ECN 4.11 agenda

- 7h45 (PT) Connection test for presenters (audio/presentation sharing)

Welcome

- 8h00 ECN4.11 mechanics and update on ECN5 calendar/registration (Gilles Bruneaux)
- 8h10 “**Educated injection rate for Spray C/D**”, Raul Payri, CMT 10min
- 8h20 "**Multi-component vapor-liquid equilibrium model and application to ECN Spray A**", Jan Matheis, TUM, 15 min
- 8h35 “**Lift-off and soot characterization of Spray C and D**”, Noud Maes, IFPEn/Tue, 15 min
- 8h50 "**Study of ECN-spray A under inert and reacting conditions in a Rapid Compression Machine**", M. Ben-Houidi, J. Sotton, C. Strozzi, M. Bellenoue, Pprime Institute, 15min
- 9h05 “**On- and Off-Resonant CH2O Imaging and Transient Flame Development in Multiple Injections**”, Noud Maes, TU/e, 15min
- 9h20 “**RANS simulation of spray A with a tabulated flamelet combustion model and a sectional soot model**”, Olivier Colin, IFPEN, 15 min
- 9h35 “**Soot and spectral radiation modeling for Spray A**”, Dan Haworth, PSU, 15 min
- 9h50 End of meeting

ECN5

- ECN5 Friday march 31 and Saturday april 1, 2017,
  Prior to SAE World Congress
  Location: Wayne State University, Detroit
  Local organizer: Marcis Jansons

- Organization of the technical session is on going

To participate, contact the topic organizers (available on the website https://ecn.sandia.gov/ecn-workshop/ecn5-workshop/)

Check the guidelines and the corresponding submissions

- Registration of ECN5 at Wayne State is opened:

https://commerce.wayne.edu/events/engineering-events/ecn5-workshop-engine-combustion-network.html

The link will be sent to the participants after the webex.

- Early registration is encouraged
  - the number of registration will be limited
  - early registration fees until January 31

UNIVERSITAT POLITÈCNICA DE VALÈNCIA

motores térmicos

Engine Combustion Network web meeting

ECN 4.11. CMT Motores Térmicos

Educated Injection Rate for Spray C&D

November 3rd 2016

Raúl Payri
Jaime Gimeno
Mary Alarcón

Index

- Injector Numbering
- Methodology
- Set up
- Text matrix
- ROI data
- Educated Injection Rate
- Conclusions

Injector Numbering

Spray C – 210003
Spray C – 210034
Spray C – 210037*
Spray C – 210044
Spray C – 210105

$\varnothing_{nominal} = 200\ \mu m$
$K = 0$

Spray D – 209103
Spray D – 209104
Spray D – 209133
Spray D – 209134*
Spray D – 209135

$\varnothing_{nominal} = 180\ \mu m$
$K = 1.5$

*Previous tomography data available

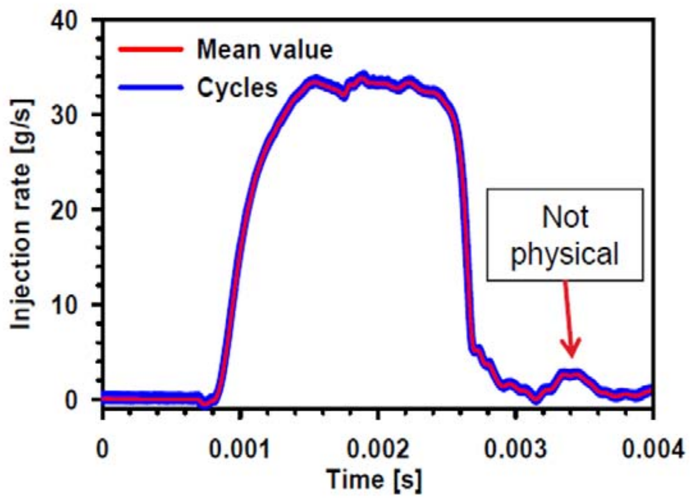
Methodology

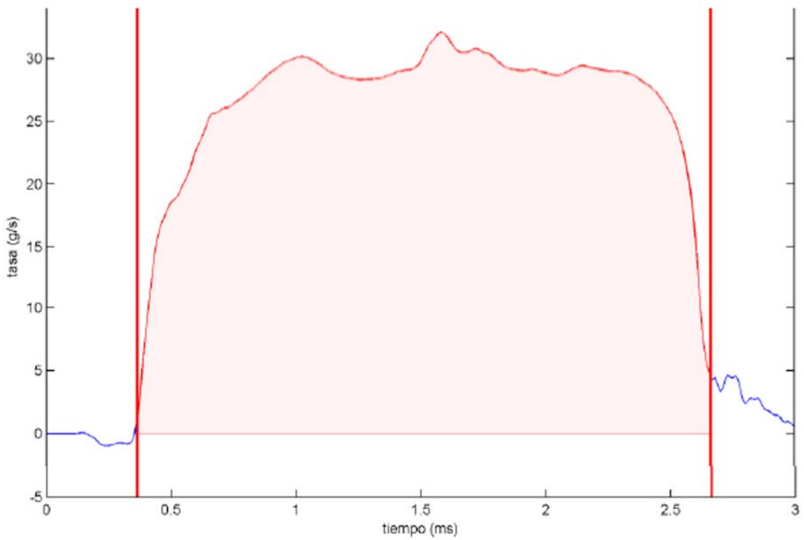
- To characterize the mass flow rate an ***EVI device based on Bosch method*** was used:

- The injected fuel produces an increment in the pressure inside the tube which is proportional to the mass flow rate.
- A pressure sensor detects this pressure increase and a data acquisition system further processes the recorded data and renders it visible.
- There is a proportional relationship between the integral value of the pressure signal and the total injected fuel mass.
- In order to validate the measurements, a gravimetric scales is used downstream of the EVI device.
- The Injection pressure is regulated in the common-rail and measured in the high pressure line.

Methodology

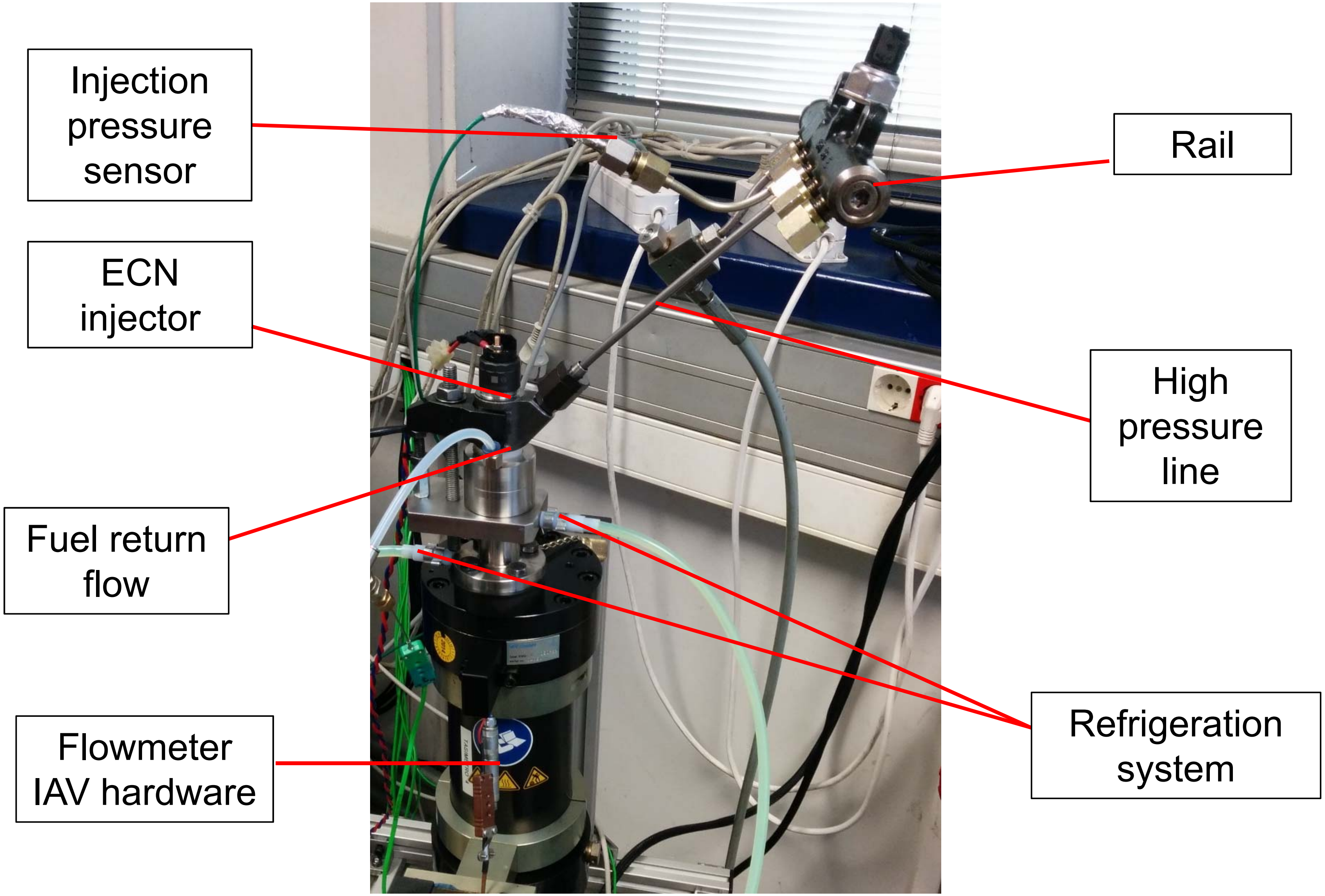
- **50** injections are performed: It means **50** curves of ΔP versus time.
- A coefficient factor is applied to the **50** curves in such a way that the integral of the mean curve should be the injected mass measured with the gravimetric balance.
- To set the integration limits, two points of the opening slope are taken and a linear fit is performed within them. The intersection of this fit with the X-axis yields the integration limit. The same applies for the closing slope.





- R. Payri, F.J. Salvador, J. Gimeno, G. Bracho, *A new methodology for correcting the signal cumulative phenomenon on injection rate measurements*, Experimental techniques. Volumen: 32 (1) pp. 46-49, 2008

Set-up

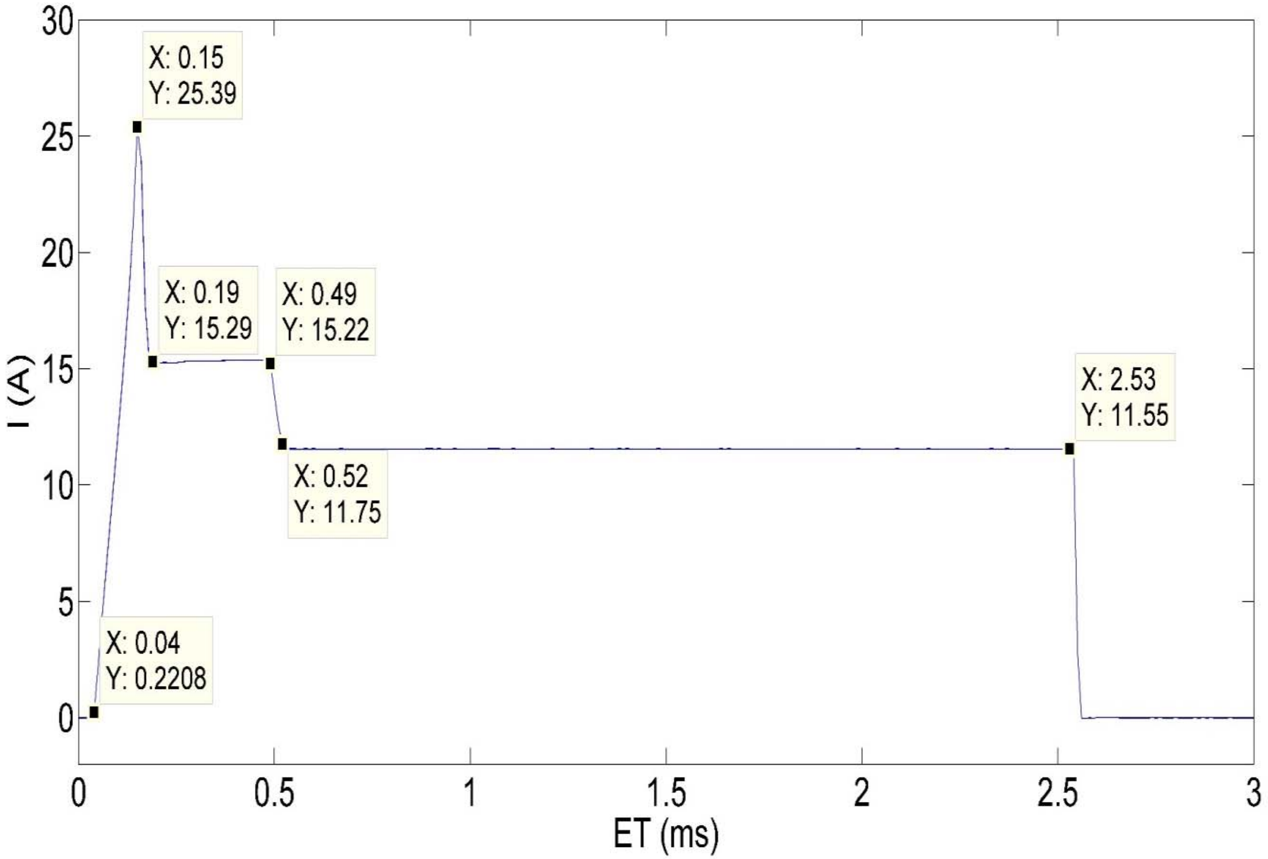

Injection pressure sensor
ECN injector
Fuel return flow
Flowmeter IAV hardware
Rail
High pressure line
Refrigeration system

Set-up

- High pressure line (200 mm) from rail to injector (M16 injector & M14 rail nuts), line internal diameter 3 mm.
- Rail with 22 cc volume and no flow restrictions in the connection to the line.
- Piece to collect return flow of the injector (will be supplied with the injectors)
- Injector body temperature 70 ºC (independent refrigeration system)

Set-up

- **Electrical signal of command**

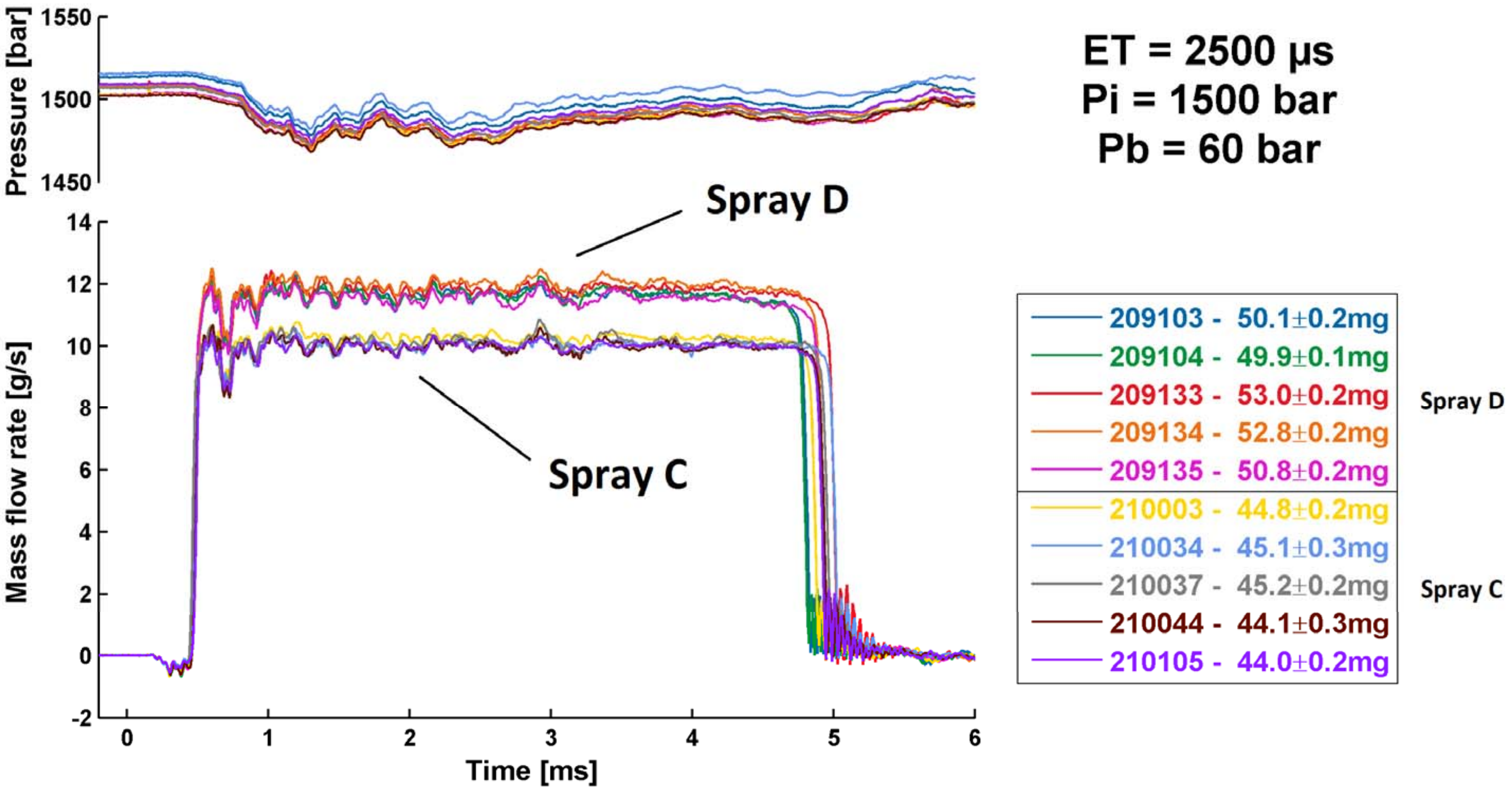


T_{dwell} = 500 µs
T_{boost} = 110 µs
T_{decay} = 15 µs
T_{h1} = 450 µs
T_{h2} = 1000/2500 µs

I_{boost} = 25 A
I_{h1} = 15 A
I_{h2} = 11 A

ROI data

- **Example result**



ROI data

- **Summarized mass flow rate data per orifice [g/s].**
  N-dodecane, 1500-60 bar.

Spray C	
Nozzle	Measured (g/s)
#210003	10.3
#210034	10.0
#210037	10.1
#210044	10.0
#210105	10.0
Mean	**10.1**

Spray D	
Nozzle	Measured (g/s)
#209103	11.7
#209104	11.6
#209133	11.8
#209134	11.9
#209135	11.5
Mean	**11.7**

The results are presented in the work: Payri, R., Gimeno, J., Cuisano, J., Arco, J. (2016). Hydraulic characterization of diesel engine single-hole injectors. Fuel, 180, 357-366. http://doi.org/10.1016/j.fuel.2016.03.083

Index

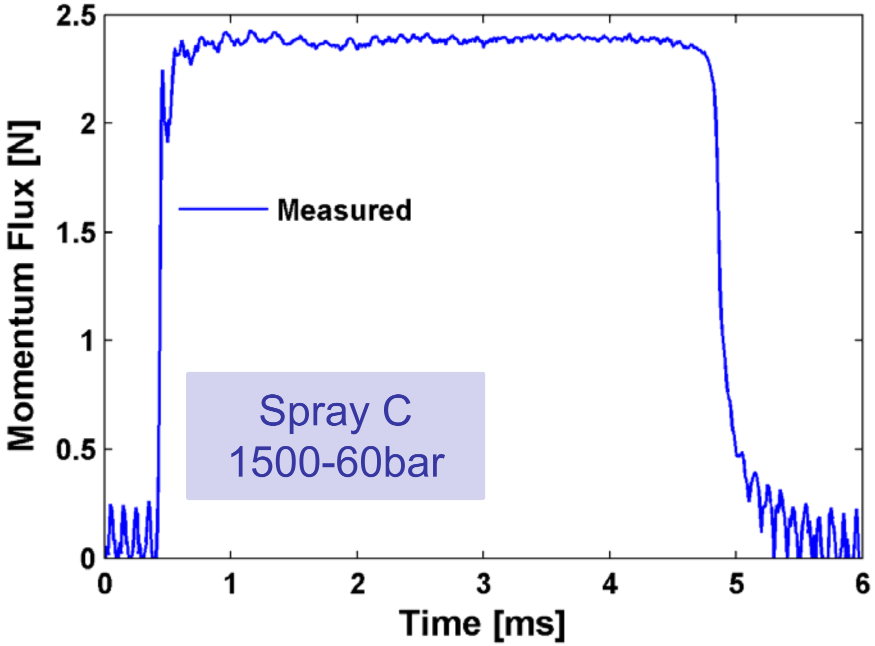
Educated Injection Rate

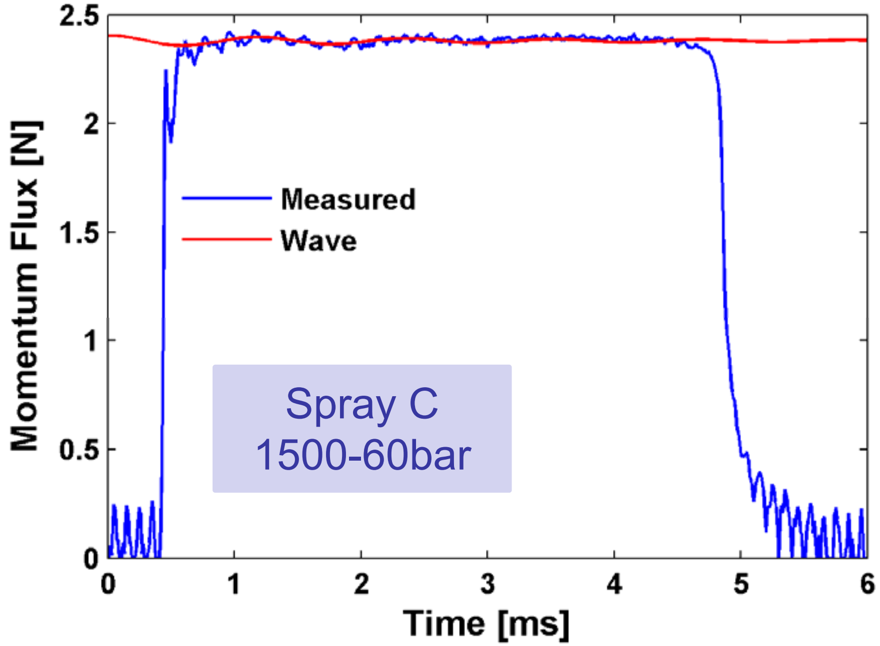
- **Signal can be divided in two parts:**
  1. **Wave expression** (from Momentum flux):
  2. Shape function

Shape function

$$\dot{m}(t) = \dot{m} \cdot W(t) \cdot S(t)$$

Wave expression



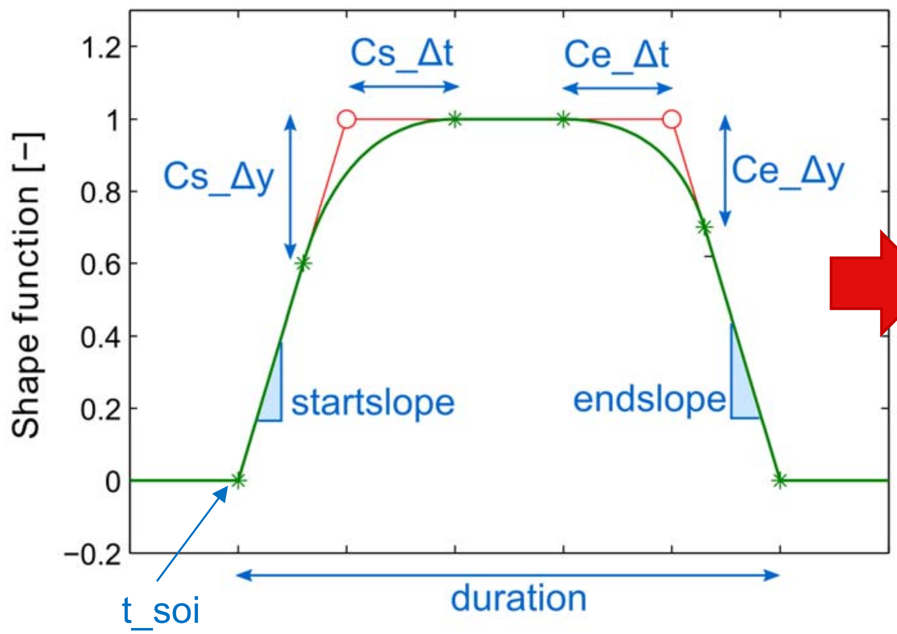


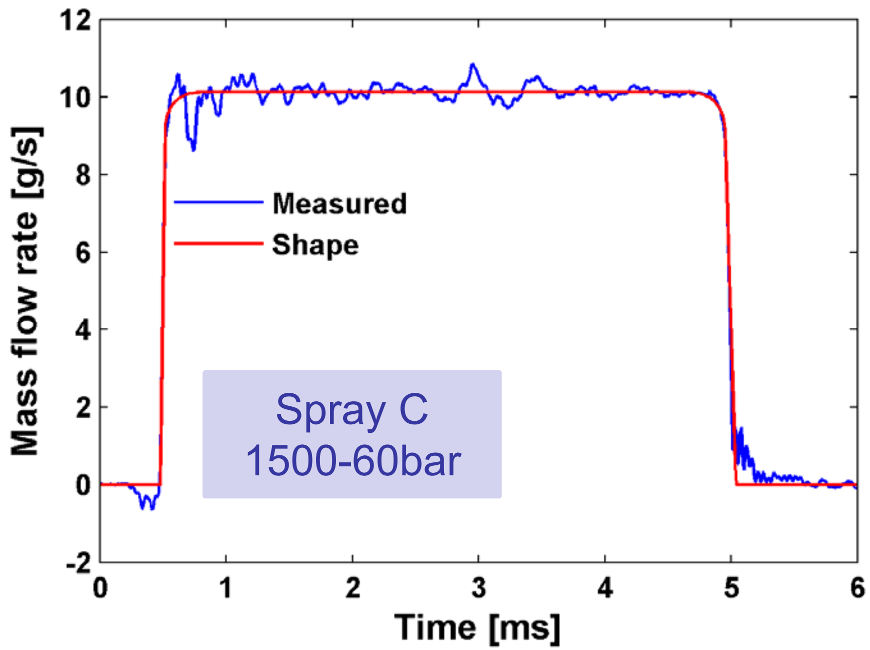
Educated Injection Rate

- **Signal can be divided in two parts:**
  1. Wave expression
  2. **Shape function:** Trapezoid with the corners softened using 2nd order Bezier curves.

Shape function

$$\dot{m}(t) = \dot{m} \cdot W(t) \cdot S(t)$$





Educated Injection Rate

- **Example results:** Spray C 1500-60bar. ET=2500μs

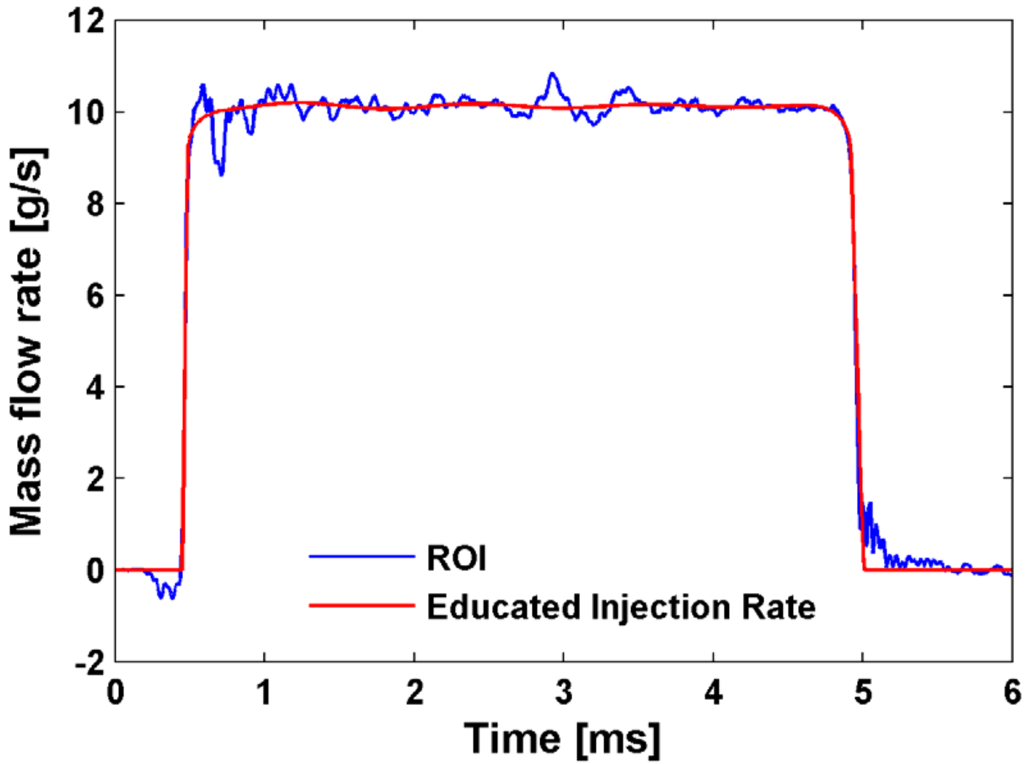
Stationary mass flow rate from ROI

Shape function from Momentum Flux

$$\dot{m}(t) = \dot{m} \cdot W(t) \cdot S(t)$$

Educated Injection Rate

Wave expression from ROI



Non-dimensional shape of ROI → $W(t) \cdot S(t)$

Raul Payri; Jaime Gimeno; Ricardo Novella; Gabriela Bracho, On the Rate of Injection Modelling applied to Direct Injection Compression Ignition Engines, IJER, doi: 10.1177/1468087416636281

Educated Injection Rate

- In order to generate a preliminary ROI, the nominal mass flow rate of the corresponding nozzle orifice is multiplied by the normalized non-dimensional shape of ROI.

Educated ROI = mass_flow * non-dim_ROI

- The references values of all nozzles can be downloaded here: http://www.cmt.upv.es/ECN05.aspx

- The normalized non-dimensional shape of ROI for long injection duration can be downloaded here: http://www.cmt.upv.es/ECN03.aspx

Conclusions

- Mass flow rate is higher for Spray D than for Spray C injectors.
- For the same injector type (C & D) and ET, slightly different closing times appear probably due to the difference in internal geometry from injector to injector.
- Injection duration is dependent on particular injector number.
- The hydraulic results are presented in the work: Payri, R., Gimeno, J., Cuisano, J., & Arco, J. (2016). Hydraulic characterization of diesel engine single-hole injectors. Fuel, 180, 357-366.

  http://doi.org/10.1016/j.fuel.2016.03.083

Multi-component vapor-liquid equilibrium model for LES and application to ECN Spray A

Jan Matheis[1] and Stefan Hickel[1,2]

[1] Institute for Aerodynamics and Fluid Mechanics, Technical University Munich, Germany.
[2] Faculty of Aerospace Engineering, Delft University of Technology, The Netherlands.

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Institute of Aerodynamics and Fluid Mechanics,
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Faculty of Aerospace Engineering,
Technische Universiteit Delft,
The Netherlands

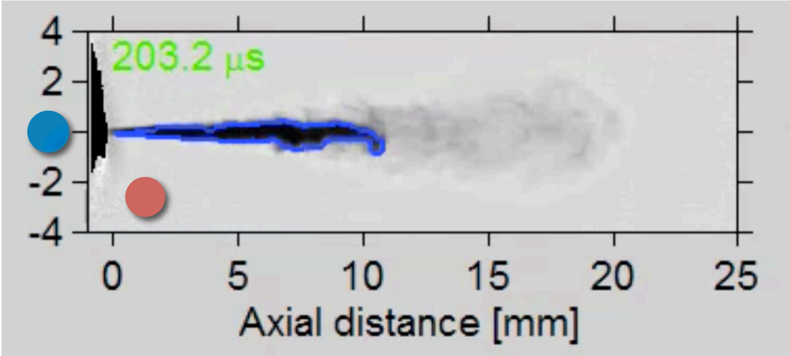
German Research Foundation
(Deutsche Forschungsgemeinschaft - DFG)
Collaborative Research Centre SFB TRR-40

Computational resources have been provided by the Leibniz Rechenzentrum München (LRZ).

Introduction

Test Case for LES: inert ECN Spray A

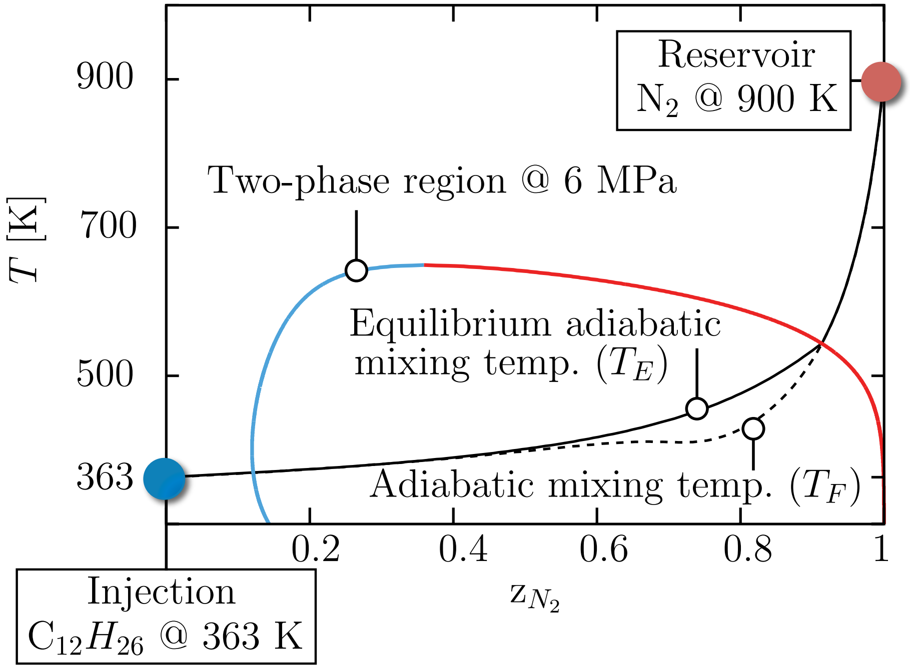
- n-dodecane jet **363K, ~600m/s**
- N_2 atmosphere at **900K, 6MPa**



http://www.sandia.gov/ecn/cvdata/assets/datafiles/liq/DBI675.php

Research Question:

- Spray A seems to be more on the subcritical branch[1]
  - How to take care of the two-phase region in a multi-component **Eulerian** framework?[2]



[1]Crua C., Manin J., and Pickett L. M. (2015) in ICLASS 2015

[2]Qiu, L. & Reitz, R. (2015) Int. J. of Multiphas. Flow **72**

Physical and Numerical Models (1/4)

Governing Equations

- Compressible multi-component Navier-Stokes equations

$$\partial_t \rho + \nabla \cdot (\rho \mathbf{u}) = 0$$

$$\partial_t \rho \mathbf{u} + \nabla \cdot (\rho \mathbf{u} \cdot \mathbf{u}^\top + \mathbf{I} p) = \nabla \cdot \boldsymbol{\tau}$$

$$\partial_t \rho Y_i + \nabla \cdot (\rho Y_i \mathbf{u}) = \nabla \cdot \mathbf{J}_i$$

$$\partial_t E + \nabla \cdot [(E + p)\mathbf{u}] = \nabla \cdot (\boldsymbol{\tau} \cdot \mathbf{u} - \mathbf{q})$$

- Viscosity and thermal conductivity by correlation of Chung *et al.* (1988)
- Diffusion coefficients according to Chapman and Enskog theory
- Navier-Stokes equations are closed by a thermodynamic model that relates pressure, temperature and density

Physical and Numerical Models (2/4)

Multi-Component Equation of State (EOS)

- Cubic EOS (Peng-Robinson: $u = 2, w = -1$)

$$p(\underline{v}, T, \mathbf{z}) = \frac{\mathcal{R}T}{\underline{v} - b} - \frac{a\alpha\,(T)}{\underline{v}^2 + u\,b\,\underline{v} + wb^2}$$

\underline{} := molar quantity

$\mathbf{z} = \{z_1 \ldots z_N\}$:= molar composition

- Extension to mixtures via van-der-Waals type mixing rules

$$a\alpha(T) = \sum_{i=1}^{N}\sum_{j=1}^{N} z_i z_j a_{ij}\alpha_{ij}(T) \qquad b = \sum_{i=1}^{N} z_i b_i$$

- Combining rules based on pseudo-critical parameters[1]

$$T_{c,ij} = \sqrt{T_{c,i}T_{c,j}}(1 - \delta'_{ij}), \quad p_{c,ij} = Z_{c,ij}(\mathcal{R}T_{c,ij}/v_{c,ij}), \quad \ldots$$

- Caloric properties (e.g. internal energy) via departure function formalism

$$\underline{e}(T, \underline{v}, \mathbf{z}) = \underline{e}^{\circ}(T, \mathbf{z}) + \int_{\infty}^{\underline{v}} \left[T \left.\frac{\partial p}{\partial T}\right|_{\underline{v}} - p \right] d\underline{v}$$

[1]Harstad, K., Miller, R. S. & Bellan, J. (1997) Efficient high-pressure state equations. AIChE J. 43 (6).

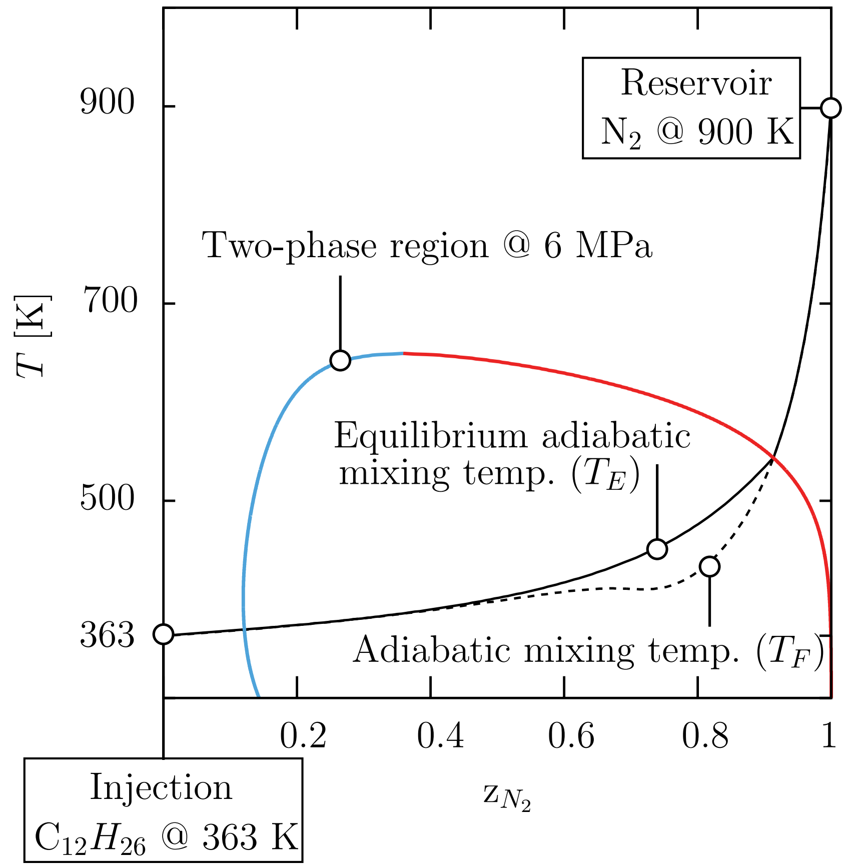
Physical and Numerical Models (3/4)

Multi-Component Two-Phase Model

- Input variables for thermodynamics solver:

$\underline{e}_{LES}$	(molar internal energy)	$\underline{v}_{LES}$	(specific molar volume)
$\mathbf{z}_{LES} = \{z_1, \ldots, z_N\}$	(overall molar composition)		

- Stability test of the thermodynamic state in each computational cell via "Tangent-Plane-Distance" function
  - **If stable**
    - Do nothing special (== Single-phase model)
  - **If unstable (within two-phase)**
    - Solve isochoric-isoenergetic flash problem



! Qiu, L. & Reitz, R. (2015) An investigation of thermodynamic states during high- pressure fuel injection using equilibrium thermodynamics. Int. J. of Multiphas. Flow **72**

! Michelsen M. L. and Mollerup J. M., Thermodynamic Models: Fundamentals & Computational Aspects. Tie-Line Publications, 2007

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Objective function:

$$F_e = \frac{\underline{e}_{LES} - \underline{e}(T, \underline{v}_{LES}, \mathbf{z}_{LES})}{\underline{e}_{LES}}$$

Iteration only of **temperature**

$$p = f(\underline{v}_{LES}, T, \mathbf{z}_{LES})$$

! Qiu, L. & Reitz, R. (2015) An investigation of thermodynamic states during high- pressure fuel injection using equilibrium thermodynamics. Int. J. of Multiphas. Flow **72**

! Michelsen M. L. and Mollerup J. M., Thermodynamic Models: Fundamentals & Computational Aspects. Tie-Line Publications, 2007

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  - **If stable**
    - Do nothing special (== Single-phase model)
  - **If unstable (within two-phase)**
    - Solve isochoric-isoenergetic flash problem

Objective function:

$$\mathbf{F} = \left\{ \frac{\underline{v}_{LES} - \underline{v}_{EQ}(T, p, \mathbf{z}_{LES})}{\underline{v}_{LES}}, \ldots \frac{\underline{e}_{LES} - \underline{e}_{EQ}(T, p, \mathbf{z}_{LES})}{\underline{e}_{LES}} \right\}$$

Simultaneous iteration of **temperature and pressure**

TPn Flash

$$\underline{e}_{EQ} = \psi_v \, \underline{e}_v + (1 - \psi_v)\underline{e}_l$$

$$\underline{v}_{EQ} = \psi_v \, \underline{v}_v + (1 - \psi_v)\underline{v}_l$$

$$v_l = f(T, p, \mathbf{x}) \qquad \underline{e}_l = f(T, \underline{v}_l, \mathbf{x})$$

$$v_v = f(T, p, \mathbf{y}) \qquad \underline{e}_v = f(T, \underline{v}_v, \mathbf{y})$$

$$\psi_v = f(T, p, \mathbf{z}) := \text{Vapor fraction}$$

$$\mathbf{y} = \{y_1, \ldots, y_N\} := \text{Vapor phase comp.}$$

$$\mathbf{x} = \{x_1, \ldots, x_N\} := \text{Liquid phase comp.}$$

! Qiu, L. & Reitz, R. (2015) An investigation of thermodynamic states during high- pressure fuel injection using equilibrium thermodynamics. Int. J. of Multiphas. Flow **72**

! Michelsen M. L. and Mollerup J. M., Thermodynamic Models: Fundamentals & Computational Aspects. Tie-Line Publications, 2007

Physical and Numerical Models (4/4)

Discretization Method and Turbulence Model

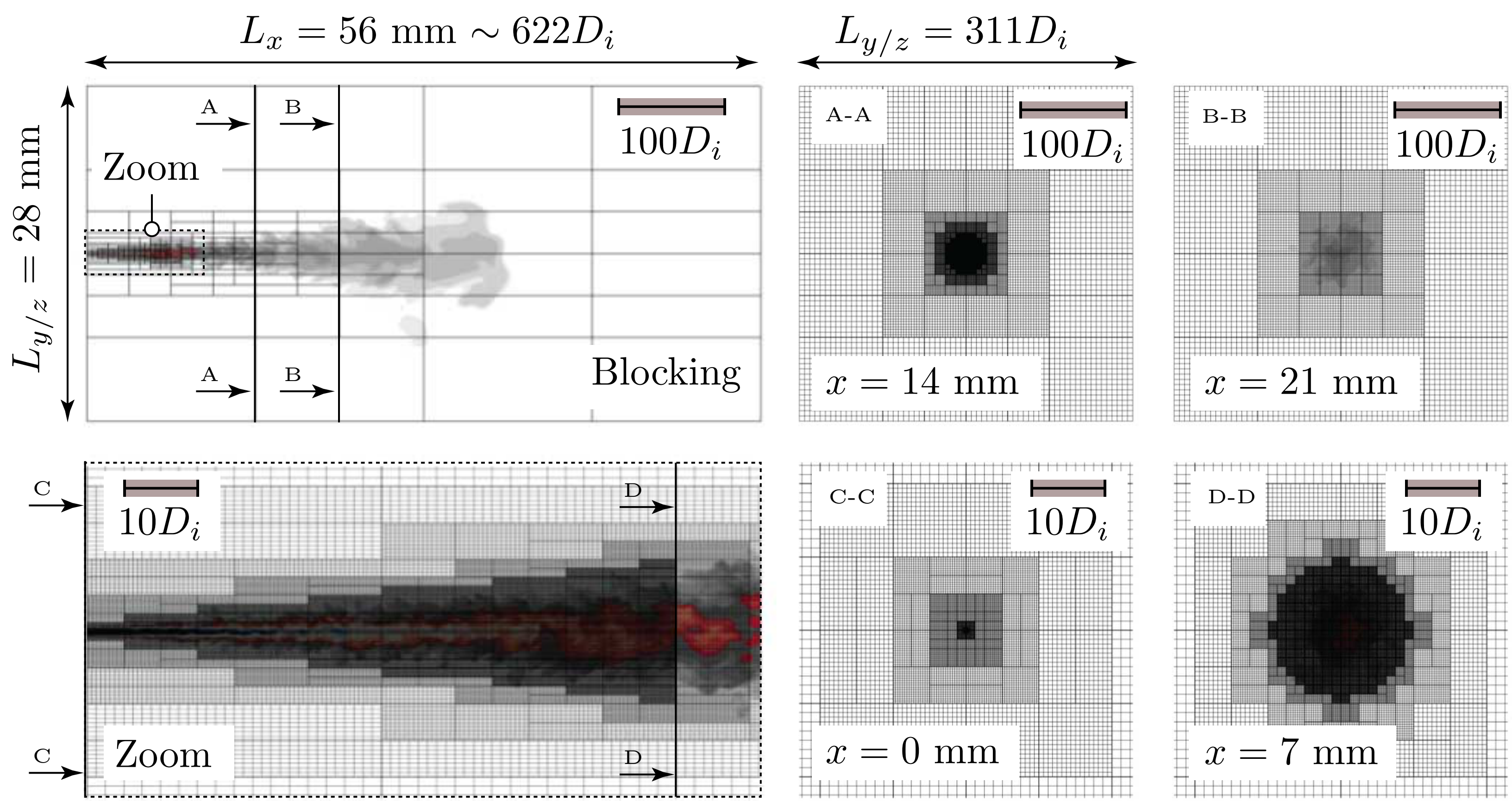
Finite Volume Method: *INCA*

- Spatial discretization for implicit LES:
  - Advection terms in momentum eqn.: Adaptive Local Deconvolution Method[1]
  - Advection of mass and internal energy 2nd order upwind biased numerical flux function with van Albada limiter
  - Viscous fluxes: 2nd order central scheme
- Explicit time marching:
  - 3rd order Runge-Kutta
- Adaptive Cartesian grids.

[1] Hickel, S., Egerer, C. P., Larsson, J., (2014) Subgrid-scale modeling for implicit large eddy simulation of compressible flows and shock-turbulence interaction. Physics of Fluids **26**, 106101.

Numerical Setup (1/2)

Geometry and Grid

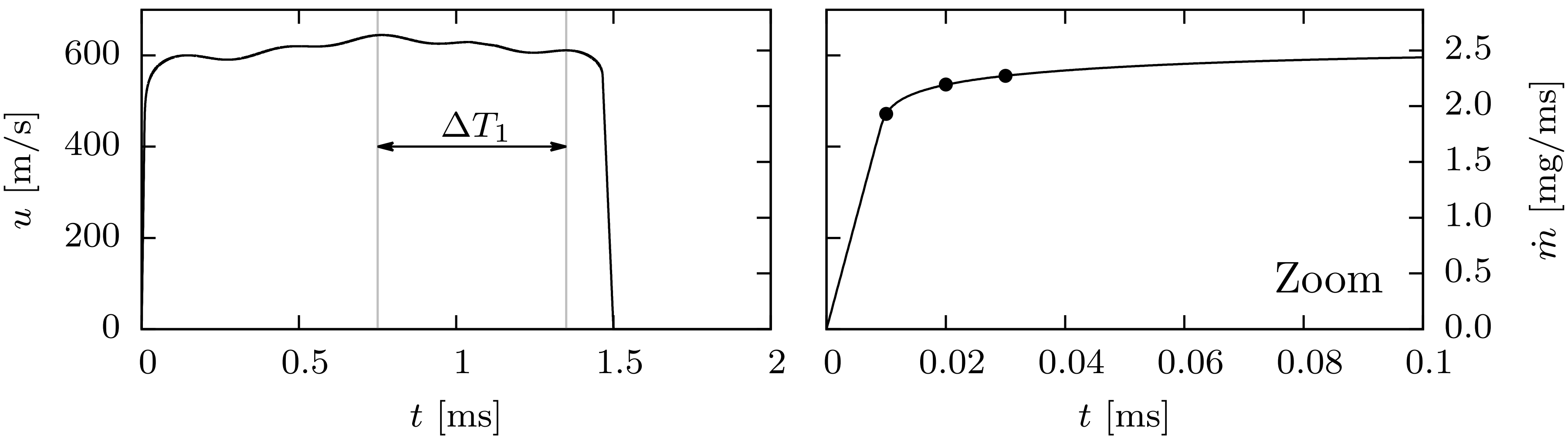


- Cartesian block-structured grid with 7 levels of static local refinement
- 2766 blocks with a total of about 15.1 mio. cells
- $\Delta y_{min} = \Delta z_{min} \sim 6.84\ \mu m$ | $\Delta y_{max} = \Delta z_{max} \sim 0.44$ mm (~ 13 cells per D_i)
- Run on 1918 CPUs (Intel Xenon E5-260 à 2.7GHz) at LRZ SuperMUC

Numerical Setup (2/2)

Boundary Conditions

- Transient mass flow rate imposed on inflow patch
  - No nozzle attached to domain: velocity block profile, no inflow turbulence
  - Data from http://www.cmt.upv.es/ECN03.aspx



- Subsonic outflow with p = 6 MPa
- All walls are modeled as adiabatic

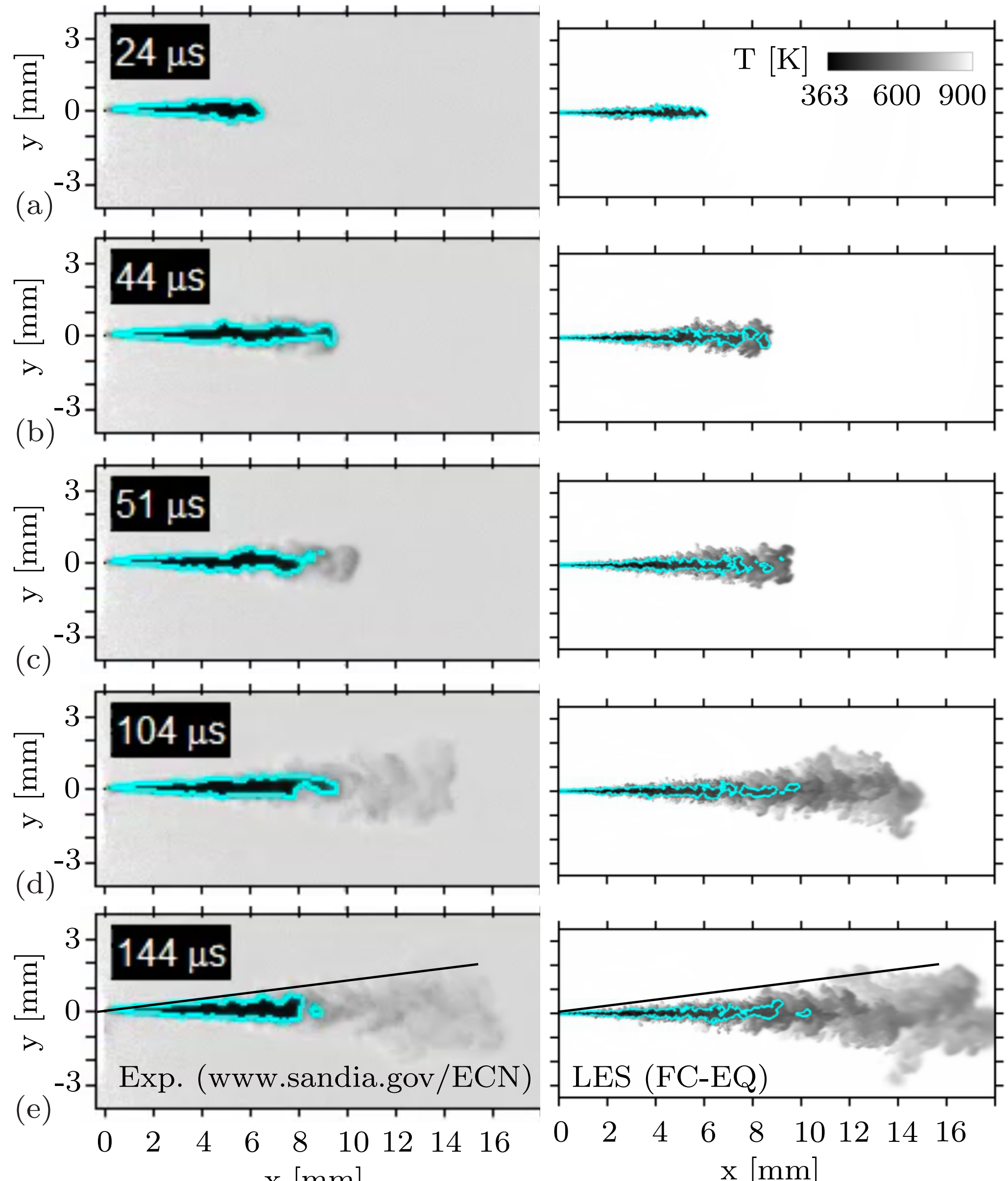
LES of ECN Spray A

Comparison to Experimental Data (1/3)

Qualitative:

- good agreement between FC-EQ LES model and Experiment

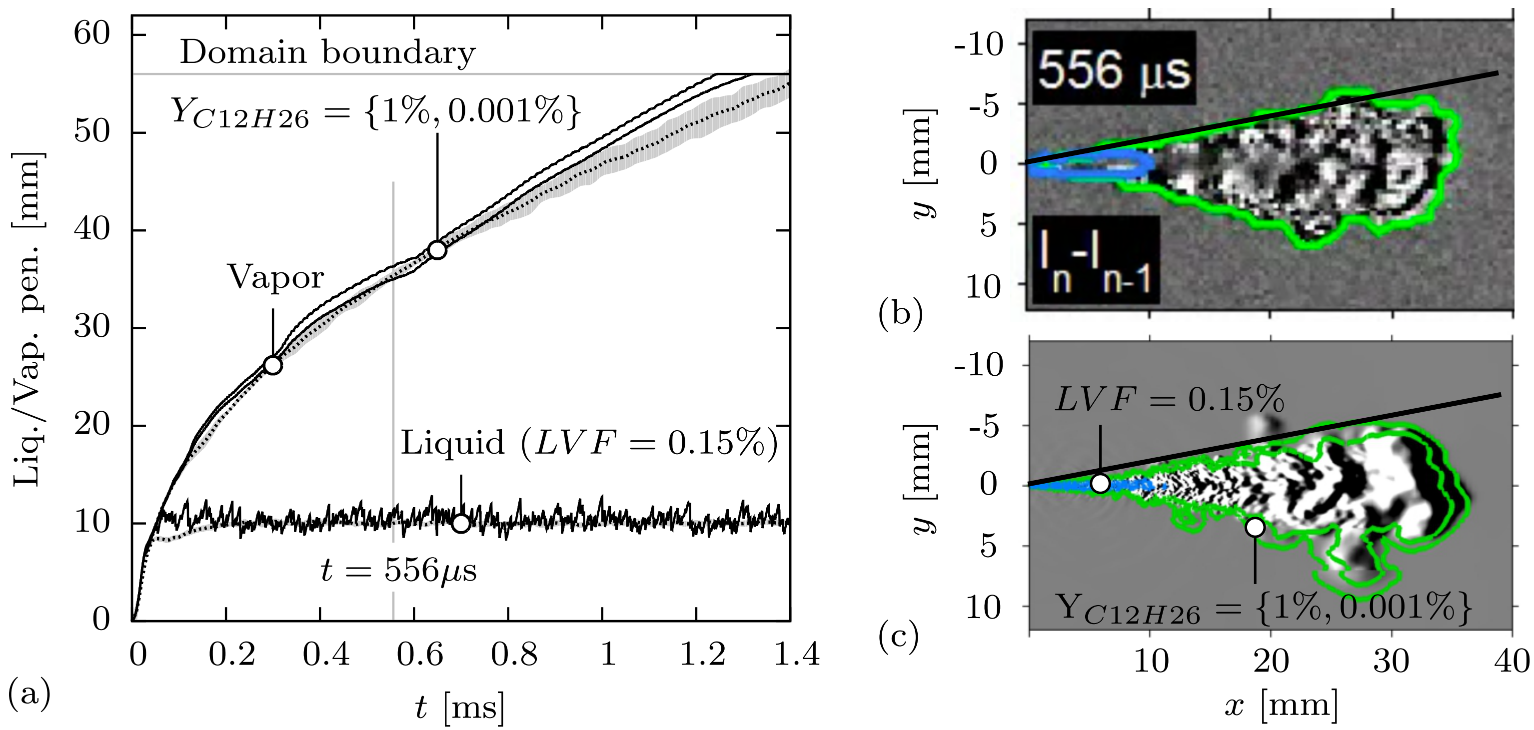
- Liquid penetration length (L_l) visualized as iso-contour line along which the liquid volume fraction LVF = 0.15%



Experimental data: http://www.sandia.gov/ecn/cvdata/assets/movies/bkldaAL1movie.php

LES of ECN Spray A

Comparison to Experimental Data (2/3)

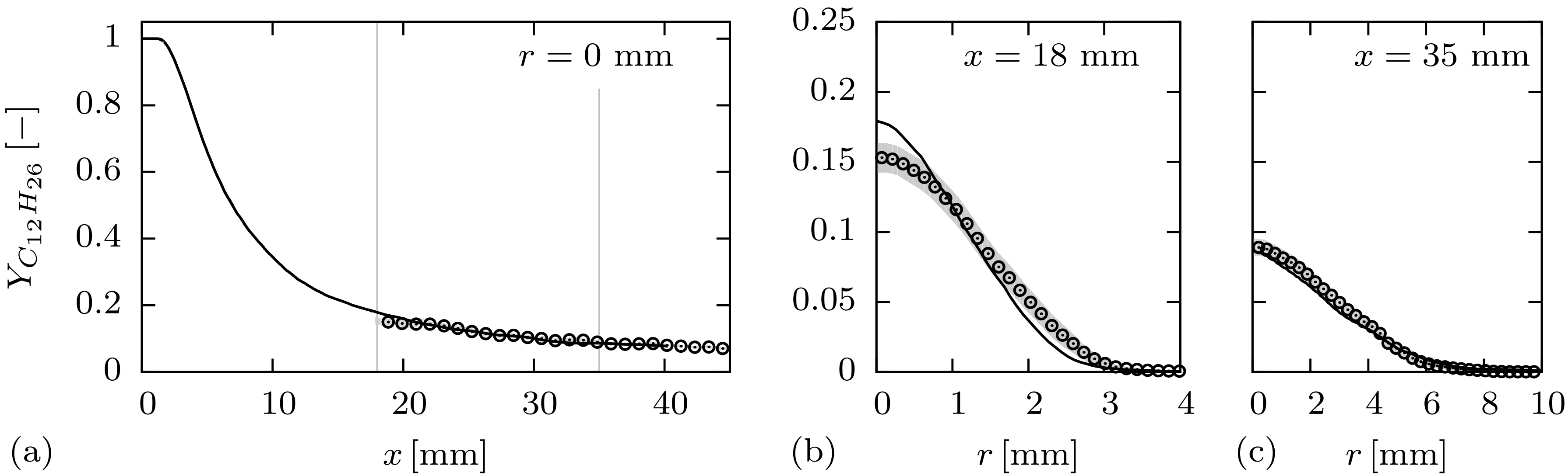


- L_l is defined as max{x(LVF = 0.15%)}
  - Excellent agreement with experimental time resolved signal
  - mean(L_l) = {8.83, 9.91, 10.40, 10.49} mm for LVF = {3%, 1%, 0.15%, 0.05%}
- Vapor penetration is defined as max{x(Y_{C12H26} = 1% / 0.001%)}
  - Good agreement up to ~0.6 ms; slight over prediction at t > 0.8ms

Experimental data: http://www.sandia.gov/ecn & Pickett, L. M. et al (2011) Measurement Uncertainty of Liquid Penetration in Evaporating Diesel Sprays. In Proceedings of the 23rd Annual Conference on Liquid Atomization and Spray Systems

LES of ECN Spray A

Comparison to Experimental Data (3/3)

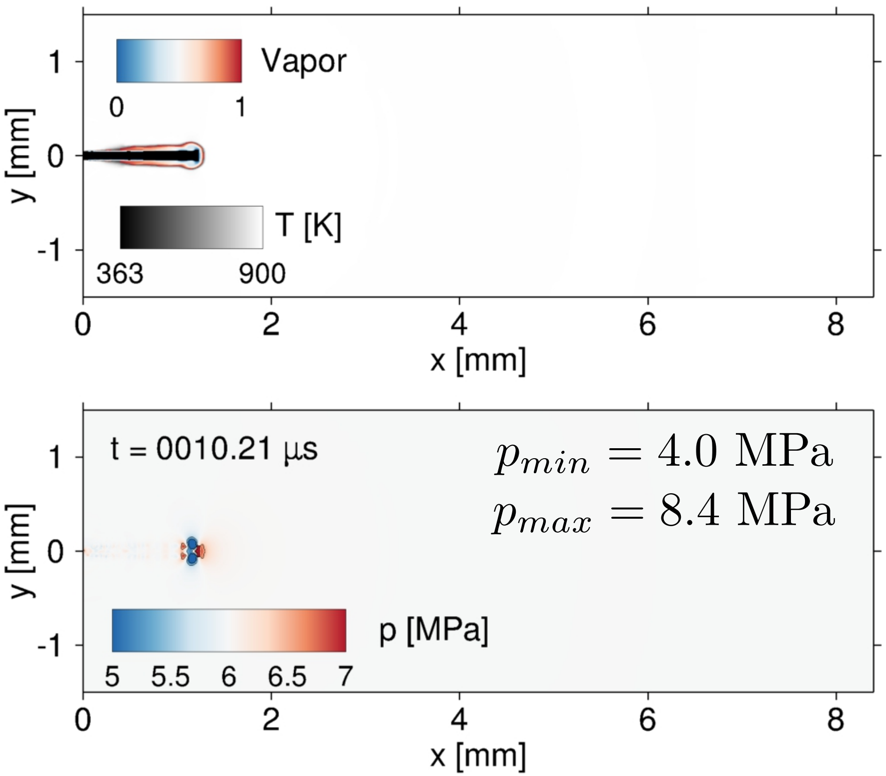


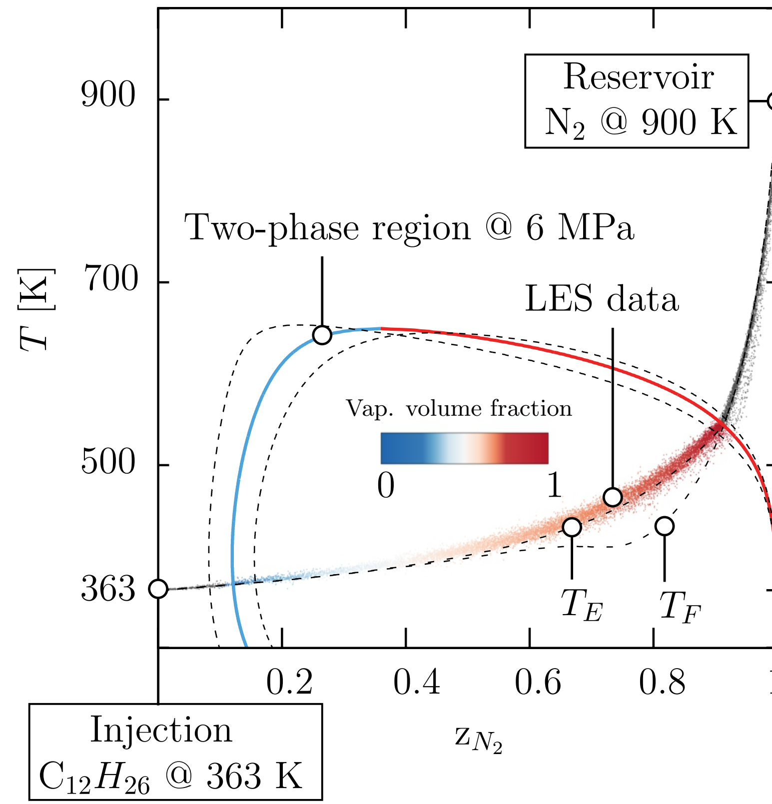
- Overall good agreement with experimental data
- Over-prediction of the mixture fraction at 18mm, very good agreement at 35mm
- Looking forward to new experimental data from Sandia (see ECN4.6)

> › Confidence in numerical approach
> - NOTE: No parameter fitting!
> - What will affect the results?
>   Turbulence model, EOS, Binary interaction parameter, Numerics (!)

LES of ECN Spray A

Early Injection Event

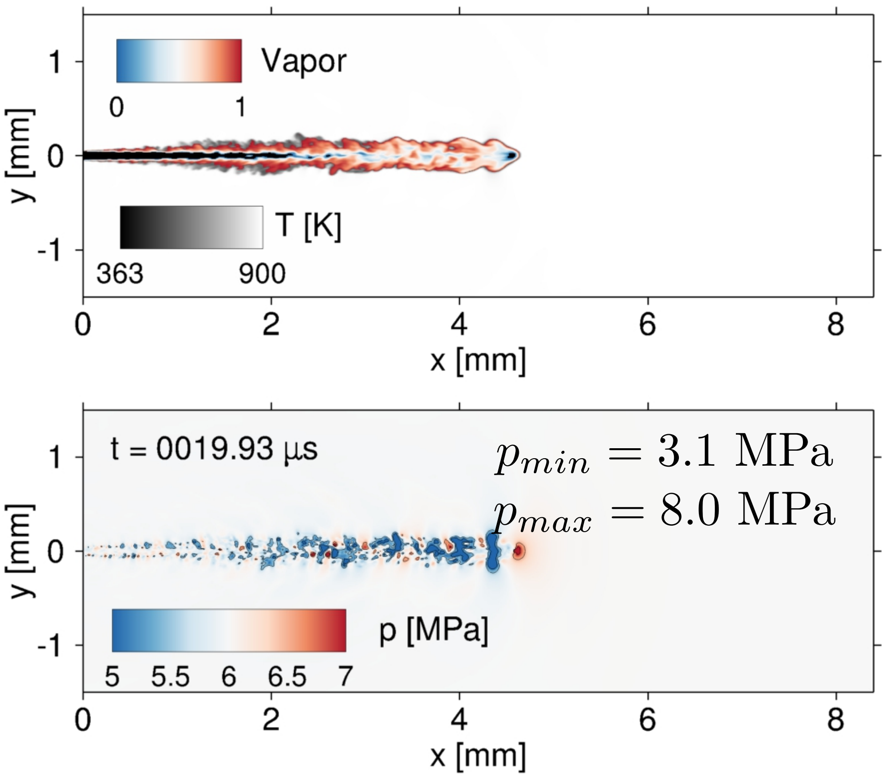


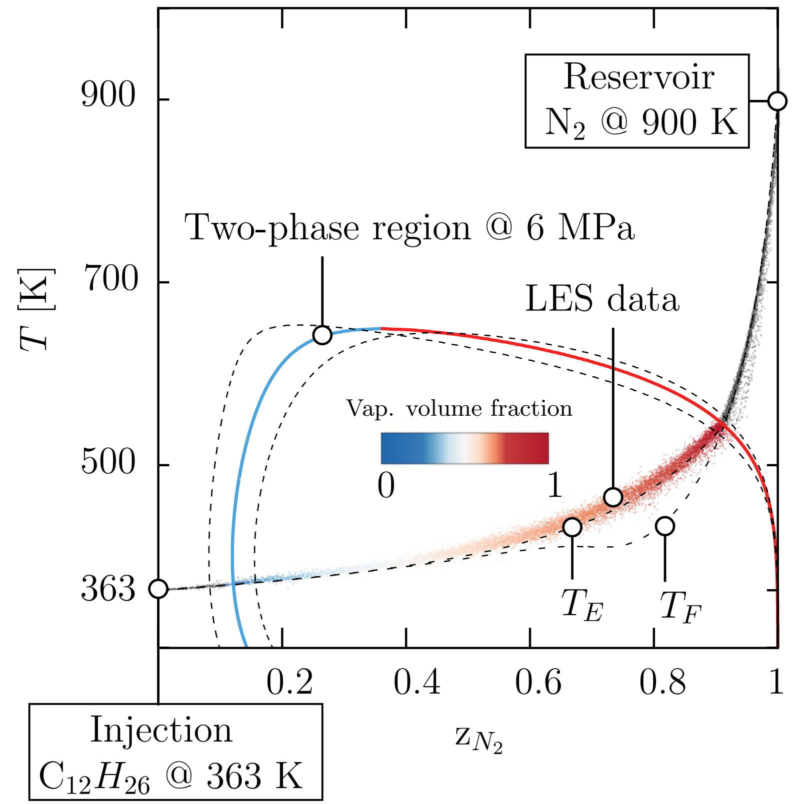


- Very low pressure (~ 3 MPa) at the tip of the jet due to the start-up vortex ring
- Local pressure much different from the average ambient pressure
  - Fully developed steady state pressure fluctuations in the shear layer in the order of ±10 bar.
- Single-phase PR EOS with pseudo-critical mixing rules here insufficient

LES of ECN Spray A

Early Injection Event





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LES of ECN Spray A

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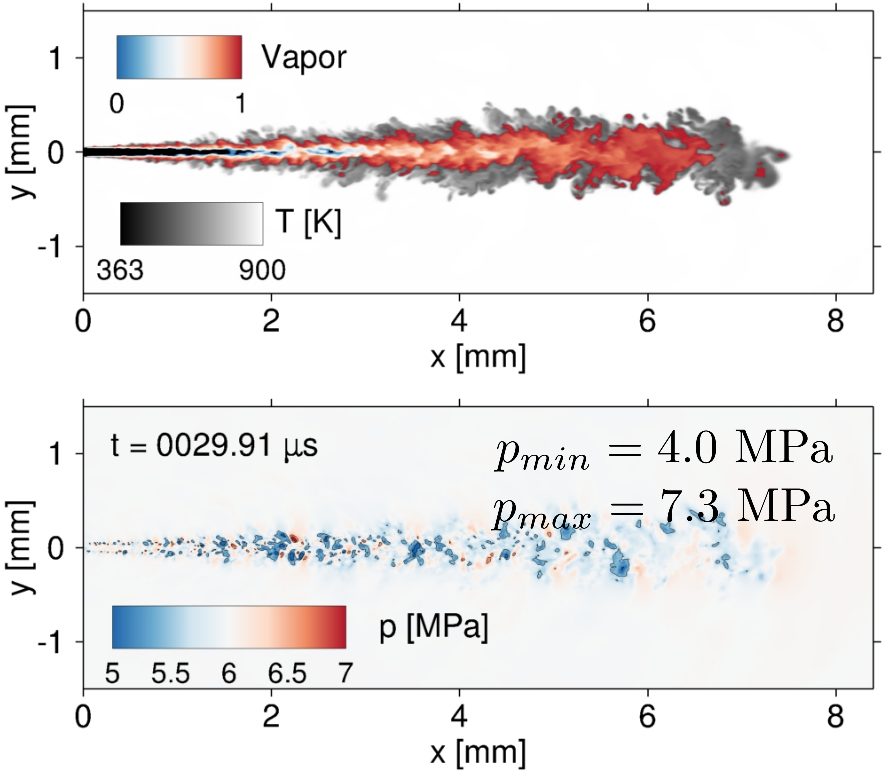

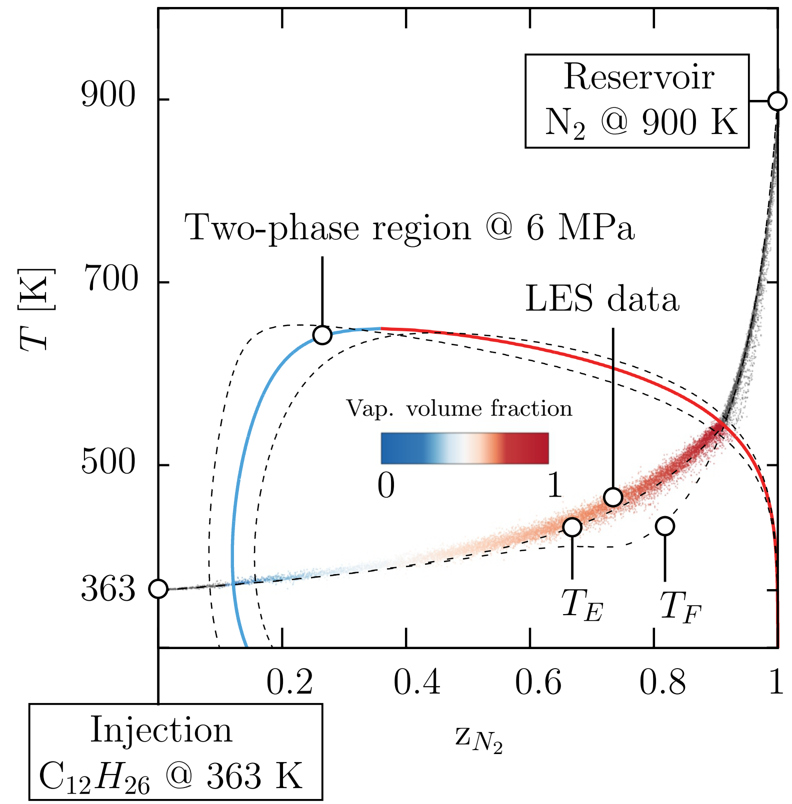

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Conclusions

- **High-fidelity Eulerian LES of ECN Spray A with fully conservative Vapor-Liquid-Equilibrium (VLE) model**
  - Very good agreement between LES and available experimental data
  - Non-arbitrary definition of the liquid penetration length via liquid volume fraction
  - No fitting of model parameters to match experimental data
  - VLE calculations seem necessary for a **stable and physically meaningful** Eulerian LES of Spray A

Preliminary CTR report available under:

https://arxiv.org/abs/1609.08533

LIFT-OFF AND SOOT CHARACTERIZATION OF SPRAY C & D

ECN FRANCE 2016 CAMPAIGN – PRELIMINARY RESULTS

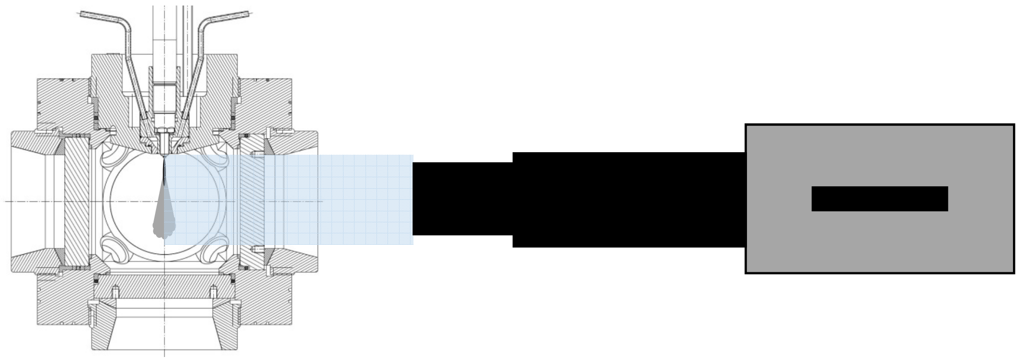
NOUD MAES (TU/e), MICHELE BARDI,
LOUIS-MARIE MALBEC, GILLES BRUNEAUX

CONTENT

- Spray C & D – campaign design
- Preliminary results
  - Lift-off trends & transients
  - 2D soot extinction - LED VS laser (Cavitar)
  - Soot trends & transients
- Conclusions and future work

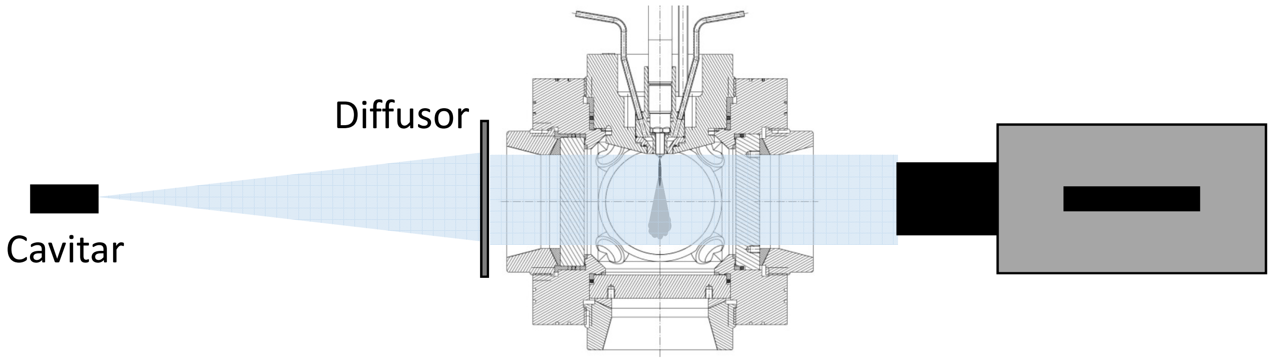
SPRAY C & D - CAMPAIGN DESIGN

- Optical diagnostic techniques:
  - Schlieren - (vapor phase)
  - Diffused back-illumination (DBI) - (liquid phase)
  - High-speedOH* chemiluminescence - (high-temperature reactions, FLOL, ID)



SPRAY C & D - CAMPAIGN DESIGN

- Optical diagnostic techniques:
  - Schlieren - (vapor phase)
  - Diffused back-illumination (DBI) - (liquid phase)
  - High-speed OH* chemiluminescence - (high-temperature reactions, FLOL, ID)
  - High-speed 2D soot extinction DBI
    - LED based
    - High-speed laser based



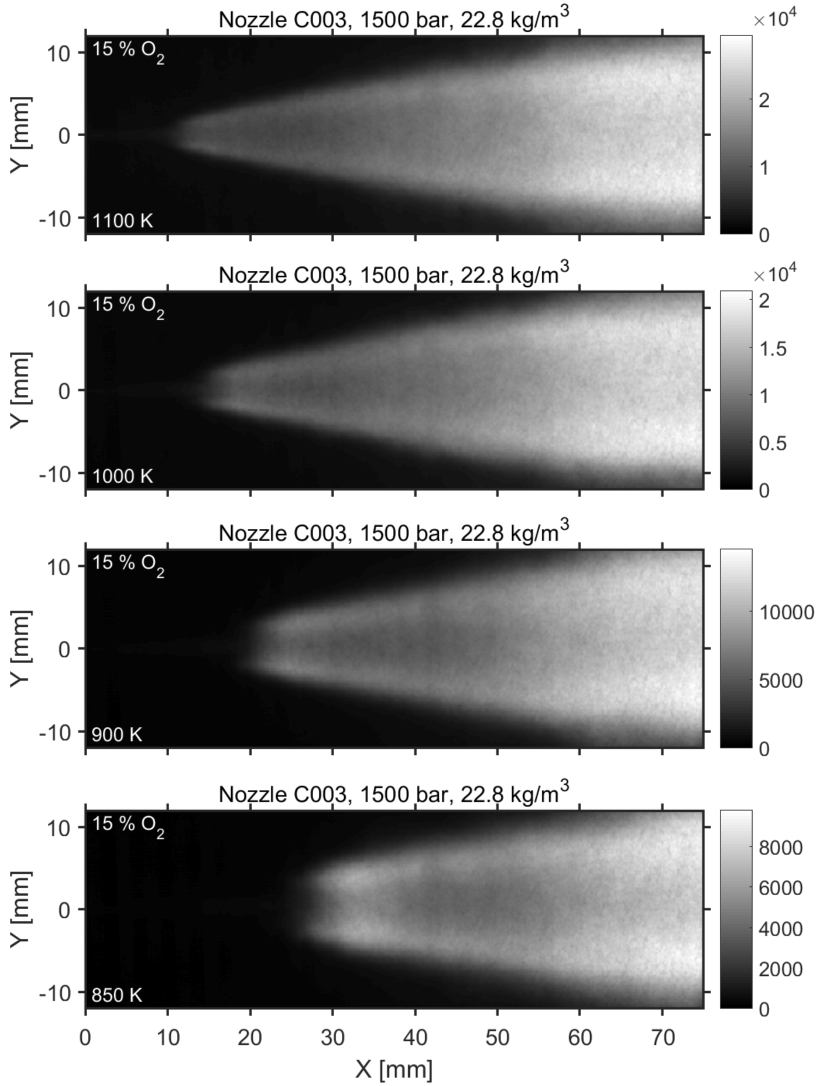
SPRAY C & D - CAMPAIGN DESIGN

- Boundary conditions & variations
  - Spray C003 & D135 (186 & 200µm, $\dot{m}$)
    Spray C diverging & D converging
    (900 K, 22.8 kg/m^3, 15% O_2, 1500 bar)
  - T – 1100 K, 1000 K, 900 K & 850 K
  - p_{inj} 1500 bar → 400 bar
  - LED vs laser extinction (soot)

- Goals
  - Influence cavitation (C for cavitation)
    $\dot{m}_C$ ~14% lower than intended
    → The Spray A baseline
  - Influence on (transient) soot, high-T reactions and (liquid) spray pen.
  - Influence cavitation with reduced pressure drop
  - Influence of wavelength and intensity

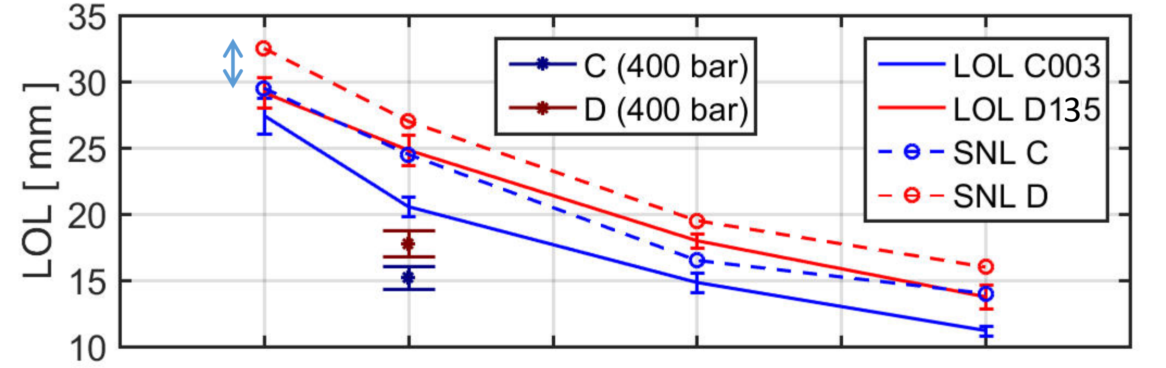
PRELIMINARY RESULTS – HIGH-SPEED OH* CHEMILUMINESCENCE

Decreasing temperature

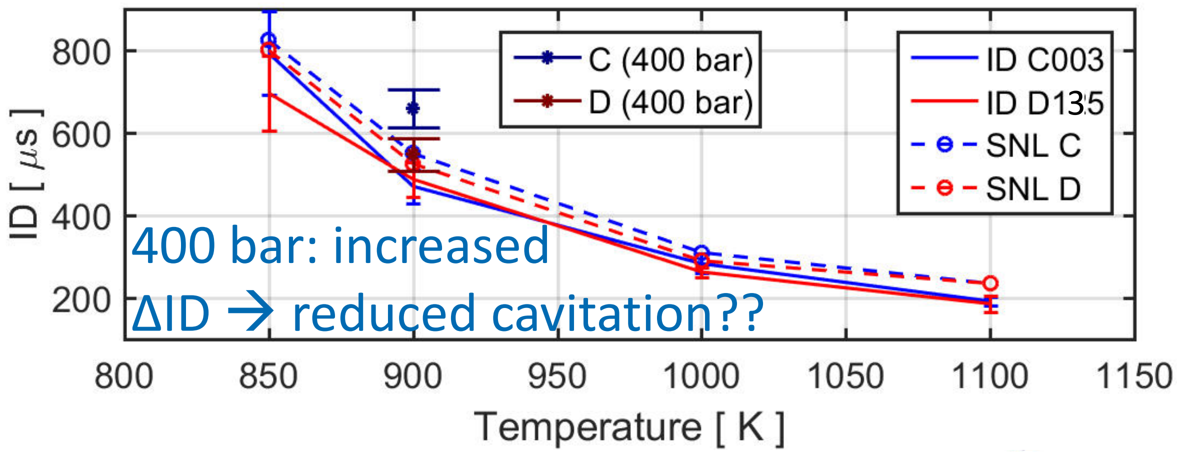


400 bar: no apparent reduced cavitation effects

2-4 mm difference?



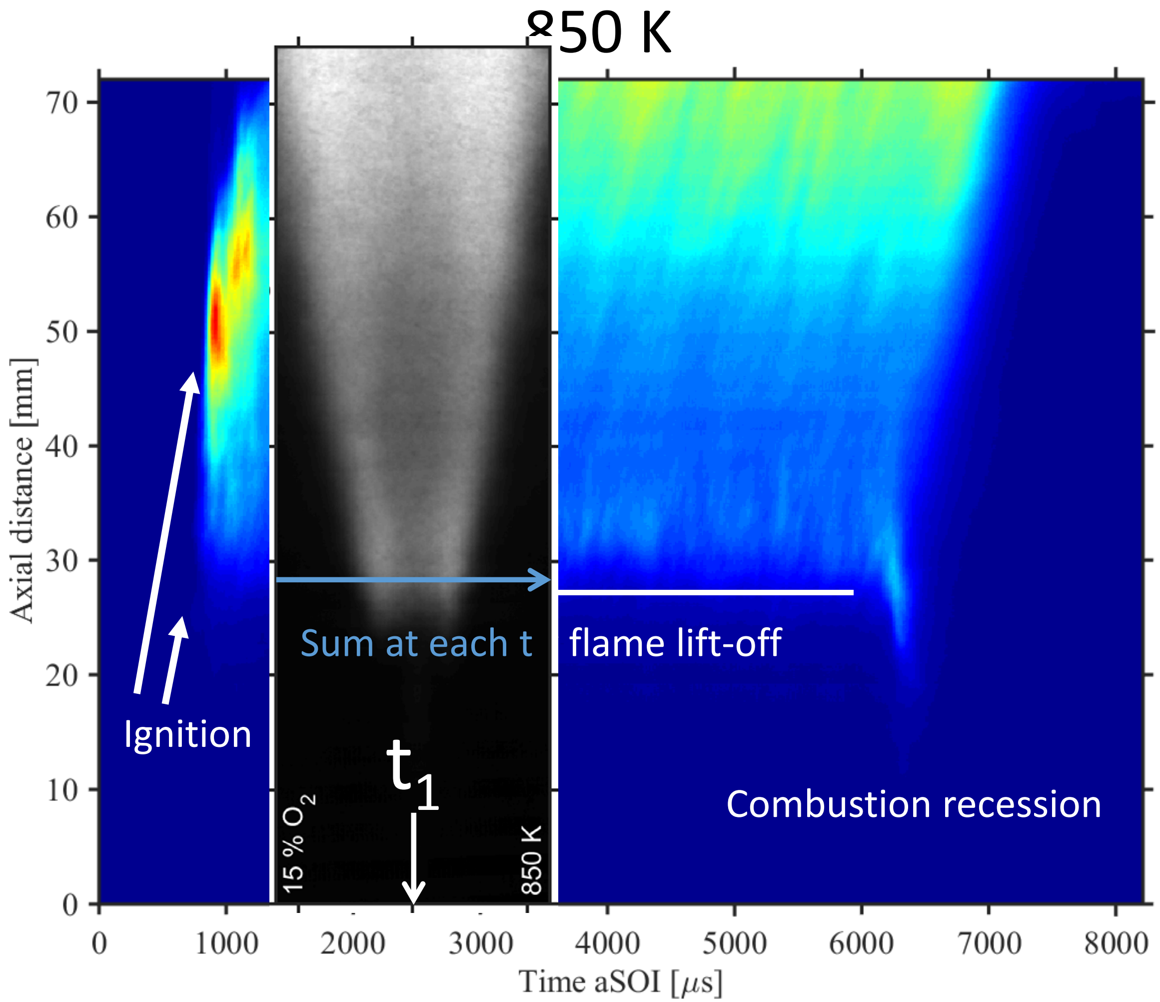
Caterpillar results, ṁ and Ṁ, raw images?



400 bar: increased ΔID → reduced cavitation??

PRELIMINARY RESULTS – HIGH-SPEED OH* CHEMILUMINESCENCE

- Transients → I_{xt}-plot
  - Total intensity as function of (x,t)
- Spray C – Transients
  - 2-step ignition
    - Large premixed region!
  - Quasi-steady flame lift-off
  - Combustion recession



PRELIMINARY RESULTS – HIGH-SPEED OH* CHEMILUMINESCENCE

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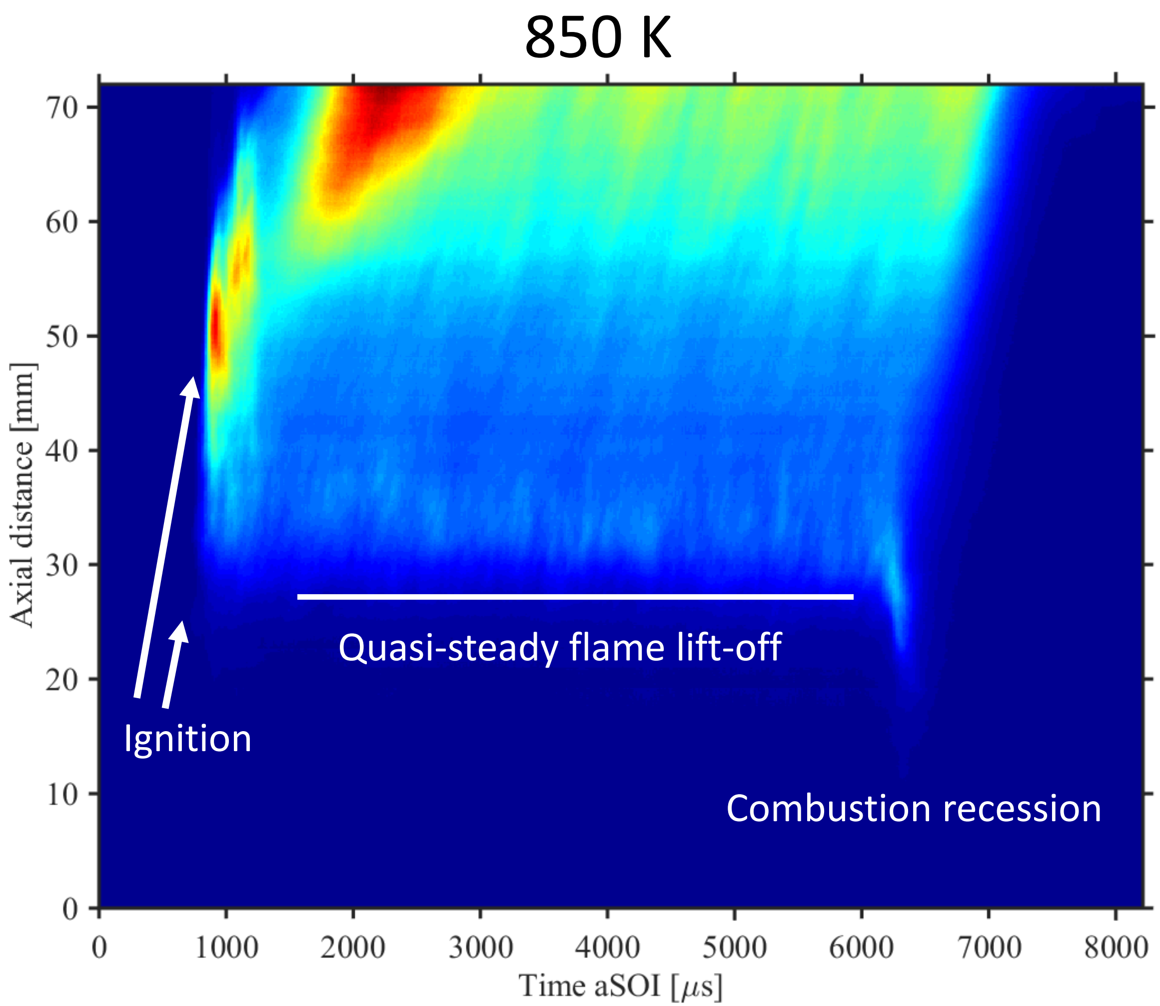


PRELIMINARY RESULTS – SOOT EXTINCTION – LED VS LASER

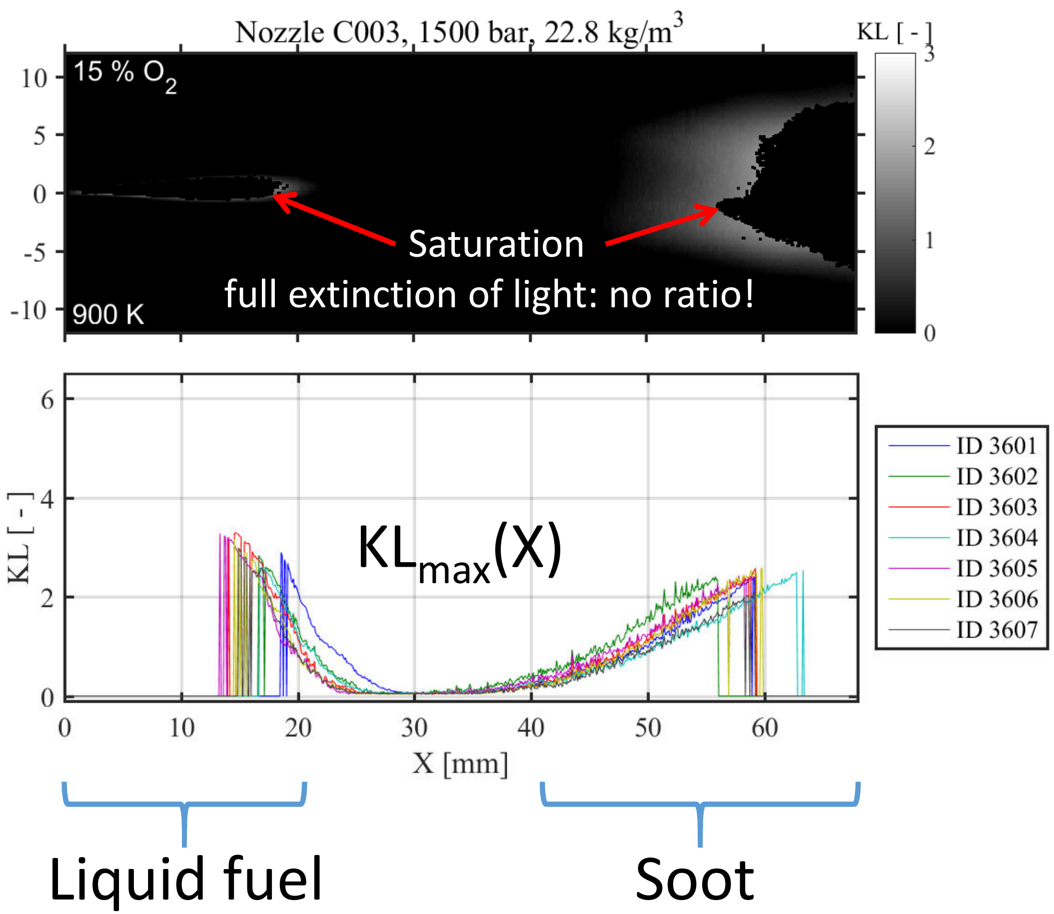
- 460 nm LED vs 810 nm laser
- $KL = -\log(\frac{I - I_{chem}}{I_0})$ Beer-Lambert
- $f_v = \frac{K\lambda}{k_e}$ Mie-theory
- $\frac{K_{LED}}{K_{Laser}} = a\frac{810}{460} = 1.76\, a$

Unknown!

- I / I_0 = Soot image / background image
- K = Extinction coefficient
- L = Path length
- f_v = Soot volume fraction
- λ = wavelength
- k_e = dimensionless extinction coeff.
  - Refractive index & morphology of soot, wavelength, absorption, scattering, …
- a = $k_{e,LED}/k_{e,Laser}$

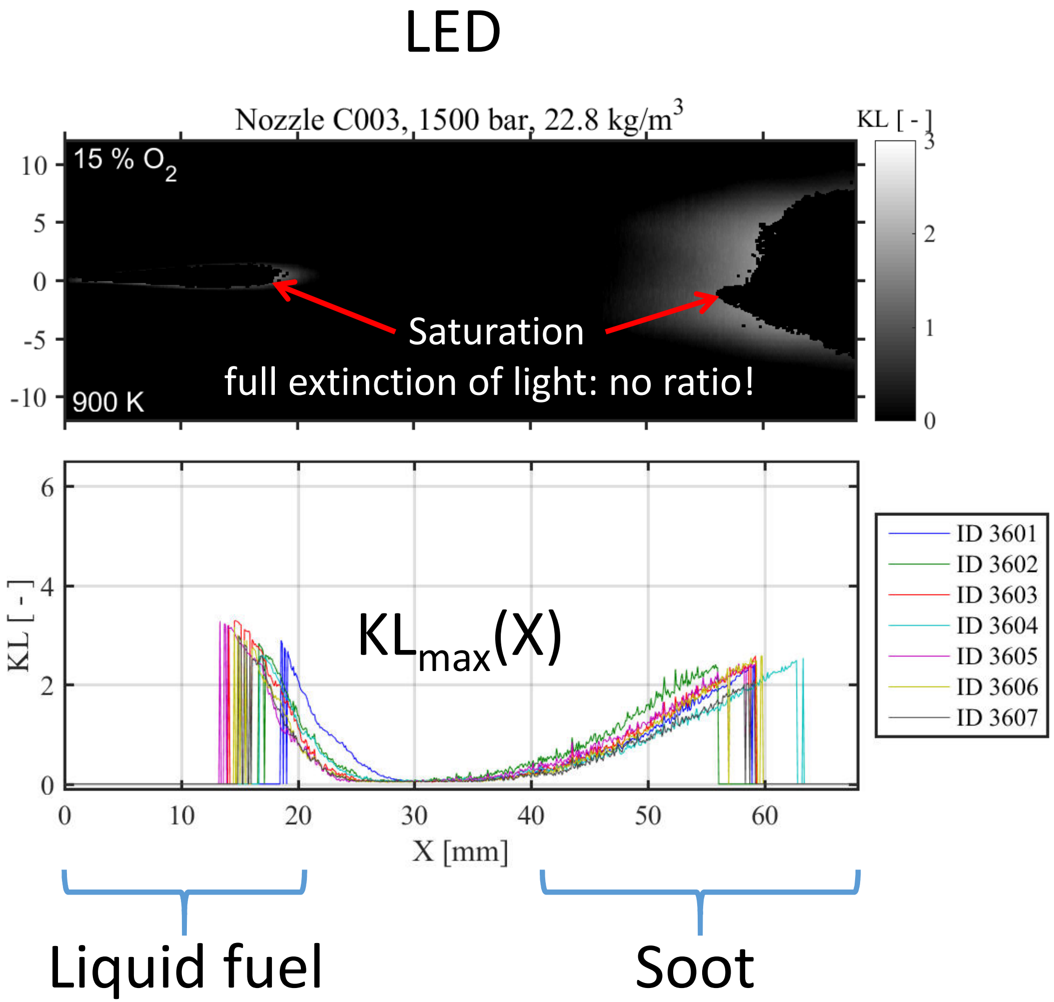
PRELIMINARY RESULTS – SOOT EXTINCTION – LED VS LASER

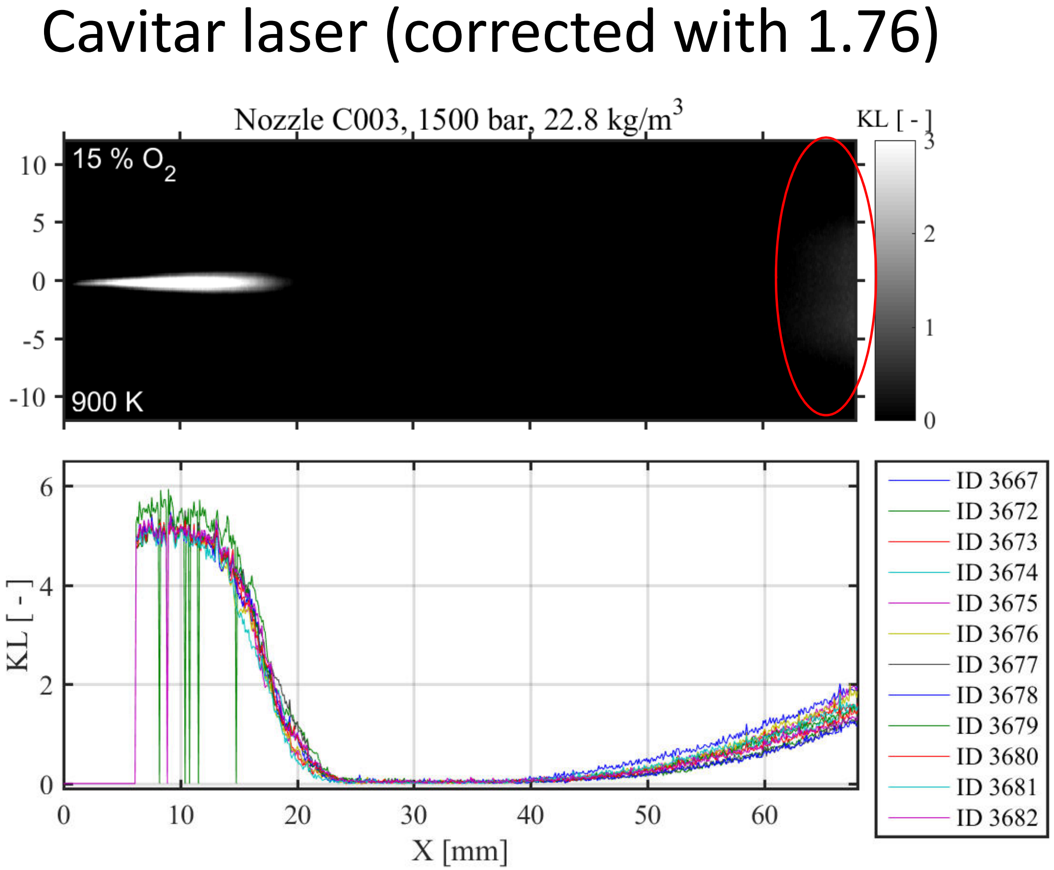
LED



- Challenge
  - Decrease temperature: soot > 65 mm
  - Increase temperature, more saturation

PRELIMINARY RESULTS – SOOT EXTINCTION – LED VS LASER



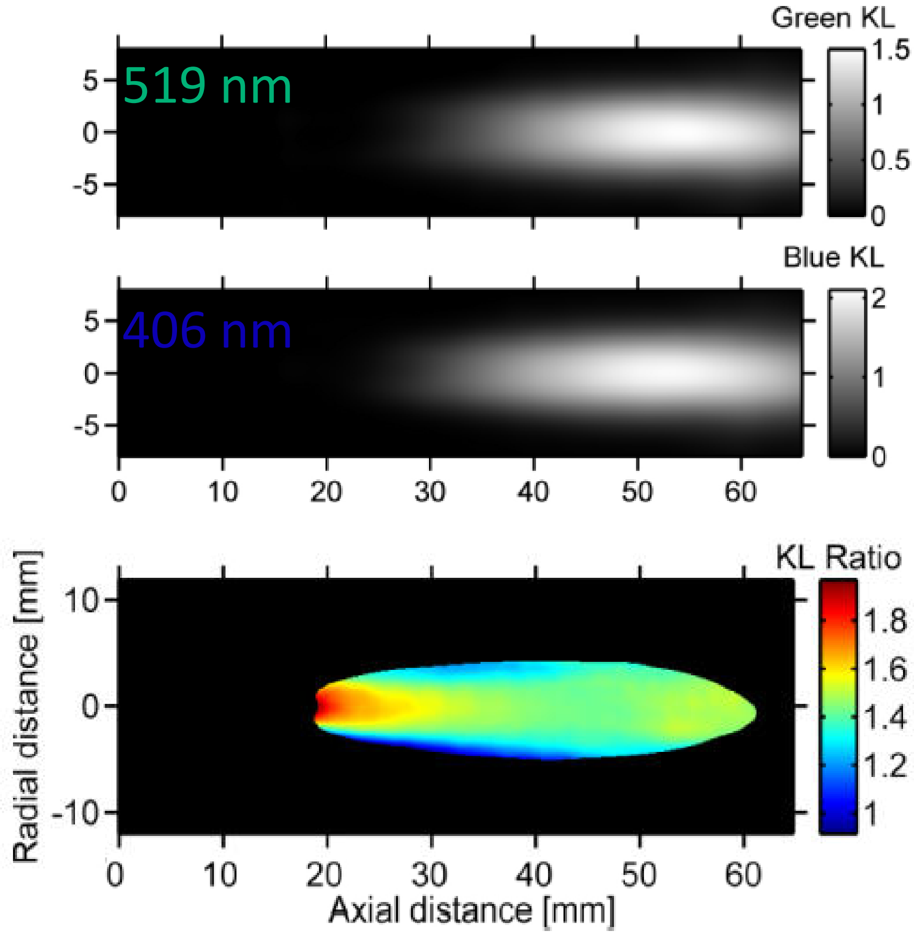


PRELIMINARY RESULTS – SOOT EXTINCTION – LED VS LASER

- Sandia: 110 nm separation (blue vs green)
- More soot extinction by shorter wavelength
  - Best explained by variations in refractive index

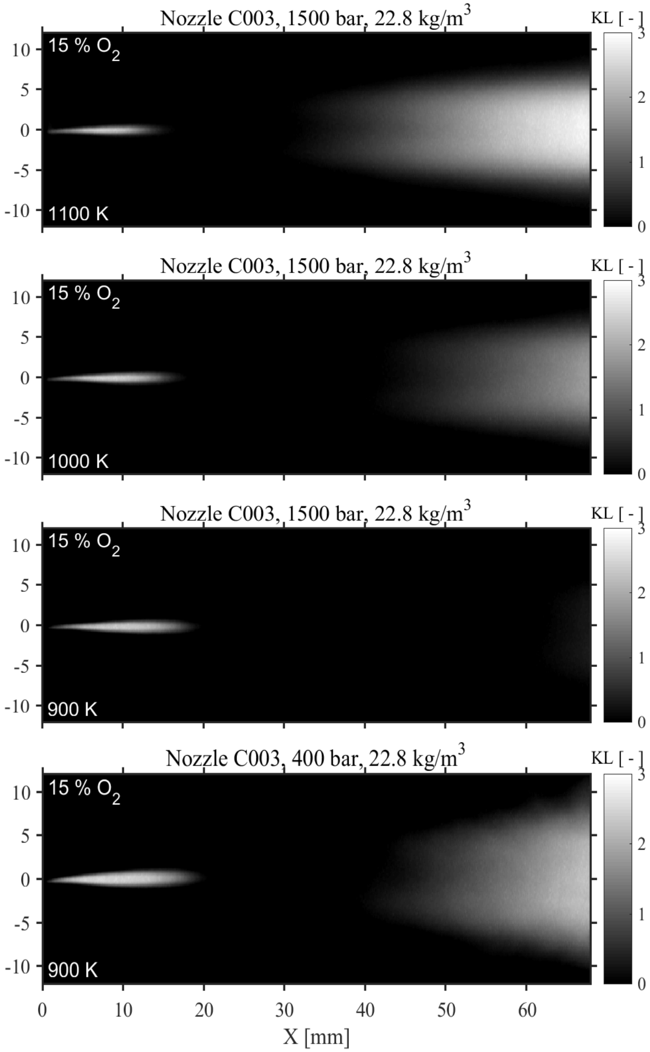
- IFPEn: 350 nm separation
- Difficult for direct comparison (@ Spray C/D)
  - Cavitar soot = LED saturation
  - a = $k_{e,LED}/k_{e,Laser}$ > 1
- Allows high-soot conditions
- Less sensitive to nascent soot
- Proceeding with Cavitar laser extinction

SAE 2013-01-2548



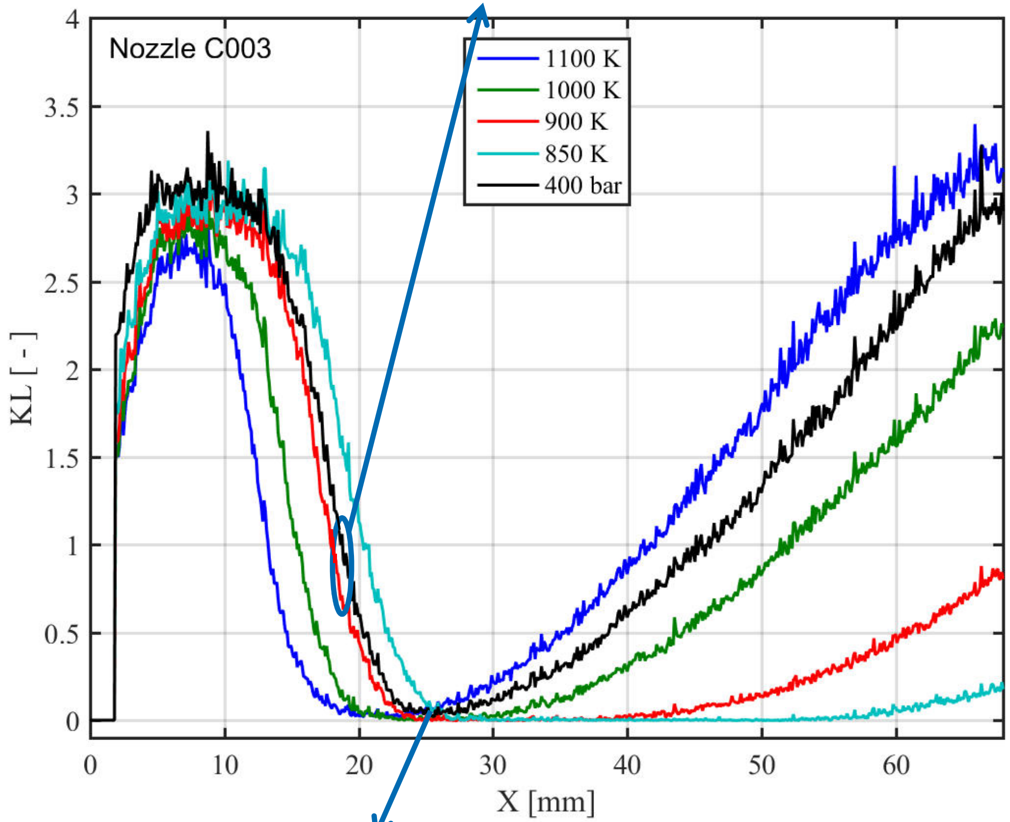
PRELIMINARY RESULTS – SOOT EXTINCTION – SPRAY C003

Decreasing temperature



Decreasing injection pressure

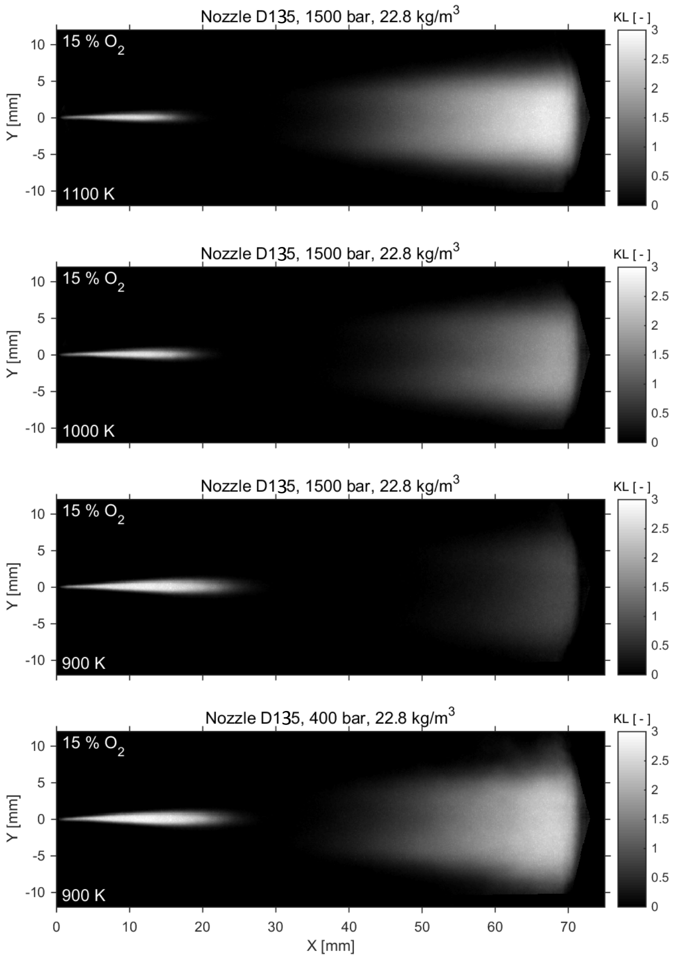
Mixing-limited vaporization



Liquid → soot: ~ 5 mm

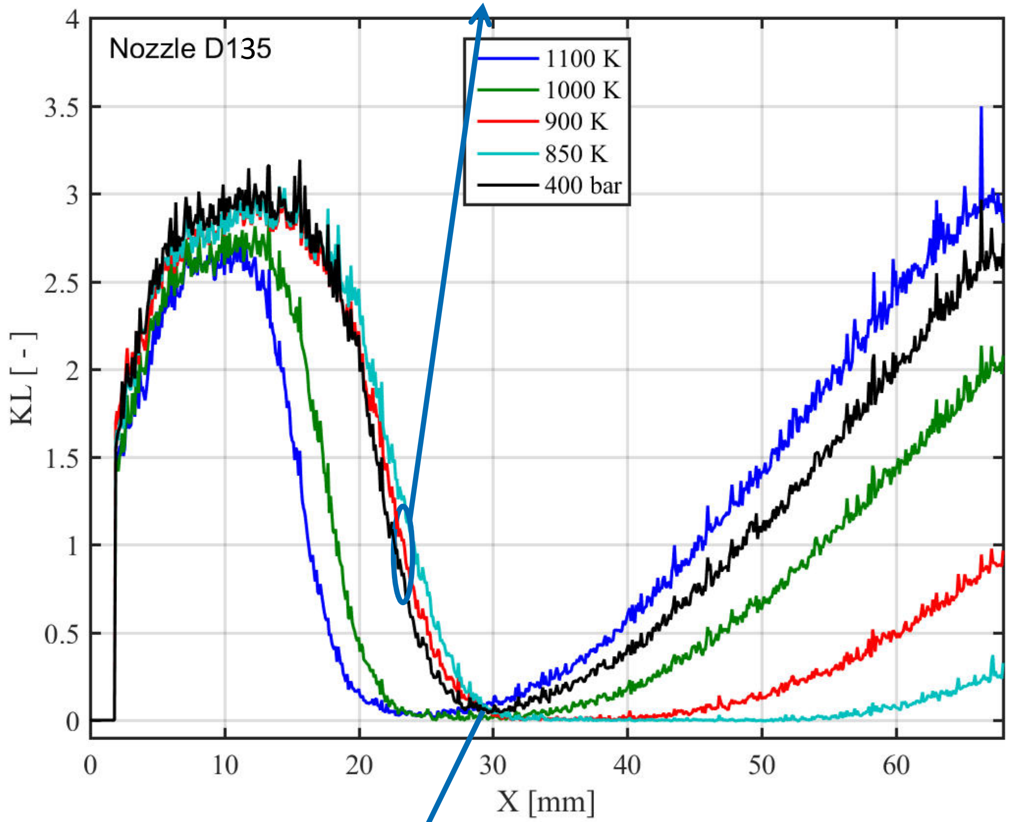
PRELIMINARY RESULTS – SOOT EXTINCTION – SPRAY D135

Decreasing temperature



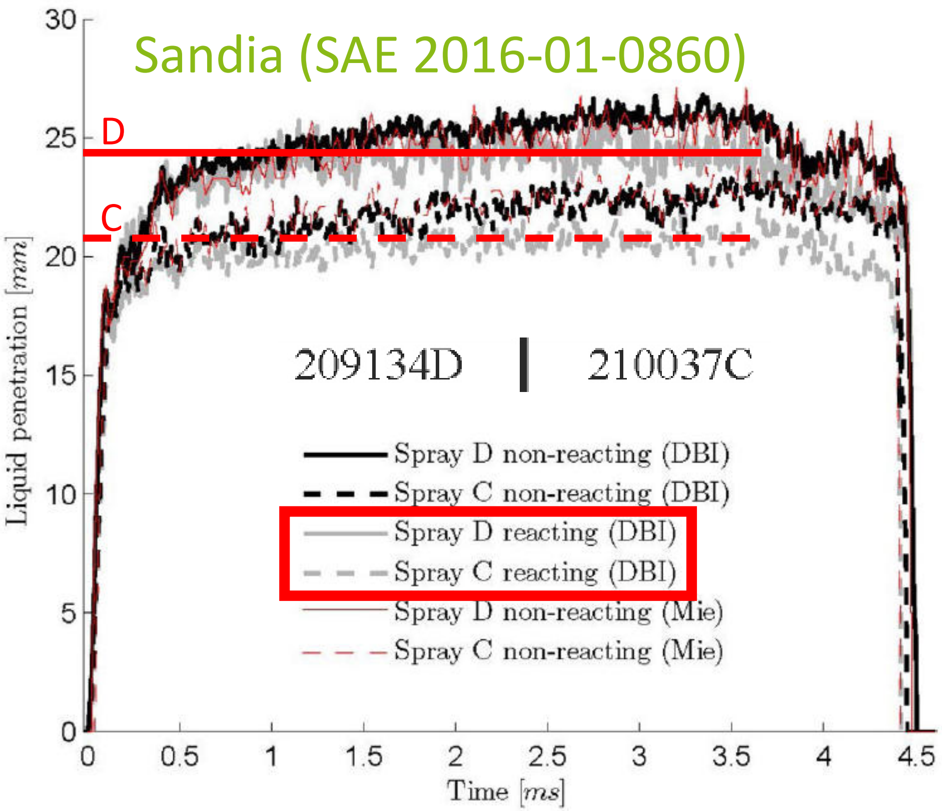
Decreasing injection pressure

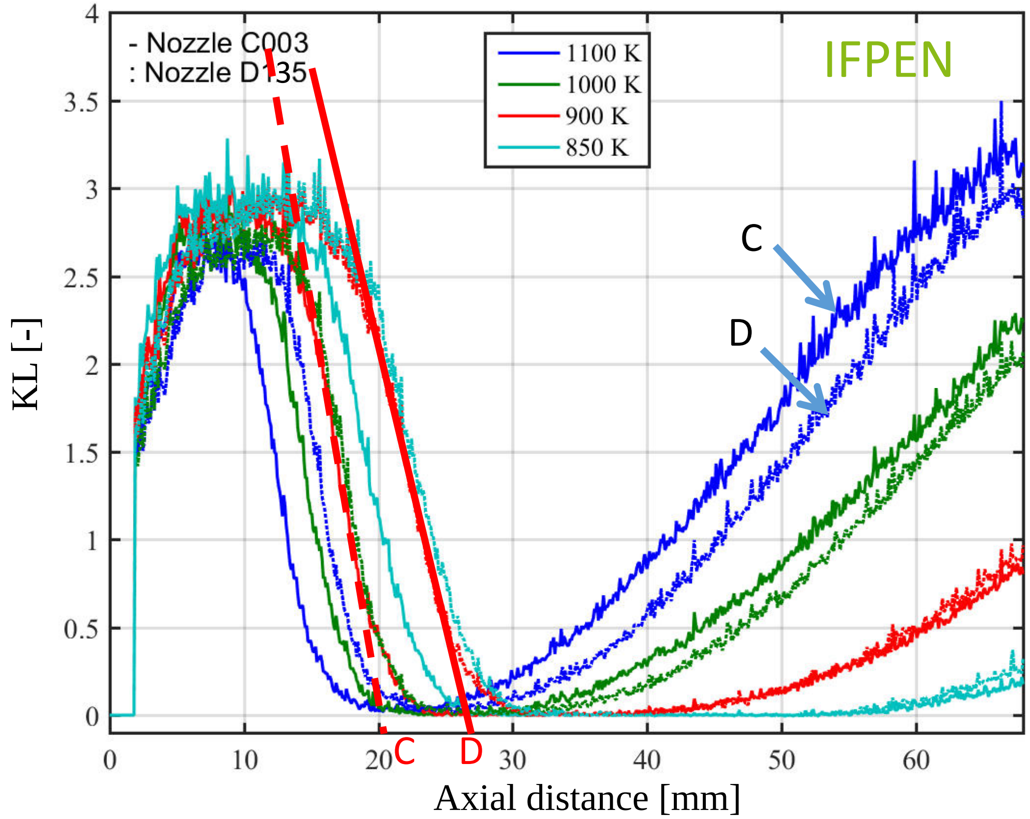
Mixing-limited vaporization



Liquid → soot: < 5 mm

PRELIMINARY RESULTS – SOOT EXTINCTION – SPRAY C003 & D135





SNL C ≈ 20.7 mm

SNL D ≈ 24.3 mm

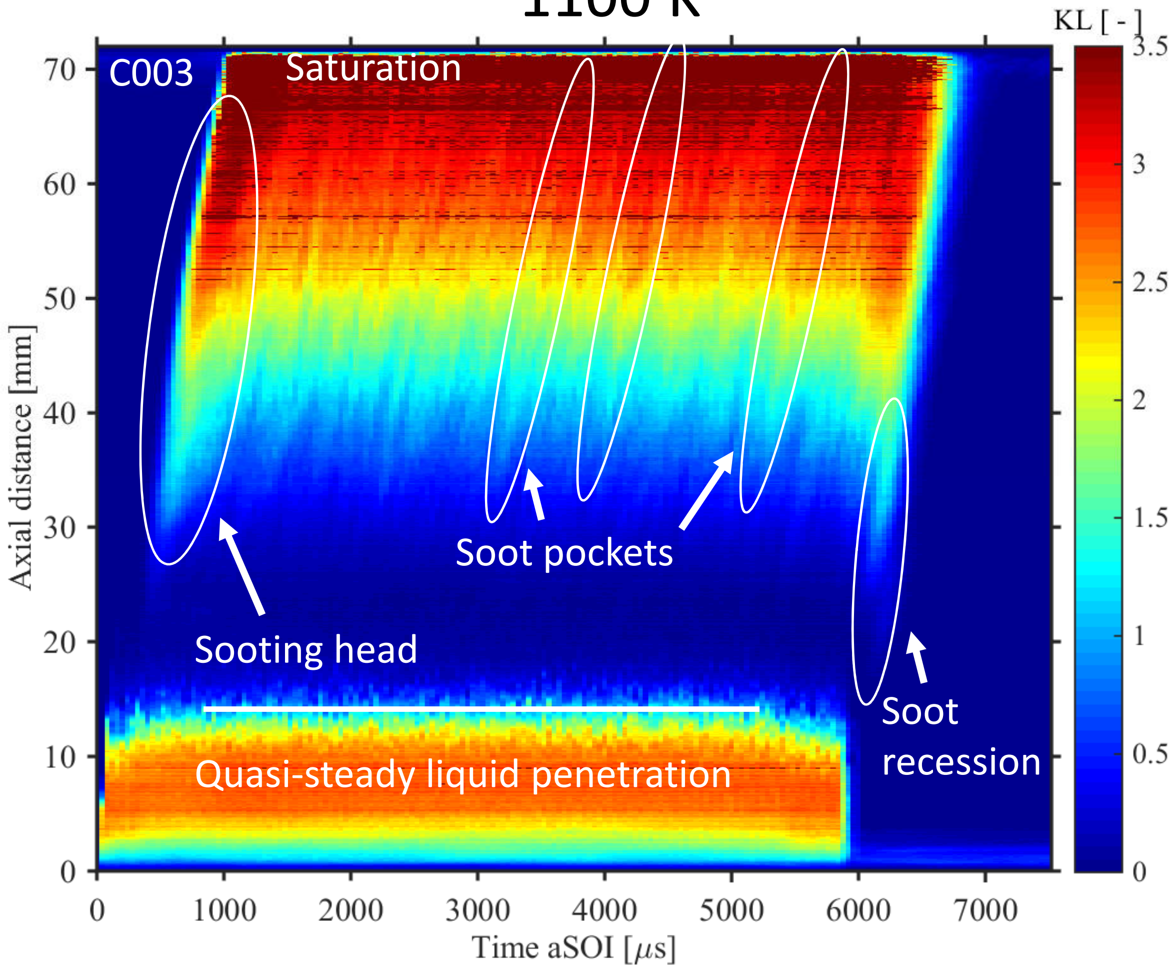
IFPEN C ≈ 20.4 mm

IFPEN D ≈ 26.6 mm

PRELIMINARY RESULTS – SOOT EXTINCTION – SPRAY C003

- Transients → $KL_{max\text{-}xt}$-plot
- Spray C – Transients
  - Sooting head of the spray
  - Large soot pockets travelling downstream
  - "Soot recession" aEOI (though not upstream FLOL!)

1100 K



CONCLUSIONS AND FUTURE WORK

- Laser DBI soot extinction: high-soot conditions ☺ - lower sensitivity to nascent soot ☹
- Spray C characterization → Soot/OH* ($T_{ambient}$, $p_{inj.}$)
  - Unexplained difference between IFPEn/Sandia – Caterpillar results, $\dot{m}$ and $\dot{M}$ & raw data?
  - Spray C vs Spray D soot: $KL_C > KL_D$, but only for high-soot conditions!
  - Interesting transients: e.g. 2-step ignition and soot recession (downstream of FLOL)

Next steps:

- Finalize Spray C/D characterization
  - Liquid and vapor penetration
  - Further investigate LED vs. laser extinction → approximations for k_e and determine f_v
- Investigation of ignition
  - Setup high-speed fuel-tracer LIF/3D ignition diagnostic
  - Spray A/C/D

Engine Combustion Network France

Project fund: French Research Agency (ANRT)
Project leader: G. Bruneaux from IFP-EN

Progress meeting 03/11/2016

Introduction of the PPRIME Institute contribution

"Study of ECN-spray A under inert and reacting conditions in a Rapid Compression Machine"

M. Ben-Houidi, J. Sotton, C. Strozzi, M. Bellenoue

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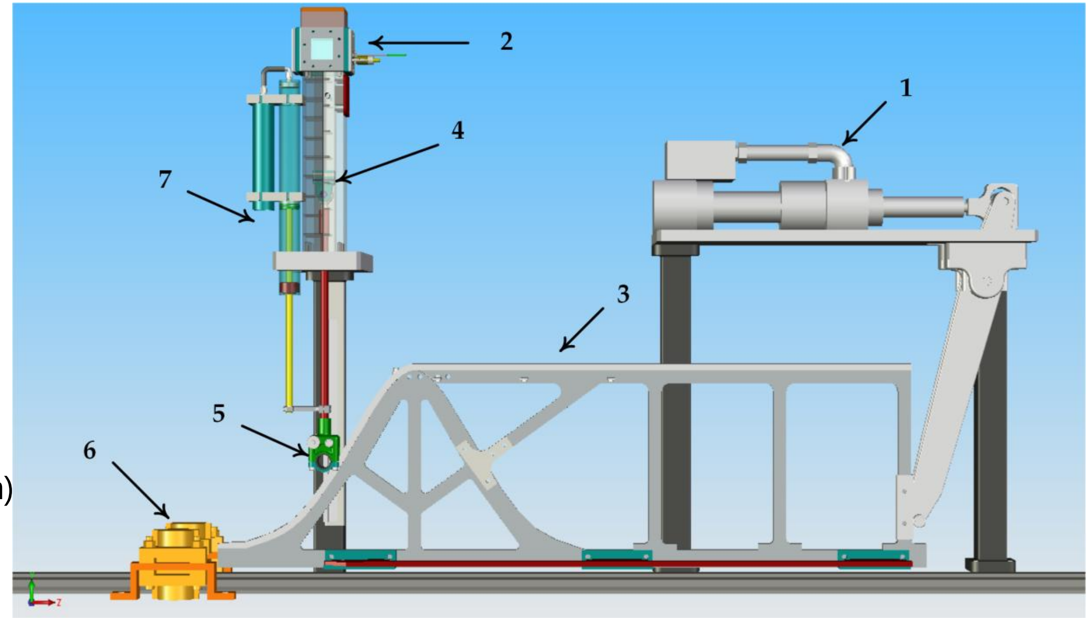
Outlines

I. Rapid Compression Machine (RCM) for Spray A
   1. Experimental set up
   2. Aerodynamics inside the RCM
II. Validation of Spray A conditions
   1. Velocity fields inside the RCM
   2. Optimization of the inert gas composition
   3. Temperature measurement
III. First results
   1. Vapor phase penetration
   2. Liquid length
   3. Ignition delays and lift-off length
IV. Perspectives

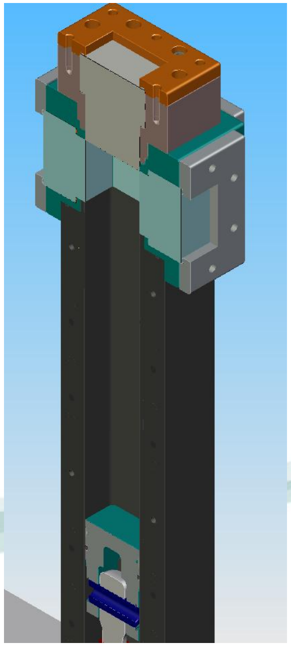
I. Rapid Compression Machine for Spray A

I.1 Experimental set up



- Spray A target conditions
  - T = 900 K
  - ρ = 22.8 kg/m^3
  - Gas composition: 15 % O_2 + inert (molar fraction)
  - V<1m/s
  - $T_{injector}$ = 90°C

- RCM parameters:
  - Fixed :
    - Initial temperature : T_0 = 90°C
    - Compression Ratio : 9 (lowest) => constant volume (130cm^3) after compression
  - Adjusted:
    - Initial pressure : P_0
    - Inert gas composition: Ar/N_2



I. Rapid Compression Machine for Spray A

I.2 Aerodynamics inside the RCM

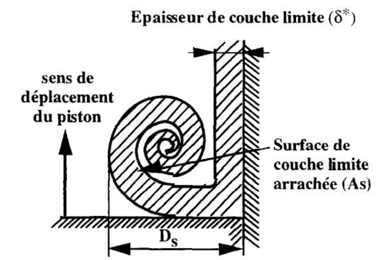
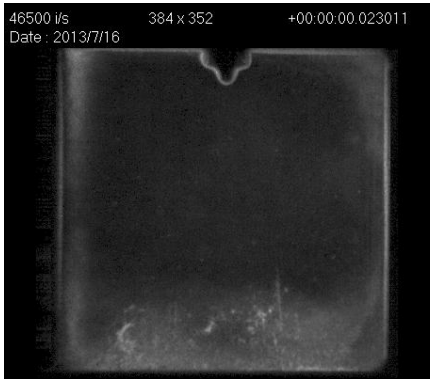
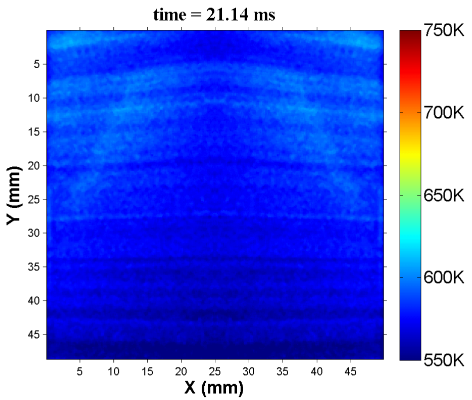


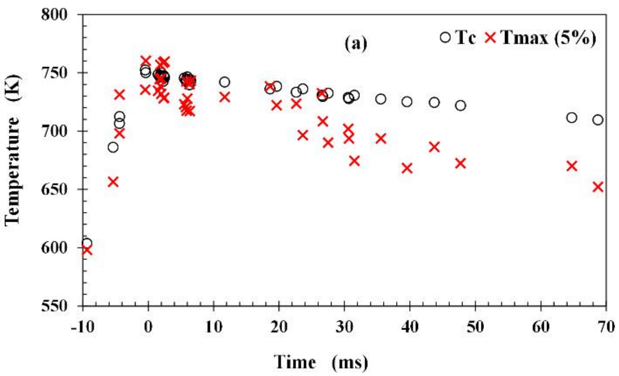
Fig 4. *Formation du tourbillon de coin.*
Fig 4. Corner vortex formation.

[Guézet & Kageyama 1997]



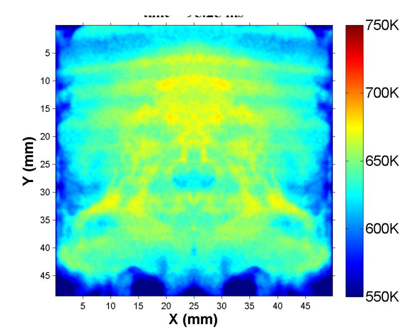
Toluene PLIF
Test conditions: gas composition toluene/N_2/CO_2/Ar, P_c=10,7bar, T_c=750K (TDC), ρ=7,2kg/m^3 au PMH





[M. Ben-Houidi et al. Fuel, vol. 186, 2016, 476-495]

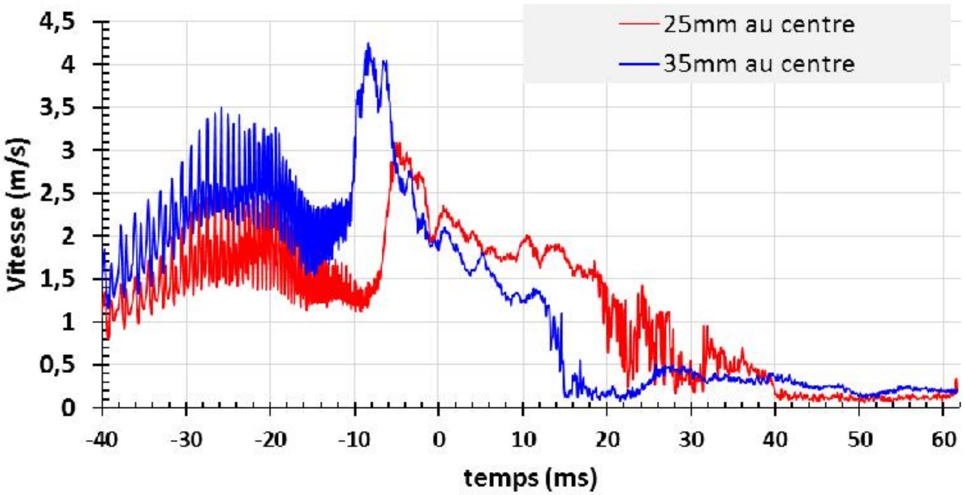
$$\int_{T_0}^{T_c} \frac{\gamma}{\gamma - 1} \frac{dT}{T} = \ln\left(\frac{P_c}{P_0}\right)$$

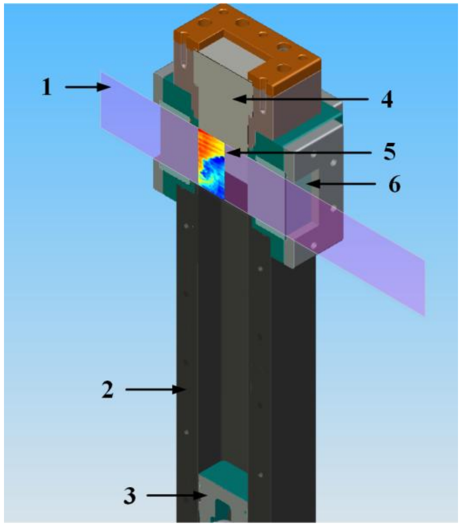


Toluene PLIF at the same CR has demonstrated a relatively homogeneous temperature 60ms after the end of the compression

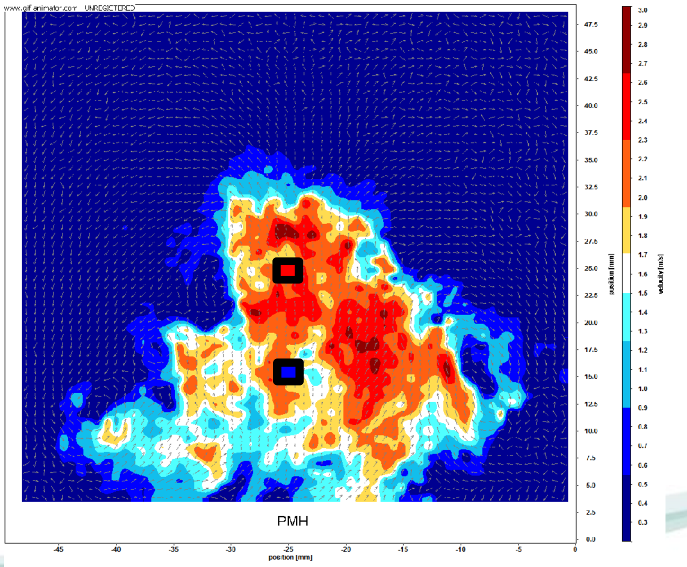
II. Validation of Spray A conditions

II.1 Velocity fields inside the RCM





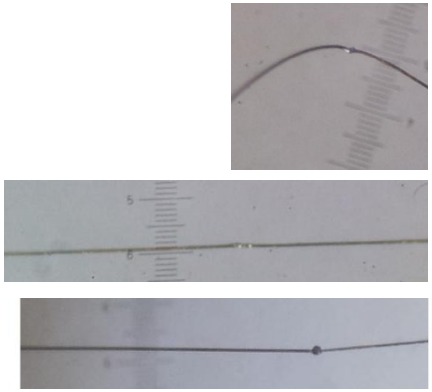
High-speed PIV at density level similar to the spray A conditions confirmed: V<1m/s at 50ms after TDC



II. Validation of Spray A conditions

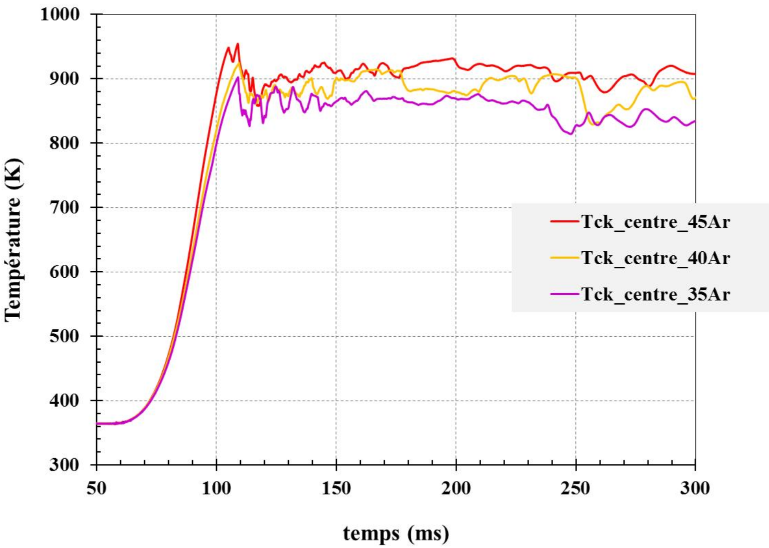
II.2 Optimization of the inert gas composition

- Different tests at target density with different Argon molar fractions : temperature inside RCM measured with a thin wire type K thermocouples
- Correction to convert $T_{junction}$ to T_{gas}
  - $T_{gas} = T_{junction} + convection_{error} + radiation_{error}$
  - $T_g = T_j + \tau \frac{dT_j}{dt} + \frac{\varepsilon\sigma}{h}(T_j{}^4 - T_w{}^4)$
  - 1st approximation $h = \frac{0{,}56\, k\, \mu^{0{,}45}}{d^{0{,}55}\, \nu^{0{,}45}}$ from ASTM STP 1427



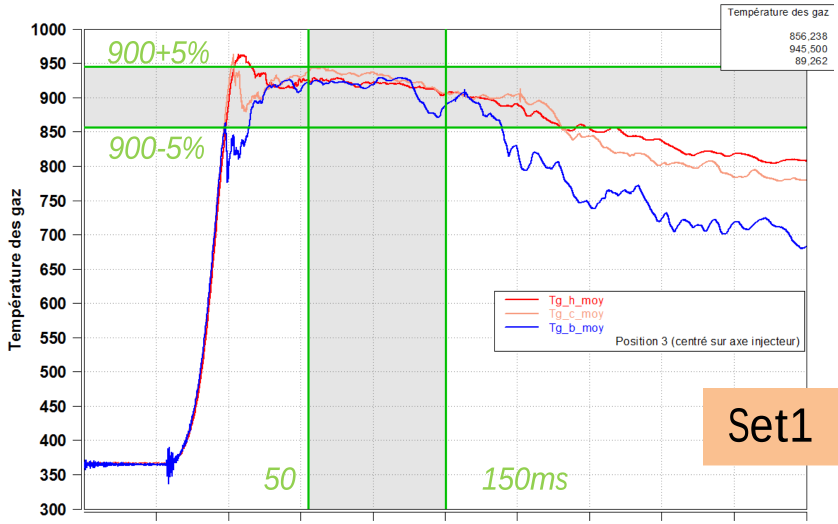
Thin wires (7,6µm) type K thermocouples

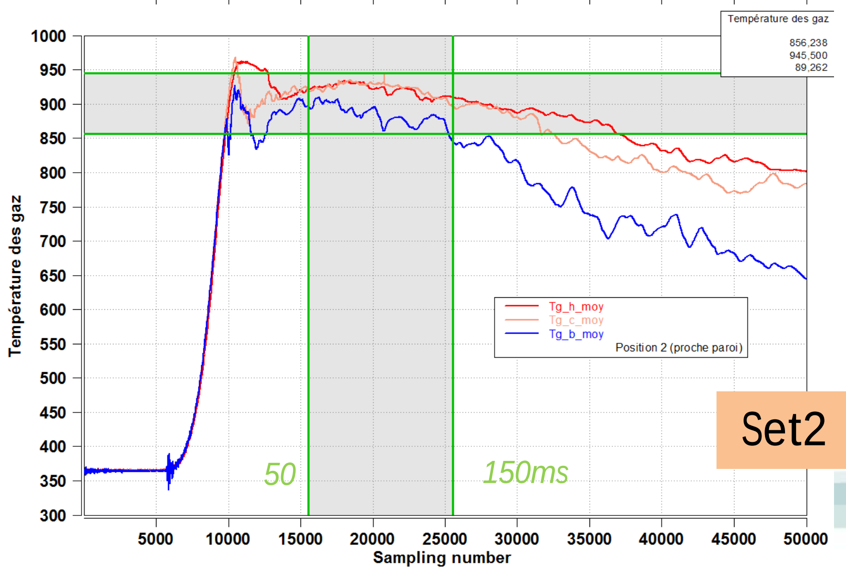
First tests encourage to use Argon with 45% molar fraction



II. Validation of Spray A conditions

II.3 Temperature mesurement (45%mol Ar)

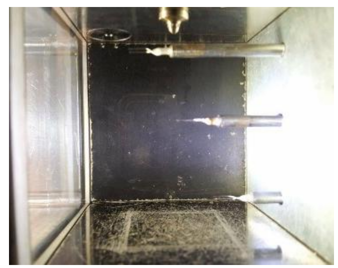




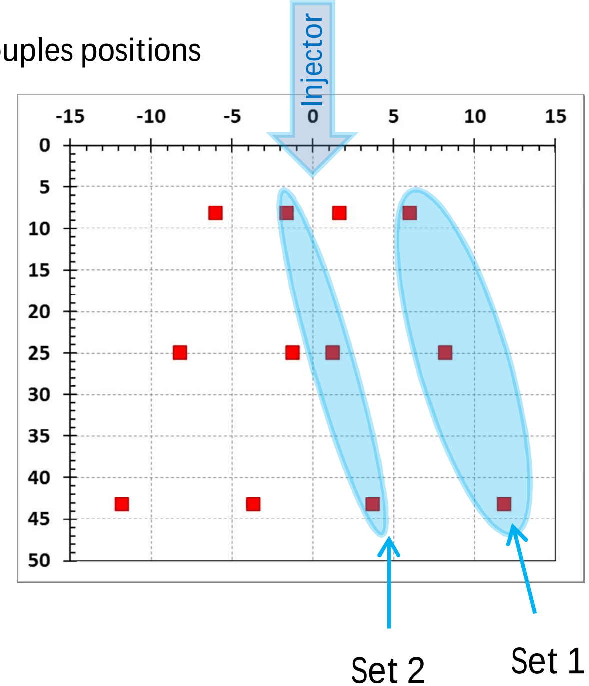
Tg_h (cylinder head side)

Tg_c (center bulk volume)

Tg_b (piston side)



Thermocouples positions



Assuming planar symmetry, temperature estimation can be extended

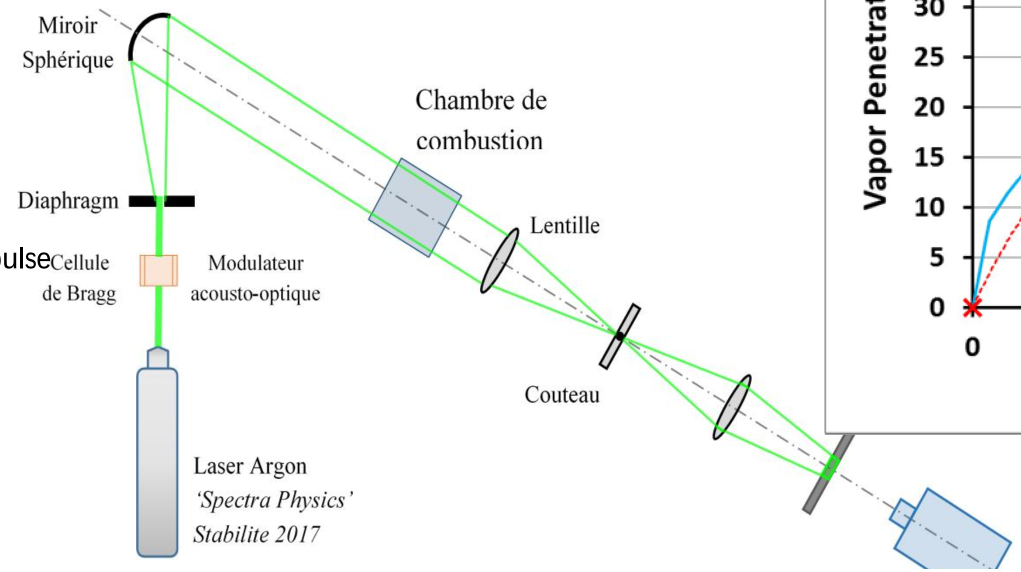
Tg = 900K ± 5%
(in the time range 50 - 100ms after TDC)

The injection will be placed at 75ms after TDC

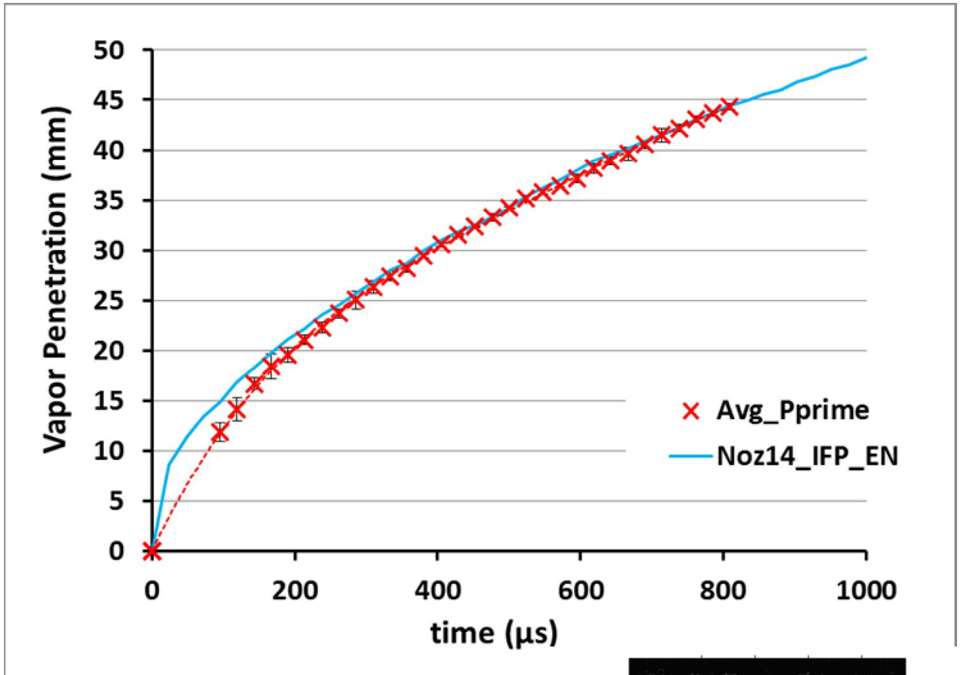
III. First results

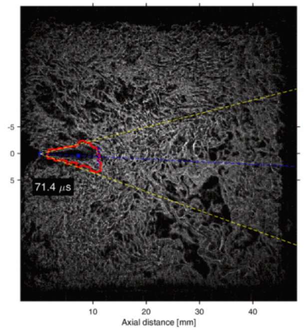
III.1 Vapor phase penetration

Schlieren setup



Photron SAZ at 42k fps



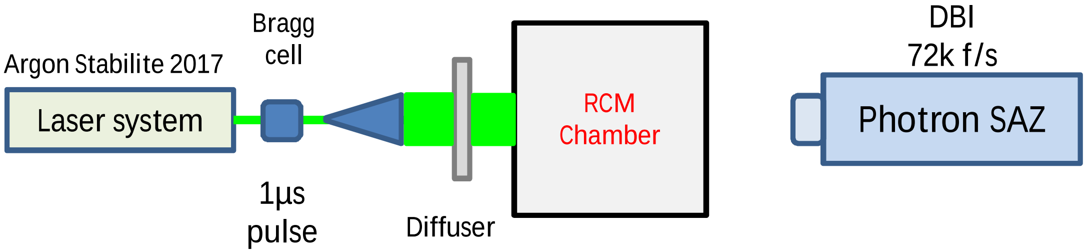


Measured VP fits well the IFPEN data in the time range 150µs to 800µs

Discrepancies at first instants of injection may be explained with the sensitivity of the Schlieren setup which make harder the processing of the first images

III. First results

III.2 Liquid Length (LL) DBI



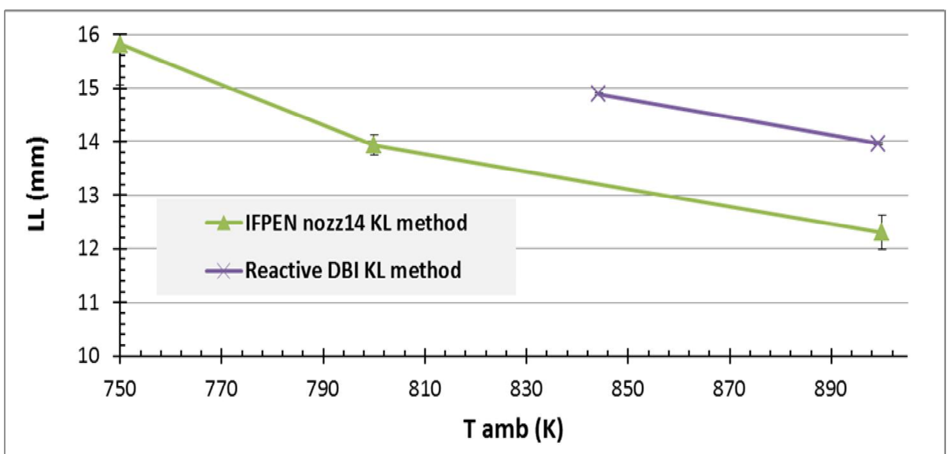
Processing based on the estimation of light extinction

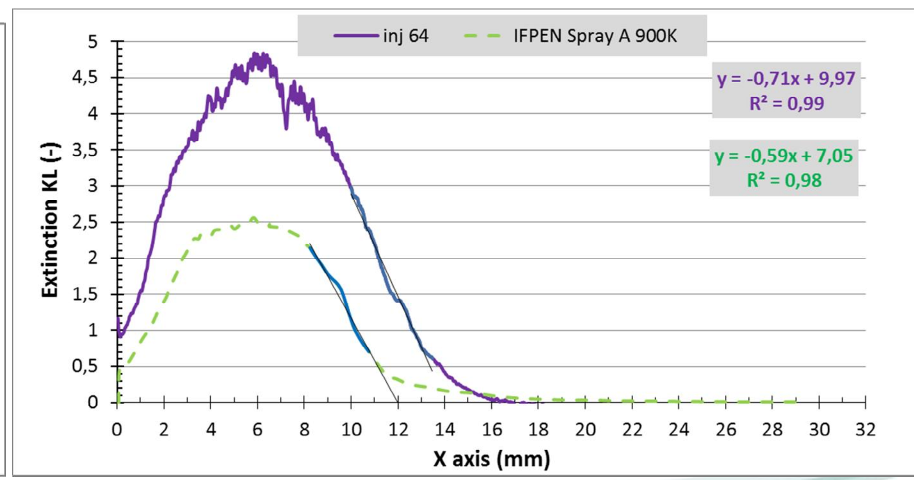
$$\tau = -ln\left(\frac{I_{col}}{I_0}\right)$$

Nozzel 14	Avg LL (mm)	Std LL (%)
Pprime (10 tests)	14,2	2,4%
IFPEN (5tests)	12,3	2,6%

=> Significant difference in LL

=> Dependence to ambient temperature seems to be similar



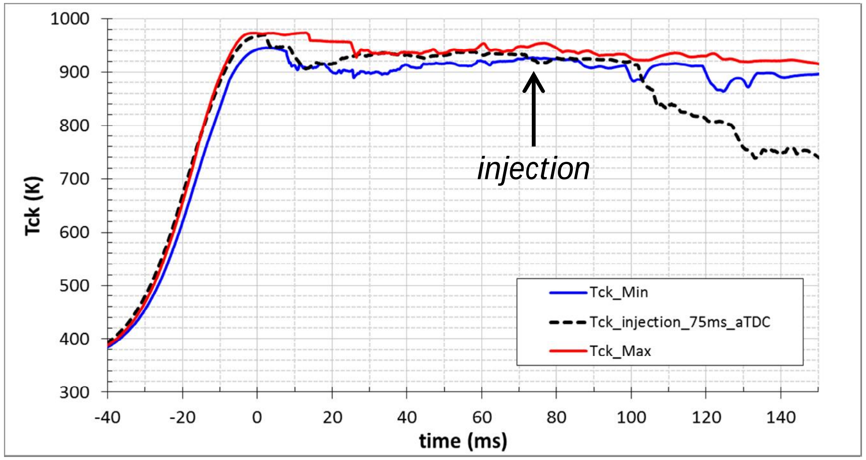


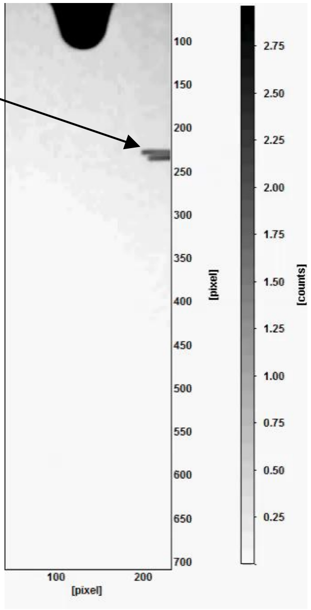
III. First results

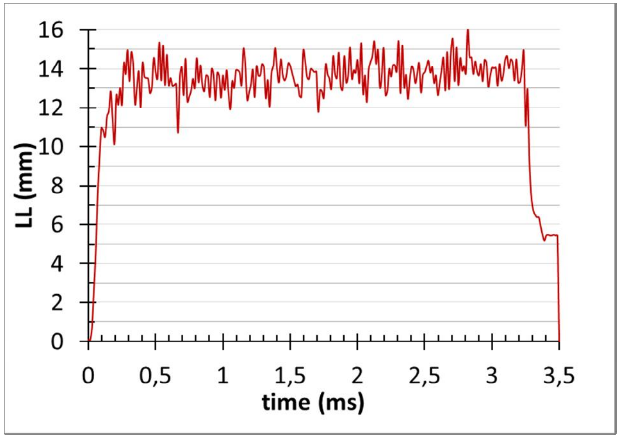
III.2 Liquid Length (LL) DBI: hypothesis to explain the discrepancies

1- Temperature issues

Measurement with 7,6µm thermocouples



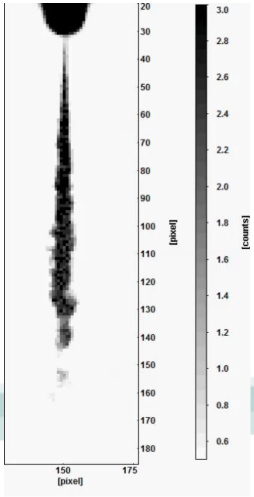


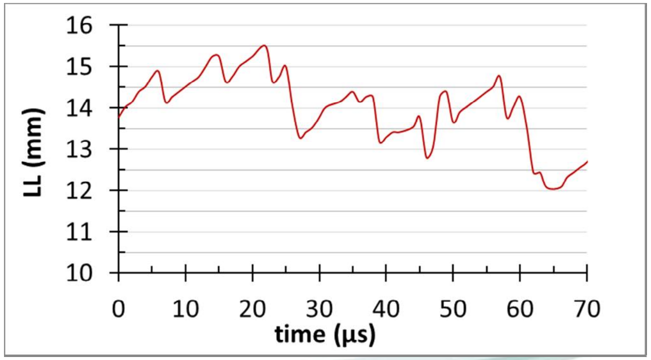


Complementary tests with thermocouples placed closer to the spray are planned

2- DBI method issues

The set up will be further optimized using different light source and engineered diffuser





3- Density issues

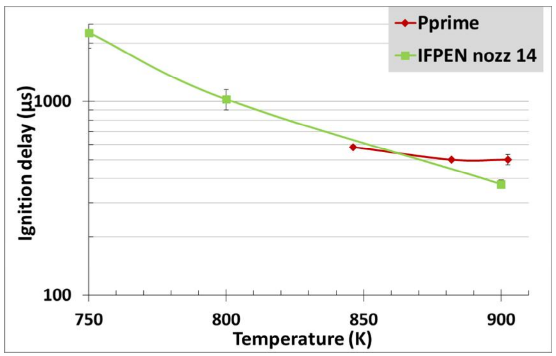
The impact of small variations of density on the LL will be investigated

III. First results

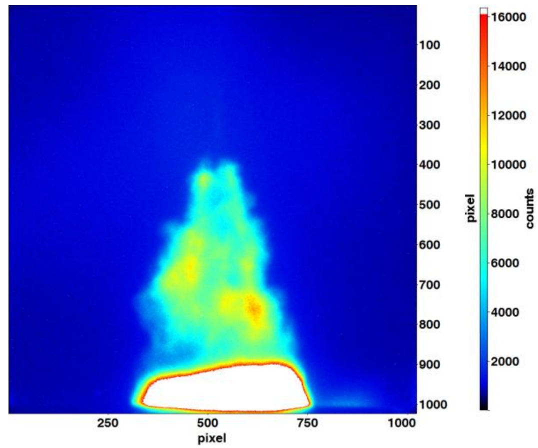
III.3 Ignition delays and LOL from OH* chemiluminescence

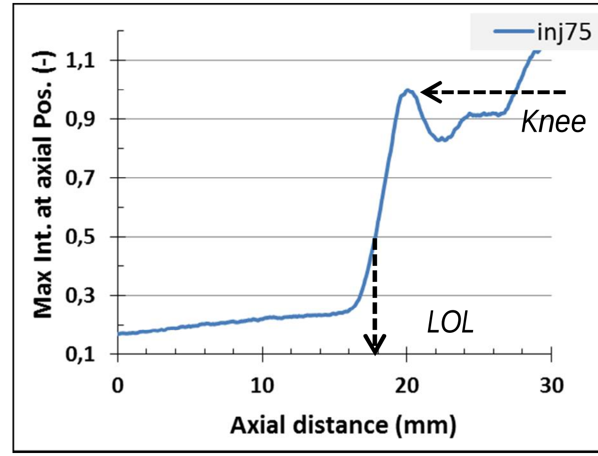
High-speed :
SBP filter (Asahi 310 nm) + intensifier (hamamatsu) + CMOS camera (photron SAZ)

Lab	ID (µs)
Pprime	500+/-31
IFPEN	375+/-18



Single shot – long exposure :
SBP filter (Asahi 310 nm) + ICCD camera (Princeton PIMAX 2)

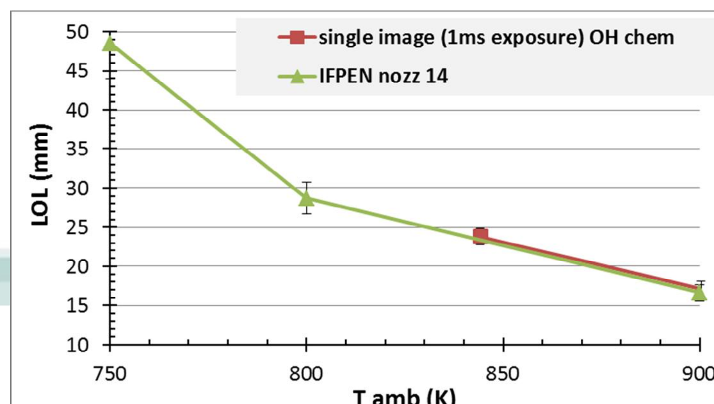




Lab	LOL (mm)
Pprime	17,1 ± 1,2
IFPEN	16,6 ± 1

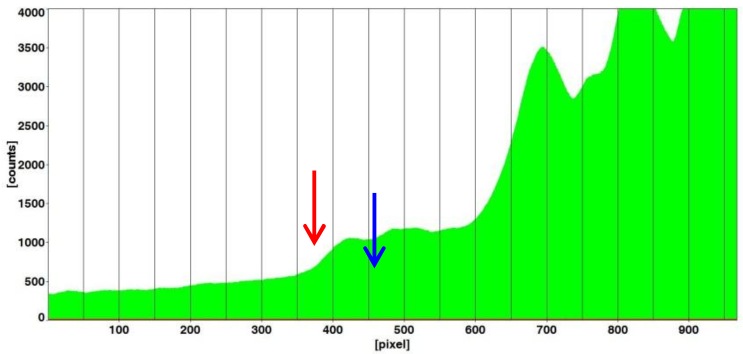
⇒ LOL measured with the time averaged method is consistent with the IFP measurements (exposure is placed at 1ms after the auto-ignition)

⇒ Dependence to ambient temperature is similar

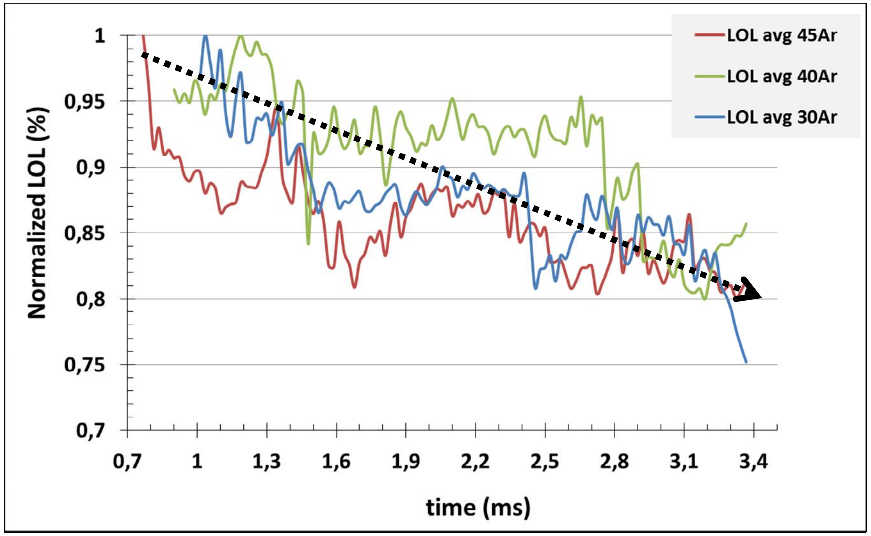


III. First results

III.3 LOL vs. time



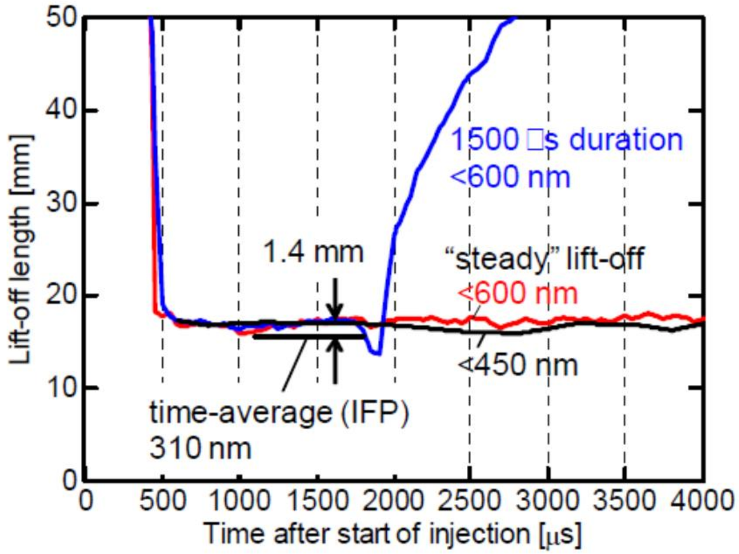
Example of OH* signal profiles (in center line) at different instants



An ensemble-average of lift-off length versus time after SOI : results from tests with different Ar molar fraction

⇒ 20% decrease in LOL observed during the injection.

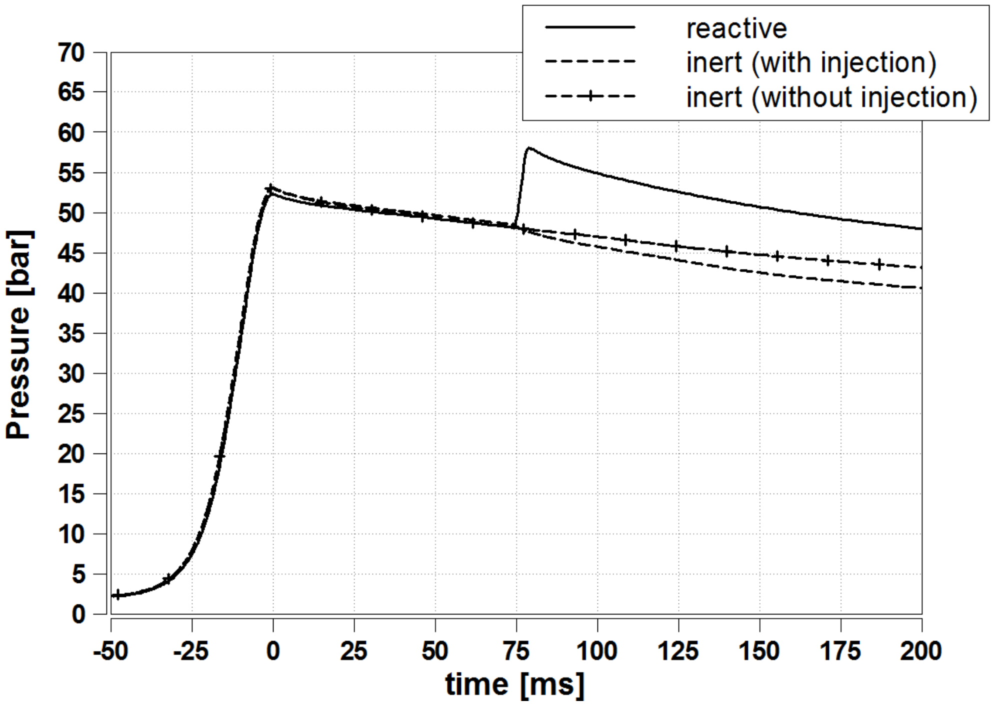
⇒ A clear stabilized window is not obseved unlike the reported behavior of LOL in SAE 2010-01-2106



An ensemble-average of lift-off length versus time after SOI : results from different short BP filter [SAE 2010-01-2106]

III. First results

III.3 LOL vs. Time: hypothesis to explain the lift-off decrease



⇒ The combustion induce a 10 bar increase in pressure, which can significantly increase the unburned gas temperature during the injection

⇒ The impact of the combustion on the temperature will be measured with thermocouples in reactive cases

IV. Perspectives

- Complementary tests are planned to explain the results obtained
- Background Oriented Schlieren set up will used to investigate the vaporization process during the injection
  - Density gradient characterization
  - Comparison with Schlieren

On- and Off-Resonant CH_2O Imaging and Transient Flame Development in Multiple Injections

Noud Maes*, Peter-Christian Bakker,
Nico Dam, Bart Somers
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Technische Universiteit
Eindhoven
University of Technology

Where innovation starts

Outline

- Motivation
- Optical diagnostic techniques
- Quasi-steady CH_2O validation
- Transients in multiple injections
- Non-CH_2O background in PLIF images
- Conclusions

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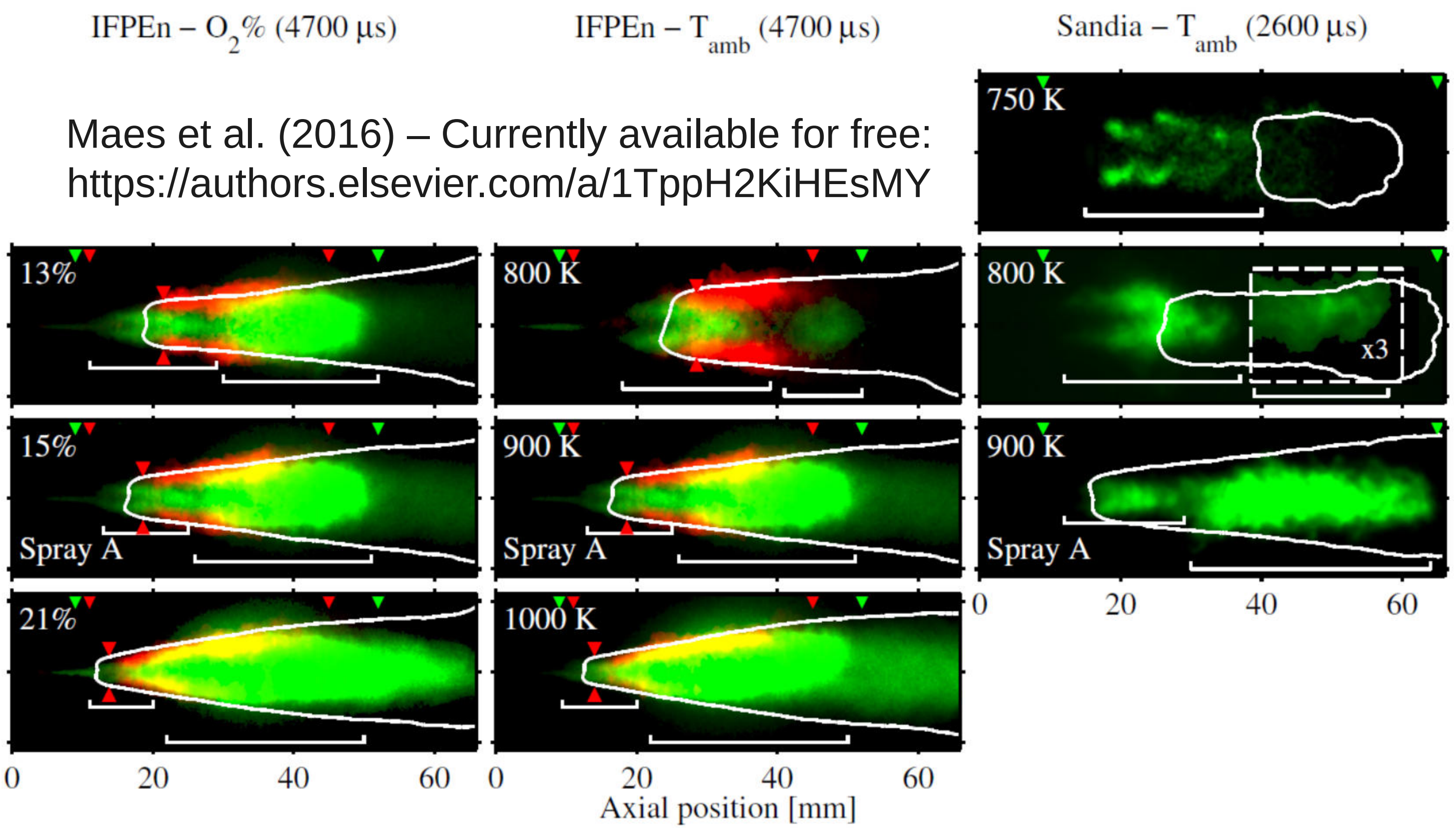
Motivation

- CH_2O PLIF: generally 355-nm excitation
- But: always mind PAH (and potential overlap!)

Maes et al. (2016) – Currently available for free:
https://authors.elsevier.com/a/1TppH2KiHEsMY



Liquid, CH_2O & PAH
OH PLIF
White contour: OH*

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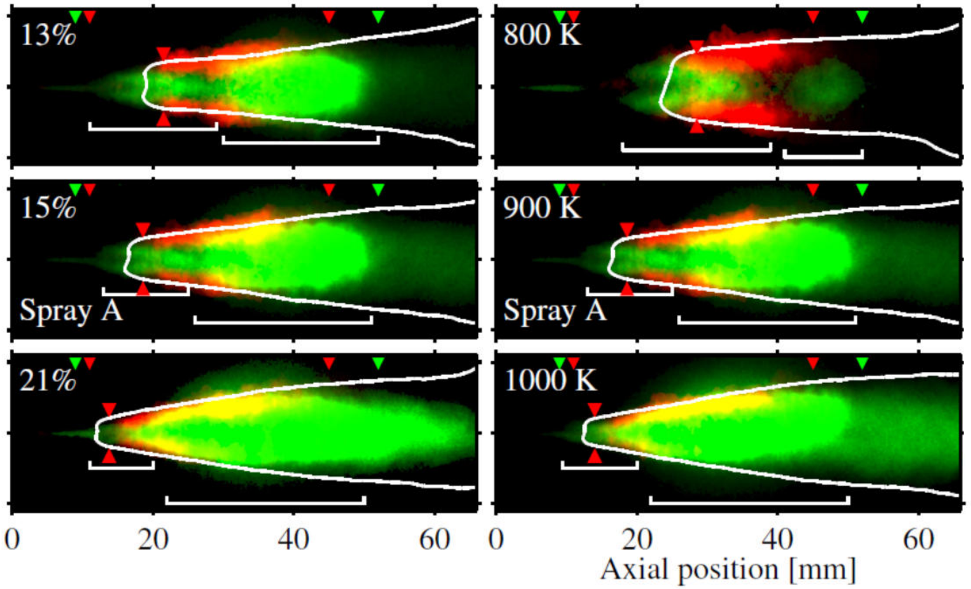
Motivation

- CH_2O PLIF: generally 355-nm excitation
- But: always mind PAH (and potential overlap!)
- Formaldehyde identification through:

Maes et al. (2016) – Currently available for free:
https://authors.elsevier.com/a/1TppH2KiHEsMY



- Known trends & spatiotemporal evolution;
  - Maes et al., Combust. Flame 2016
  - Skeen et al., Proc. Combust. Inst. 2014
- Spectral imaging and analysis (non ECN);
  - Bruneaux, Int. J. Engine 2008
  - Donkerbroek et al., Combust. Flame 2009
  - Lachaux and Musculus, ProCI 2007
- ***(Limited to 1D due to spectrograph)***

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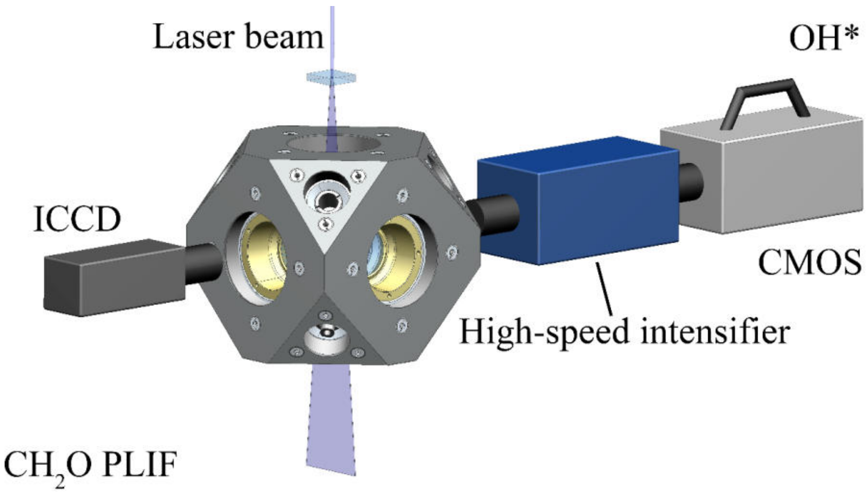
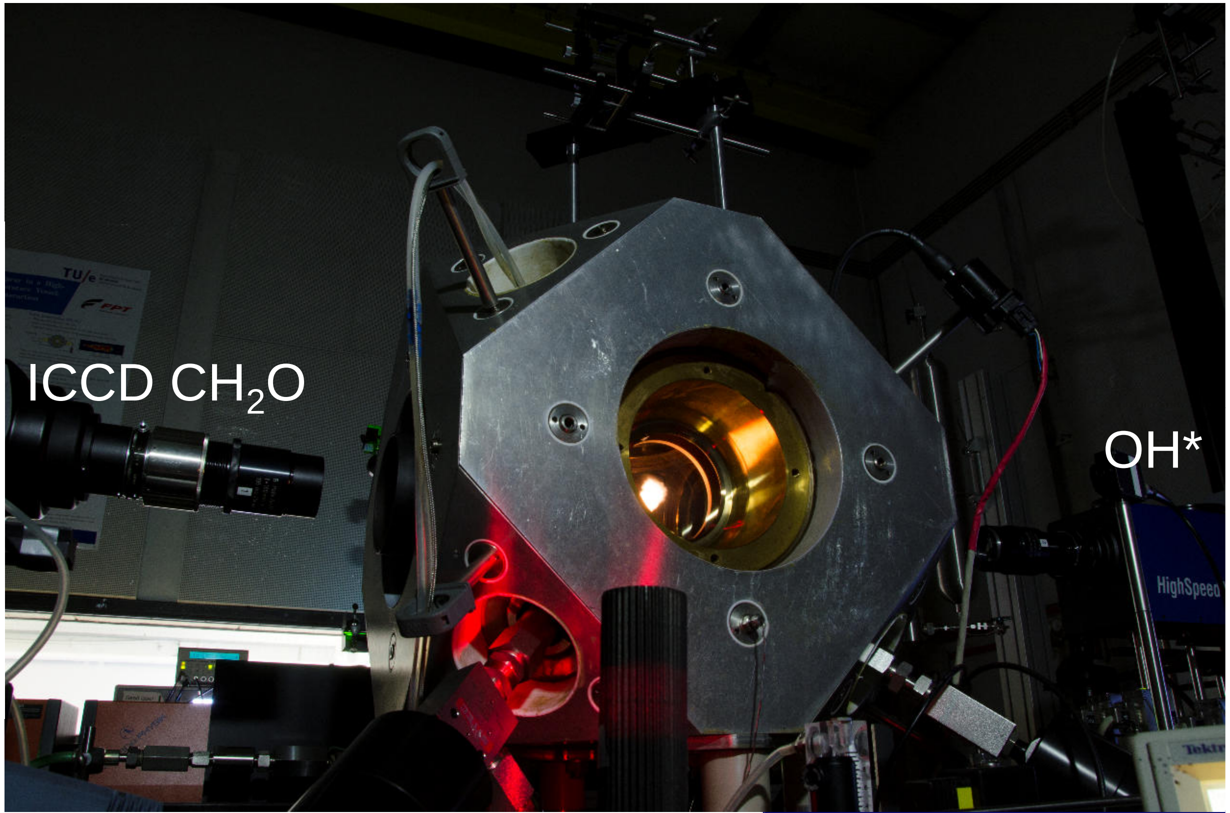
Optical diagnostic techniques

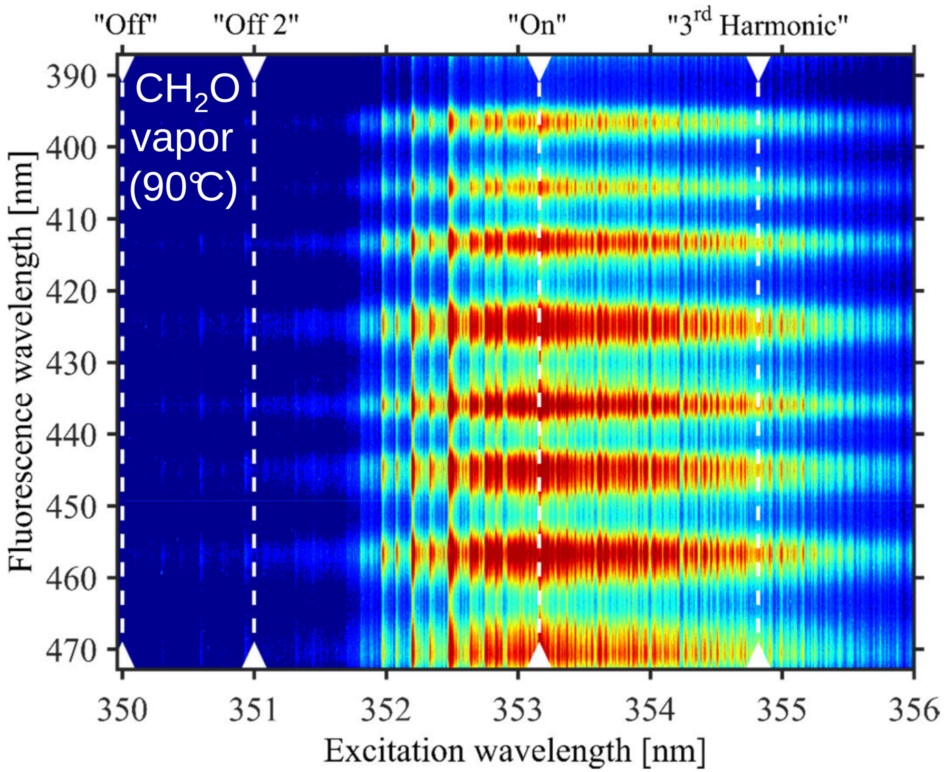
- CH_2O PLIF: on- and off-resonant excitation
- High-speed OH* chemiluminescence (70 – 100 kHz)
- High-speed natural luminosity (70 kHz, <600 nm)





Optical diagnostic techniques

- CH_2O PLIF: on- and off-resonant excitation
- High-speed OH* chemiluminescence (70 – 100 kHz)
- High-speed natural luminosity (70 kHz, <600 nm)
- 353.16-nm excitation – 350.00 nm for off-resonant

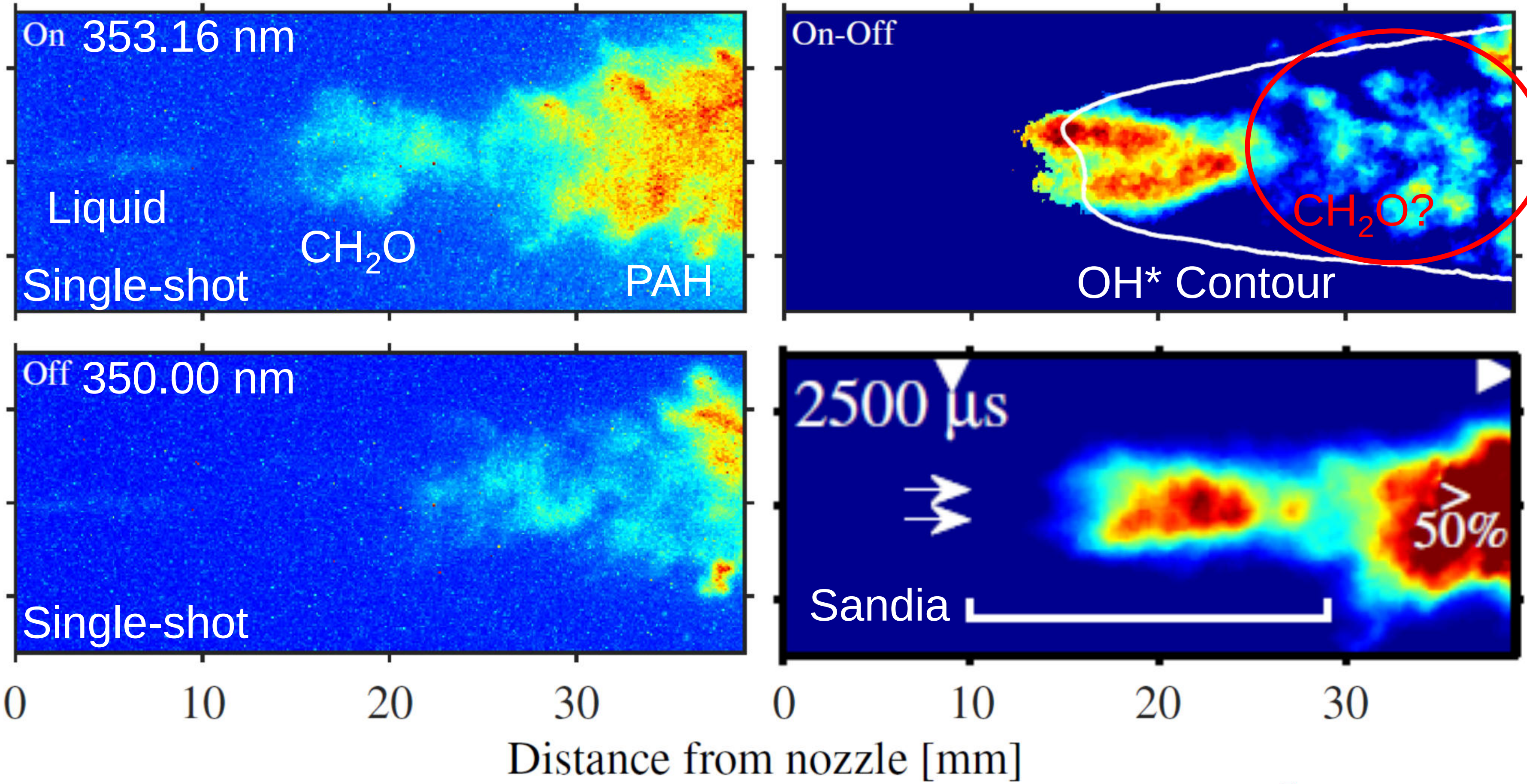


50-mm f/1.4 Nikkor
500-nm short-pass
WG360 long-pass

353.16 nm vs 354.82 nm:
x2.5 excitation efficiency

Quasi-steady CH_2O validation

- **Spray A @ 900 K, 22.8 kg/m³, 15% O_2 & 1500 bar inj.**

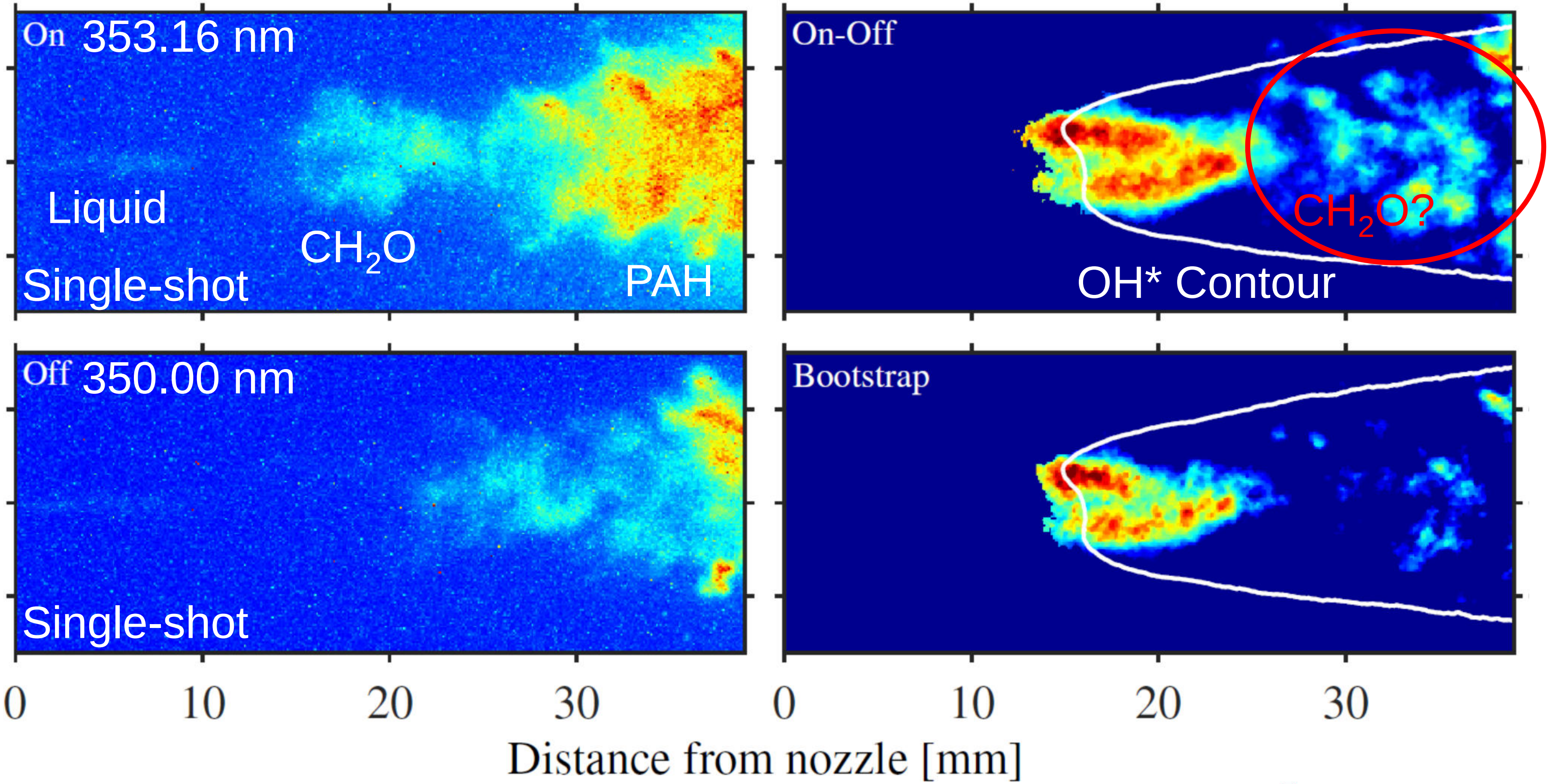


Bootstrap: random resampling with replacement

e.g. 4x exp. 3, etc.: Illustrative for persistent structures

Quasi-steady CH_2O validation

- **Spray A @ 900 K, 22.8 kg/m^3, 15% O_2 & 1500 bar inj.**



Bootstrap: random resampling with replacement
e.g. 4x exp. 3, etc.: Illustrative for persistent structures

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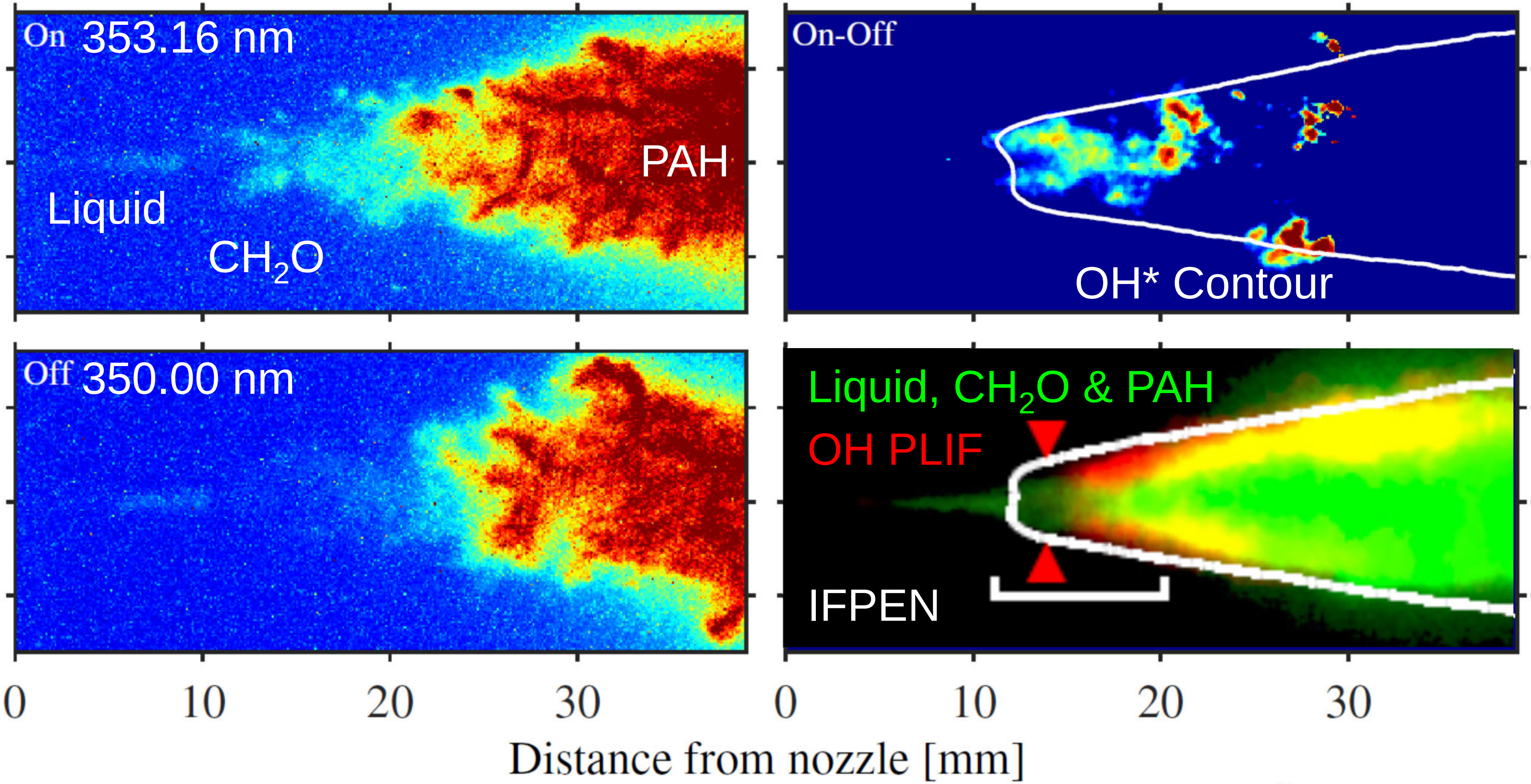
Quasi-steady CH_2O validation – 21% O_2

- **Spray A @ 900 K, 22.8 kg/m³, 21% O_2 & 1500 bar inj.**



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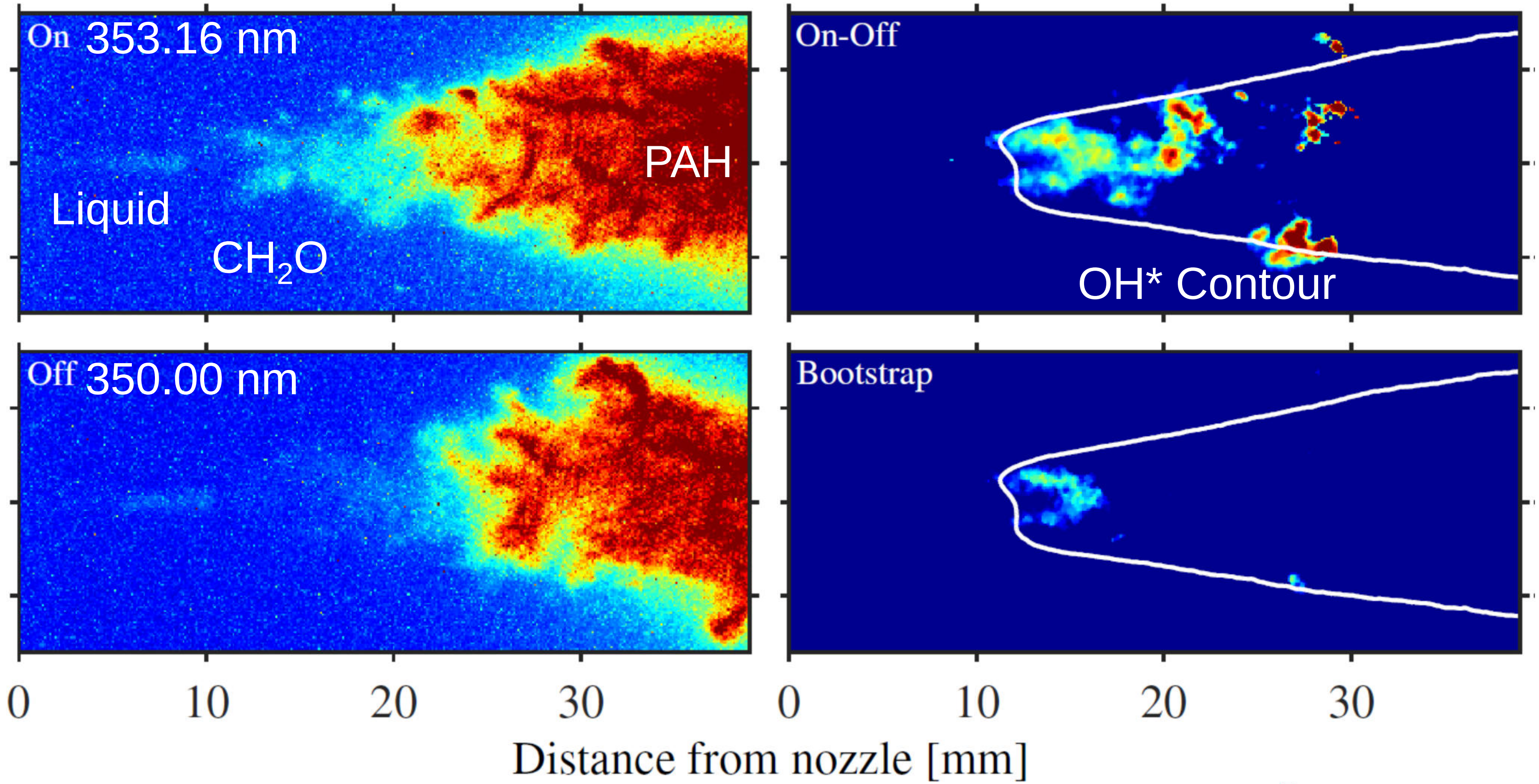
Quasi-steady CH_2O validation – 21% O_2

- **Spray A @ 900 K, 22.8 kg/m³, 21% O_2 & 1500 bar inj.**



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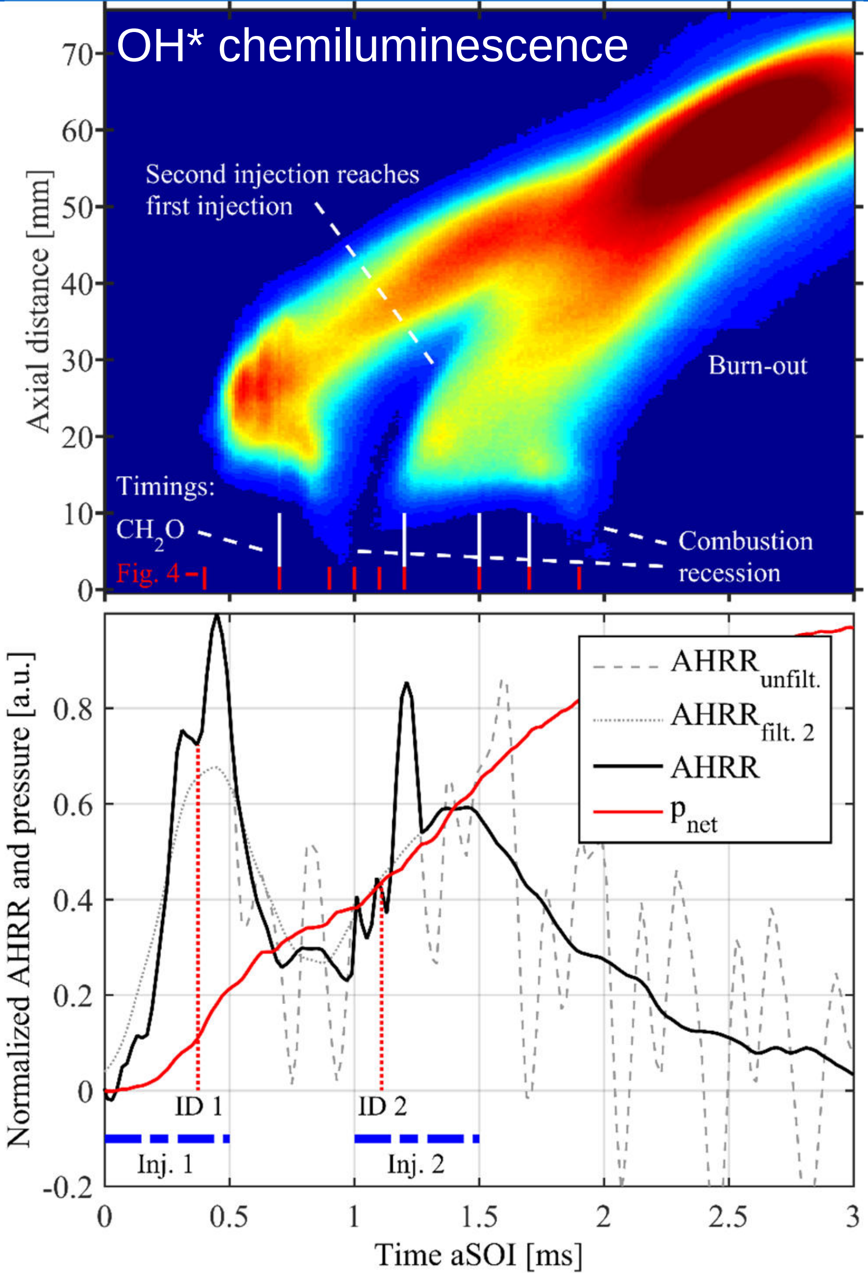
Quasi-steady CH_2O validation

- On- and off-resonant imaging of CH_2O:
  - Substantiates identified structures in previous work
  - Enhances interpretation (bootstrapping can aid in this)
  - Permits identification in overlapping regions

- Next: application in transients
  - Aided by high-speed diagnostic techniques

Transients in multiple injections



- **0.5 ms / 0.5 ms / 0.5 ms**
- **Injection / dwell / injection**
- **I_{xt} – plot: transients as a function of time**

- **Heat-release analysis**

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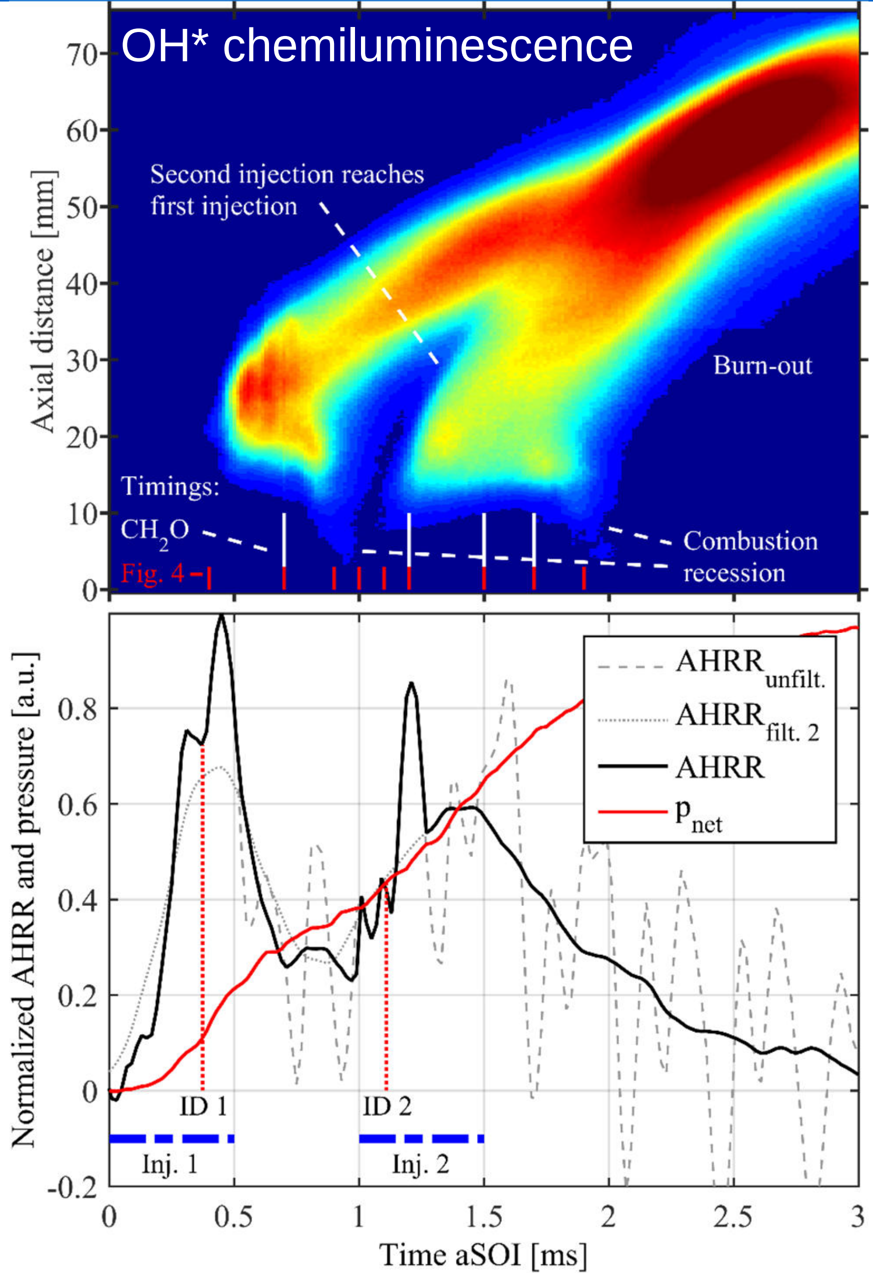
Transients in multiple injections



- **0.0 ms**: SOI
- **0.4 ms**: high-T ignition
- **0.5 ms**: EOI 1
- **1.0 ms**: max. recess., SOI 2
- **1.1 ms**: high-T igniton 2
- **1.5 ms**: EOI 2
- **2.0 ms**: max. recession

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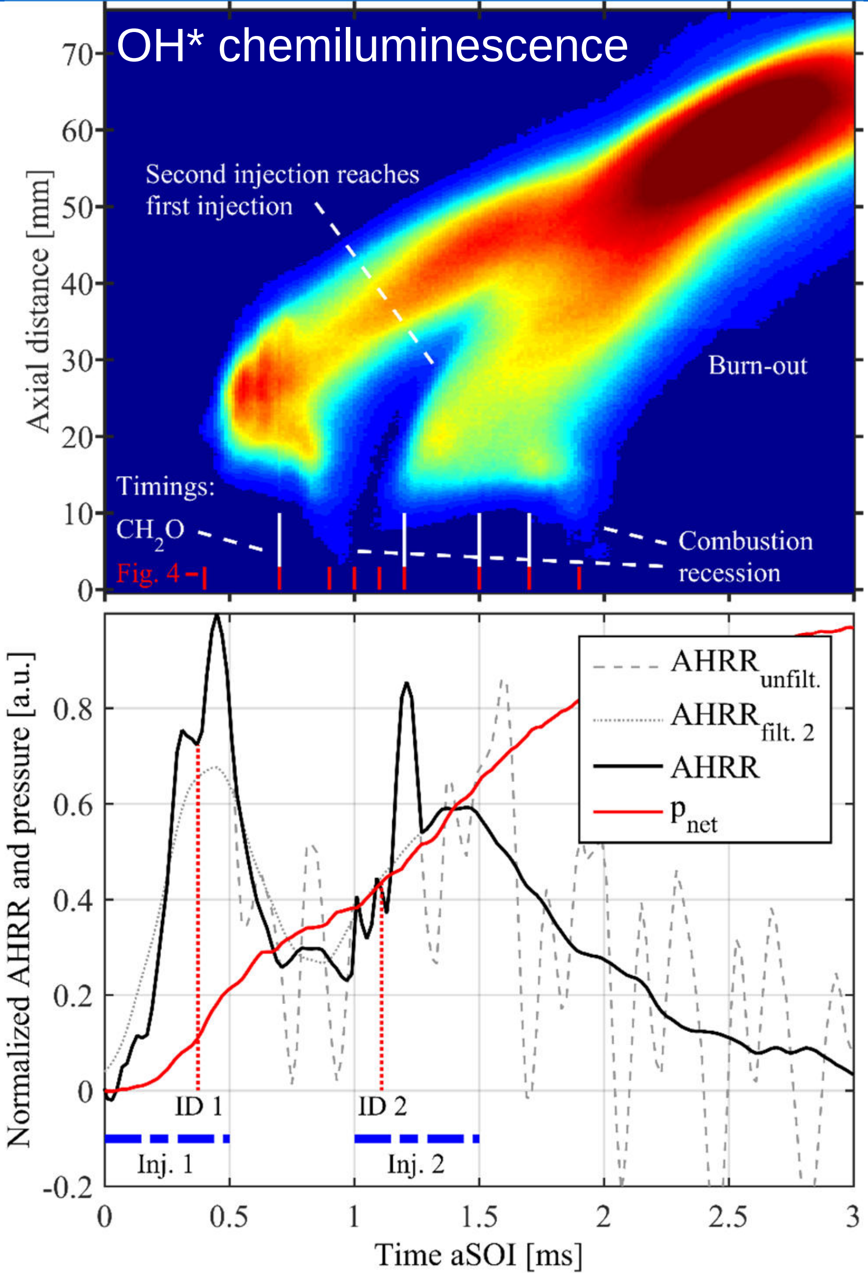
Transients in multiple injections



- **Ignition delay 1**
  - **Pressure: 30 mbar**
  - **OH*: 2% of max. intensity**
- **Ignition delay 2:**
  - **Pressure : 15 mbar**
    - **More gradual ignition!**
  - **OH*: 2% of max. intensity**

	1st injection	2nd injection	
$ID_{OH^*\ Ixt}$	0.40 ± 0.02	0.11 ± 0.02	ms
$ID_{pressure}$	0.37 ± 0.10	0.11 ± 0.08	ms

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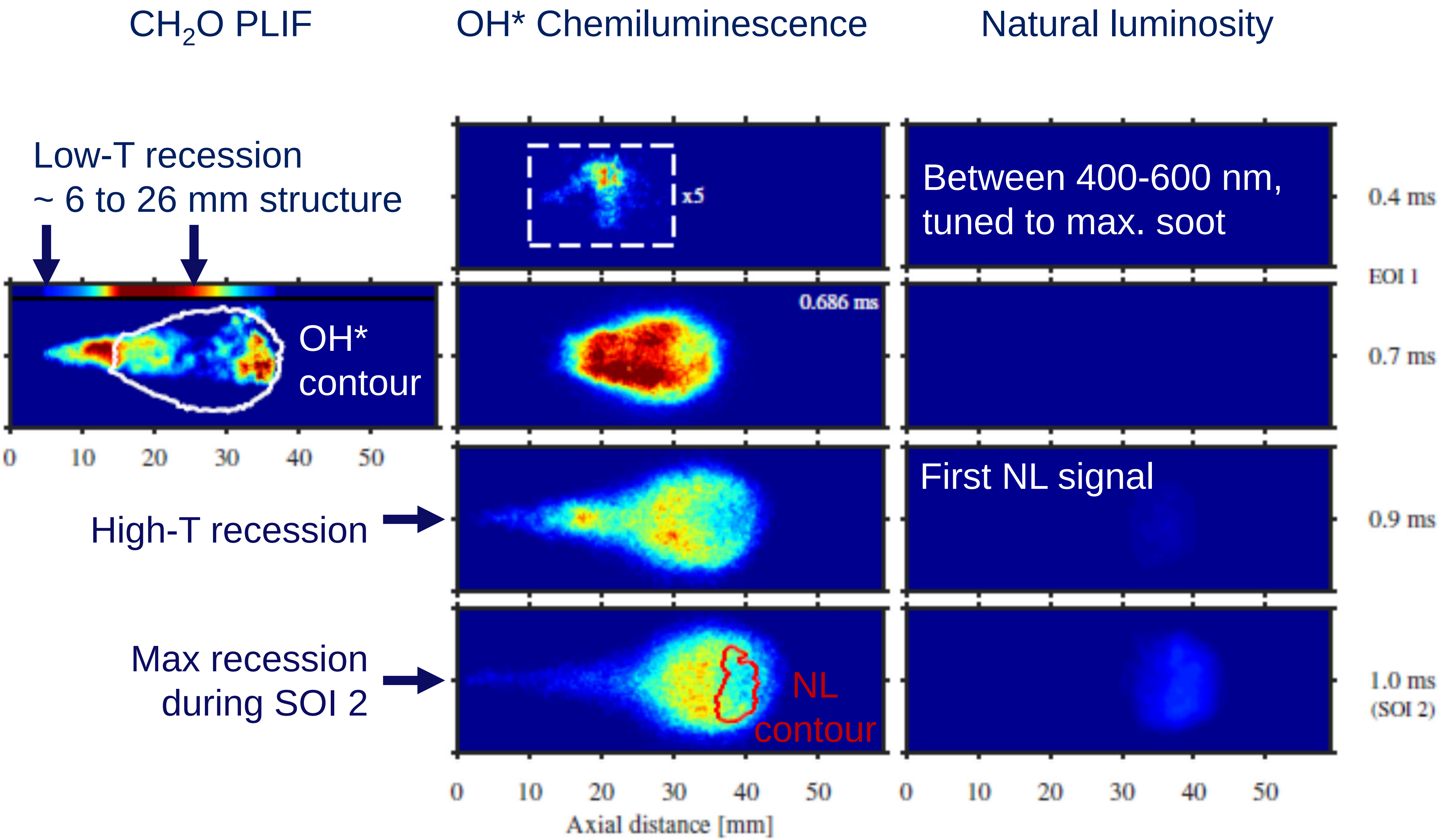
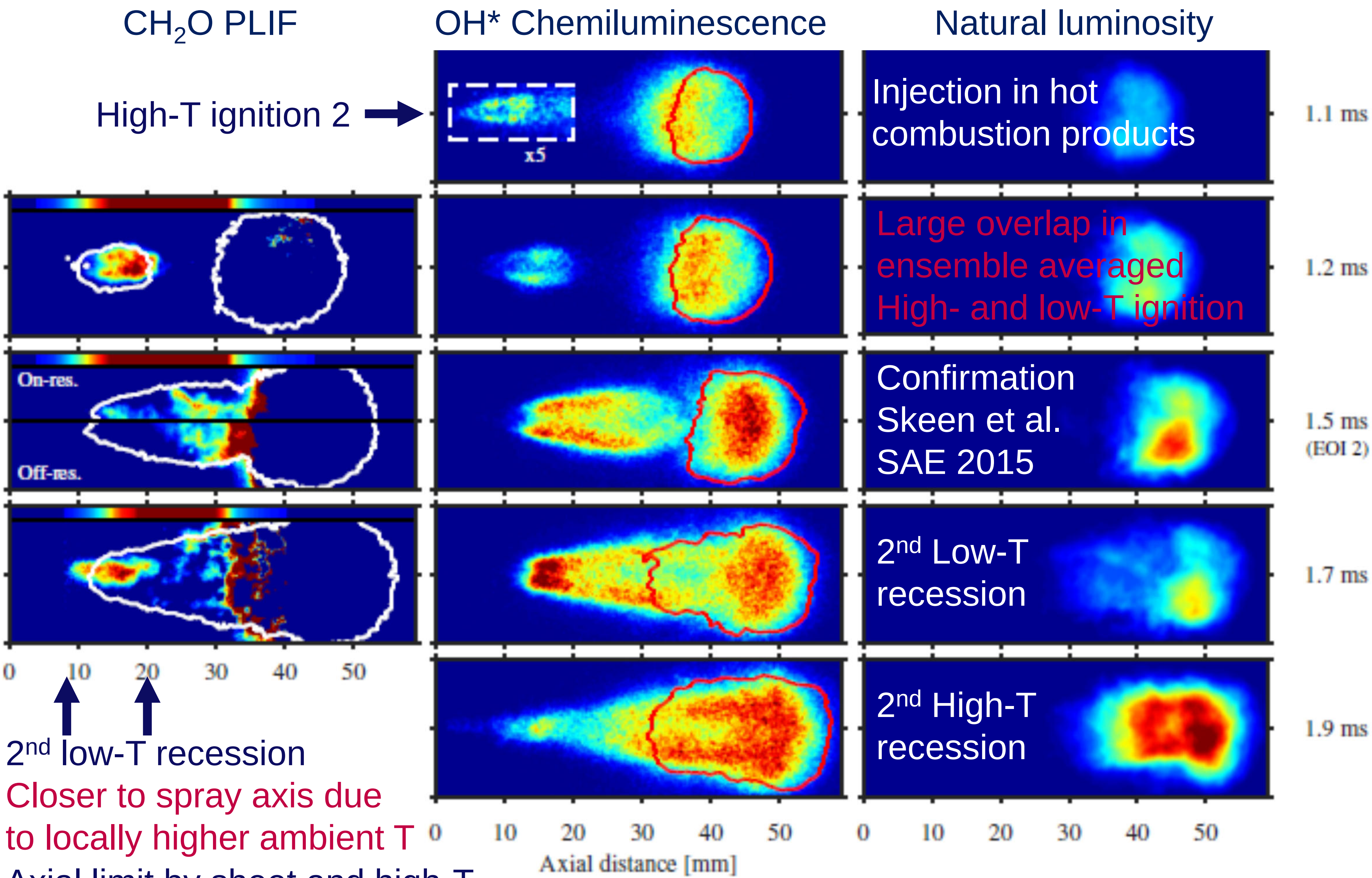
Transients in multiple injections up to SOI 2



Up to combustion recession 2



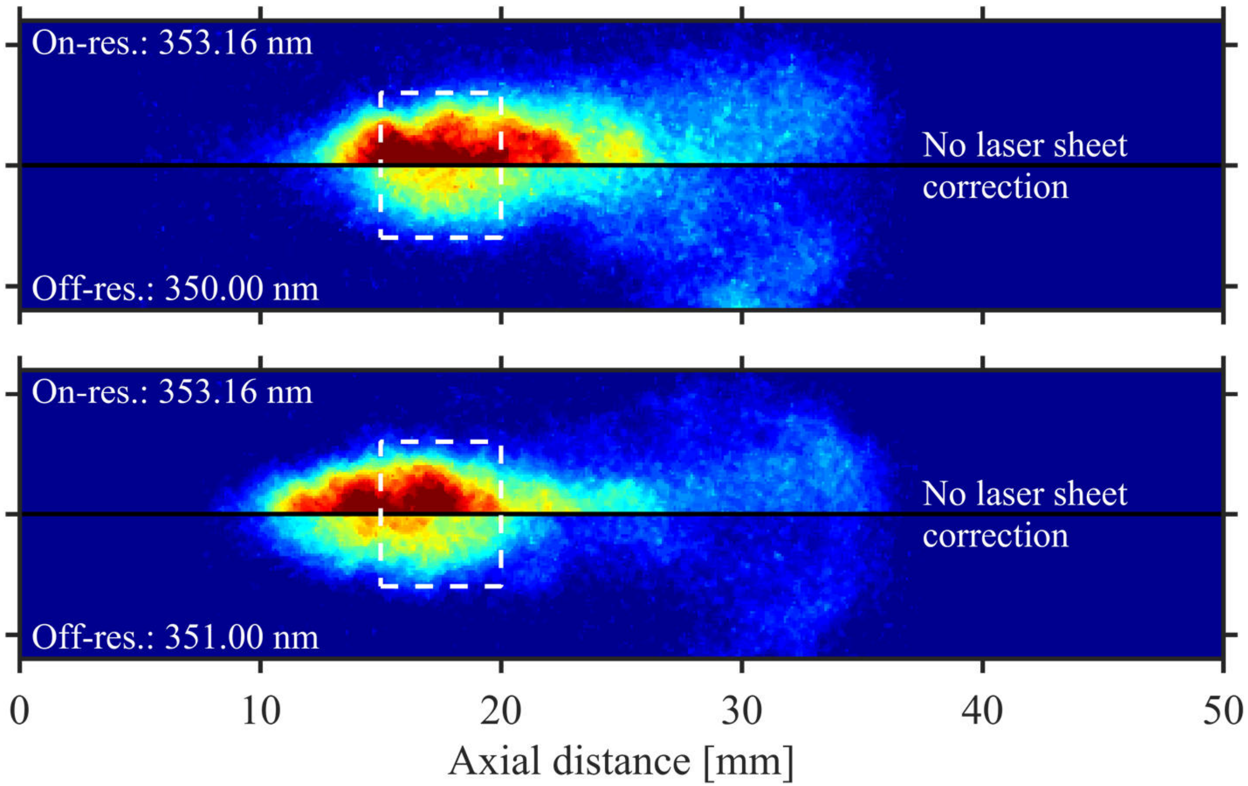
2nd low-T recession

Closer to spray axis due to locally higher ambient T

Axial limit by sheet and high-T

Non-CH_2O background in PLIF images

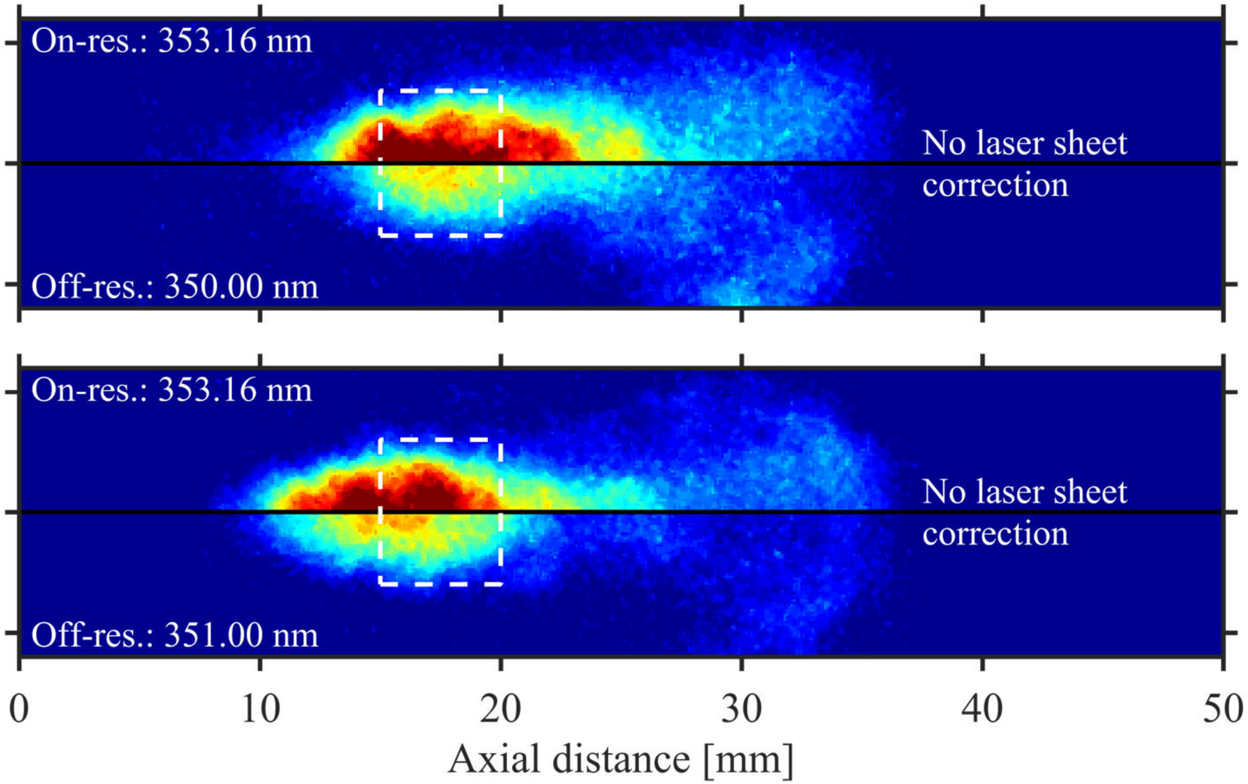
- **Determining background within indicated dashed white rectangle → CH_2O in all images**



Different laser sheet locations cause an apparent shift in signal without the laser sheet correction

Non-CH_2O background in PLIF images

	0.7 ms 350 nm	1.2 ms	1.5 ms	1.7 ms	0.7 ms 351 nm	2.5 ms QS spray	
Background contribution	46 ± 1	37 ± 2	21 ± 4	46 ± 6	51 ± 1	33 ± 1	%



Low during quasi-steady spray

Suggestive for significant PAH PLIF during low-temperature combustion recession!

Conclusions

- Validation of on- and off-resonant strategy
- Confirmed CH_2O location for multiple cases:
  - Quasi-steady Spray A and 21% O_2 variation
  - 0.7, 1.2, 1.5 and 1.7 ms aSOI for multiple injection
- Detection of increased background in transients

Publications and additional work

- “The Potential of On- and Off-Resonant Formaldehyde Imaging in Diesel Sprays”
  - Submitted to CNF
- “Transient Flame Development in a Constant-Volume Vessel using a Split-Scheme Injection Strategy”
  - Submitted to SAE (April 2017, Detroit)

- Multiple injections: OH-PLIF & dwell variations
- Long injection-duration: 100 kHz OH*

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Soot and Spectral Radiation Modelling for Spray A

D.C. Haworth (Penn State) and M.F. Modest (UC Merced)

Graduate students & postdocs (Penn State):
A. Imren, C. Paul, A. Sircar and S. Ferreyro-Fernandez

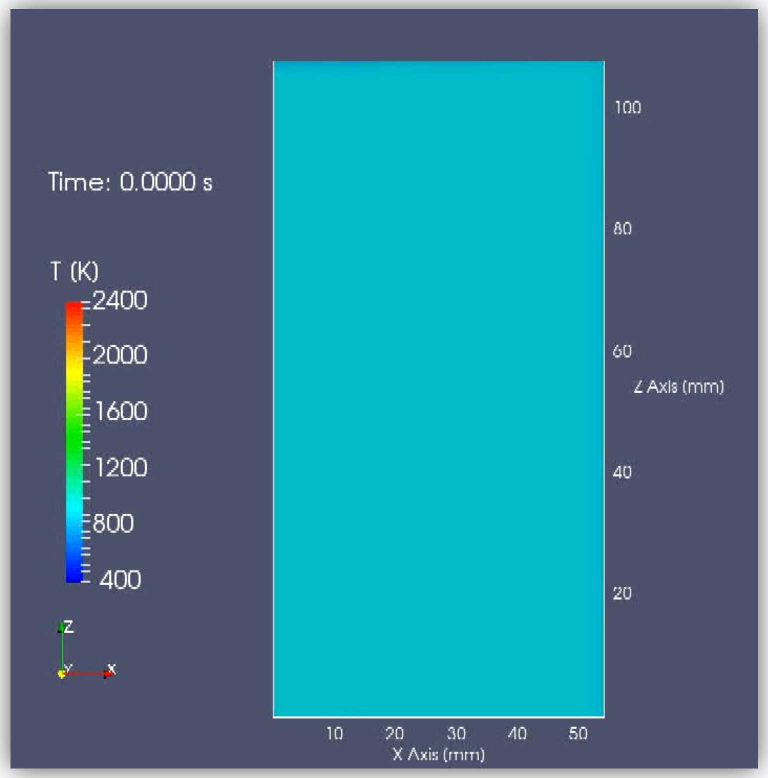
Graduate students & postdocs (UC Merced):
W. Ge and S.P. Roy

Funding:
NSF 1258613
DoE DE-EE0007278

November 2016

Unsteady RANS has been performed using OpenFOAM

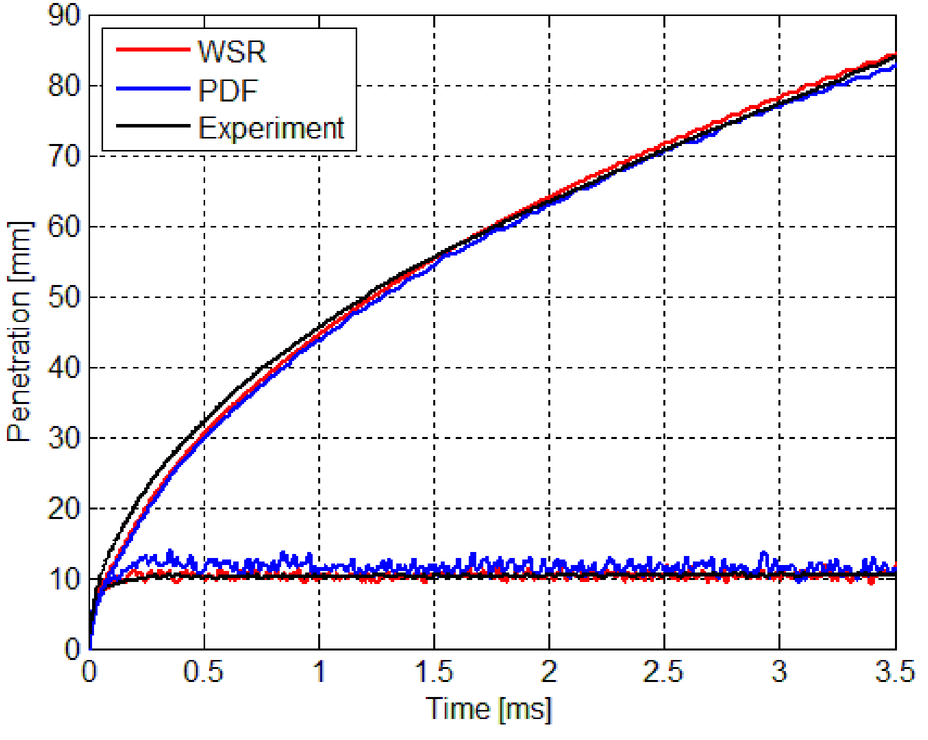
- Ambient mixture (reacting)
  - 900 K, 22.8 kg/m^3 (60 bar)
  - 15% O_2, 6.2% CO_2, 3.6% H_2O
- n-Dodecane fuel
  - 150 MPa, 6 ms duration
- Unsteady RANS
  - 2D axisymmetric (wedge) mesh
  - Nonuniform, ~10K finite-volume cells
  - Standard two-equation turbulence model
- Conventional stochastic Lagrangian parcel fuel injection and spray models
- 52-species chemical mechanism
- Semi-empirical two-equation soot model
- With and without radiation
- WSR or PDF models
  - 50-100 particles per cell for PDF



*www.sandia.gov/ecn/

Models have been adjusted to match global behavior for the nonreacting case

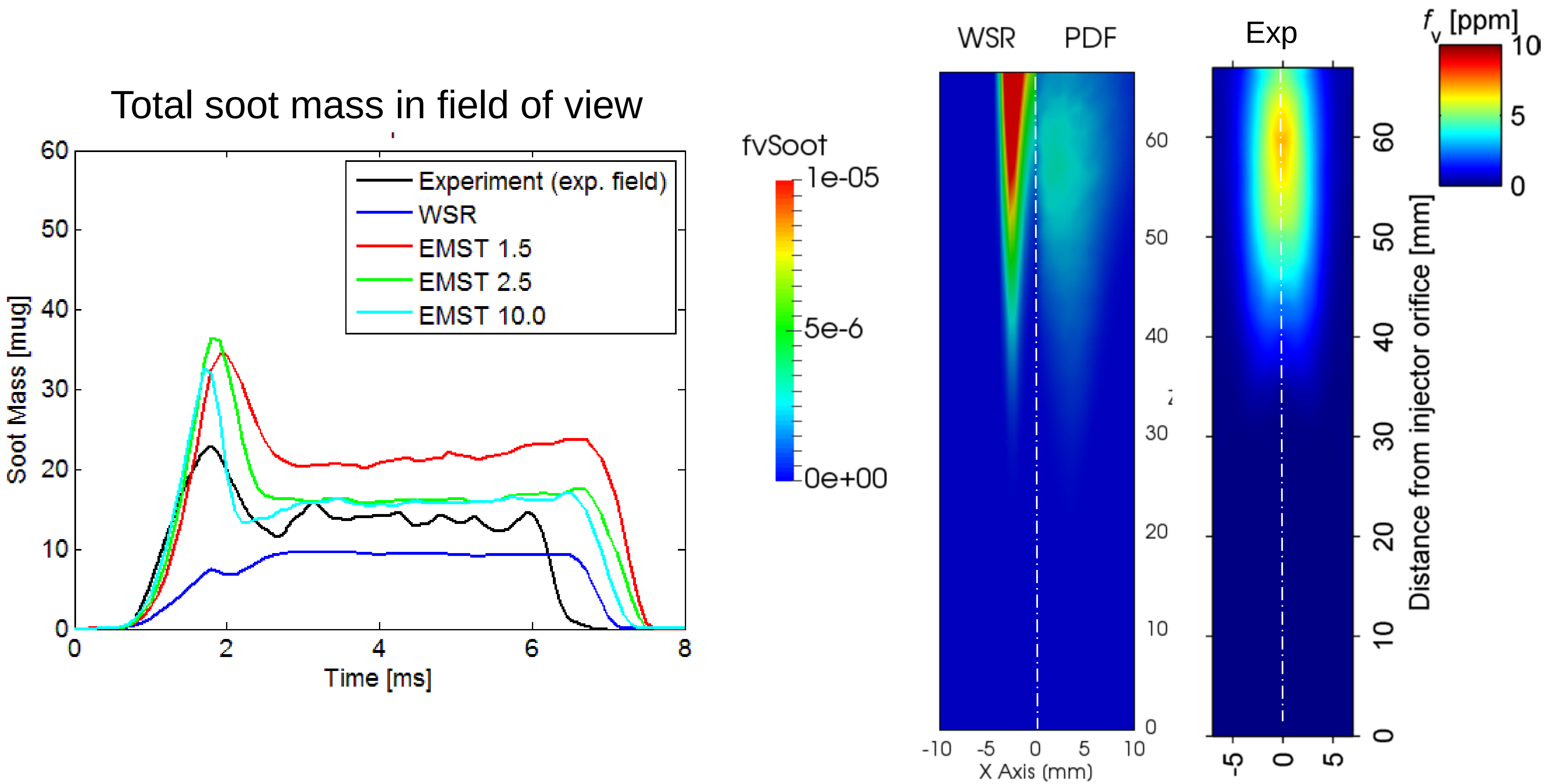
Computed and measured liquid and vapor penetration vs. time for nonreacting case



Computed and measured lift-off length and ignition delay for reacting case

Case	LOL (mm)	ID dT/dt (ms)	ID OH (ms)
Experiment	16.1	0.40	
WSR/NoRad	17.7	0.43	0.35
PDF/NoRad	16.2	0.35	0.34
PDF/OT/TRI	16.3	0.38	0.35
PDF/OT/NoTRI	17.5	0.40	0.38

tPDF model gives more realistic soot evolution



Experimental data: /www.sandia.gov/ecn/

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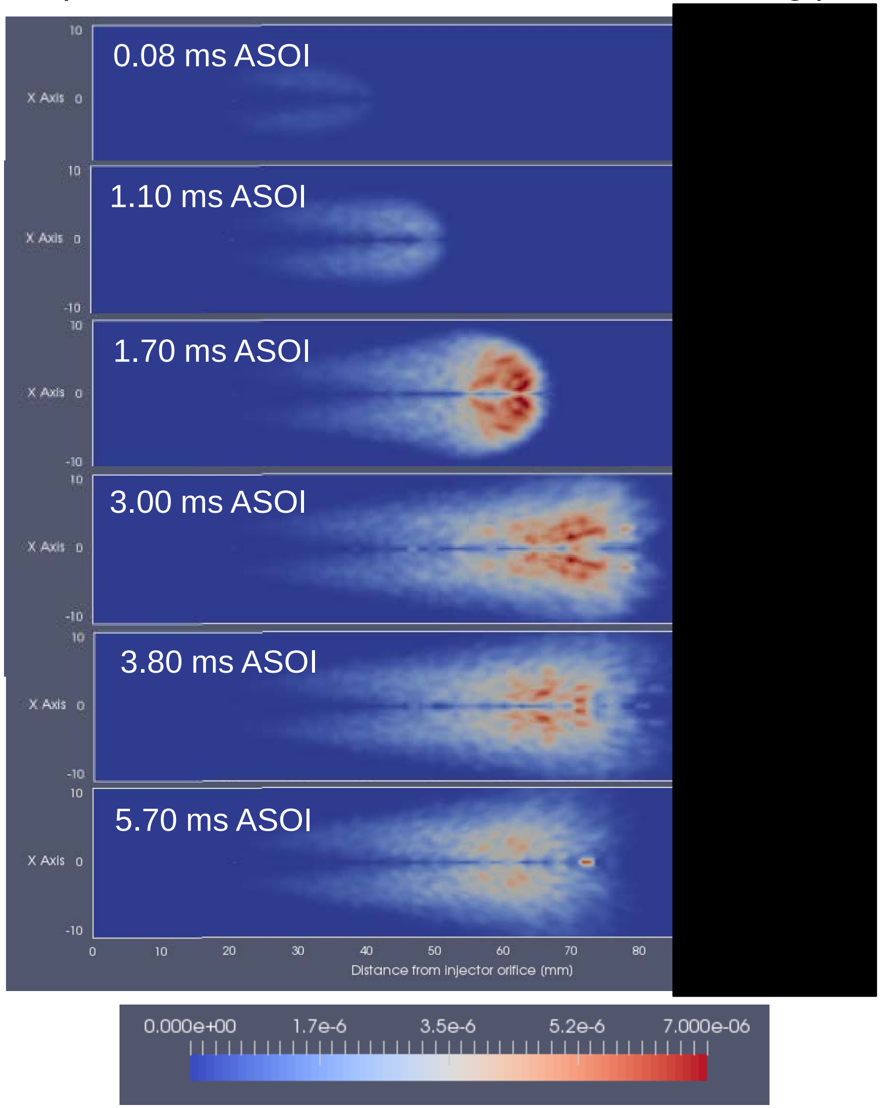
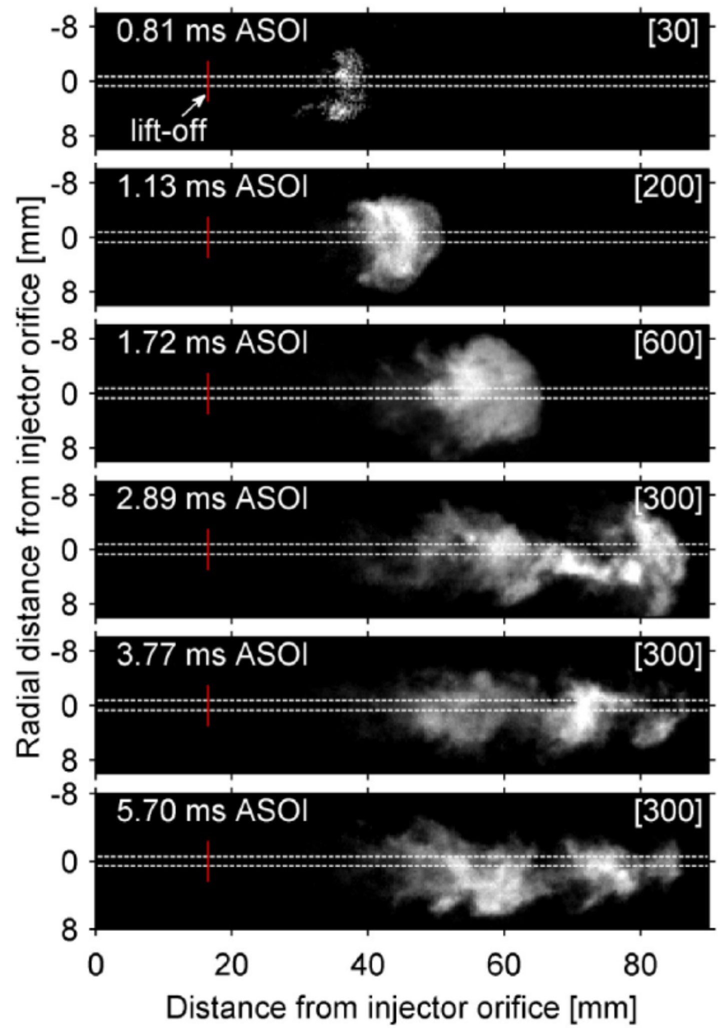
Computed soot spatial distributions show some features qualitatively consistent with luminosity measurements

Computed mean soot volume fraction on a cutting plane



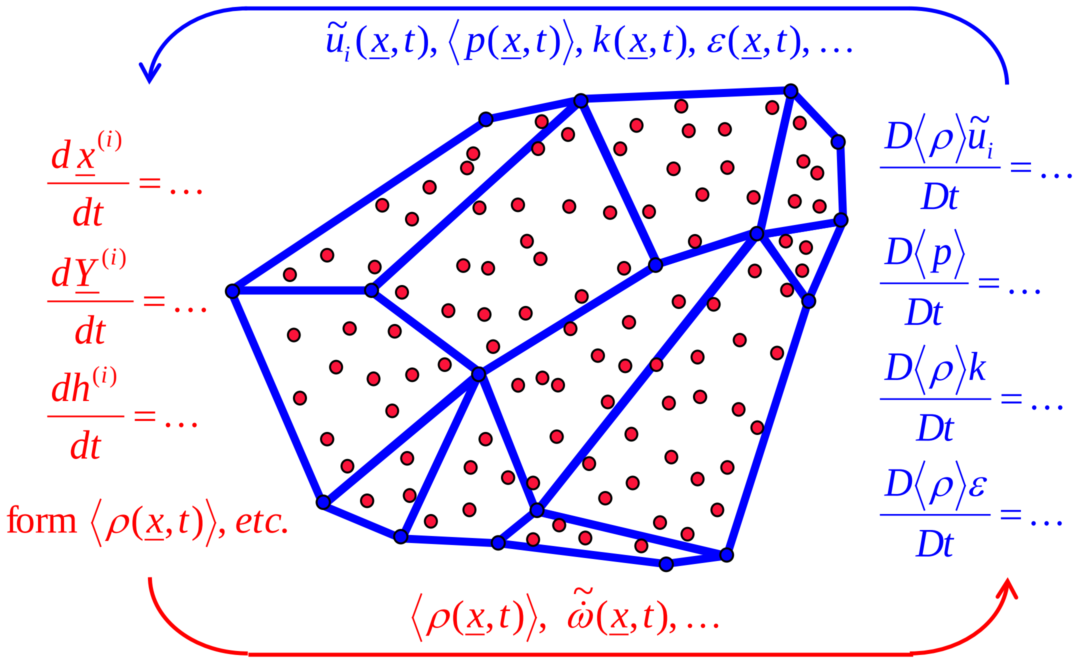
Measured soot luminosity



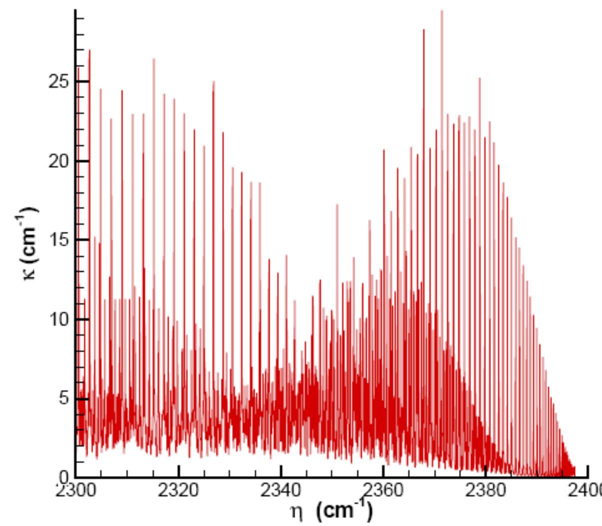
Skeen et al. SAE 2014-01-1252

In PMC/LBL, stochastic ray tracing provides an "exact"* treatment of radiative transfer

Consistent hybrid Lagrangian particle/finite-volume transported composition probability density function (PDF) method



Spectral photon Monte Carlo (PMC) method

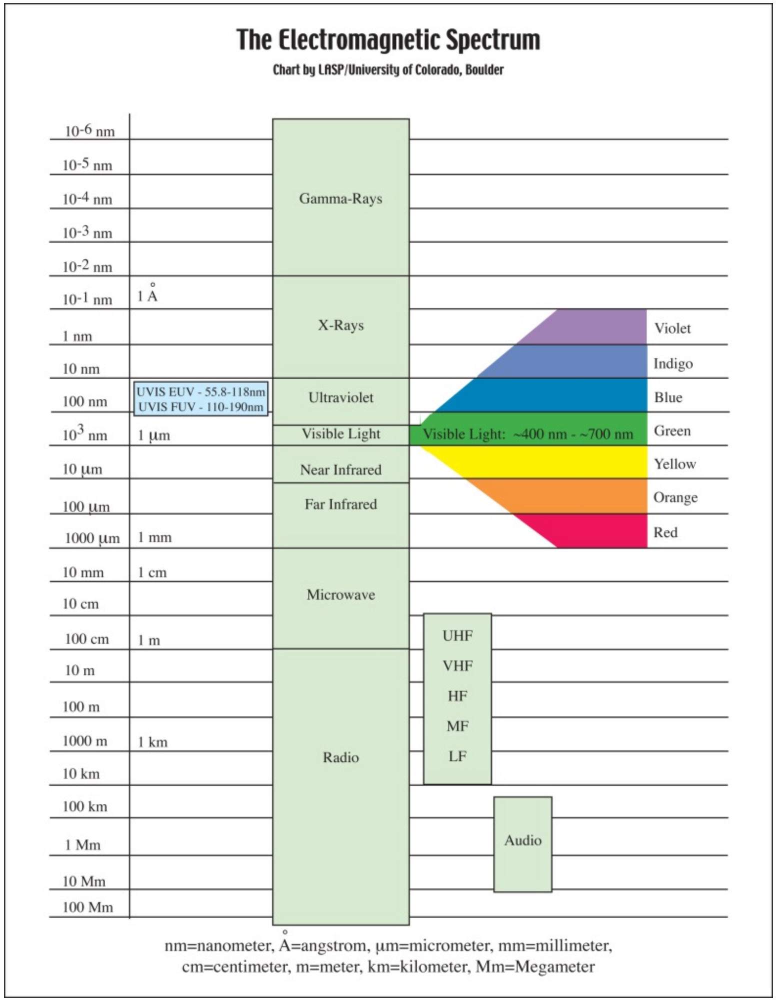


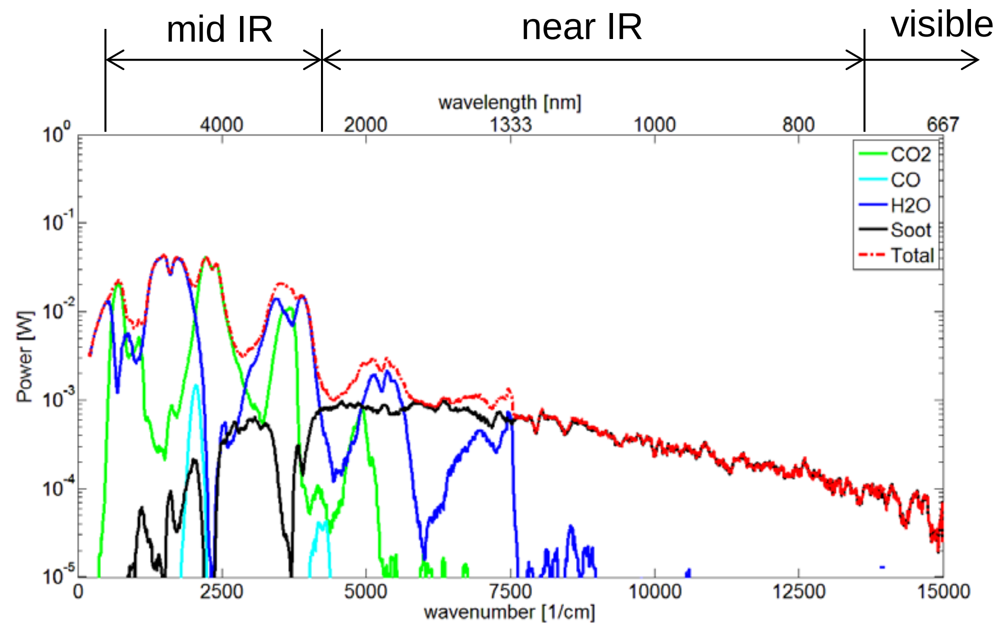
Small portion of 4.2 µm narrow band of CO_2

*"Exact" to the extent that:

- Radiative properties are known
- Statistical error is controlled
- Computed composition and temperature fields are correct

Near-to-mid infrared is most relevant for combustion heat transfer





Computed spectrum of radiation reaching walls for ECN Spray A

Visible:	380 –	750 nm
Near IR:	750 –	2 ,500 nm
Mid IR:	2,500 –	25,000 nm
Far IR:	25,000 –	100,000 nm

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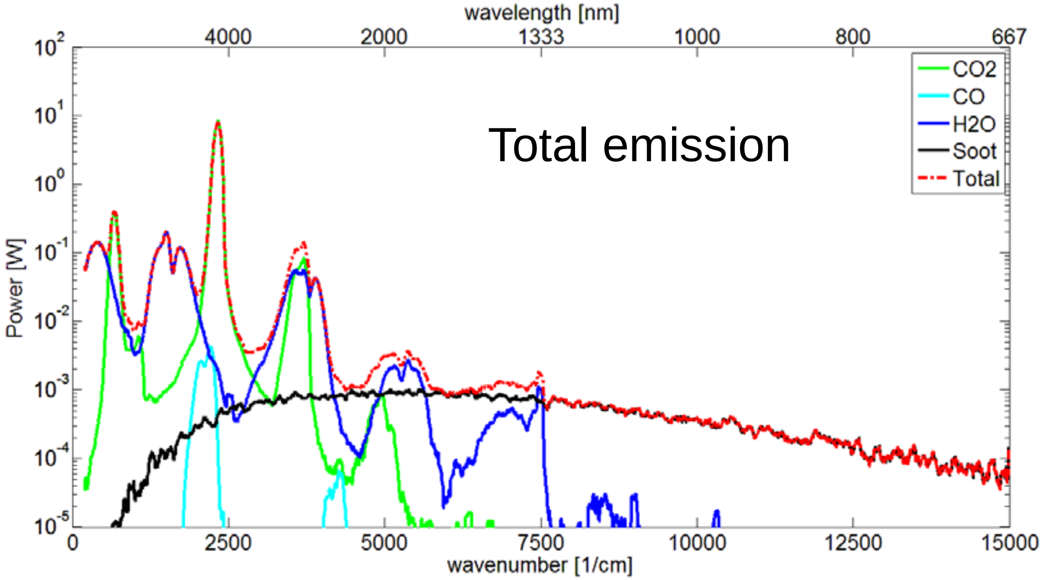
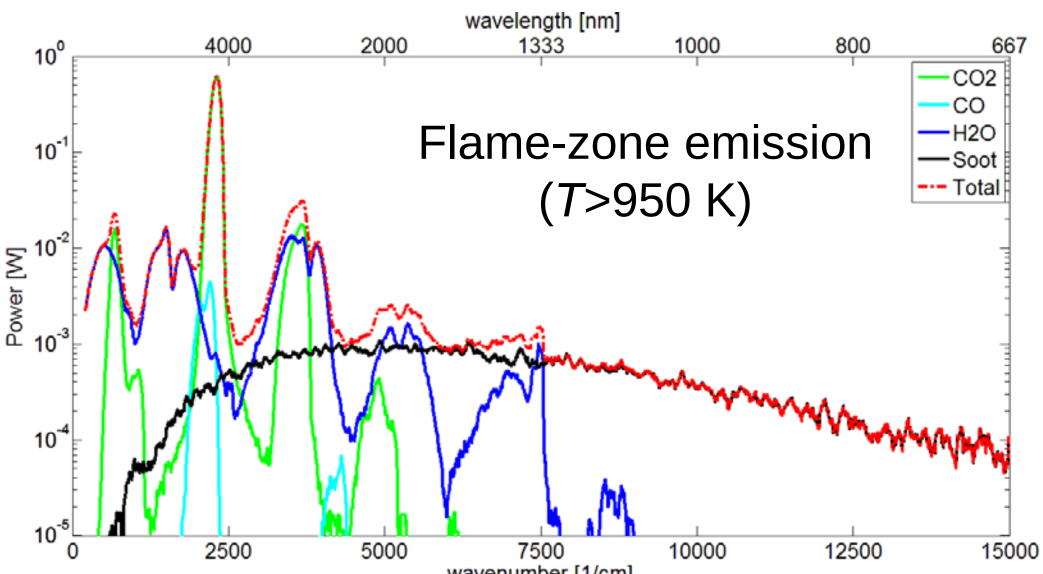
Spectral radiation is computed @ 3 ms aSOI using PMC/LBL

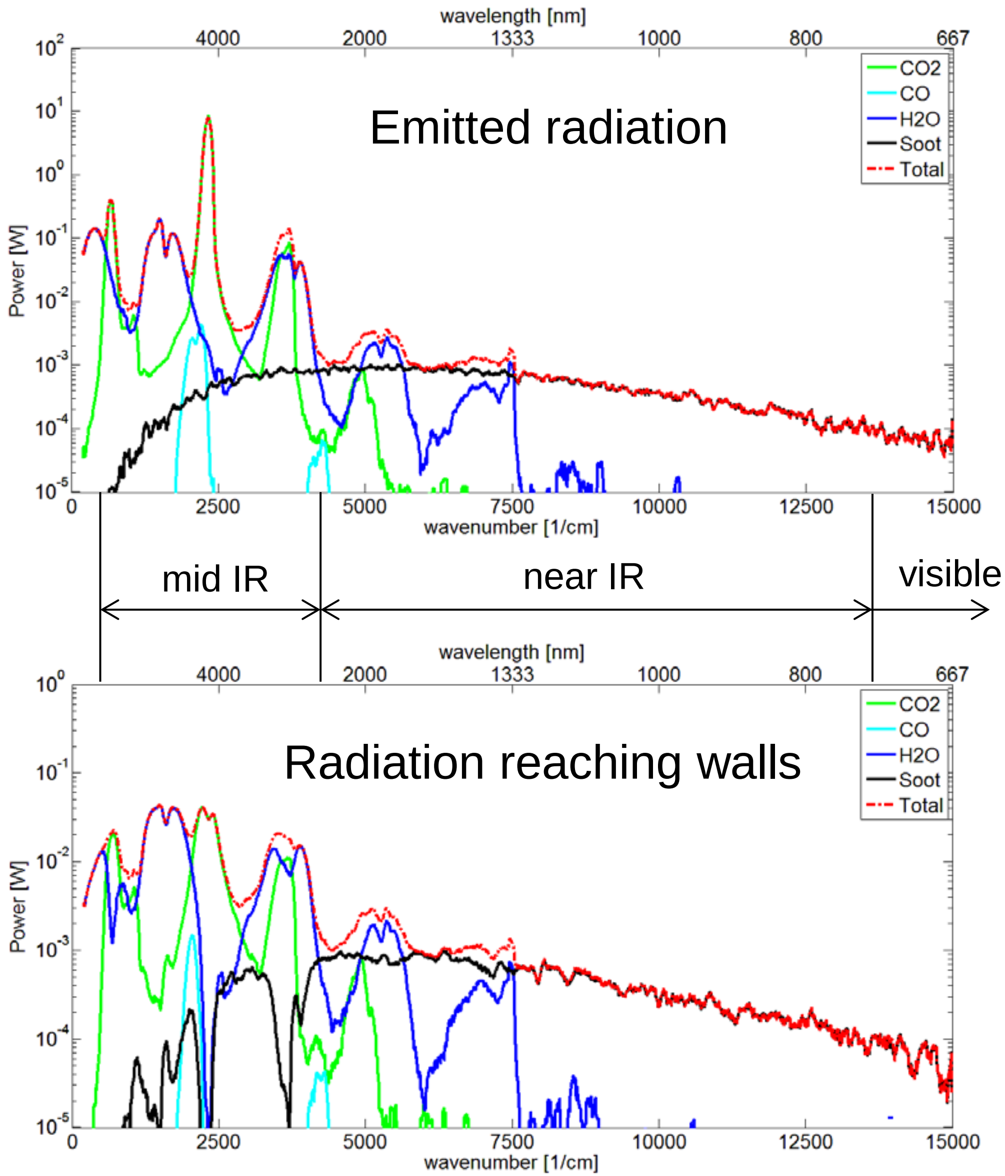




Source	Total emission (W)	Flame-zone emission (W)	% of emission from flame zone
CO	0.20	0.20	100.0
CO2	221.5	21.7	9.8
H2O	32.4	4.6	14.0
Soot	1.30	1.3	100.0
Total	254.4	27.7	10.9

Fuel power = 1572 W

Spectral radiation is computed @ 3 ms aSOI using PMC/LBL (cont.)

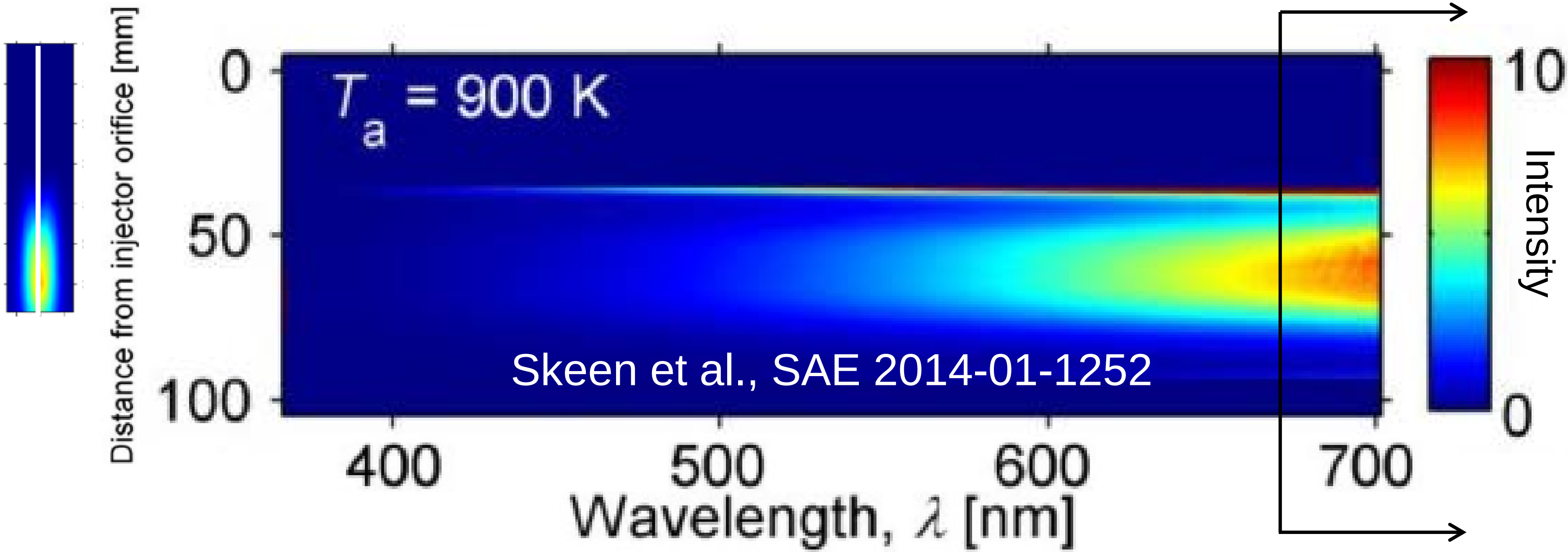


Source	Total emission (W)	Flame-zone emission (W)	Radiation reaching wall (W)
CO	0.20	0.20	0.05
CO2	221.5	21.7	5.3
H2O	32.4	4.6	8.9
Soot	1.30	1.3	1.1
Total	254.4	27.7	15.3

Fuel power = 1572 W
Radiant fraction ≈ 1%
Soot radiant fraction ≈ 0.07%*
CO_2 and H_2O dominate

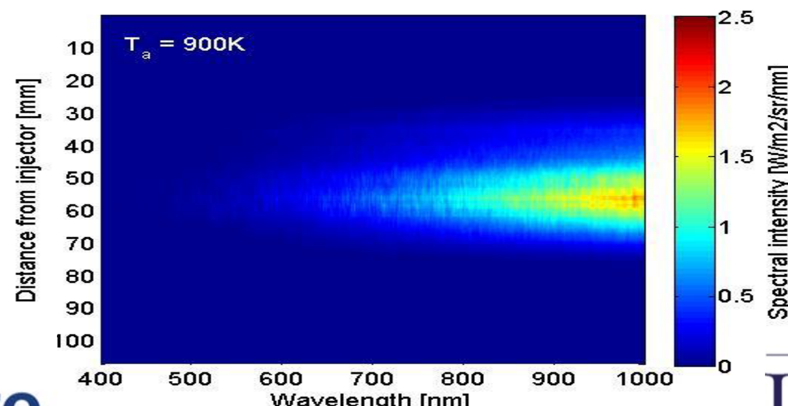
*0.068%, per Skeen et al. SAE 2014-01-1252

Comparisons with spatially and spectrally resolved radiation measurements are in progress



Original
LBL database

Preliminary
simulation results



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Conclusions

- Soot modeling
  - At high pressures, soot kinetics are fast: turbulent transport and mixing become relatively more rate-controlling
  - It is important to account for unresolved turbulent fluctuations, but less important to consider their spatial coherence
  - The overly slow decrease in computed soot after end of injection is probably due to the C_2H_2-based soot model
- Spectral radiation modeling
  - Molecular gas radiation dominates over soot radiation
  - There are complex spectral interactions that would be difficult (impossible?) to unravel without PMC/LBL
  - PMC/LBL provides insight that can help to interpret experimental measurements

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