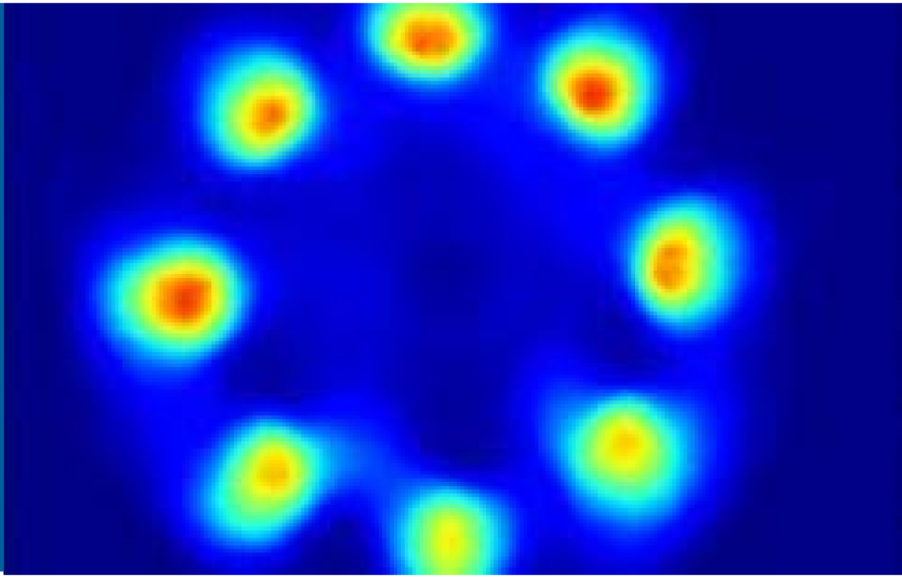
PROJECT ID ACS010

FUEL INJECTION AND SPRAY RESEARCH USING X-RAY DIAGNOSTICS



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Argonne National Laboratory
19 June 2018

TEAM LEADERS:
Gurpreet Singh
Michael Weismiller

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OVERVIEW

Timeline

- Project begain under FY2017 DOE Lab Call

Budget

- FY2017: $557K
- FY2018: $398K (reduced spend rate)

Partners

- Engine Combustion Network, UMass-Amherst, Argonne, Sandia, Oak Ridge
- Aramco, Georgia Tech, Co-Optima, Delphi Diesel, Spray Combustion Consortium, CMT-Motores Térmicos, Caterpillar

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

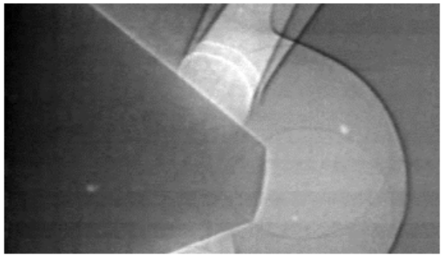
- **Use our unique ability to measure near the nozzle to improve the fundamental understanding of fuel injection and sprays (low TRL)**
- **Assist in development of improved spray models using quantitative spray diagnostics**
- **Make these measurements accessible to our industrial partners and the wider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

OBJECTIVES AND MILESTONES

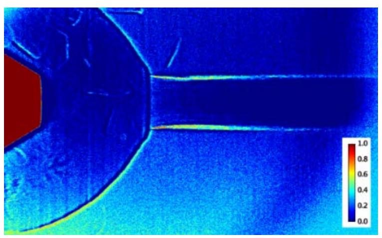
Date	Objective	Technique	Status
March 2018	Complete measurements of the near-nozzle fuel distribution from the ECN "Spray C" diesel injector, quantifying the impact of cavitation on the fuel and air mixing.	Fuel Density	Complete
June 2018	Complete measurements of the near-nozzle droplet size, comparing cavitating with non-cavitating nozzles in order to provide validation for coupled simulations of internal flow and spray breakup.	Near-Nozzle Surface Area	Complete

TECHNICAL APPROACH: X-RAY DIAGNOSTICS

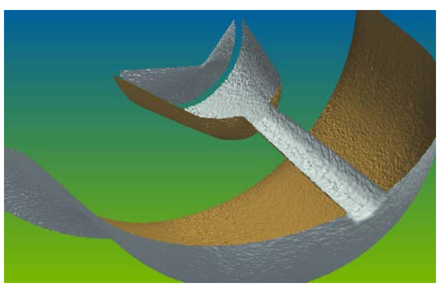
Needle Motion

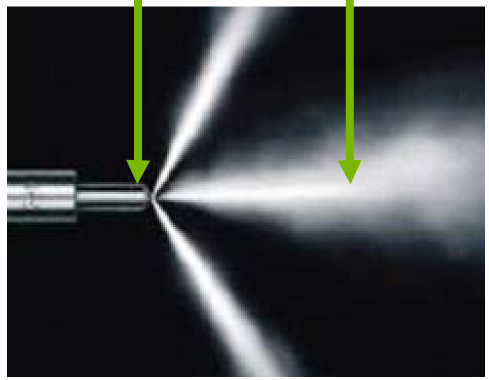


Nozzle Cavitation



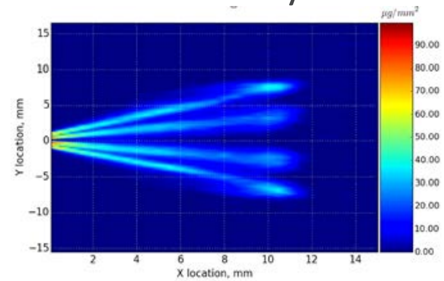
High Precision Nozzle Geometry



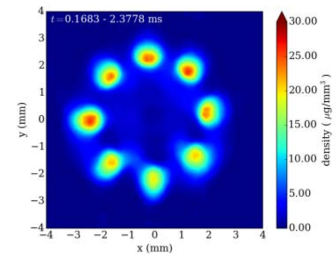


X-rays enable unique capabilities, both *inside* and *outside* the nozzle

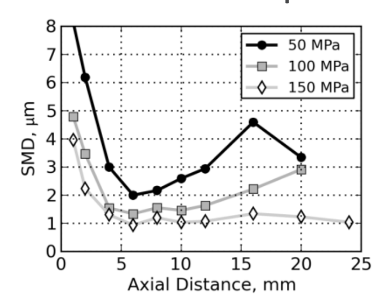
Near-Nozzle Fuel Density



Spray Tomography



Near-Nozzle Drop Sizing



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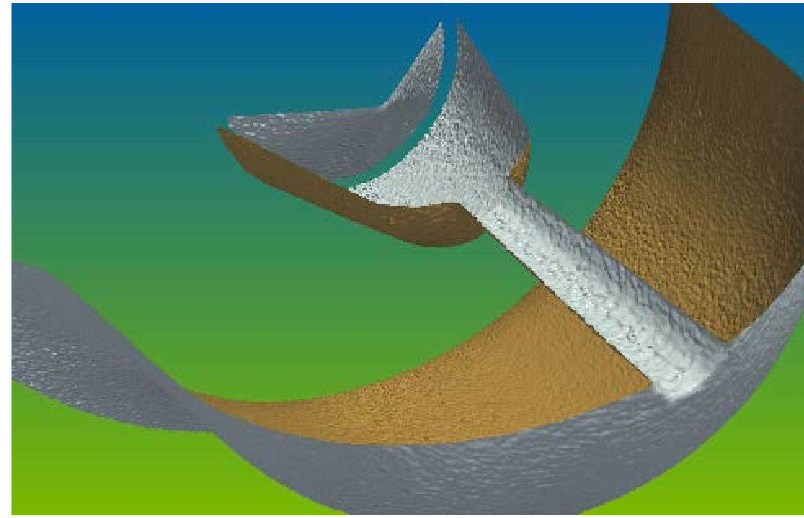
TECHNICAL APPROACH FOR 2017

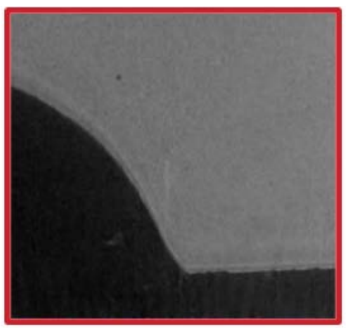
- Gasoline Injection
  - Flash boiling is a challenge for low-load conditions
  - There is little experimental data available
  - **Measure the near-nozzle fuel distribution in flash-boiling GDI sprays**
  - **Partner with simulation groups to incorporate our results into advanced models**

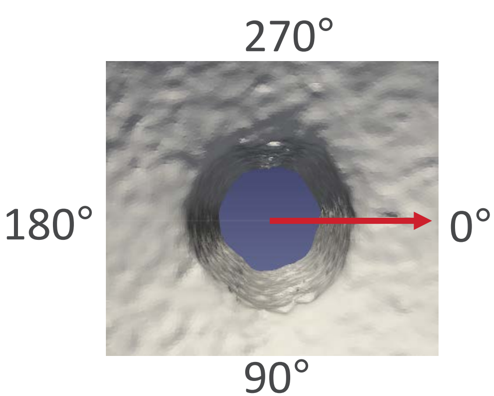
- Diesel Injection
  - The link between nozzle geometry and fuel distribution is not well understood
  - Simulations combining internal nozzle flow with spray formation are now becoming possible
  - **Use our unique in-nozzle and near-nozzle diagnostics to generate a rich data set on two canonical diesel geometries**
  - **Partner with simulation groups to incorporate our results into advanced models**

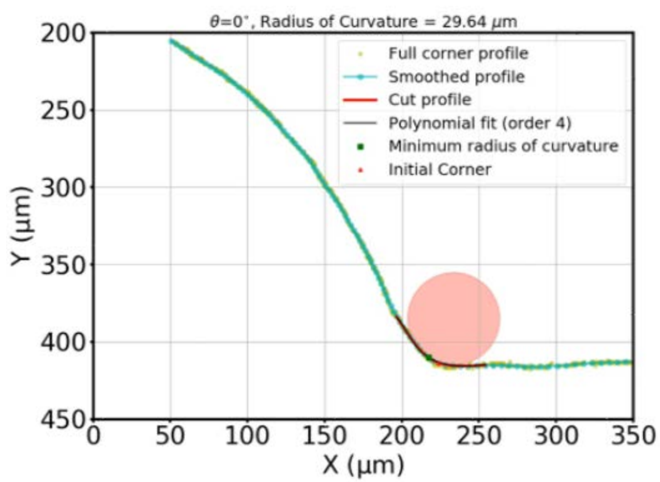
DIESEL INJECTION: LINKING CAVITATION TO INJECTOR GEOMETRY

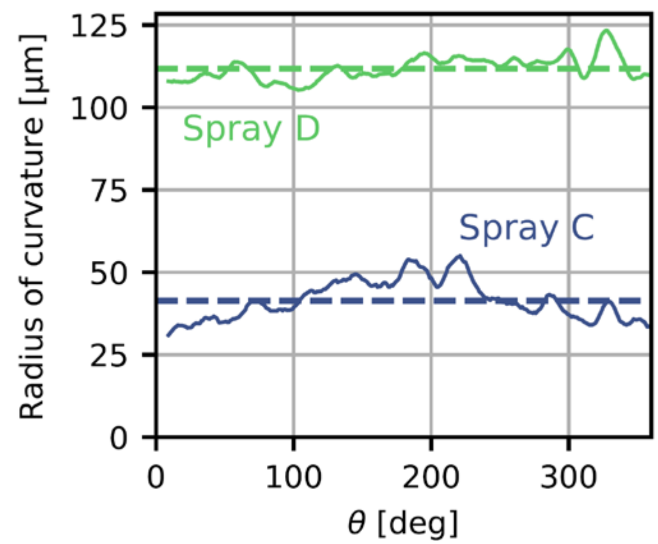
- ECN Spray D: Extensive hydrogrinding, rounded inlet corner
- ECN Spray C: Minimal hydrogrinding, sharp inlet corner
- High resolution geometry measurements enable tracking inlet corner radius with azimuthal angle











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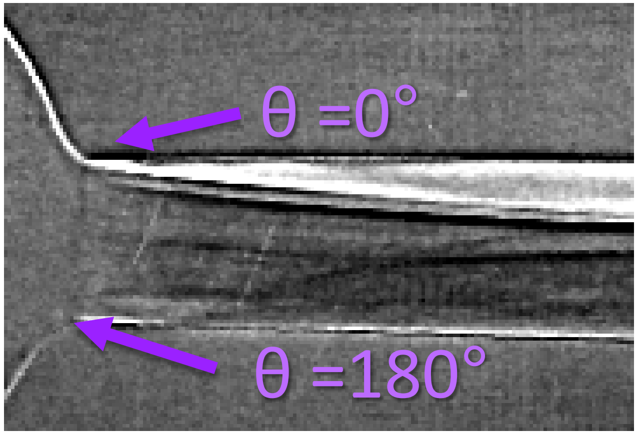
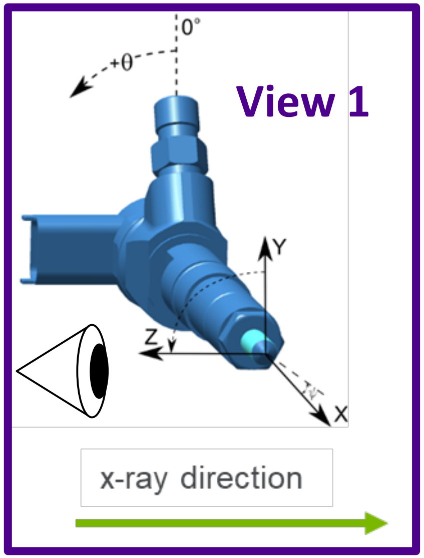
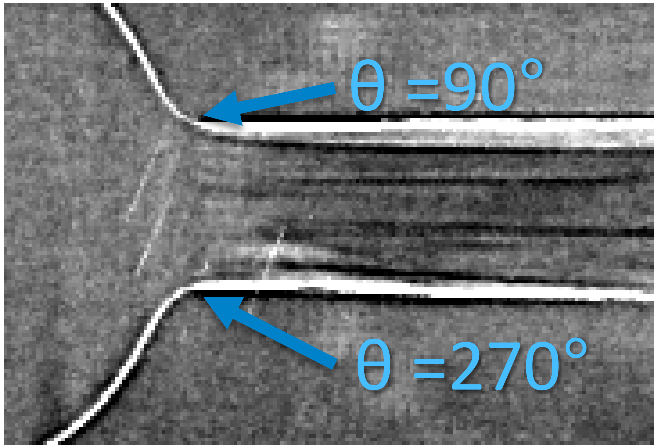
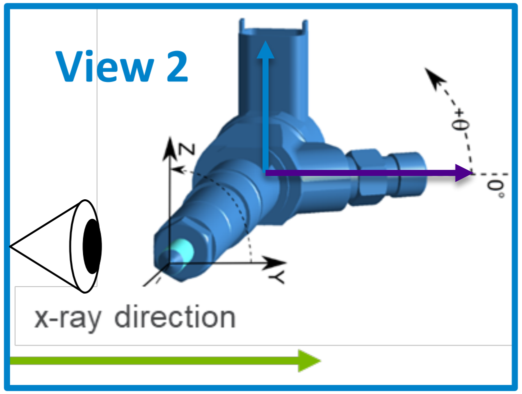
HIGH SPEED X-RAY IMAGING OF IN-NOZZLE CAVITATION

Visualization of fuel-vapor interface



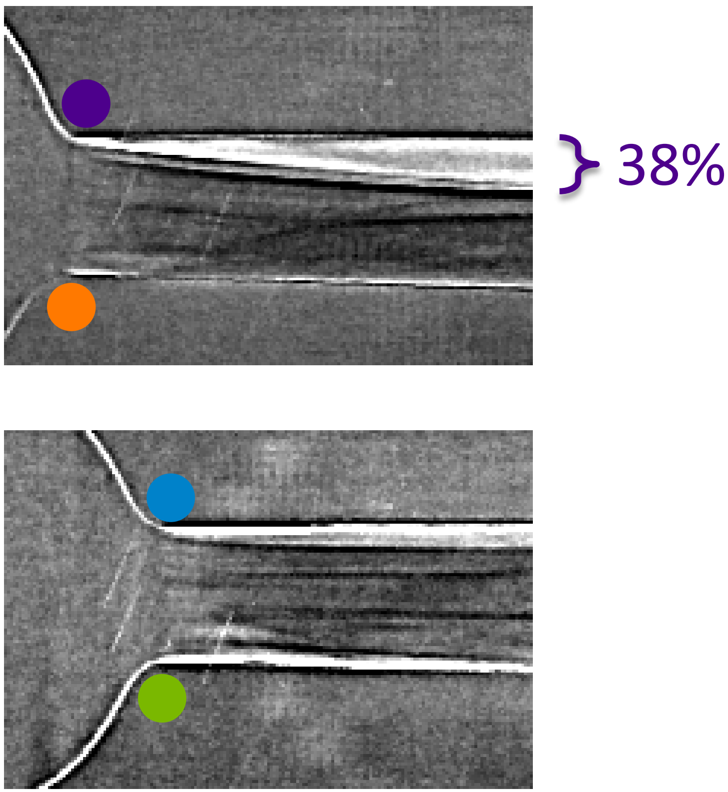


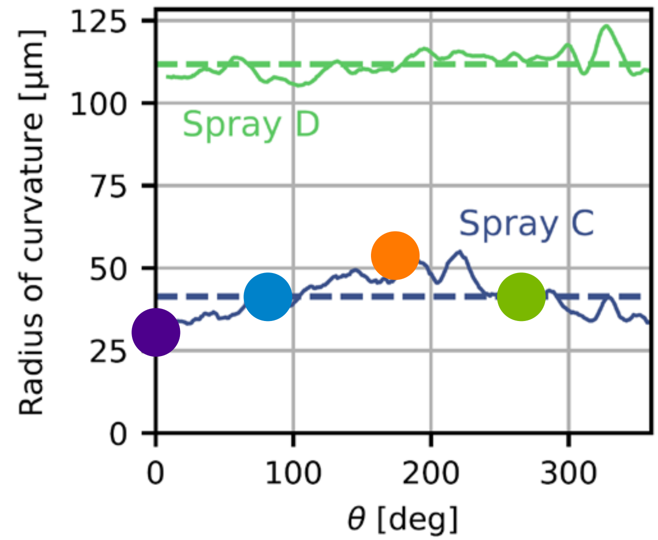




CAVITATION FOLLOWS THE EXPECTED TREND WITH INLET CORNER RADIUS

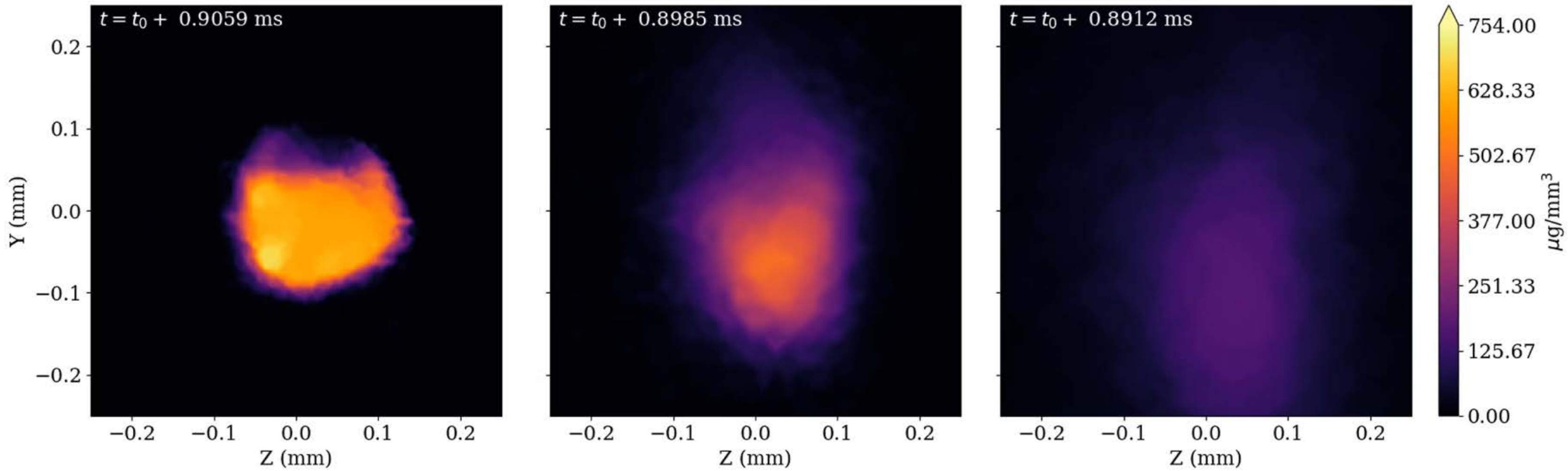
First imaging of cavitation in steel without a fuel additive



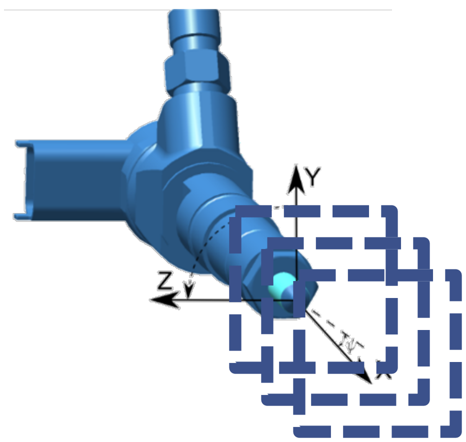


- Extensive cavitation at θ = 0° corner, weak cavitation at θ = 180°
  - Blocks 38% of diameter by 425 µm upstream of orifice exit
- Moderate cavitation at θ = 90° and θ = 270°

SPRAY TOMOGRAPHY QUANTIFIES THE IMPACT OF CAVITATION ON THE FUEL DISTRIBUTION



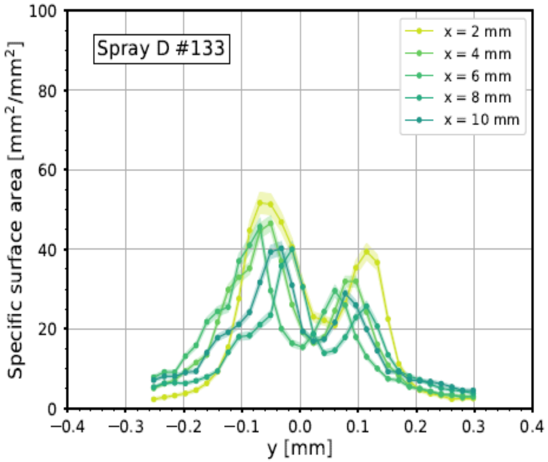
X = 0.1 **X = 2.0** **X = 5.0**

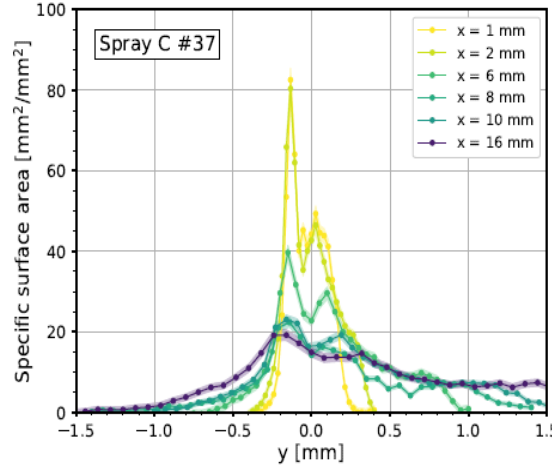


- 20 bar ambient, 55 °C injector
- Hole exit (0.1mm) shows vapor void
- Mass distribution highly transient
- Subtle changes in geometry strongly influence downstream fuel distributions

SMALL-ANGLE X-RAY SCATTERING MEASURES THE NEAR-NOZZLE SURFACE AREA

500 bar, 1 bar ambient

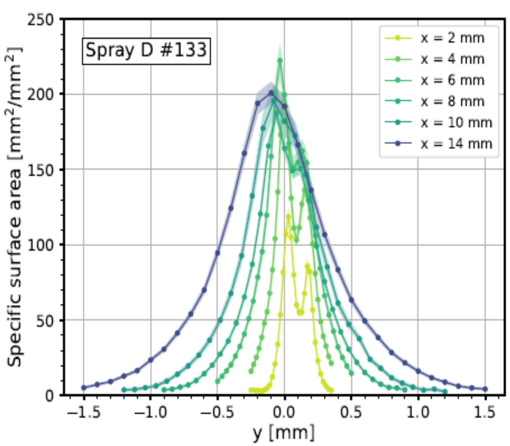




- Spray C shows higher surface area near-nozzle, presumably because of cavitation
- Spray C shows lower surface area downstream because it has spread more rapidly, and there is less fuel in the probe volume

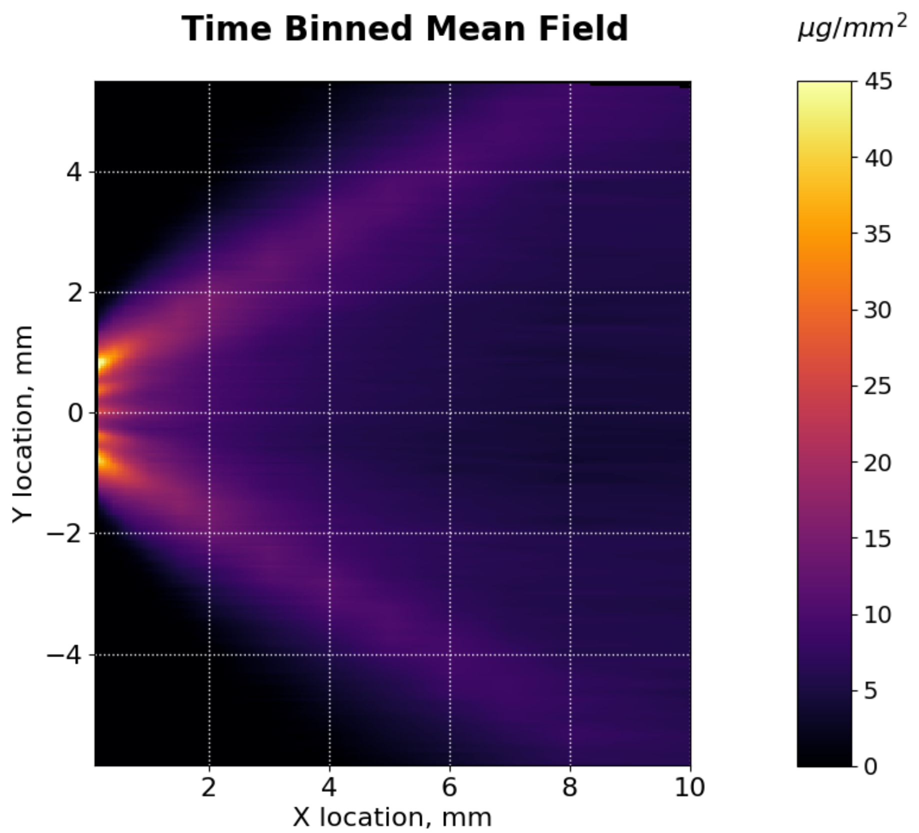
- “Valley” in surface area at center of spray likely caused by ligament structure. These disappear as the spray moves downstream, and more quickly with higher injection or ambient pressure
- We have now measured nozzle geometry, needle motion, near-nozzle spray density, and near-nozzle surface area for both Spray C and D
- These have been shared with ECN modeling groups, simulations will be compared to these results at the upcoming ECN6 Workshop

1500 bar, 2 bar ambient



FIRST NEAR-NOZZLE DENSITY MEASUREMENTS IN FLASH-BOILING SPRAYS

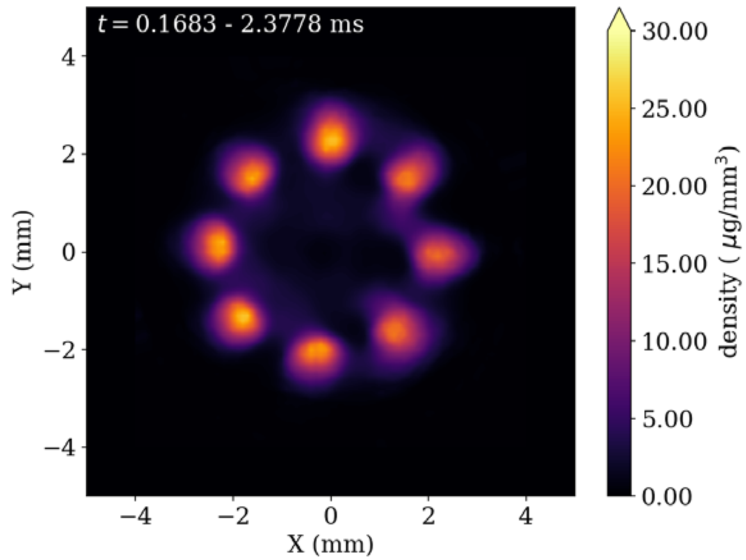
- Flash-boiling is a challenging condition for GDI at low-load
- Low cylinder pressure and high fuel temperature leads to rapid fuel boiling, and a drastic change in the fuel distribution
- The phenomenon is not well-understood, little experimental data exists, and it is difficult to simulate
- Quantitative data will be shared with ECN to validate simulations of the “Spray G2” condition
- Blends of iso-octane with 20% BuOH or EtOH completed under Co-Optima project

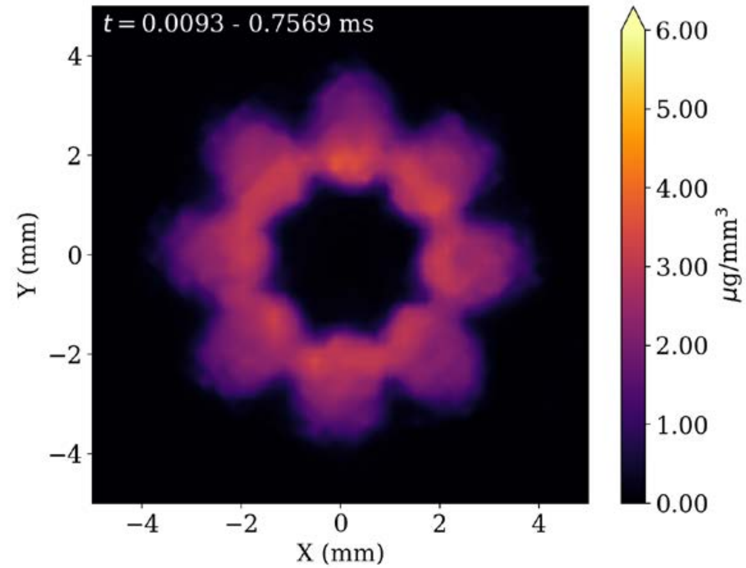


Iso-octane @ 90°C, 1500 bar, 0.5 bar ambient

3D SPRAY TOMOGRAPHY UNDER FLASHING AND NON-FLASHING CONDITIONS

Spray tomography at 2mm from injector





- As expected, spray plumes are much more diffuse under flash-boiling conditions
- Measurements are suitable for direct comparison with 3D CFD
- Measurement conditions nearly match ECN's "Spray G2" flash-boiling condition
- Simulations from several groups will be compared with the measurements at the ECN6 Workshop

RESPONSES TO FY2017 REVIEWERS' COMMENTS

"the project should focus on the ranking of injector features most important to the spray and ultimately combustion and emissions"

- We agree, and this is one of the long-term goals of the project. This task is included in our future work.

"the study of cavitation and erosion could be accompanied by examination of nozzles showing the severity of cavitation, correlated with usage"

- We agree, and are hoping to find an industrial partner for this work. This task is included in our future work

"the collaborative team should be expanded to include members to help steer the work to a more practical and industrial framework."

- We hope to do this through collaboration

ACTIVE COLLABORATIONS IN 2017-2018

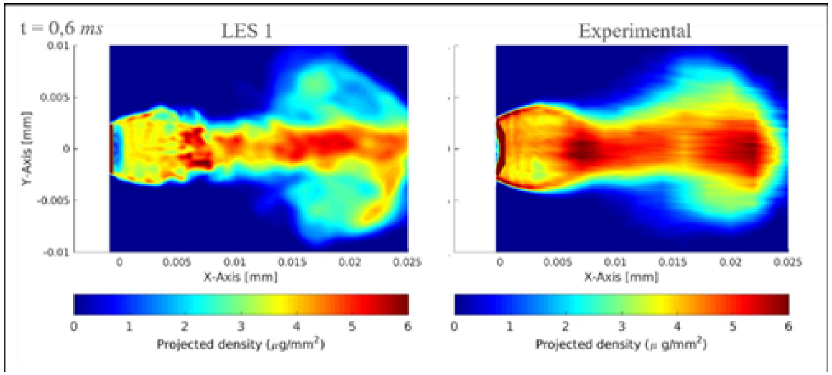
- **Engine Combustion Network**
  - Measurements of nozzle geometry, needle lift, near-nozzle fuel distribution, droplet size
  - Both GDI and diesel
  - Close collaboration with simulation groups to interpret measurement results
  - Leadership role within ECN
  - Planning of future experimental and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

- **Argonne**
  - Joint development of experimental and modeling targets
  - Close collaboration to interpret measurement and simulation results

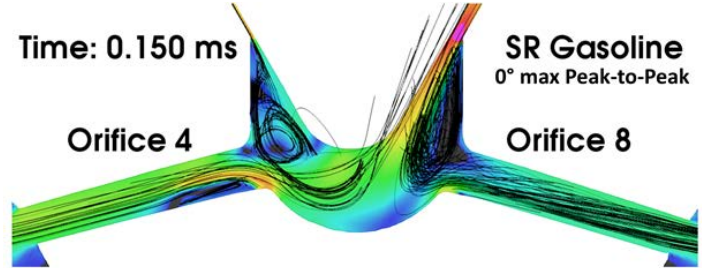
- **Oak Ridge National Lab**
  - Argonne team took part in measurements at ORNL
  - Argonne characterized GDI injector used for ORNL projects on advanced combustion and spray model development
  - Discussions on data analysis and image processing
  - ANL/ORNL organized panel session at 2018 SAE World Congress

- **UMass-Amherst**
  - Joint development of experimental and modeling targets
  - UMass-Amherst does code development
  - Close collaboration to interpret measurement and simulation results

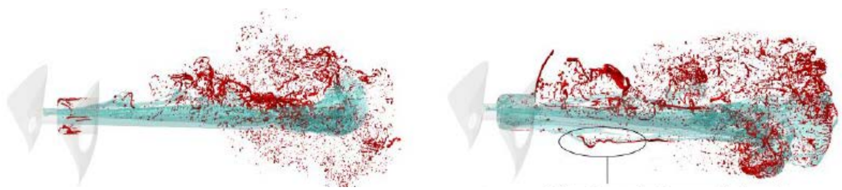
ARGONNE'S DATA IS ACTIVELY USED FOR MODEL DEVELOPMENT AND VALIDATION



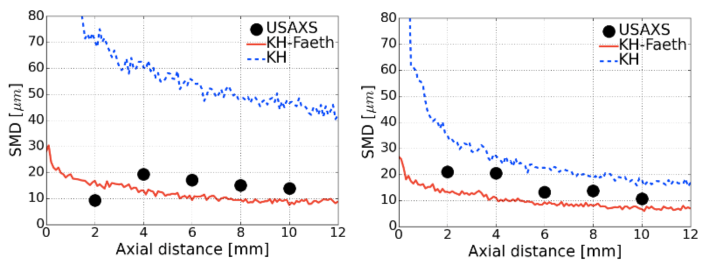
LES Simulations at University of Rome Tor Vergata
Utilized density measurements of natural gas jets
Bartolucci *et al.*, 2018



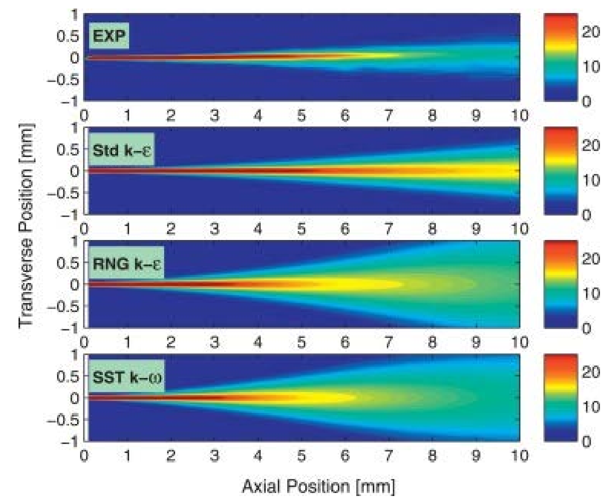
Simulations of diesel injector flow at Argonne
Utilized nozzle geometry, needle lift
Torelli *et al.*, 2018



Comparison of nominal and real geometry at Argonne
Utilized nozzle geometry, needle lift
Yue *et al.*, 2018



New Turbulence-Induced Breakup Model at GA Tech
Utilized spray density, surface area
Kim *et al.*, 2018



Development of Σ-Y Model at CMT
Utilized spray density, surface area
Pandal *et al.*, 2017

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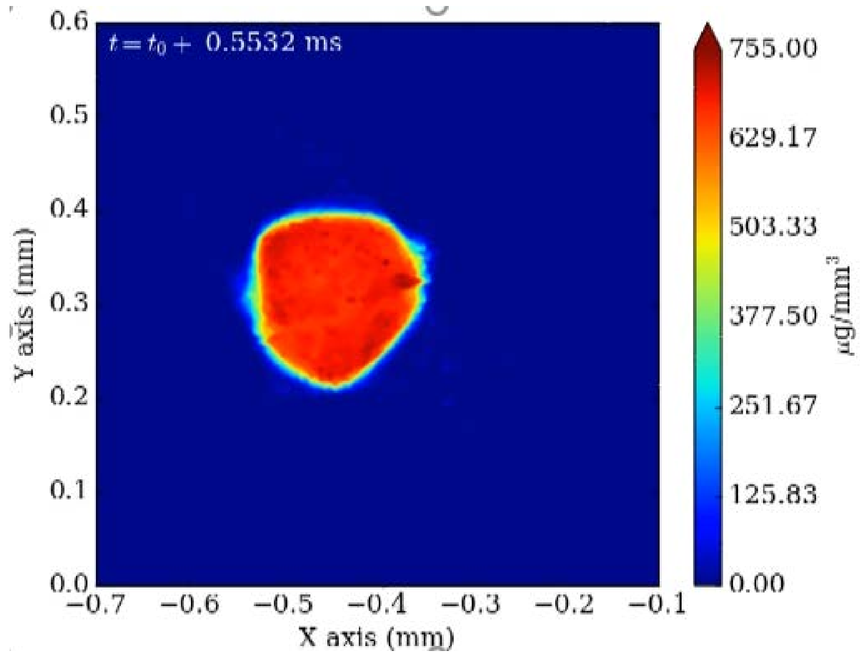
REMAINING CHALLENGES AND BARRIERS

Near-Nozzle Fuel Density is Lower Than Expected in Diesel Injection

Only 100 microns from the nozzle exit, maximum liquid volume fraction is ~0.9

- Is this real?
  - Repeated measurements have confirmed this for a range of injectors, injection pressures, ambient pressures
  - Tomographic reconstruction software is a “black box” to us, but initial validation tests confirm the result, more are underway
- We aren’t sure of the physics that may cause this
  - Temperature?
  - Cavitation?
  - Dissolved air?

Density in ECN Spray D, 100 μm from Nozzle



New spray models may be needed to capture this effect

PROPOSED FUTURE WORK IN FY2016 AND FY2017

- Investigate near-nozzle spray density
  - Exhaustively validate measurement results
  - Measurements of spray temperature using x-ray scattering
  - Measurements of dissolved gas using x-ray fluorescence

- Engine Combustion Network
  - Evaluate Spray C, D, G under several parametric variations
  - Continue work developing “standard” geometries for Spray C, D, G
  - Speed the process of generating a CFD mesh from our geometries

- Measurements of cavitation erosion
  - Non-destructive x-ray measurements of geometry can track nozzle erosion over time
  - Data will be used to support development of erosion models

- Investigations of nozzle geometry and the link to sprays
  - Obtain 10-20 samples of “used” injectors
  - Measure the geometries and near-nozzle fuel distributions
  - Evaluate the link between geometry and spray
  - Through collaboration with simulations groups, estimate the effect of geometric features on combustion, emissions

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

SUMMARY

- Improve the understanding of fuel injection and sprays by measuring fundamental spray phenomena
  - Measurements of internal injector geometry and flow
  - Measurements of near-nozzle breakup
  - These are unique capabilities of x-ray diagnostics
- Assist in development of improved spray models
  - Partnerships on nozzle and spray modeling with UMass Amherst, CMT, Georgia Tech, Perugia, Rome, Som, Scarcelli
  - Data contributed to ECN is assisting model development at IFP, CMT, Sandia, Argonne, UMass, GM, Convergent Science, others.
  - SPPs with Caterpillar, CMT, Spray Combustion Consortium, CRADAs with Aramco, Delphi Diesel, FOA with Georgia Tech
- Share the results
  - Nozzle geometry, needle motion, near-nozzle spray density, near-nozzle surface area
  - ECN Spray A, B, C, D, G
  - Openly available at https://anl.box.com/v/XRaySpray

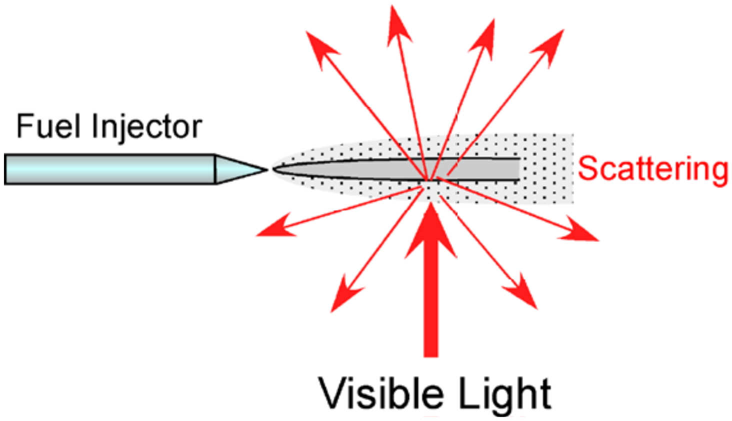
Technical Back-Up Slides

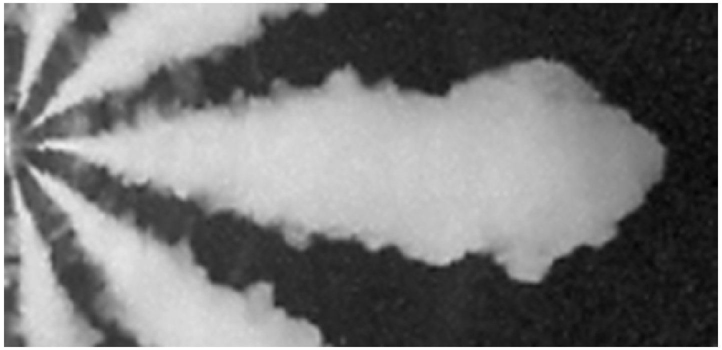
(Note: please include this “separator” slide if you are including back-up technical slides (maximum of five). These back-up technical slides will be available for your presentation and will be included in the DVD and Web PDF files released to the public.)

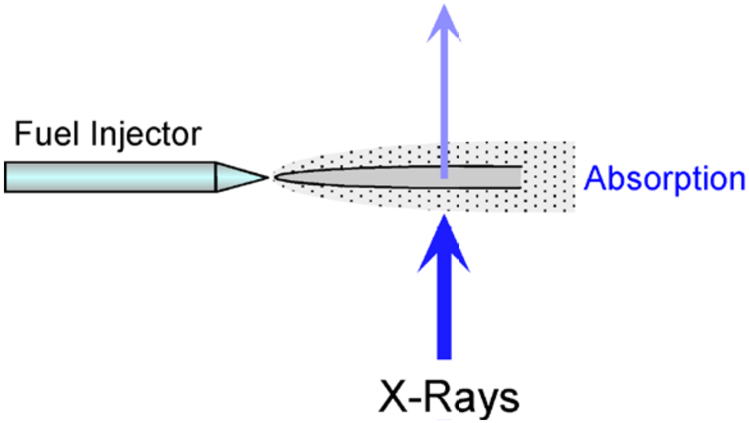
TECHNICAL APPROACH – X-RAY DIAGNOSTICS

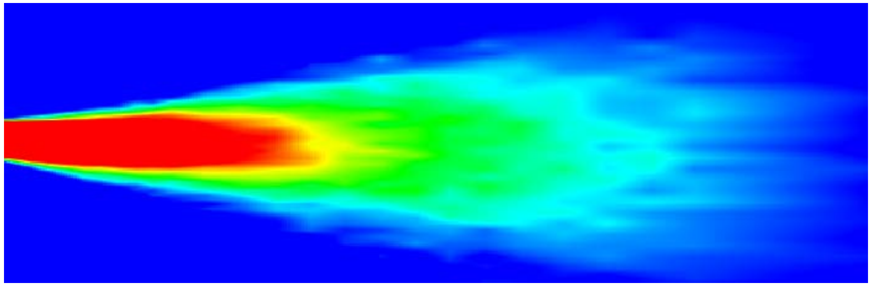
- **X-rays enable unique diagnostics**
  - Near-nozzle measurements of fuel injection
  - Mass-based measurements of the fuel distribution
  - Penetrate through steel to measure geometry, flow, motion
  - Fast time resolution (<5 ms)
  - Fine spatial resolution (< 5 μm)
- **Limitations**
  - Can't penetrate 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





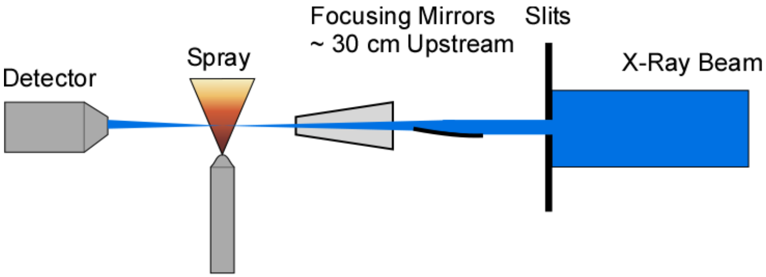


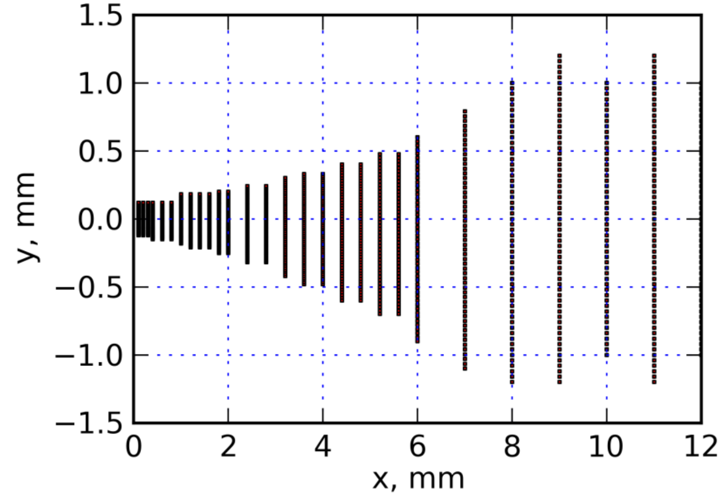


- Room temperature
- Ensemble averaged
- Pressure up to 30 bar

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: 3.7×10^{-4} mm^2/µg
  - Accounts for displacement of chamber gas by liquid
  - Maximum absorption in dodecane ~2%





Example Measurement Grid

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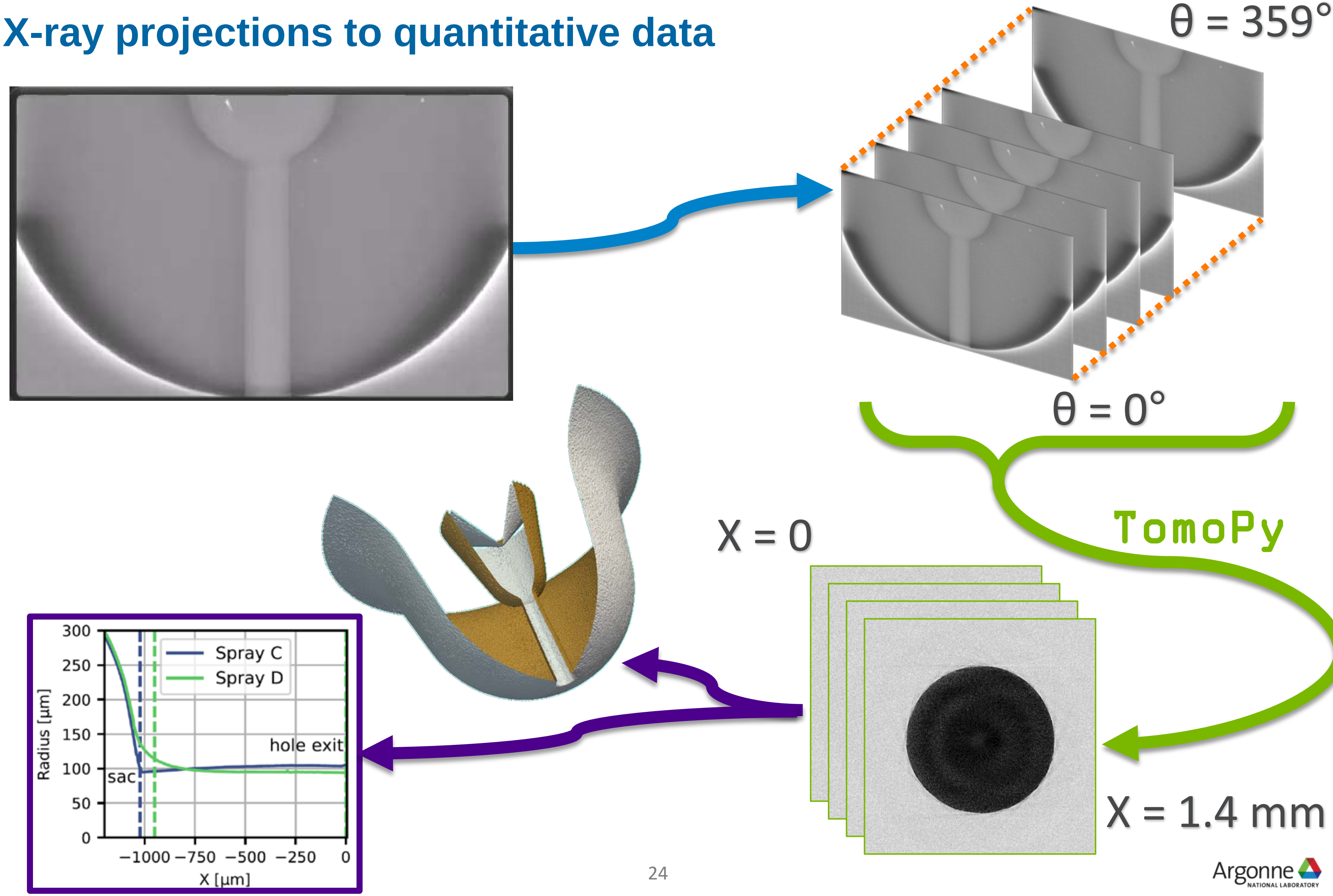
NOZZLE TOMOGRAPHY PROCESSING

X-ray projections to quantitative data



THE PATHWAY TO STUDIES OF 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 last 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: Completed February 2018
- Seeking funding to fabricate facility for high temperature sprays, combustion