Fuel Injection and Spray Research Using X-Ray Diagnostics

Project ID ACE10

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VT Annual Merit Review
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This presentation does not contain any proprietary, confidential, or otherwise restricted information

Overview

Timeline

- Project Start: FY2000

Budget

- FY2012: $1100K
- FY2013: $1000K
- FY2014: $850K

Partners

- Engine Combustion Network, Delphi Diesel, UMass, Infineum, *Caterpillar*

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

Understanding of fuel injection is a significant barrier to improving efficiency and emissions

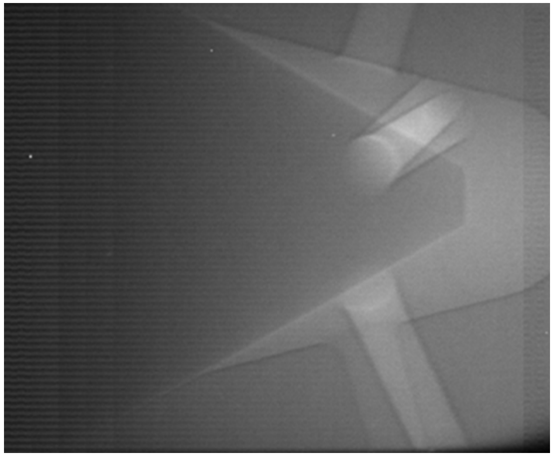
- Improve the fundamental understanding of fuel injection and sprays
- Assist in development of improved spray models using our unique spray diagnostics

Milestones, FY2014

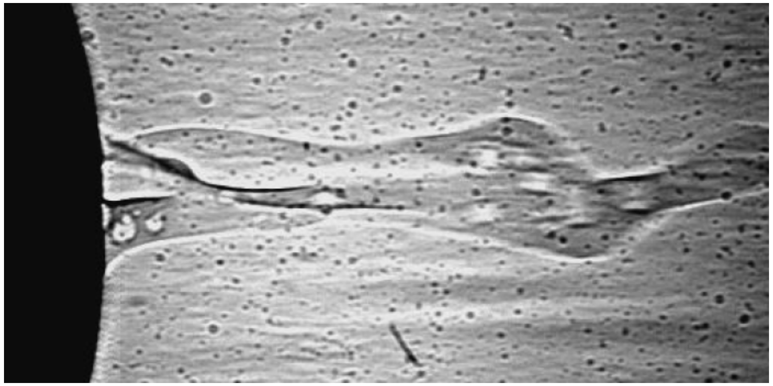
- Q1 FY2014: Measurements of Delphi Diesel injectors
- Q2 FY2014: Measurements of ECN Multi-Hole Diesel: "Spray B"
- Q3 FY2014: Measurements of ECN GDI Injectors: "Spray G"
- Q4 FY2014: Deliver analysis of measurements to Delphi

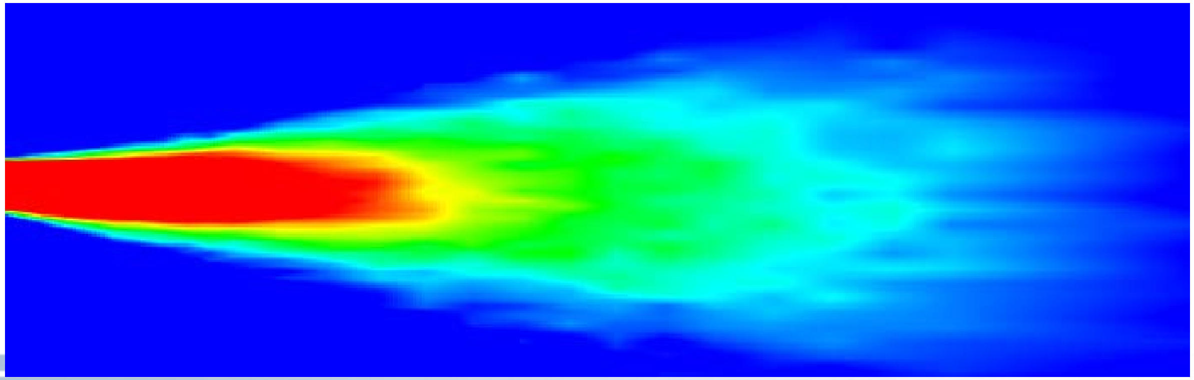
Technical Approach - X-rays Diagnostics of Sprays

- Phase Contrast Imaging
  - Broadband x-rays
  - High-speed, single-shot images
  - Nozzles, injectors, sprays
  - Room temperature ambient (plastic windows)



- Radiography
  - Monochromatic x-rays
  - Absorption of x-rays by the fuel
  - Ensemble averaged (flux limited)
  - Room temperature ambient
  - Quantitative measure of fuel distribution



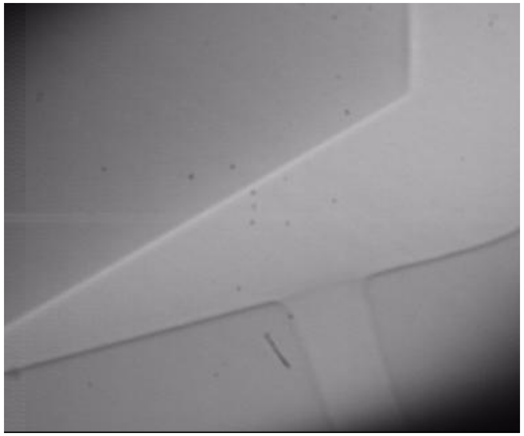


Argonne's Measurements With the Engine Combustion Network

- Collaboration of spray and combustion research groups worldwide
- Common operating conditions, shared hardware
- Argonne has contributed (ECN web site)
  - spray density,
  - nozzle geometry
  - needle motion
- Recently completed multi-hole diesel injectors ("Spray B")
- ECN3 Workshop April 2014
  - Significant growth in modeling contributions
  - Argonne leads
    - Topic 1: Diesel Injection
    - Topic 1.1: In-Nozzle Experiments and Simulations
    - Topic 1.2: Near-Field Structure and Breakup

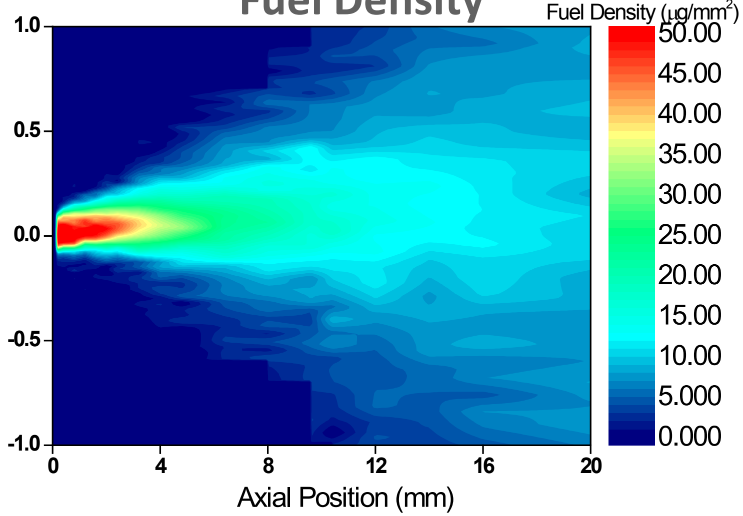
Argonne Contributions to ECN in FY2014

Needle Motion

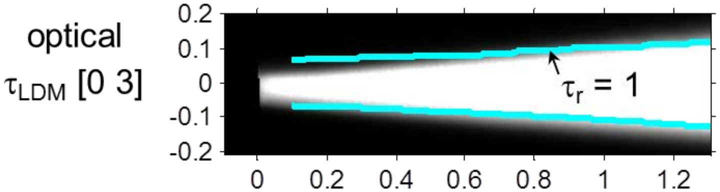


Used by Argonne, CMT, UMass, IFPen, Aachen, Sandia, for internal flow simulations

Fuel Density



Used by validation of near–nozzle breakup simulations by Argonne, Sandia, CMT, UMass, IFPen



Pickett et al. SAE 2014-01-1412

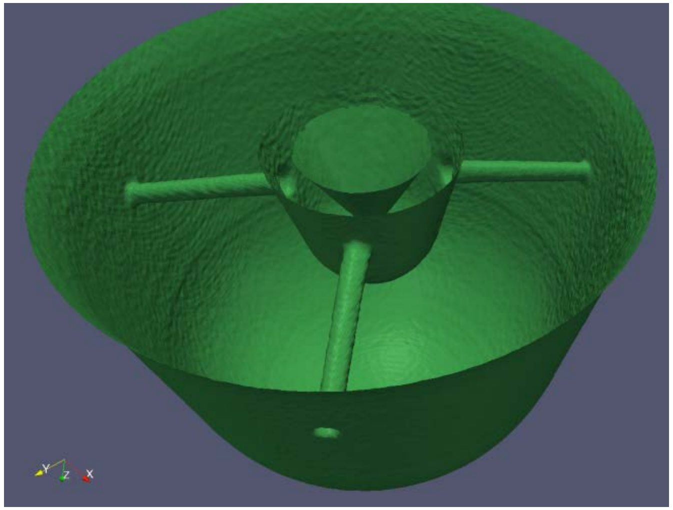
Comparison with Sandia Spray Imaging

- Calculate optical thickness from Argonne's measurements
- Compares well to optical measurements
- Proposes a unified definition of "spray boundary"

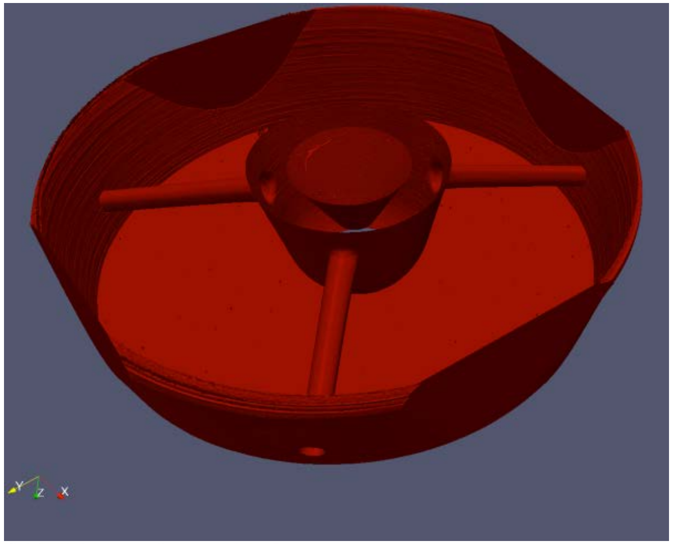
Measurements of Nozzle Geometry

- Several groups simulating fuel flow inside injector: Argonne, IFPen, Sandia, UMass
- Accurate measurements of flow passages are required
- Several groups have contributed measurements
  - Benchtop x-ray tomography
  - Synchrotron x-ray tomography
- Systematic difference between the two techniques
  - Believed to be an error in correcting for beam properties
- Recently completed measurements at ESRF of all 12 ECN Gasoline Injectors (collaboration with Infineum)

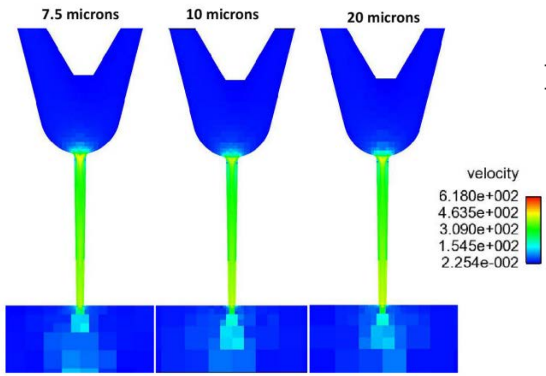
Benchtop X-Rays – 8 μm



Synchrotron X-Rays – 0.6 μm

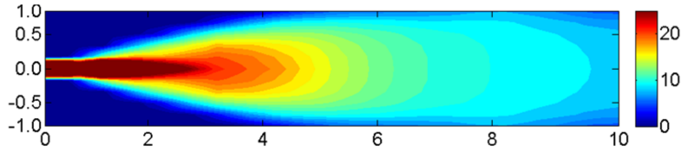


ECN Has Helped to Put Argonne's Data into the Hands of Researchers Worldwide



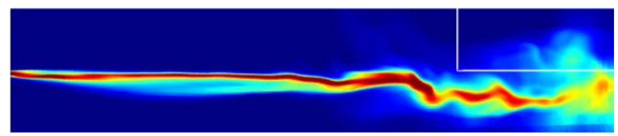
Convergent Science & Argonne

ASME ICEF2013-19167



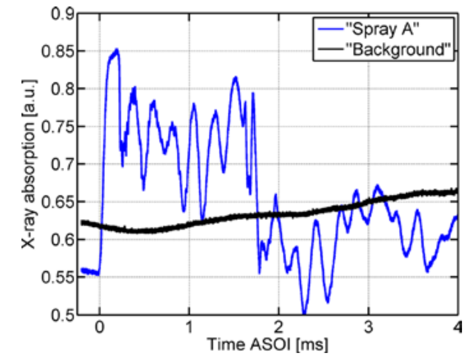
CMT Motores Termicos

ECN3



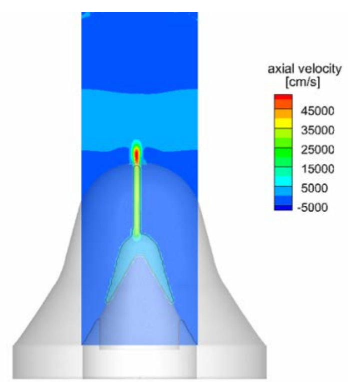
IFPEN

ECN3



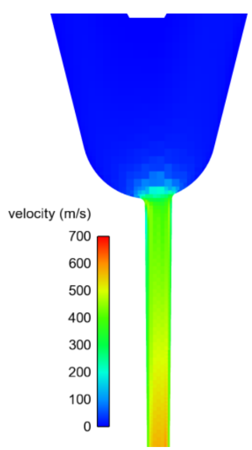
Sandia, Argonne, CMT

J. Eng. Gas Turbines Power 134(12), 122801



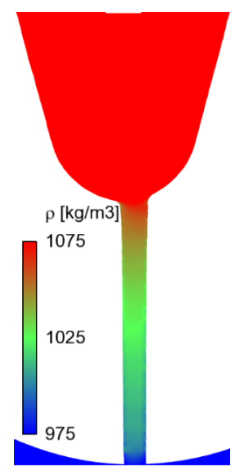
Sandia National Laboratories

ECN3



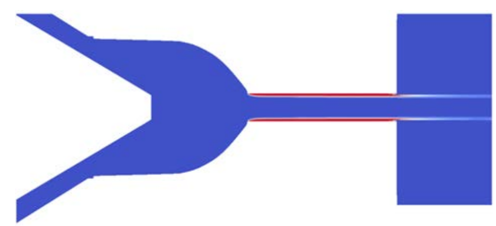
Argonne

ECN3



IFPEN

ECN3



UMass Amherst

SAE 2014-01-1404

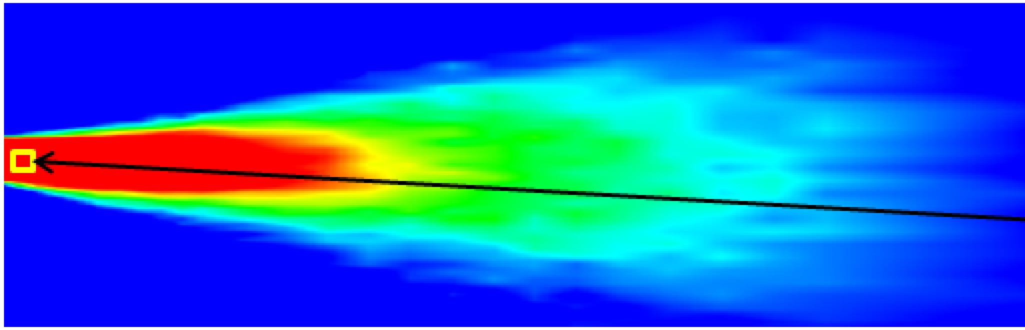
Shot to Shot Variation in Sprays

- Historically, all our measurements have been ensemble averaged
  - Not enough x-ray flux to do single-shot images of mass
  - Feedback from Annual Merit Review notes this limitation

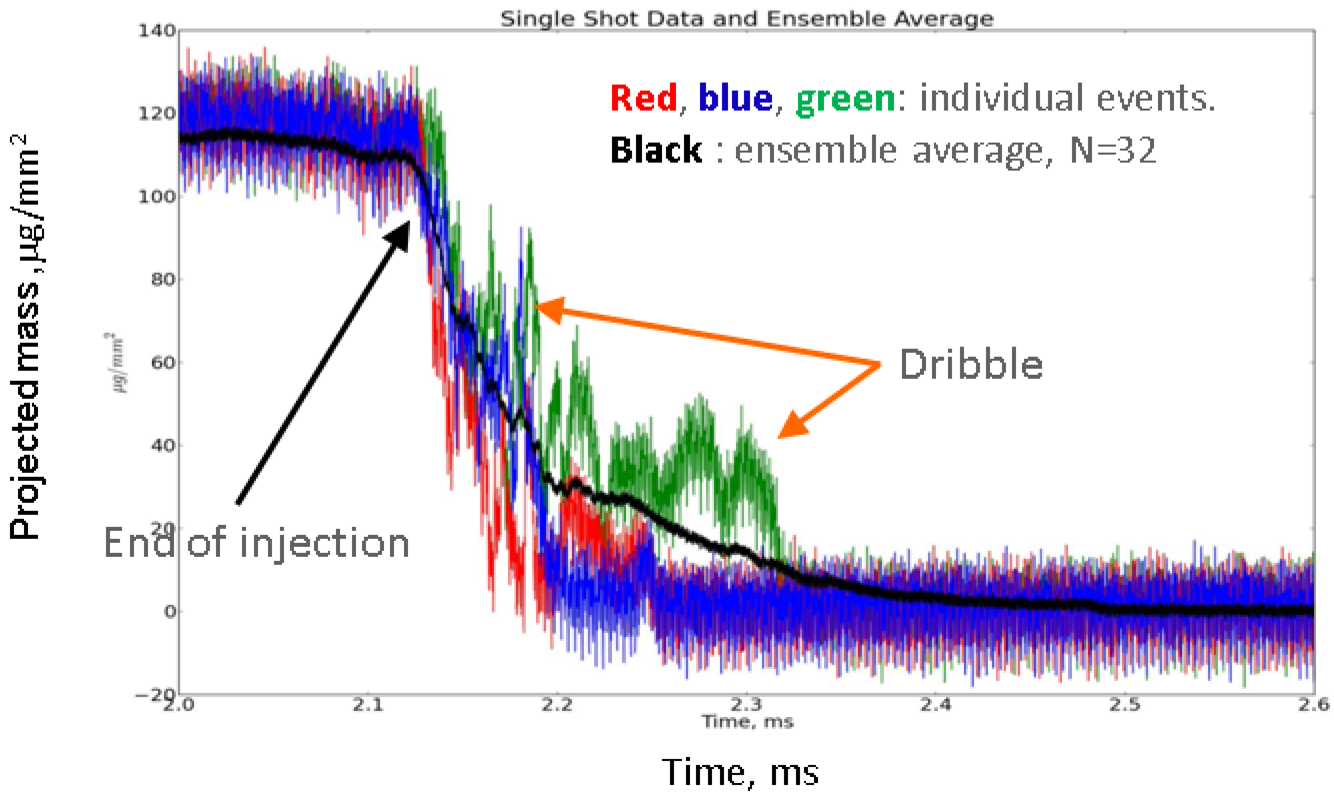
- Relevance:
  1. Spray and Mixing variations may contribute to combustion variations
  2. LES turbulence models make predictions of shot-shot variation
  - The underlying sources of randomness are often untested
  - The overall spray-to-spray variation has not been validated against quantitative data

- Two Approaches to study shot-shot variation:
  1. Radiography
  2. Phase Contrast Imaging

Single Shot Radiography Data

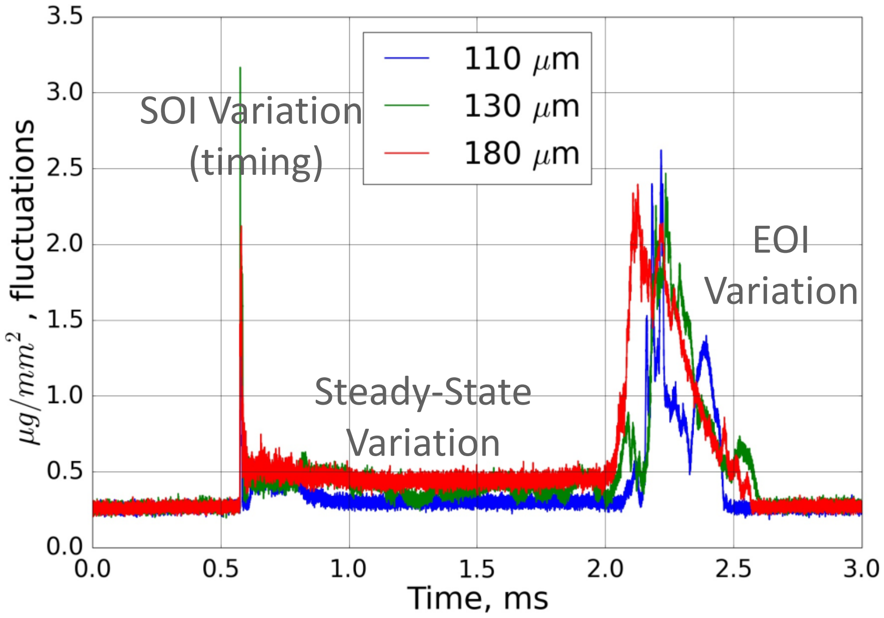


- We do not have enough x-ray flux to make a single shot 2D image
- Instead, quantify the shot-shot variation one pixel at a time



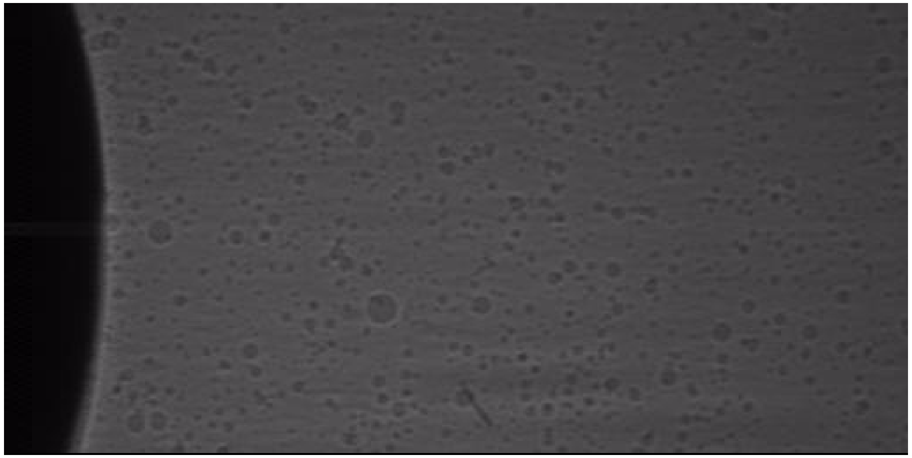
P_{inj}=500 bar
P_{amb}=1 bar
Ø 180 µm
X = 100 µm

Quantifying the Shot-to-Shot Variations



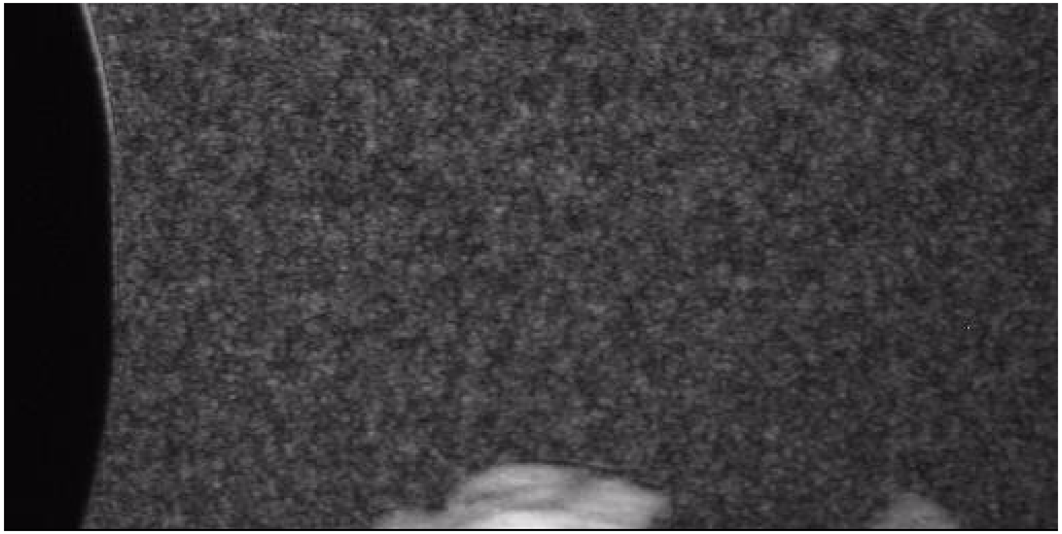
- At each position in the spray, we measure of standard deviation as a function of time
- Spike in fluctuations at beginning of event is due to timing
- During steady-state, largest nozzle nozzle has highest variation
- End of injection dribble is highly variable, increases with orifice size.
- This can be used as a metric to quantify variations from different conditions, injectors

Single Shot Spray Imaging



- High speed imaging of single spray event
- Imaging emphasizes sharp density gradients
- Spatial resolution ~2 μm

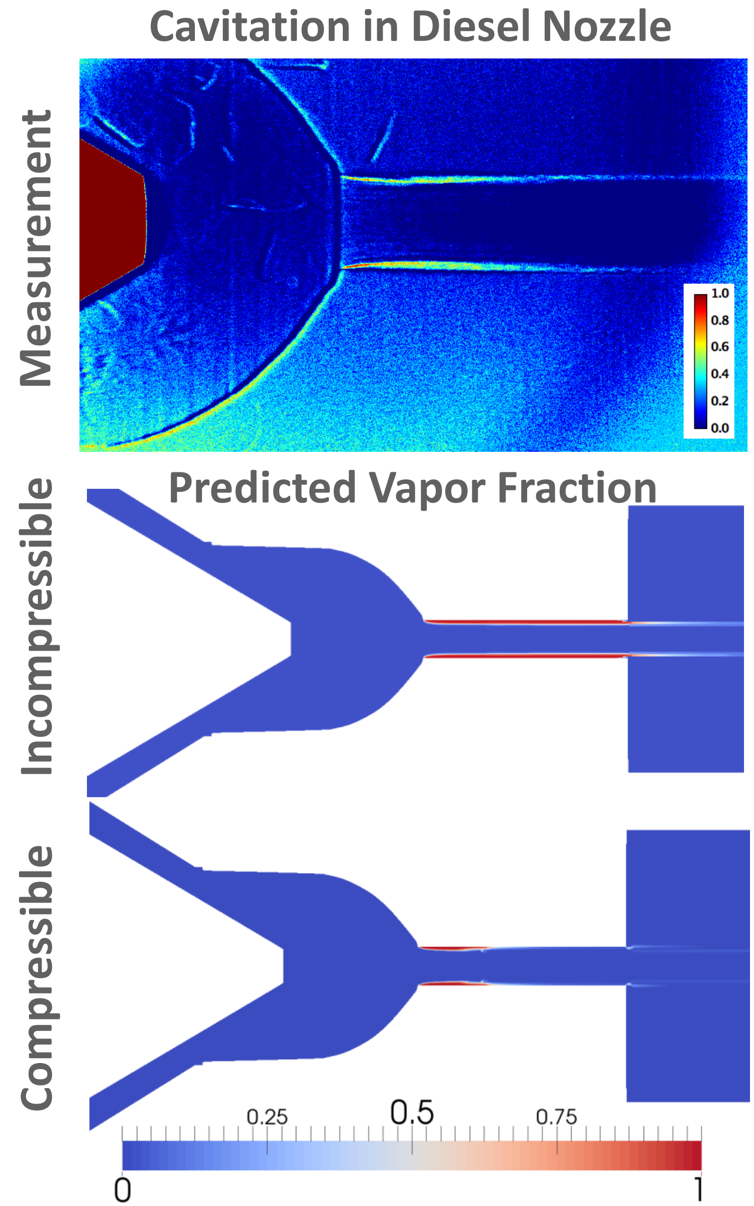
- Standard deviation "image"
- Shows variations from 30 spray events
- Brightness indicates high variability
- "Map" of spray variability can be compared to LES predictions



P_{rail} = **500** bar, P_{amb} = **1** bar, 110 μm nozzle

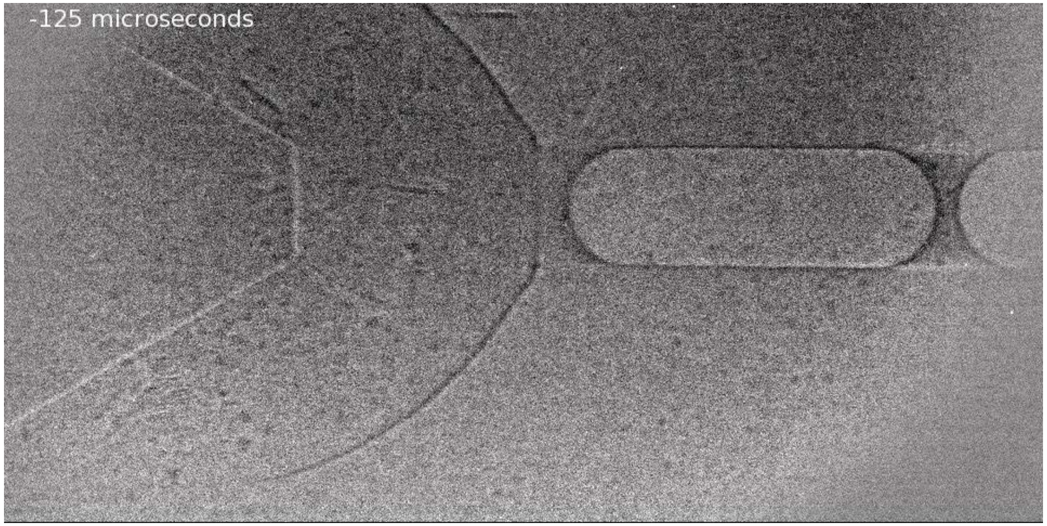
Measurements and Simulation of Cavitation

- In 2013 we demonstrated the new capability to measure cavitation in both plastic and steel nozzles
- Modeling collaboration with UMass-Amherst
- LES, Homogeneous Relaxation Model
  - 12M cells, Incompressible & Compressible
- Argonne provides computational time
- Fixes and improvements to Schmidt's HRMFoam model - GM
- Argonne HPC group optimized OpenFOAM to improve scalability on hundreds of processors – 17% faster
- Cavitation measurements also used by Convergent Science, Argonne



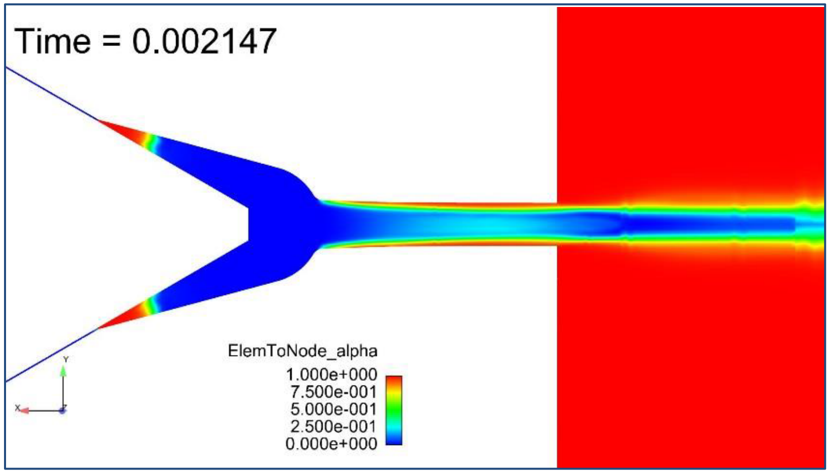
Duke et al. SAE 2014-01-1404

Bubbles in the Sac After End of Injection



- Last year, showed that bubbles are pulled into the sac after the end of injection
- Used a momentum argument to explain.

- Simulations (same geometry and conditions) predict cavitation as the needle closes.
- Cavitation bubbles collapse, sac pressure decreases, gas is pulled in.
- Bubbles will expand as cylinder pressure decreases. Fuel will be pushed into cold engine (Musculus “late dribble”)
- Additional simulations ongoing
- Gas in sac may affect SOI transient
- Simulations with empty sac are encouraged

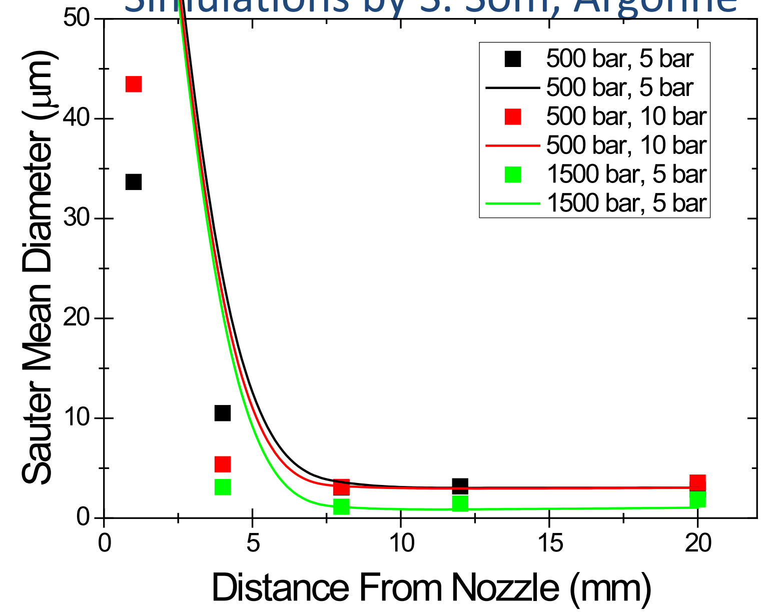


Battistoni & Som, Argonne

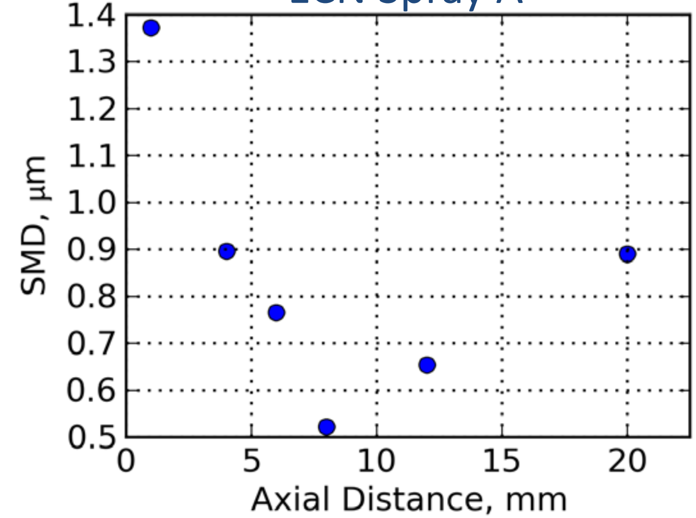
Development of a New Diagnostic: X-ray Small Angle Scattering

- Droplet size is a critical parameter for sprays
- Little is known about spray structure in near-nozzle region
- 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
- Good agreement with KH model predictions.
- New measurements:
  - ECN Spray A – smaller nozzle, more volatile fuel
  - Multi-hole nozzles
- Another constraint on spray simulations: Quantitative measurements of near-nozzle spray breakup

Simulations by S. Som, Argonne



ECN Spray A



Upgrades to X-Ray Beamline

- X-Ray Flourescence will be needed for evaporating or combusting sprays
  - Existing Absorption measurements cannot measure in dilute regions of spray
  - At high temperature, fuel density will be significantly lower
  - X-ray Flourescence is much more sensitive
- In January 2014, expanded the wavelength range of our x-ray beamline
  - $10K in materials paid for by project
  - All engineering and labor paid for by BES (~$75K)
- This enables x-ray flourescence
  - Higher energy (shorter wavelength) x-rays
  - Necessary to excite fluorescence of fuel additives
  - Better penetration through windows, pressurized gas
  - Lower detection limits
  - X-rays not susceptible to beam steering from density gradients
- First combustion experiments at our beamline: April & July 2014
  - Collaborations with Argonne Chemistry, USAF
  - Looking at gas jet flames
  - Used to develop diagnostics and expertise.

Responses to FY2013 Reviewers' Comments

"limited to room-temperature conditions "

"evaporation effects difficult to assess "

- Last year we reported successful test of high P,T x-ray windows
- New capabilities for x-ray flourescence
- Proof-of-concept experiments being planned: flash boiling at room temperature

"only producing ensemble-average data"

- New effort this year to develop single-shot capability
- Hope to use for validation of LES predictions

"engagement with fuel-system suppliers would be useful "

"more collaborations with the industry fuel-injector suppliers"

- CRADA with Delphi Diesel
- New WFO contract with Caterpillar

Collaborations

- **DOE Advanced Engine Combustion Working Group**
  - All results presented at these meetings
  - Often results in new collaborations
- **Engine Combustion Network**
  - Our data is integral for validation of internal flow simulaitions
  - Unique for validation of near-nozzle breakup models
- **Collaboration with Sibendu Som's group**
  - Cavitation
  - Bubbles in sac
  - Needle motion effects
  - ECN
- **University of Massachusetts Amherst**
  - Cavitation
  - Improvements to HRM Model
- **International Energy Agency Combustion Agreement**
  - Simulations of Natural Gas Jet measurements by Aalto Univerity
- **Industrial Contracts:**
  - Delphi Diesel
  - Caterpillar

Remaining Challenges and Barriers: High Temperature Sprays

Barriers:

1. X-ray windows
2. Low fuel density
3. How to generate the temperature?

X-Ray Windows

1. X-ray transparent
2. High T, P

- Diamond has been demonstrated
- Need source that can certify P,T rating

Low Fuel Density

1. Absorption not sensitive enough
2. Need high x-ray flux

- New beamline optics in place
- Testing later this year

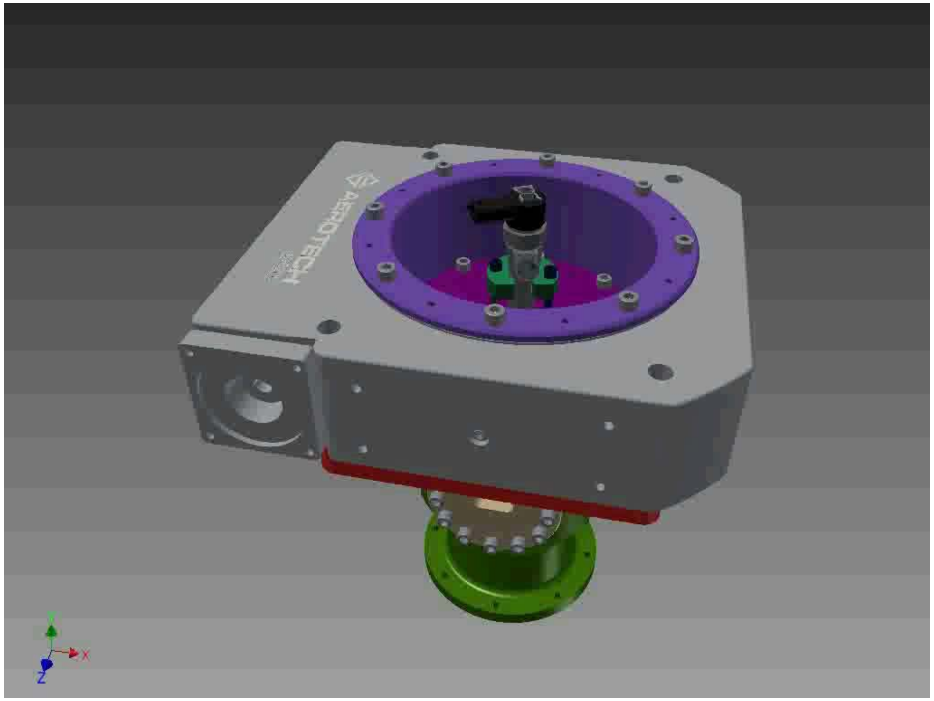
Temperature

1. Electric? Pre-burn, Shock Tube?, RCM?, Engine?

- We think shock tube is a promising path
- Submitted proposal to secure the funding

Proposed Future Work in FY2014 and FY2015

- Engine Combustion Network
  - GDI sprays
  - 3D Tomography under pressurized conditions
- Cavitation Studies
  - Improved measurements of cavitation density in plastic nozzle
  - Improved nozzle design, control over dissolved gases, more stable flow
  - Continued modeling collaborations
  - Real-size, real pressure transparent nozzles
- Bubbles & Injector Dribble
  - Improve sensitivity of the measurements
  - Measure broader range of nozzles
- Combustion and Evaporation
  - Additional Gas jet experiments in July
  - Flash boiling sprays next year



Summary

- Improve the understanding of fuel injection and sprays
  - Fundamental measurements of spray phenomena
    - Cavitation
    - Stochastics
    - Near-nozzle SMD
  - Collaboration with ECN
    - Needle lift and motion
    - Near-nozzle fuel density
    - Nozzle geometry
- Assist in development of improved spray models
  - Partnerships on cavitation modeling with UMass Amherst, Argonne
  - Data contributed to ECN is assisting model development at IFP, CMT, Sandia, Argonne, UMass, Convergent Science, others.
  - WFO with Caterpillar, CRADA with Delphi Diesel

Technical Back-Up Slides

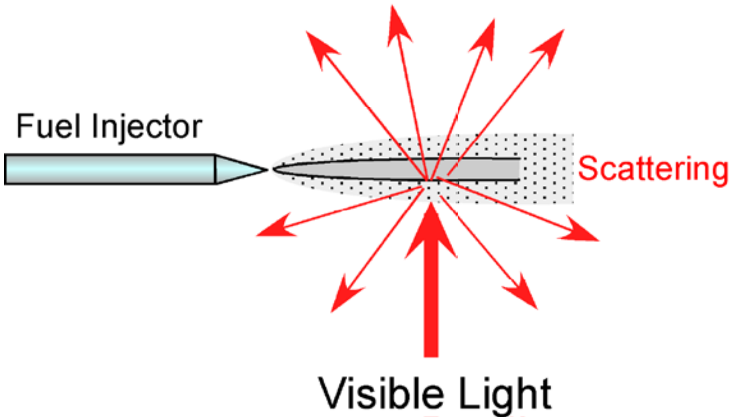
(Note: please include this “separator” slide if you are including back-up technical slides (maximum of five). These back-up technical slides will be available for your presentation and will be included in the DVD and Web PDF files released to the public.)

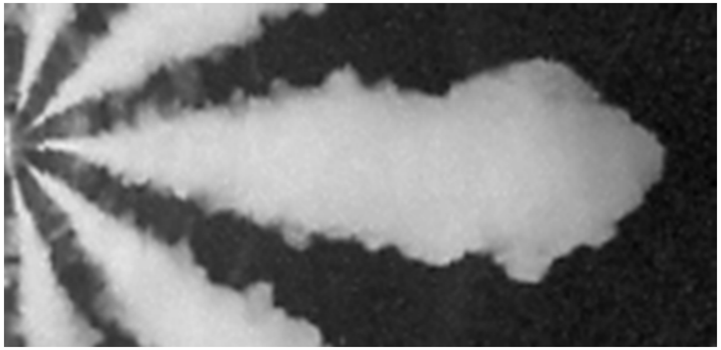
Technical Approach

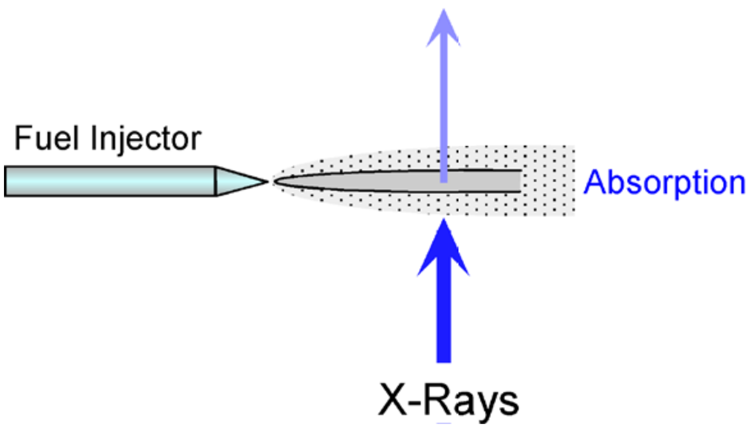
- **Perform injector and spray measurements that increase fundamental understanding**
  - Engine Combustion Network
  - Measurements of cavitation
  - Measurements of needle motion
  - Measurements of internal nozzle flow
  - Droplet sizing

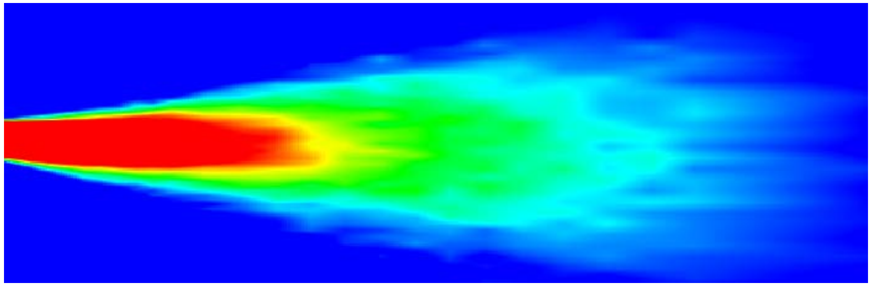
- **Use our measurements to assist the development of computational spray models**
  - Collaboration with UMass Amherst
  - Engine Combustion Network
  - Collaboration with Argonne modeling group
  - Delphi Diesel CRADA, Caterpillar WFO

Technical Approach – X-rays Reveal Fundamental Spray Structure





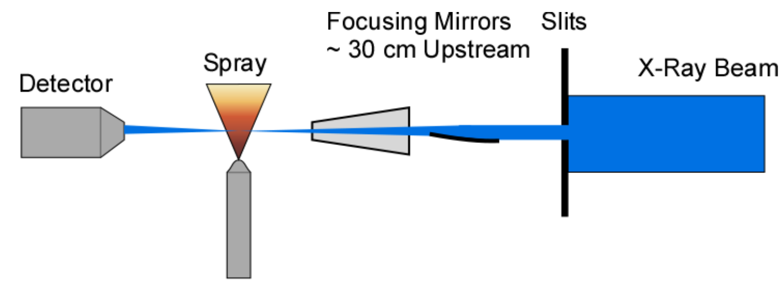


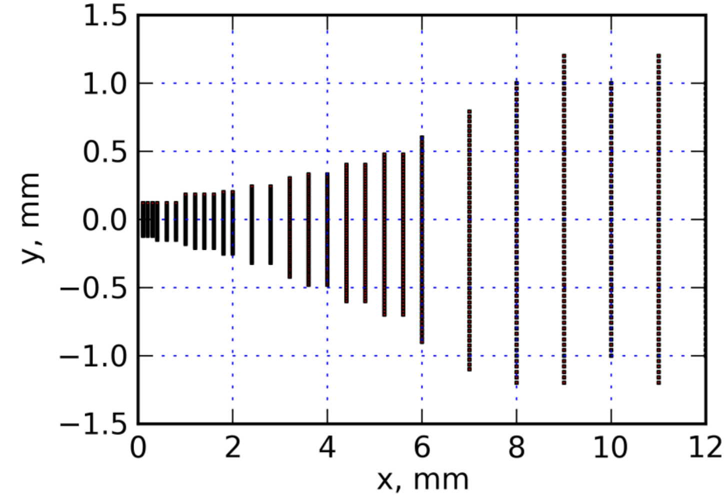


- Room temperature
- Ensemble averaged
- Pressure up to 30 bar

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} $mm^2/\mu g$
  - Accounts for displacement of chamber gas by liquid
  - Maximum absorption in dodecane ~2%





Example Measurement Grid

Interpreting X-Ray Phase Contrast Images of Sprays

Images not to scale, different injectors

IR Laser Imaging

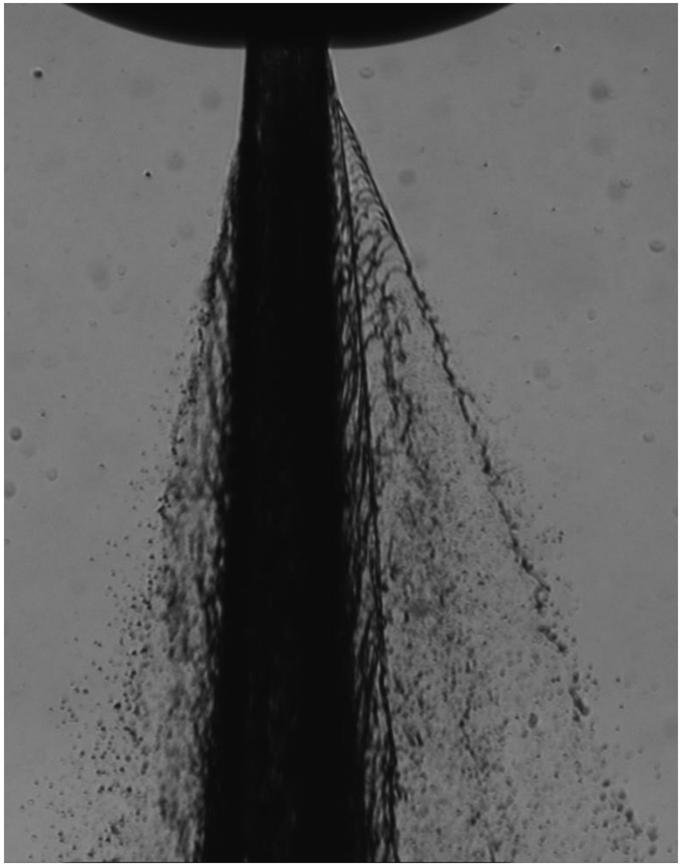
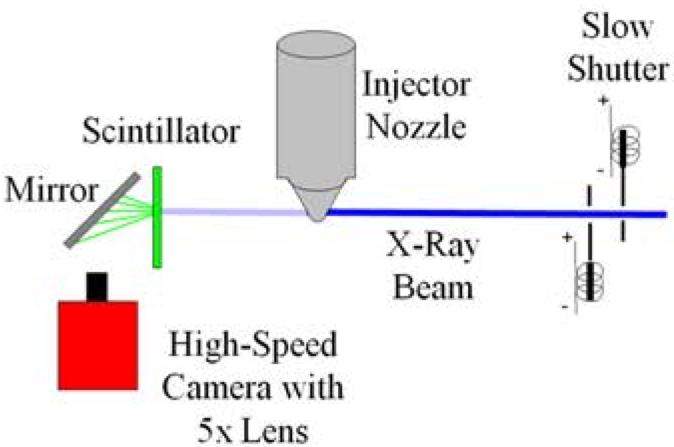


Image courtesy of Philippe Leick, Robert Bosch GmbH

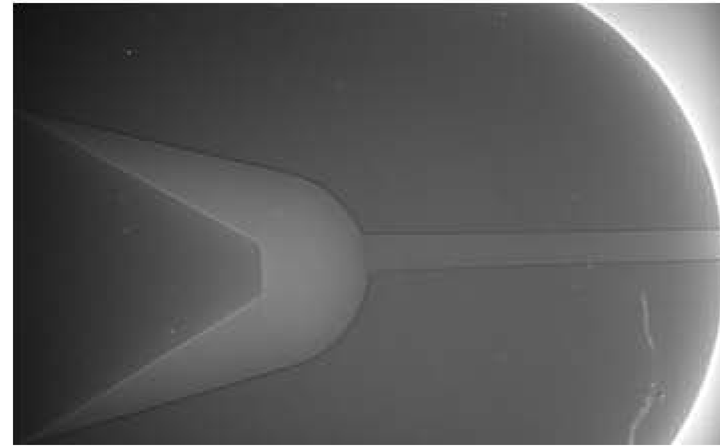
X-Ray Phase Contrast

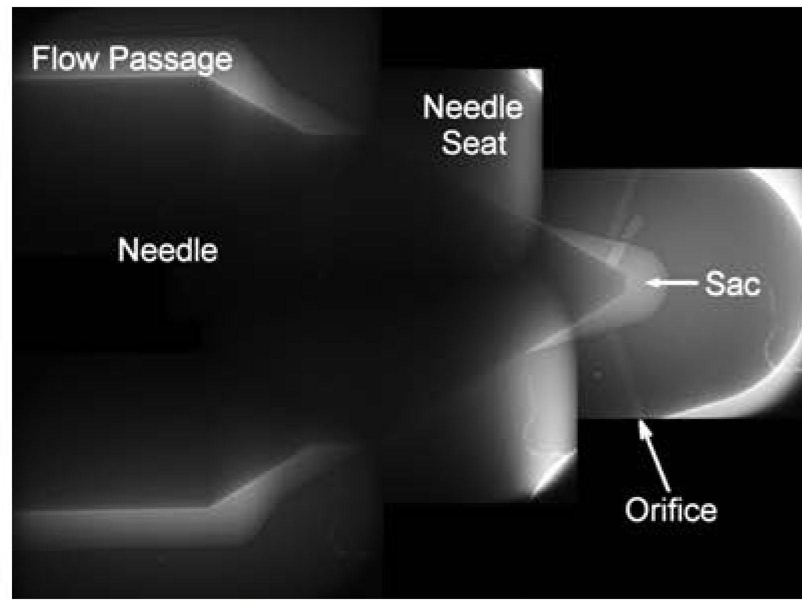
X-Ray Imaging Through Steel Nozzles



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
  - Construction 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

Future Work with ECN: Gasoline Sprays

- Modern GDI injectors have closely-spaced sprays, single line of sight gives limited information
- X-ray tomography allows 3D reconstruction of fuel density and mixing
- Existing hardware not optimized for this
  - Measurements slow
  - Limited to 1 bar ambient

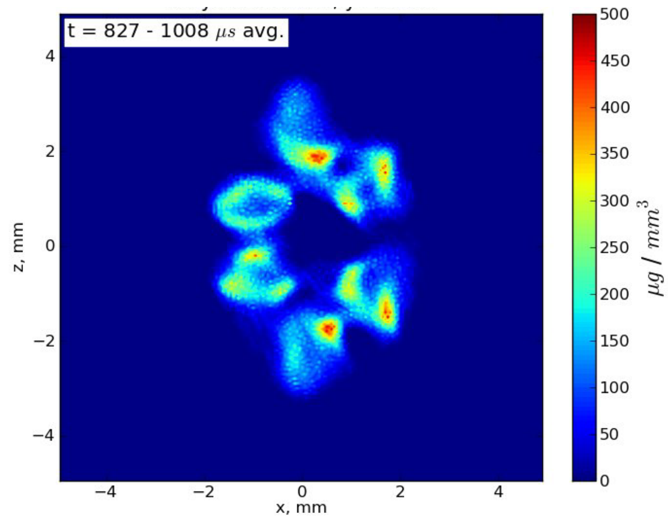
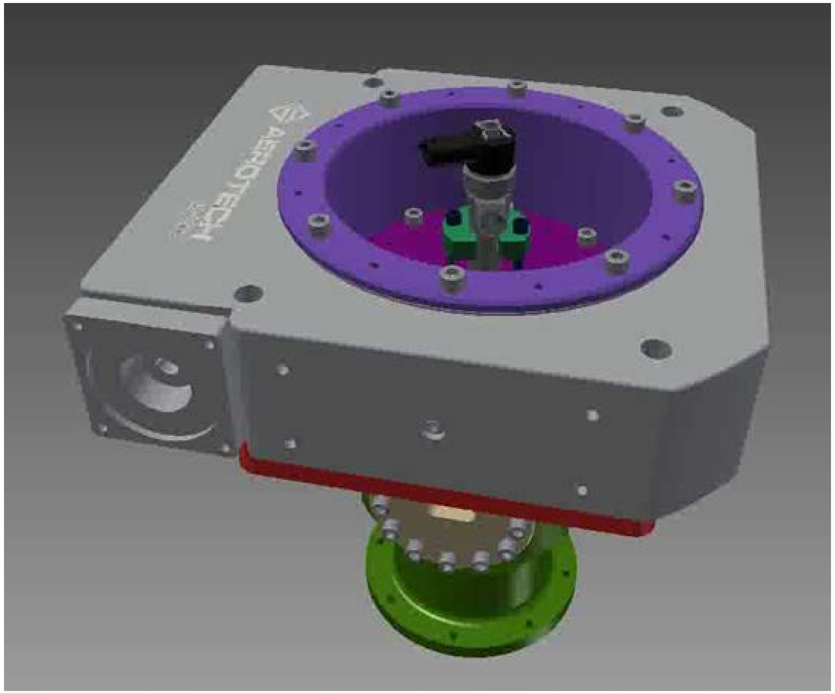


Image Courtesy of Chrysler



New Tomography Pressure Chamber

- Designed to speed 3D tomography
- Pressure up to 33 bar
- Suitable for both gasoline and diesel injectors