Fuel Injection and Spray Research Using X-Ray Diagnostics

Project ID ACE10

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This presentation does not contain any proprietary, confidential, or otherwise restricted information

Overview

Timeline

- Project Start: FY2000

Budget

- FY2010: $830K
- FY2011: $835K

Partners

- Sandia, Engine Combustion Network
- Delphi Diesel, Bosch, Westport, Chrysler

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”

These barriers impact:

- Low-Temperature Combustion
- Thermal Efficiency
- System Cost

Objectives

- **Overall Goals:**
  - ⇨ Serve industry by providing unique injector and spray diagnostics
  - ⇨ Improve the fundamental understanding of fuel injection and sprays
  - ⇨ Assist in development of improved spray models using unique quantitative measurements of sprays

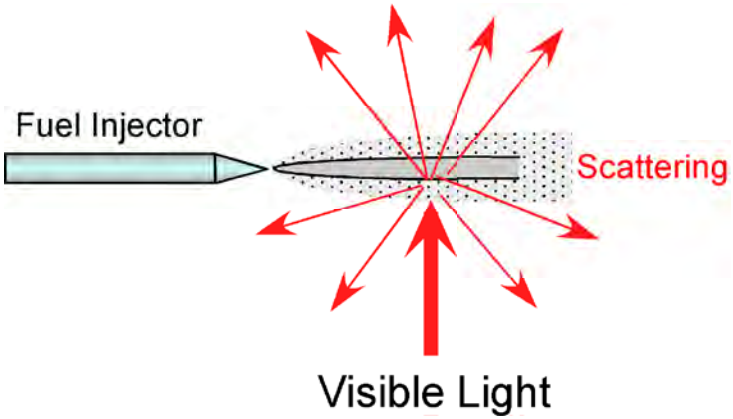
- **FY2011:**
  - ⇨ Complete Vehicle Technologies X-Ray Beamline
  - ⇨ Investigations studying multiple injection
  - ⇨ Experiments supporting Argonne's LTC research on the GM 1.9 platform
  - ⇨ Spray and needle lift measurements for the Engine Combustion Network
  - ⇨ Begin new collaboration with Delphi Diesel

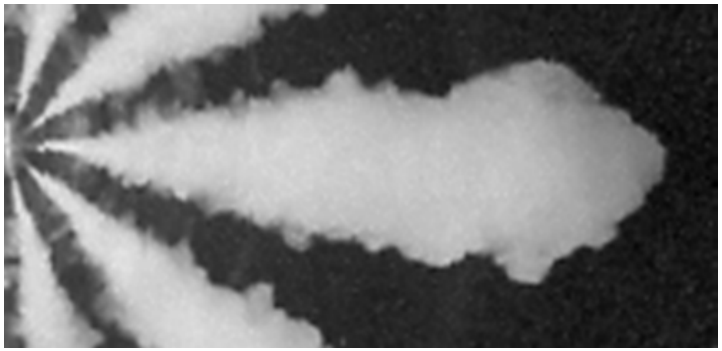
Milestones, 2010 and 2011

- Oct 2010: Complete fabrication of GM 1.9 fuel system
- Nov 2010: Measurements of Main-Post injections
- Feb 2011: Measurements of GM 1.9 sprays
- Feb 2011: Complete hardware upgrades for Engine Combustion Network
- March 2011: Needle lift measurements for Engine Combustion Network
- April 2011: Spray measurements for Engine Combustion Network
- May 2011: Measurements of Westport Natural Gas Injector
- Aug 2011: Cavitation measurements
- Sep 2011: New projects with Delphi Diesel, Chrysler underway

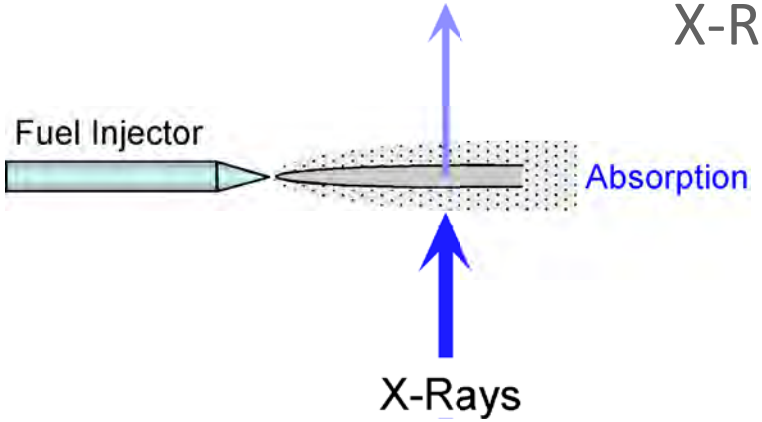
Technical Approach – X-rays Reveal Fundamental Spray Structure

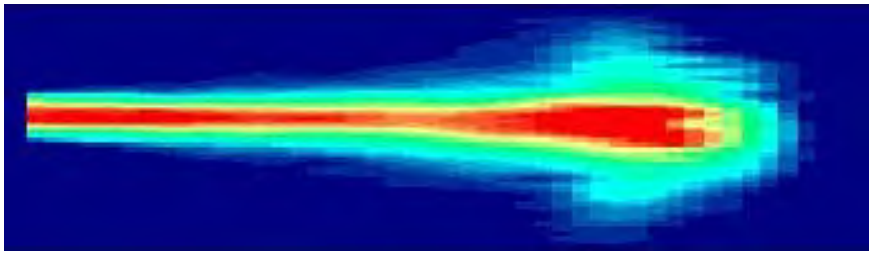
Visible Light Imaging





X-Ray 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 deciding which beamlines will be included in upgrade
  - Review committee "Strongly Recommended" that this beamline be upgraded

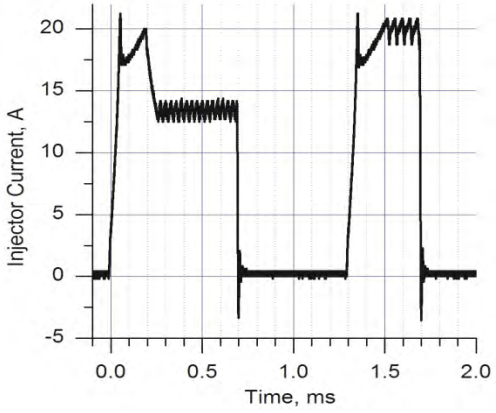
The Advanced Photon Source
Argonne National Laboratory

Measurements of Multiple Injection

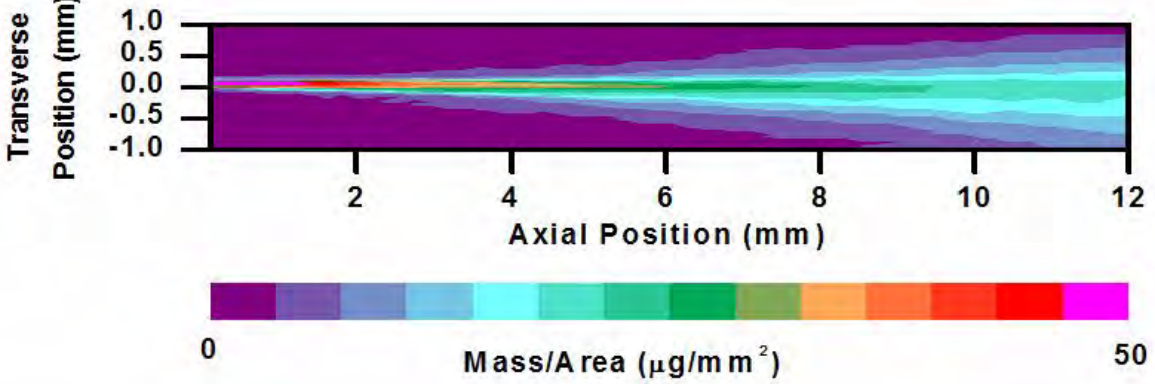
- Major advantage of modern common rail systems is the ability to perform split injection events
  - Pilot injections for noise control
  - Post injections to supply HC for aftertreatment system
- Multiple injections pose a challenge for computational modeling
  - Unknown ambient conditions after the end of the first injection
  - Flows induced by first injection
- Measurements of multiple injections are difficult for optical techniques
  - Scattering from residual droplets obscures second spray
  - There is little experimental work, almost all is focused on long dwell times
  - Recent paper measuring pressure fluctuations predicted significant impact on second spray
- X-ray absorption is not affected by stray droplets, and can clearly resolve two events
- Measurements designed to maximize impact of first spray on second
  - Short dwell between injection events
  - Large volume of fuel in first injection

Sprays Merge at Short Dwell Times

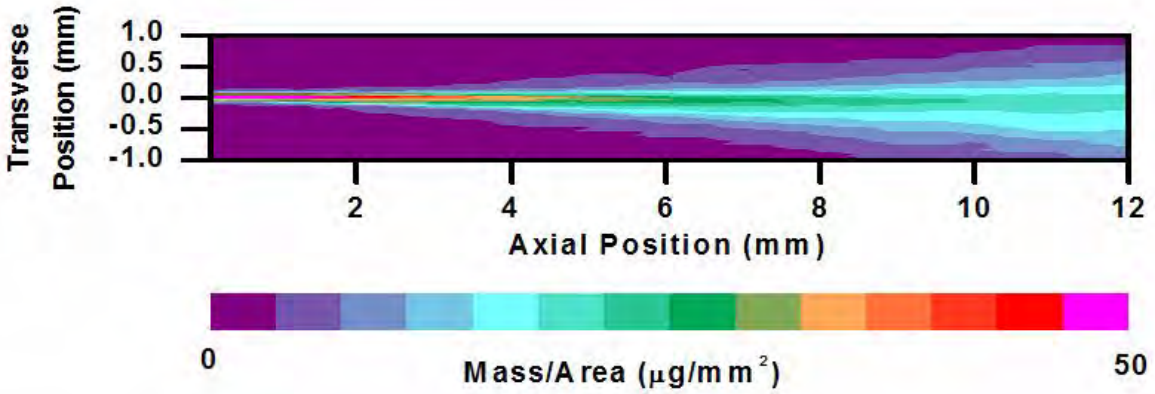
650 µs



1100 bar, 650 µs Dwell

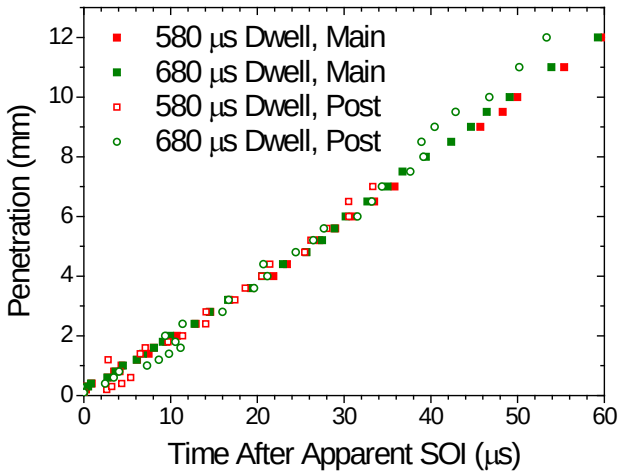


1100 bar, 700 µs Dwell

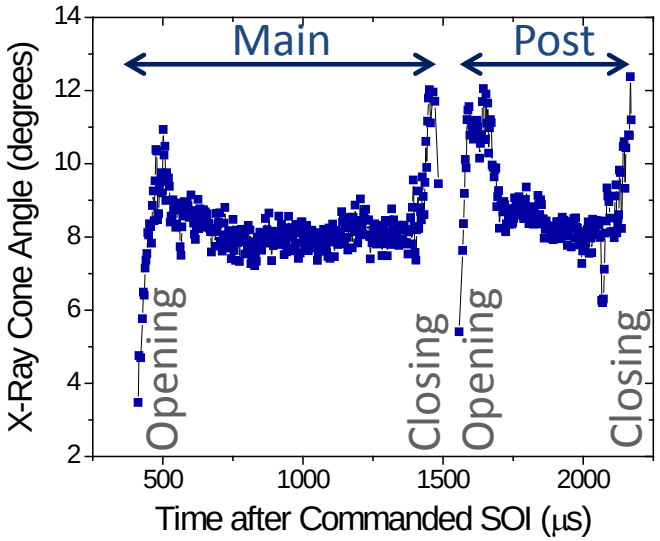


Influence of Main Injection on Post Injection

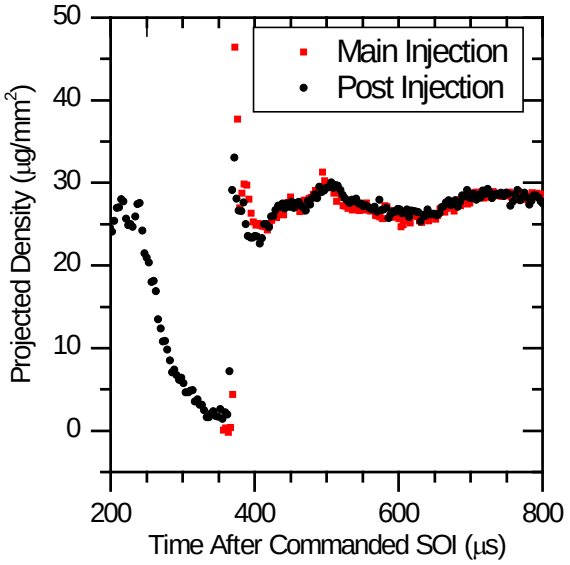
- Does the first injection impact the fuel distribution for the second injection?
- Measure spray penetration, x-ray cone angle, projected density
- Several different rail pressures, dwell times
- For two distinct spray events, the first injection appears to have little influence



660 bar Rail Pressure



660 bar Rail Pressure
700 μs Dwell

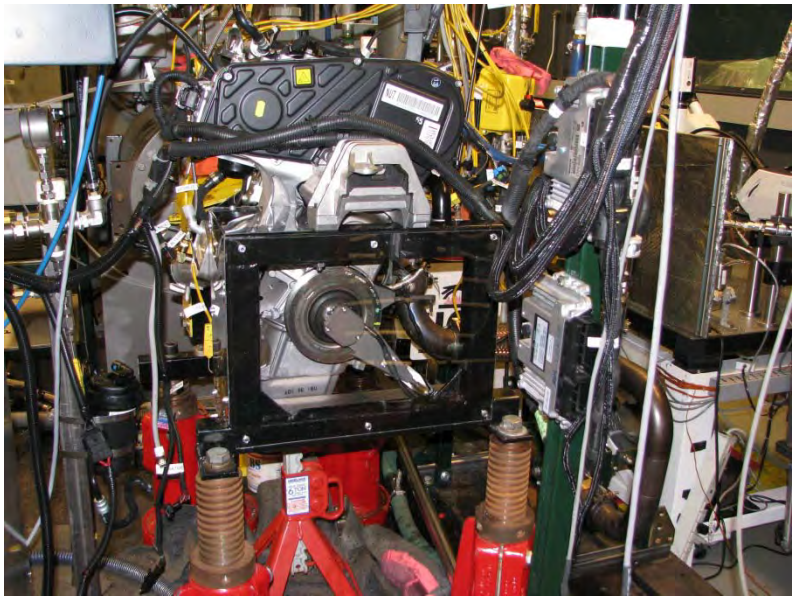


1065 bar Rail Pressure
700 μs Dwell
4.0 mm from Nozzle

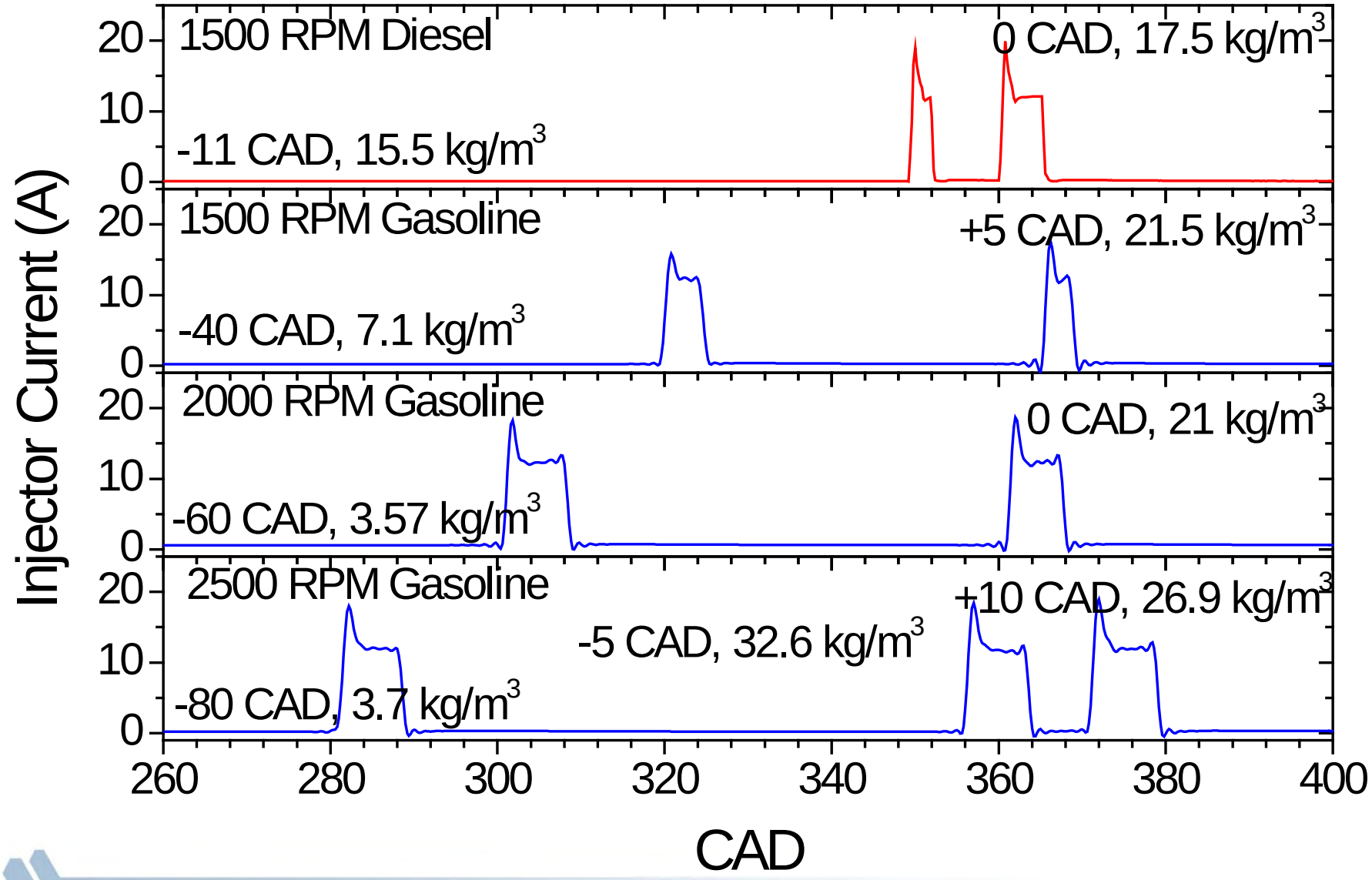
"Correlation of Split-Injection Needle Lift and Spray Structure", Kastengren *et al.*, SAE Congress 2011

Spray Measurements in Support of *Compression Ignition using Low-Cetane Fuels*

- GM 1.9 TDI engine, flexible engine controller
- Advanced combustion strategy:
  - Low-cetane fuels and compression ignition
  - Difficult-to-ignite fuel allows early injection with partial premix
  - Balance of fuel injected at TDC for control of combustion timing
- Endoscopic imaging will be used quantify the envelope of operation (quality of combustion)
- X-ray measurements of the fuel injection
  - Measure the fuel/air mixing
  - Development and validation of computational modeling

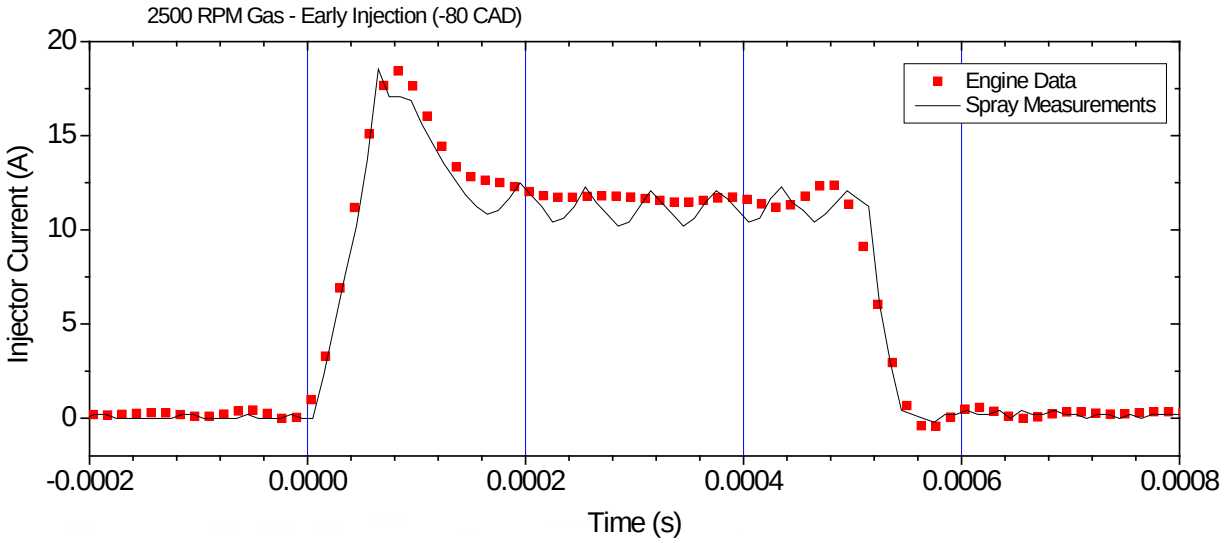


Fuel Injection Strategies Used in GM 1.9 Engine Studies

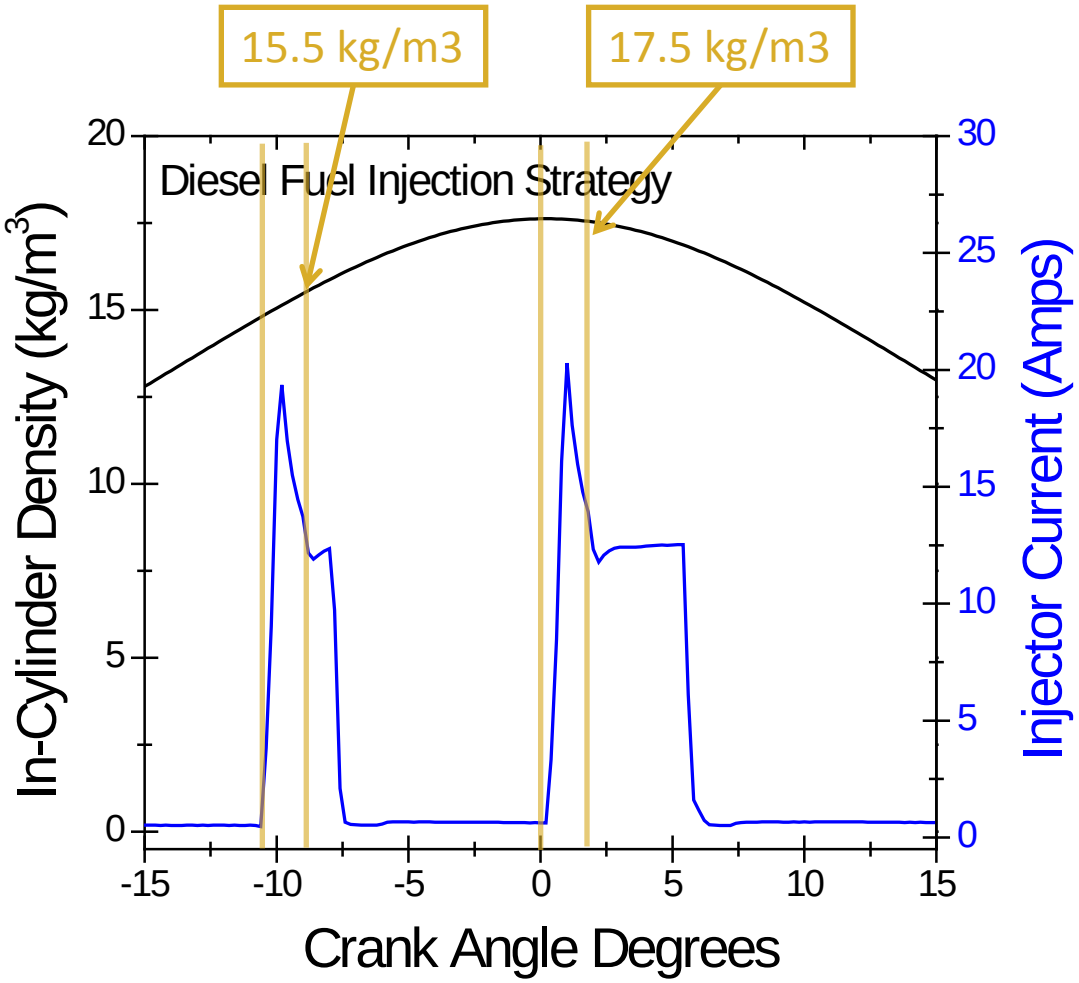


Measurements in Support of Compression Ignition of Low-Cetane Fuel

- To maximize the relevance of the measurements, match engine as closely as possible
  - Identical injector, pump, common rail, fuel lines
  - Similar flexible controller
  - 3-hole injector nozzle, hole geometry matches production 7-hole nozzle
  - Fuel is gasoline-type calibration fluid with lubricity additive (0.05%), no x-ray contrast additive
  - Spray measurement conditions chosen to match typical engine conditions
  - Fueling varies for each engine condition, must match engine measurements



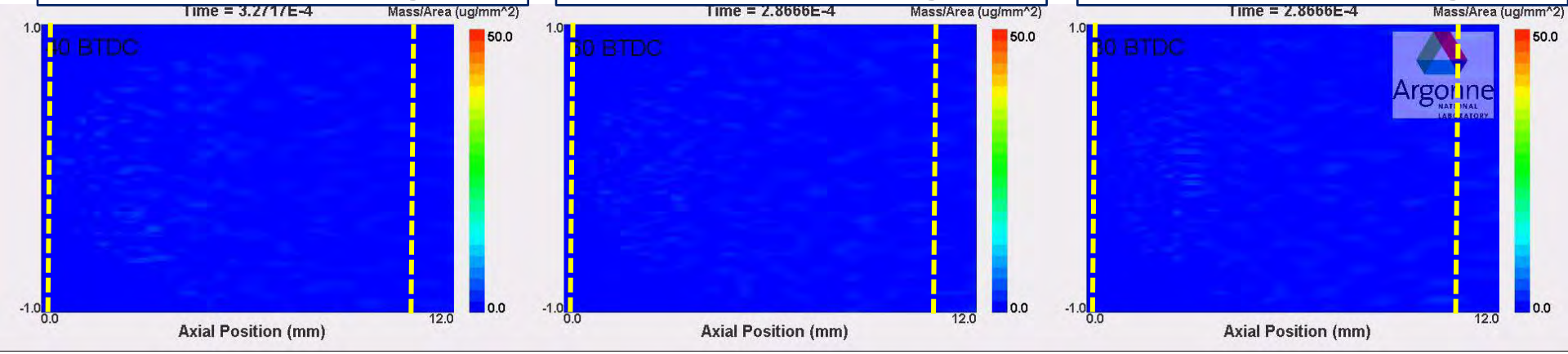
Simulating the In-Cylinder Density in a Static Pressure Chamber

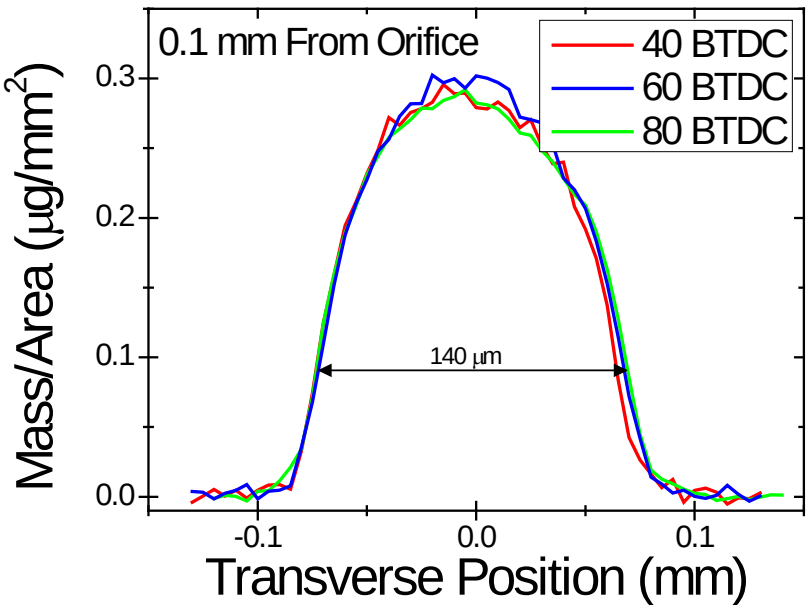


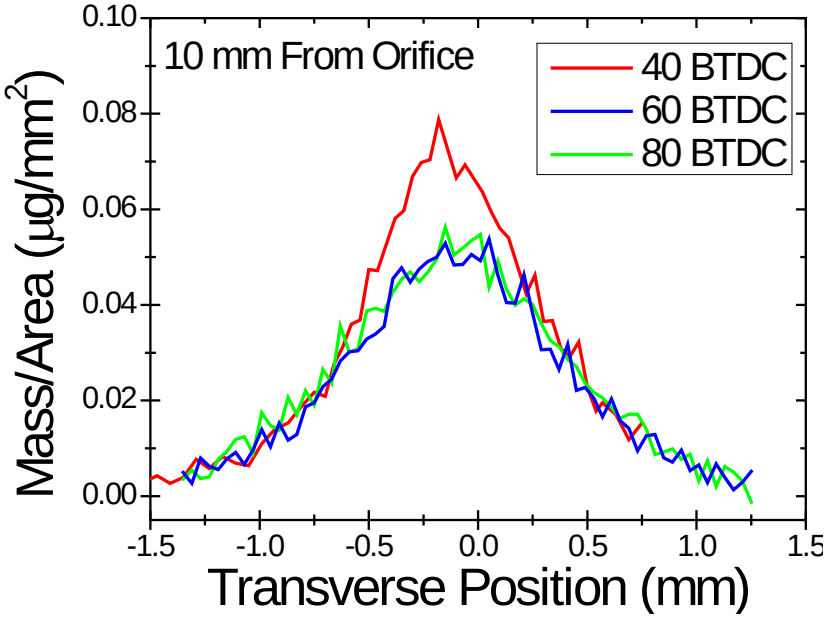
- Ambient density has direct impact on penetration, mixing, etc (more important than ambient pressure)
- In-Cylinder density changes with crank angle
- Must choose a density for measurements in static chamber
- Plot shows electrical signal, fuel emerges 2 CAD later
- Density changes during injection event are neglected

Gasoline Injection at three Engine Operating Points

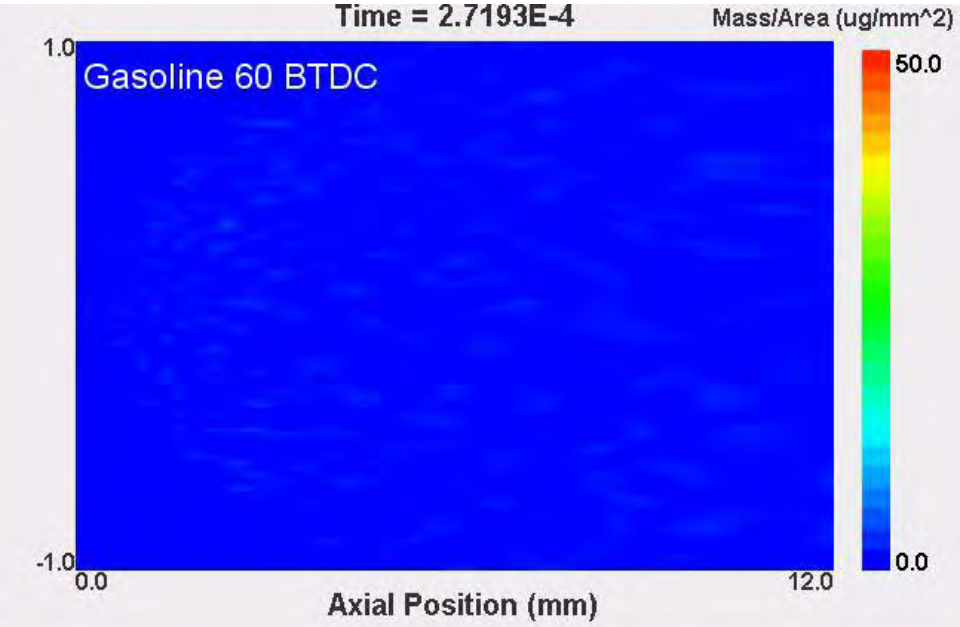
40 BTDC	7.1 kg/m^3	60 BTDC	3.6 kg/m^3	80 BTDC	3.7 kg/m^3

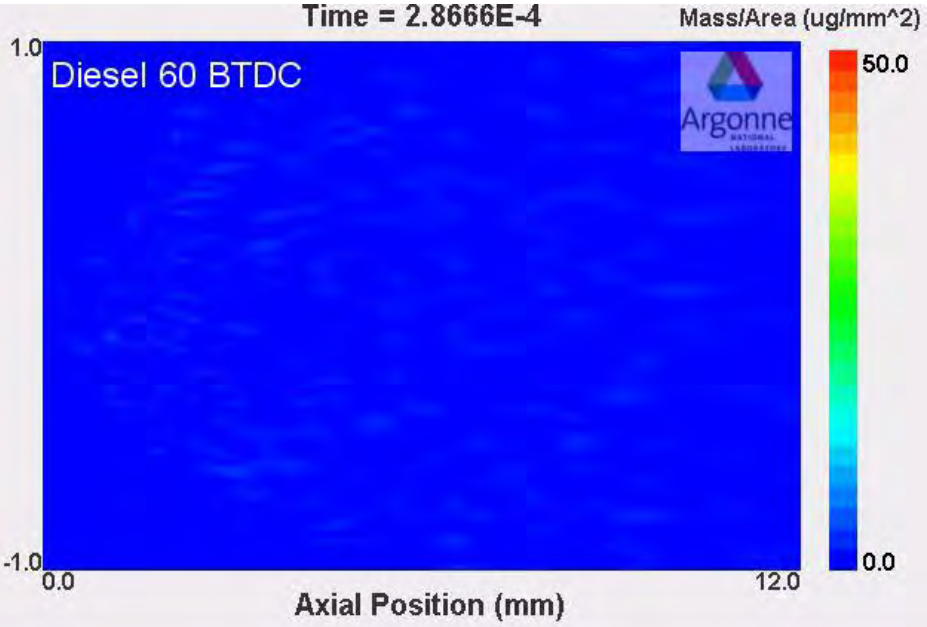


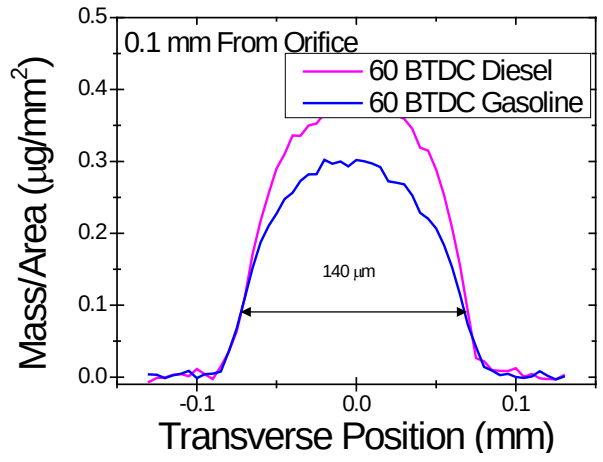


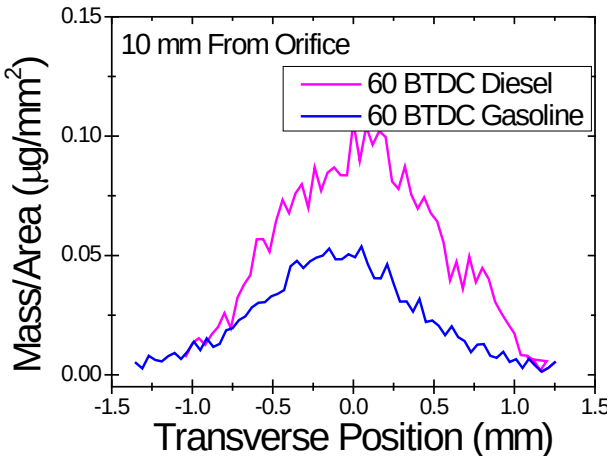


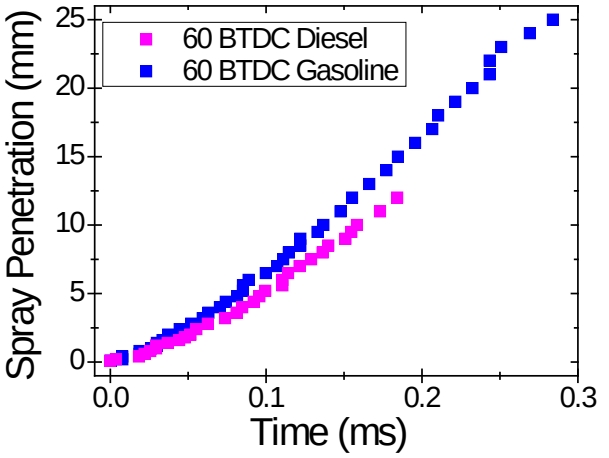
Comparison of Diesel and Gasoline Type Fuels Under Identical Conditions







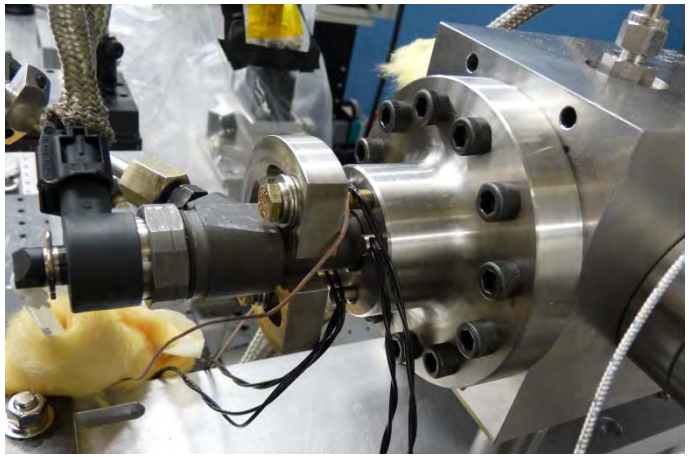




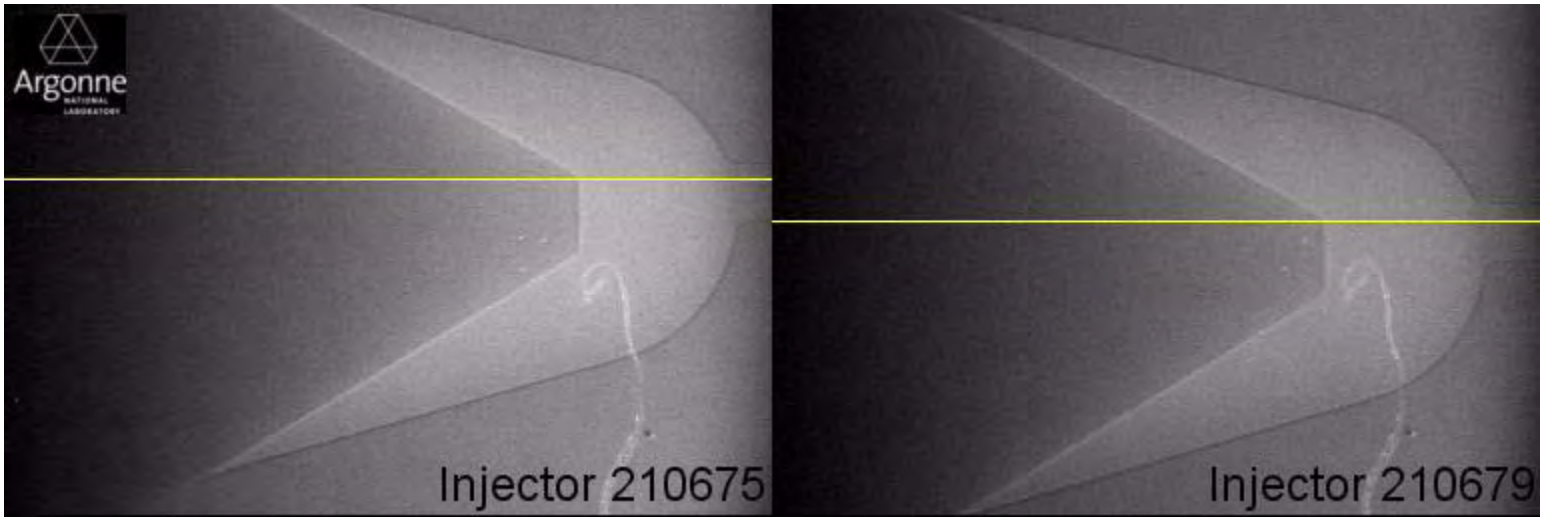
"Correlation of Diesel Spray Structure to LTC Engine Combustion", A. L. Kastengren *et al.*, ASME-ICE Fall Technical Conference, September 2011.

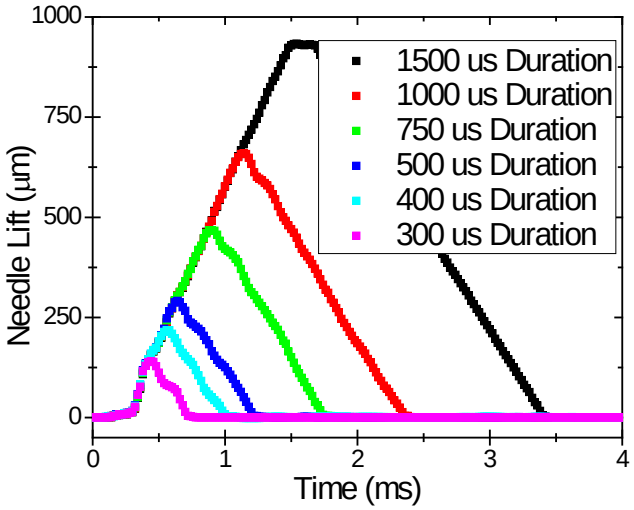
Measurements in Support of Sandia's Engine Combustion Network

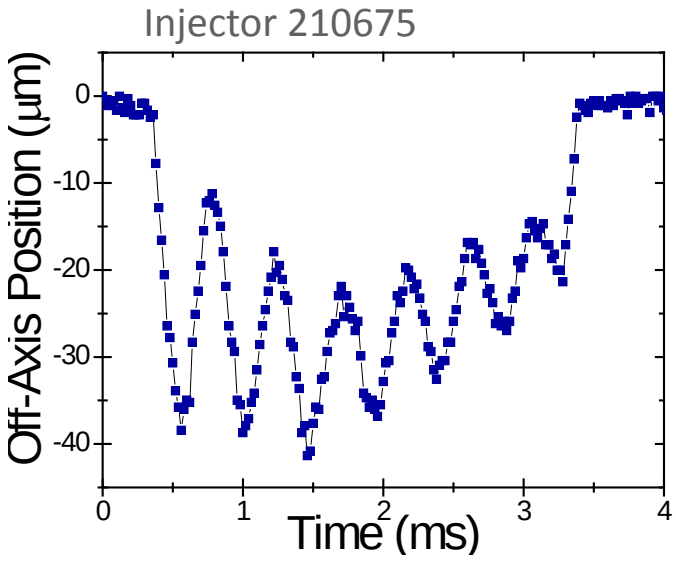
- Collaboration of 12 leading spray and combustion groups worldwide
- All groups studying same "Spray A" operating condition
  - Common injection hardware
  - Well-defined fuel, pressure, temperatures, ambient density, etc
- Data will be shared with partners, modeling groups worldwide
- Argonne will contribute x-ray measurements of spray and needle motion
  - Needle lift defines initial conditions for modeling
  - Spray measurements for validation
- Required significant hardware improvements
  - 1500 bar Injection pressure
  - Heated injector mount and spray chamber
  - Measurements of needle lift under pressurized conditions



High-Speed X-Ray Imaging of ECN Single-Hole Nozzles







- Injectors are nominally Identical, but needle motion is different
- Imaging completed for three of the 10 ECN injectors. (two single, one three-hole)
- Corresponding Spray measurements in April 2011

Future Work in FY2011 and FY2012

- Additional work on GM 1.9 Hardware
  - Additional engine conditions as needed
  - Measurements with new spray nozzles
  - Comparisons of spray data with in-cylinder visualizations
  - Data used for spray/engine model validation
- Further experiments with Engine Combustion Network
  - Spray radiography measurements of nozzles currently at Argonne
  - Needle lift measurements of other injectors/nozzles sent by ECN partners
  - Needle lift and spray data provided to computational modelers
- Cavitation in a model nozzle
  - Proof-of-concept measurements of a scaled-up nozzle
  - Visiting Fulbright Scholar from Monash University in Australia
  - Unique, quantitative measurements of cavitation
  - Couple with cavitation modeling performed at Argonne
- Projects with industrial partners
  - Delphi Diesel – studies of injector geometry
  - Westport Innovations – image internal components of gas injectors
  - Chrysler – spray imaging to support advanced combustion engine, includes GDI sprays

Summary

- X-Ray diagnostics are being used to address a range of research challenges
  - Studying sprays under engine-relevant conditions
  - Providing data for spray model development and validation
  - Understanding the fundamentals of atomization
  - Provide a diagnostic for industrial partners

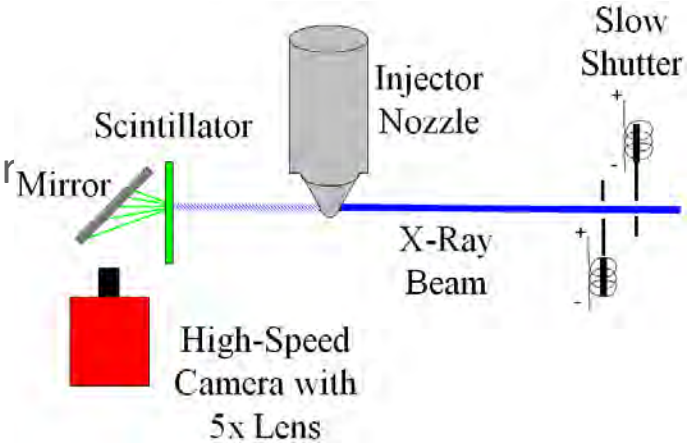
- New experiment station dedicated to our research will make these measurements easier and available to a wider group of collaborators

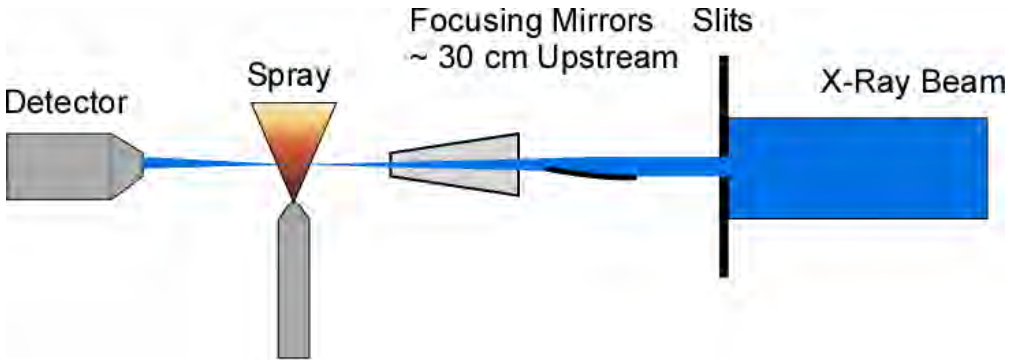
Technical Back-Up Slides

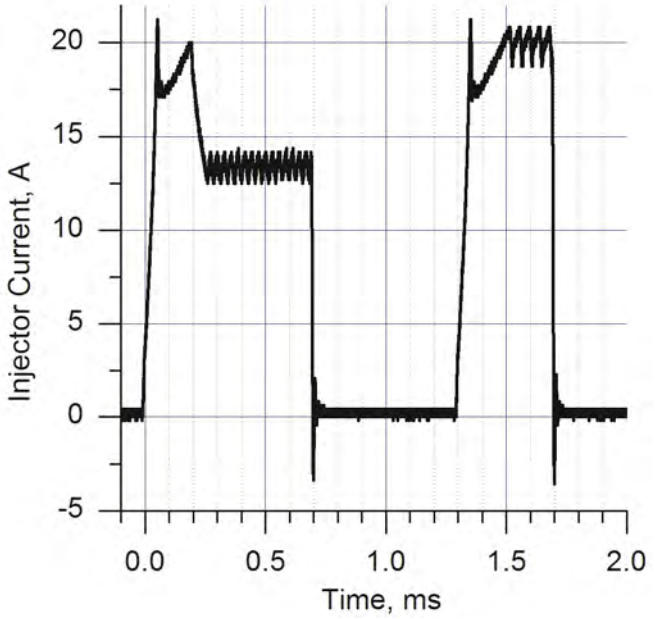
(Note: please include this “separator” slide if you are including back-up technical slides (maximum of five). These back-up technical slides will be available for your presentation and will be included in the DVD and Web PDF files released to the public.)

Experimental Setup

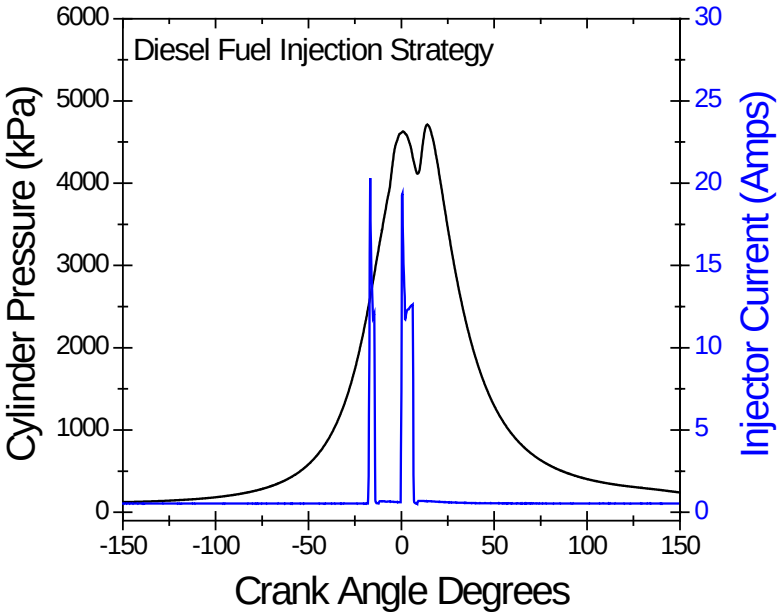
- Combine radiography measurements of spray structure and phase-contrast imaging
- Axial single-hole nozzle, nominally 110 µm diameter
- Bosch Generation 2 injector; same injector as GM 1.9 L engine
- For this work, 700 µs main injection commanded duration, 400 µs post
- Spray into 5 bar N_2 for radiography,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

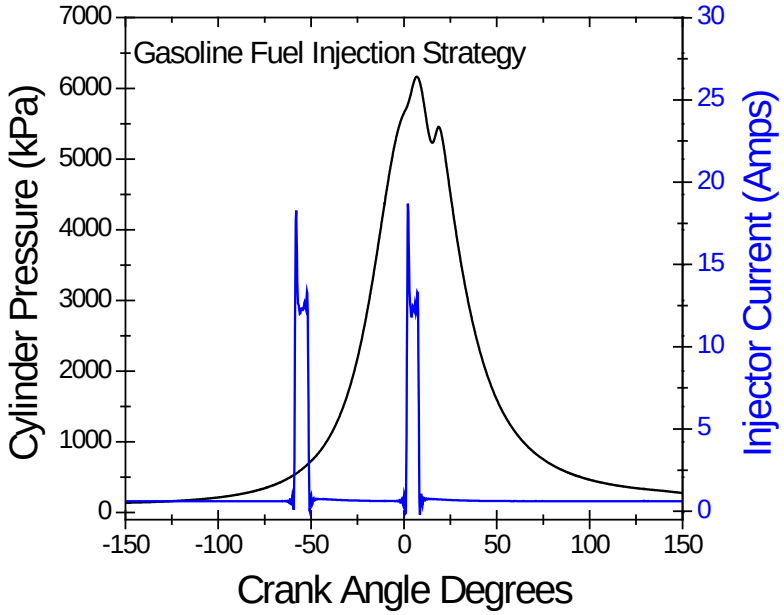






Injection Strategies Being Studied





	Early Injection		Main Injection	
Stock Diesel Strategy	-11 CAD	15.5 kg/m^3	0 CAD	17.5 kg/m^3

	Early Injection		Main Injection	
Compression Ignition Gasoline Strategies	-40 CAD	2.2 kg/m^3	0 CAD	19.8 kg/m^3
	-60	4	0	19.8
	-80	7.6	0	19.8

Gasoline Injection at three Engine Operating Points

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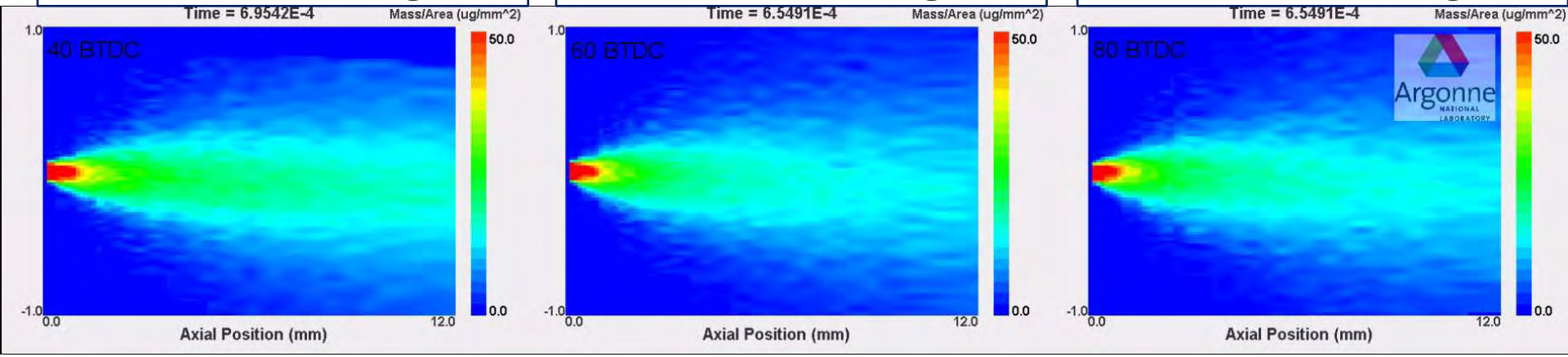

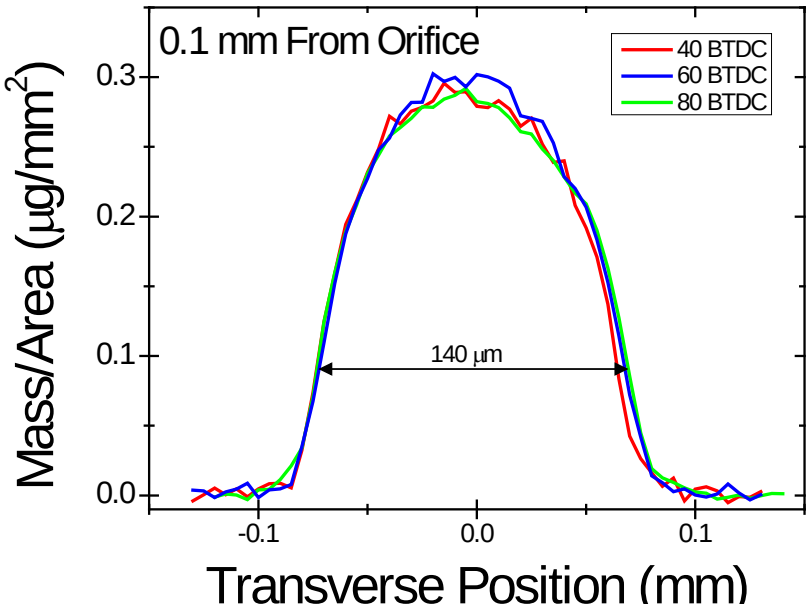

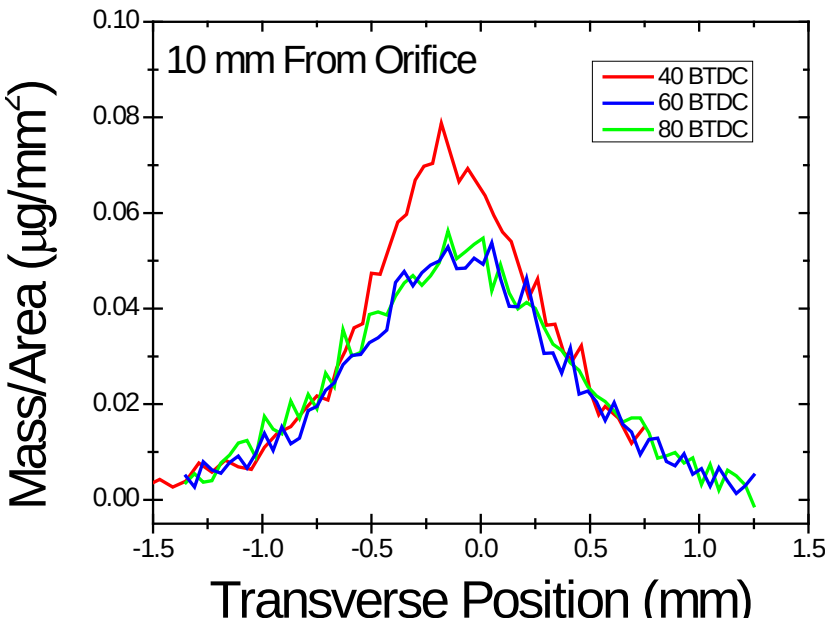

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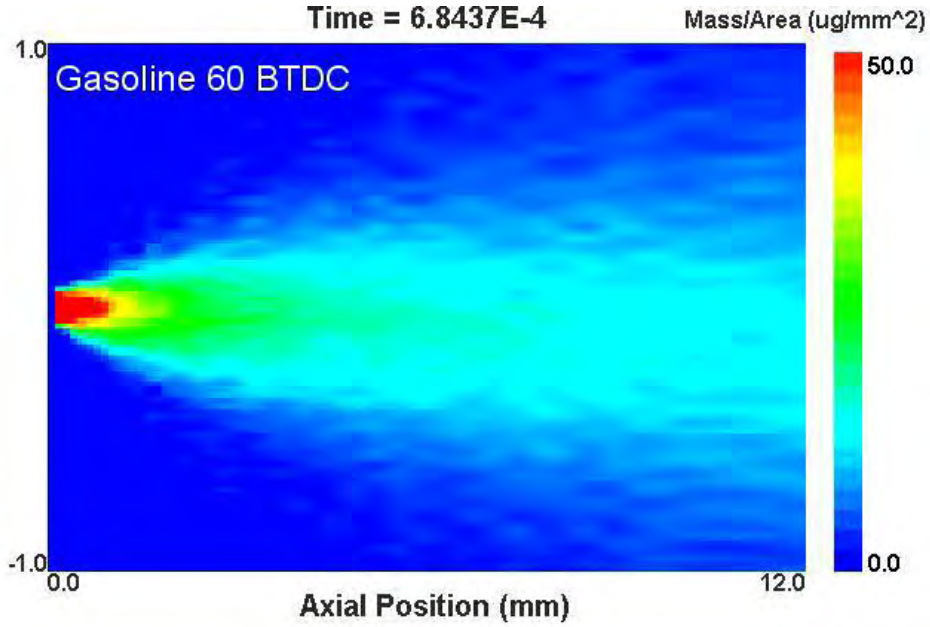

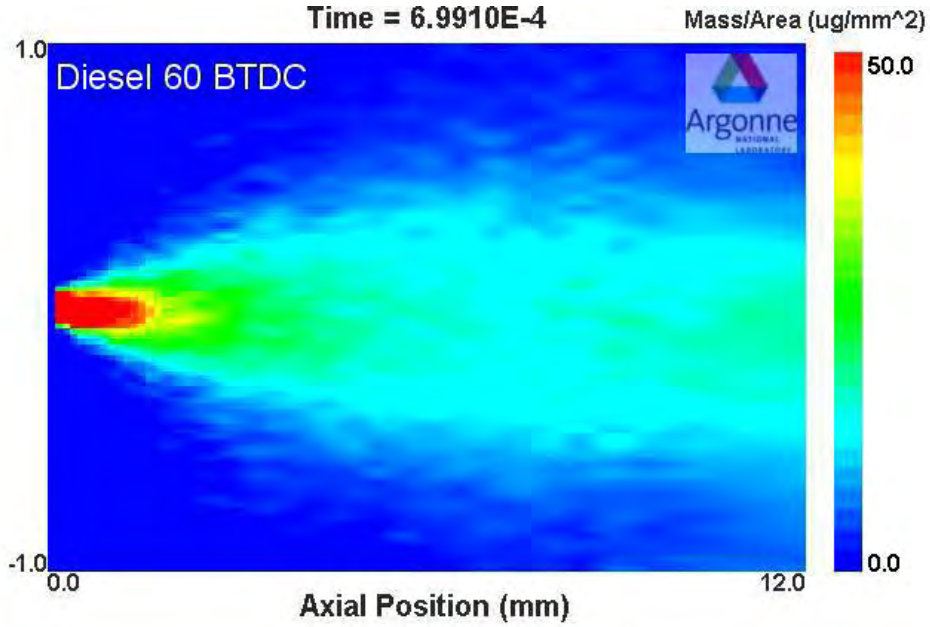

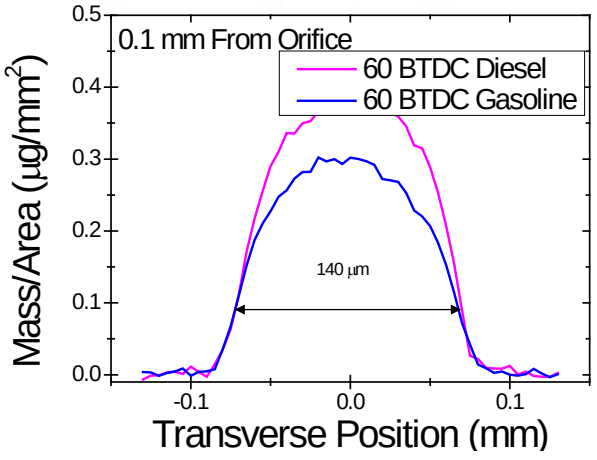

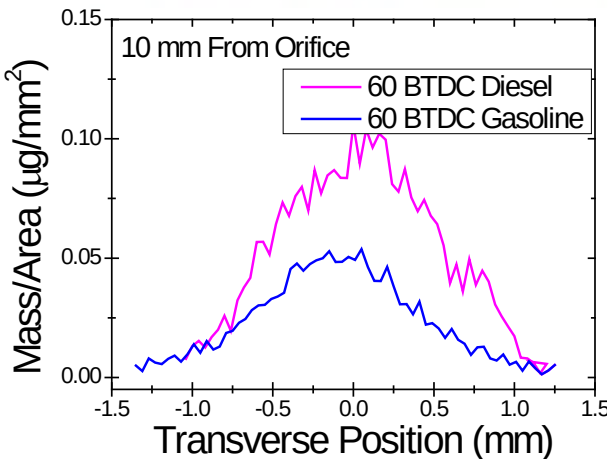

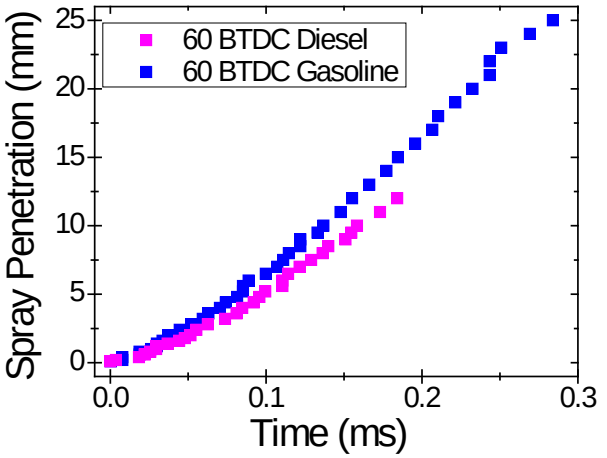

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