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Effect of Ambient Pressure on Diesel Spray Axial Velocity and Internal Structure

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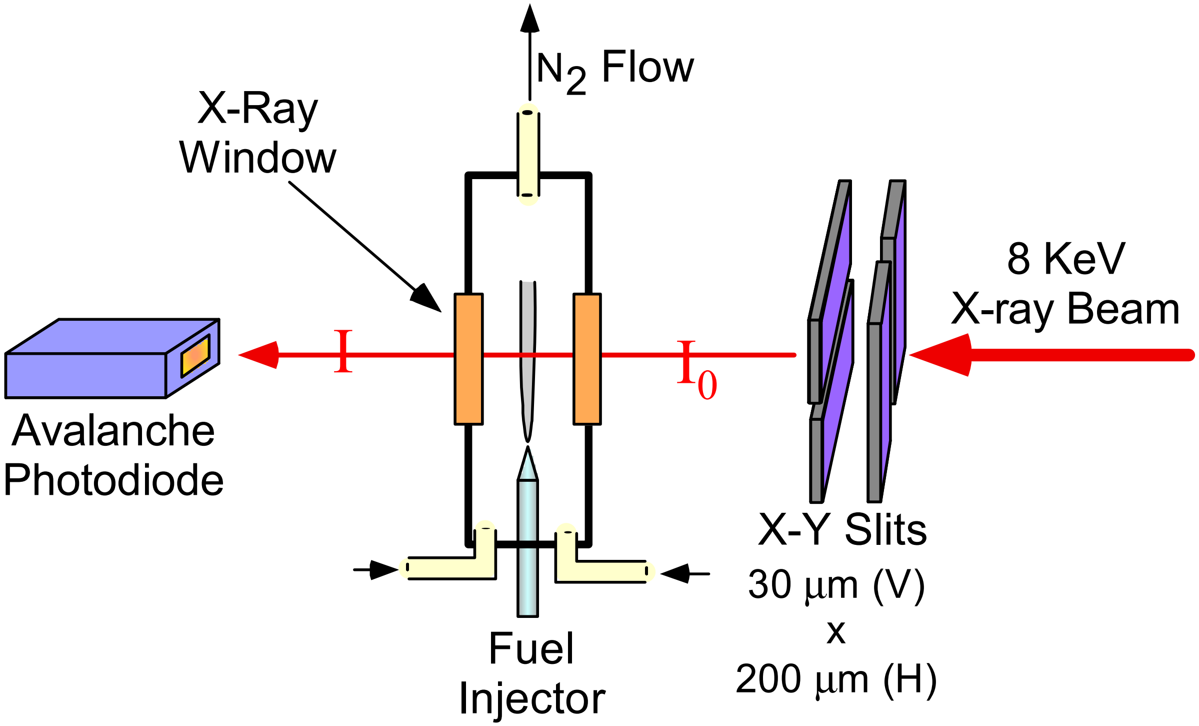
Good Understanding of Spray Structure is Important in Diesel Combustion

- Performance and emissions of diesel engines are closely tied to the spray from the injector
  - Excessive penetration → wall wetting → UHC emissions
  - Poor spray pattern → poor fuel-air mixing → increased emissions
- Two of the most important variables that effect spray behavior are injection pressure and ambient density
  - Penetration speed increased by higher injection pressure and lower ambient density
  - Cone angle seems to increase as ambient density increases

Current Spray Diagnostic Techniques Are Inadequate

- Most spray measurements are based on optical measurements
  - Adequate for measuring penetration speed
  - Can’t probe internal spray structure in dense regions
  - Often not quantitative, due to strong scattering effects
- There are important parameters these optical techniques can’t show
  - Mass distribution of fuel in the spray
  - Fuel velocity away from the leading edge
- **Need a nonintrusive, quantitative technique to measure sprays**

X-Rays Give a Quantitative Determination of Fuel Distribution



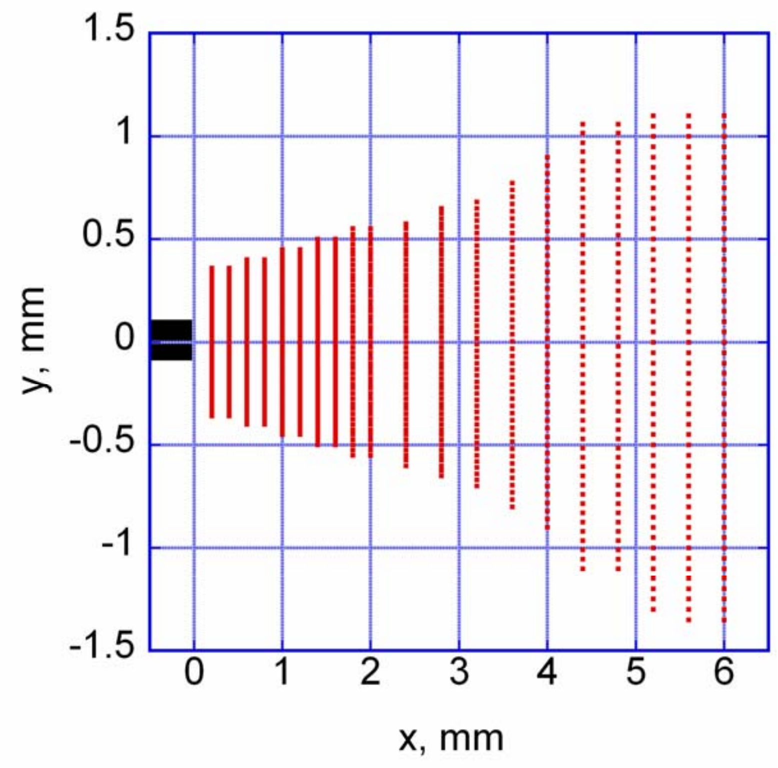
I_0	Incident x-ray intensity
I	Measured x-ray intensity
μ_M	Fuel absorption coefficient
M	Projected mass density, mass/area

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

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

Radiography Has Good Spatial and Time Resolution

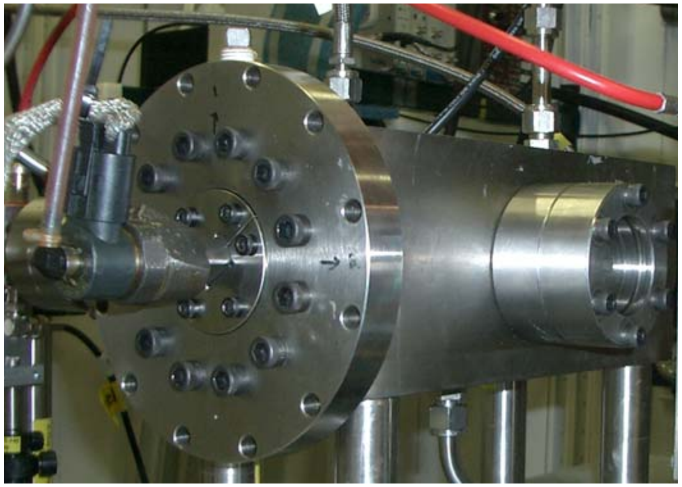
Measurement Grid



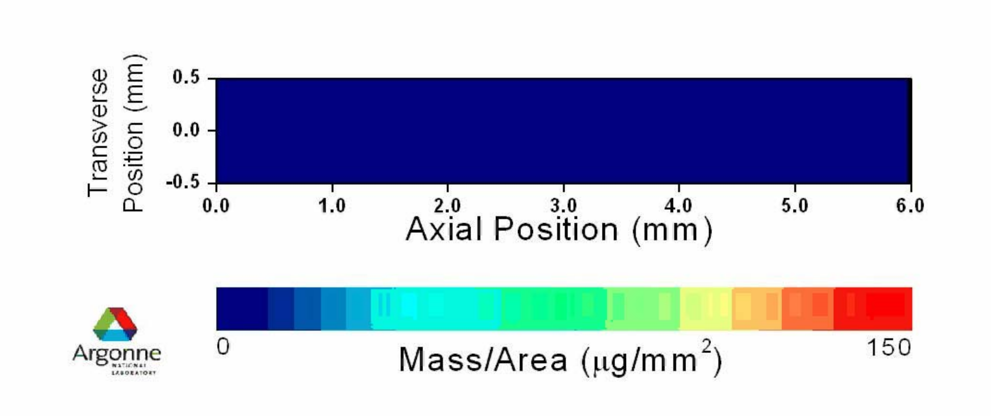
- Resulting data: 2-D fuel mass distribution as a function of time
- Measurement range
  - 0.2 – 6.0 mm axial
  - -1.4 – 1.2 mm transverse
  - 2 ms of data
- Time step 3.68 µs
  - 0.07 CAD at 3000 rpm

Experiment Details

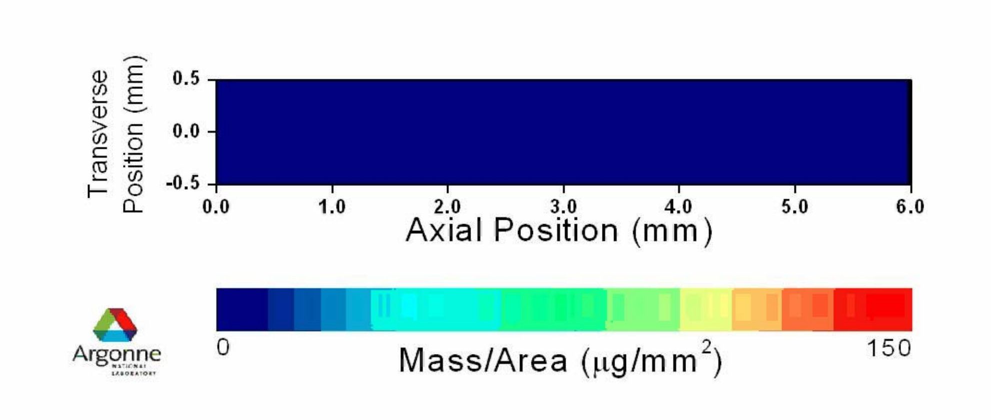
- Light-duty diesel common-rail injector: solenoid driven
- Axial single hole
  - Non-hydroground: r/D = 0.2
  - Orifice diameter 207 µm
  - L/D = 4.7
- Injection parameters
  - Injection pressure: 500 and 1000 bar
  - Injection duration: 1000 µs
  - Ambient gas: N_2 at room temperature
  - Ambient pressure: 5 bar and 20 bar
  - Liquid: Diesel calibration fluid with cerium additive



Spray Evolution for Different Ambient Densities, 1000 bar Injection Pressure

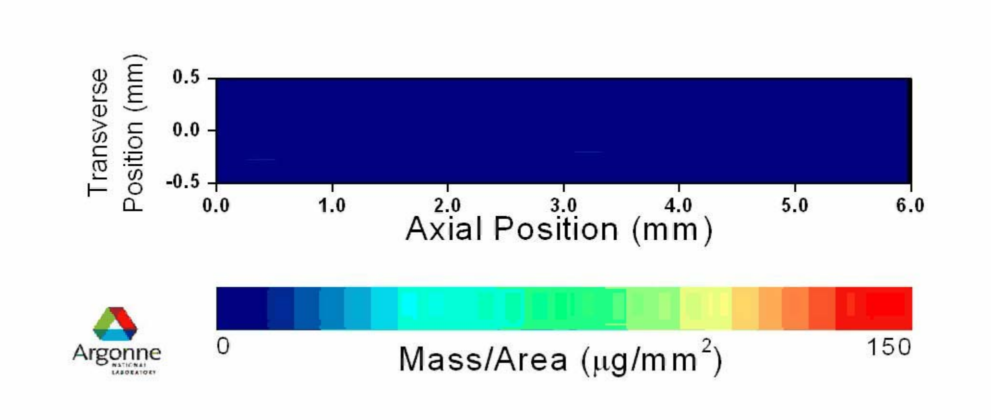


5 Bar N_2

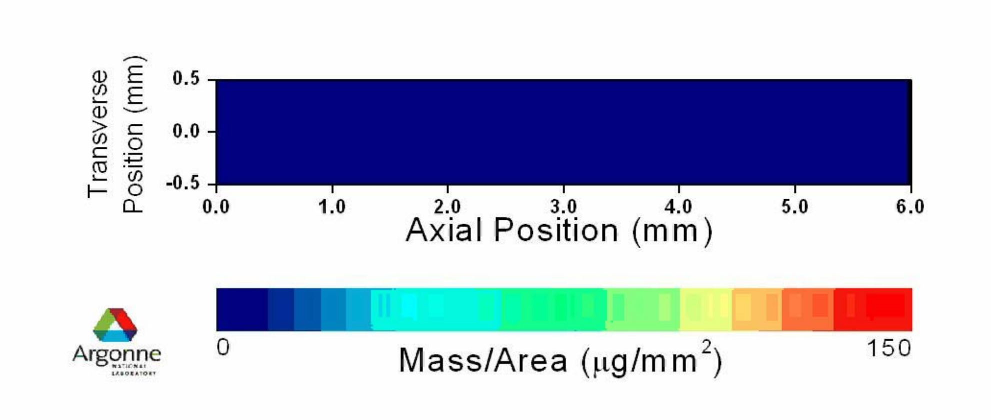


20 Bar N_2

Spray Evolution for Different Injection Pressures, 5 Bar Ambient N_2



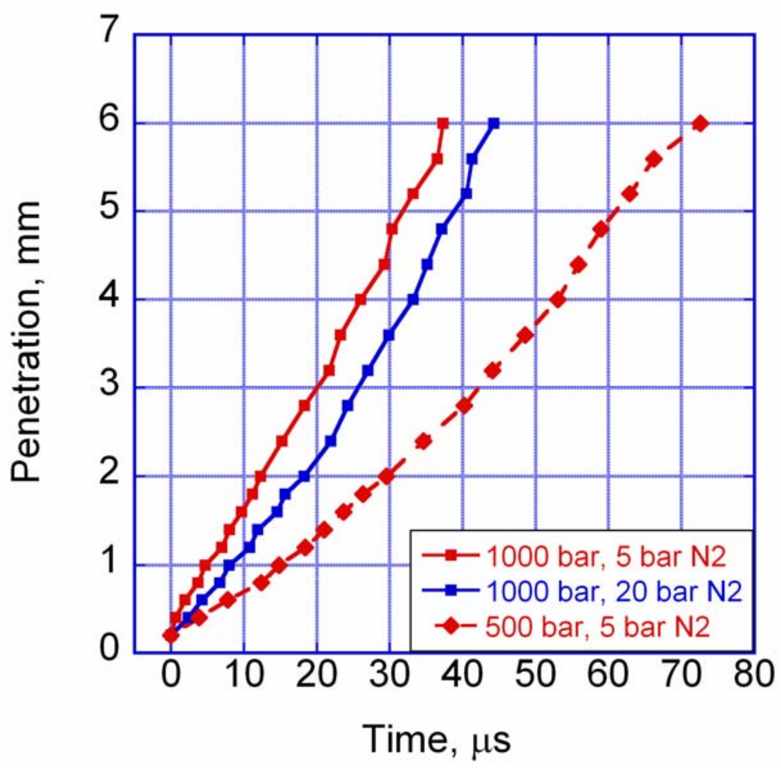
500 bar



1000 bar

Penetration Results

- Penetration of leading edge vs. time
- Increased ambient density reduces penetration speed
  - Not as much as accepted correlations indicate
- Lower injection pressure reduces penetration speed
  - More than expected
- Dynamics of injector opening are important to early penetration results

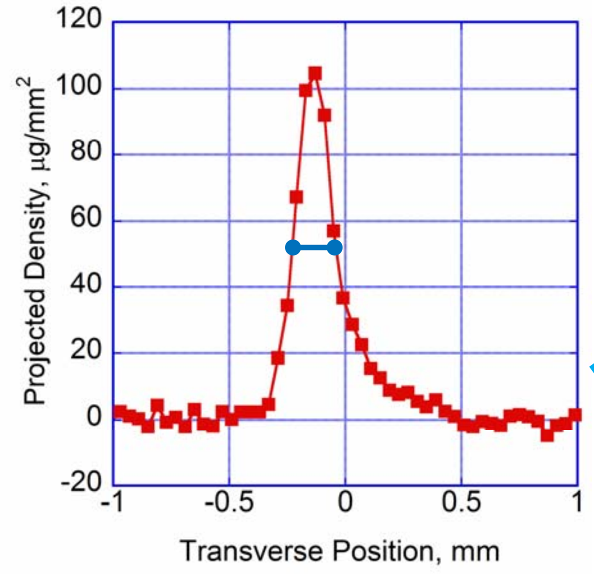


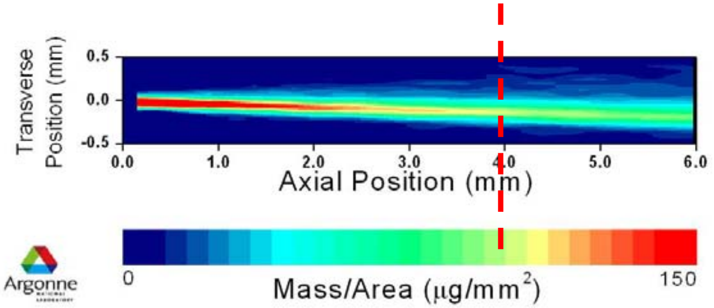
Penetration

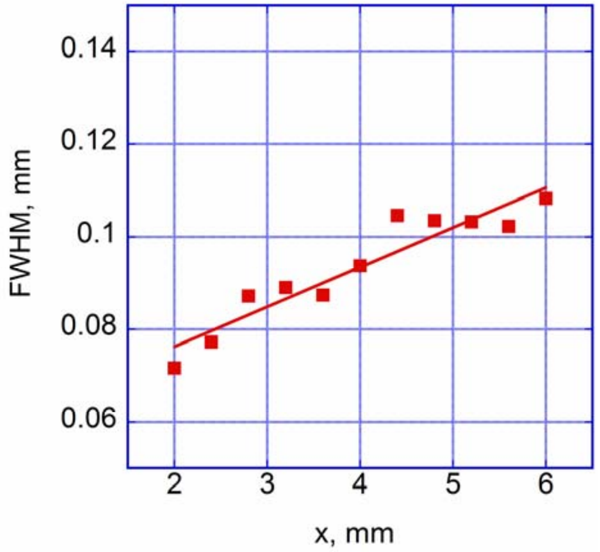
Previous Cone Angle Results

- Cone angle measurements help explain how the fuel mixes with the ambient gas
- Typically found by examining optical spray images
- X-ray radiography gives much more detail than optical measurements on the internal mass distribution
  - Based on a well-defined, quantitative measure of the fuel distribution
  - Can record cone angle as a function of time

Use of Radiography to Find Cone Angle

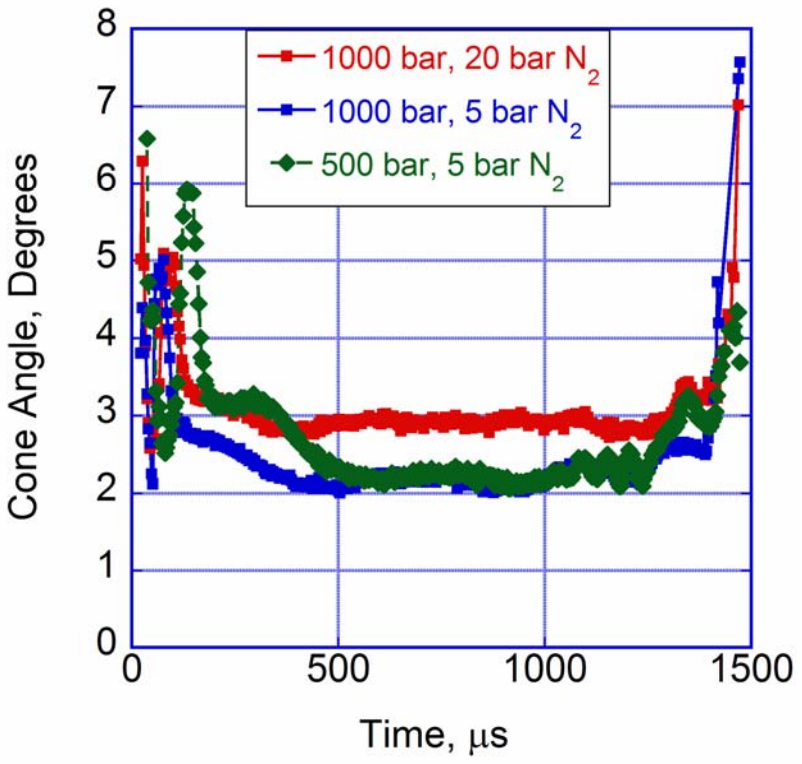






Cone Angle Changes Significantly with Time

- Define cone angle based on the mass distributions across the spray
- Time period of few hundred µs for cone angle to reach steady state
- Much smaller than typical optical cone angles
  - Examining spray core
  - Optical measurements show spray periphery
- Injection pressure has little effect on steady state cone angle
- Increased chamber pressure increases cone angle

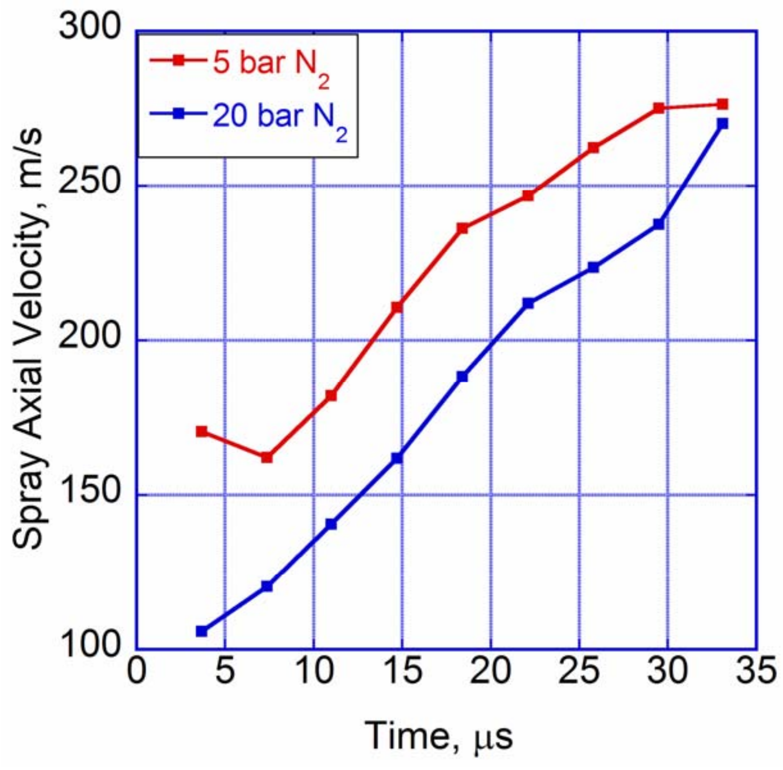


Spray Axial Velocity Determination

- Axial velocity of spray in dense regions of the spray is not well known
- Axial velocity affects:
  - Penetration speed
  - Shear with ambient gas
  - Initialize spray breakup models
- Radiography can be used to determine the mass-averaged axial velocity of the spray for limited time spans near the beginning of the spray event
  - Due to quantitative measurement of mass as a function of time
  - Velocity measured as a function of both x and t
  - Limited to time just after the start of injection

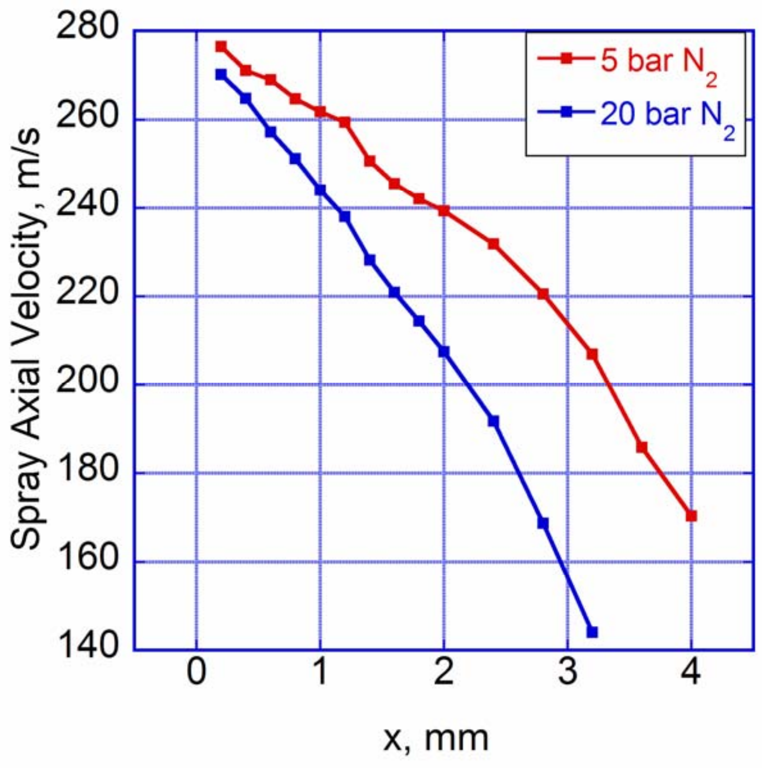
Spray Axial Velocity Increases Over Several Microseconds

- Spray velocity vs. time near the nozzle exit (x = 0.2 mm)
- Both cases have same commanded injection timing and injection pressure (1000 bar)
- Seeing the transient in the spray velocity as the needle opens
- Same slope of injection velocity vs. t, but offset by 5-7 μs
- Bernoulli velocity = 474 m/s, so the needle is probably not yet fully open in either case



Spray Axial Velocity Is Strongly Affected by Ambient Density

- Spray velocity vs. x 33 μs after SOI
- Spray moves more slowly as distance from nozzle increases
  - Reduction in spray velocity due to aerodynamic interactions
  - Fluid at spray tip was injected at a slower velocity and so should move more slowly
- Difference in the two curves suggests that aerodynamic interactions slow the spray down more quickly with axial distance at higher ambient density

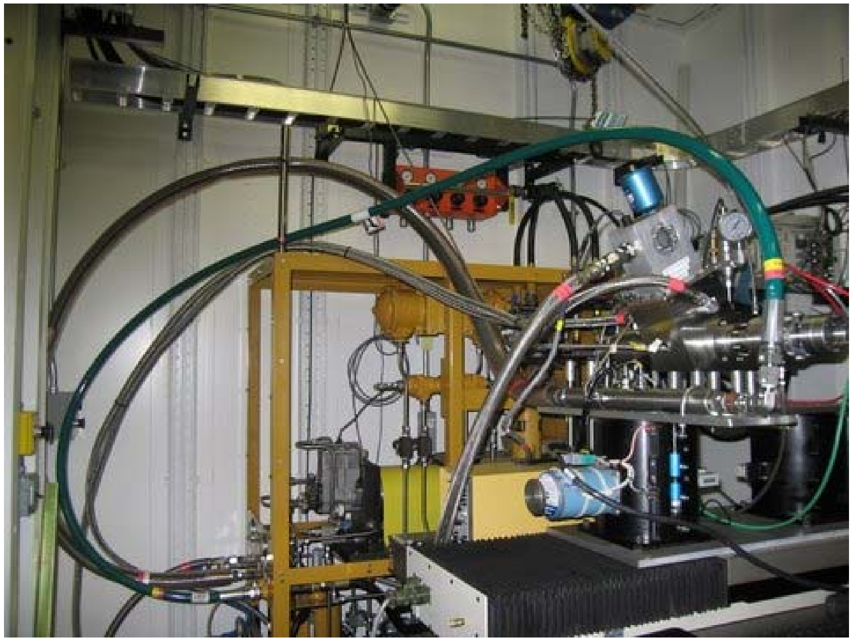


Future Work

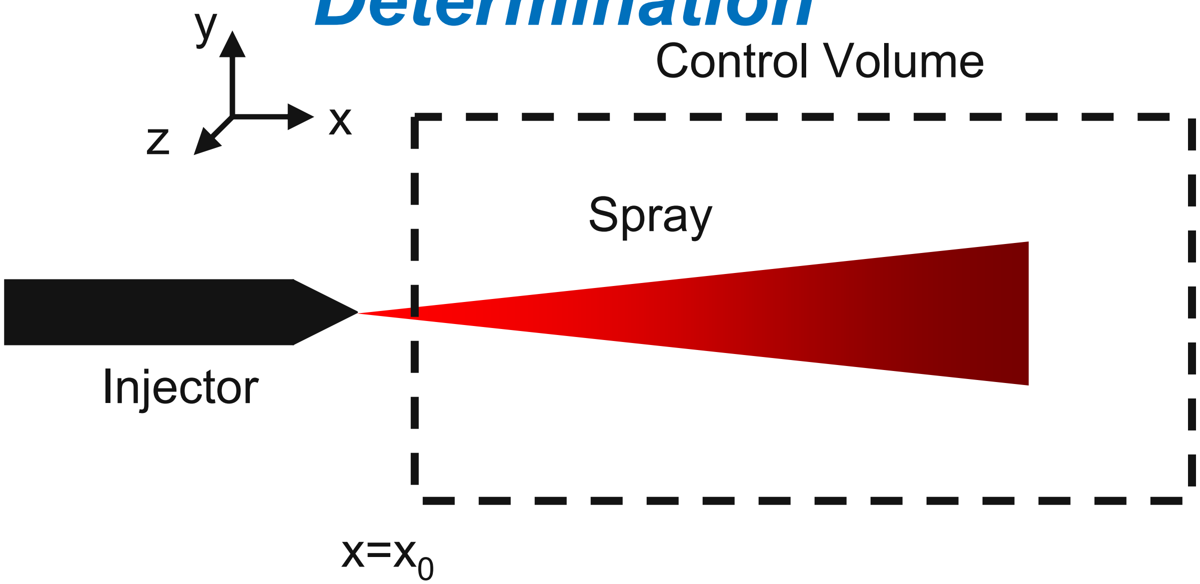
- Continue to increase ambient pressure (density) of measurements
  - Further measurements at 30 bar ambient pressure in the near future
  - Near the ambient density in-cylinder near TDC
- Perform measurements on multi-hole nozzles
  - More representative of applied nozzle geometries
  - More parameters to explore: spray angle, VCO vs. minisac
- Further refine the velocity determination
  - Improve signal/noise of measurements
  - Attempt to incorporate mechanical ROI measurements with the x-ray density measurements

Future Work (cont.)

- Measurements on a heavy-duty HEUI injector
  - Full 6-hole production nozzle
  - Measurements in progress
- Measurements with biofuels
  - Completed initial measurements with a biodiesel blend fuel
- Dedicated transportation applications x-ray facility under construction
  - Limited access to x-ray source in the past
  - Dedicated facility will increase access to x-ray source



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]