Diagnostics for fuel spray research at high pressure and temperature

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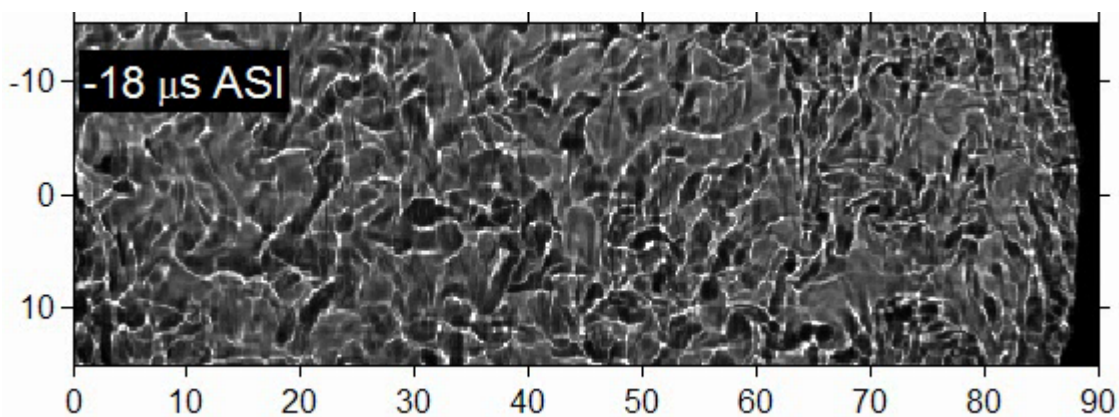
Sandia National Laboratories

Workshop on techniques for high-pressure combustion
29 Aug to 1 Sept 2011



Schlieren imaging of diesel fuel spray: 60 bar, 900 K, 15% O_2

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

Acknowledgements

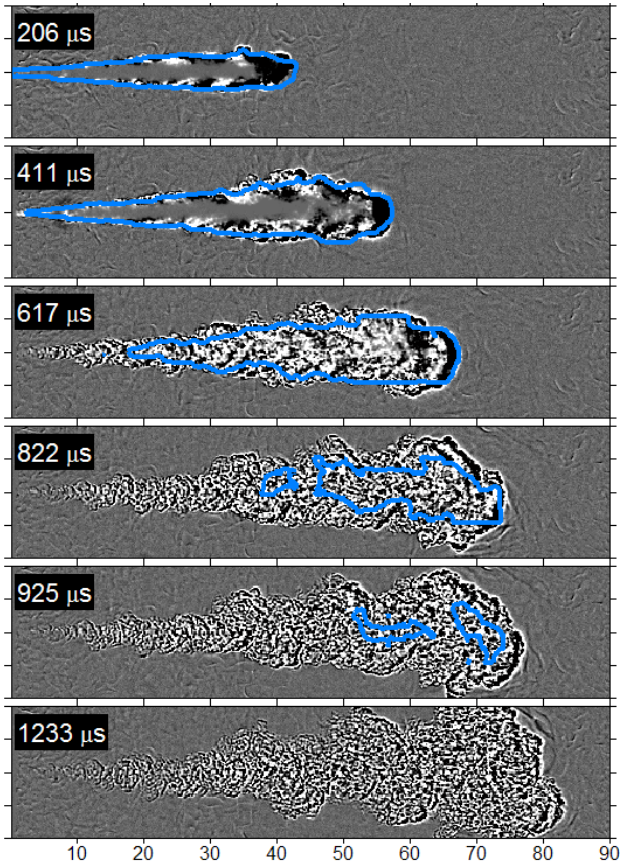
- Dennis Siebers, Mark Musculus, Julien Manin, *Sandia National Laboratories*
- Caroline Genzale, *Georgia Institute of Technology*
- Gilles Bruneaux, Laurent Hermant, Louis-Marie Malbec, *IFP Energies nouvelle*
- Chris Powell, Alan Kastengren, Sibendu Som, *Argonne National Laboratory*
- Tim Bazyn and Glen Martin, *Caterpillar Inc.*
- Cherian Idicheria, *GM R&D*
- Sanghoon Kook and Evatt Hawkes, *UNSW Australia*
- Raul Payri, Michele Bardi, *CMT Motores Térmicos*
- Gurpreet Singh, *Funding provided by US DOE Office of Vehicle Technologies*
- *French Ministry of Ecology, Energy, Sustainable Development and Sea*
- David Cook and Godehard Nentwig, *Robert Bosch LLC*, *donation of injectors*.

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.
  - Multiple injections
  - Mixing driven by spray
  - Two-phase system
  - Complicated internal flows within injectors
- Optimum engine designs discovered only when spray modeling becomes predictive.

Schlieren: vapor boundary

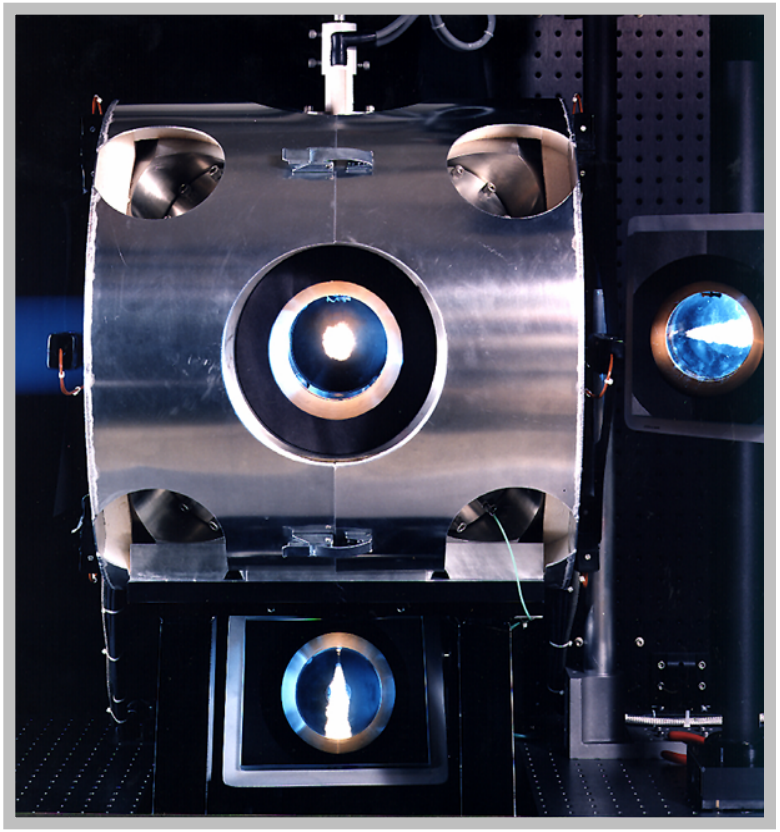
BLUE: liquid boundary

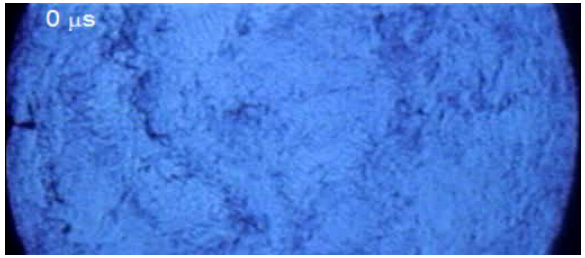


What barriers prevent quantitative diagnostics in sprays at engine conditions?

- Problems with sprays:
  - Dense, near-injector region.
  - Understanding internal injector geometry, movement, flows, cavitation.
  - But these problems exist even for cold, atmospheric sprays.
- Problems with high-pressure and temperature:
  - Small length and time scales for spray development and ignition.
  - Significant beam steering caused by intense refractive index gradients.
  - Significant temperature/composition uncertainties for laser-induced fluorescence.
  - Optical access may create stress-induced birefringence, complicating polarization-sensitive diagnostics.
- I will speak about how we might overcome barriers associated with the high pressure and temperature environment.

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, gasoline, jet
- 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.

Experiences with spray visualization at low pressure and temperature.

Schlieren responds to refractive index gradients due to density, temperature: f(dn/dx) ≈ f(dr/dx) ≈ f(dT/dx)

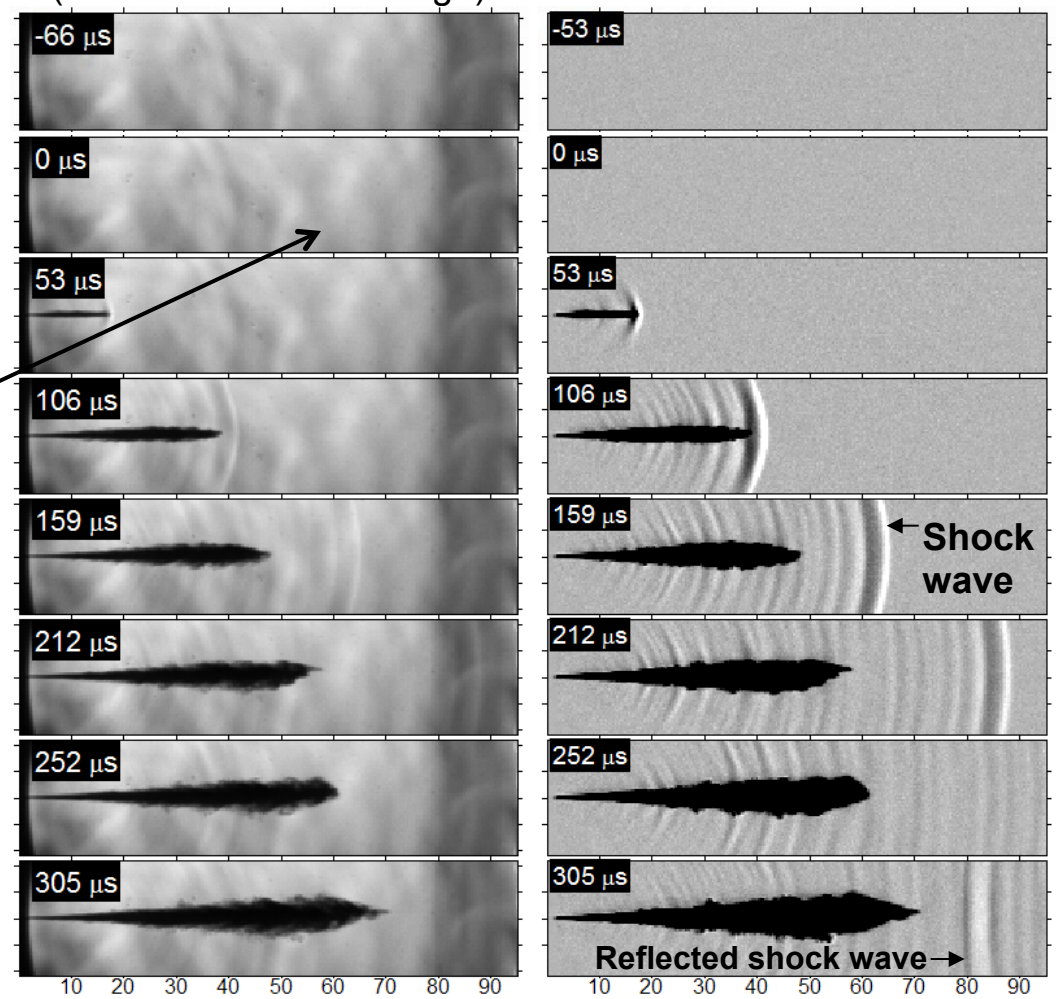
Non-uniformities caused by free-convection boundary layer between hot, 455-K vessel and 300-K room air.

Example 1:

Ambient	Injector	Camera
455 K	373 K	256 × 64 pix.
2.6 kg/m^3	diesel	75.5 kfps
3.5 bar	1500 bar	2 ms exp.

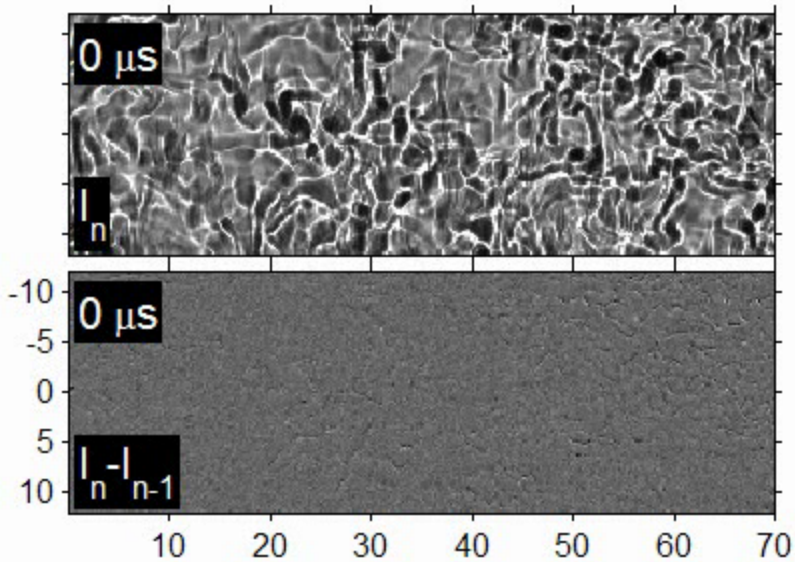
Original schlieren
(80% cutoff on knife edge)

Corrected: $I - I_0$

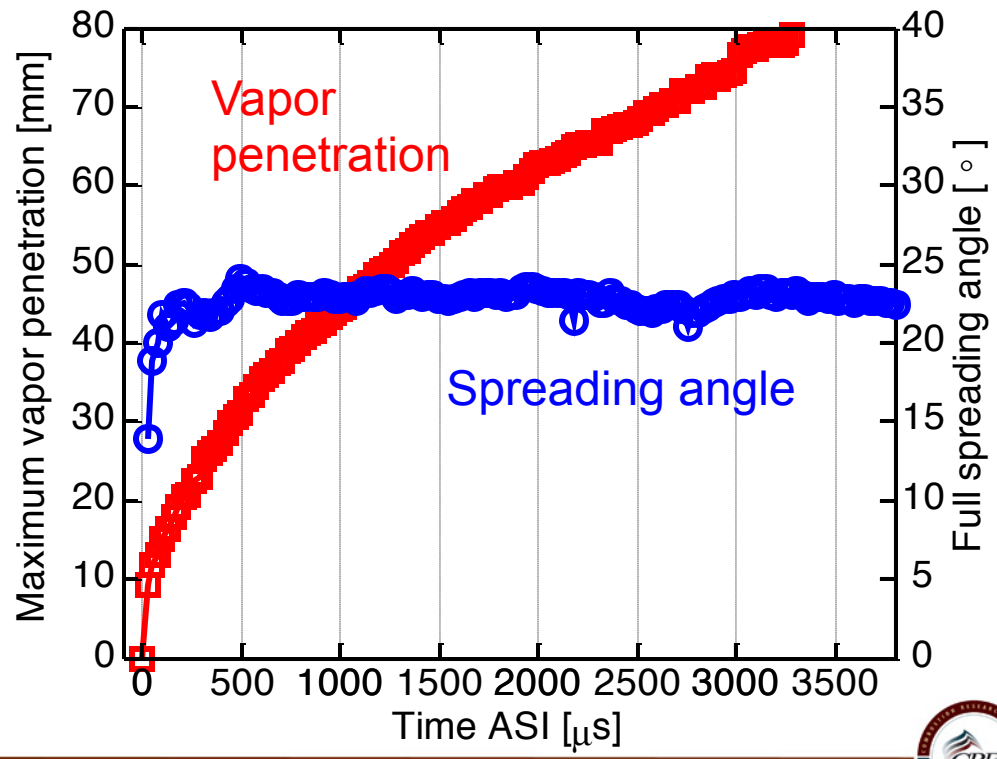


But at high gas temperature, temperature non-uniformities exist at walls and within ambient.

High-speed schlieren imaging (vapor), BLUE: Liquid



- Image corrections needed because of strong "background" gradients along windows and within the ambient gases.



Experimental Conditions

"Spray A": www.sandia.gov/ECN

900 K gas temperature

22.8 kg/m^3 gas density – 60 bar

0% O_2-inert

1500 bar injection pressure

0.090 mm nozzle orifice

n-dodecane

Extreme refractive index gradients affect optical diagnostics.

- Schlieren visualization, as shown.
- Laser extinction for soot or liquid concentration.
- Diffuser back-illumination imaging.
- Quality and position of imaging systems.
- Planar laser sheet intensity distribution.

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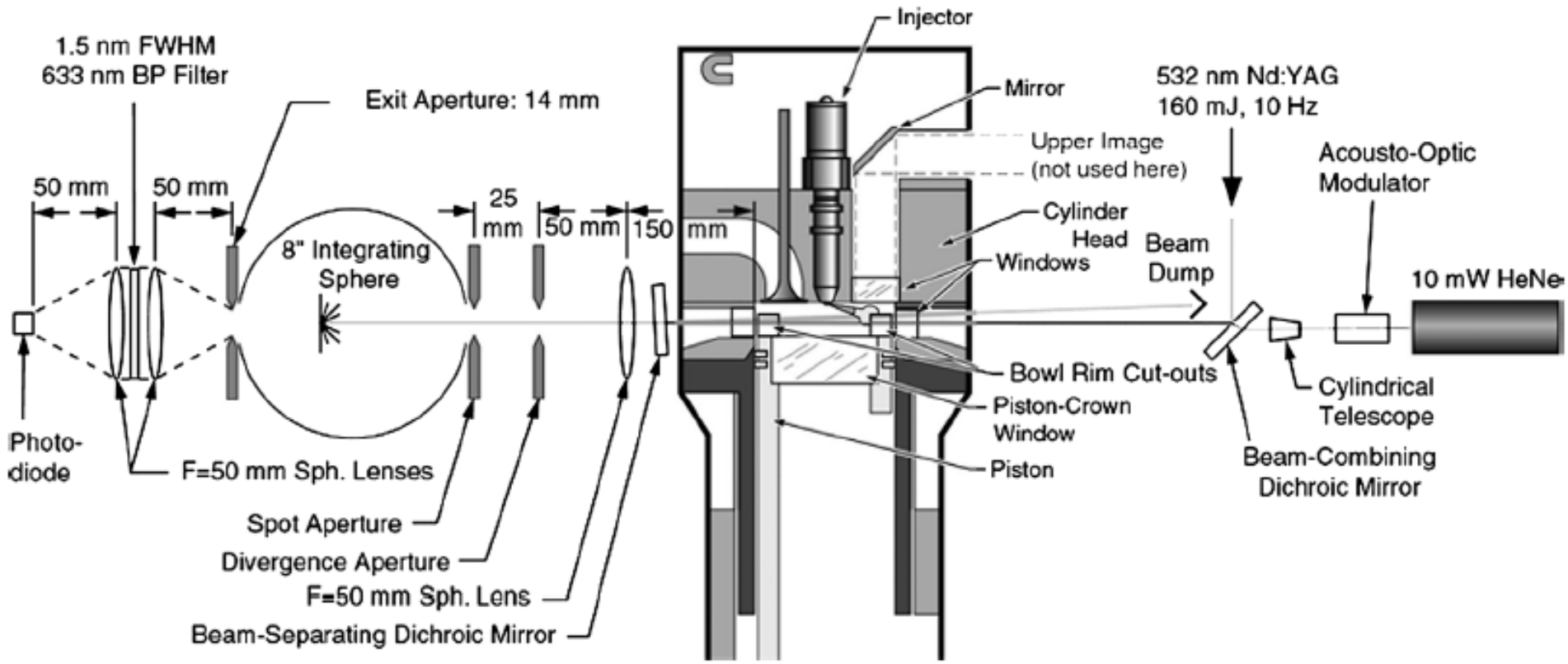
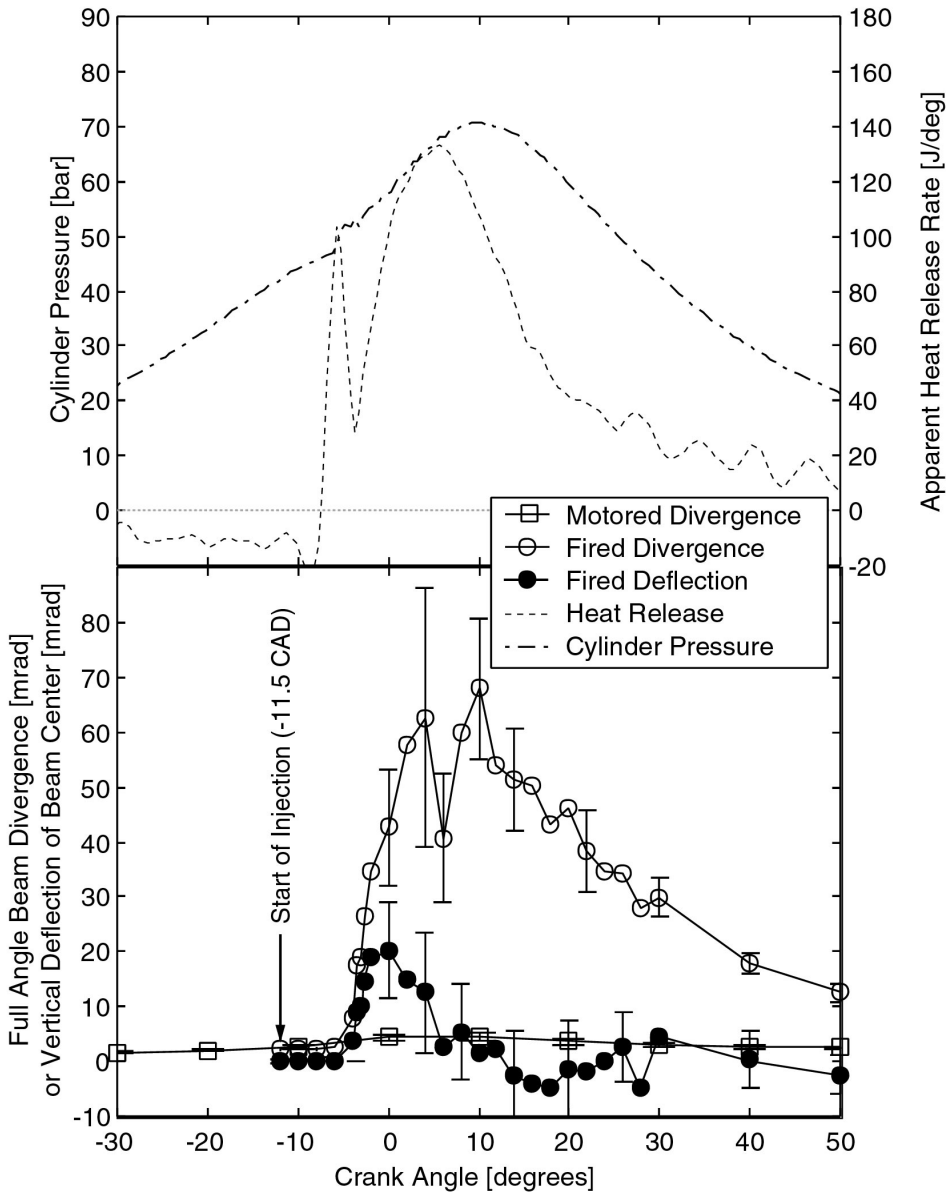
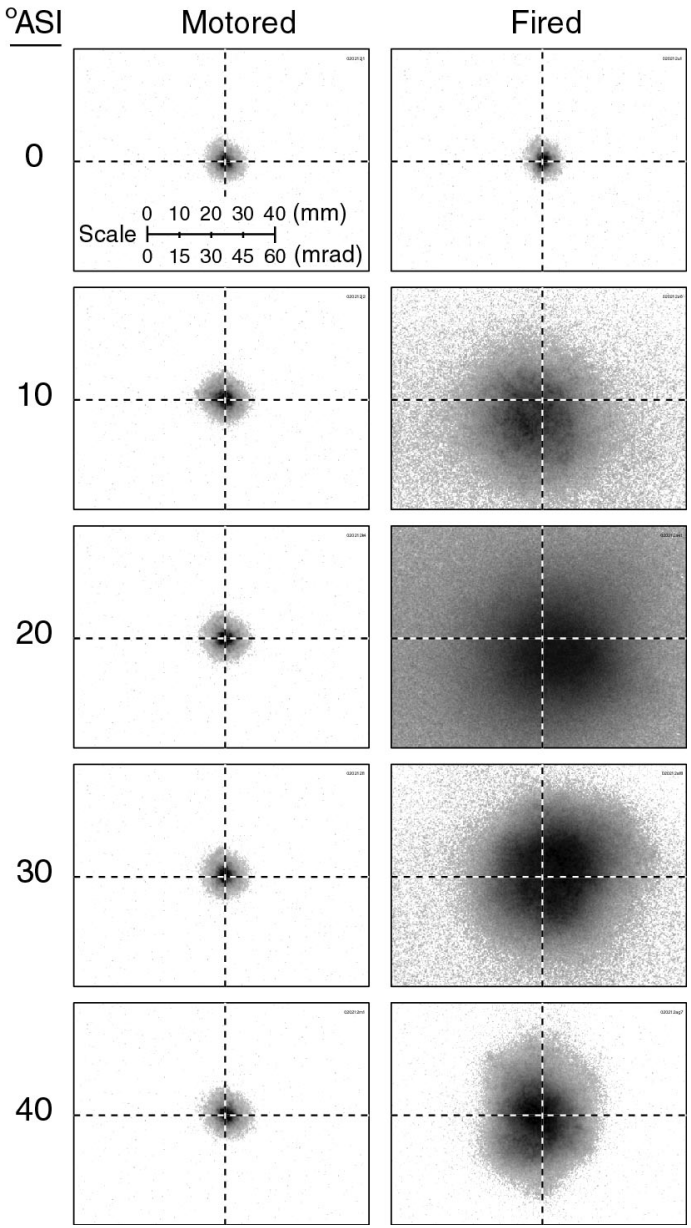
Laser extinction diagnostics for engine sprays.



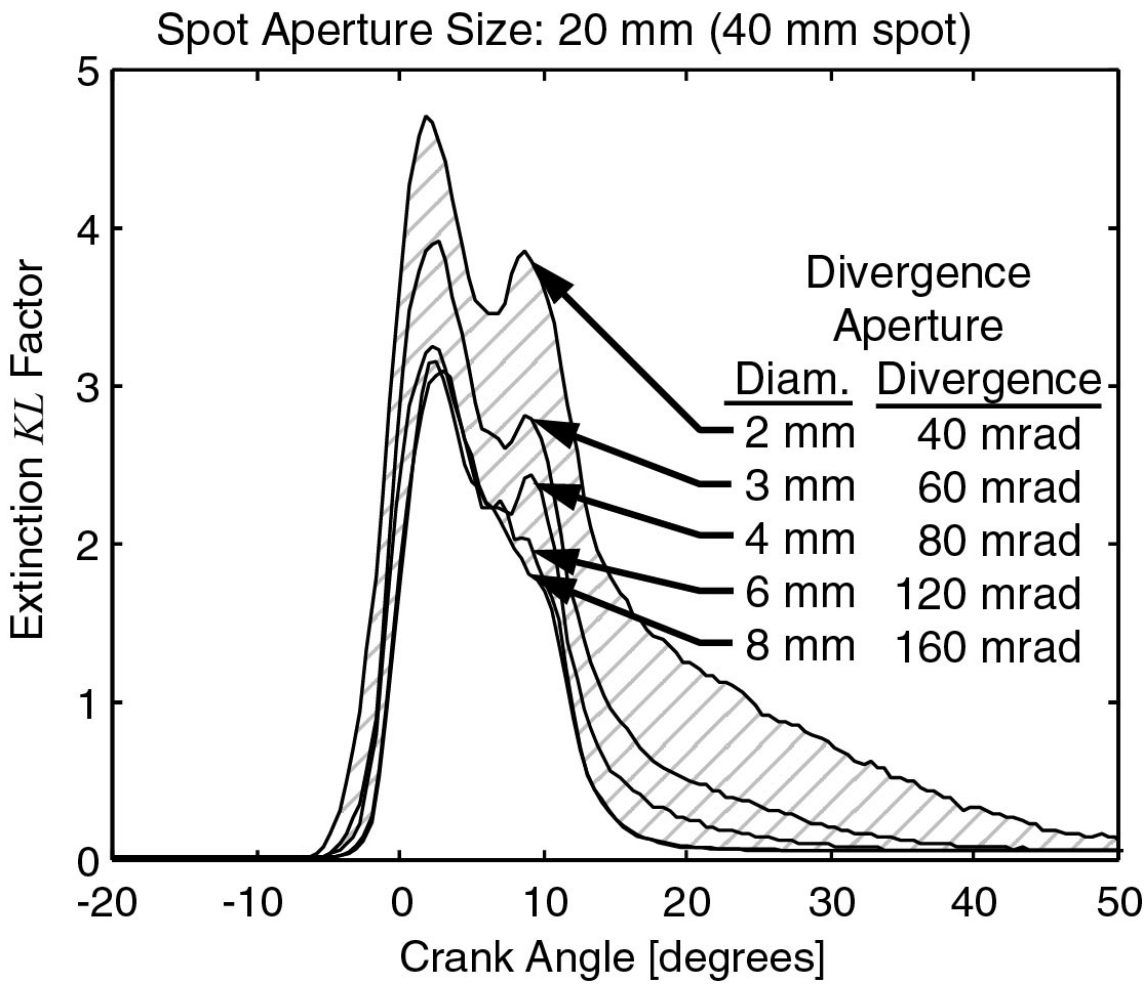
Musculus and Pickett, Combust. Flame, 2005.

Beam divergence from the reacting spray is apparent.

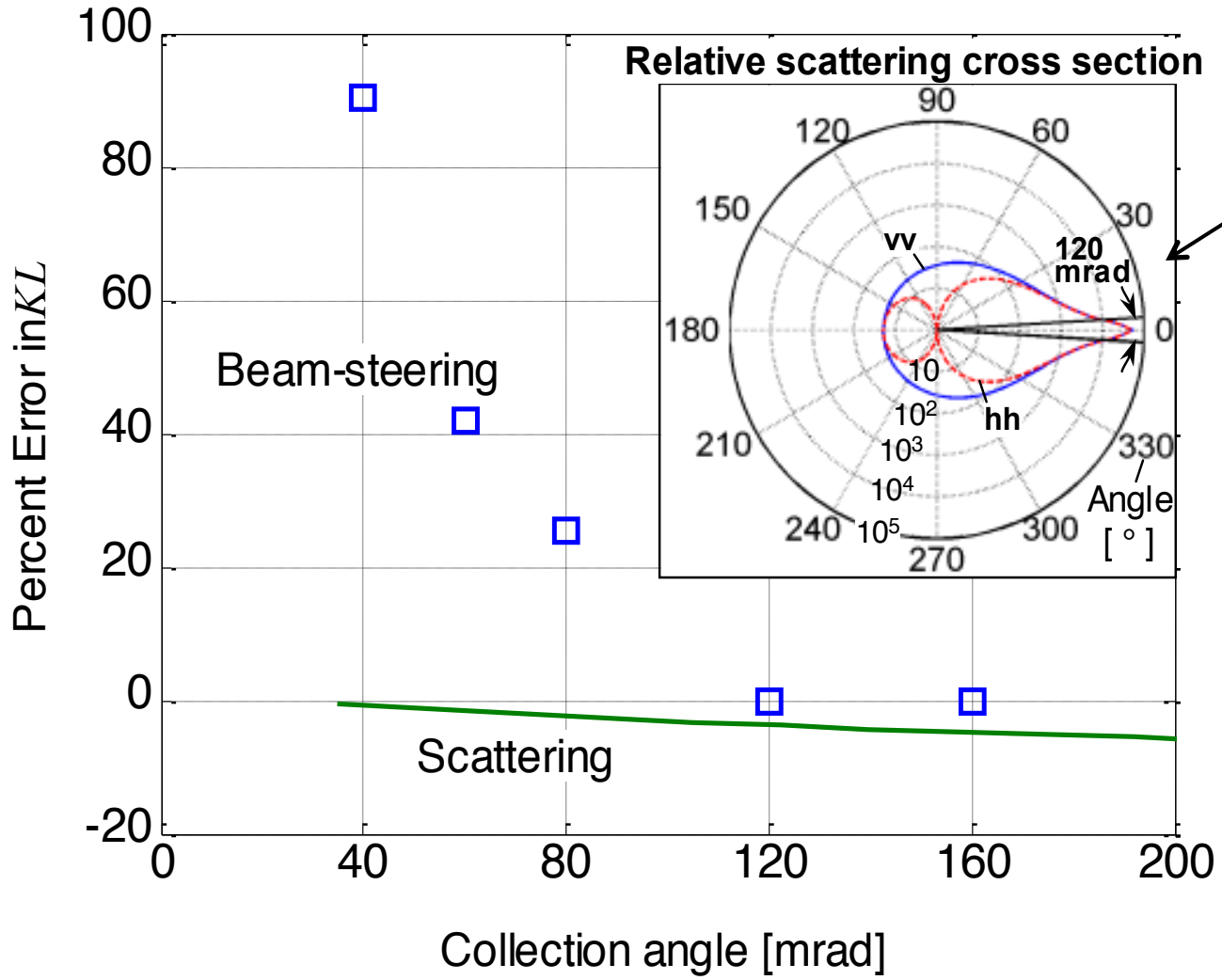




Serious errors result if beam steering is interpreted as soot extinction.

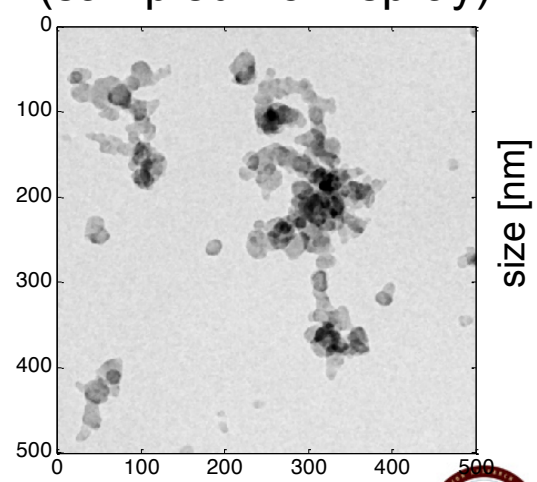


Tradeoff between beam-steering and increased forward-scattering shows beam-steering most important.



Calculated using Rayleigh-Debye-Gans theory for fractal aggregates

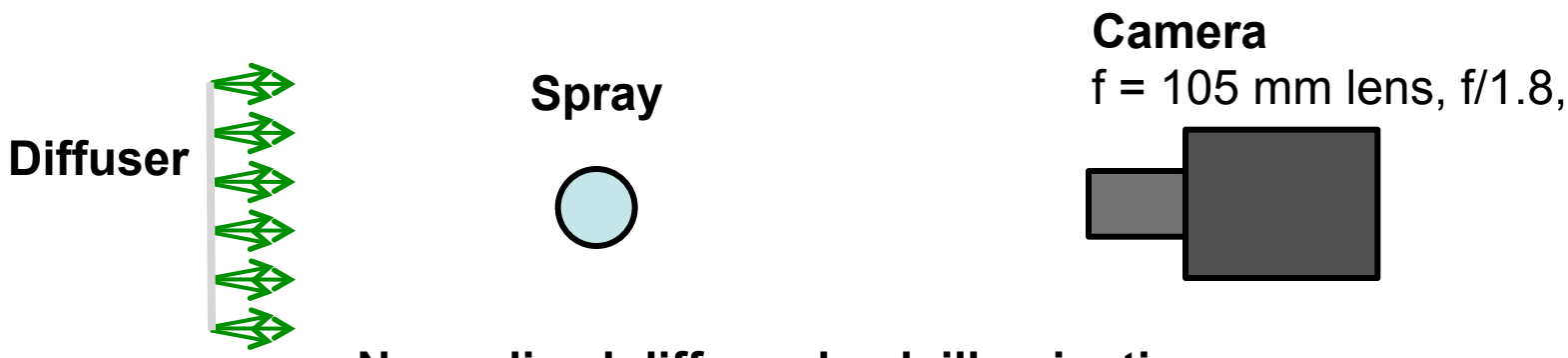
Soot aggregate (sampled from spray)



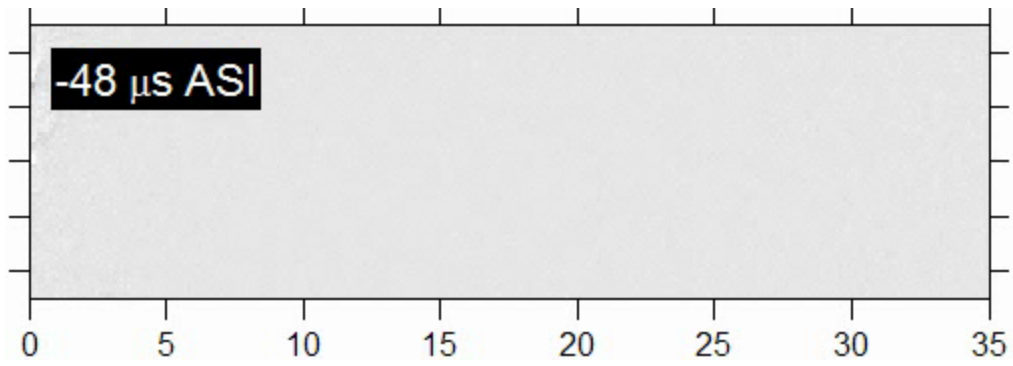
Extreme refractive index gradients affect optical diagnostics.

- Schlieren visualization, as shown.
- Laser extinction for soot or liquid concentration.
- Diffuser back-illumination imaging.
- Quality and position of imaging systems.
- Planar laser sheet intensity distribution.

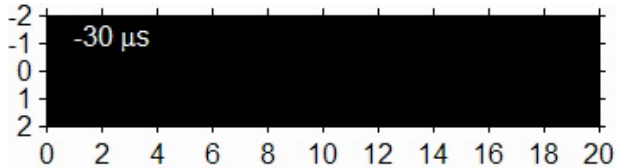
Quantification of liquid-phase penetration using diffuser back illumination.



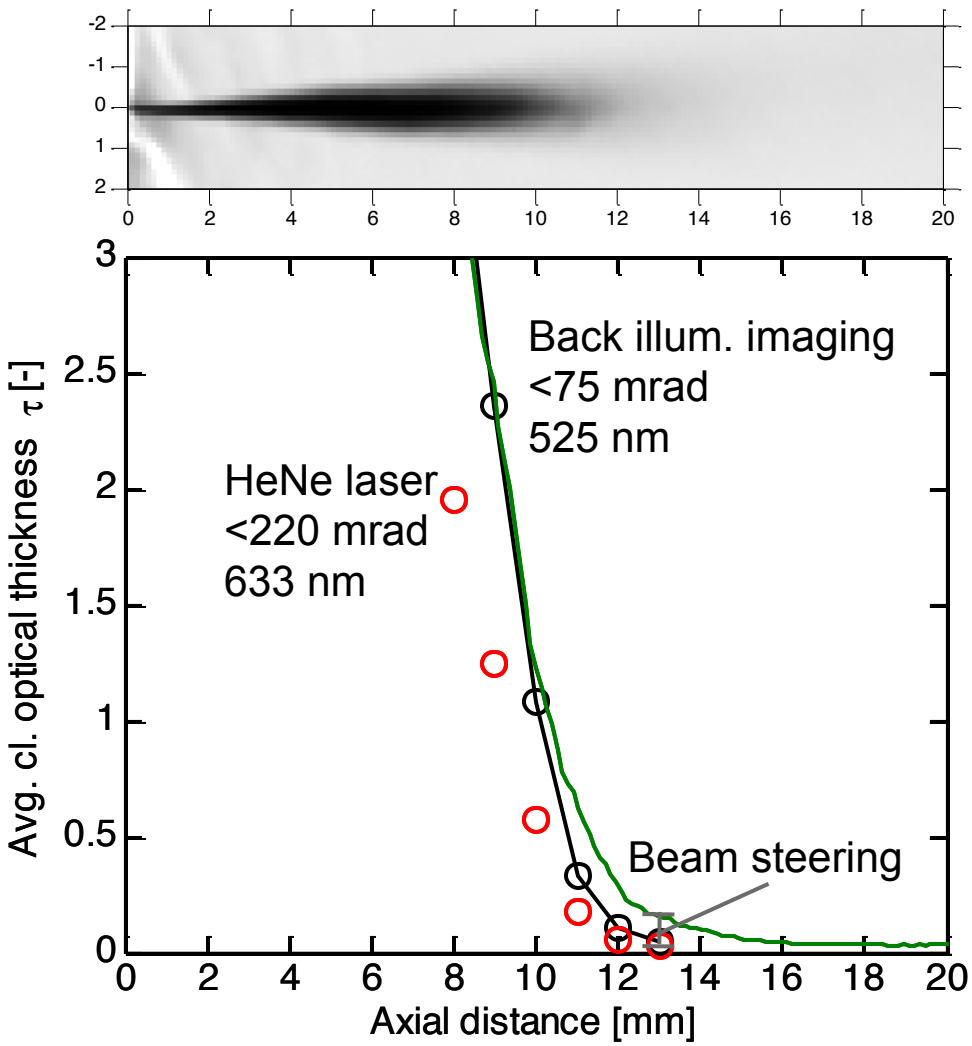
Normalized diffuser back illumination



Elastic scatter with side illumination



Diffuser back-illumination imaging is still somewhat sensitive to beam steering.



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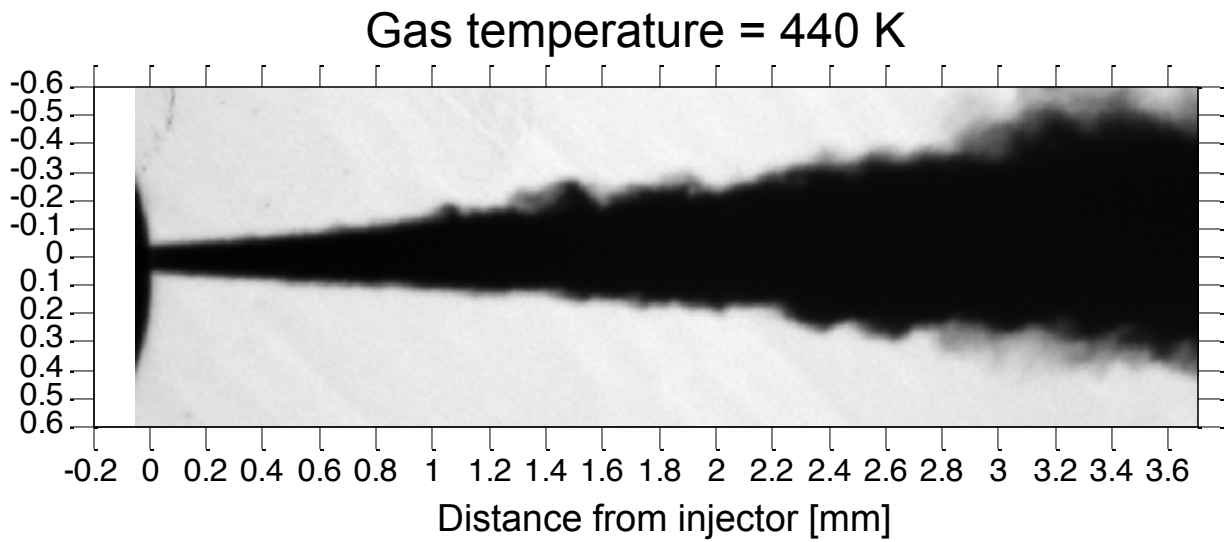
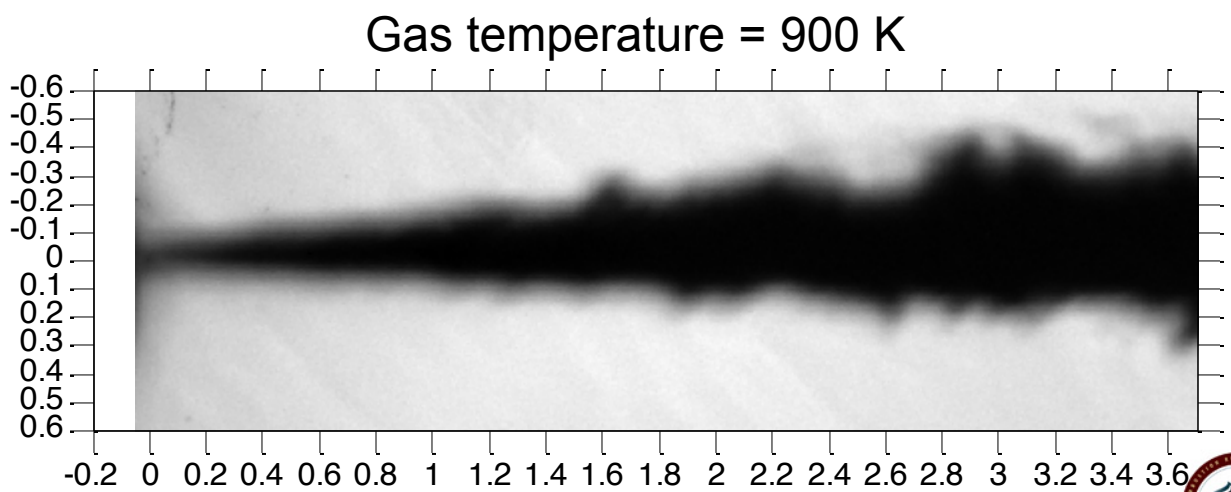
High gas temperature blurs edge of spray in micro-visualization imaging.

Optical setup
Diffuser back illumination
100 ns LED pulse
Infinity microscope lens
3[illegible] magnification objective
256 pixels/mm
approx. 0.1 mm DOF

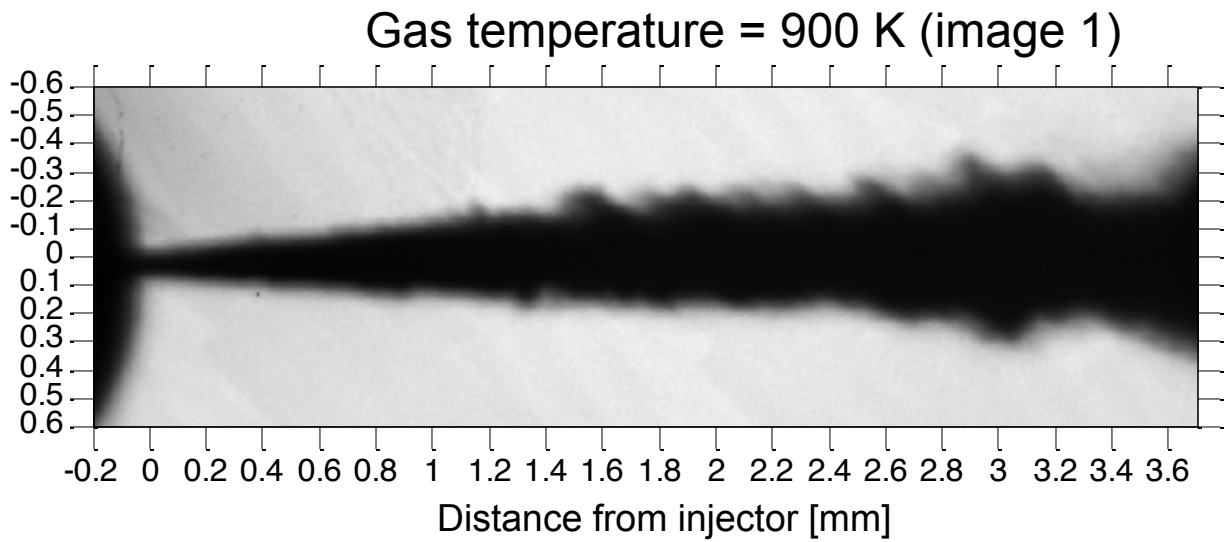
Experimental Conditions
"Spray A
22.8 kg/m^3 gas density
1500 bar injection pressure
0.090 mm nozzle orifice
n-dodecane, 363 K





Adjusting camera position recovers some, but not all, of the image clarity.

<u>Optical setup</u>
Same, except camera moved by 0.6 mm away from object plane.



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"Spray A
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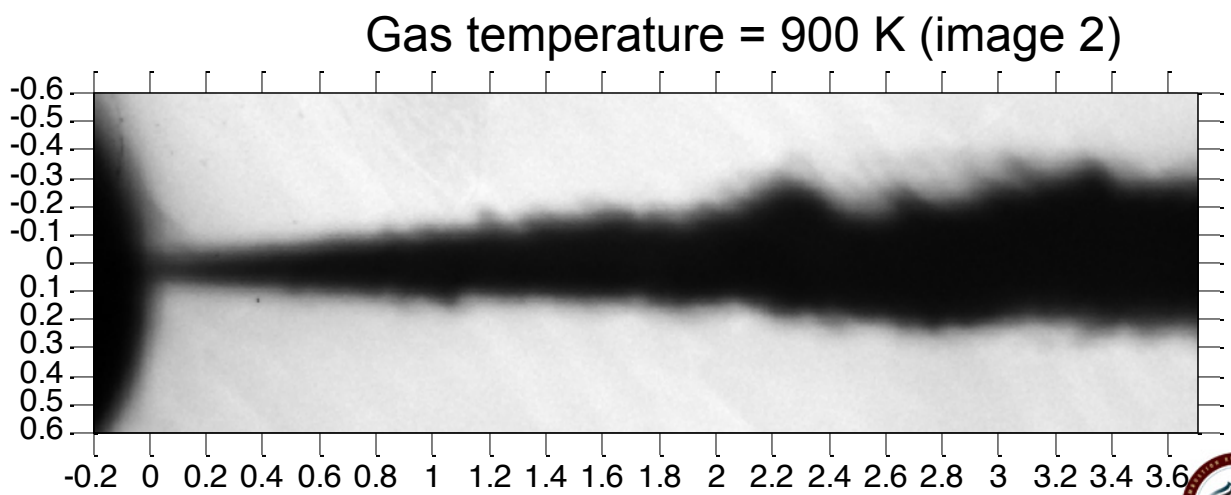
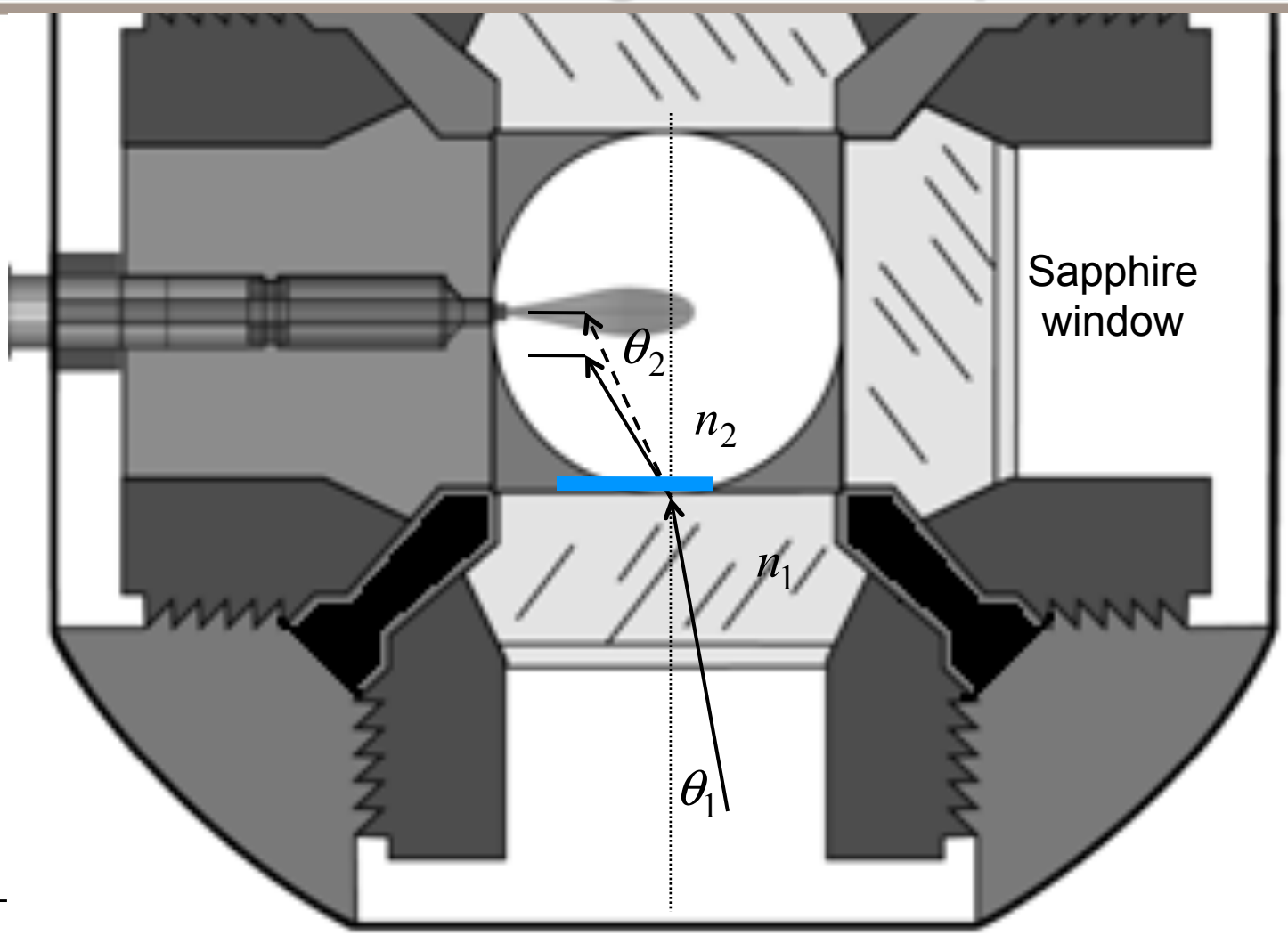


What could cause a change in focus position?



Snell's Law

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1}$$

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- Schlieren visualization, as shown.
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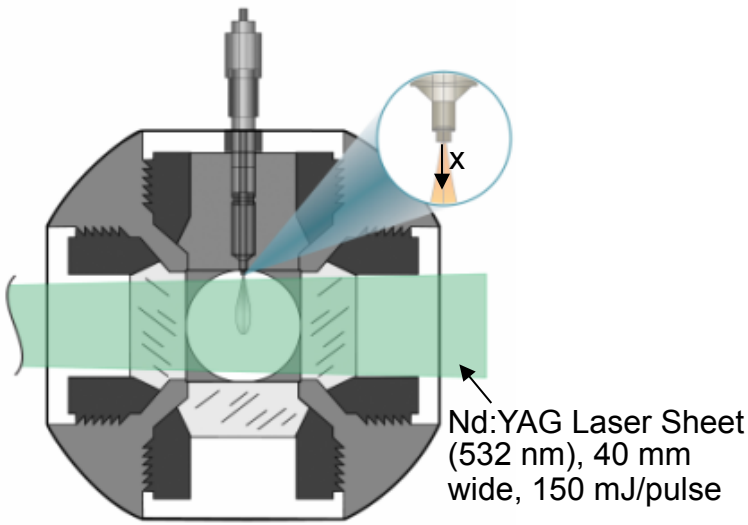
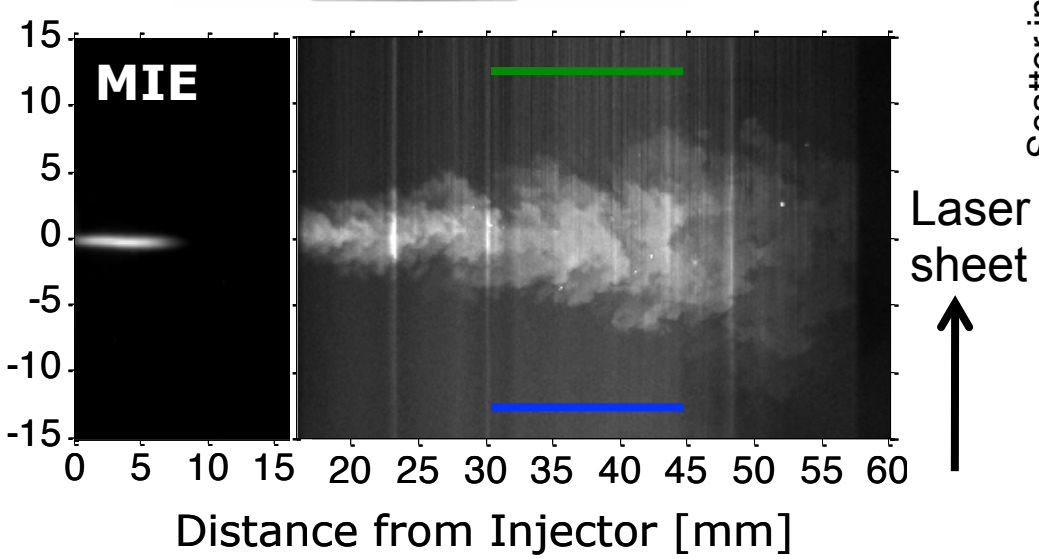
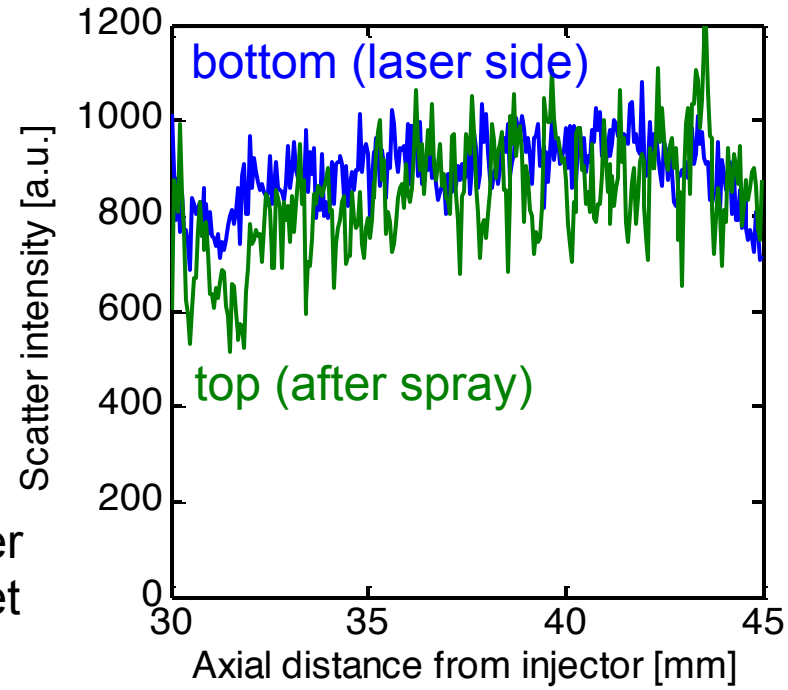
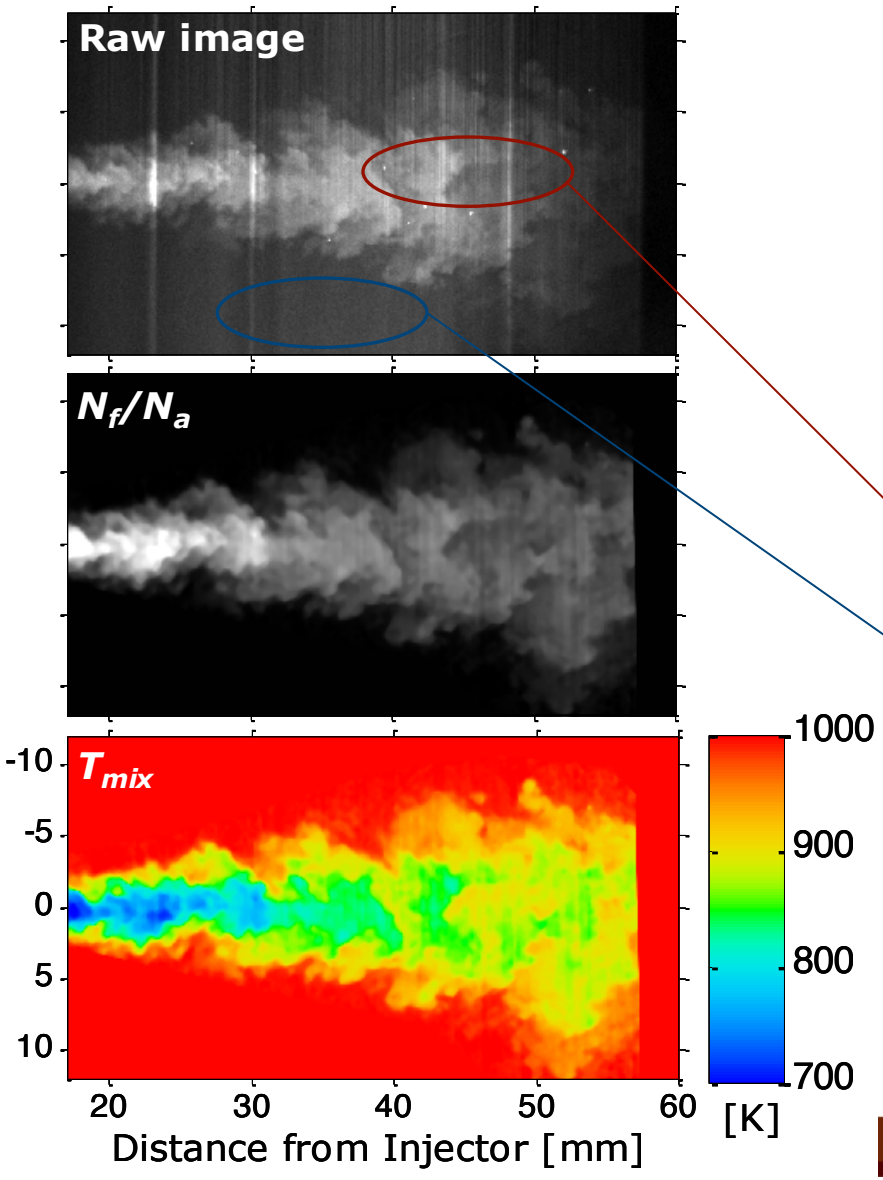
Rayleigh signature from the ambient gases shows significant beam steering.







Quantitative mixing diagnostic in harsh high-temperature, high-pressure environment.



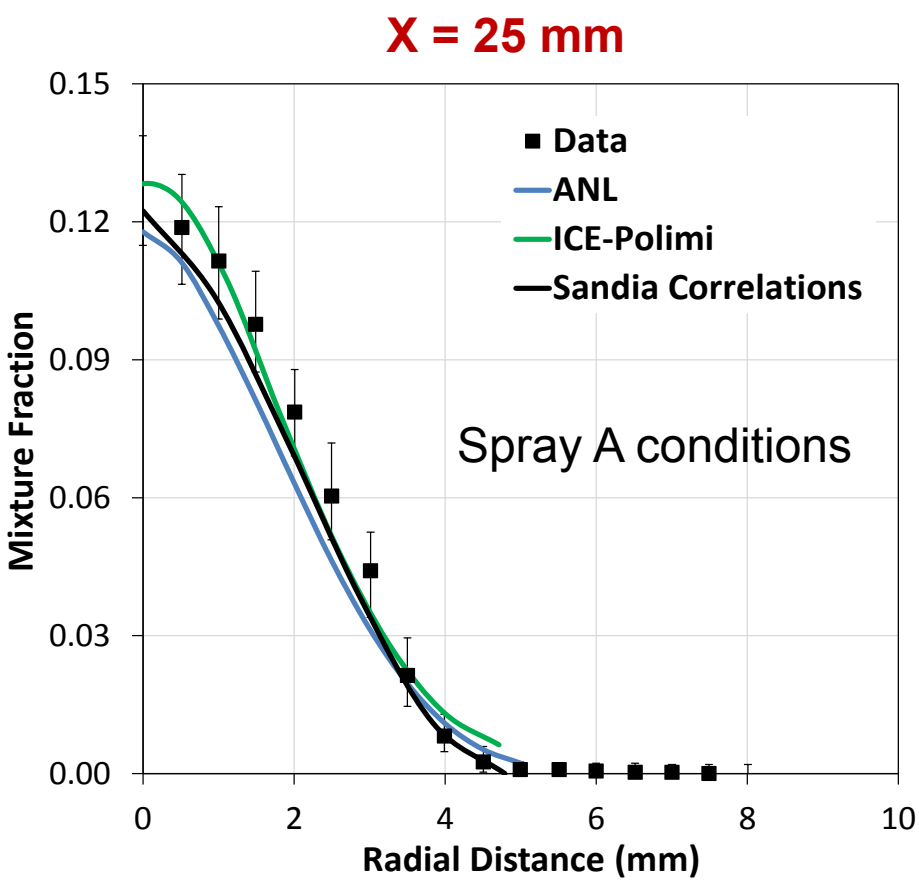
- Use Rayleigh scattering in vapor portion of fuel jet.
  - Overcomes significant temperature/ composition uncertainties compared to laser-induced fluorescence.
- Measure both $I_{R,a}$, $I_{R,j}$
  - Allows in-situ calibration for $I_{R,a}$ variation in laser sheet intensity.
  - Beam-steering or divergence addressed by using $I_{R,a}$ on bottom and top of jet.

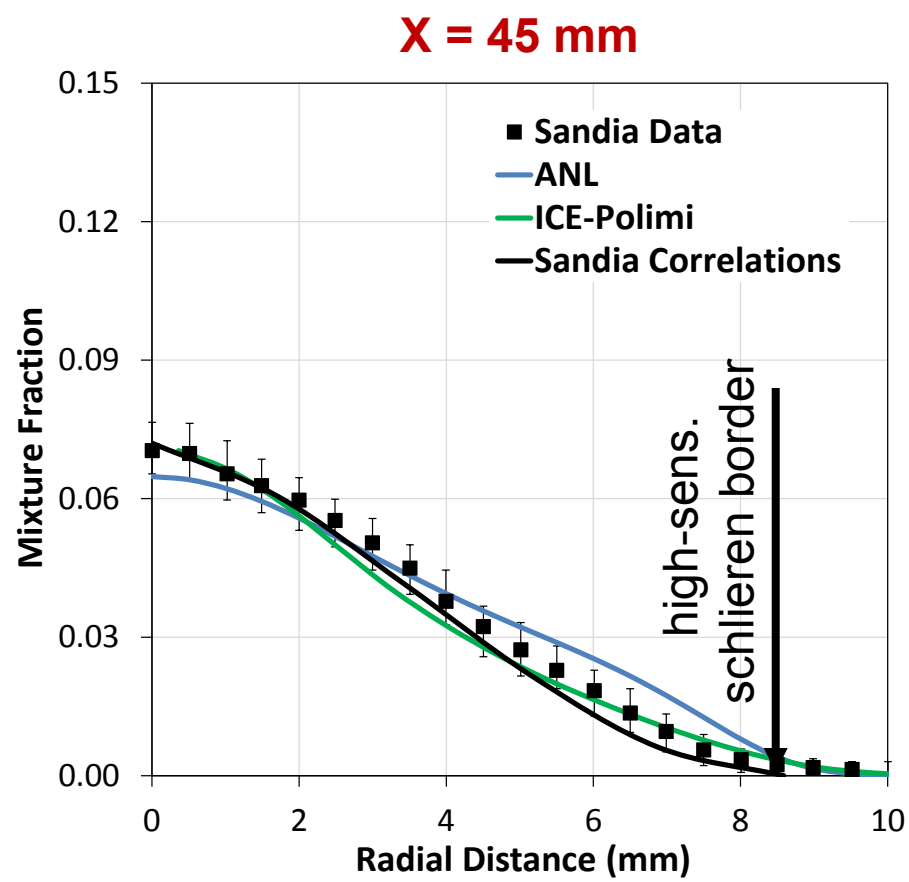
$$\frac{I_{R,j}}{I_{R,a}} = \left(\frac{\sigma_f/\sigma_a + N_a/N_f}{1 + N_a/N_f} \right) \frac{T_a}{T_{mix}}$$

$$T_{mix} = f(N_a/N_f)$$

- Measurement provides
  - Fuel mixture fraction (mass fraction)
  - Mixture temperature

CFD predictions, now compared quantitatively to experiment.





See SAE 2011-01-0686

Experimental considerations to deal with extreme gradients.

- Knowing that beam steering of about 100 mrad is expected, what diagnostics will work?
- Diagnostics that accommodate high divergence.
- Diagnostics that don't require complete transmission.
  - 2f/1f wave modulation spectroscopy (Stanford)
  - Wavelength agile spectroscopy (UW-Madison)

Building quantitative diesel spray datasets through the Engine Combustion Network.

- Collaborative modeling/experimental data archive.
- http://www.sandia.gov/ECN

Address http://www.ca.sandia.gov/ecn/index.php

Engine Combustion Network

- ECN Home
- Experimental Data
- Related Internet Sites
- References
- Tutorial: Diesel Spray Visualization

Overview

The purpose of this site is to provide an open forum for international collaboration among experimental and computational researchers in engine combustion. Patterned after the Turbulent Nonpremixed Flame Workshop, the objectives of the Engine Combustion Network (ECN) are to:

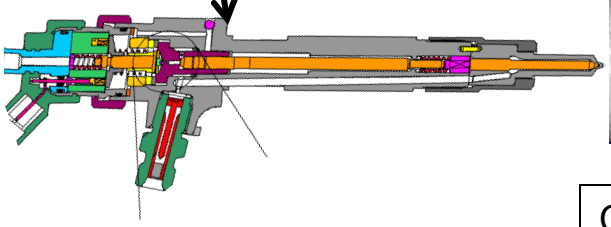
1. Establish an internet library of well-documented experiments that are appropriate for model validation and the advancement of scientific understanding of combustion at conditions specific to engines.
2. Provide a framework for collaborative comparisons of measured and modeled results.
3. Identify priorities for further experimental and computational research.

Maintained by the Engine Combustion Department of Sandia National Laboratories, data currently available on the website includes reacting and non-reacting sprays in a constant-volume chamber at conditions typical of diesel combustion. The website will be expanded in the future to include datasets and modeling results of scientific interest to participants in the ECN.

Industrial and academic collaboration in the Engine Combustion Network for "Spray A"

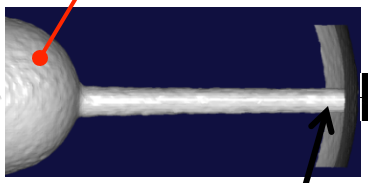
BOSCH

Bosch
Donates 10 "identical" common-rail injectors



Argonne (x-ray source)
Internal needle movement
Near-nozzle liquid volume

90° C, 1500 bar



Caterpillar
Int. nozzle geometry
Penetration

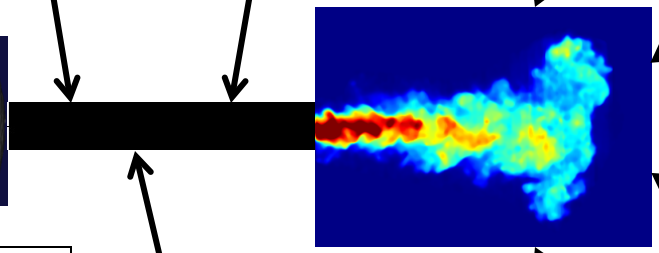
CATERPILLAR

GM

General Motors
Mixing
Droplet sizing

Michigan Tech. Univ.
Vessel temperature composition

IFP (France)
Spray velocity
Combustion



900 K, 60 bar

Meiji (Japan)
Soot formation

CMT (Spain)
Rate of injection
Spray momentum

Sandia
Liquid and vapor mixing
Combustion diagnostics

- Operation at the same injector ambient conditions.
- Voluntary participation.

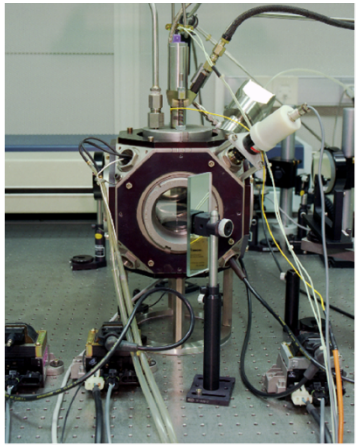
Controlled high-T, high-P experimental participation at Spray A.

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, Chris Morgan
Argonne	Cold V, X-ray Sync.	Chris Powell, Alan Kastengren
Caterpillar	Flow PV	Tim Bazyn, Glen Martin
Aachen	Flow PV	Heinz Pitsch, Joachim Beeckmann
Meiji U.	Preburn CV	Tetsuya Aizawa
Seoul Nat. U.	Preburn CV	Kyoungdoug Min
Eindhoven U.	Preburn CV	Maarten Meijor, Bart Somers

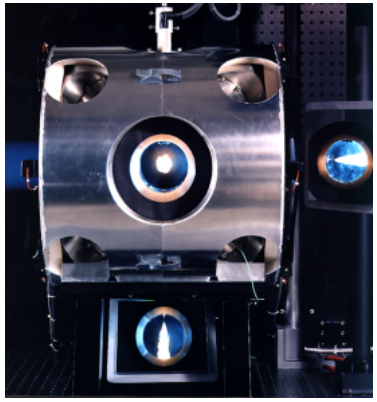
BLUE: In progress Red: Commencing soon.

Spray A vapor penetration shows reasonable agreement at 4 different institutions.

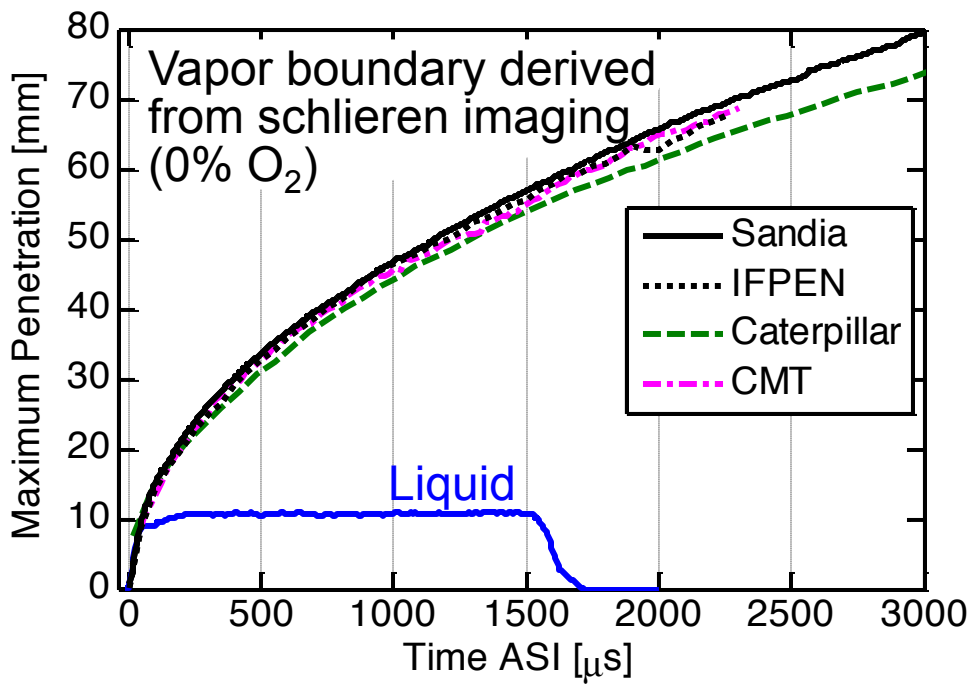
IFP



Sandia

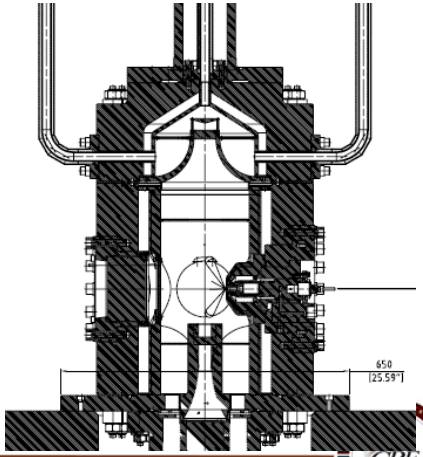


- Despite the significant challenge to control high-T, high-P boundary conditions.
- Ongoing work to understand the sources of discrepancy, including post-processing.



CMT

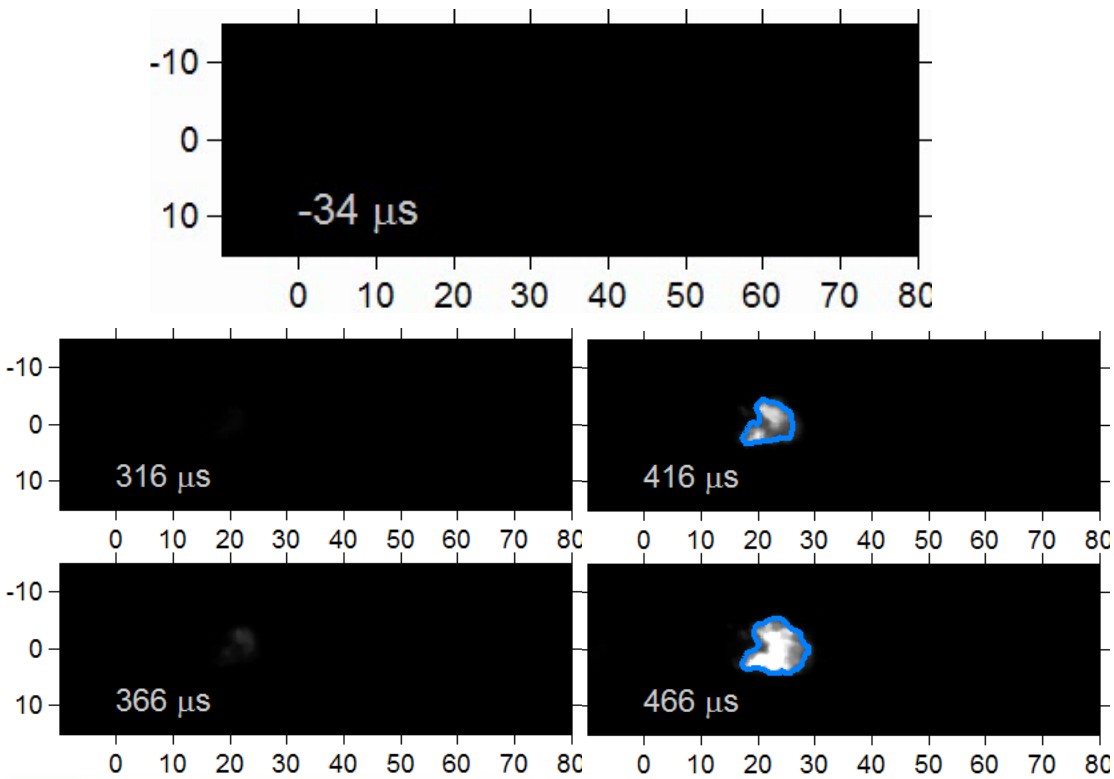
Caterpillar



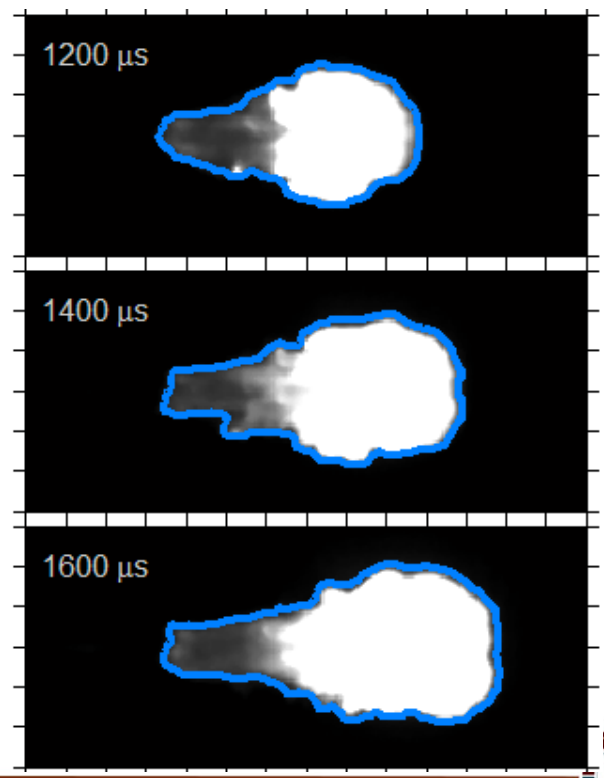
Observing ignition and lift-off length using high-speed chemiluminescence.

Sandia

<600 nm (short-pass filter)
46 ms exposure
Phantom (non intensified)
Dynamic background correct.

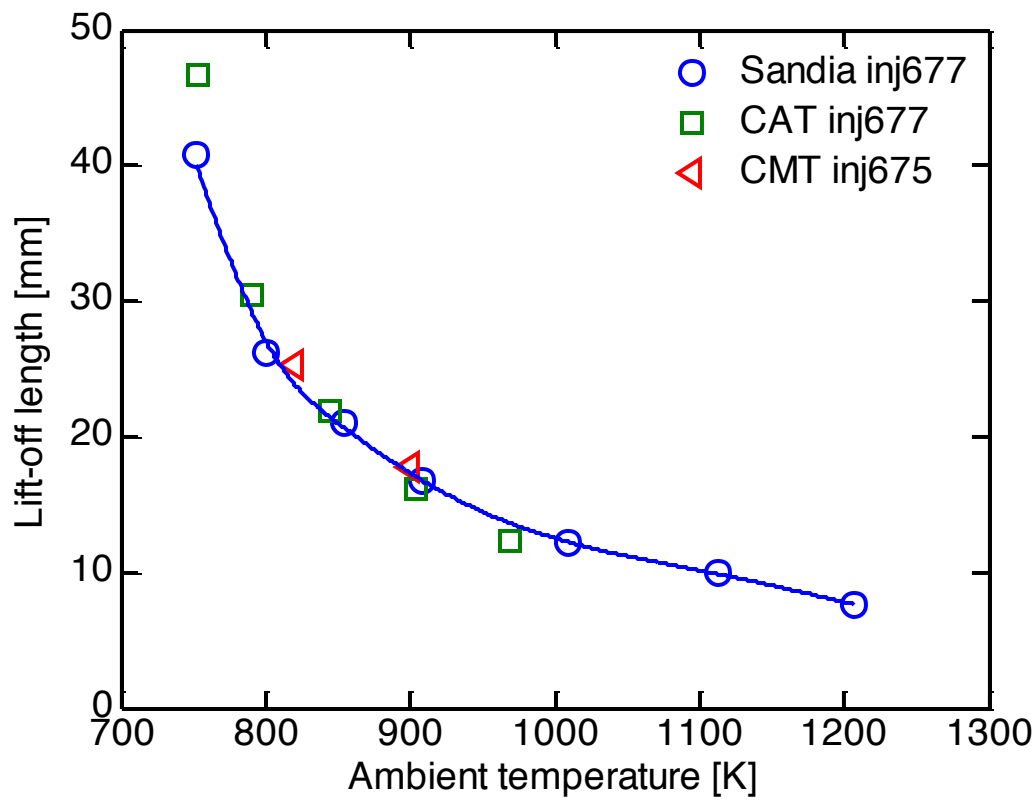


<450 nm (short-pass filter)
197 ms exposure
Phantom (non intensified)
Dynamic background correct.

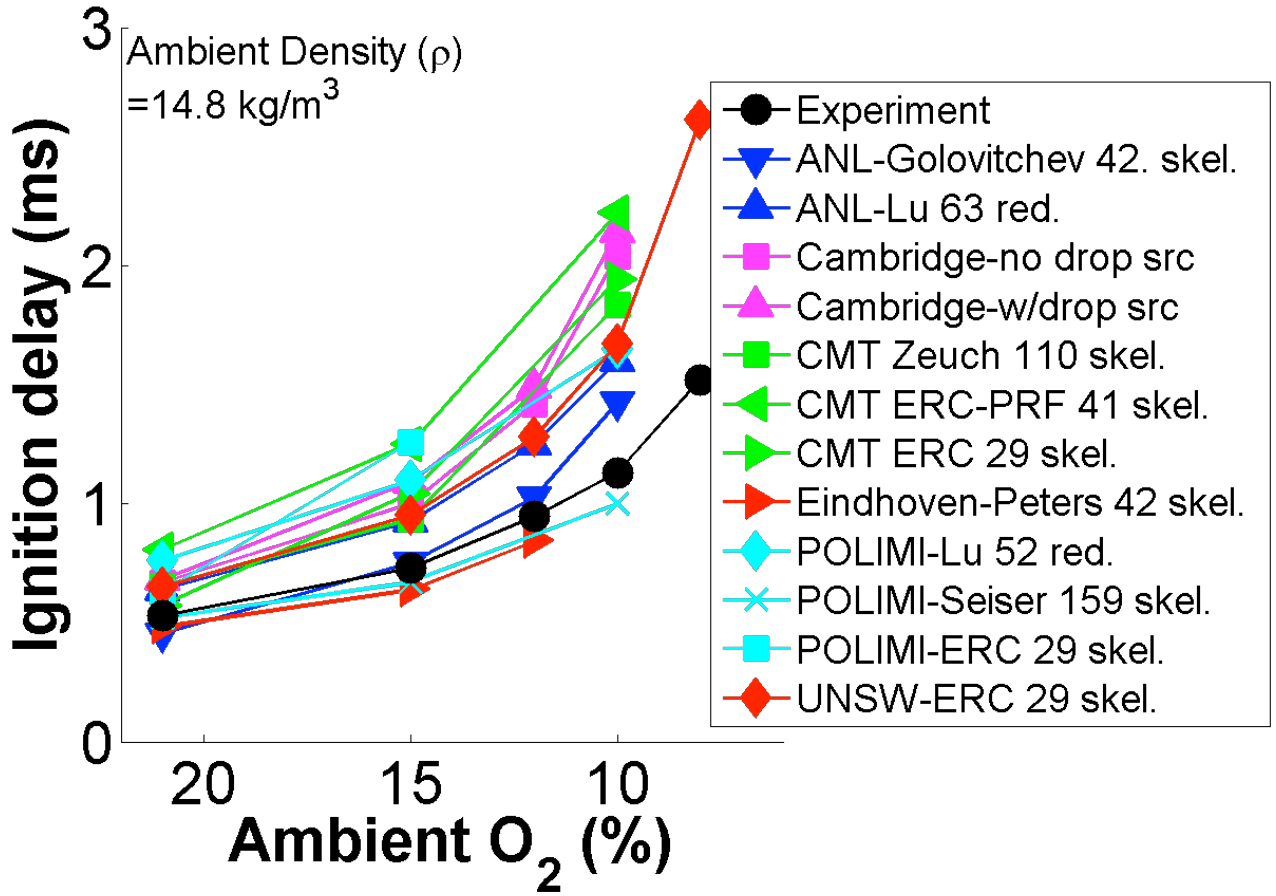


When standardizing method, lift-off length measurements are consistent at different facilities.

- Consistent lift-off measurements form a sound database.
- Suggests that datasets can be linked between flow vessels and preburn vessels!



Modeled ignition delay versus %O_2 at baseline n-heptane conditions.



- Ignition affected by chemical mechanism, grid resolution, turbulence model, definition, ….

Summary

- Experimental diagnostics of sprays at engine conditions are complicated by the high pressure and temperature.
  - Small length and time scales.
  - Extreme gradients of refractive index and intense beam steering.
  - Inhibits quantitative measurement.
- Quantitative mixing measurements performed, considering sources of uncertainty.
  - Rayleigh signature from ambient gas used as reference to correct beam-steering.
- "Spray A" initiative for the Engine Combustion Network seeks to advance diagnostics, reduce uncertainties.
  - Filling the need for an advanced (quantitative) experimental dataset.
  - Provides a pathway towards more predictive spray combustion, more efficient optimized engines.
- Results demonstrate reasonable similarity between institutions.
  - Opportunity to leverage experimental effort.
  - CFD model improvement may proceed in a more quantitative way.

Slides for questions

Questions remain when experimental "boundaries" of spray are compared to models:

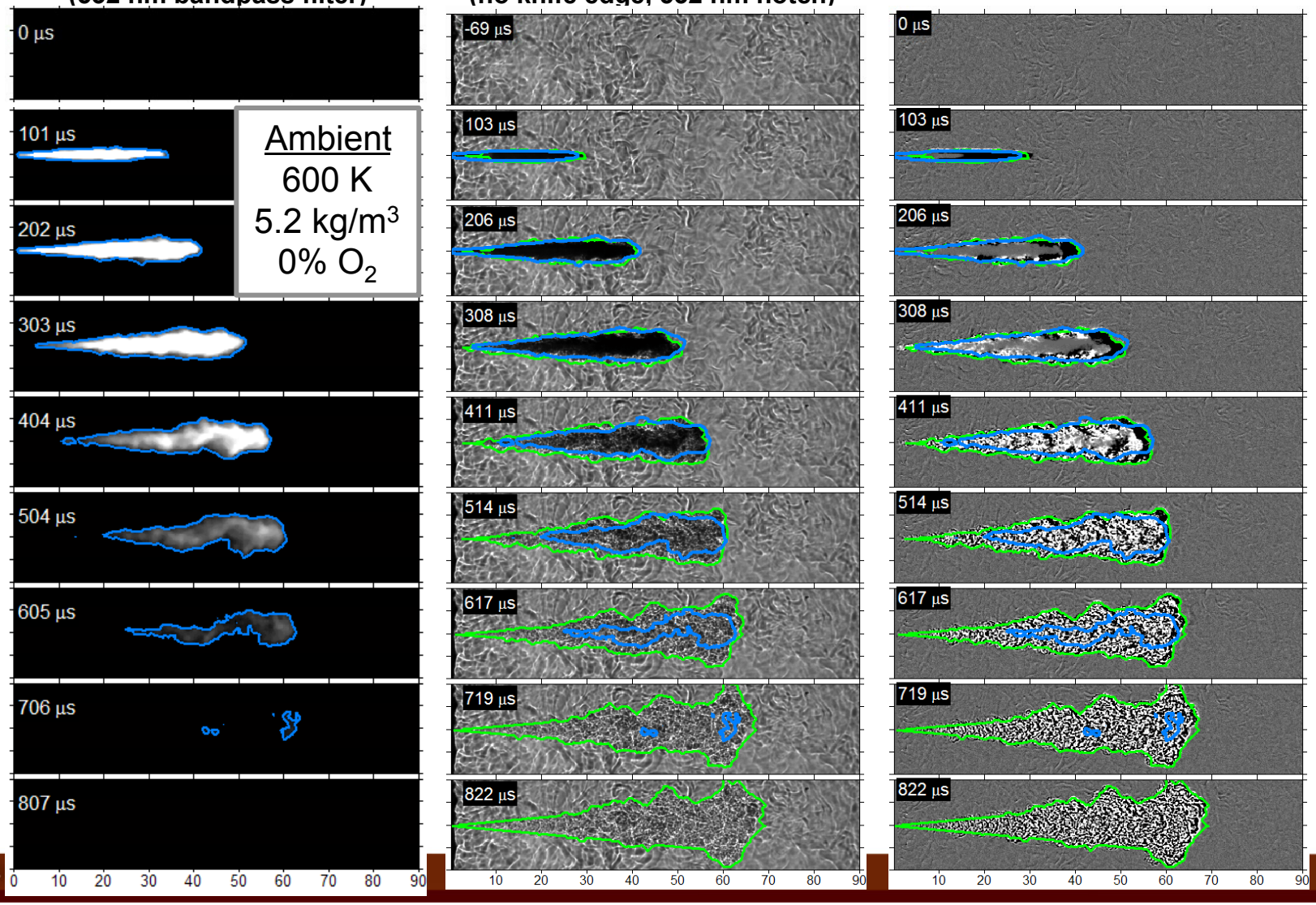
- What does a spreading angle measured by schlieren really mean?
  - Low or intermediate fuel mass fraction or mixture fraction?
  - How does schlieren measurement sensitivity change with conditions?
- Is the "liquid" spreading angle the same as that of the "vapor"?
- Should the model be tuned for spreading angle or spray penetration?
  - Are spreading angle and spray penetration consistent?
- Guidance is needed because spray model constants are often tuned based on spreading angle.
- Quantitative mixing data is needed.

Simultaneous high-speed imaging allows detection of liquid and vapor boundaries.

Mie-scatter
(532 nm bandpass filter)

Schlieren+Borders
(no knife edge, 532 nm notch)

Corrected: $I_n - I_{n-1}$



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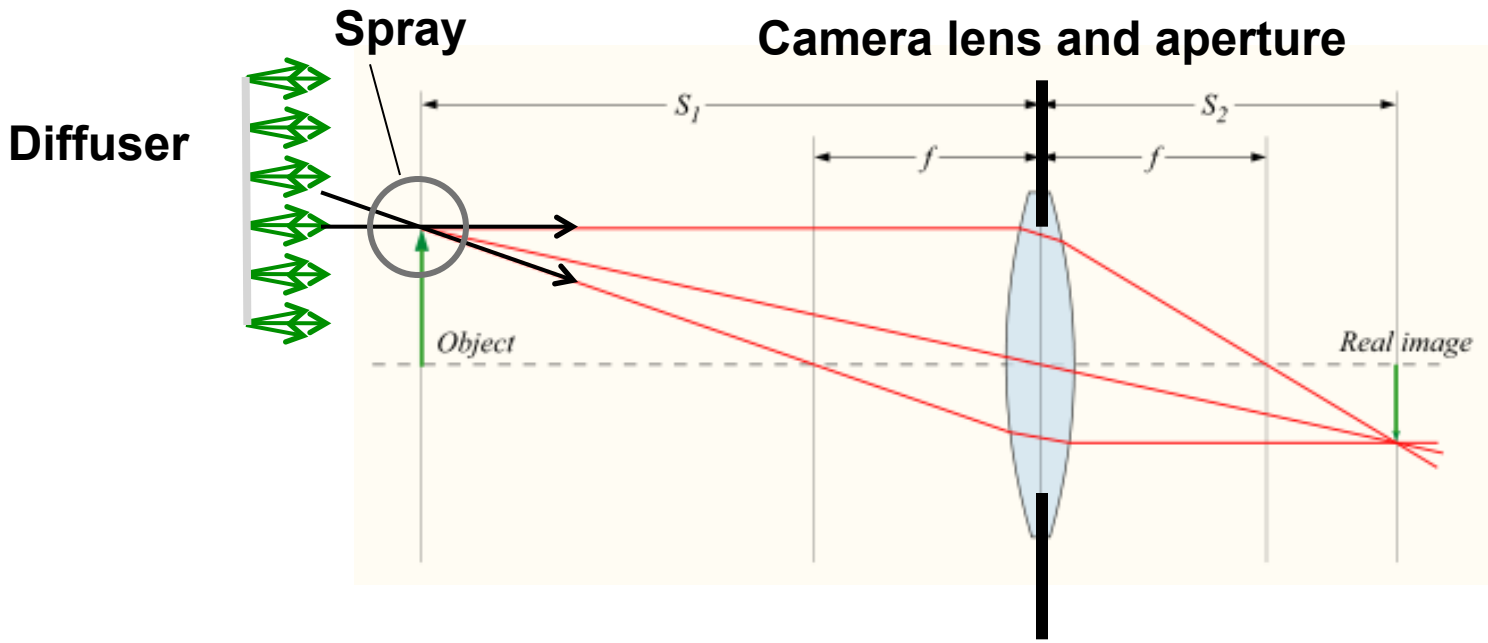
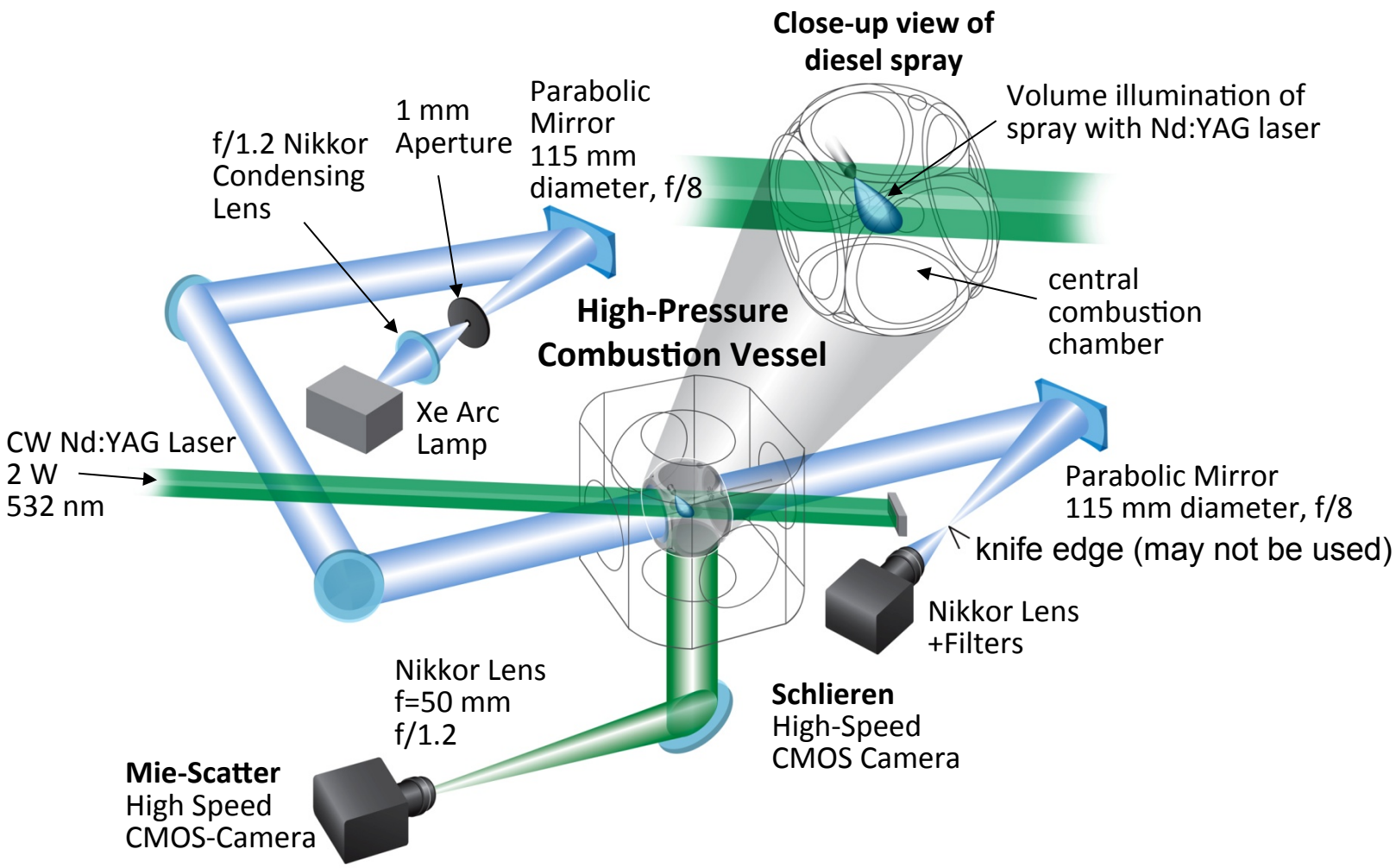
Diffuser illumination does not eliminate, but multiple ray directions obscure beam steering.

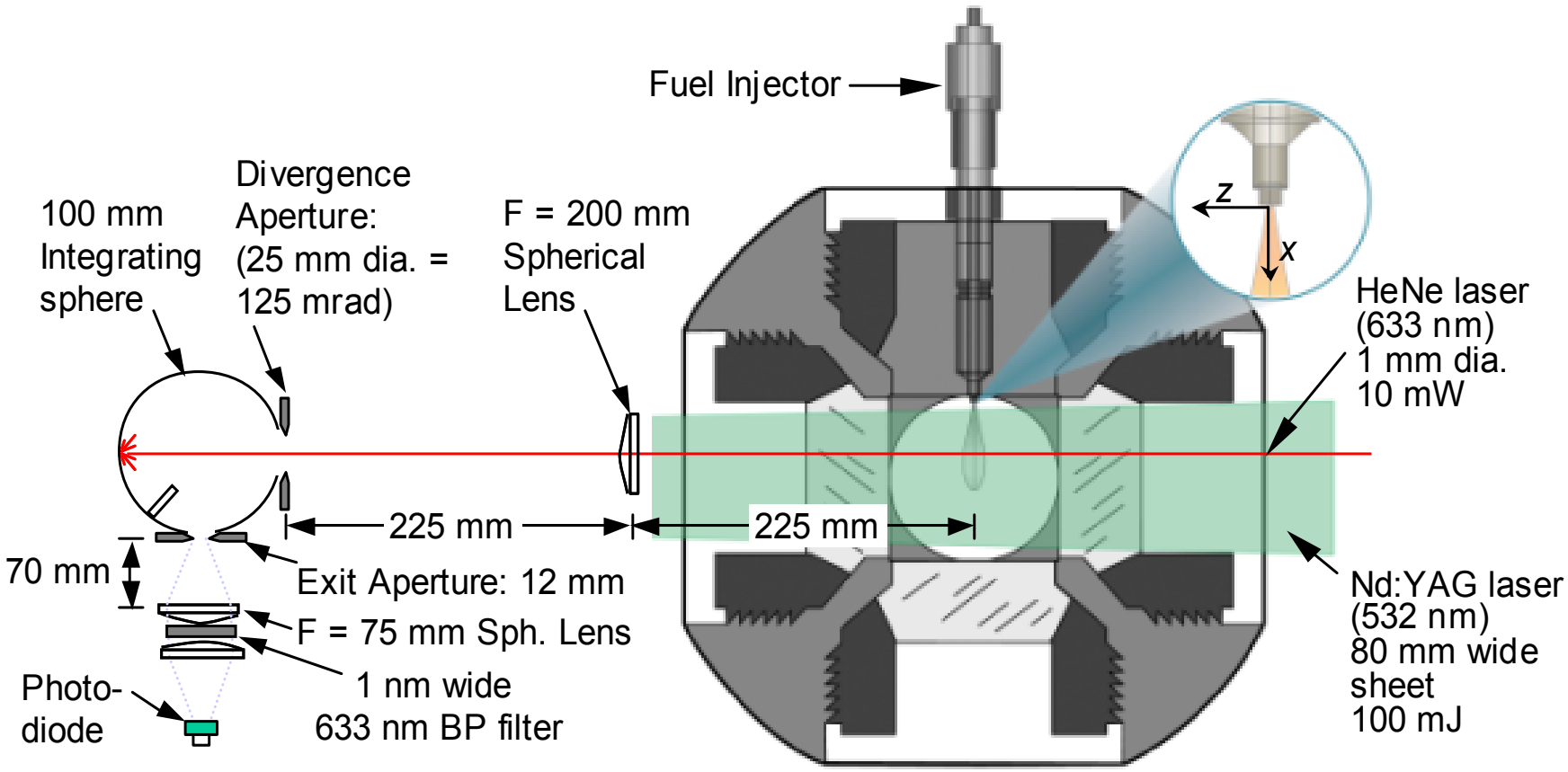


- Rays take different paths through the spray but arrive at the same pixel.
- Droplet light-scattering causes extinction and is interpreted as low transmission.
- Non-uniform beam steering of vapor may also reduce or increase intensity at a given pixel.

Schlieren and Mie-scatter optical diagnostics experimental setup.

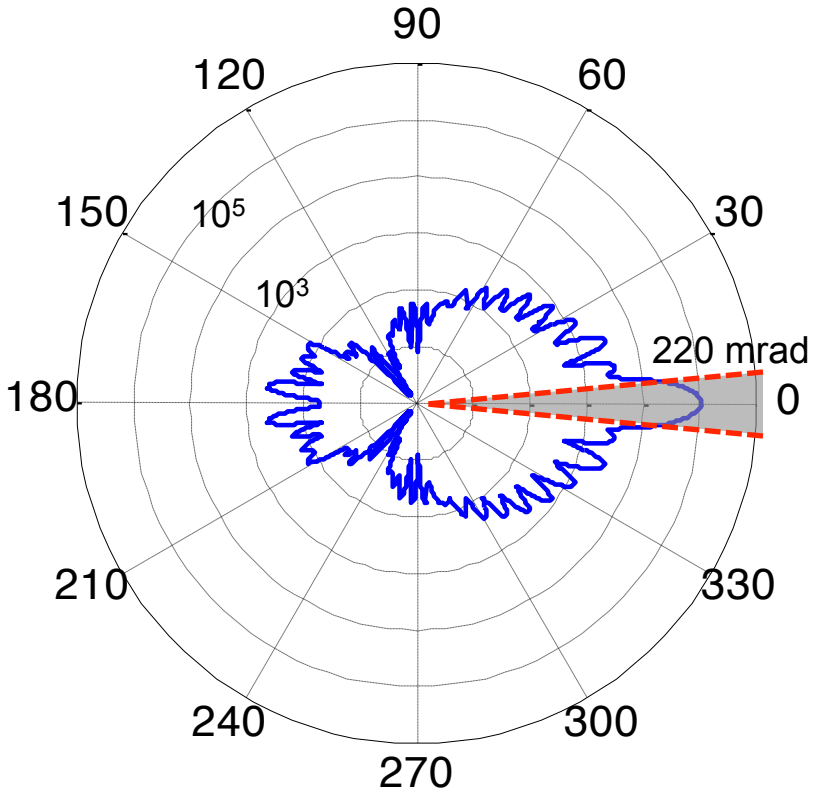


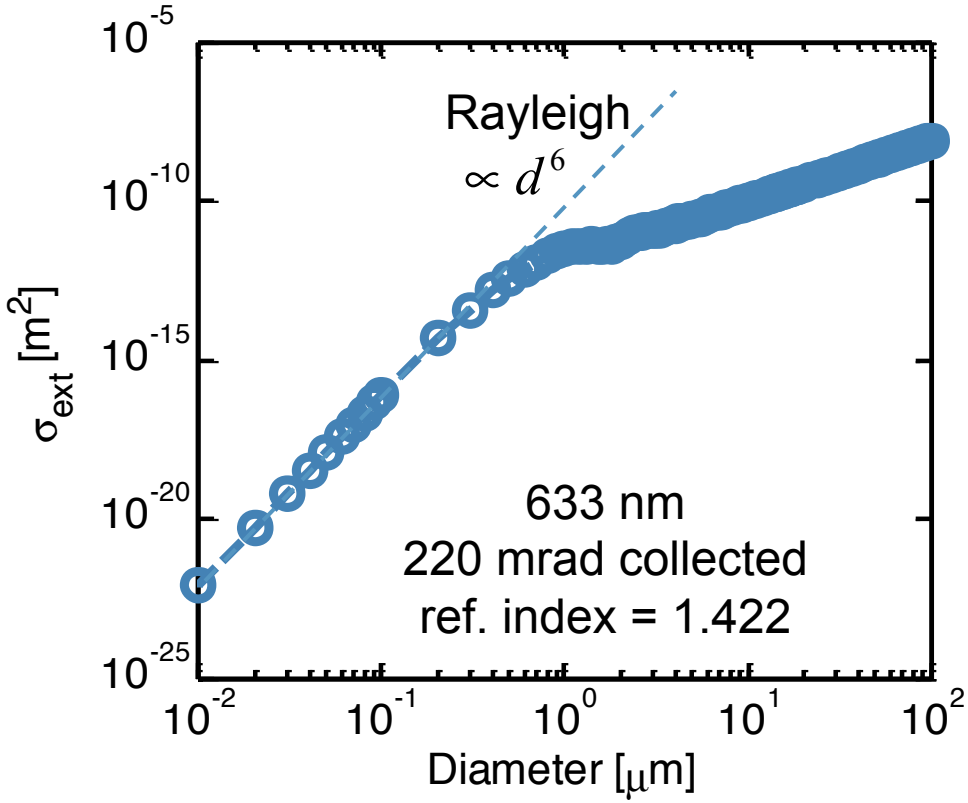
Laser extinction for soot concentration within the spray.



Larger collection angle accepts more forward scatter, reducing the extinction cross-section.

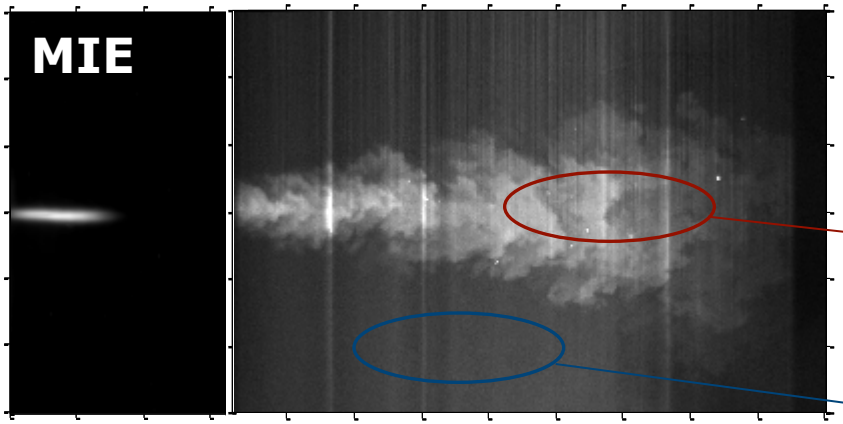
Angular scattering intensity for a 5 mm n-dodecane droplet in air





Rayleigh scattering theory

- Rayleigh signal in mixture $I_R = \eta I_I N \sum_i X_i \sigma_i$
- Rayleigh scattering cross-section $\sigma_i = \frac{4\pi^2}{\lambda^4}\left(\frac{n_i - 1}{N_O}\right)^2 \frac{3}{3 - 4\rho_V}$



$$I_{R,j} = \eta I_I N_{mix}\left[X_f \sigma_f + X_a \sigma_a\right]$$

$$I_{R,a} = \eta I_I N_{a,o}\, \sigma_a$$

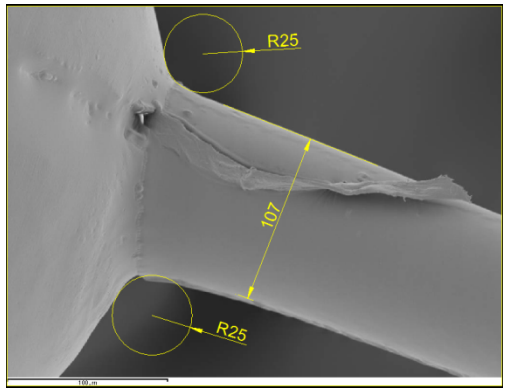
- Ideal gas $N_{mix}/N_{a,o} = T_a/T_{mix}$; $N_{mix} = N_a + N_f$
- Adiabatic mixing assumption $T_{mix} = f(N_a/N_f)$ (Espey, Dec [1996])

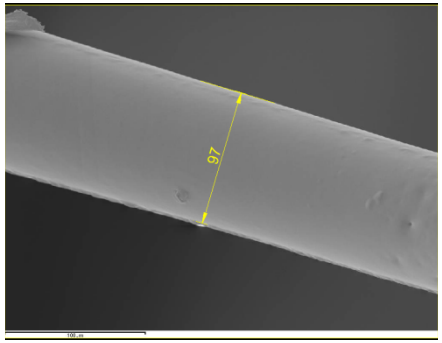
$$\frac{I_{R,j}}{I_{R,a}} = \left(\frac{\sigma_f/\sigma_a + N_a/N_f}{1 + N_a/N_f}\right)\frac{T_a}{T_{mix}}$$

Nozzle internal geometry measurements

X-ray phase-contrast imaging (Argonne)

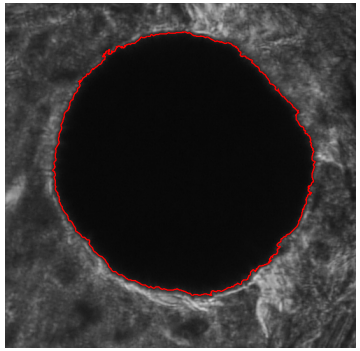
Silicone molds (CMT)



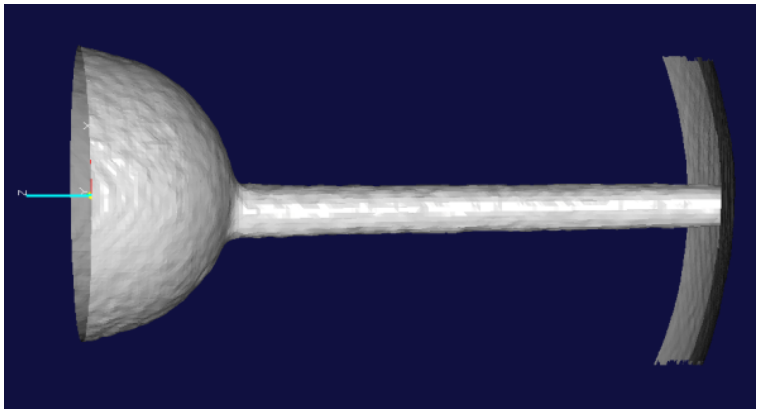


SEM (Sandia)

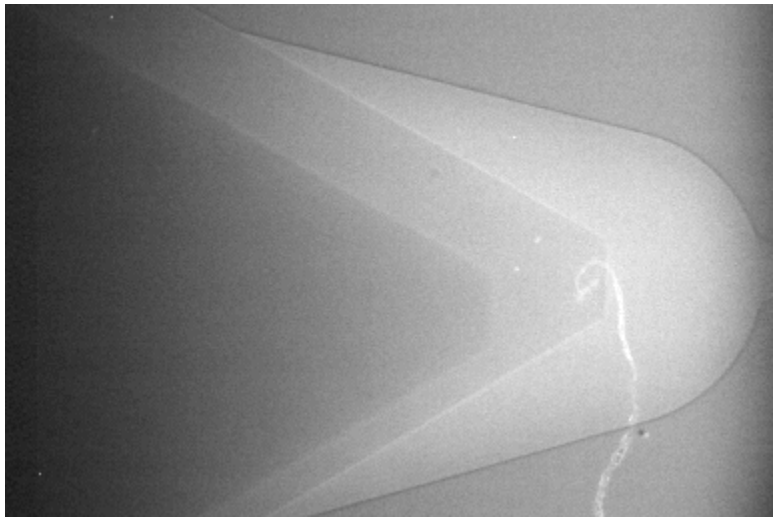
Optical (Sandia)

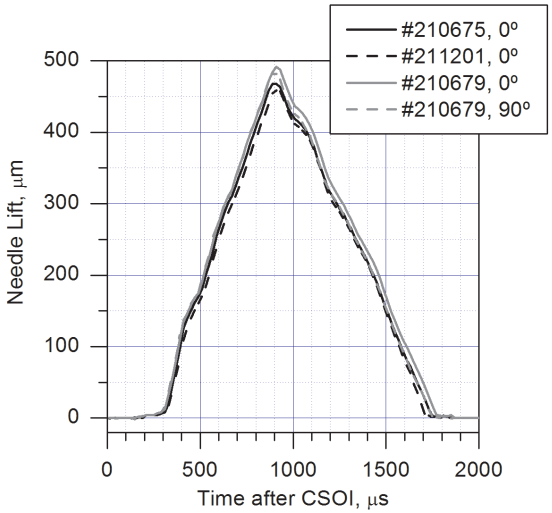


X-ray tomography (Caterpillar)

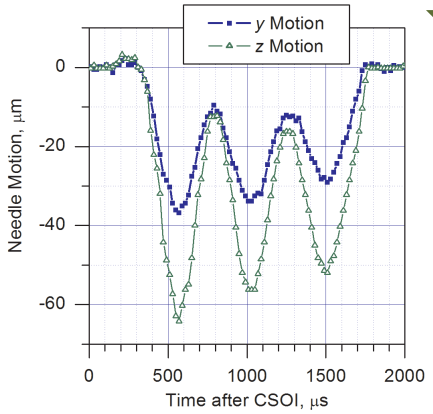


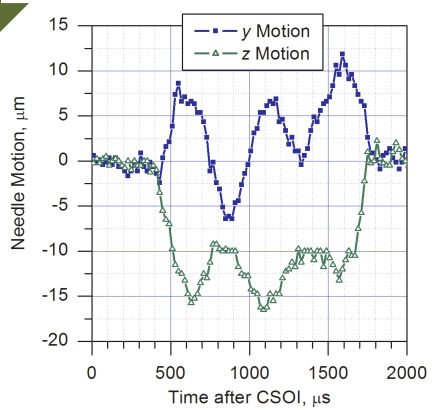
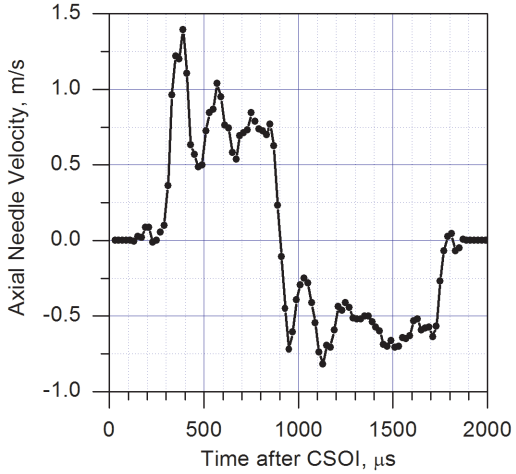
Phase-Contrast Imaging of Needle Motion





Argonne National Laboratory

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