Fuel Injection and Spray Research Using X-Ray Diagnostics

Project ID ACE10

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Overview

Timeline

- Project Start: FY2000

Budget

- FY2011: $1100K
- FY2012: $825K + 175K

Partners

- Engine Combustion Network, Delphi Diesel, Westport, *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”

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
- Support industrial partners by giving them access to unique injector and spray diagnostics

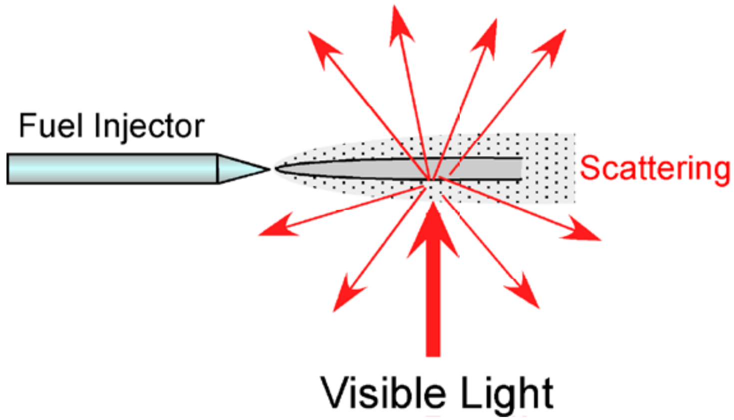
Milestones, FY2011 and FY2012

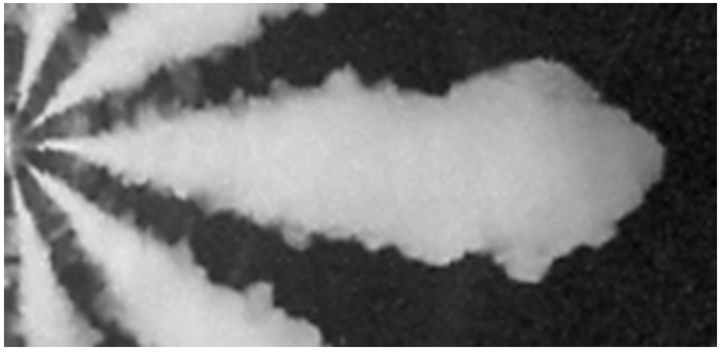
- **June 2011: World's first x-ray measurements of gaseous fuel injection**
- **July 2011: Measure nozzle geometry and needle lift with Engine Combustion Network**
- **Aug 2011: Spray measurements of ECN Injectors**
- **Dec 2012: Measurements of Rocket Injector for USAF**
- **Feb 2012: World's first measurements studying shock tube at x-ray source**
- **Feb 2012: First tests of high temperature, high pressure x-ray windows**
- **March 2012: World's first x-ray measurements of cavitation**

Three "World's First" measurements this year, made possible by dedicated lab at x-ray source.

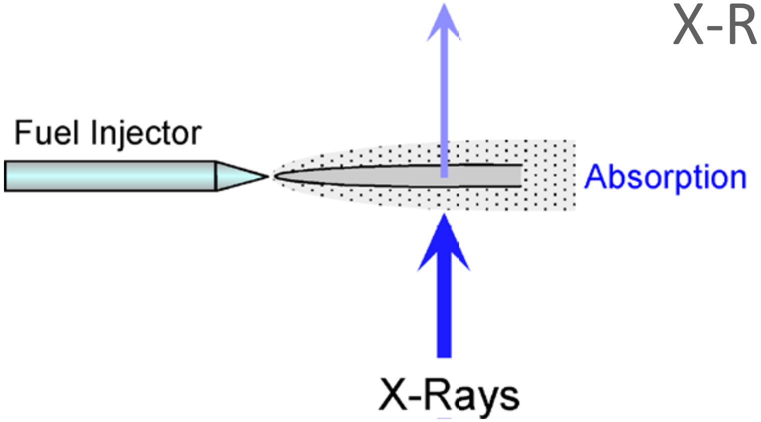
Technical Approach - X-rays Reveal Fundamental Spray Structure

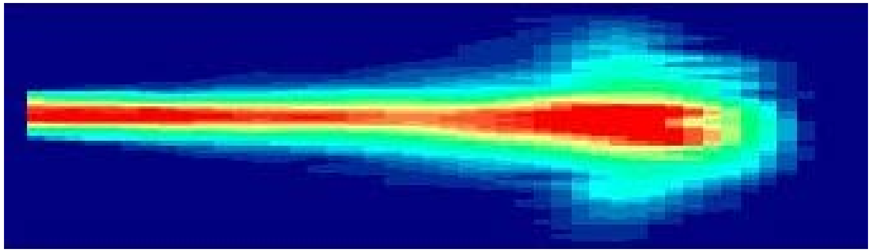
Visible Light Imaging





X-Ray Imaging





Technical Approach for FY2012

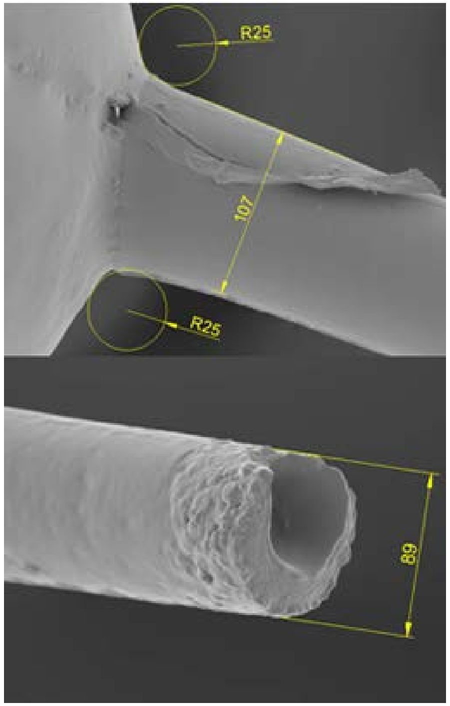
- Measurements in collaboration with Engine Combustion Network
  - Develop fundamental understanding of sprays
  - Validate measurement techniques
  - Study engine-like conditions
  - Collaboration with modeling
- Support development of KH-ACT spray model
  - Incorporate effects of nozzle geometry in spray models
- Test of Westport gas injector
  - Supports development of turbulent gas flow modeling
- Measurements of shock tube gas flows
  - Improve measurements of reaction rates
  - Supports combustion modeling
- Prepare for measurements with Delphi: Effect of Nozzle Geometry
  - Understand the link between nozzle geometry and fuel distribution
  - Supports industrial partner with nozzle design

Measurements Supporting Sandia's Engine Combustion Network

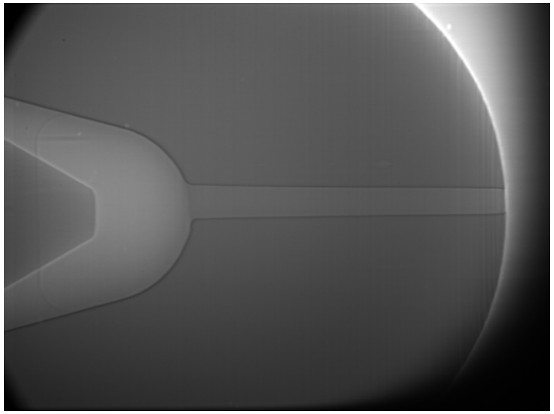
- Collaboration of 12 leading spray and combustion groups worldwide
- All groups studying same "Spray A" operating condition
  - Common injection hardware (four shared injectors)
  - Well-defined fuel, pressure, temperatures, ambient density, etc
- Data will be shared with partners, modeling groups worldwide
- Argonne will contribute x-ray measurements of spray, nozzle geometry, and needle motion
  - Geometry defines flow boundaries for modeling
  - Near-nozzle spray measurements for validation

ECN Measurements of Nozzle Geometry

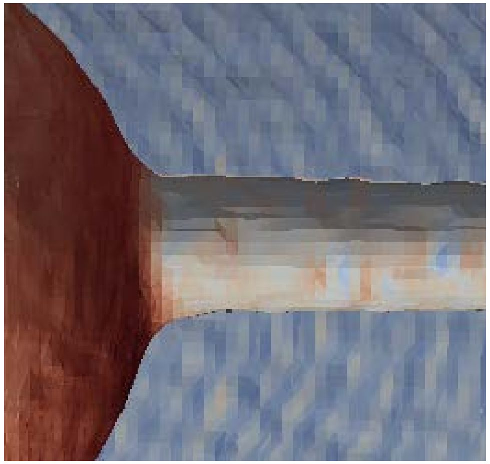
- Argonne leads subgroup on nozzle geometry and internal flow
- Goal is to improve predictive capability of modeling
- Comparing models requires starting from a common geometry
  - Injectors are not identical
  - Need to define a reference geometry for each injector
- Geometry measured by ECN using several different techniques
  - Silicone molds (Valencia)
  - X-ray absorption tomography (CAT)
  - X-Ray phase contrast imaging (Argonne)
  - Microscopy (Sandia)
- No single measurement gives the complete geometry



Silicone Mold, CMT Motores Térmicos Universidad Politécnica de Valencia



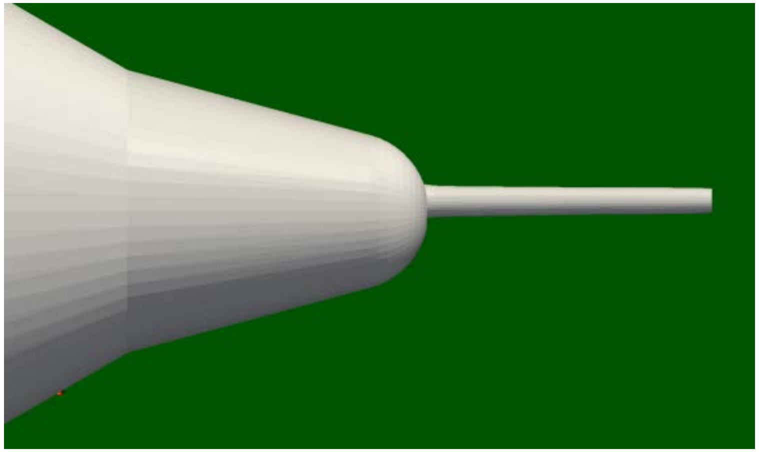
X-Ray Phase Contrast Image, Argonne

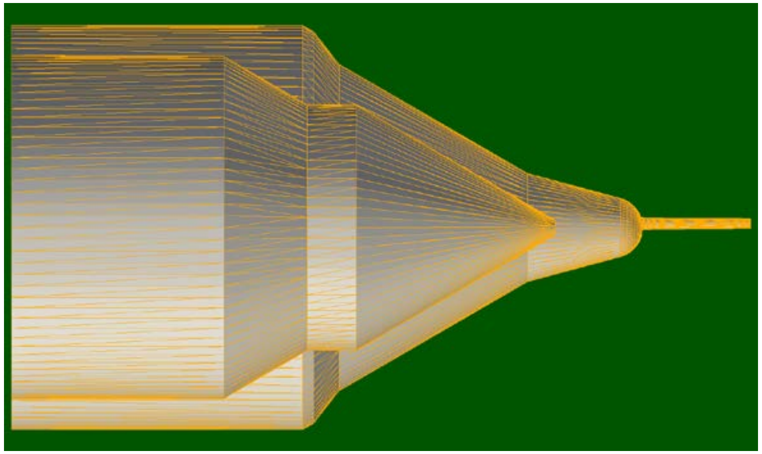


X-ray Tomography, Caterpillar

Argonne is Building ECN Reference Geometries

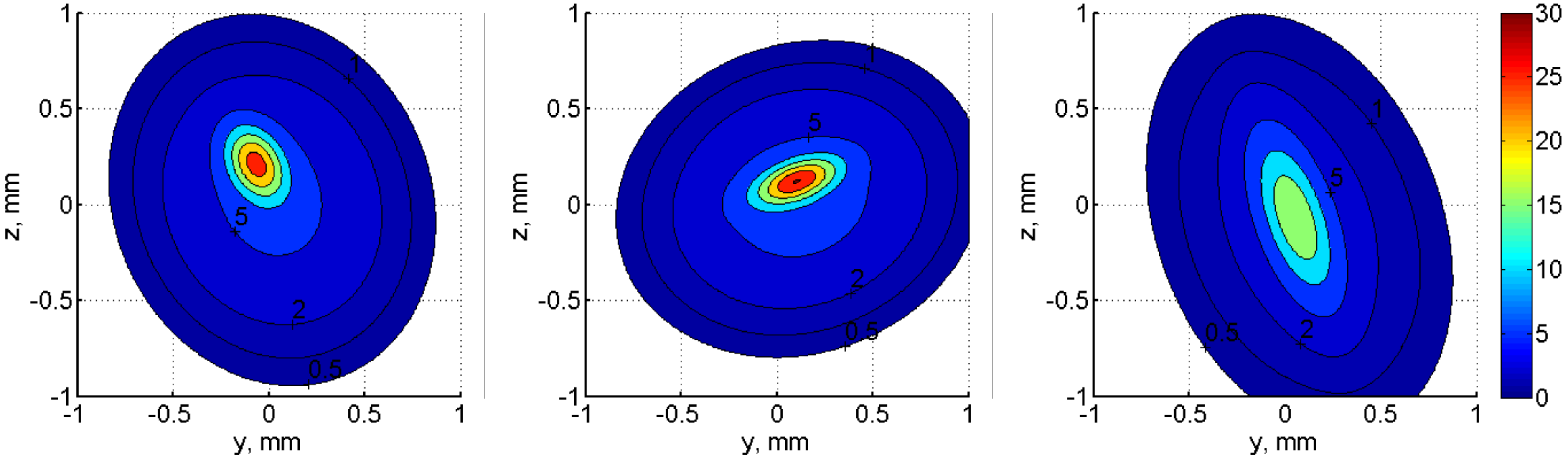
- Provides common starting point so that models can be compared
- Must combine the best available knowledge from each of the measurement techniques
- Argonne has begun to develop the reference geometries, will publish on the web as a CAD file
- Future measurements:
  - "Spray B" (multi-hole injectors)
  - "Spray H" (n-heptane)
  - GDI





Preliminary CAD model of ECN Injector nozzle

X-Ray Measurements of Fuel Distribution from ECN Injectors



Nozzle 210675 **Nozzle 210678** **Nozzle 210679**

Similarities:

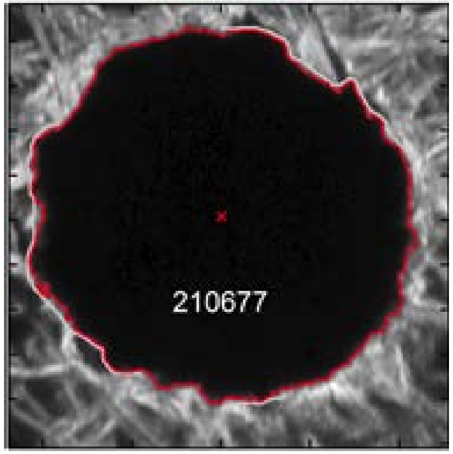
- All elliptical
- Relatively dense core
- Same total mass in cross section

Differences:

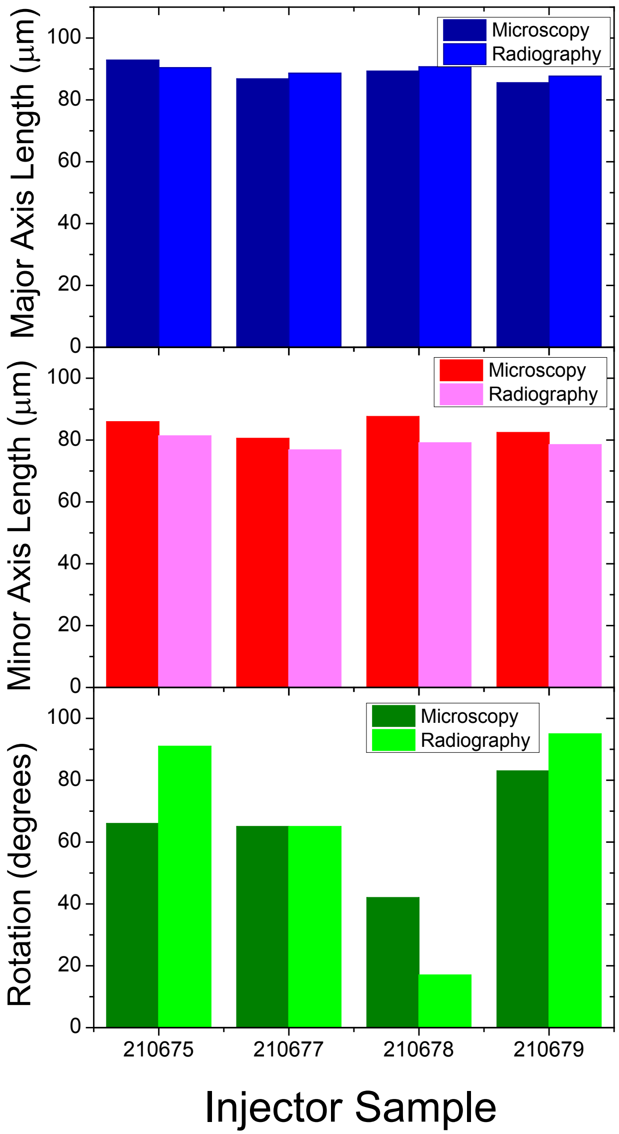
- Orientation of the ellipse
- Fraction of fuel in the core (20-40%)
- Peak density value

Elliptical Spray is Generated by Elliptical Nozzle

- Sandia used optical microscopy to measure nozzle outlet, found elliptical holes
- Measured hole shape correlates well with our measurements of near-nozzle spray
  - First experimental evidence linking nozzle and spray shape
  - Models assume cylindrical symmetry
- Current diagnostics cannot measure elliptical shape *inside* injector
  - We are investigating x-ray imaging with 0.6 μm resolution
  - Version 2 of reference geometries would include elliptical flow passage

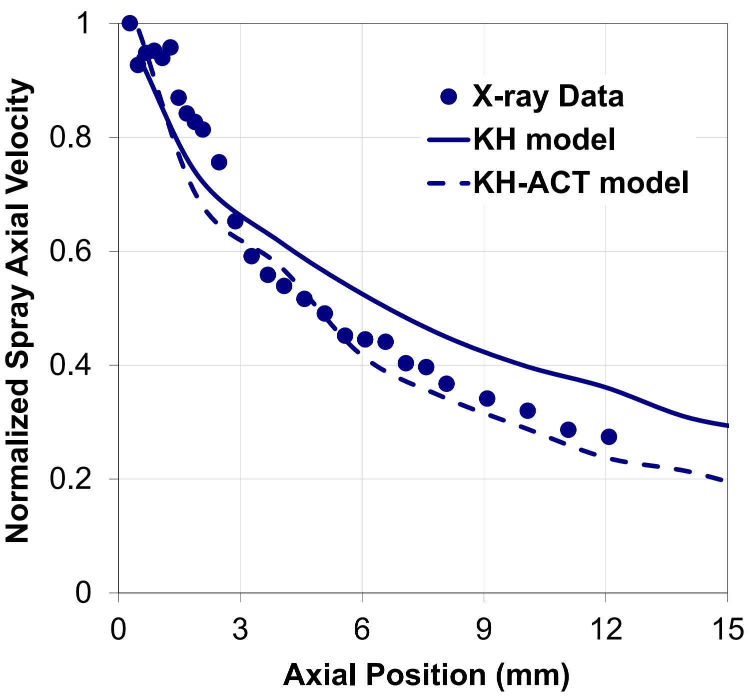


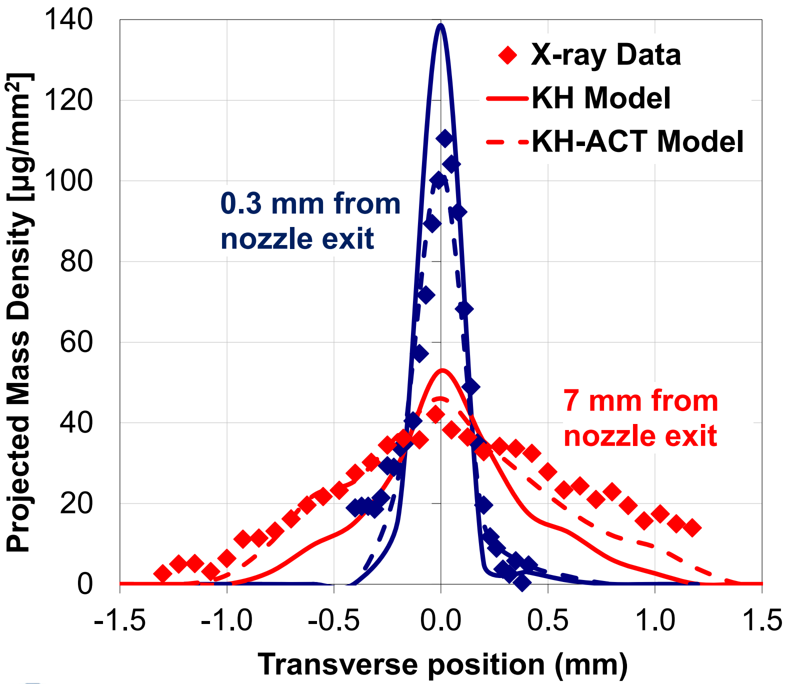
Optical microscopy of nozzle hole, Sandia



Validation of KH-ACT Using X-ray Data

- New modeling framework for near-nozzle spray breakup (Som, ANL)
- Contributions from aerodynamics, cavitation, turbulence
- Includes effect of nozzle geometry

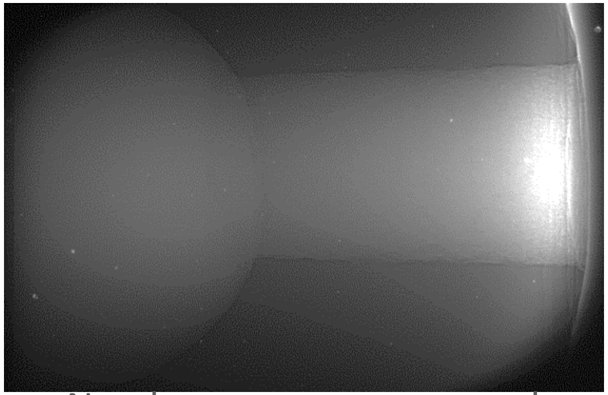




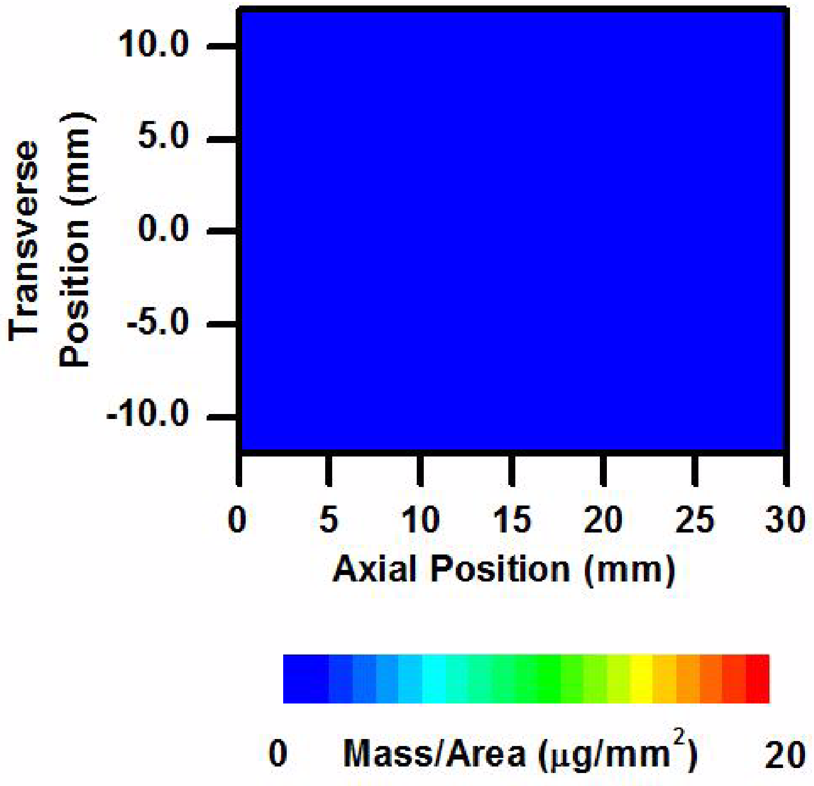
- Model validation using x-ray data
- KH-ACT more accurate for fuel dispersion speed
- Implemented by Caterpillar, CONVERGE, and UW-ERC.

Investigating Gaseous Fuel Jets

- Industrial collaborator (Westport Innovations) interested in improving their piezo DI gas injectors
- Quantitative measurements of gas jets difficult, density gradients cause refraction of visible light
- X-rays can quantify the fuel density
- First measurements completed August 2011, used argon gas
  - Large x-ray absorption simplifies experiment
  - Still relevant, since computational model can account for variations in density, diffusivity, etc.
- Provides quantitative data never before available

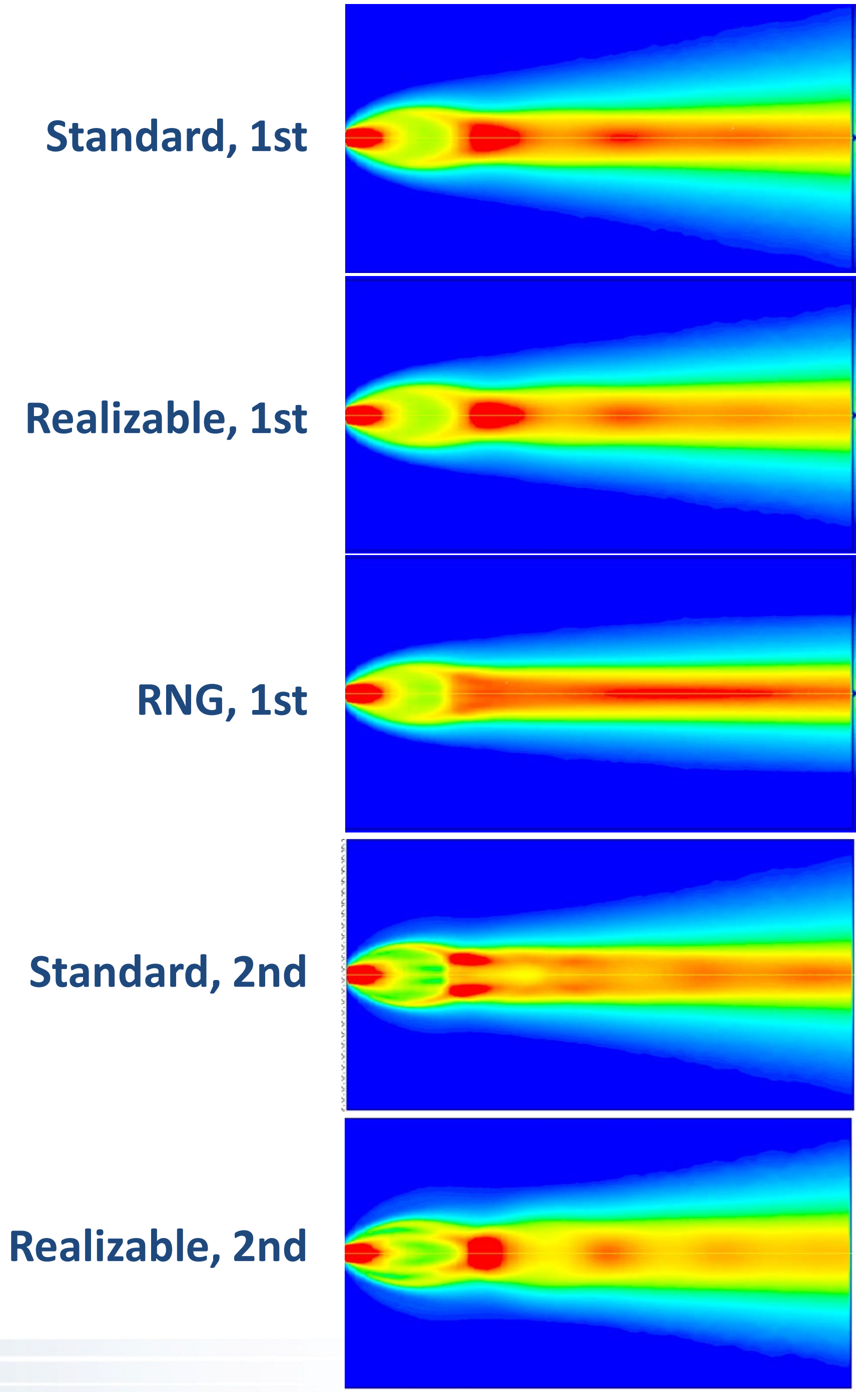


Nozzle geometry measured using x-ray imaging



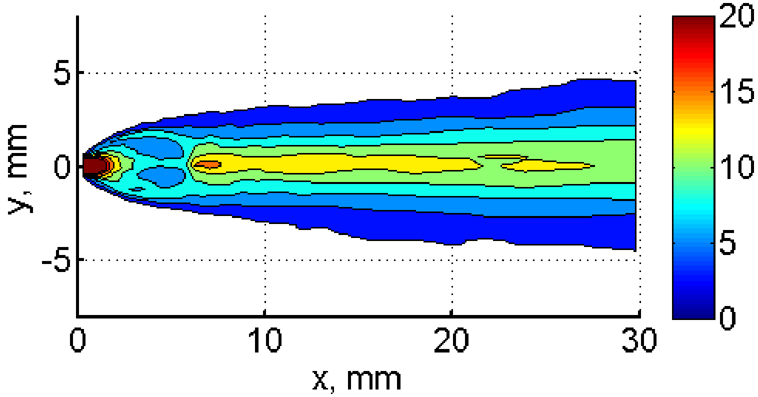
Initial Modeling Results

- Gas jet simulations being done by Riccardo Scarcelli
- Need to make several choices in the modeling approach
  - Turbulence model (k-e standard, k-e realizable, k-e RNG)
  - Order of discretization of field variables (pressure, density, momentum, turbulence, species, energy)
  - Computational time-step
- Modeling approach is guided by the data

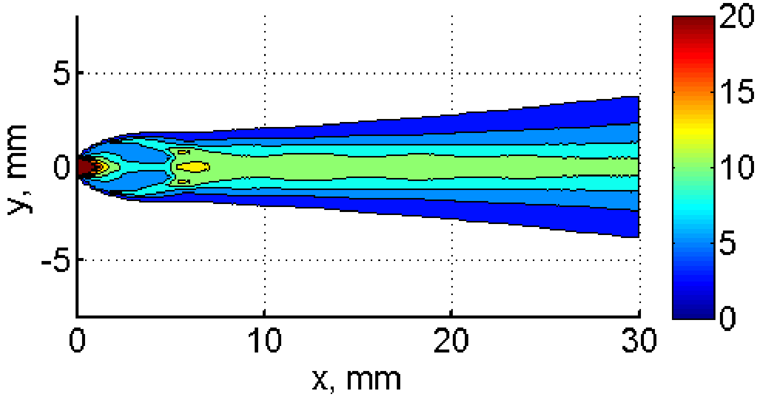


X-Ray Measurements used for Validation of Gaseous Injection Modeling

- Measured internal nozzle geometry
  - Defines flow boundaries for model
- Measured gas jet density
  - Comparison with modeling predictions
  - Allowed selection of best RANS turbulence models and discretization schemes
- Knowledge applicable to natural gas engines



Experimental Gas Distribution

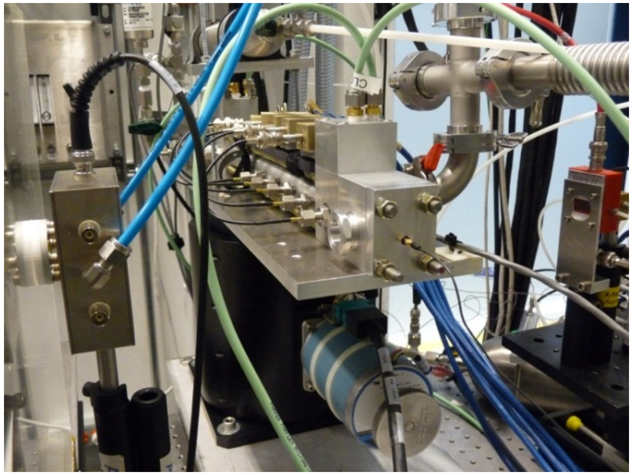


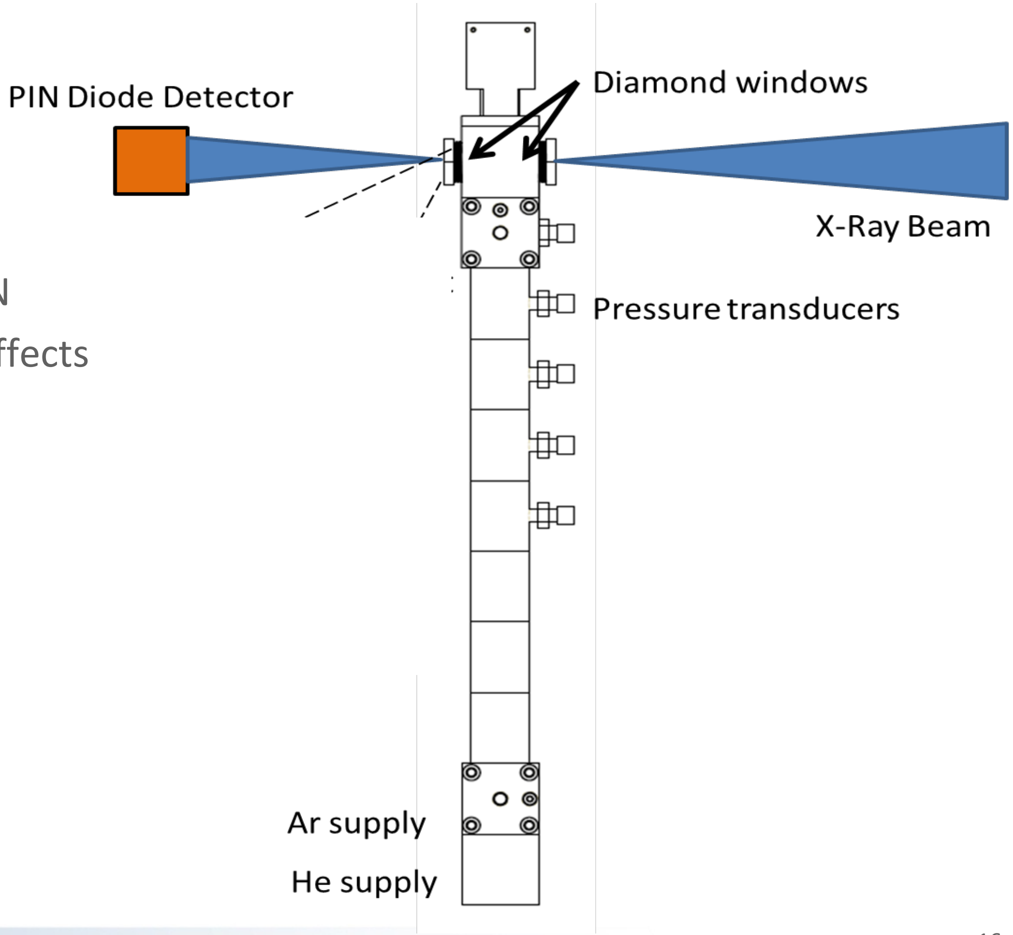
CFD Results: Standard k-ε Model

Scarcelli et al., COMODIA-2012, Fukuoka, Japan, July 2012

X-ray Studies of Shock Tube Prototype

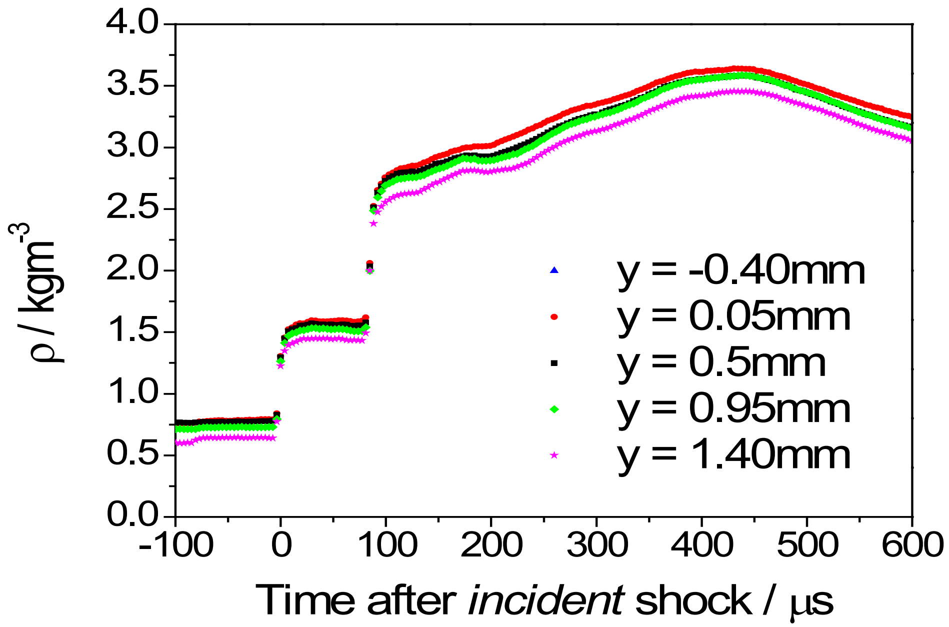
- Argonne collaboration "Bridging the Gap" between fundamental combustion (Chemistry) and IC engines (Transportation)
- Argonne chemistry (DOE-BES) has developed a "Baby Shock Tube" for measuring combustion using x-ray diagnostics
  + Fast cycle time (up to 4 Hz), very reproducible, wide operating range
  + Allows data to be averaged for high S/N
  – Small diameter, large boundary layer effects





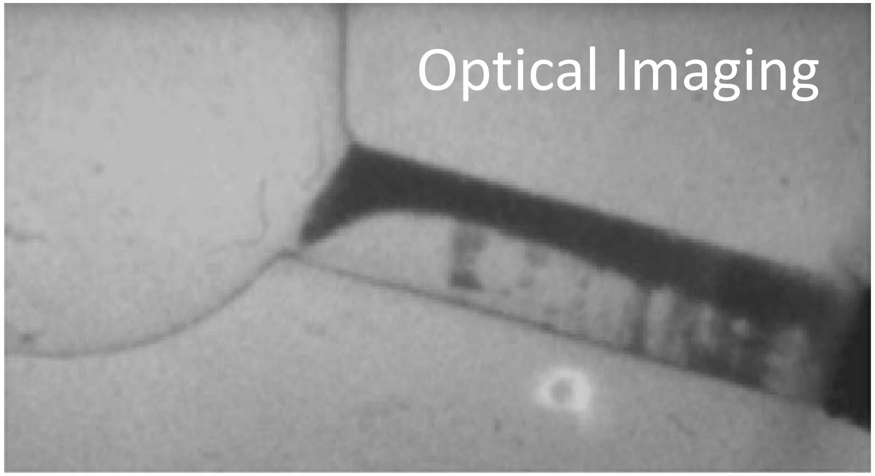
First Measurements of Shock Tube Boundary Layers

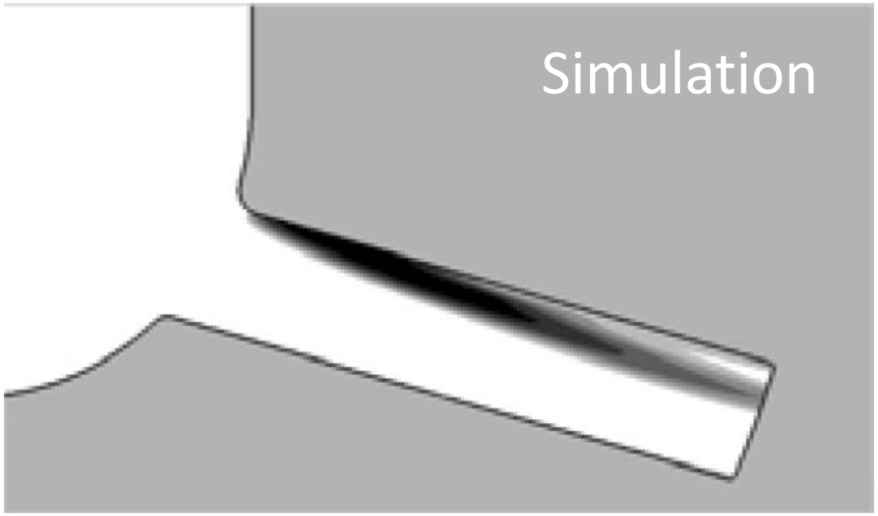
- For accurate measurements of chemical kinetics, need to quantify the boundary layer (P, T, ρ)
  - CFD must be validated
- X-rays are ideal tool for this
  - Absorption independent of T
  - No refraction from temperature gradients
  - Gives quantitative measurement of density distribution and history
- Will allow studies of chemical kinetics, autoignition
  - DOE Barrier: "Incorporating more detailed chemical kinetics into fluid dynamics simulations"



- Shock tube used diamond windows
  - Demonstrated to withstand high P,T (10 bar, 700 °C for short time)
  - Inexpensive
  - May allow spray measurements at elevated P,T

The Importance of Cavitation



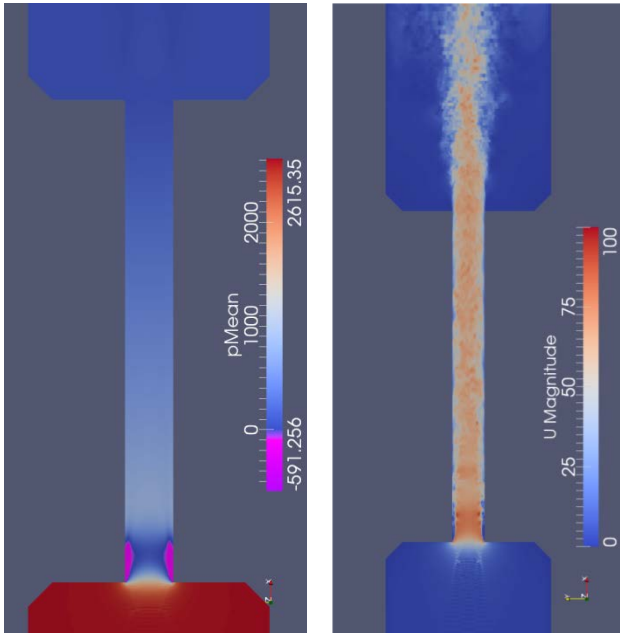


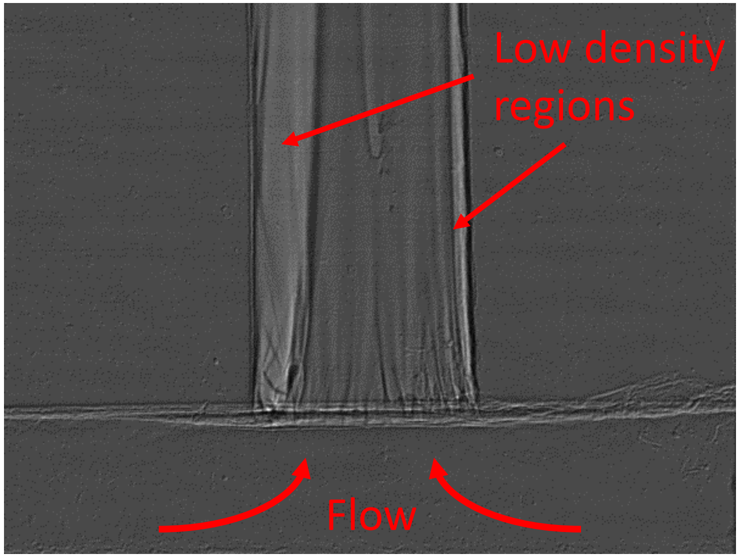
Blessing et al., SAE 2003-01-1358

- Cavitation is important in fuel injection process
  - Enhances atomization
  - Can lead to nozzle damage
- Current production nozzles minimize cavitation
- Industry research to try to confine cavitation to the center of the flow
  - Requires detailed understanding of cavitation, accurate models
- Existing models have limited predictive power
- Existing experimental data is limited

X-Ray Measurements of Cavitation for Model Validation

- X-ray radiography can measure the density distribution in a cavitating flow
- First measurements in March 2012
  - Large-scale (1 mm) plastic nozzle with sharp corners
  - Ethanol used as working fluid
- OpenFOAM simulations used to guide the choice of measurement conditions
- Data will be shared with modelers at Stanford University Center for Turbulence Research, possibly Bosch, UMass



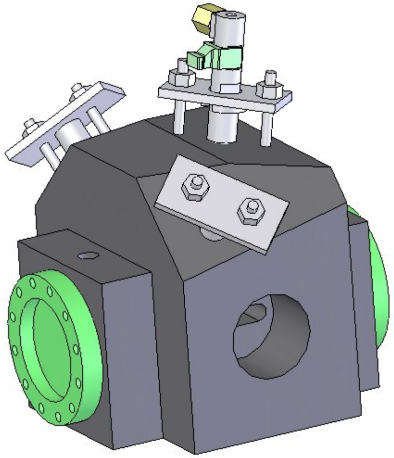


X-ray image of cavitating flow, ΔP = 8 bar

Proposed Future Work in FY2012 and FY2013

- Engine Combustion Network
  - Provide reference geometries for in-nozzle flow modeling
  - Measurements on multi-hole nozzles
  - ECN Gasoline spray group
- Cavitation in a model nozzle
  - Measurements on a nozzle closer to engine geometry
  - OpenFOAM model validation, collaboration with modelers at Stanford, Bosch, UMass
- Projects with industrial partners
  - Delphi Diesel
    - CRADA signed in January 2012
    - Studies of injector geometry and its impact on sprays
    - First x-ray measurements in September 2012
  - Chrysler (Super Truck) – spray imaging to support advanced combustion engine, includes GDI sprays
  - Infineum – interested in how viscosity, density, surface tension, etc., affect spray pattern
  - Bosch – high speed imaging of internal components of prototype injector

New GDI fuel system funded by Chrysler collaboration



Spray Chamber being built by Delphi for multiple views of multi-hole nozzles

Summary

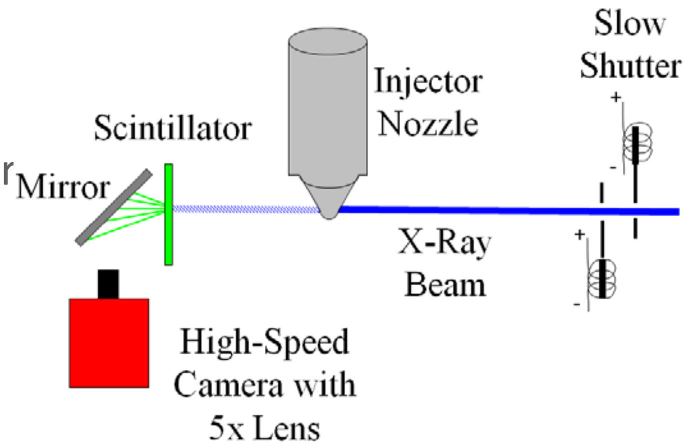
- Improve the understanding of fuel injection and sprays
  - Collaboration with ECN, cavitation measurements
- Assist in development of improved spray models
  - “Big unknowns”: turbulent fluid dynamics, chemical kinetics, cavitation
  - Work on KH-ACT, gaseous injectors, ECN, cavitation
- Support industrial partners
  - Westport, Delphi, Chrysler, AFRL

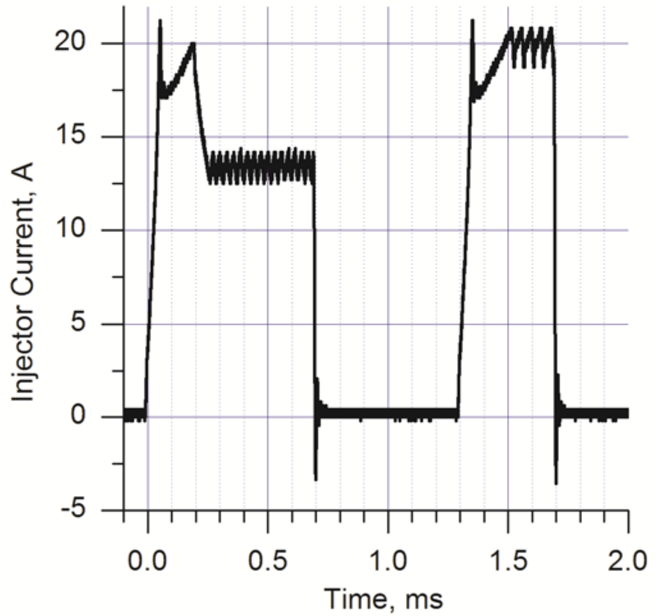
Technical Back-Up Slides

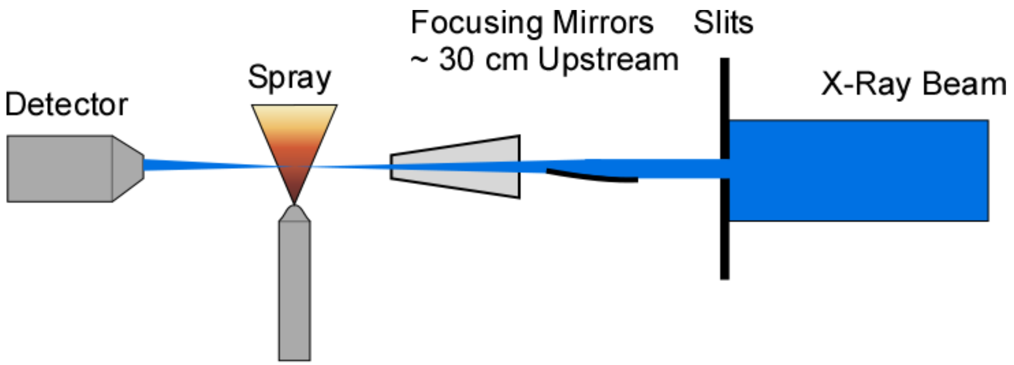
(Note: please include this “separator” slide if you are including back-up technical slides (maximum of five). These back-up technical slides will be available for your presentation and will be included in the DVD and Web PDF files released to the public.)

Experimental Setup

- Combine radiography measurements of spray structure and phase-contrast imaging
- Axial single-hole nozzle, nominally 110 µm diameter
- Bosch Generation 2 injector; same injector as GM 1.9 L engine
- For this work, 700 µs main injection commanded duration, 400 µs post
- Spray into 5 bar N_2 for radiography, 1 bar for phase-contrast imaging







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
- Upgraded x-ray optics in FY2011
  - Allows us to resolve finer structures in spray
    - Old beamline: 150 µm x 14 µm
    - New beamline, 2010: 10 µm x 8 µm
    - New mirrors, 2011: 4 µm x 5 µm
  - 20X more x-ray flux than 2008
    - More precise, faster measurements
    - Can study pure fuels without additive
- DOE has approved APS Upgrade (ca. 2015)
  - APS is currently planning the upgrade roadmap
  - Review committee “Strongly Recommended” that this beamline be upgraded

The Advanced Photon Source
Argonne National Laboratory