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

- FY2014: $850K
- FY2015: $775K

Partners

- Army Research Laboratory, Engine Combustion Network, UMass, U. Perugia, *Robert Bosch, Caterpillar, Delphi Diesel*

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
- Argonne's world-class x-ray source and facilities enable unique measurements of fuel injection

- **Use our unique ability to measure near the nozzle to improve the fundamental understanding of fuel injection and sprays**
- **Assist in development of improved spray models using quantitative spray diagnostics**

Objectives and Milestones

Date	Objective	Status
June 2014	Measurements of cavitation and dissolved gas	Complete
September 2014	Measurements for Argonne's VT GDI Ignition Project	Complete
December 2014	Measurements for Army Research Lab	Complete
March 2015	Spray Measurements of ECN Gasoline Injector	Complete
June 2015	Needle Motion Measurements of ECN Gasoline Injector	On Track
September 2015	Cavitation Measurements in High Precision Transparent Nozzle	On Track

Technical Approach – X-rays Diagnostics of Sprays

- **X-rays enable unique diagnostics**
  - Mass-based measurements of the fuel distribution
  - Penetrate through steel to measure geometry, flow, motion
  - Can quantify shot-to-shot variation
  - Fast time resolution (<5 μs)
  - Fine spatial resolution (5 μm)
- **Limitations**
  - Room temperature ambient (plastic windows)
  - Can't penetrate more than ~10 mm of steel
- **Strategy**
  - Measurements of relevant injectors and conditions (ECN, industrial partners, other VT)
  - Partnerships with model developers to utilize these measurements (ECN, other VT, industry, universities)

Technical Accomplishments in Brief

- Measurements for Army Research Laboratory
  - Injector geometry and needle motion
  - Boundary conditions for injector flow modeling

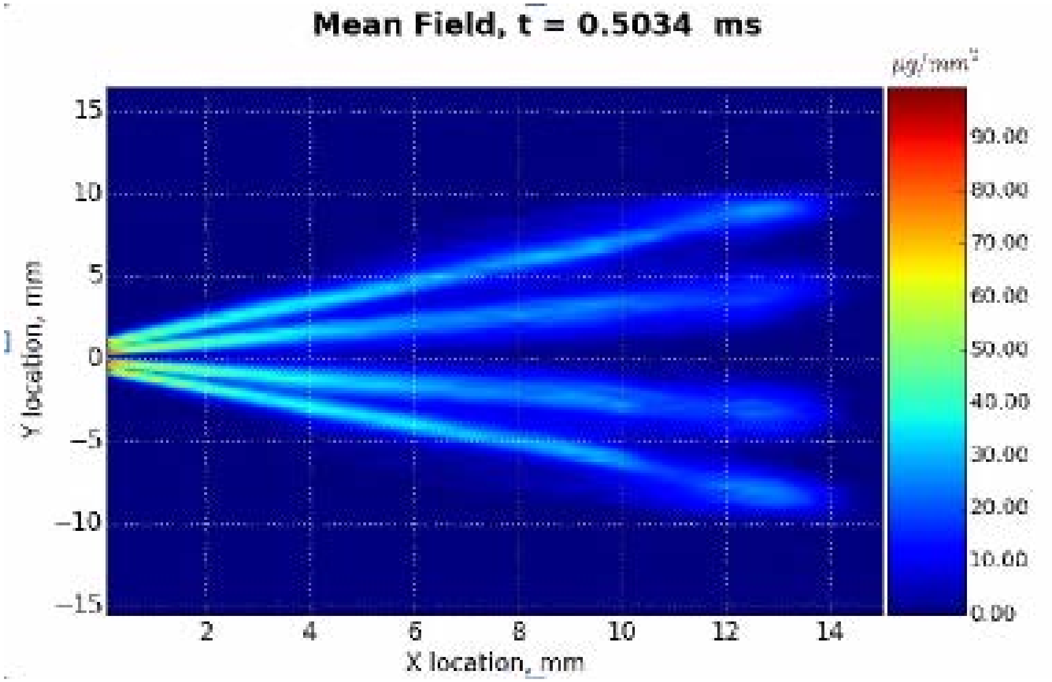
- Measurements of Injectors for GDI Ignition Project
  - Used for simulation development and validation

- Measurements of Sparks for GDI Ignition Project
  - Use x-rays to measure gas density in spark plug gap
  - Proof of Concept completed this year

- Measurements of SMD in Near-Nozzle Region
  - Used for validation of ECN Spray A

Measured Density Distribution of ECN Spray G

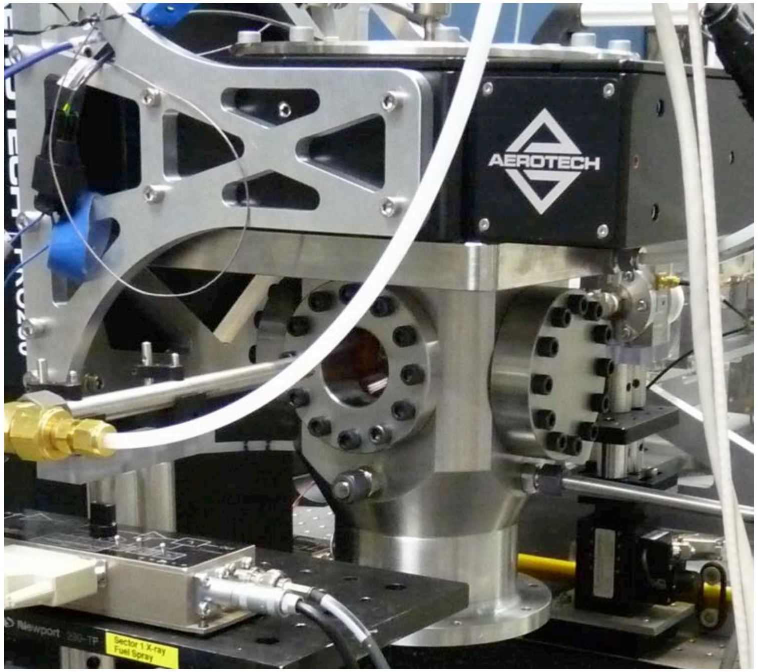
- Gasoline sprays present unique challenges:
  - Sprays are close together, spray interactions
  - Often impossible to isolate a single spray
  - Line-of-sight measurements can be confusing
- New capability for x-ray tomography at elevated ambient pressures

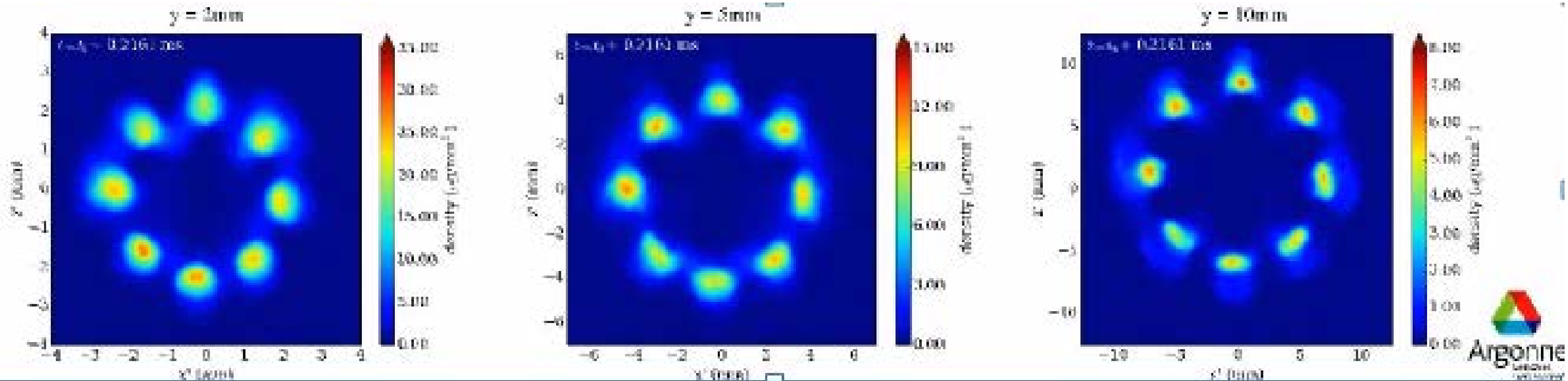


ECN Spray G
Delphi GDI Injectors

Completed 3D Reconstruction of ECN Spray G

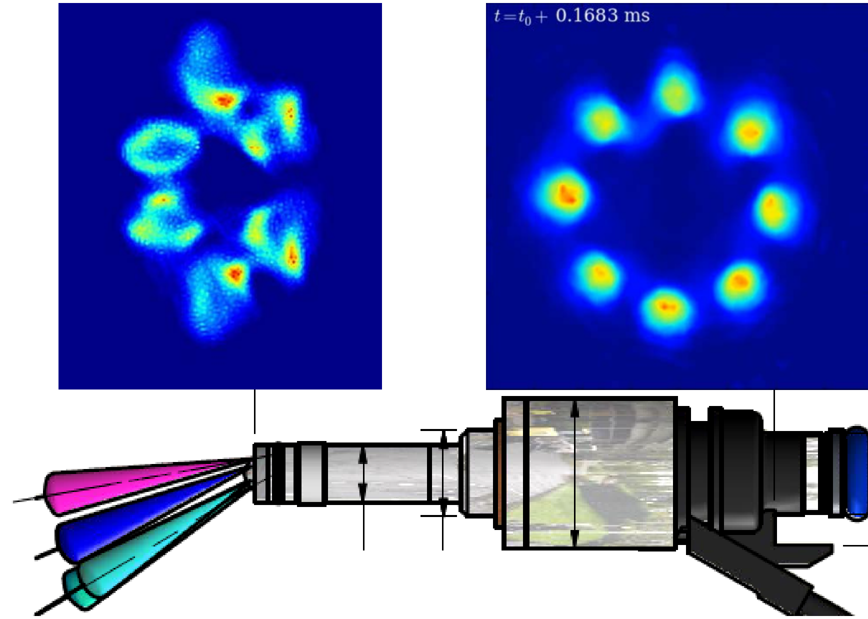
- Tomography is only applicable to mass-based diagnostics
- Many lines of sight, mathematical reconstruction
- Argonne expertise in tomo reconstruction
- Shows average, time-resolved density at several "slices" through the spray
- Fine space, time resolution (25 μm, 5 μs)
- Data shared with ECN partners for model validation

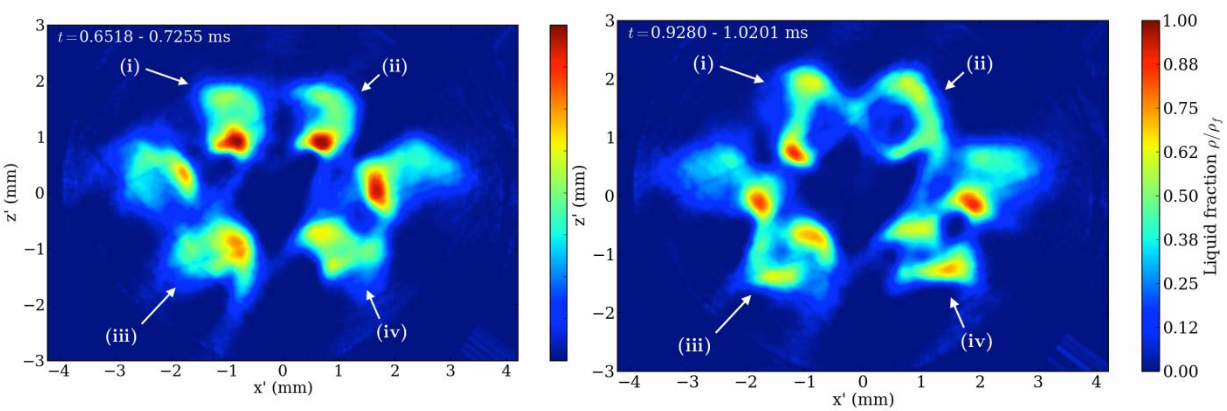




What we are Learning About GDI Sprays?

- Previous work with Chrysler showed highly asymmetric sprays
- At the time we attributed this to stepped-hole geometry
- Further work with GDI Ignition Project and ECN Spray G has shown good symmetry from stepped-hole nozzles
- Asymmetry may be a result of “canted” injector holes

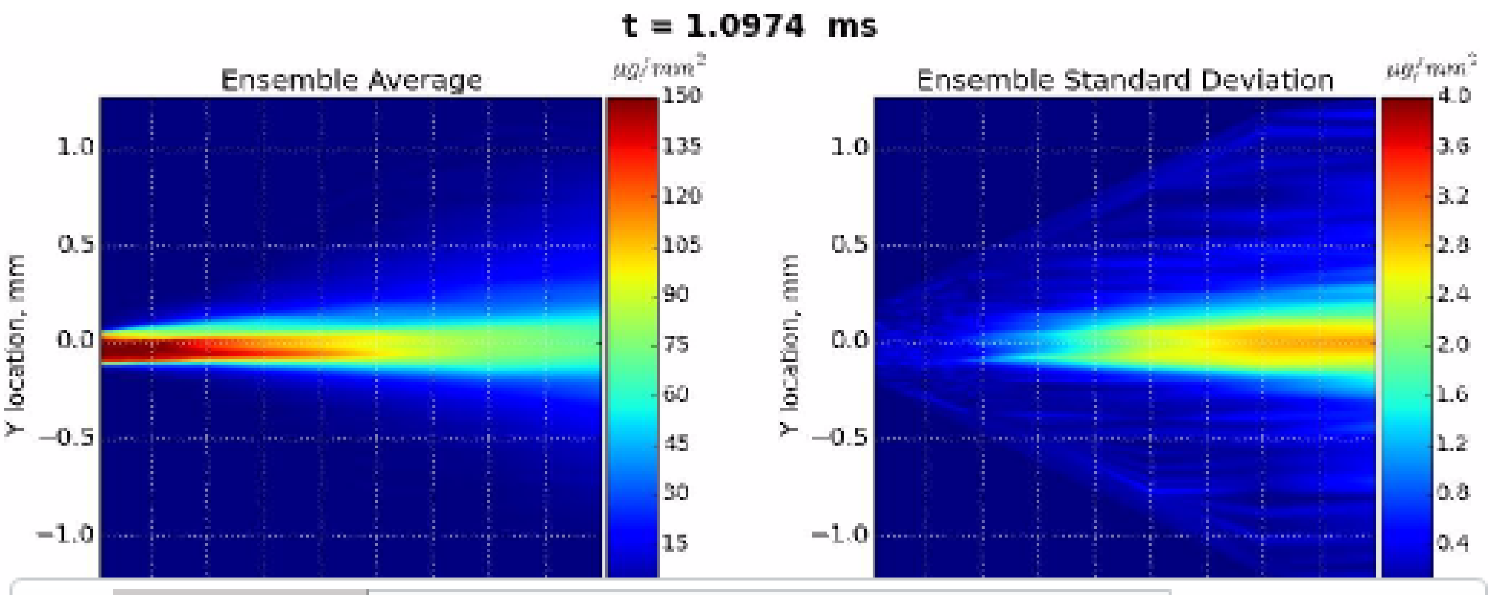




- GDI sprays show more variability during the “steady-state” period than diesel sprays

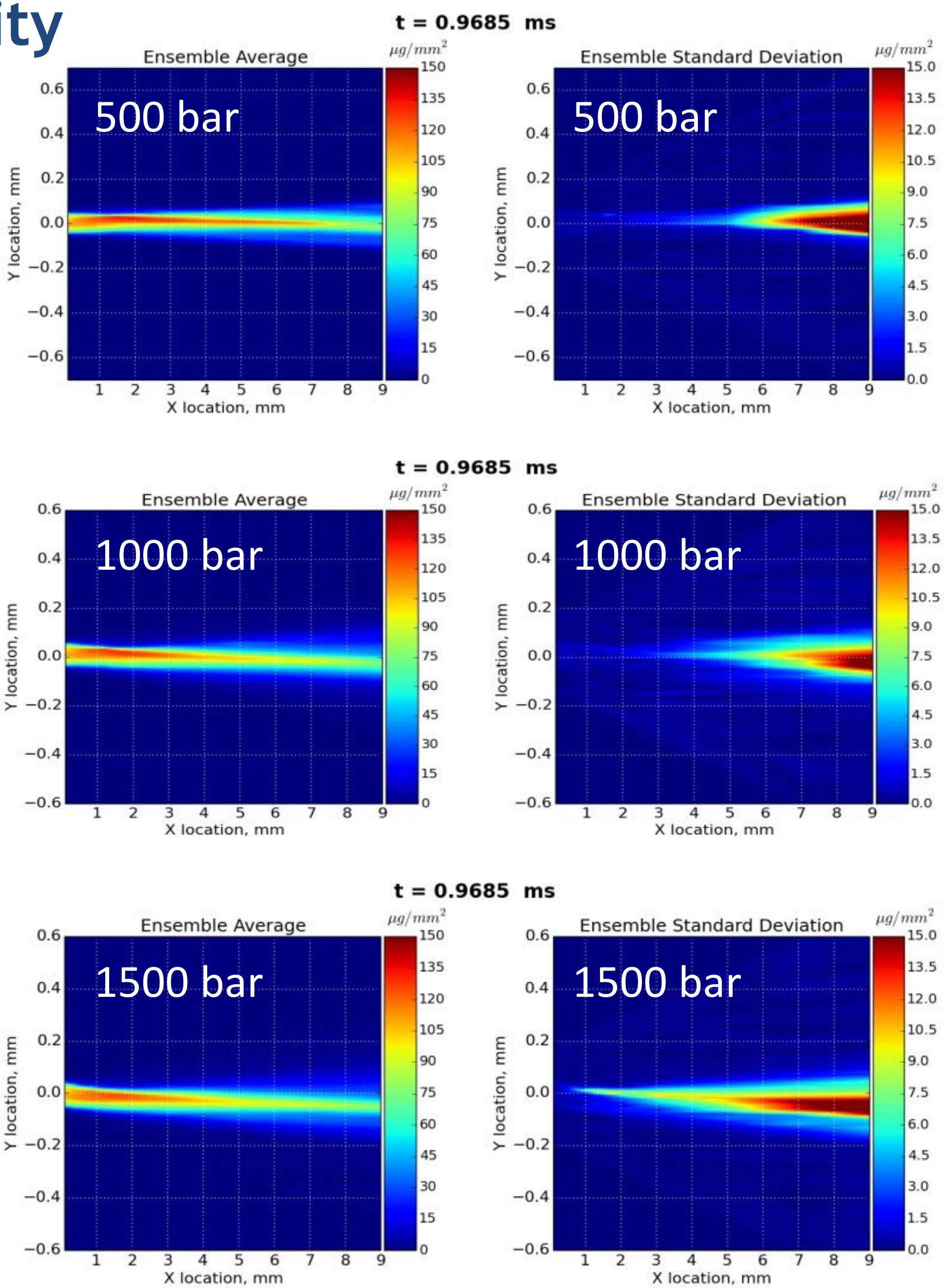
Shot to Shot Variation in Sprays

- Historically, our measurements were ensemble averaged
  - Feedback from Annual Merit Reviews have noted this limitation
  - Recent improvements to x-ray optics enabled single-shot measurements
- Relevance:
  1. Injector, 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
  - Spray-to-spray variation has not been validated against quantitative data



New Metric for Spray Variability

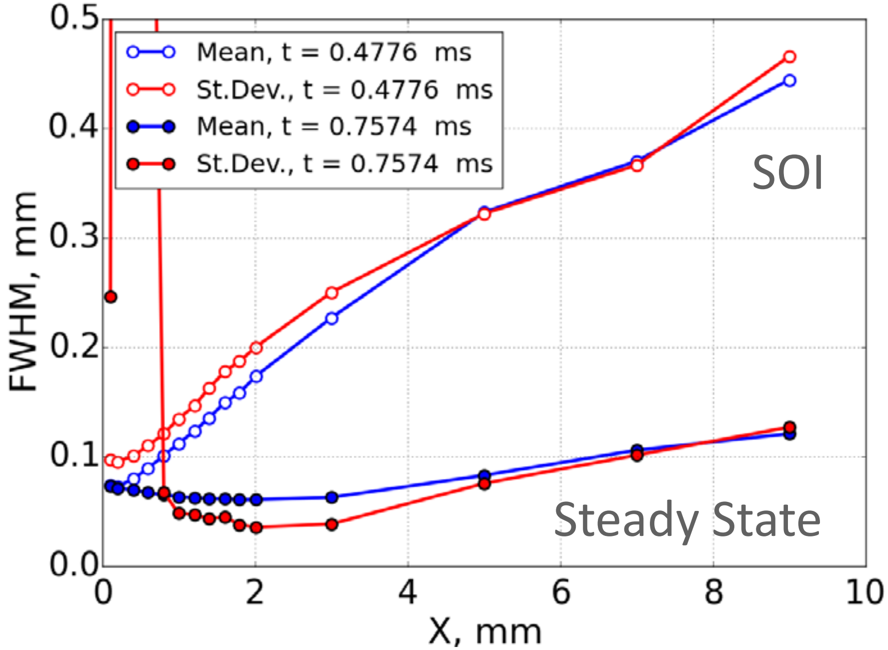
- Standard deviation of mass/area is used as a metric for spray variability
- During steady part of spray, very little variability at nozzle outlet
- Region of high variability moves closer to the nozzle with increasing injection pressure
- Parametric studies with P_{amb}, nozzle diameter,
- May be a marker for spray breakup, turbulent mixing
- Exploring ways to use for model validation



Swantek *et al*, SAE World Congress 2015

Discovered that Spray has High Variability Near Start of Injection

- Pickett and others have observed that optical spray cone angle is wider at SOI than steady state
- Measurements of standard deviation show that spray has more variability during this time period
- Hypotheses:
  - Clearing of gas from sac
  - Throttling at low needle lift
- Measurements with CMT using direct-acting piezo this summer
  - Direct control of needle lift

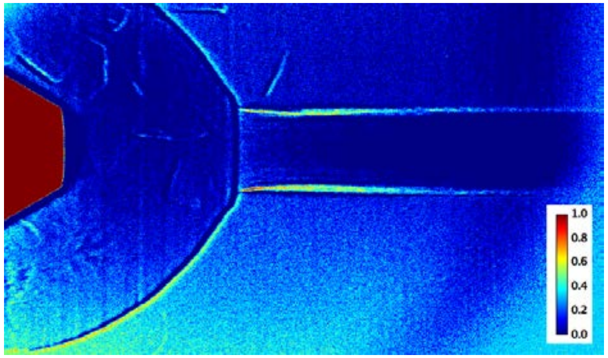


Measurements and Simulation of Cavitation

- Over the past two years we have developed quantitative measurements of cavitation
- Measurements have been used to validate simulations by Som, Schmidt, Battistoni
- Can measure the density of a bubbly fluid, but cannot resolve between dissolved gas and cavitation.
- Modeling work showed that dissolved gases are important
- Real fuel systems contain dissolved gases

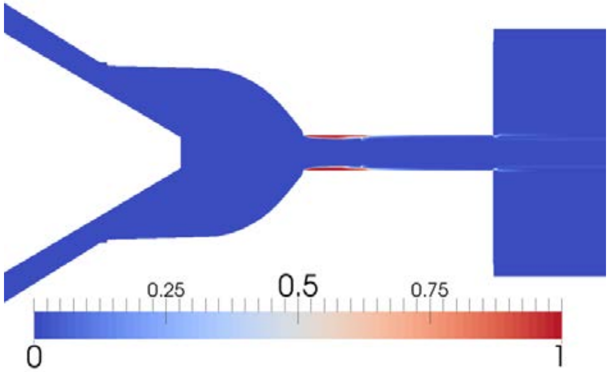
Cavitation in Diesel Nozzle

Measurement

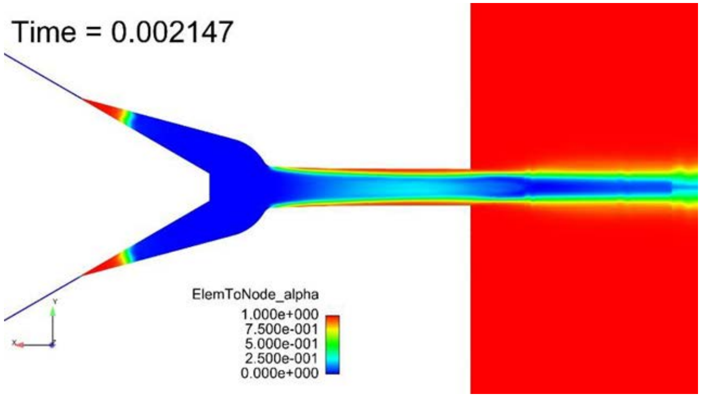


Predicted Vapor Fraction

Simulation



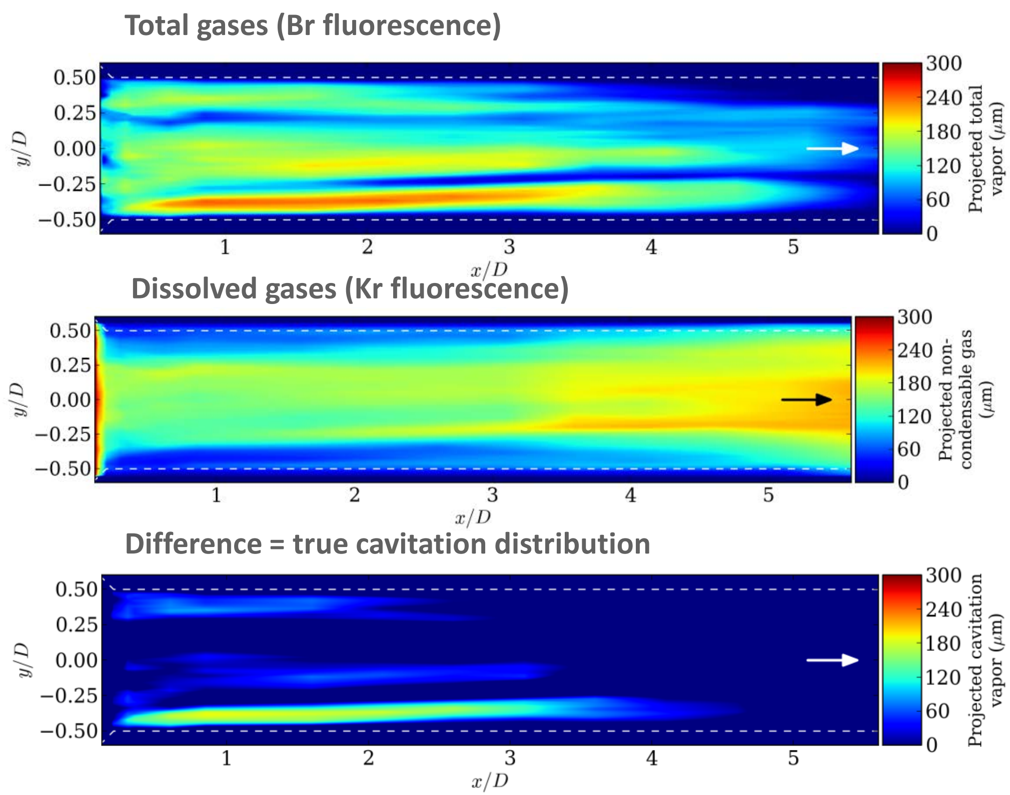
Duke et al. SAE 2014-01-1404



Battistoni et al, Atomization & Sprays 2015

First Measurements of Cavitation and Dissolved Gas

- X-ray fluorescence
  - Bromine tracer dissolved in the fuel
  - Saturate fuel with krypton gas
  - Br and Kr emit x-rays of different wavelengths
- Under non-cavitating conditions
  - Uniform distributions of Br and Kr
- Under cavitating conditions
  - Regions of low bromine concentration indicate gas and/or vapor
  - If these regions contain krypton, it indicates dissolved gas coming out of solution
  - First measurement that can resolve dissolved gas and cavitation

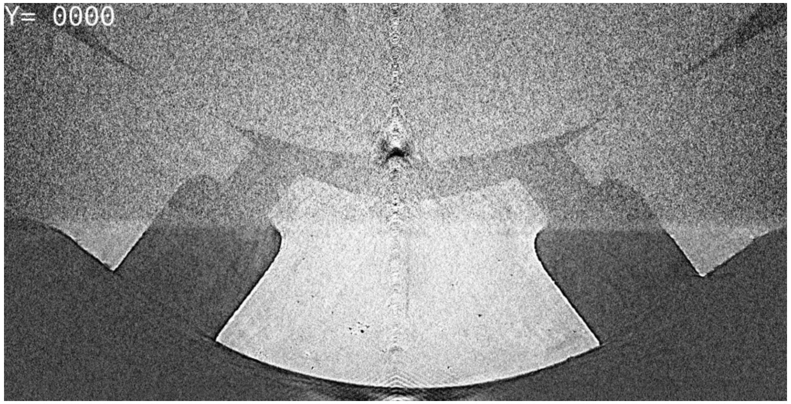


- Collaboration with modeling groups: Battistoni (U. Perugia), Som (Argonne), Schmidt (UMass)
  - Unprecedented data are advancing model development for in-nozzle flow

Duke et al, SAE 2015-01-0198

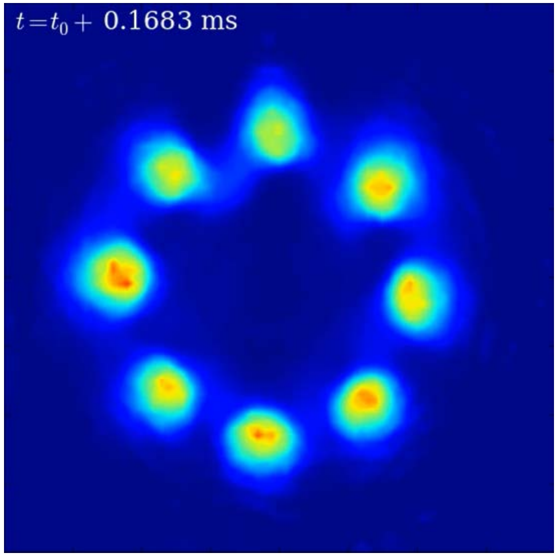
Argonne Contributions to ECN in FY2015

Nozzle Geometry



Will be used for internal flow simulations

Fuel Density

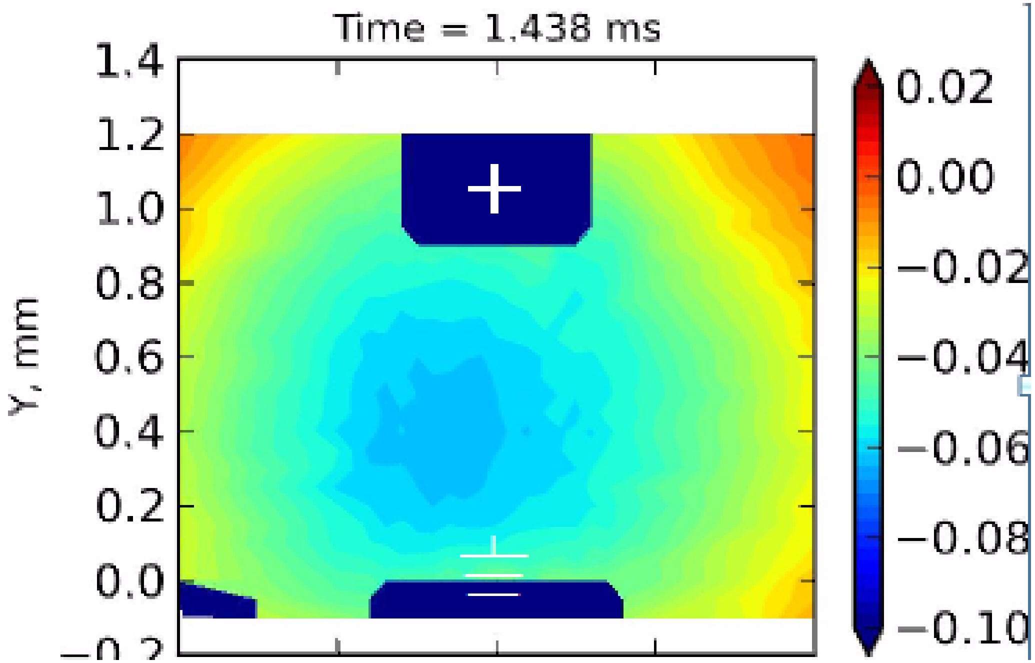


Will be used for validation of near–nozzle breakup simulations

- Argonne is processing x-ray measurements of nozzle geometry to build high precision 3D models of all 12 injectors (<1 μm resolution)
- Measurements of Needle Motion in April 2015
- Argonne leads Topic 8: Spray G Internal Flow

Measurements Supporting GDI Ignition Research

- Can x-rays help understand sparks?
  - Proof of concept measurements
- Ignition is an important topic for advanced combustion
  - Lack of systematic assessment of ignition systems
  - Absence of robust modeling tools
- The physics of spark ignition is poorly understood
  - Fast time scale
  - Bright IR/UV/Visible emission
- We observe region of low density between the electrodes, probably plasma or hot gas
- We see changes with charging time, ambient pressure, ambient gas
- We will consult experts at Ford and Transient Plasma Systems, Inc to understand these results
- Hope is to improve ignition and ignition simulations through a better understanding of sparks



Responses to FY2014 Reviewers' Comments

"encouraged to migrate towards gasoline sprays"

- Several new GDI efforts this year:
  - SAE 2015-01-0931, Wang *et al*.
  - ECN Spray G
  - Injectors from VT Ignition Project
- Will still pursue diesel spray work, significant interest from industry

"modelers are investigating Eulerian-to-Lagrangian transition formulations, PI is encouraged to … help determine a proper transition between the two"

- We have been working in this direction:
  - Bravo et al, ASME Power Conference, July 2015
  - Xue et al, SAE Fuels & Lubricants, 2015
- Collaboration with Som's group will be used to validate implementation in Converge

Collaboration

- **DOE Advanced Engine Combustion Working Group**
  - All results presented at these meetings
  - Often leads to new collaborations
- **Engine Combustion Network**
  - Our data is integral for model validation:
    - Internal flow simulations
    - Near-nozzle breakup models
- **Collaboration with Sibendu Som's group**
  - Cavitation, bubbles in sac
  - Needle motion effects
- **US Army Research Lab**
  - Data for simulation of injector internal flow
  - Measurements of sprays in the future
- **University of Massachusetts Amherst**
  - Cavitation
  - Improvements to HRM Model
- **Industrial Contracts:**
  - Delphi Diesel
  - Caterpillar
  - Bosch

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

- Broadband x-rays next year, 5x increase
- 5x increase in flux in 2020

Temperature

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

- Start by heating fuel to explore flash-boiling gasoline
- Build facility for high temperature sprays

Proposed Future Work in FY2015 and FY2016

- Engine Combustion Network, GDI Injection
  - CAD models of all 12 "Spray G" GDI Injectors
  - Measurements of Needle Motion
  - Flash boiling conditions
  - GDI Injection into a barrier
- Cavitation Studies
  - Improved nozzles made of x-ray transparent beryllium
  - Spraying nozzles for simultaneous measurements of internal/external flow
  - Measurements of bubble size
  - Flash-boiling fluids
  - Real-size, real pressure transparent nozzles
- Shot-to-Shot Variation
  - Proper Orthogonal Decomposition to investigate coherent fluctuations
  - Direct-acting piezo injector to control needle lift
  - Apply to GDI sprays
  - Validation of LES Simulations
- Spark Studies
  - May pursue further measurements after consultation with experts

Summary

- Improve the understanding of fuel injection and sprays
  - Fundamental measurements of spray phenomena
    - Cavitation
    - Shot-to-Shot Variation
  - Collaboration with ECN
    - Needle lift and motion
    - Near-nozzle fuel density
    - Nozzle geometry
- Assist in development of improved spray models
  - Partnerships on nozzle flow modeling with Som, UMass Amherst, Univ. Perugia, Army Research Lab
  - Data contributed to ECN is assisting model development at IFP, CMT, Sandia, Argonne, UMass, Convergent Science, others.
  - SPPs with Bosch, Caterpillar, CRADA with Delphi Diesel

Technical Back-Up Slides

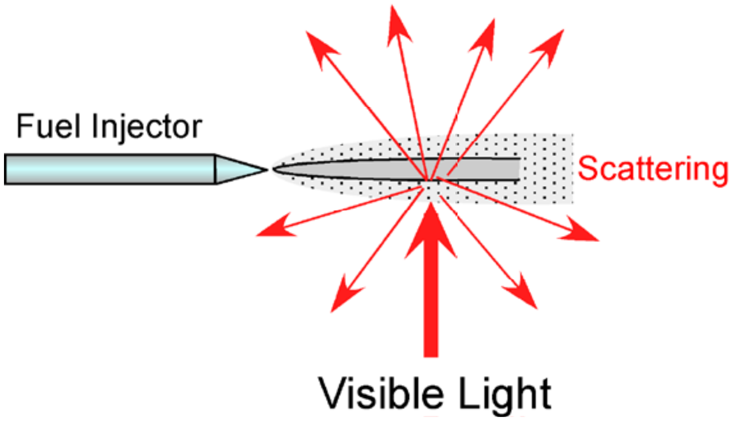
(Note: please include this “separator” slide if you are including back-up technical slides (maximum of five). These back-up technical slides will be available for your presentation and will be included in the DVD and Web PDF files released to the public.)

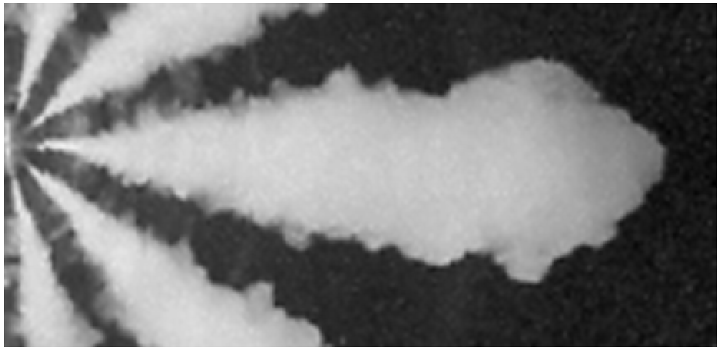
Technical Approach

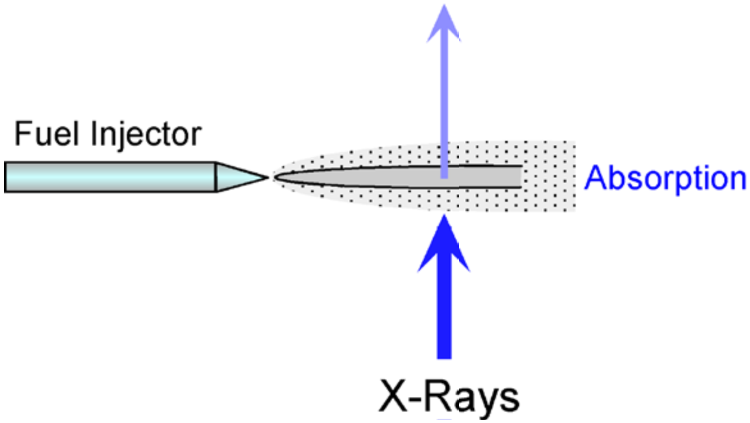
- **Perform injector and spray measurements that increase fundamental understanding**
  - Engine Combustion Network
  - Measurements of cavitation
  - Measurements of needle motion
  - Measurements of internal nozzle flow
  - Droplet sizing

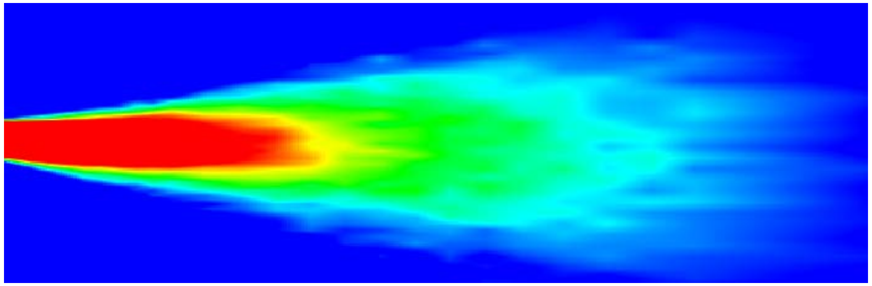
- **Use our measurements to assist the development of computational spray models**
  - Collaboration with Som, UMass Amherst, Univ. Perugia, ARL
  - Engine Combustion Network
  - Collaboration with Argonne modeling group
  - Delphi Diesel CRADA, Caterpillar WFO, Bosch WFO

Technical Approach - X-rays Reveal Fundamental Spray Structure





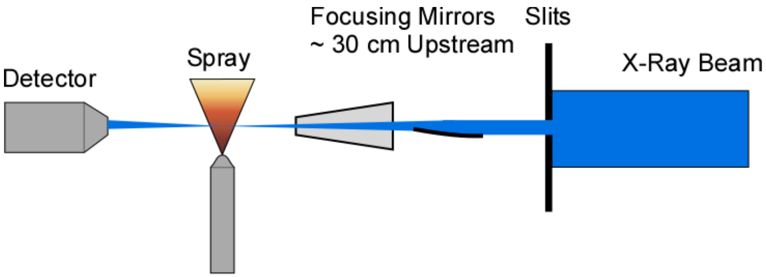


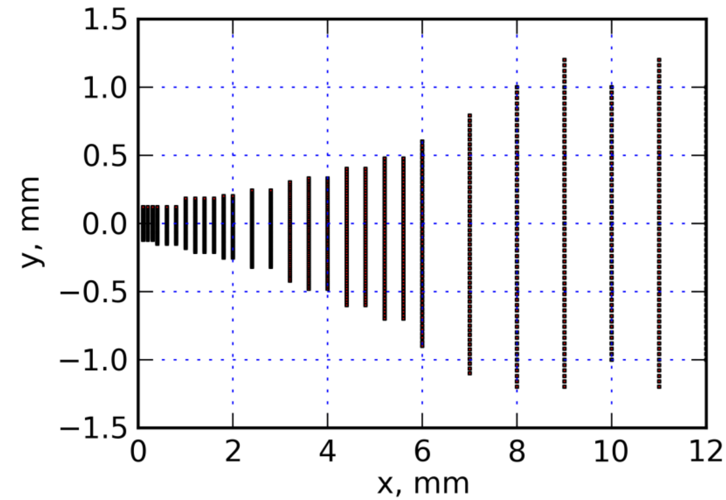


- Room temperature
- Ensemble averaged
- Pressure up to 30 bar

Experimental Method

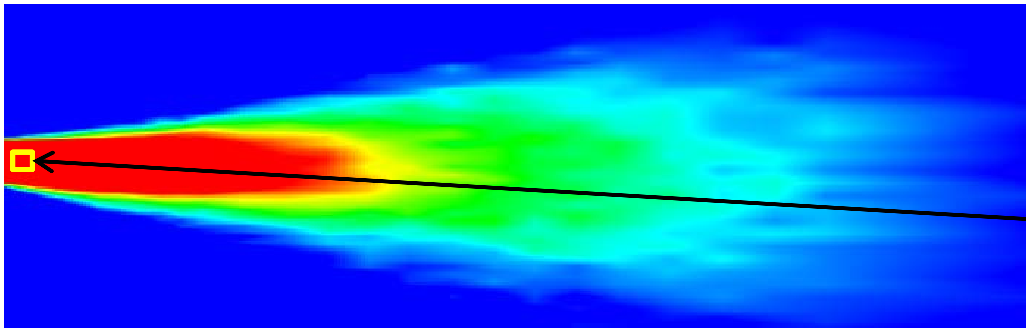
- Focused beam in raster-scan mode
- Beam size 5 x 6 μm FWHM
  - Divergence 3 mrad H x 2 mrad V
  - Beam size constant across spray
- Time resolution: 3.68 μs
- Each point an average of 32-256 injection events
- Beer's law to convert x-ray transmission to mass/area in beam
- Fuel absorption coefficient: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



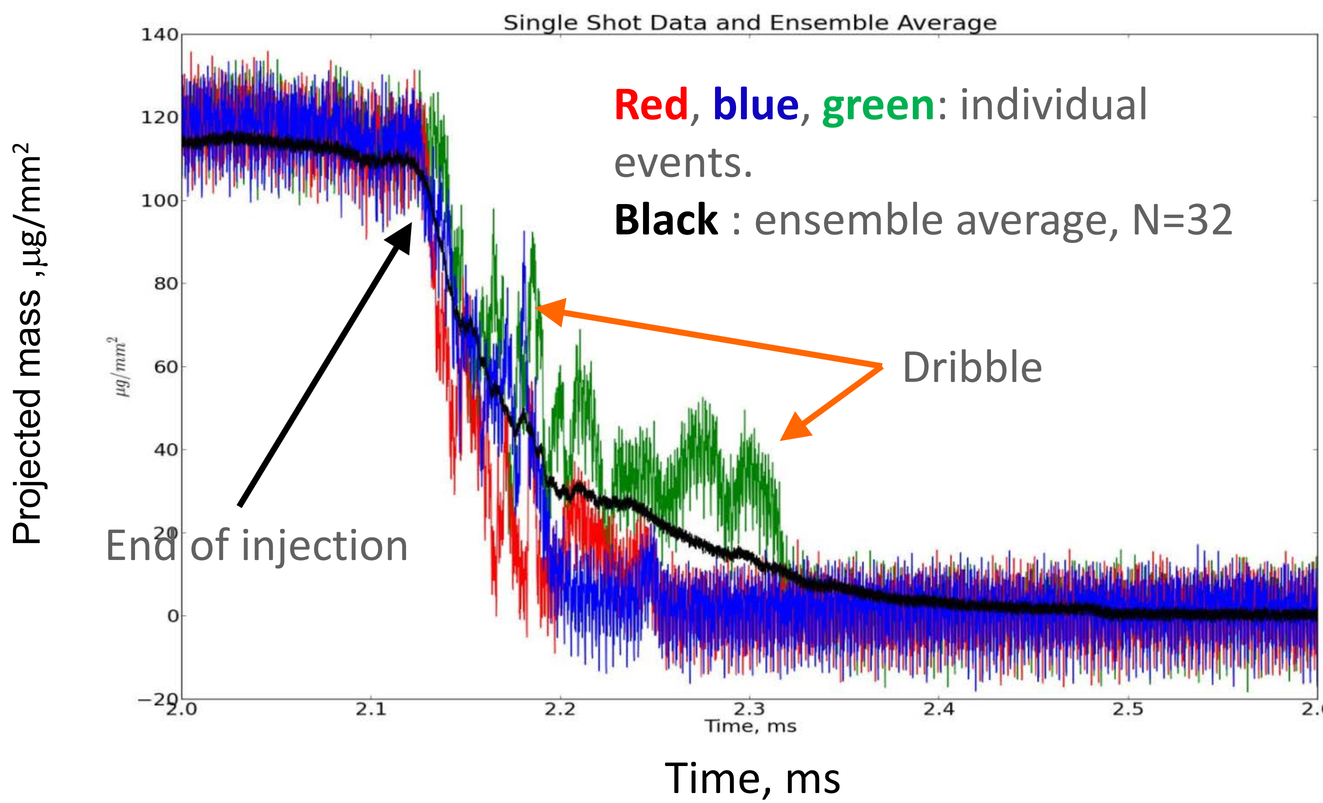


Example Measurement Grid

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

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.