Spray Combustion Cross-Cut Engine Research

Lyle M. Pickett

Sandia National Laboratories

FY 2013 DOE Vehicle Technologies Program Annual Merit Review
Project ACE005, 10:00 – 10:30 AM, Tuesday, May 14, 2013

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:
  FY12 - $730K
  FY13 - $700K

Barriers

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

Partners

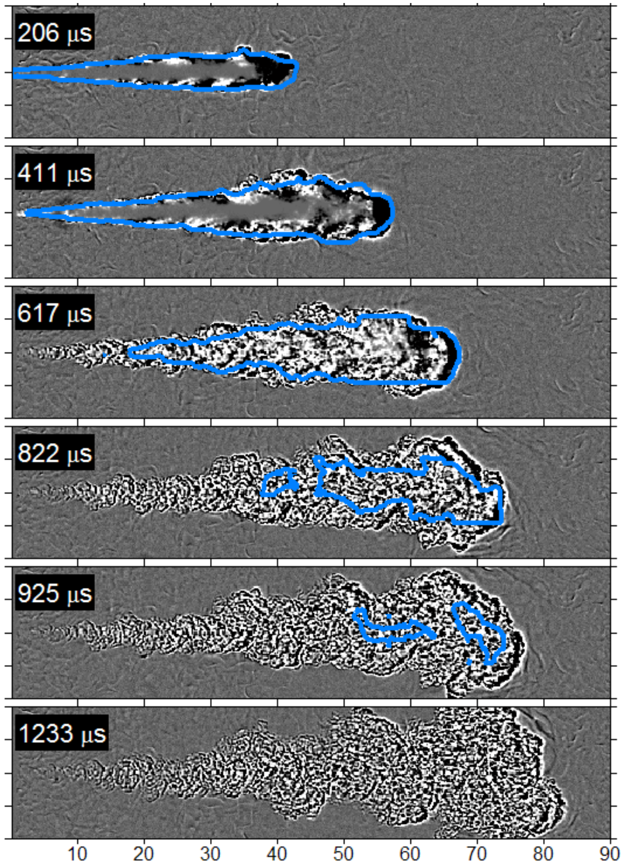
- 15 Industry partners in MOU: Advanced Engine Combustion
- Engine Combustion Network
  - >10 experimental + 16 modeling
  - >100 participants attend ECN2
- Project lead: Sandia
  - Lyle Pickett (PI)

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

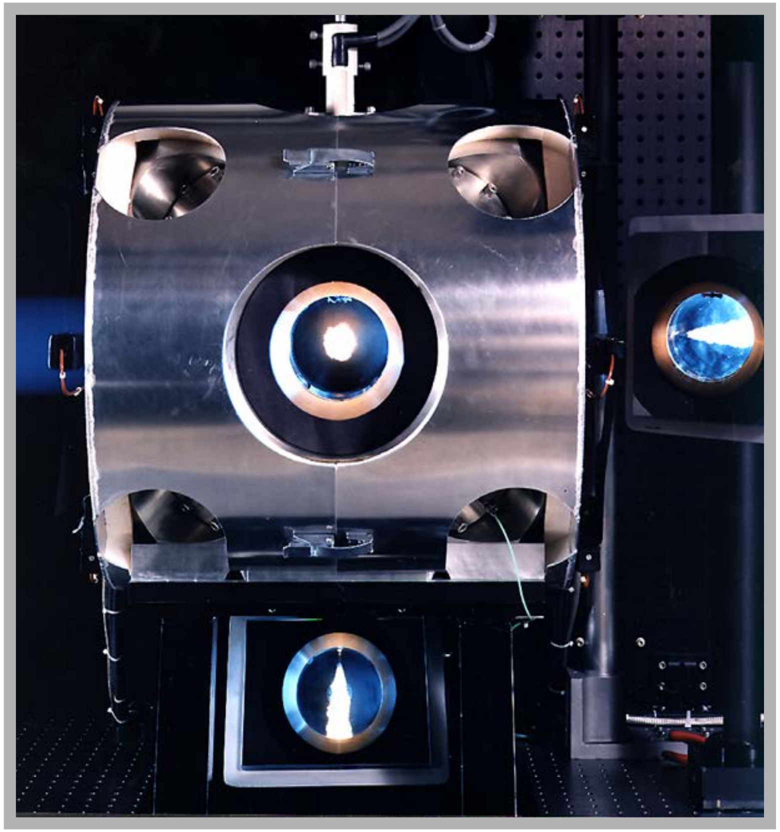
- Future high-efficiency engines use direct injection.
  - Diesel, gasoline direct injection, partially-premixed compression ignition
- Complex interactions between sprays, mixing, and chemistry.
  - Two-phase system, including multiple injections
  - Spray-induced mixture preparation
  - Complicated 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



Experimental approach utilizes well-controlled conditions 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.

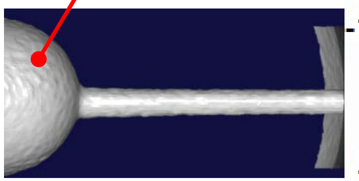
Objectives/Milestones

- Aid the development of computational models for engine design and optimization (ongoing).
  - Lead an experimental and modeling collaboration through the Engine Combustion Network with >100 participants (http://www.sandia.gov/ECN)
  - Target conditions specific to low-temperature diesel and DI gasoline.
    - ECN activities focus on quantification, standardization, leveraging, detailed analysis.
    - Provides a pathway from experimental results to more predictive CFD modeling.
    - Activities, progress, and future directions listed under ECN2 Workshop proceedings.
    - Represents major advances in terms of diagnostics, modeling tools, and so forth.
- (1) Expand datasets to a larger range of conditions for more extensive model evaluation, including
- (2) Apply quantitative soot diagnostics in optically thick diesel sprays, providing opportunity for needed improvement in PM predictions.
- (3) Evaluate liquid/vapor penetration and plume-plume interactions in DI gasoline sprays, forming unique model-target dataset.

ECN collaborative research at specific target conditions

Injector

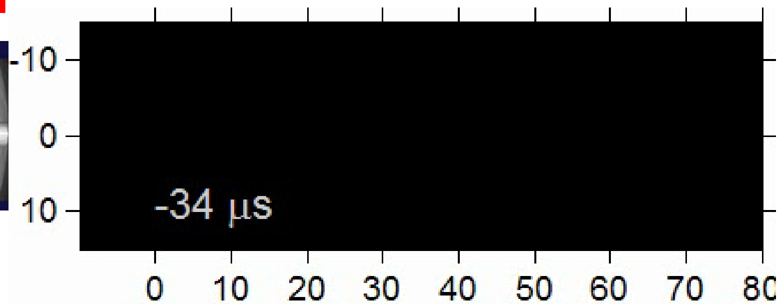
90° C, 1500 bar



Internal nozzle geometry

Ambient

900 K, 60 bar



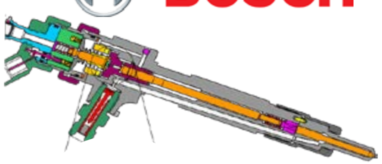
Spray A

Other defined targets:

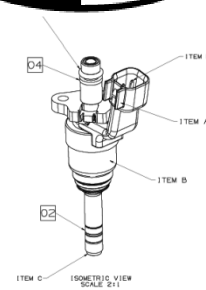
- Spray H (baseline n-heptane)
- Spray B (3-hole version of Spray A).
- Gasoline DI and engine flows.

- Opportunity for the greatest exchange and deepest collaboration.
  - Understanding facilities/boundary conditions.
  - Understanding diagnostics and quantification.
  - 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.
- Methodology now applied to parametric variants about Spray A.

BOSCH



DELPHI



Measurements to date at Spray A conditions

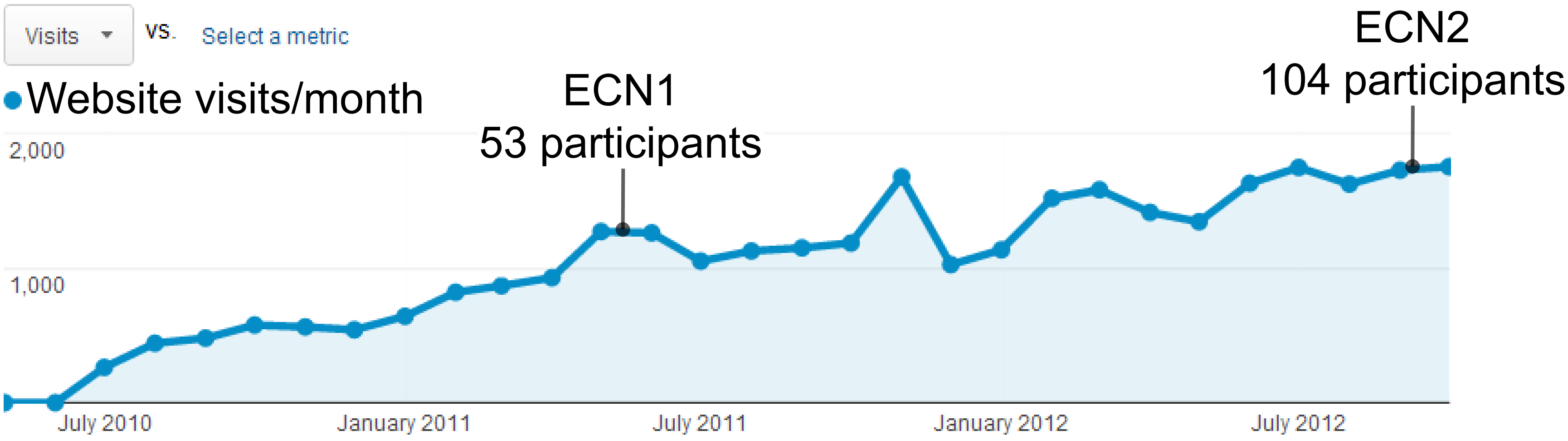
26 types of experiments

10 different international institutions

Quantity	Experiment	Contributors (Inst. and/or person)
Gas T distribution	fine-wire TC, variable diameter TC	CAT®, CMT, Sandia, IFPEN, TU/e, KAIST, Chalmers
Nozzle internal temperature	thermocouple	Sandia, CAT, IFPEN, CMT, TU/e, Aachen, Chalmers
Nozzle surface temperature	laser-induced phosphorescence	IFPEN (Louis-Marie Malbec, Gilles Bruneaux)
Nozzle geometry	x-ray tomography	CAT (Tim Bazyn), Infineum (Peter Hutchins)
Needle movement/noz. geom.	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), TU/e
Mass rate of injection	bosch tube method	CMT, KAIST
Rate of momentum	force piezo	CMT, Sandia, CAT
Total mass injected	gravimetric scale	CMT, Sandia, IFPEN
Nozzle Cd, Ca	momentum + mass	CMT, Sandia
Liquid penetration	Mie scatter	IFPEN, Sandia, CMT, CAT, TU/e
Liquid penetration	Diffused back illumination (DBI)	Sandia, CMT, IFPEN, TU/e
Liquid optical thickness	laser extinction	Sandia (Julien Manin, Lyle Pickett)
Liquid structure	long-distance microscopy	Sandia, CMT (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, TU/e
Fuel mixture/mass fraction	Rayleigh scattering	Sandia
Velocity (gas-phase)	PIV	IFPEN (L.-M. Malbec, G. Bruneaux, M. Meijer)
Ignition delay	high-speed chemiluminescence	Sandia, CAT, CMT, IFPEN, TU/e
Lift-off length	OH or broadband chemilum.	Sandia, IFPEN, CAT, CMT, TU/e
Transient lift-off/ignition	intensified OH chemiluminescence	Sandia, IFPEN, CAT, CMT, TU/e
Pressure rise/AHRR	high-speed pressure	Sandia, IFPEN, TU/e
Soot luminosity/Radiation	high-speed luminosity imaging	Sandia, IFPEN, CAT, CMT, TU/e, DTU
Soot volume fraction	laser-induced incandescence, laser extinction, DBI	IFPEN/Duisberg-Essen, Sandia (Scott Skeen)

Past
FY13

Workshops organized with voluntary participation (for ECN2: 8 experimental, 16 modeling teams)

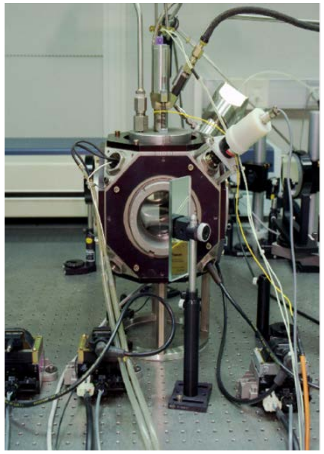


Organizers facilitate side-by-side comparison and analysis to provide an expert review of the current state of the art for diagnostics and engine modeling:

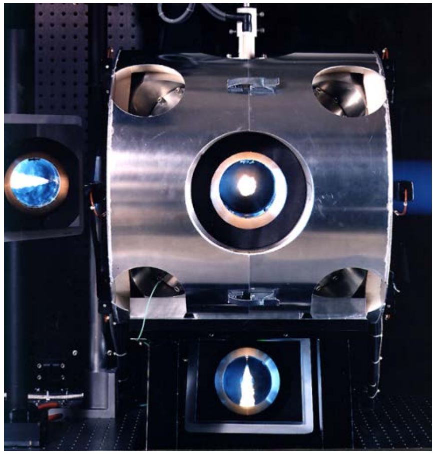
- ECN2 overall organization:
  - Gilles Bruneaux (IFPEN), Lyle Pickett (Sandia)
- Internal Nozzle Flow
  - Chris Powell (Argonne), David Schmidt (UMassAmherst), Marco Arienti (Sandia)
- Spray Development and Vaporization
  - Julien Manin (Sandia) , Sibendu Som (Argonne), Chawki Habchi (IFPEN)
- Mixing and Velocity
  - Louis-Marie Malbec (IFPEN), Gianluca D'Errico (Pol. Milano)
- Ignition and Lift-off Length
  - Michele Bardi (CMT), Evatt Hawkes (UNSW), Christian Angelberger (IFPEN)
- Soot
  - Emre Cenker (Duisburg/IFPEN), Dan Haworth (Penn St.)
- Gasoline Sprays
  - Scott Parrish (GM)
- Engine Flows
  - Sebastian Kaiser (Duisburg-Essen)

Ignition and lift-off length measurements are consistent for different types of HP-HT facilities.

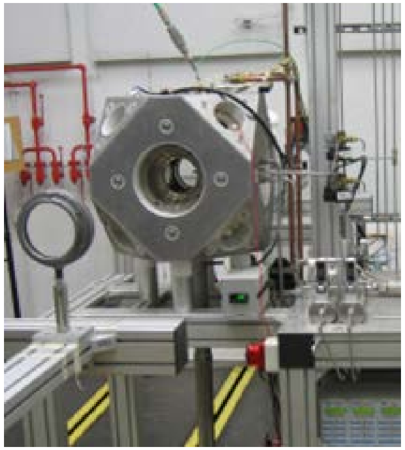
IFPEn



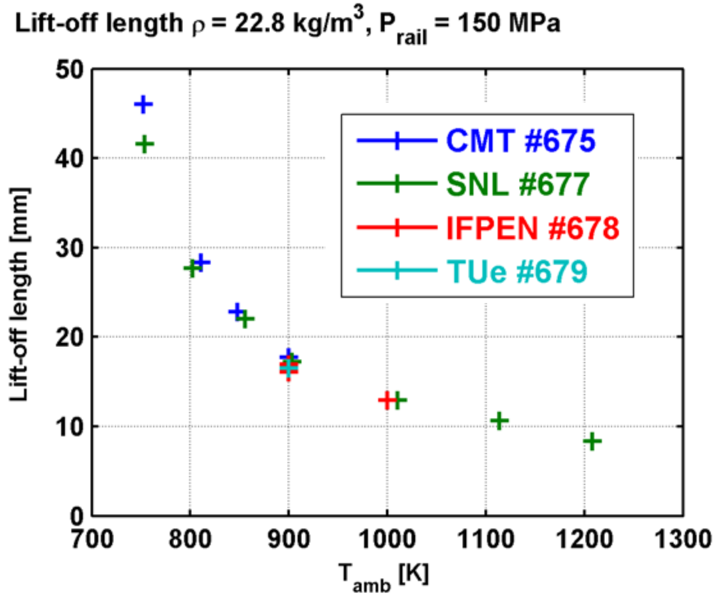
SNL

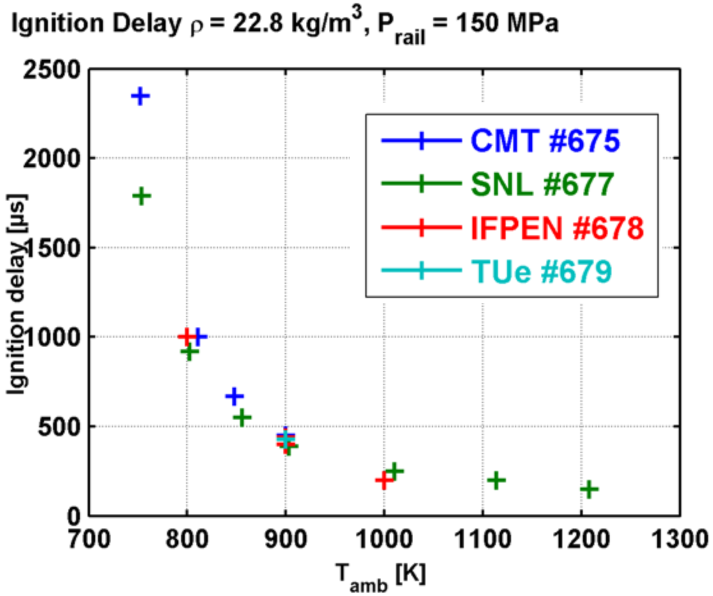


TU/e

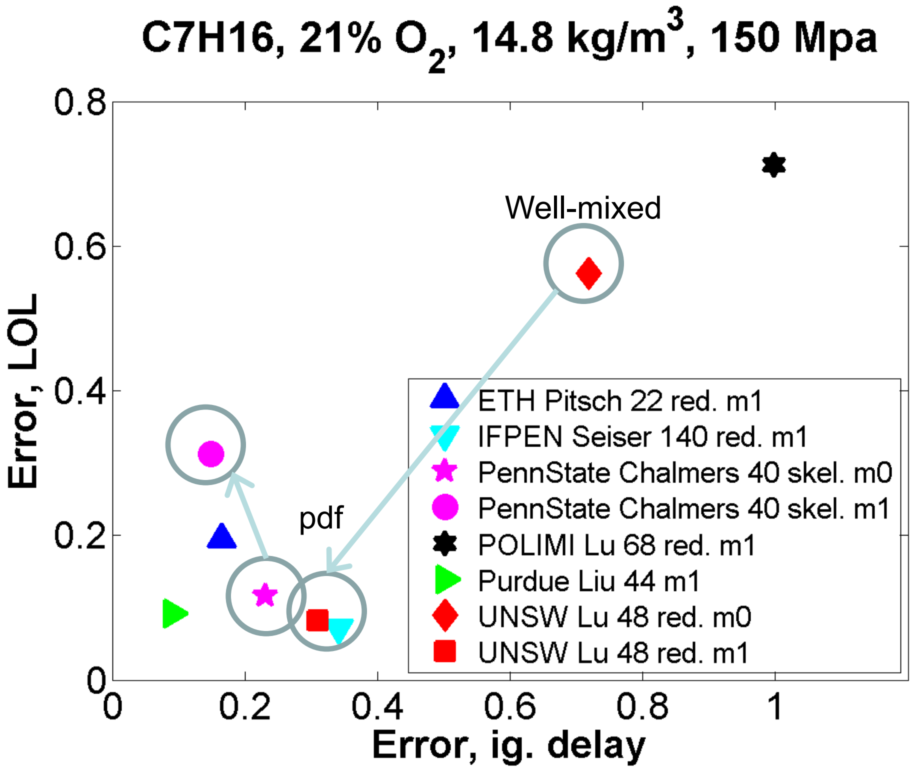


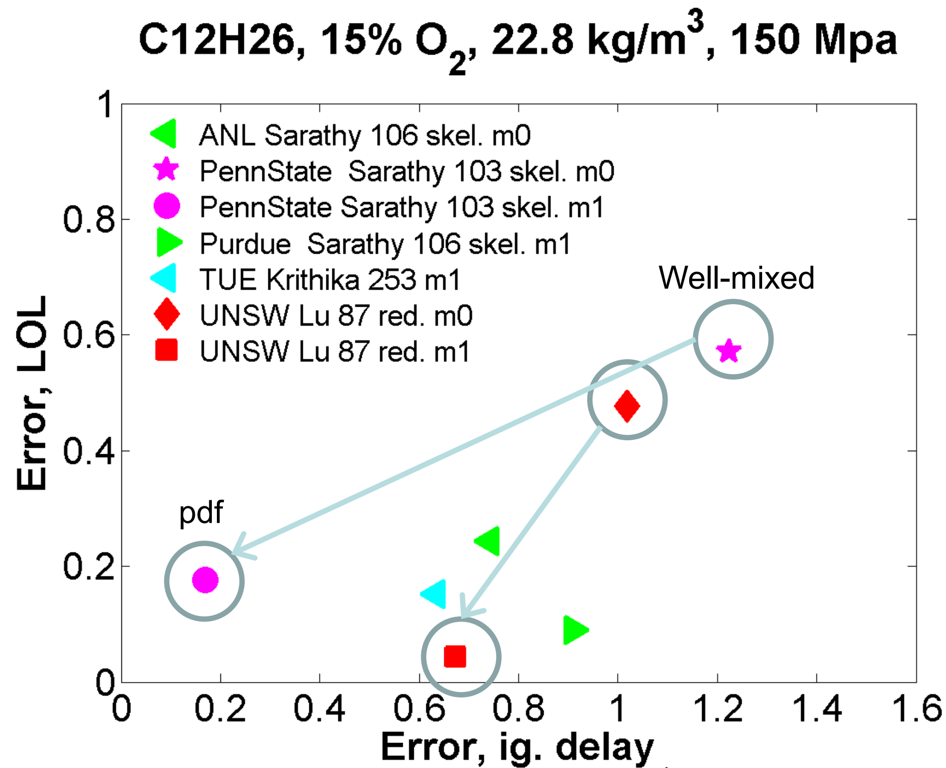
CMT





ECN2 parametric variations show modeling improvement, but no superior combustion model.

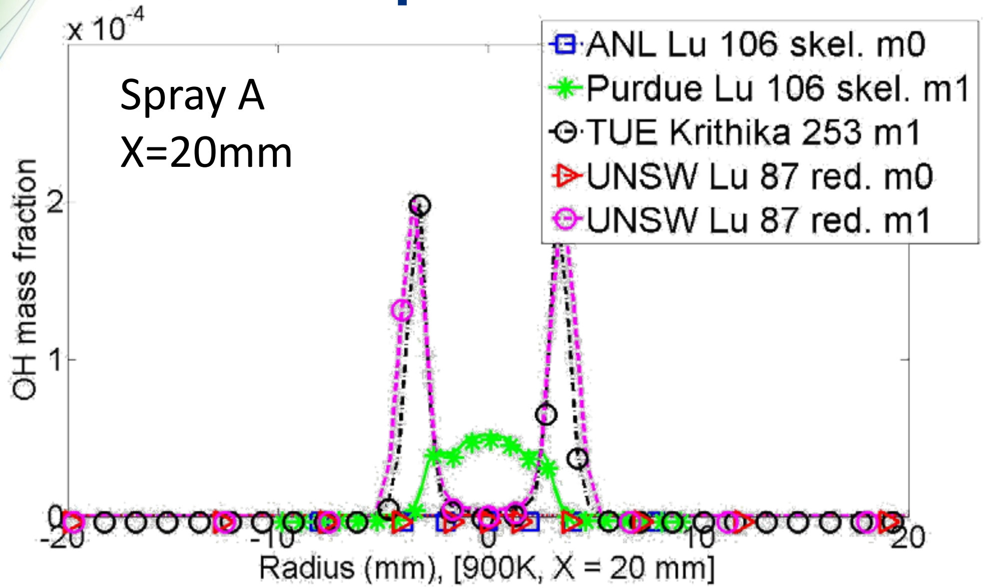


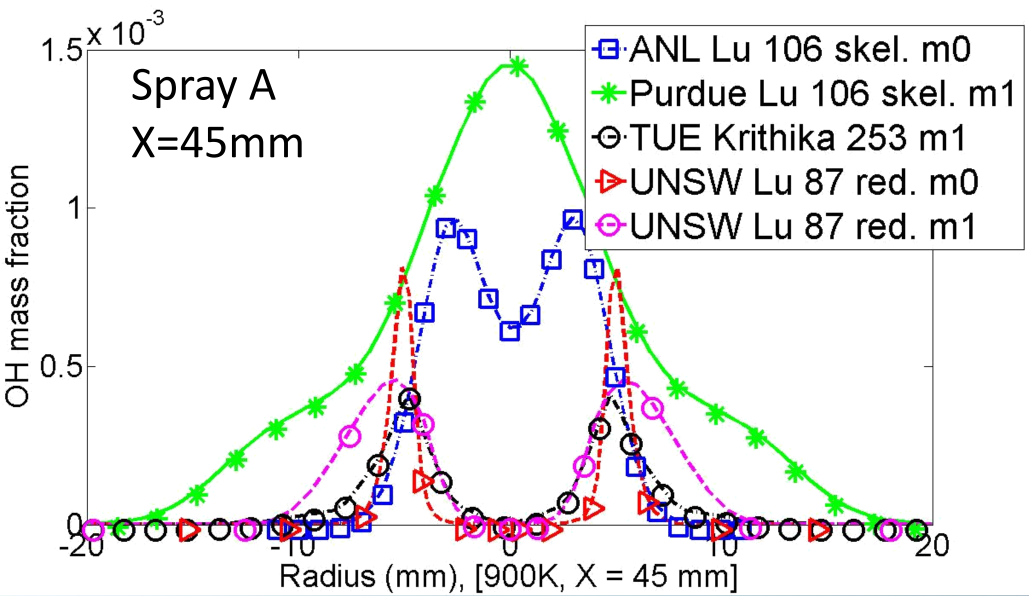


No ignition at 900 K at ECN1 !

- Difficult to achieve predictive ignition delay and lift-off length.
  - Lift-off length predictions better than ignition delay.
  - Predictions better for n-heptane than n-dodecane.
- Serious questions remain about the chemical mechanisms and combustion models.
  - More advanced combustion models (pdf) show improvements for one set of data, but not others.
  - Errors of 20-40% could easily translate to sooting vs non-sooting sprays.

Side by side analysis reveals differences in models, and points to the need for further experiments.





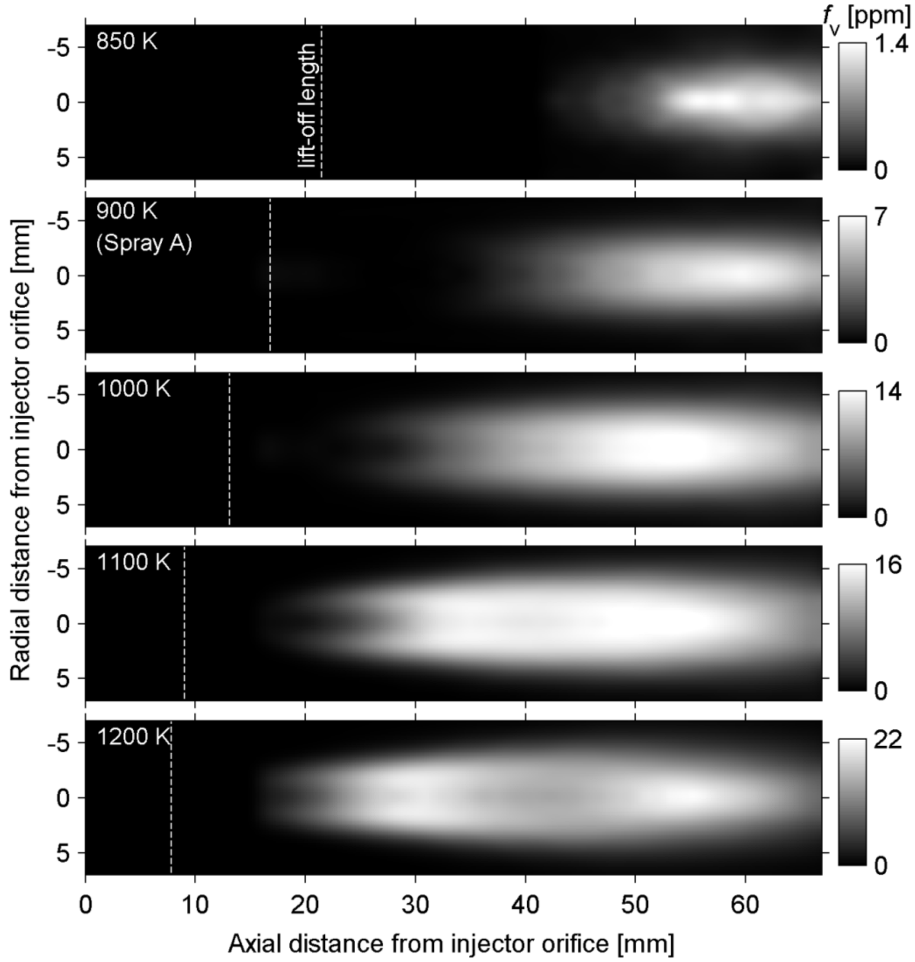
- Lift-off length:
  - Expt: 17.5 mm
  - ANL: 22.8 mm
  - Purdue: 20.3 mm
  - Tue: 18.1 mm
  - UNSW m0: 27.0 mm
  - UNSW m1: 16.8 mm

- Similar lift-off length but very different OH profiles.
- ECN experimental participants plan to perform planar OH measurements.

Soot level is quantified within reacting sprays

- Soot mitigation stands as a major barrier to efficiency.
- Soot modeling is far from predictive.
- We developed a new technique to quantify soot concentration based on high-speed extinction imaging.
- Applied to variants of the Spray A condition.
  - Ambient temperature
  - Ambient density
  - Ambient oxygen (EGR level)
- Measurements also address soot size and soot precursors.
- Dataset is now available for detailed soot model development.
  - Target for future ECN modeling.

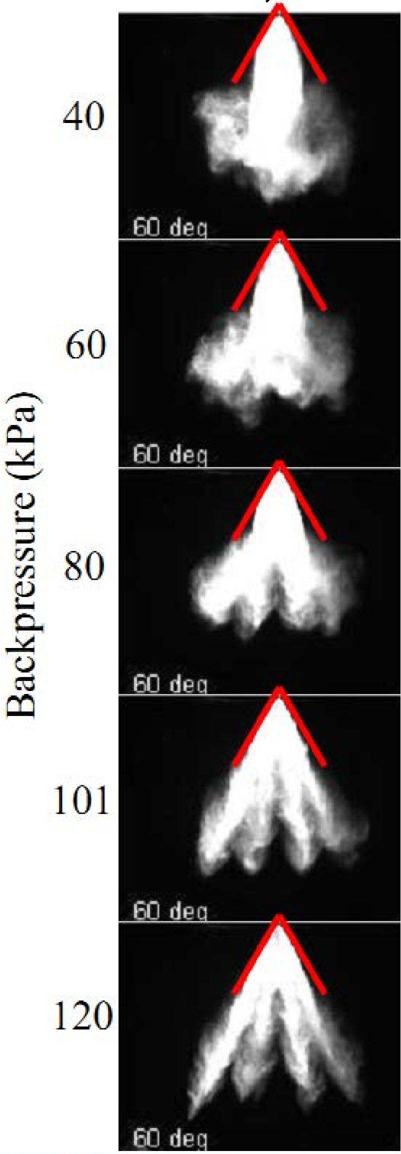
Diffused back illumination (DBI) high-speed imaging technique developed by Scott Skeen and Julien Manin, Sandia



DI gasoline sprays have special modeling challenges

- Feedback from last AMR:
  - "extend the work to direct-injection gasoline"
  - "greatly accelerate gasoline injection diagnostics"
- Efficiency gains met with DI gasoline, but challenges exist:
  - Wall wetting, early DI (stoichiometric), late DI (fuel-lean), spray-guided ignition, knock mitigation, particulate matter, coking, spark-assist HCCI, HCCI, etc.
- Specific challenges:
  - Plume-to-plume interaction, flash boiling, flow-field spray interactions, ignition in stratified or high-pressure environment
  - Stochastic variability in these processes—do these originate from the spray (injector) or something else?
- Approach:
  - Eliminating the complexity of an engine by injecting in our quiescent constant-volume vessel
  - Address individual plume, and global spray, liquid and vapor
  - Quantify mixtures (equivalence ratios) along a plane for detailed CFD evaluation

Parrish, 2008



Liquid and vapor visualization of multi-hole DI injector

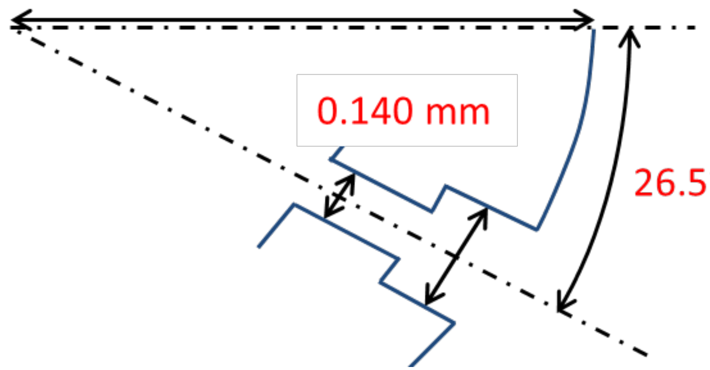
<u>Ambient Conditions:</u>

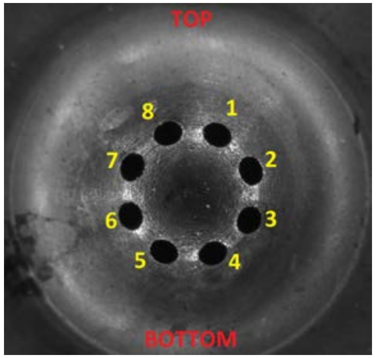
Temperature	700 K
Pressure	12.3 bar
Density	6 kg/m^3
Oxygen (by volume)	0% O_2

<u>Injector Conditions:</u>

Fuel	Iso-octane
Pressure	200 bar

Valve-covered orifice with counterbore



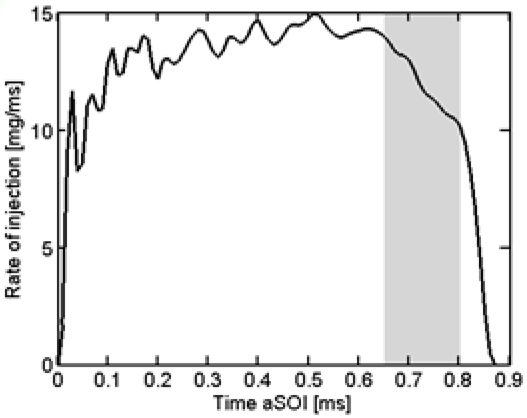


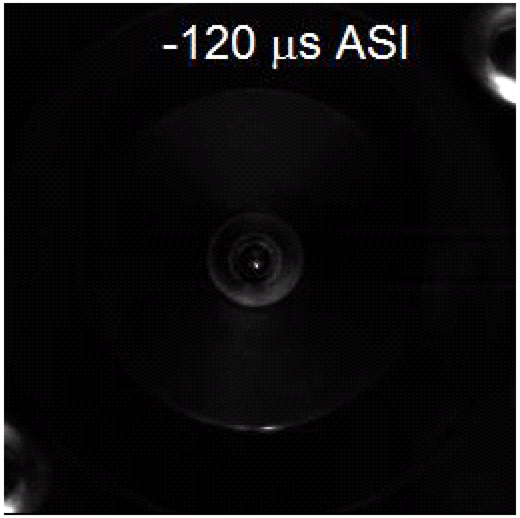
Schlieren (Side)

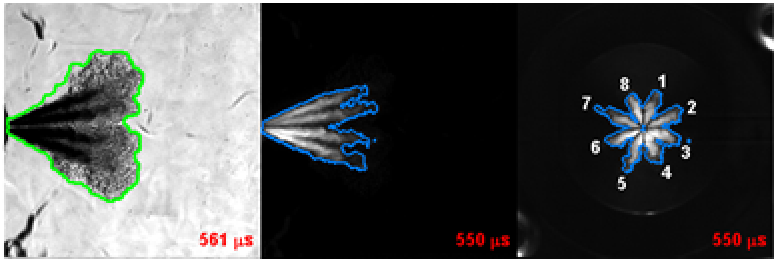
Mie-scatter (Side)

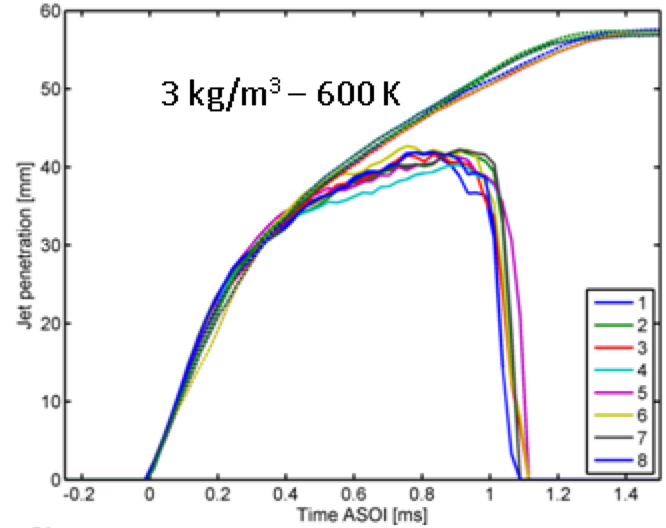
Mie-scatter (Front)

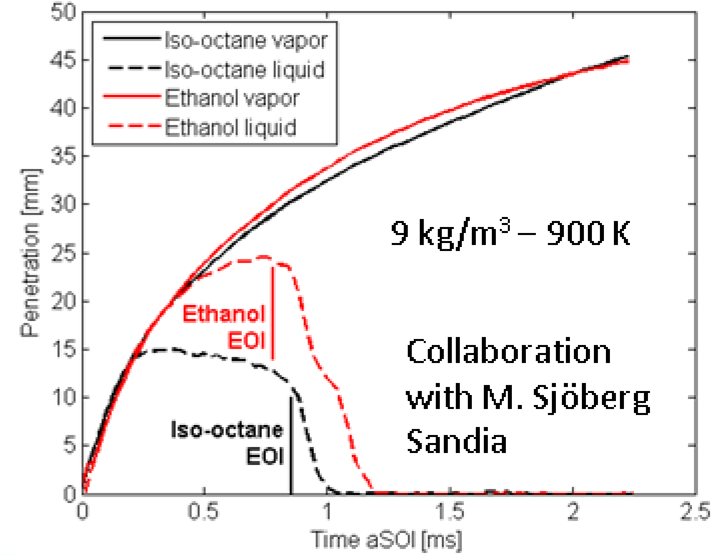
Plume pointing vector (in 3D) with liquid and vapor penetration





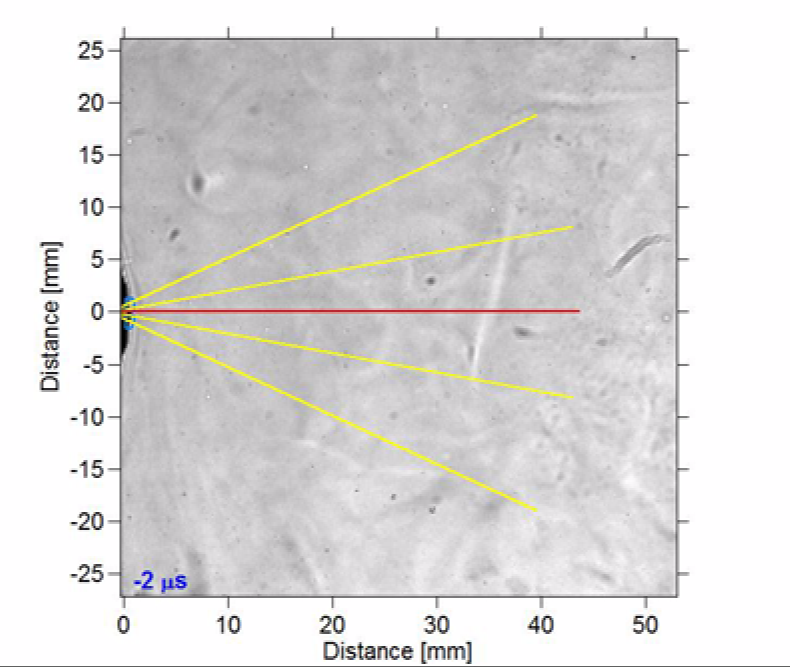




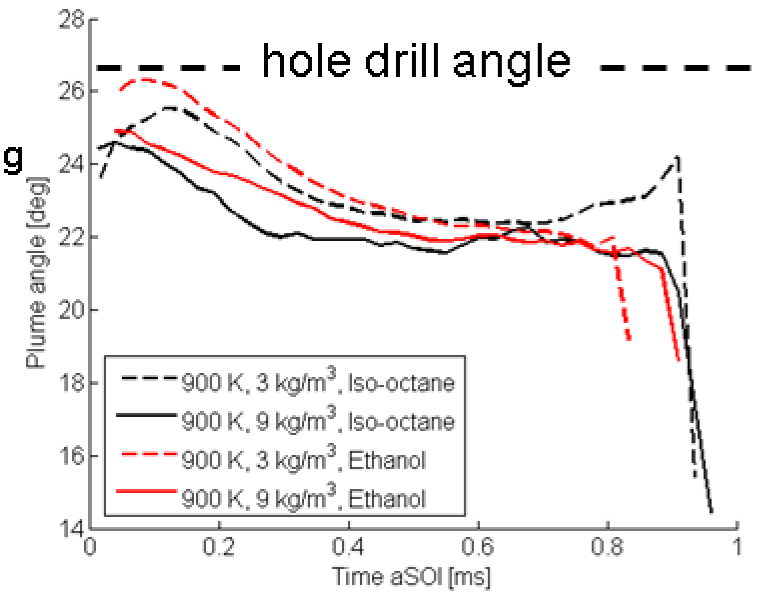


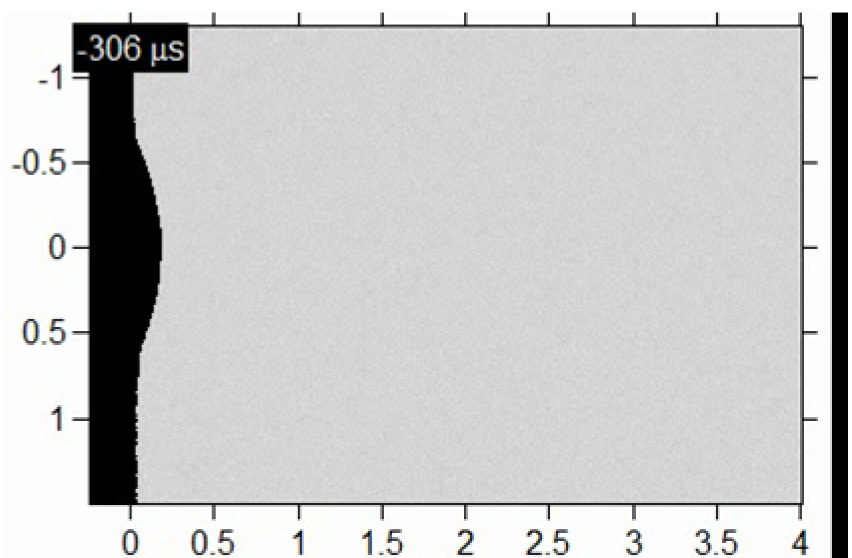
- 3D penetration is relatively close for the 8 plumes (less than 10 % max. deviation)
  - Plume-plume variation at EOI
- Ethanol vs. iso-octane:
  - Similar vapor penetration.
  - Longer liquid penetration for ethanol.
  - Longer time after EOI for vaporization.

Understanding the causes of attracting/merging plumes is critical for DI gasoline spray modeling.

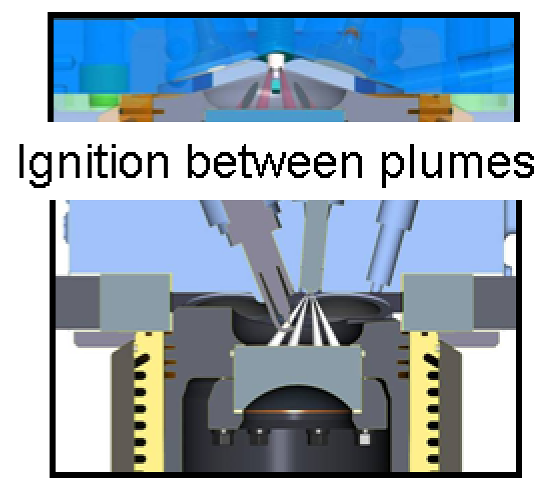


yellow:
drill angle
red:
plume pointing vector



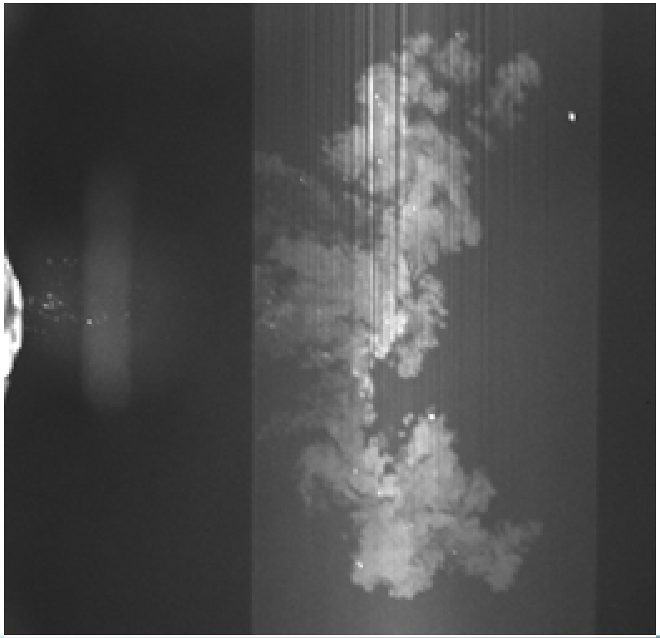


long-distance microscopy

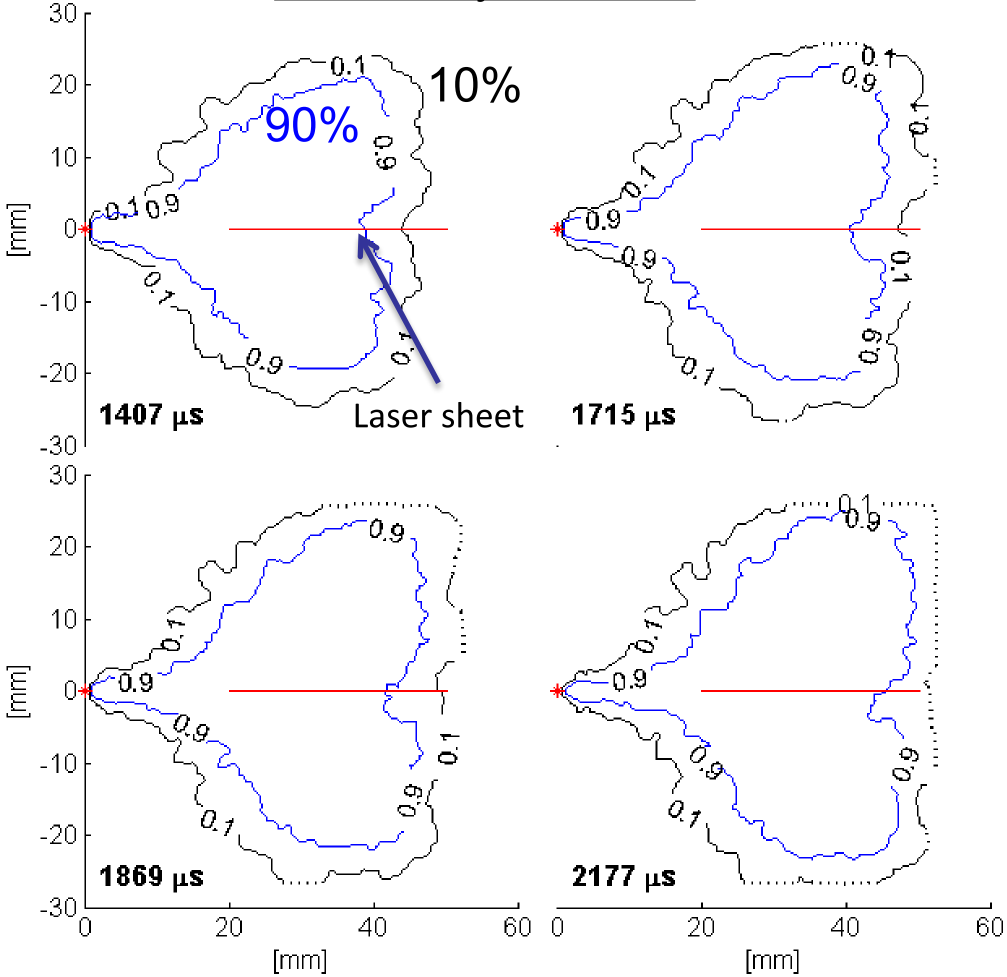


Injection-to-injection variability in vapor penetration is a potential cause for irregular combustion.

- Contour plots showing the probability for the presence of vapor (schlieren) from repeated injections.
  - <10 mm variation
  - along line of sight!
- The region between plumes is probed using a planar diagnostic:
  - Rayleigh scattering

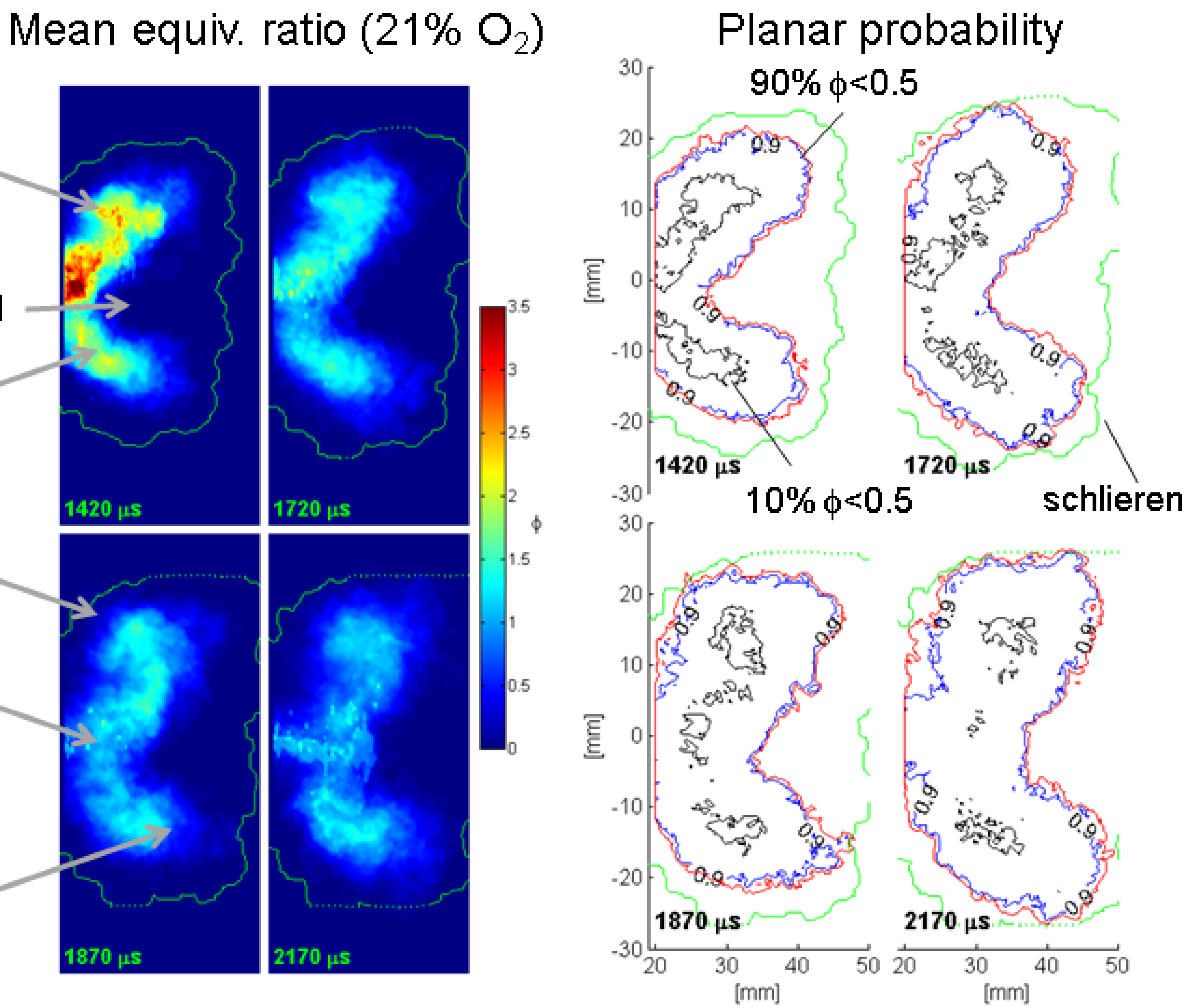


Probability contours



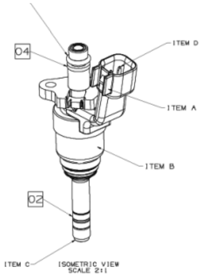
Planar mixing (equivalence ratio) measurements quantify plume interaction after EOI.

- Plumes 2 and 3 collapse first
- Extent of hollow cone revealed
- Stronger momentum at EOI for plumes 6 and 7
- Progressively becoming more fuel lean
- Central, collapsed jet with occasional large droplets
- Extended penetration for plume pair 6-7



Future work

- Develop "Spray A" philosophy and dataset for ECN DI gasoline injector set.
  - Delphi has donated 12 gasoline injectors for future ECN research.
  - Apply similar diagnostics and tools presented today.
  - Coordinate research worldwide.



- Extend research to Spray B, 3-hole injectors with the same specification as Spray A.
- Use large-nozzle injectors (0.2 mm diameter) to create interaction between liquid regions and combustion regions of the spray, and to significantly change stoichiometry.
  - Spray A variants typically have lift-off downstream of liquid length.
  - ECN measurements show variation in near-nozzle spray, but less impact/variation on ignition and lift-off length.
- Quantify soot precursors near first soot and total soot radiation downstream.
- Quantify the minor species that exist in preburn environments, along with their impact on ignition and combustion.

Presentation Summary

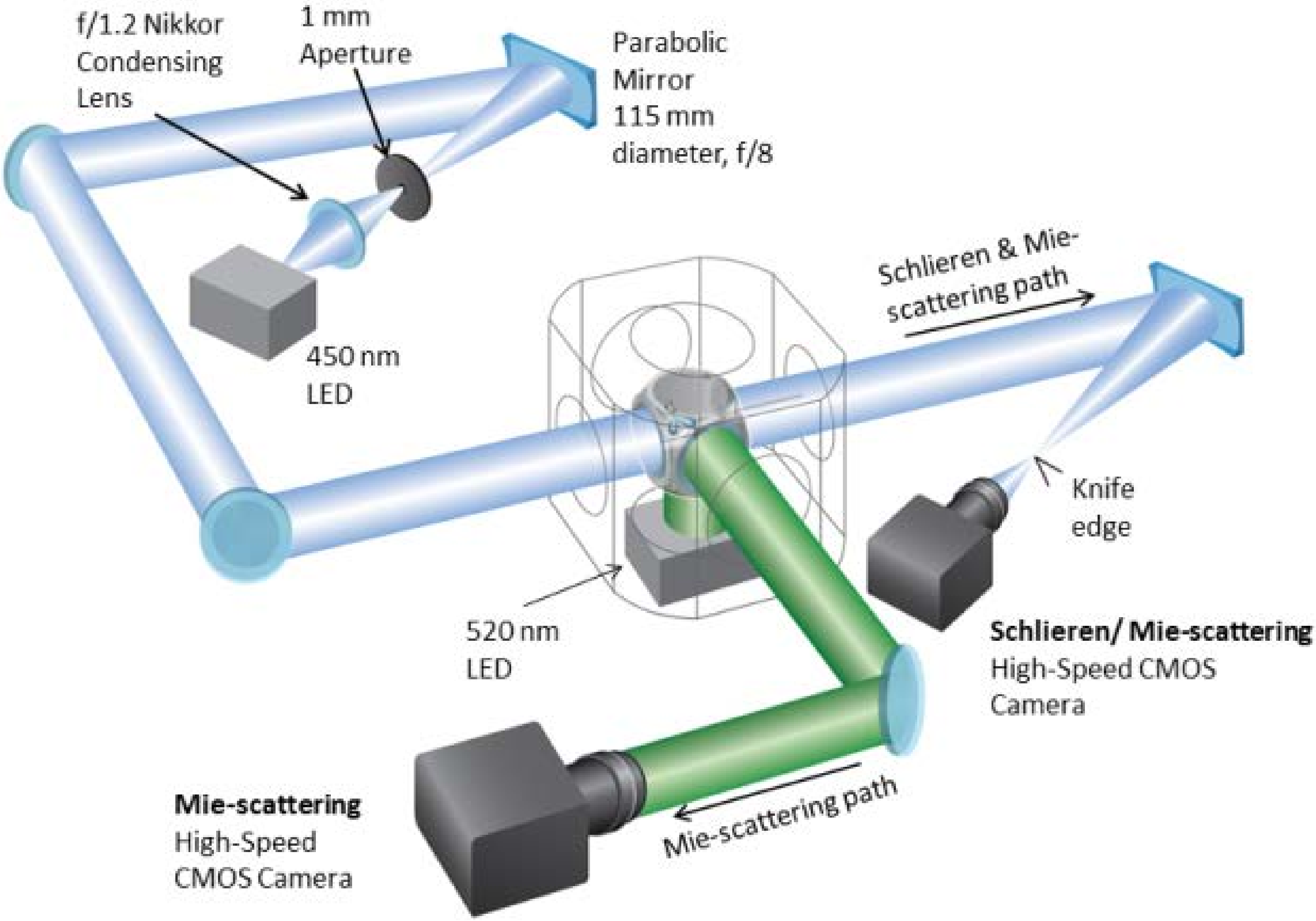
- Project is relevant to the development of high-efficiency, low-emission engines.
  - Observations of combustion in controlled environment lead to improved understanding/models for engine development.
- FY13 approach addresses deficiencies in spray combustion modeling.
  - Understanding of plume interaction and mixing effects developed for gasoline DI injectors, including planar, quantitative measurements for model evaluation.
  - Massive Spray A dataset expanded significantly, outlining clear needs for future model improvement with respect to ignition delay and lift-off length.
  - New DBI technique provides quantitative soot measurements in optically thick sprays.
  - 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.

Acknowledging FY13 staff and visitors performing spray combustion research at Sandia

- Scott Skeen, Sandia National Laboratories
- Julien Manin, Sandia National Laboratories
- Maarten Meijer, Technical University of Eindhoven
- Matt Blessinger, University of Wisconsin-Madison
- Kristine Dalen, Technical University of Denmark

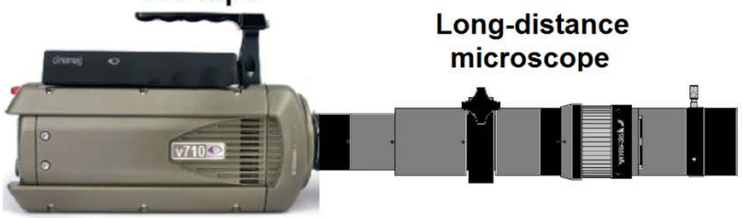
Technical Backup Slides

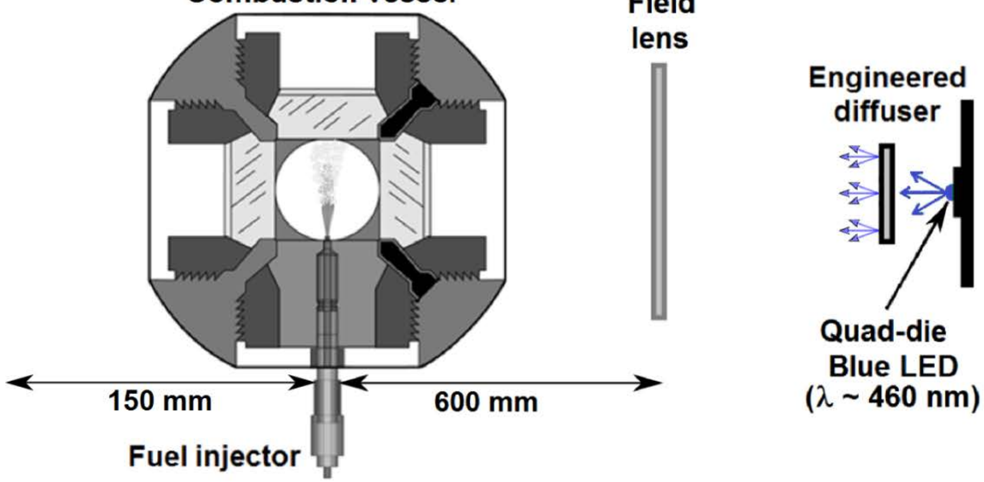
Dual high-speed imaging system for vapor and liquid

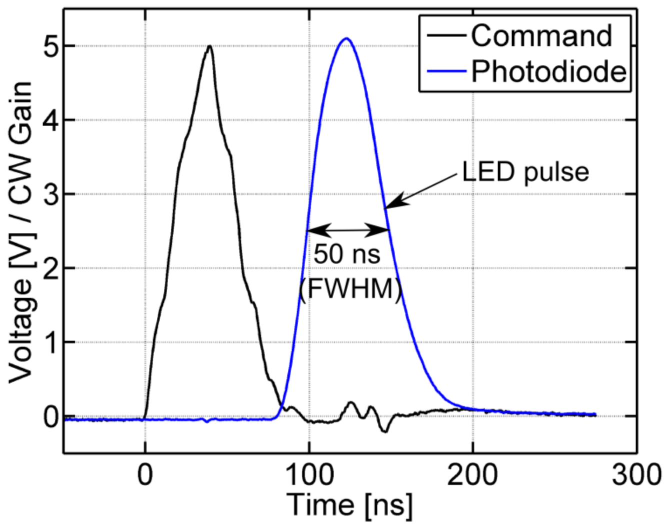


Microscopic high-speed imaging setup

- 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

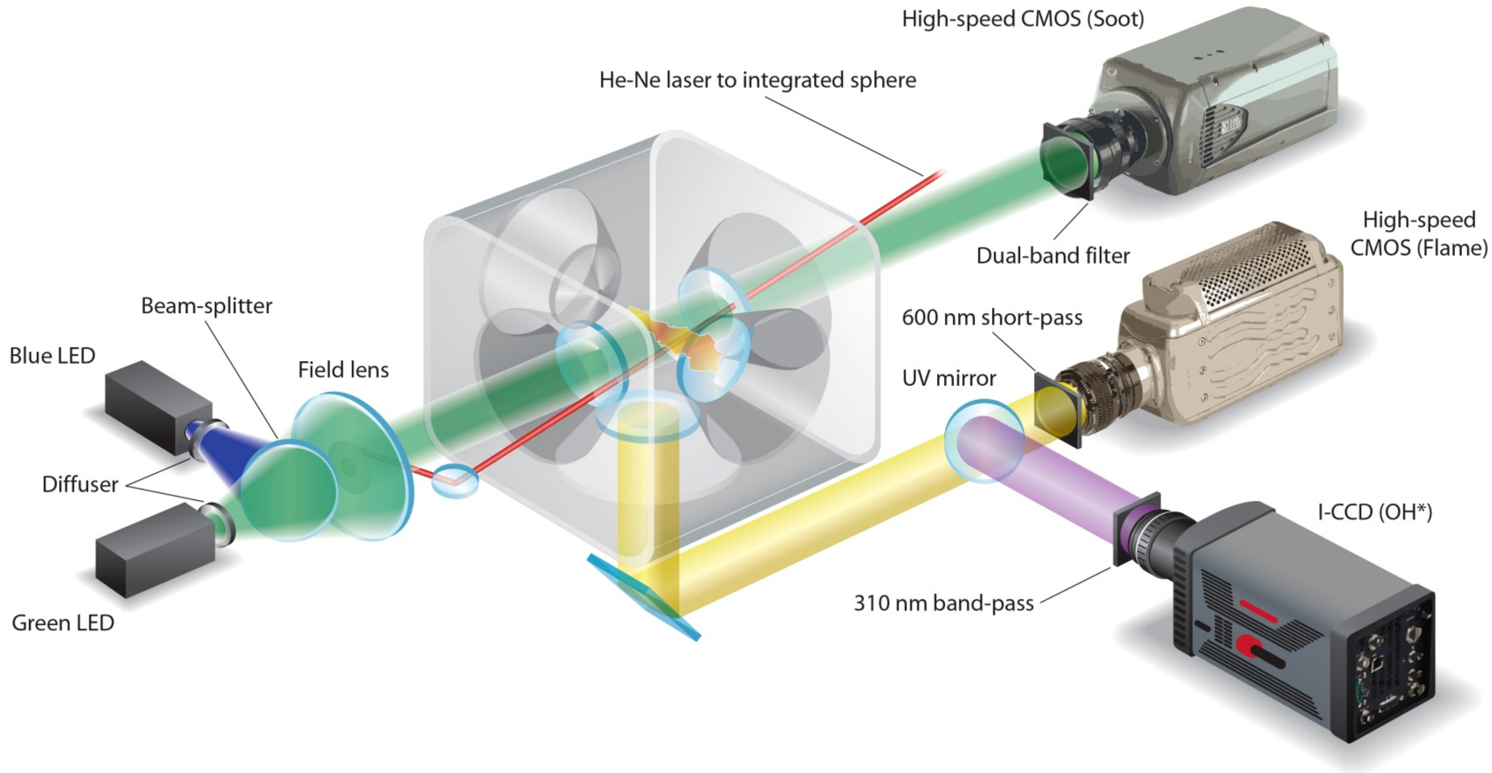






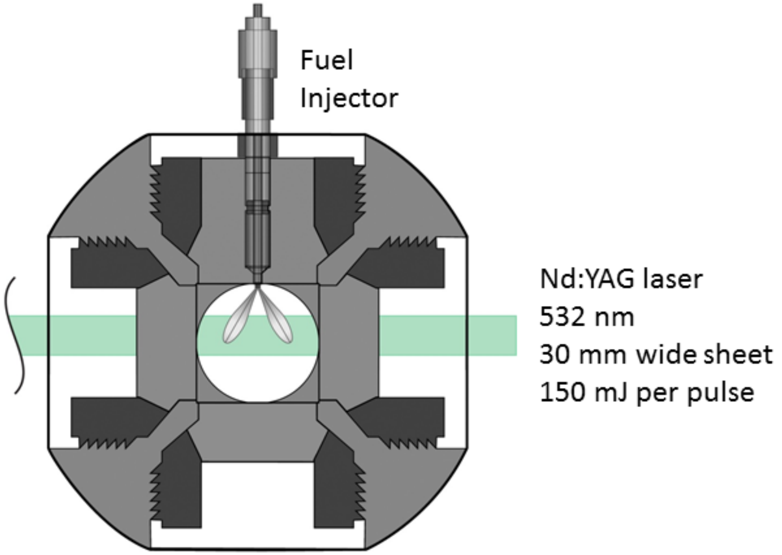
- 150 kHz normal operation (up to 400 kHz)
- LED operated in burst mode producing more than 5 times the CW output luminosity
- 50 ns LED pulse duration to freeze the flow (exiting at more than 500 m/s)

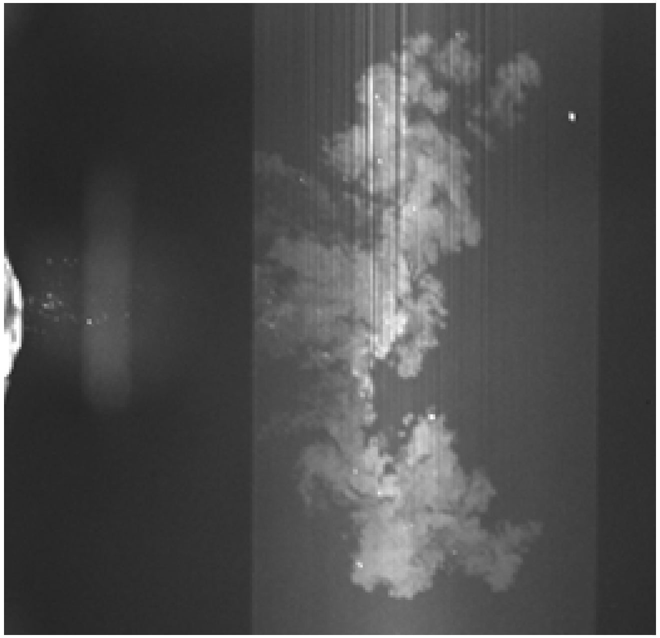
Diffused Back Illumination for quantification of soot



Mixing measurements via Rayleigh scattering

- Rayleigh scattering has been employed to measure the concentration of fuel in the vaporized spray
- A Nd:YAG laser generates a 30 mm wide laser sheet placed between the plumes around the axis of the injector

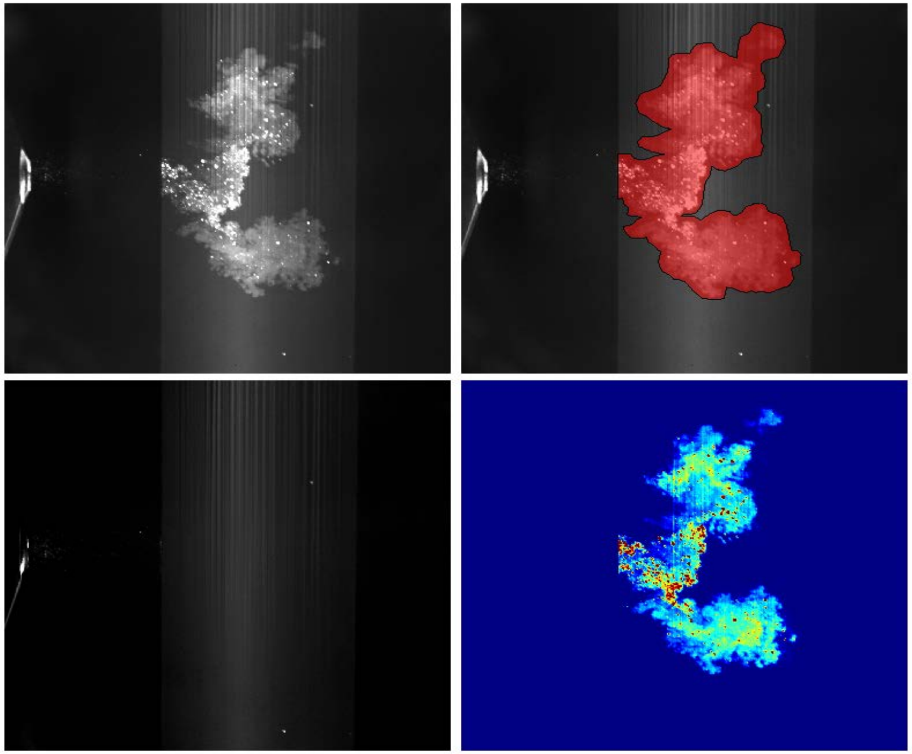




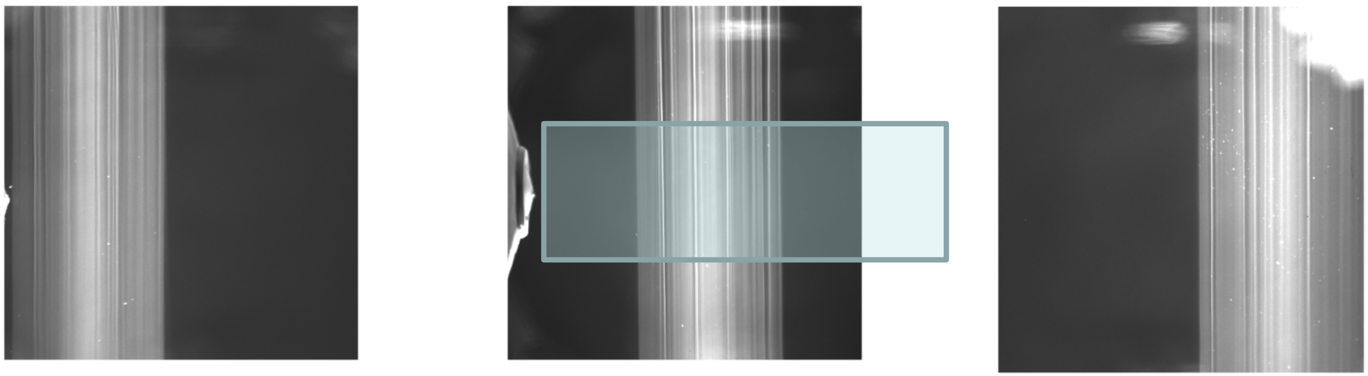
- Specific fused silica window slits on the laser path to optically "seal" the vessel and reduce stress-induced birefringence
- A high quantum efficiency back-illuminated CCD has been used to acquire high-sensitivity/low noise Rayleigh signal
- High resolution images with pixel size of less than 70 µm (≈70 mm field of view)

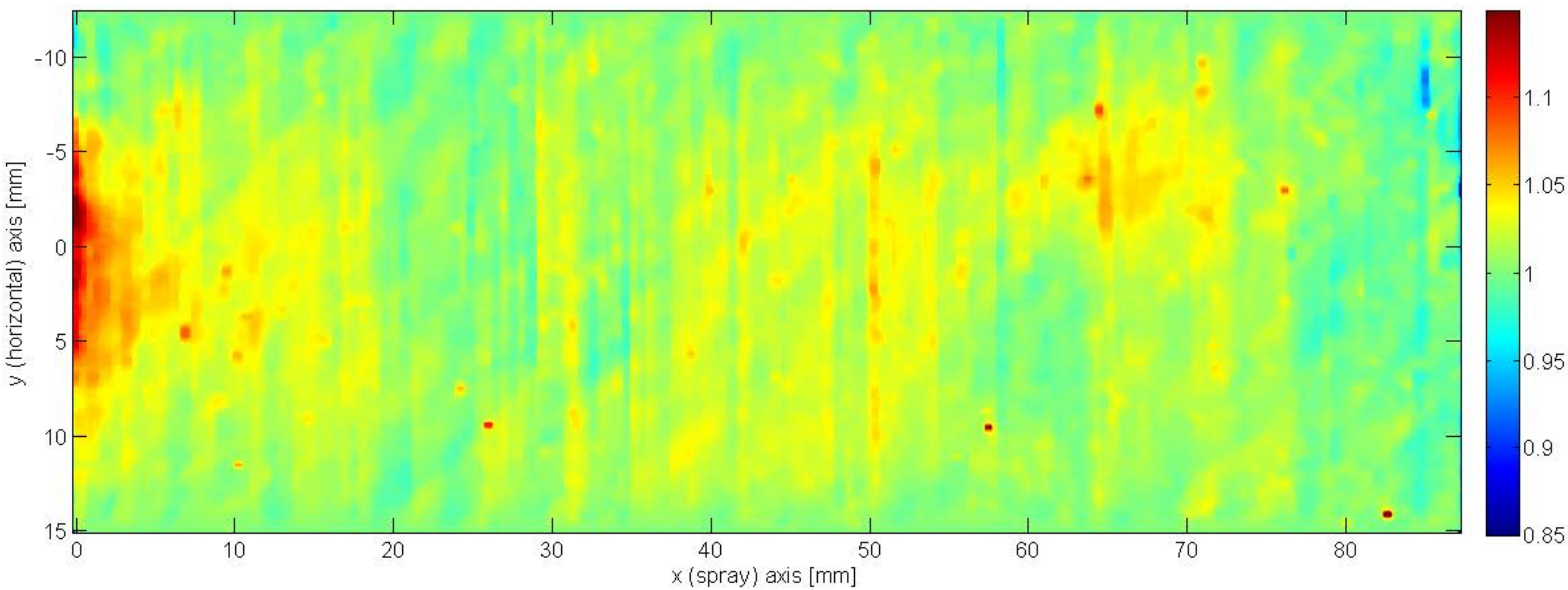
Calibration of equivalence ratio (Rayleigh)

- The relationship between recorded intensity and number density is drawn assuming adiabatic mixing of the species $$\frac{I_{R,mix}}{I_{R,amb}} = \left(\frac{\sigma_{fuel}/\sigma_{amb} + N_{amb}/N_{fuel}}{1 + N_{amb}/N_{fuel}} \right) \frac{T_{amb}}{T_{mix}}$$
- Ambient temperature and species are known, Rayleigh cross-sections are also known for all the species: σ_{fuel} = 397 x 10^{-27} cm^2
- Process steps (summary):
  - Select spray boundaries
  - Reconstruct “jet-free” laser sheet intensity (beam steering)
  - Ratio intensities
- This process is self-calibrated as both signal intensities (ambient and spray) are used
- Beam steering is well corrected thanks to the linear gradient reconstruction of the laser sheet



Rayleigh Scattering: axial profile





Boundary layer near injector will influence spray properties.

- Possibility to calibrate the Rayleigh data via direct TC measurement