Fuel Injection and Spray Research Using X-Ray Diagnostics

Project ID ACE10

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Argonne National Laboratory

VT Annual Merit Review
14 May 2013
Crystal City, VA

Team Leader: Gurpreet Singh

Overview

Timeline

- Project Start: FY2000

Budget

- FY2012: $1100K
- FY2013: $1000K

Partners

- Engine Combustion Network, Delphi Diesel, Infineum, Monash University, *Chrysler, Air Force Research Lab*

Barriers

- “Inadequate understanding of the fundamentals of fuel injection”
- “Inadequate capability to simulate this process”
- “The capability to accurately model and simulate the complex fuel and air flows”

Relevance and Objectives of this Research

Fuel injection is a significant barrier to improving efficiency and emissions

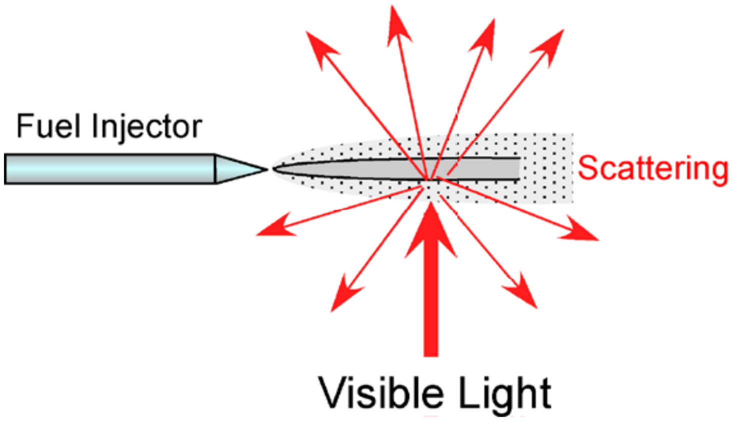
- Improve the fundamental understanding of fuel injection and sprays
- Assist in development of improved spray models using unique quantitative measurements of sprays

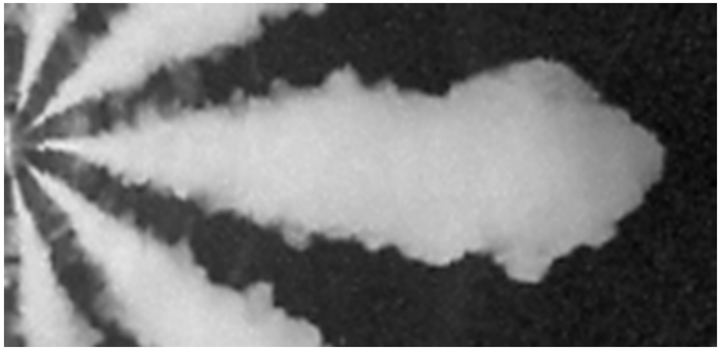
Milestones, FY2012 and FY2013

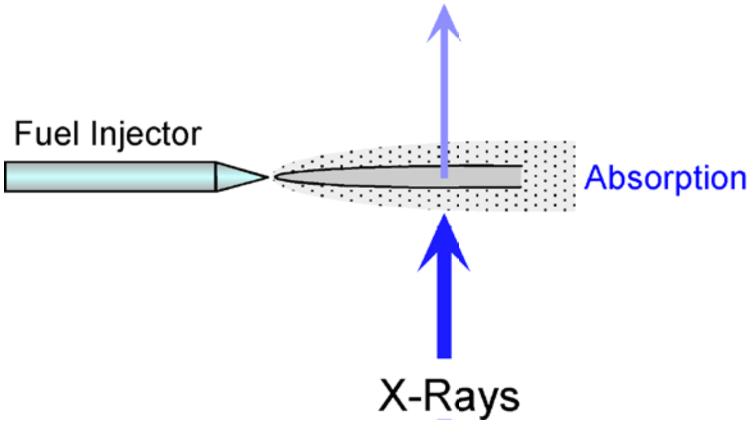
- July 2012: First measurements of cavitation in a diesel injector
- July 2012: First measurements of density in a cavitating flow
- Sep 2012: ECN2 Conference
  - Collect experimental and modeling results on internal flow
  - Distribute x-ray measurement data to ECN modeling groups for validation
- Oct 2012: Chrysler GDI measurements
- Dec 2012: Proof-of-Concept: X-ray measurements of near-nozzle SMD
- Dec 2012: Measurements of Rocket Injector for USAF
- Feb 2012: Tests of Bosch piezo injector

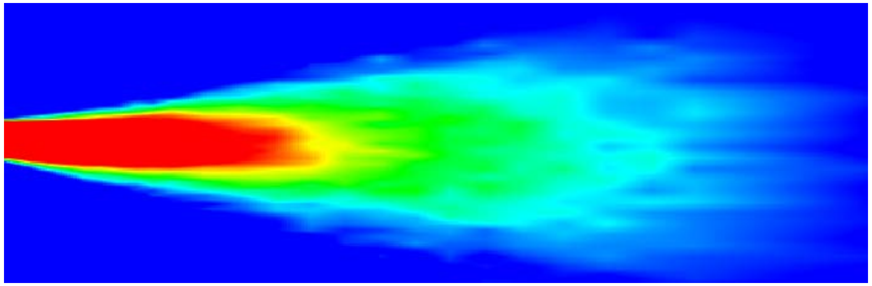
Three “World’s First” measurements this year, made possible by dedicated lab at x-ray source.

Technical Approach - X-rays Reveal Fundamental Spray Structure









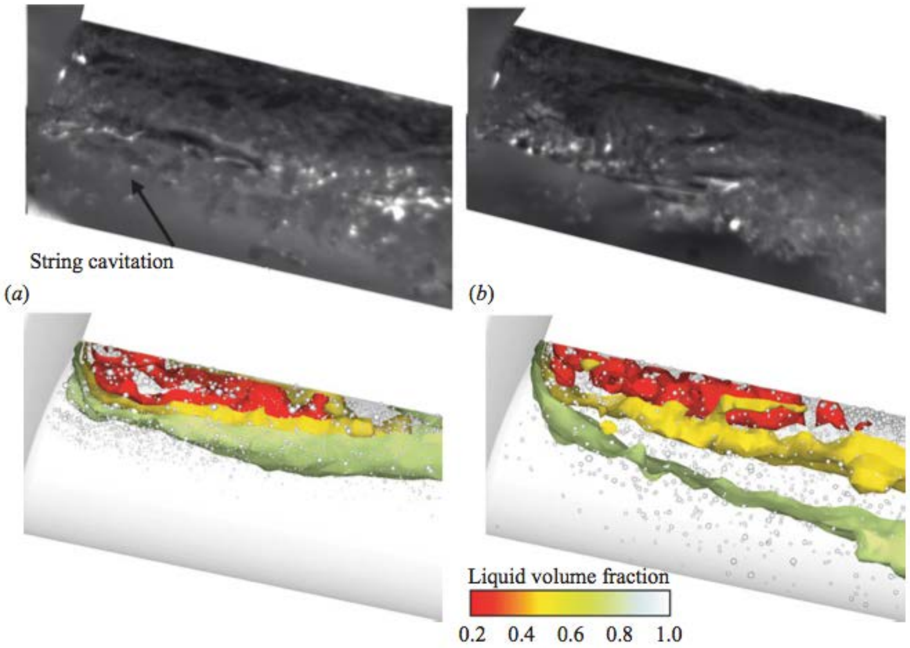
- Room temperature
- Ensemble averaged
- Pressure up to 30 bar

Technical Approach for FY2012

- **Perform injector and spray measurements that increase fundamental understanding**
  - Engine Combustion Network
  - Measurements of cavitation
  - Measurements of internal nozzle flow
  - Spray-spray interactions

- **Use our measurements to assist the development of computational spray models**
  - Chrysler project
  - Collaboration with UMass Amherst
  - Engine Combustion Network

The Importance of Cavitation

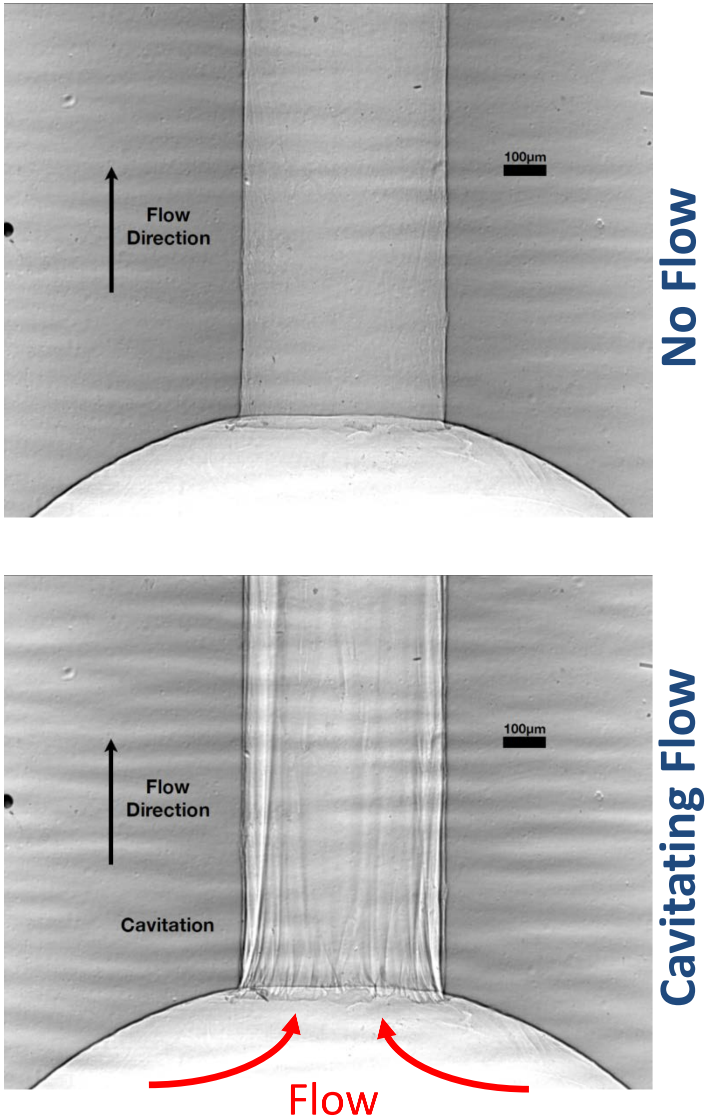


Giannadakis et al.
J. Fluid Mech ***616*** *p. 186 (2008)*

- Cavitation is important in fuel injection process
  - Enhances atomization
  - Can lead to nozzle damage
  - Not well understood
- Very difficult to measure vapor distribution
- Existing computational models
  - Limited data for validation (low pressure, large scale)
  - Limited predictive power

Cavitation Measurements in a Transparent Nozzle

- Goal is to measure density of a bubbly fluid
  - Measure absorption of nozzle filled with fuel
  - When fuel is flowing, vapor causes absorption to decrease
- Need weakly penetrating x-rays to get absorption by fuel
  - Must use plastic nozzle to allow x-rays to penetrate
- Allows quantitative measurement of fluid density

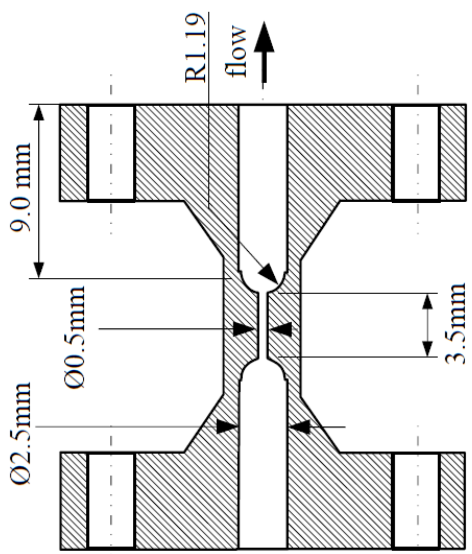


Experiment

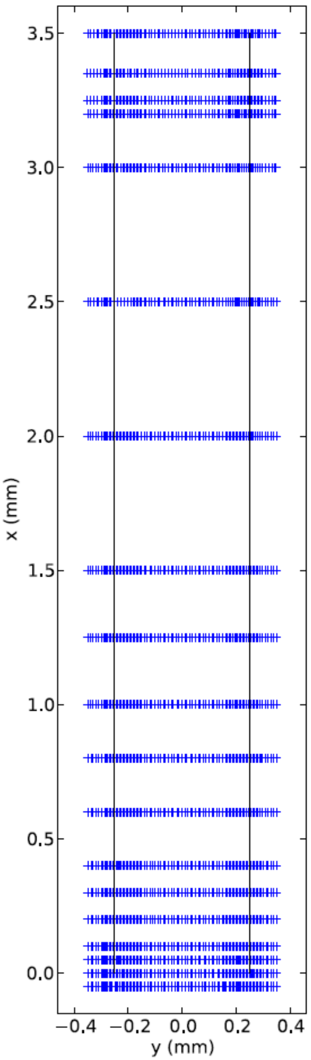
- Polycarbonate Nozzle
- Gasoline Cal.Fluid

Limitations

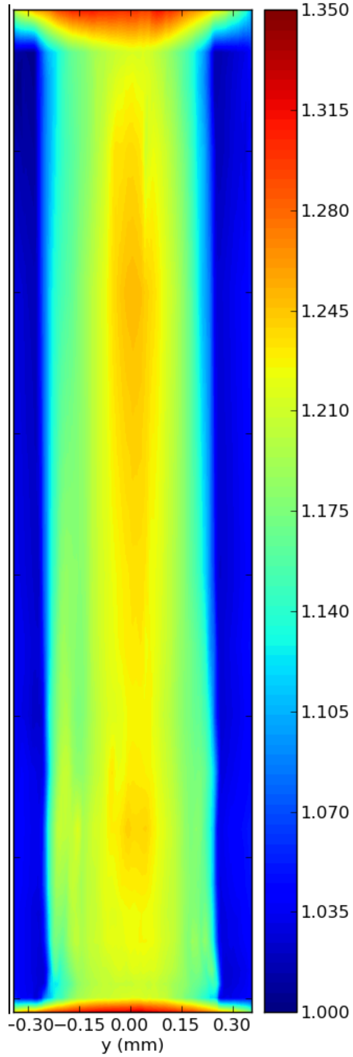
- Large size (0.5 mm)
- Max Pressure 2 MPa



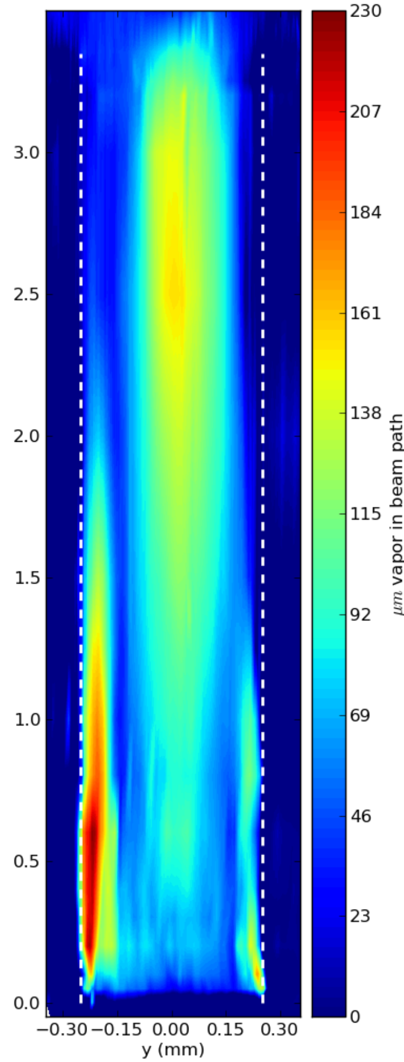
Quantitative Measurements of Cavitation



Measurement Grid

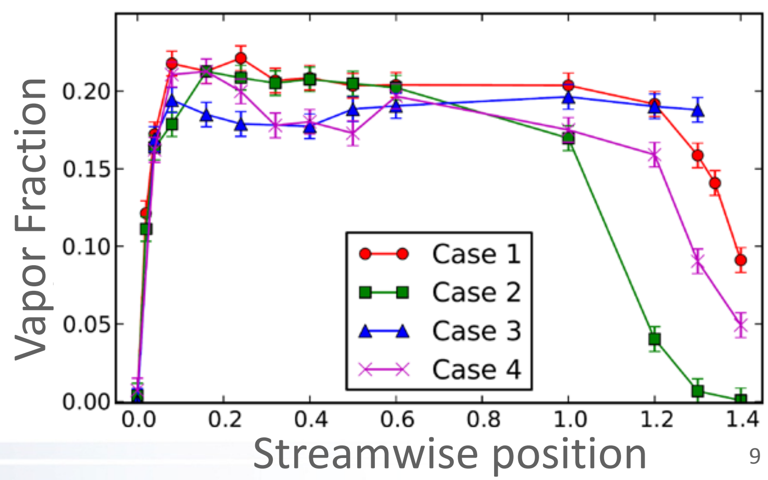


Normalized "Image"



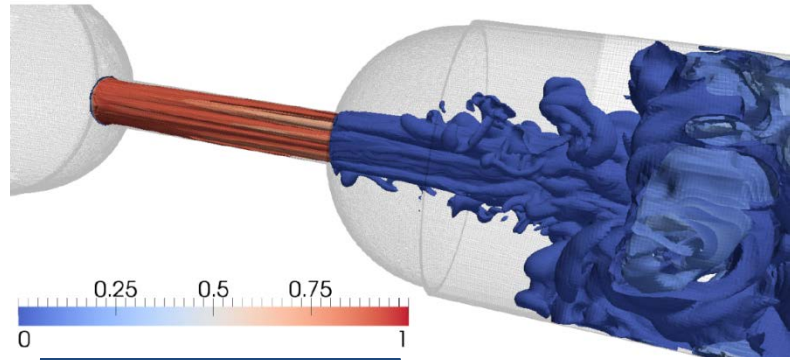
Microns of Vapor

- The highest precision data is obtained using raster scan
  - Better signal/noise
  - Faster time resolution
  - Better spatial resolution
  - Eliminates artifacts
- Cavitation near the inlet corners, as expected
- Downstream, vapor moves to center of flow
- Quantity of vapor is constant

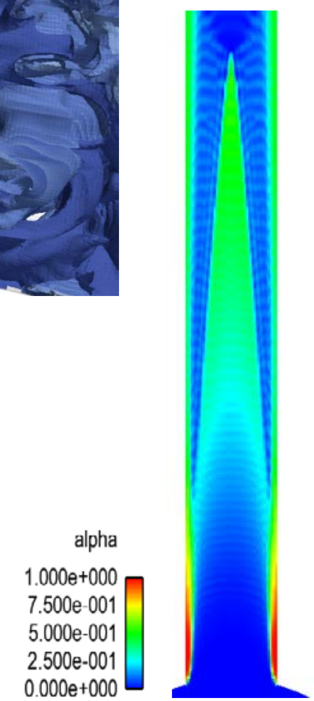


Simulation of Cavitation Measurements

- Collaboration with Schmidt & Neroorkar, UMASS Amherst
- Single-fluid non-equilibrium LES
- OpenFOAM, 8.4 million cells
  - Homogeneous Relaxation Model (**HRM**)
  - Homogeneous Equilibrium Model (**HEM**)
- Argonne provides computational time
- Models do not show vapor in center of flow
- Full 3-D compressible LES underway

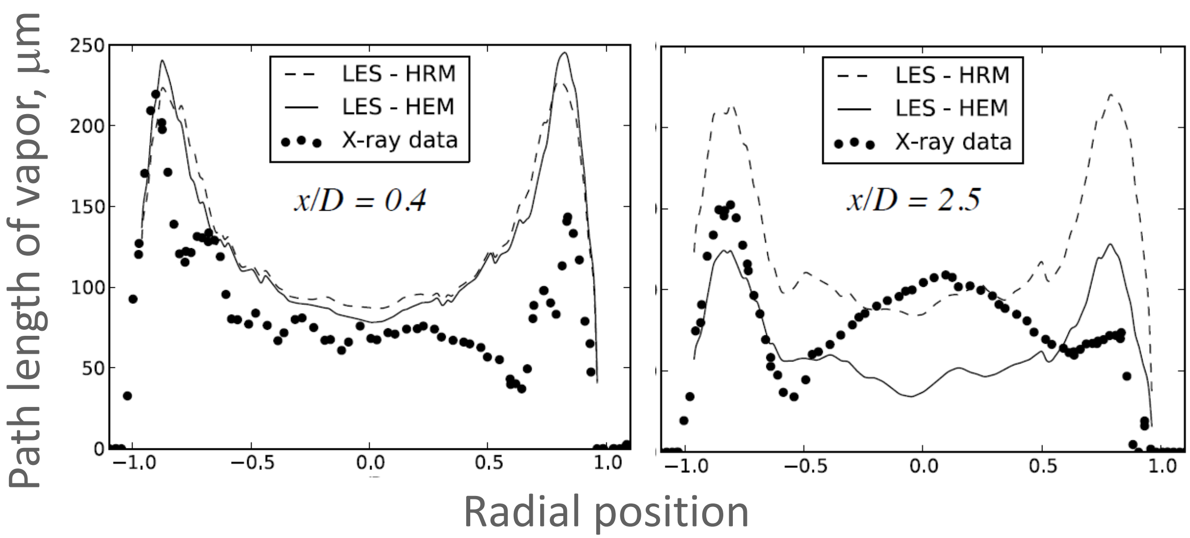


0.5 lpm
Re = 15,800



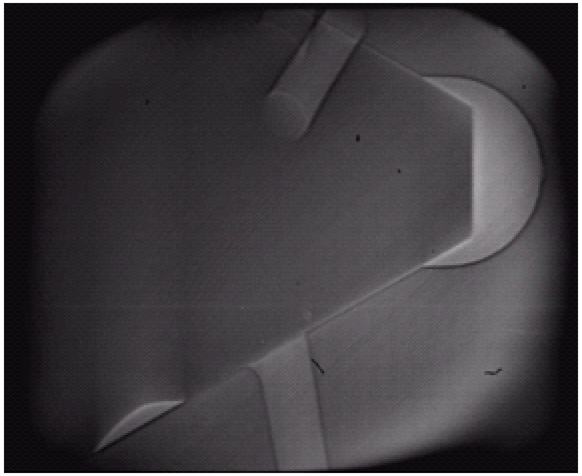
Battistoni & Som

- Predicts vapor in center of flow
- Assumes significant dissolved gas in fuel



Duke, Neroorkar, & Schmidt

X-ray Imaging of Fluid Flow Inside Diesel Injectors

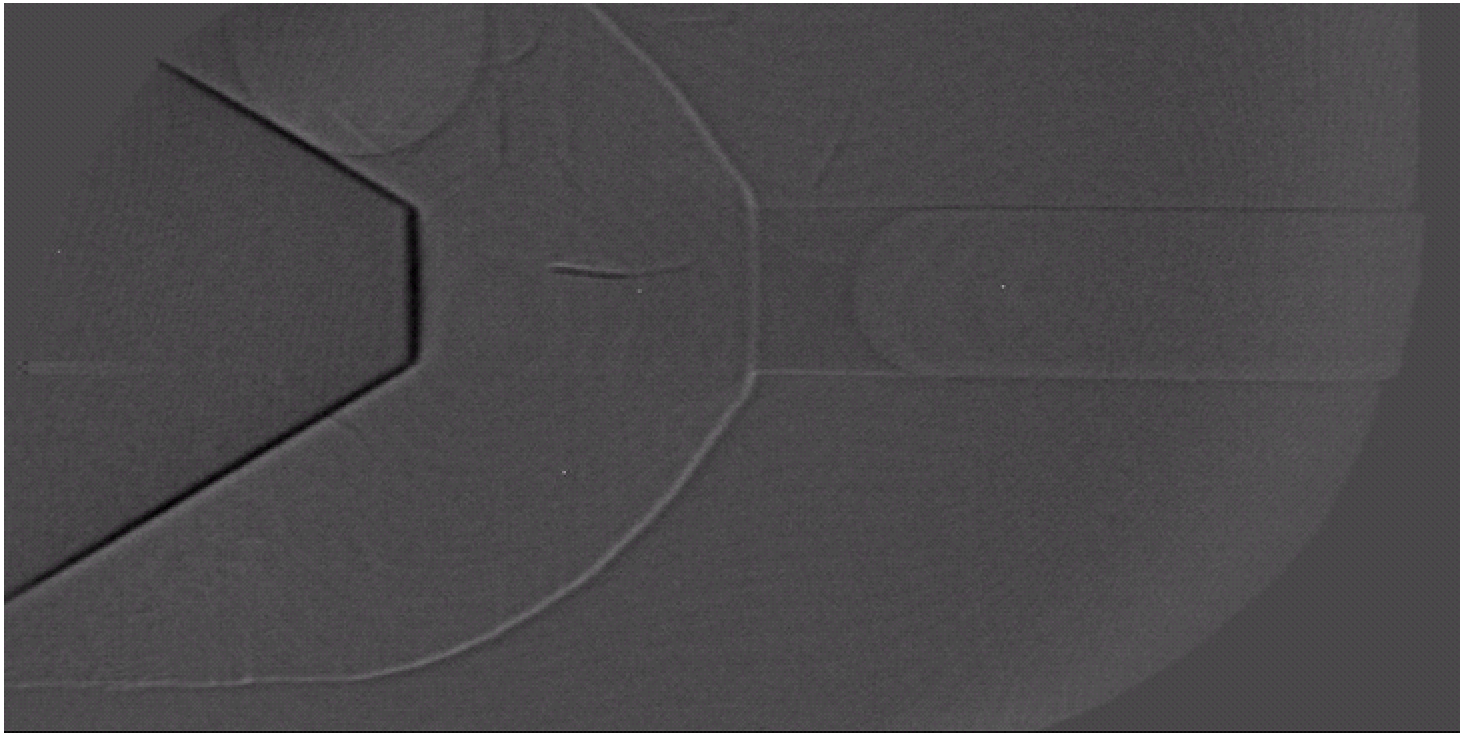


High-speed x-ray imaging of pintle motion was developed in 2004

The first question:
"Can you see the fuel?"

Bubbles!

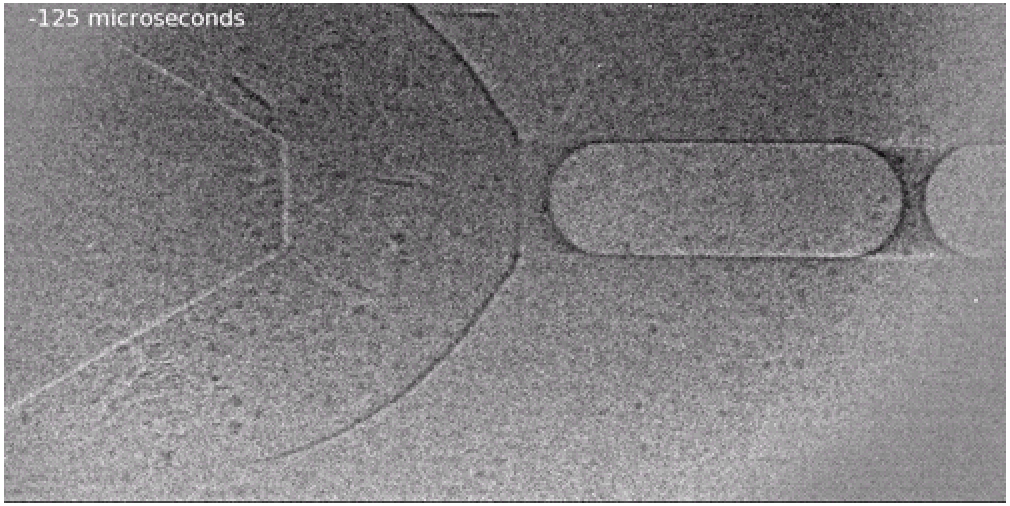
Cavitation!



Bubbles in the Sac

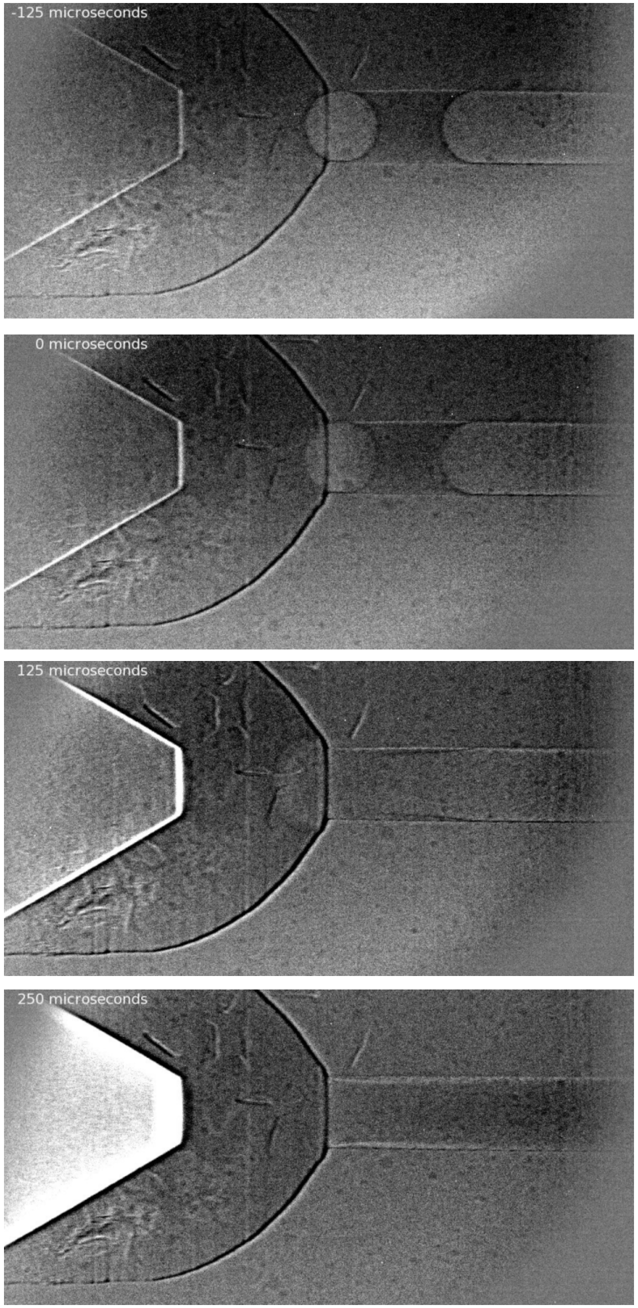
End of Injection

- At EOI, gas is pulled from the orifice into the sac



Start of Injection

- At very low needle lift, bubble from orifice is pulled into sac.
  - Consistent with work from Sandia, Leibniz University Hanover
- Bubble expands, reflecting decreased sac pressure
- As the pressure builds, the bubble is compressed and ejected

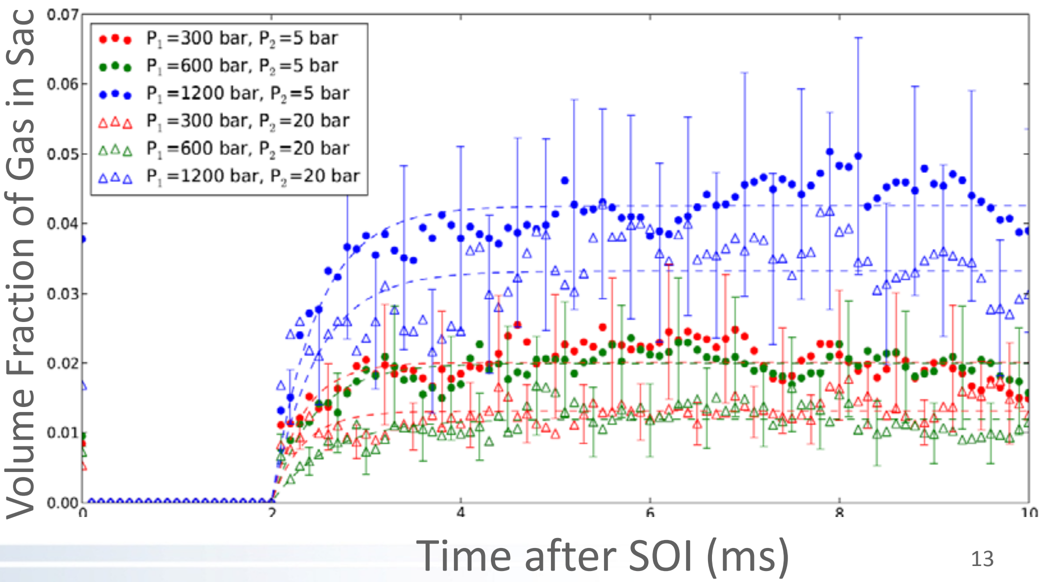


Are These Bubbles Important in Engines?

- Measurements are room temperature
  - At engine temperatures, vaporization is likely to increase the volume of gas
- Measurements in a static chamber
  - At EOI, hot combustion gases will be pulled into the injector: **coking, damage**
  - When the exhaust valve opens, pressure decreases. Bubbles will expand, pushing fuel into a cold engine cylinder: **UHC, soot**
- Sac is likely to be partially filled with gas at SOI
  - Boundary conditions for internal flow modeling
  - Dissolved gas in fuel, especially at SOI

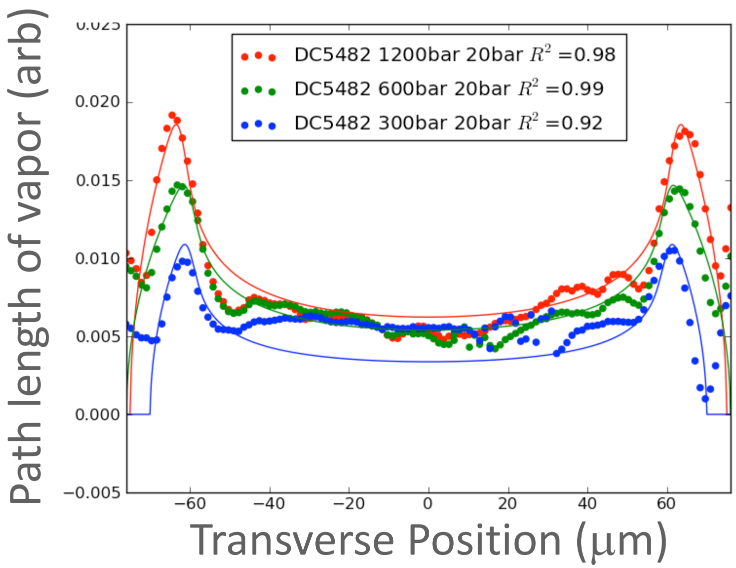
Observed Trends from Bubble Measurements

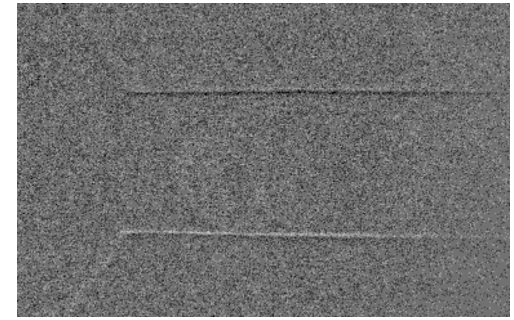
- Quantity of gas in sac increases with hole area
  - Multi-hole > single hole
  - Large single hole > small single hole
- Quantity of gas in sac increases with injection pressure
- Ambient pressure has some effect at low injection pressure

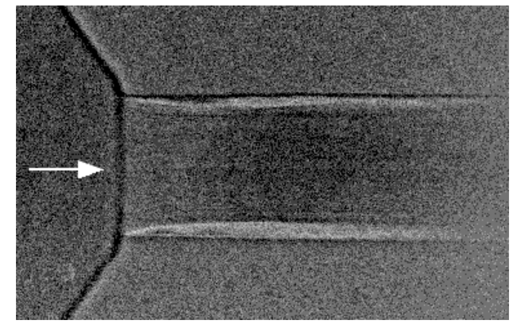


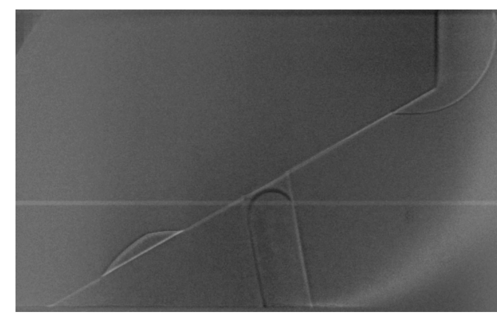
In Situ Imaging of Diesel Cavitation

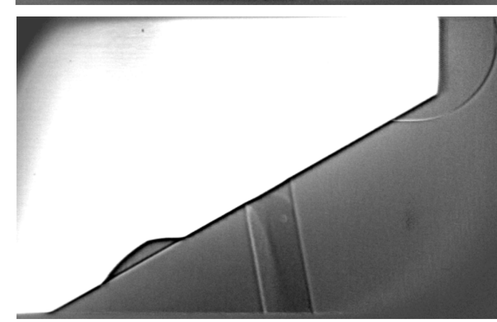
- Studied a range of nozzle designs
- Quantity of vapor increases with injection pressure
- In single-hole nozzle, vapor distribution is consistent with an annular cavitation region.
- Unique *in situ* data for model validation and development









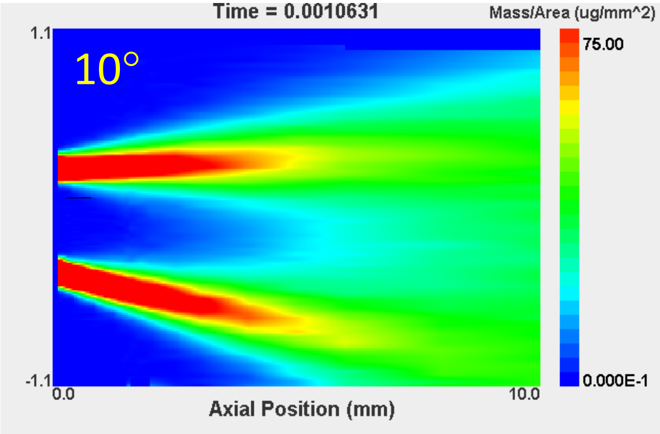


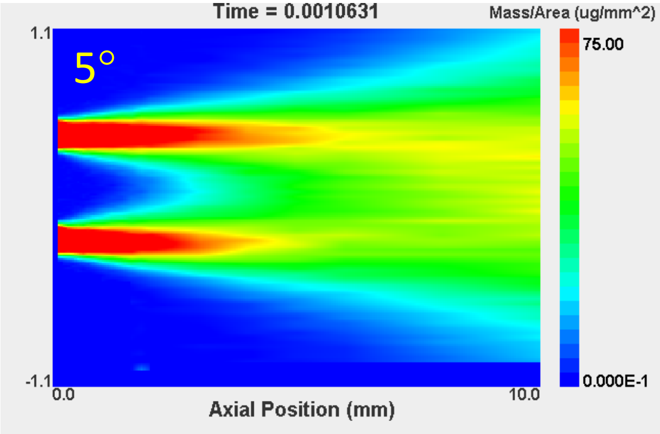
Observed Trends from Cavitation Measurements

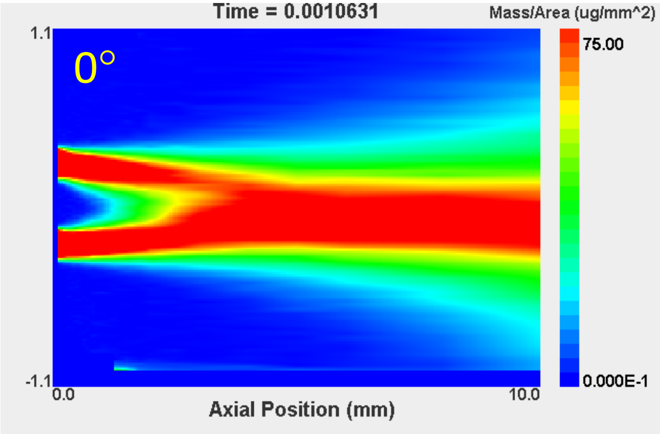
- Cylindrical nozzles cavitate, whether sharp-edged or rounded
- No cavitation was seen in tapered conical nozzles.

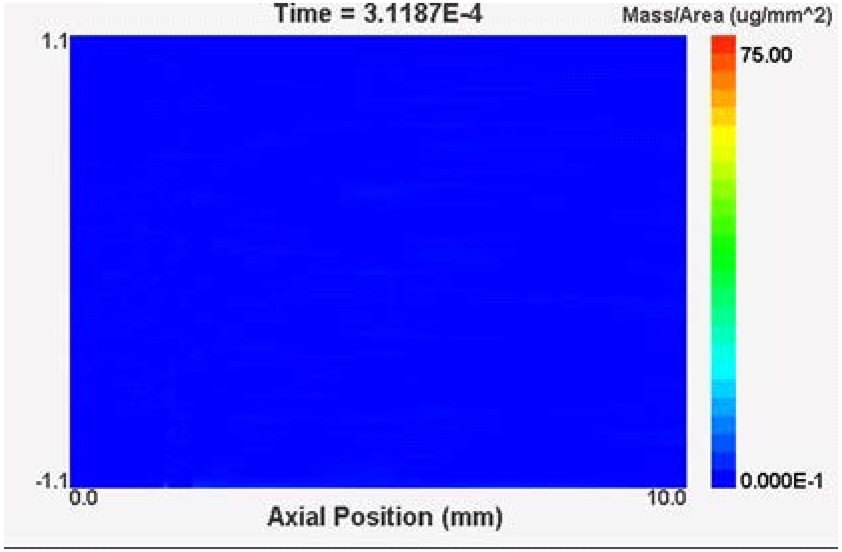
Studies of Spray-Spray Interactions

- Collaboration with Monash Univ, Australia
- Measurements of group-hole diesel nozzles
- 3 injectors with different angles between the nozzle holes
- Significant dynamics, overlap between the sprays
- Monash is using data for CFD validation



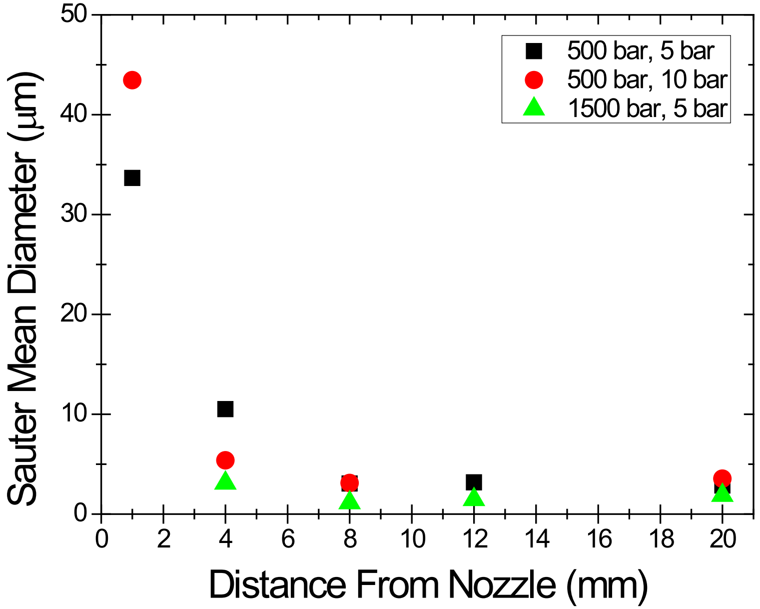






Development of a New Diagnostic: X-ray Small Angle Scattering

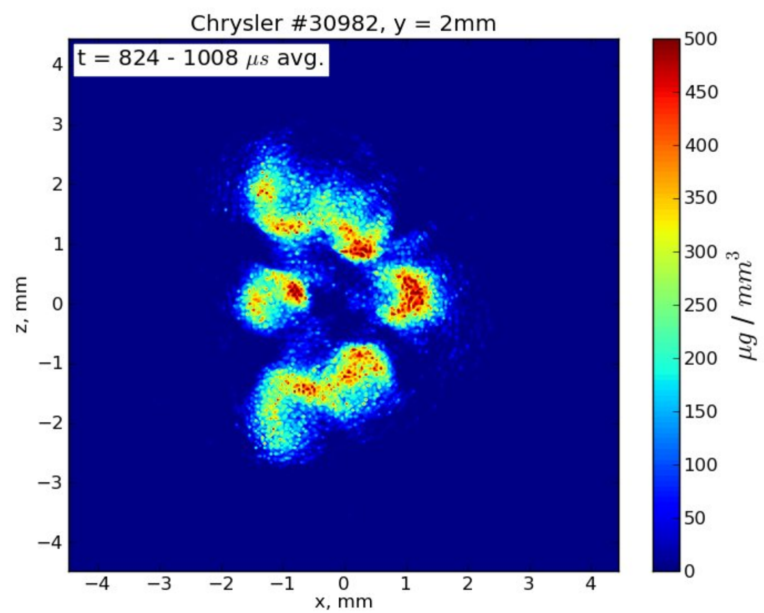
- Droplet size is a critical parameter for sprays
- Little is known about spray structure in near-nozzle region
- Ultra-small angle x-ray scattering can measure Sauter Mean Diameter in dense environments. (diameter of a sphere with the same volume/surface area ratio)
- Size dramatically decreases within the first few mm of the nozzle
- Higher injection pressure, smaller SMD
- Future work to examine
  - Time evolution
  - Nozzle geometry effects
  - Single vs. multi-hole nozzles
- Another constraint on spray simulations: Quantitative measurements of near-nozzle spray breakup

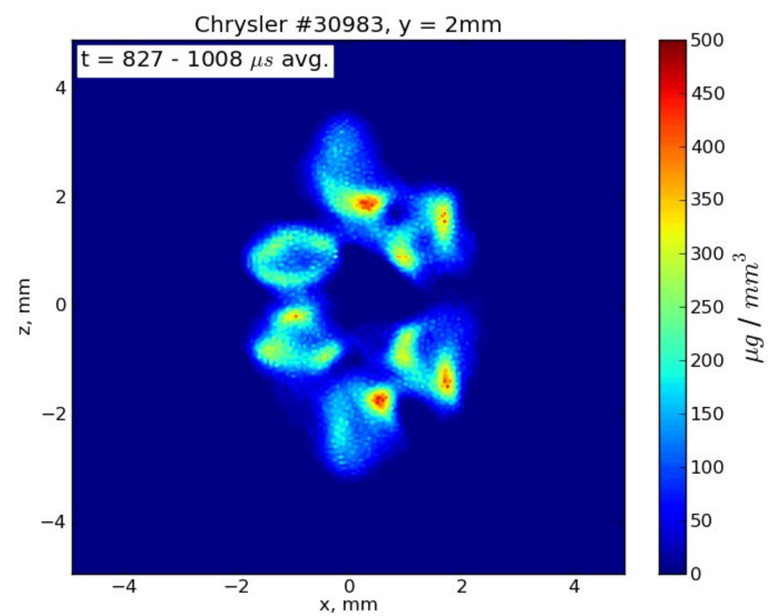


Trends in Sauter Mean Diameter
110 μm Single-Hole Nozzle
5 ms Injection Duration

Studies of GDI Sprays with Chrysler

- Chrysler-funded work looking at sprays from GDI Injectors
- Two different hole patterns
- Used x-ray tomography to reconstruct fuel density in 3-D
  - Sprays are not full-cone
  - One injector shows crescent-shaped sprays
  - Other injector similar to hollow-cone sprays
- Data is being used by Chrysler for validation of spray and engine models





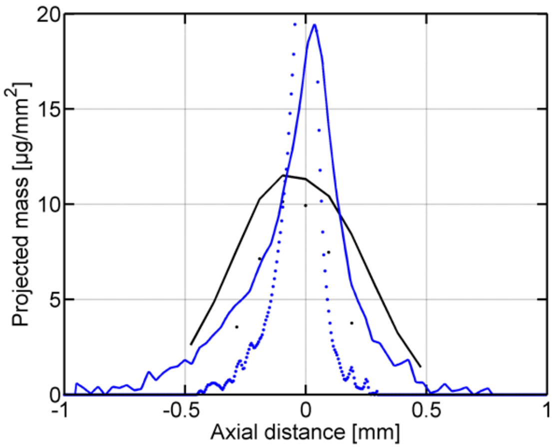
Measurements Supporting Sandia's Engine Combustion Network

- Collaboration of 12 leading spray and combustion groups worldwide
- All groups studying same "Spray A" operating condition
- Argonne has contributed x-ray measurements of spray density, nozzle geometry, and needle motion (ECN web site)

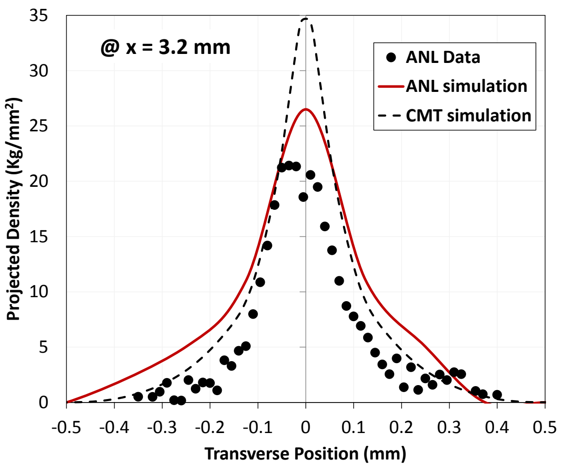
- ECN2 Meeting September 2012
  - Argonne chaired Geometry and Internal Flow
  - Significant growth in modeling contributions

- Future Work
  - Multi-hole injectors
  - GDI Injectors

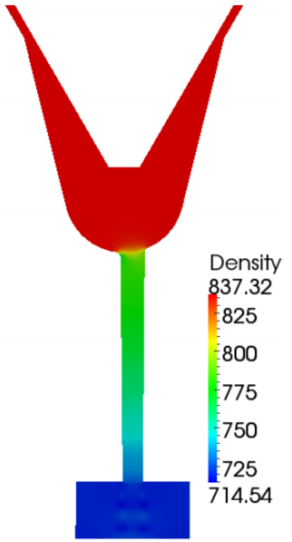
ECN Has Helped Put our Data into the Hands of Researchers Worldwide



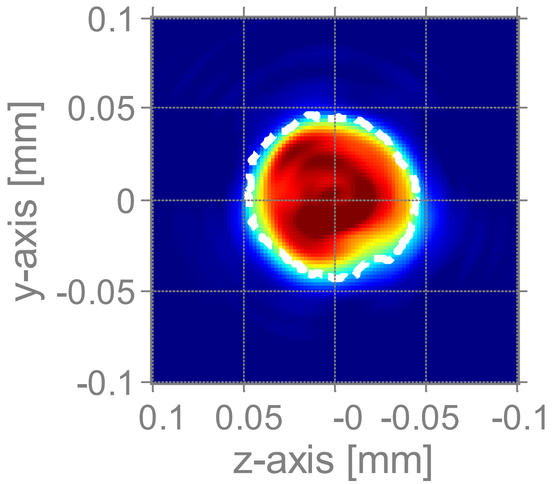
IFPen, France



CMT, Spain & Argonne

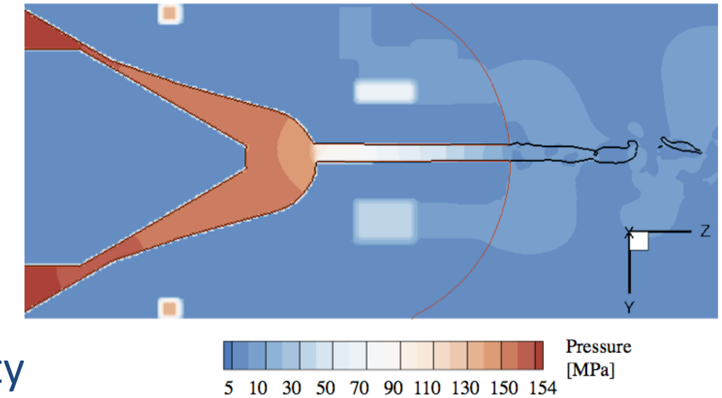


UMass Amherst



Sandia National Laboratories

Georgia Tech University

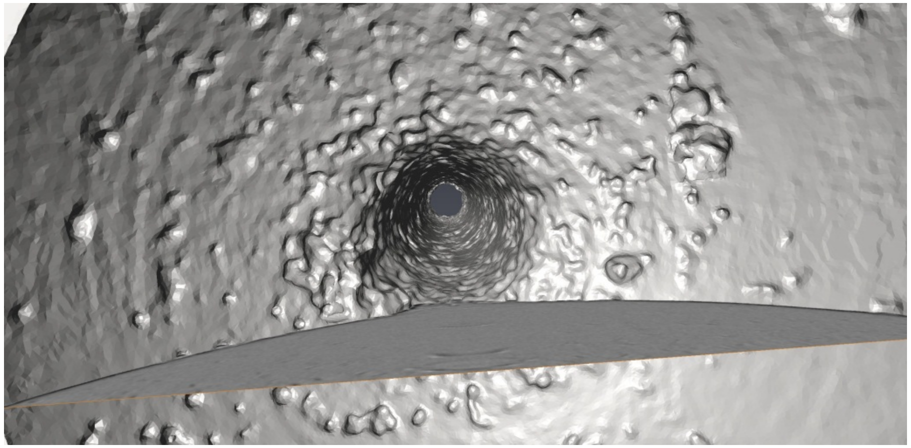


Sandia National Laboratories

Proposed Future Work in FY2013 and FY2014

- Cavitation Studies
  - Full 3D measurement of cavitation density in plastic nozzle
  - Continued modeling collaborations
  - Collaboration with Sandia on real-size, real pressure transparent nozzles
    - X-ray measurements of fluid density inside and outside nozzle
    - High speed optical measurements inside and outside nozzle
    - Detailed simulations of internal flow
- Bubbles
  - Improve sensitivity of the measurements
  - Measure broader range of nozzles
- Engine Combustion Network
  - Effect of surface roughness
  - Measurements on multi-hole nozzles
  - GDI sprays
- Shock Tube for High Temp Measurements
  - Collaboration with Argonne Chemistry
  - Proposal for internal Argonne funding

High resolution x-ray image of ECN Spray A sac & nozzle
Courtesy Peter Hutchins, Infineum



Summary

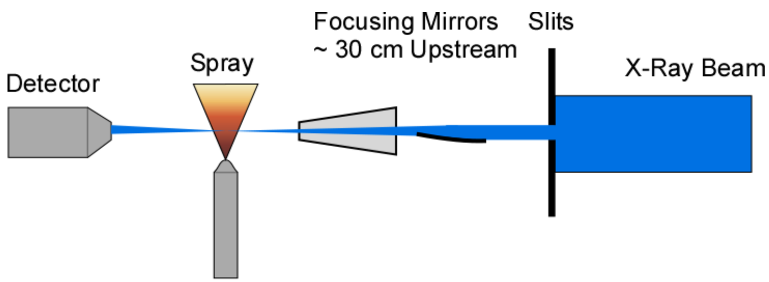
- Improve the understanding of fuel injection and sprays
  - Fundamental measurements of spray phenomena
    - Cavitation
    - Bubbles at SOI and EOI
  - Collaboration with ECN
    - Needle lift and motion
    - Near-nozzle spray density
    - Nozzle geometry
- Assist in development of improved spray models
  - Partnerships on cavitation modeling with UMass Amherst, and Sandia, and Argonne
  - Data contributed to ECN is assisting model development at IFP, CMT, Sandia, Argonne, others.
  - Future collaboration with Sandia on internal flow

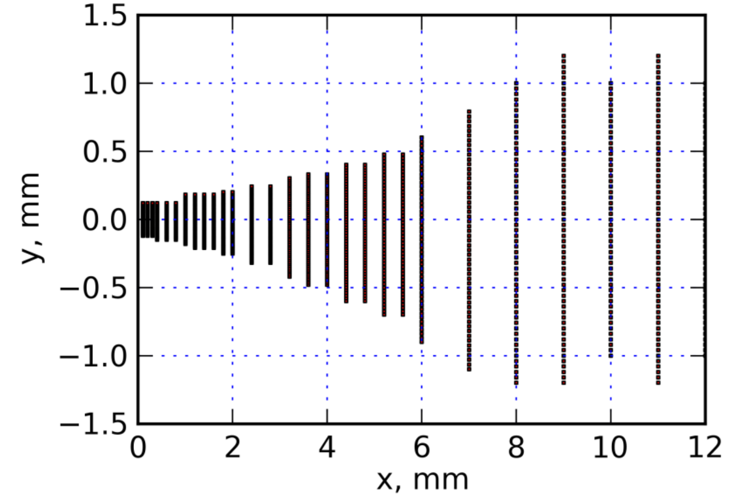
Technical Back-Up Slides

(Note: please include this “separator” slide if you are including back-up technical slides (maximum of five). These back-up technical slides will be available for your presentation and will be included in the DVD and Web PDF files released to the public.)

Experimental Method

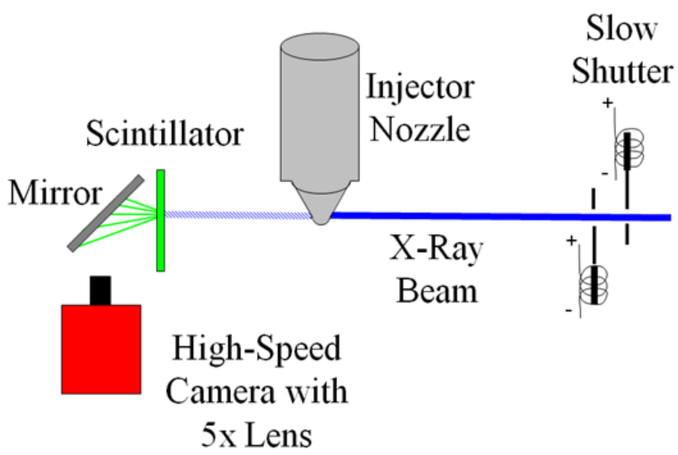
- Focused beam in raster-scan mode
- Beam size 5 x 6 µm FWHM
  - Divergence 3 mrad H x 2 mrad V
  - Beam size constant across spray
- Time resolution: 3.68 µs
- Each point an average of 32-256 injection events
- Beer's law to convert x-ray transmission to mass/area in beam
- Fuel absorption coefficient: 3.7×10^{-4} mm^2/µg
  - Accounts for displacement of chamber gas by liquid
  - Maximum absorption in dodecane ~2%





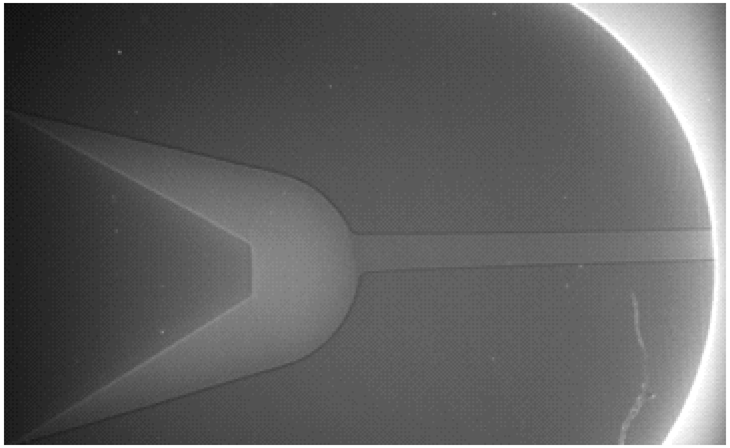
Example Measurement Grid

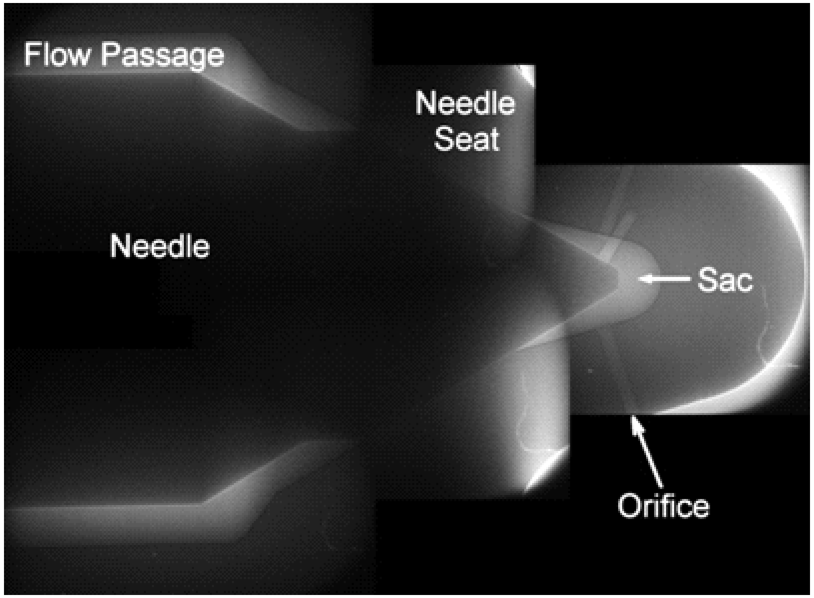
X-Ray Imaging Through Steel Nozzles



Experimental Setup

Injector #210675





Injector #211201

Vehicle Technologies X-Ray Beamline

- Dedicated laboratory at x-ray source
  - Previous experiments were done in a shared, general-purpose laboratory
  - Dedicated lab funded by cost-share between BES and Vehicle Technologies
  - More time for measurements, collaborations
  - Explore new capabilities, applications

The Advanced Photon Source
Argonne National Laboratory

- DOE has approved APS Upgrade (ca. 2015)
  - Vehicle Technologies will be moved to a new beamline
  - Currently planning improvements
    - Increased x-ray flux
    - More space for support equipment
    - Better x-ray optics