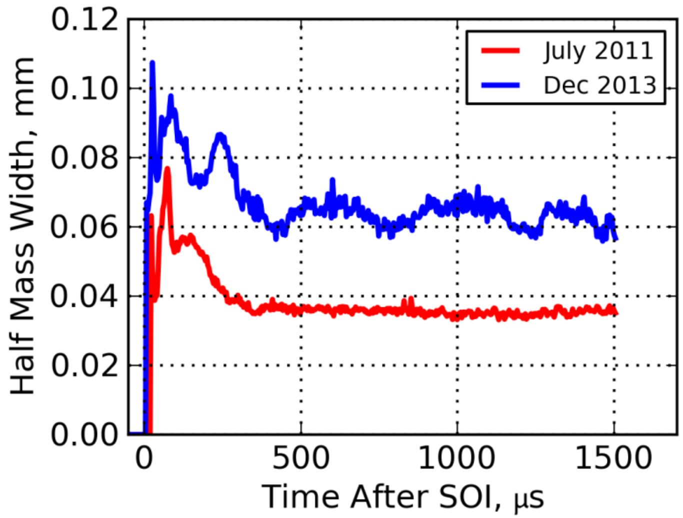
2011 **2013**

- Spray A injector 210679 initially measured in July 2011 with 210677, 210678
- Measurements repeated in November 2013 for USAXS measurements
- Transverse integrated mass (TIM) at nozzle exit appears to be about 10 % higher than in 2011

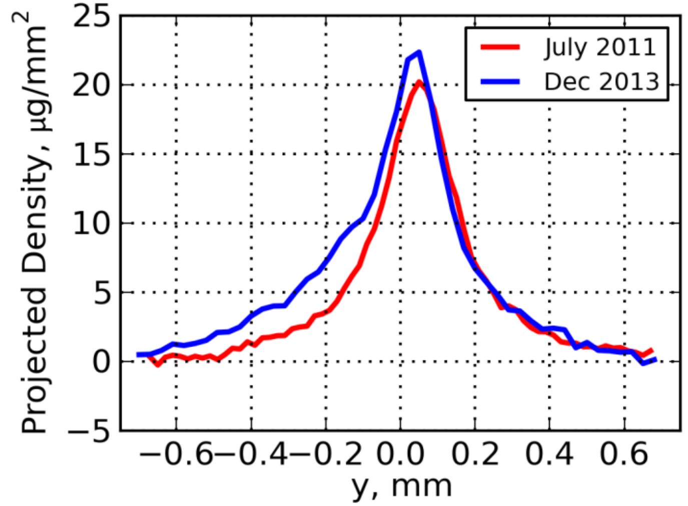
New Spray A (679) radiography measurements

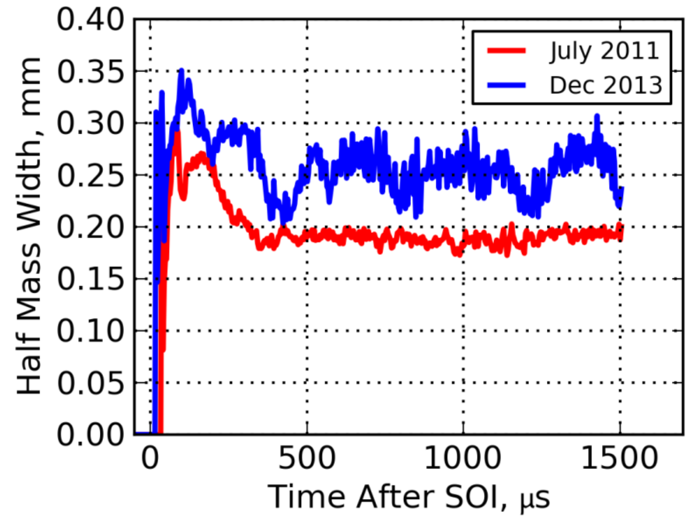
x = 2.0 mm





x = 6.0 mm





Conclusions: Experimental

- New measurements and analyses of Spray A have yielded new insights
  - Improved tomography for radiography measurements near-nozzle
  - More highly resolved optical measurements, both with microscopy and ballistic imaging
  - Droplet sizes are very small for nozzle 679. Is this universal for all Spray A nozzles?
- First radiography measurements of Spray B have been performed
- Important similarities and differences between Spray A and Spray B
  - Spray B penetrates more slowly. Consistent with slower ROI. Maybe lower sac pressure?
  - Spray B tends to be wider and slightly more dilute on-axis.
  - Spray B has larger TIM outside the nozzle due to larger d. Difference grows after x = 5 mm
  - Spray B far more dynamic. Even with 1.5 ms injection duration, never quite reaches a steady state in either radiography or optical imaging.
- Nozzle ageing is a serious and growing problem.
  - Causes both quantitative and qualitative changes in spray behavior
  - Need to better understand how this occurs. These nozzles run for thousands of hours on the road.
  - Need to better adhere to guidelines for care and use of injectors

Goals for ECN4: Experimental

- Better understanding of droplet size in both Spray A and Spray B
  - Influence of multi- vs. single-hole nozzles
  - Influence of ambient pressure, rail pressure, and fuel
  - Time resolution
- More extensive measurements and analysis comparing Spray A and Spray B
- Quantification of differences between Spray B injectors
  - Some holes are more defective than others
  - Spray A showed substantial differences between holes
  - Should we focus on holes other than hole #3?
- More complete measurements of parametric variations of major parameters
  - Some done for Spray B
  - Would form a better test for models
- Better understanding of how to avoid nozzle ageing effects

What do Experimentalists Want from Modelers?

- What is the sac pressure inside the injector?
- What is the state of the flow exiting the injector? Temperature? Cavitation?
- What is the root cause of the spray transients, especially in spray width?
- Do the dense fluid / thermodynamics issues raised recently fundamentally change how we have to view sprays at high temperature?
- What causes dribble at end of injection? Important for engine emissions.