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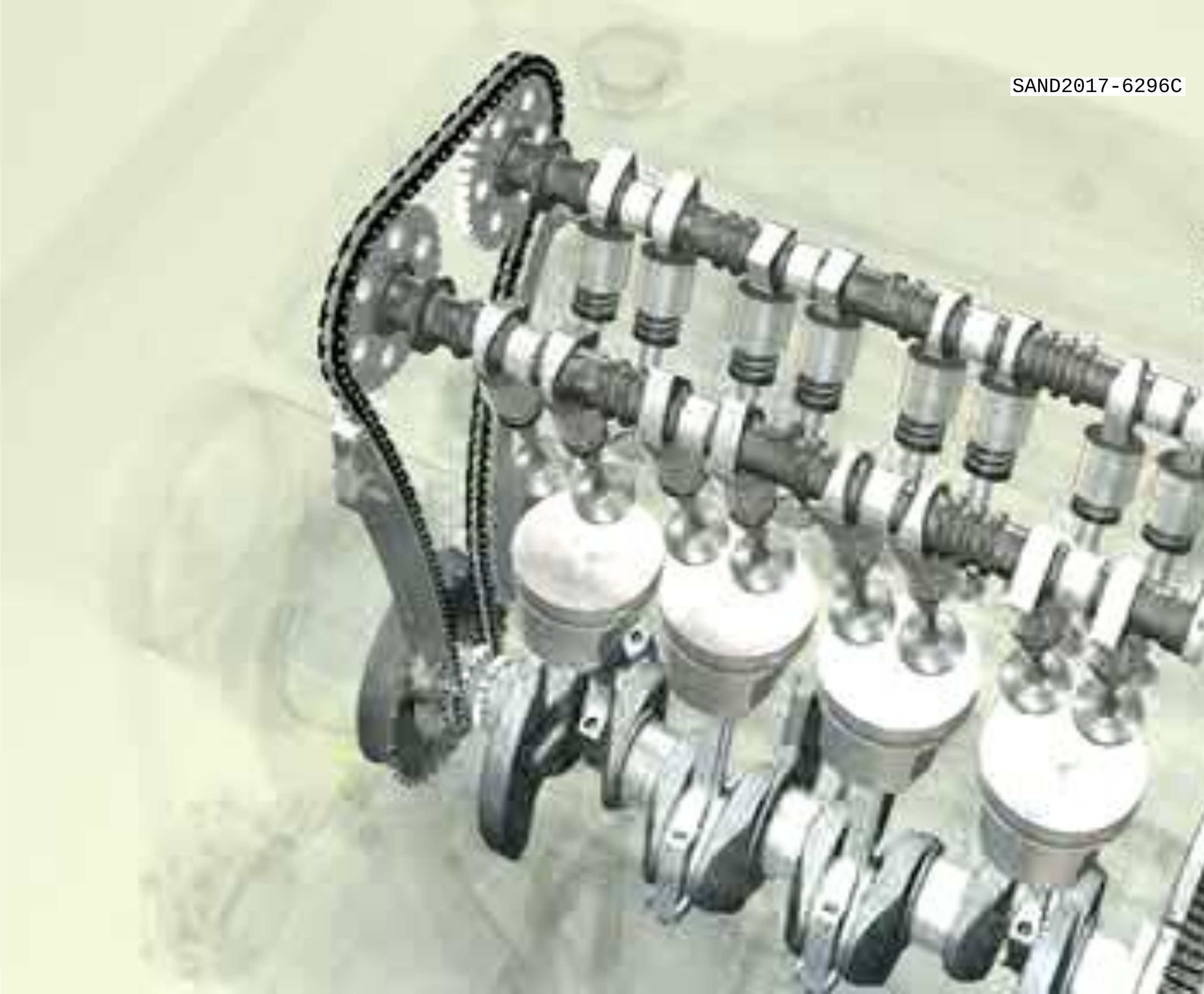


Opening slide credit:
Deutz AG

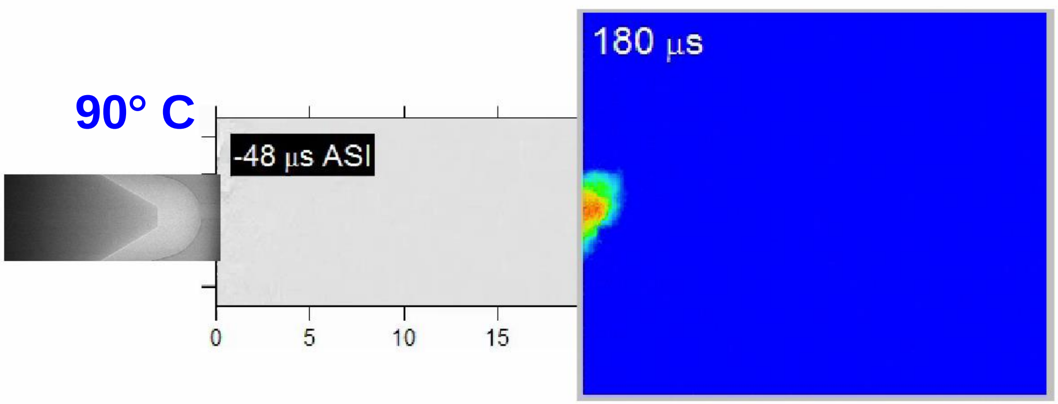
Spray Combustion Research for the Engine Combustion Network

Lyle M. Pickett
Sandia National Laboratories

Diesel
Spray A

900 K
60 bar

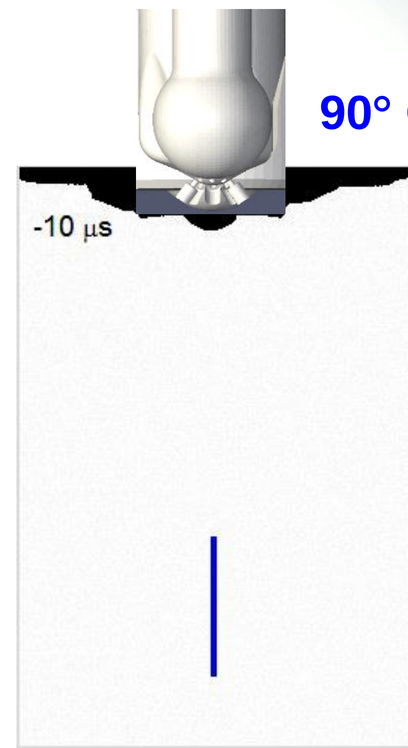
90° C



Gasoline
Spray G

573 K
6 bar

90° C



Acknowledgements

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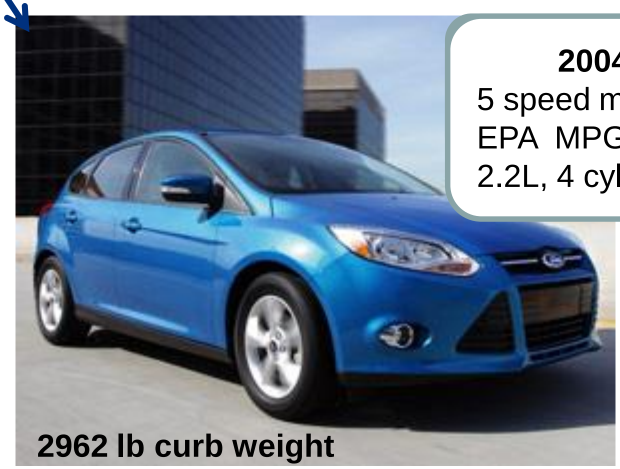
- Dan Varble and Lee Markle, *Delphi, donation of injectors.*

Racing to increase fuel economy

Thing 1

2014 Ford Focus SFE



2962 lb curb weight

2004 Cavalier
5 speed manual, 2630 lb
EPA MPG: 21 city / 31 hwy
2.2L, 4 cyl, 115 hP, 183 N·m

2014 Chevrolet Cruze Eco

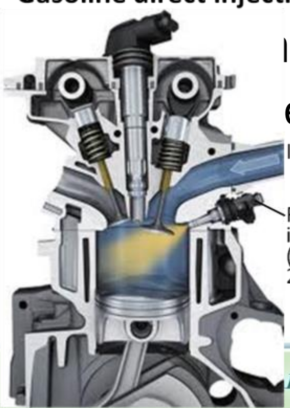
Thing 2

3029 lb curb weight

	2014 Ford Focus SFE	2014 Chevrolet Cruze Eco
EPA MPG:	28 city / 40 hwy	28 city / 42 hwy
~Price:	$20K	$20K
Engine:	2.0 L, 4 cyl, var. cam. direct injection, nat. asp. CR = 12:1, 6 sp. auto	1.4 L, 4 cyl, Ecotec port injection, turbocharged CR = 9.5:1, 6 sp. manual 138 hP, 201 N·m

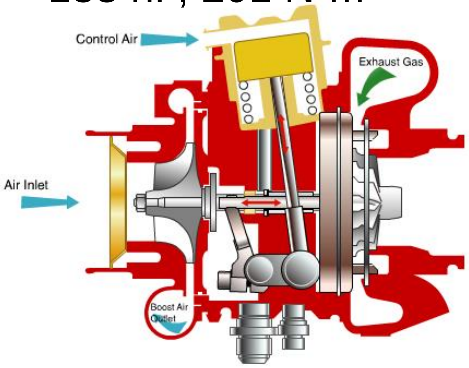
A few other options:
Honda Civic HF (29/41)
Hyundai Elantra (29/40)
Mazda3 (28/40)

Gasoline direct injection



omy.gov ... in fuel savings ov
ed to typ ... 23 mpg)

Port fuel injection



Racing to increase fuel economy

Thing 1

2016 Ford Focus SE

2960 lb curb weight

2016 Chevrolet Cruze LT

Thing 2

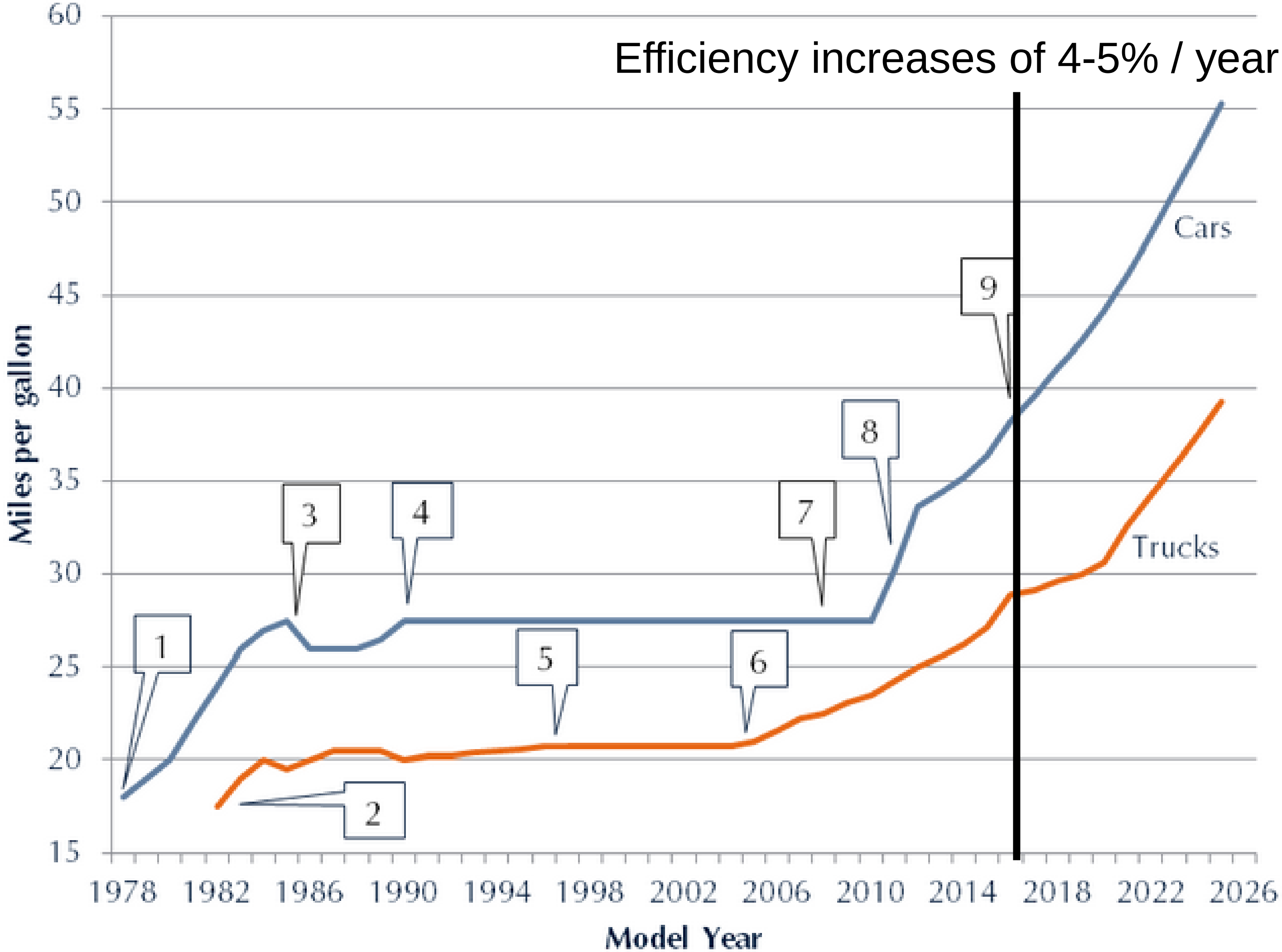
2932 lb curb weight

	2016 Ford Focus SE	2016 Chevrolet Cruze LT
EPA MPG:	30 city / 42 hwy	30 city / 42 hwy
~Price:	$20K	$20K
Engine:	1.0 L, 3 cyl direct injection, turbocharged CR = 10:1, 6 sp. manual 123 hP (6000 rpm), 169 N-m	1.4 L, 4 cyl, "new" Ecotec direct injection, turbocharged CR = 10:1, 6 sp. auto 153 hP (5600 rpm), 240 N·m

- Chevy announces that it will release a 1.6L Cruze diesel in 2017
  - 2014 2.0L diesel gets EPA 46 mpg hwy. Expect 48-50 mpg hwy for 1.6L?

A time of innovation for vehicle development

Corporate Average Fuel Economy (CAFE) standard timeline

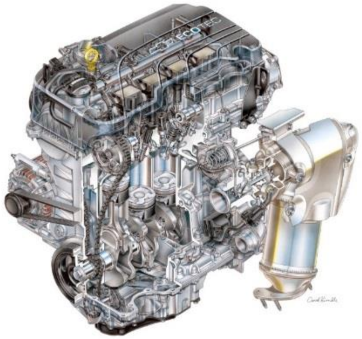


The cost of engine development is enormous

- Typical vehicle development cycle
  - Performance, emissions, fuel economy, durability
  - Round-the-clock tests with 3 work shifts

GM Powertrain Engineering Development Center
120 test cells completed in 2008: $465 Million
Expanded to include R&D, racing in 2016: $200 Million

How new engines are developed



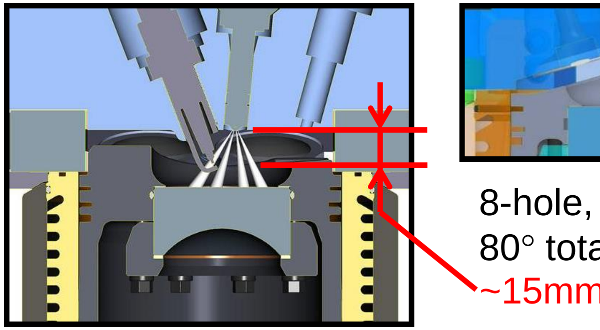
GM 2016 news release on new Ecotec I4 engine:
Computer simulation and modeling were instrumental in developing the new engine. GM's engineers at Global Propulsion Systems centers around the globe were able to design and test parts virtually and immediately share the results with their colleagues.

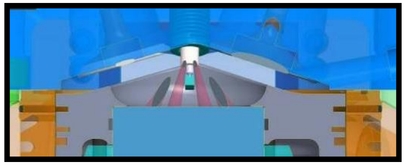
In addition to designing the engines' basic components electronically, friction, temperature, emissions, efficiency and other performance attributes were modeled and simulated multiple times to make the most of performance before the first physical components were produced. Modeling also helped cylinder block design and other components with structural and acoustic considerations.

Tom Sutter, GM Ecotec global chief engineer:
"By doing the majority of the development with math data, the time to design, validate and bring to market an all-new engine family was greatly reduced"

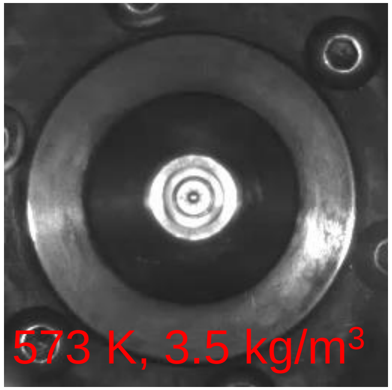
But to date, the fuel spray processes are not adequately modeled

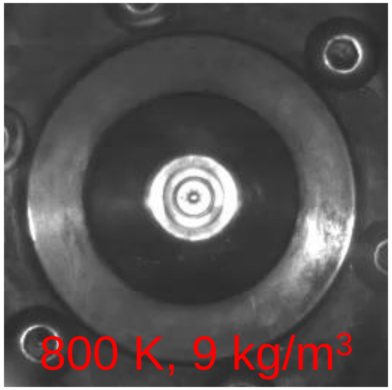
- Lack of predictive spray modeling is a barrier to high-efficiency gasoline
  - Particulate emissions
  - Engine knock or preignition
  - Slow burn rate or partial burn
  - Heat release control when using compression ignition
- Influence of direct-injection spray
  - Fuel films on piston/injector, rich pockets from plume collapse, and poorly atomized fuel
  - Affects temperature non-uniformities
  - Mixture/flow preparation near spark
  - Intentional control of stratification/residence time to stage heat release

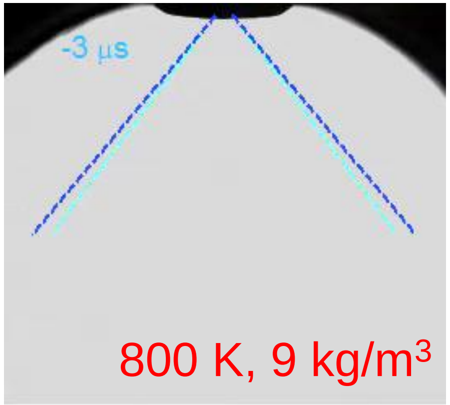




8-hole, gasoline
80° total angle

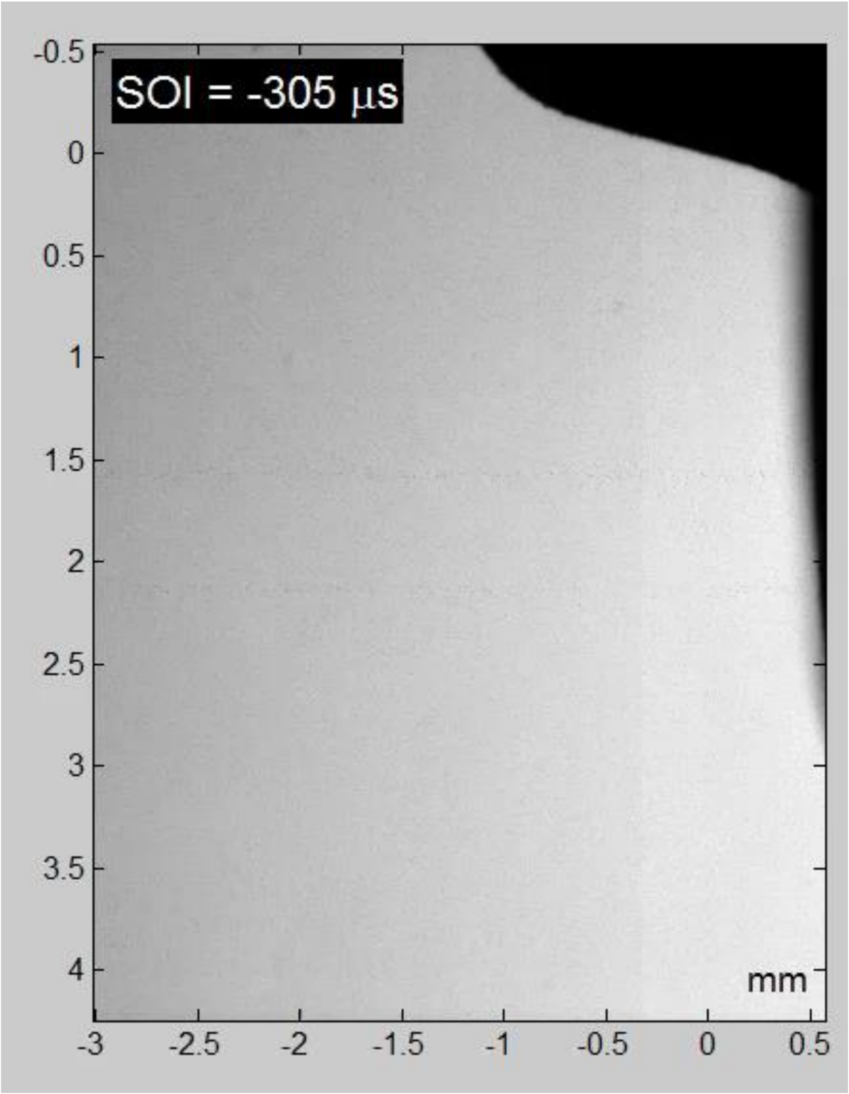




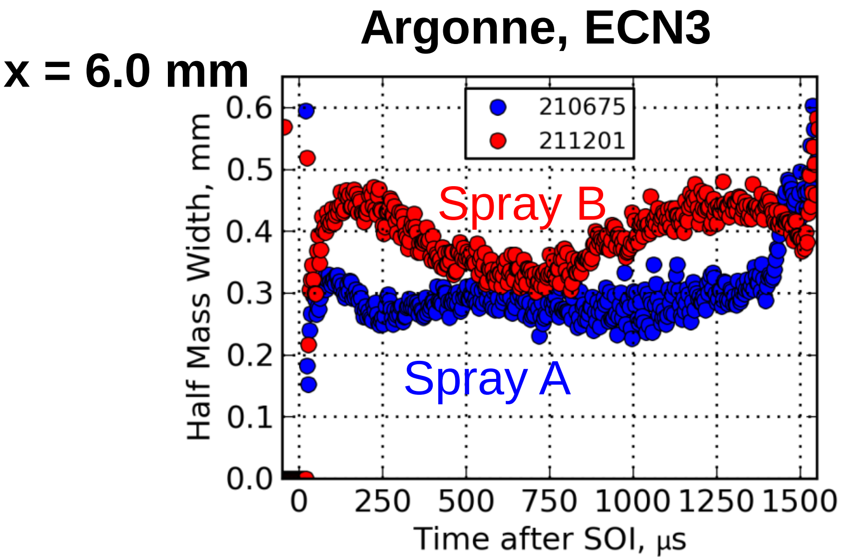


Example of spray modeling need

ECN Diesel Spray B



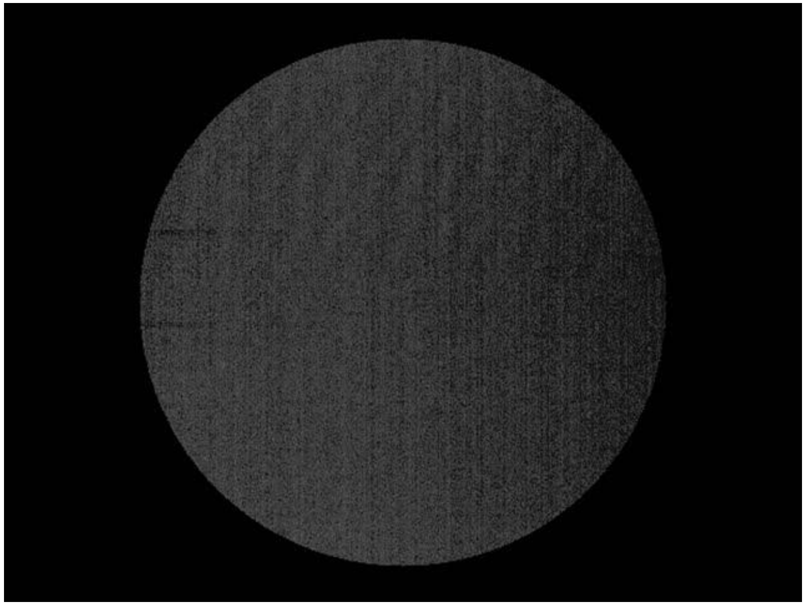
- Work is needed to model the transients of spray development
  - Causes for variation in spray dispersion with respect to time are often unknown
- and spray mixing generally
  - Still a need to simply understand "where the fuel goes"

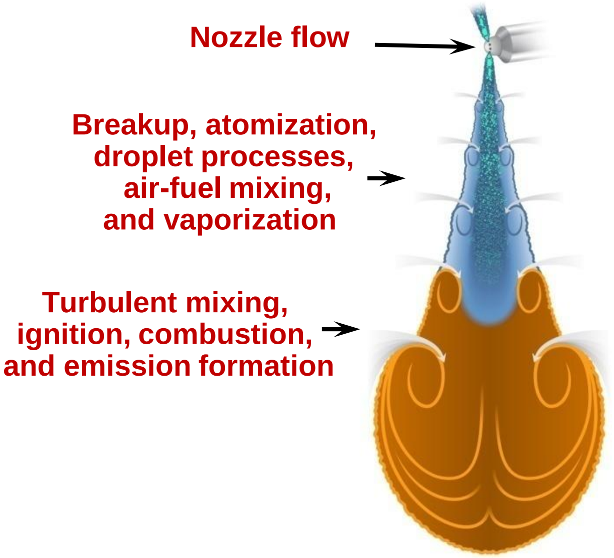


Spray combustion in an engine

Diesel spray combustion imaging through transparent piston

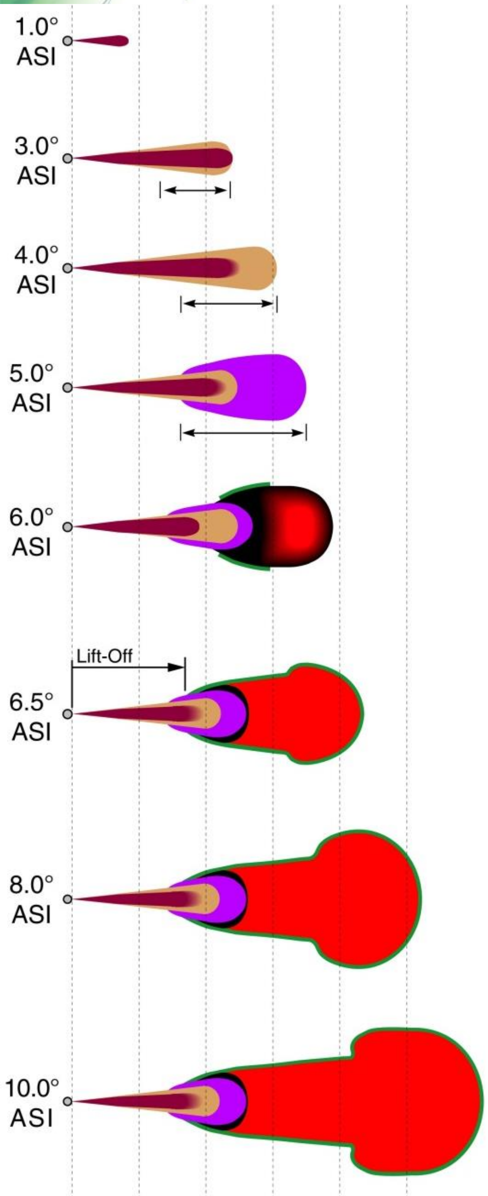
Mark Musculus, Sandia



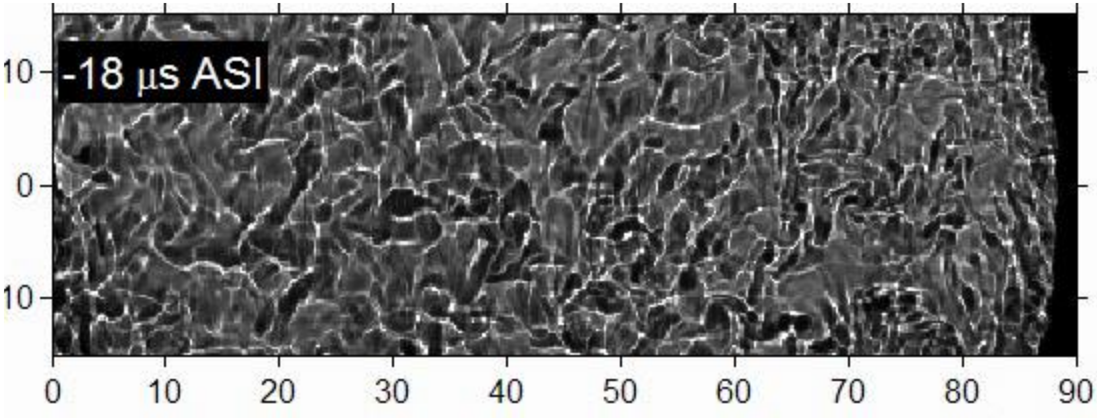


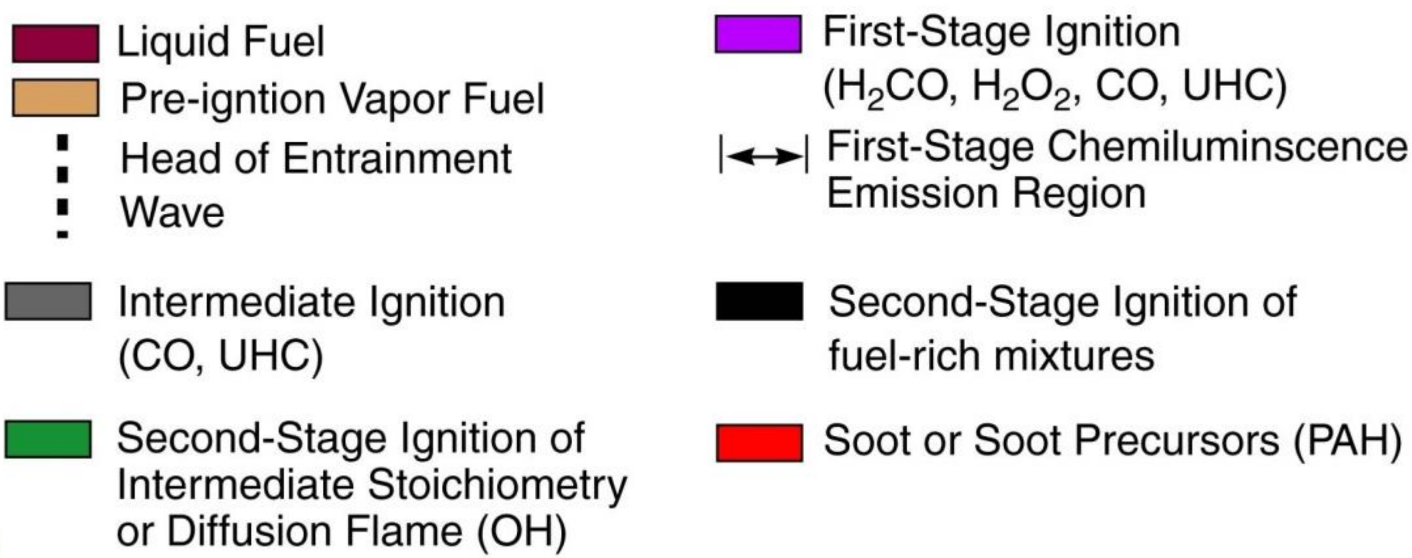
- Future high-efficiency engine concepts are all direct-injection
  - Diesel
  - Gasoline direct-injection
  - Partially-premixed gasoline compression ignition

Current understanding of diesel combustion, summarized by a conceptual model



Schlieren & Mie-scatter high-speed imaging





based on conceptual model of John Dec, 1997

Introducing the Engine Combustion Network https://ecn.sandia.gov

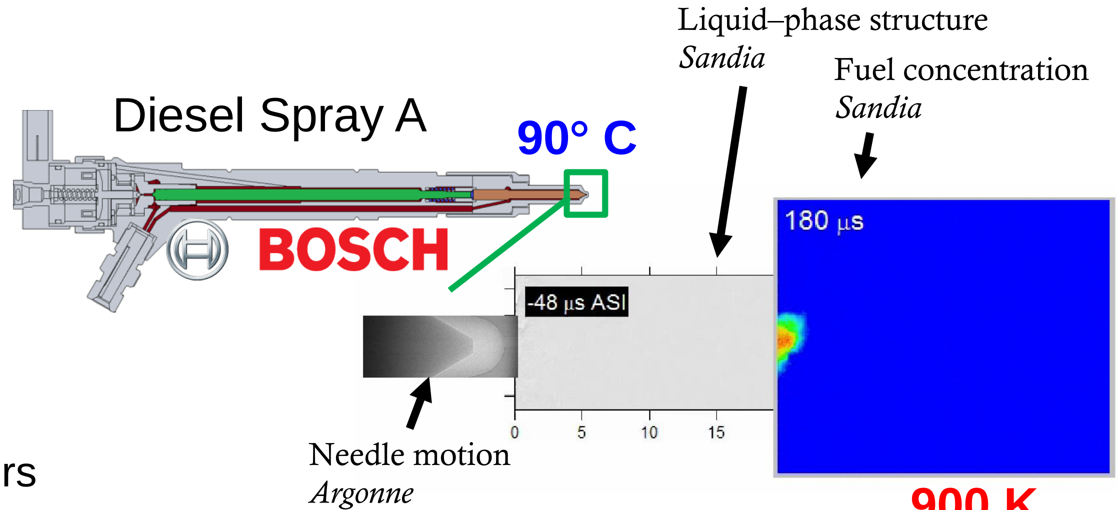
ECN Targets

- Develop diesel and gasoline target conditions with emphasis on CFD modeling shortcomings
- Comprehensive experimental and modeling contributions
- Diesel Spray A, B, C, D
- Gasoline Spray G
- Engine datasets using these injectors are now available online

ECN workshop organization

- Organizers gather experimental and modeling data, perform analysis, understand differences, provide expert review, in 10 different topics
- Monthly web meetings
- In-person workshop
  - ECN4 September 2015
  - ECN5 April 2017 at Wayne State (before SAE World Congress)

Diesel Spray A

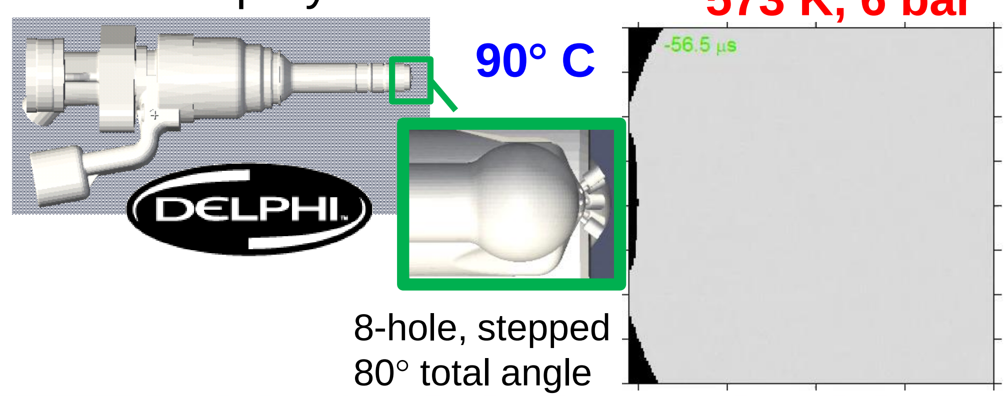


900 K
60 bar

>60 measurements/diagnostics contributed from >15 institutions

Gasoline Spray G

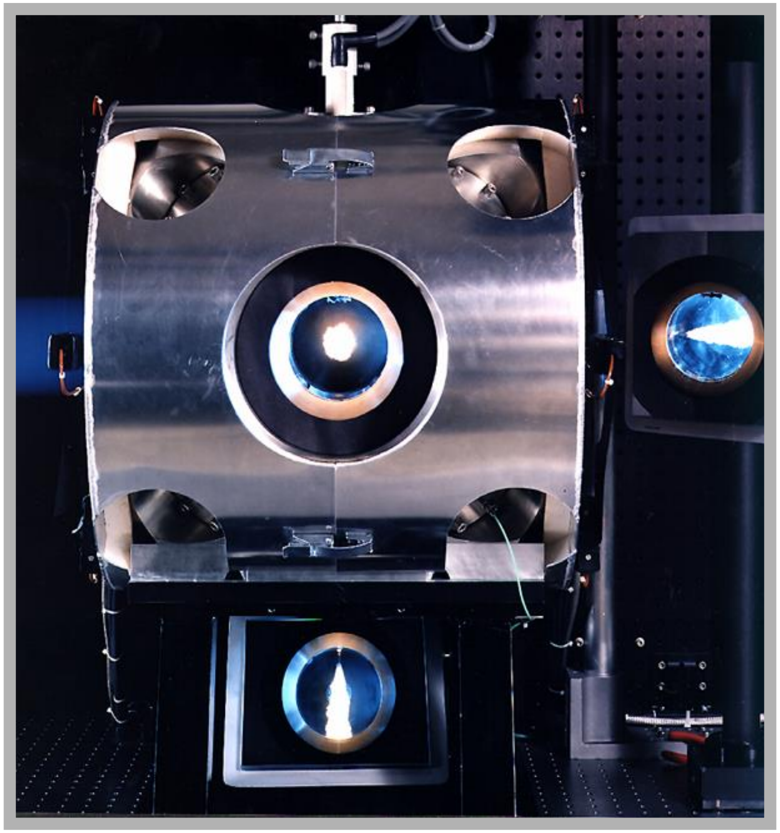
573 K, 6 bar



ECN seeks to obtain quantitative (CFD validation) data, beyond a conceptual model understanding

- Liquid volume fraction and droplet size in the dense spray region and near the liquid length
- Mixture fraction (fuel/air ratio) distribution
- Velocity and turbulence
- Soot volume fraction and structure distribution, particularly during transients
- Ignition location and timing
- Internal injector geometry for working injectors
- Information about internal injector cavitation and flows
- Aerodynamics (velocity) of plume-plume interaction and collapse

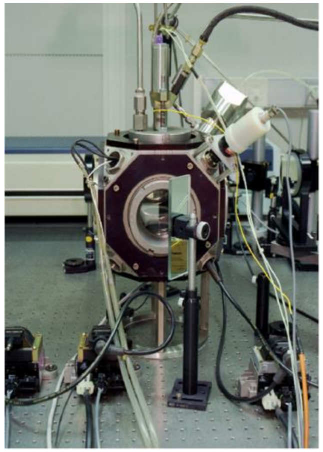
Using a constant-volume chamber to mimic engine conditions for spray combustion studies.



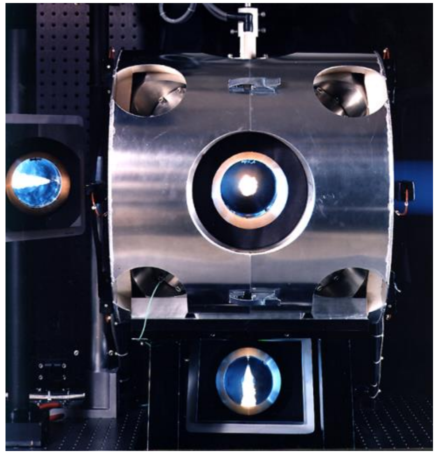
- Well-defined ambient conditions:
  - 300 to 1300 K
  - up to 350 bar
  - 0-21% O_2 (EGR)
- Injector
  - single- or multi-hole injectors
  - diesel or gasoline
- Full optical access
  - 100 mm on a side
- Boundary condition control needed for CFD model development and validation.
  - Better control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

Use multiple facilities to improve accuracy / remove uncertainties and leverage datasets

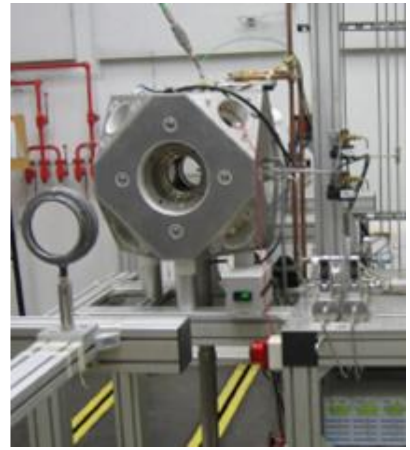
IFPEn



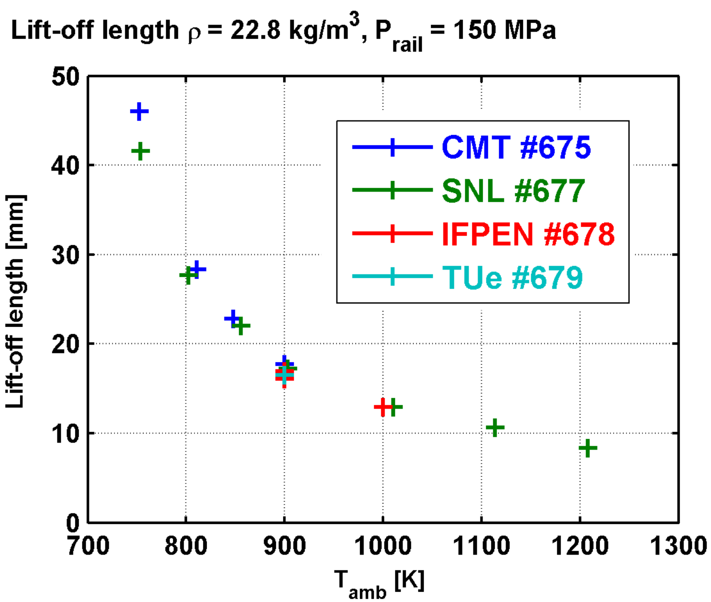
SNL

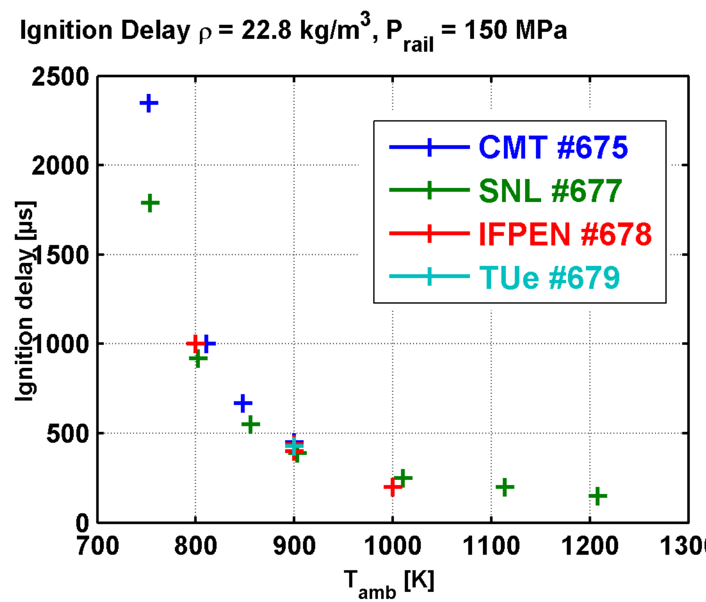


TU/e

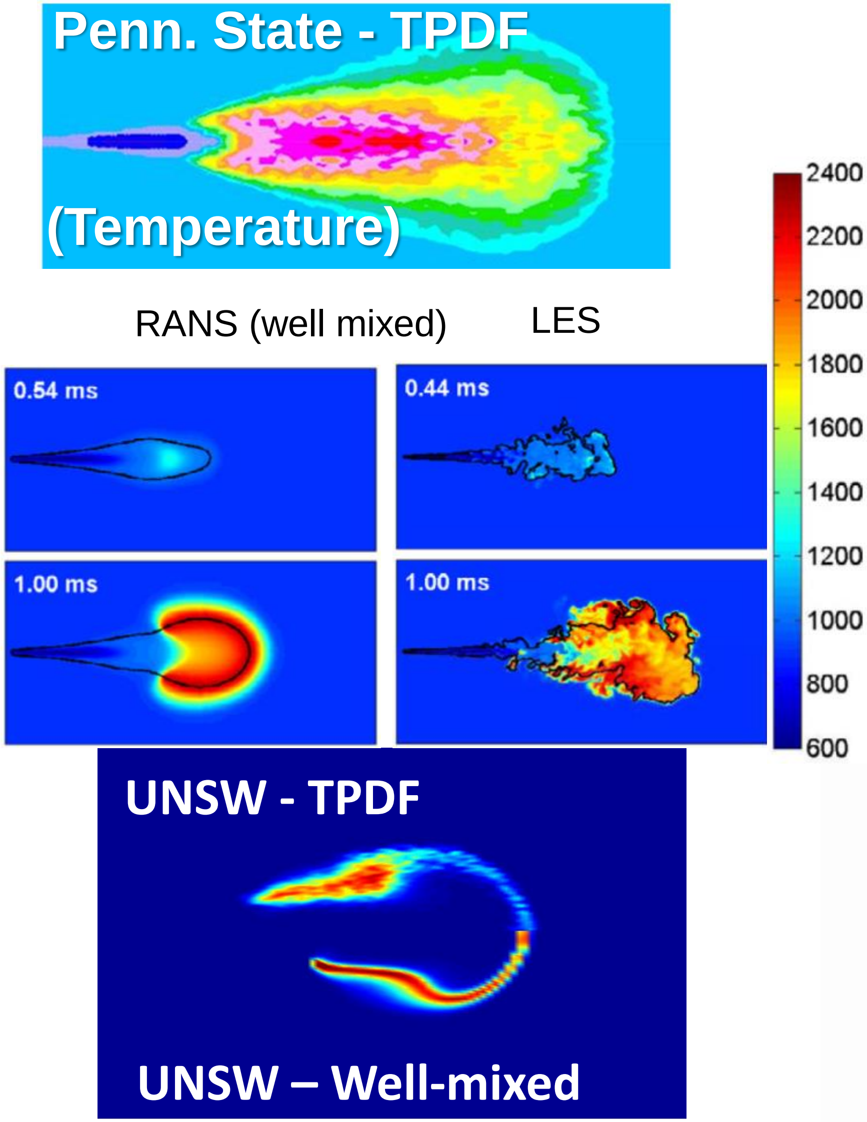


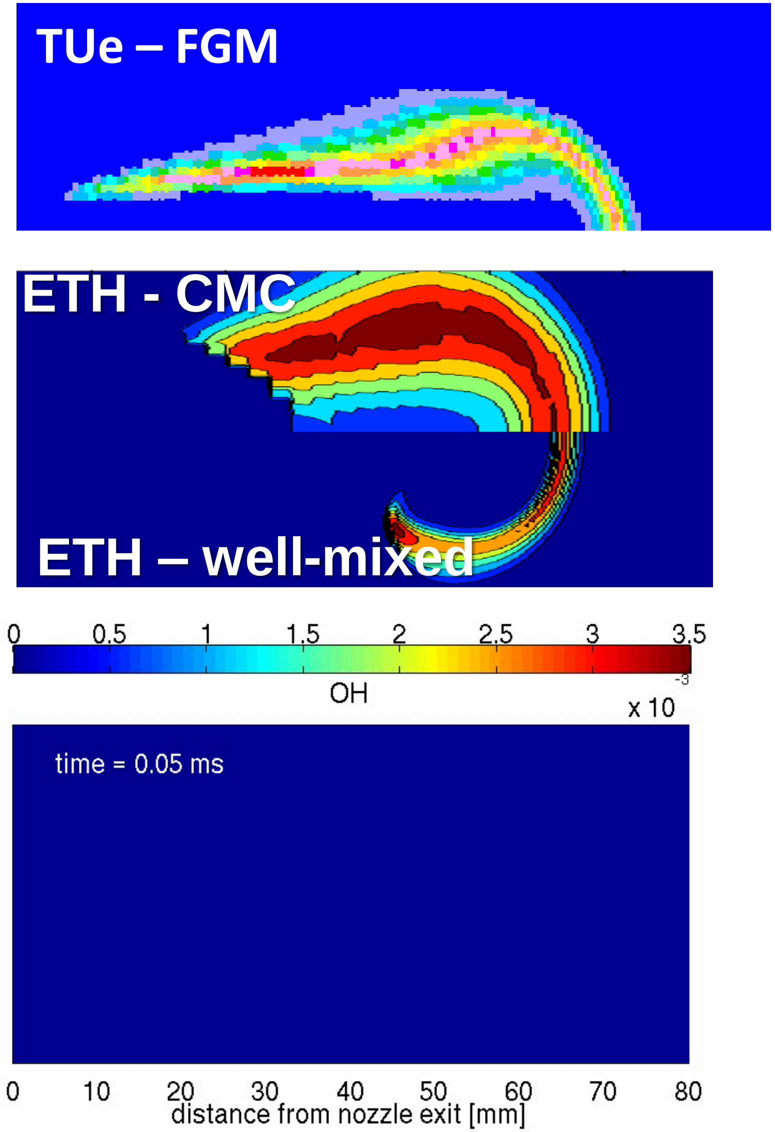
CMT



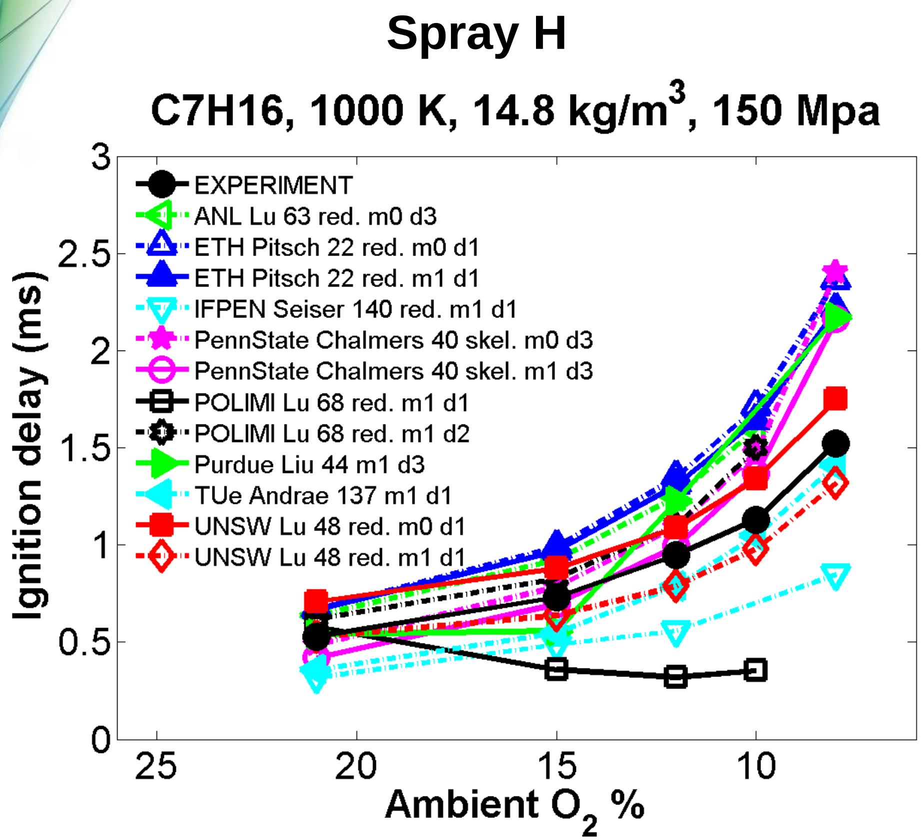


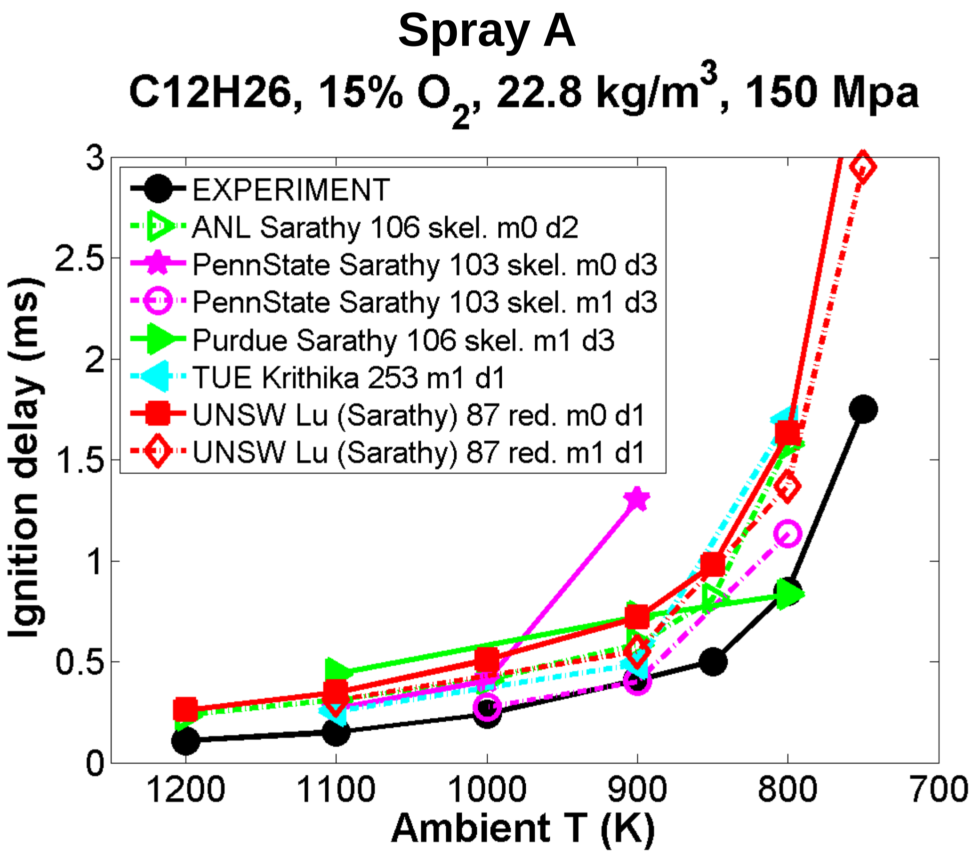
Qualitative modeling comparison





Ignition delay predictions at ECN2



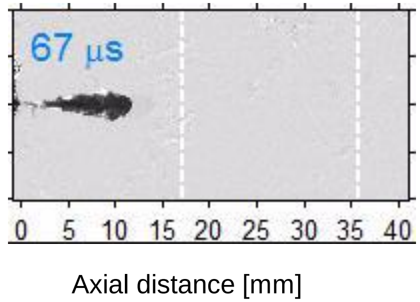


Diesel ignition/combustion linked to transient mixing

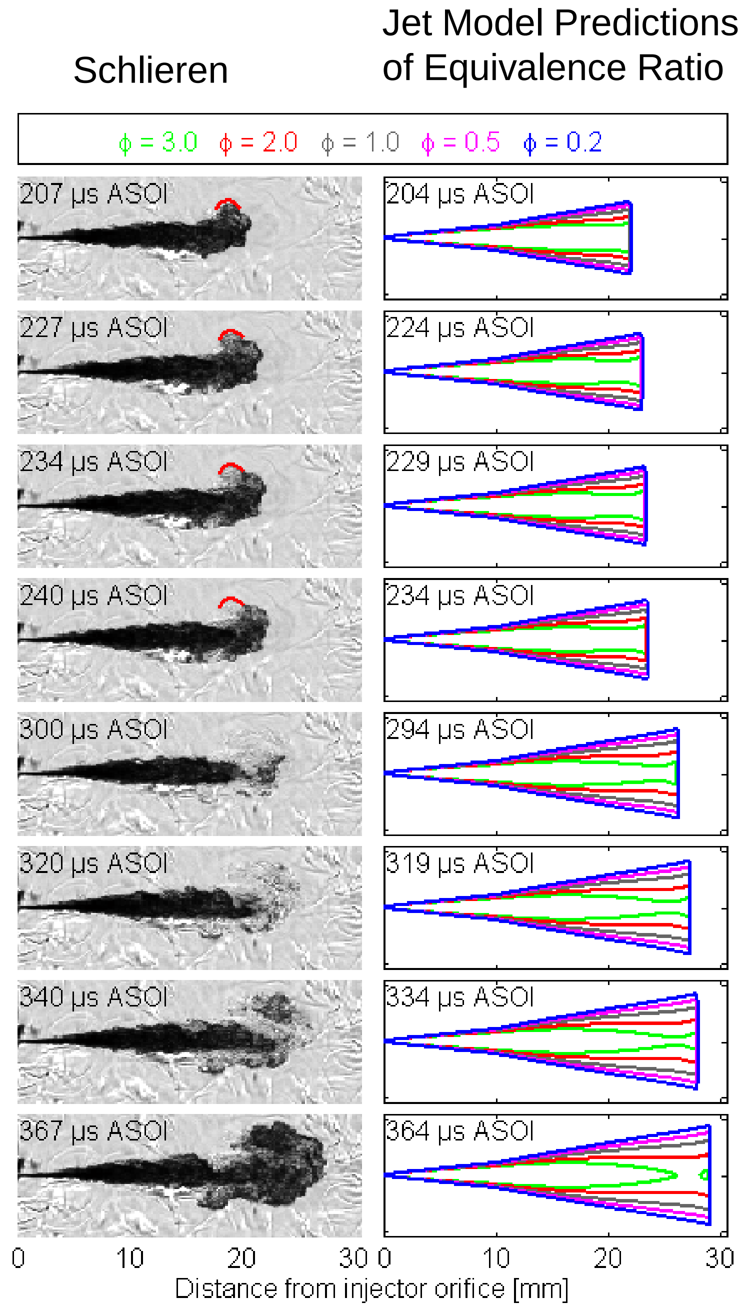
Diesel “Spray A” conditions

Ambient Gas	Fuel
900 K	373 K
60 bar	1500 bar
15% O_2	n-dodecane
	90 μm nozzle

150 kHz schlieren imaging



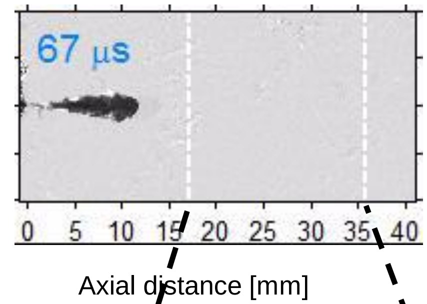
- Cool flame initiates in radial periphery
  - schlieren “transparency” along a line-of-sight suggests large-scale organization
  - cool flame temperature close to 900 K
- High-temperature ignition occurs in the “head” region
  - low-density (2000 K) zones appear again
  - Flame “lift-off” stabilizes at approx. 17 mm
- Accurate CFD modeling of ignition is needed



Transient spray mixture fraction measured (non-reacting) in vaporized region

- Rayleigh imaging quantifies transient mixture fraction / equivalence ratio for the first time
  - Performed at 100 kHz
- Jet mixing characterized by large structures shed to the side and re-entrained
  - Larger residence time in hot mixtures
- Obvious target for high-fidelity LES studies
  - verify accurate mixing field as a preliminary step towards predicting ignition/combustion
  - quantify variance, intermittency, scalar gradients

150 kHz schlieren imaging

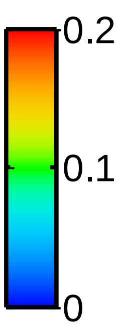


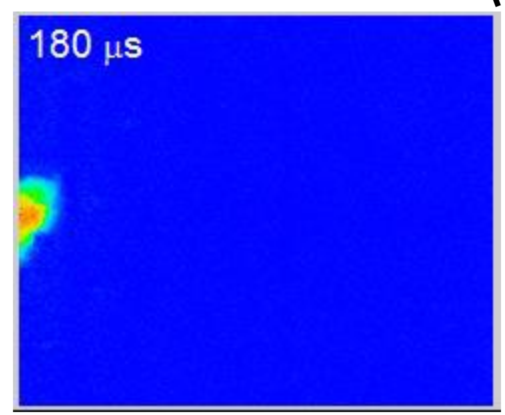
Ambient Gas
900 K
60 bar
15% O_2

Region of interest for ignition and lift-off stabilization

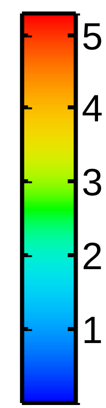
Planar Rayleigh

Fuel mixture fraction



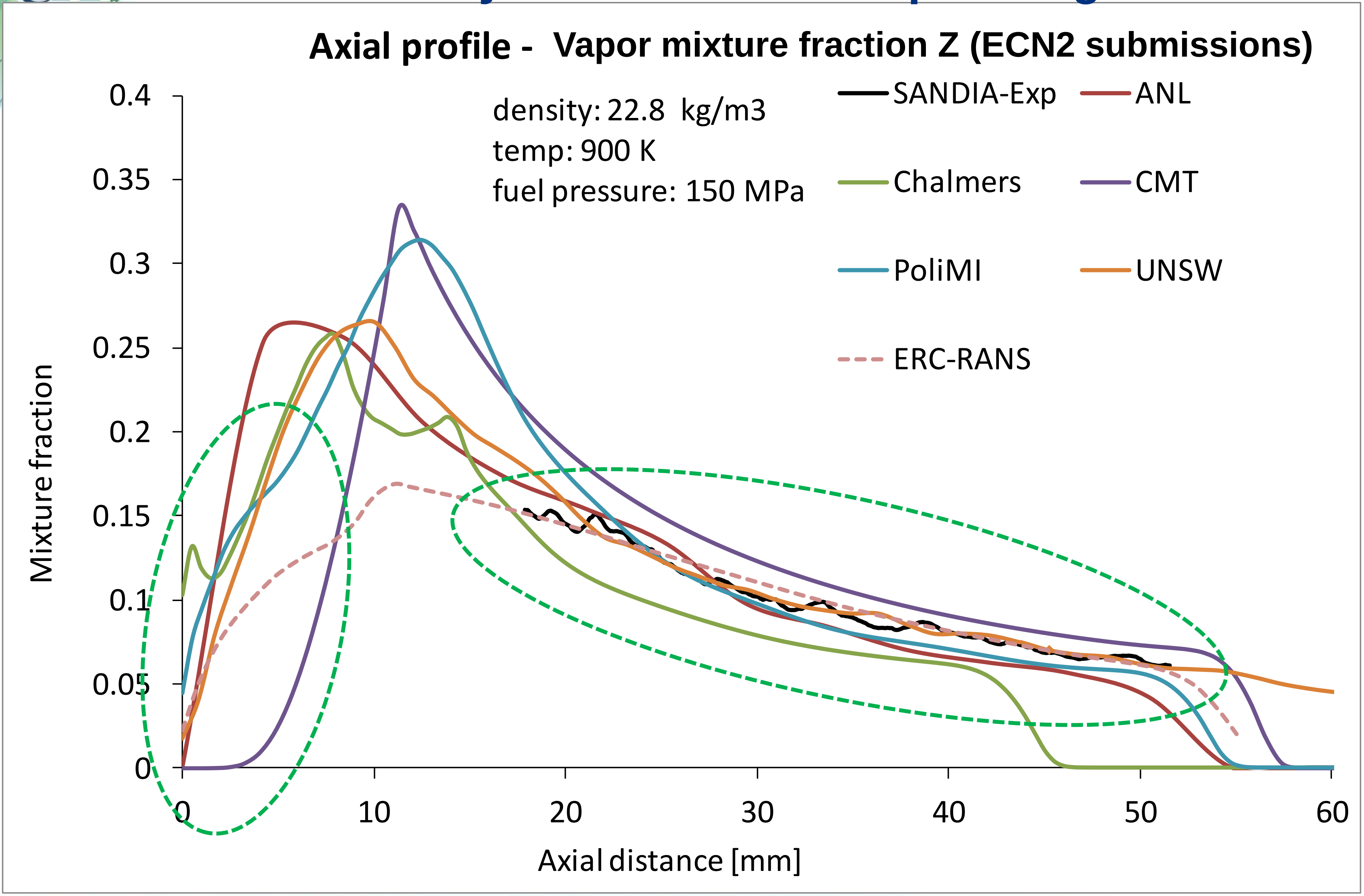


Equiv. Ratio (15% O_2)

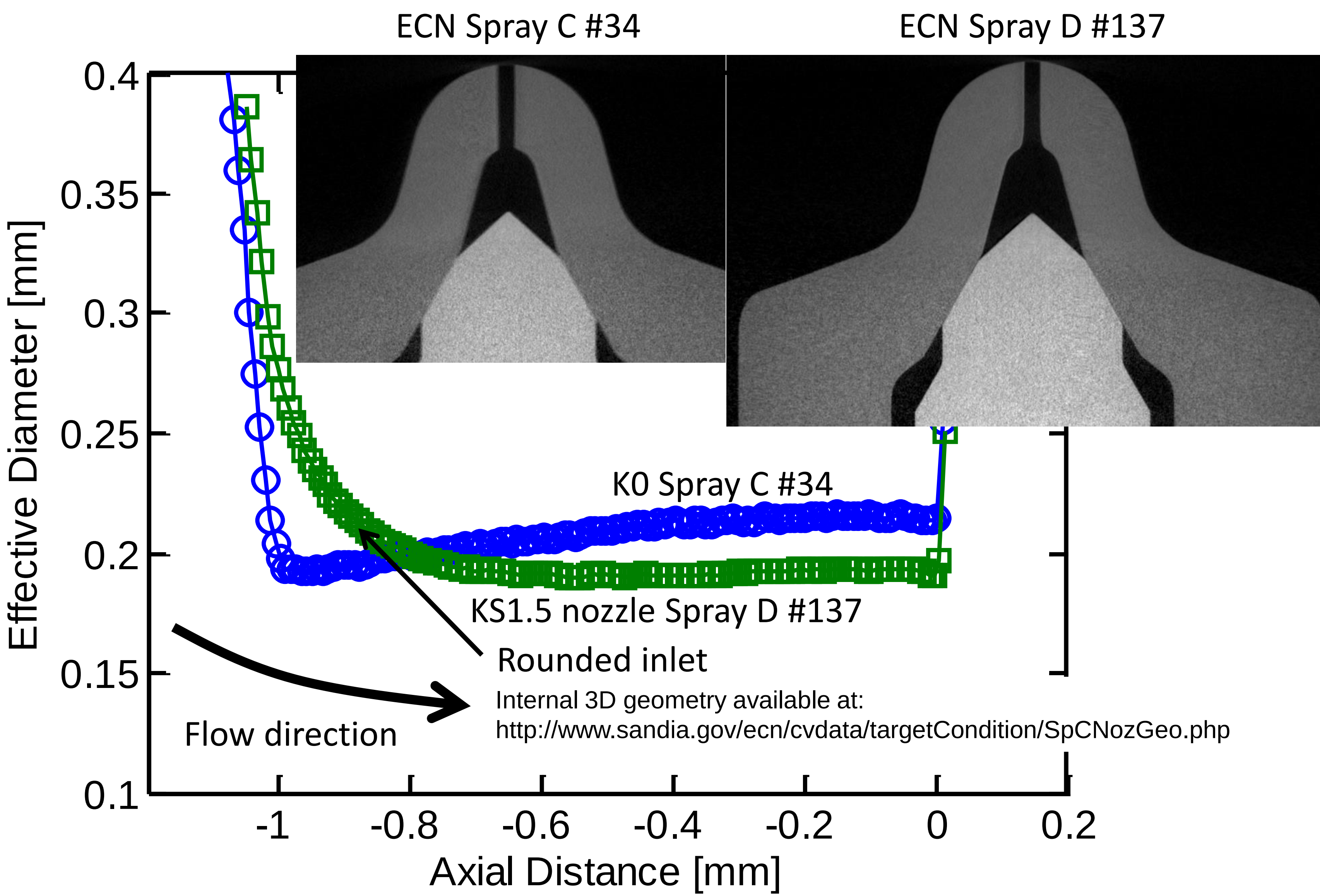


Ambient Gas
900 K
60 bar
0% O_2

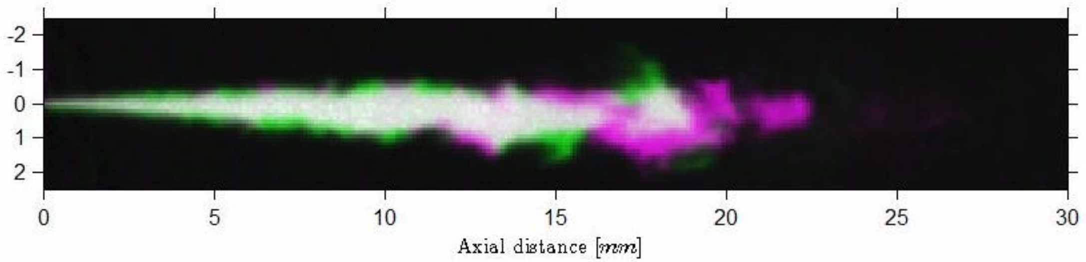
Models show variance in near-nozzle region, self-similarity downstream of liquid length



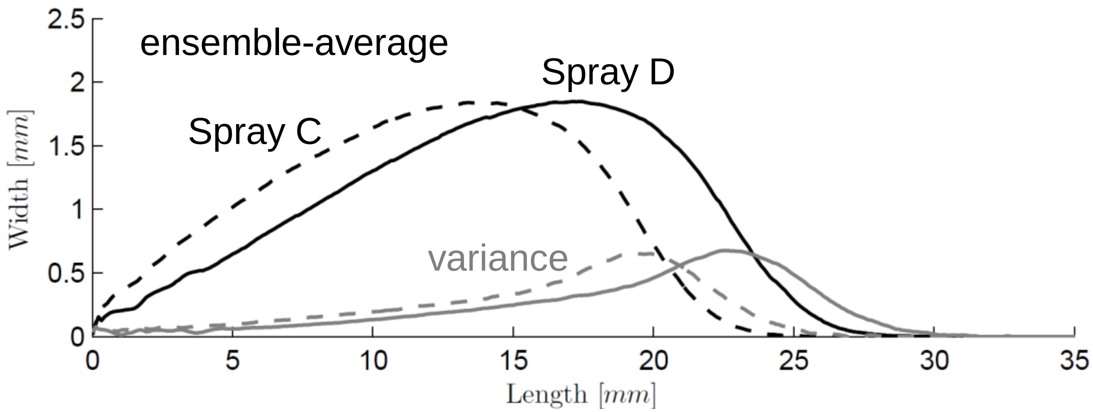
Characterizing spray combustion with nozzles of different shape



Comparison of liquid penetration and evaporation



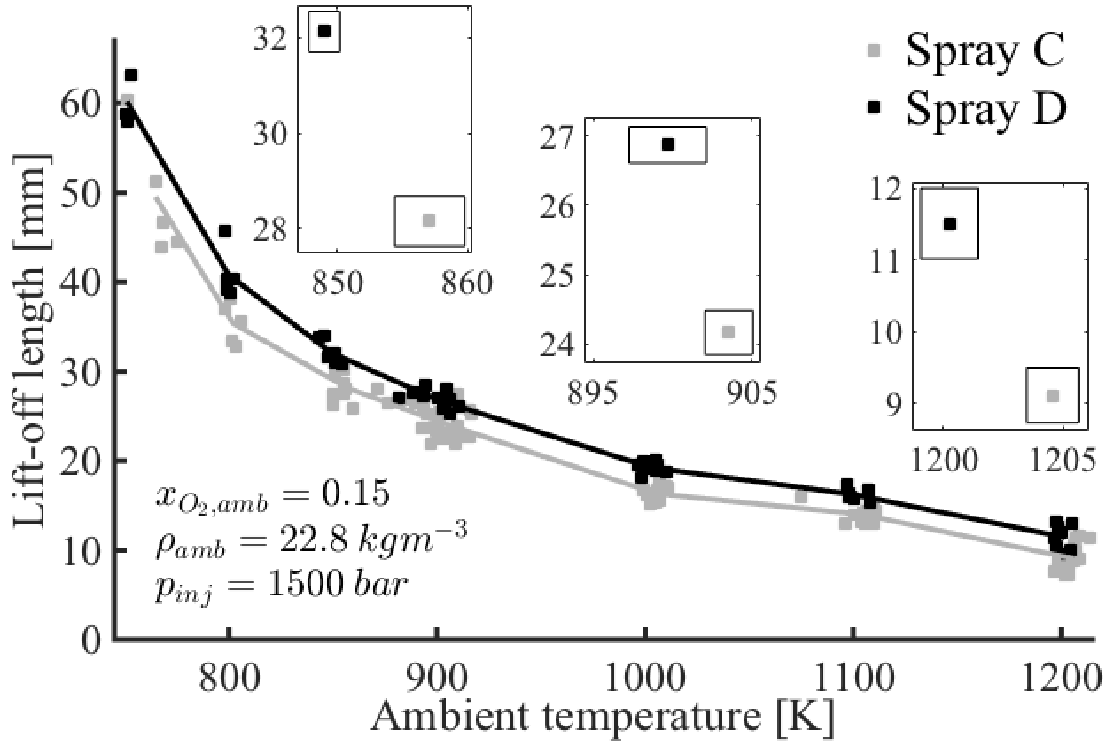
Spray C - green
Spray D - magenta

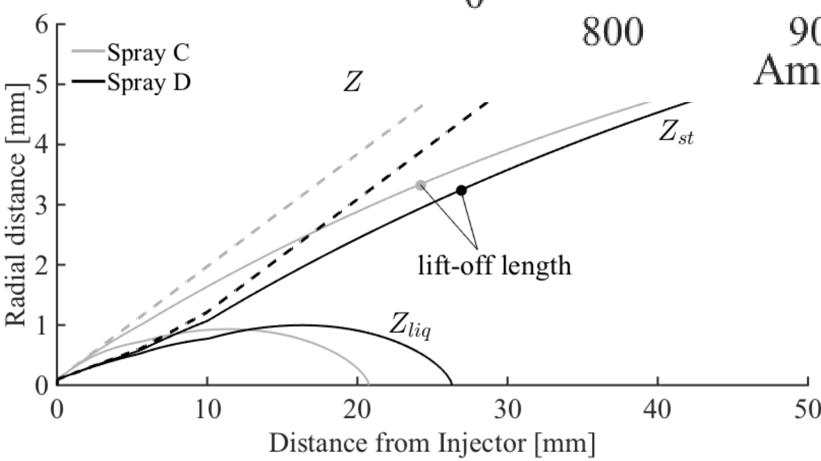


Ambient Gas	Fuel
900 K	363 K
60 bar	1500 bar
15% O_2	n-dodecane

- Liquid/vapor boundary is wider and more deformed closer to the nozzle for Spray C
- Width of spray correlates with magnitude of variance at the boundary

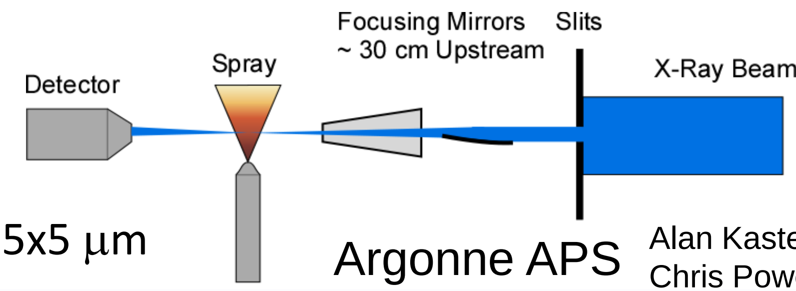
While ignition delay is essentially equal, there is an offset in lift-off length that persists over a wide parameter space





- Wider near-field spray ultimately produces shorter lift-off length
- Substantial difference!

ECN study of near-field of Spray A using optical microscopy (Sandia) and radiography (Argonne)

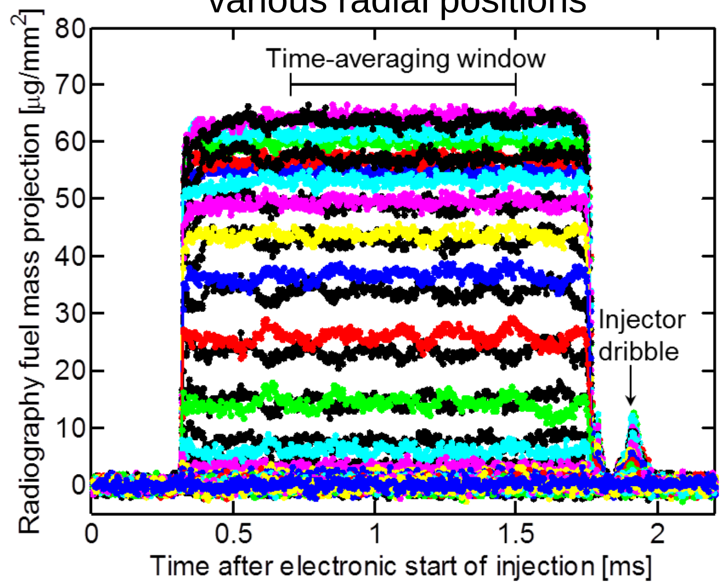


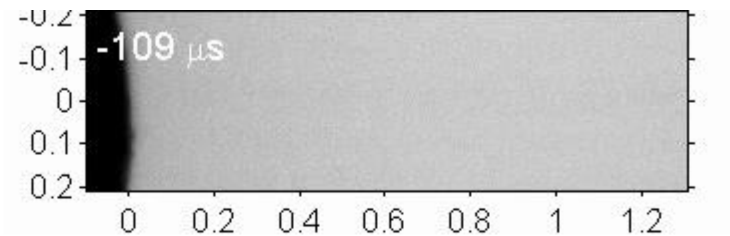
5x5 μm

Argonne APS

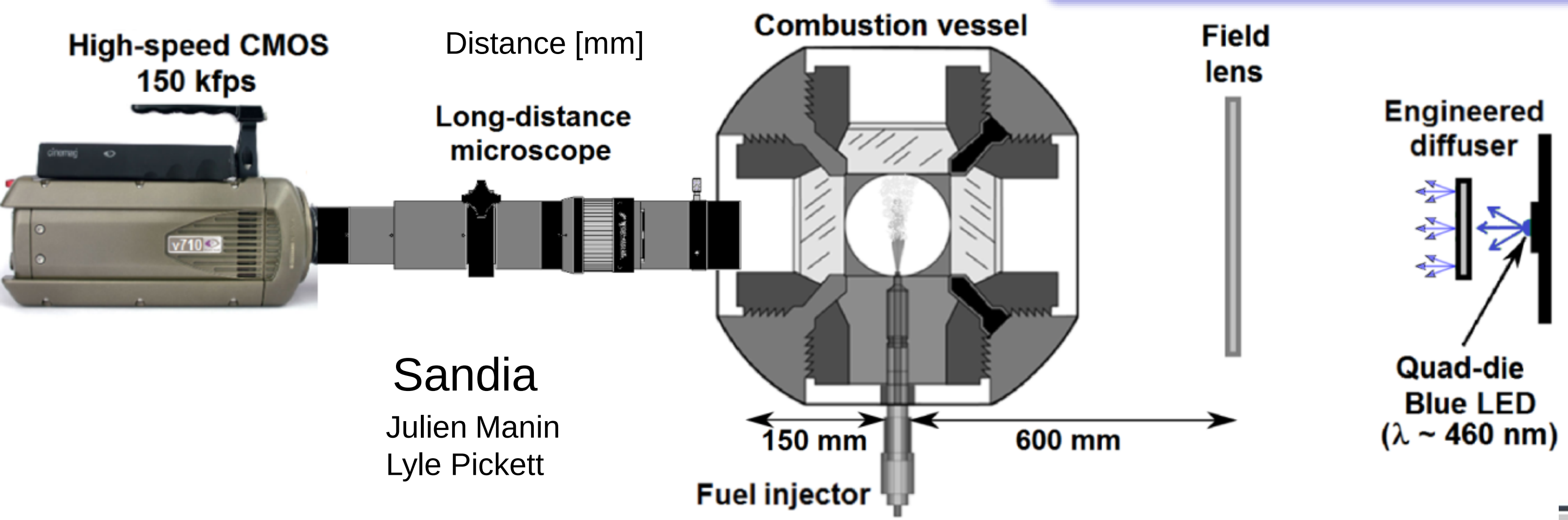
Alan Kastengren
Chris Powell

various radial positions





Distance [mm]



<50 ns pulse

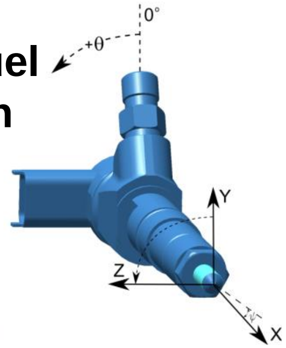
Sandia

Julien Manin
Lyle Pickett

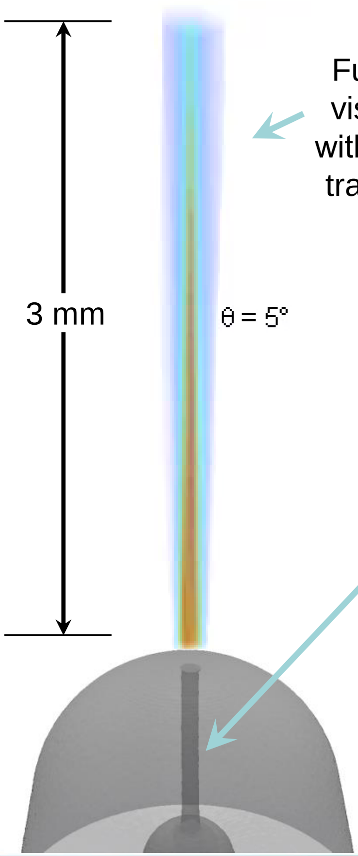
x-ray radiography mixing measurements performed in dense region of the spray (and further downstream)

<u>Measured</u> fuel distribution

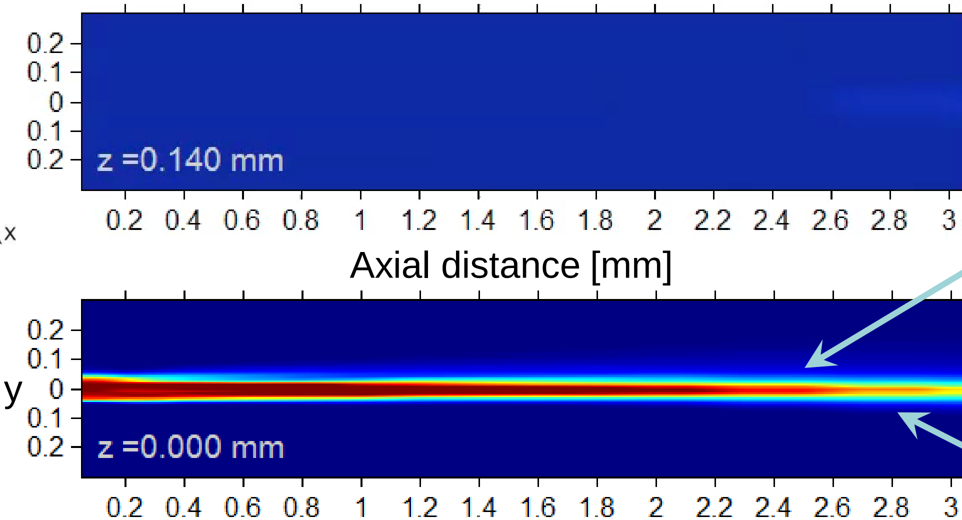
Azimuthal perspective variation



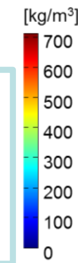
Fuel density visualization with “ramp-up” transparency



“Fly through” of slices in z direction



Mean of the steady-state period of injection



Layer growth stronger on top of spray (linked to hole geometry)

Intact liquid core broken up by 3 mm (ensemble- average)

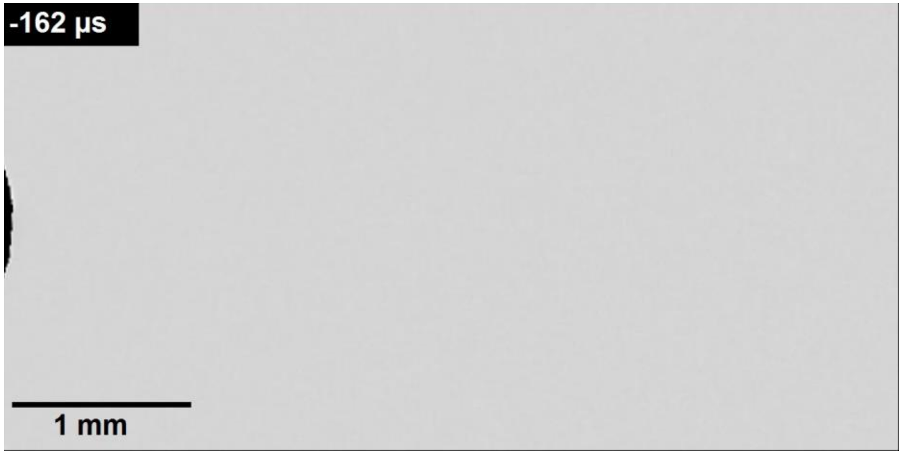
Experiment by Chris Powell & Alan Kastengren, Argonne Nat. Lab

- 3D fuel distribution extracted from tomographic reconstruction of line-of-sight radiography at 4 different angles
- External-nozzle radiography applied at many axial distances (>10 mm):
  - High liquid density “hot spots” identified with consistency along axis.
  - Elliptical spray shape originating from nozzle geometry persists downstream.

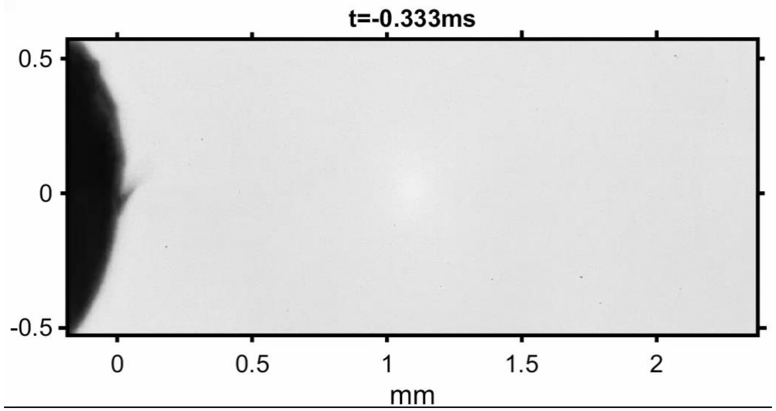
Example of spray modeling need

- Supercritical mixing processes
  - For C16: the same spray shows liquid structures that do or do not exhibit surface tension
  - For C7: No surface tension. Fluid blobs stretch, but no elastic behavior is observed

105 bar, **1200 K**, 90% N_2, 6% CO_2, 4% H_2O, 0% O_2



n-hexadecane 363 K fuel spray



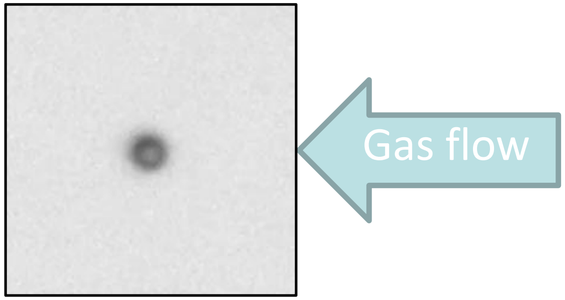
n-heptane 363 K fuel spray

Microscopy in Sandia high-T, high-P chamber: Julien Manin, Lyle M. Pickett, *Sandia*; Cyril Crua, *Brighton*

Atomization and miscible mixing

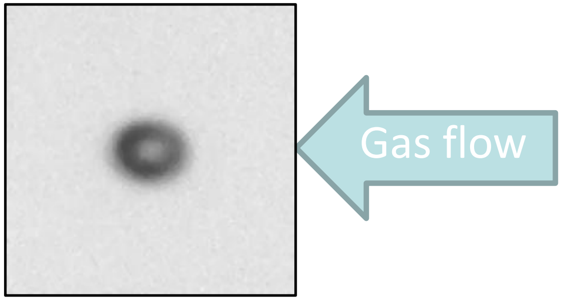
- Classical evaporation:
  - Vaporization happens on the surrounding of the droplet
  - Progressive mass transfer from liquid to gas
- Evaporation and miscible mixing
  - Rapid transition from spherical fluid spheroid into stretched fluid
  - Deforms easily and quickly disappears
- Miscible mixing
  - Fluid stretches without a clear elastic behavior (lacks surface tension)
  - Fluids with different densities mix together
  - Mixing happens quickly

n-dodecane 62 bar, 707 K (30.4 kg/m^3)



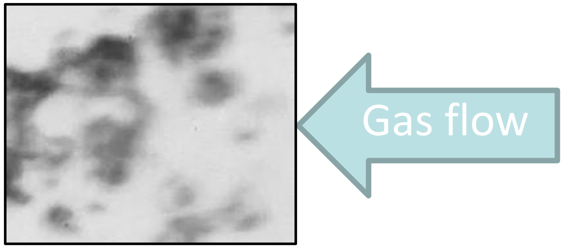
35 µm droplet

n-dodecane 88 bar, 1000 K (30.4 kg/m^3)



50 µm droplet

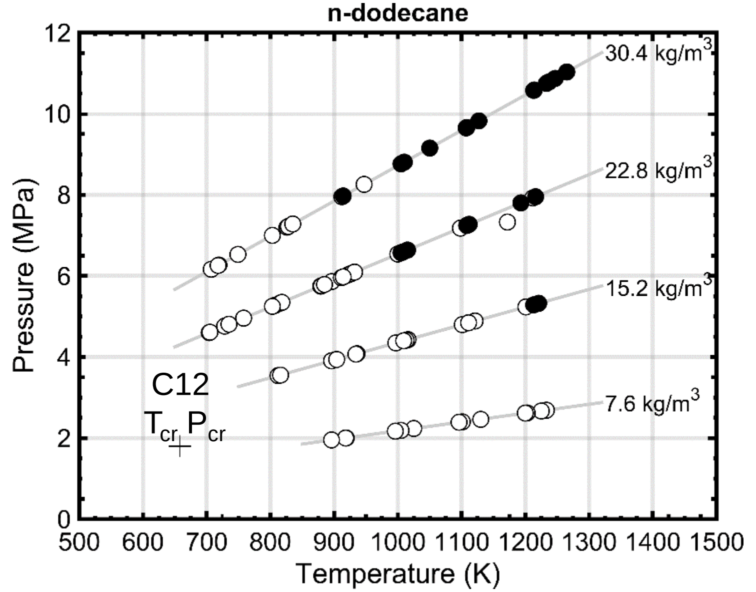
n-heptane 104 bar, 1200 K (30.4 kg/m^3)

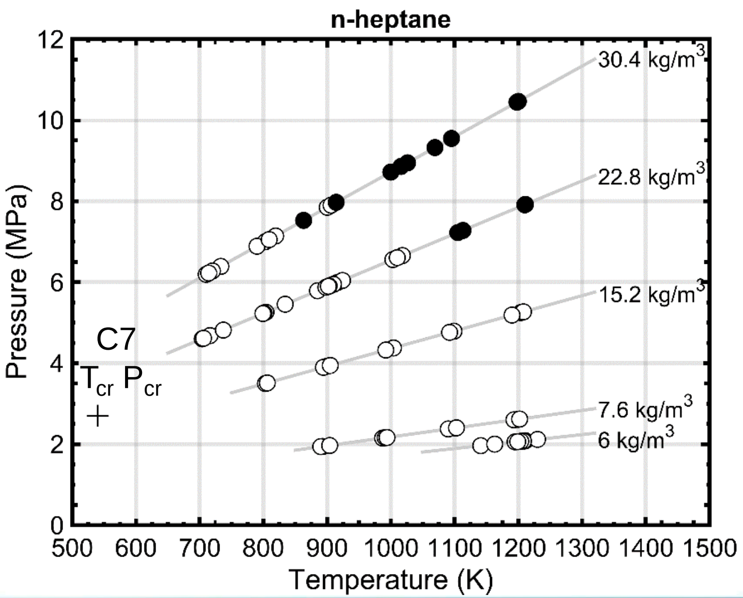


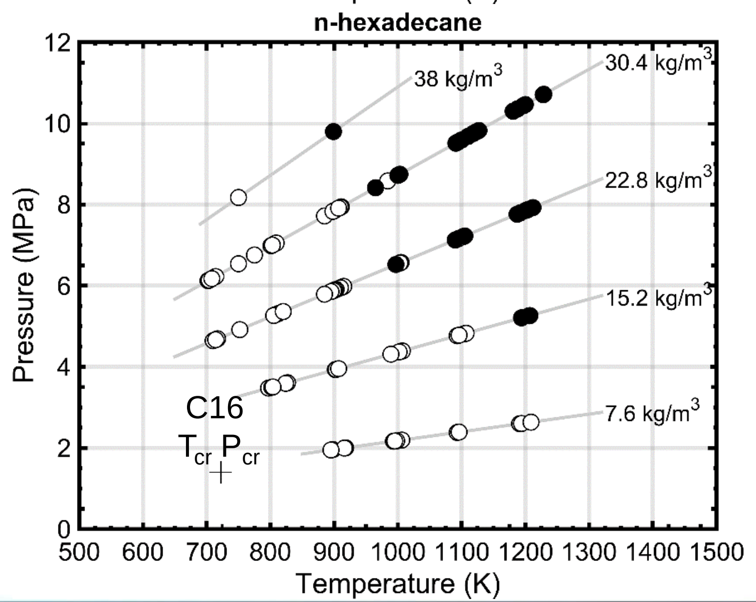
No droplet(s)

Conditions where a transition to miscible mixing is evident are well above the critical P and T

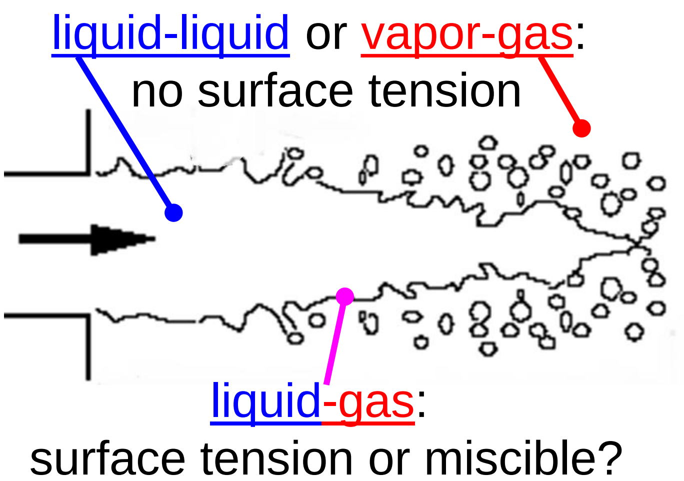
- Dark symbols are when miscible mixing behaviour was observed, but droplets and surface tension may also be present for a limited time
- Difficult to classify dense region of spray during fast periods of injection
  - Must track structure evolution (using high-speed imaging) to make classification







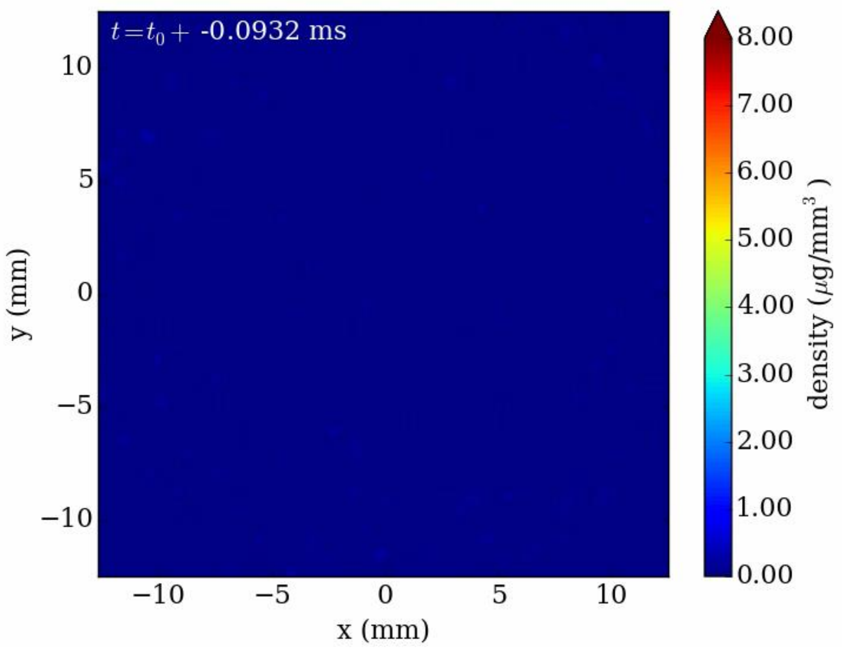
How this discovery could affect engine spray modeling:

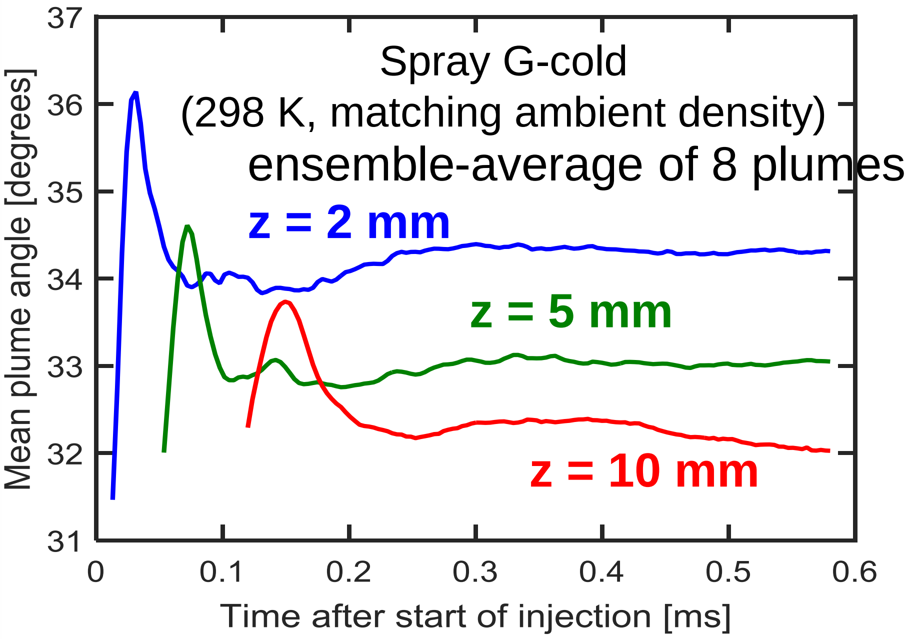


- Classic spray modeling assumes liquid breakup with surface tension forces and vaporization rates based on droplet-gas dynamics
- Dense fluid modeling assumes no effects of surface tension—Navier/Stokes equations apply throughout
- Our results show that a transition to miscible mixing is not sudden
  - Surface tension effects and "miscible mixing" zones exist *in the same spray* at a given ambient gas pressure and temperature
    - Fluid near the nozzle exhibits surface tension while downstream liquid does not
    - Suggests a finite timescale for transition
  - Transition with increasing P and T is also not immediate
    - Solely miscible-mixing occurs only at highest P and T (with n-heptane)
  - A "continuum" towards miscible mixing suggests that even droplet-dominant regimes may experience effects (faster evaporation) that depart from classic low-P theories
- Are there unexplained benefits of high-pressure engine combustion that can be linked to miscible mixing?
  - better mixing, less isolated droplet combustion, more complete combustion

Spray G fuel concentration via radiography (Argonne)

- Argonne non-vaporizing mixing measurements in the near-field using x-ray radiography and tomographic reconstruction



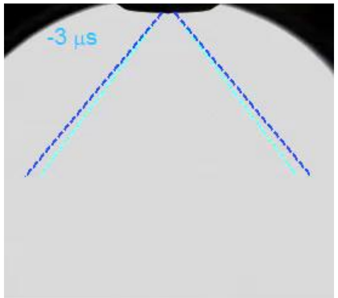


- Gradual shift of plume direction to injector axis while moving downstream
- Marked transient period at higher angle

Observations of Spray G using planar imaging

side-view liquid extinction imaging

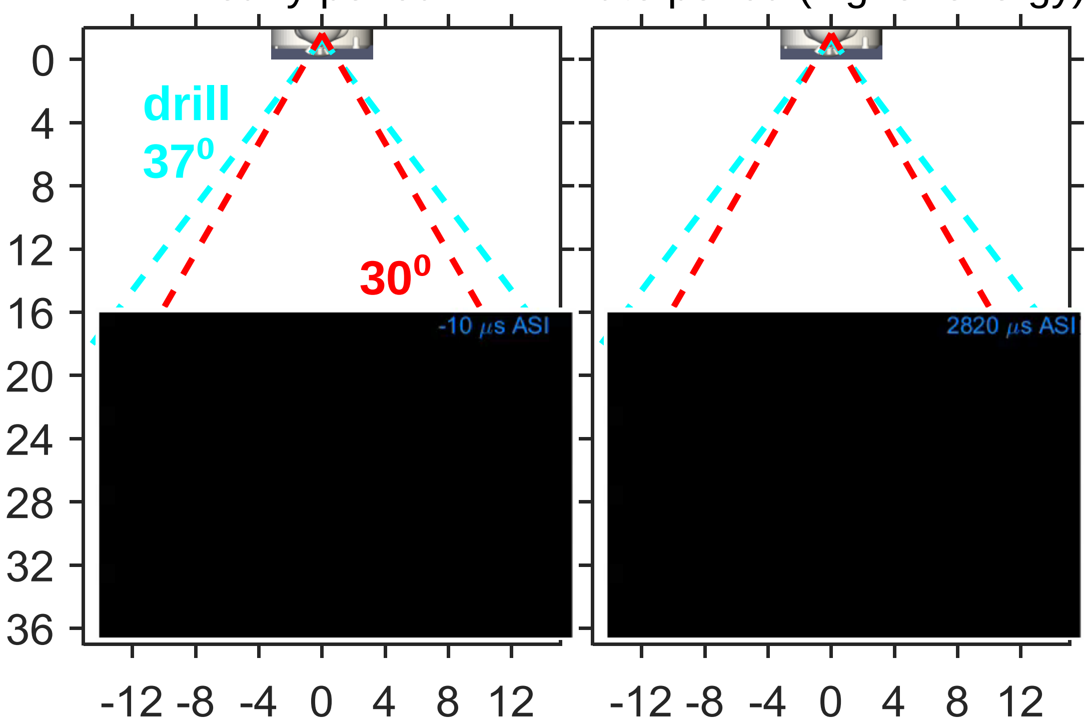
Injector #28



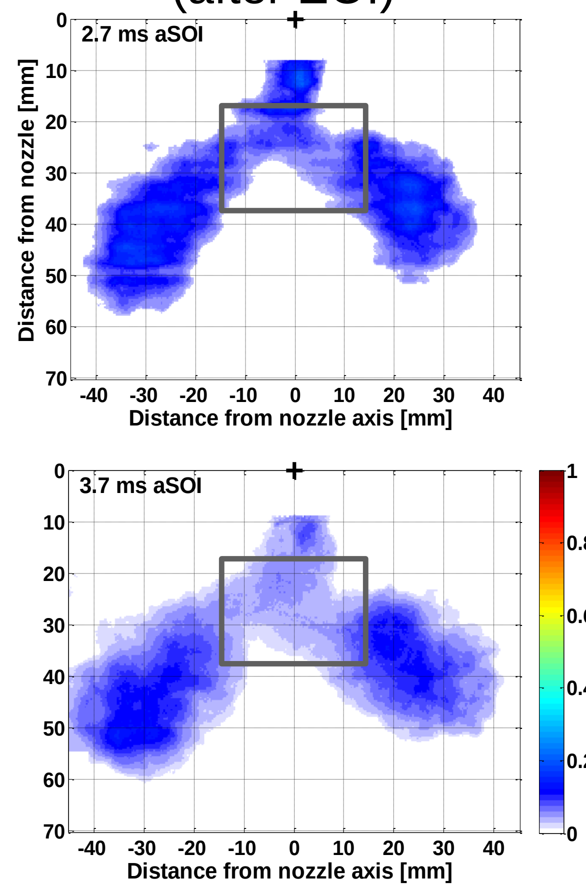
Ambient Gas	Fuel
573 K	363 K
6 bar	200 bar
0% O_2	iso-octane
	170 µm nozzle
	0.8 ms injection

100 kHz Planar Imaging

early period | late period (higher energy)

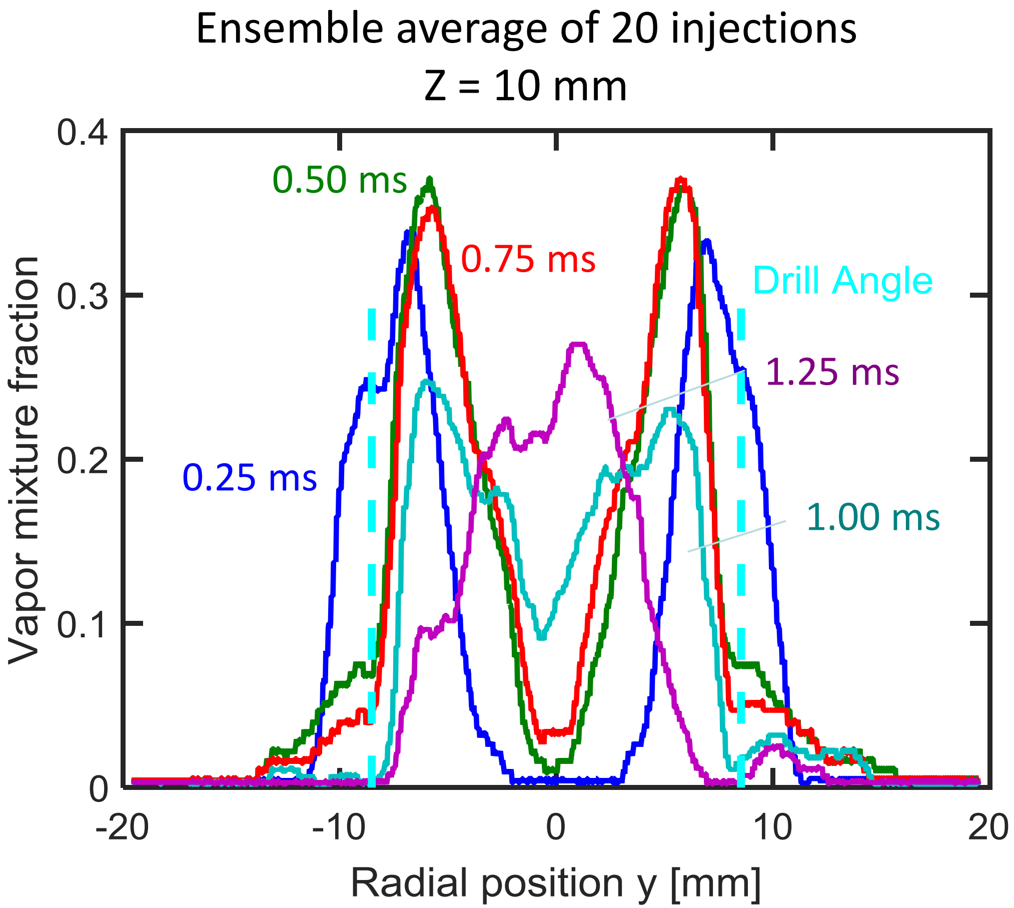


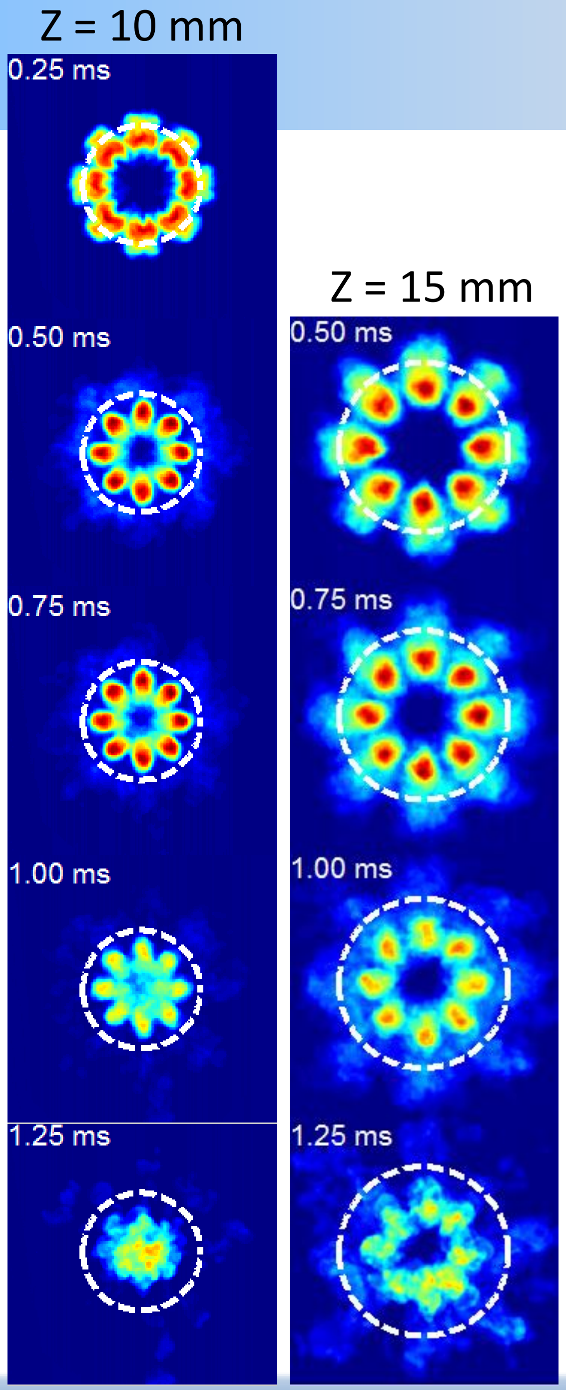
Planar LIF, IFPEN (after EOI)



SAE 2015-01-1902

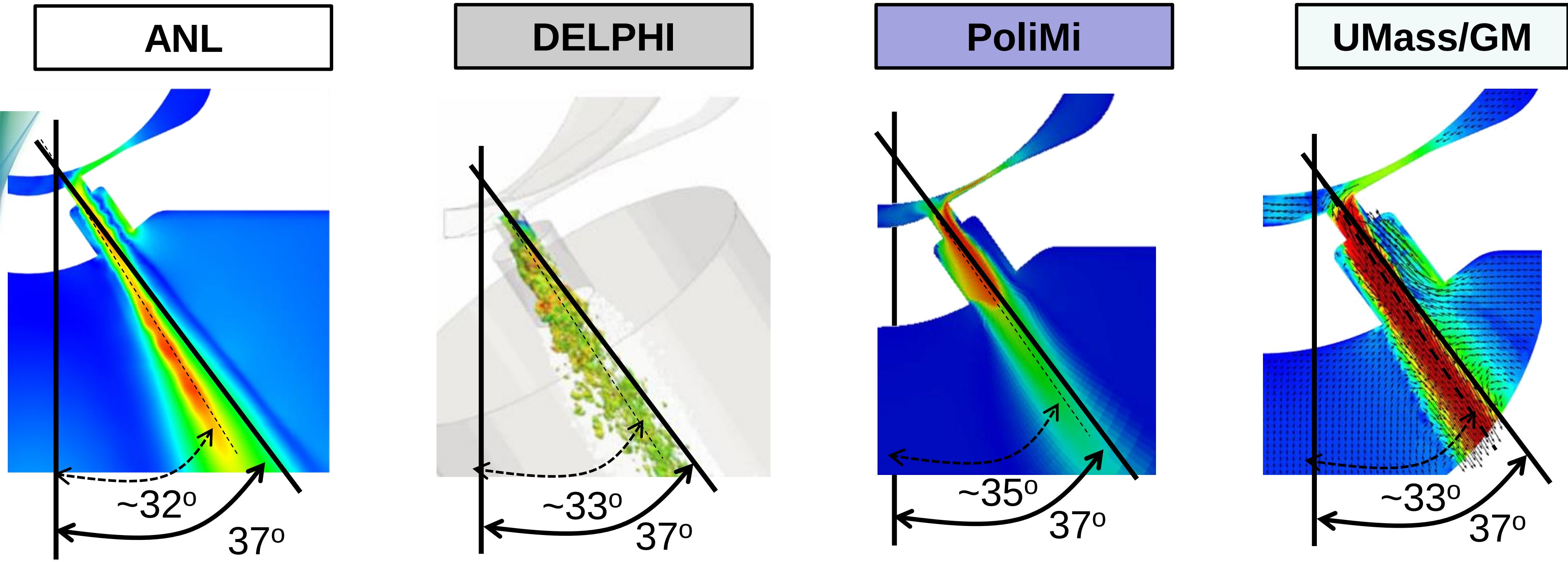
LES simulations show plume interaction





Argonne National Lab
Sibendu Som

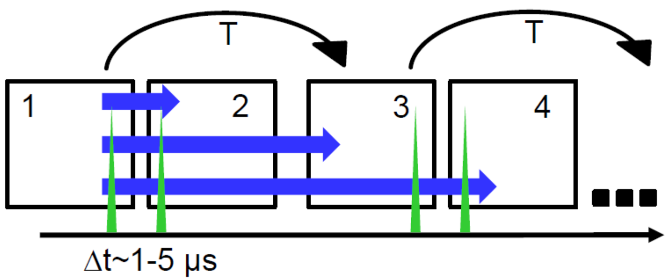
Does plume direction change because of internal flow effects?



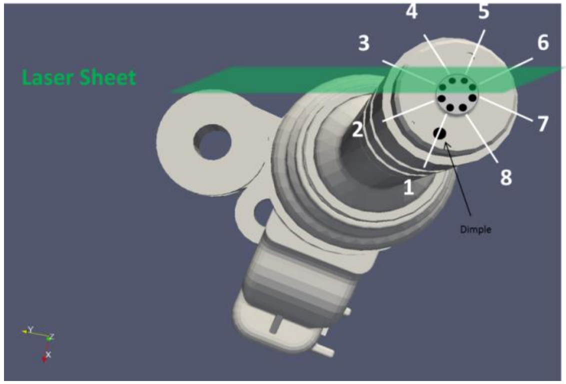
- Flow in the nozzle causes plume to diverge from drill angle, towards the injector axis and neighboring plumes
- Should not use drill angle for Lagrangian spray models

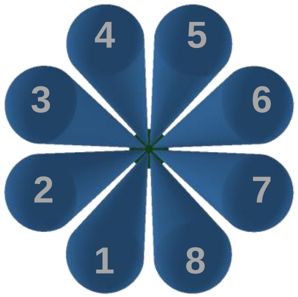
High-speed velocity diagnostic applied

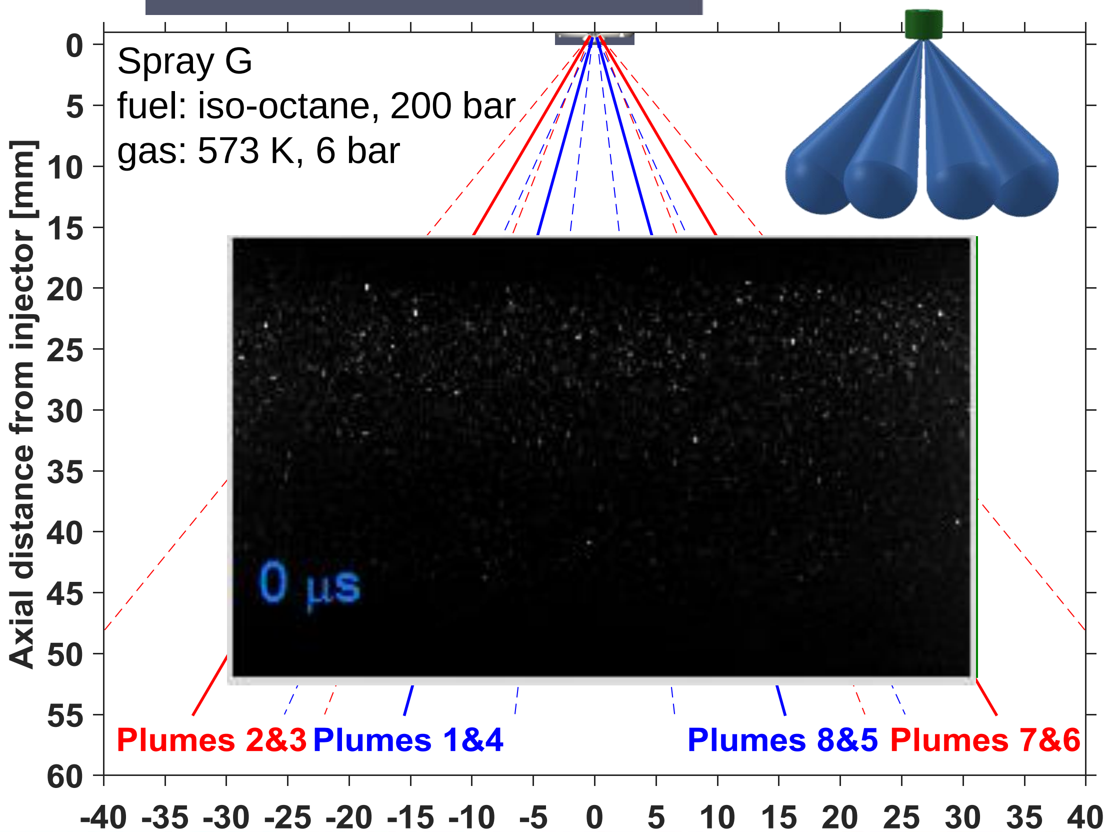
- Custom pulse-burst laser system developed
  - 100 kHz pulse pairs
  - 500 pulse pairs (5 ms burst)
  - 15 mJ/pulse at 532 nm
  - Funded by internal Sandia project (PI J. Frank)



- Applied PIV (Panos Sphicas, Imperial College)
  - 1 μm zirconia seed in gas phase
  - 200 kHz imaging
  - Liquid-phase avoided by probing between plumes and moving downstream

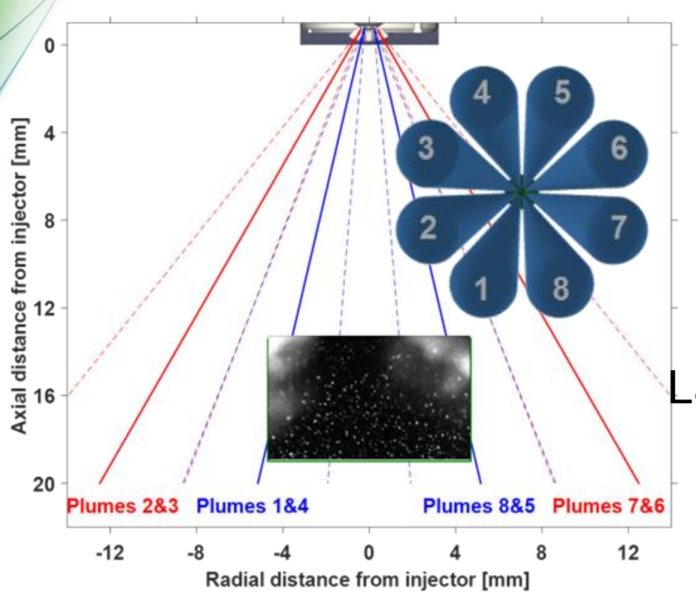




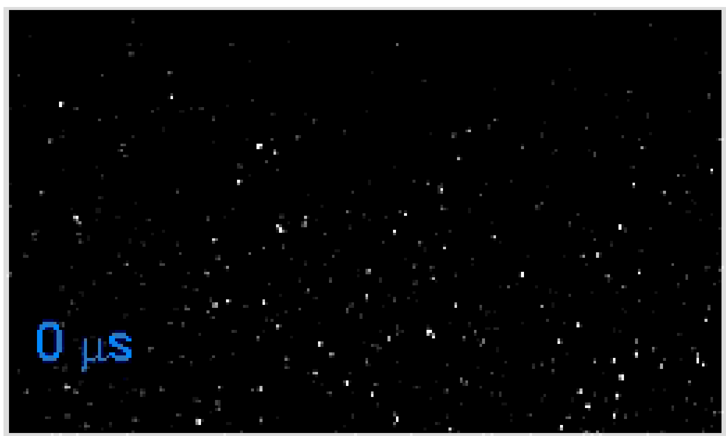


Move closer to injector tip to probe flow between plumes

PIV setup



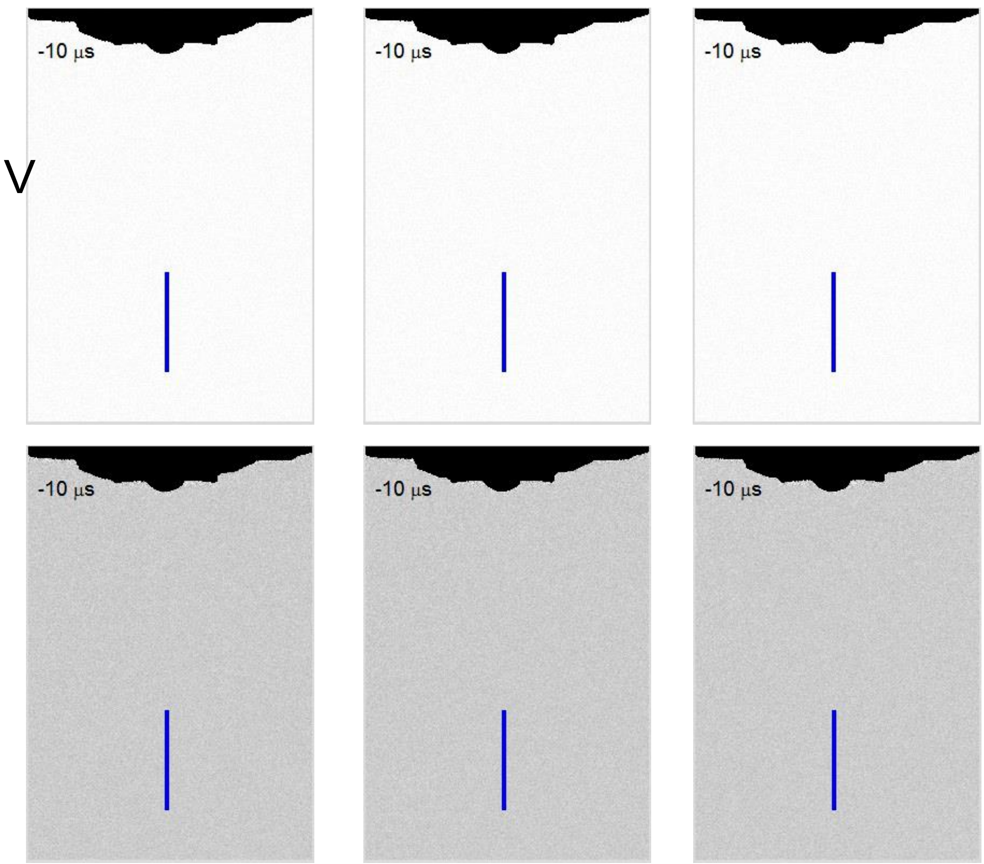
573 K



Liquid extinction imaging. Ambient density: 3.5 kg/m^3

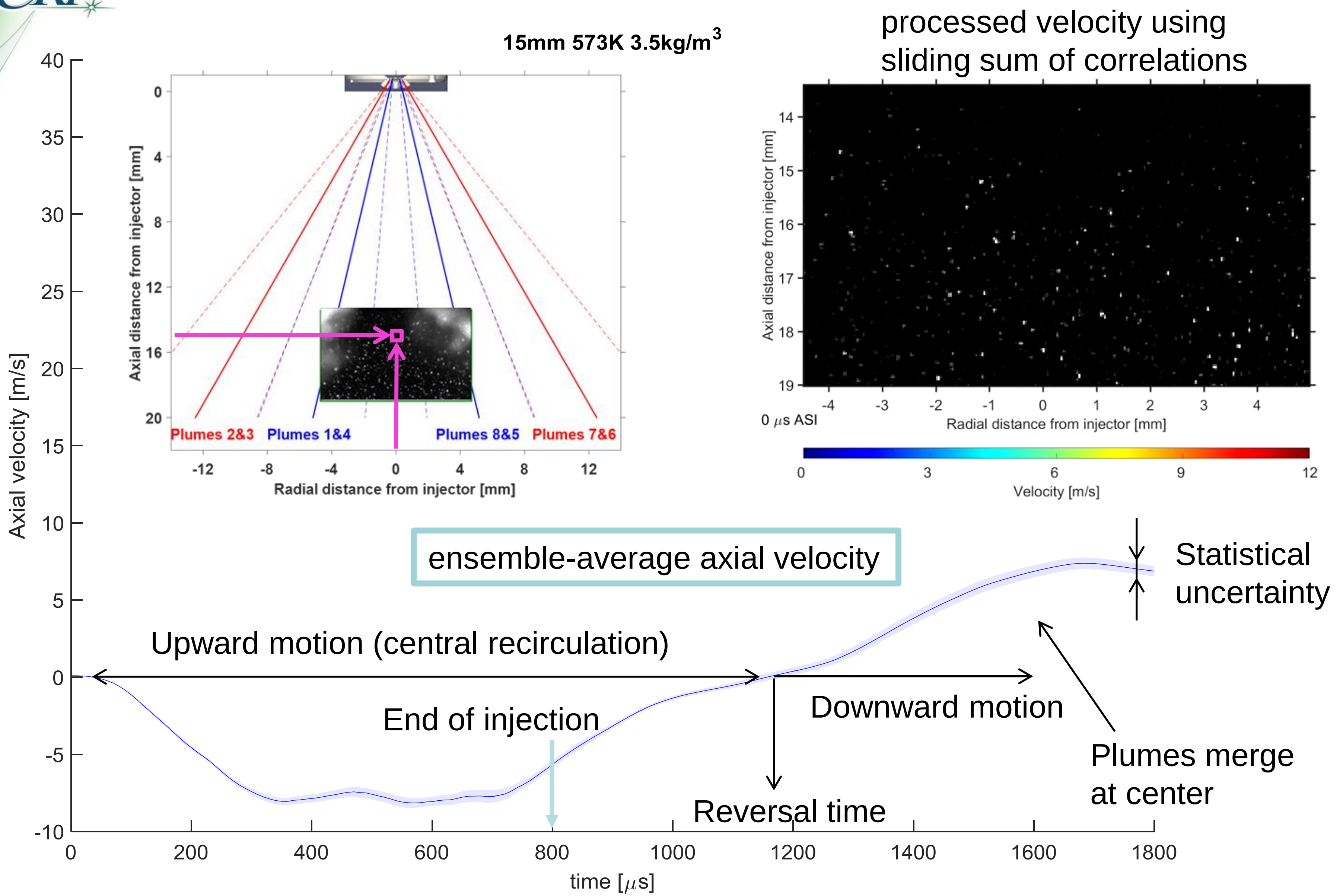
450 K　　573 K　　1000 K

Laser/PIV ROI

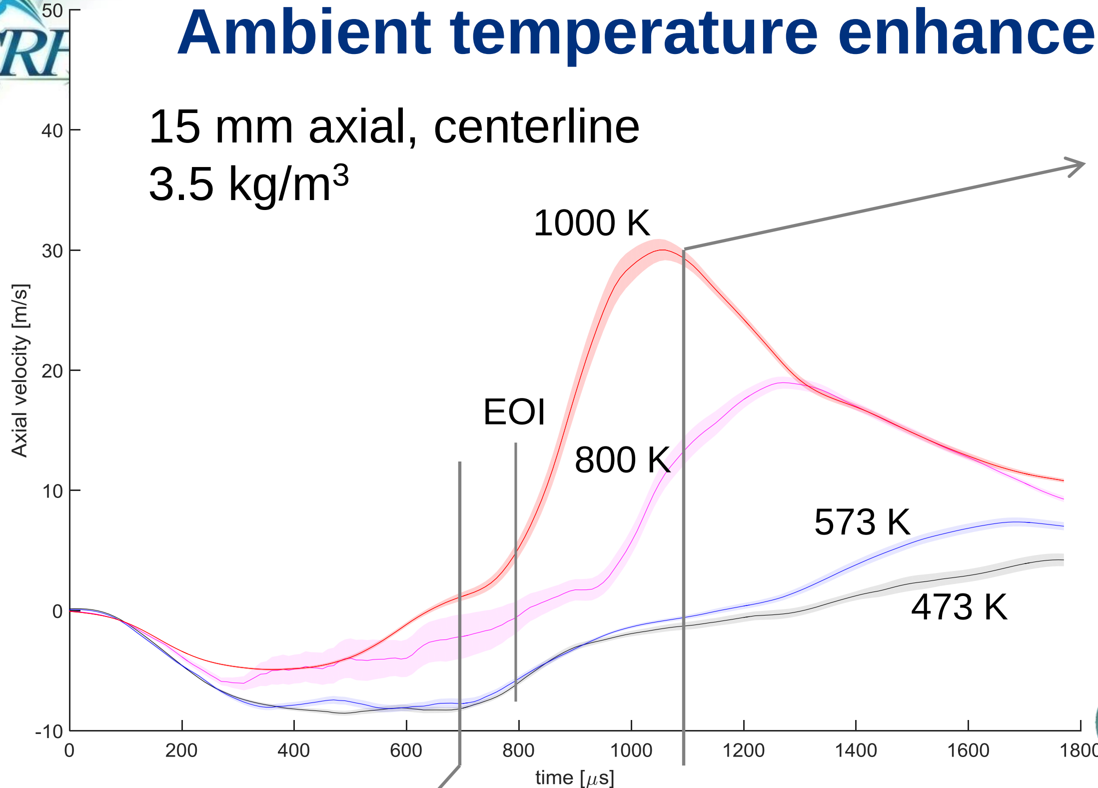


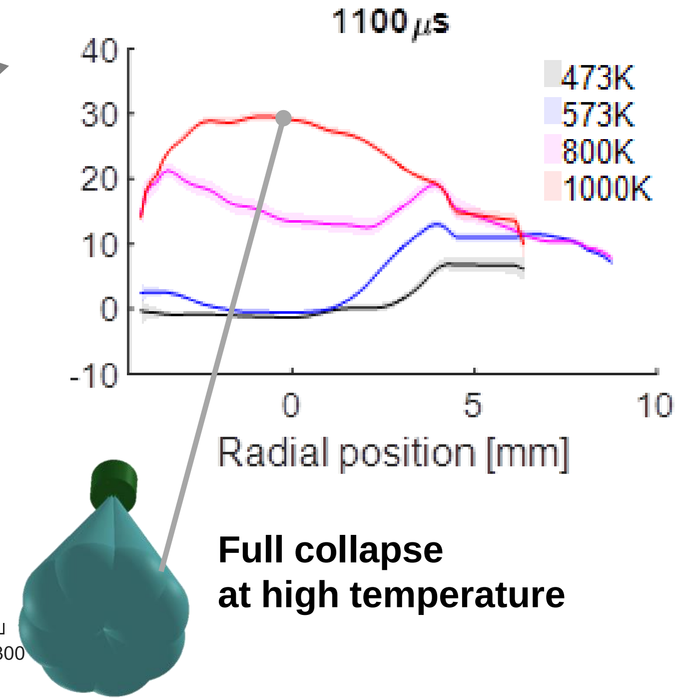
I/I_0 range: 0.7 to 1.1

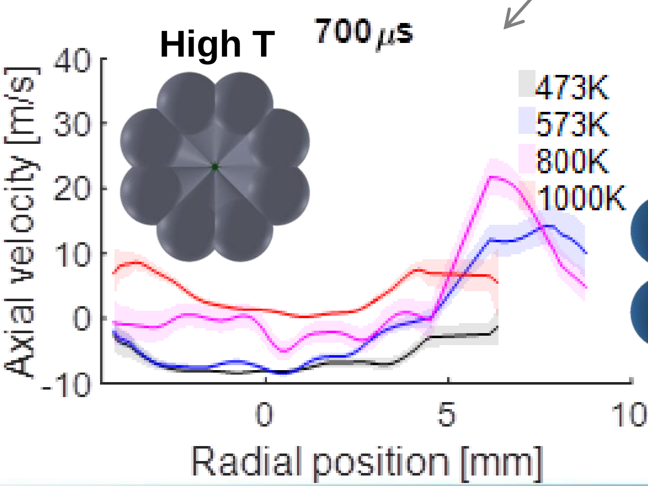
Time evolution of velocity between plumes

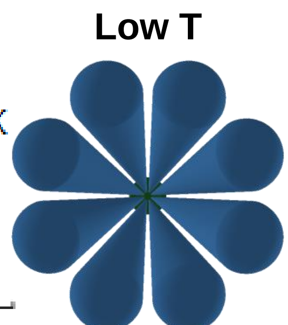


Ambient temperature enhances plume interaction







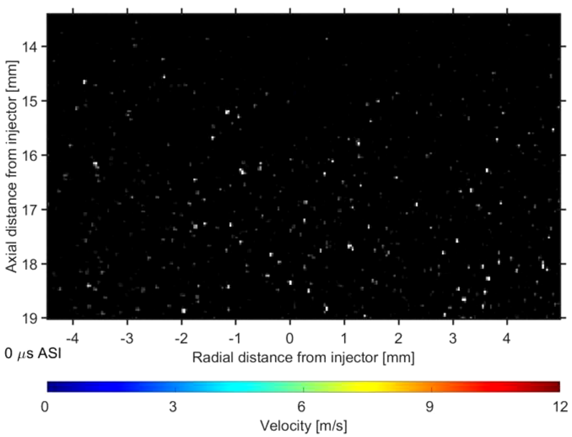


- Plume interaction modified by increasing ambient temperature
  - lower central recirculation velocities
  - faster merging of plumes
  - plume direction towards centerline
- Late-stage fuel delivery is entirely different
  - Fast-moving central plume at higher temperatures

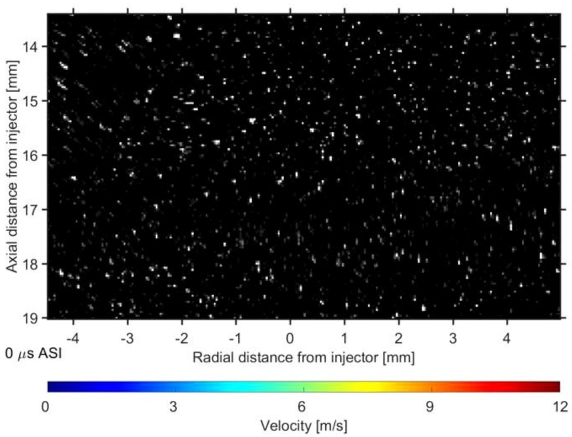
Effect of ambient temperature on plume collapse

Ambient density: 3.5 kg/m^3

573 K



1000 K

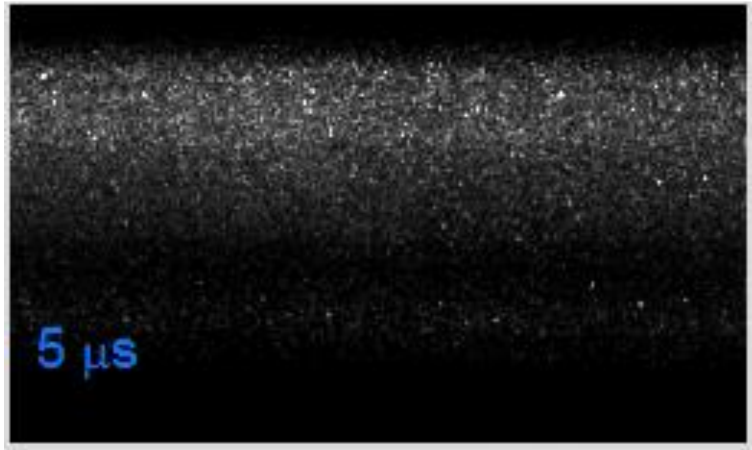


Downstream region reflects fate of upstream activity

Maintains some radial dispersion

15
20
25
30
35
40
45
50

Full collapse with high axial momentum



Many technical advances are needed to improve fuel economy

- Lightweighting materials
- Hybridization/electrification
- Controls and transients
- Transmission efficiency
- Driverless automation

Summary

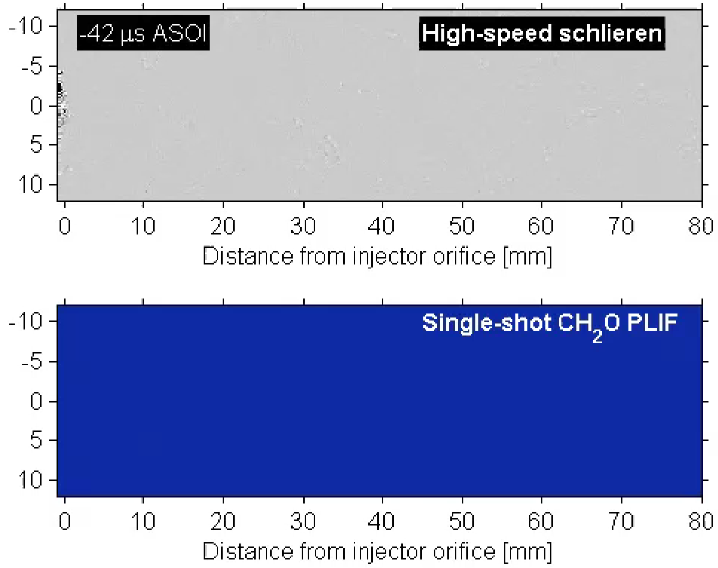
- Combustion and spray model improvements will continue to pay high dividends towards improved engines and shortened development times

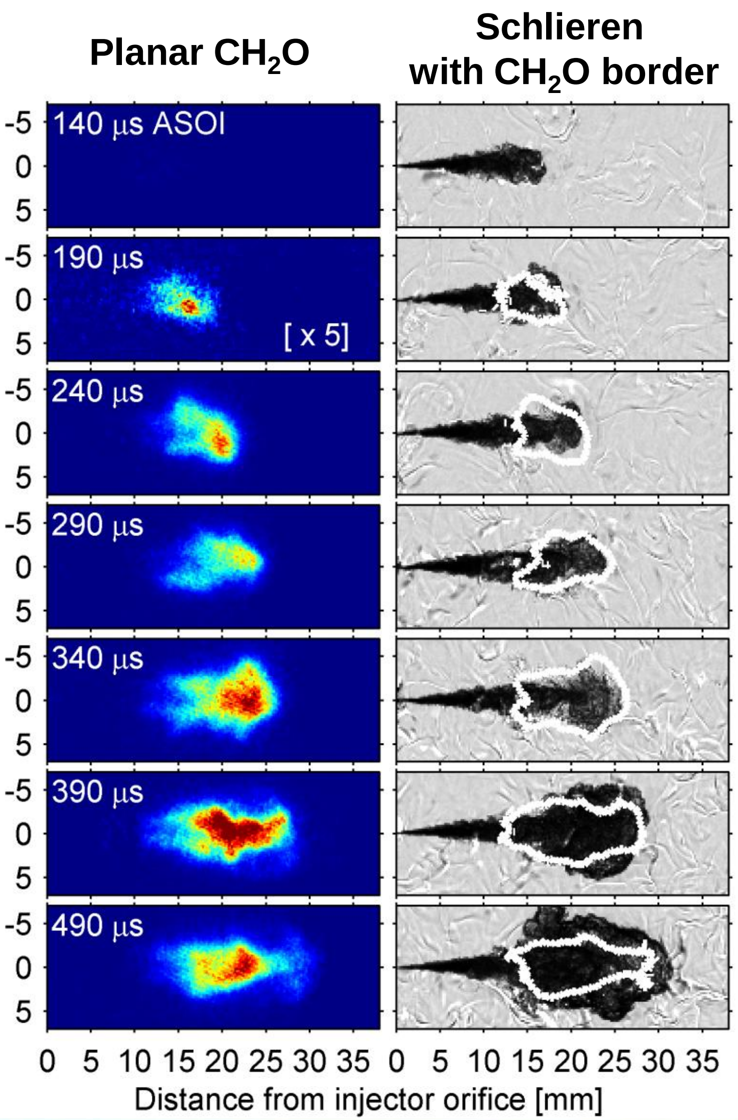
Questions

Combine high-speed schlieren with planar formaldehyde LIF to characterize diesel ignition, temporally and spatially

Schlieren (150 kHz) line-of-sight

355-nm LIF (single-shot) planar





- Refractive index gradients in schlieren soften when formaldehyde forms.
- Formaldehyde LIF occurs slightly before schlieren "softening" (expected difference between planar and line-of sight diagnostics).
- Formaldehyde disappears where high-T ignition occurs (sharp T gradient in schlieren).
- Fast (150 kHz) ign. diag. capabilities clarified.

What QUANTITATIVE data do we lack at engine (high-T, high-P) conditions?

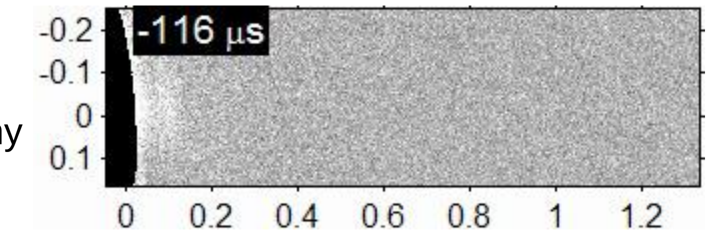
- Almost everything, at high-temperature engine conditions (>900 K).
- Liquid volume fraction and droplet size in the dense spray region and near the liquid length.
- Mixture fraction (fuel/air ratio) distribution.
- Velocity and turbulence.
- Soot volume fraction and structure distribution, particularly during transients.
- Internal injector geometry for working injectors.
- Information about internal injector cavitation and flows.
- Can we build this type of dataset?

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

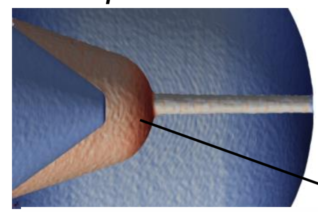
- What is the status of the sac volume at the start of injection?
  - Voids will be pressurized during compression cycle in an engine.
- Gases in the sac are pushed out by incoming liquid as the needle valve opens.
  - Vapor jet precedes liquid by approximately 10 μs.
  - Some venting/gas exchange starts 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.

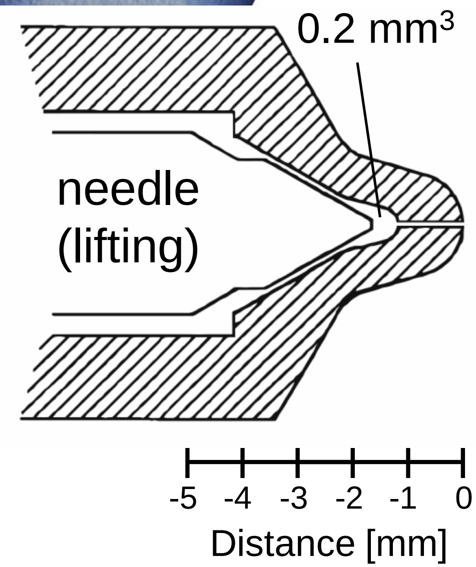
Movie adjusted for high contrast

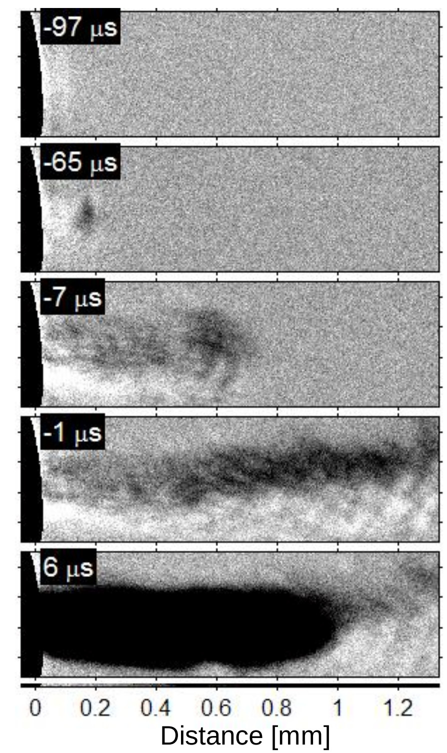
60 bar, 900 K (22.8 kg/m³)
n-dodecane, 90°C, 150 MPa



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

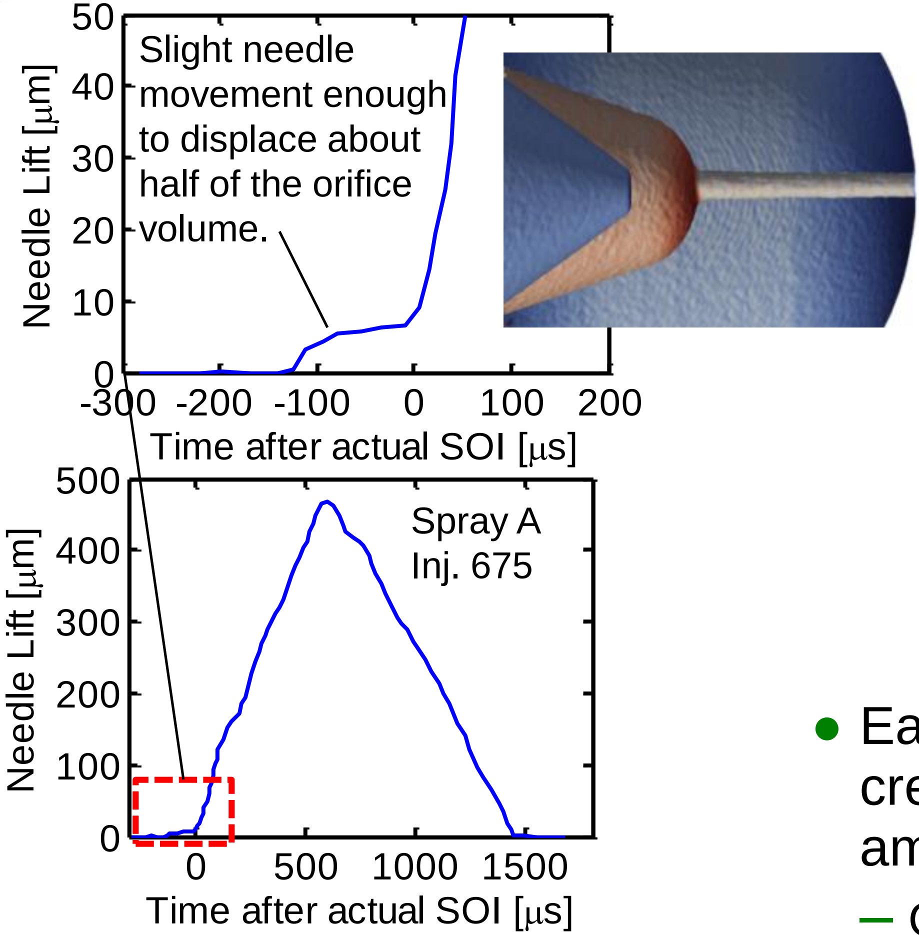






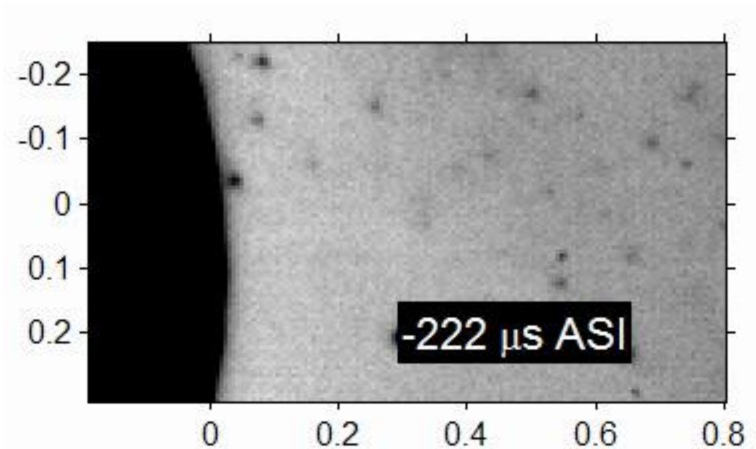
Leading vapor injection also shown recently by Crua et al. [SAE 2010-01-2247]

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



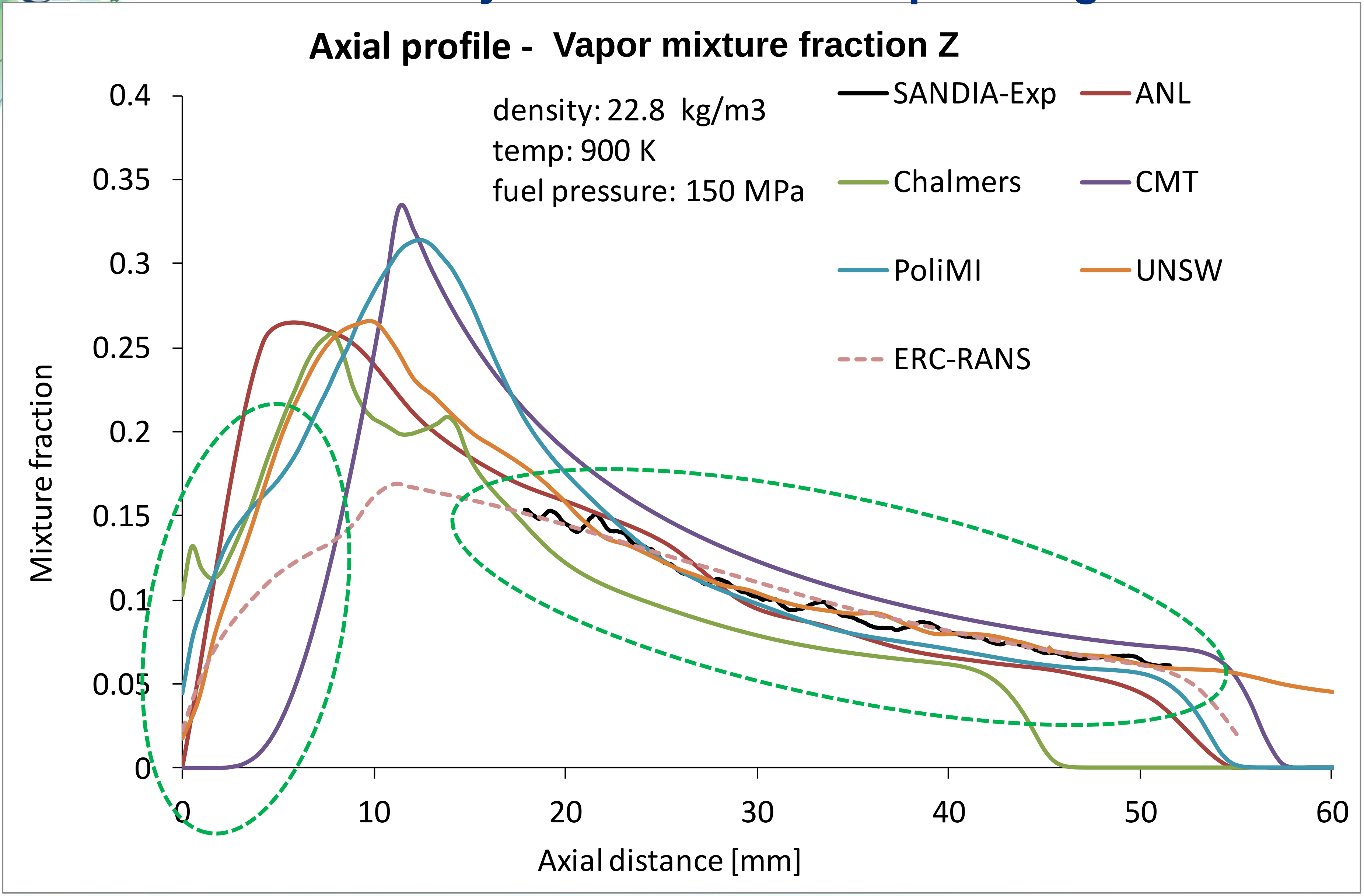
Multiple injection situation: earlier injections have left droplets inside the chamber.

440 K, 29 bar



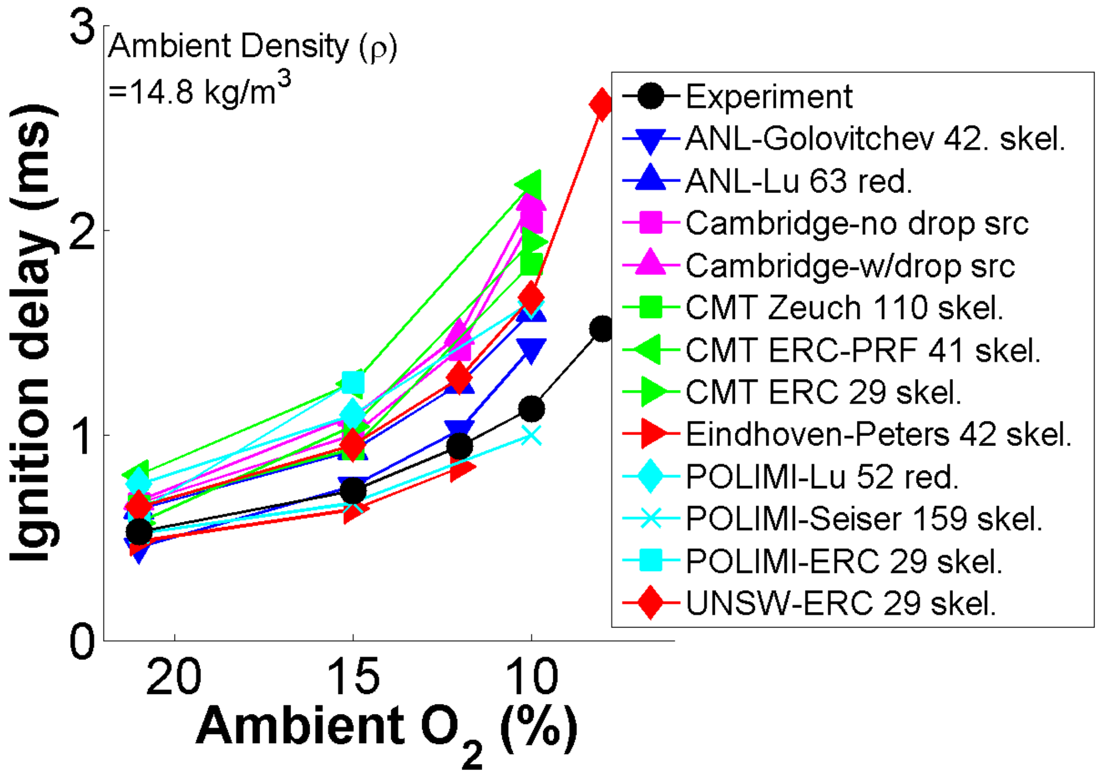
- Early needle movement momentarily creates a vacuum to pull droplet (and ambient gases) into the injector.
  - Gas transfer into the sac could draw soot particles or other debris into the sac or orifice.

Models show variance in near-nozzle region, self-similarity downstream of liquid length



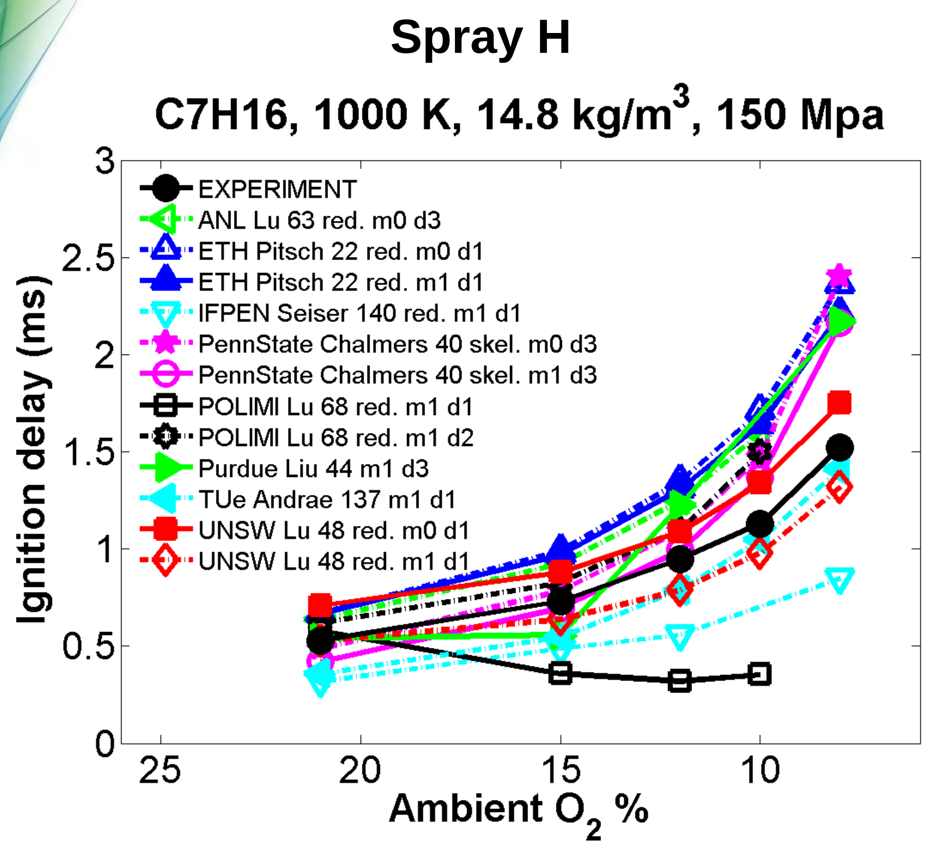
Evolution of model predictions between ECN1 and ECN2

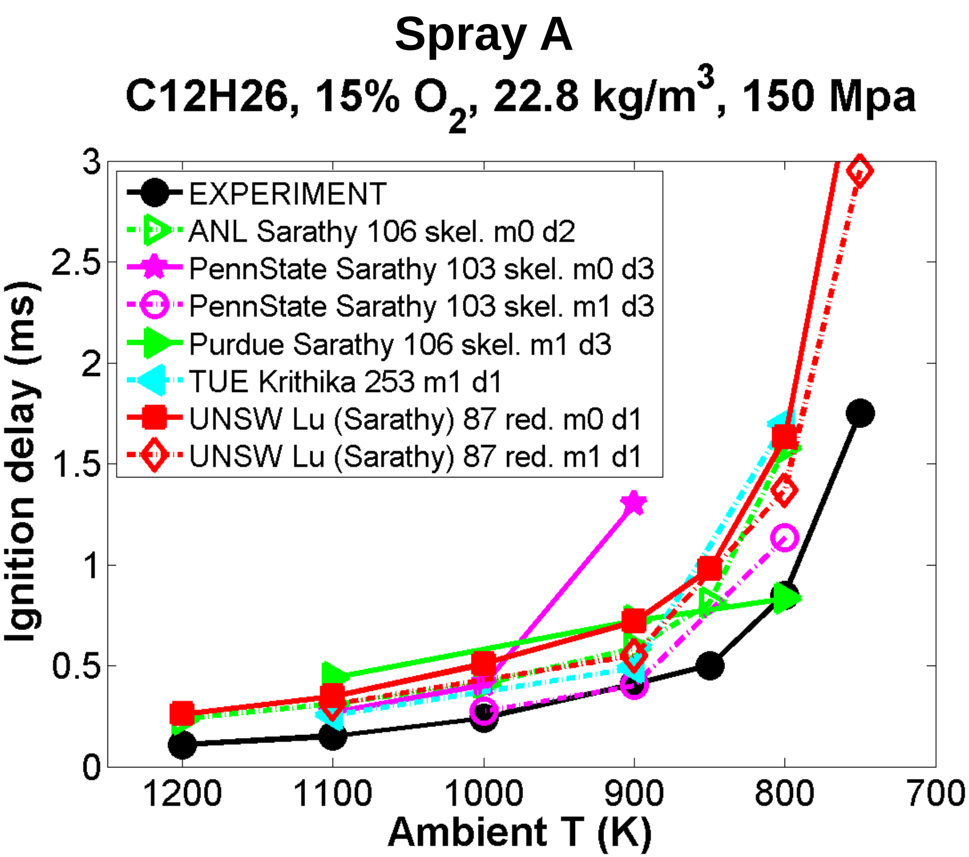
n-heptane "Spray H"



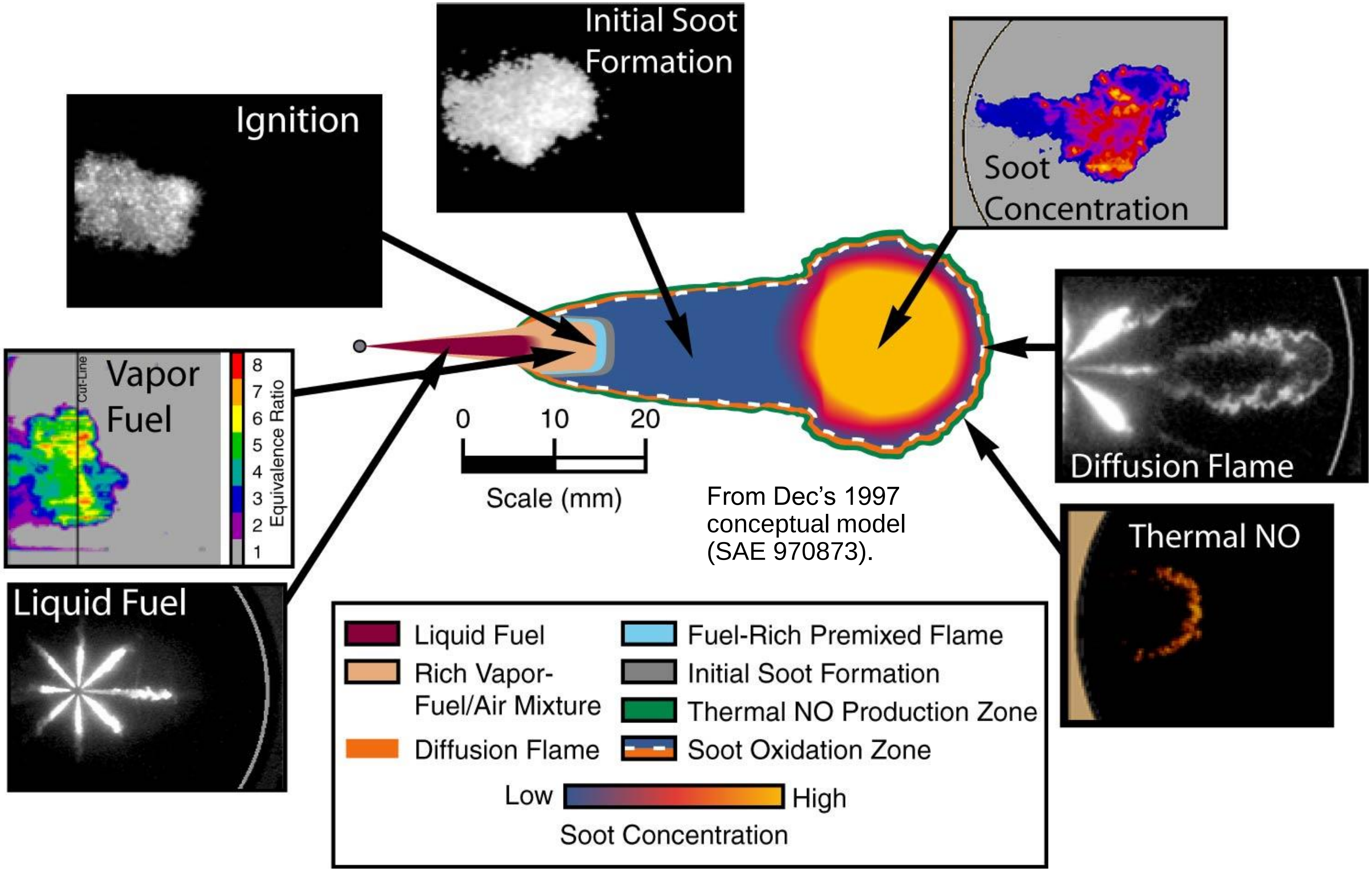
- At ECN1:
- Submissions did not necessarily have consistent definitions.
- No group successfully predicted ignition for "Spray A" using developed n-dodecane chemistry.

Ignition delay at ECN2





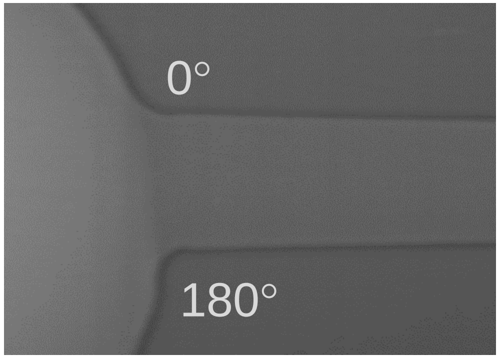
Laser diagnostics of diesel combustion (John Dec and coworkers)



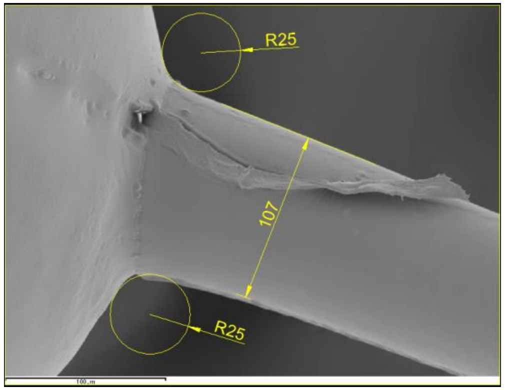
From Dec's 1997 conceptual model (SAE 970873).

Nozzle internal geometry measurements

x-ray phase-contrast (Argonne)



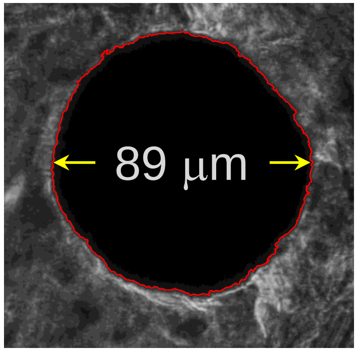
silicone molds (CMT)



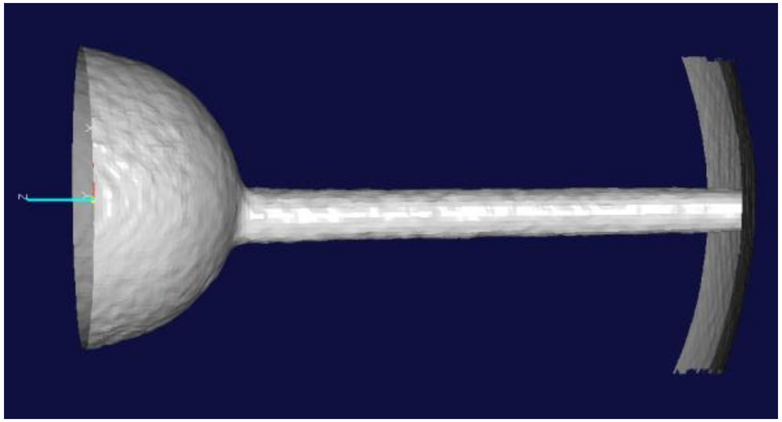
x-ray tomo. (ESRF)

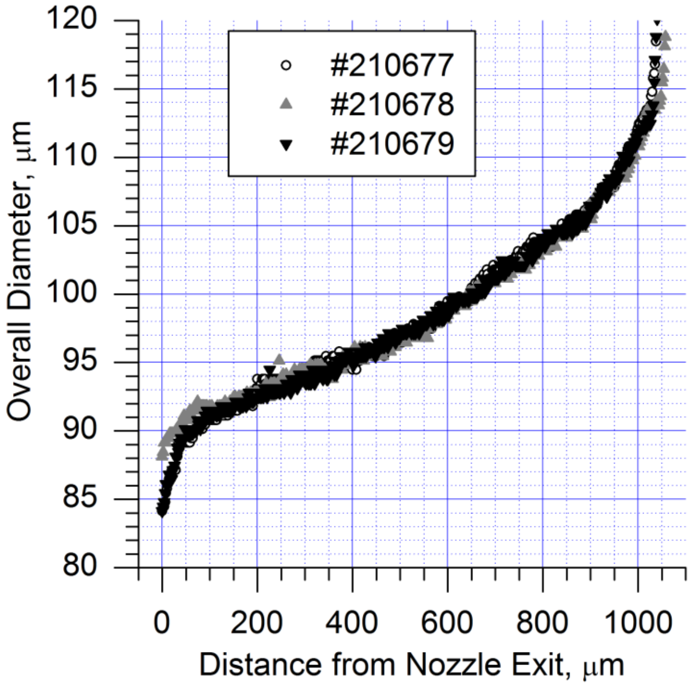
“fly-through” movie of the nozzle geometry

Optical (Sandia)

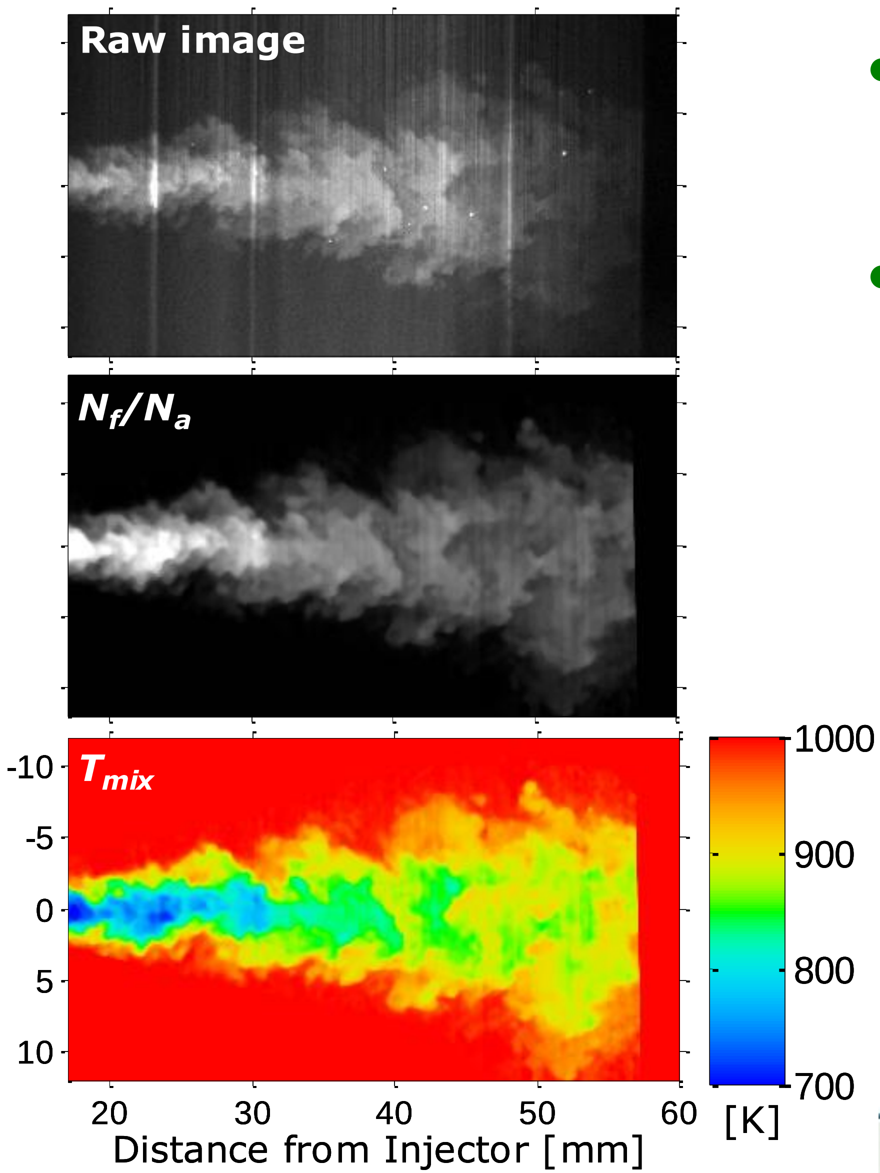


x-ray tomography (Caterpillar)



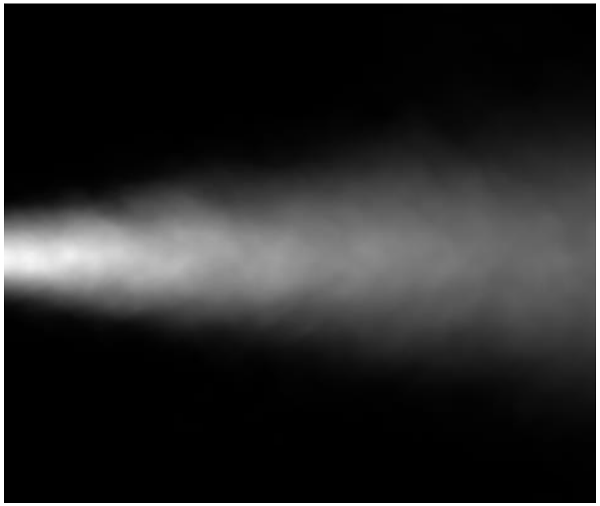


Rayleigh scattering performed to quantify mixing.



- Measurement provides
  - Fuel mixture fraction (mass fraction)
  - Mixture temperature
- Performed at Sandia
  - see SAE 2011-01-0686.

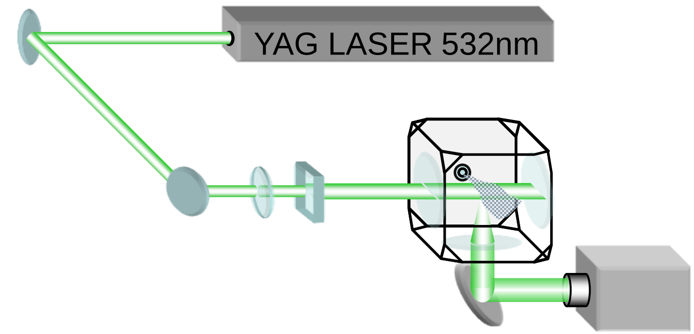
Mean mixture fraction



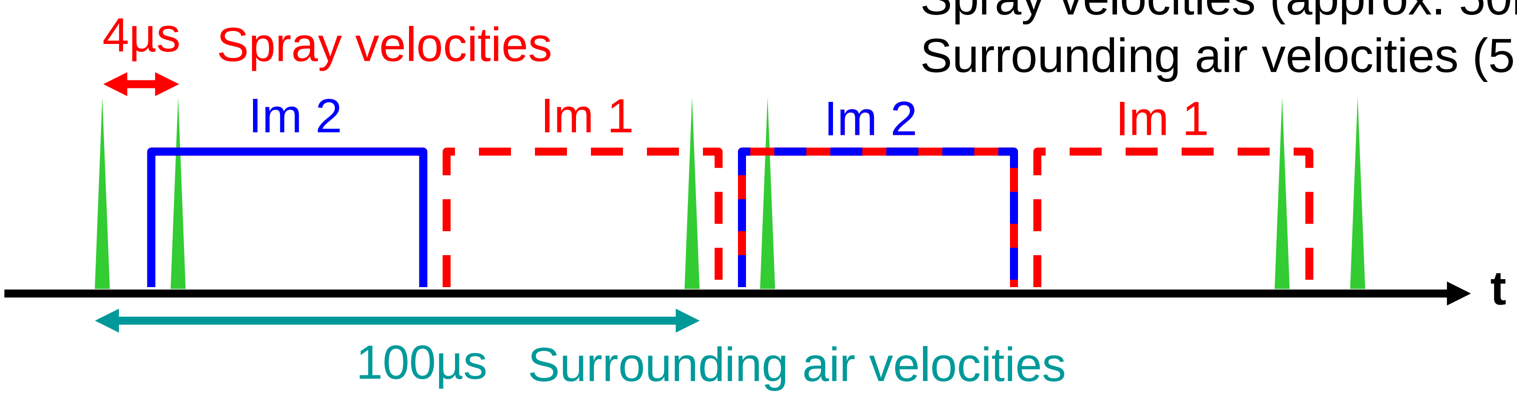
PIV measurements at IFPEN

Louis-Marie Malbec, Gilles Bruneaux

- High speed time-resolved PIV (10000 Hz)
  - Camera Photron SA1
  - YAG Laser 532nm (2 mJ per pulse)
  - Seeding particle: zirconium oxide, <5µm



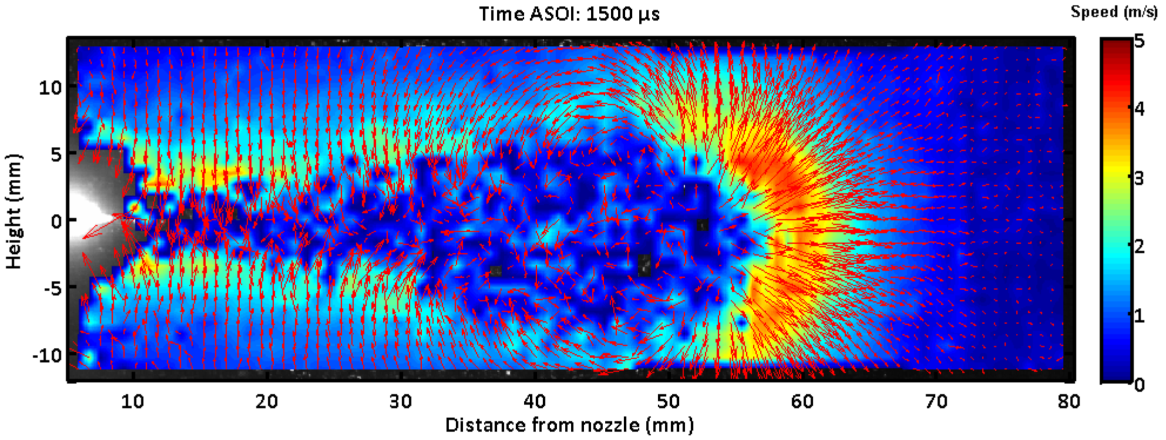
Spray velocities (approx. 50m/s)
Surrounding air velocities (5m/s)



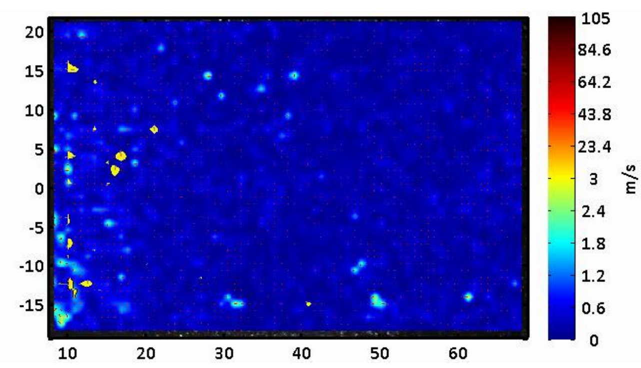
⇒On a single injection event, 2 ranges of velocities can be resolved

Velocity measurements performed downstream of the liquid region

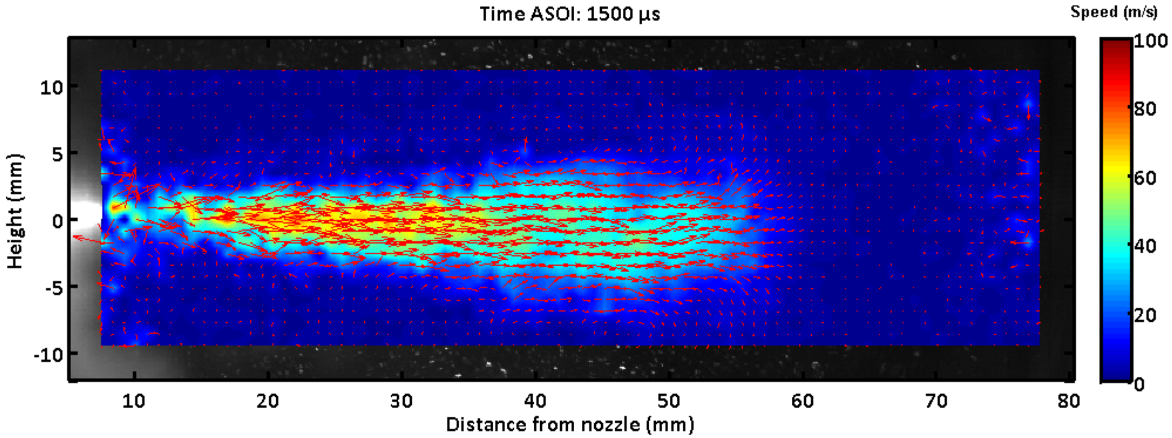
Jet velocity



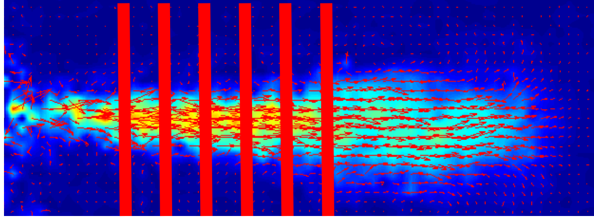
Velocity data “joined”

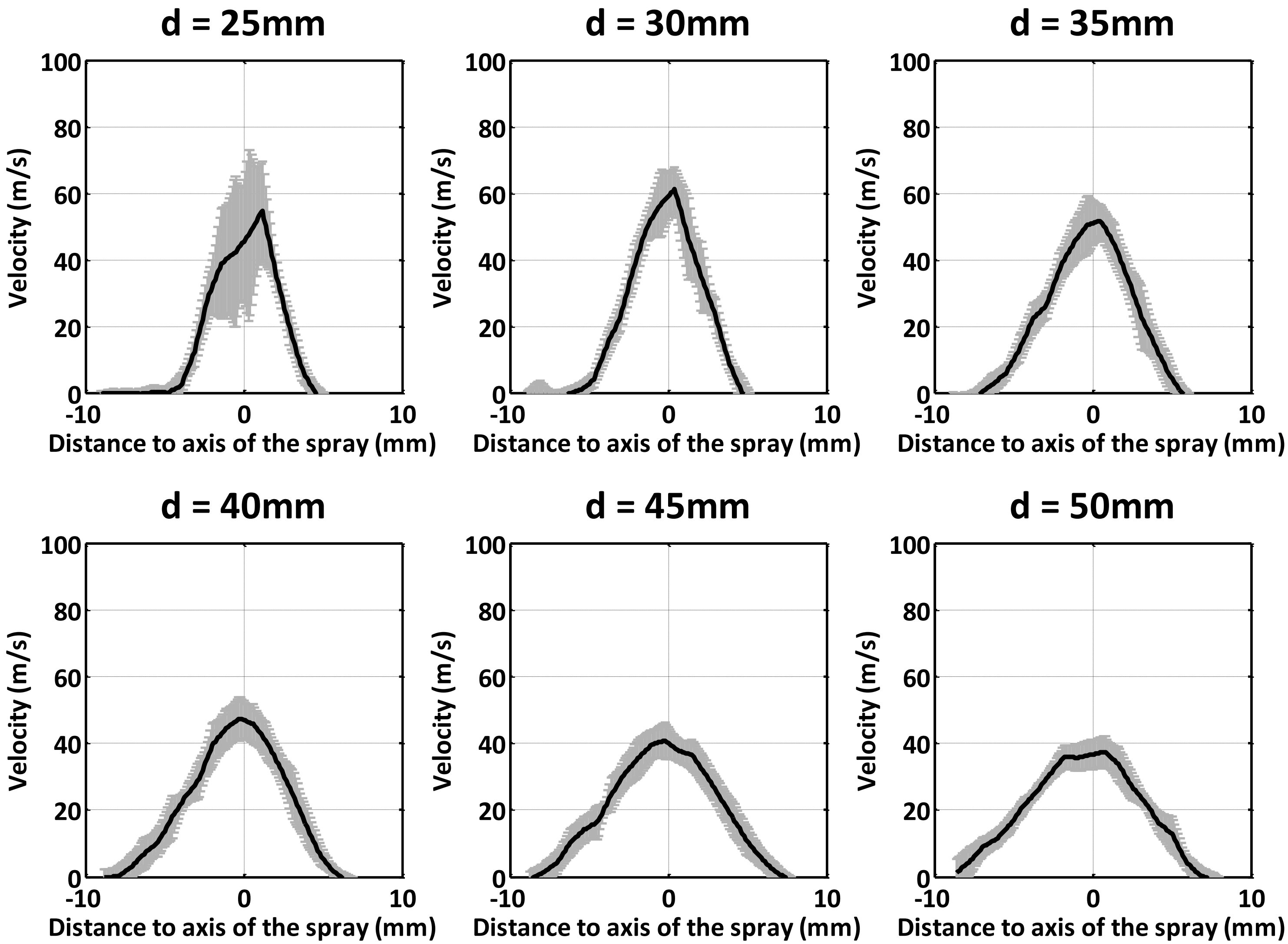


Surrounding air velocity



Radial profiles of axial velocity in steady-state





Mixing and velocity fields are self-consistent.