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SPRAY STRUCTURE MEASURED WITH X-RAY RADIOGRAPHY

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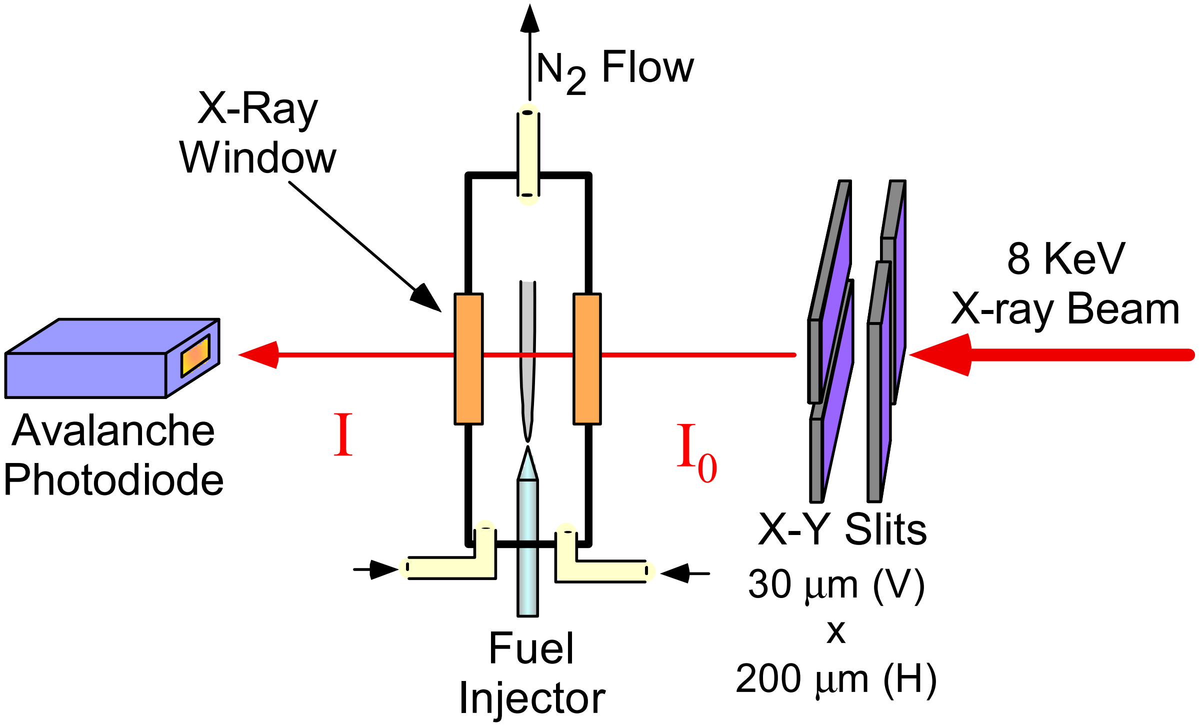
Good Understanding of Spray Structure is Important in Diesel Combustion

- Performance and emissions of diesel engines are closely tied to the spray from the injector
  - Excessive penetration → wall wetting → UHC emissions
  - Excessive premixed combustion → NOx emissions
- Led to progressive development of diesel injection systems to achieve better mixture preparation
  - Pump-Line-Nozzle → Unit Injectors →Common Rail Systems
  - Smaller injector holes
  - Higher injection pressure

Current Spray Diagnostic Techniques Inadequate

- Understanding of the atomization of diesel sprays is still incomplete
- Mechanical Measurements
  - Intrusive
- Optical Measurements
  - Can’t probe internal spray structure in dense regions
  - Often not quantitative, due to strong scattering effects
- **Need a nonintrusive, quantitative technique to measure sprays**

Schematic of X-Ray Setup



Quantitative relationship between x-ray transmission and projected mass density

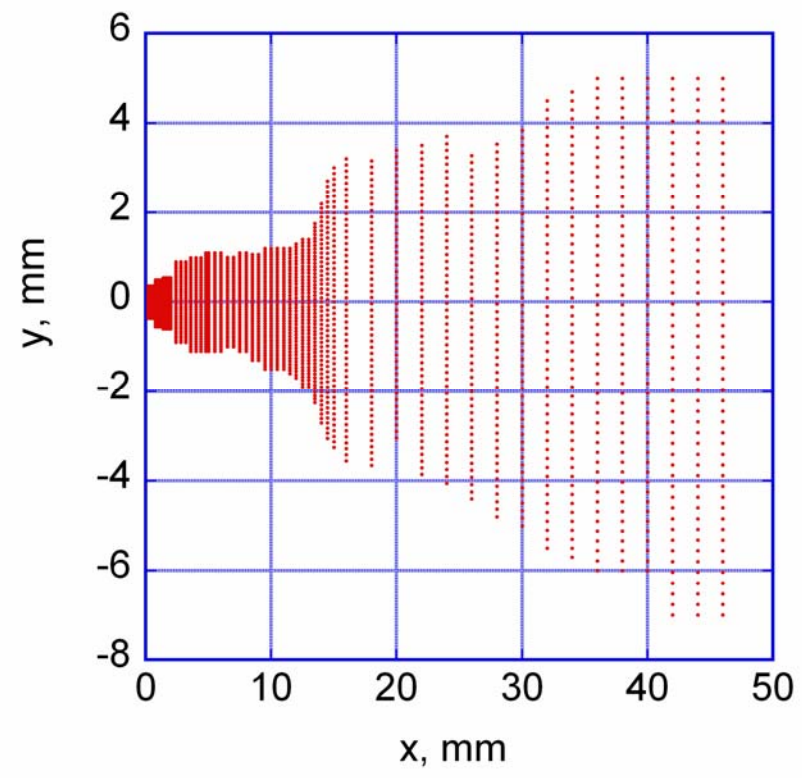
I_0	Incident x-ray intensity
I	Measured x-ray intensity
μ_M	Fuel absorption constant, area/mass
M	Projected mass density, mass/area

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

$$M = \frac{\ln(I_0 / I)}{\mu_M}$$

Radiography Has Good Spatial and Time Resolution

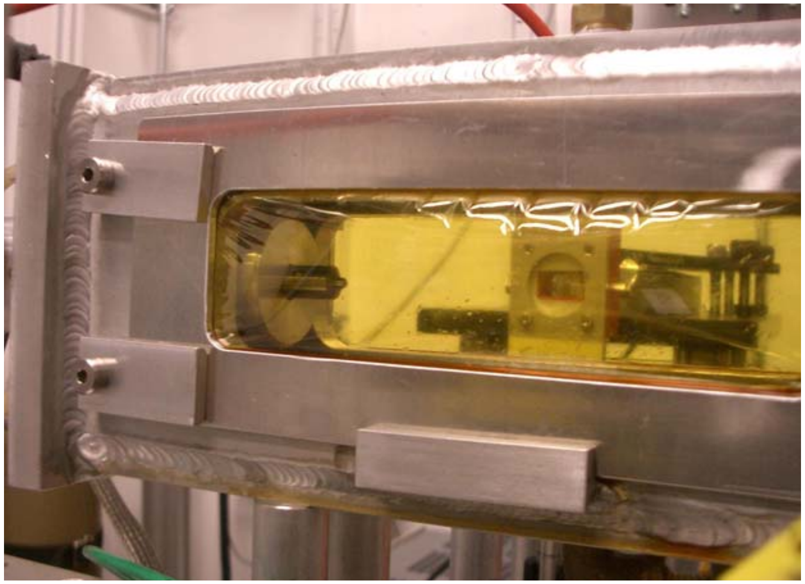
Measurement Grid



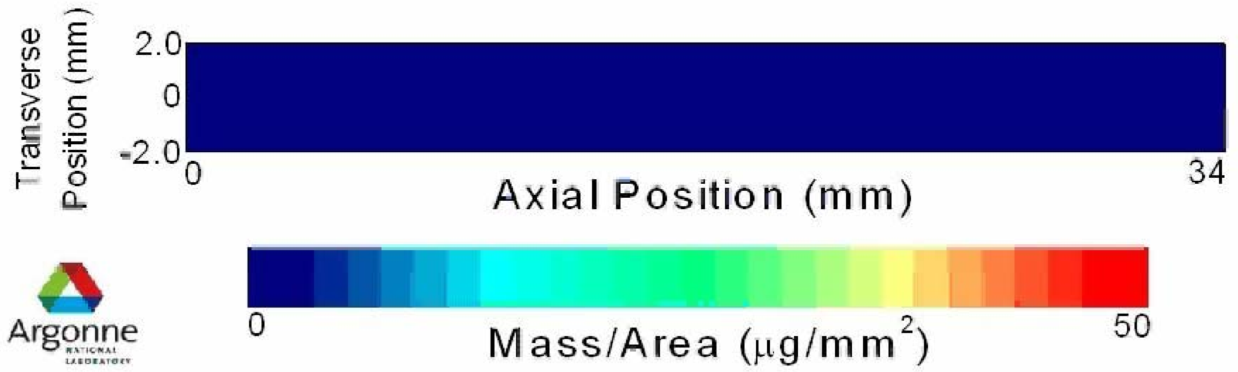
- Radiography is a pointwise measurement
  - Raster injector to build up measurement grid
  - Example grid: 2250 points
  - Data in discrete columns
- Also good temporal resolution: time step 3.68 μs
  - 1 CAD at 3000 rpm = 56 μs

Experiment Details

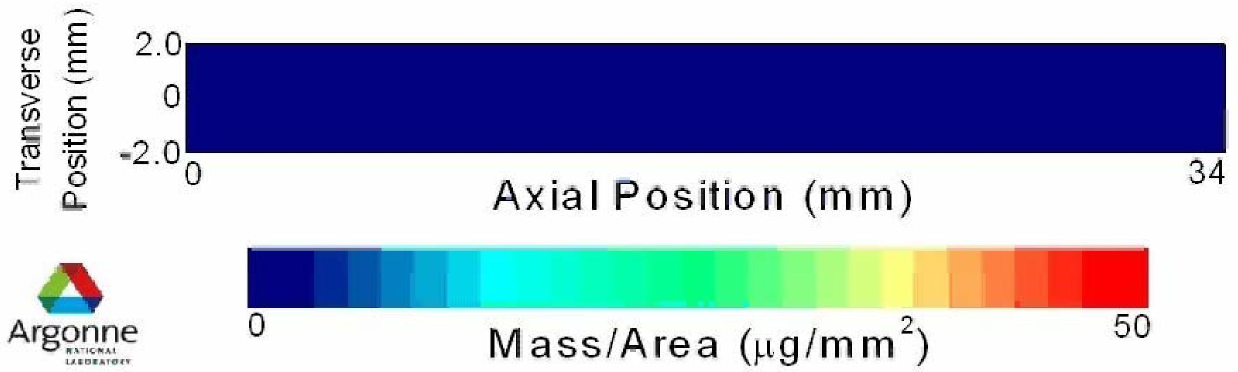
- Light-duty diesel common-rail injector
- Two nozzles: axial single hole
  - Hydroground
    - *Subjected to 24% hydrogrinding*
    - *Orifice diameter: 183 µm*
  - Non-hydroground
    - *Orifice diameter 207 µm*
  - Designed to have the same steady-state flowrate
- Injection parameters
  - Injection pressure: 250 bar
  - Injection duration: 400 and 1000 µs
  - Ambient gas: N_2
  - Ambient pressure: 1 bar
  - Averaged over 64 injections
  - Liquid: Calibration fluid with cerium additive



Spray Evolution: 400 µs Injection

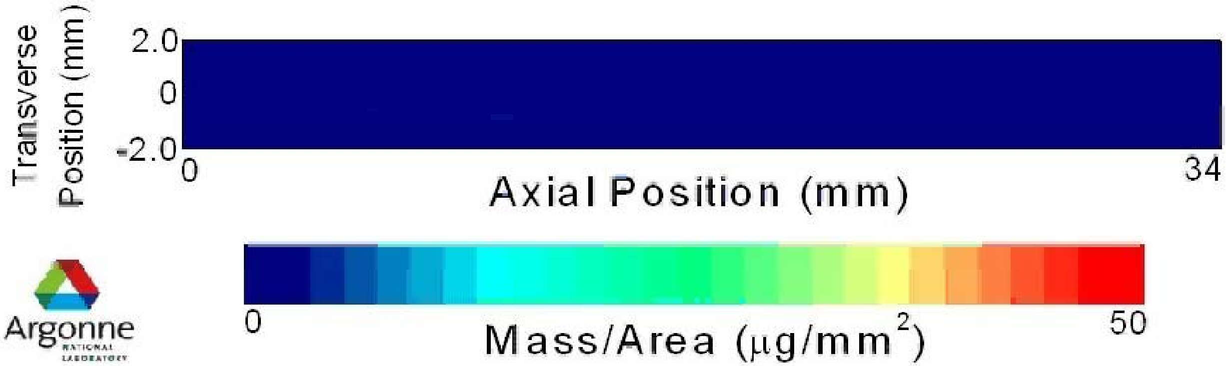


Hydroground

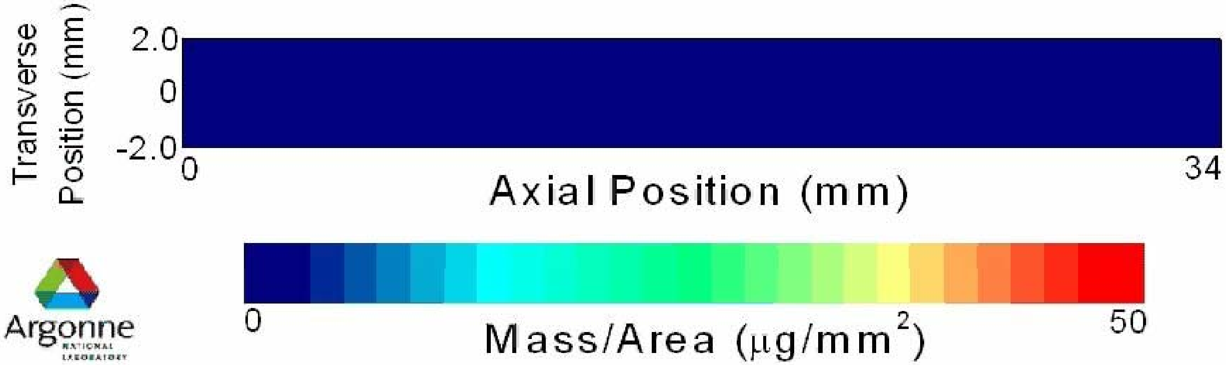


Non-hydroground

Spray Evolution: 1000 µs Injection

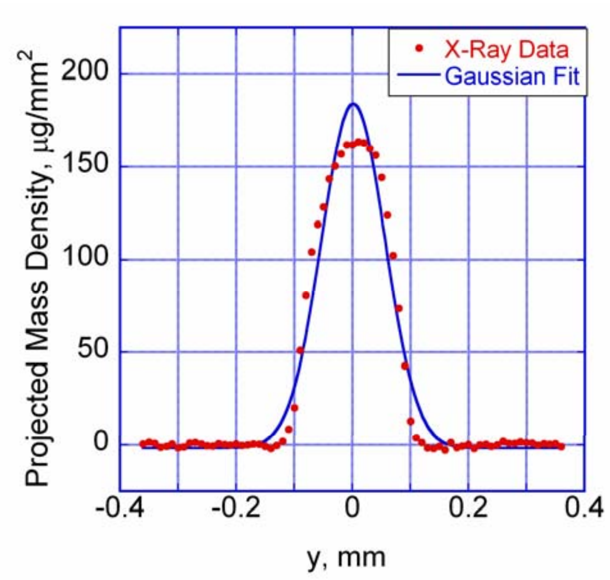


Hydroground



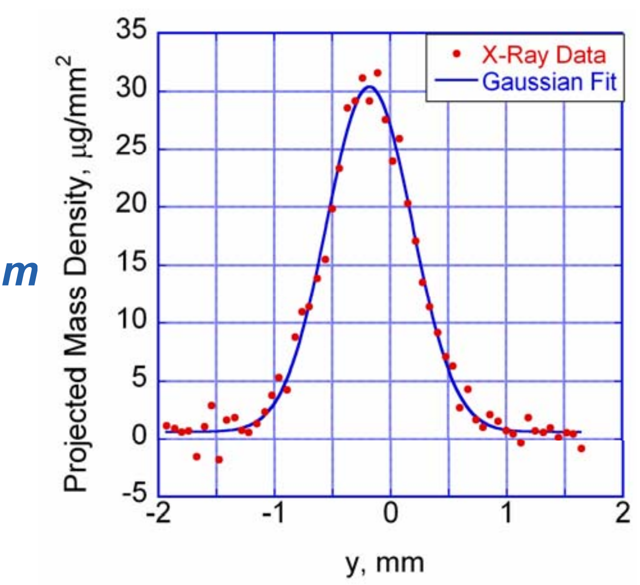
Non-hydroground

Transverse Mass Distributions Gaussian Except Near Nozzle



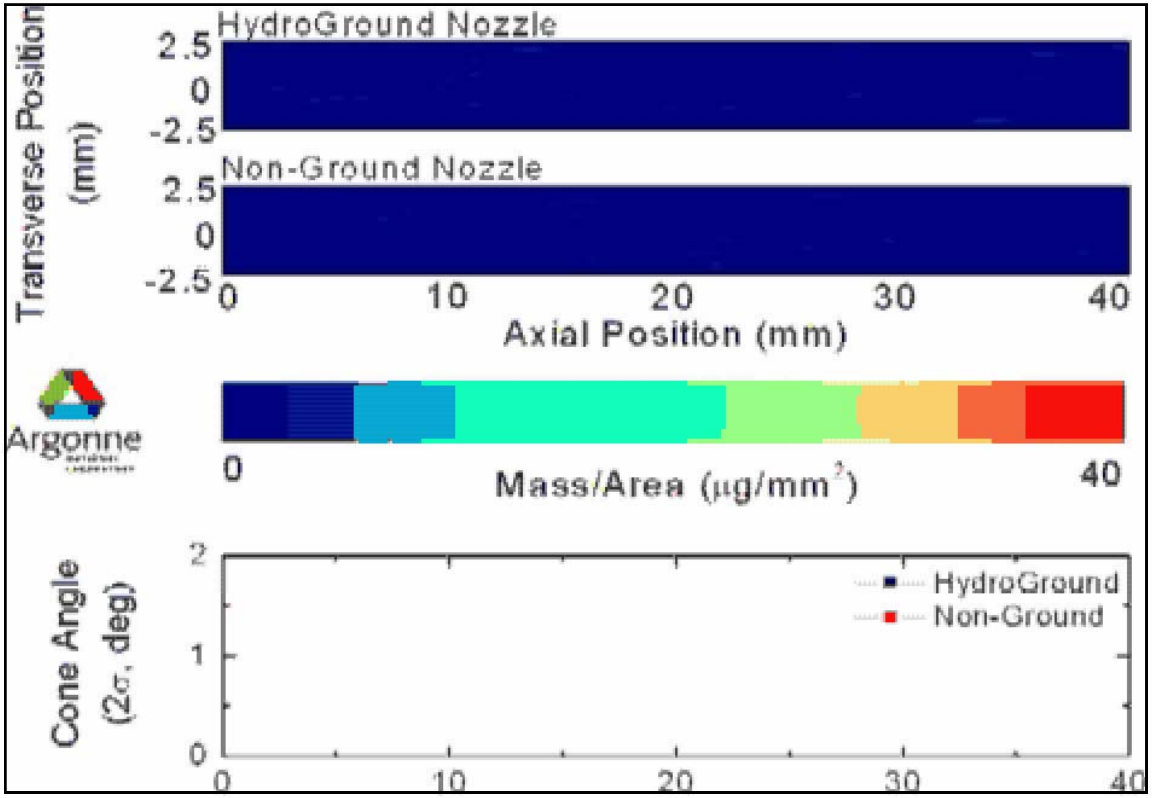
x = 0.2 mm

x = 10.0 mm



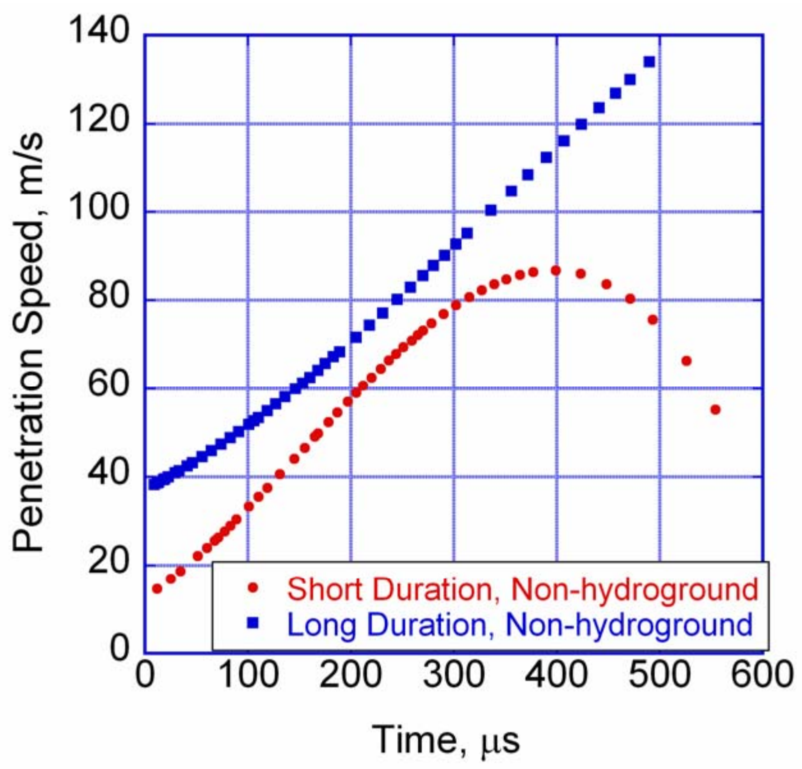
- Examine the mass density of the spray along a slice perpendicular to the spray axis
- Generally Gaussian shape
  - Matches expected behavior of a fully developed jet
- Distribution has flatter top than a Gaussian within 1 mm of the nozzle
  - Suggests that there is a relatively high-density core of fuel

Radiography Can Measure Cone Angle Dynamics



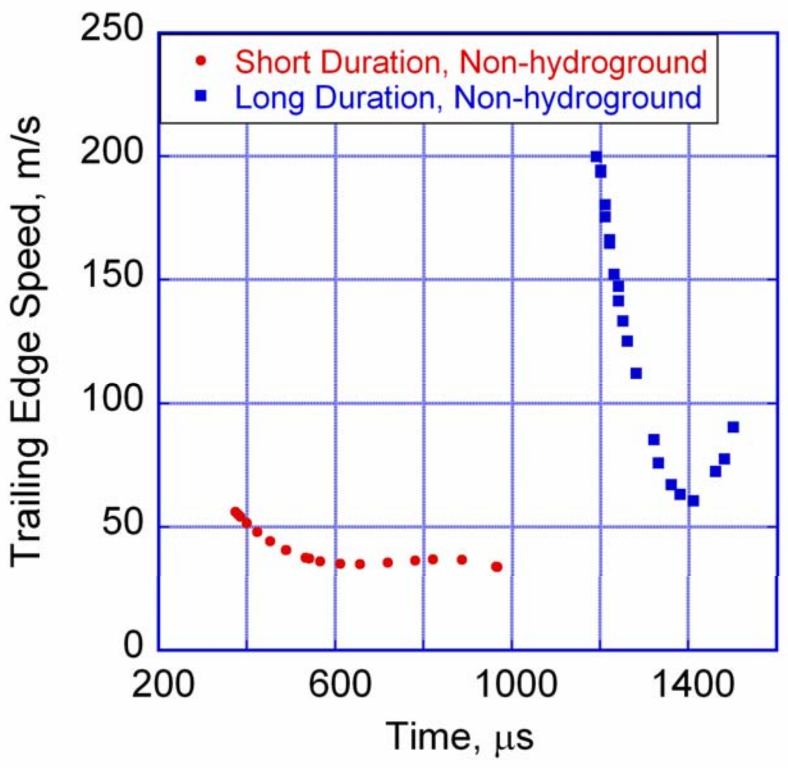
- Benefits of radiography over optical cone angle measurements
  - Dynamics
  - Based on spray core, not outside of droplet cloud

Radiography Can Measure Both Leading and Trailing Edge Speed

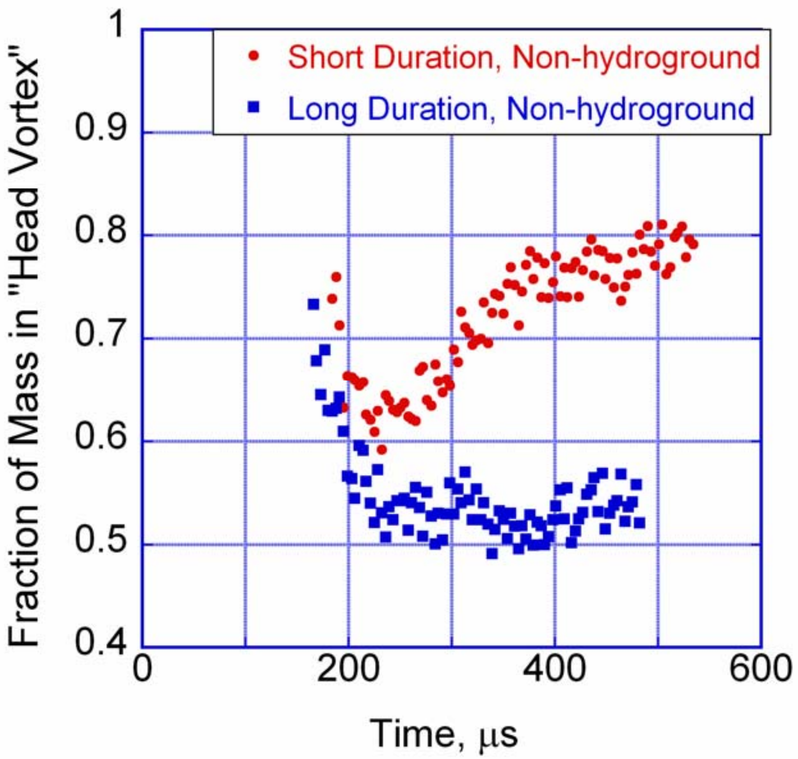


Penetration

Trailing Edge



Large Amount of Fuel in "Head Vortex"



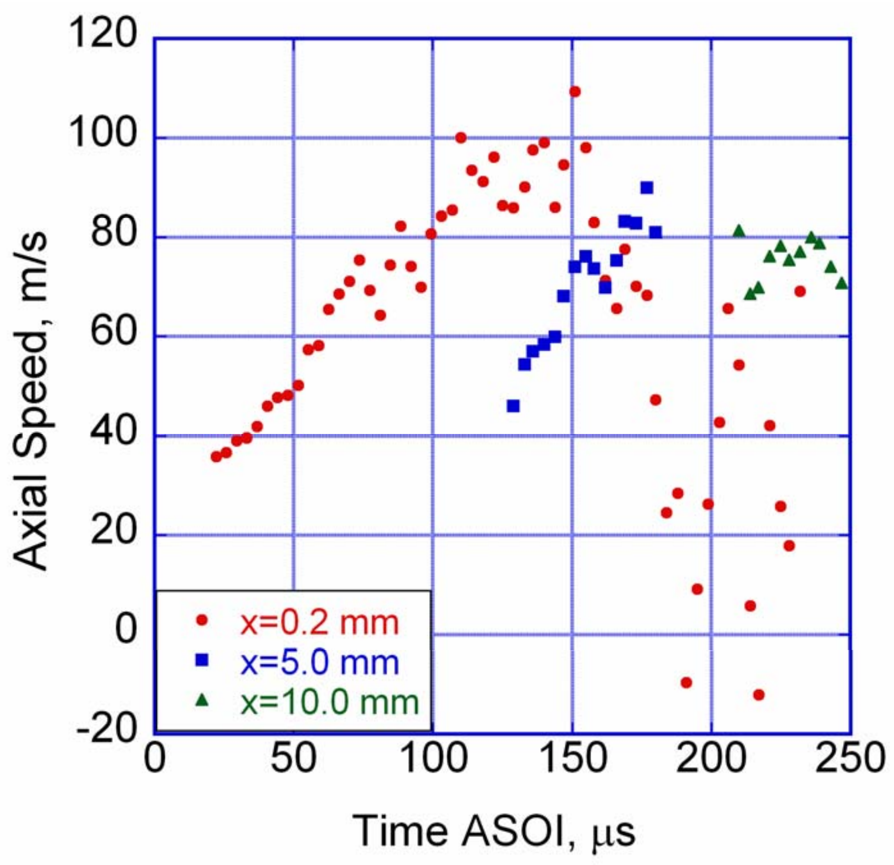
- Partition spray into "head vortex" and trailing jet
  - While entire spray remains in measurement domain
- "Head vortex" more prominent for short duration injections
  - Nearly 80% of mass after end of short duration injection
- Trailing jet remains relatively dense for long duration injections
  - "Head vortex" contains the majority of the mass
- Implications for spray modeling

Future Work

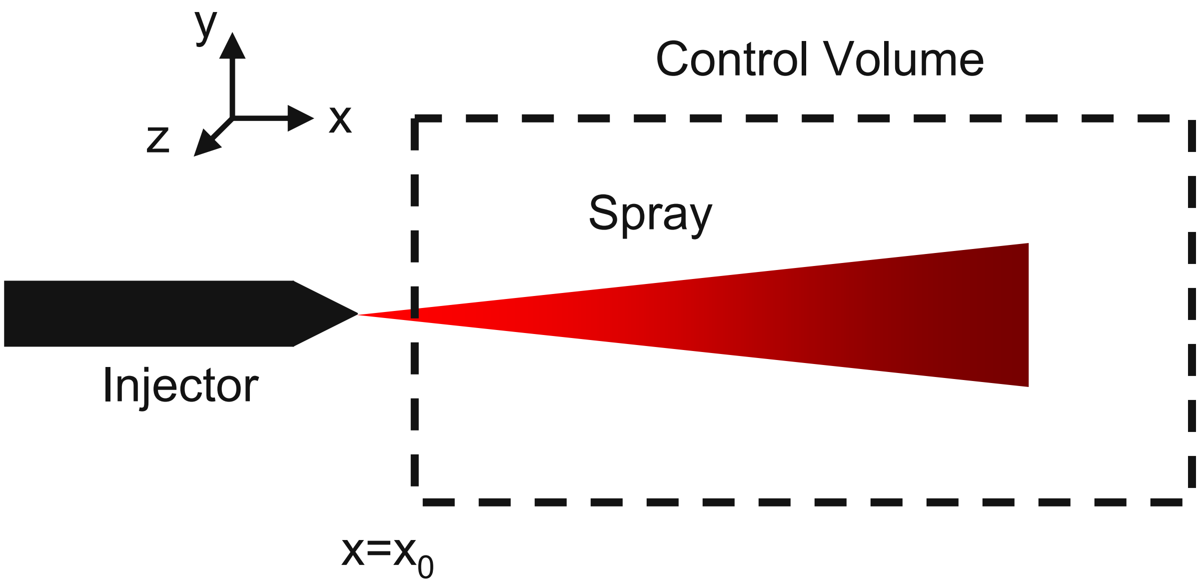
- Extend current experimental conditions
  - Shrink the size of the x-ray beam: better spatial resolution
  - Increase ambient pressure: density closer to engine conditions
    - *Recently achieved 30 bar ambient pressure*
  - Experiments in multi-hole nozzles: closer to applied equipment
  - Single-shot & image-based measurements
- Improved Data Analysis
  - Projection inversion: estimate true fluid density from projected mass density
  - Refine determination of the “head vortex”
  - Axial velocity determination

Future Work: Spray Axial Velocity Determination

- Axial velocity of spray in dense regions of the spray is not well known
- Measure mass-averaged axial velocity for each measurement column
  - Internal speed of liquid
- Axial velocity affects:
  - Penetration speed
  - Shear with ambient gas
  - Initialize spray breakup models
- Calculated axial velocity for a 400 µs spray from a hydroground nozzle
  - Speed from Bernoulli's equation: 236 m/s



Future Work: Spray Axial Velocity Determination



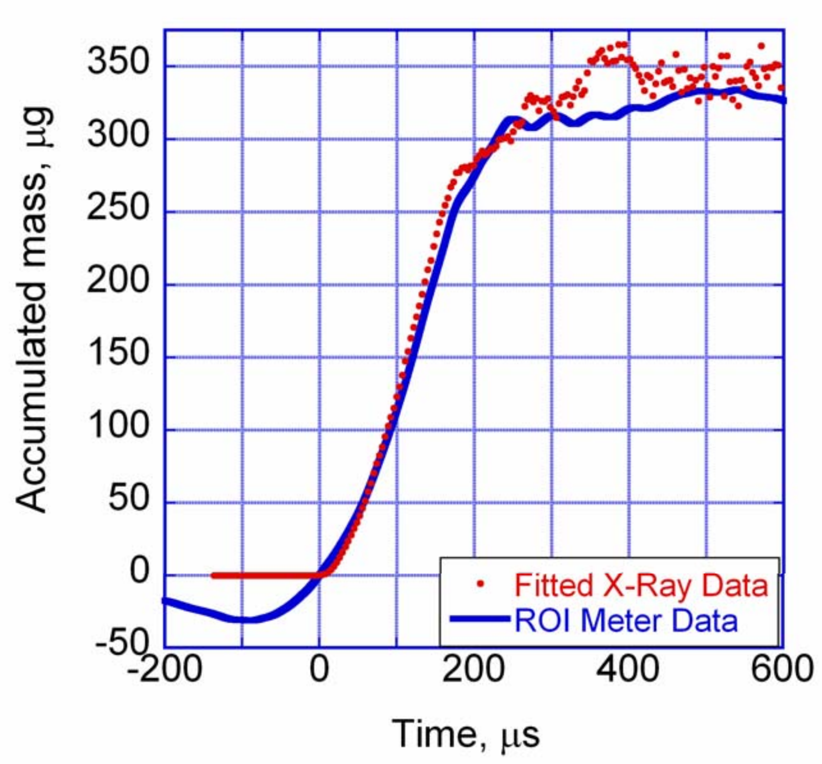
$$\dot{m}_{cv}(x > x_0, t) = -\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \rho(x_0, y, z, t)\cdot \overline{V}(x_0, y, z, t) \bullet \hat{n}\cdot dz\cdot dy$$

$$= \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \rho(x_0, y, z, t)\cdot V_x(x_0, y, z, t)\cdot dz\cdot dy$$

$$V_{ma}(x_0, t) = \frac{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \rho(x_0, y, z, t)\cdot V_x(x_0, y, z, t)\cdot dz\cdot dy}{\int_{-\infty}^{\infty}\left[\int_{-\infty}^{\infty} \rho(x_0, y, z, t)\cdot dz\right]\cdot dy}$$

[redacted]

Radiography Mass Measurements Match Mechanical Measurements

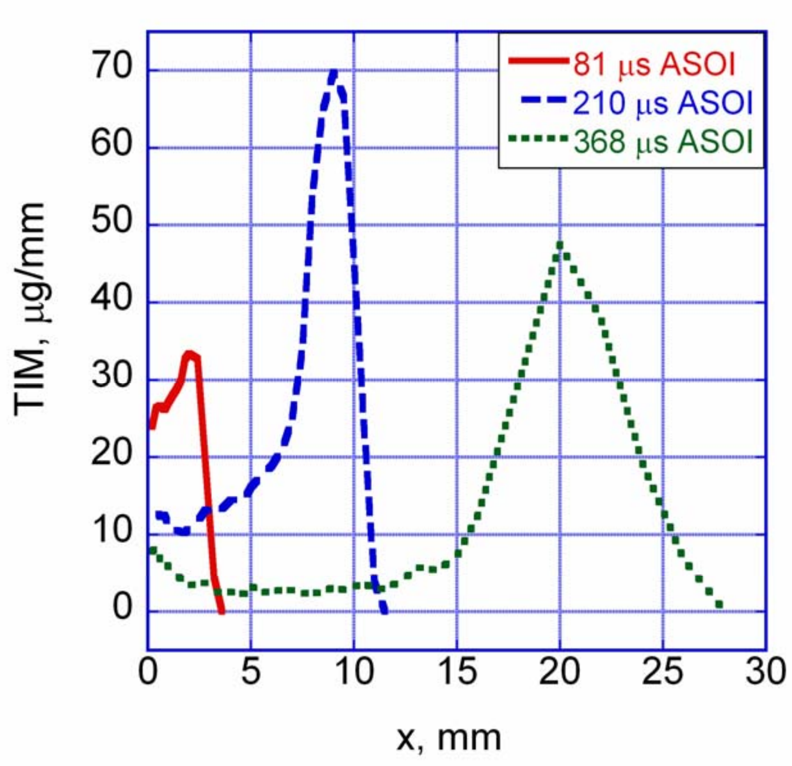


Hydroground nozzle, 400 µs spray

- Accumulated mass as a function of time
- Generally good agreement with Bosch Rate-of-Injection meter
- Total injected mass by mechanical measurement is 334 µg, which agrees well with the x-ray data

Transverse Integrated Mass

- Examine area of Gaussian fits to transverse mass distributions
  - Indicates how densely spray is packed axially
  - In units of mass/length
  - Aids in further analysis
  - Referred to as Transverse Integrated Mass (TIM)
- Peak value corresponds to leading edge structure
- TIM increases between nozzle and leading edge, suggesting spray slows down as it moves downstream
  - Expected behavior from fully developed jet theory
  - Transverse spread coupled with axial compression

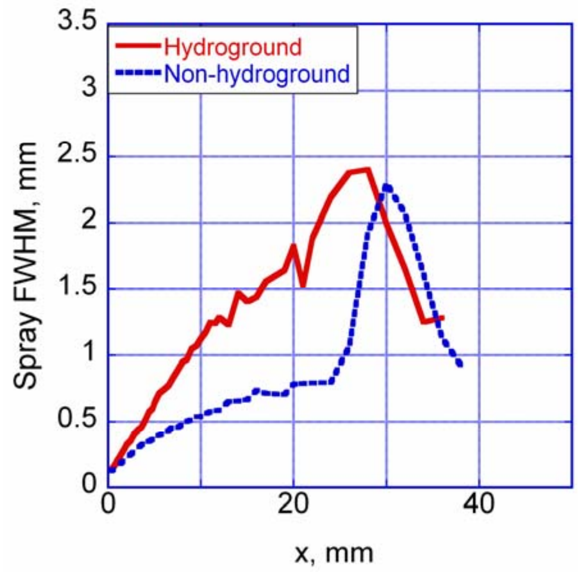


Cone Angle for 1000 μs Duration Sprays

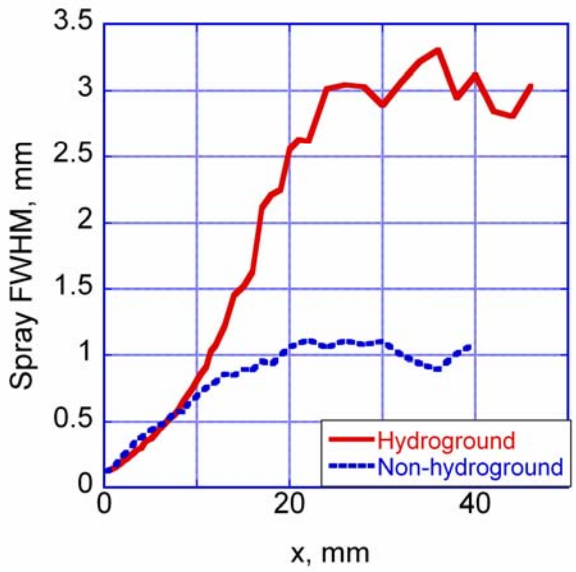
- Cone angle based on linear fit to FWHM of Gaussian fits of transverse mass distributions for 0 < x < 10 mm
- Far smaller angles than typically seen from optical measurements
  - Indicates that optical measurements focus on spray periphery
- Increase in cone angle at end of spray for both nozzles
  - Seen in optical measurements as well
- Cone angle changes significantly during the spray event

Spray Event	Cone Angle
Hydroground, 475 μs ASOI	5.9°
Non-hydroground, 475 μs ASOI	2.5°
Hydroground, 644 μs ASOI	3.9°
Non-hydroground, 644 μs ASOI	3.3°
Hydroground, 1072 μs ASOI	1.2°
Non-hydroground, 1072 μs ASOI	2.8°
Hydroground, 1219 μs ASOI	7.1°
Non-hydroground, 1219 μs ASOI	3.8°

Spray Width: Hydroground vs. Non-hydroground

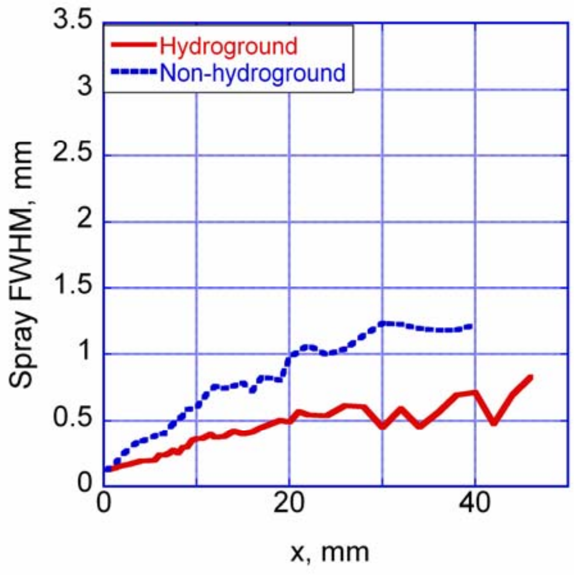


475 μs ASOI



664 μs ASOI

1072 μs ASOI



1219 μs ASOI