Fuel Spray Research on Light-Duty Injection Systems

Project ID ACE10

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Overview

Timeline

- Project Start: FY2000

Budget

- Lifetime Project Funding
  - $4M Since FY05
- Recent Funding
  - FY2009: $645K
  - FY2010: $835K

Partners

- Bosch, ERC
- Sandia, Delphi

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

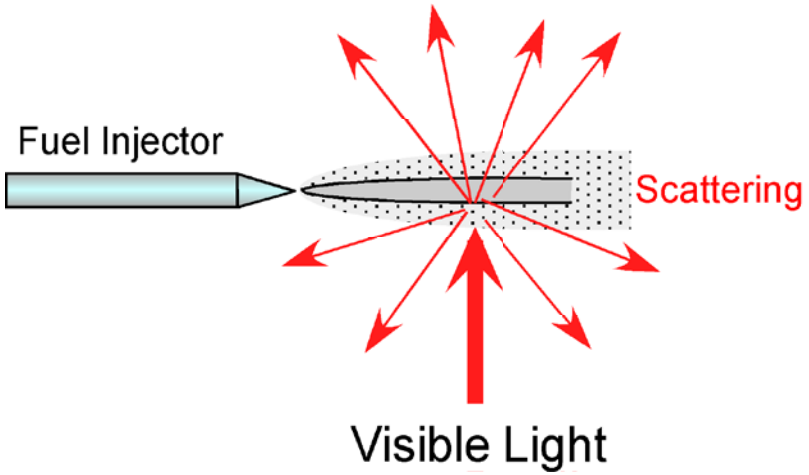
- **Overall Goals:**
  - ⇨Serve industry by providing unique injector and spray diagnostics
  - ⇨Assist in development of improved spray models using unique quantitative measurements of sprays
- **FY2010:**
  - ⇨Complete Vehicle Technologies X-Ray Beamline
  - ⇨Investigations of end of injection using Sandia nozzles
    - ⇨Test Musculus' entrainment wave hypothesis
    - ⇨Poorly atomized fuel at end of injection
  - ⇨Fabricate new components for tests of GM 1.9, Delphi Diesel, and Engine Combustion Network.
  - ⇨Begin new collaboration with Delphi Diesel
  - ⇨Analysis and publication of data from ERC collaboration

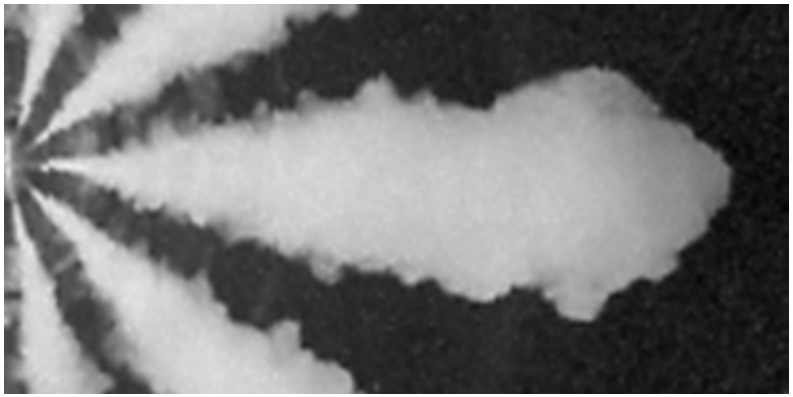
Milestones, FY2009 and FY2010

- Sep 2009: Measurements of End of Injection Effects
- June 2010: Complete fabrication of GM 1.9 fuel system
- July 2010: Measurements of GM 1.9 sprays
- Sep 2010: Measurements in support of Engine Combustion Network
- Sep 2010: Vehicle Technologies X-Ray Beamline opens to General User Proposals

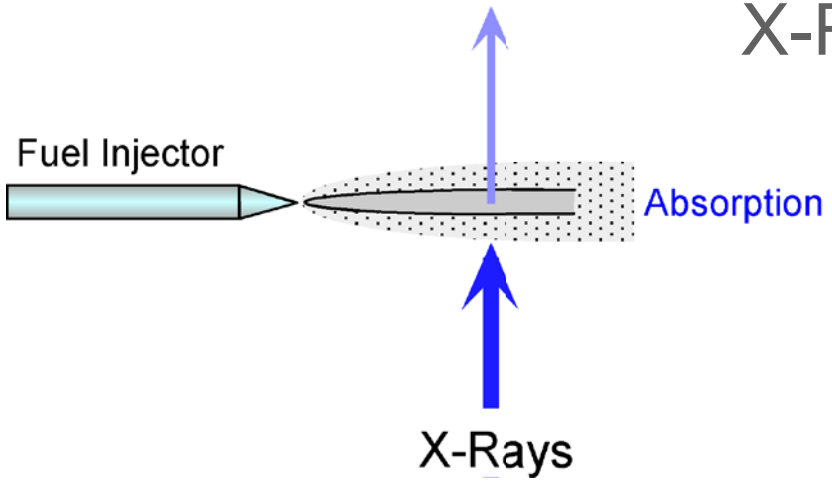
Technical Approach – X-rays Reveal Fundamental Spray Structure

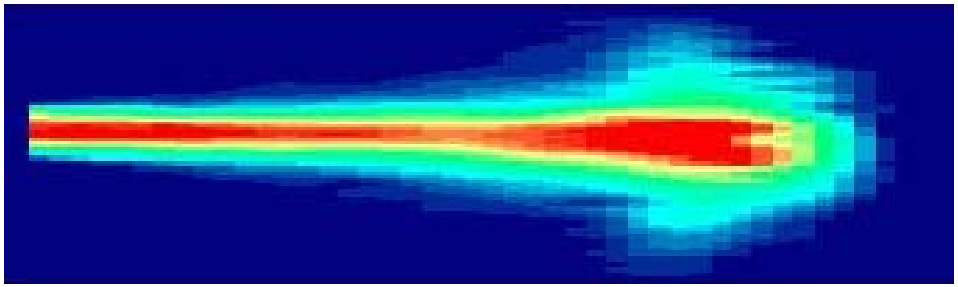
Visible Light Imaging





X-Ray Imaging





Vehicle Technologies X-Ray Beamline

- Previous experiments were done under a competitive proposal system
- Allowed 6 weeks of experiments per year
- New experimental station is dedicated to vehicle technologies, primarily fuel sprays
- 50% of the construction costs paid by BES.
- 100% of operations, maintenance, two postdocs and one staff paid by BES

⇒**Dedicated space**

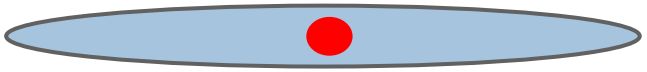
⇒**Guaranteed access to x-ray beam at no cost to project**

⇒**More time available for measurements**

⇒**Expansion of collaborations**

New Beamline Offers Significant Improvements

- Better instrumentation
  - Better control of photon wavelength and flux
  - Equipment is tailored to our needs, rather than general-purpose
- Better beam optics give better spatial resolution
  - Previously, 150 µm horizontal x 14 µm vertical
  - New beamline: 10 µm horizontal x 8 µm vertical
  - No decrease in flux
  - Better resolution of spray structure, particularly for small nozzles



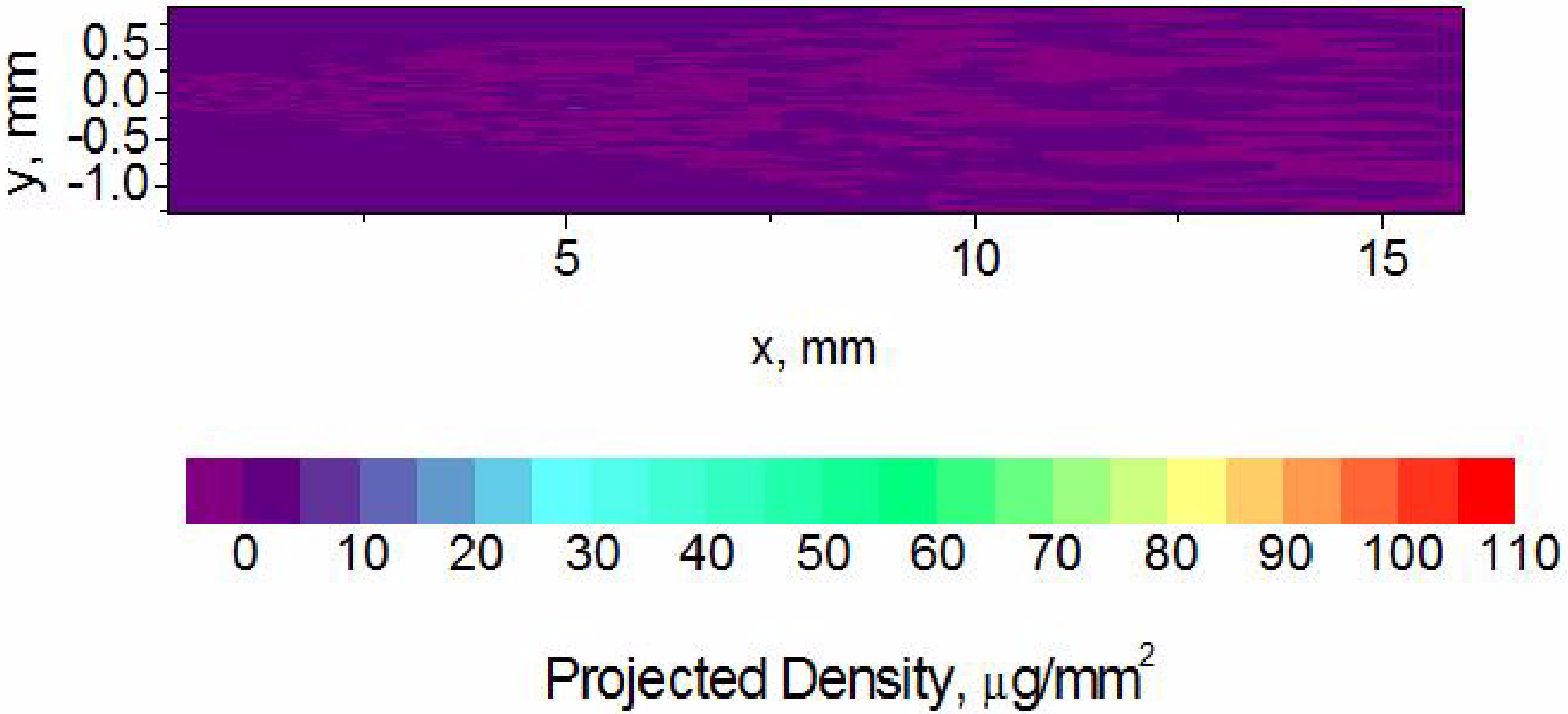
- Guaranteed access
  - Can leave equipment largely in place
  - More time to perform experiments, expansion of collaborations
  - Time to work on development: new x-ray diagnostics, new applications
- Upcoming improvements
  - New focusing mirror will increase flux by order of magnitude (June 2010)
  - New detector system and DAQ will speed measurements (July 2010)
  - Beamline open to General User Proposals (September 2010)

Investigations of End of Injection Phenomena

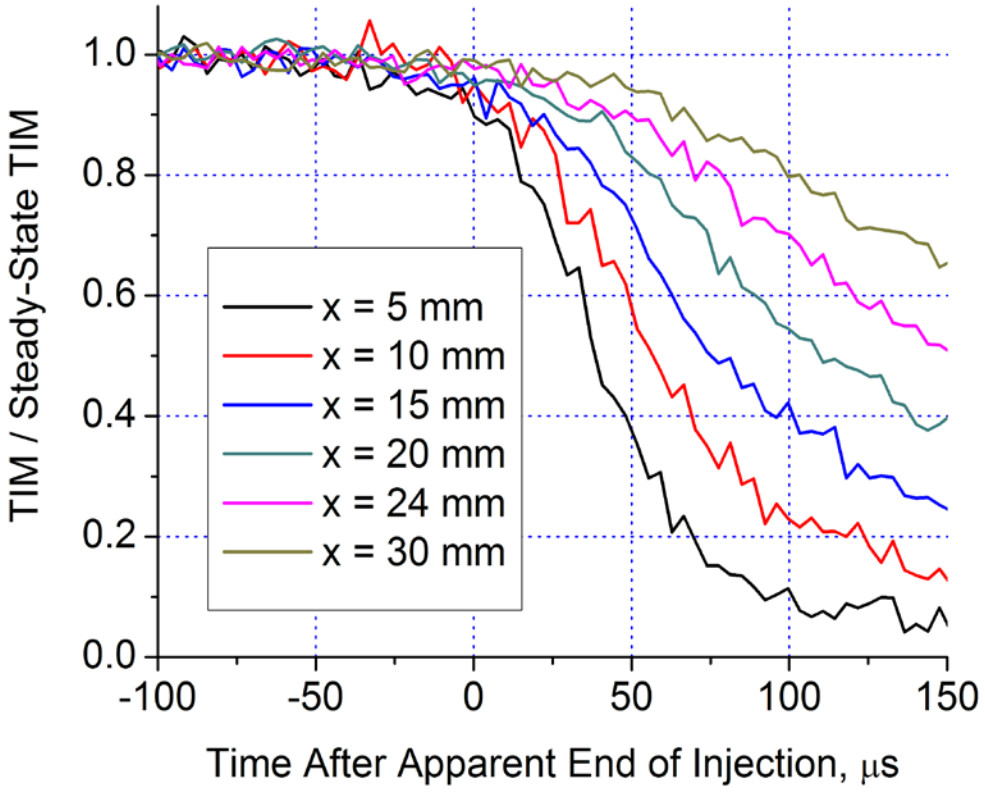
- Recent papers by Musculus *et al.* suggest very rapid mixing at end of injection
  - "Entrainment Wave" travels downstream very quickly after EOI
  - Can lead to overly lean mixtures and UHC's
  - Might be used to advantage
- X-ray radiography can observe the end of injection without interference from fog of droplets
  - Measure changes in density at EOI
  - Measure propagation speed

"Entrainment waves in decelerating transient turbulent jets", M. P. B. Musculus, Journal of Fluid Mechanics 638, pp. 117-140, 2009.

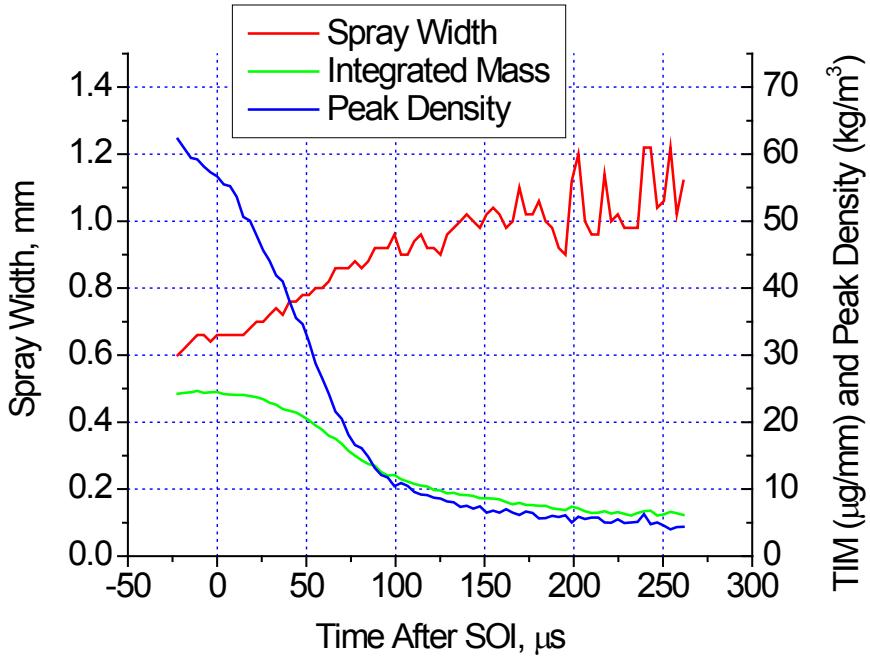
Spray Distribution, 110 µm Diameter Nozzle
700 bar Rail Pressure, 1200 µs Duration



X-Ray Measurements of the End of Injection



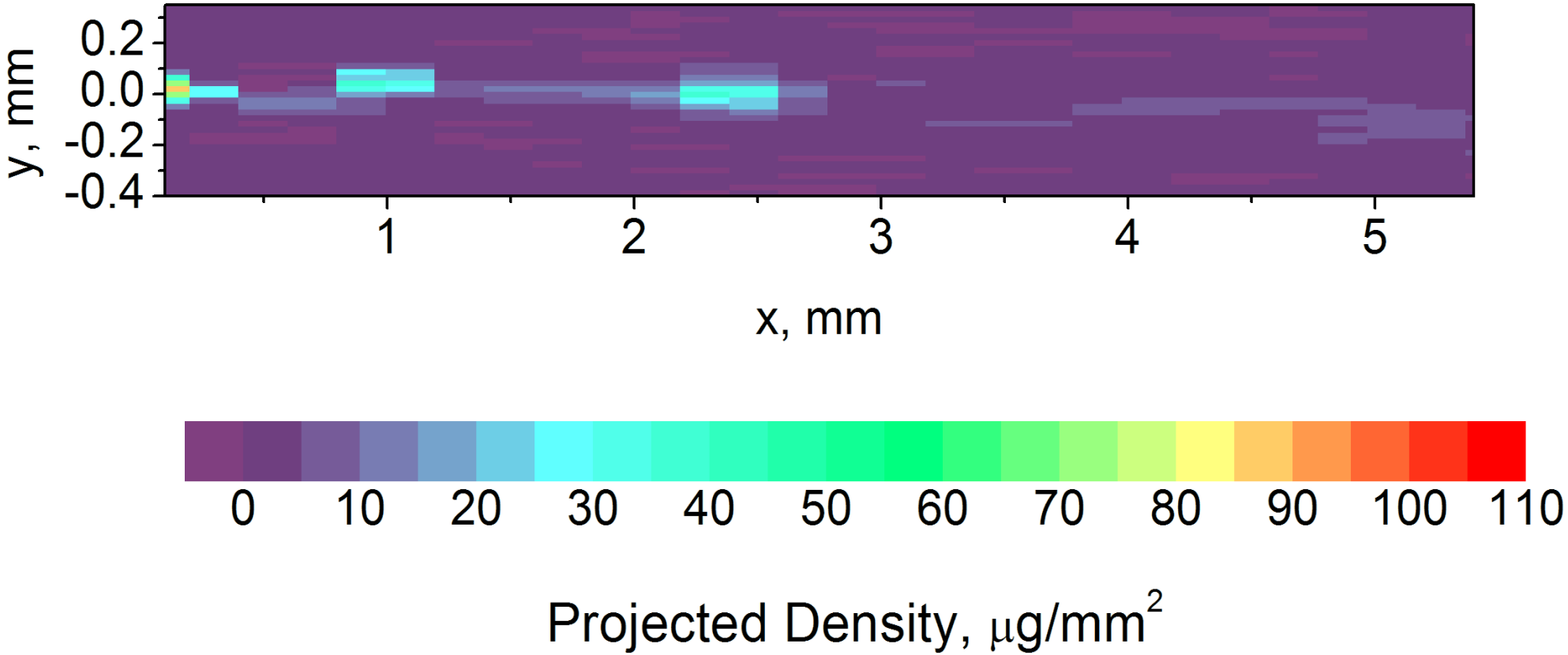
Decrease in mass propagates at 380 m/s



- Spray width increases significantly near EOI
- This combines with decrease in mass to cause *very* rapid drop in density

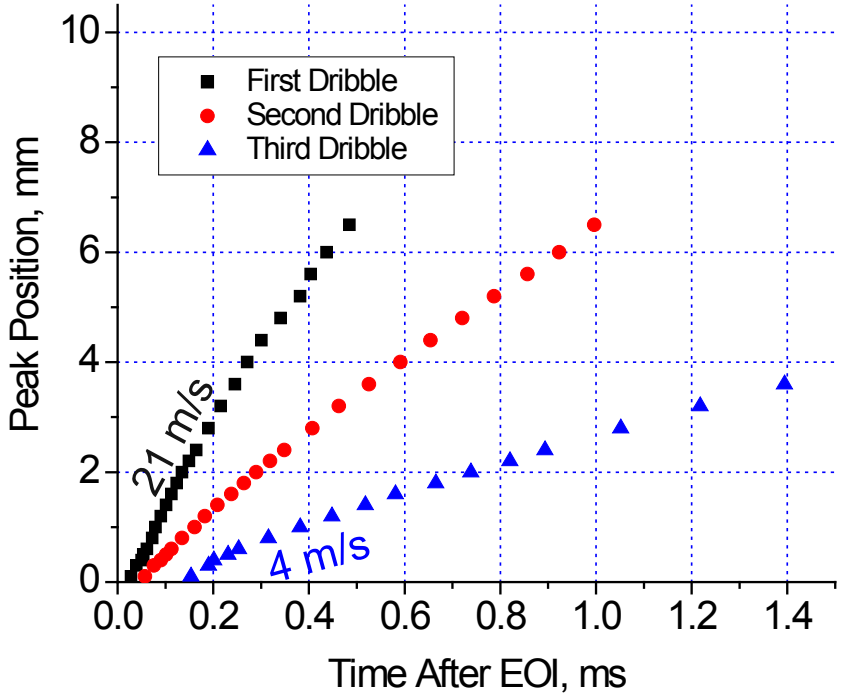
End-of-Injection Behavior of Diesel Sprays Measured with X-Ray Radiography, Kastengren *et al*, ASME-ICEF2010-35052

“Dribble” of Fuel at End of Injection

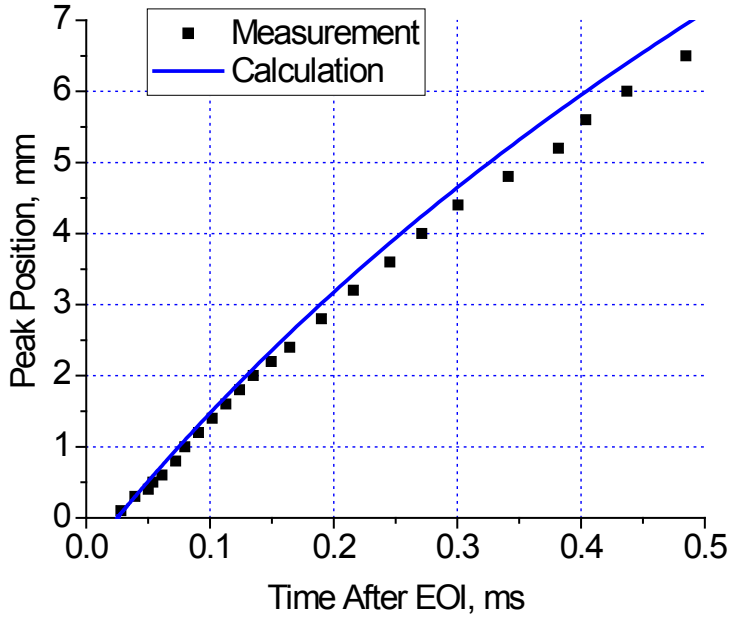


- Improvements to spatial resolution make measurement possible
- Incredibly reproducible

Tracking Fuel Parcels After End of Injection



- Parcels can be tracked to measure their speed
- Density can be used to calculate their size: All are approximately equal to nozzle diameter
- Rate of deceleration will depend on motion of ambient gas
  - Consistent with stagnant environment

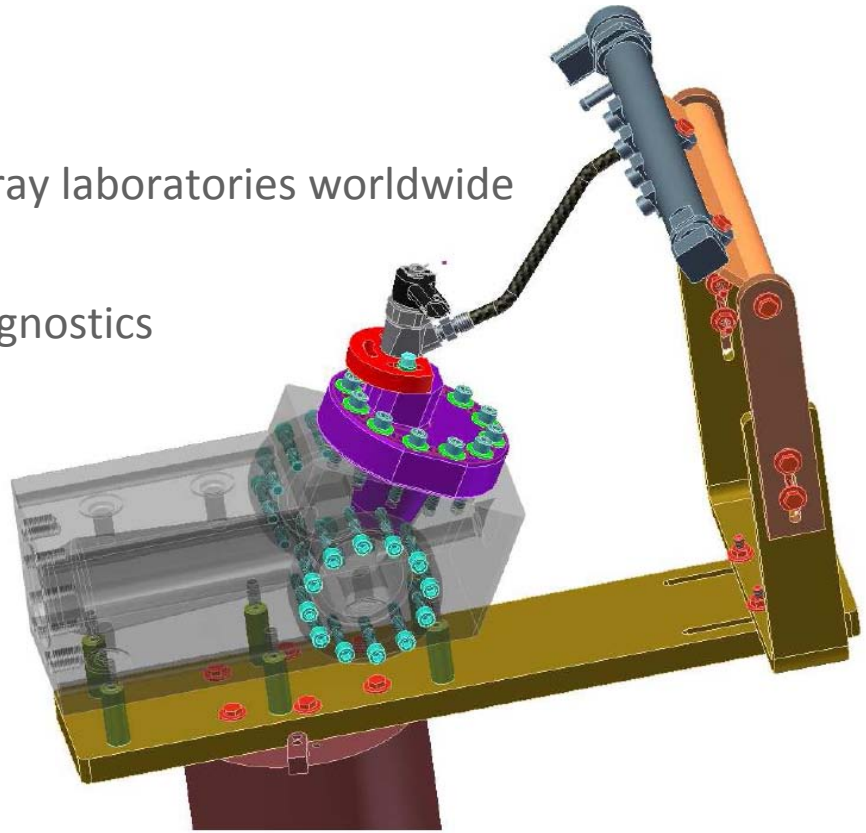


- These parcels are important!
  - Likely to contribute to soot or UHC's
  - UHC's are a target for tighter regulation
- Source of these parcels:
  - Emptying of sac?
  - Needle bounce?

Fabrication of Components for Future Tests: GM 1.9 and Engine Combustion Network

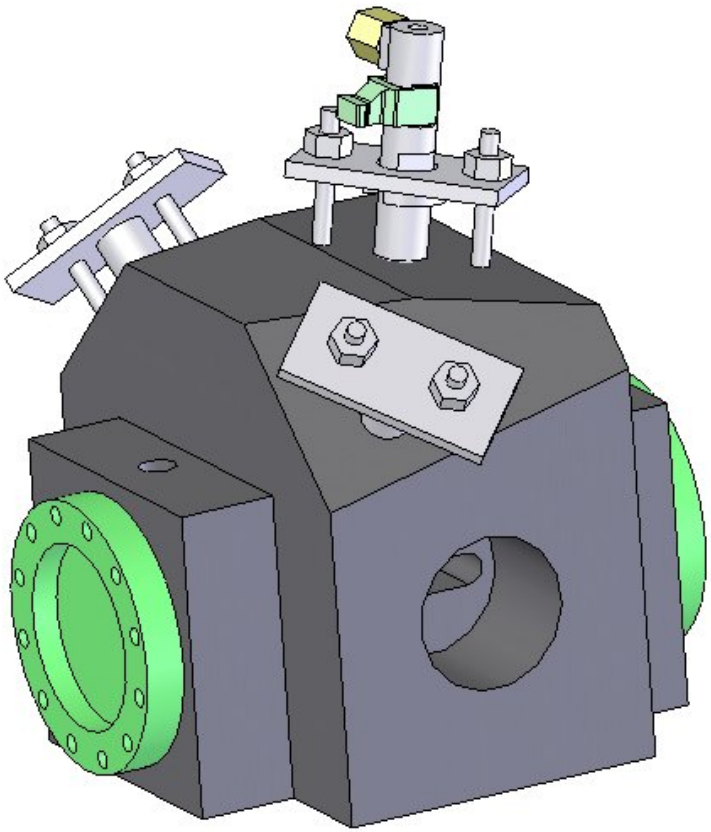
- GM 1.9
  - July 2010: study sprays using hardware, fuel, and conditions matching Ciatti's low-temperature combustion strategies in GM 1.9
  - New injector driver is being tested, all hardware is in-house
  - Will allow us to combine x-ray measurements with in-cylinder imaging, engine performance and emissions data

- Engine Combustion Network
  - Collaboration led by Sandia involving ten spray laboratories worldwide
  - Identical hardware and conditions studied
  - Argonne will contribute full suite of x-ray diagnostics
  - Results freely shared with modeling groups



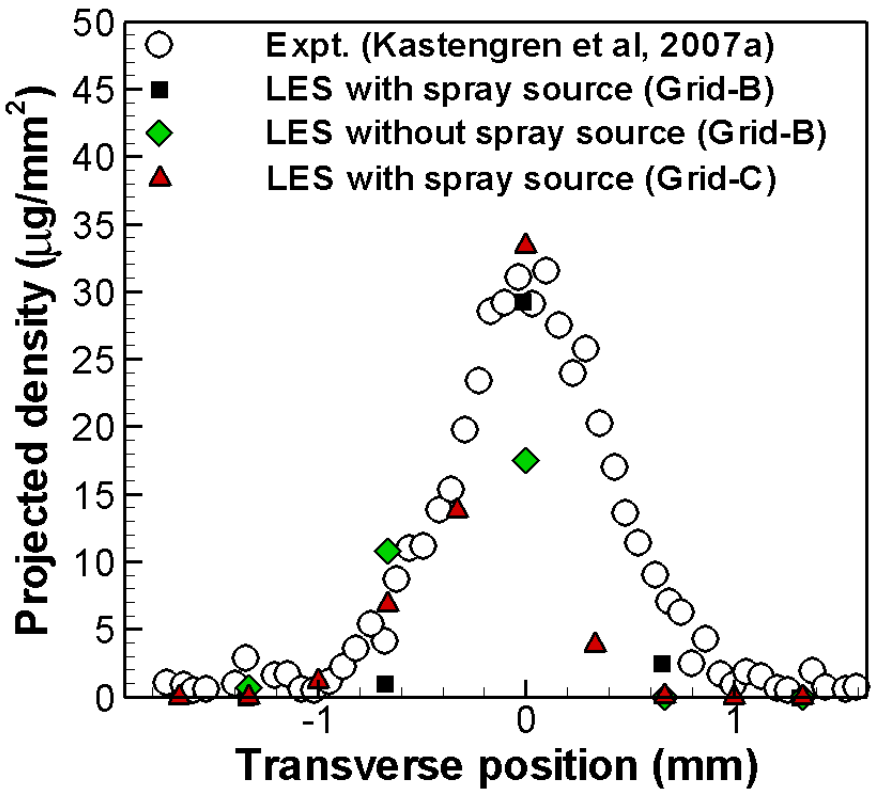
New Collaboration: Delphi Diesel

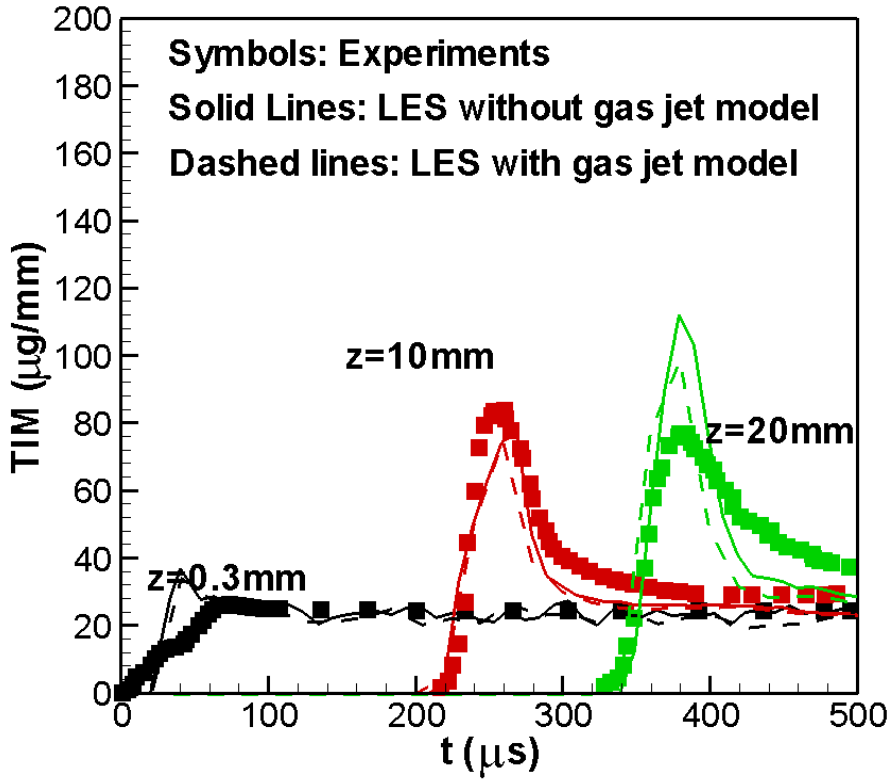
- Delphi wishes to understand the effect that nozzle geometry has on spray structure
  - Improve injector and nozzle designs
  - Improve computational spray models
- Delphi will fabricate custom spray nozzles with various geometries
- Argonne will use its full suite of injector and spray diagnostics:
  - High speed X-ray imaging of the injector components
  - X-ray radiography to measure fuel distribution
  - Ultra fast spray imaging for studying spray structure
- Status:
  - Hardware to be tested has been chosen, is being gathered
  - Spray chamber is being designed (multi-hole, multi-angle, multi-view)
  - Contract (CRADA) is being negotiated



X-Ray Data Used for Development of KIVA LES

- Nidheesh Bharadwaj spent six weeks at Argonne in May 2009
- Collaboration between Sandia, Wisconsin, and Argonne
- X-ray measurements used for development and validation of LES turbulence models incorporated into KIVA





"Droplet-ambient sub-grid interaction modeling in large eddy simulation of diesel sprays", Bharadwaj and Rutland, ILASS 2010

Collaboration and Coordination with Other Institutions

- **University of Wisconsin Engine Research Center**
  - Joint measurements, used x-ray data for modeling, publication
- **Sandia National Laboratory**
  - Measurements of their nozzles, comparison with combustion chamber data
  - Upcoming work with Engine Combustion Network
- **Delphi Diesel**
  - New collaboration this year, currently negotiating CRADA
- **Chrysler**
  - New collaboration later this year
  - Funded by ARRA
  - Statement of Work is complete, Chrysler currently negotiating with DOE

Future Work in FY2010 and FY2011

- Strengthen ties between spray experiments and engine experiments
  - Measurements supporting Argonne's work on GM 1.9
  - Match hardware, fuel, engine conditions
  - Comprehensive view of sprays, combustion, engine performance
- Experiments supporting Sandia's Engine Combustion Network
  - Argonne will provide x-ray measurements of spray and needle motion
  - Data will be provided to all partners, including spray modelers
- Projects with industrial partners
  - Delphi Diesel
  - Chrysler
- Studies of fuel additive effects
  - To date, cerium additive was required for measurements
  - With increased x-ray flux, can we reduce or eliminate additive?
- New multi-pixel detector system
  - Collaboration between Argonne and Fermilab detector groups
  - Currently being designed to our specifications
  - 100% of cost paid by BES
  - Will speed measurements, improve spatial resolution

Summary

- X-Ray diagnostics are being used to address a range of research challenges
  - Studying sprays under engine-relevant conditions
  - Providing data for srpay 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