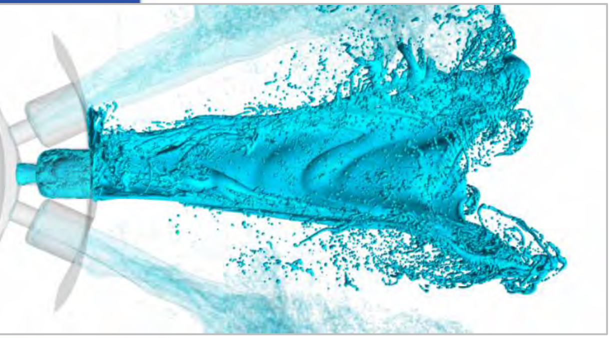
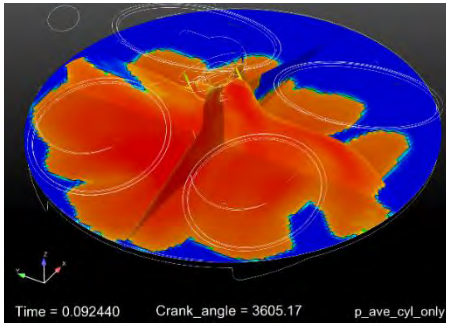
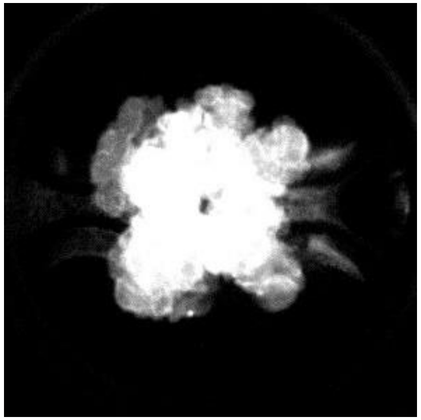
Recenti sviluppi dell'attività di ricerca sperimentale e numerica su MCI svolta presso l'Università degli Studi di Perugia

Michele Battistoni, Francesco Mariani, Gabriele Discepoli, Valentino Cruccolini, Jacopo Zembi, Carlo N. Grimaldi

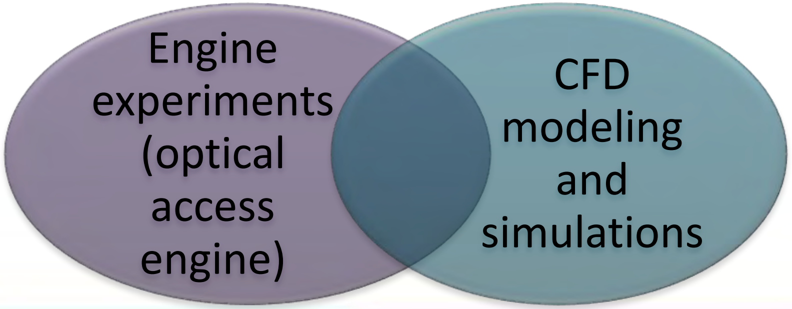




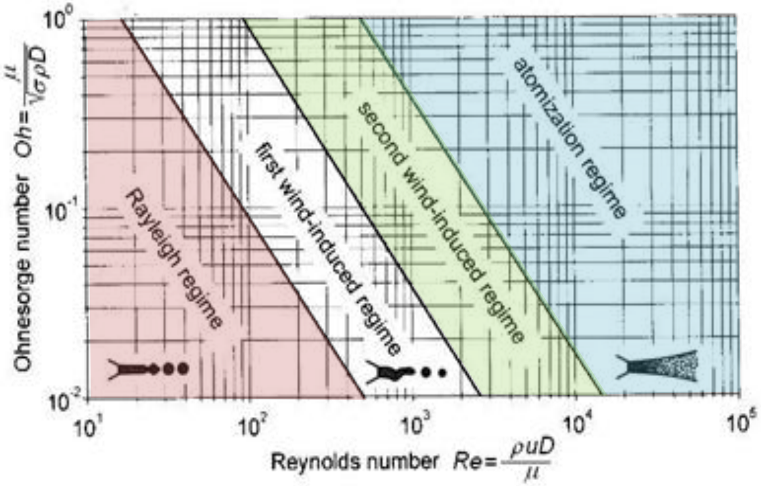


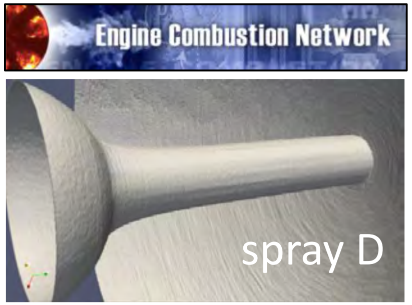
Research activities on I.C. engines - Context and background

- Fundamental studies on <u>liquid atomization</u>, phase change and supercritical flows, combustion, <u>advanced ignition systems</u>
- Conventional combustion modes: SI, CI, <u>knock</u>
- Advanced combustion modes: LTC, PPCI, <u>GCI</u>



Diesel spray: structure of atomization region

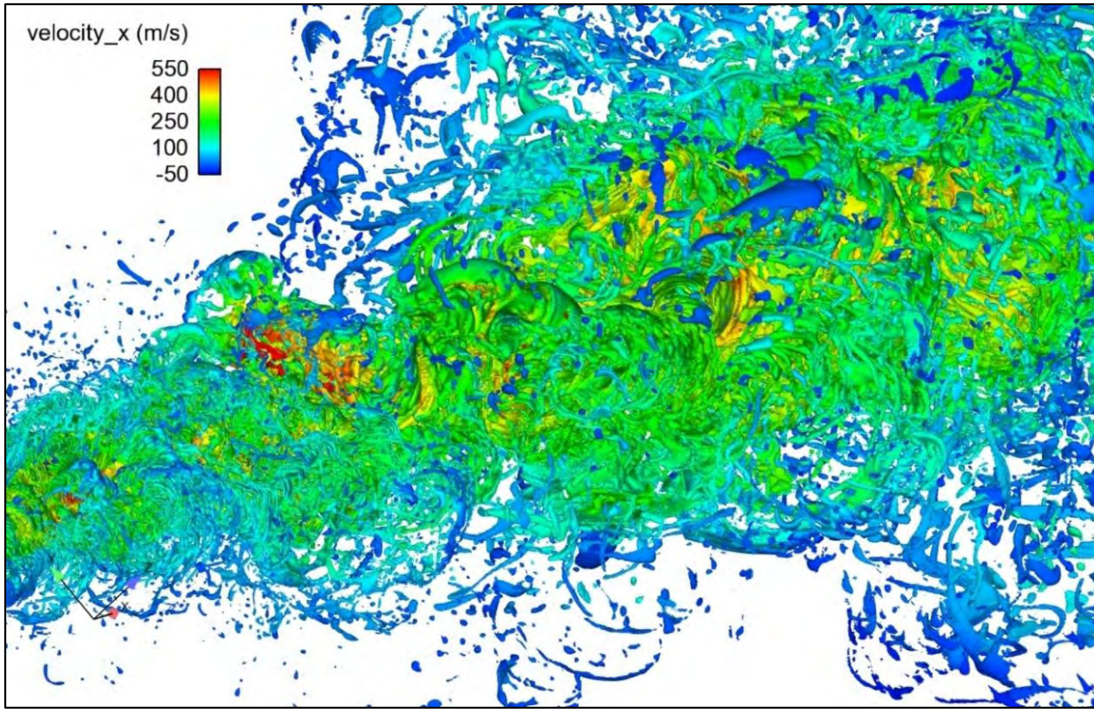




Fuel	n-dodecane
Orifice Diameter (nominal)	180 µm
K-factor (nominal)	1.5
Injection Pressure	150 MPa
Fuel Temperature	298 K
Ambient Temperature	298 K
Ambient Density	22.8 kg/m^3

Approach:

- Eulerian Volume of Fluid (VOF)
- Separated flows, with sharp interface
- Direct transport of void fraction
- Phase interface tracking is possible for moderate interfacial area



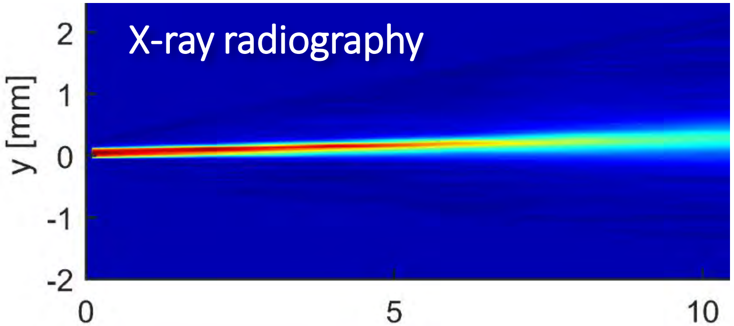
50 M cells: about two weeks on 256 cores to simulate ~10 µs

Diesel spray: structure of atomization region

Through careful design of joint experimental and computational investigations, it is possible to examine the primary atomization process

Argonne NATIONAL LABORATORY

Engine Combustion Network

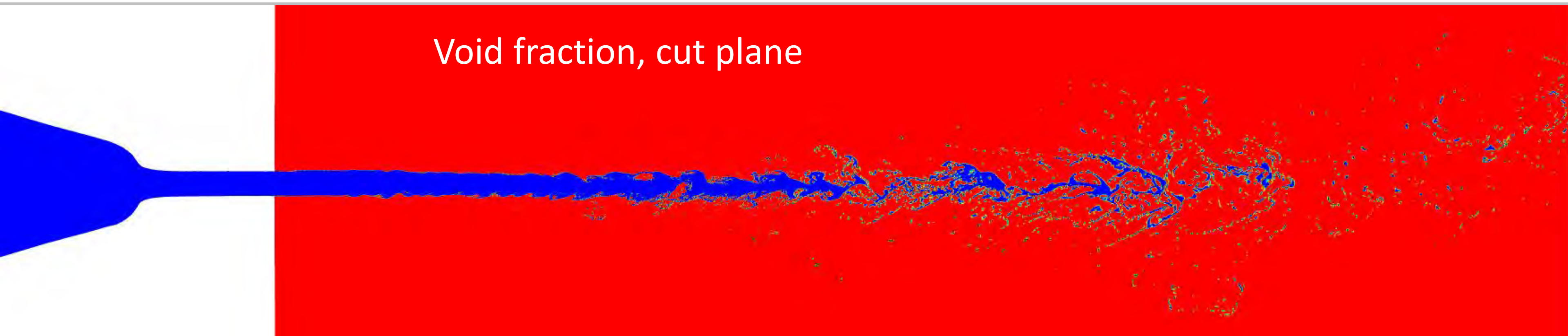


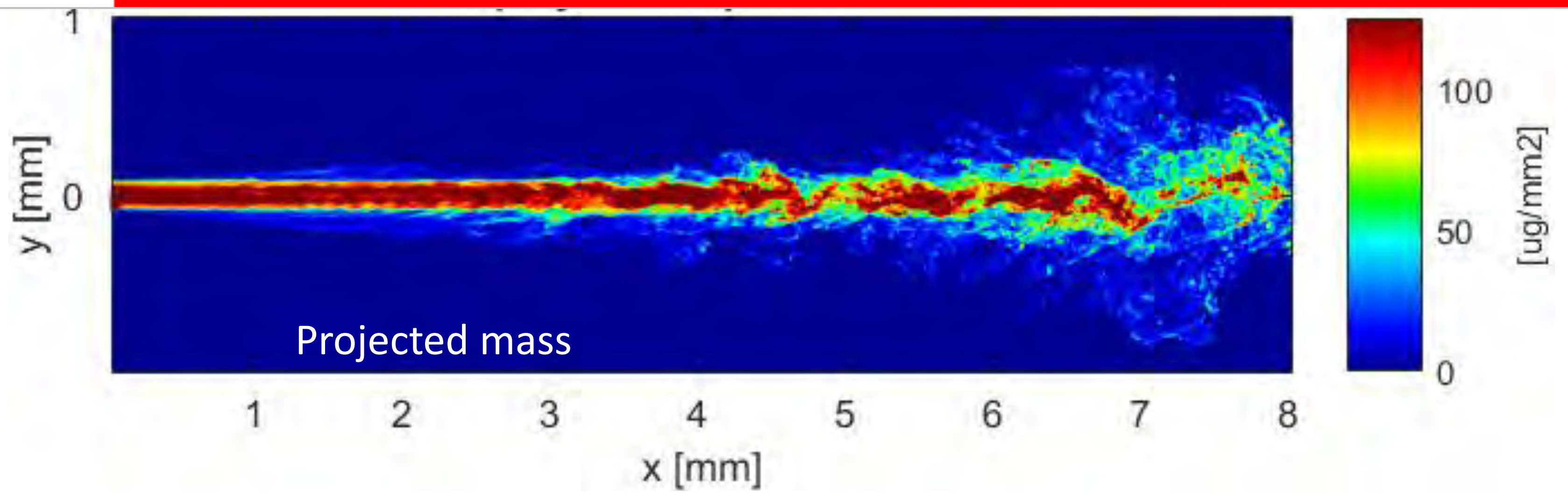
Using a suite of experimental capabilities at Argonne's Advanced Photon Source, the details of primary breakup are being characterized in terms of 2D distributions of

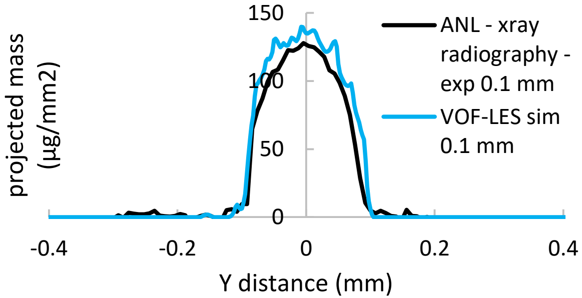
- Liquid fuel mass (***X-ray radiography***)
- Interfacial area (***Ultra-small angle x-ray scattering***)
- Droplet size – SMD (***X-ray radiography + USAXS***)

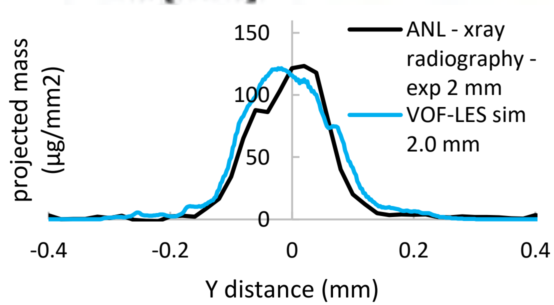
Kastengren A. et al. IJMF, 2017
Battistoni, M., Magnotti, G., et al. SAE 2018

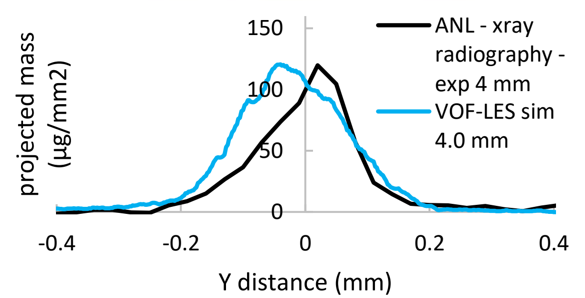
Spray D results (single snapshot)







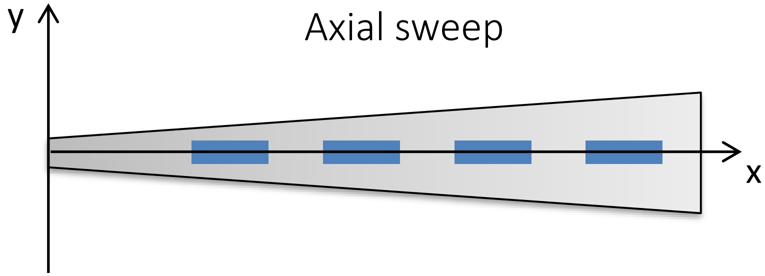




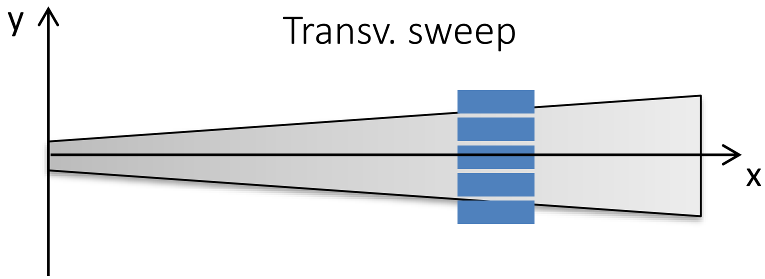
Spray D phase interface area

Experiments: USAXS
(Ultra Small Angle Xray Scattering)

Axial sweep

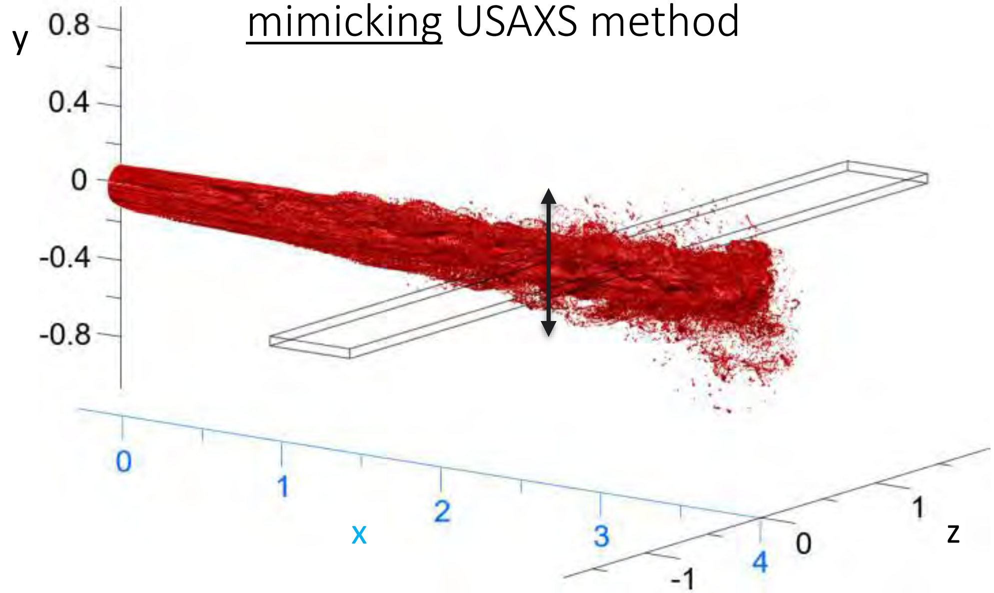


Transv. sweep



Bin size in the USAXS experiments: 50 µm × 500 µm

Simulation postprocessing:
<u>mimicking</u> USAXS method



Calculation of the total area of phase interface, A, and the total volume, V.
"USAXS-like" method: V/V_{box} & A/V_{box}
Line-of-sight box, moving along X and Y, to collect info on each structure, <u>including core</u>
On each box, collection of:

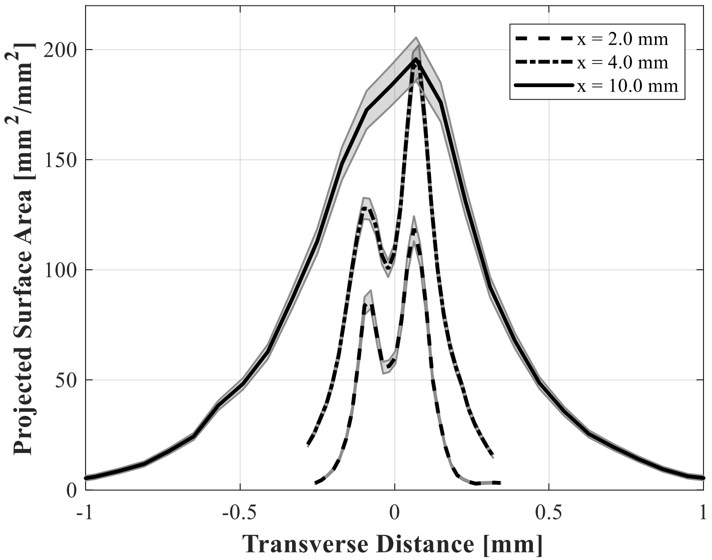
- liquid volume V
- interface area A

$$SMD = 6\frac{V/V_{box}}{A/V_{box}}$$

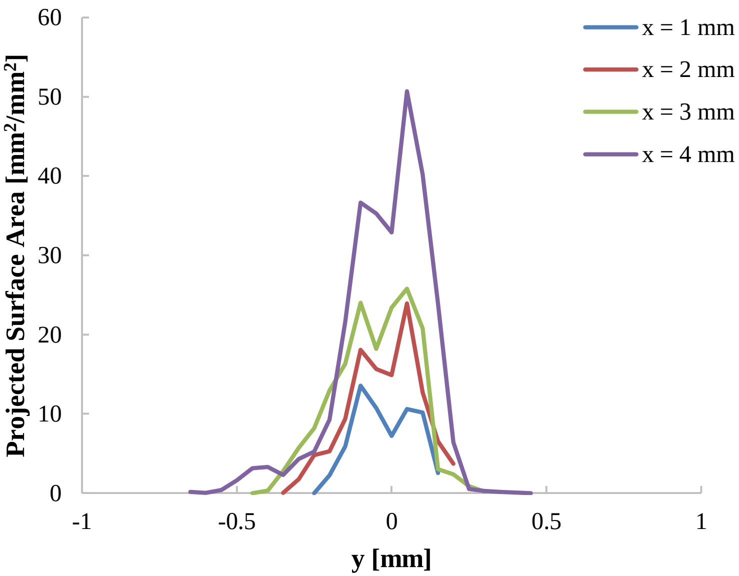
<u>26 connectivity</u> analysis

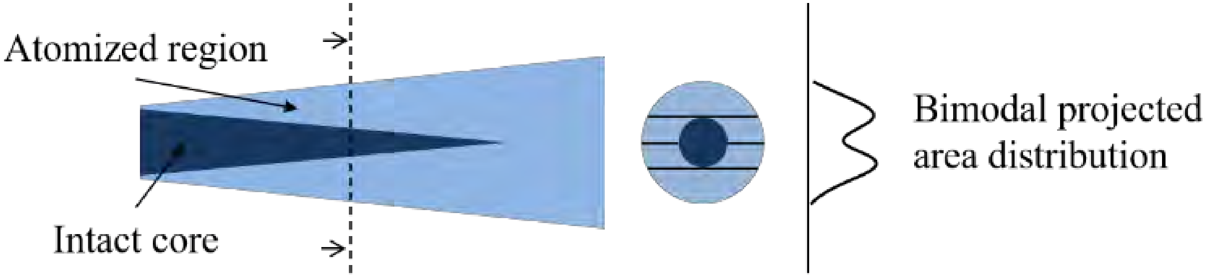
Spray D phase interface area: results

USAXS data



simulations



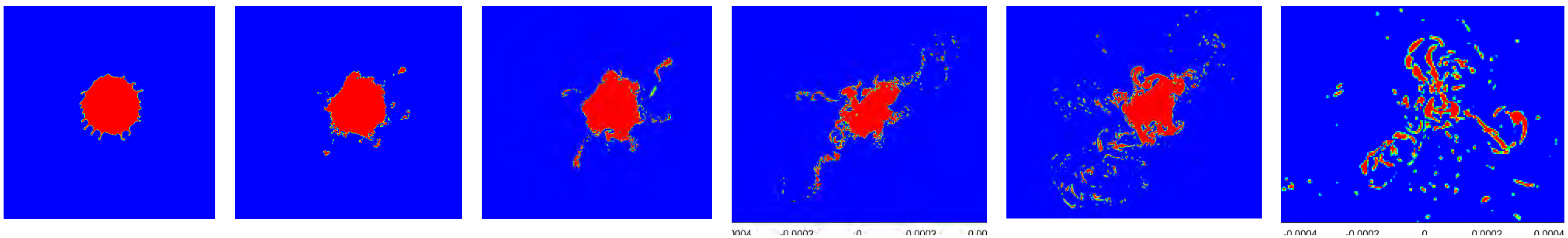


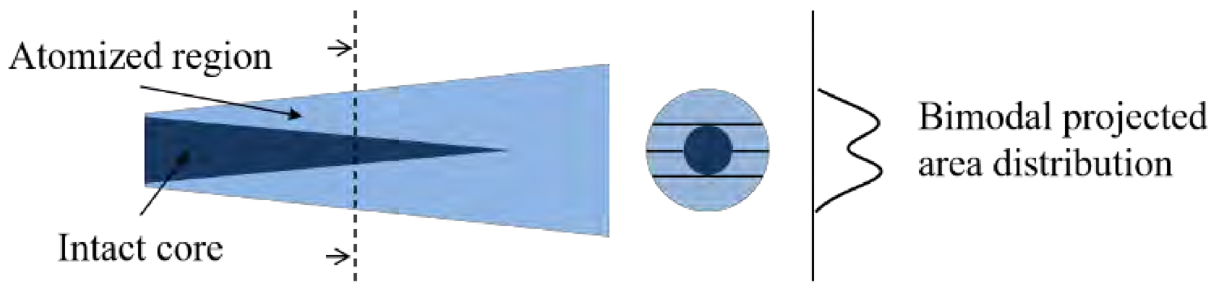
- Simulations explain the double peak area distribution: it is due to the intact core.
- It is therefore possible to identify the liquid core length. In this case about 5-6 mm

Spray D results: morphology

Simulation results

0.1 mm | 0.6 mm | 1 mm | 2 mm | 3 mm | 6 mm





- Simulations explain the double peak area distribution: it is due to the intact core.
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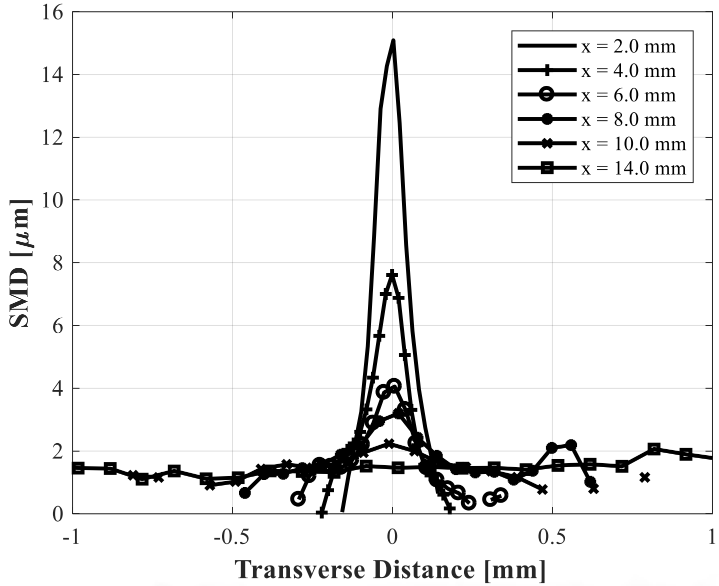
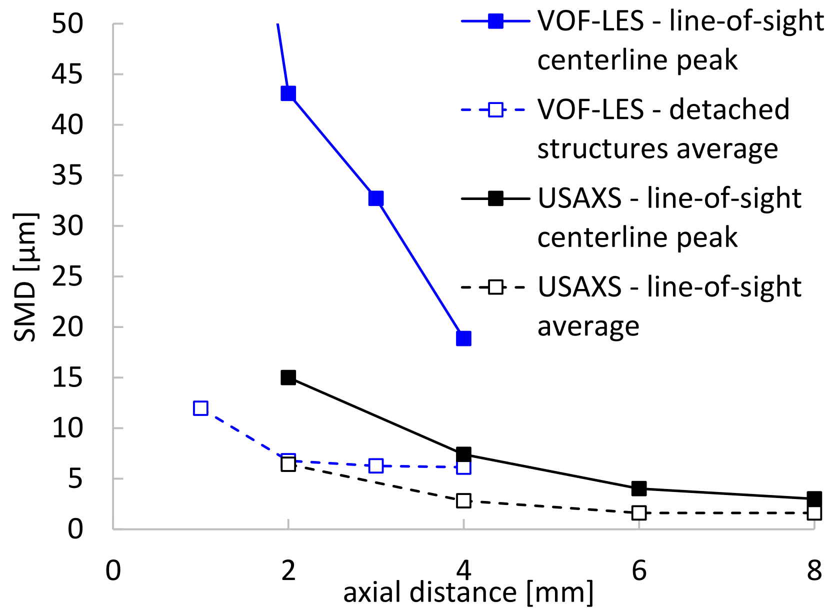
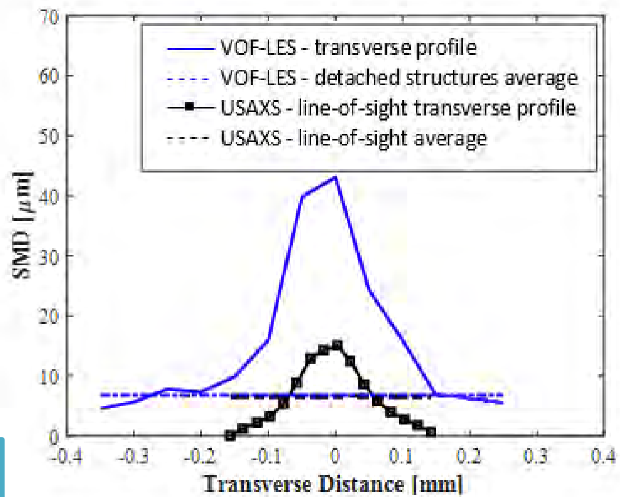
Spray D Sauter Mean Diameter: results







$$SMD = 6\frac{V/V_{box}}{A/V_{box}}$$

- Model captures the SMD trend
- Actual droplet size (detached structures) is insensitive to the axial distance
- Room for improvement: more resolution still required to be fully predictive at diesel spray conditions
- Note: USAXS data include the liquid core

Battistoni, M., Magnotti, G., et al. SAE 2018

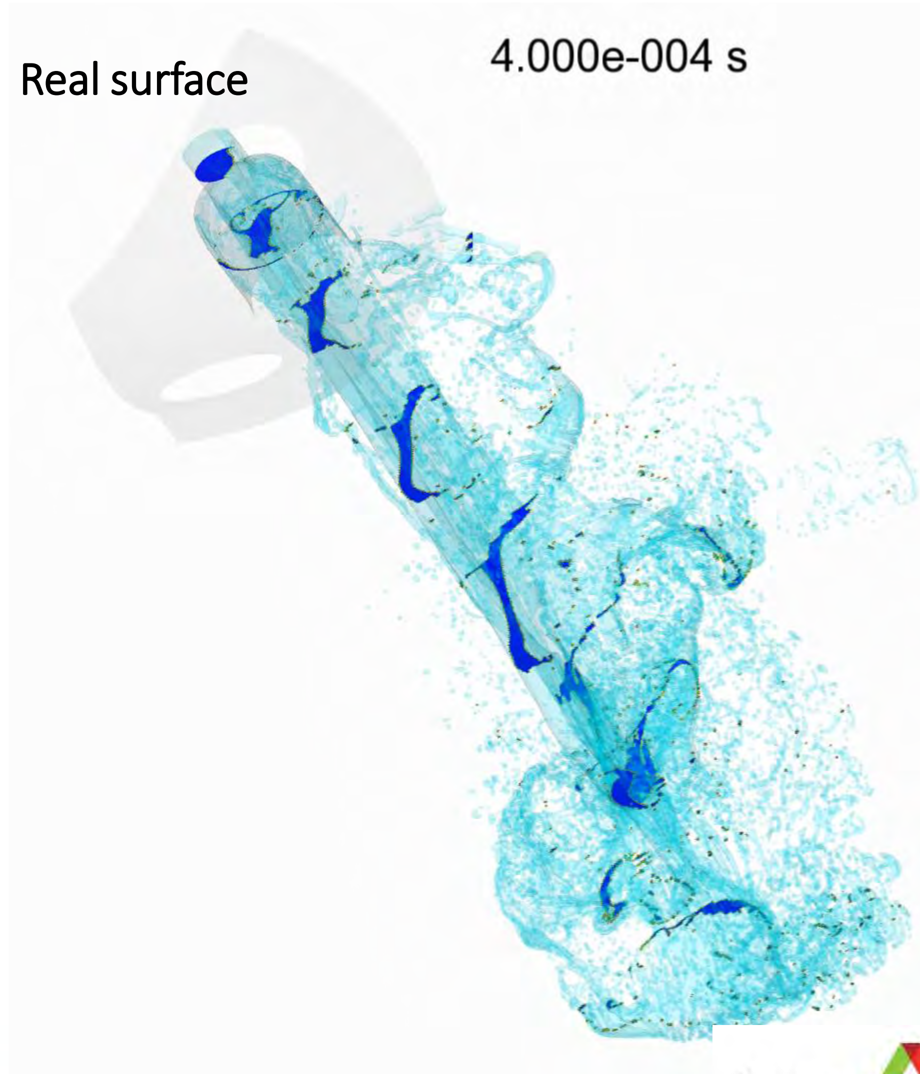
Gasoline spray (ECN spray G)

Fuel	iso-octane
Fuel Temperature	298 K
Injection Pressure	19 MPa
Ambient Temperature	298 K
Ambient Density	3.5 kg/m^3

	<u>Nominal</u>	<u>Real</u>
Orifice Diameter, D1	165 µm	175 µm
Orifice Length, L1	170 µm	150 µm
L1/D1	1.03	0.86
Hole inlet corner radius, R1	0 µm	4.93 µm
Counterbore diameter, D2	388 µm	394 µm
Counterbore length, L2	470 µm	402 µm

3 hole sector

Matusik et al., ILASS-Europe, 2017



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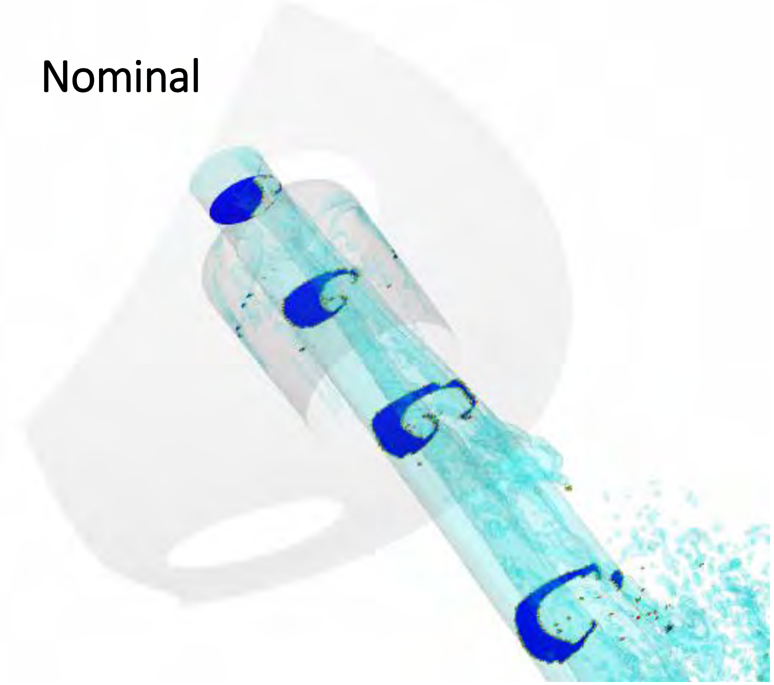
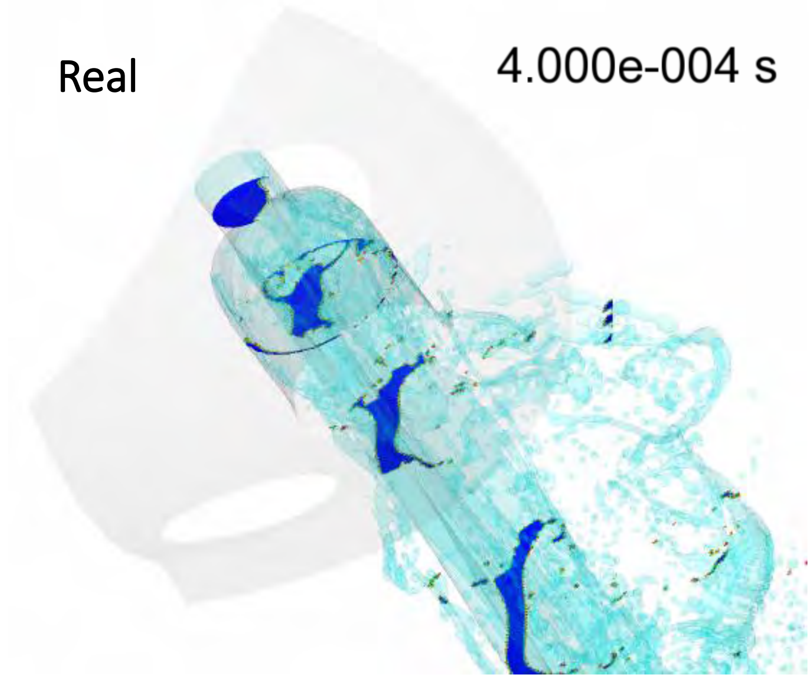
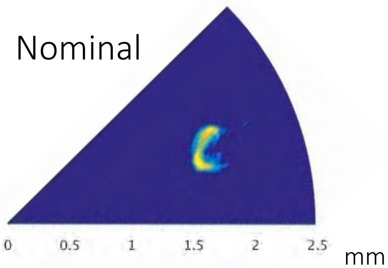
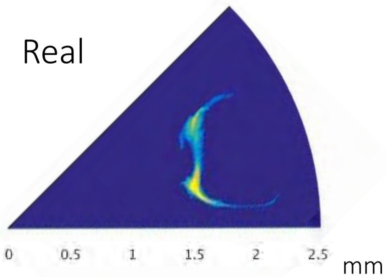
Spray G: inside and near nozzle







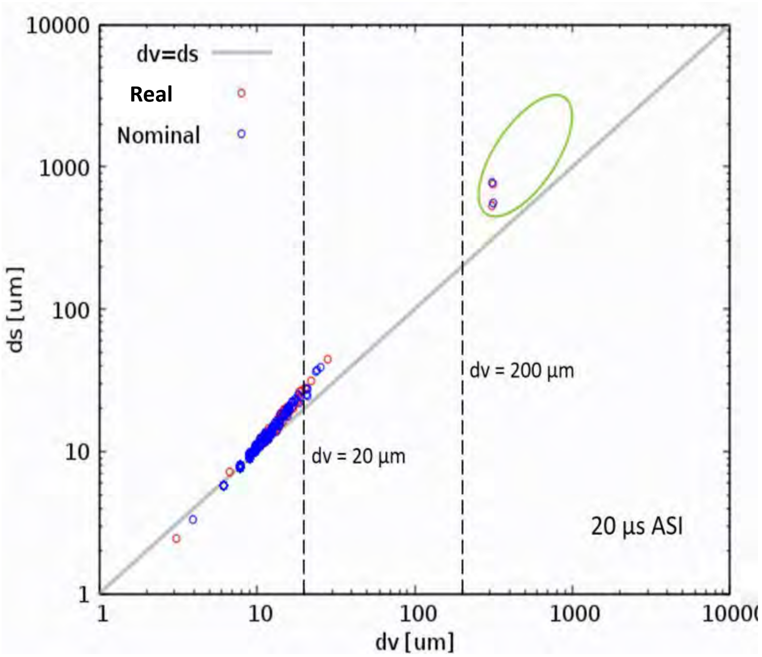
1 mm downstream mean density field
(time-averaged from 50 to 100 μs)

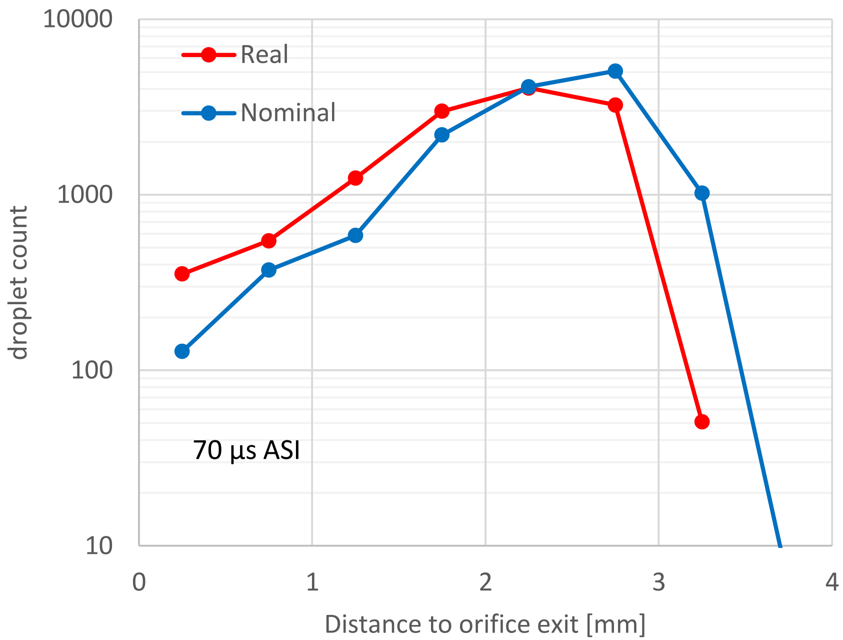


- Flow separation inside the nozzle due to sharp corner at hole inlet;
- Significant difference on spray breakup at near nozzle region (L/D ratio, surface variations).

Spray G: d_v vs. d_s

$$d_s = \sqrt{\frac{A}{\pi}} \qquad d_v = \left(\frac{6V}{\pi}\right)^{1/3}$$

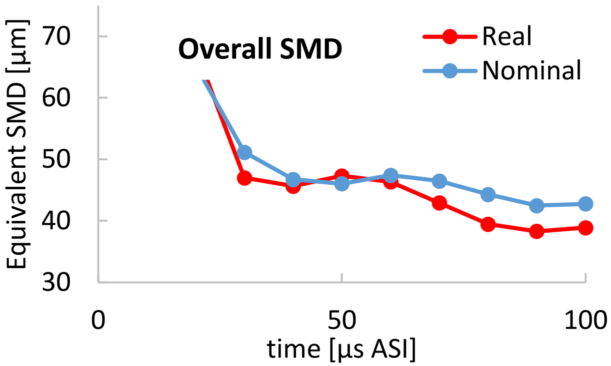


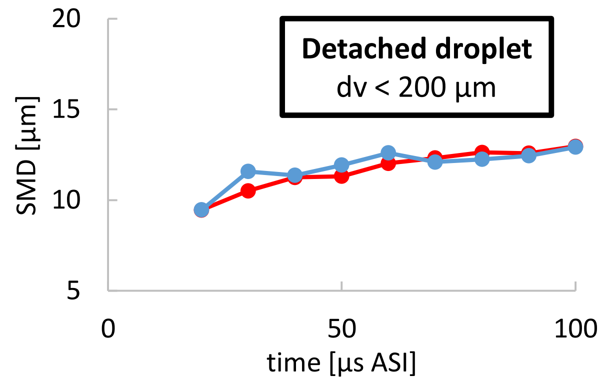


- Liquid structures with d_v < 20 µm remain spherical;
- Liquid structures with 20 < d_v < 200 µm are mainly ligaments before breaking into smaller droplets;
- Liquid structures with d_v > 200 µm are considered as intact liquid core, representing more than 90% mass of the spray.

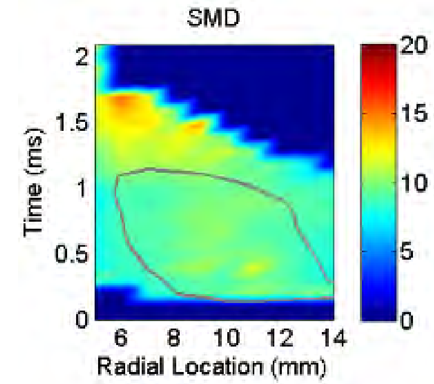
Spray G: SMD

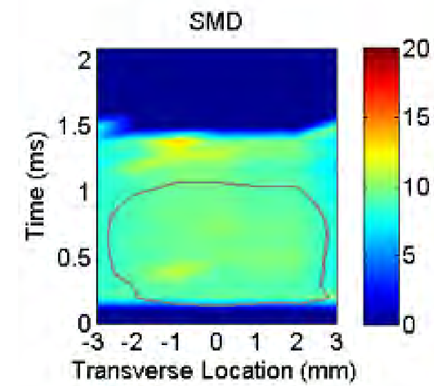
$$SMD = 6\frac{\sum V_i}{\sum A_i}$$





SMD data at z = 15 mm
(GM experiments at **ECN3**)





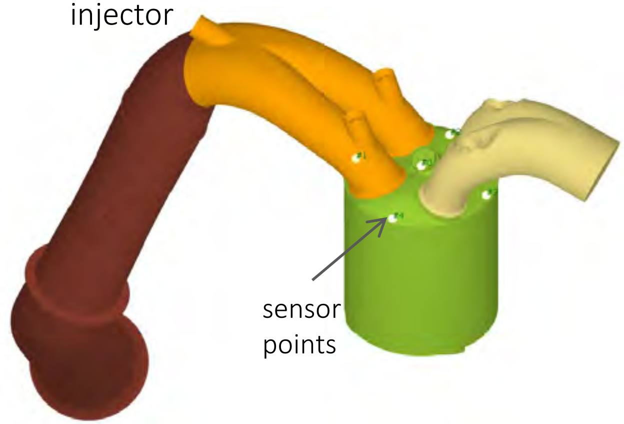
- The use of real geometry predicts 11% lower overall SMD, attributed to the difference in the intact liquid morphology
- Droplet SMD in good agreement with experimental measurements available downstream (~2.5 µm grid size).
- Future work – Perform simulations using other real geometries to study the correlations between geometric features and spray characteristics. Decouple the effects of roughness and non-nominal orifice dimensions.
- The methodology has high relevance in the area of nozzle design and spray calculations, with impact on new/advanced combustion systems design

Yue Z., Battistoni M., Som S., ICLASS 2018

Knock prediction

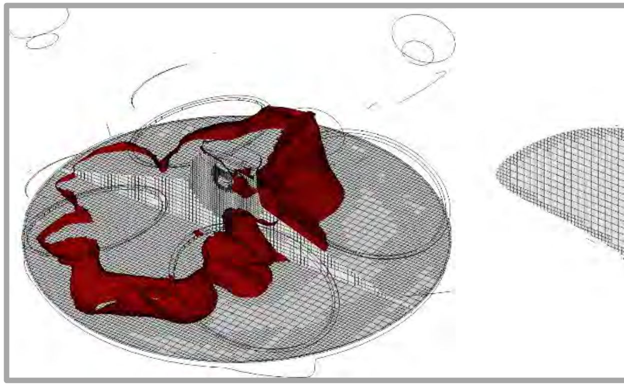
CFD model build in **CONVERGE**

- Lagrangian spray
- Turbulence: **RANS**: RNG k-eps model; vs. **LES**: 1 eq. viscosity model
- Combustion: Perfectly Stirred Reactor (**PSR**), with adaptive zoning. **TPRF** chemical kinetics (*Andrae et al. 2008*), RON=95, MON=85, blending rules based on *Morgan et al. 2010*:
- Grid: Base size = 2 mm; AMR 0.5 mm; 0.125 mm around spark
- Discretization: Space: 2nd order, finite volume; Time: 1st Euler
- Multi-cycle simulations: Restitution time: about **2 cycles per day on 48 cores**



Engine	
No. of cylinders	1
No. of valves	4
Bore	52 mm
Stroke	58.73 mm
Fueling	PFI
CR	12.5 (and 13.2)

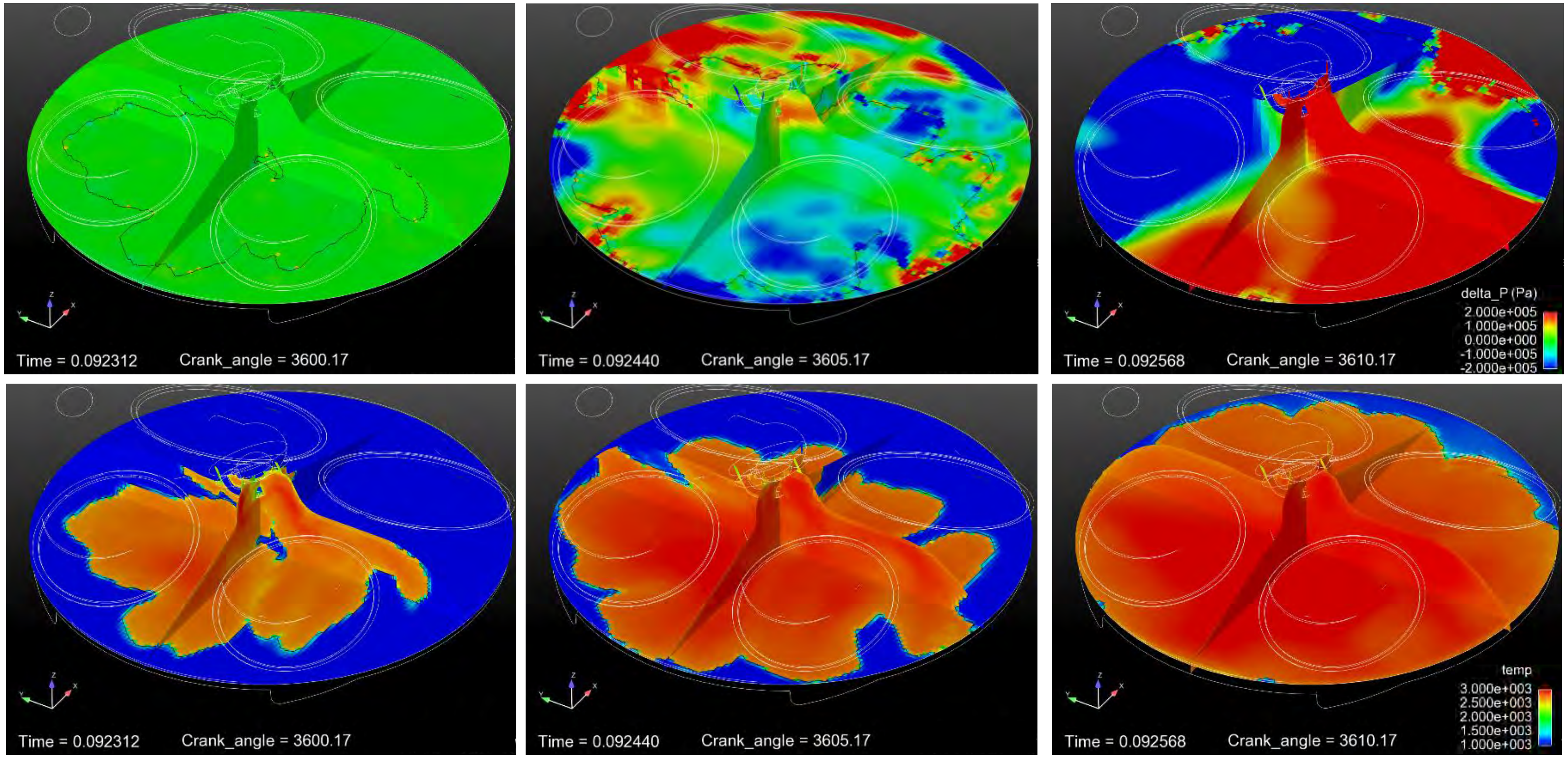
Condition (full load)	
IMEP	13 bar (wot)
Speed	6500 rpm
λ	0.9
Spark Advance	14-34 CAD bTDC
EGR	0% - 3.1%



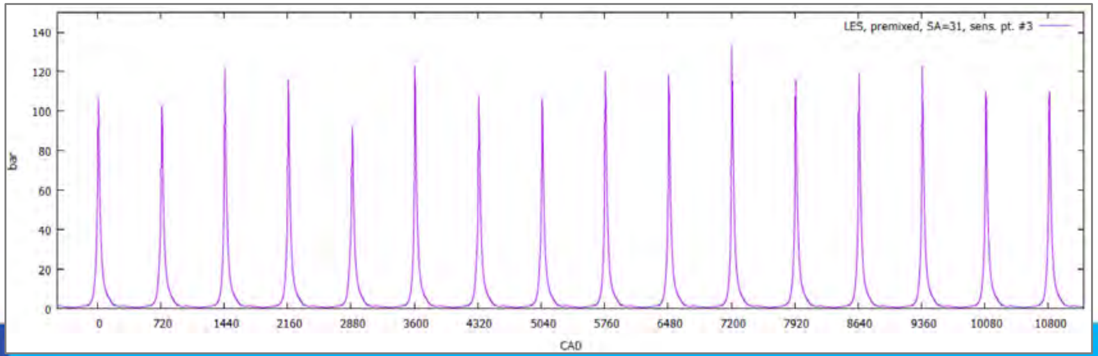
PIAGGIO

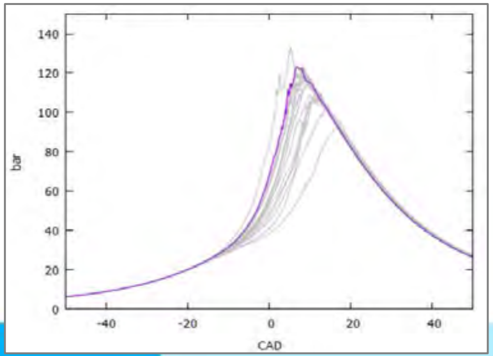
LES example: SA = 31 bTDC - premixed

Before knock | Knock just started | Pressure waves "bouncing"



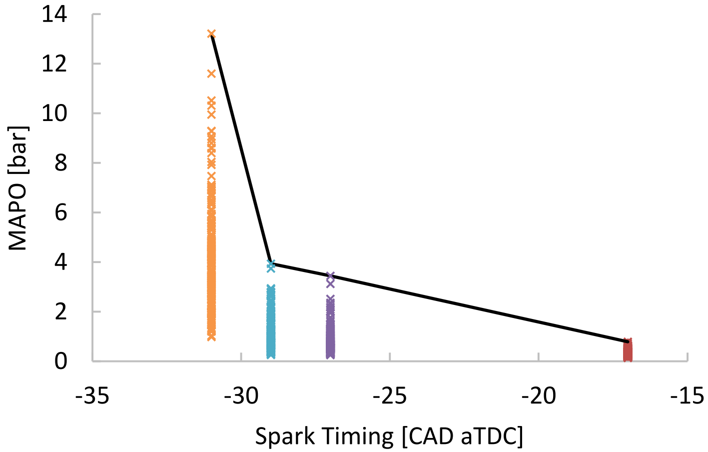
6^{th} cycle



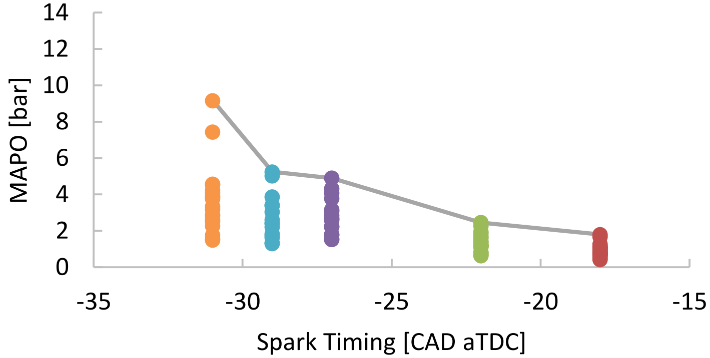


LES results: knock intensity

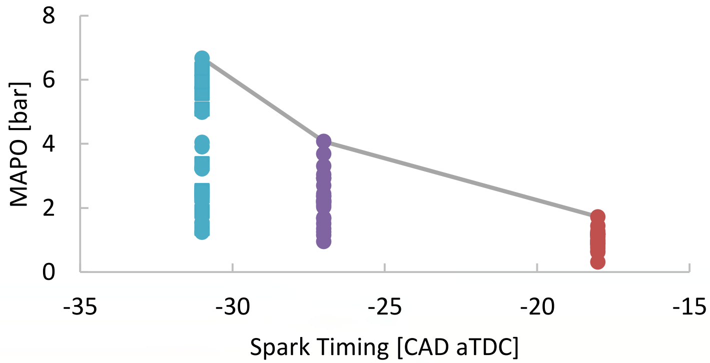
Experiments (200 cycles)



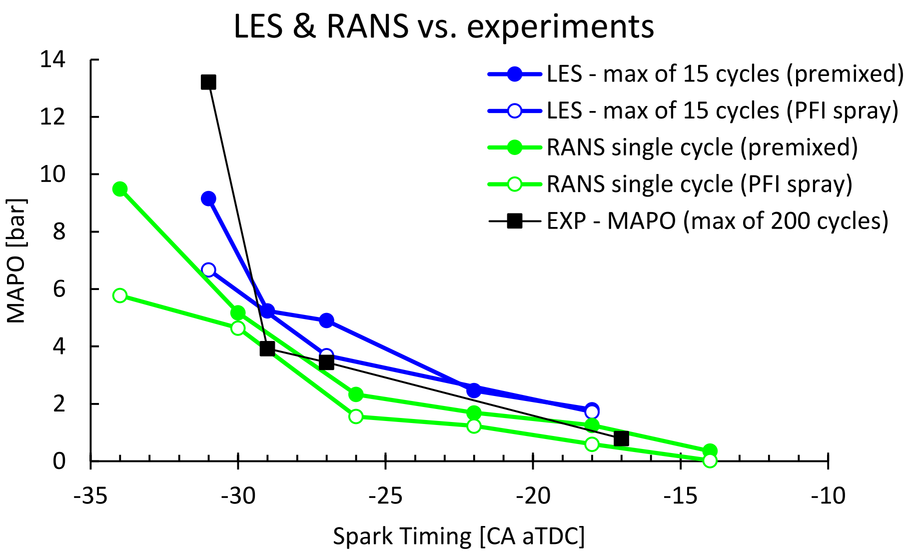
Simulations
premixed cases (15 cycles)



Simulations
PFI spray cases (15 cycles)



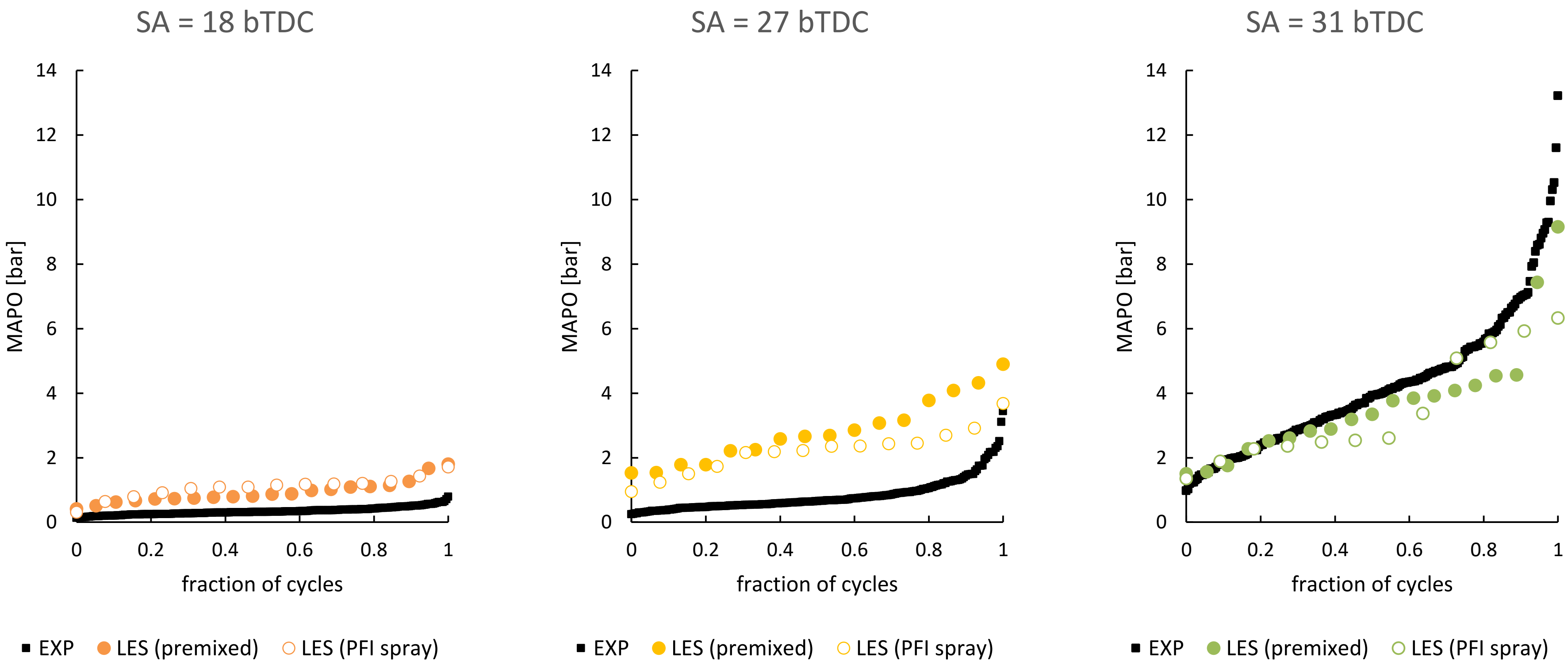
SA sweeps: LES and RANS sim. vs. EXP.



- LES multicycle cases show a sharper slope change at the onset of heavy knock.
- Spray cases show a slightly lower knock intensity

LES results

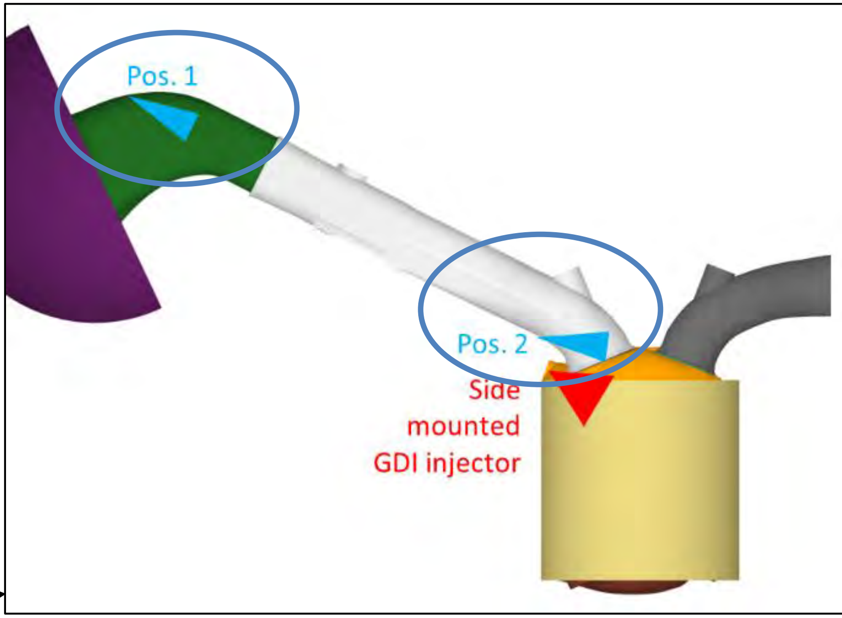
Retrieving knock statistics from LES



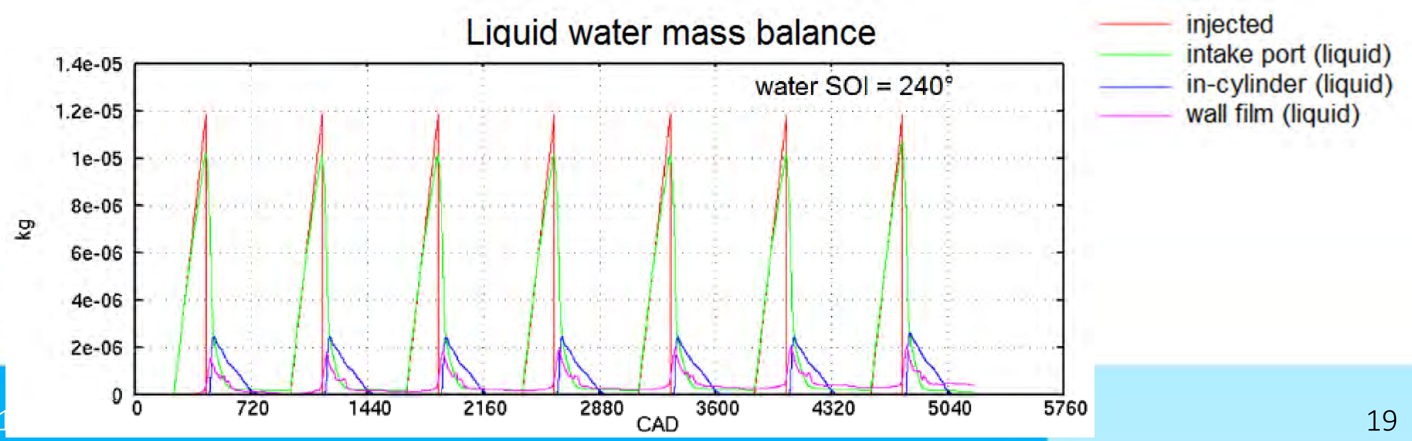
Water injection effects

- Assess port water injection (PWI) strategies on a 1.4L TSI VW engine (GDI turbocharged), on a selected engine point:

2500 rpm ~14 bar IMEP λ = 1



- Predict water effects on combustion, by means of CFD-3D simulations,
  - Spray targeting (plume shape, injection pressure, SMD)
  - Injection timing
  - Injection location

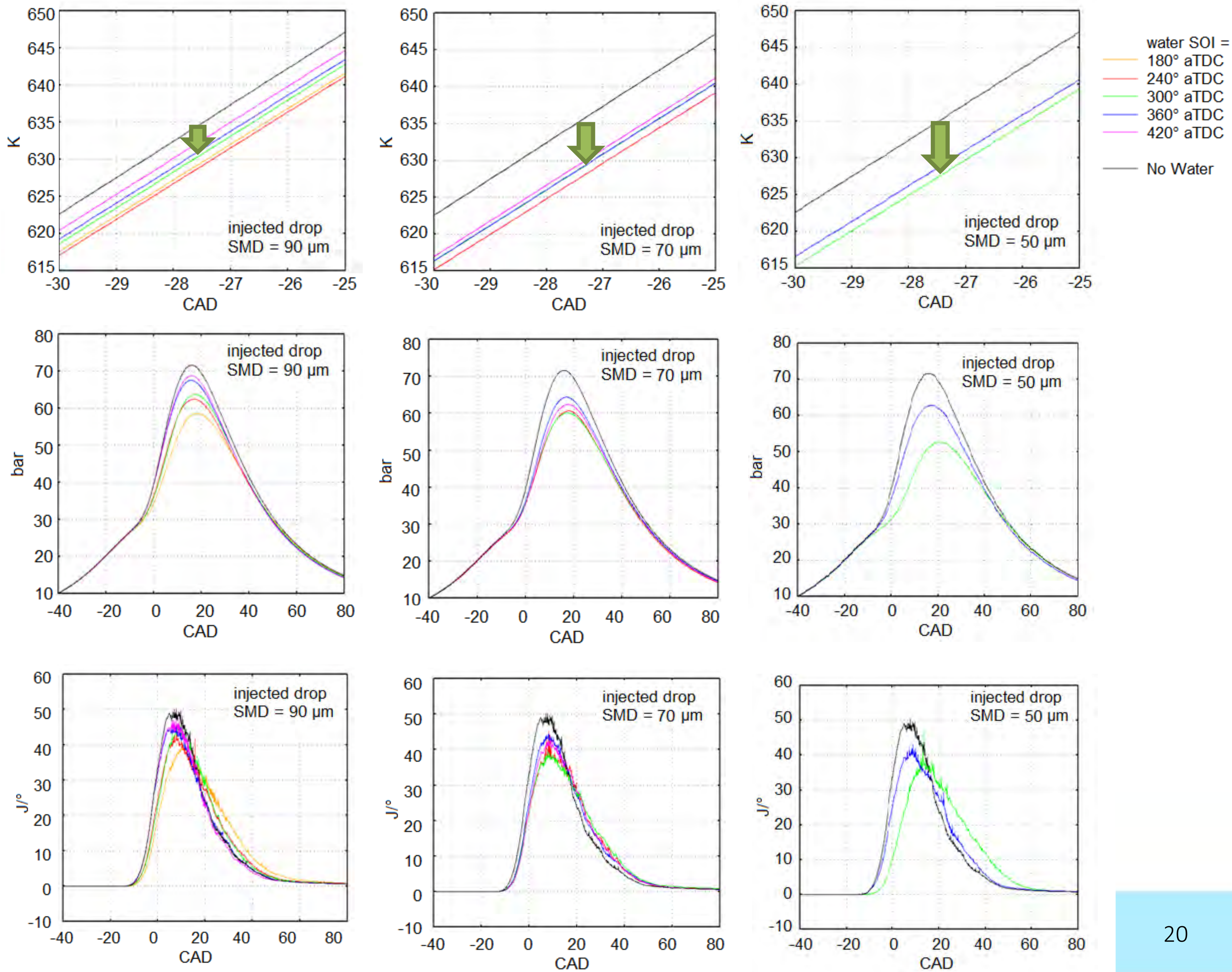


Effect of timing and atomization quality, PWI

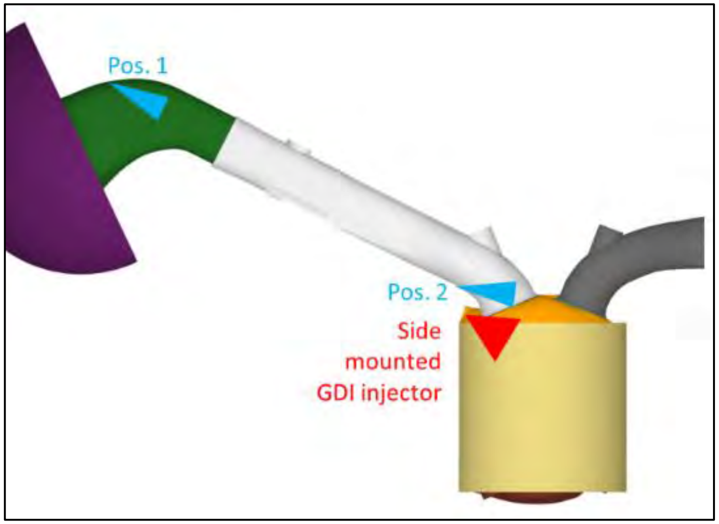
cylinder temperature (zoom before ignition)

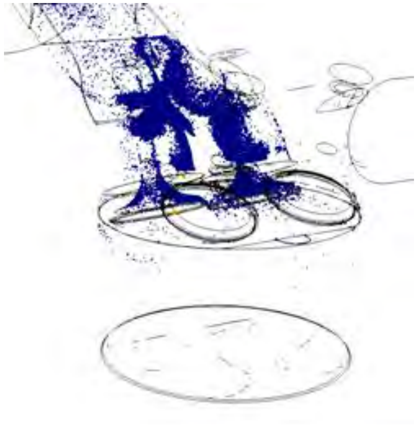
pressure

rate of heat release



Effect of injector location, PWI

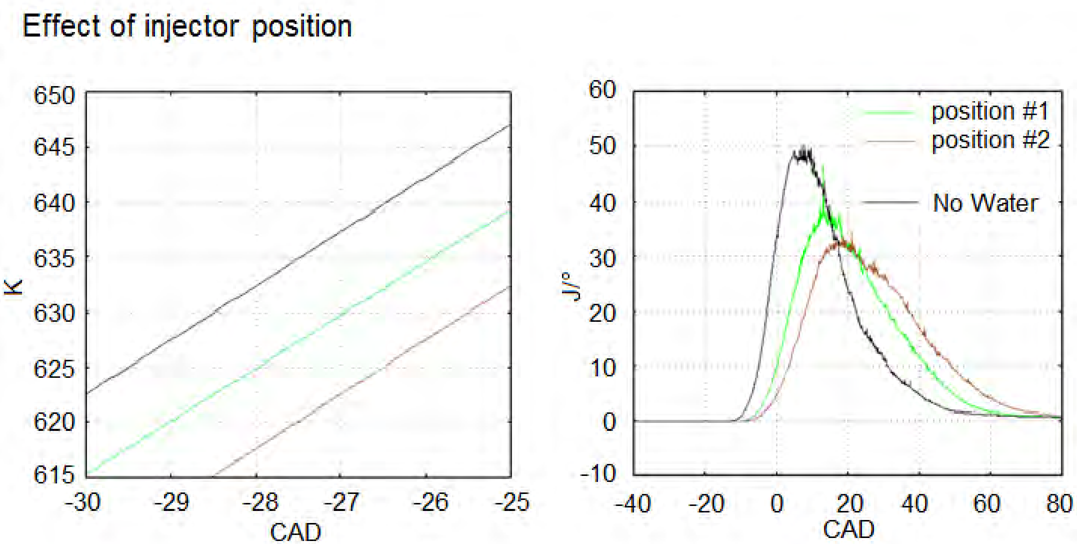




Inj. pos. #1 – **far**

View at 450 deg
(SOI = 300 deg)

Water film
Fuel film



Inj. pos. #2 – **close**

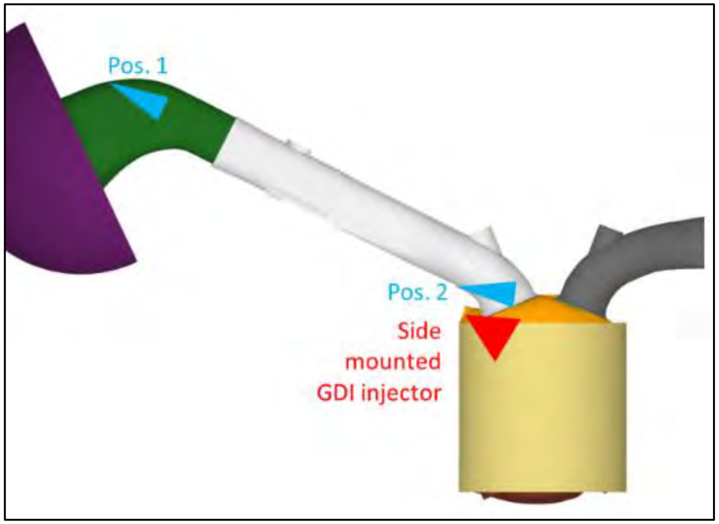
View at 540 deg
(SOI = 450 deg)

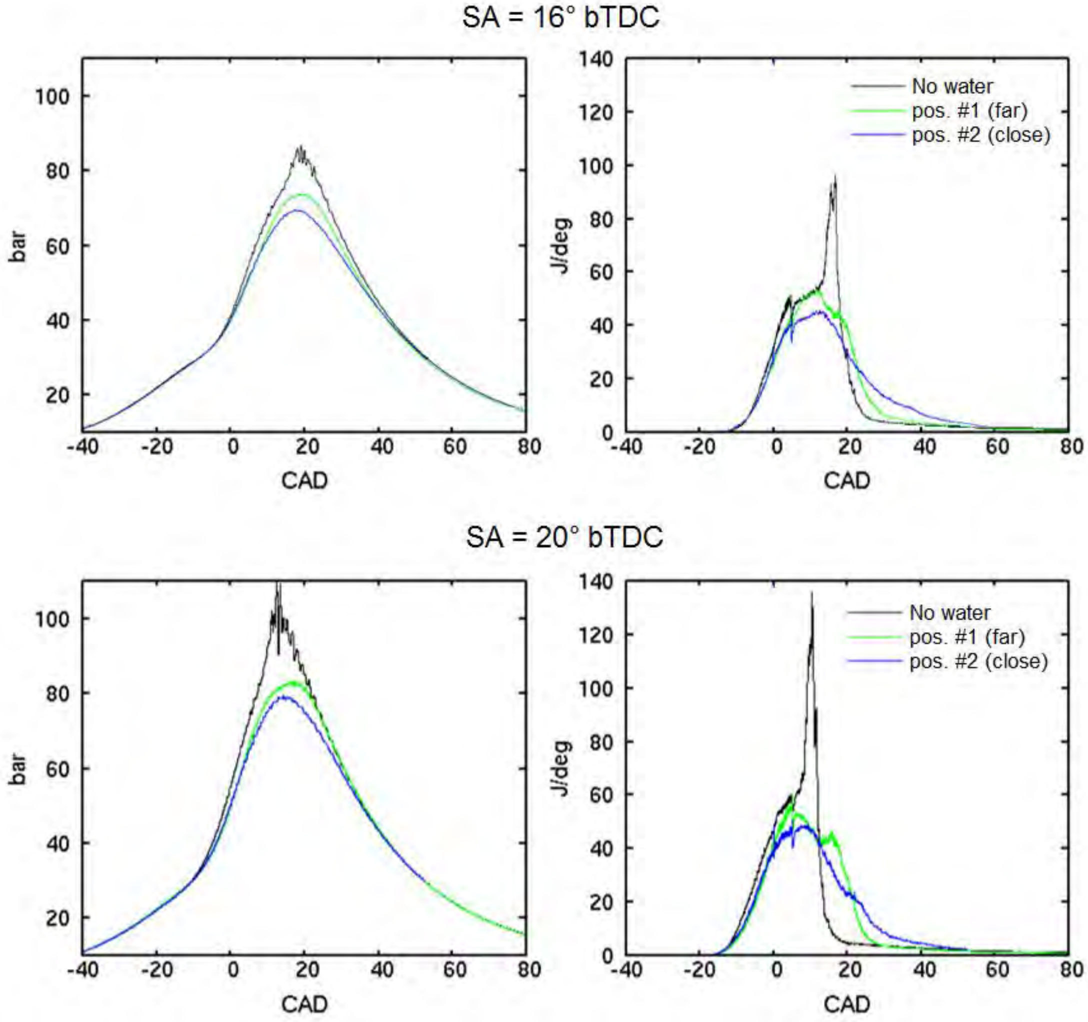
Initial SMD = 50 µm

SA = 14° bTDC

Battistoni M. et al., SAE 2018
Zembi et al., Thiesel 2018

Effect of injector location, PWI





Advancing SA:

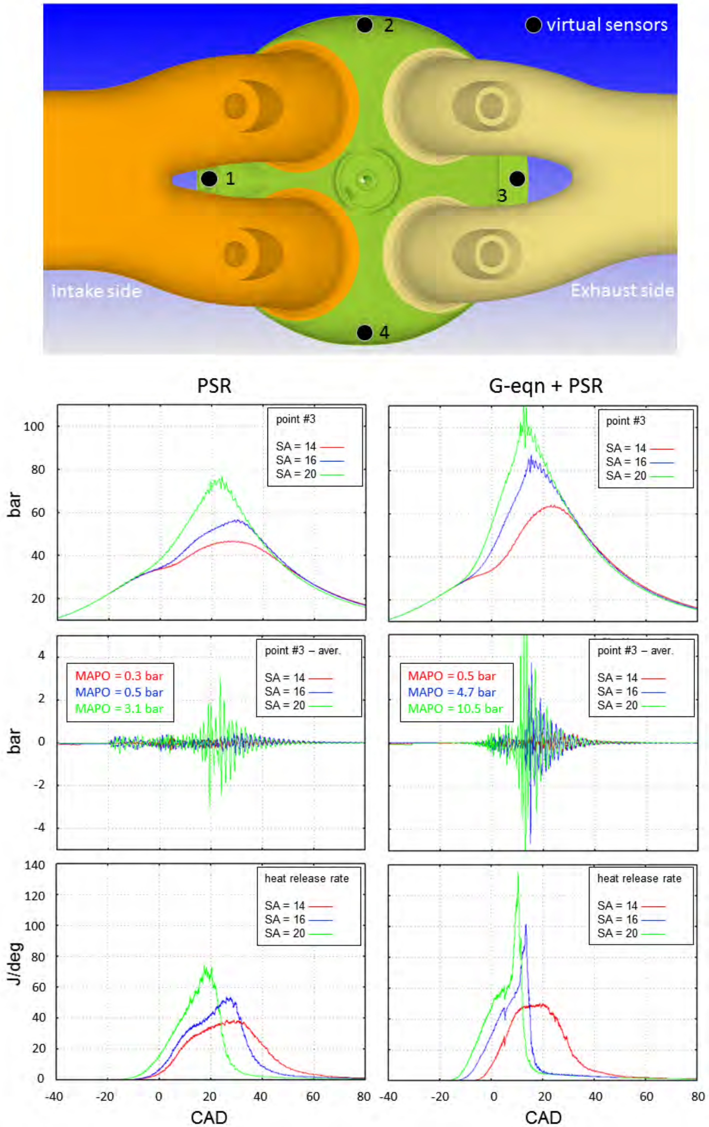
The baseline case autoignites

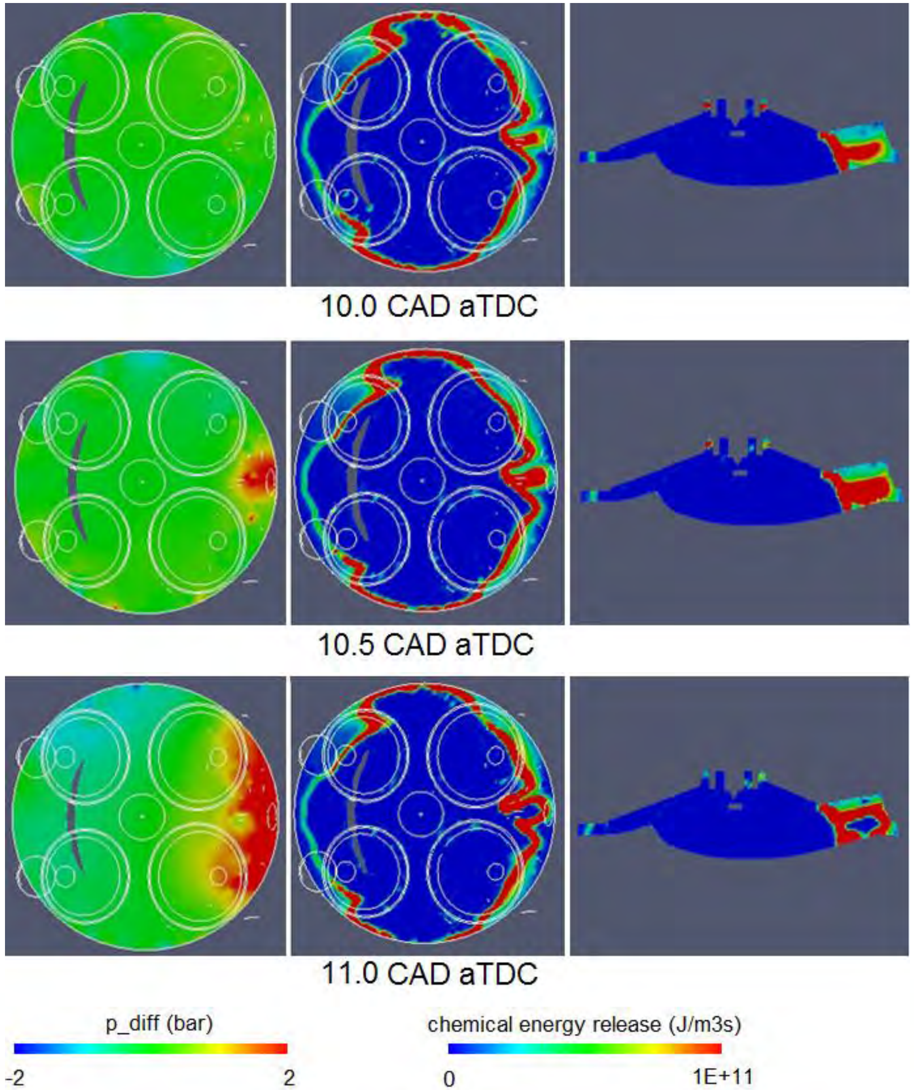
Adding water from the far injection location is already effective in suppressing knock.

Further benefits with a stronger combustion slow down are achieved using the close injection location

Baseline (no water) - knock prediction (RANS)

G-eqn + PSR

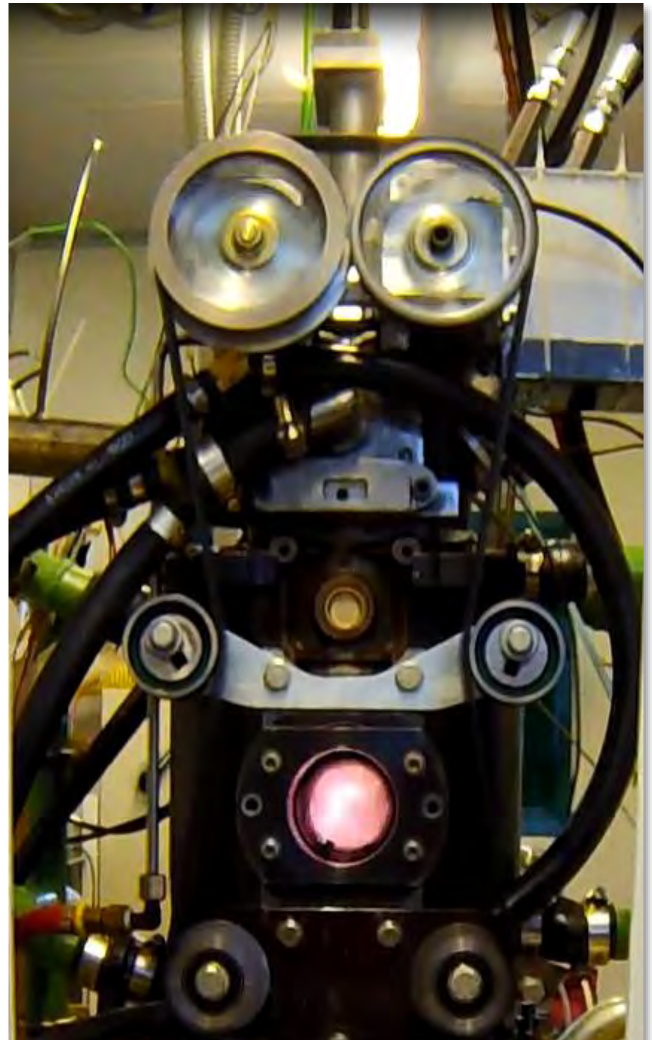


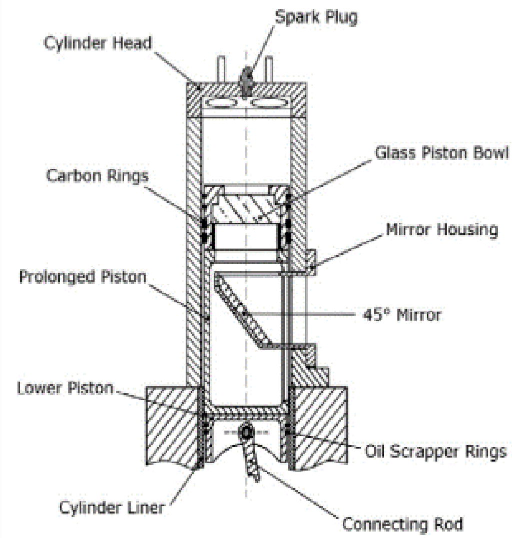


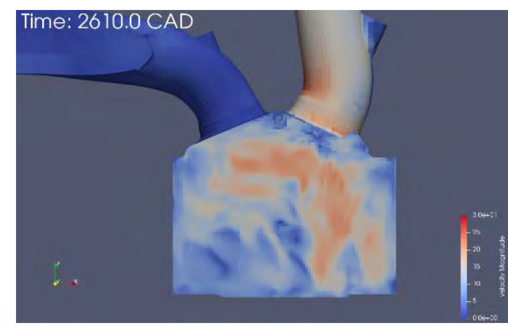
Optical access SI engine: CCV and lean limit

Engine	
No. of cylinders	1
No. of valves	4
Bore	85 mm
Stroke	88 mm
Fueling	PFI (or DI)
CR	8.8
Chamber type	Pent-roof
Optical access	Bowditch type

Conditions (low load & speed)	
IMEP	5 bar (@ λ=1)
Speed	1000 rpm
λ	1.0 to lean limit
Spark Advance	Adjusted to MBT
Mode	Fixed throttle position, varying injected fuel mass to match λ
Spark Advance	Adjusted to MBT
Fuel	Gasoline, RON95

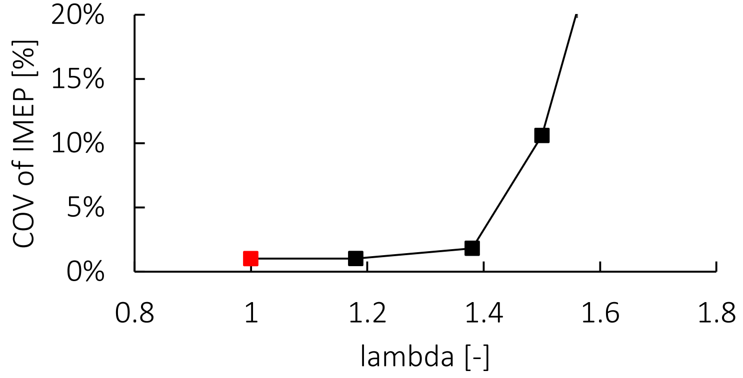




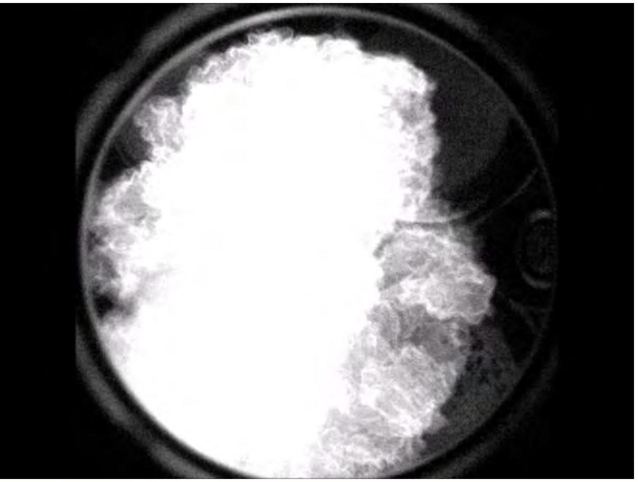


Flame Imaging

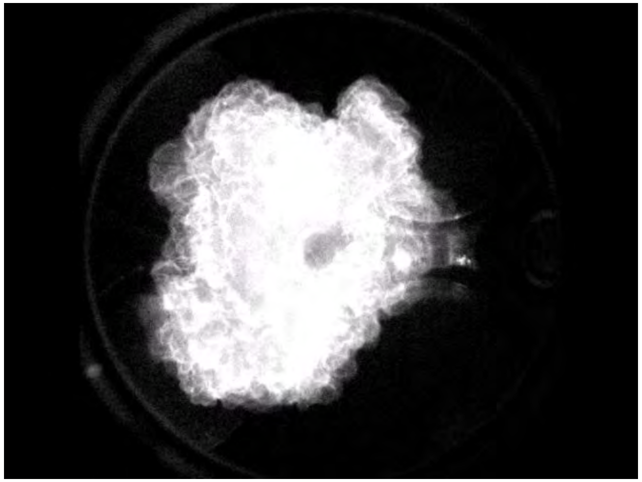
Low CCV at λ=1



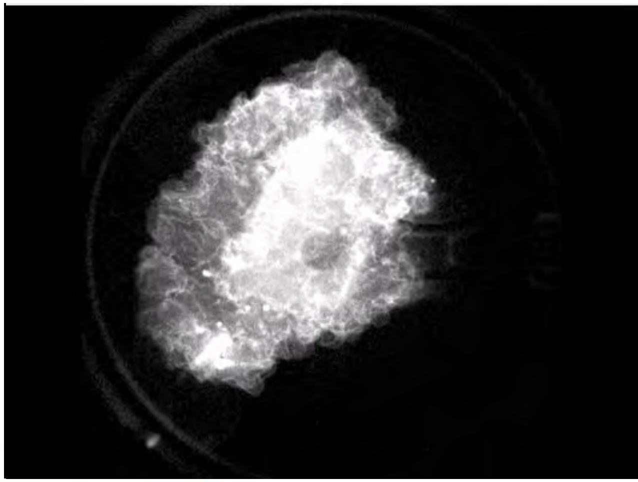
fast



medium



slow

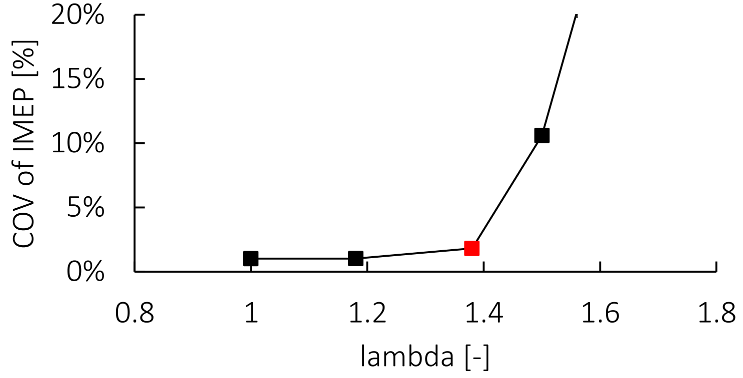


Images at the same time after SA

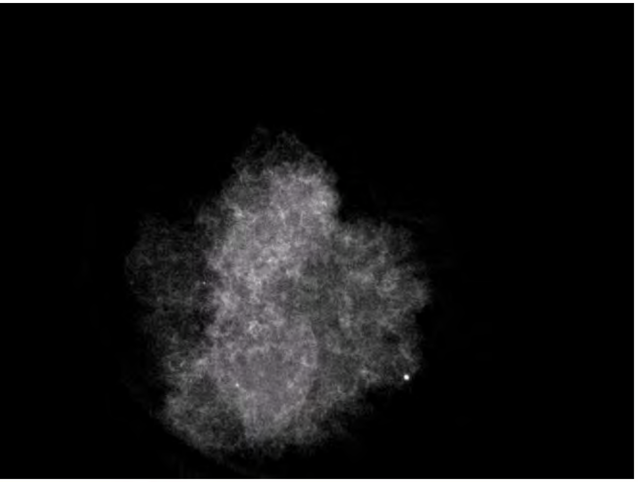
Poggiani et al. SAE paper # 2016-01-0711

Flame Imaging

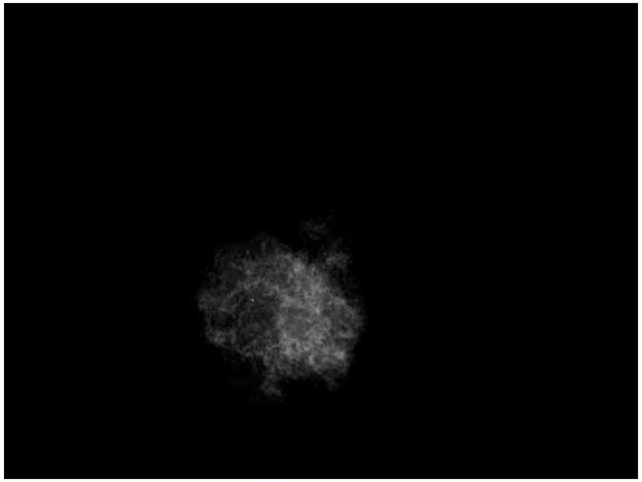
Stable lean point at λ=1.4



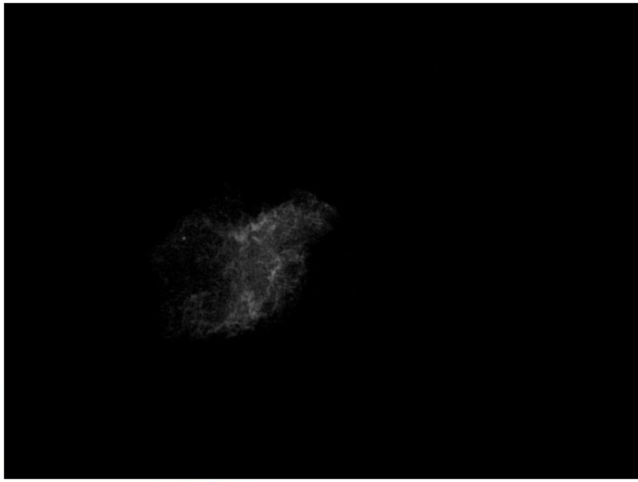
fast



medium



slow

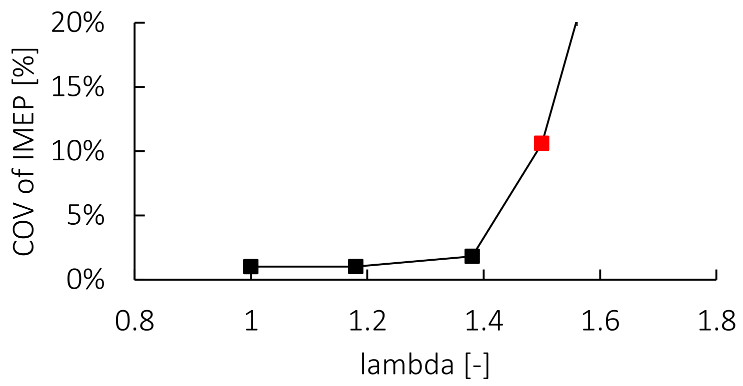


Images at the same time after SA

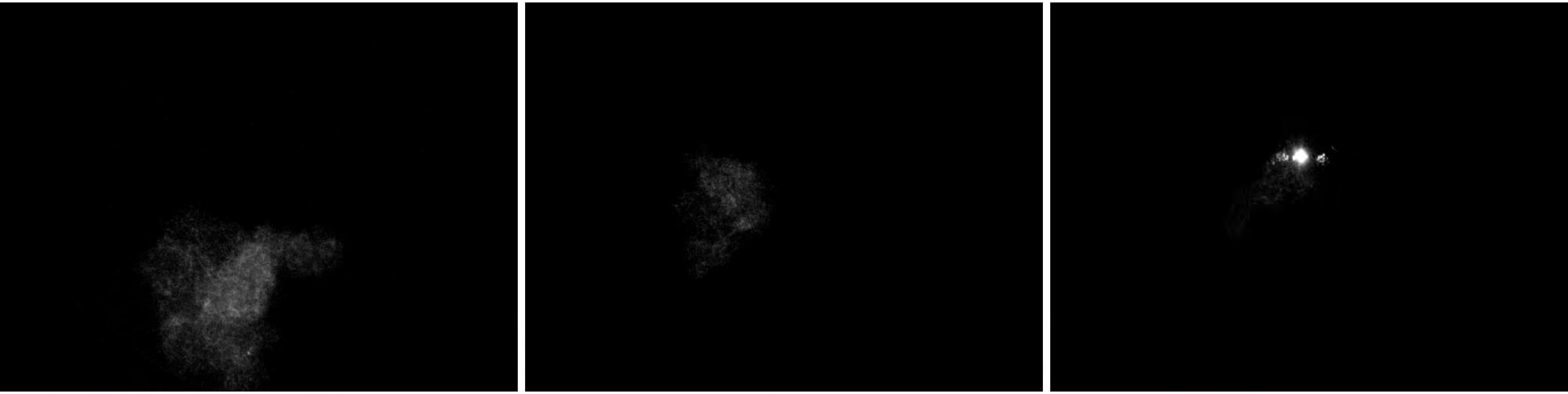
Poggiani et al. SAE paper # 2016-01-0711

Flame Imaging

Unstable lean point at λ=1.5



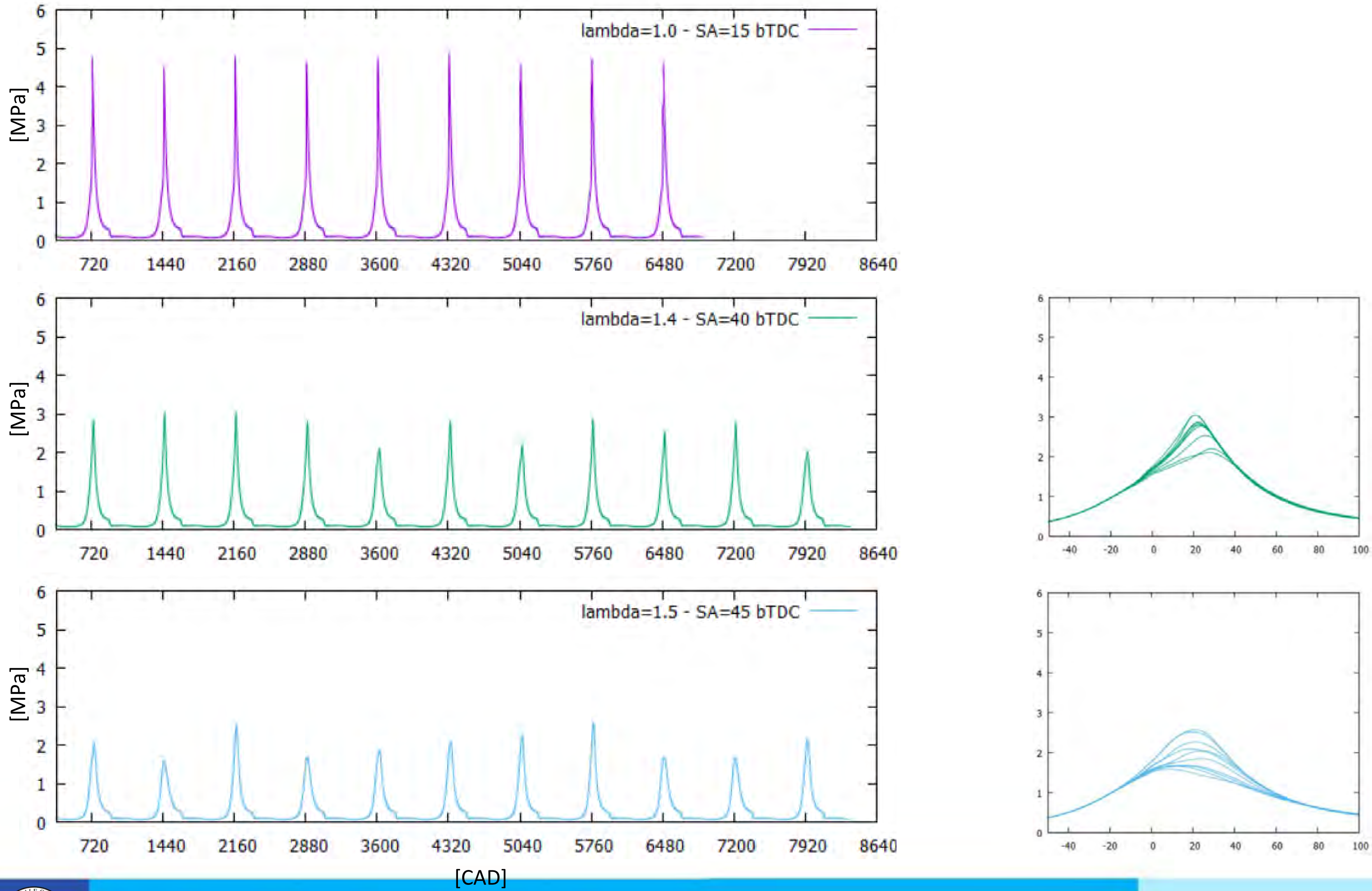
fast medium slow



Images at the same time after SA

Poggiani et al. SAE paper # 2016-01-0711

Multicycle LES simulations at different λ

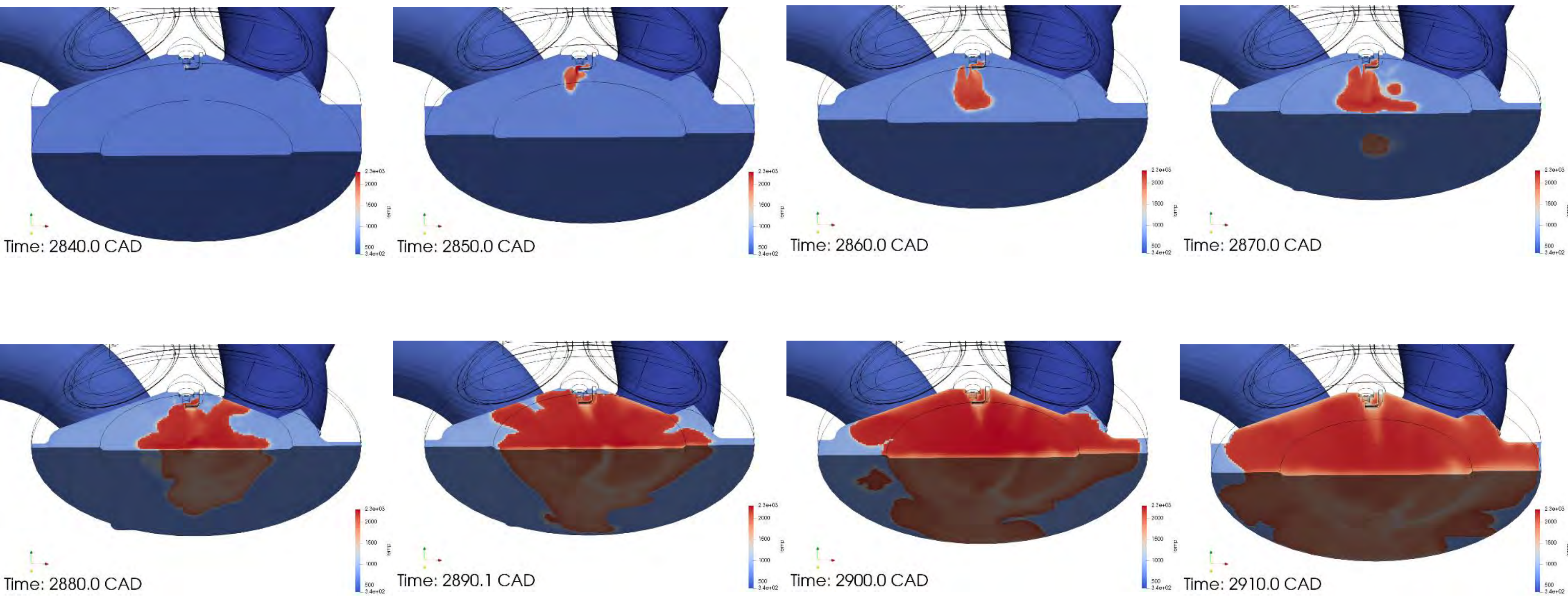


Optical access SI engine: results example

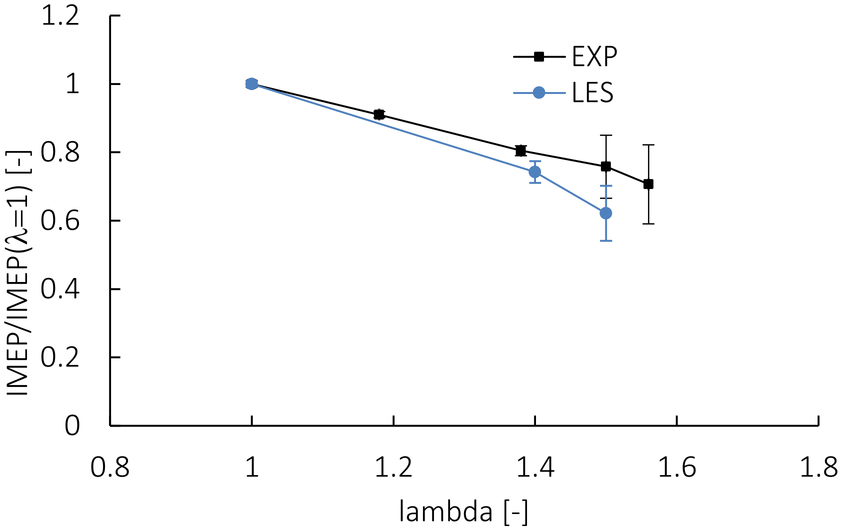
Temperature clips

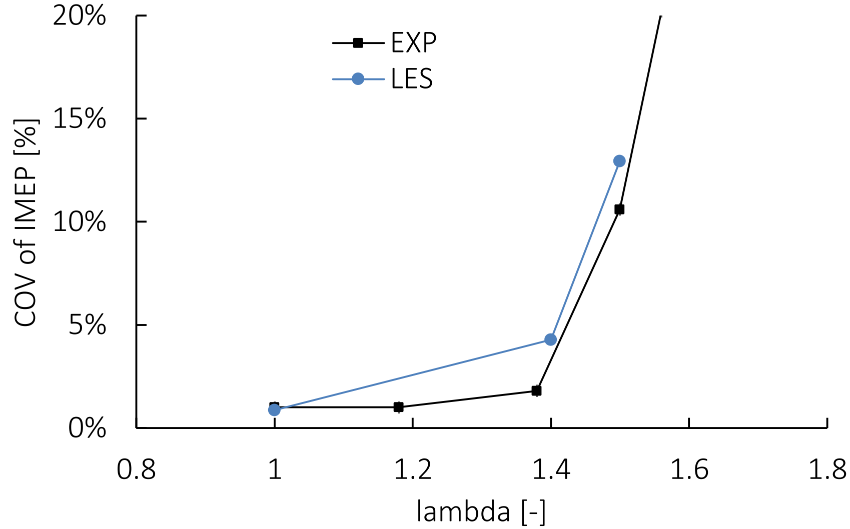
$\lambda = 1.4$

4th cycle



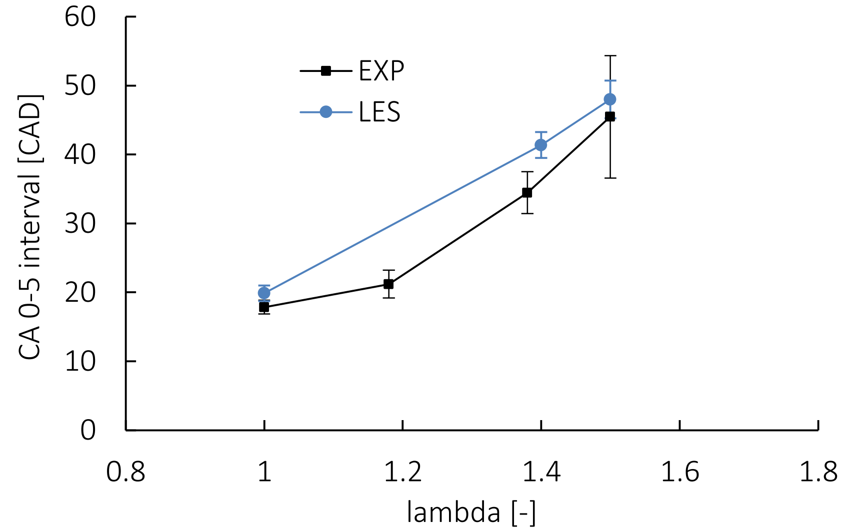
Stability vs. λ





Normalization of IMEP is because simulations have:

- slightly higher engine load (blow-by not modeled)
- not optimal SA (required MBT is different)

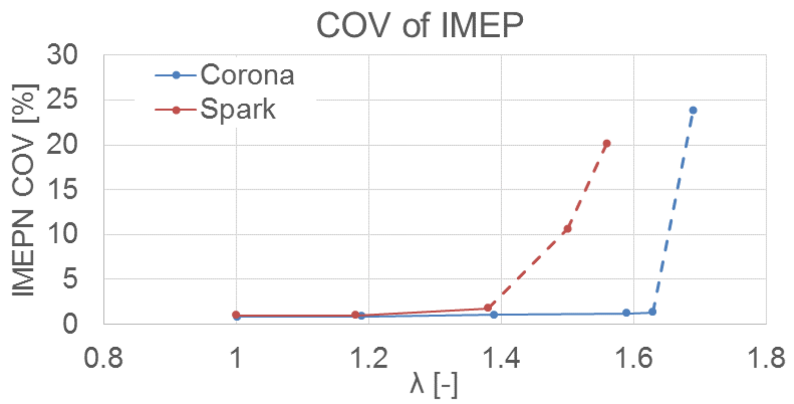


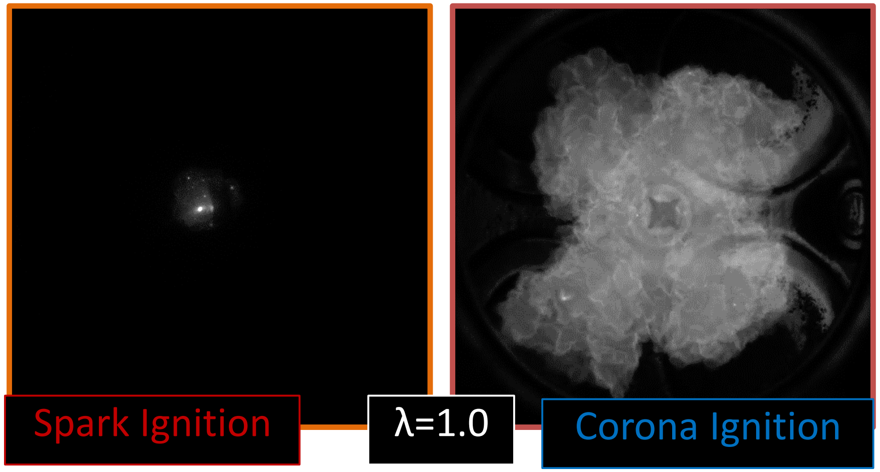
- Stable, near-limit and unstable points are fairly well reproduced: "knee" of COV of IMEP vs. lambda
- CA0-5 interval is also well reproduced, even if its variability is less marked

Cimarello et al. *SAE Paper 2017-01-0673,* 2017

Improving stability with Corona Ignition

Effect of an Advanced Corona Ignition System (ACIS) igniter tested and compared with a conventional single spark device
→ Lean limit extension of ~ 0.25 λ unit

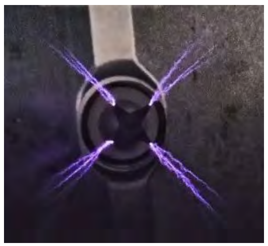


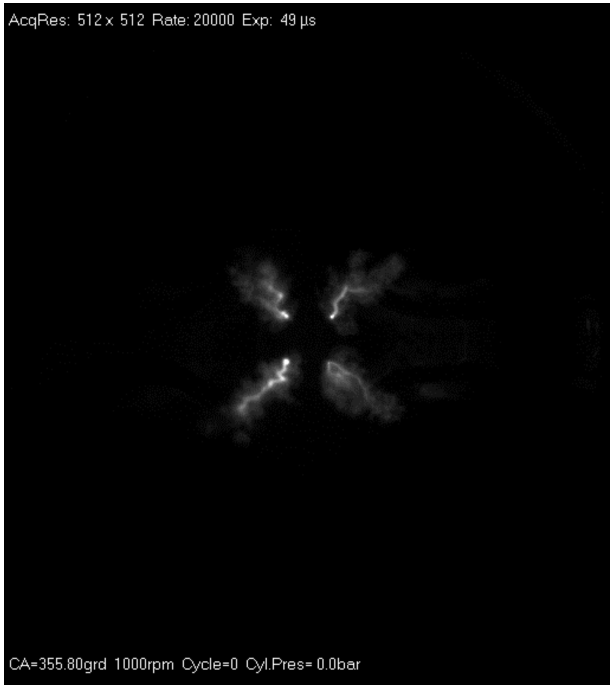


Images at the same time after SA

Cimarello et al. SAE 2017
Cimarello, Cruccolini, et al., SAE 2018

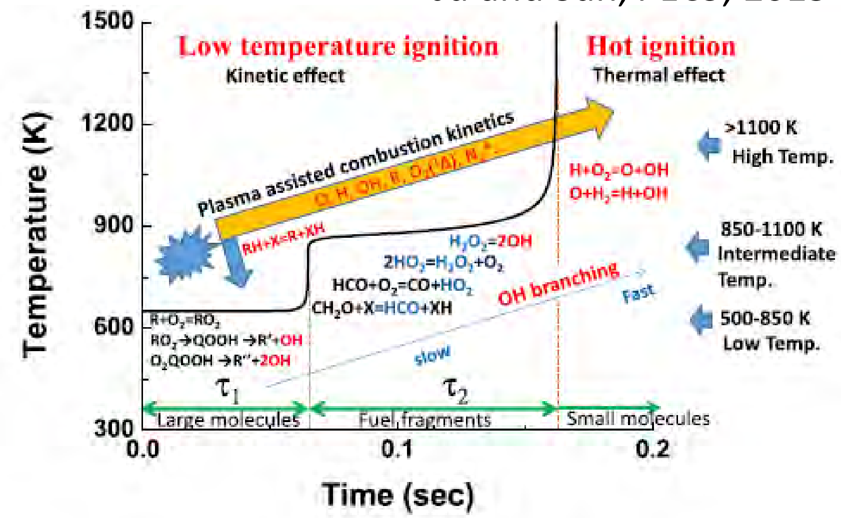
Exploring plasma assisted ignition simulations





Schematics of kinetic and thermal enhancement pathways of plasma assisted combustion for liquid fuels

Ju and Sun, *PECS*, 2015



Corona discharges:
electrical discharges generated by strong electric field. The non-equilibrium plasma related to the discharge can be considered as an enhancement of the ignition:

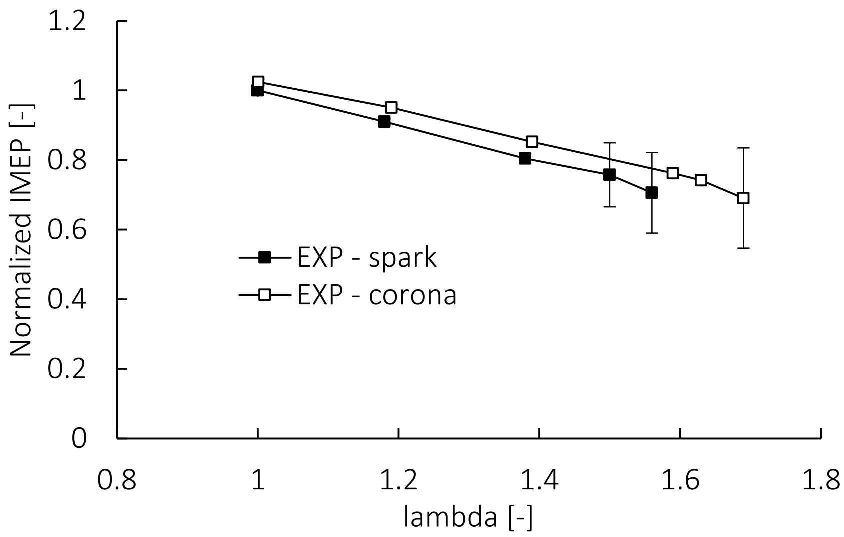
- *Thermal Effect*
- *Kinetic Effect* (production of active radicals via electron impact dissociation)
- *Transport Effect* (corona wind)

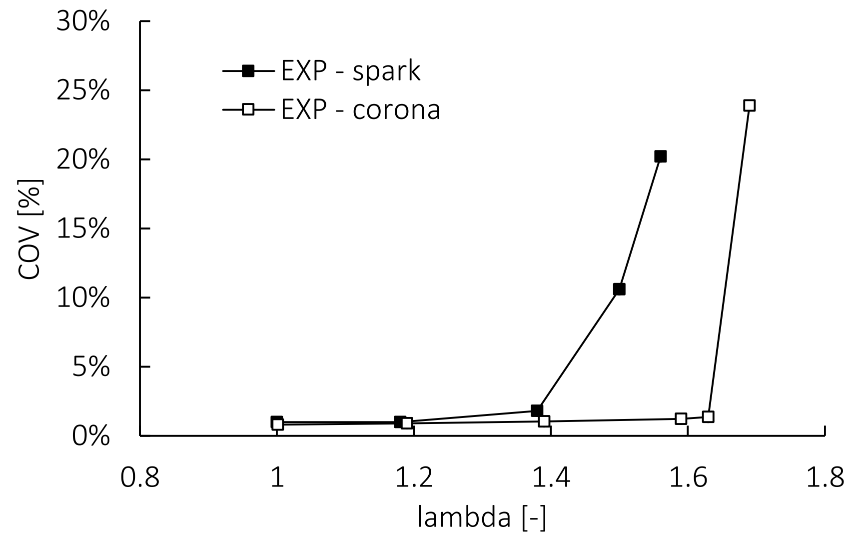
Numerical experiment

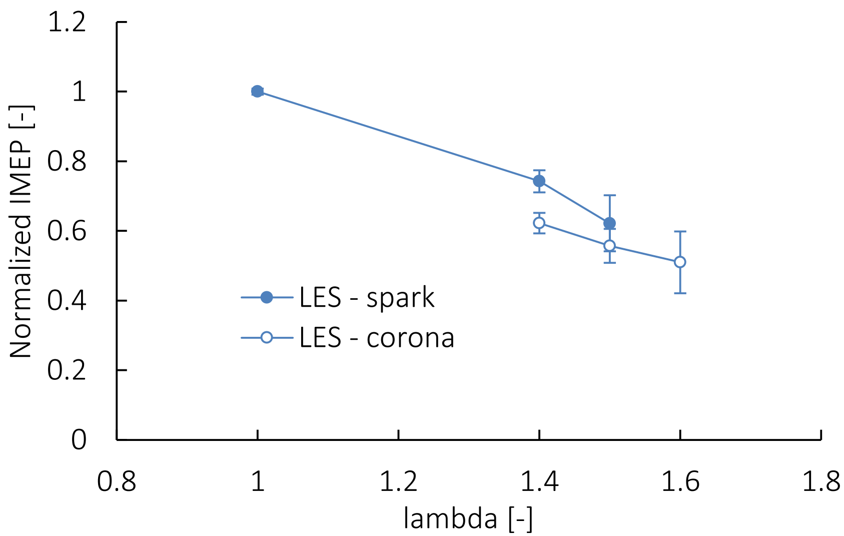
Enhanced ignition:

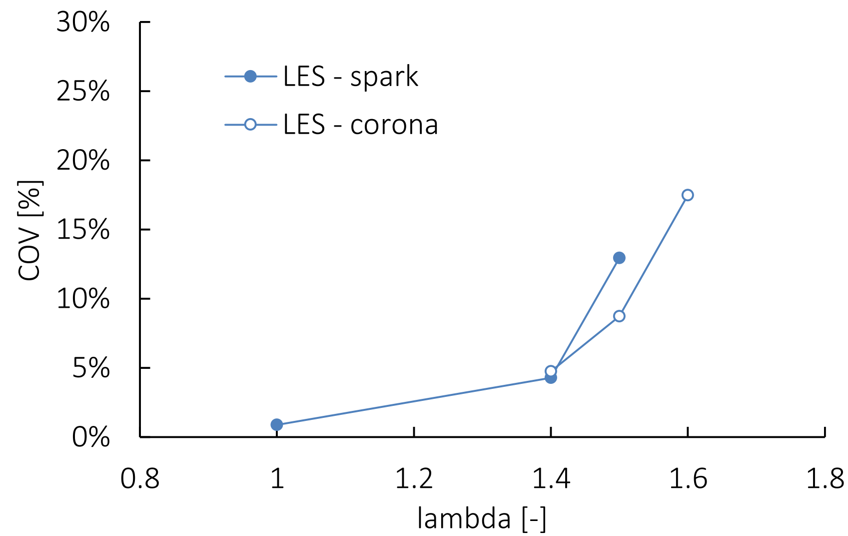
- energy deposition = 40 mJ, on a wider region (breakdown: 20 mJ over 0.25 CAD; arc-glow: 20 mJ over 4 CAD)
- radicals deposition: OH, O, H, N, on a wider region (breakdown: 1E-10 kg over 0.25 CAD)

Spark and Corona Ignition: Stability vs. λ









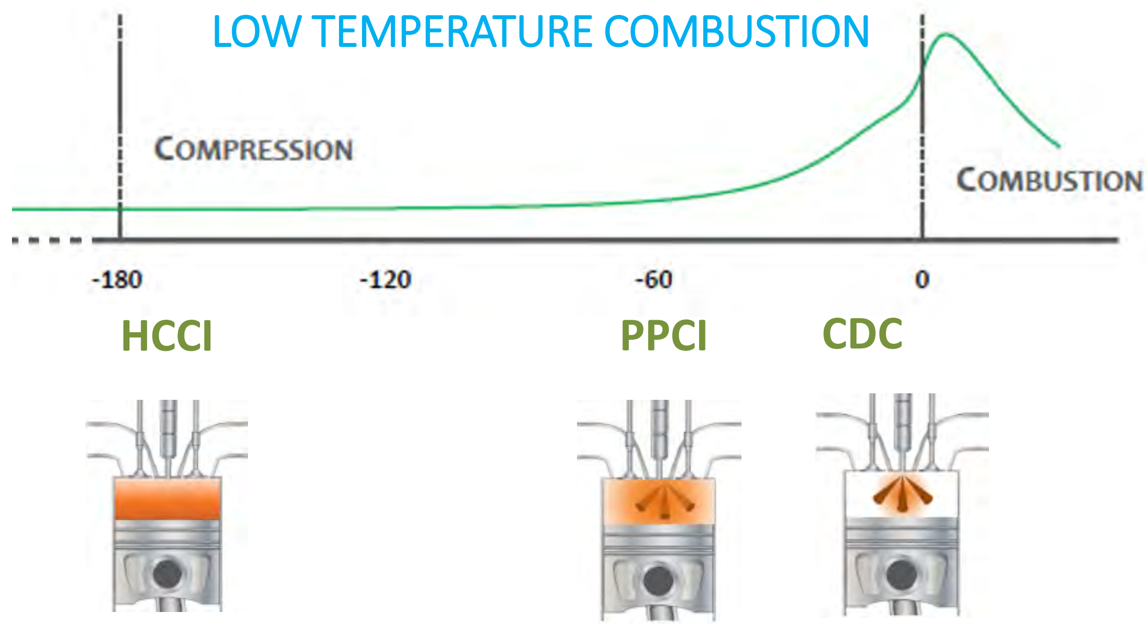
Experimental data:
Cimarello et al. *SAE Paper 2017-01-0673,* 2017

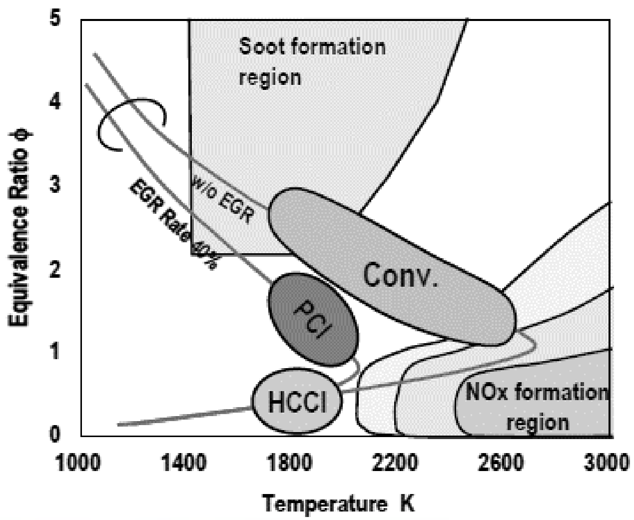
Gasoline Compression Ignition (GCI)

- Necessità di migliorare le efficienze energetiche, e di contenere le emissioni di NOX e PM

VANTAGGI DEI COMBUSTIBILI BENZINA

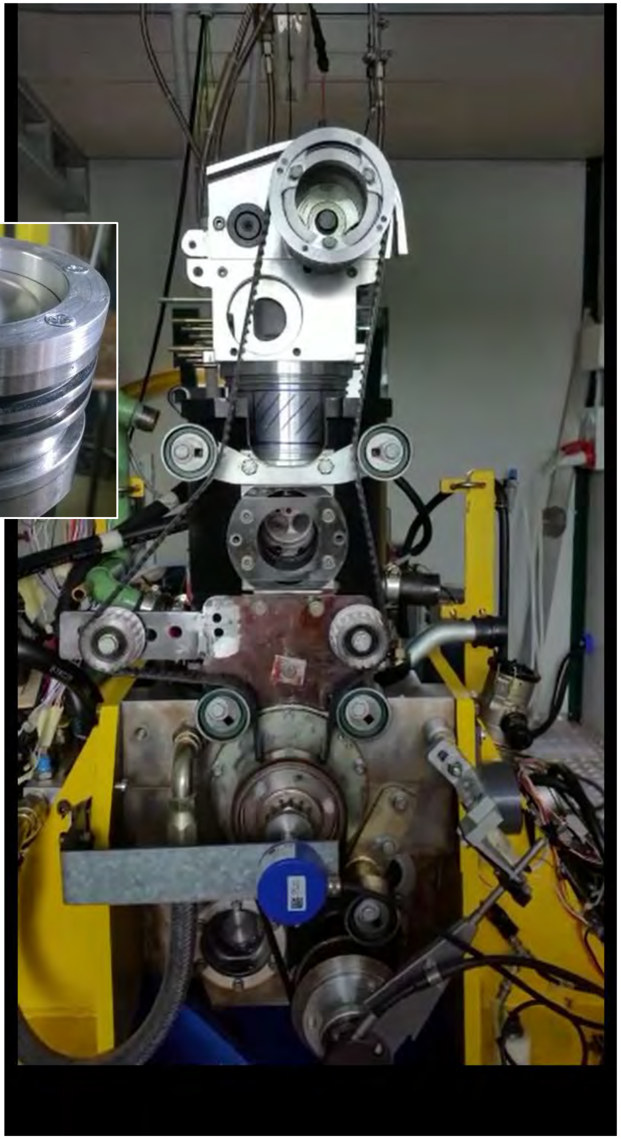
- Ritardo all'accensione maggiore
- Maggiore volatilità



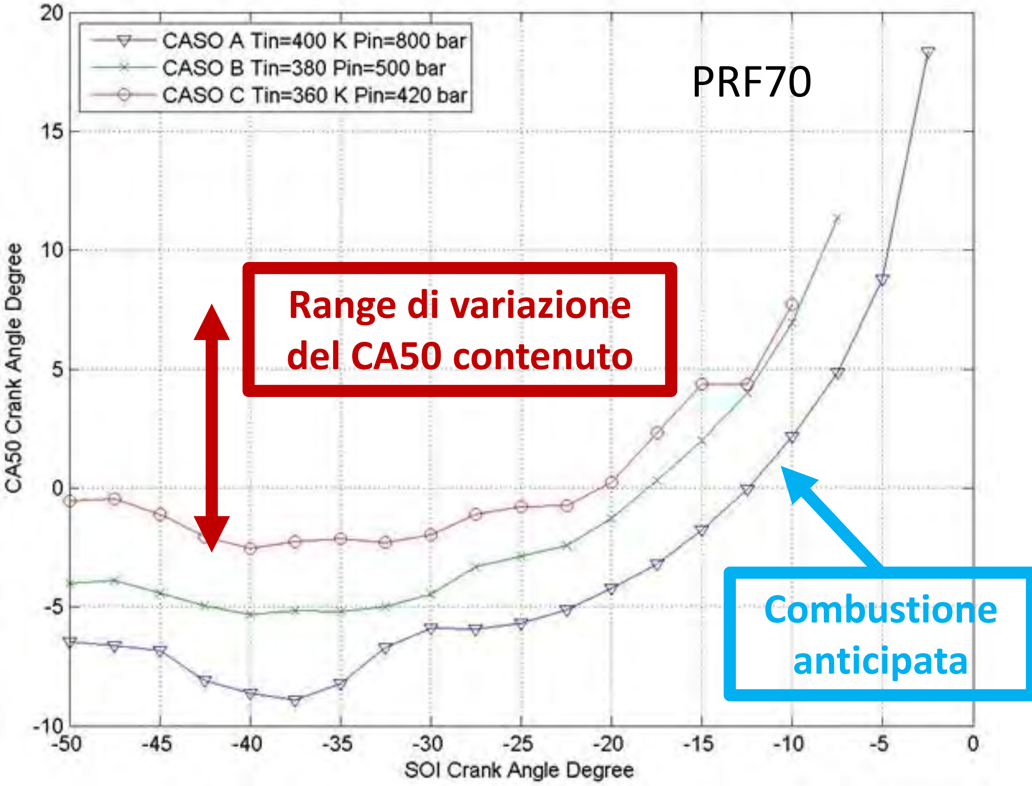


HCCI – Homogeneous Charge Compression Ignition
PPCI – Partially Premixed Compression Ignition
CDC – Conventional Diesel Combustion

Gasoline Compression Ignition (GCI)



Combustion phasing (CA50)

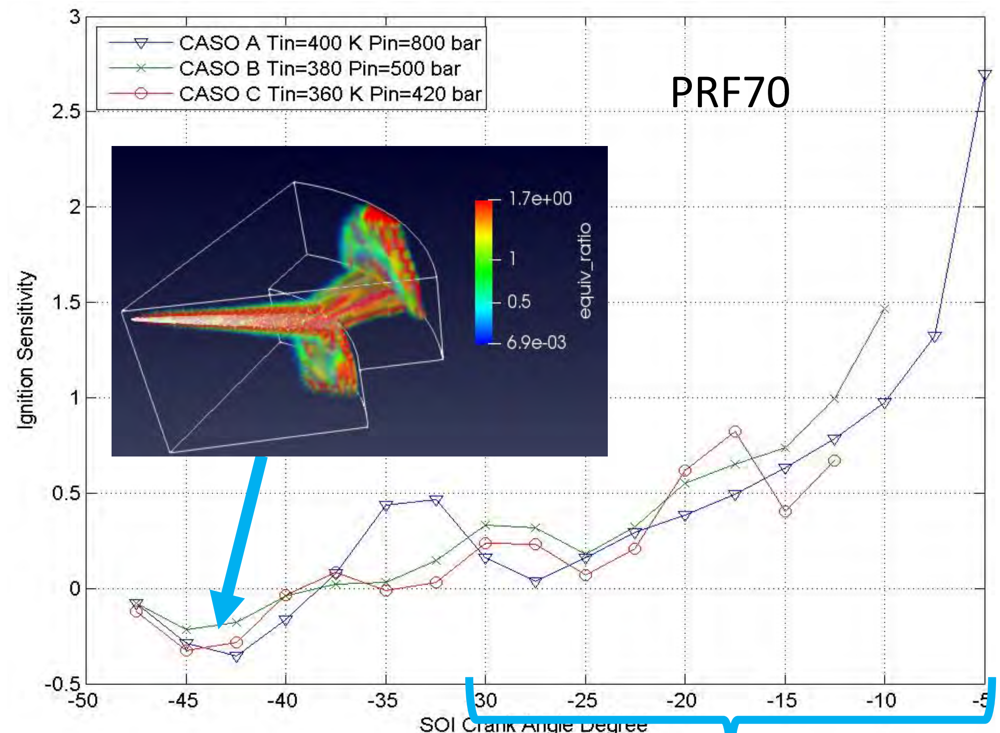


Preliminary ***simulation*** *results*

Gasoline Compression Ignition (GCI)

Ignition sensitivity

$$I = \frac{CA50_{SOI=i+1} - CA50_{SOI=i-1}}{SOI_{i+1} - SOI_{i-1}}$$



Intervallo di controllabilità diretta

*Preliminary **simulation** results*

Acknowledgments

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  Sibendu Som, Zongyu Yue, Gina Magnotti, Riccardo Scarcelli, Kastengren, Powell, Matusik,

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  Kelly Senecal, Eric Pomraning, Shaoping Quan, Priyesh Srivastava

- **Cineca SCAI**

  HPC center

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  Zagreb Univ., prof. J. Jasak

  Univ. Bologna, prof. N. Cavina

Thank you !!