Engine Combustion Network

ECN 4 Spray G mixing experiments and modeling

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CMT – Motores Térmicos

Contributors

Experiment

- Argonne National Laboratory
  - Radiography/tomography measurements: Daniel Duke, Chris Powell, Alan Kastengren, Andrew Swantek, Nick Sovis
- General Motors R&D
  - Droplet velocity/sizing: Scott Parrish
- IFPEN
  - LIF mixing: Lama Itani, Gilles Bruneaux, Laurent Hermant
- Sandia National Laboratories
  - High-speed planar imaging: Scott Skeen, Julien Manin, Lyle Pickett, Jonathan Frank, Panos Sphicas

Modeling

- Argonne National Laboratory
  - Modeling: Sibendu Som, Kaushik Saha, Z. Weng, Y. Pei, Chao Xu, (UConn student)
- Politecnico di Milano
  - Tommaso Lucchini, Tarcisio Cerri
- General Motors R&D
  - Ron Grover

Spray G experiments and modeling have progressed…we can now ask more detailed questions about gasoline DI modeling

- Significant spray G experimental contributions

Velocity & Turbulence

90° C

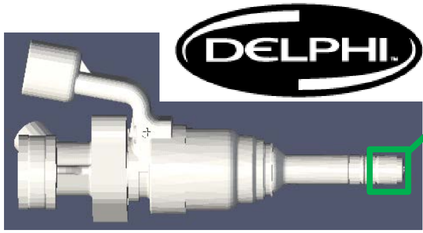
573 K, 6 bar

Liq. & vap. penetration
Mie/Schlieren/DBI

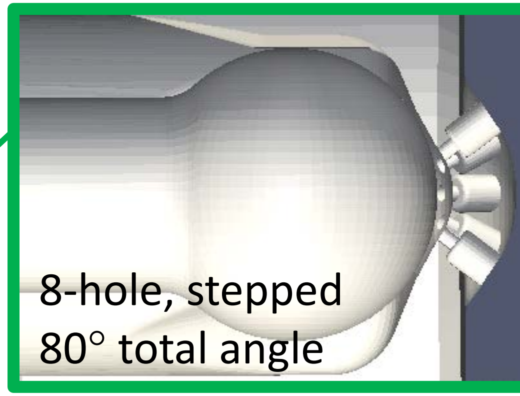
Liquid mixture fraction

Vapor mixture fraction
in Engine

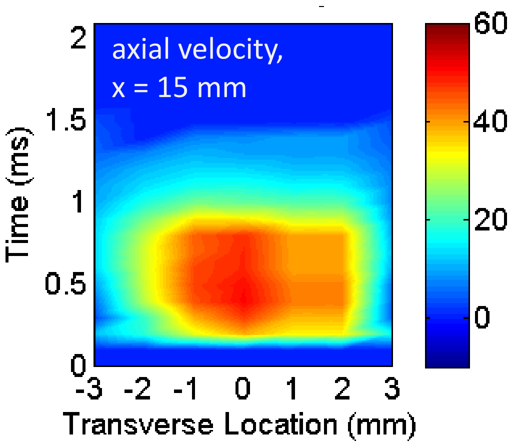
Spray structure
HS microscopy



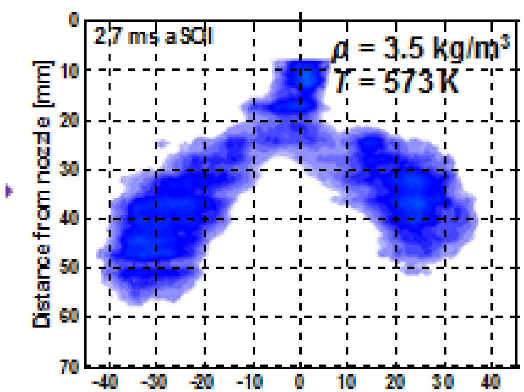
Gasoline Spray G



droplet size,
velocity via PDI
GM

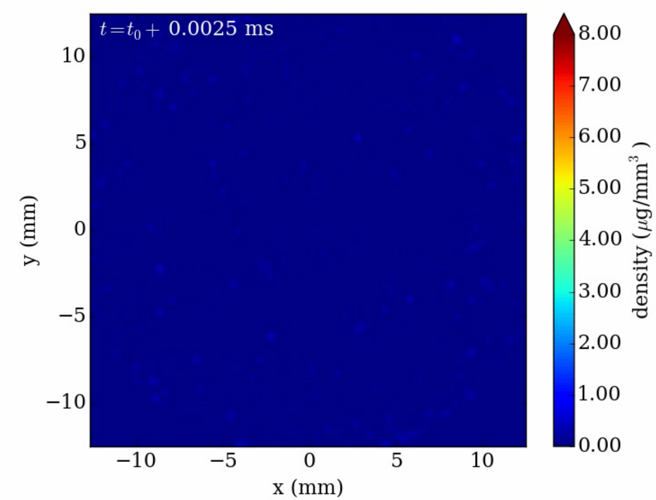


Vapor mixture
late ASI
IFPEn



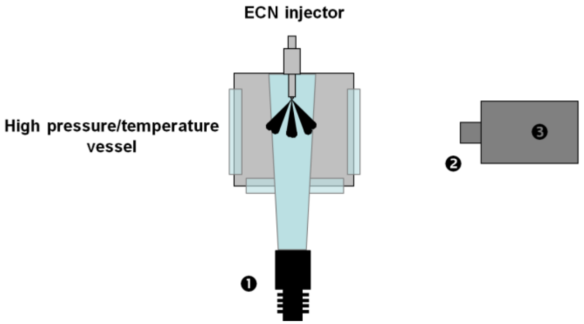
Non-vaporizing
mixing
Argonne

z = 10 mm



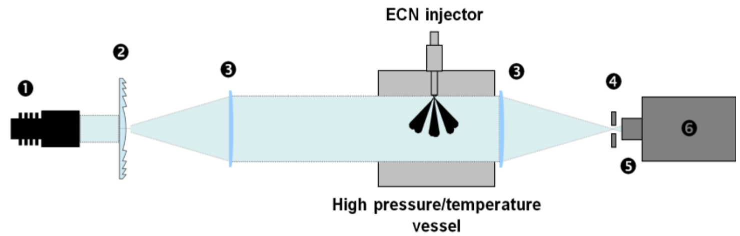
Laser-induced fluorescence for planar mixing measurements

Mie-scattering



Tag	Label
❶	White LED (Thorlabs, 4.0V powered)
❷	Nikkor lens: f = 85 mm
❸	Photron SA1 camera

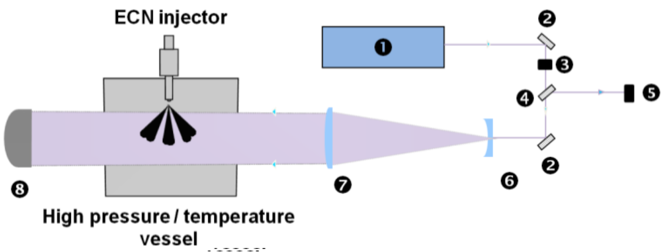
Schlieren



Tag	Label
❶	White LED (Thorlabs, 4.0V powered)
❷	Fresnel lens
❸	Spherical lens (f = 600 mm, diameter = 100 mm)
❹	Iris
❺	Nikkor lens: f = 85 mm
❻	Photron SA1 (768×752)

LIF

- Use fuel blend: iso-octane (purity grade = 99.8%) + 0.03% vol. p-DFB
- 1) two-color LIF collection, measure temperature and fuel concentration
- 2) single-color LIF collection with calibration by total injected fuel
- see SAE 2015-01-1902



Tag	Label
❶	Fourth harmonic of a Nd:YAG laser (266 nm)
❷	25 mm mirrors at 266 nm
❸	Attenuator
❹	Beam sampler
❺	Laser energy sensor
❻	Cylindrical lens (f = -76.2 mm, 60 mm × 27 mm)
❼	Spherical lens (f = 500 mm, ϕ= 100 mm)
❽	Beam dump

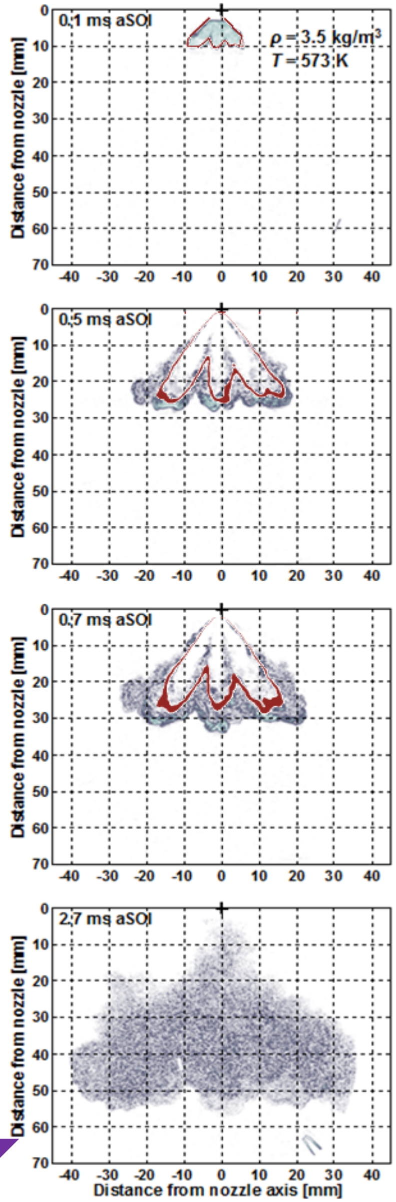
IFPEN

Background: evolution of mixing at different ambient densities

Spray G

ambient density

time aSOI



Results: Jet Evolution

- Four stages in the spray development were defined (0.1, 0.5, 0.7 and 2.7 ms aSOI).
- Red contours derived from instantaneous Mie-scattering images.
- Until 0.7 ms: Jet momentum is mainly driving the mixing process.
- For timings >> 0.7 ms: Jet concentrated on the injector axis where mixing is driven by aerodynamic motion created by air entrainment

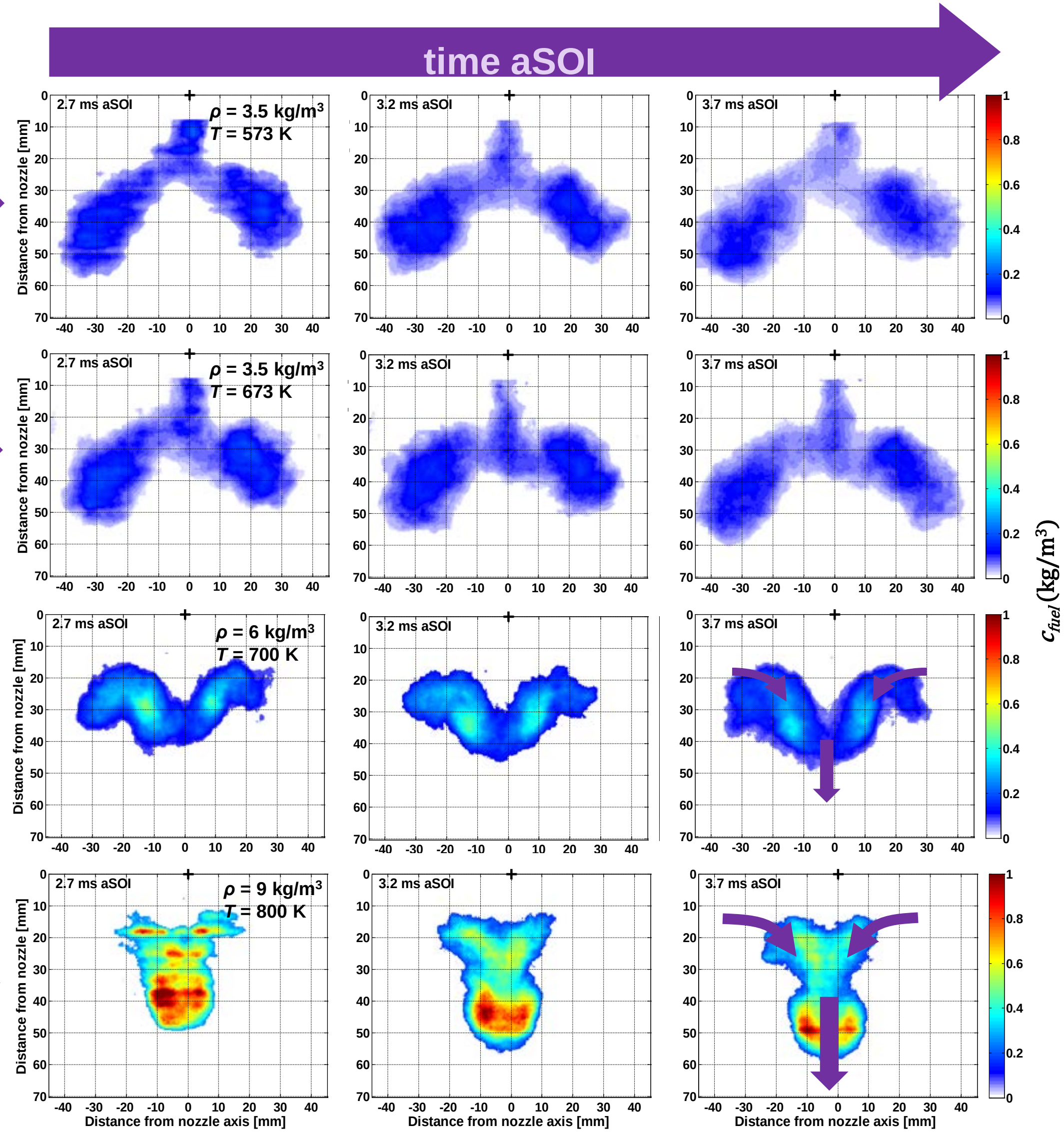
Fuel concentration with p-DFB LIF imaging

Spray G

ρ = 3.5 kg/m³
T = 673 K

ρ = 6 kg/m³
T = 700 K

ρ = 9 kg/m³
T = 800 K



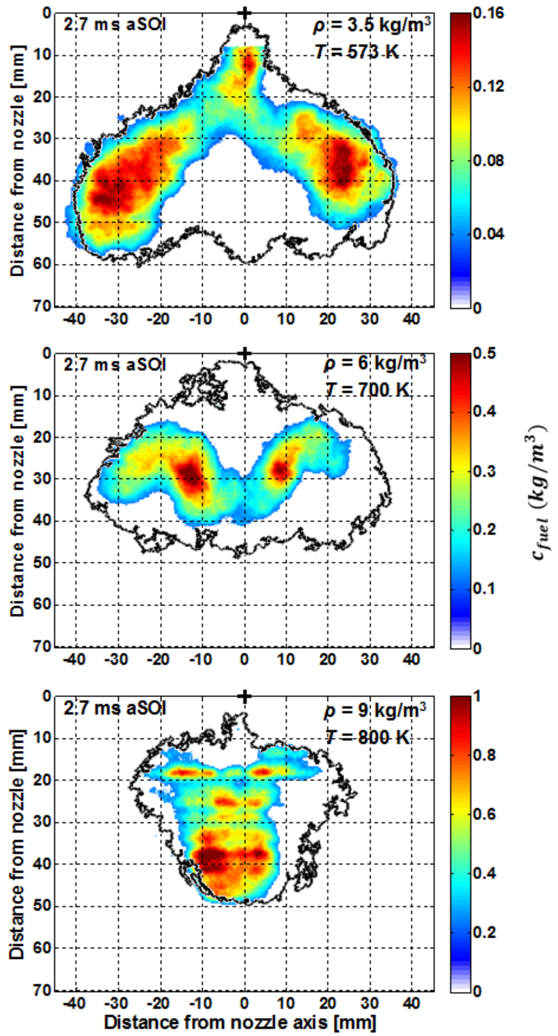
Planar measurements self consistent with line-of-sight schlieren imaging

- pLIF images lie within schlieren contour
- reveal the extent of mixing at the center of the spray

Spray G

ρ = 6 kg/m³
T = 700 K

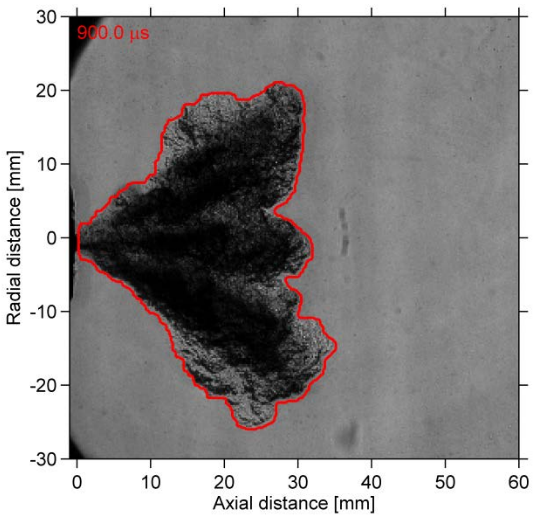
ρ = 9 kg/m³
T = 800 K

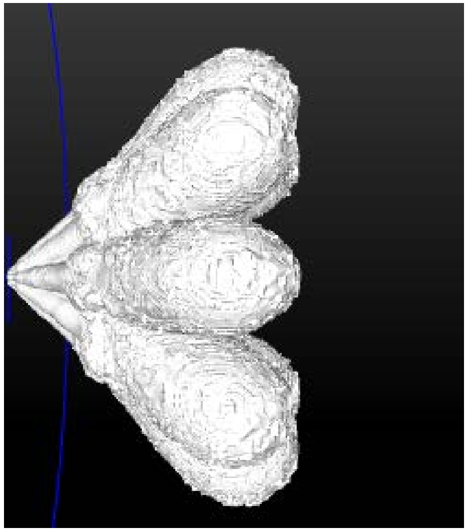


Modeling contributions from ECN3

0.9 ms ASOI

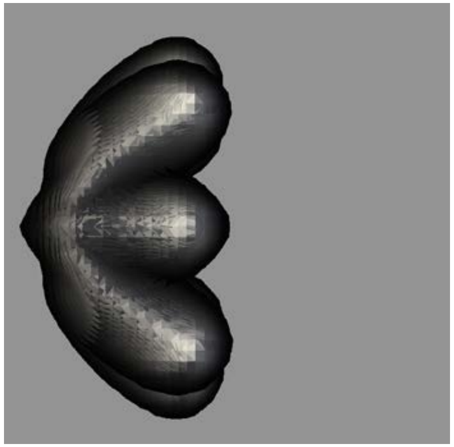
Experiment

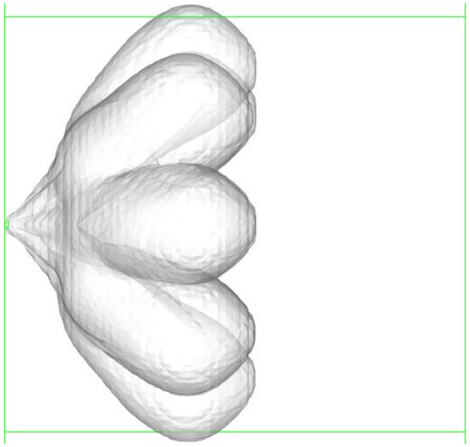




ANL

PoliMi





UW

ECN3 RANS Modeling Approaches

	ANL	Polimi	UW
CFD Code	Converge 2.1.0	OpenFOAM + Lib-ICE	KIVA3V-r2-ERC
Turbulence Model	Standard k-ε	Standard k-ε	RNG k-ε
Injection Model	Lagrangian/Blob	Lagrangian/Huh	Lagrangian/Blob
Primary Break-up Model	KH-RT (B1 7; RT Length 0.0)	Huh-Gosman	KH-RT (B1 40; RT Length 1.0)
Secondary Break-up		Wave	
Vaporization	Frössling	Spalding Number-based (mass-based)	Frössling
Heat Transfer	O'Rourke	Ranz-Marshall	Ranz-Marshall
Collision	NTC	None	
Turbulent Dispersion	O'Rourke	None	Gaussian Distribution
Droplet Drag	Dynamic	Dynamic w/ non-spherical correction	Dynamic w/ non-spherical correction

ECN3 RANS models: Mesh Details

	ANL	Polimi	UW
Domain Dimensions	108 Ø x 108 mm	169 x 248 mm	100 x 100 x 60 mm
Base Cell Size	2 mm	4 mm	1 mm
Min Cell Size	0.25 mm	1 mm	-
Adaptive or Static Refinement	Both	Adaptive	Uniform
Cell Type	Cartesian	Cartesian	Cartesian Hexahedron
Total/Maximum Cell Count	1.53 Million	115,000	600,000

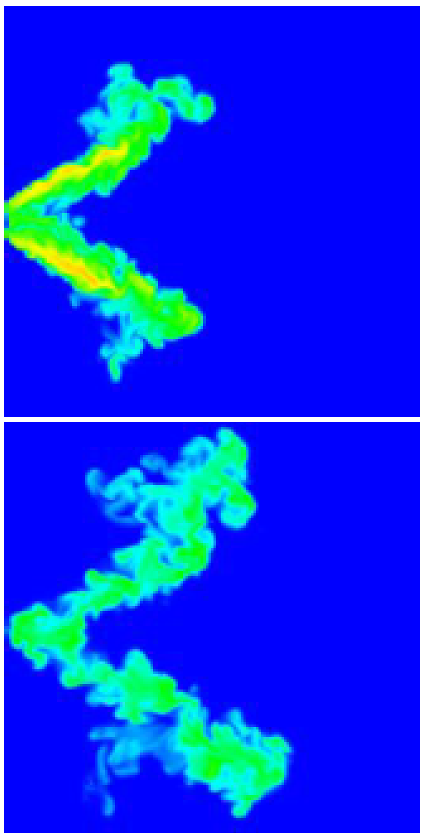
LES and RANS simulations offered at ECN4

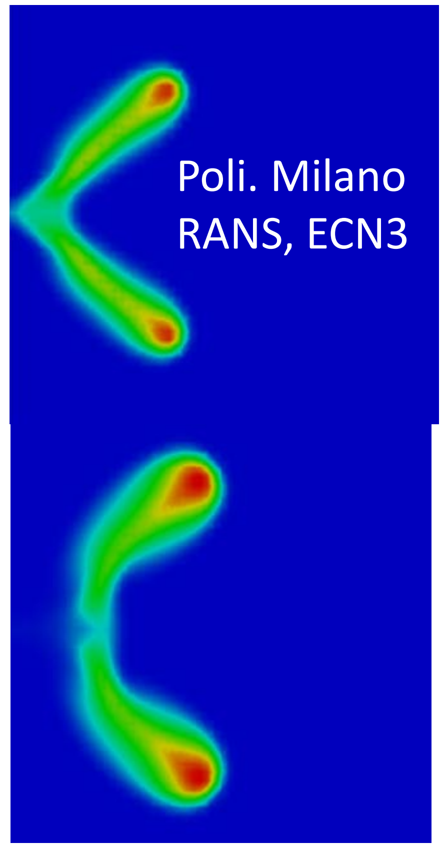
Argonne National Lab
LES
Som, Wang, Pei et al.
ASME ICE 2015-1003

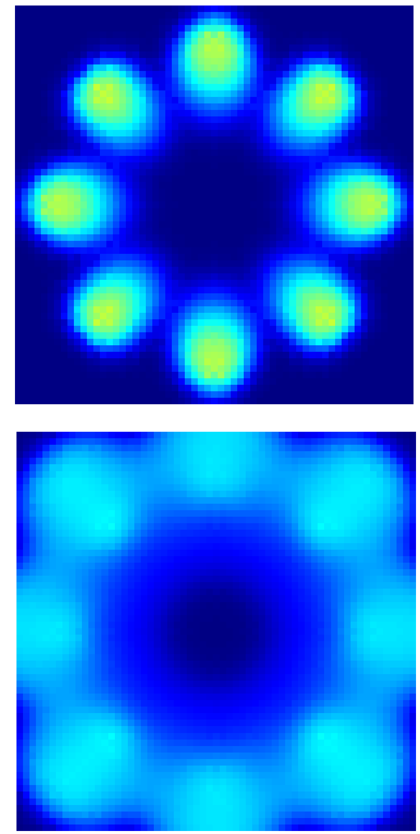
Poli. Milano
RANS, ECN4

0.6 ms

1.0 ms







0.5 ms

1.0 ms

Fuel mixture fraction on Y-Z plane

Vapor fuel mixture fraction on X-Y plane, Z = 15 mm

Simulation Set-up at ANL

Modeling tool	CONVERGE
Dimensionality and type of grid	3D, Cartesian
Grid embedding management	Base mesh size fixed to 1 mm, 0.125 mm min. cell size (a) Fixed embedding near injectors and boundaries (b) Gradient based AMR on the velocity and temp. fields
Number of processors used	Most simulations on 64 processors
Turbulence model	LES: Dynamic Structure*
Spray models	Injection: Blob injection model Breakup: KH-RT without breakup length concept Collision model: NTC (No Time Counter) Coalescence model: Post Collision outcomes Drag-law: Dynamic model
Time step	Variable based on spray, evaporation processes

Sub-grid stress tensor τ_{ij} needs to be modeled

Momentum Equation

$$\frac{\partial \bar{\rho}\tilde{u}_i}{\partial t} + \frac{\partial \bar{\rho}\tilde{u}_i\tilde{u}_j}{\partial x_j} = -\frac{\partial \bar{P}}{\partial x_i} + \frac{\partial \bar{\sigma}_{ij}}{\partial x_j} - \frac{\partial \tau_{ij}}{\partial x_j}$$

Dynamic Structure Model

$$\tau_{ij} = 2k\bar{\rho}\frac{L_{ij}}{L_{kk}}$$

$$L_{ij} = \widehat{\tilde{u}_i\tilde{u}_j} - \hat{\tilde{u}}_i\hat{\tilde{u}}_j \qquad k = \frac{1}{2}\left(\widetilde{u_i u_j} - \tilde{u}_i\tilde{u}_j\right)$$

* Dynamic structure model was chosen since it provided best predictions against diesel spray experimental data compared to the other SGS models by our team (Xue & Som et al., AAS paper, 2013)

Model Settings for LES simulation

Constant	Brief Description	Value
B_0	KH model droplet size constant	0.6
B_1	KH model breakup time constant	5
C_1	KH model droplet normal velocity	0.188
C_t	RT model breakup time constant	1.0
C_{RT}	RT model droplet size constant	0.6
Shed factor	Percentage of mass given to child droplets by parent droplet	0.25
Pr_{sgs}	k-equation constant	1.39
C_ε	LES dissipation rate model constant	1.0
C_{ps}	Drop turbulent dispersion constant	0.01

Expense of Argonne LES simulations

Base cell size (mm)	AMR & Embed scale	Minimum cell size (mm)	Number of injected parcels	Peak cell count at 1 ms (millions)	Wall clock time (hours) till 1 ms on 64 CPUs
1	3	0.125	50,000	~ 13.3	7.2

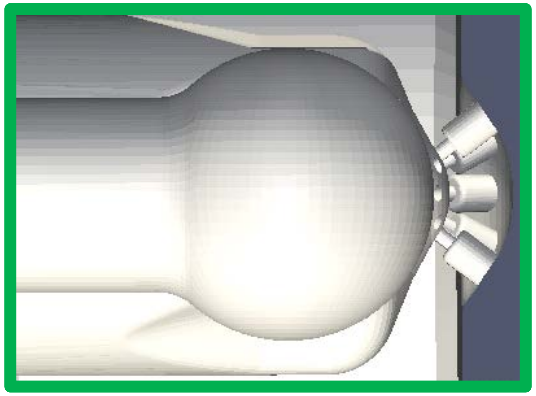
- 20 realizations with random number seeding (injections) performed (720 CPU hrs per injection)
  - 14,400 total CPU hrs

RANS setup at Poli. Milano

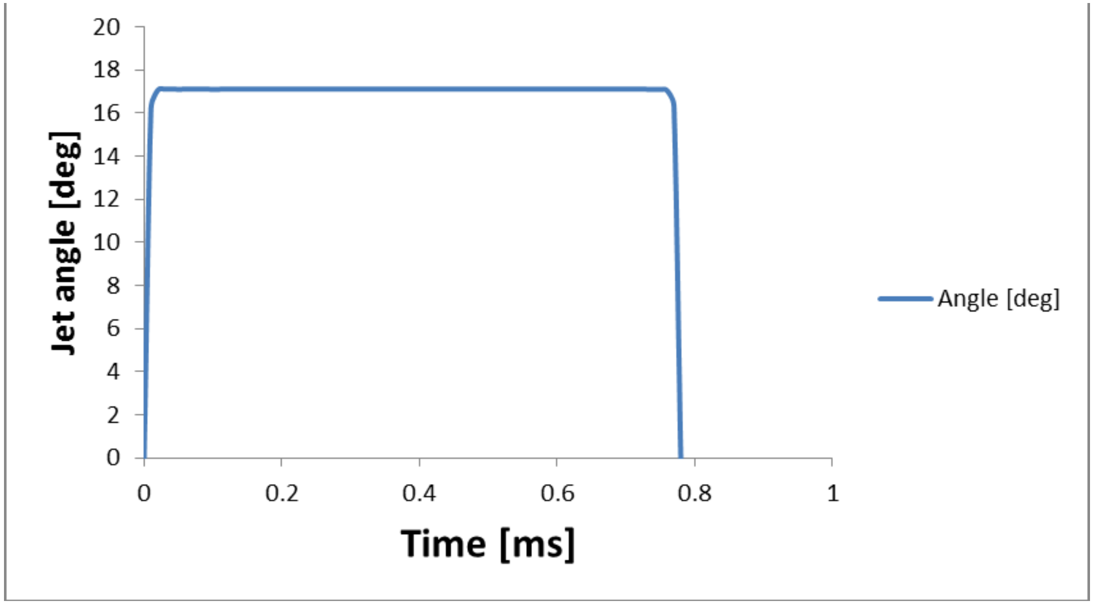
CFD Code details	
Software	OpenFOAM + LibICE libraries by Politecnico di Milano (spray, combustion, mesh management, …)
Solver	RANS, unsteady, compressible solver. Spray modeled with lagrangian approach
Turbulence model	Standard k-epsilon with modified C1 (1.5 instead of 1.44)
Fuel type	Iso-octane
Liquid properties	Iso-octane NIST data
Gas properties	Iso-octane and N2 Janaf coefficient
Temporal Discretizazion scheme	Euler Implicit
Convection discretization scheme	Limited (TVD), second-order
Diffusion discretization	Including the non-orthogonal component of the gradient
Lagrangian spray model details	
Atomization Model	Huh-Gosman, tuned following LES Data presented in SAE Paper 2014-01-0149
Injection Model	Huh
Secondary Breakup model	Pilch-Erdman
Collision model	off
Evaporation model	Based on Spalding mass number
Heat transfer model	Ranz-Marshall
Turbulent dispersion model	Stochastic
Mesh details	
Cell size	Ranging from 1 to 4 mm using Adaptive Local Mesh refinement

Plume vector and spreading angle considerations

- Plume vector, or inclination angle, set at specified 37 degrees (rel. to injector), for both Argonne LES & RANS and PoliMi RANS simulations
- Plume origin at designed radius
- Plume “spreading angle” allowed to change with time based upon nozzle velocity, turbulence, etc
- Plume vector / inclination angle does not change with time

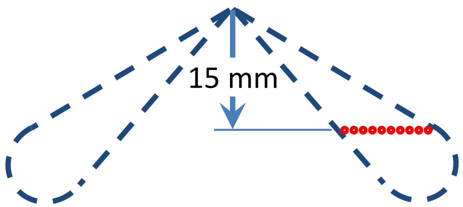


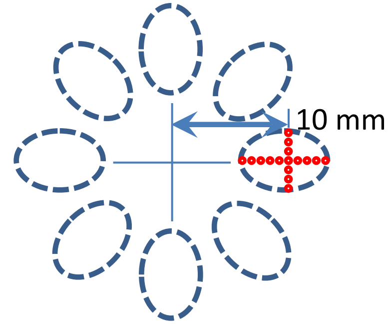
PoliMi plume angle during injection



Spray G – Velocity and drop size observations

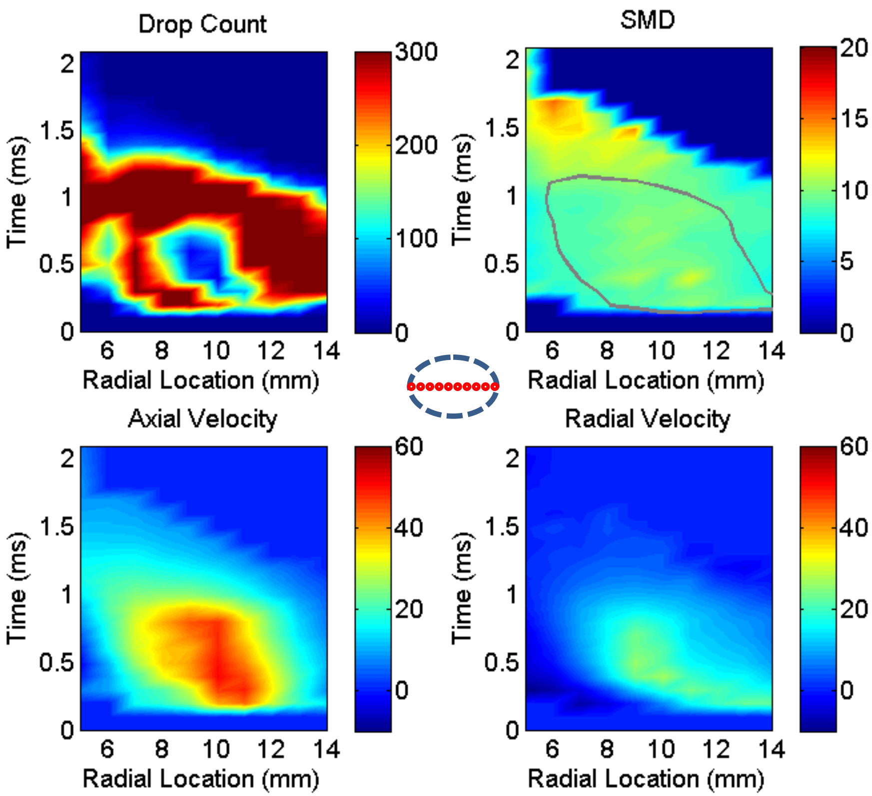
Scott Parrish, GM
ECN3



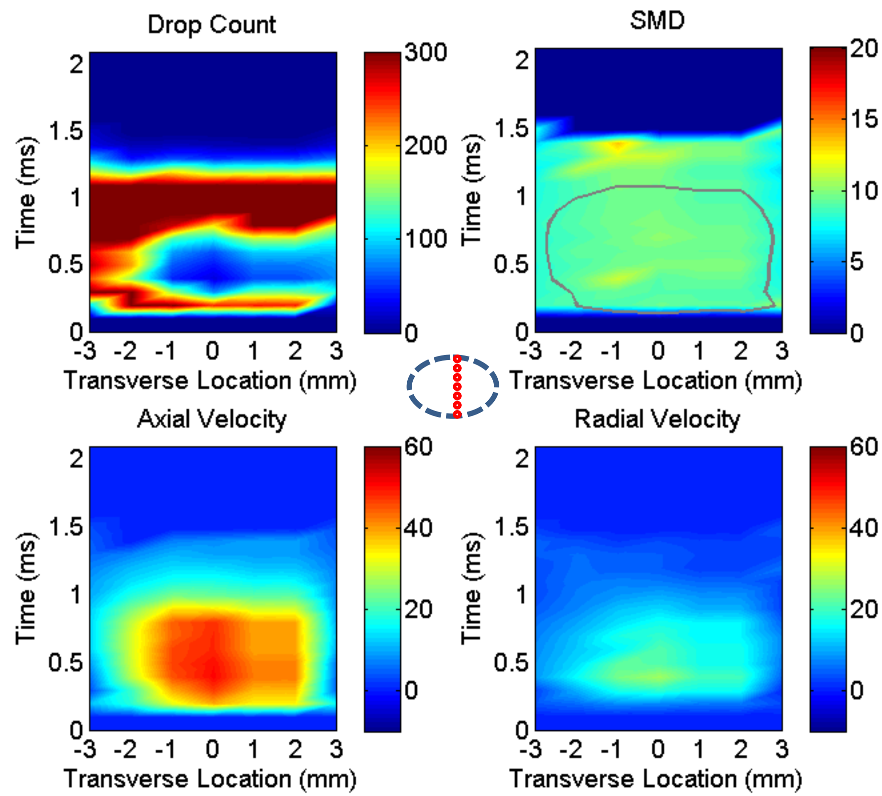


for injector #16,
plume #1:
Substantial dataset with
~ 10,000 injections

Radial Scan

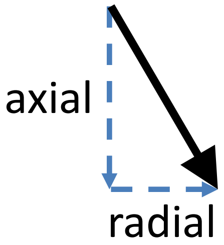


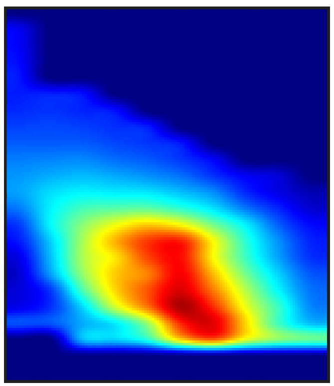
Transverse Scan

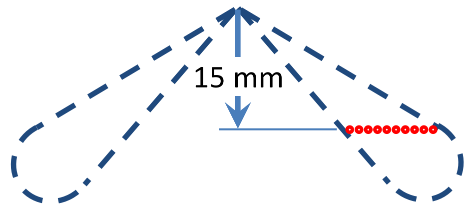


Plume center moves towards injector axis with time ASI

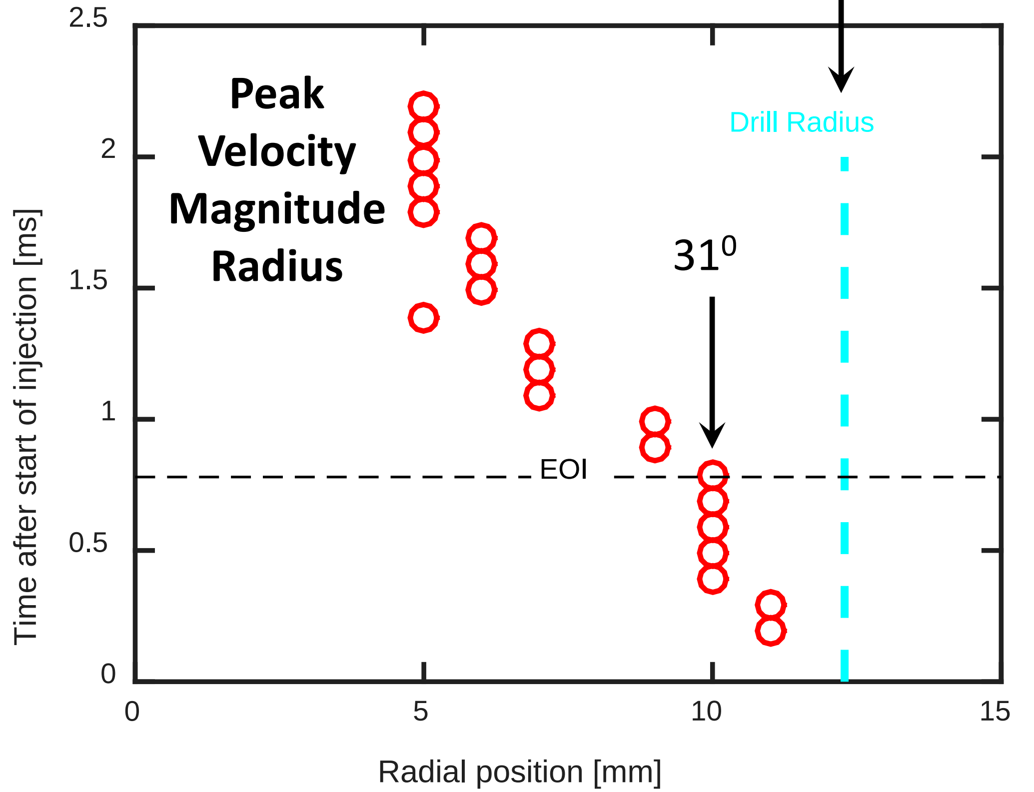
Velocity magnitude



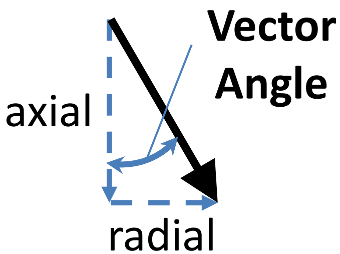


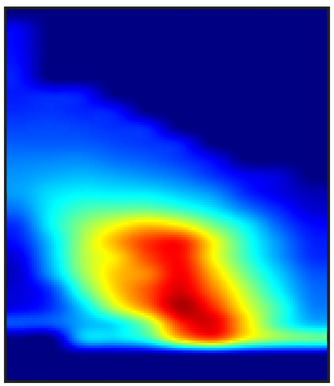


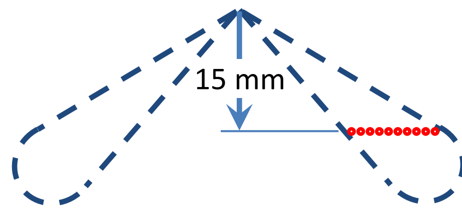
radius at 15 mm for 37^0 drill angle

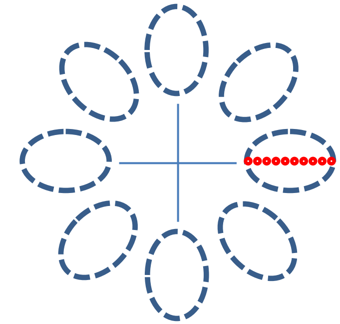


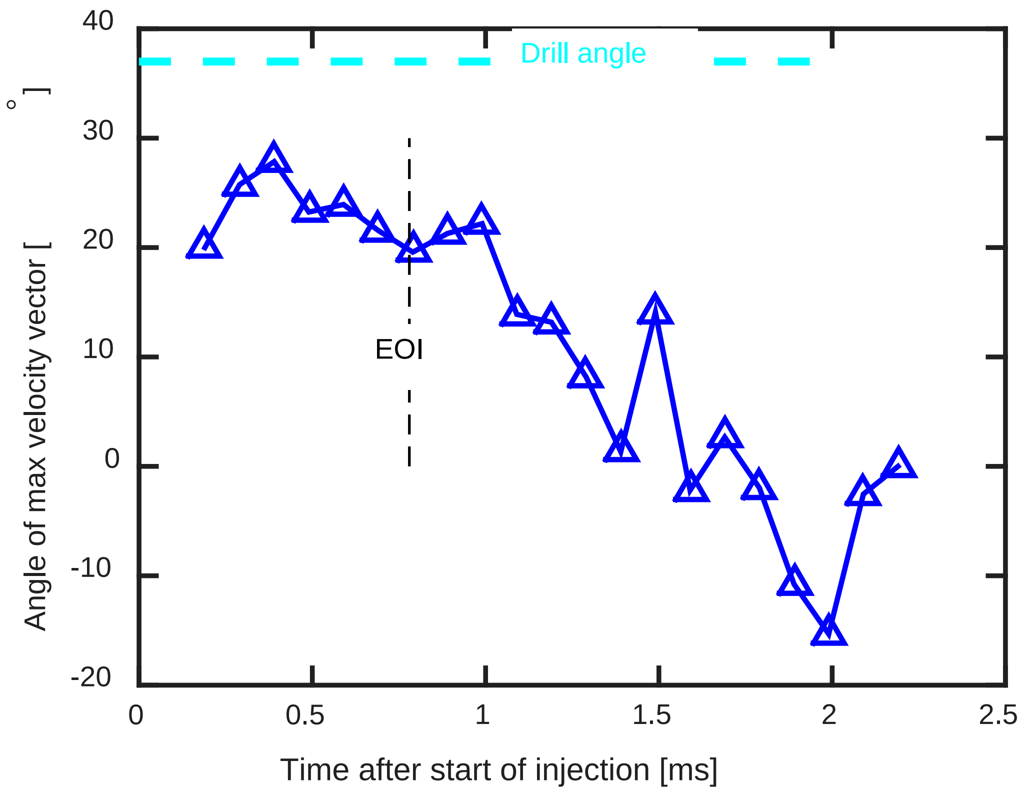
Plume inclination angle decreases with time





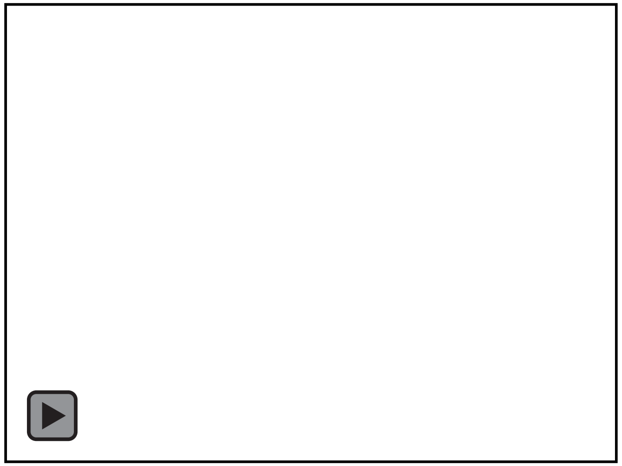




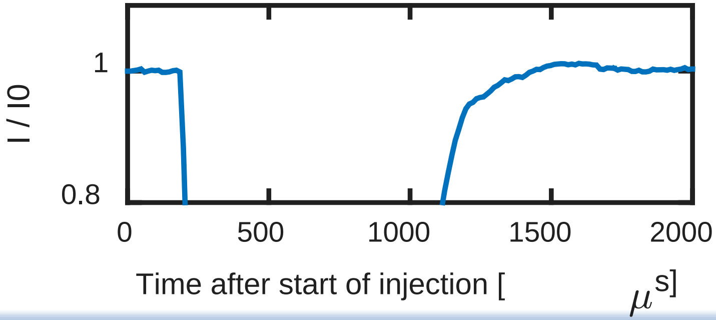


Other planar visualization shows plume redirect

Line of sight
Diffused back illumination
contrast set to I/I0 = 0.9 to 1.0



Measured intensity in dark ROI

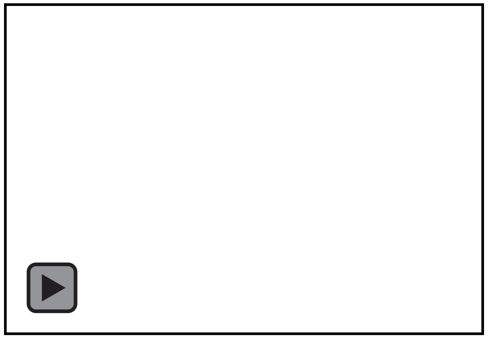


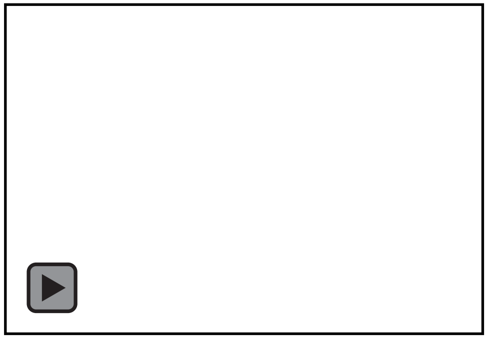
100 kHz Planar Rayleigh imaging attempt at Sandia
Standard Spray G conditions
3.5 kg/m^3 , 573 K

lower laser energy

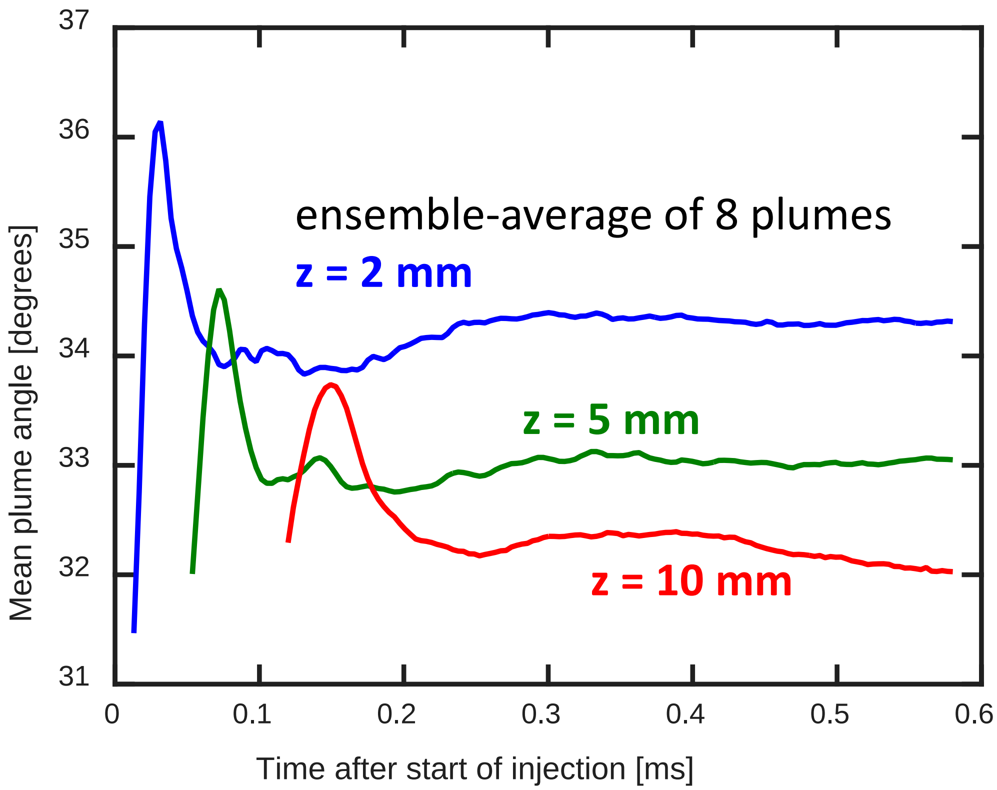
higher laser energy

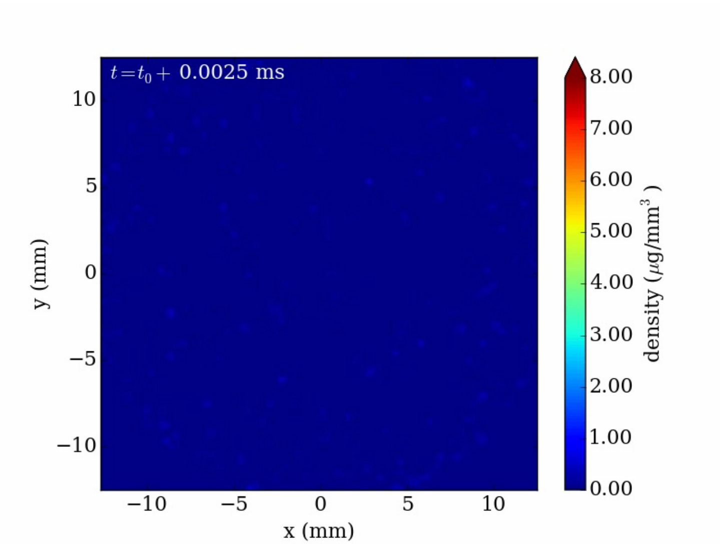
30°





Plume pointing vector derived from radiography at different axial positions





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

Plumes completely merge during injection at high T, high ρ

Schlieren imaging
9 kg/m^3, 573 K

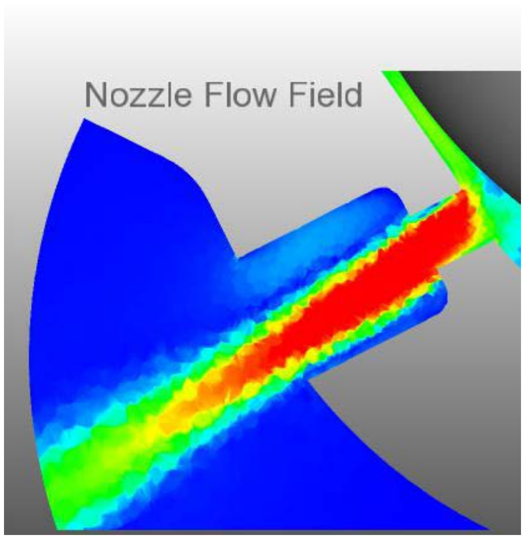
100 kHz Planar Rayleigh
Standard Spray G conditions
9 kg/m^3 , 1050 K

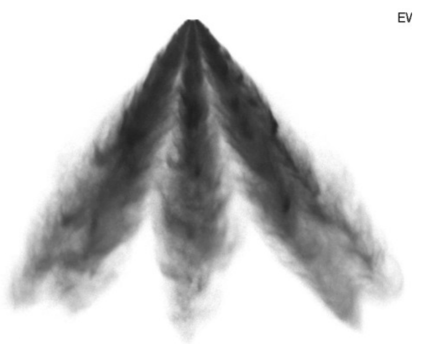
30^{o}

Plume-plume interaction questions

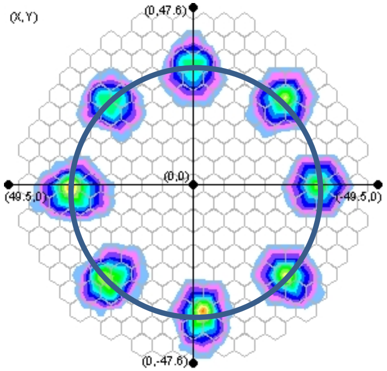
- Is the plume vector redirection caused by internal flow or downstream fluid mechanics?
- If imposing a constant plume vector (and plume spreading angle), will Lagrangian-droplet RANS and LES simulations predict plume interaction and merge?
- Lacking detailed spray measurements, how does the Lagrangian-droplet modeler predict plume vector (as a function of time)?

Spray G at ECN3
Ron Grover, GM



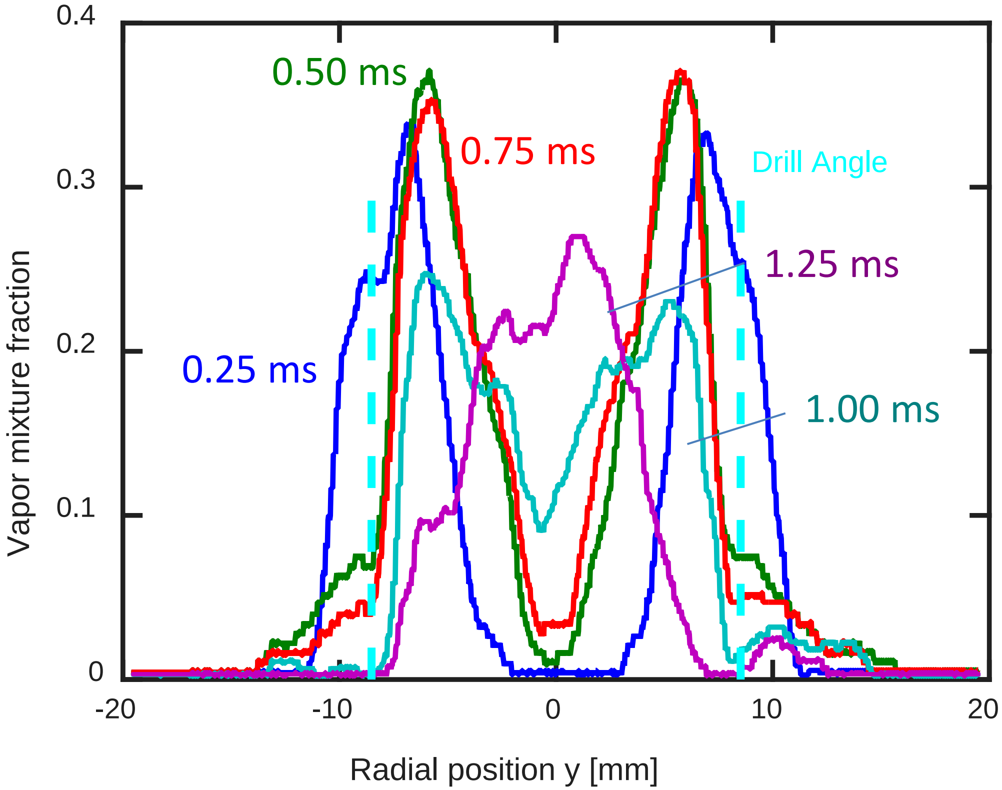


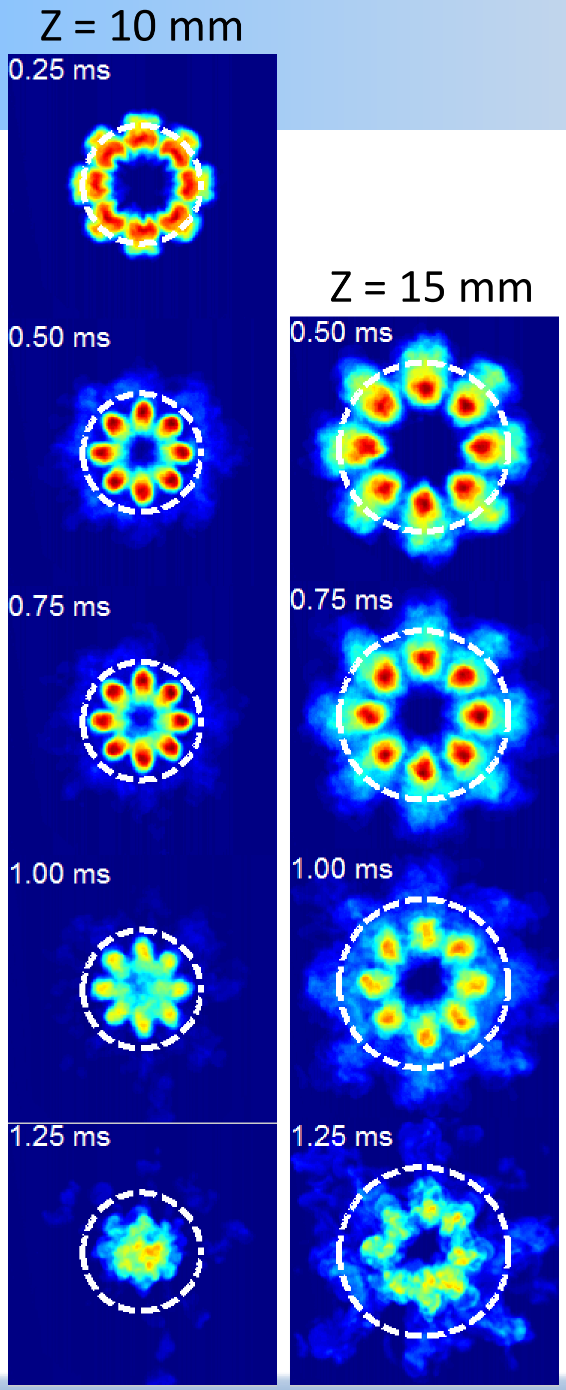
Delphi patternation at 1 atm:
z = 50 mm, R_{plume}= 33.2 mm
plume vector angle = 33°



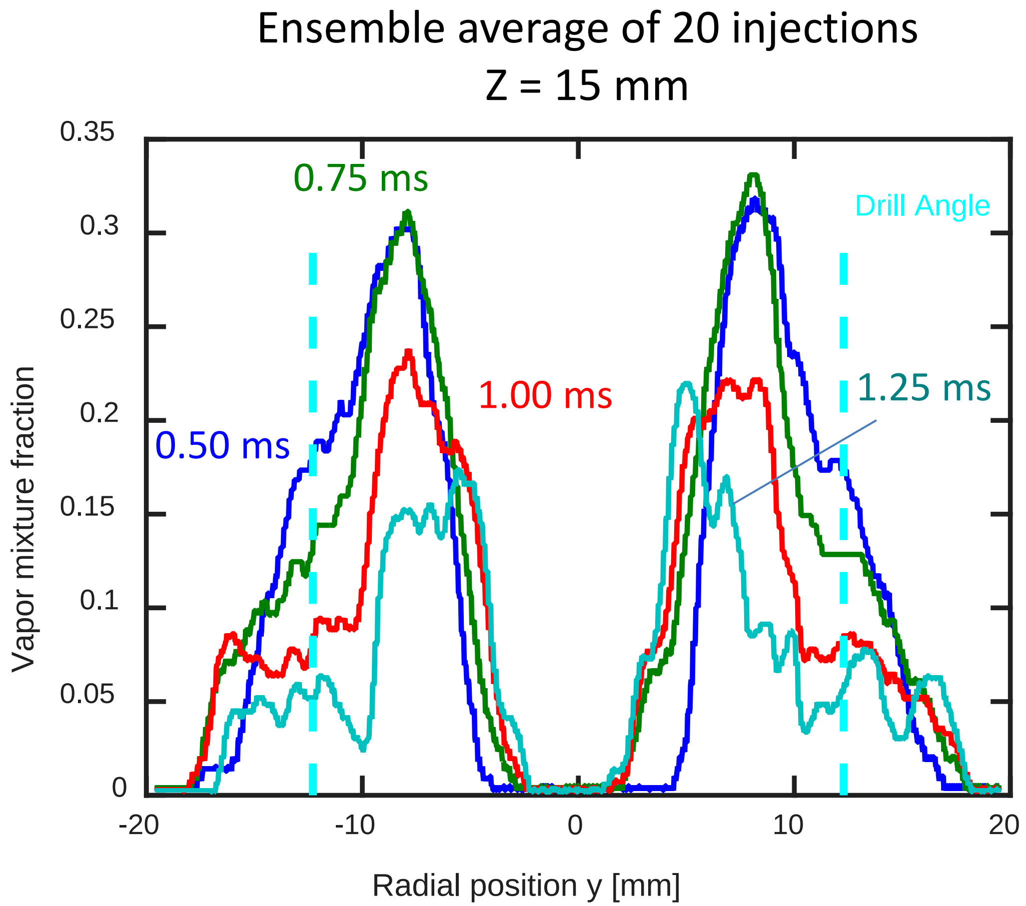
Argonne LES simulations

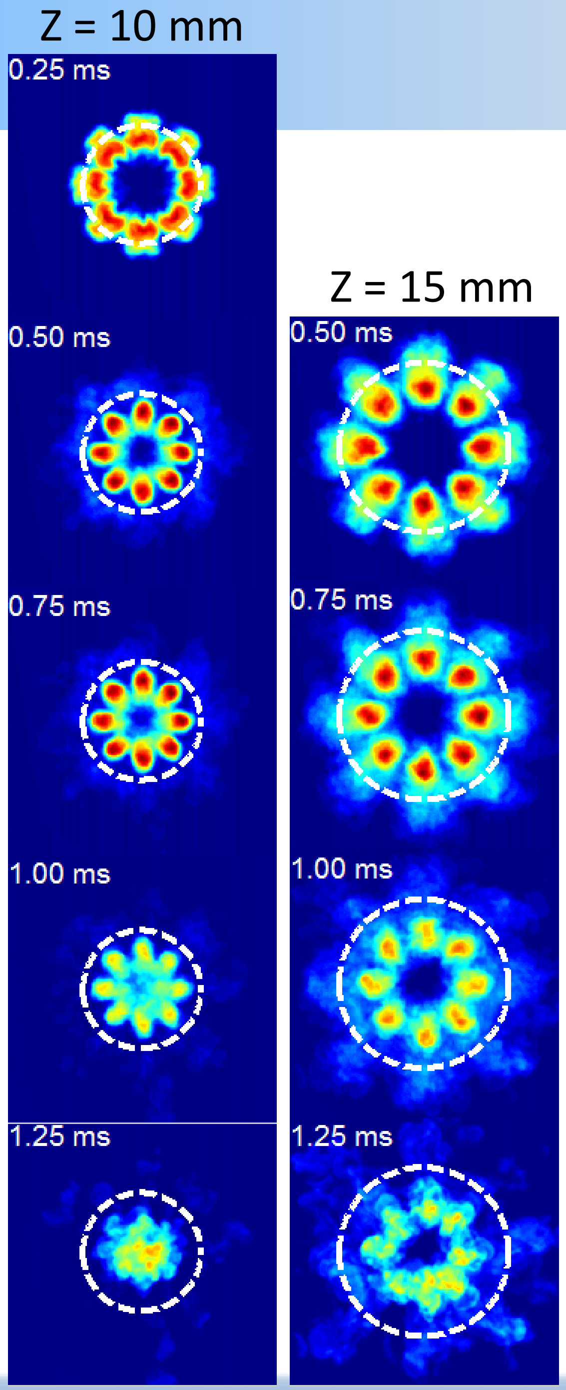
Ensemble average of 20 injections
Z = 10 mm



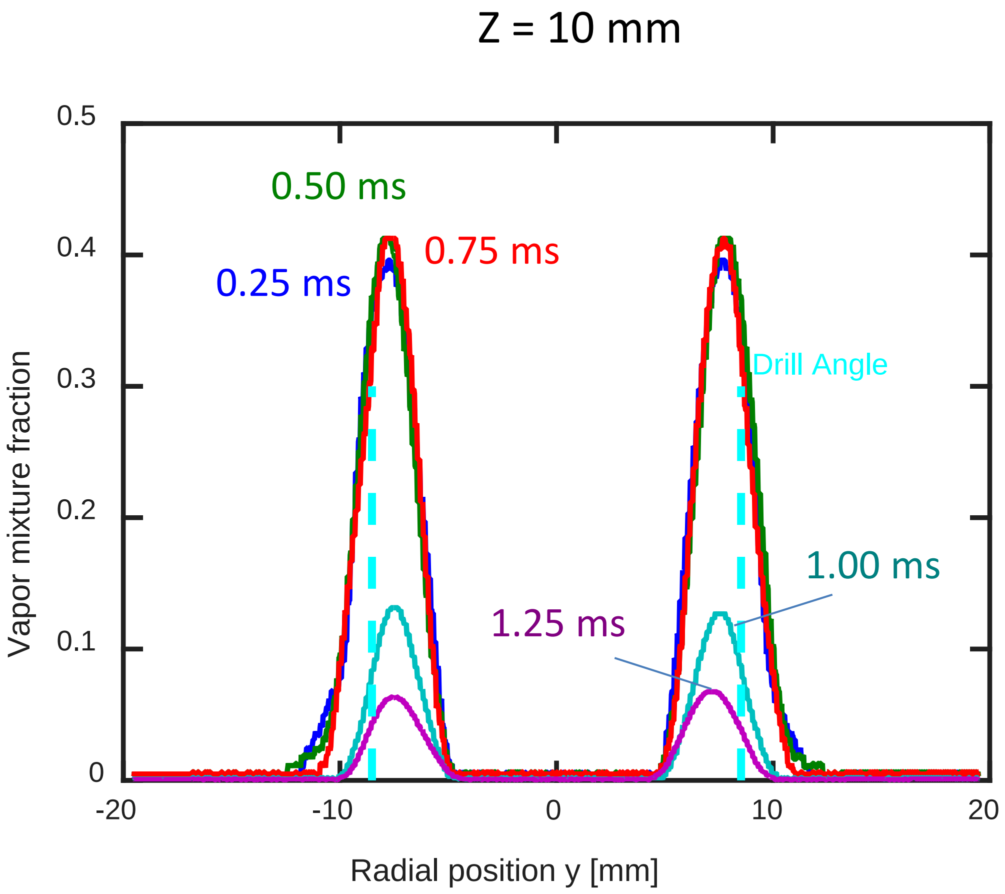


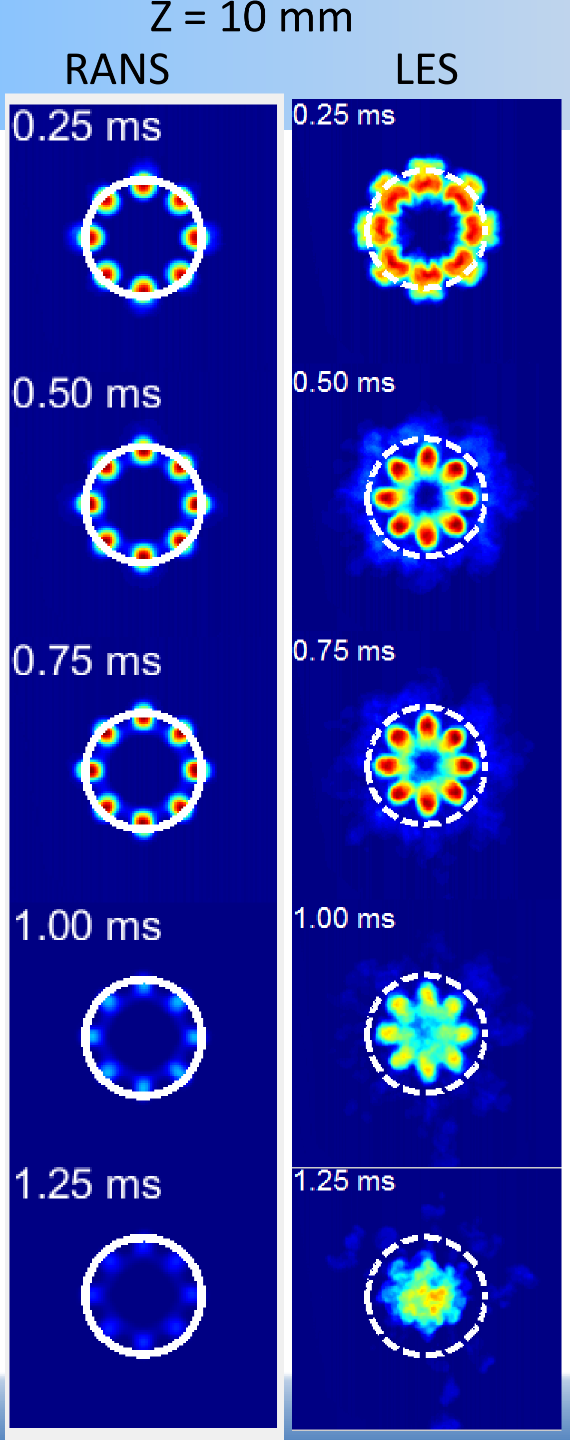
Argonne LES simulations



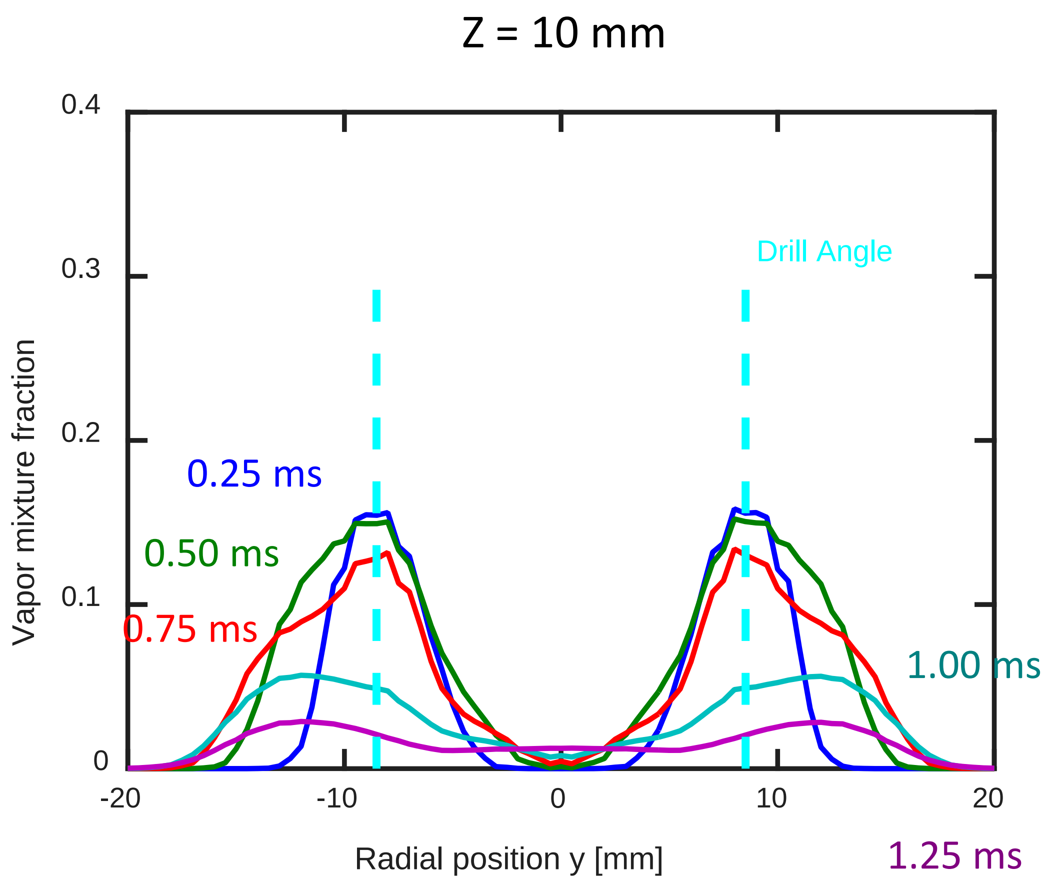


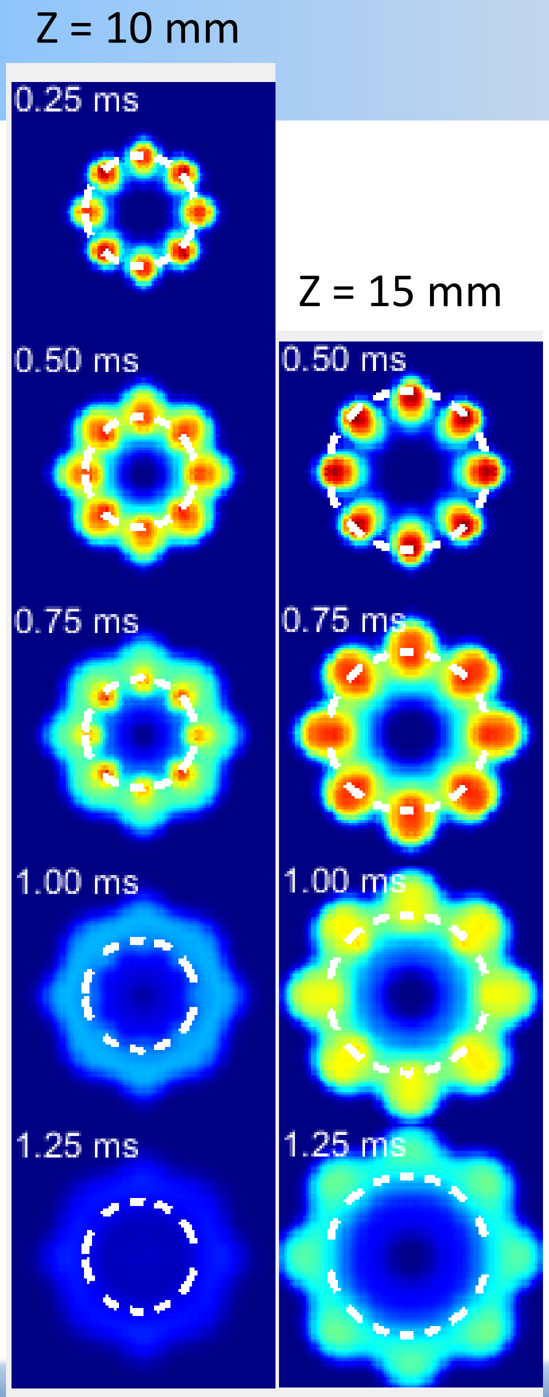
Argonne RANS vs LES simulations



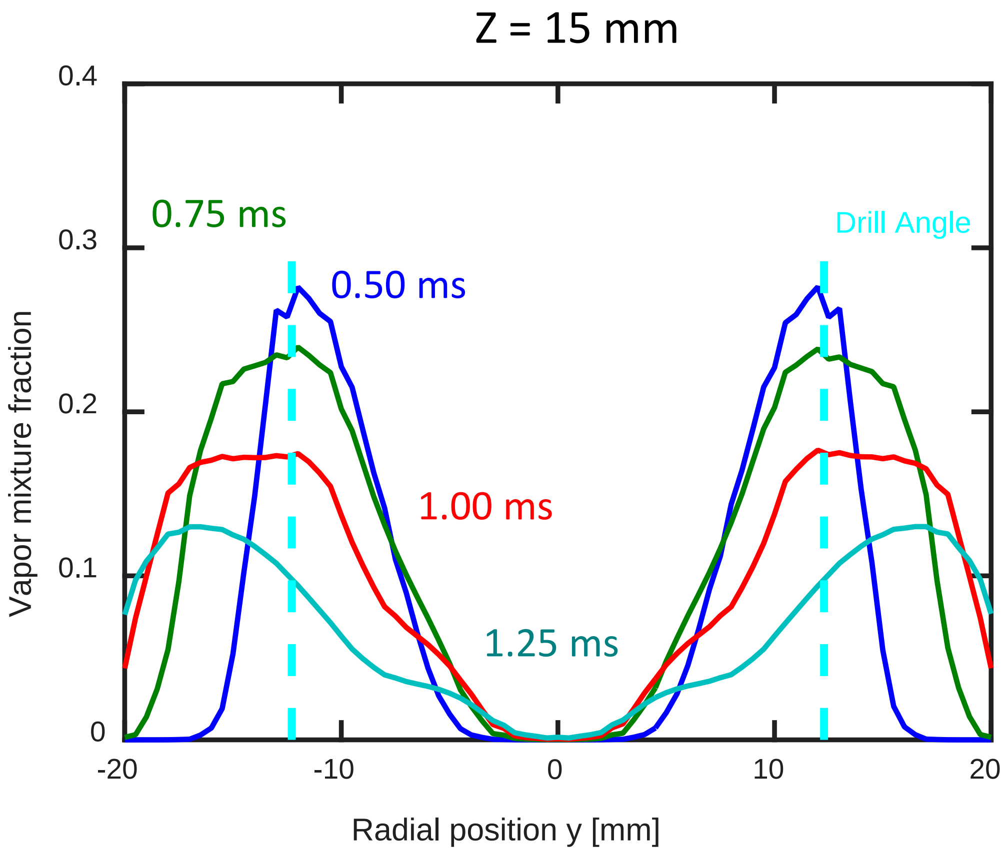


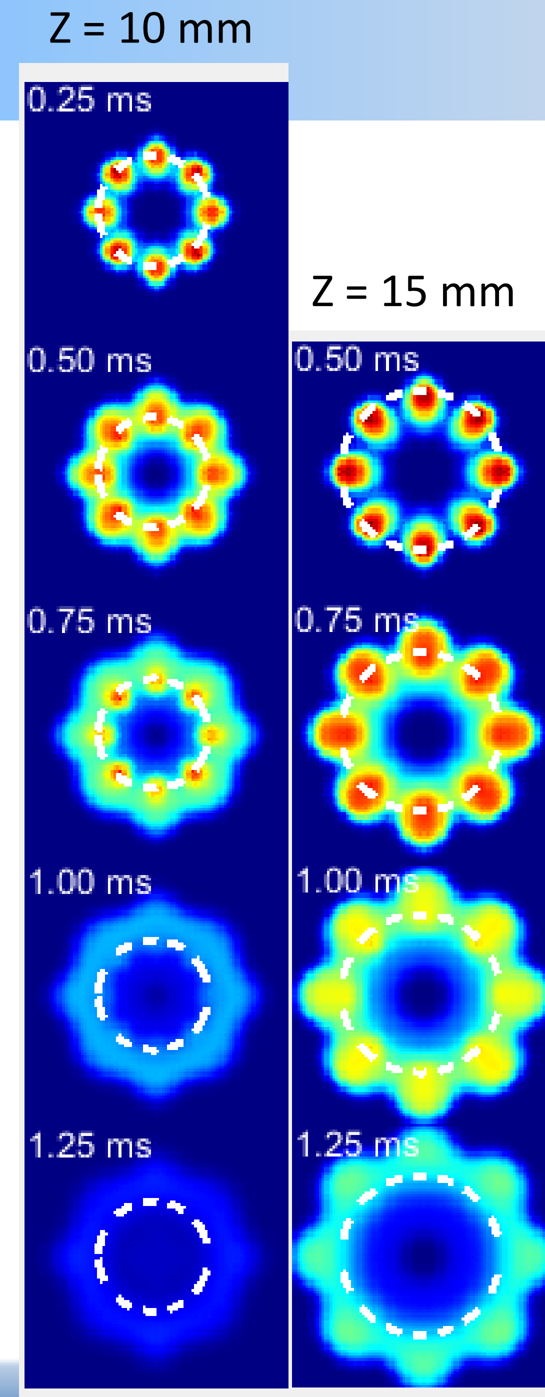
PoliMi RANS simulations





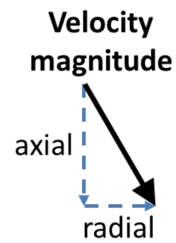
PoliMi RANS simulations



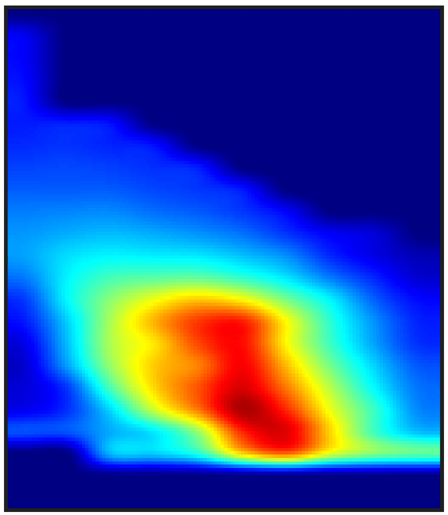


- Plume movement to injector axis does not happen in either Argonne or PoliMi RANS simulations
  - Different than experiment or LES simulations

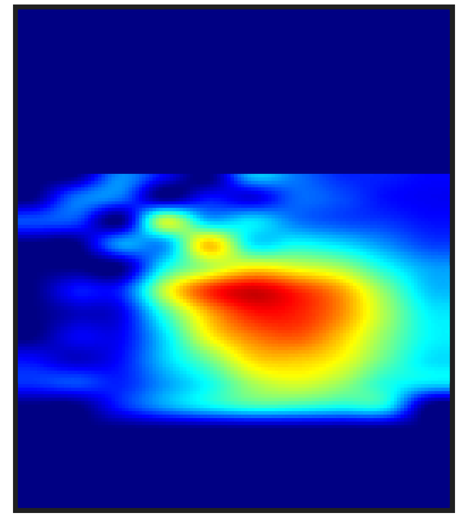
Plume center movement with time ASI



experimental
GM

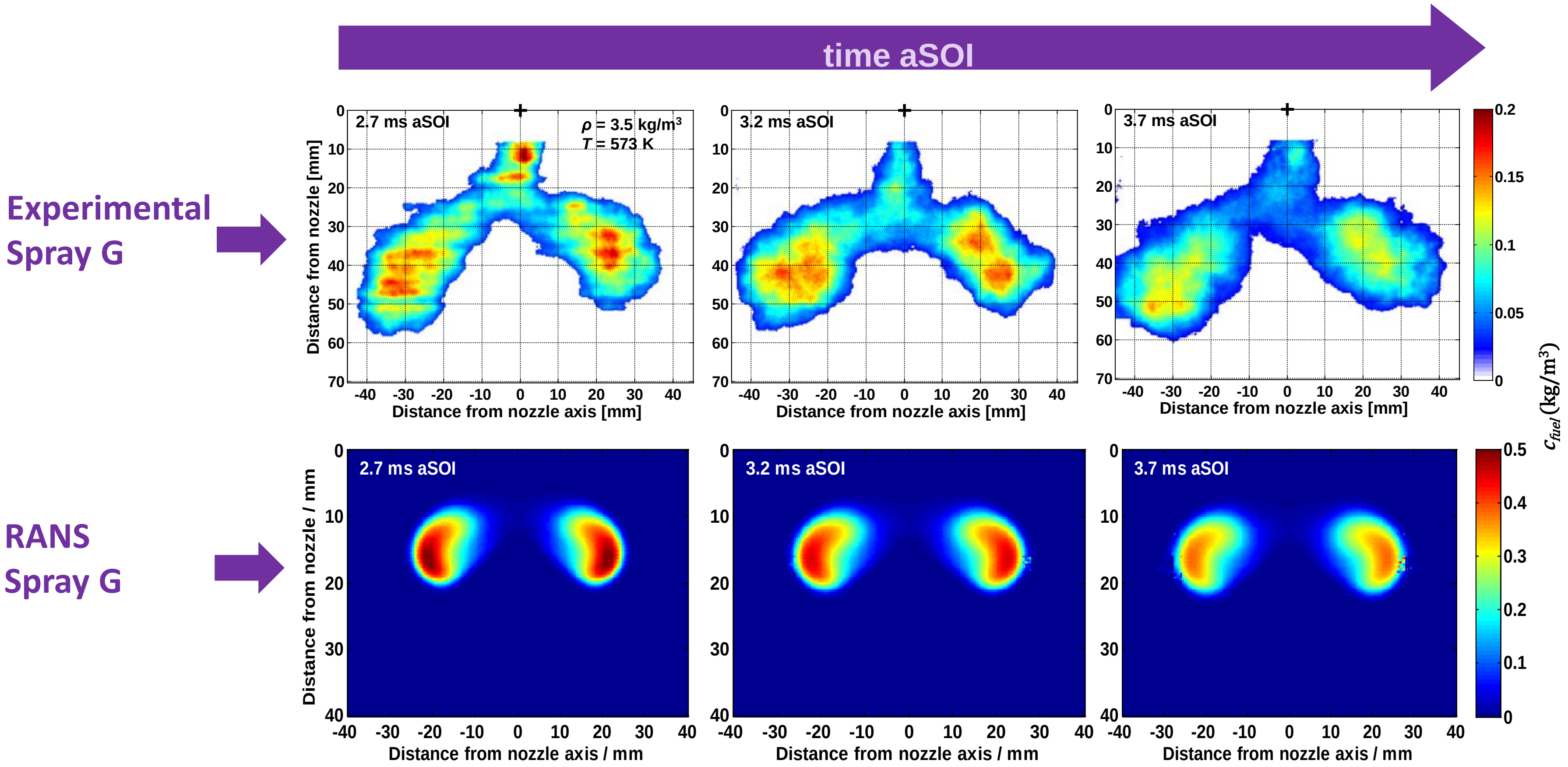


RANS model
PoliMi



Z = 15 mm

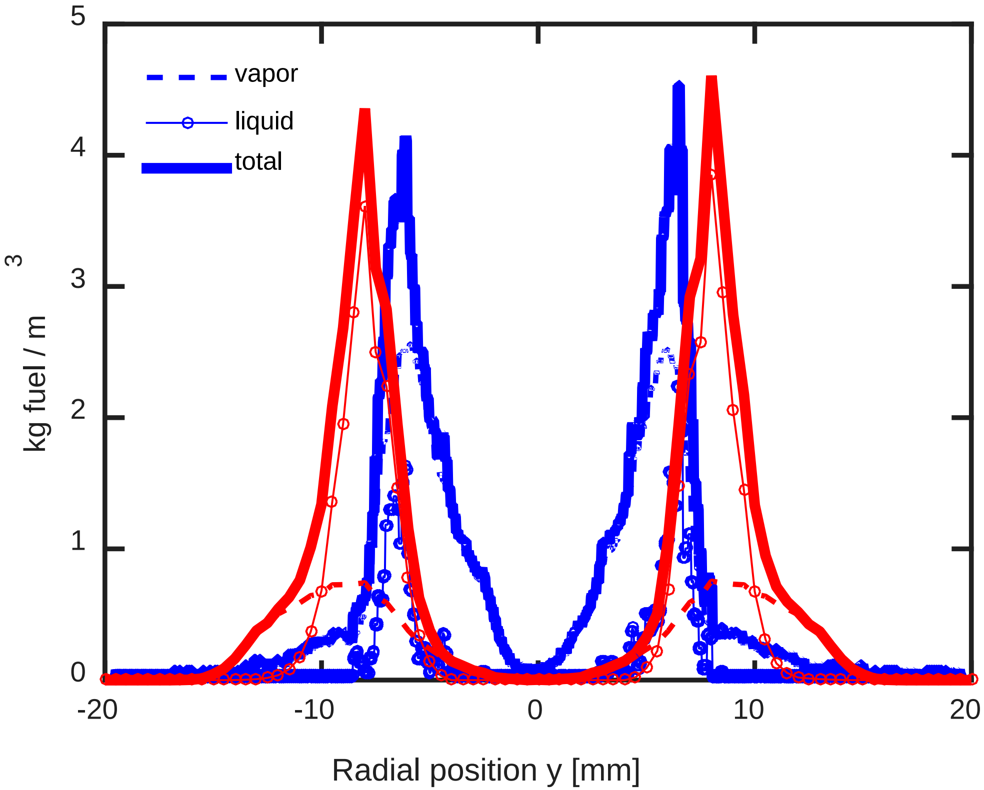
PoliMi RANS vs IFPEN mixing

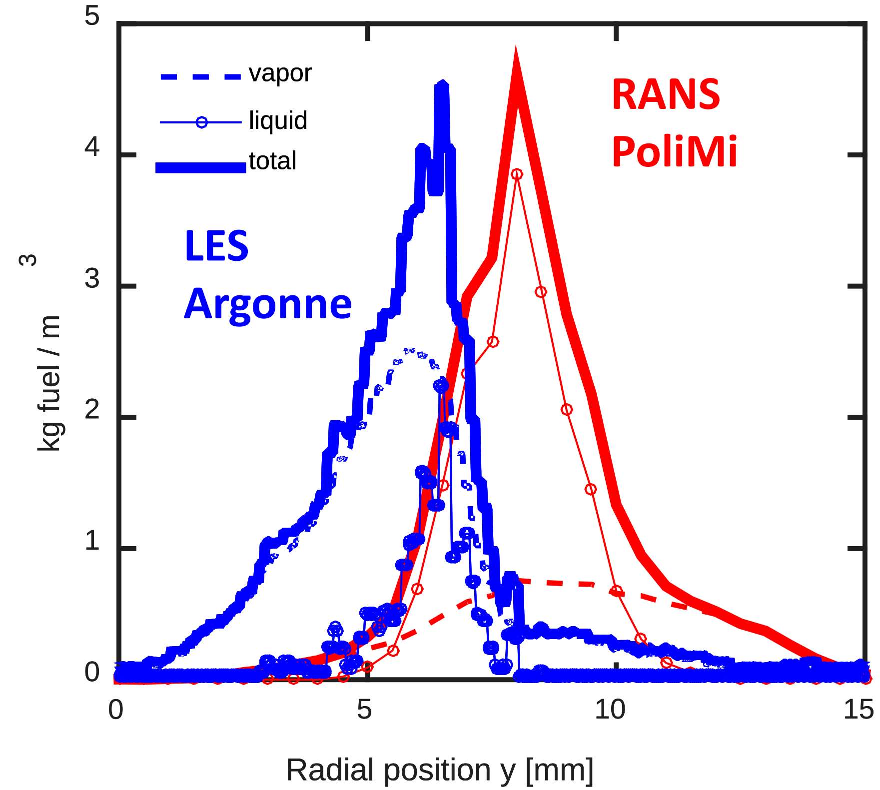


- Spray penetration RANS < LIF measurements
- Spray width/length RANS < LIF measurements

- Substantially more vaporization in the LES simulation

Z = 10 mm, 0.5 ms ASI

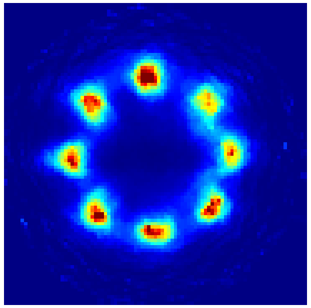




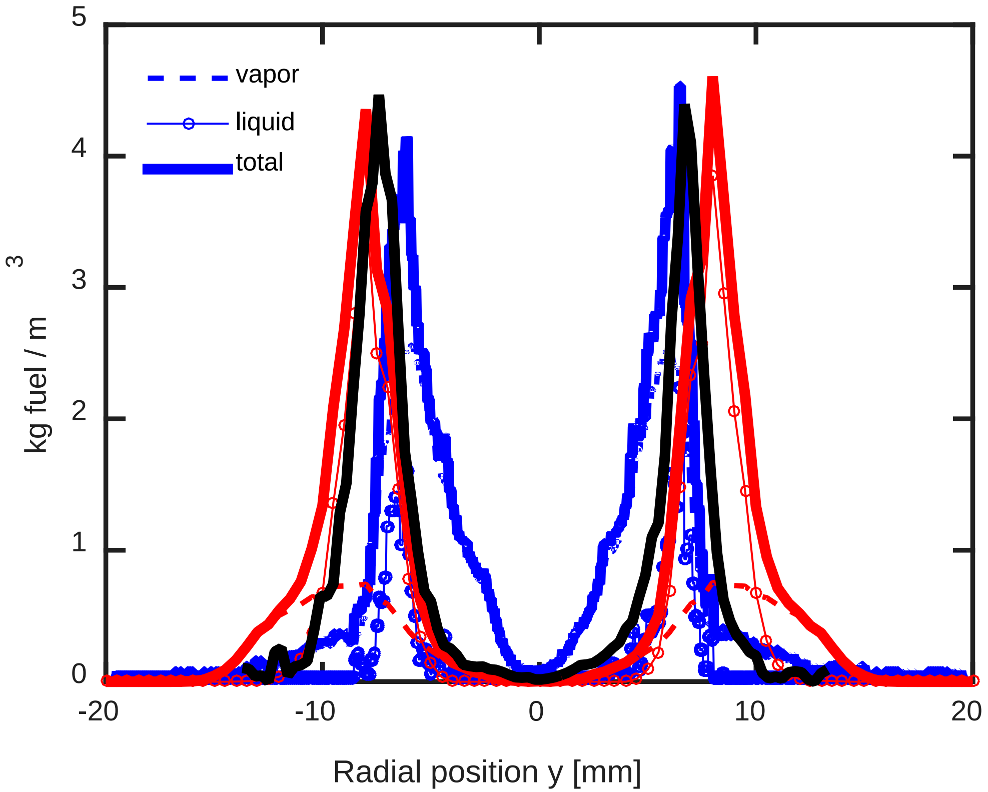
Is vaporization rate a factor for plume shift?

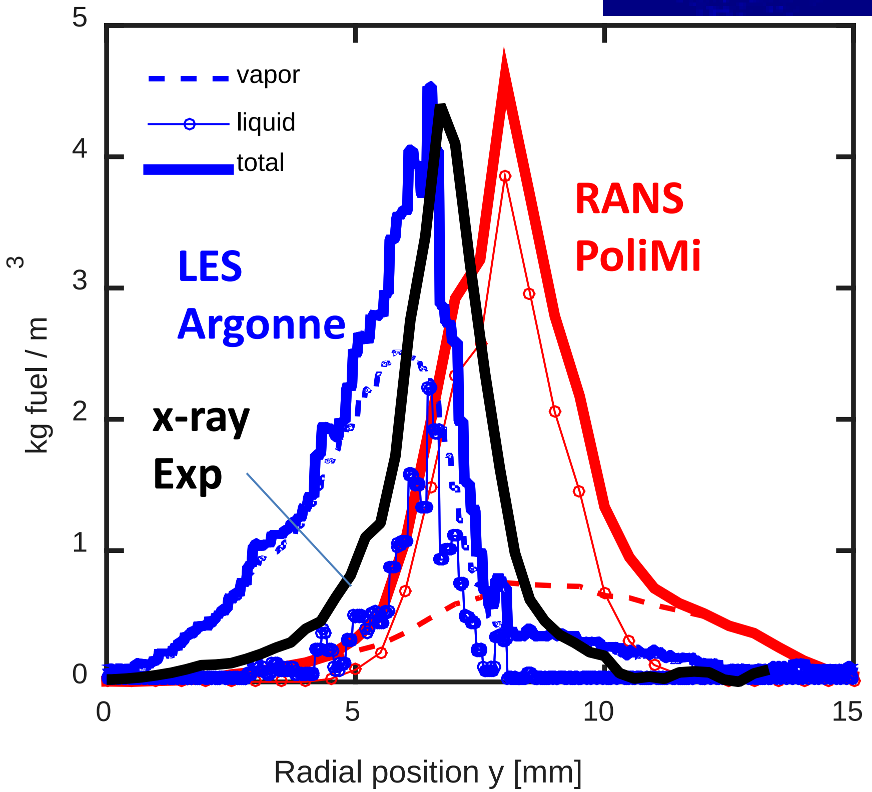
- Non-vaporizing radiography experiments show less plume dispersion
- Shift of plume center to injector axis more pronounced for LES simulation

Argonne radiography 0.5 ms ASI



Z = 10 mm, 0.5 ms ASI



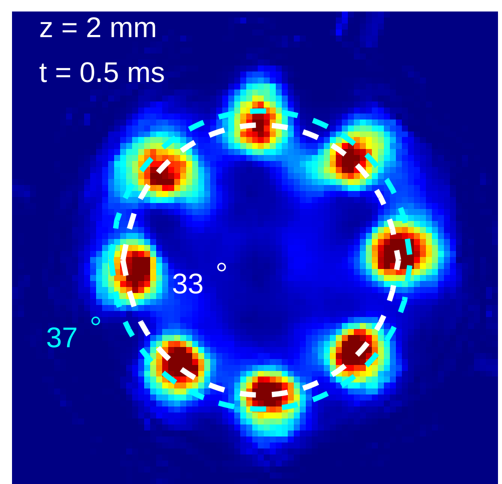


Questions for discussion

- Plume center moves toward injector axis during and after injection. What is the cause?
  - Experimental evidence is convincing
    - PDI velocity measurements at z = 15 mm indicate plume vector (or inclination angle) is $< 31^{\circ}$
    - Delphi patternation data show plume vector angle = 33°
    - Argonne radiography shows plume vector angle from 34° to 32° by z = 10 mm
    - Always less than drill angle (37°)
  - Quantitative data describing the velocity between plumes, time resolved during injection, would be useful.
  - Measurements showing the plume direction right at the exit of the nozzle are needed.
    - Closest radiography at z = 2 mm
  - Help from internal flow modeling is needed

Questions for discussion

- We need recommended practices for "affordable" CFD simulations
  - Lagrangian spray modeler with somewhat coarse mesh
  - What is best practice for specifying plume vector as a function of time?
  - For only "steady" period of injection: Drill angle is too large, downstream measurements too small (plume interaction driven)
  - What grid size is simply too coarse to pick up plume interaction?
  - Method for treating counterbore and tip geometry protrusion?



Argonne radiography kg fuel / m^3

Current weaknesses

- Experiments
  - Have not provided quantitative vapor/liquid in “mixed” regions
  - Radiography limited to non-vaporizing conditions
  - Droplet velocity measurements made, but gas/doplet velocity over larger ROI is needed
- CFD (Lagrangian)
  - Generally, RANS simulations too coarse to resolve inter-plume fluid mechanics
  - Do not consider that plume direction (moving out of the nozzle) changes with time
    - consider that small- and multi-injection cycles are common
  - Appear to have widely varying vaporization predictions