Argonne NATIONAL LABORATORY

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Fuel Spray Research on Light-Duty Injection Systems

Project ID ace_10_powell

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2009 OVT Merit Review
19 May 2009
Crystal City, VA

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U.S. Department of Energy

UChicago Argonne LLC

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Overview

Timeline

- Project Start: FY2000

Budget

- Lifetime Project Funding
  - $3.13M Since FY05
- Recent Funding
  - FY2008: $500K
  - FY2009: $645K

Partners

- Bosch, ERC, Sandia
- Delphi, Caterpillar

Barriers

- "Inadequate understanding of the fundamentals of fuel injection"
- "Inadequate capability to simulate this process"
- "Inadequate understanding of fuel injector parameters (timing, spray type, orifice geometry, injection pressure, single-pulse vs. multi-pulse)"

These barriers impact:

- Low-Temperature Combustion
- Thermal Efficiency
- System Cost

Objectives

- **Entire Project:**
  - ⇨ Serve industry by providing unique injector and spray diagnostics
  - ⇨ Assist in development of improved spray models using unique quantitative measurements of sprays

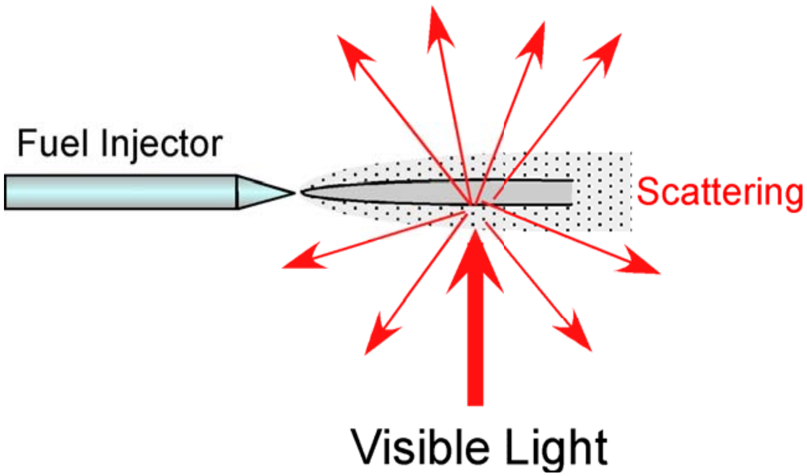
- **FY2009:**
  - ⇨ Study the effect of the number of orifices on spray structure
  - ⇨ Develop new technique for measuring 3D spray density
  - ⇨ Develop non-destructive needle lift diagnostic
    - ⇨ Useful tool for injector manufacturers
    - ⇨ Allows generation of realistic time-resolved mesh for modeling

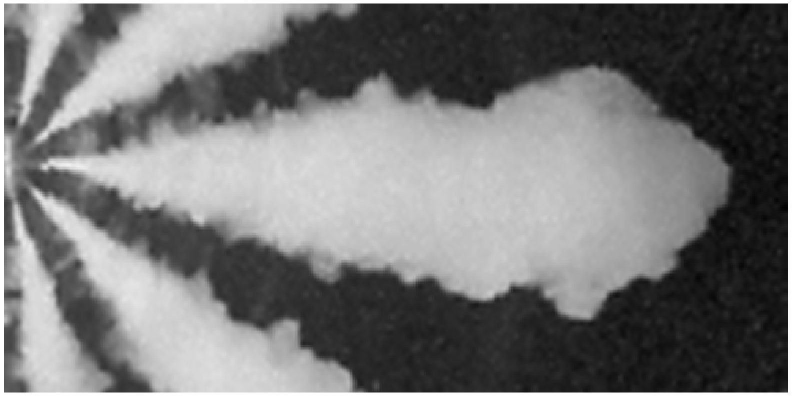
Milestones, FY2008 and FY2009

- **May 2008: Publication of study showing how spray width varies with spray chamber density**
- **June 2008; Completion of measurements showing how number of holes affects spray structure**
- **Aug 2008, Mar 2009: Real-time measurements of injector needle motion**
- **May 2009: Completion of x-ray laboratory dedicated to sprays and transportation research**

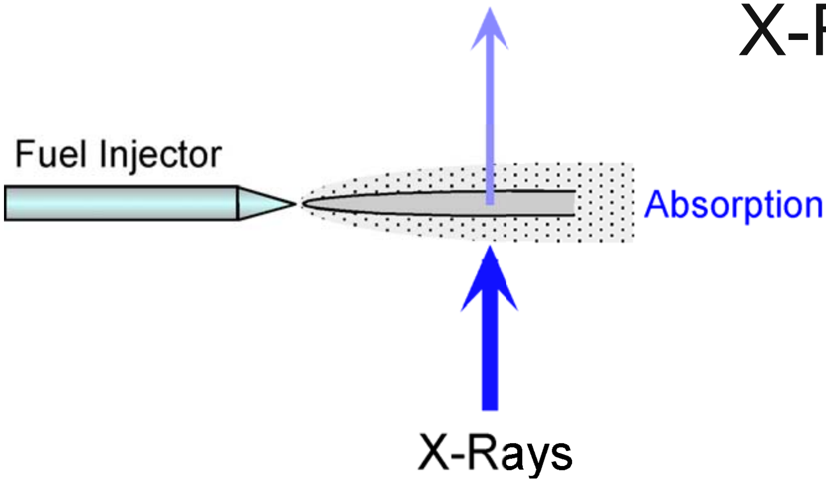
Technical Approach – X-rays Reveal Fundamental Spray Structure

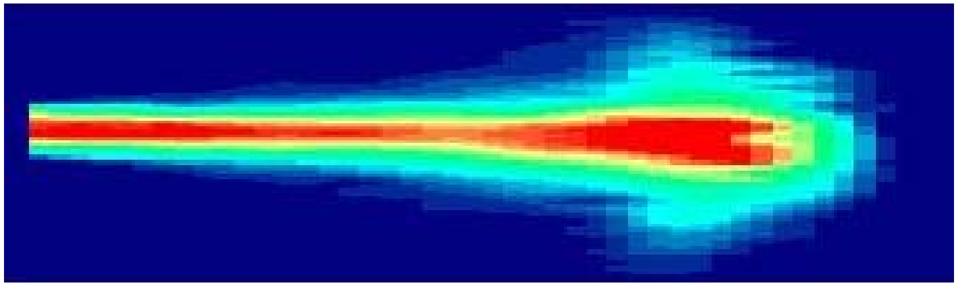
Visible Light Imaging



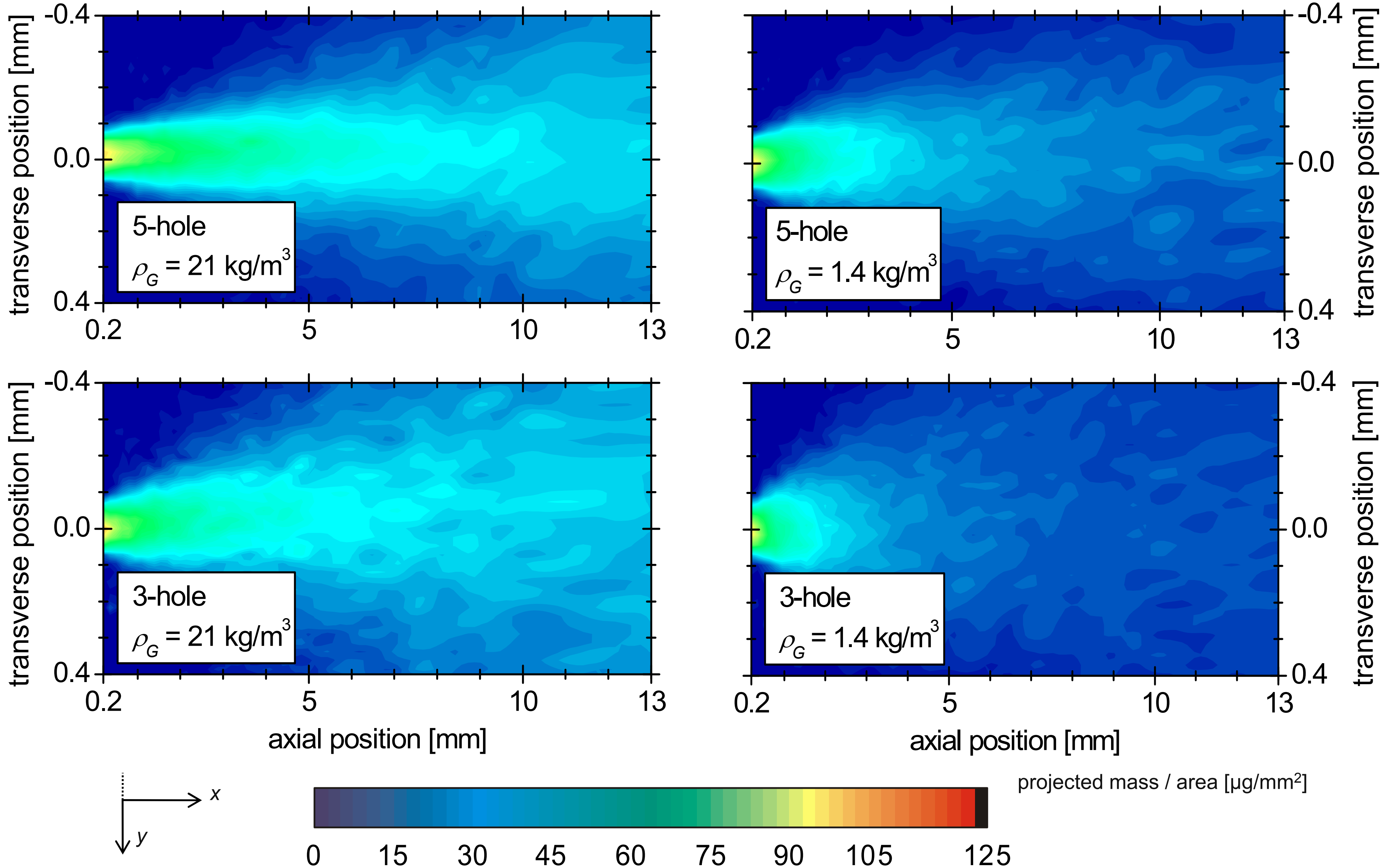


X-Ray Imaging

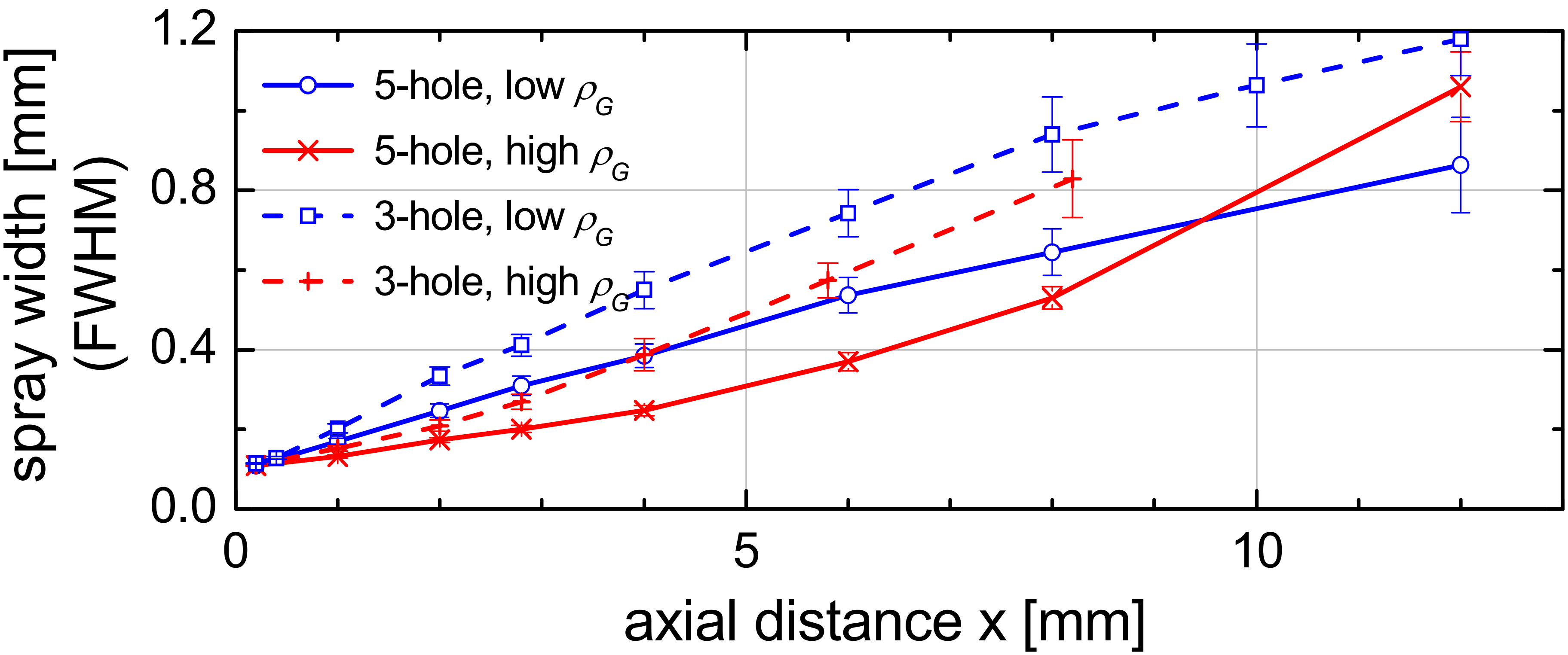




Studying the Effects of the Number of Spray Holes



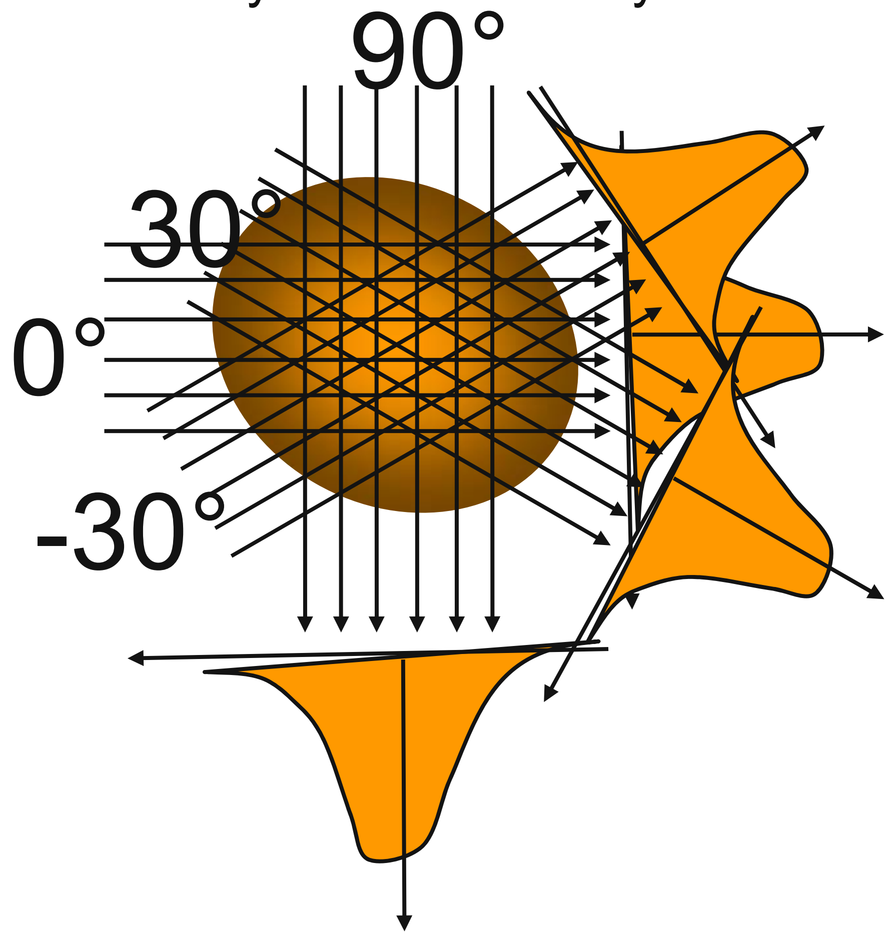
Studying the Effects of the Number of Spray Holes



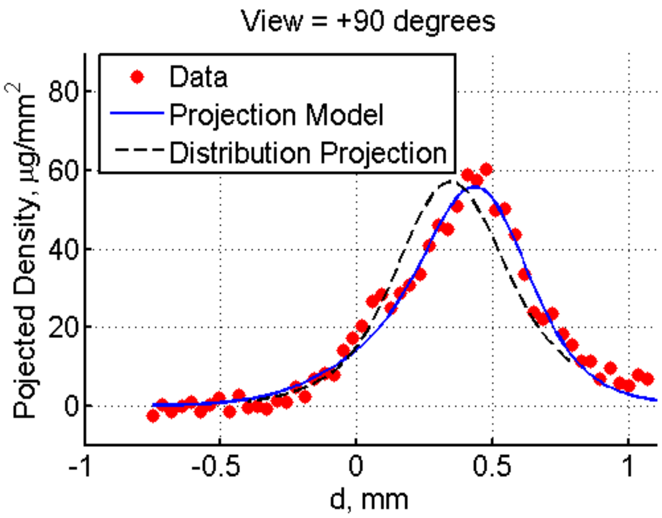
- 3-hole nozzle generates wider fuel distribution
- This agrees with predictions of Bosch CFD models
  - 3-hole nozzle has fewer “sinks” for the pressure
  - Leads to more/larger recirculation regions inside sac
  - Increase in turbulence inside the nozzle results in broader spray

3D Fuel Density Reconstruction

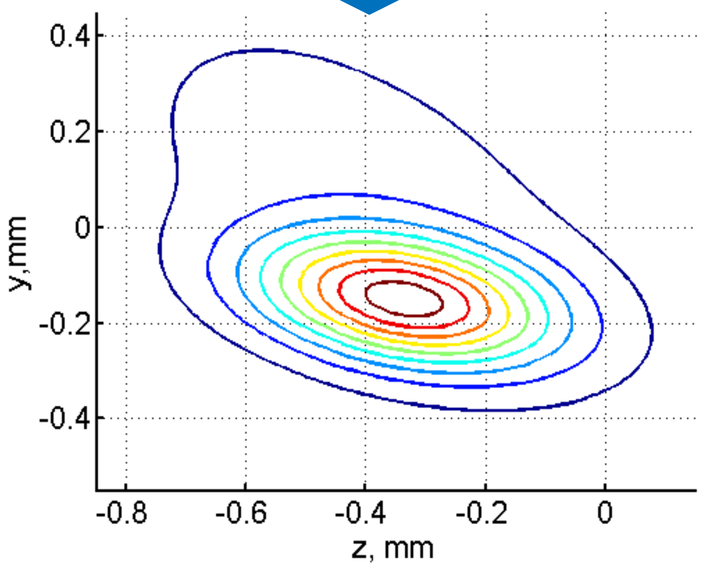
- Single measurement is line-of-sight projection, does not resolve 3D structure
- Density can be estimated only by making assumptions, e.g. axisymmetry
- Multiple projections allow more accurate determination of structure, density
- With only four projections, some assumptions are still required
- Can calculate true 3D density with uncertainty of ~10%

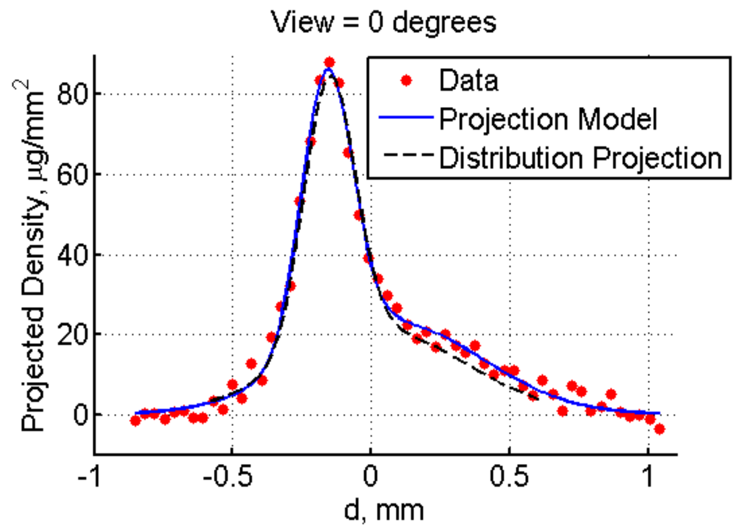


Model Reconstruction Procedure



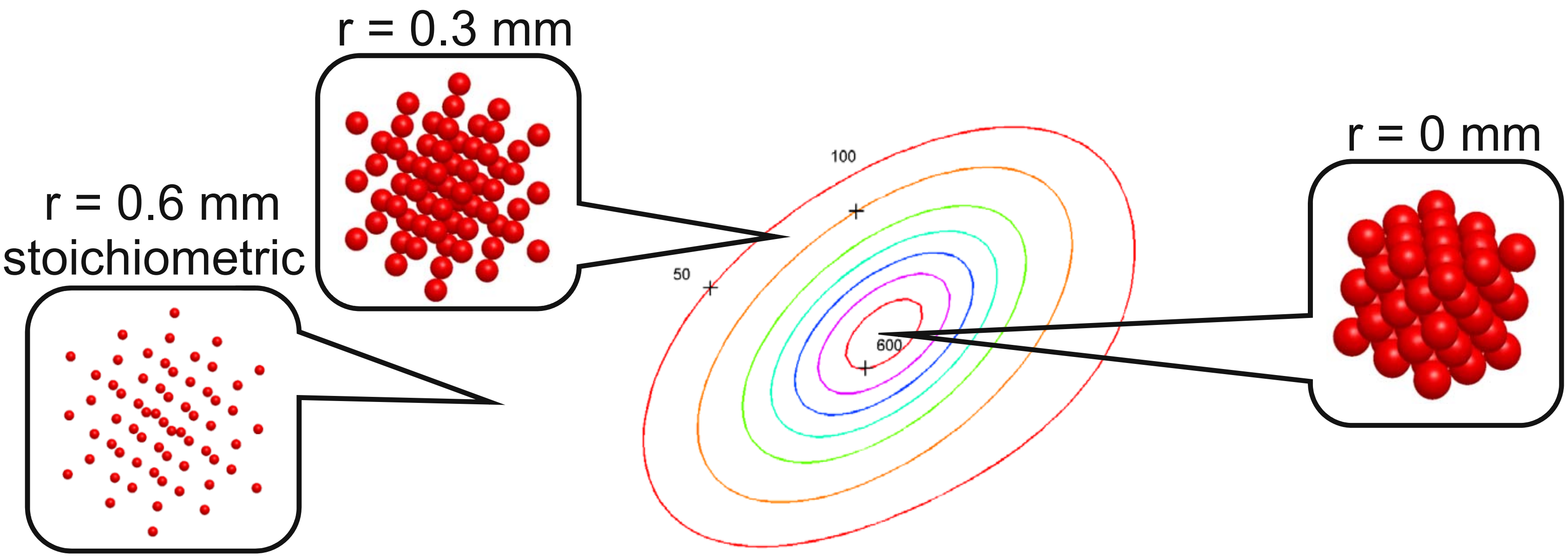
- Obtain data across spray
- Fit data from all viewing angles with the same model
- Reconcile the fit parameters to give 2-D fuel distribution





X-Ray Measurements Highlight Flaws in Common Spray Models

- 3D fuel distribution allows you to make a visualization of the spray structure
- Assumptions:
  - The spray is composed of spherical droplets
  - The droplets are all the same size



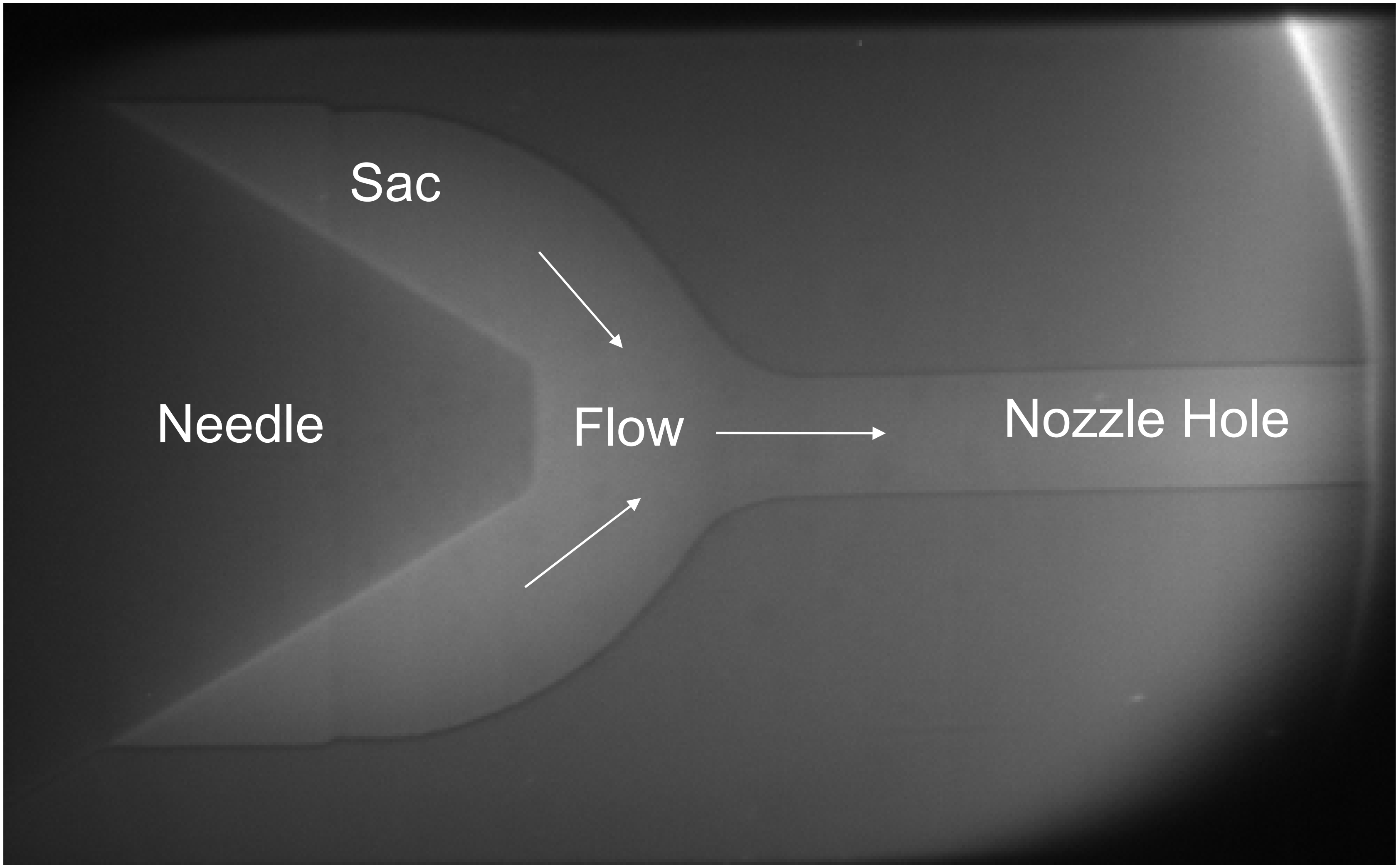
Density contours of a slice through the spray 6 mm from nozzle, and droplet packing at several locations

- Many spray models assume spray is composed of discrete droplets, and that drag on one droplet is not influenced by neighboring droplets
- Will also affect evaporation, mixing, gas entrainment, penetration, etc.
- **Illustrates the need for advances in computational spray modeling**

Real-Time Non-Destructive Nozzle Imaging

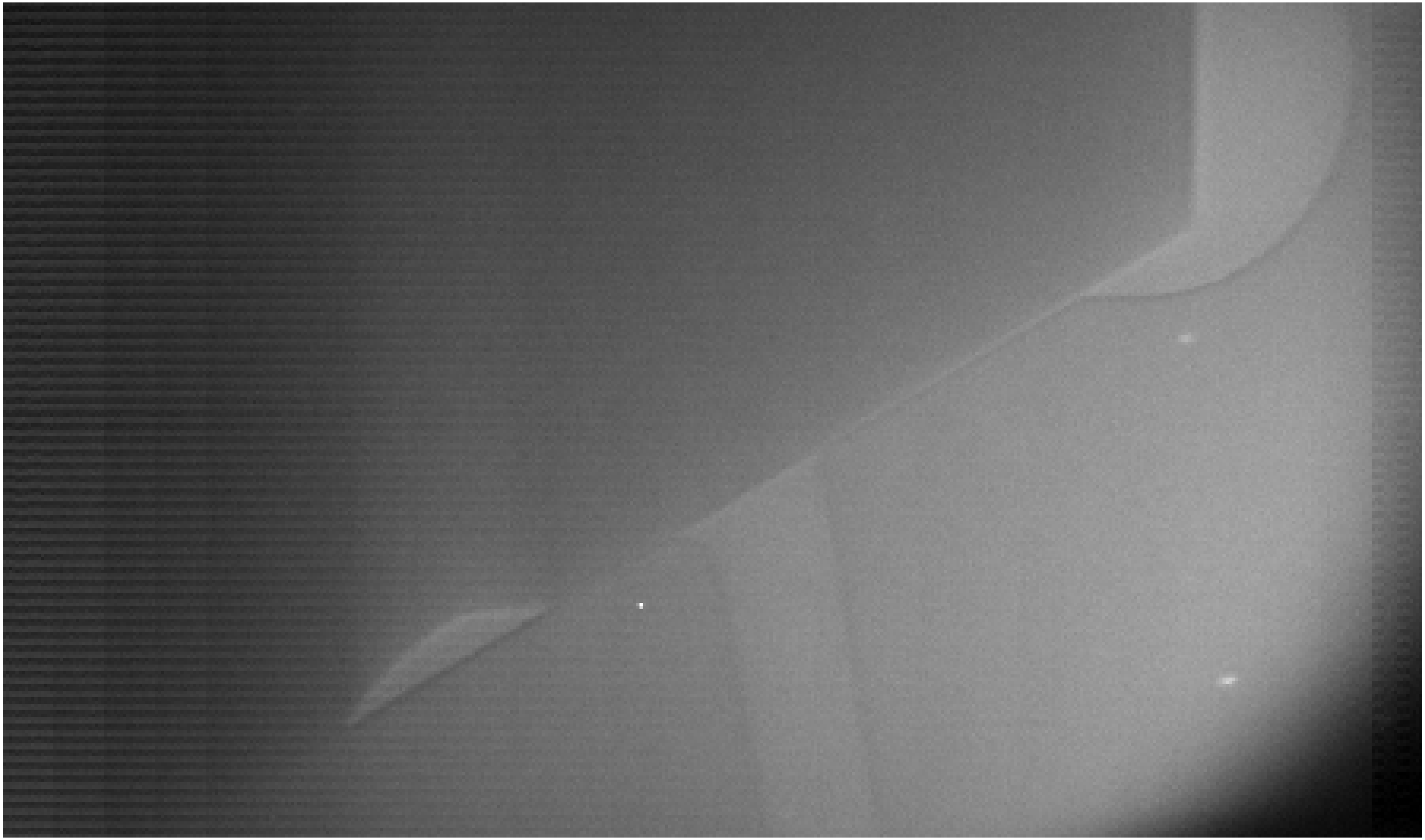
- High penetration of x-rays allows measurement of nozzle geometry through the steel of the nozzle
- Argonne demonstrated this capability in 2004
- High flux at the Advanced Photon Source allows this to be done with microsecond (or better) time resolution
- With multiple lines-of-sight, 3D motion of needle can be measured
- Needle lift and nozzle geometry can be used to generate accurate time-dependent mesh for computational models
- Unique diagnostic for injector manufacturers

Asymmetric Spray Results from Asymmetries in Nozzle?

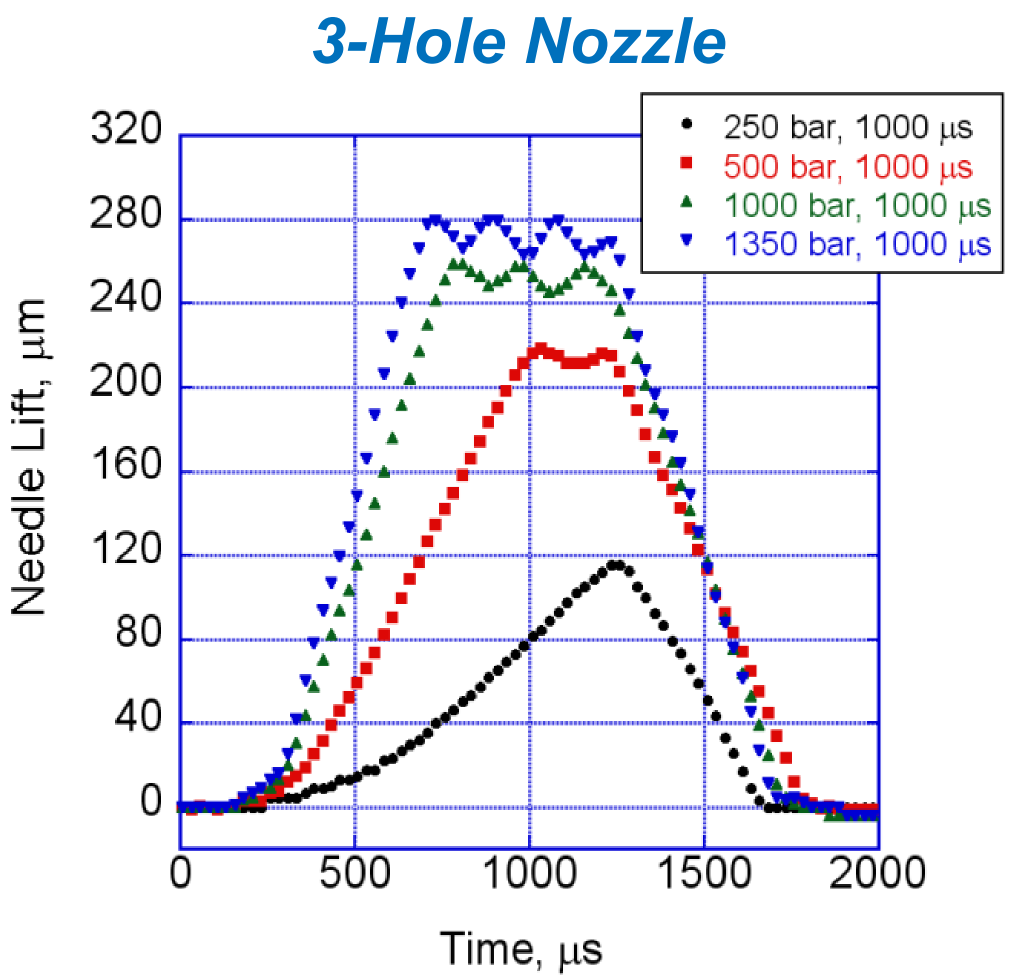


- Use static images to examine details of nozzle geometry
- Can see that our “axisymmetric” nozzles have notable defects: hole misalignment and differences in entrance rounding

High-Speed Imaging of Pintle Motion: 3-Hole VCO Nozzle

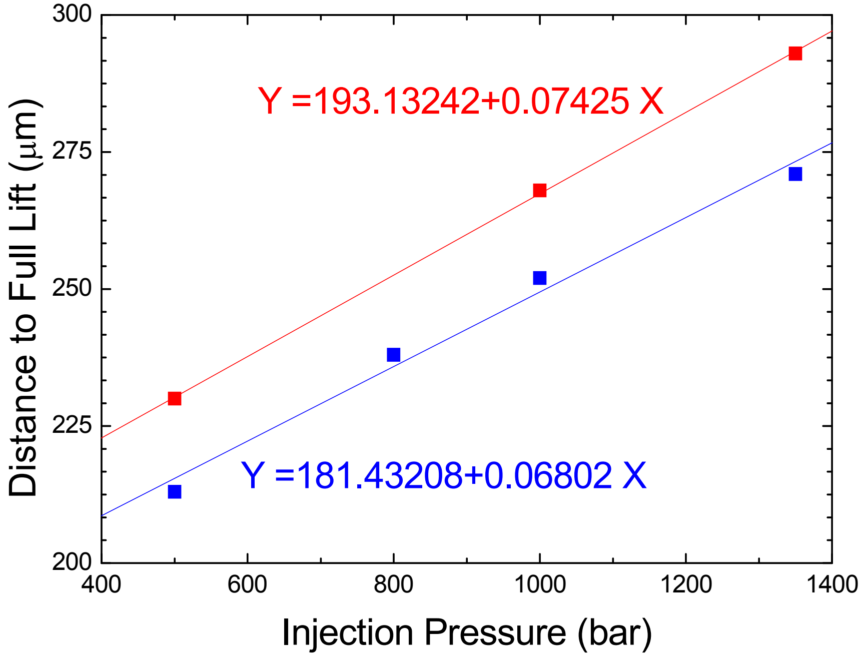


Needle Axial Motion: Lift vs. Time



- Variation in full lift position
- Oscillation at full lift (~6.5 kHz)

Variation In Height at Full Lift Position

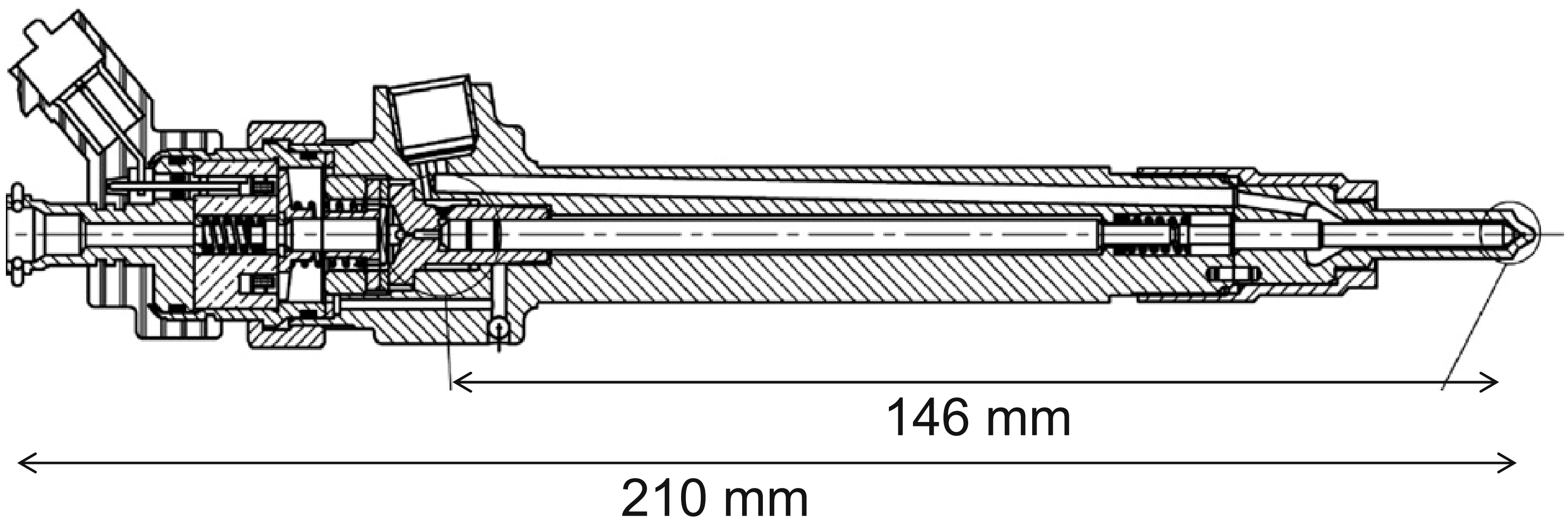


- Linear increase in needle position with rail pressure, ~0.72 µm/MPa
- Compression of the needle and control rod?

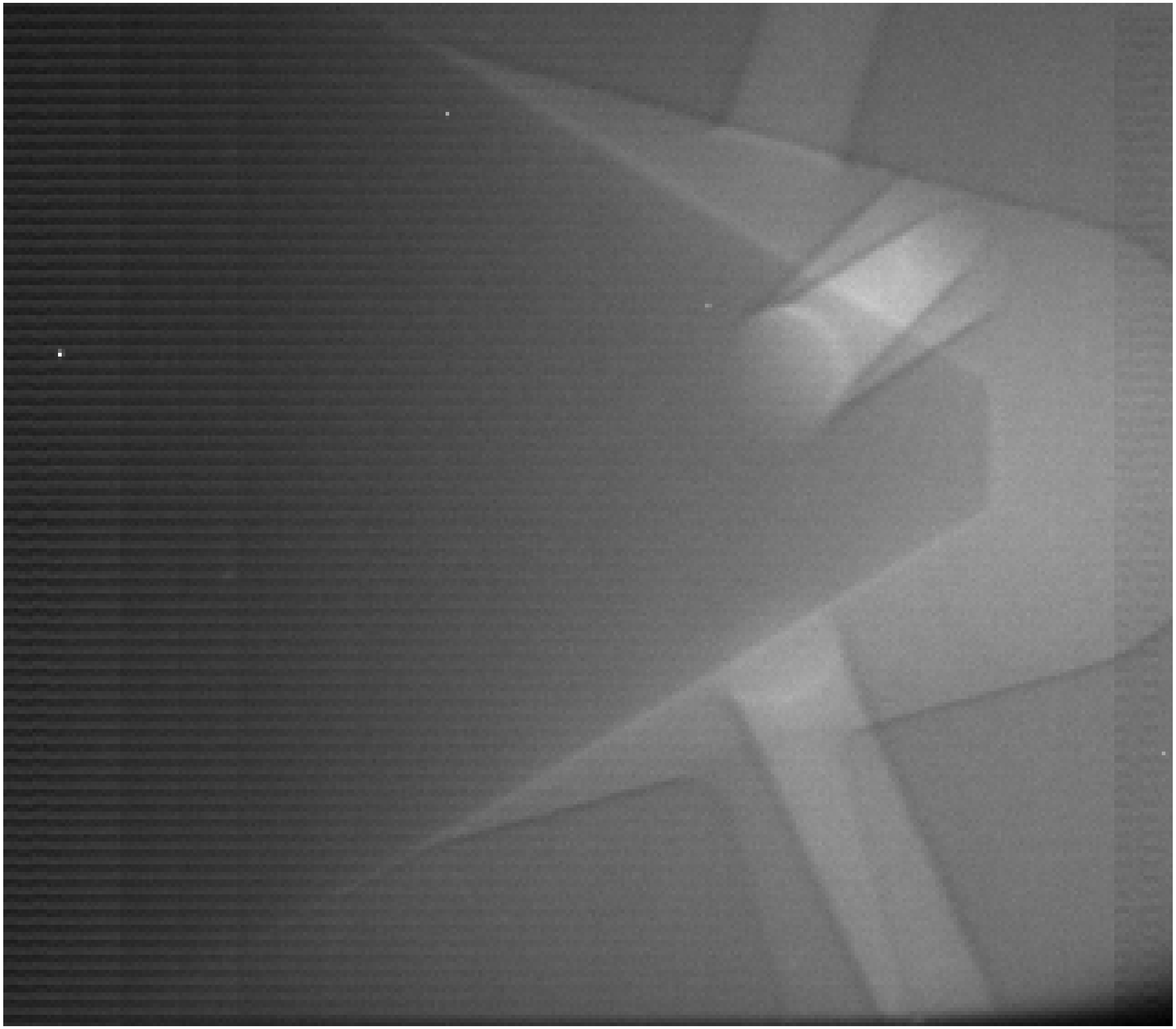
$$length = E\frac{dl}{dP}$$

  - Typical modulus for steel E ~200 GPa
  - Needle + rod length should be ~150mm
- If this *is* caused by compression, conventional sensors may not capture the lift correctly

Coppo *et al.*, Sensors and Actuators A 134 (2007) 366–373

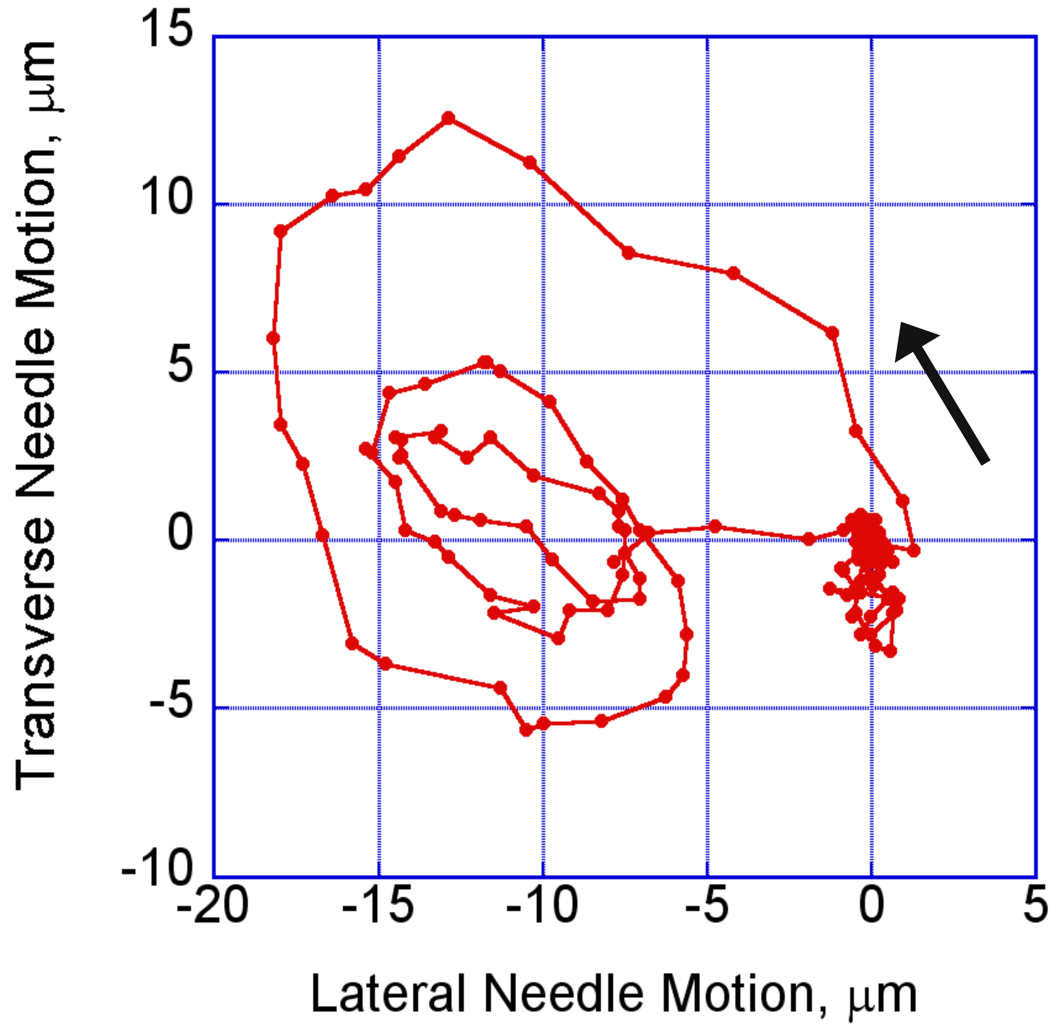


High-Speed Imaging of Pintle Motion: 7-Hole Mini-Sac



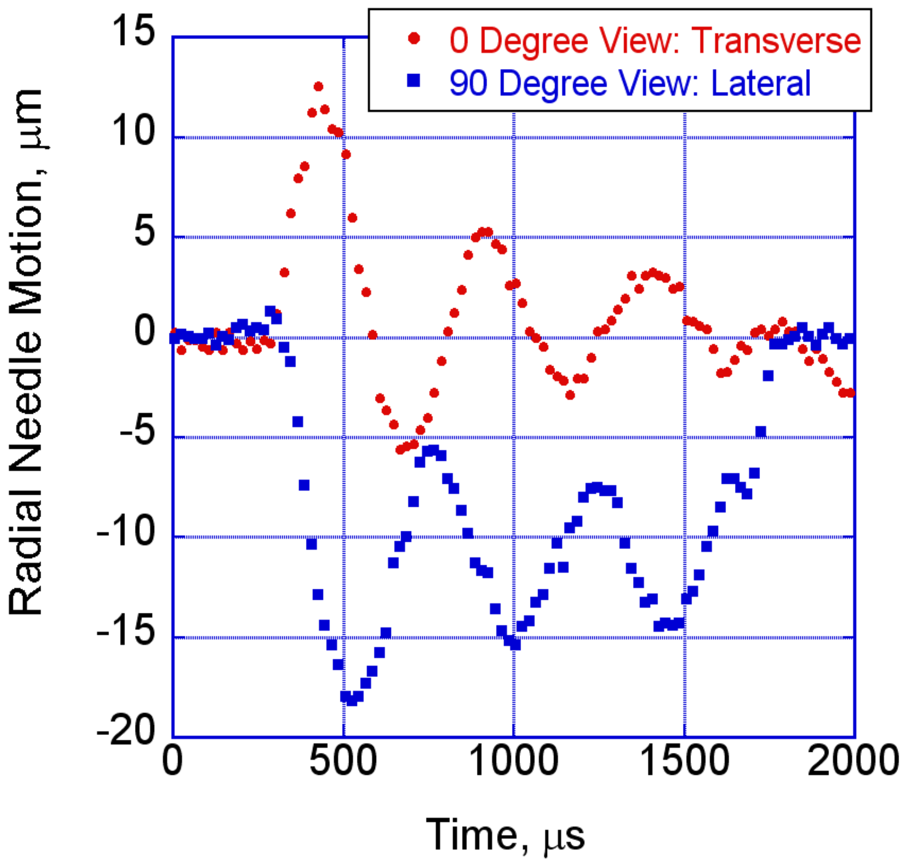
Measurements From Two Views Shows 3-D Pintle Motion

Transverse Motion vs. Lateral Motion

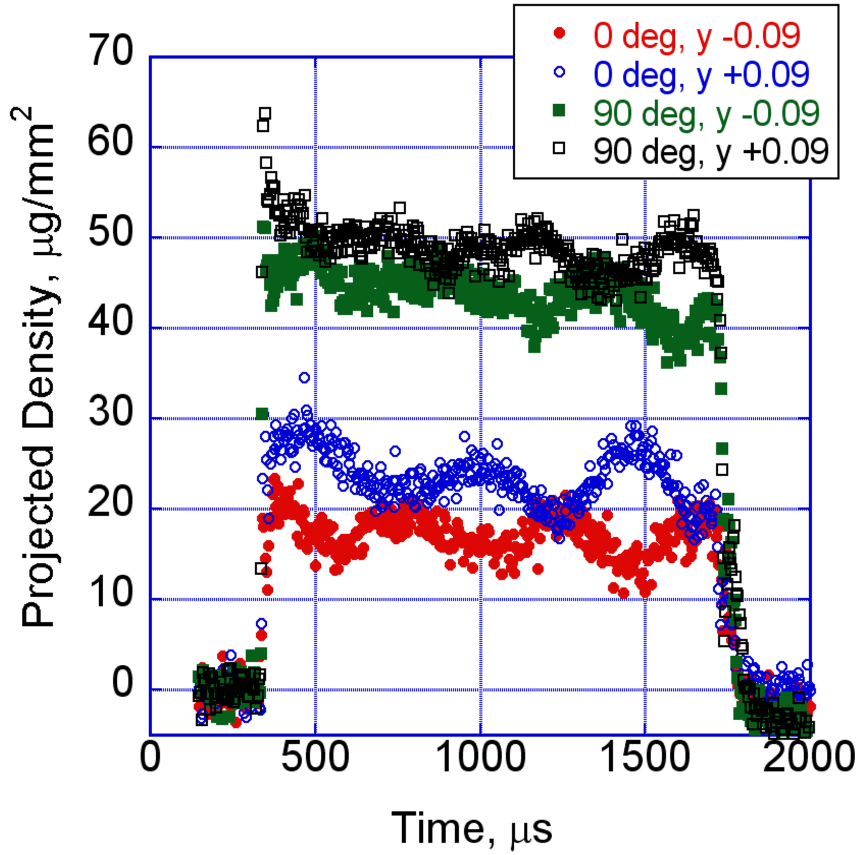


- Plot shows average behavior
- Time moves in direction of arrow

Fluctuations in Spray Density Linked to Needle Eccentricity



Needle Eccentricity

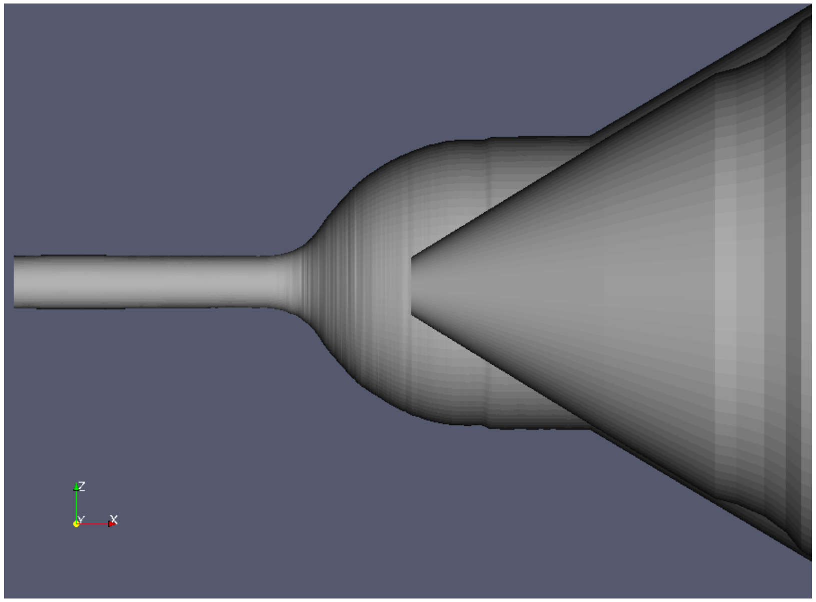


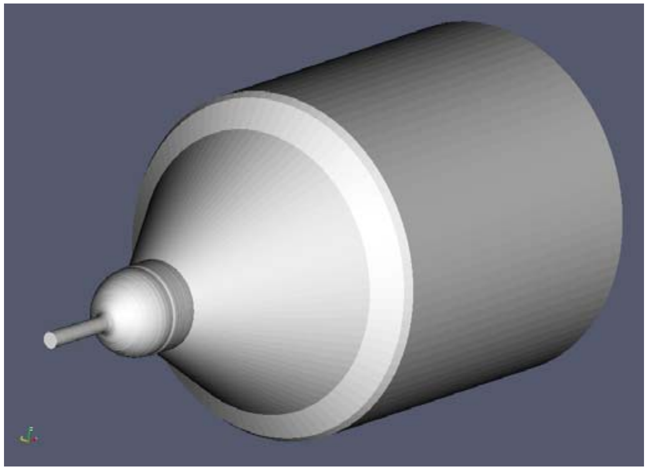
Spray Density

- Period of oscillations ~ 450 µs
  - Appears to be caused by cantilever vibration
  - Only significant in single-guided needles

Nozzle Measurements Used to Generate 4D Mesh

- Time resolved measurements of nozzle geometry and needle motion were used to generate a mesh for CFD models of in-nozzle flow
- Accurately depicts needle lift as measured at the valve seat
- Includes eccentricities in needle motion
- Recently completed measurements of a nozzle being used by Sandia and UW's Engine Research Center
- Will contribute time-resolved images of nozzle, time-resolved needle motion, measured nozzle surface.





Completion of New Dedicated Experiment Station

- Previous experiments were done under a competitive proposal system
- Allowed about 6 weeks of experiments per year
- New experimental station is nearly complete
- Dedicated to transportation research, primarily fuel sprays
- >50% of the cost paid by BES

Advanced Photon Source
Argonne National Laboratory

⇒ **Dedicated space**

⇒ **Guaranteed access to x-ray beam at no cost**

⇒ **More time available for measurements**

⇒ **Enables expansion of collaborations**

Future Work in FY2009

- Strengthen ties between spray experiments and engine experiments
  - Bosch has donated fuel injection equipment matching the GM 1.9L engine, including custom spray nozzles
  - Spray measurements will be performed under conditions matching engine operating conditions
  - Argonne, other labs and Universities all using this platform
- Experiments supporting Sandia's Engine Combustion Network
  - Common injection hardware will be distributed to 10 leading spray measurement labs worldwide
  - Argonne will provide x-ray measurements of spray and needle motion
  - Data will be provided to all partners, including spray modelers
- Strengthen ties between experiments and spray modeling
  - ERC modeling student to spend 6-8 weeks at Argonne, May 2009
  - New collaboration with Gavaises and Arcoumanis studying cavitation
- Attempt to link the motion of the needle with spray structure
  - Bosch will donate injectors and nozzles with eccentric needle motion
  - Argonne will measure 3D needle motion, 3D spray structure