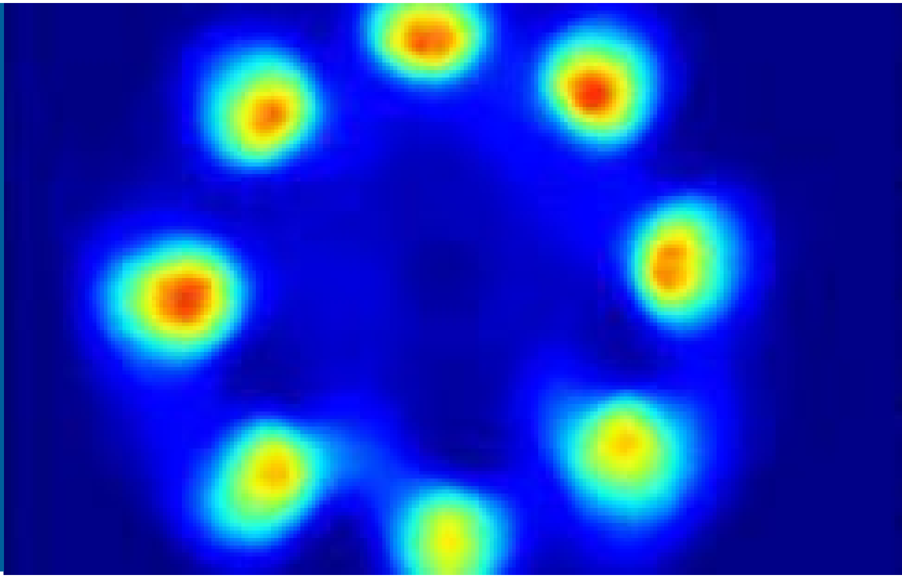
PROJECT ID ACS010

FUEL INJECTION AND SPRAY RESEARCH USING X-RAY DIAGNOSTICS



CHRISTOPHER POWELL, DANIEL DUKE, KATARZYNA MATUSIK, ALAN KASTENGREN

Argonne National Laboratory
7 June 2017

TEAM LEADERS:
Gurpreet Singh
Leo Breton

OVERVIEW

Timeline

- FY2017: Funded under DOE Lab Call

Budget

- FY2016: $700K
- FY2017: $505K (reduced spend rate)

Partners

- Engine Combustion Network, UMass-Amherst, Georgia Tech, CMT-Motores Térmicos, Sandia, Oak Ridge, General Motors
- Delphi Diesel, Toyota, Spray Combustion Consortium, GE Global Research

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

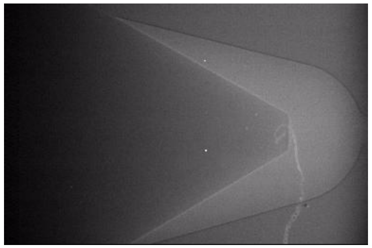
- **Use our unique ability to measure near the nozzle to improve the fundamental understanding of fuel injection and sprays**
- **Assist in development of improved spray models using quantitative spray diagnostics**
- **Make these measurements accessible to our industrial partners and the wider community**

OBJECTIVES AND MILESTONES

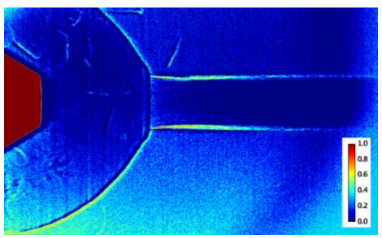
Date	Objective	Technique	Status
December 2016	Simultaneous measurements of cavitation and spray density.	Fuel Density	Complete
March 2017	Measurements of ducted combustion	Fuel Density	Complete
June 2017	X-ray and neutron tomography of GDI Injector	Nozzle Geometry	Complete
September 2017	Measurements of needle motion in ECN Spray C and Spray D	Needle Motion	On Track
Annual Milestone	Demonstrate routine nozzle geometry measurements with resolution < 5 μm	Needle Motion	Complete

TECHNICAL APPROACH: X-RAY DIAGNOSTICS

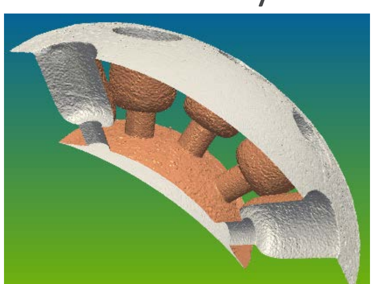
Needle Motion

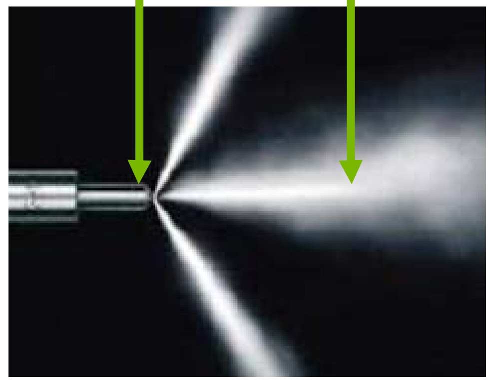


Nozzle Cavitation



High Precision Nozzle Geometry

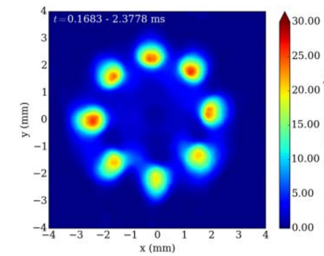




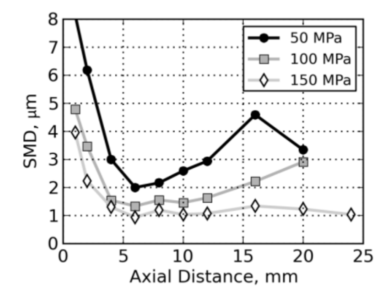
X-rays enable unique capabilities, both *inside* and *outside* the nozzle

Near-Nozzle Fuel Density

Spray Tomography



Near-Nozzle Drop Sizing



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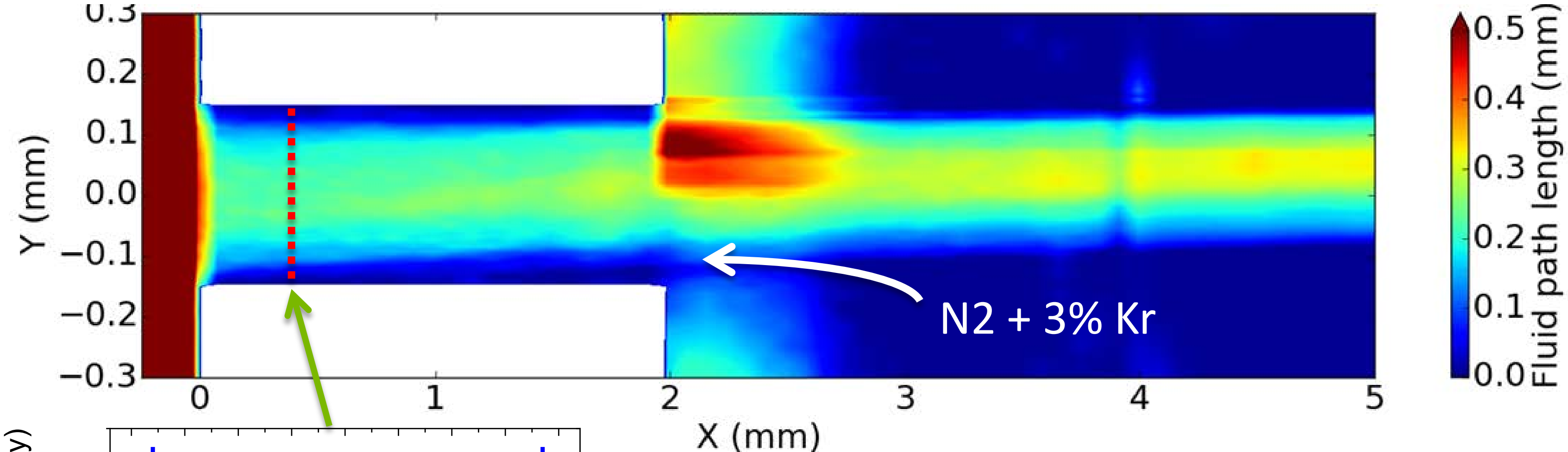
TECHNICAL APPROACH FOR 2017

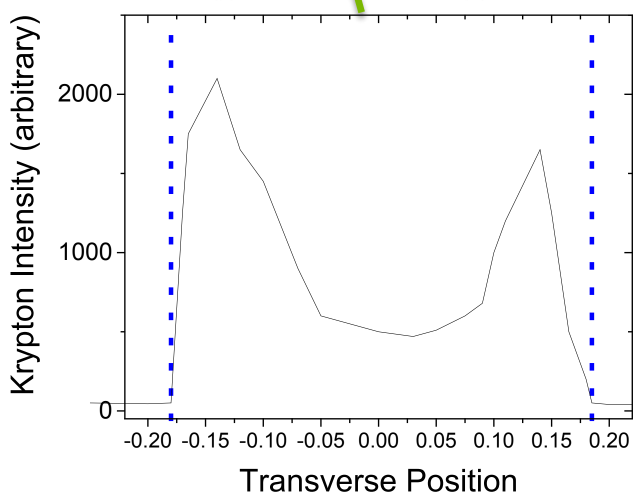
- **Nozzle cavitation and erosion is a challenge for industry**
  - Not understood at fundamental level, realistic measurements are difficult
  - **Utilize x-ray measurements to study fundamentals of cavitation**
  - **Partner with simulation groups to incorporate our results into advanced models**
- **CFD Simulations are routinely performed at the micron scale**
  - Using nominal geometry in CFD causes discrepancies when comparing to experiment
  - Commercial x-ray CT has spatial resolution >10 mm
  - **We will improve our capability for nozzle geometry measurements with micron spatial resolution, and make the results available to partners**
- **The link between nozzle geometry and fuel distribution is not understood**
  - Nozzle design is often trial-and-error
  - **We will attempt to quantify the link between geometric features of the nozzle and the near-nozzle fuel distribution**
- **Discrepancy in near-nozzle fuel distribution in diesel sprays**
  - Recent simulation results (Arienti, Schmidt) don’t match experiments
  - Existing measurement data were 2D, coarse resolution
  - **Need new Spray D data set, high resolution, 3D**

X-RAY MEASUREMENTS OF CAVITATION

Near-Simultaneous Measurements Inside and Outside Nozzle

- Under hydraulic flip conditions, ambient gas is expected to enter the nozzle
- When cavitation extends to the end of the nozzle, ambient gas may enter, and stabilize flow separation
- Measurements using krypton in the ambient have confirmed, quantified this

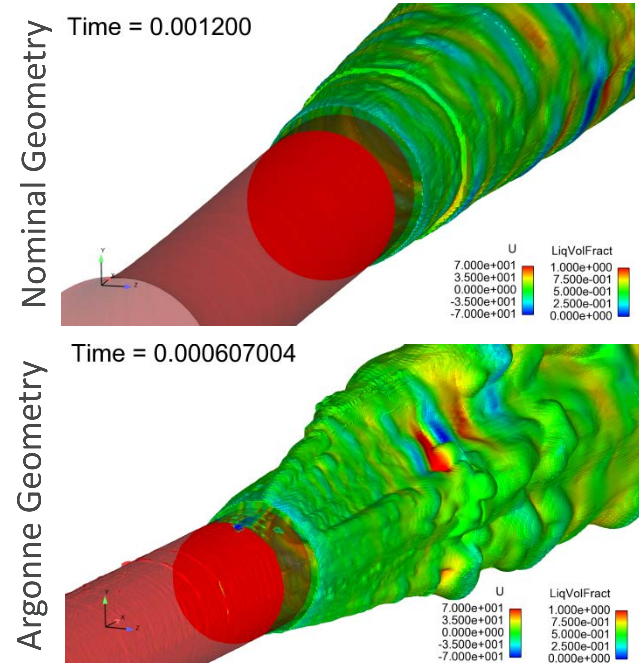




- These measurements were done in x-ray transparent beryllium nozzle, Ø300 μm
- Simulations in collaboration with UMass-Amherst
- New measurements completed in a Ø200 μm aluminum nozzle
- Less expensive, pressure up to 1000 bar

X-RAY TOMOGRAPHY OF FUEL INJECTOR NOZZLES

- 3D measurements of internal nozzle geometry
  - Enables realistic CFD meshing
  - Manufacturing diagnostic
- Hardware upgrades have improved spatial resolution to 1.8 microns
  - An order of magnitude better than commercial services
- In 2017 we have measured nozzles and delivered 3D geometries for:
  - Engine Combustion Network
  - Georgia Tech University
  - Toyota
  - Aramco
  - Spray Combustion Consortium
  - Tsinghua University
  - Sandia National Labs (Busch)



Battistoni, Univ. of Perugia

Engine Combustion Network, Georgia Tech University: Used to develop CFD mesh, openly available

Toyota, Aramco, Spray Combustion Consortium: Privately funded, used to develop CFD mesh

Tsinghua University: Measurement of deposits in GDI injectors

Sandia National Labs (Busch): Investigation of jet-jet variability in engine

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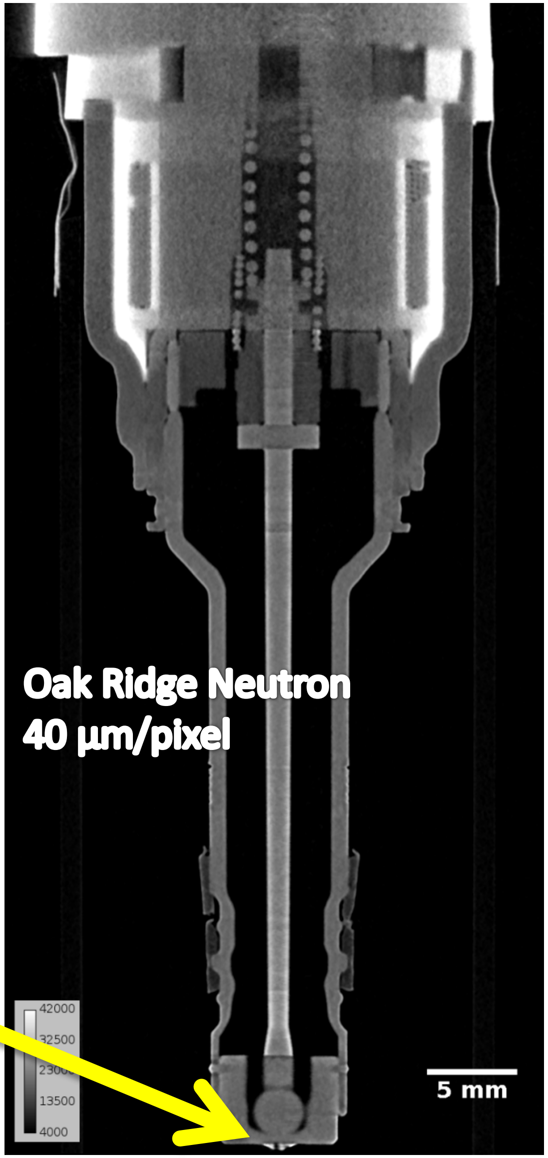
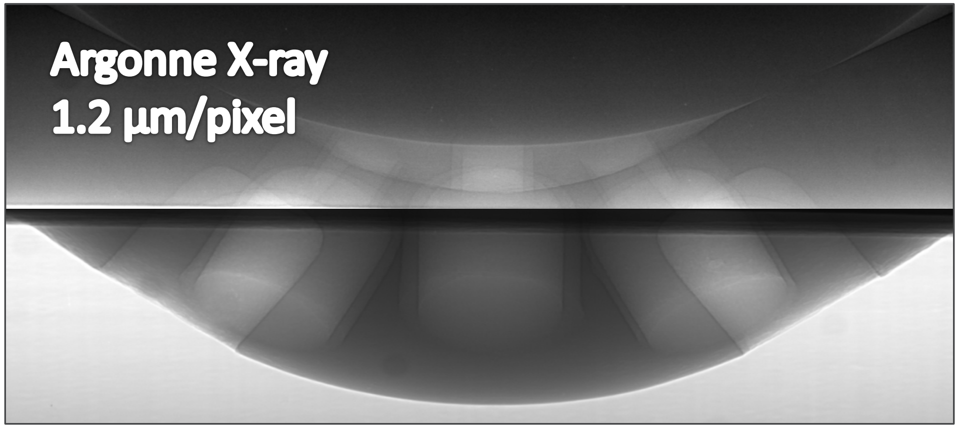
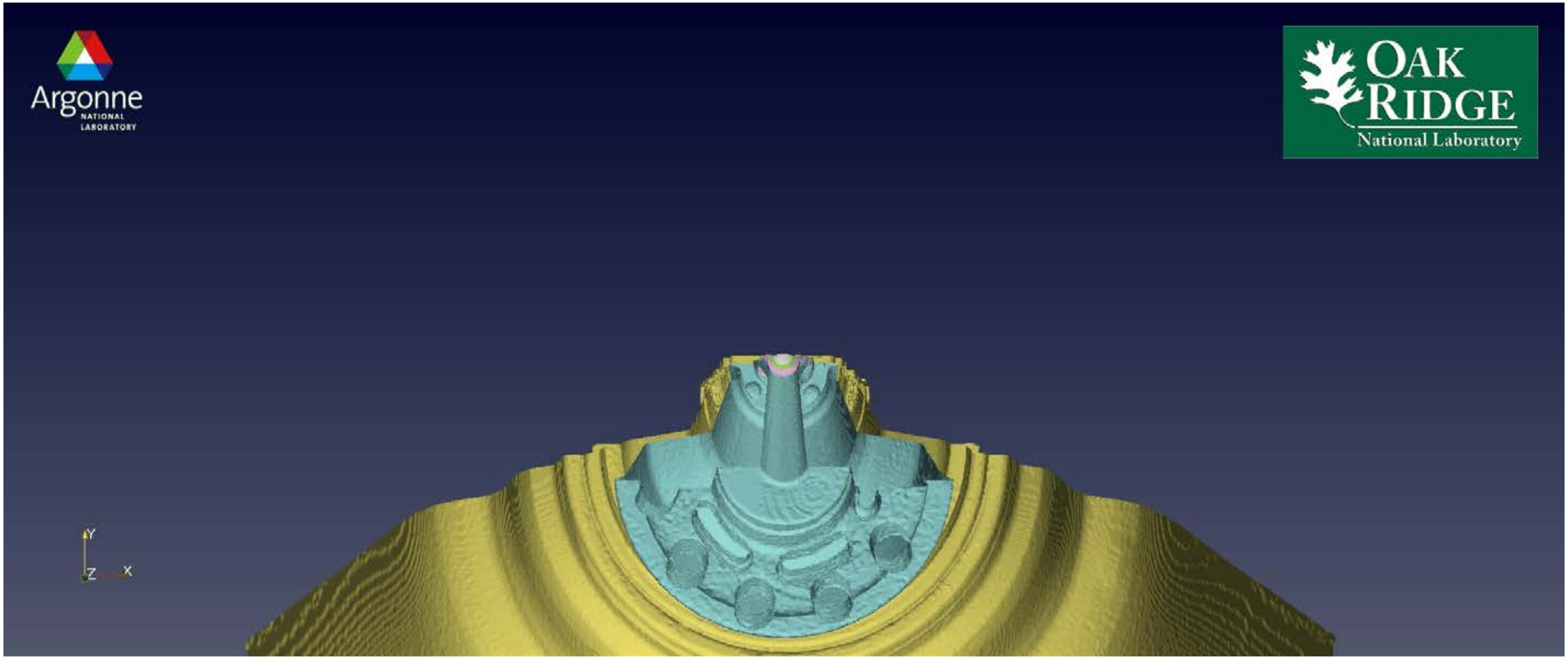
COLLABORATION WITH OAK RIDGE: 3D GEOMETRY MEASUREMENT OF COMPLETE GDI INJECTOR

- X-rays cannot easily penetrate the thicker parts of the injector
- Neutrons are more penetrating in metals, but spatial resolution is lower
- Combined measurements give complete geometry, with high spatial resolution where it is needed most
- Upstream geometry predicts pressure losses and acoustics above the seat





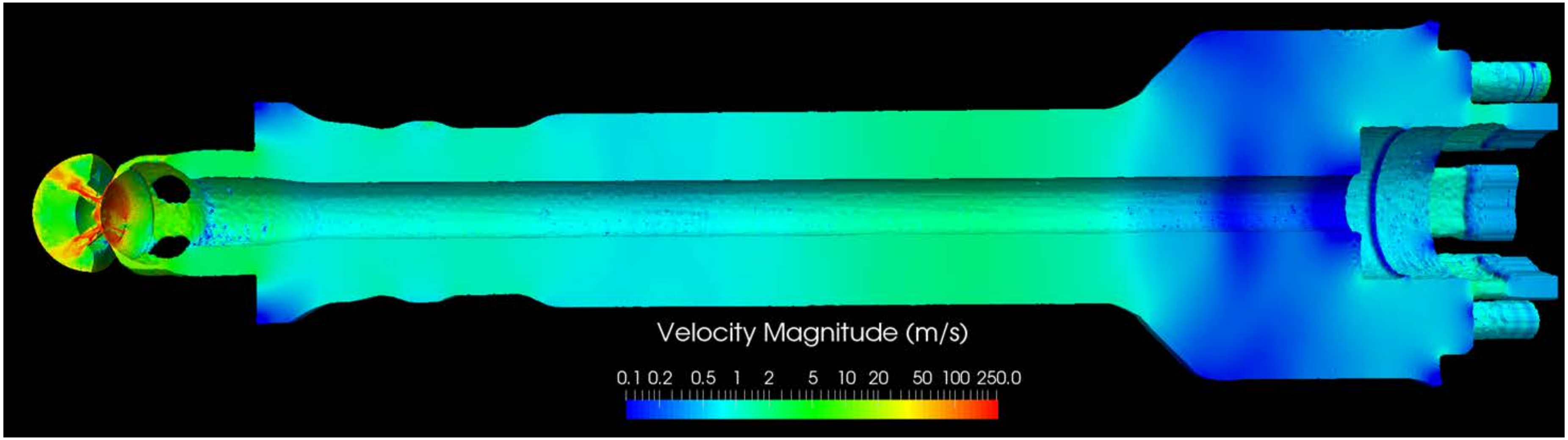
GEOMETRY OF COMPLETE GDI INJECTOR



- Geometry measurements provide realistic boundary conditions for 3D CFD

SIMULATION OF COMPLETE INJECTOR FLOW

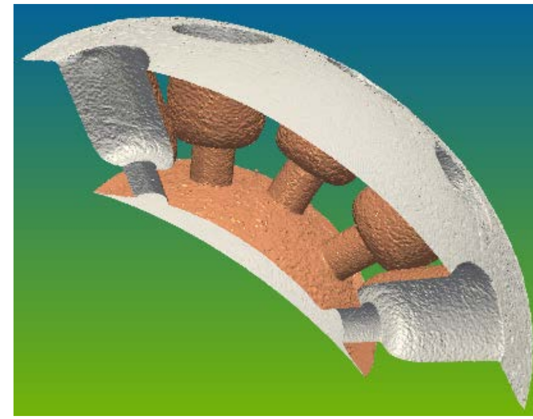
- CFD boundary conditions at the valve seat are typically steady state, and match the fuel rail.
- 3D CFD using HRMFoam (ORNL, UMass Amherst)
- Found significant acoustic waves in the injector body, but small pressure fluctuations at the valve seat.
- Simulations such as these can be used to developing accurate, time-dependent boundary conditions for nozzle flow and spray simulations

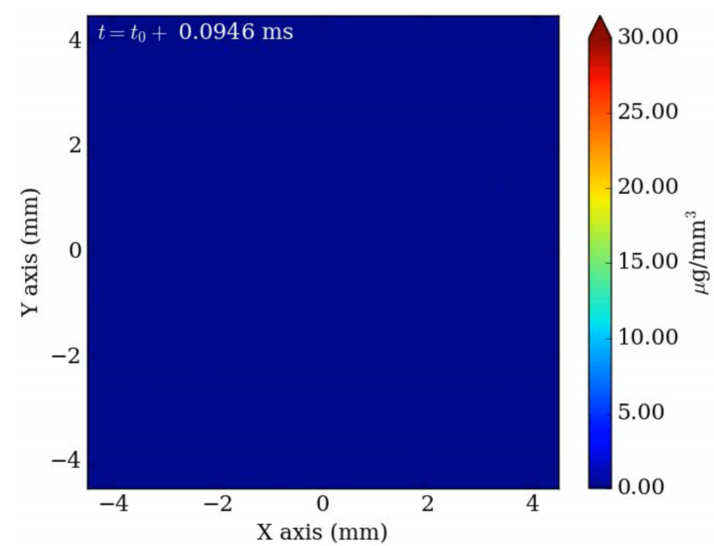


MEASUREMENTS OF GEOMETRY AND NEAR-NOZZLE SPRAY

Linking nozzle geometry to the near-nozzle fuel distribution

- Last year, showed geometry and spray density for one ECN Spray G injector
- This year, 8 Spray G injectors have been completed. Statistics on 64 spray holes, sprays
  - Variability in hole geometry
  - Variability in fuel distribution
- We can attempt to link geometry and fuel distribution
  - How does variability in fuel mass correlate with variability in geometric features?





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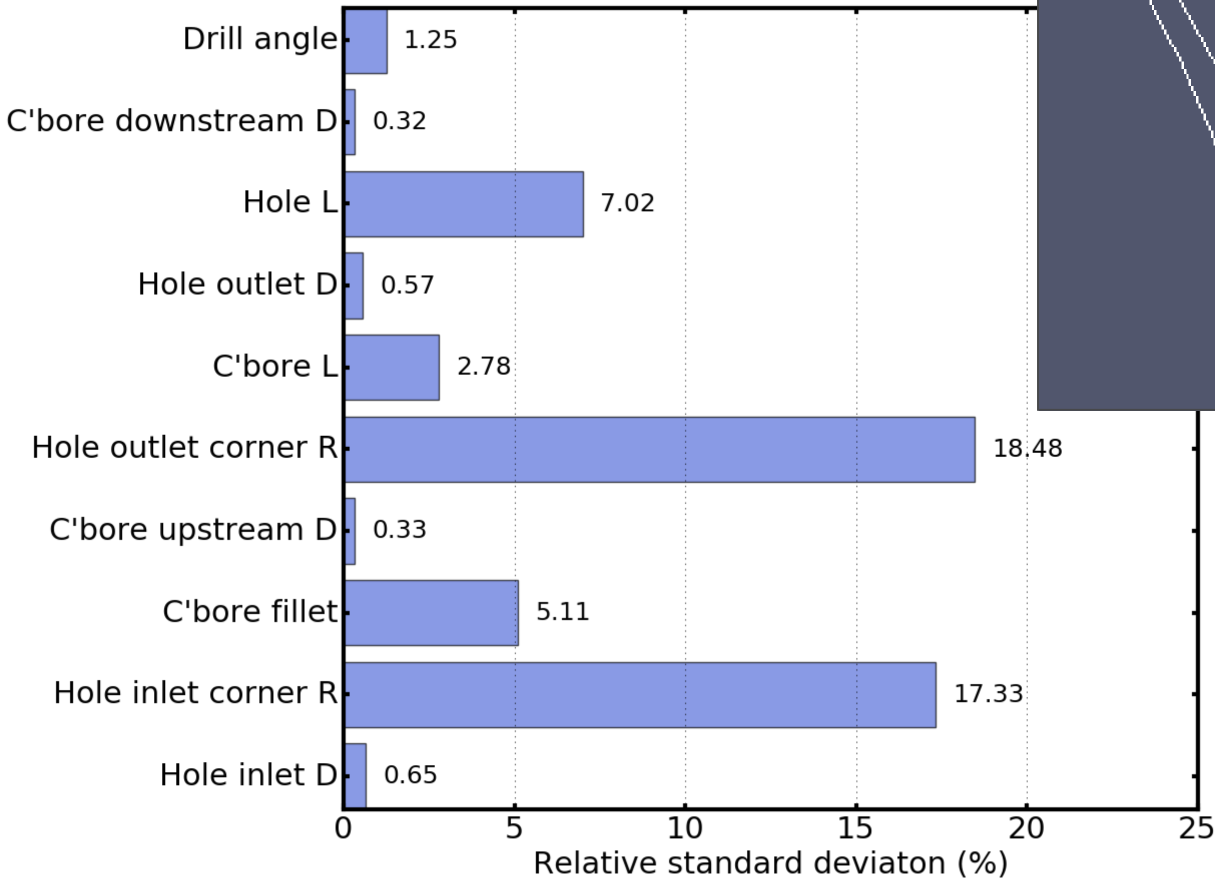
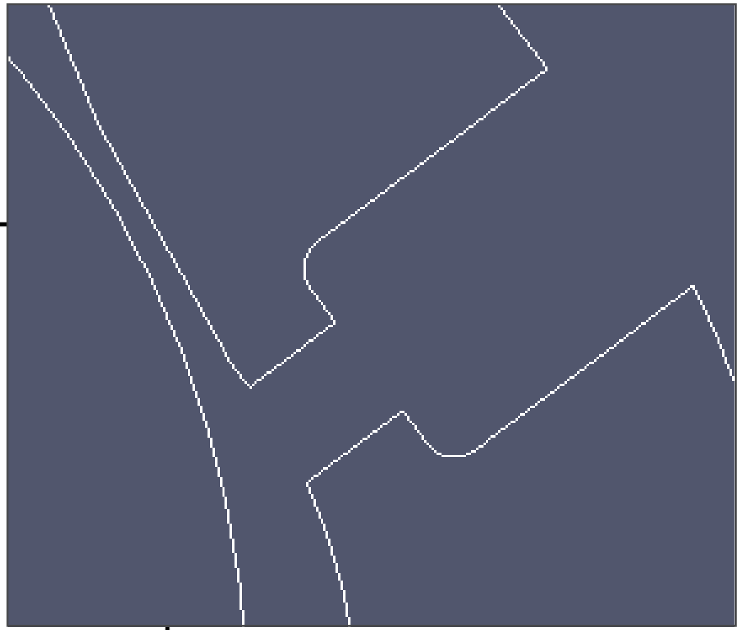
ECN SPRAY G: GEOMETRIC VARIABILITY

Variability Across 64 Nozzle Holes

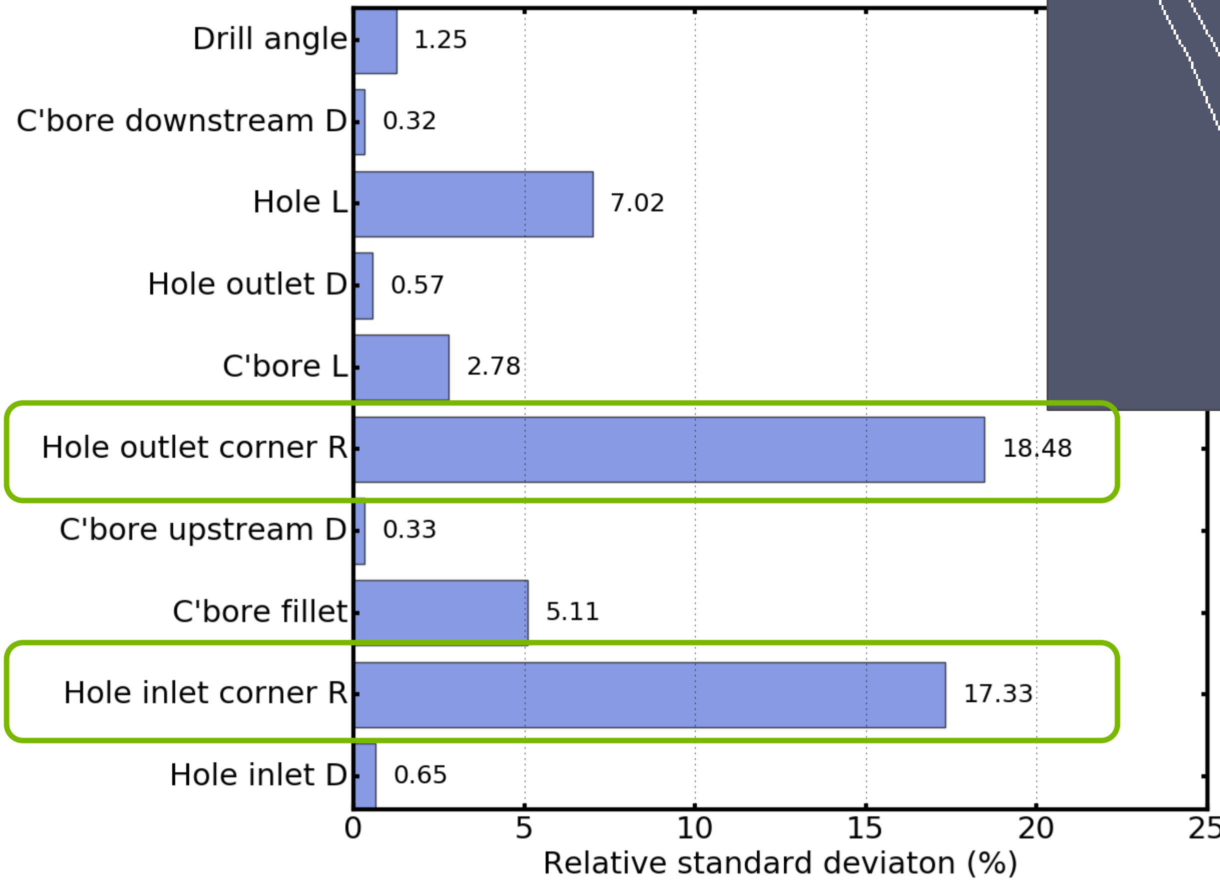


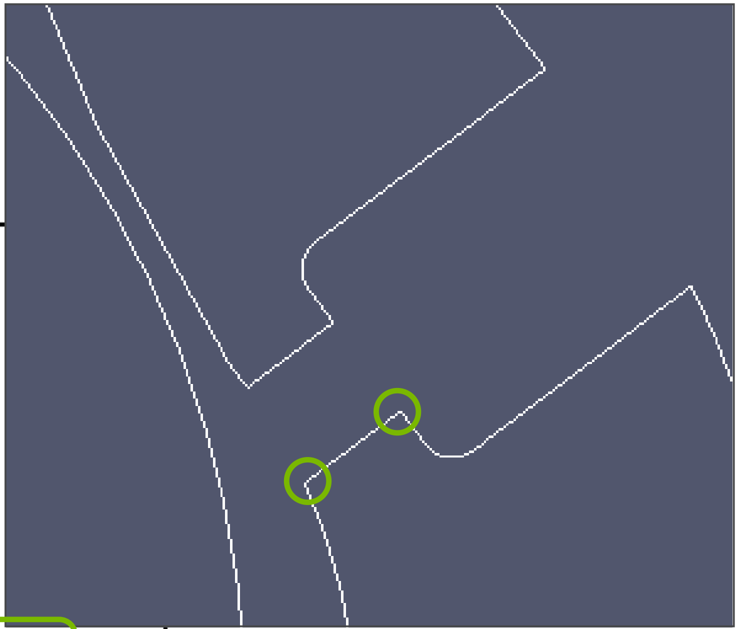


- Inlet and outlet corner radii are within our spatial resolution

ECN SPRAY G: GEOMETRIC VARIABILITY

Variability Across 64 Nozzle Holes





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ECN SPRAY G: GEOMETRIC VARIABILITY

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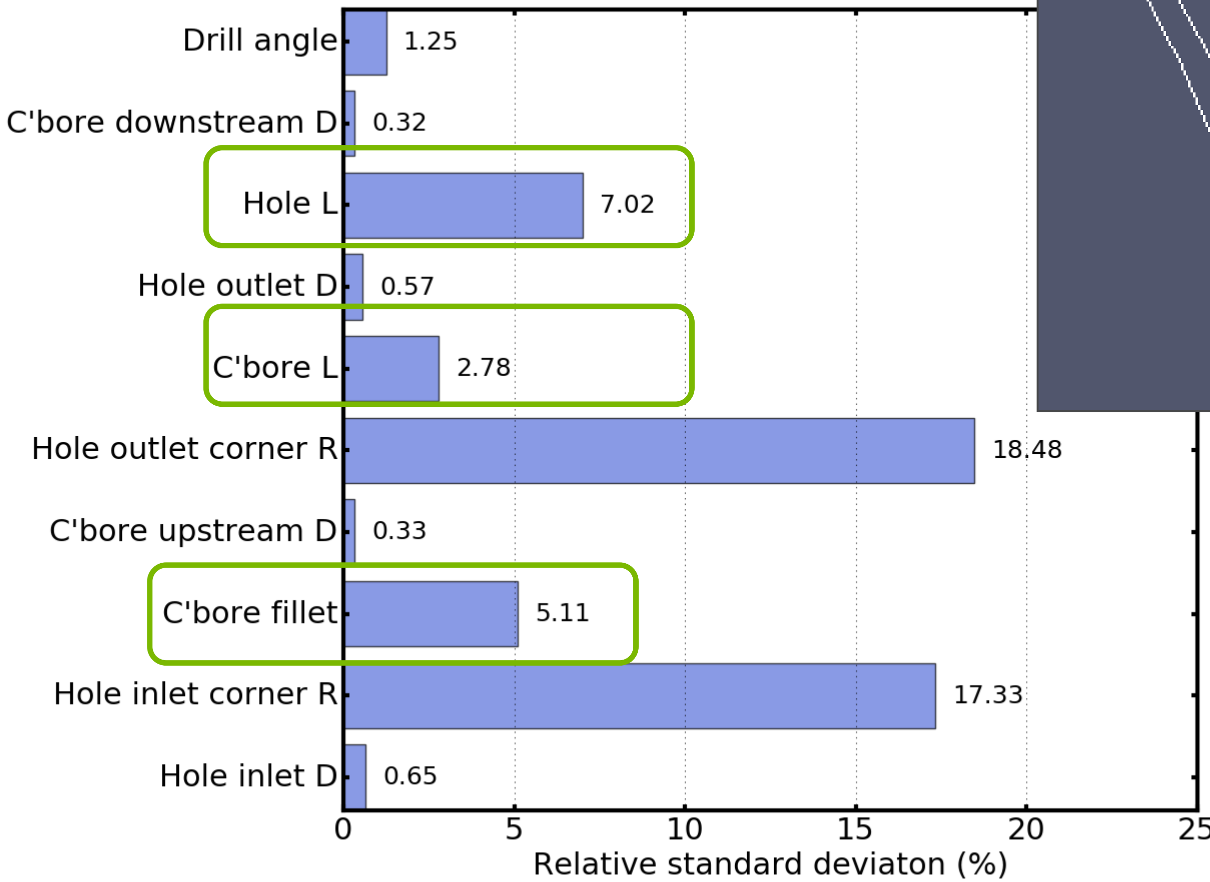
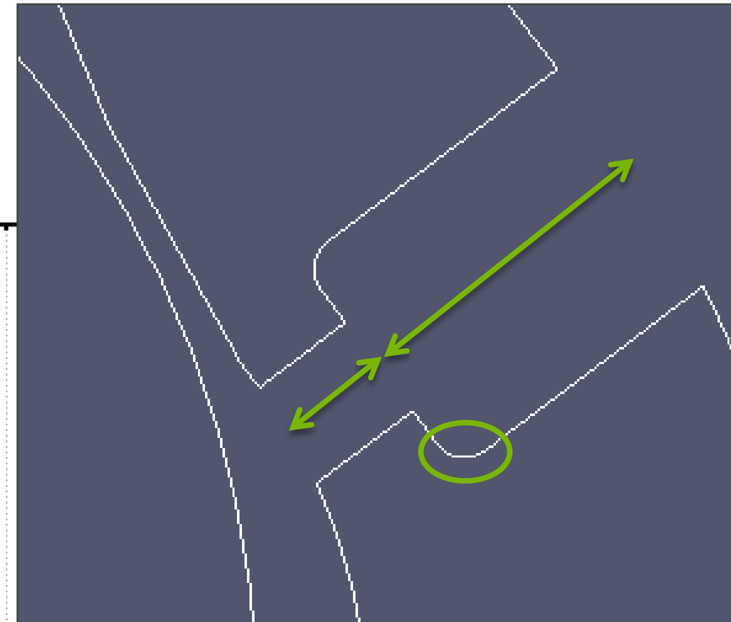
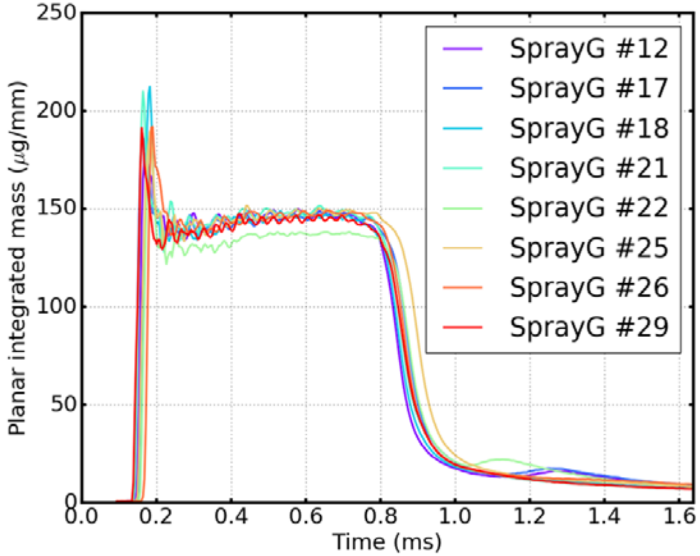
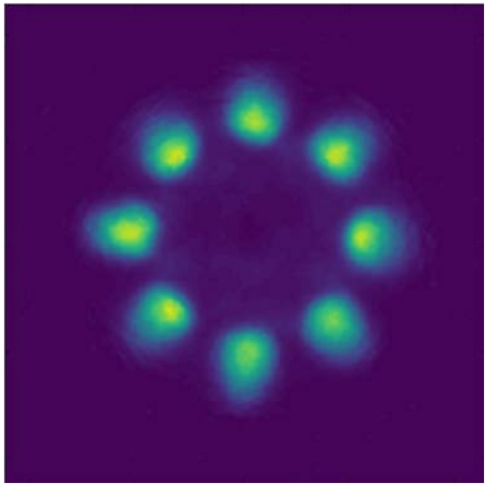




- Inlet and outlet corner radii are within our spatial resolution

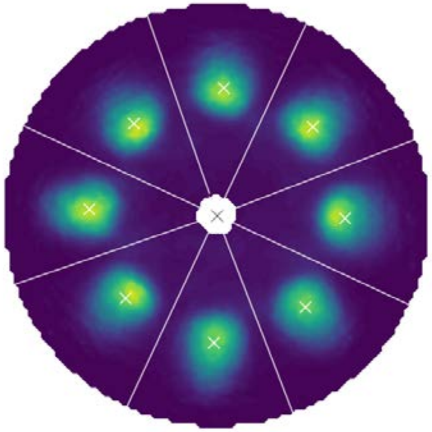
ECN SPRAY G: FUEL MASS VARIABILITY





Full spray field

- Our Metric: Total mass in slice through fuel distribution.
- Can be evaluated injector-to-injector, hole-to-hole
  - Injector-Injector: 2.4%
  - Hole-Hole: 5.0%



Segmented Hole-Hole

SENSITIVITY ANALYSIS: LINKING GEOMETRIC FEATURES TO NOZZLE FLOW

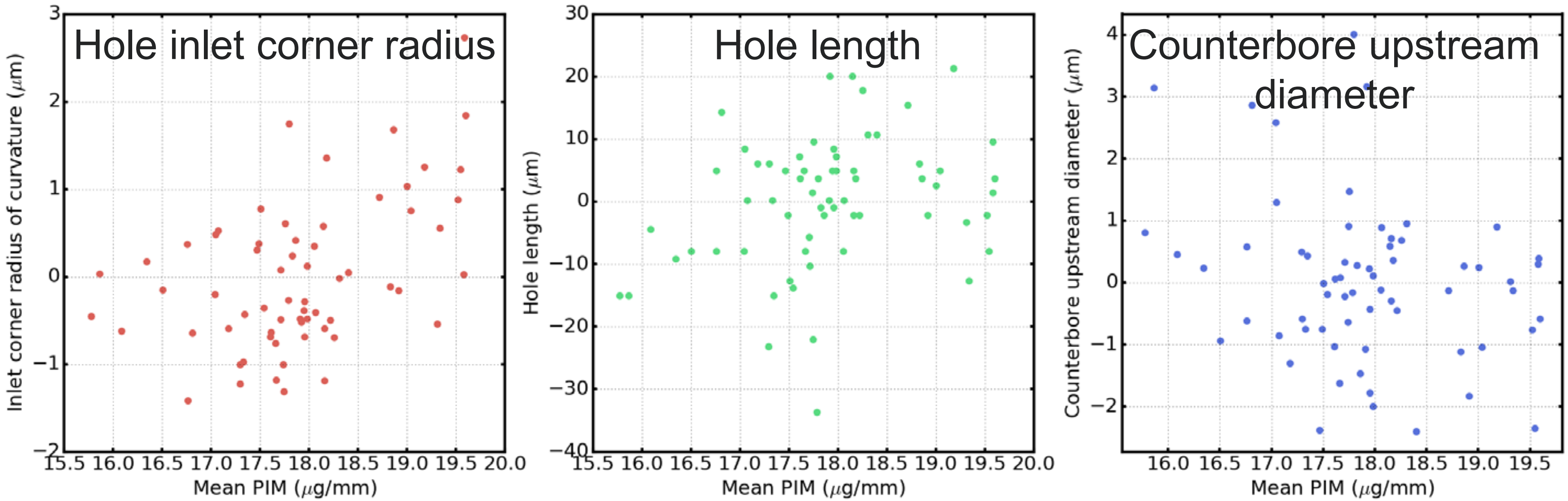
- Quantify how the variability in fuel mass correlates with variability of each geometric feature
- Fit a linear equation to observed data in the form of:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 \ldots \beta_n x_n$$

- Response *y* = average planar integrated mass
- Predictors x_i =
  1. Hole inlet D
  2. Hole outlet D
  3. Hole inlet corner radius
  4. Hole outlet corner radius
  5. Hole length
  6. Drill angle
  7. Counterbore upstream diameter
  8. Counterbore downstream diameter
  9. Counterbore fillet
  10. Counterbore length

GEOMETRIC FEATURES THAT HAVE MOST SIGNIFICANT IMPACT ON FUEL MASS

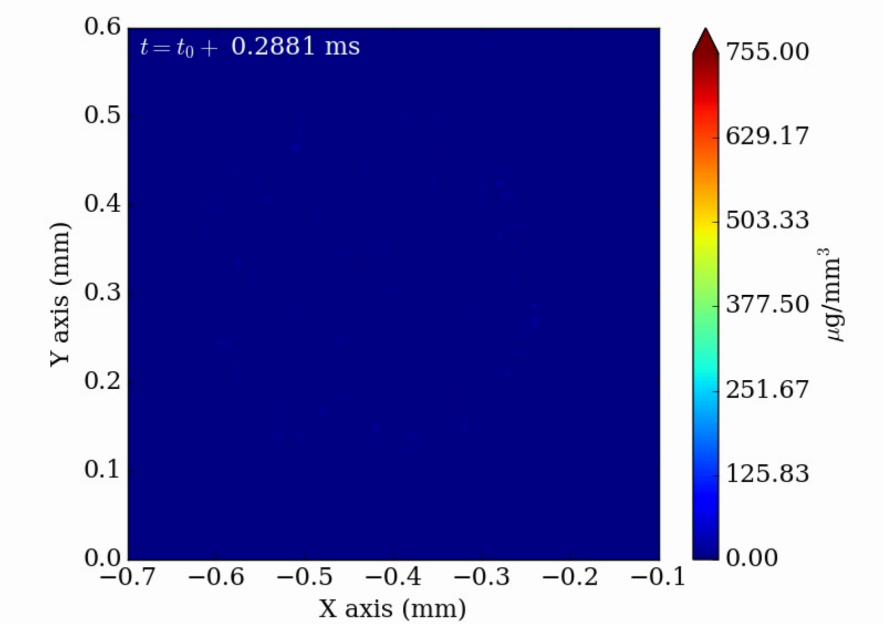
- About 35% of variation in average mass can be attributed to three geometric features



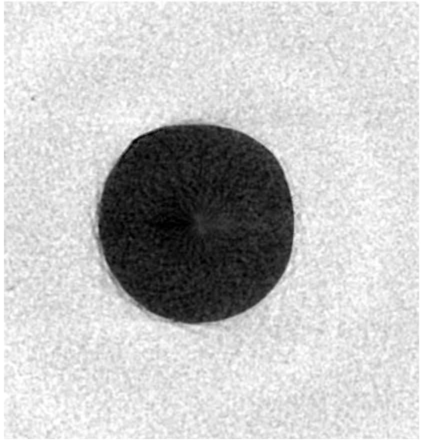
- Correlations are relatively weak: variability across Spray G injectors is small
- Injectors with more geometric variability would provide a better data set for evaluation
- Average total mass is one metric. Exploring average density, peak density
- In discussion with simulation groups to vary geometric features in CFD

3D DENSITY MEASUREMENT OF DIESEL JET

- 90 line-of-sight projections through the spray used to generate 3D reconstruction
- ECN Spray D: Injection pressure 1500 bar, ambient pressure 20 bar
- Density slices at several distances downstream to track primary breakup
- Even at 0.1 mm from nozzle, density is less than bulk liquid
- Evidence of flow separation in “non-cavitating” nozzle
- Results contributed to ECN, to be compared with simulation predictions

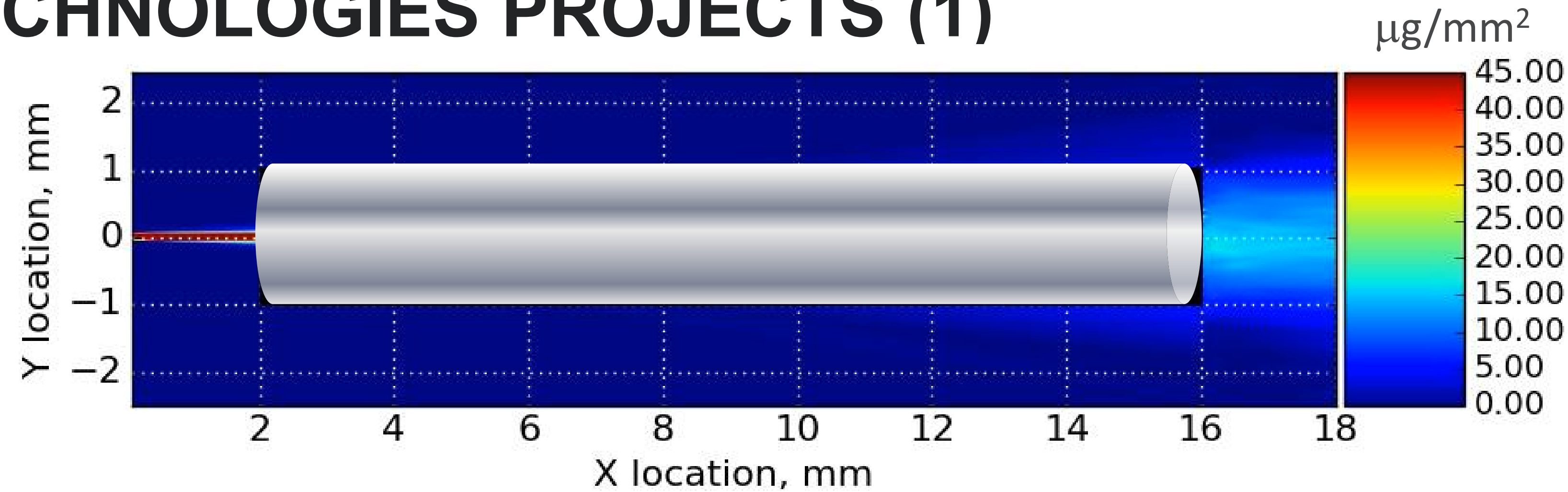


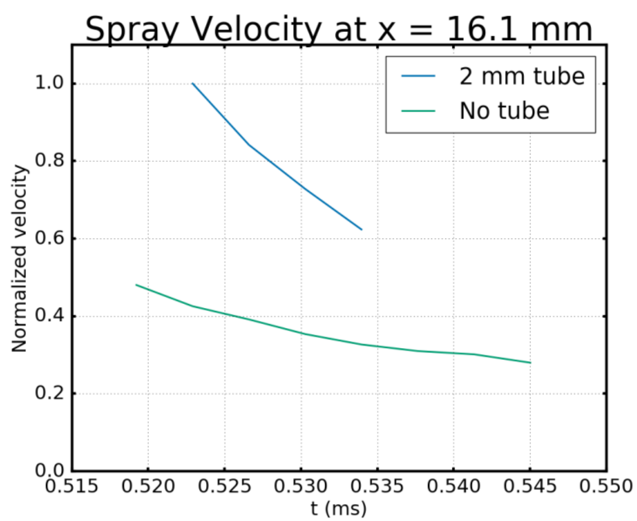
Density slice 0.1 mm from nozzle exit

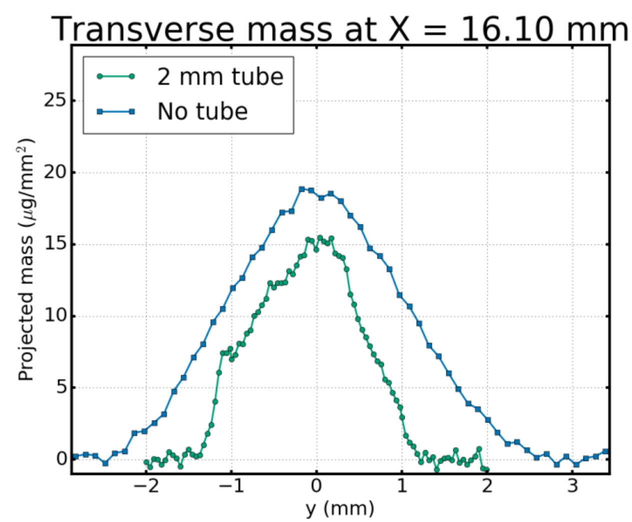


Geometry at nozzle exit

CONTRIBUTIONS TO OTHER VEHICLE TECHNOLOGIES PROJECTS (1)







Measurements of Ducted Fuel Injection for Sandia (Mueller)

Trying to understand how ducted injection leads to lower soot formation

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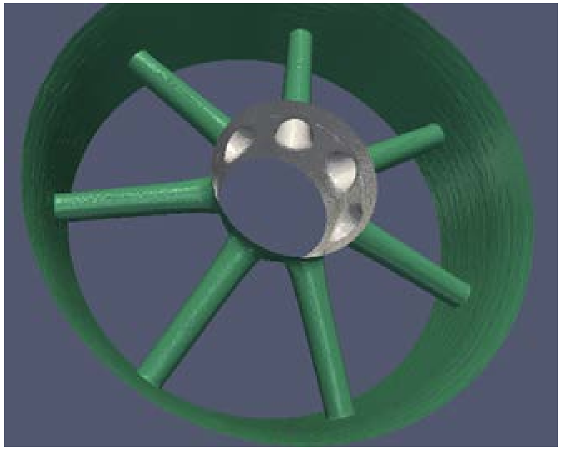
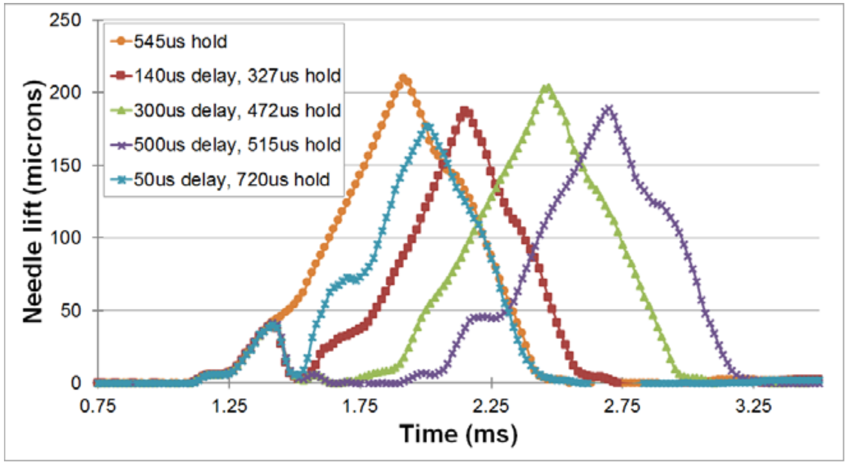
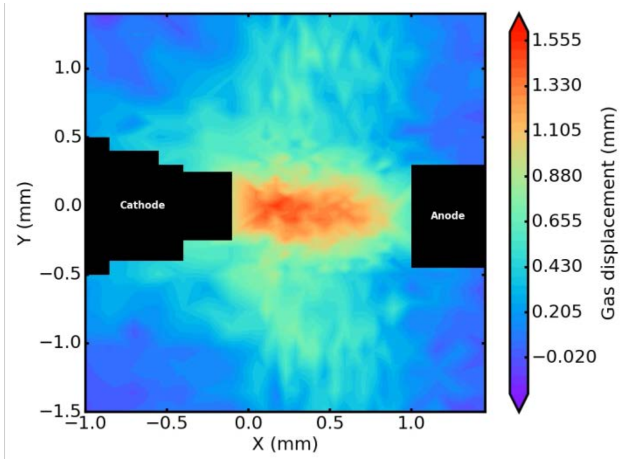
CONTRIBUTIONS TO OTHER VT PROJECTS (2)





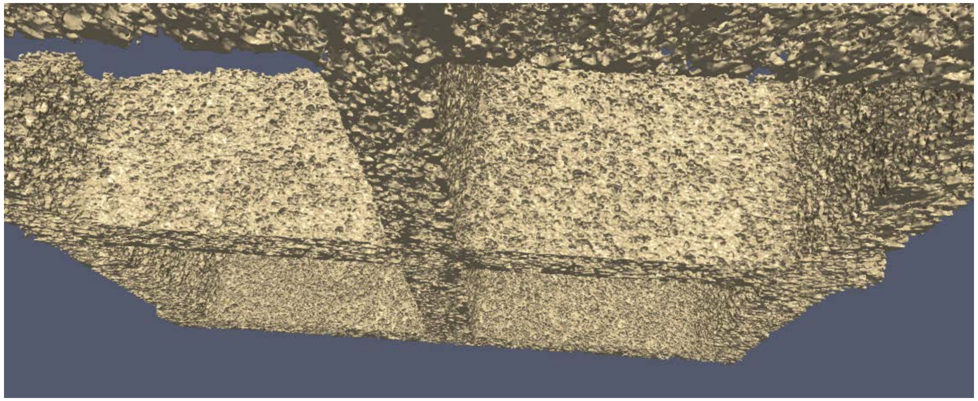
Nozzle Geometry and Needle Motion for Sandia (Busch)

Trying to understand jet-to-jet variability of mixture formation and combustion



Measurement of Gas Density in Spark Gap for Argonne (Scarcelli)

Measurement of total energy deposited by spark



Measurements of DPF Geometry for Argonne (Seong)

Goal is to understand ash loading in GPF, effect on flow

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RESPONSES TO FY2016 REVIEWERS' COMMENTS

"the impression given is that there is little integration of this work with actual modeling"

- We rely on collaboration for advancements in modeling
- We have many partnerships with simulation groups worldwide
- Partnerships range from "one-way" downloading of experimental results, to tight collaboration
- Six publications this year in collaboration with CFD groups

"collaborators should be expanded to include the major manufactures of atomizers"

- We would welcome this
- We have projects with injector manufacturers, but these are almost always proprietary

ACTIVE COLLABORATIONS IN 2016-2017

- **Engine Combustion Network**
  - Measurements of nozzle geometry, needle lift, near-nozzle fuel distribution, droplet size
  - Both GDI and diesel
  - Close collaboration with simulation groups to interpret measurement results
  - Leadership role within ECN
  - Planning of future experimental and modeling targets

- **UMass-Amherst**
  - Joint development of experimental and modeling targets
  - UMass-Amherst does code development, new Σ-Y model
  - Argonne provides time on cluster computer
  - Close collaboration to interpret measurement and simulation results
  - Three publications this year

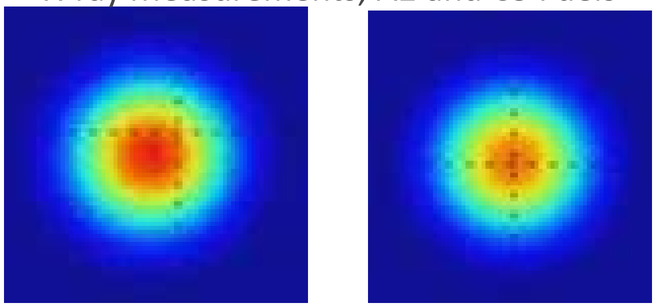
- **Oak Ridge National Lab**
  - Sharing of injector, measurement data
  - Analysis done using staff and computing resources from both labs
  - One publication this year

- **Sandia National Labs: Mueller**
  - Joint design of Argonne test rig
  - Coordination of experimental conditions for study
  - Interpretation of experimental results

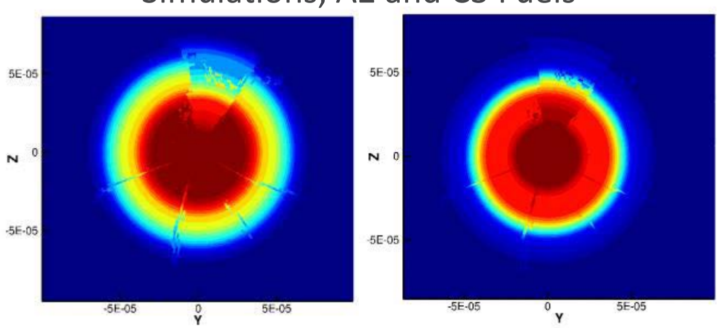
- **CMT Motores Termicos, Valencia**
  - Two Ph.D. students spent 7 months at Argonne
  - Shared measurements from both institutions
  - Four publications this year

ARGONNE'S DATA IS ACTIVELY USED FOR MODEL DEVELOPMENT AND VALIDATION

X-ray Measurements, A2 and C3 Fuels

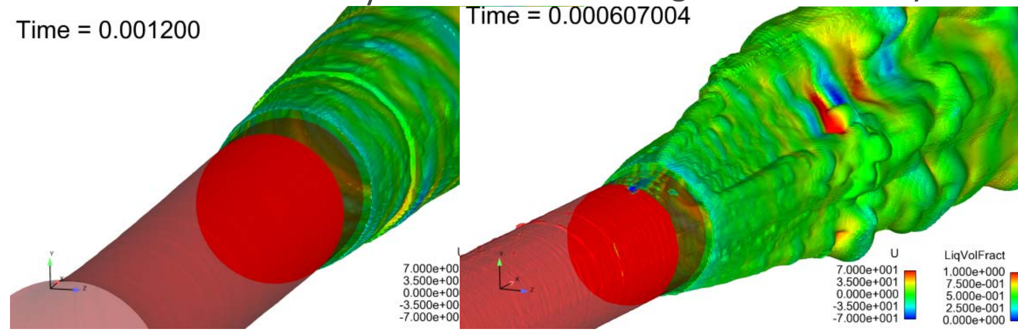


Simulations, A2 and C3 Fuels

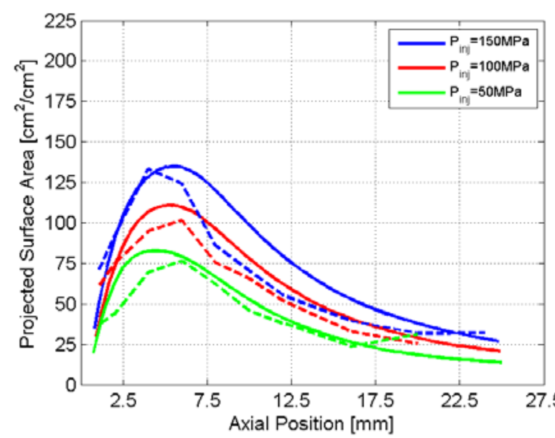


DNS/LES Simulations at ARL
Utilized geometry, needle lift, spray density
Bravo *et al*.

Nominal Geometry   Argonne Geometry



Simulations of Spray D at Univ. of Perugia
Utilized geometry, needle lift, spray density
Battistoni *et al*.



Development of Σ-Y Model at CMT, UMass
Utilized geometry, spray density, drop size
Schmidt *et al*.

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REMAINING CHALLENGES AND BARRIERS

- Need a better understanding of internal nozzle flow
  - Cavitation erosion is a significant problem for industry
  - Link between nozzle geometry and fuel distribution is unclear

- Need a better understanding of near-nozzle spray breakup
  - "Blob" injection model is still widespread in simulations, but this fails near-nozzle
  - Several teams are working on new approaches to primary atomization: Trujillo, Schmidt, Genzale
  - These require experimental data for development and validation

PROPOSED FUTURE WORK IN FY2016 AND FY2017

- Fundamental Measurements of Cavitation
  - Future work in aluminum nozzles
  - Investigate cavitation erosion

- Engine Combustion Network
  - Additional measurements of GDI needle lift
  - Needle motion of diesel Spray C, Spray D

- Nozzle Geometry Measurements
  - Injectors with deposits
  - Cavitation erosion

- Support to Other VT Projects
  - Chuck Mueller: Measure fuel/air mixing *inside* the duct
  - Stephen Busch: X-ray diagnostics of needle motion, internal flow, and near-nozzle behavior with multiple injections

Any proposed future work is subject to change based on funding levels

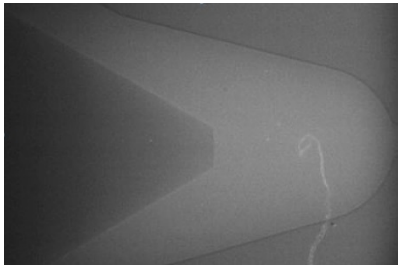
SUMMARY

- Improve the understanding of fuel injection and sprays
  - Fundamental measurements of spray phenomena
    - Cavitation
    - Primary atomization
- Assist in development of improved spray models
  - Partnerships on nozzle flow modeling with UMass Amherst, CMT, Georgia Tech, Perugia, Som, Scarcelli,
  - Data contributed to ECN is assisting model development at IFP, CMT, Sandia, Argonne, UMass, Convergent Science, others.
  - SPPs with Toyota, Army Research, Spray Combustion Consortium, CRADA with Delphi Diesel, FOA with Georgia Tech

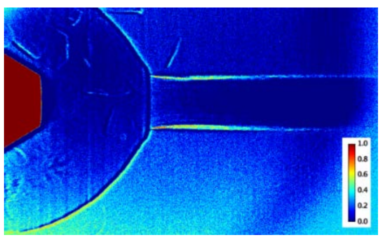
Technical Back-Up Slides

TECHNICAL APPROACH: X-RAY DIAGNOSTICS

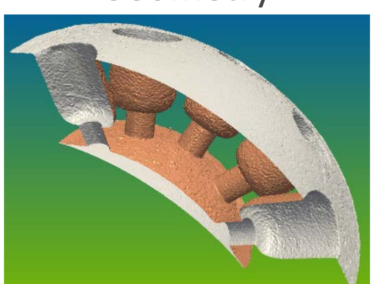
Needle Motion

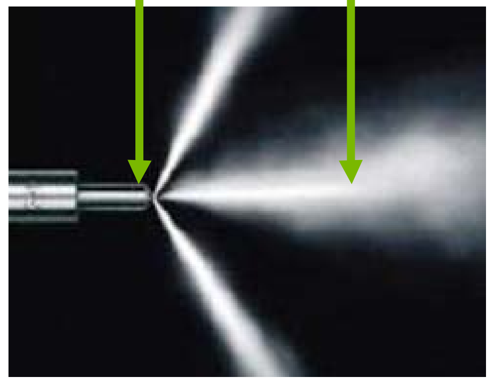


Nozzle Cavitation



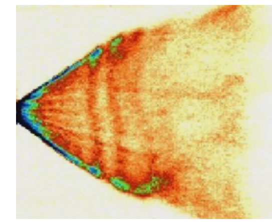
High Precision Nozzle Geometry



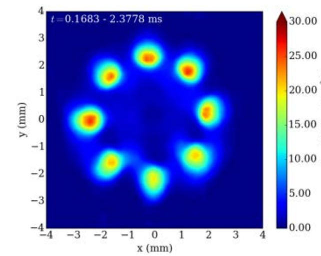


X-rays enable unique capabilities, both *inside* and *outside* the nozzle

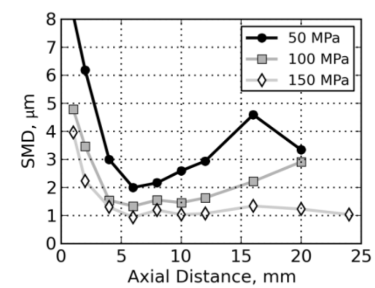
Near-Nozzle Fuel Density



Spray Tomography



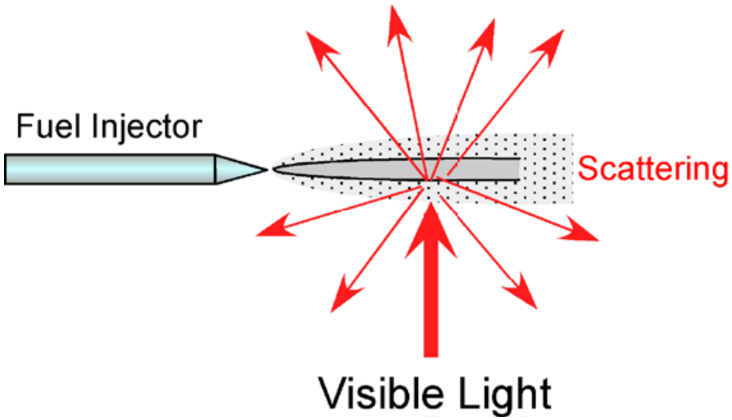
Near-Nozzle Drop Sizing

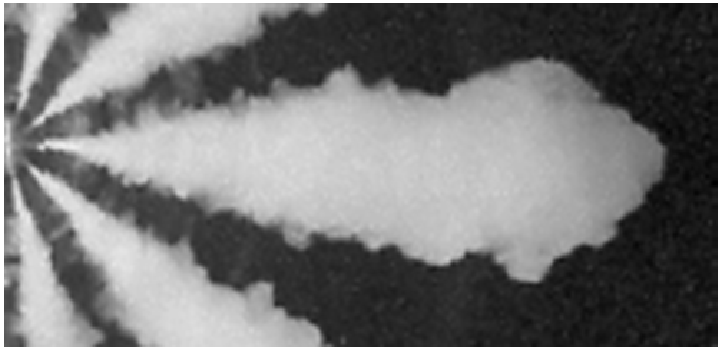


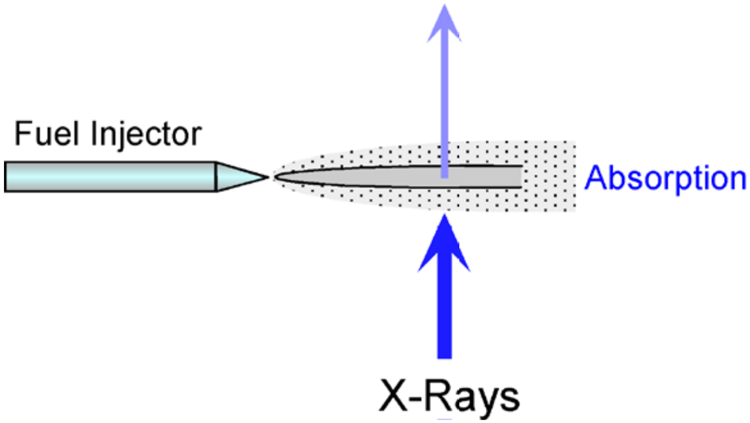
TECHNICAL APPROACH – X-RAY DIAGNOSTICS

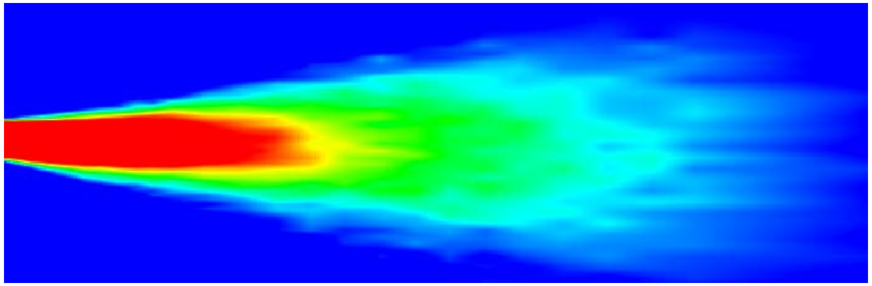
- **X-rays enable unique diagnostics**
  - Near-nozzle measurements of fuel injection
  - Mass-based measurements of the fuel distribution
  - Penetrate through steel to measure geometry, flow, motion
  - Fast time resolution (<5 ms)
  - Fine spatial resolution (< 5 μm)
- **Limitations**
  - Can’t penetrate more than ~10 mm of steel (or glass, sapphire)
  - Room temperature ambient (plastic windows)
  - Techniques developed require a synchrotron x-ray source
- **Strategy**
  1. Measurements of relevant injectors and conditions
  2. Partnerships with model developers to utilize these measurements

TECHNICAL APPROACH – X-RAYS REVEAL FUNDAMENTAL SPRAY STRUCTURE





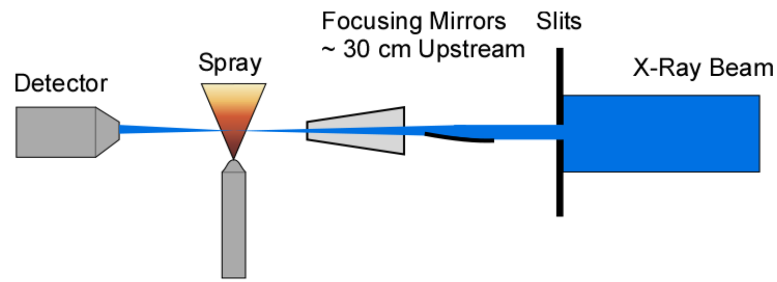


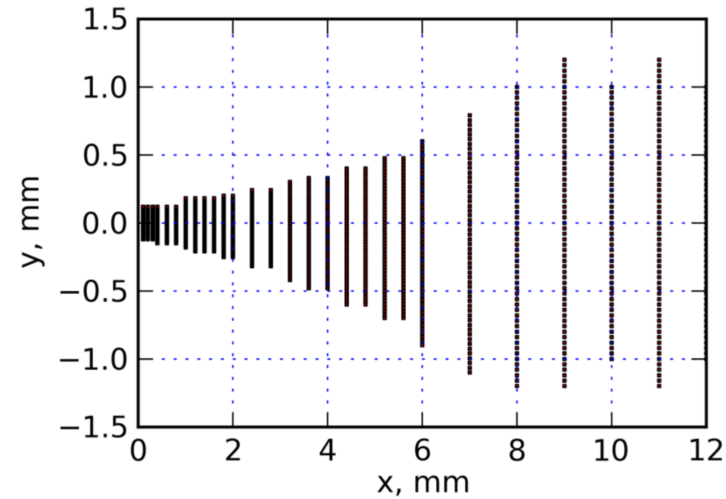


- Room temperature
- Ensemble averaged
- Pressure up to 30 bar

EXPERIMENTAL METHOD

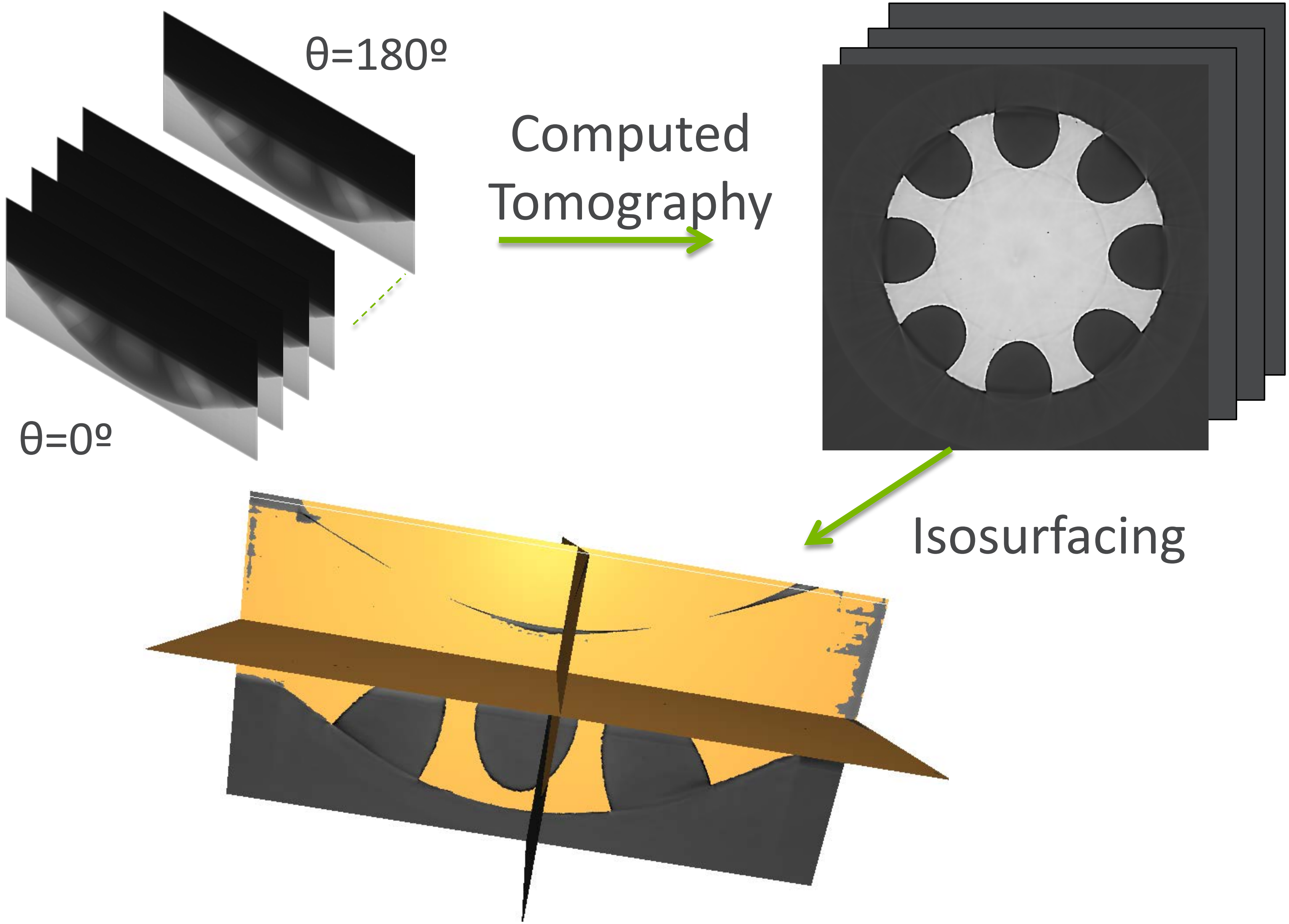
- Focused beam in raster-scan mode
- Beam size 5 x 6 μm FWHM
  - Divergence 3 mrad H x 2 mrad V
  - Beam size constant across spray
- Time resolution: 3.68 μs
- Each point an average of 32-256 injection events
- Beer's law to convert x-ray transmission to mass/area in beam
- Fuel absorption coefficient: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





Example Measurement Grid

PROCEDURE TO CONSTRUCT 3D GEOMETRY



Optimizing the original images simplifies subsequent steps

ACTIVE COLLABORATIONS IN 2016-2017

- **Needle Motion**
  - ECN: contributed Spray G needle motion
  - CMT Valencia: measurements linking needle lift and ROI
  - UMass-Amherst: GDI needle lift for nozzle flow simulations
- **Nozzle Cavitation**
  - UMass-Amherst: provided data, computer time for cavitation simulations
  - CMT: provided data for cavitation simulations
- **Injector Geometry**
  - ECN: Measured 8 GDI injectors
  - Sandia: measured injector from Stephen Busch's engine
  - Oak Ridge: measurements on common GDI injector, joint paper on injector flow simulations
- **Near-Nozzle Fuel Density**
  - ECN: Fuel distribution of Spray D
  - Georgia Tech: Diesel data used for model validation, visible light comparison
  - Argonne (Som): Shot-shot variation measurements for LES validation
- **Spray Tomography**
  - ECN: 3D fuel distribution of Spray G and comparison with model predictions
  - UMass-Amherst: Provided 3D fuel distribution of GDI spray, used for model validation and improvements to HRM
- **Near-Nozzle Drop Sizing**
  - CMT Valencia: Joint experiments on diesel spray drop size
  - Georgia Tech: Measured diesel spray drop size, comparison with simulation and visible light size measurements