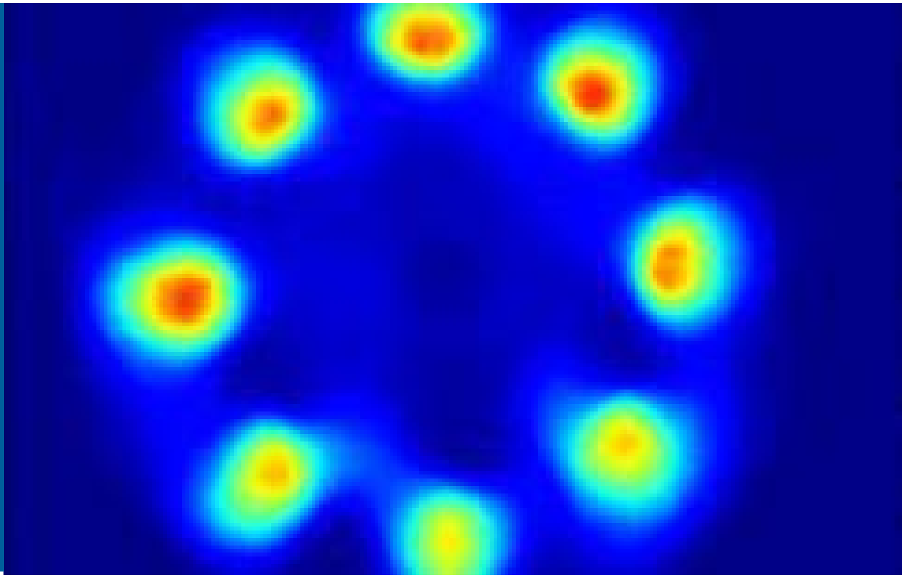
PROJECT ID ACE10

FUEL INJECTION AND SPRAY RESEARCH USING X-RAY DIAGNOSTICS



CHRISTOPHER POWELL, DANIEL DUKE, KATARZYNA MATUSIK, ALAN KASTENGREN, ANDREW SWANTEK

Argonne National Laboratory
8 June 2016

TEAM LEADERS:
Gurpreet Singh
Leo Breton

OVERVIEW

Timeline

- FY2000: Project Start
- FY2017: DOE Lab Call

Budget

- FY2015: $775K
- FY2016: $700K

Partners

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

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

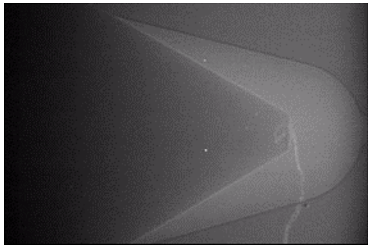
- **Use our unique ability to measure near the nozzle to improve the fundamental understanding of fuel injection and sprays**
- **Assist in development of improved spray models using quantitative spray diagnostics**

OBJECTIVES AND MILESTONES

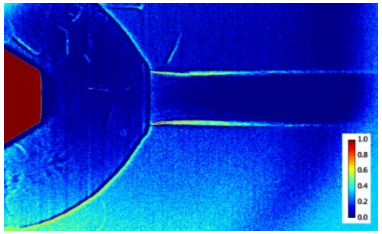
Date	Objective	Technique	Status
September 2015	Cavitation Measurements in High Precision Transparent Nozzle	Nozzle Cavitation	Complete
December 2015	Needle motion measurements of ECN Spray G injectors	Needle Motion	Complete
March 2016	Complete investigation of link between spray angle and needle motion	Needle Motion, Fuel Density	Complete
June 2016	High resolution measurements of cavitation in x-ray transparent nozzle	Nozzle Cavitation	On Track
September 2016	Droplet size measurements of sprays from ECN injectors	Droplet Sizing	On Track

TECHNICAL APPROACH: X-RAY DIAGNOSTICS

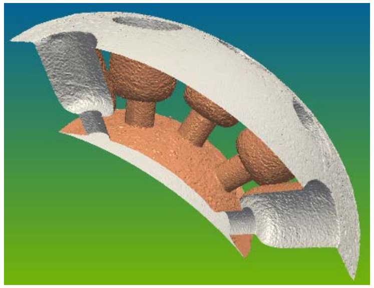
Needle Motion

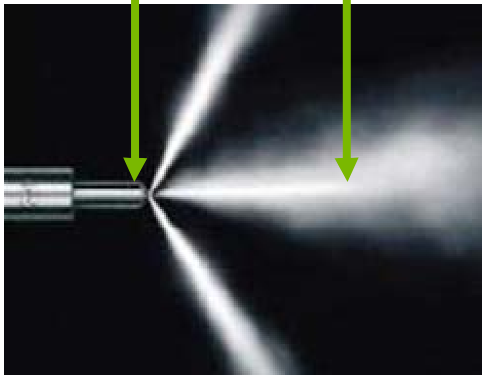


Nozzle Cavitation



High Precision Nozzle Geometry

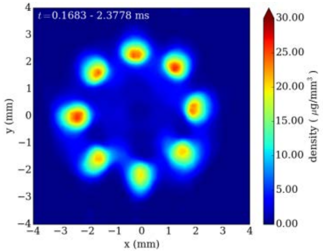




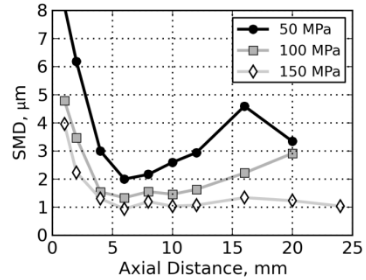
X-rays enable unique capabilities, both *inside* and *outside* the nozzle

Near-Nozzle Fuel Density

Spray Tomogaphy



Near-Nozzle Drop Sizing



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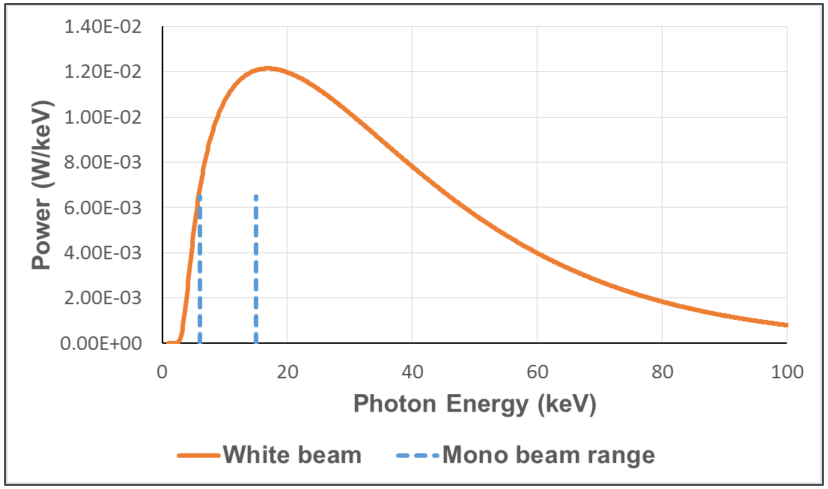
TECHNICAL APPROACH – X-RAY DIAGNOSTICS

- **X-rays enable unique diagnostics**
  - 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**
  - Room temperature ambient (plastic windows)
  - Can't penetrate more than ~10 mm of steel
- **Strategy**
  1. Measurements of relevant injectors and conditions
     - ECN, industrial partners, other VT Projects
  2. Partnerships with model developers to utilize these measurements
     - ECN, industrial partners, other VT Projects, universities

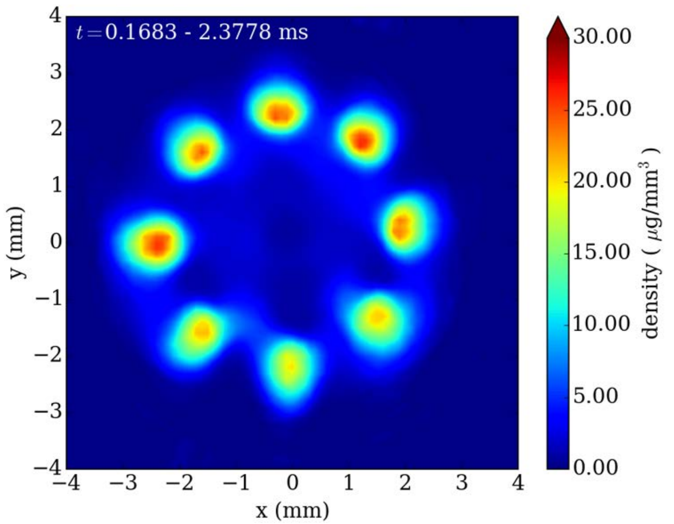
UPGRADE TO X-RAY LAB ENABLES HIGH PRECISION INJECTOR MEASUREMENTS

Broadband spectrum of x-ray energies now available



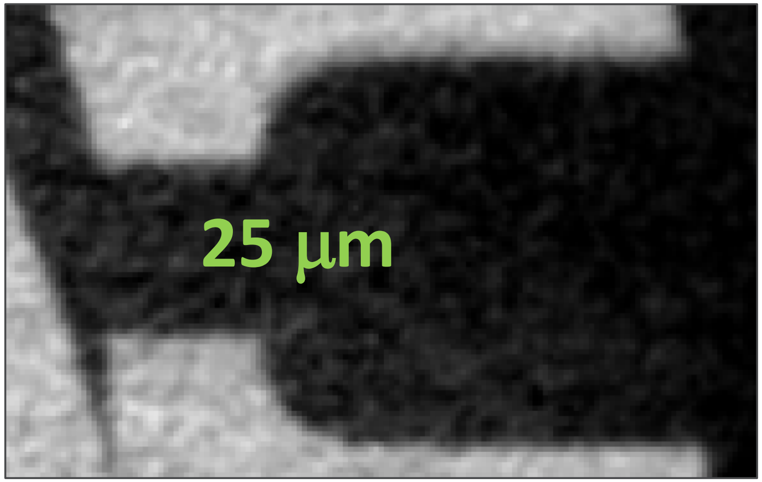
- Increased flux & energy improve penetration through steel
- Enables high quality measurements of nozzle geometry

- Geometry measurements are crucial for flow simulations
  - ECN Spray G hole diameters vary by 11 μm, ±20% mass flux
  - Radius of curvature at hole entrance varies from 6-17 μm

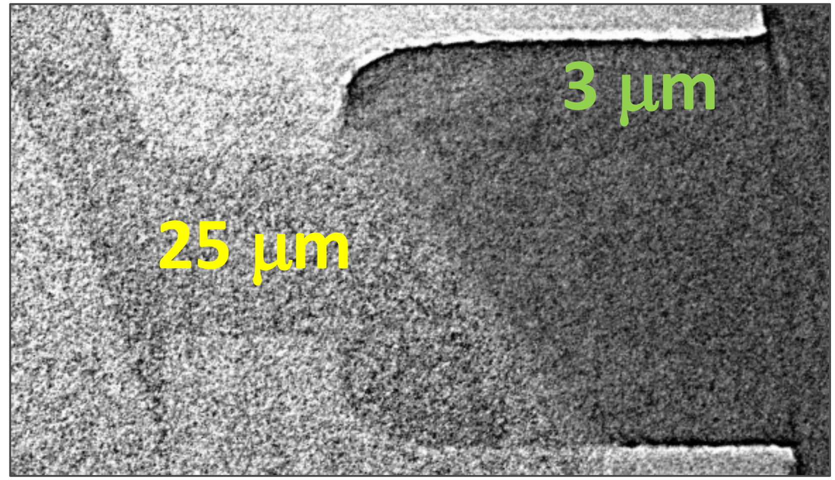


HIGH PRECISION HAS BEEN ACHIEVED

Comparison of Spray G Nozzle Geometry from Different Sources

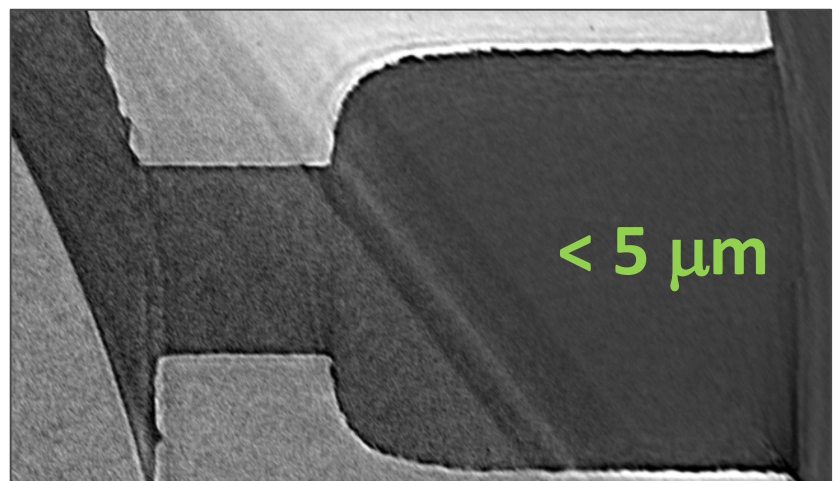


Northstar Imaging



European Synchrotron

- Nozzle geometries are available from other sources, but limited resolution
- Optimized x-ray beam, optics, data processing
- World-class spatial resolution



Argonne Vehicle Technologies

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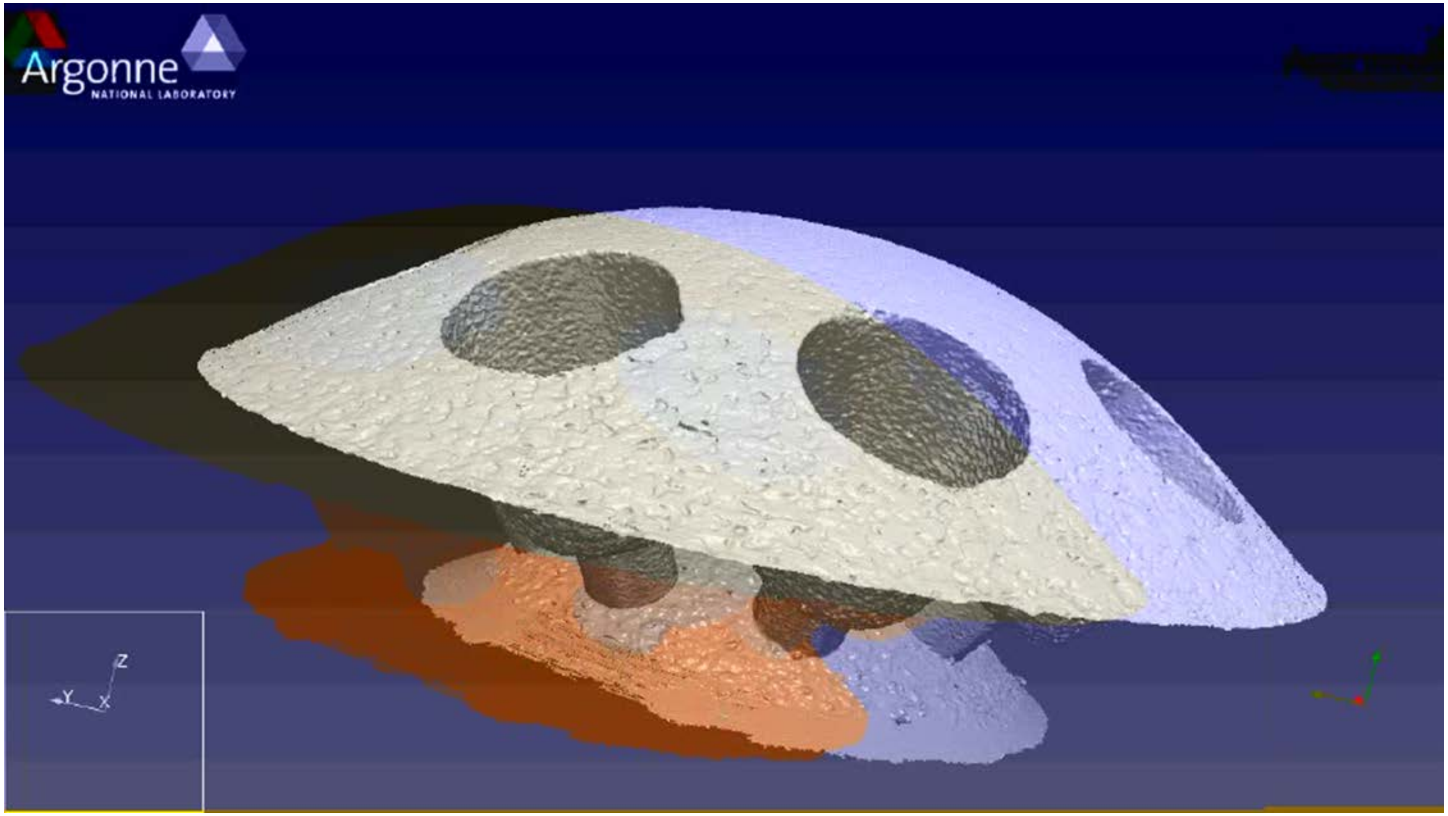
3D MODEL OF ECN SPRAY G NOZZLE

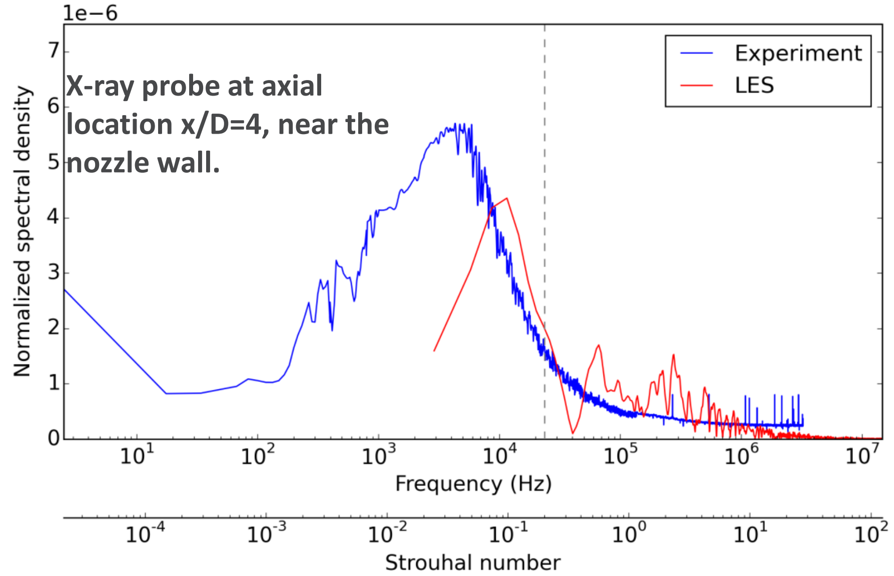


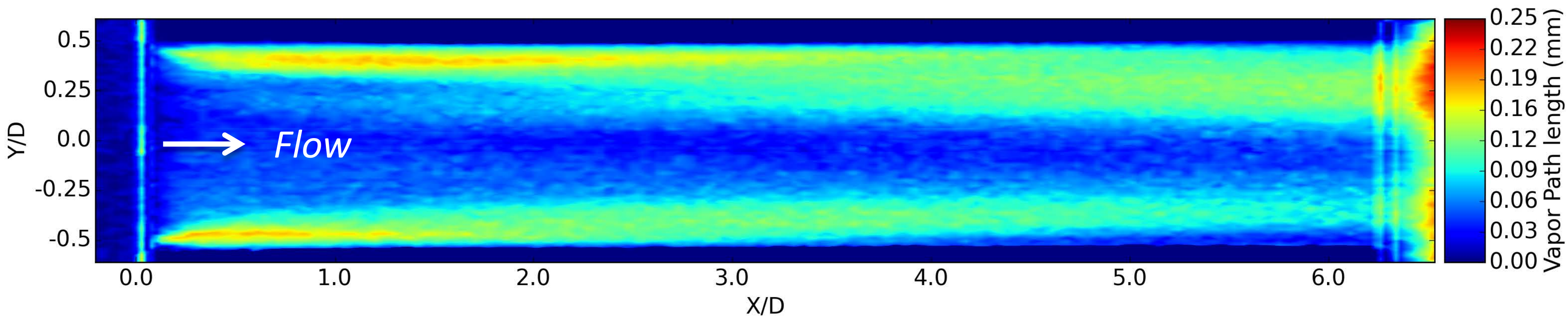
- Geometry has been shared with ECN
- Significant interest from industrial partners, other labs
- Other applications:
  - Assess nozzle manufacturing process
  - Deposits
  - Cavitation erosion

X-RAY MEASUREMENTS OF CAVITATION

Submerged Cavitating Jet in a Metal Nozzle

- Previous work was time-averaged using plastic nozzles.
- New beryllium nozzle: x-ray transparent, higher pressures, good surface finish
- Time resolved measurements of vapor fraction in cavitating flows
- Engine-relevant Re (25-30,000) and cavitation numbers
- Quantitative measurements of fluctuations and spectral content (3 MHz, faster than with visible light)
- Comparison with UMass simulations





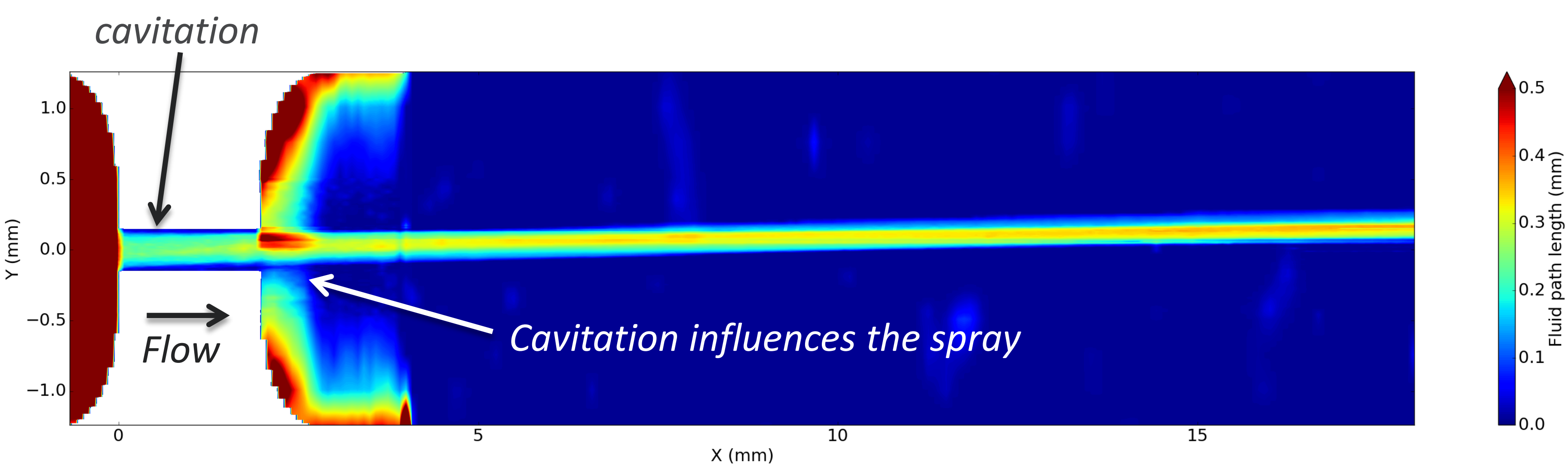
P_{in} = 23.7 bar, P_{out} = 0.3 bar

Duke et al. ILASS 2016

X-RAY MEASUREMENTS OF CAVITATION

Simultaneous Measurement of Cavitation and Spray

- Previous work was a submerged cavitating jet.
- New *spraying* beryllium nozzle with GDI shape, 300 μm diameter
- Simultaneous measurement of vapor fraction inside and outside the nozzle
- Several combinations of ambient gas composition and pressure
  - Allows isolation of the effects of cavitation and shear-driven breakup



P_{inj} = 23 bar, P_{amb} = 2.3 bar

Publication in Preparation

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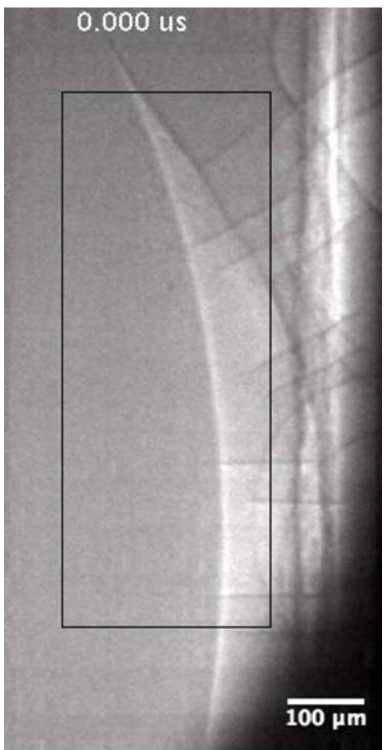
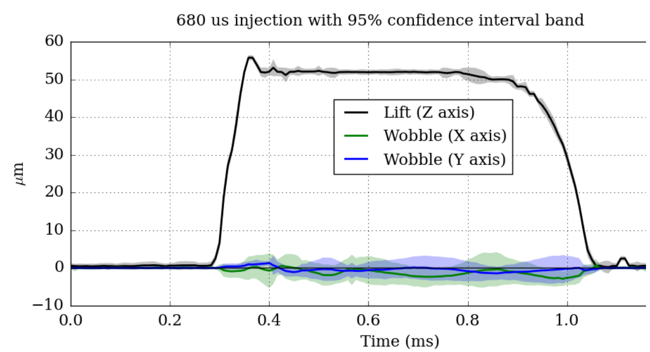
TECHNICAL ACCOMPLISHMENT: CONTRIBUTIONS TO THE ENGINE COMBUSTION NETWORK

- Our contributions to ECN include:
  - Injector geometry
  - Needle motion
  - Near-nozzle spray density
  - Near-nozzle Sauter Mean Diameter
- Collaboration with simulation groups



GDI Needle Motion

- Needle lift is highly repeatable
- Off-Axis needle motion is minimal in this injector



GDI Nozzle Geometry

- Significant surface roughness in flow passages
- Significant hole-hole variations in injector geometry
- These are important for simulations

RESPONSES TO FY2015 REVIEWERS' COMMENTS

"interaction with the engine groups at SNL or ORNL may also be valuable"

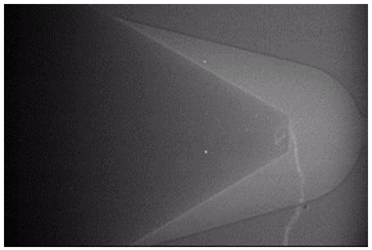
- Upcoming work on Leaner-Lifted Combustion
- Recently measured injector geometry for Stephen Busch
- Collaboration with Oak Ridge neutron group

"efforts which can increase the degree of similarity between the metal injector and the x-ray accessible hardware will be of highest value"

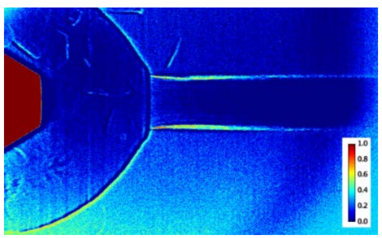
- We have been working in this direction:
  - Cavitation density now measured in metal nozzle, matching GDI shape, Reynolds, and cavitation numbers
  - Measurements this year focused on multi-hole rather than single-hole geometries

TECHNICAL APPROACH: X-RAY DIAGNOSTICS

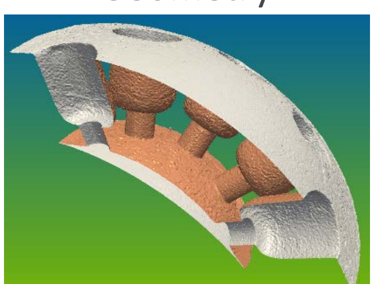
Needle Motion

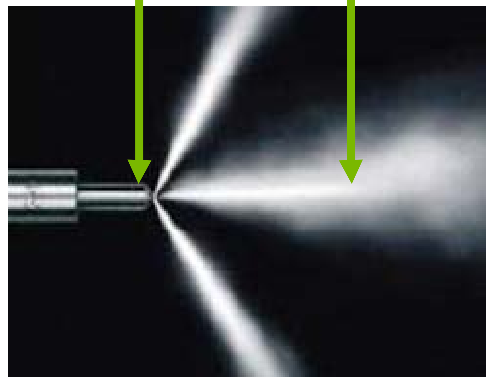


Nozzle Cavitation



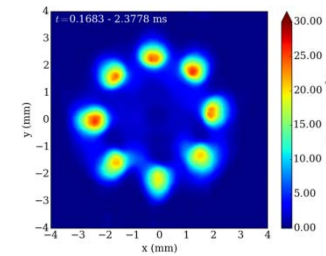
High Precision Nozzle Geometry



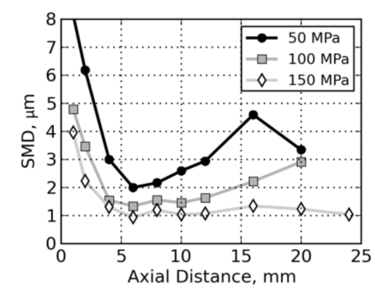


Near-Nozzle Fuel Density

Spray Tomography



Near-Nozzle Drop Sizing



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

ACTIVE COLLABORATIONS IN 2015-2016

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
- Argonne (Som):

Nozzle Cavitation
- UMass-Amherst: provided data, computer time for cavitation simulations
- University of Perugia: provided data for cavitation simulations
- Argonne (Som): provided data for cavitation simulations

Injector Geometry
- ECN: Measured 7 ECN injectors
- Cummins: provided 2 injector geometries
- Sandia: measured injector from Stephen Busch's engine
- Oak Ridge: measurements on common GDI injector

Near-Nozzle Fuel Density
- ECN: Fuel distribution of Spray B
- CMT Valencia: measurements linking fuel distribution and needle lift
- 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 laser drop size measurements

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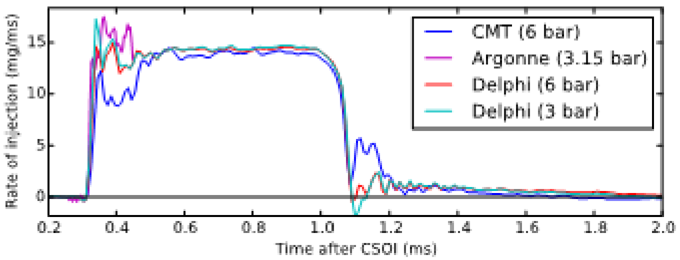
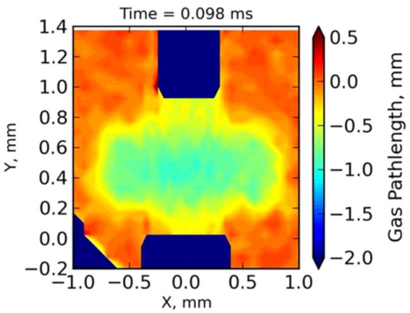
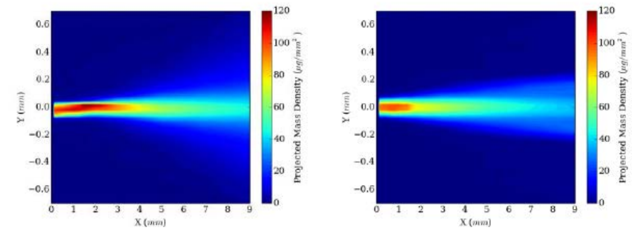
ARGONNE'S DATA IS ACTIVELY USED WORLDWIDE



ECN4

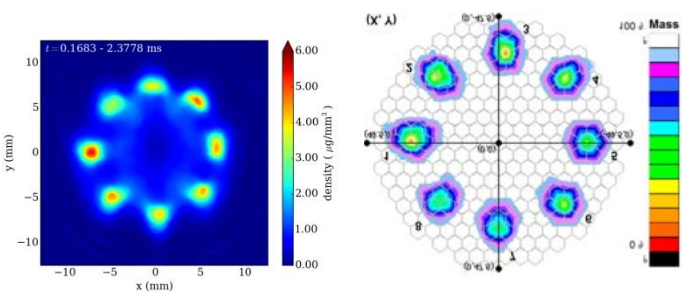


TPS, Inc

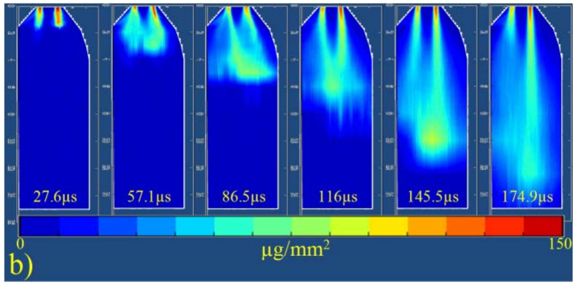


Argonne

Van Dam et al, ILASS 2016

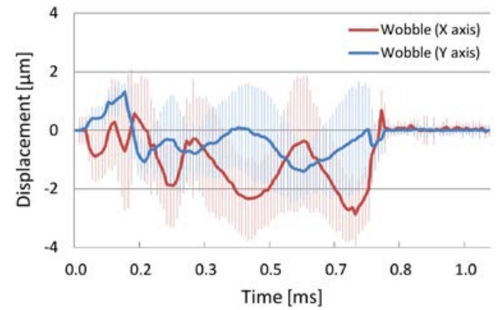


ECN4



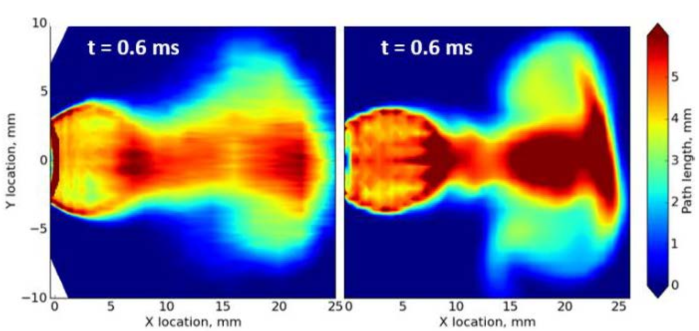
Monash University

Nguyen et al, Aust Comb Symp 2015



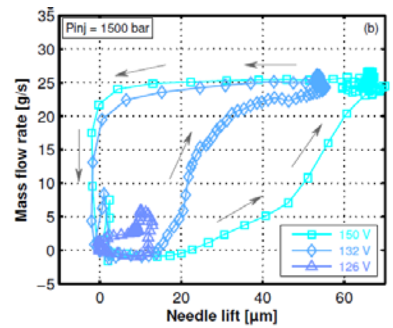
UMass, GM

Baldwin et al, ILASS 2016



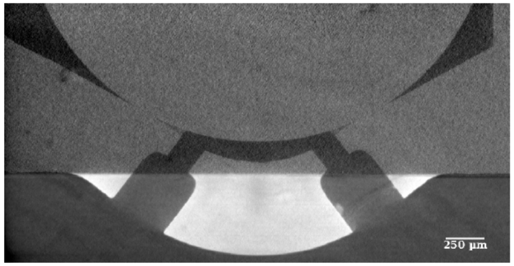
Argonne

Bartolucci et al, SAE 2016-01-0850



CMT Motores Termicos

Viera et al, Energy Conv & Man, 2016



UMass Amherst

Strek et al, SAE 2016-01-0858

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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

- New capability for broadband x-rays this year, 5x increase
- 5x increase in flux with APS upgrade

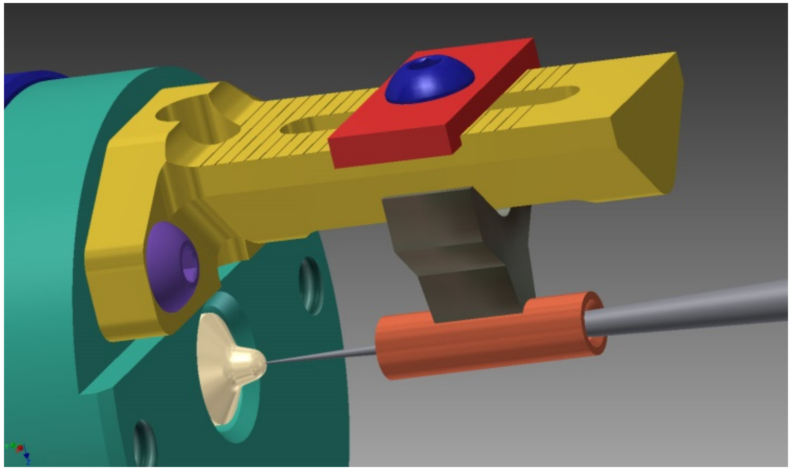
Temperature

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

- Start by heating fuel to explore flash-boiling gasoline: September 2016
- APS Upgrade: Proposed facility for high temperature sprays, combustion

PROPOSED FUTURE WORK IN FY2016 AND FY2017

- Engine Combustion Network
  - Additional measurements of GDI nozzle geometry, spray density
  - Sprays, needle motion, geometry of Spray C, Spray D
  - Serving as Topic Lead for GDI Geometry and Internal Flow
- Cavitation Studies
  - Measurements of bubble size
  - Real-size, real pressure transparent nozzles
- Investigation of mixing for Leaner Lifted-Flame Combustion
  - Measure fuel/air mixing inside the duct
- Evaporating Sprays
  - Funded by the Co-Optimization of Fuels & Engines project, measurements of flash-boiling sprays will be completed later this year.
- Spark and Laser Ignition
  - Supporting ignition research projects
- Nozzle Geometry Measurements
  - Collaboration with Oak Ridge
  - Improvements to hardware and workflow
  - Make technique a resource for our partners



SUMMARY

- Improve the understanding of fuel injection and sprays
  - Fundamental measurements of spray phenomena
    - Cavitation
    - Needle lift and its relation to ROI
  - 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 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,

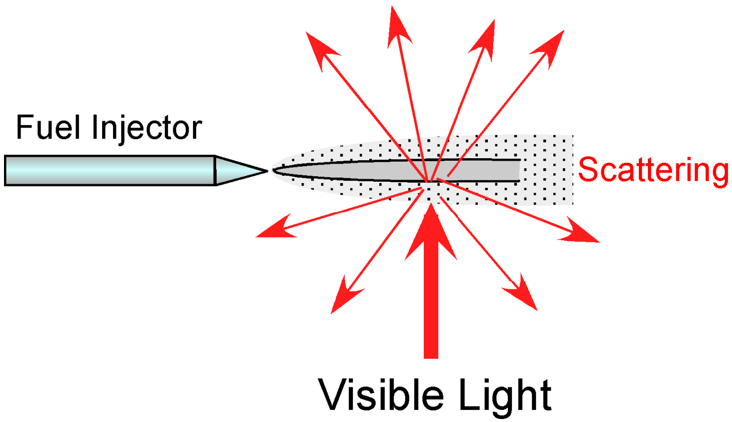
Technical Back-Up Slides

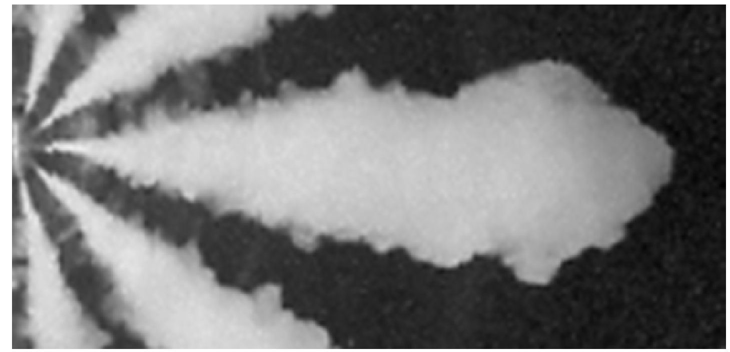
TECHNICAL APPROACH

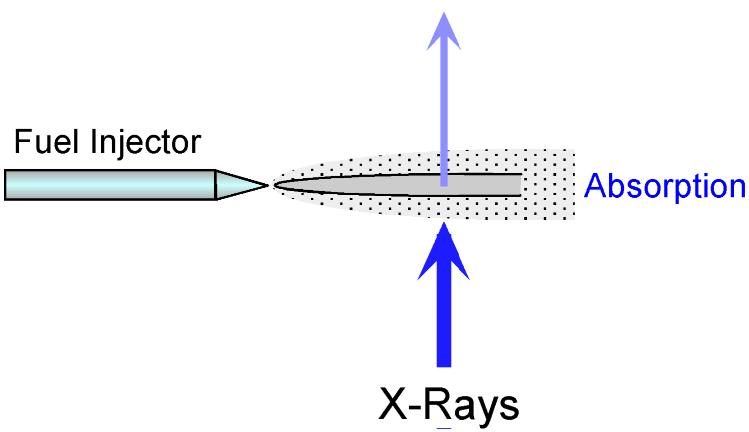
- **Perform injector and spray measurements that increase fundamental understanding**
  - Engine Combustion Network
  - Measurements of cavitation
  - Measurements of needle motion
  - Measurements of internal nozzle flow
  - Droplet sizing

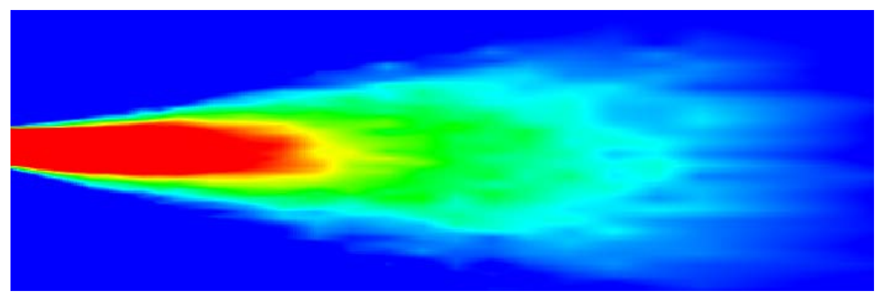
- **Use our measurements to assist the development of computational spray models**
  - Collaboration with Som, UMass Amherst, Univ. Perugia, ARL
  - Engine Combustion Network
  - Collaboration with Argonne modeling group
  - Delphi Diesel CRADA, Caterpillar WFO, Bosch WFO

TECHNICAL APPROACH – X-RAYS REVEAL FUNDAMENTAL SPRAY STRUCTURE





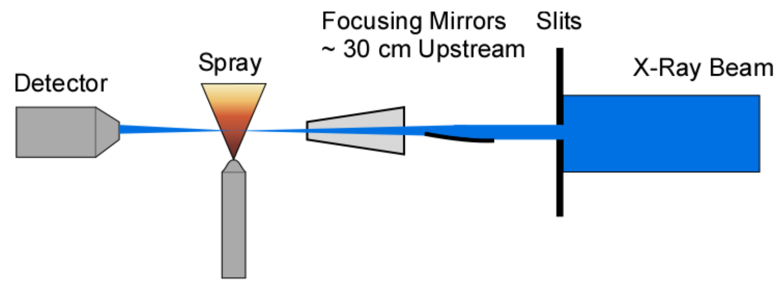


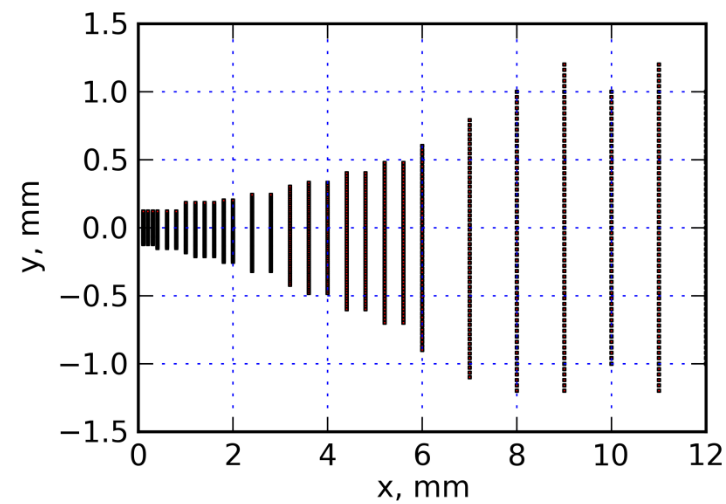


- Room temperature
- Ensemble averaged
- Pressure up to 30 bar

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%



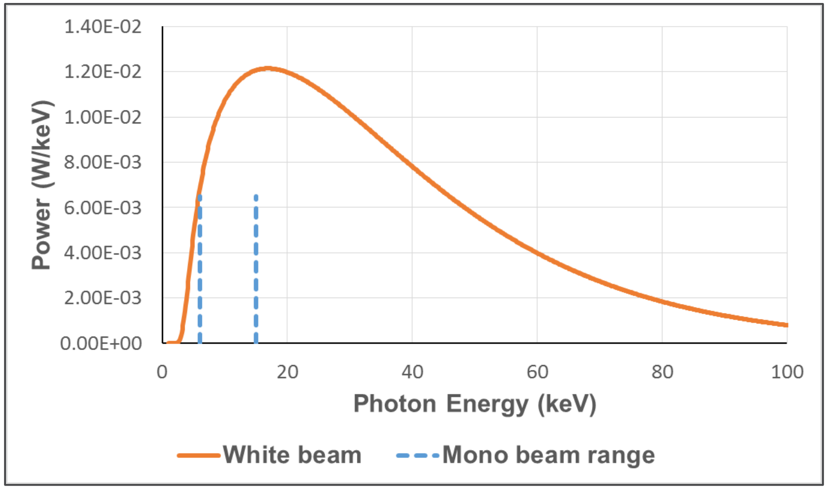


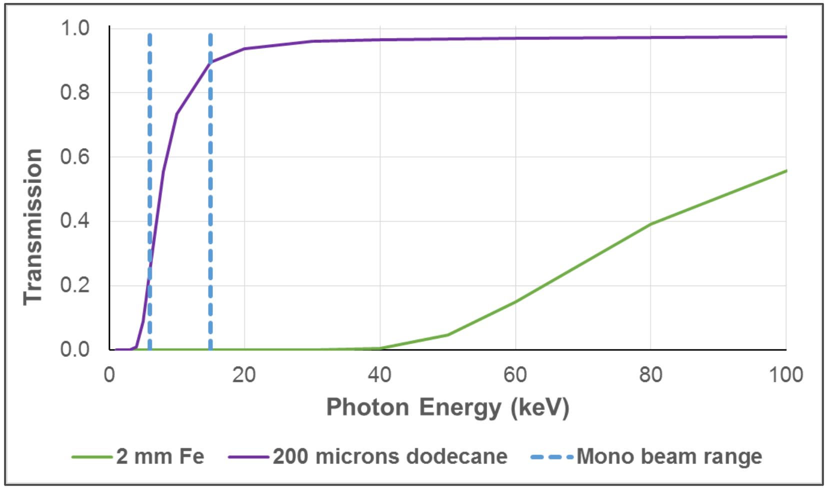
Example Measurement Grid

UPGRADE TO ARGONNE'S VEHICLE TECHNOLOGIES X-RAY BEAMLINE

"White" Beam Capability

- Recent upgrade to beamline now enables use of broadband x-rays





- Increased flux & energy enable nozzle tomography
- Deeper penetration of x-rays through nozzle body
  - High contrast images
  - High spatial resolution

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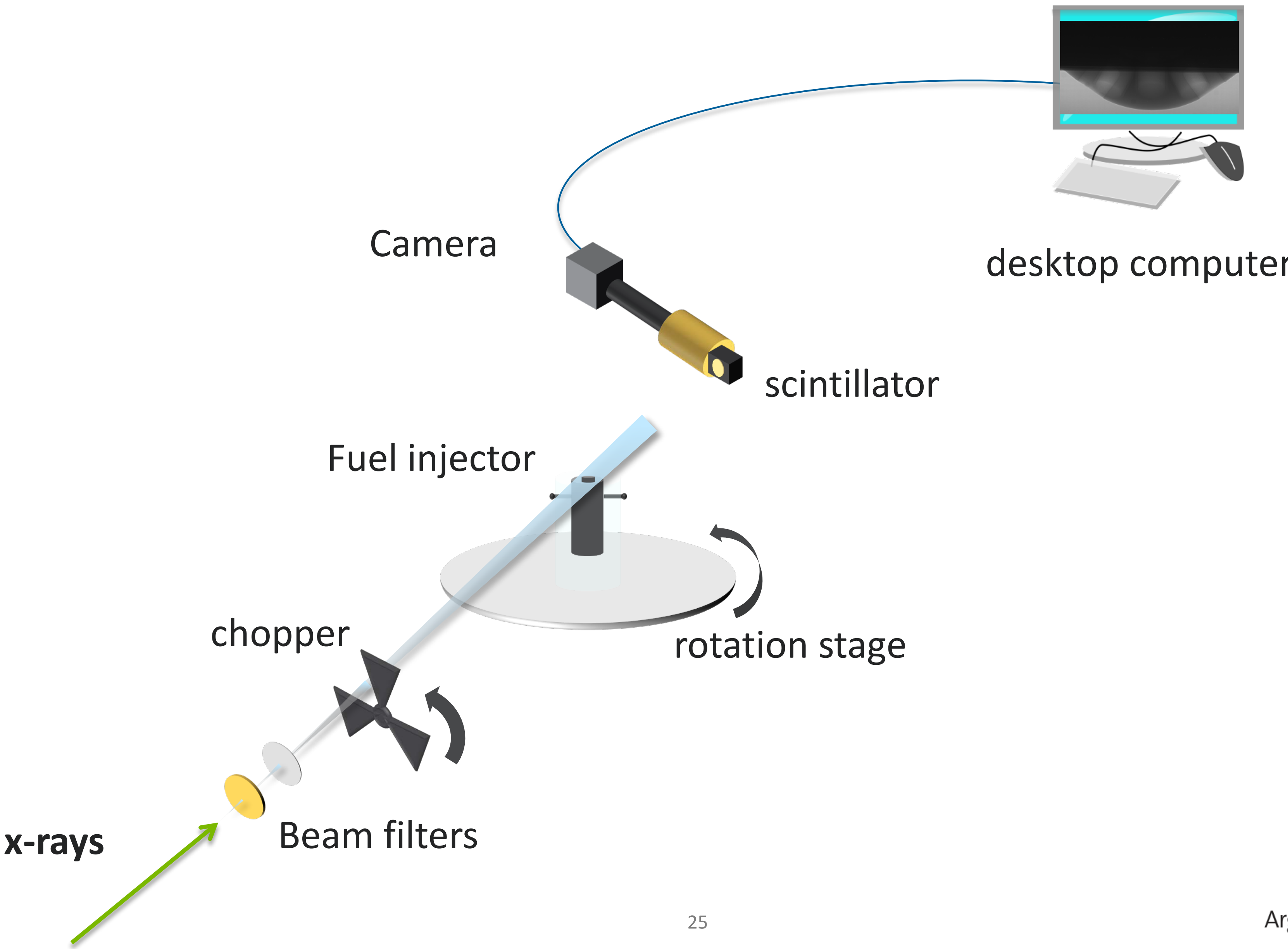
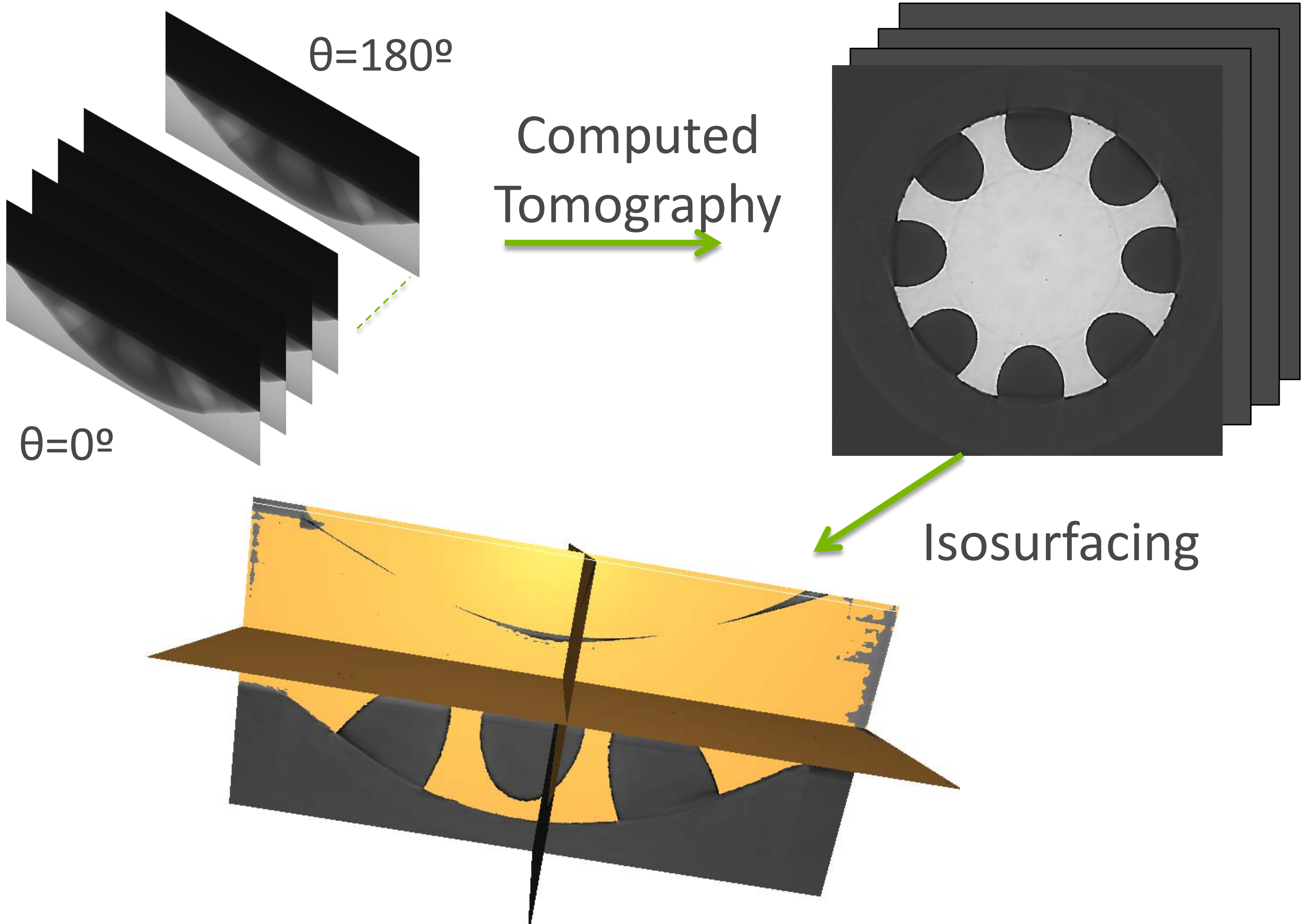
EXPERIMENTAL SCHEMATIC



PROCEDURE TO CONSTRUCT 3D GEOMETRY



Optimizing the original images simplifies subsequent steps

FUTURE WORK

Collaboration with ORNL on nozzle geometry

- ORNL neutron diagnostics excel at large and dense objects
  - Capable of scanning entire injector with ~ 30 μm resolution
- APS offers better spatial resolution but cannot penetrate as deeply
  - High resolution most important at injector tip