Engine Combustion Network

ECN3: Spray G optical measurements

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Thrid Workshop of the Engine Combustion Network,

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Introduction

- Spray visualization has been behind most of the data shared by the different institutions on the ECN website since its creation
- Visualization of sprays generated by several Spray G injectors have been performed by five groups:
  - Istuto Motori, IFPEN, University of Melbourne, GM and Sandia
- The bulk of the experiments is liquid and vapor penetration to compare the global spray development parameters of the different injectors
- The ECN recommends using diffused back-illumination (DBI) to measure liquid length, but Mie scattering has also been used for comparison
- Vapor penetration has been obtained via schlieren
- The primary focus is Spray G with the conventional orientation (#1)
  - Ambient temperature: 573 K, Ambient density: 3.5 kg/m^3, Injection pressure: 200 bar
- Additional conditions (other than Spray G) varying ambient density (and temperature) have been tested by some institutions
- Additional experiments such as front Mie scatter or long-distance microscopy (LDM) have been performed by Sandia

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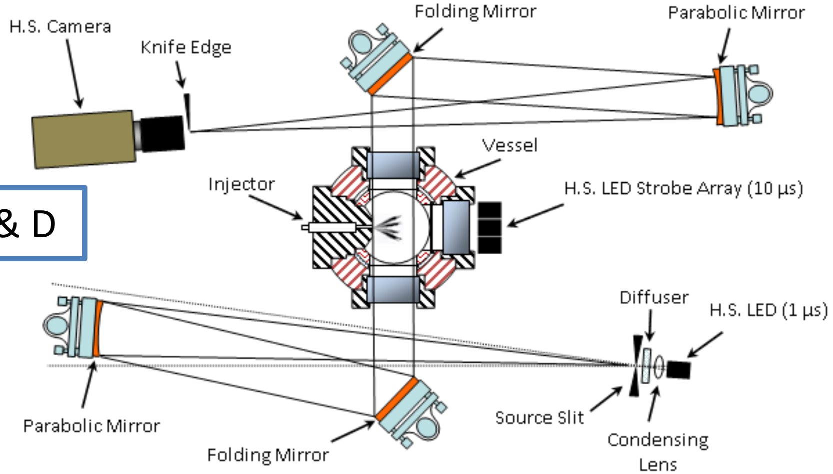
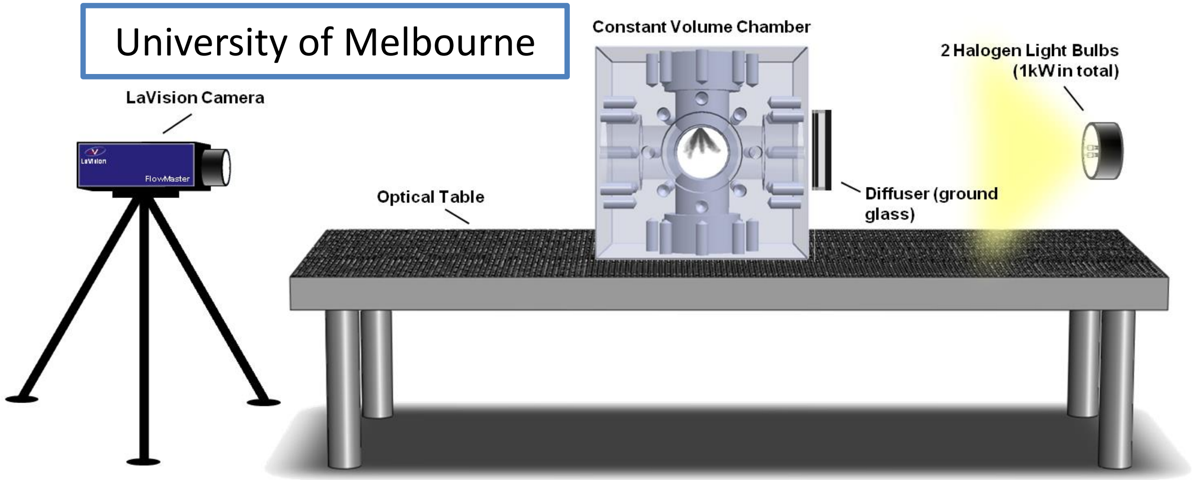
- Five institutions, with different facilities, capabilities and experience performed the first ECN Spray G experimental work

Istituto Motori

GM R & D



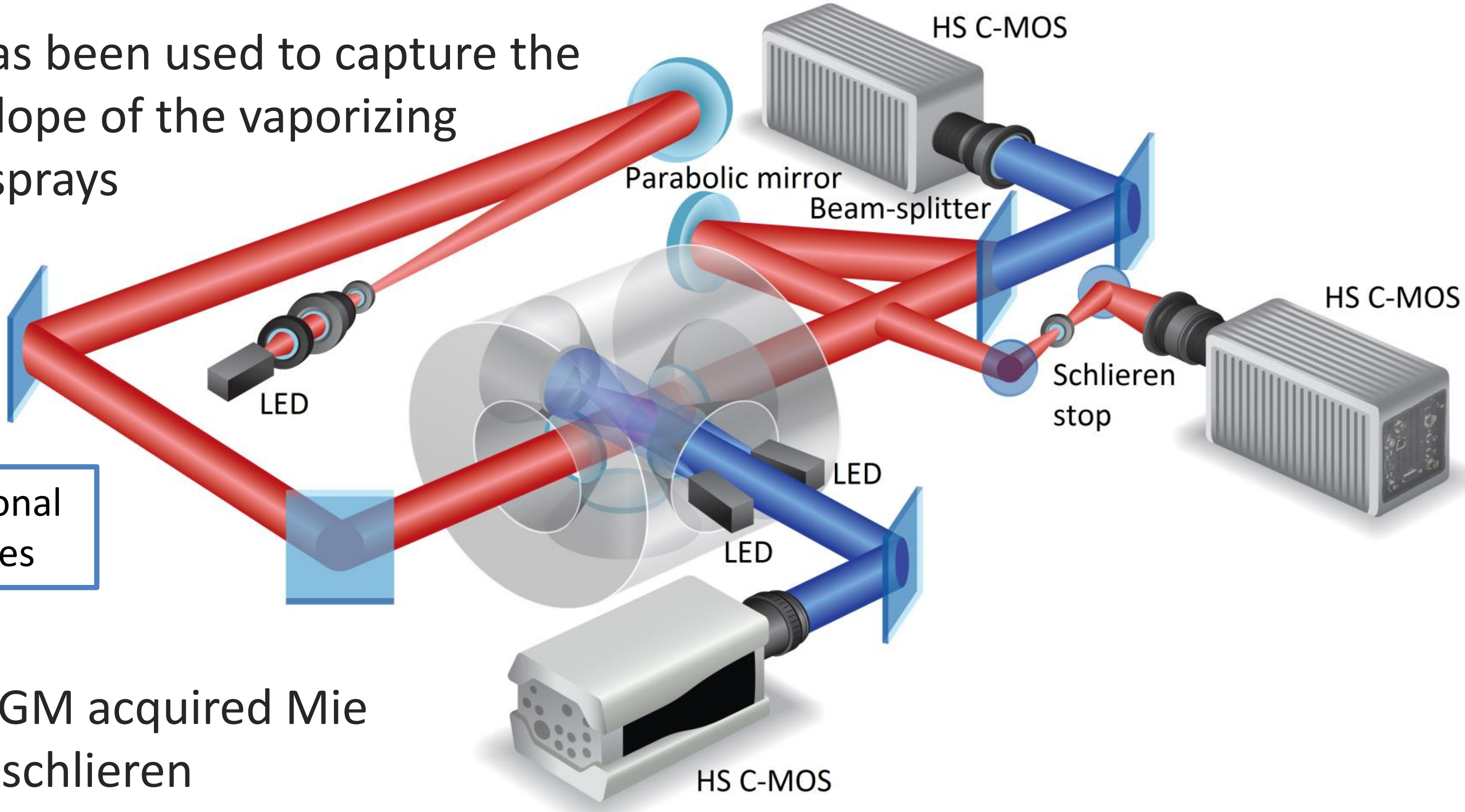
University of Melbourne



IFPEN

Optical arrangements: Mie scatter/Schlieren

- Mie scatter has been used by Sandia, GM and Istituto Motori to measure liquid penetration
- Schlieren has been used to capture the global envelope of the vaporizing iso-octane sprays

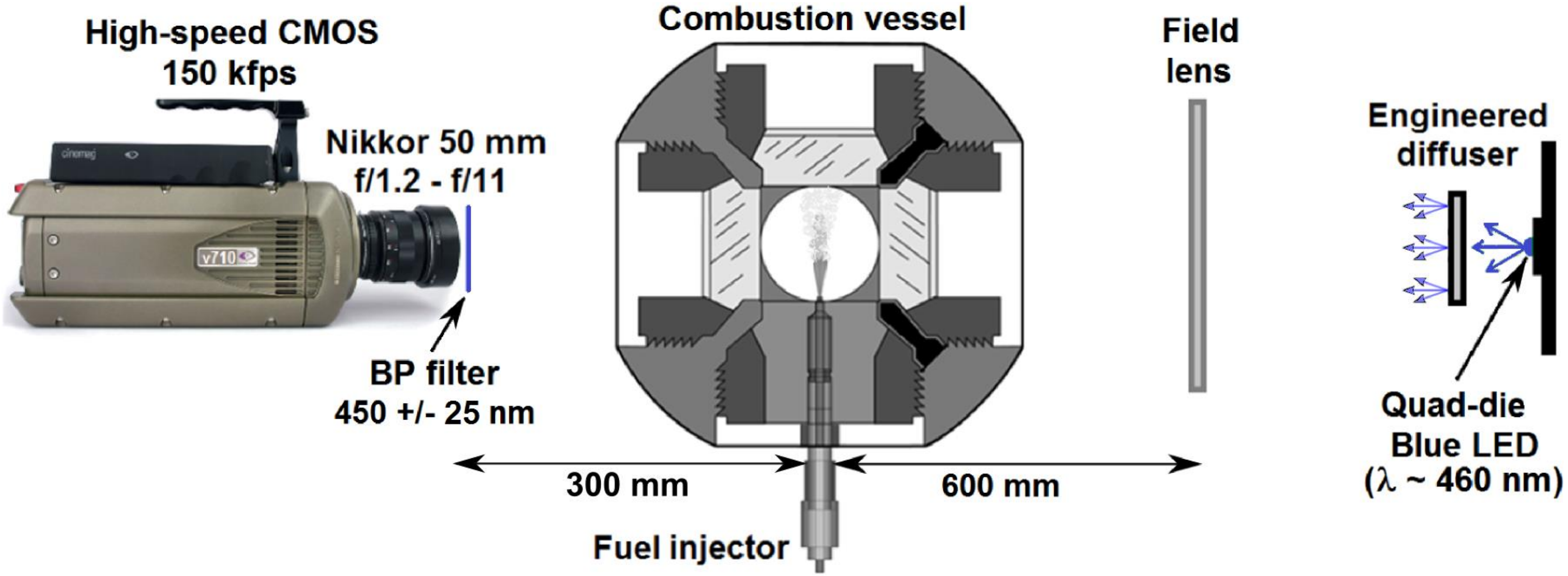


Sandia National Laboratories

- Sandia and GM acquired Mie scatter and schlieren simultaneously
- Note that GM used an image straddling strategy (1 frame Mie, 1 schlieren)
- Sandia also performed front-view Mie scatter visualization of the sprays

Optical arrangements: Diffused back-illumination

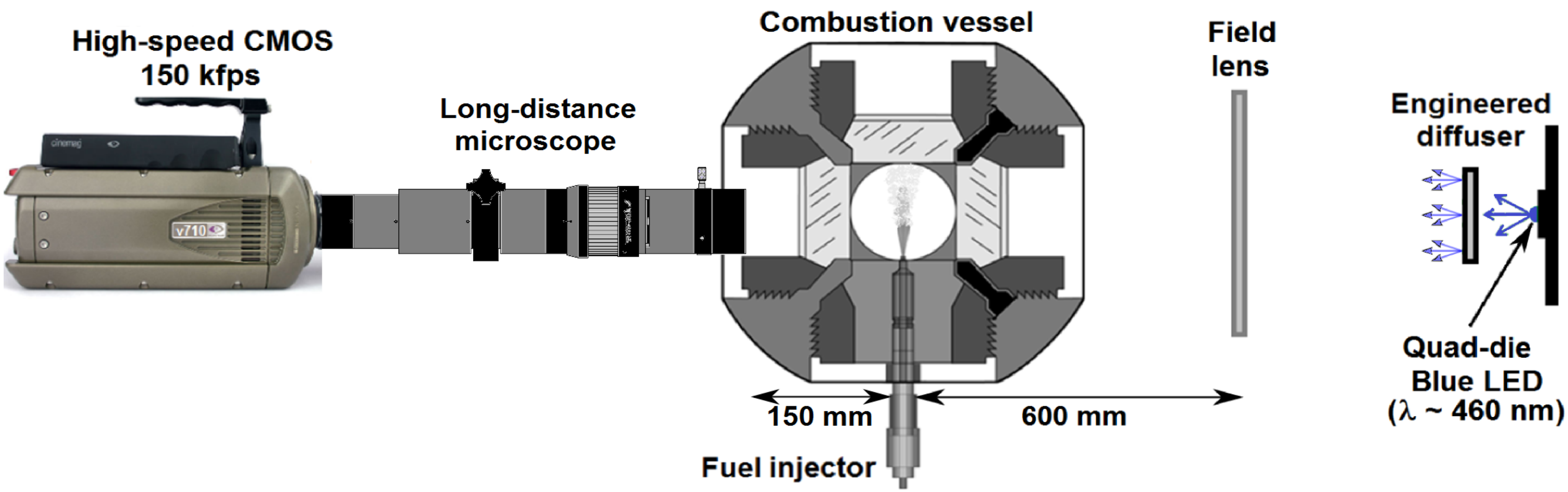
- As recommended by the ECN, diffused back-illumination has been used to probe liquid penetration under vaporizing conditions (SNL, IFPEN and UM)



- Diffused back-illumination uses the extinction produced by the spray droplets to provide a measure related to the liquid volume fraction
- This method is also recommended by the GDI spray community (J2715)
- Even though DBI offers a self-calibrated measure of extinction, the measured extinction has been observed to be system-dependent

Optical arrangements: Long-distance microscopy

- Long-distance microscopy (LDM) has been used to take a close look at the flow right at the nozzle exit
- Near-nozzle field and visualization with approx. 8 µm resolution, offering a detail description of the first millimeters of the spray



- High-speed C-MOS equipped with long-distance microscope lens (K2/Distamax)
- Specially designed ultra-fast LED capable of MHz operation with short (≈ 10 ns) pulse duration
  - Offers continuous high-speed imaging to track liquid structures and fuel stream atomization

Experiments summary

- Below is a non-exhaustive list of the experimental contributions from the different institutions for this effort:
  - Istituto Motori: Cold vessel – 300 K ambient temperature – 3.5 kg/m^3 density – 200 bar injection pressure – Injector 17
    - Liquid penetration: Mie scatter - side illumination, side view
    - Central plume penetration and global spray average spreading angle for non-vaporizing sprays
  - University of Melbourne: Constant volume vessel – Spray G (573 K ambient temperature – 3.5 kg/m^3 density – 200 bar injection pressure) – Injector 18
    - Liquid length: Diffused back-illumination
    - Global penetration for the liquid portion
  - IFPEN: Preburn vessel – Spray G and 6 kg/m^3 – 700 K, 9 kg/m^3 – 800 K– Injector 22
    - Liquid length: Diffused back-illumination and Mie scattering – front illumination, side view
    - Vapor boundary: Schlieren
    - Global penetration for both liquid and vapor and liquid extinction profiles
  - GM: Constant flow vessel – Spray G – Injector 16 and 28
    - Liquid length: Mie scattering – front illumination, side view
    - Vapor boundary: Schlieren
    - Global penetration, spreading angle and probability envelopes for both liquid and vapor
  - Sandia: Preburn vessel – Spray G and 6 kg/m^3 – 700 K, 9 kg/m^3 – 800 K– Injector 28
    - Liquid length: Diffused back-illumination and Mie scattering – front illumination, front and side view
    - Vapor boundary: Schlieren
    - Global penetration and spreading angle for both liquid and vapor and liquid extinction profiles
    - High-speed near-nozzle microscopy

Image processing definitions

- Even though we tried to keep the experimental diagnostics and processing methodologies similar, real-world constraints got the last word
- Liquid length has been measured by diffused back-illumination and Mie-scattering
  - Diffused back-illumination looked at the extinction: $I/I_0 = 0.9$ to defined liquid boundary
  - Mie scattering used the recommendations from the diesel effort of 3 % of the maximum scattered intensity
- Vapor was measured by schlieren and the jet boundary was obtained with the algorithm available on the ECN website
  - The standard deviation of the high-speed images is evaluated to determine the border
- Both liquid and vapor penetrations correspond to the maximum axial penetration of the processed boundary
- Spreading angle is measured as the angle between the orifice and the spray width taken from the processed liquid and vapor boundaries at 11 mm

These are preliminary processed results of measurements performed over the last few days!

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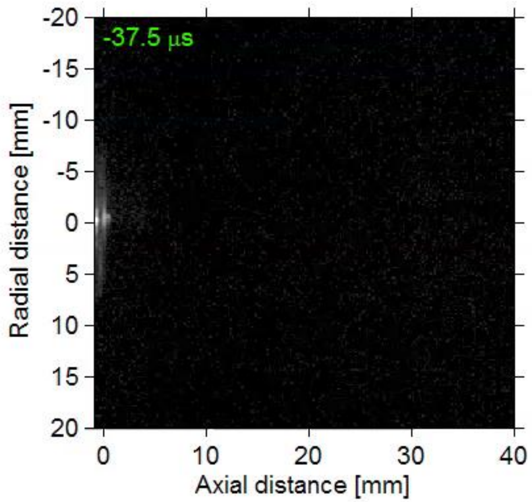
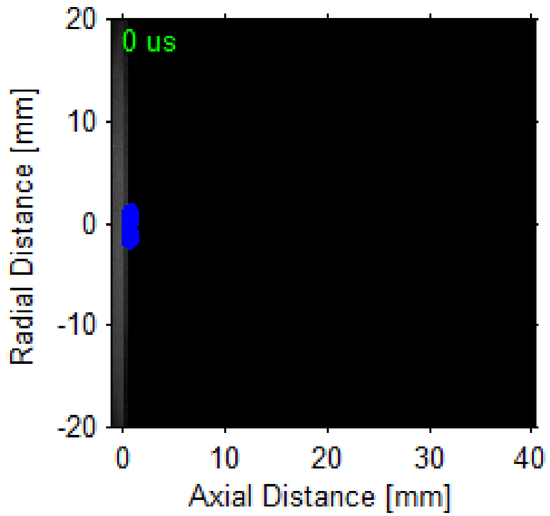
High-speed visualization: Liquid length (Mie)

SNL



GM



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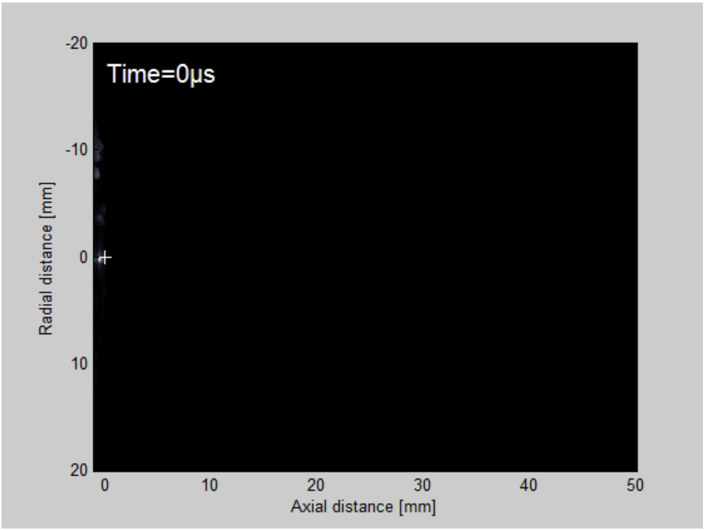
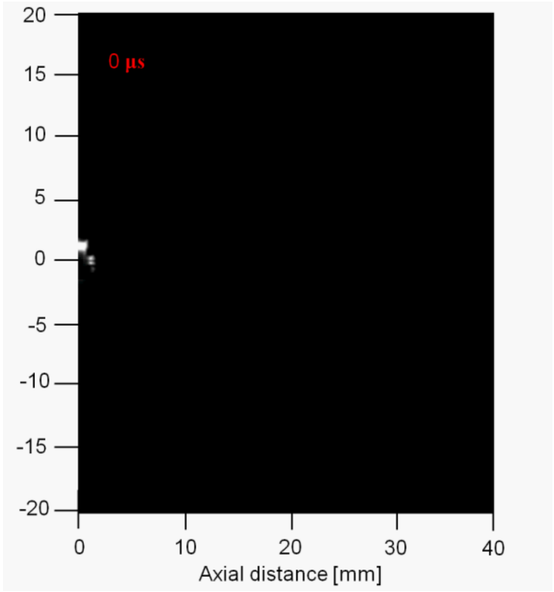
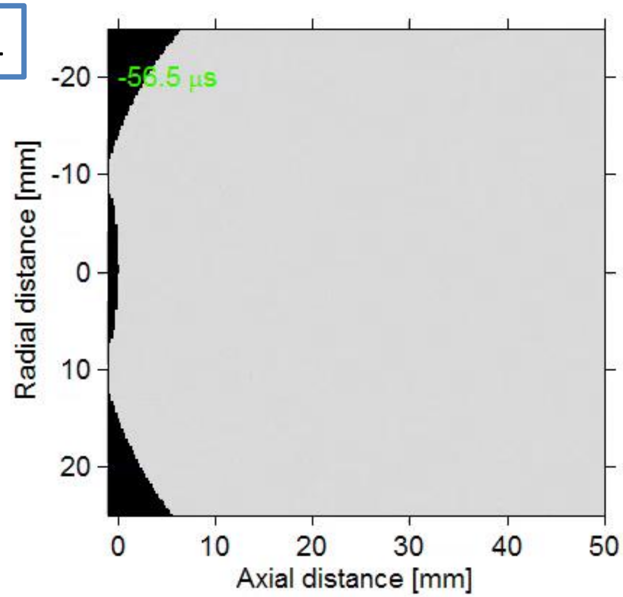


IM



High-speed visualization: Liquid length (DBI)

SNL



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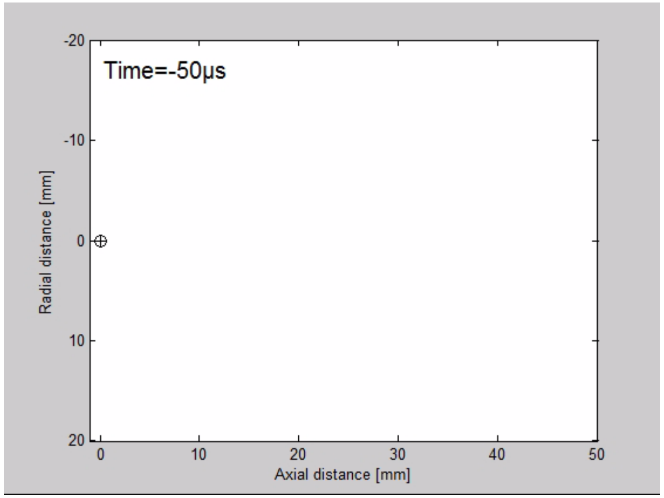
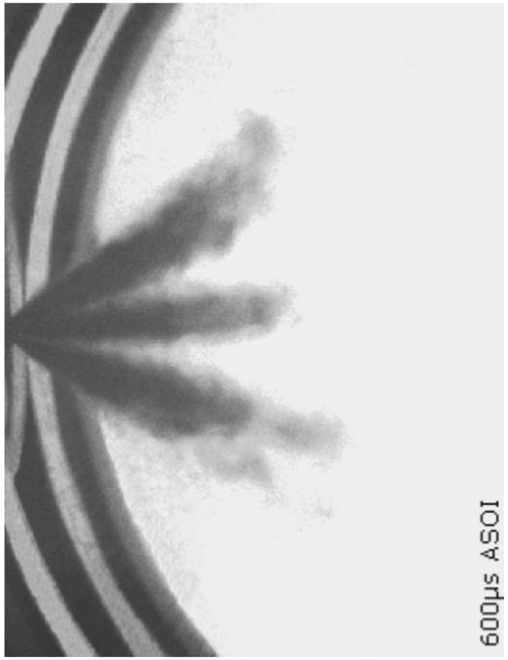


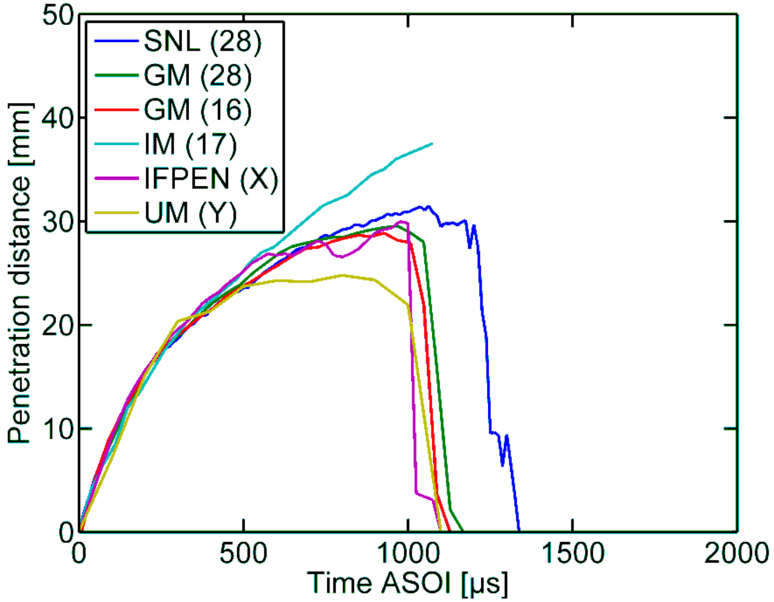
UM

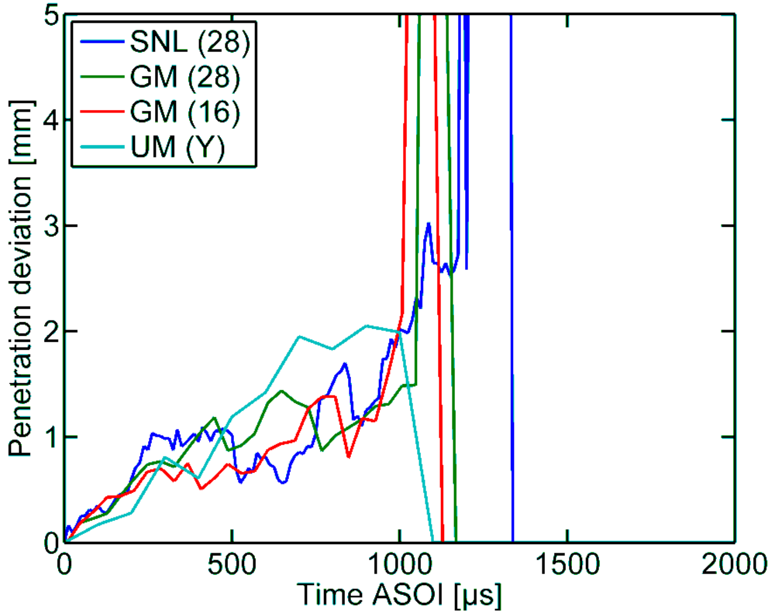


- Three groups used diffused back-illumination to measure liquid length
  - DBI is the standard diagnostic recommended by the ECN for liquid length
- IFPEN movie is for an average of 10 repetitions
- Melbourne did not have a high-speed camera for these experiments

Liquid length comparisons

- Liquid penetration measured via Mie scattering shows relatively good agreement between facilities and injectors
- Istituto Motori's sprays are non-vaporizing, explaining the longer liquid penetration
- University of Melbourne processed the liquid length of the central plumes instead of the global axial liquid penetration

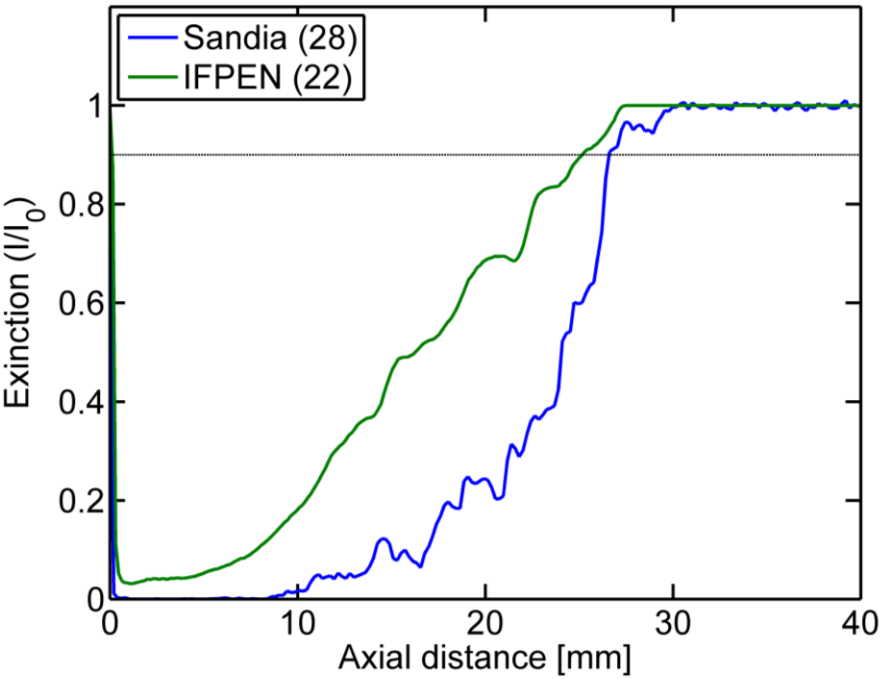




- Sandia's longer liquid persistence seems to be attributed to low SNR for these runs
- The standard deviation across the many repetitions show similar results for all laboratories
- The high deviation at the end is due to the scatter in evaporation rates after injection until full vaporization

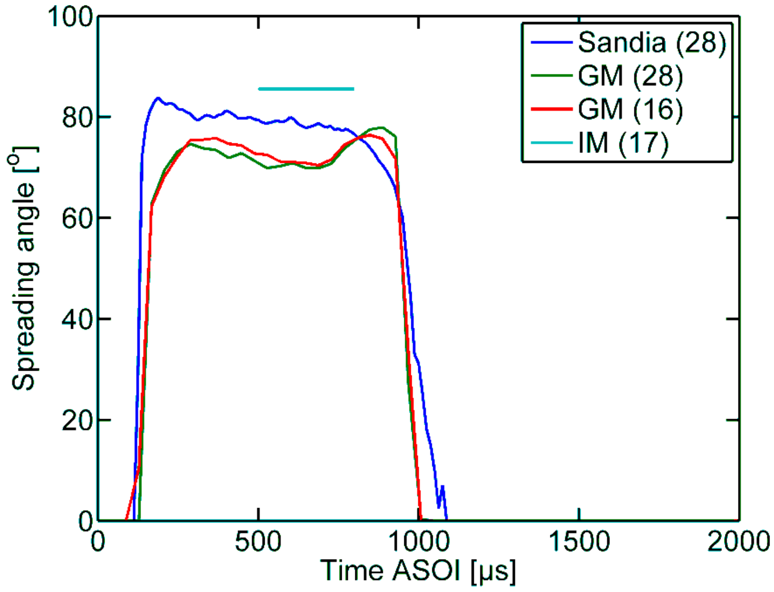
DBI threshold impact on liquid length

- Diffused back-illumination offers a “built-in” calibration as it is extinction based, unlike Mie scattering techniques
- However, it has been seen that the extinction measured via such technique depends upon optical setup
  - Collection angle, illumination distribution or wavelength are parameters that affect the measured scattering cross-section of the spray droplets and therefore the optical extinction
- In addition, the methodology applied to provide a value for liquid length has a strong impact on the measurements and renders comparisons invalid
- Comparing the profiles acquired by two institutions demonstrates the differences between setups
- Even though Sandia and IFPEN have used the same extinction threshold I/I_0, some discrepancies remain
  - Such differences in DBI measurements have been observed for diesel sprays at ECN 2

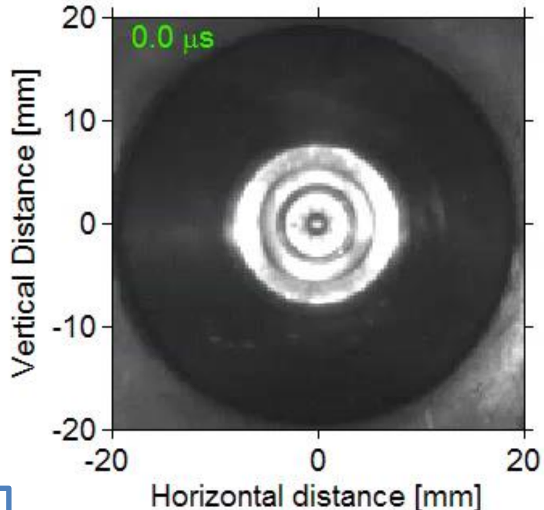


Liquid spray included angle

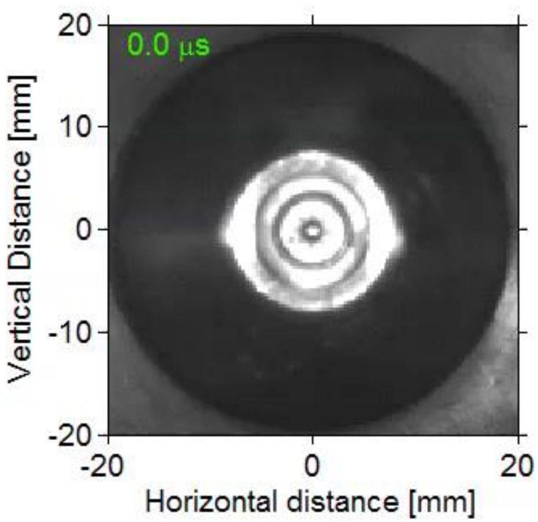
- The spreading angle of the spray envelope is expected to be around 80° as specified by the design of the injectors
  - Gasoline sprays included angle is specified as the full angle of the jet, unlike the included angle in diesel sprays specified by the geometrical angle
- Istituto Motori evaluated the included angle on a non-vaporizing spray during the quasi-steady period of the injection
- The results between injectors and facilities are fairly close, but GM's measurements show narrower sprays than those measured at Sandia
- A slight difference between the processing methodologies used by Sandia and GM seems to be the correct explanation for the discrepancy
  - Sandia used the spray width at 11 mm to evaluate the angle of a triangle formed by the spray width and the injector tip
  - GM calculated the angle between two lines linking 1 and 11 mm from the tip on both sides of the spray, this effectively put the apex of the triangle behind the injector nozzle tip

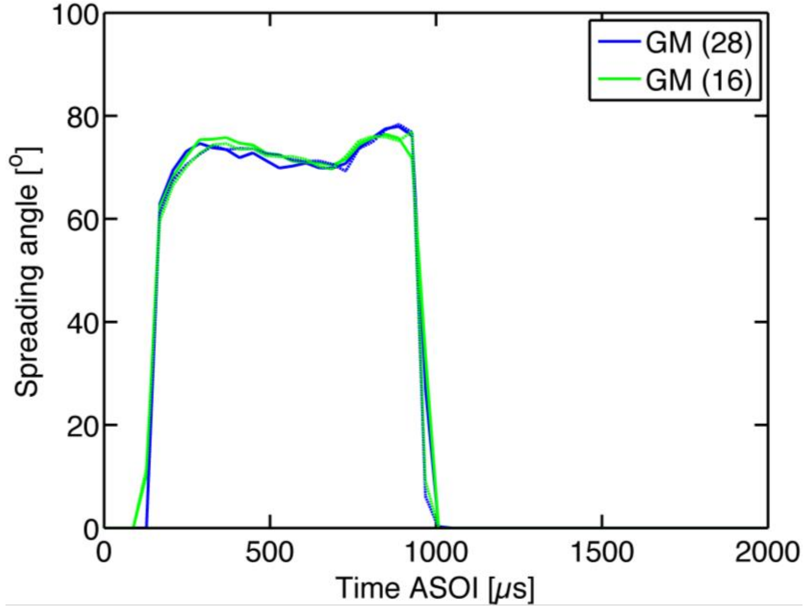


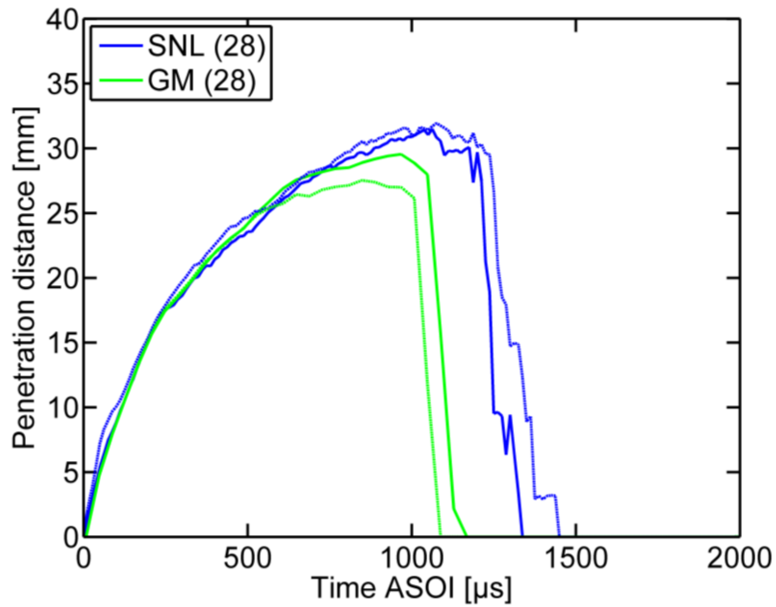
Spray orientation comparisons



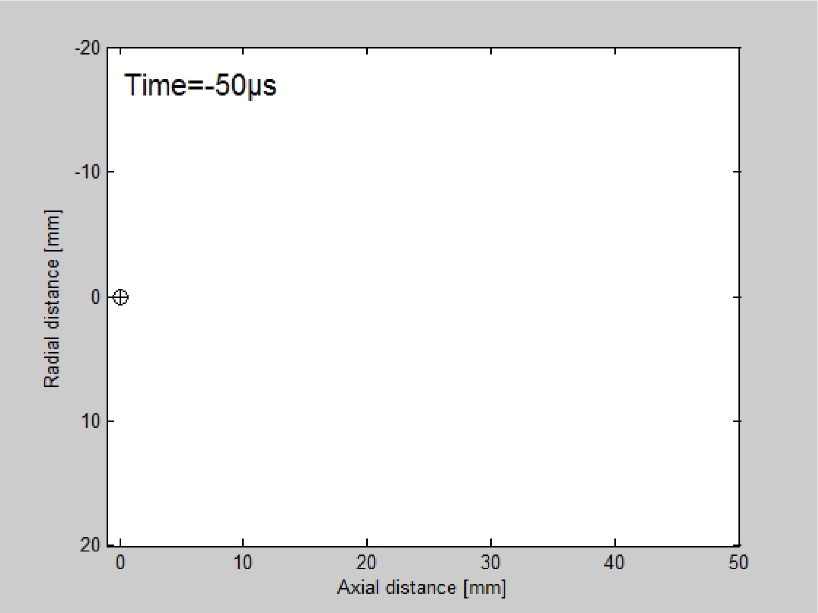
SNL







Ambient density impact on liquid development



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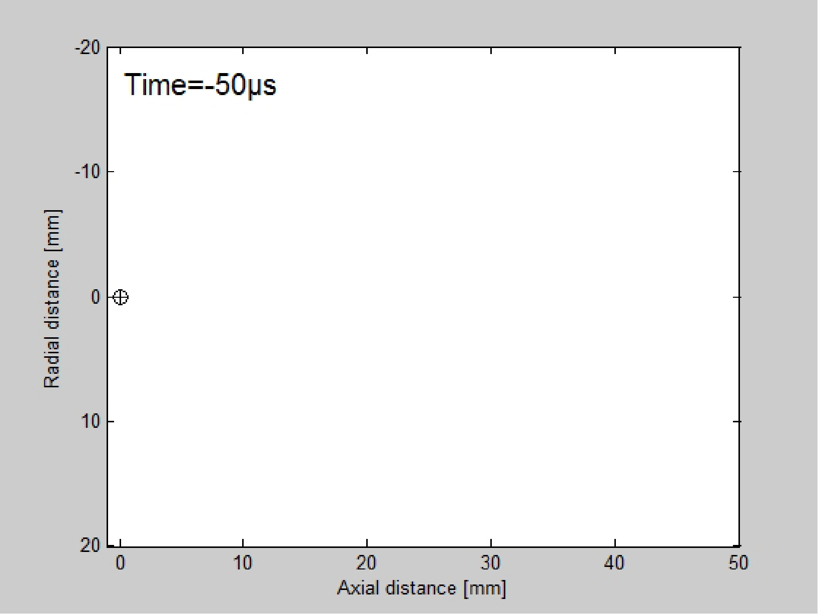
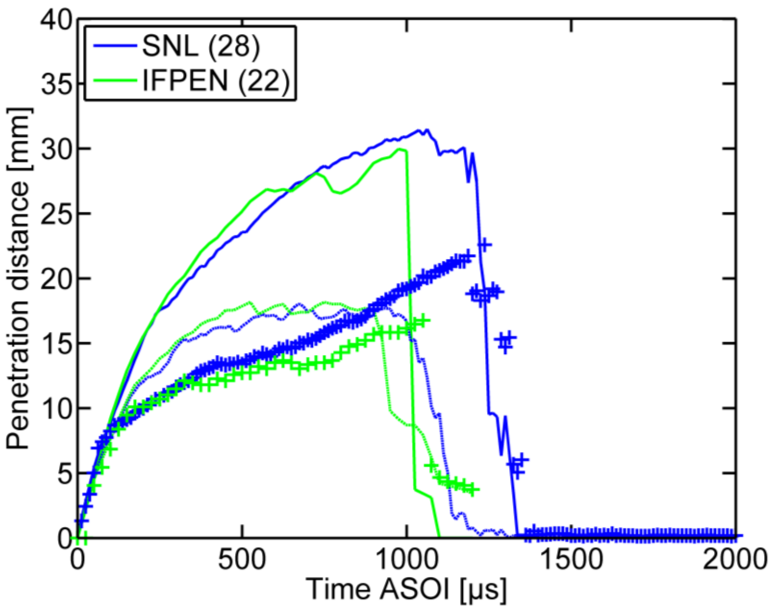


- Impact of ambient density on liquid penetration is, as expected, quite important
- Differences in spray development and mixing are easily observable, with a collapse of the plumes to the injector axis during injection for the higher density case (9 kg/m3) tested



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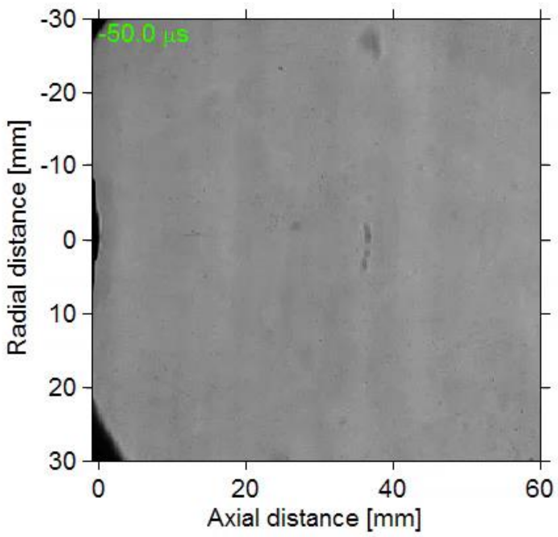
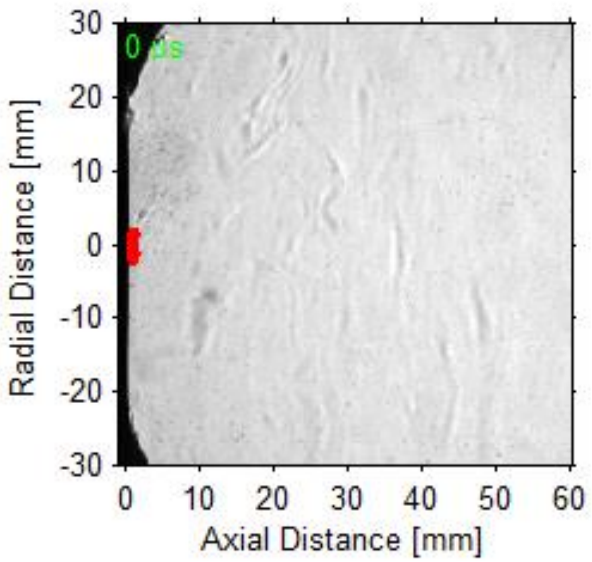
- Liquid region measurements comparisons
- Global (vapor) spray development comparisons
- Near-field microscopy
- Conclusions and ongoing tasks

High-speed visualization: Jet penetration

SNL

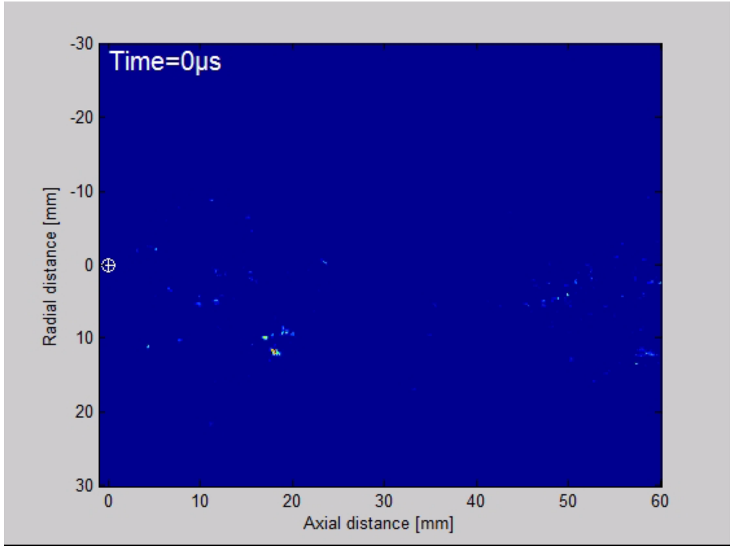


GM



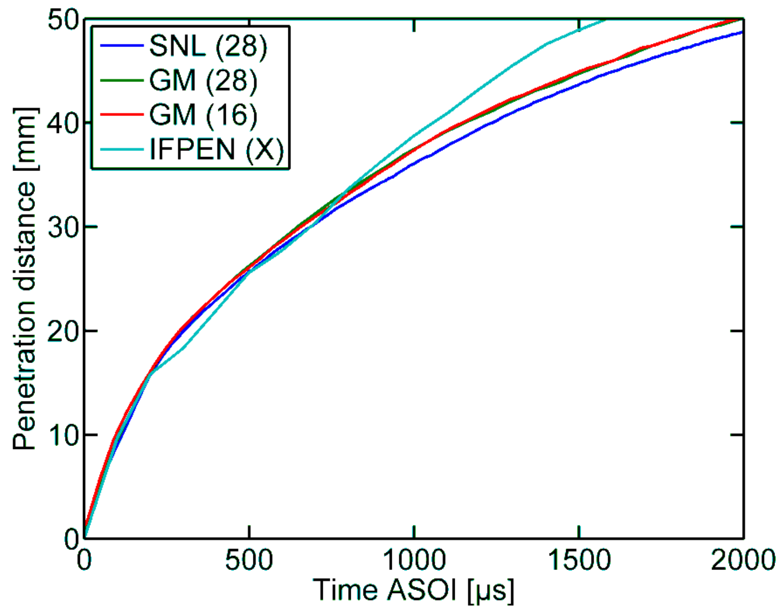
- Three groups applied schlieren to measure vapor penetration
- IFPEN movie shows the standard deviation for an average of 10 repetitions
- Melbourne is planning on doing such experiments after the meeting
- As for the liquid portion of the spray, GM and Sandia exhibit similarities

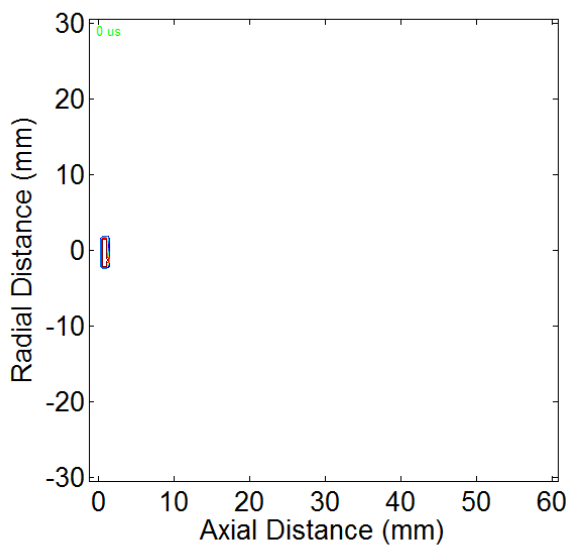
IFPEN



Global penetration and envelope comparisons

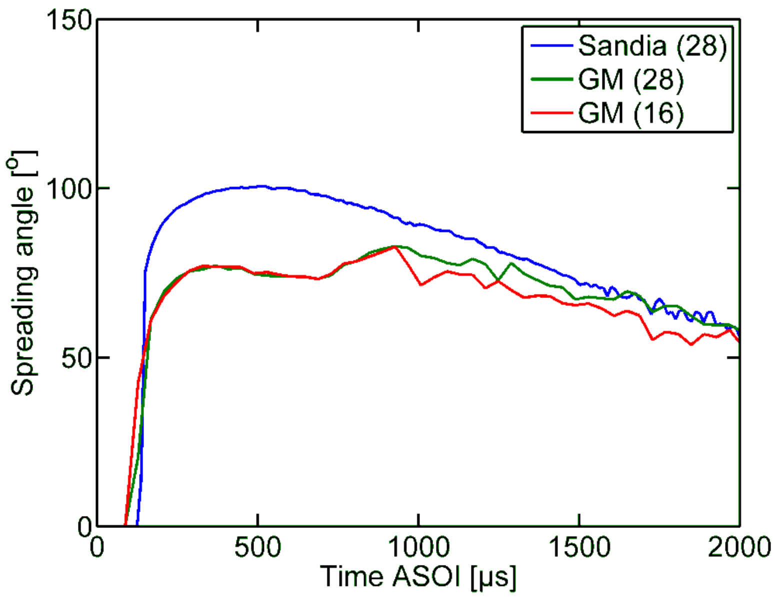
- There is a fair agreement between facilities and injectors concerning global jet penetration
- IFPEN is measuring slightly longer penetration starting after the end of injection
  - For some unknown reasons at this time, it seems like vapor penetration keeps moving faster after the end of injection at IFPEN than at the other facilities (or injectors)





- The vapor boundary probability contours show the amount of scatter expected between repetitions
- The 0 – 100 % probability contours are relatively close to each other, showing the relatively good repeatability of the injector
- Note that IFPEN's vapor penetration is out of these bonds after the end of injection

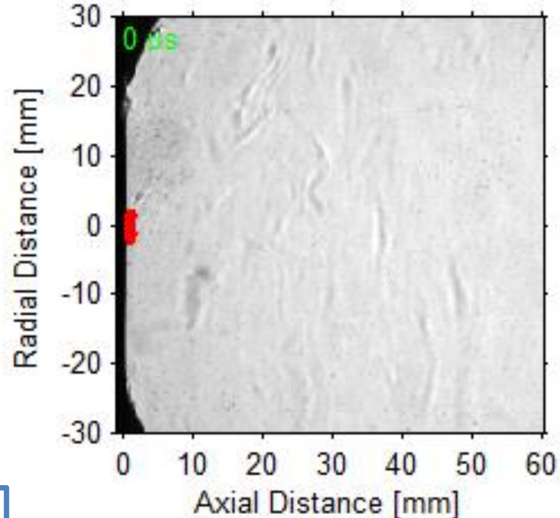
Global spray included angle

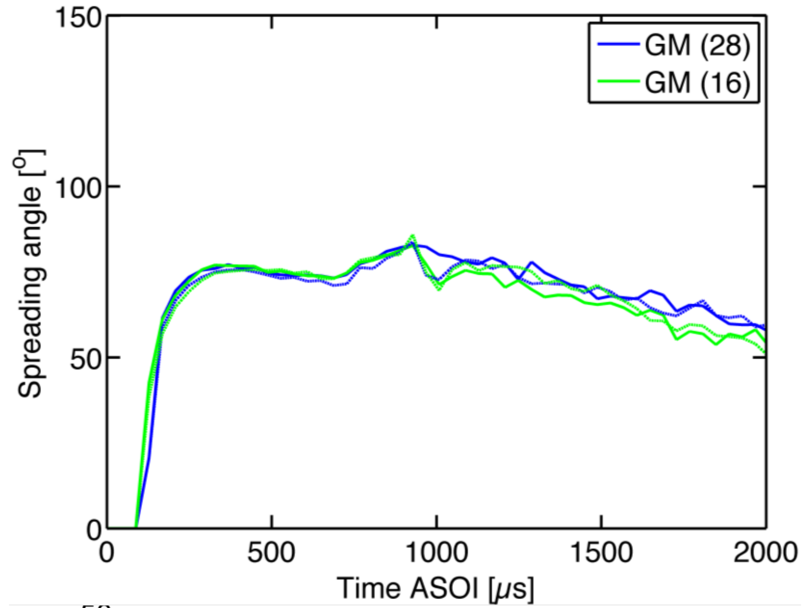


- Measuring the angle of the vapor envelope with schlieren is expected to show more scatter and deviation than on the liquid portion
  - Measured spreading angle has been seen to be affected by the sensitivity of the schlieren system
- Still, GM's measurements during injection are relatively close to the specified 80°

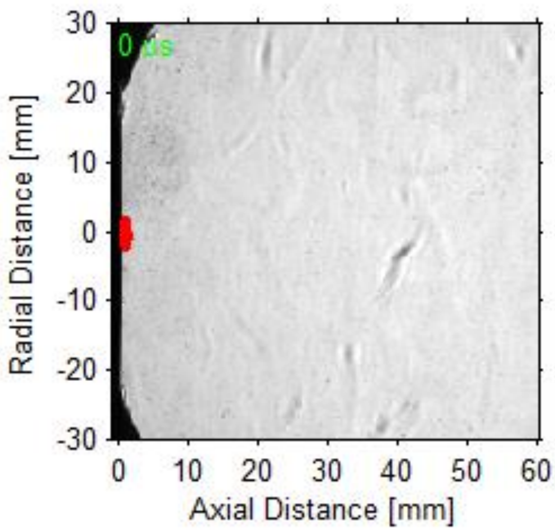
- The two injectors measured at GM show very similar included angle, in line with the rest of the measurements for these two units
- Sandia's measured included angle is approximately 20° wider than GM's during injection
- The processing methodology differences between the two groups detailed previously for the liquid portion are likely to explain the measurement discrepancies

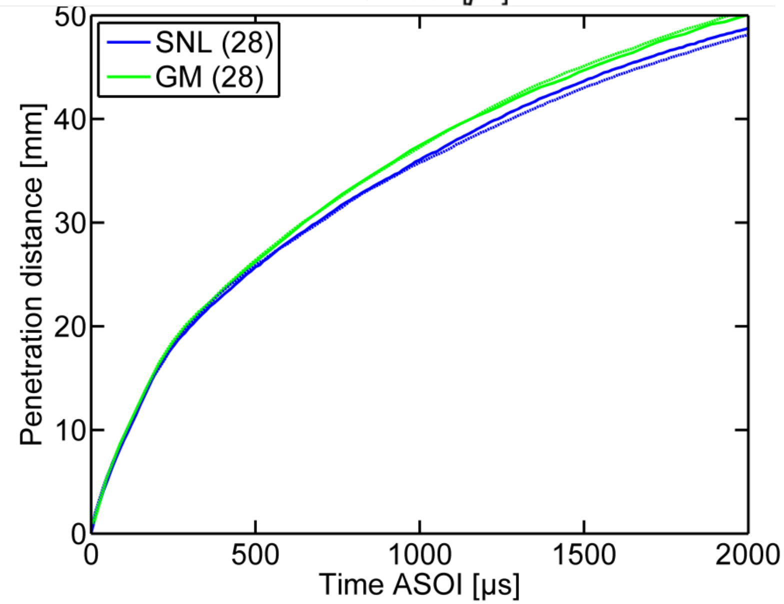
Spray orientation comparisons



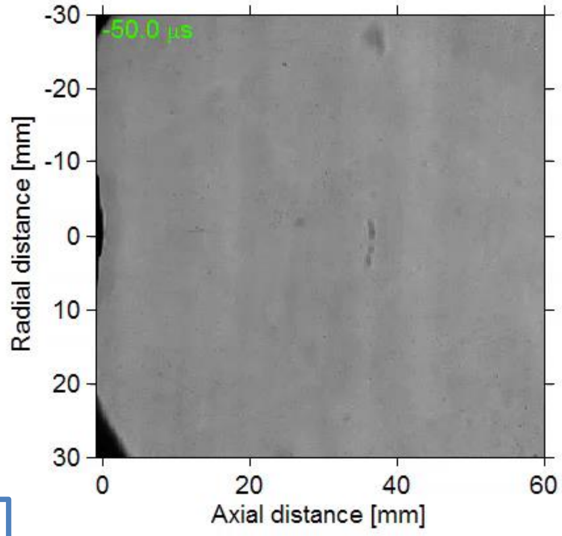


GM

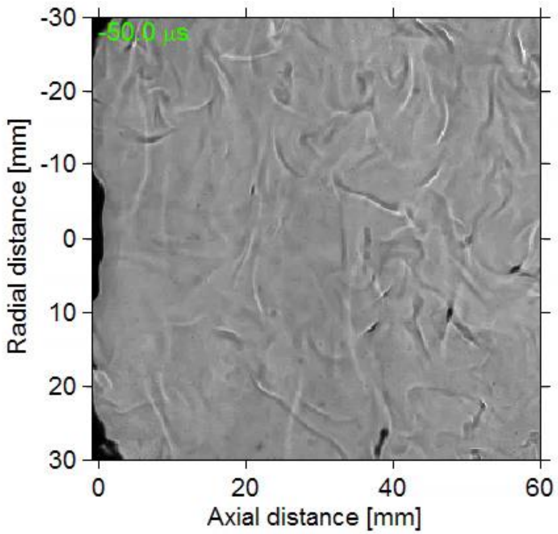




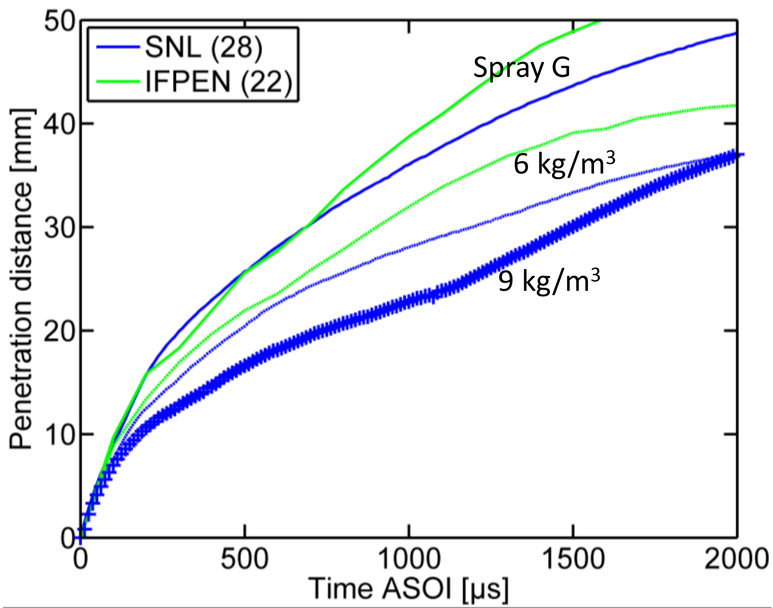
Ambient density impact on spray development



SNL



- As for the liquid portion of the spray, increasing ambient density has a strong impact on global spray development
- The jet is more compact and the collapse observed earlier for the liquid spray changes the momentum direction to be closer to the injector axis
  - Jet penetrates faster after the end of injection than lower density injections



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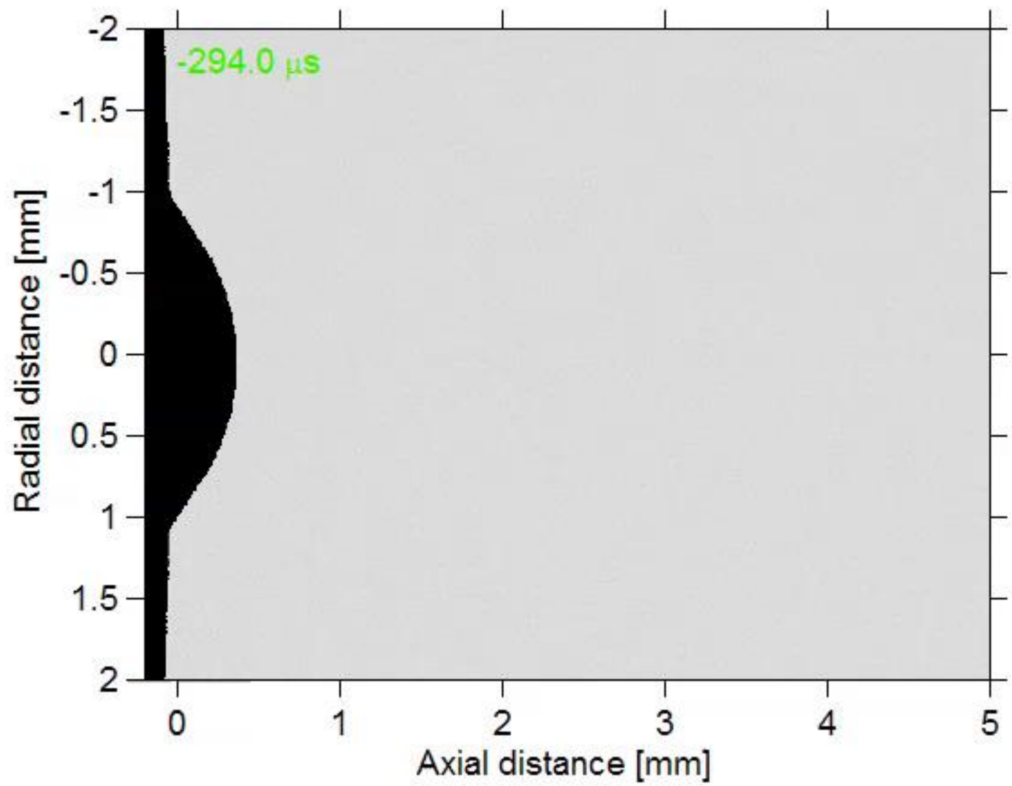
Near-nozzle microscopic imaging

- Near-nozzle microscopy reveals some interesting aspect of the injection
- It seems like one side of the nozzle holes is closing earlier than the other, probably explained by a needle effect (VCO nozzles)
- Droplets formed at the end of injection appear to move in a more axial direction than during the main event
- Relatively large droplets are seen at the end of injection, typical of such injector geometry (VCO)
- Based on our experience, this injector atomizes the spray better than previous generations



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Conclusions and what's next!

- The first Spray G experiments have been performed by five institutions (five injectors) spanning across three continents
- The results, even though preliminary, showed promising comparison performance between facilities for both liquid and vapor
  - Most of the differences should be attributed to processing methods more than to the sprays and/or boundary conditions, hopefully!
- It is important to note that the two injectors tested by GM showed very good agreement , providing the group with the necessary confidence to go further and share the injectors with other institutions

- Some additional processing would be required before the data can be made available through the ECN website once the processing methodologies have converged
- Most of the research laboratories contributing to this session have plans for further experimental activities after the meeting
- Some institutions already have a Spray G unit and are scheduling some experiments for the near future

ECN3: Spray G optical measurements

Thank you for your attention

Please remind and keep your questions and comments for the discussion session

Julien Manin

Thrid Workshop of the Engine Combustion Network,

Ann Arbor, Michigan, April 2014