Spray Combustion Cross-Cut Engine Research

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Sandia National Laboratories

FY 2012 DOE Vehicle Technologies Program Annual Merit Review
Project ACE005, Salon E, 10:00 – 10:30 AM, Tuesday, May 15, 2012

Sponsor: **DOE Vehicle Technologies Program**
Program Manager: **Gurpreet Singh**

Overview

Timeline

- Project provides fundamental research that supports DOE/ industry advanced engine development projects.
- Project directions and continuation are evaluated annually.

Budget

- Project funded by DOE/VT:
  FY11 - $730K
  FY12 - $730K

Barriers

- Engine efficiency and emissions
- Understanding direct-injection sprays
- CFD model improvement for engine design/optimization

Partners

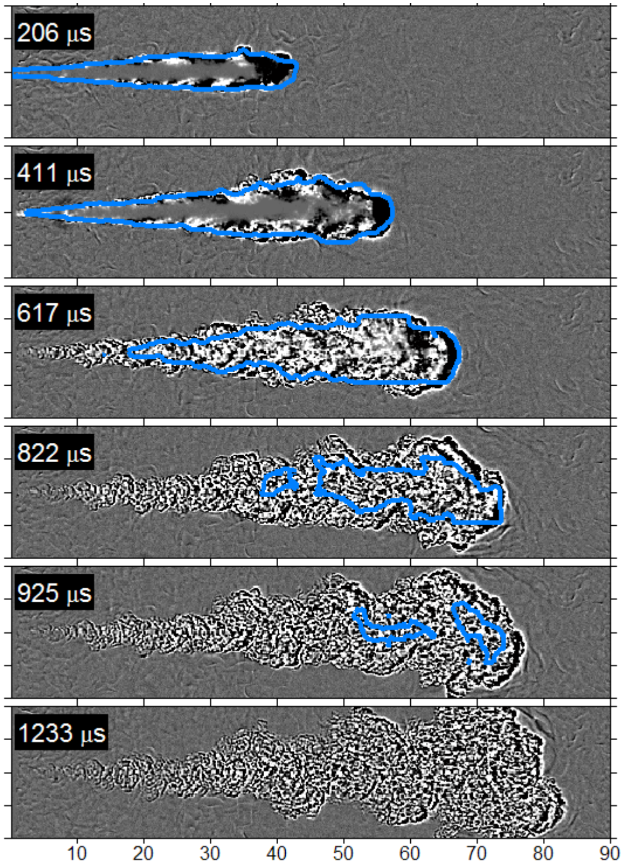
- 15 Industry partners in the Advanced Engine Combustion MOU
- Engine Combustion Network
  - >10 experimental + 15 modeling
- Project lead: Sandia
  - Lyle Pickett (PI)

The role of spray combustion research for high-efficiency engines.

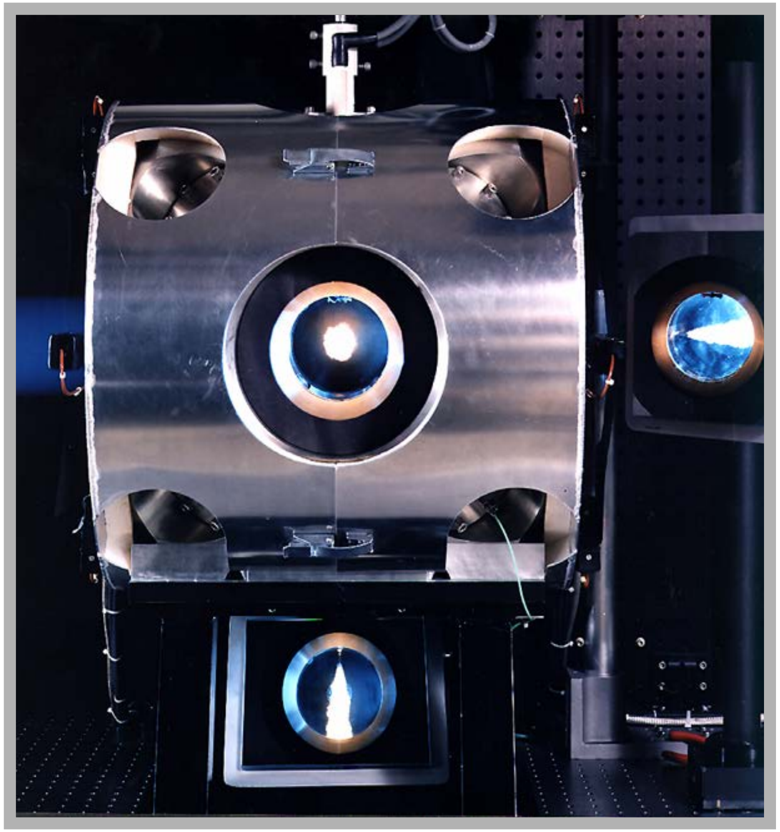
- Future high-efficiency engines use direct injection.
  - Diesel, gasoline direct injection, partially-premixed compression ignition
- Complex interactions between sprays, mixing, and chemistry.
  - Two-phase system, including multiple injections
  - Spray-induced mixture preparation
  - Complicated internal flows within injectors
- Optimum engine designs discovered only when spray modeling becomes predictive.
  - Predictive modeling shortens development time and lowers development cost.
  - Makes efficient engines more affordable.
- Relevant to EERE Advanced Combustion Engine research and development goals.

Schlieren: vapor boundary

BLUE: liquid boundary



Studies of spray combustion in constant-volume chamber.



- Well-defined ambient conditions:
  - 300 to 1300 K
  - up to 350 bar
  - 0-21% O_2 (EGR)
- Injector
  - single- or multi-hole injectors
  - diesel or gasoline (cross-cut)
- Full optical access
  - 100 mm on a side
- Boundary condition control needed for CFD model development and validation.
  - Better control than an engine.
  - Easier to grid.

Objectives/Milestones

- Aid the development of computational models for engine design and optimization (ongoing).
  - Experimental and modeling collaboration through the Engine Combustion Network tied to specific low-temperature diesel target conditions: http://www.sandia.gov/ECN
  - FY12(1): Sandia leads the ECN and contributes many diagnostics (12) and datasets.
    - Sponsorship of ECN workshops to provide a pathway from experimental results to more predictive CFD modeling.
    - Working collaboratively with ECN participants, we provide major new findings on boundary condition control, nozzle geometry and needle movement, spray development, ignition, lift-off length.
- FY12(2): Evaluate spray liquid-phase penetration in quantitative fashion.
- FY12(3): Develop an understanding of the spray structure at high-temperature, high-pressure condition by high-speed microscopic imaging.

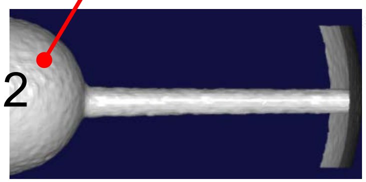
ECN activities at specific target conditions.

Spray A

Injector

90° C, 1500 bar

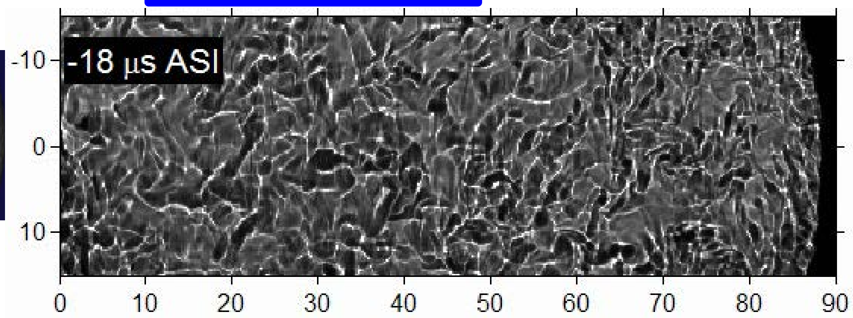
n-c12



Internal nozzle geometry

Ambient

900 K, 60 bar



Other defined targets:

- Spray H (baseline n-heptane)
- Spray B (3-hole version of Spray A).
- Gasoline and engine targets TBD.

- Opportunity for the greatest exchange and deepest collaboration.
  - Understanding facilities/boundary conditions and diagnostics.
  - Standardize methodologies for post-processing.
- Leverages the development of quantitative, complete datasets.
  - Unique diagnostics to build upon past understanding.
  - Moves from “qualitative” to “quantitative”.
  - Sharing results/meshes/code/methods saves time and effort.
- Activity led by our research group
  - with more than 10 experimental + 15 modeling participants (next 2 slides).

ECN experimental participation at Spray A.

Institution	Facilities	Personnel
Sandia	Preburn CV	Lyle Pickett, Julien Manin
IFPEN	Preburn CV	Gilles Bruneaux, Louis-Marie Malbec
CMT	Cold CV, Flow PV	Raul Payri, Michele Bardi
Chalmers	Flow PV	Mark Linne
GM	Flow PV	Scott Parrish
Mich. Tech. U.	Preburn CV	Jeff Naber, Jaclyn Nesbitt Johnson
Argonne	Cold V, X-ray Sync.	Chris Powell, Alan Kastengren
Caterpillar	Flow PV	Tim Bazyn, Glen Martin
Aachen	Flow PV	Heinz Pitsch, Maung Maung Aye
Meiji U.	Preburn CV	Tetsuya Aizawa
Seoul Nat. U.	Preburn CV	Kyoungdoug Min
Eindhoven U.	Preburn CV	Maarten Meijer, Bart Somers

BLUE: In progress Red: Commencing soon.

Modeling input at ECN1 workshop

- Coordinators: Evatt Hawkes, UNSW and Sibendu Som, Argonne
- Input from 9 groups at the same target conditions for ECN1.
- 15 groups have already registered commitment/interest for ECN2.

- **Argonne National Laboratory:** Sibendu Som, Douglas Longman
- **Cambridge University:** Giulio Borghesi, Epanimondas Mastorakos
- **Universitat Politècnica de València CMT**: Ricardo Novella, José Pastor, Francisco Payri, J.M. Desantes
- **TU Eindhoven**: Bart Somers, Cemil Bekdemir, L.P.H. de Goey
- **Penn. State**: Dan Haworth, Hedan Zhang, Subhasish Bhattacharjee
- **Politecnico di Milano**: Gianluca D'Errico, Tommaso Lucchini, Daniele Ettore
- **Purdue**: John Abraham, Chetan Bajaj
- **UNSW**: Yuanjiang Pei, Sanghoon Kook, Evatt Hawkes
- **U. Wisconsin ERC**: Yue Wang, Gokul Vishwanathan, Rolf Reitz, Chris Rutland

Experimental accomplishments at Spray A conditions

Quantity	Experiment	Contributors (Inst. and/or person)
Gas T distribution	fine-wire TC, variable diameter TC	CAT, CMT, Sandia, IFPEN, Eindhoven
Ambient gas minor species existence and effects	kinetics modeling	Mich. Tech. U. (Jaclyn Nesbitt Johnson)
Nozzle internal temperature	thermocouple	Sandia, CAT, IFPEN, CMT, Eindhoven
Nozzle surface temperature	laser-induced phosphorescence	IFPEN (Louis-Marie Malbec, Gilles Bruneaux)
Nozzle geometry	x-ray tomography	Caterpillar (Tim Bazyn)
Nozzle geometry	x-ray phase-contrast imaging	Argonne (Alan Kastengren, Chris Powell)
Nozzle geometry	silicone molds	CMT (Raul Payri, Julien Manin)
Nozzle exit shape	optical microscopy, SEM	Sandia (Julien Manin, Lyle Pickett)
Mass rate of injection	bosch tube method	CMT (Raul Payri, Julien Manin)
Rate of momentum	force piezo	CMT, Sandia, CAT
Total mass injected	gravimetric scale	CMT, Sandia
Nozzle Cd, Ca	momentum + mass	CMT, Sandia
Liquid penetration	Mie scatter	IFPEN, Sandia, CMT, CAT
Liquid penetration	Diffused back illumination	Sandia, CMT
Liquid optical thickness	laser extinction	Sandia (Julien Manin, Lyle Pickett)
Liquid structure	long-distance microscopy	Sandia (Julien Manin, Lyle Pickett)
Liquid vol. fraction (300 K)	x-ray radiography extinction	Argonne (Alan Kastengren, Chris Powell)
Vapor boundary/penetration	schlieren / shadowgraphy	Sandia, IFPEN, CAT, CMT
Fuel mixture/mass fraction	Rayleigh scattering	Sandia
Ignition delay	high-speed chemiluminescence	Sandia, CAT
Lift-off length	OH or broadband chemilum.	Sandia, IFPEN, CAT, CMT
Pressure rise/AHRR	high-speed pressure	Sandia, IFPEN
Soot luminosity	high-speed luminosity imaging	Sandia, IFPEN, CAT, CMT

23 different diagnostics

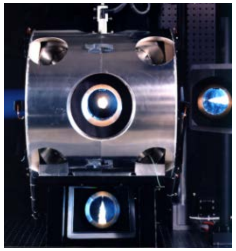
FY11
FY12

(1) Summary of ECN activities during FY12

see www.sandia.gov/ECN

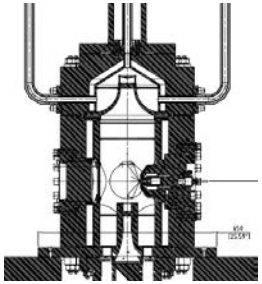
- Workshops sponsored
  - May 2011 (ECN1): 60 participants met for 2-day event before ILASS meeting.
  - Jan 2012: 120 participants attend 3-day web meeting.
  - Sept 2012 (ECN2): 15 modeling groups have agreed to participate.
- Key findings
  - Facility temperature distribution of gases and fuel is critical.
  - Nozzle geometry, needle movement are provided using multiple comparative diagnostics.
  - Ignition and lift-off length measurements are consistent with different types of HP-HT facilities.
    - > Datasets can be linked and leveraged!

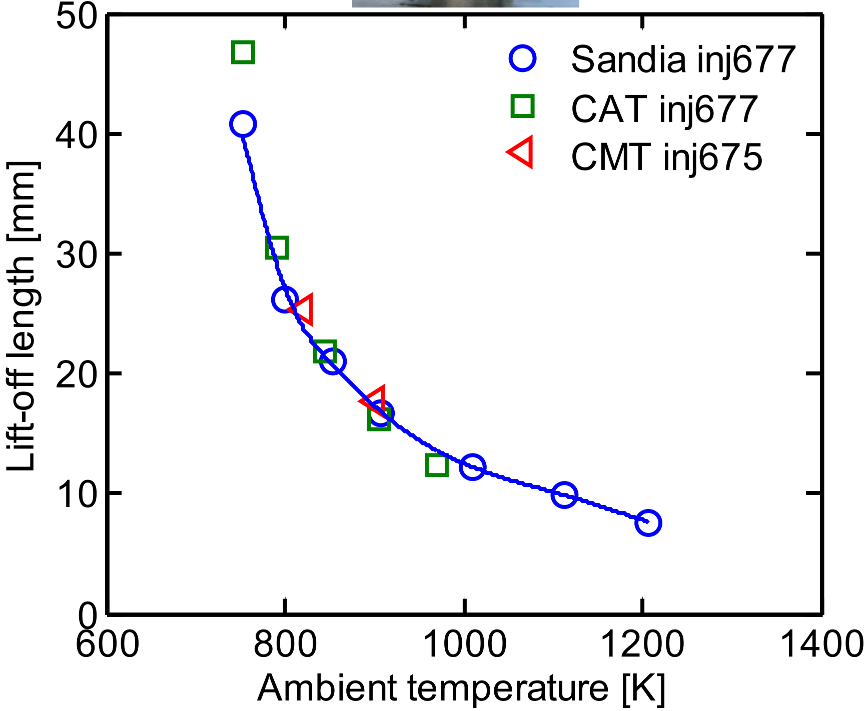
Sandia



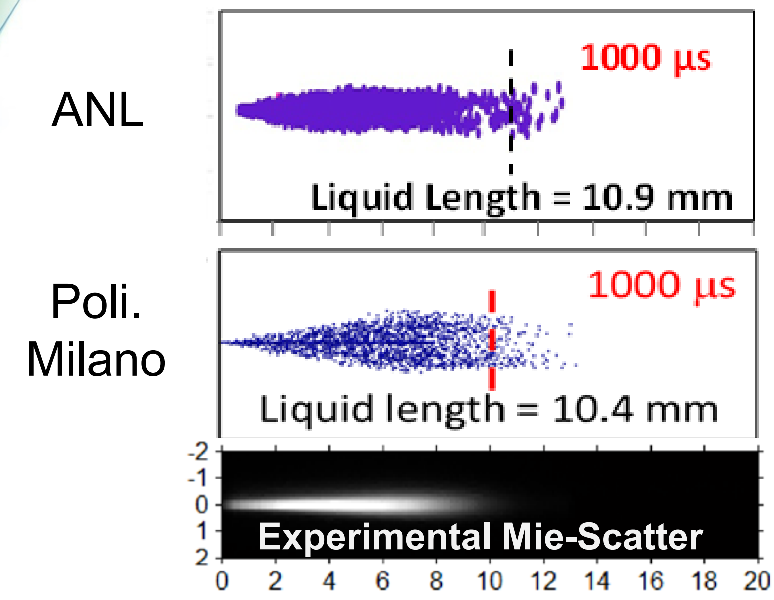
CMT

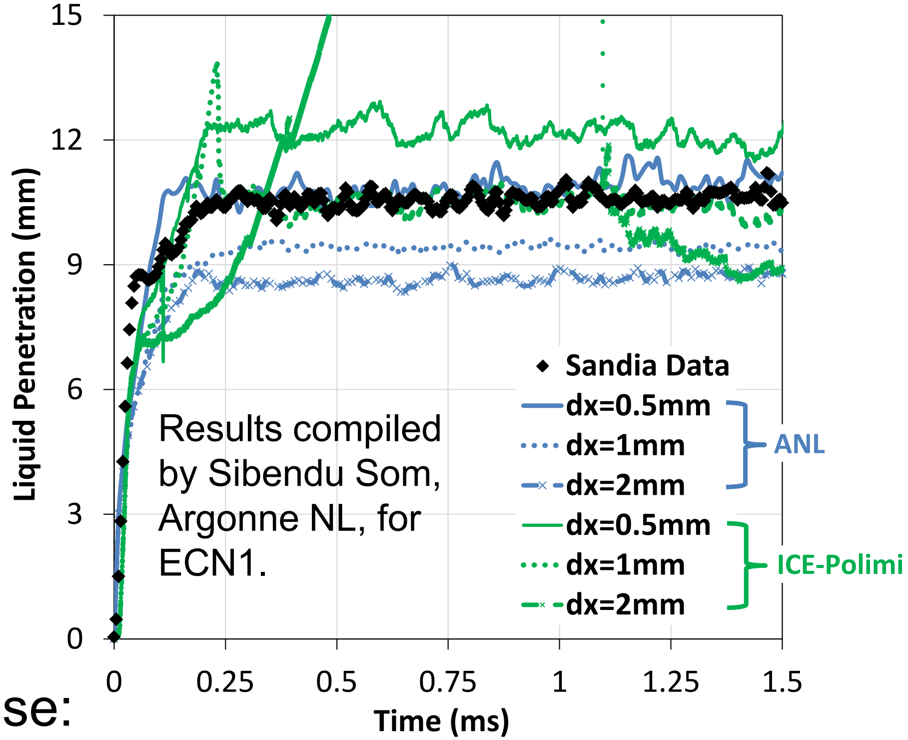
Caterpillar





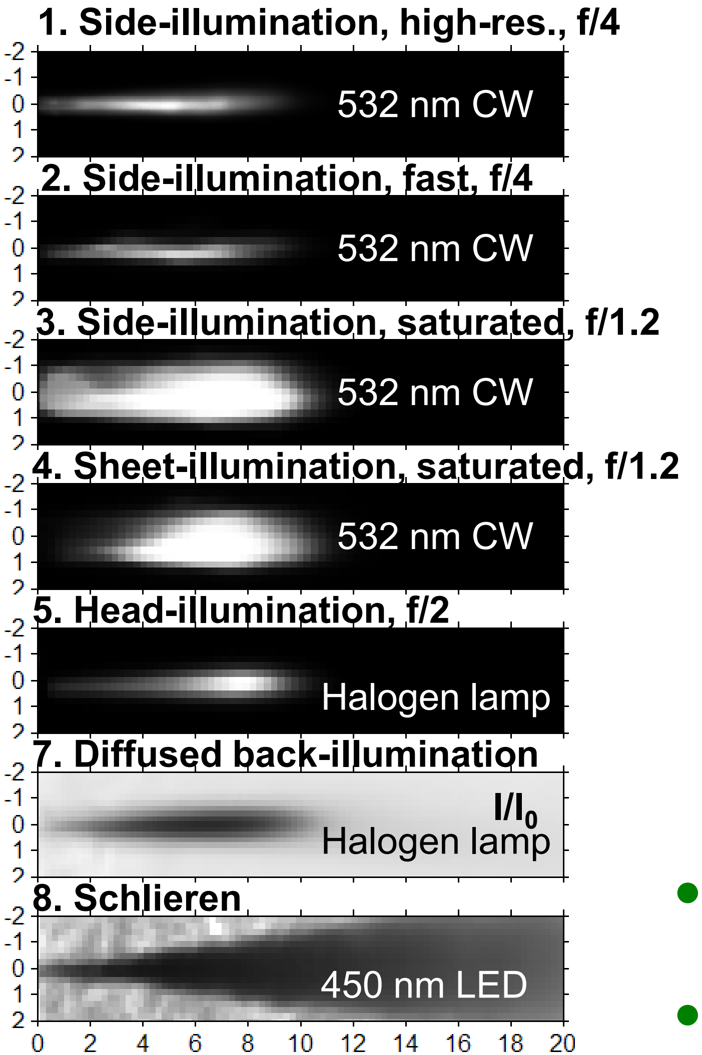
Overcoming barriers towards predictive spray modeling: (2) examination of liquid penetration

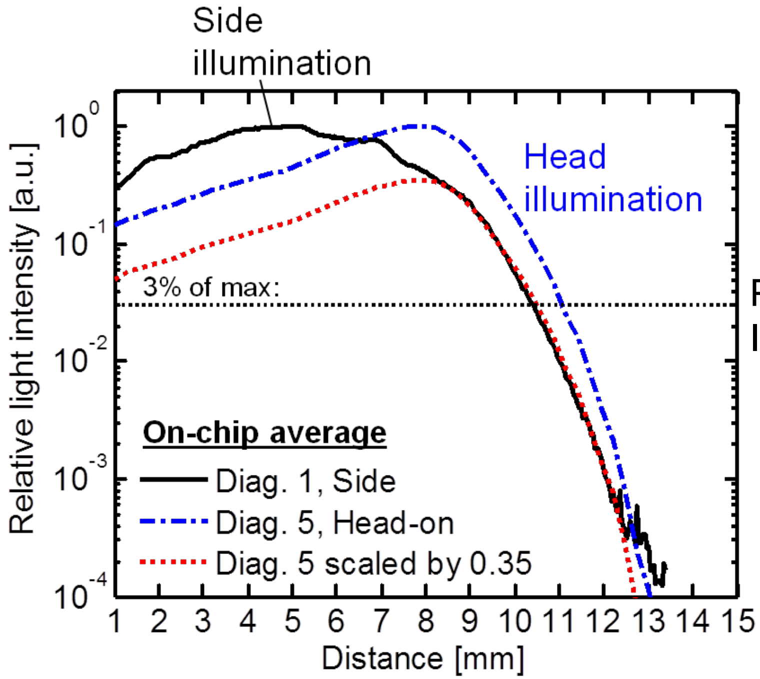




- CFD comparisons fall short because:
  - Lagrangian particle tracking requires mesh to be much larger than liquid.
    - near-field spray is unresolved and mesh-size dependency is common.
  - Different definitions for "liquid length" are used.
    - ANL: "Axial distance encompassing 97% of injected liquid fuel mass."
    - Poli. Milano: "Distance from the injector where 99% of the liquid mass is found."
  - But experimental method does not directly measure liquid concentration.
    - "Axial distance where Mie-scatter light intensity is 3% of ensemble-average maximum."

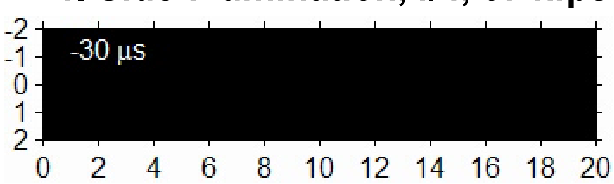
Derived liquid length depends upon experimental lighting arrangement.





Pickett et al. ILASS 2011-111

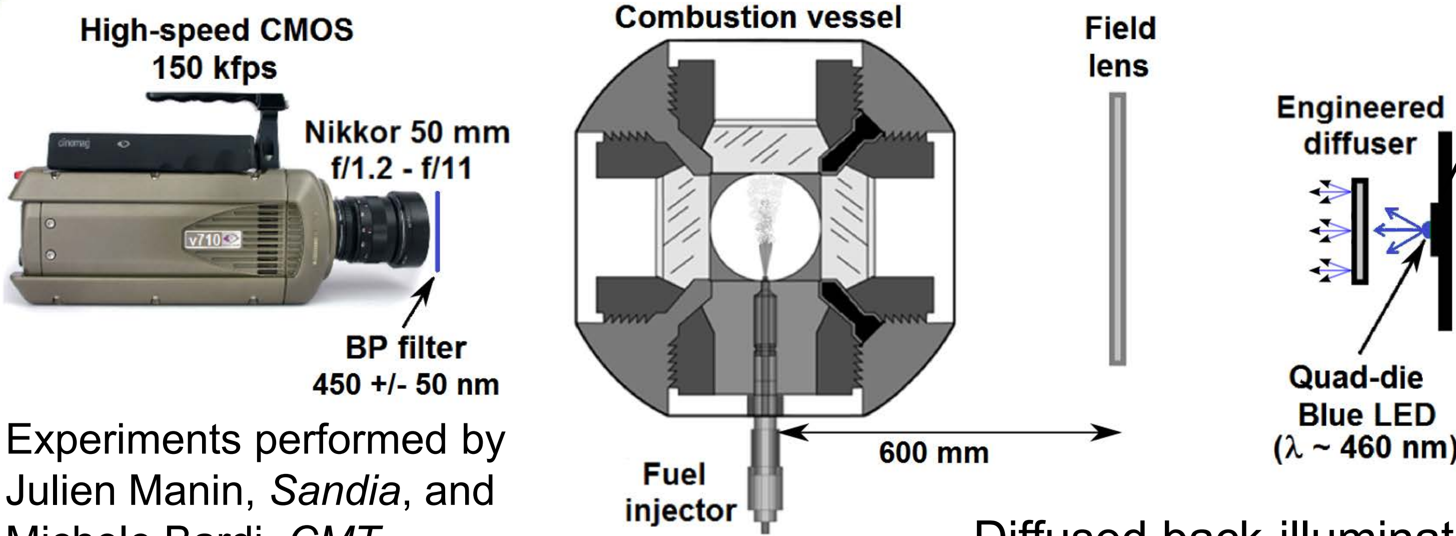
1. Side-illumination, f/4, 67 kfps



3% of max. (Siebers): Liq. Length = 10.4 mm

- Scattered light is proportional to local liquid volume fraction, NOT upstream integrated mass.
- Need to quantify liquid volume fraction, if possible.

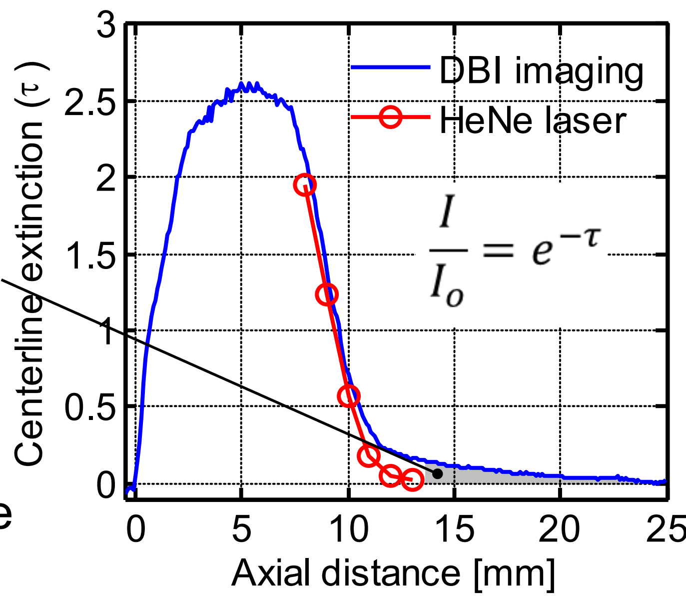
Back illumination permits light intensity normalization for more quantitative extinction.



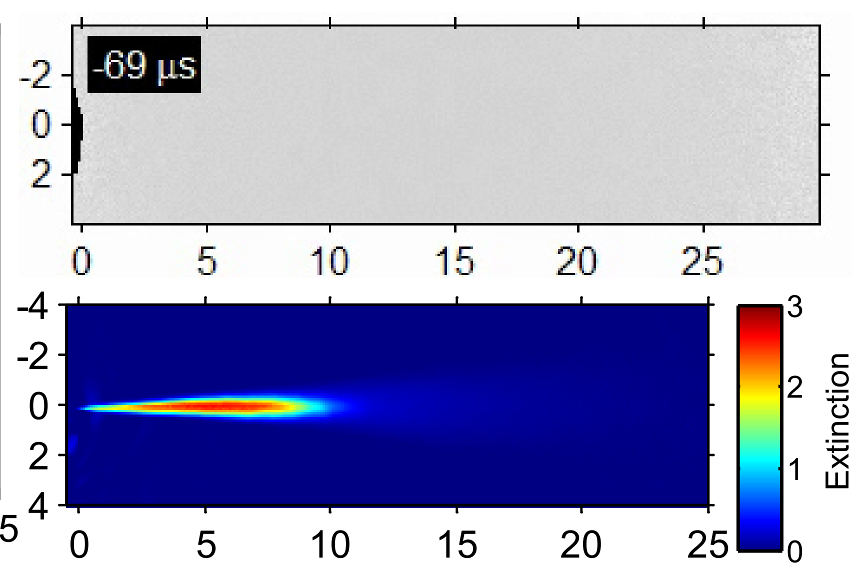
Custom-designed with <50 ns pulse at high, variable frequency.
Chris Carlen, *Sandia*

Experiments performed by Julien Manin, *Sandia*, and Michele Bardi, *CMT*.

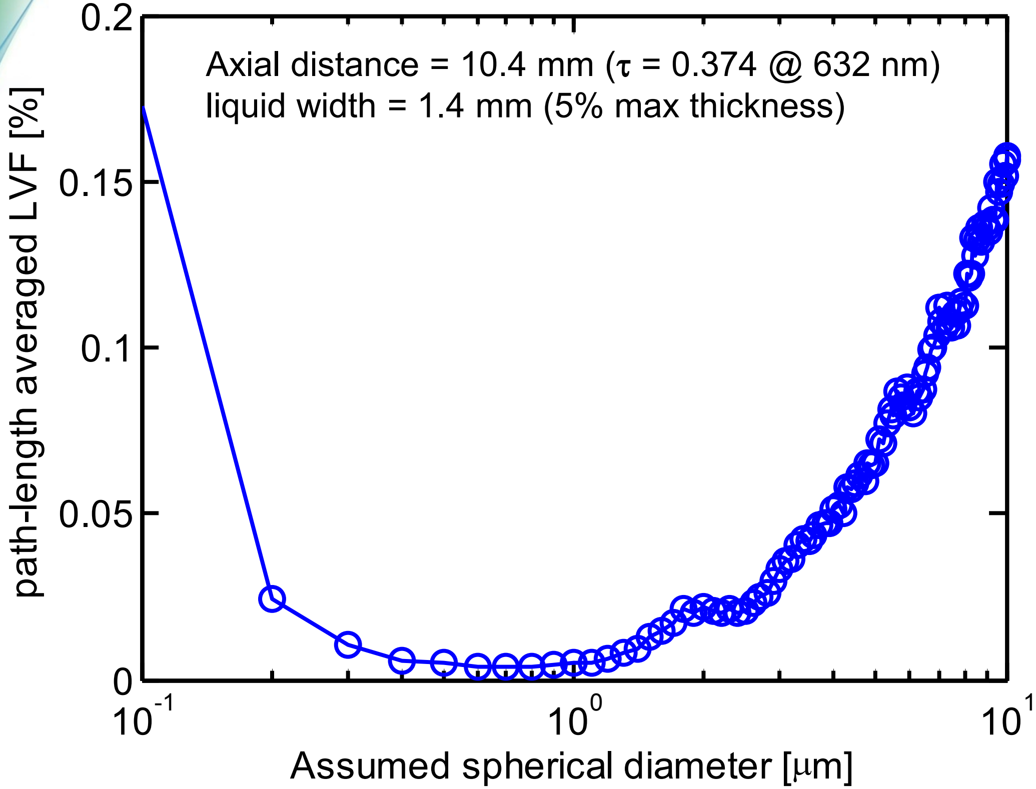
Artificial extinction because of vapor-phase beam steering. Confirmed by laser extinction with larger collection angle (>200 mrad)



Diffused back-illumination at 150 kfps



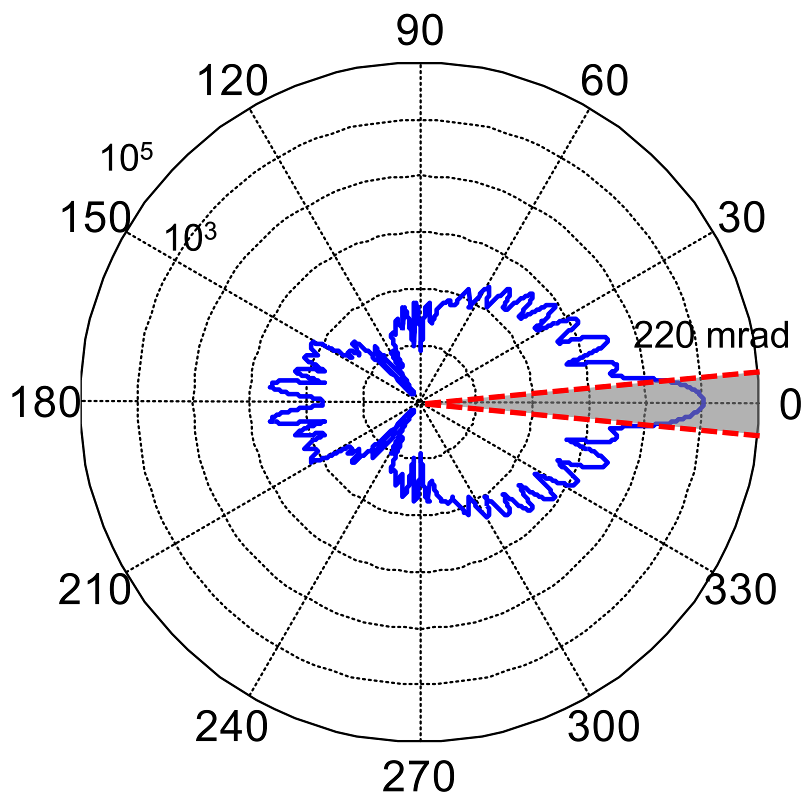
Line-of-sight extinction measurements can provide an estimate for liquid vol. frac. near the liquid length.



$$\frac{I}{I_o} = e^{-\tau}$$

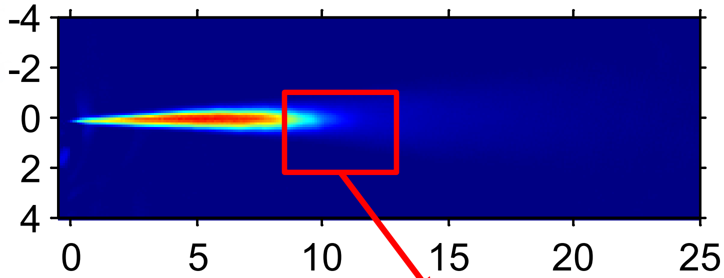
$$\tau = \int_{-Z_\infty}^{Z_\infty} C_{ext} N dz = C_{ext} \int_{-Z_\infty}^{Z_\infty} \frac{LVF}{\pi d^3/6} dz$$

Angular scattering intensity for a 5 μm n-dodecane sphere in air, refractive index = 1.422



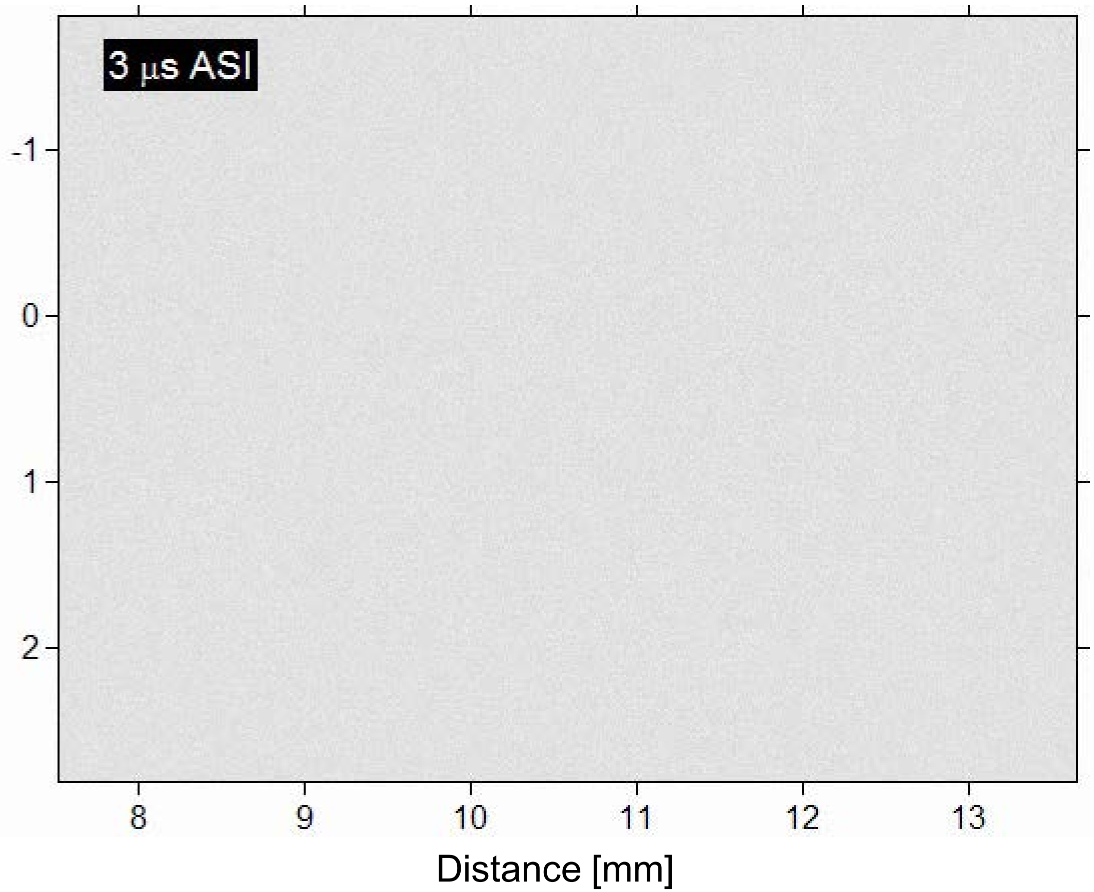
(3) Visualization of spray structure using back-illumination, long-distance microscopy

Liquid extinction: 900 K, 22.8 kg/m³



Visualization region

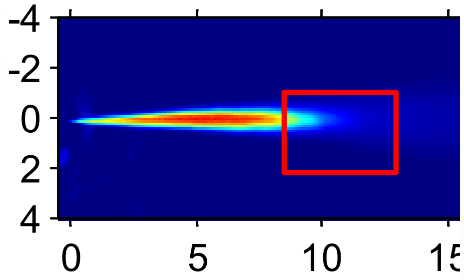
440 K, 22.8 kg/m³, 29 bar
512×384 pixels, 33 kfps
1.5 ms injection duration



- Setup permits direct visualization of droplets.
  - Droplets visible outside of main spray.
  - Re-entrained into the spray following the passage of large structures.
  - Larger droplets (~50 μm) come into view after the end of injection.

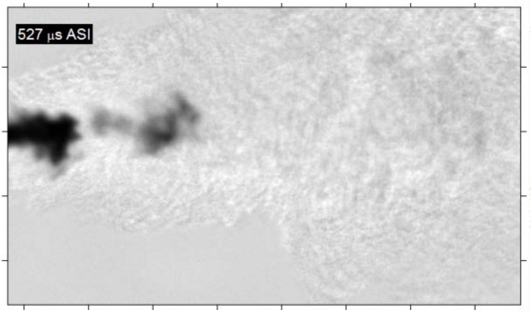
(3) Microscopic visualization at high-temperature, vaporizing conditions.

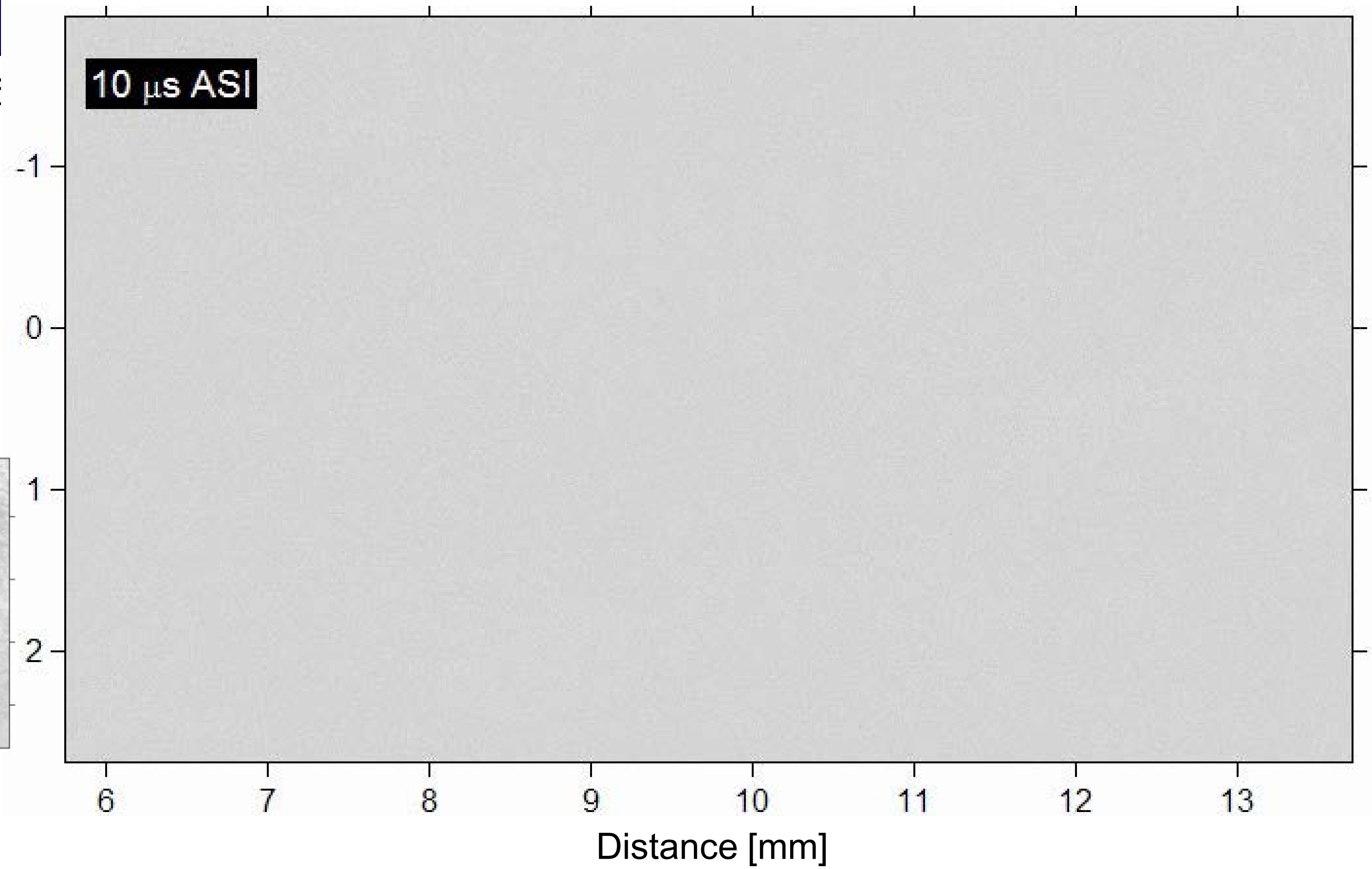
Liquid extinction



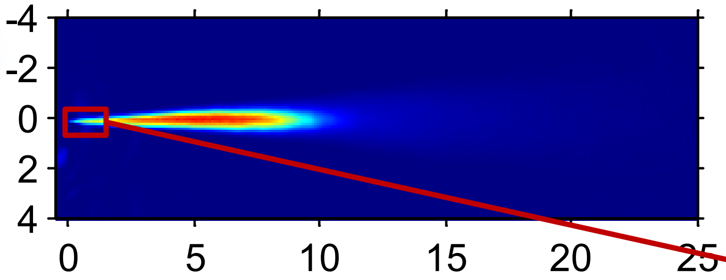
900 K, 22.8 kg/m^3
60bar

- Pockets of liquid surrounded by vapor.
  - Beam-steering from cold vapor phase remains apparent.
  - No direct evidence of droplets.



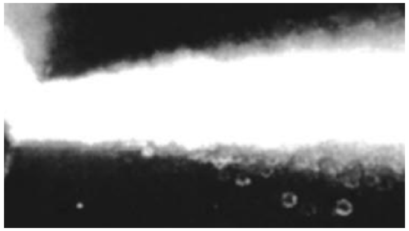


Near-field spray visualization provides critical information about spray development.

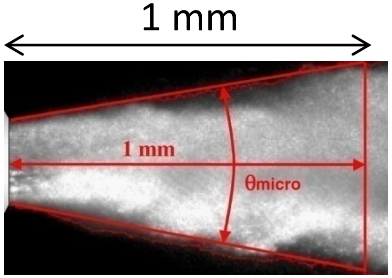


- Literature review shows attempts to visualize the breakup and atomization of sprays at the microscopic scale.
  - Room temperature conditions →
- Exploration at engine-relevant conditions is critical.
  - High pressure and temperature.
  - Affects fluid and interface properties.
- High-speed (time-resolved) visualization deepens understanding.

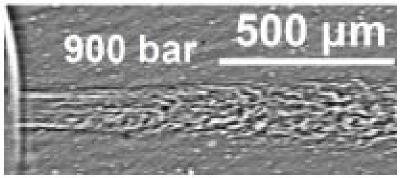
Review of near-nozzle microvisualization



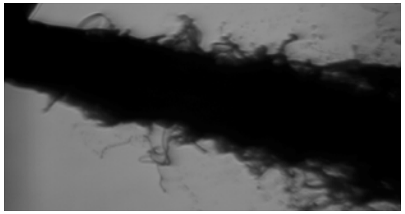
Wang et al. [2003]
Wayne State



Heimgärtner et al. [2000]
LTT

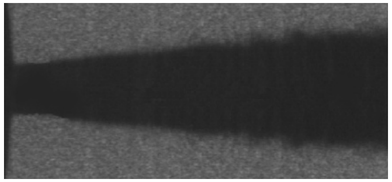


Gao et al. [2010]
Argonne



Bae et al. [2006]
KAIST

Crua et al. [2010]
Brighton

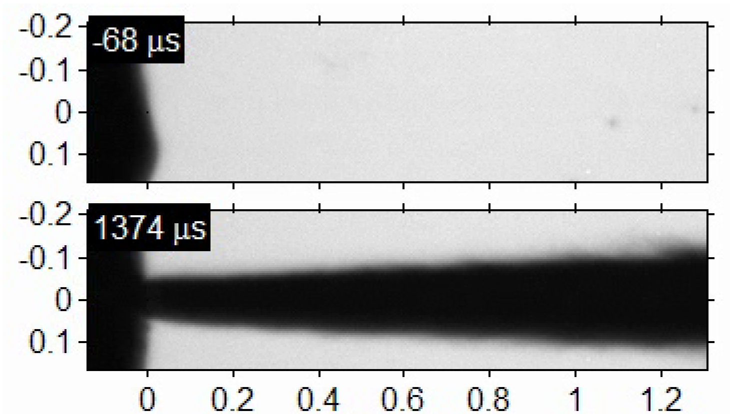


De la Morena [2011]
CMT

With cooler gas temperature, surface tension effects are apparent after the end of injection.

5 bar, 440 K (3.8 kg/m³)
n-dodecane, 150 MPa, 90°C

320×80 pixels, 4.7 μm/pix, 180 kfps!



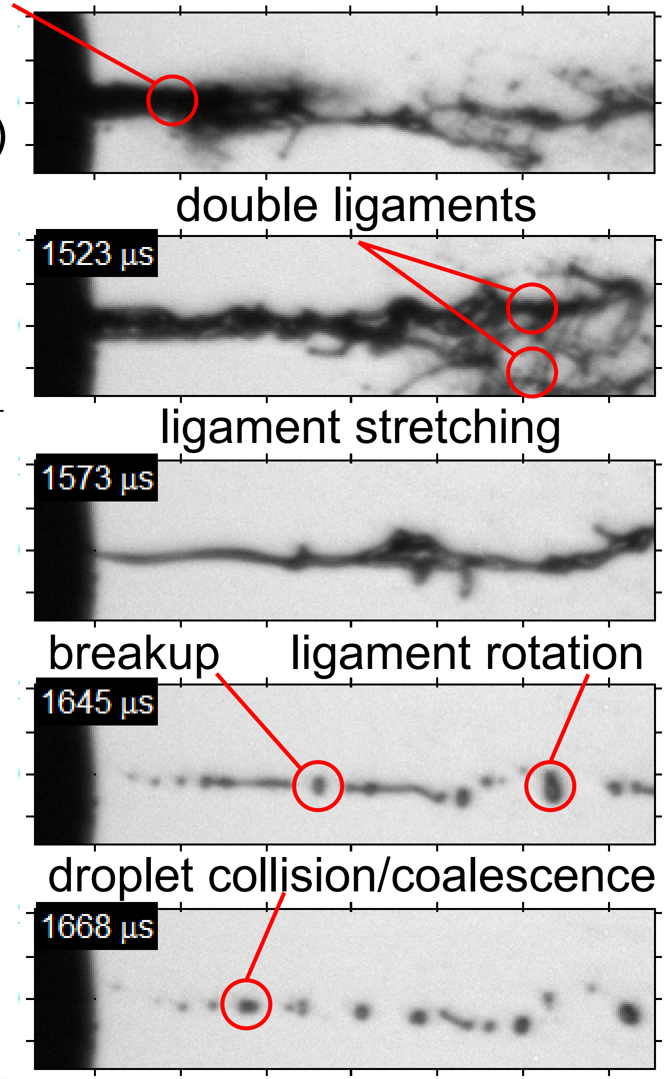
start of injection

end of injection

$$We = \frac{\rho_a u^2 d}{\sigma}$$

mini trailing injection (needle bounce?)

Features observed



- Liquid structures slow down during the end of injection and size increases (lower Weber number).
- Even though interfacial thickness is unresolved, time-history provides clear effects of surface tension.
  - Connected ligaments that eventually break into droplets.
  - Persistence of round objects that maintain shape.
  - Cascade of sizes captured by high-speed imaging.

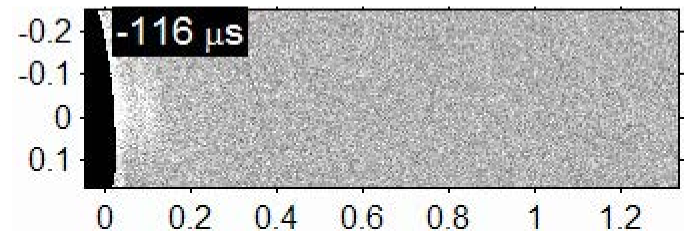
The beginning stages of injection show a vapor injection leading a liquid injection.

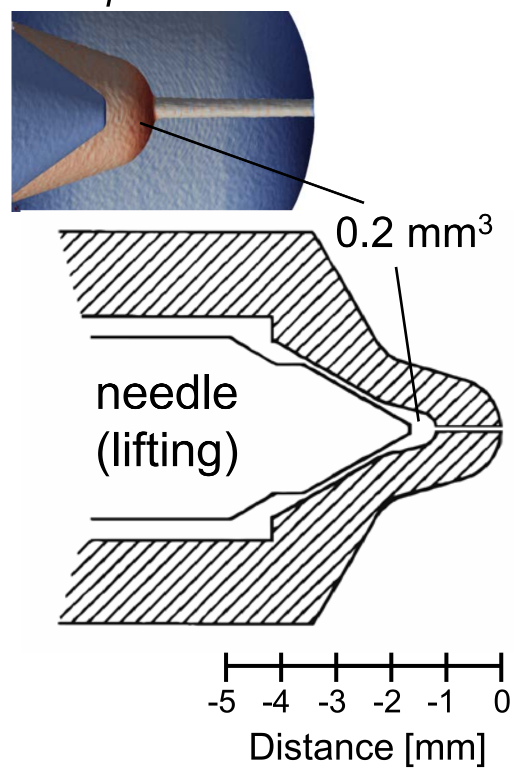
- What is the status of the sac volume at the start of injection?
  - Voids will be pressurized during compression cycle in an engine.
- Gases in the sac are pushed out by incoming liquid as the needle valve opens.
  - Vapor jet precedes liquid by approximately 10 μs.
  - Some venting/gas exchange starts at about -70 μs.
  - Volume of the early vapor injection appears similar to that of the 1-mm long orifice.
  - Will affect initial rate of injection and penetration.
    - > Typical targets for experimental/ modeling comparison.

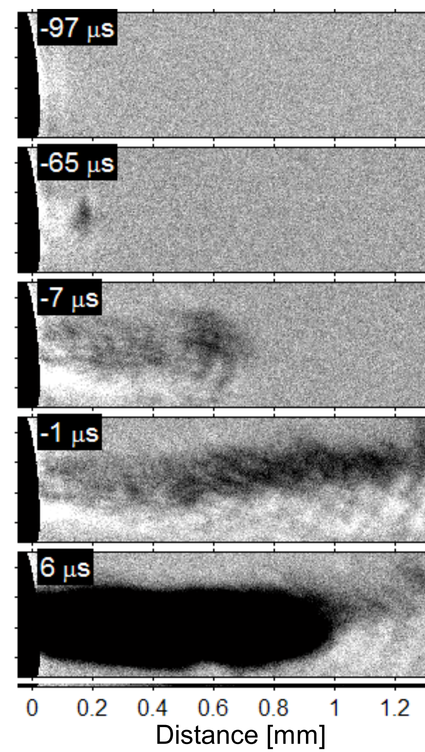
Movie adjusted for high contrast

60 bar, 900 K (22.8 kg/m³)
n-dodecane, 90°C, 150 MPa

Spray A Inj. 675
x-ray tomography
Tim Bazyn,
Caterpillar

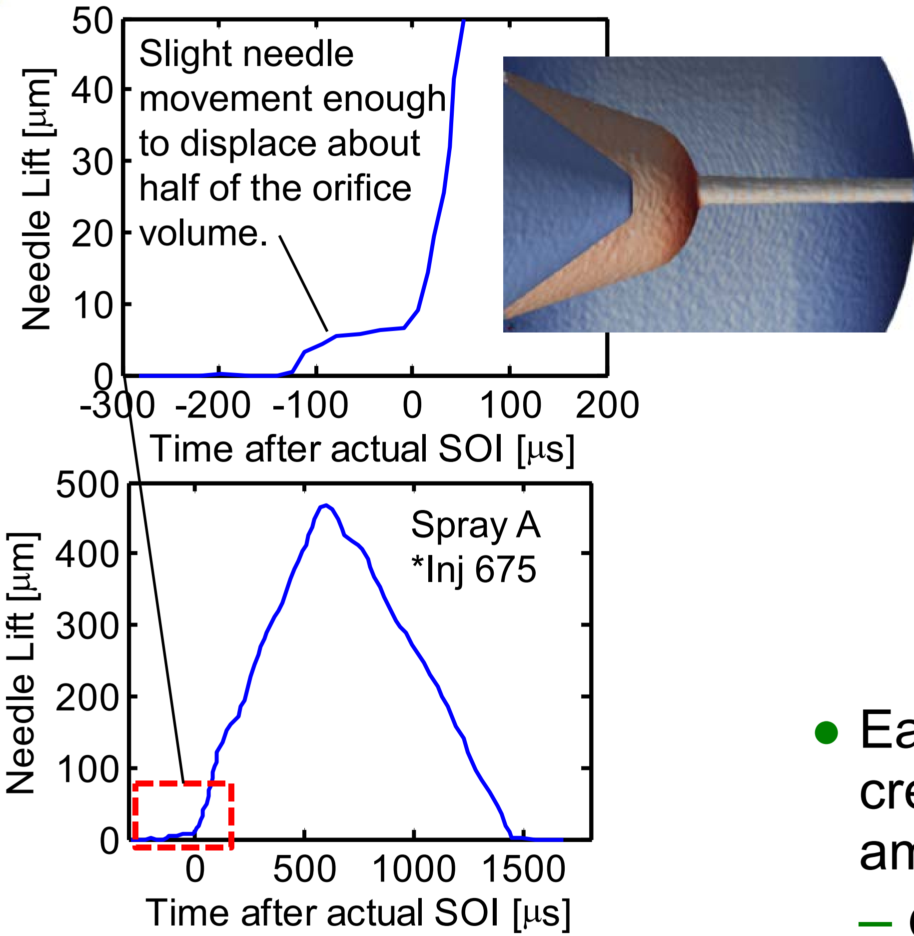






Leading vapor injection also shown recently by Crua et al. [SAE 2010-01-2247]

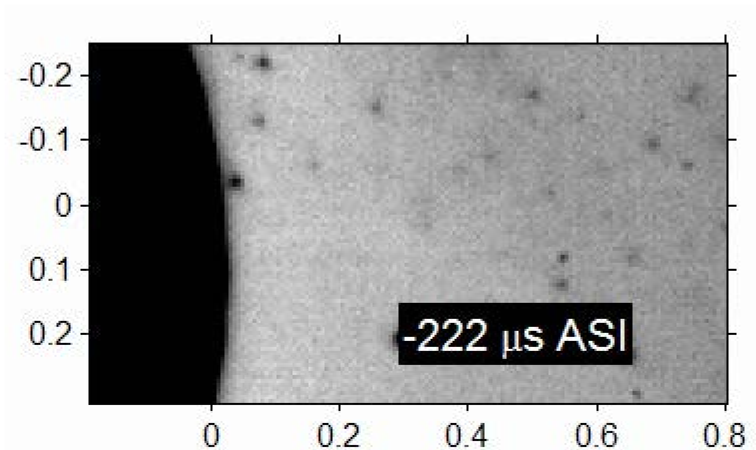
Needle movement actually pulls gas into the sac/orifice during first opening.



*Needle lift measurements performed by x-ray phase contrast imaging for the ECN.
A. Kastengren, C. Powell.
Argonne National Laboratory

Multiple injection situation: earlier injections have left droplets inside the chamber.

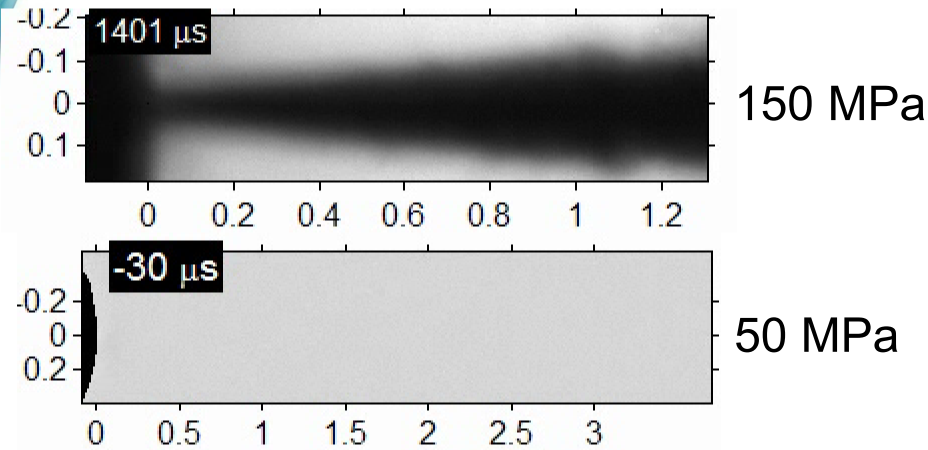
440 K, 29 bar

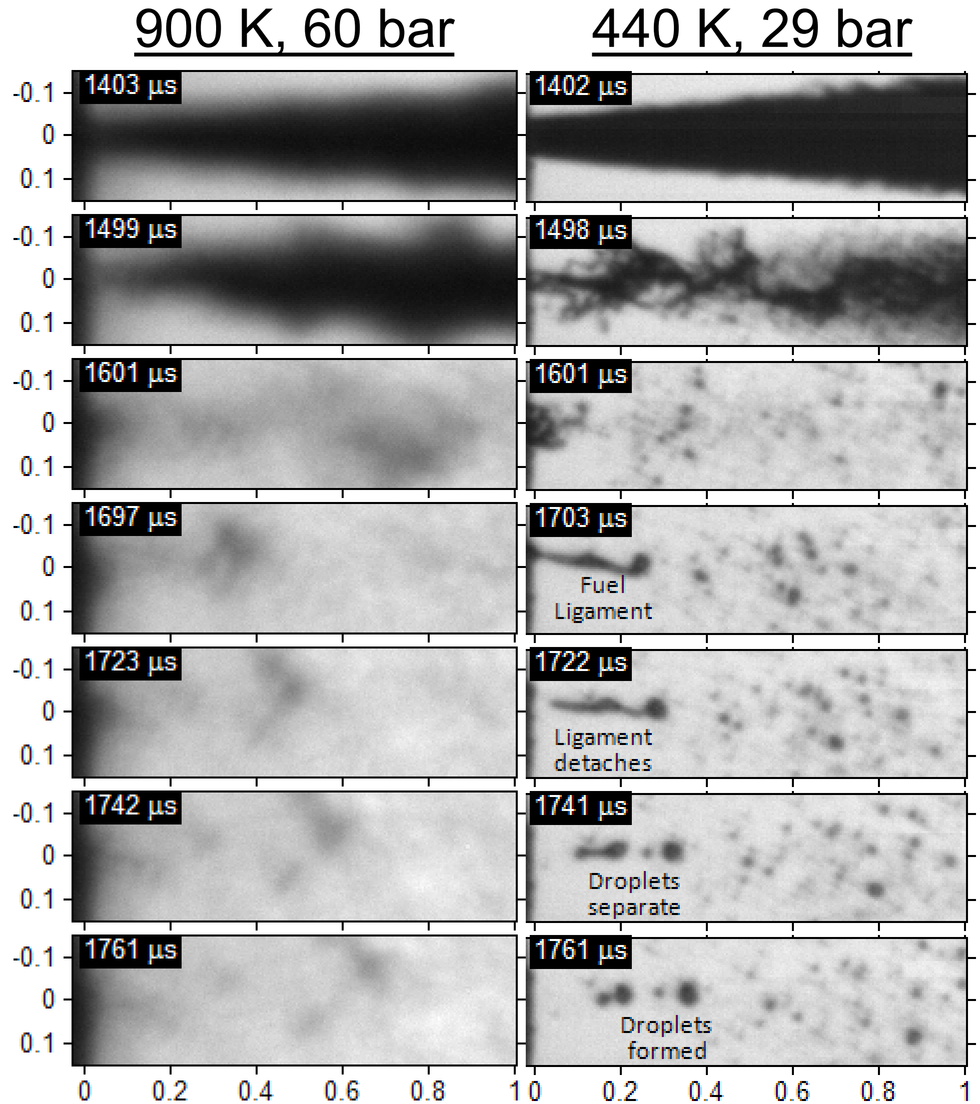


- Early needle movement momentarily creates a vacuum to pull droplet (and ambient gases) into the injector.
  - Gas transfer into the sac could draw soot particles or other debris into the sac or orifice.

At Spray A conditions (900 K, 60 bar), the near-nozzle region shows only diffuse structures at EOI.

60 bar, 900 K (22.8 kg/m^3)
n-dodecane, 90^{o}C

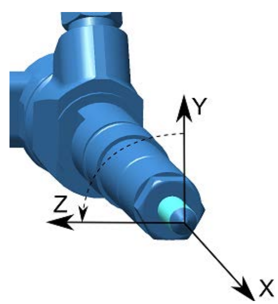




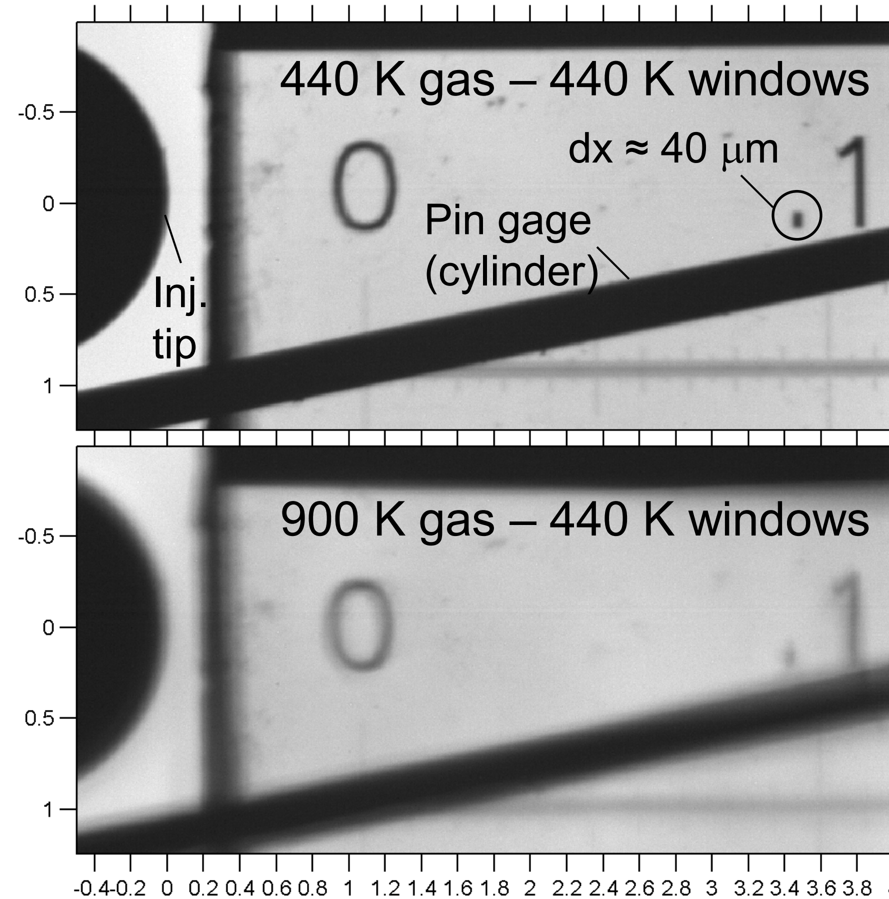
- Why don't we see droplets and ligaments at Spray A conditions?
  - Near the nozzle or near the liquid length.
- Possible explanations:
  - (1) Artifacts have degraded the optical quality of our imaging system, creating blurry images.
  - (2) The object (the spray) has only diffuse physical features, i.e., perhaps structures with sharp interfaces do not exist.

Optical resolution is degraded at hot, pressurized conditions because of beam steering.

- Optical quality at 900 K:
  - Refractive index gradients defocus sharp object plane (glass scale).
  - Optical system circle of confusion analysis shows that structures of approx. 25 μm are resolvable.
  - Smaller structures may also be measureable if they are isolated.
- Depth of field analysis:
  - Camera/lens traversed over distance Δz.
  - Under 440-K conditions, droplets and ligaments remain sharp over Δz ≈ 1.3 mm.
  - Explains why liquid droplets are observable at 440 K at x = 10 mm, where the spray width is several mm.



Glass scale positioned at focal plane



Pressurized: Density = 22.8 kg/m^3

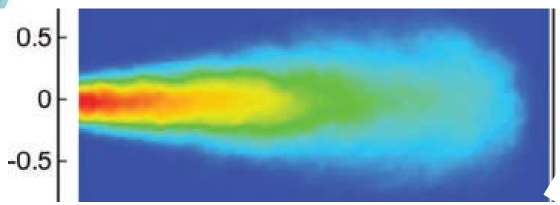
Experiment shows less evidence of surface tension effects at high pressure and temperature.

- Further experiments performed over a range of ambient gas temperature and pressure.
- While the optical system is degraded, the temporal evolution of larger (25 μm) structures would still be tractable after the end of injection.
- Possible explanations:
  - There are many structures (droplets) significantly smaller than 25 μm in close proximity to each other.
  - Gas-liquid interfaces are more diffuse and have diminished surface tension.
- Raises an important question because of the obvious implications towards modeling engine sprays.
- Especially considering our experimental limitations, guidance is needed to describe gas/liquid interfaces at these engine-relevant conditions.
  - We have enjoyed a very useful collaboration with Joe Oefelein and Rainer Dahms of Sandia on this topic.
  - Please watch ACE007 (Joe Oefelein) review presentation here at 11:30 am for more information.

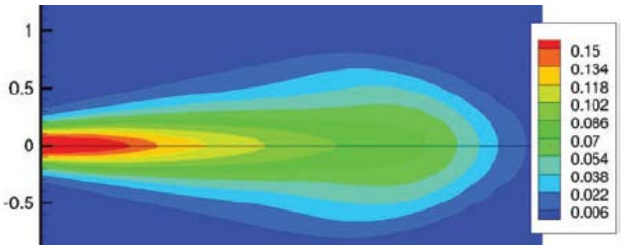
Future Work

Exp/Model Comparison at ECN1

Experimental mixture fraction



Model mixture fraction



- Direct-injection gasoline research currently underway.
  - Quantitative mixture fraction.
  - ECN gasoline injectors chosen with assistance from Scott Parrish, GM.
- Near-field liquid structure, ignition, combustion and soot characteristics of multi-hole Spray B injectors. Quantitative soot and soot precursor history.

Deeper analysis →

Maintain Spray A conditions

- More detailed, quantitative diagnostics at Spray A conditions
  - Velocity, turbulence, liquid volume fraction, liquid structure, soot, cool flame, radical species, …

Broader conditions →

Variation about Spray A conditions

- Vary ambient conditions
  - Spray A-800 K, Spray A-1000 K
  - Spray A-21% O_2
- Vary injector conditions
  - Injection pressure
  - Multi-hole Spray B, gasoline injector

Organization of ECN2

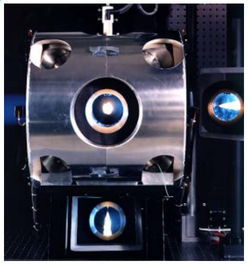
- Visualize liquid structure with improved optical setup to overcome difficult beam steering environment. Larger collection angle. “Insertion” windows to lesson boundary layer effects.
- ECN workshops to seriously evaluate experimental and modeling results: ECN2.

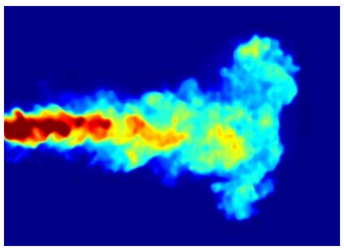
Presentation Summary

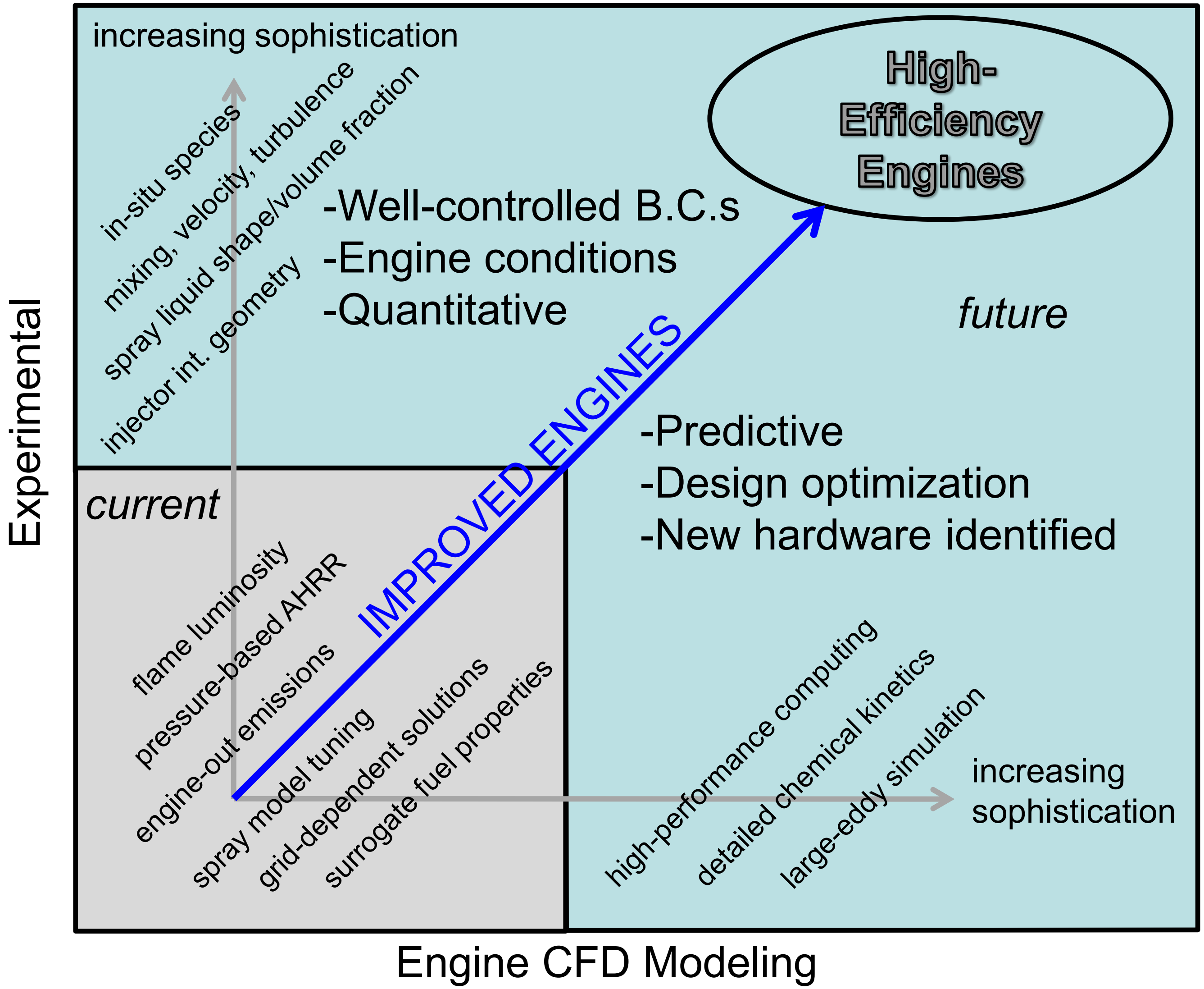
- Project is relevant to the development of high-efficiency, low-emission engines.
  - Observations of combustion in controlled environment lead to improved understanding/models for engine development.
- FY12 approach addresses deficiencies in spray modeling.
  - Massive Spray A dataset is being generated, which will be a key component for future model improvement.
  - Evaluation of liquid extinction as a way to quantify liquid-phase penetration.
  - High-speed microscopy reveals liquid structure as it transitions from cold to engine-relevant conditions.
  - Enhanced knowledge about injector startup (vapor injection) as a modeling boundary condition.
- Collaboration expanded to accelerate research and provide greatest impact (MOU, leading Engine Combustion Network).
- Future plans will continue ECN-type diesel and gasoline research.

Technical Backup Slides

A combined experimental/modeling pathway towards clean, high-efficiency engines.

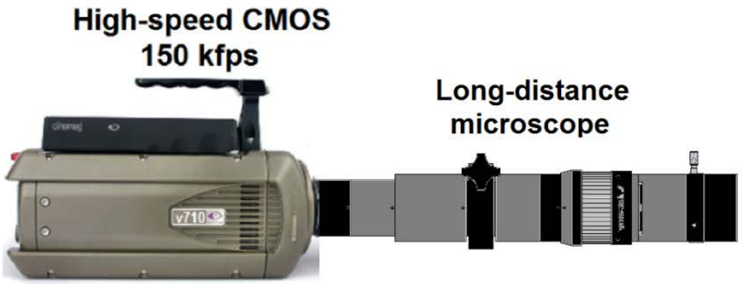


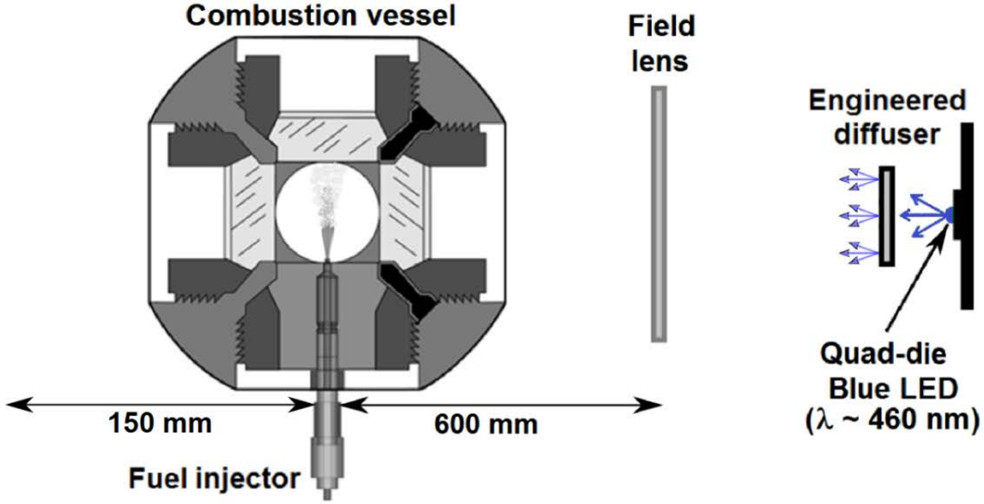


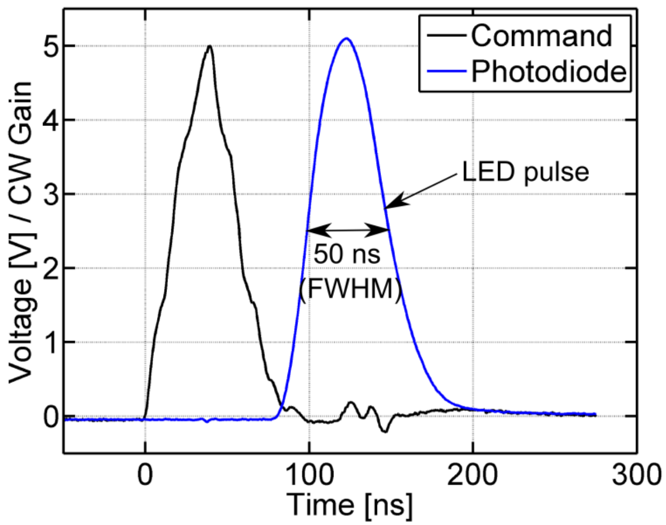


Microscopic high-speed imaging setup

- 50 mm objective replaced by a long-distance microscope lens (mag.≈ 4x)
- Field of view slightly longer than 1 mm (4 µm/pixel)
- Still and high-speed imaging to record the event and follow the features





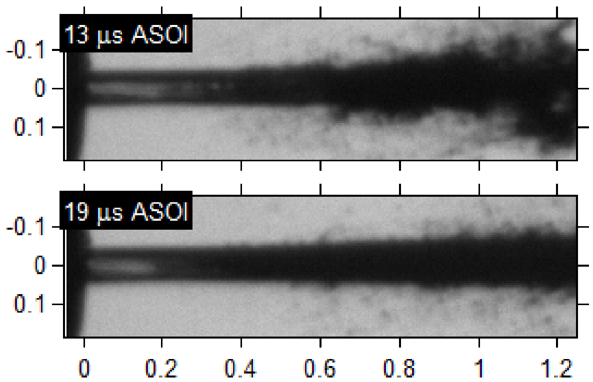


- 150 kHz normal operation (up to 400 kHz)
- LED operated in burst mode producing more than 5 times the CW output luminosity
- 50 ns LED pulse duration to freeze the flow (exiting at more than 500 m/s)

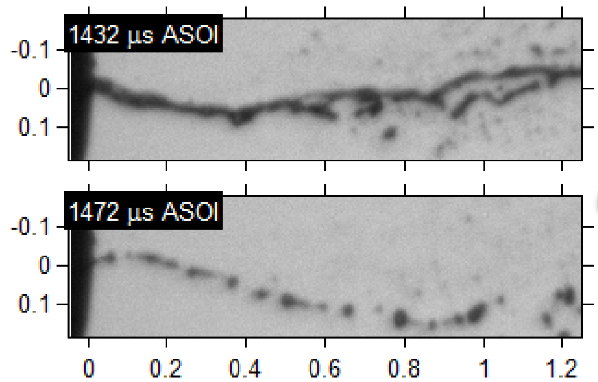
Mixing evolution with temperature and pressure

Low pressure, low temperature

- Transparent liquid core



- Droplets and ligaments

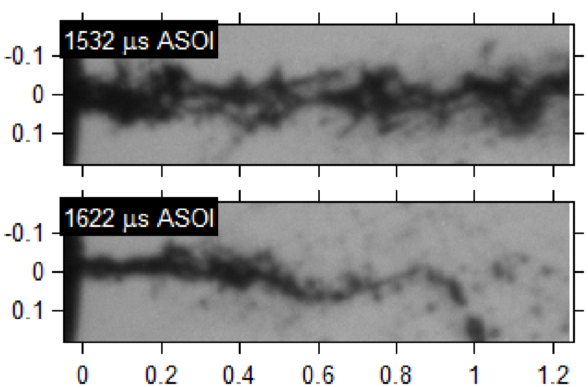


- Droplet collision

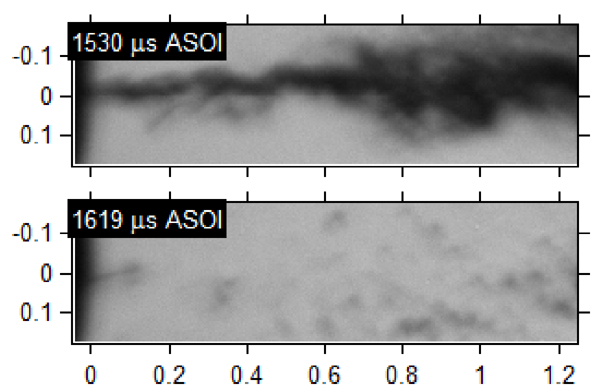
→ Presence of surface tension to hold the fluid structures together

When temperature and pressure increase

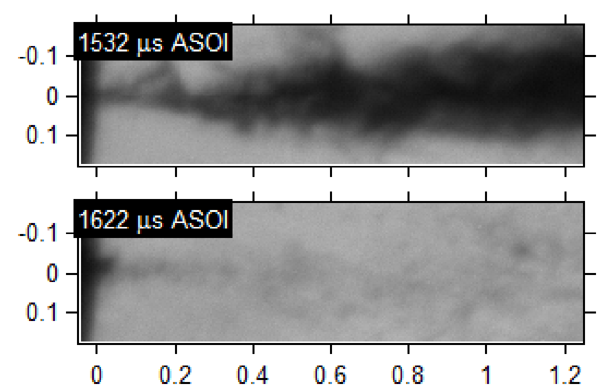
10 bar (3.8 kg/m^3), 900 K, 150 MPa



20 bar (7.6 kg/m^3), 900 K, 150 MPa



40 bar (22.8 kg/m^3), 900 K, 150 MPa



Further long-distance microscopy imaging considerations under 900 K, 60 bar conditions.

- Beam steering by the vapor plume surrounding liquid will also degrade image quality.
  - 25 micron droplets visible under cold conditions, may be less sharp, when surrounded by an irregular vapor plume.
- Image quality analysis performed without the spray.
- There is less fuel vapor and beam steering after the end of injection.
- Applying a light model to detailed numerical results would provide insight.