ECN 4: New standard for high temporal DBI extinction imaging

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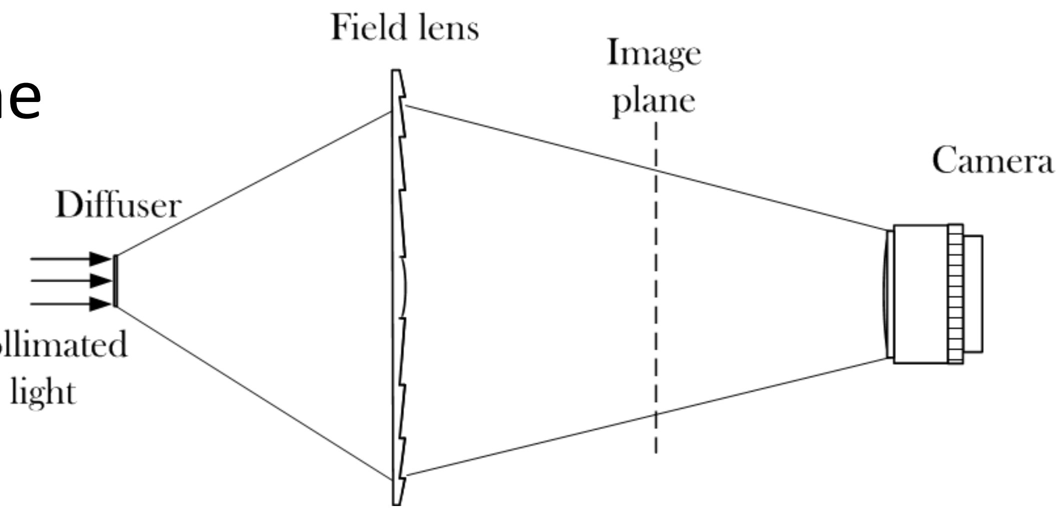
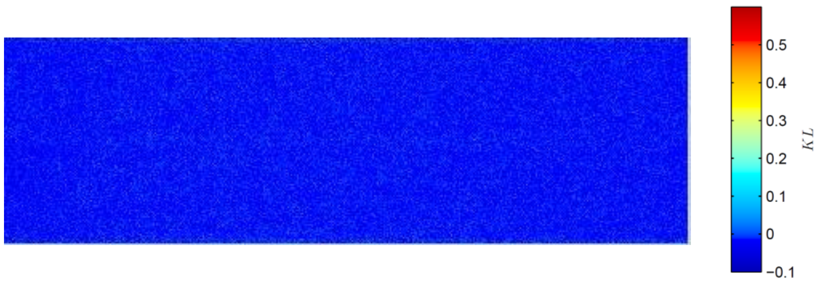
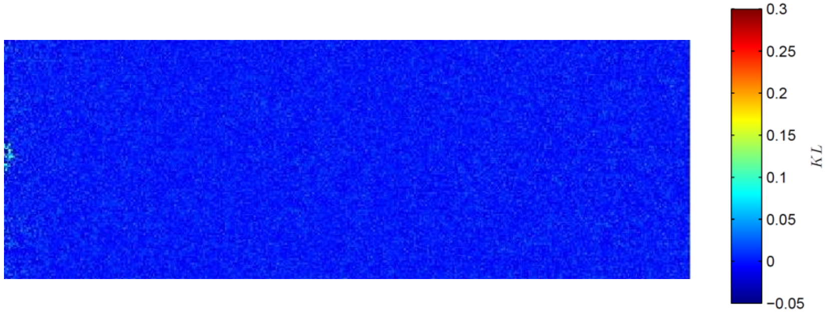
Abstract: An optical setup has been developed for diffused back-illumination imaging of liquid and soot extinction with high temporal capabilities. It has been specifically designed to isolate attenuation by absorption/scattering from light displacement by refractive gradients through a heated and pressurized environment. The design criteria have been determined from a conceptual description of beam-steering effect on quantification using simple ray tracing. These criteria are used to optimize for collection efficiency for high temporal capabilities. The improvements observed show that beam-steering effects on quantification is suppressed down to within the noise of the camera, thereby higher sensitivity and accuracy of soot extinction and liquid penetration measurements is achieved.

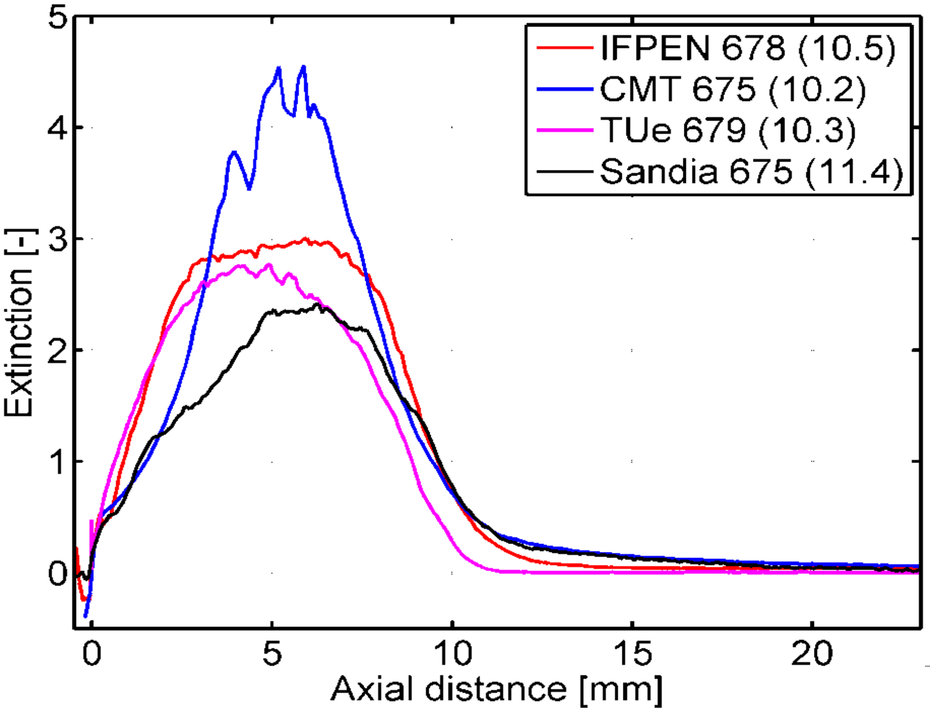
Previous DBI extinction imaging setup

- Quantitative soot volume fraction and qualitative liquid penetration measurements at high temporal resolution



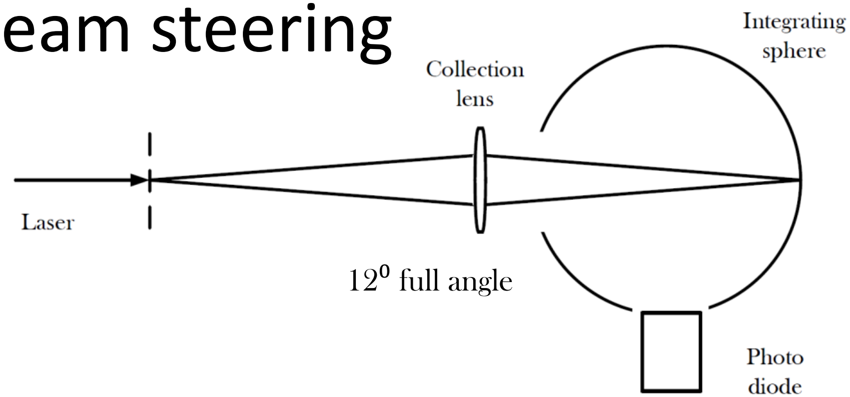




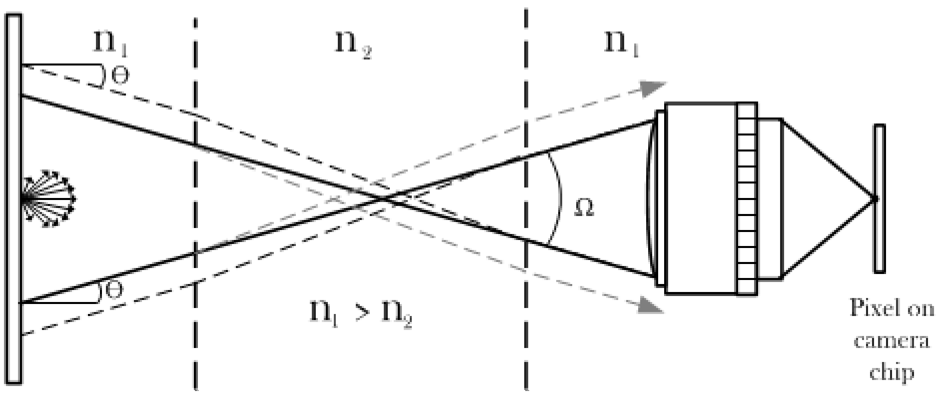


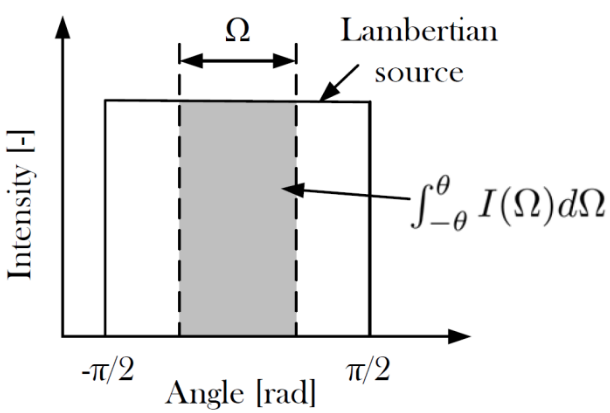
Eliminating beam-steering

- Laser extinction requires wide collection angle to account for beam steering



- Image extinction requires wide angular distribution of the light to suppress beam steering

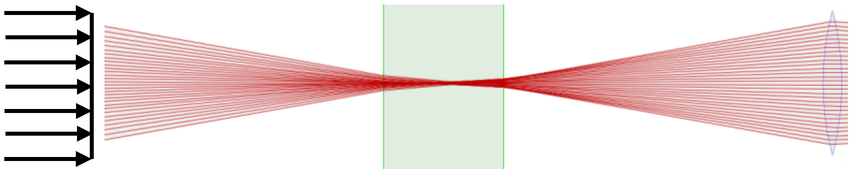




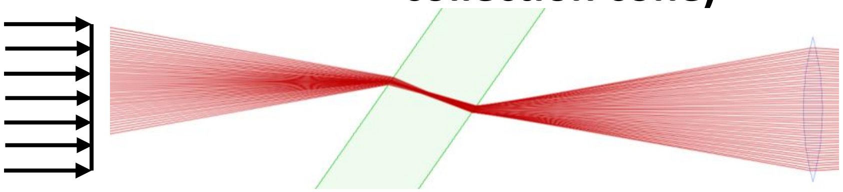
Eliminating beam-steering

Refracting media can have a mix of many interactions with the incident light

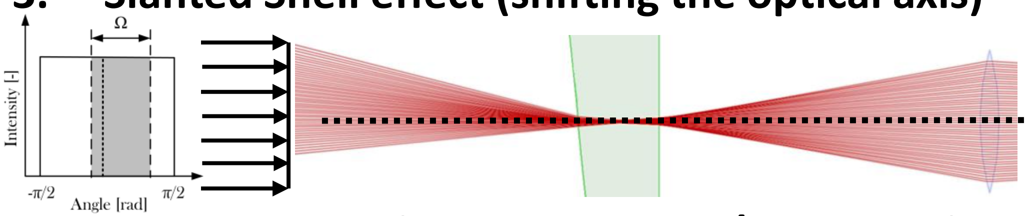
1. Snell effect (modifying effective focal length)



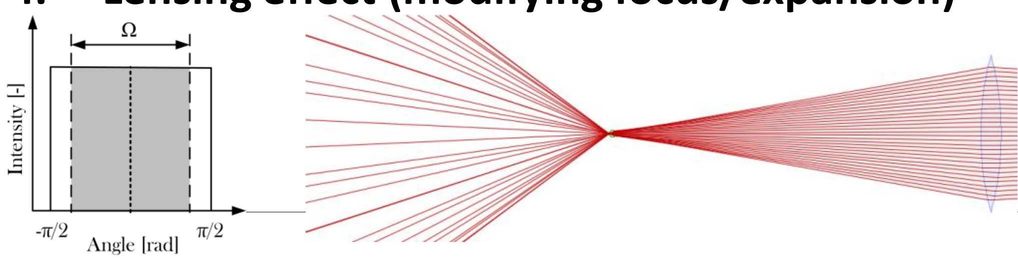
2. Oblique Snell effect (Translation of the collection cone)



3. Slanted Snell effect (shifting the optical axis)



4. Lensing effect (modifying focus/expansion)



How to make undesired refraction effects invisible:

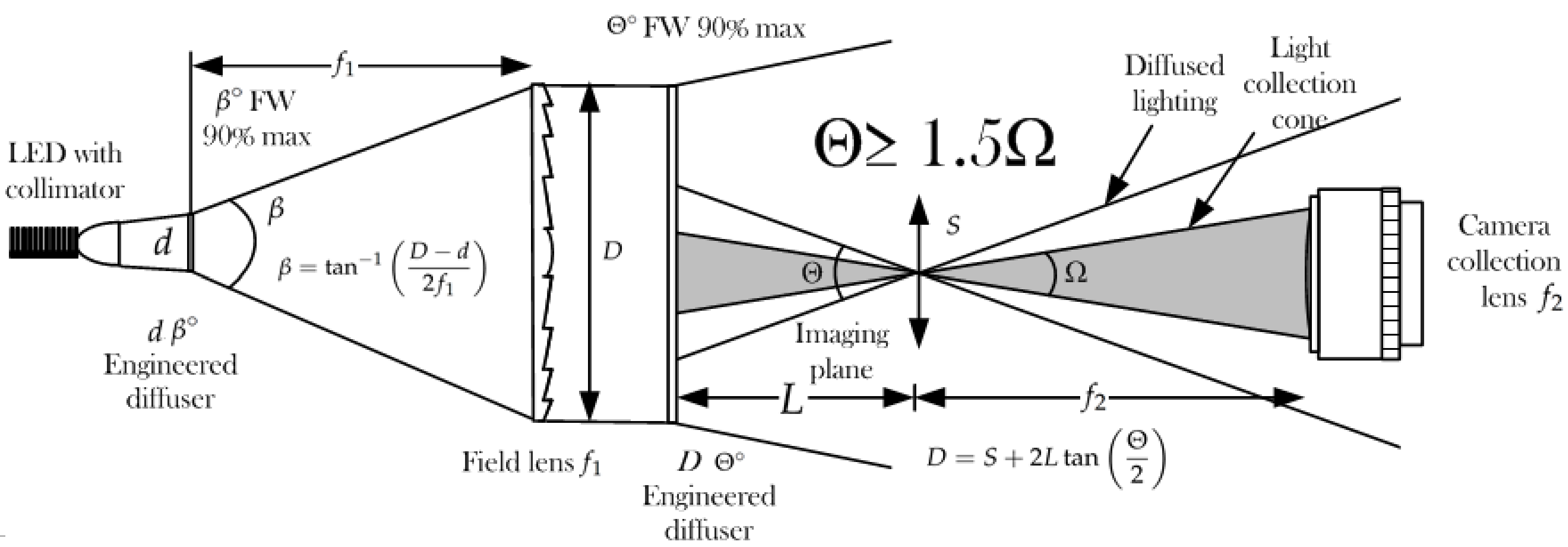
1. And 2. Spatial homogeneity of illumination across the source

3. Even angular distribution wider than the collection angle

4. Cannot be corrected with diffused lighting

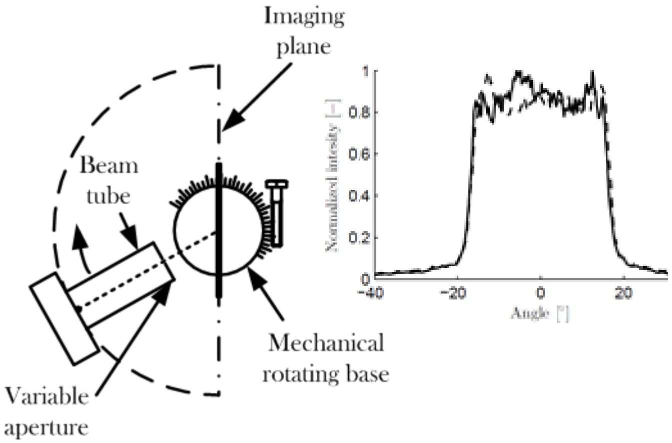
Dimensioning DBI setup

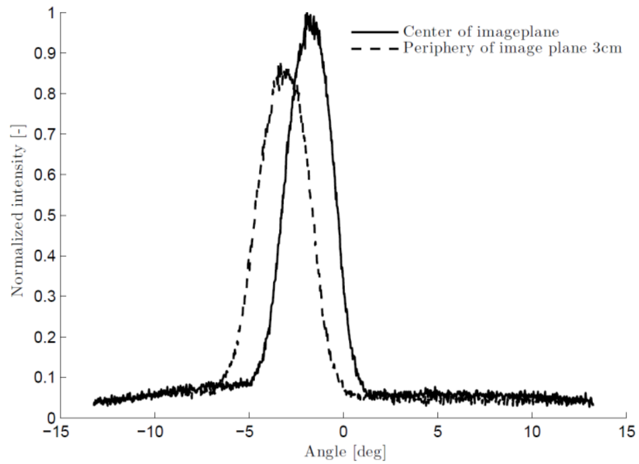
- Collection efficiency is important to promote high temporal resolution capabilities
- Spreading angle of large engineered diffuser should be 1.5 time the collection angle
- Large collimated beam needed for diffuser to work optimally

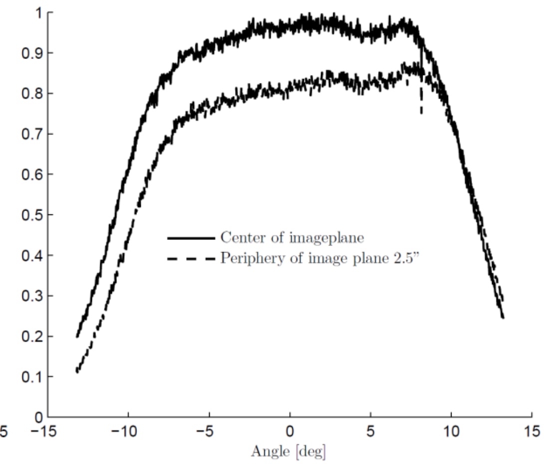


Measuring angular distribution

- 1D measurement

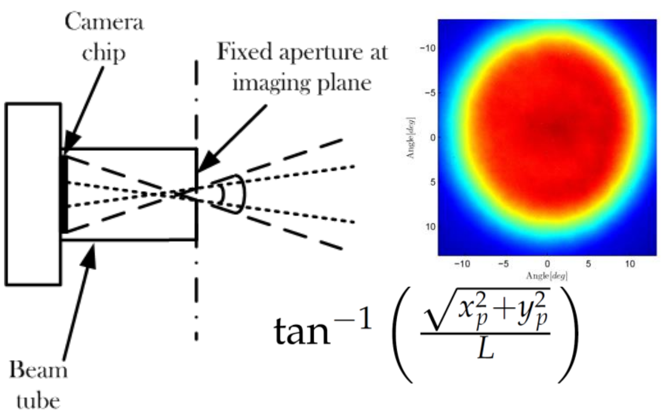




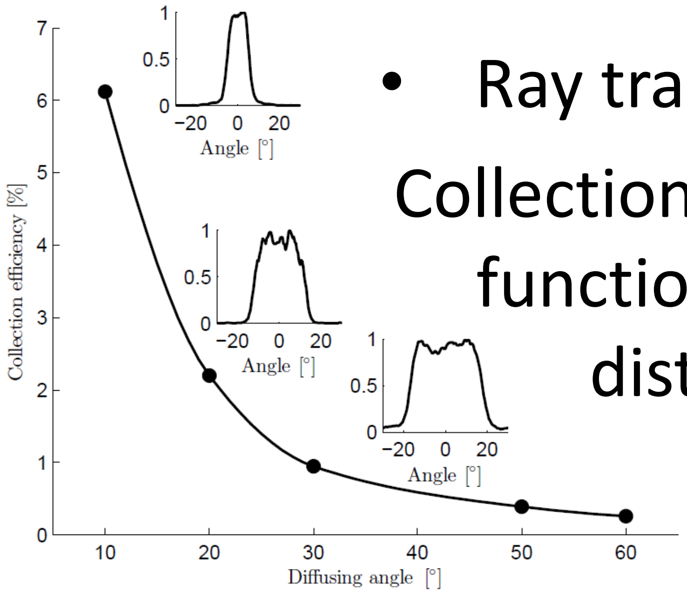


- Old setup
- New setup

- 2D measurement



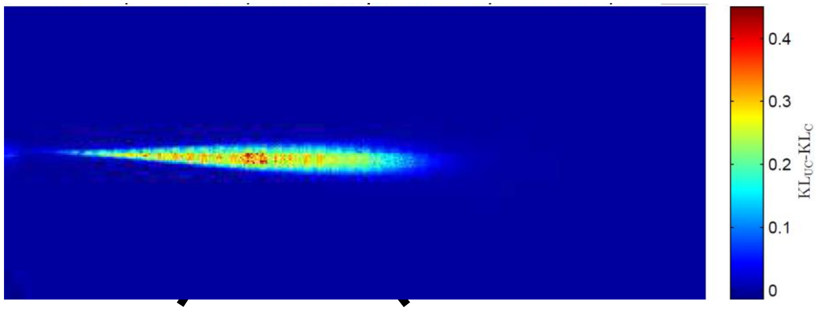
$$\tan^{-1}\left(\frac{\sqrt{x_p^2+y_p^2}}{L}\right)$$

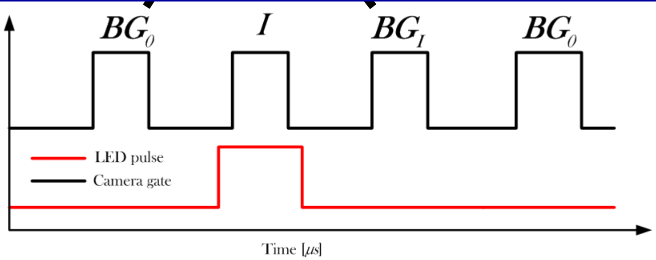


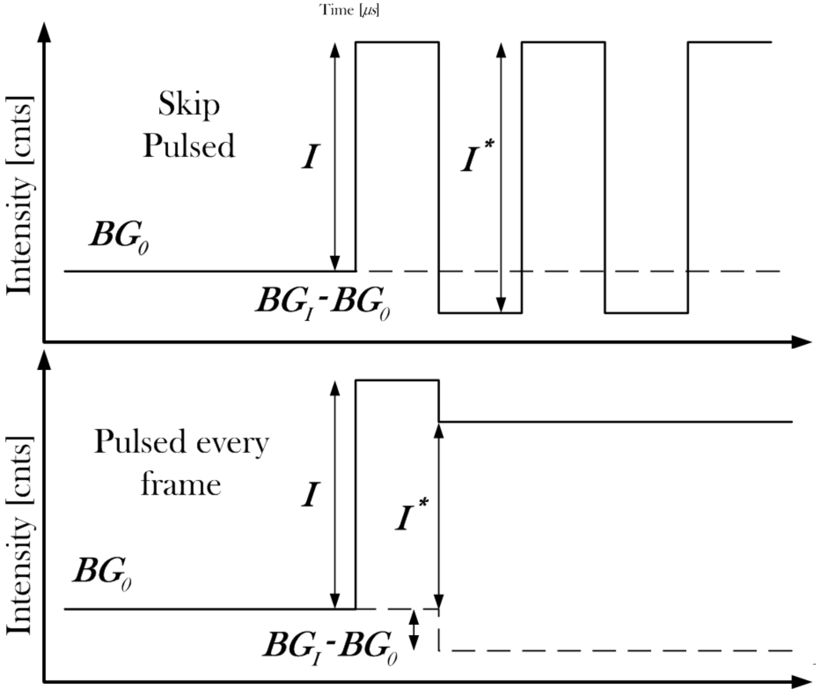
- Ray tracing

Collection efficiency as a function of angular distribution

Camera issues







- Fixed pattern noise is affected by the camera readout
- Noise level restored after one dark frame

KL↓ $-\ln\left(\frac{I^*}{I_0}\right) < -\ln\left(\frac{I}{I_0}\right)$

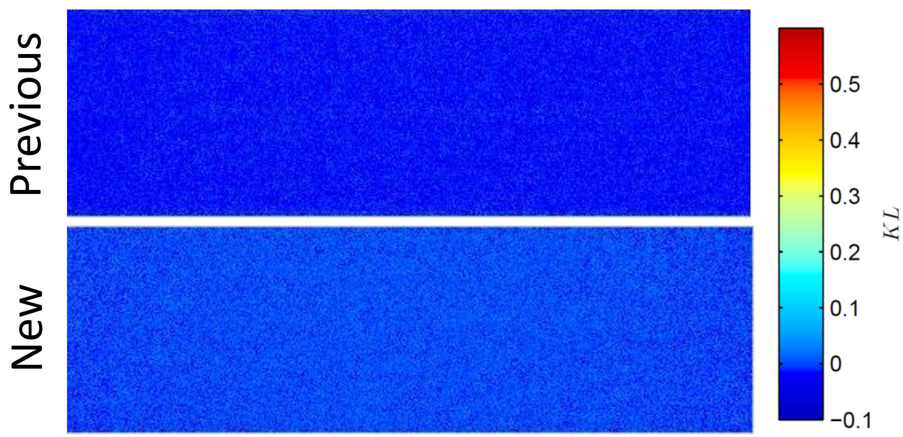
- Correction brings dark BG_I up to BG_0

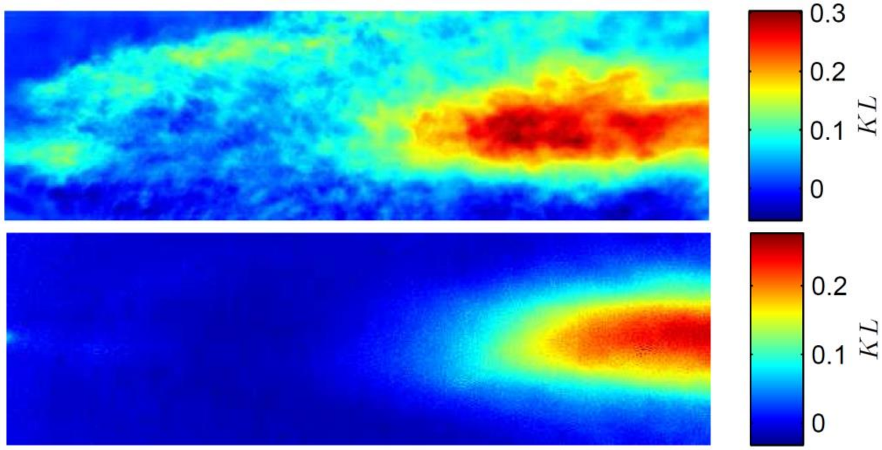
KL↑ $-\ln\left(\frac{I^*}{I_0}\right) > -\ln\left(\frac{I}{I_0}\right)$

- Correction brings BG_0 down to BG_I

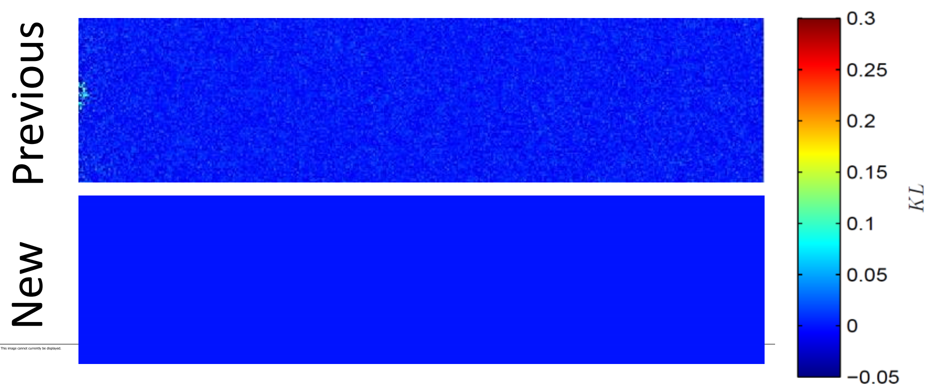
New DBI setup performance

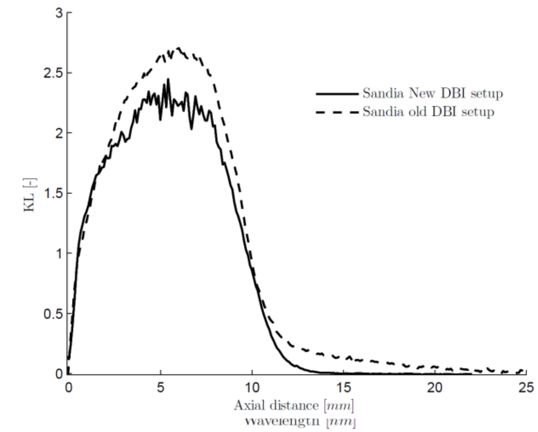
- Quantification is affected when beam-steering effects introduce erroneous extinction





- Beam-steering effects smear out the sharp contrasts of the dense liquid vapor boundary





Checklist

- Report optical arrangement with distances, components and sizes
- Measure lighting characteristics with either 1D or 2D arrangement

  Recommendations:

  1. Angular distribution should be chosen to be 1.5 times the collection angle and be homogenous across the image plane.
  2. Spatial intensity should not fall more than 20% from the center to the periphery of the image plane.
- Report camera corrections made in post-processing and camera software corrections used

Summary

- The need for a new standard DBI setup is realized
- The effect of beam-steering when spatially resolving extinction measurements is systematically identified
- From these effects, the lighting criteria for a new DBI setup are established
- A DBI setup dimensioned wrt ideal lighting and high temporal resolution capabilities, is proposed
- Issues with the high speed camera when performing high temporal extinction imaging are addressed
- The performance of the setup reveals significant improvement in suppressing beam-steering while maintaining high temporal capabilities
- Sensitivity of extinction imaging measurements is increased and errors associated with beam-steering are suppressed within the noise of the measurement

ECN 4: Spray C and D liquid and vapor penetration

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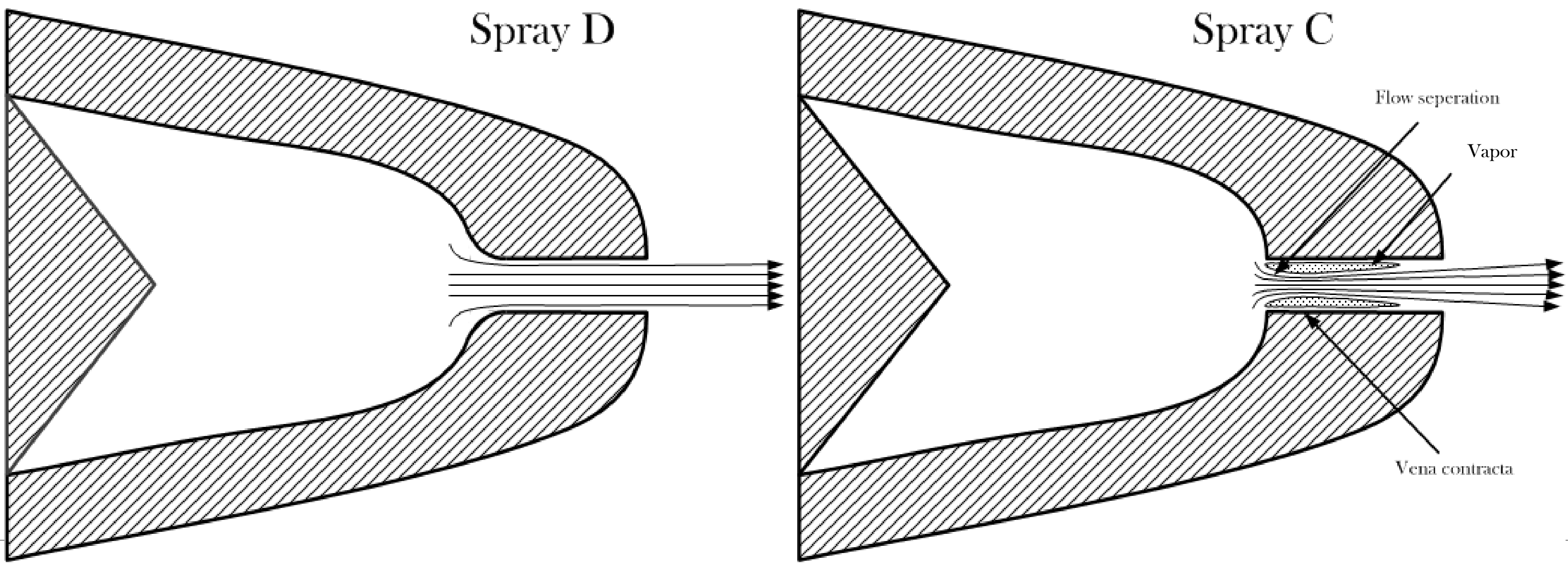
Abstract: Liquid and vapor penetration measurements are performed on a cavitating and non-cavitating automotive fuel injector (Spray C and D). The measurements are performed simultaneously using DBI and Mie scattering to image liquid phase and focused shadowgraph to image vapor phase in a dual line of sight accessible constant volume combustion vessel. The aim is visualize qualitatively the effect of cavitation on fuel spray characteristics. The experiments were performed under non-reacting and reacting Spray A std conditions. Results show that vapor phase penetrates faster and liquid phase longer for non-cavitating nozzle. The main reason being that the spray angle is wider for cavitating nozzle. There are some uncertainties as to what causes a wider spray angle and if it is cavitation related, as there are several other factors that may be responsible for this phenomena. CFD modelling can help answer questions about the origin of the wider spray angle.

Break-up of liquid sprays

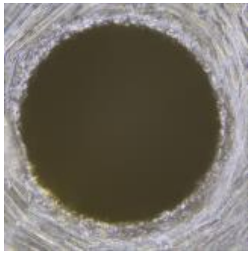
- Primary break-up: Stripping of ligaments and droplets from the in tact liquid core
- Secondary break-up: formation of spherical droplets.
- These break-up processes are confined close to the nozzle exit.
- Studies have shown that instabilities caused by cavitation within the nozzle, greatly promotes this break-up process.



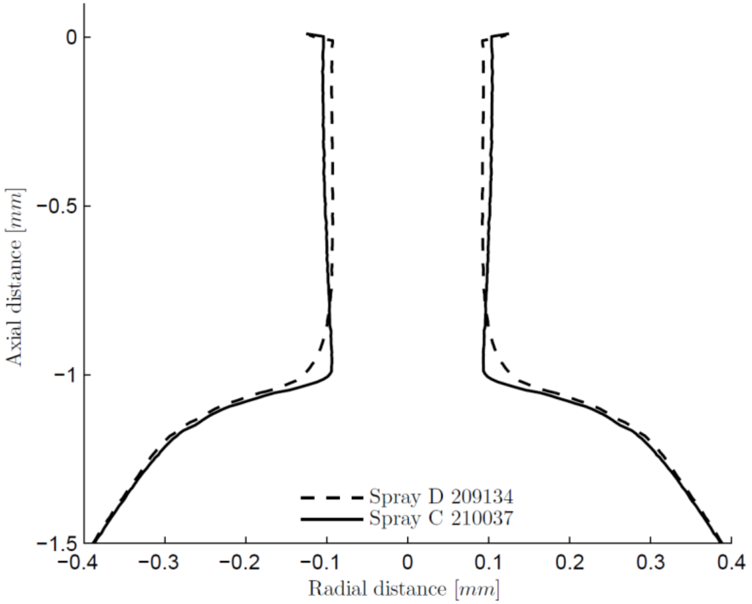
Spray C and D Nozzles

Spray C 210037

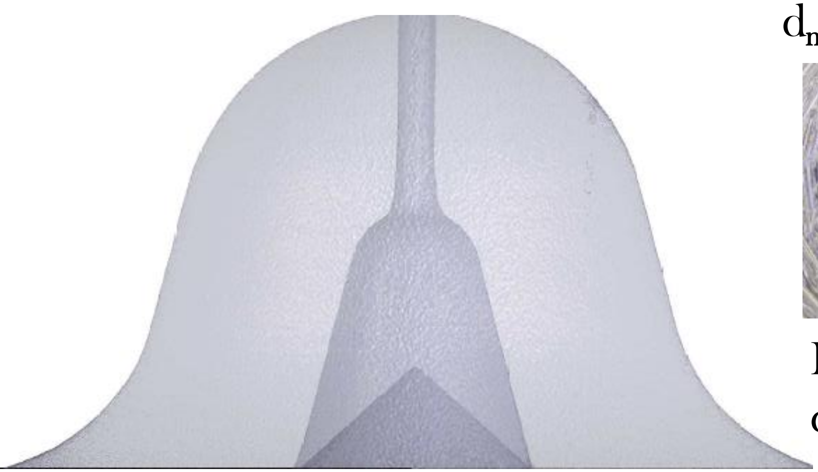
K-factor 0
d=0.2mm



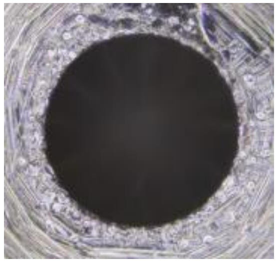
Mass 43.2mg/inj
Duration 2.5ms



Spray D 209134



Minimum diameter the same
d_{min}=0.186mm



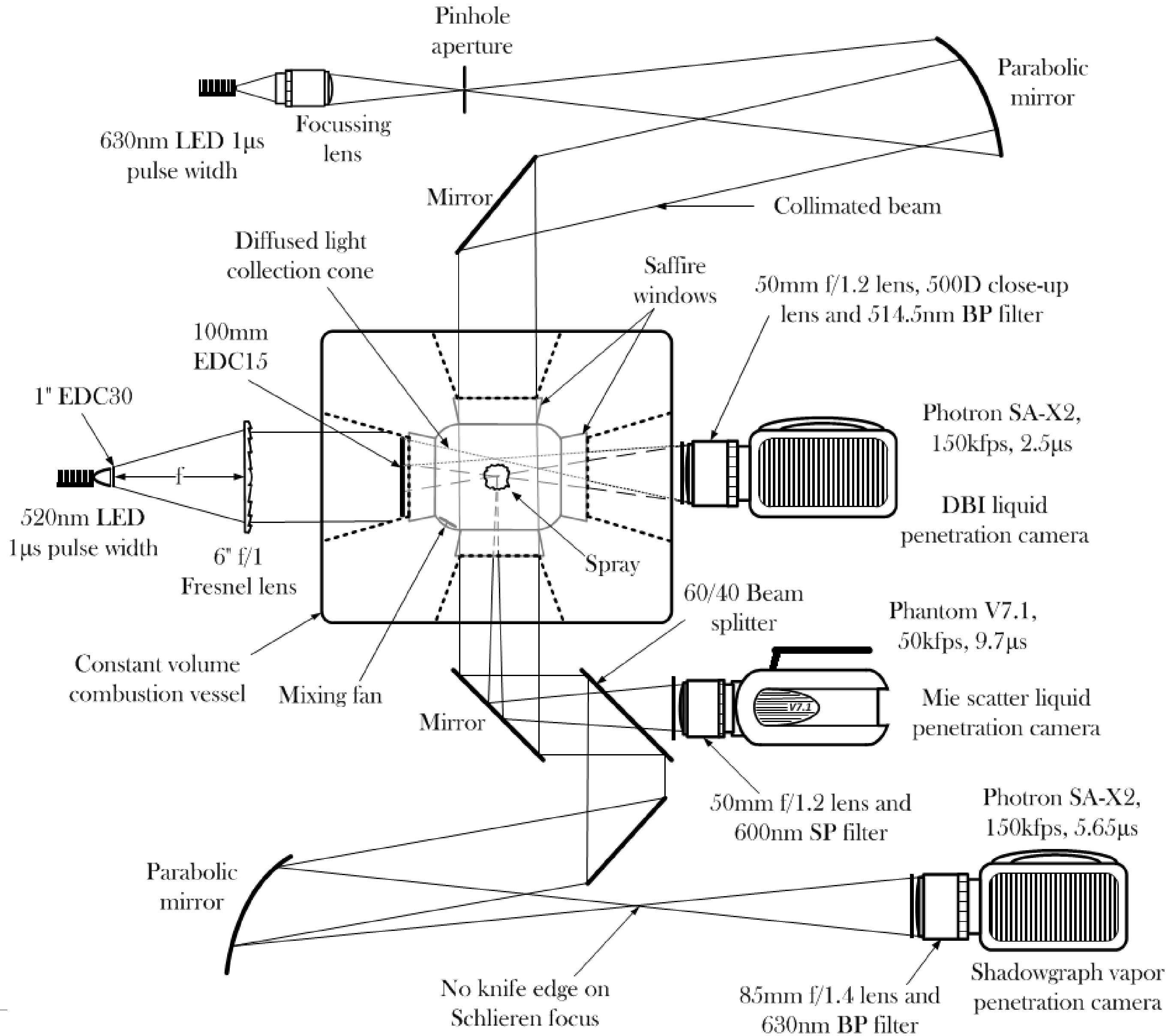
K-factor 1.5
d=0.18

Mass 50.75mg/inj
Duration 2.5ms

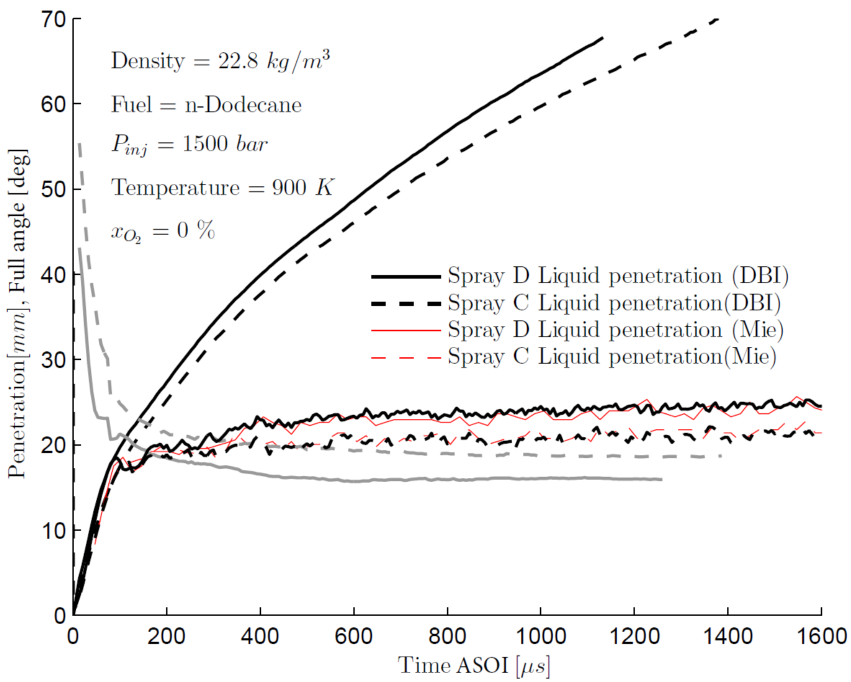
Experimental methods

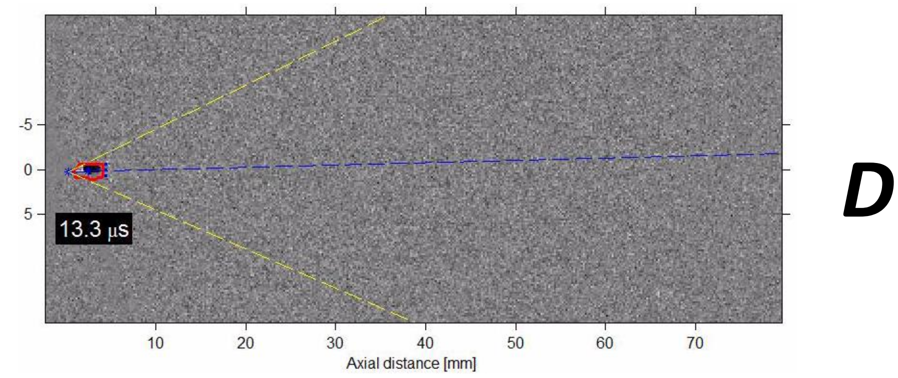
- High speed jet penetration measurements with focused shadowgraph technique
- High speed liquid penetration measurements with new standard DBI technique
- Liquid penetration measurements with Mie scatter technique at 90 degree solid angle
- All measurements were made simultaneously for every injection event
- Results are based on 10 injections with each nozzle at the standard reacting and non-reacting Spray A condition

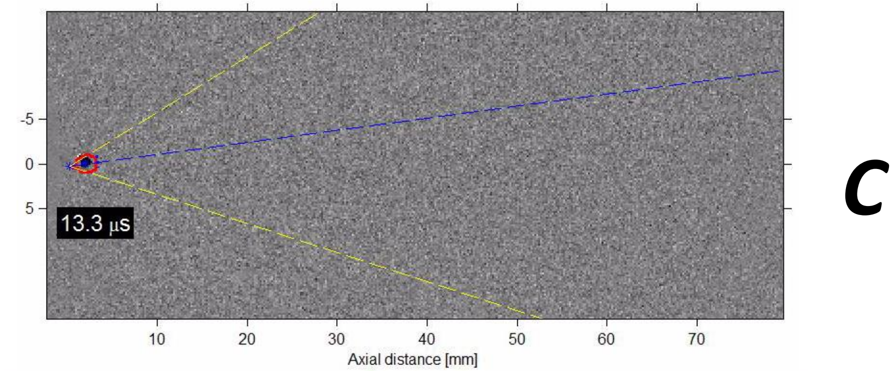
Experimental setup

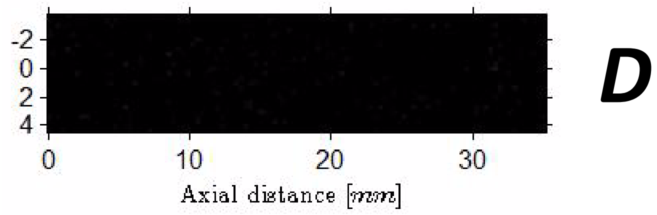


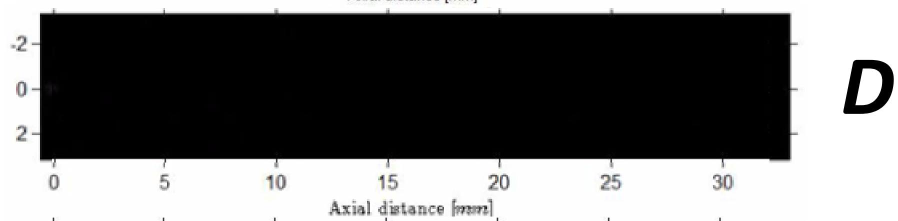
Results Non-reacting

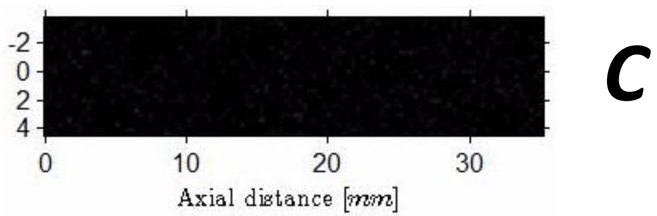


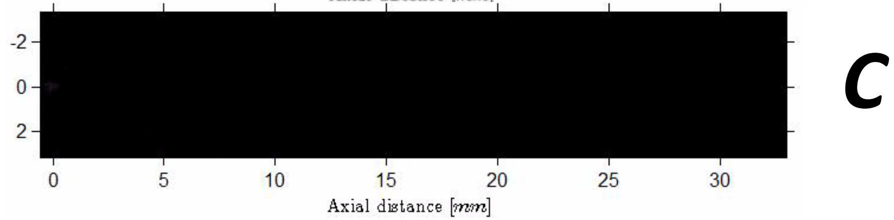




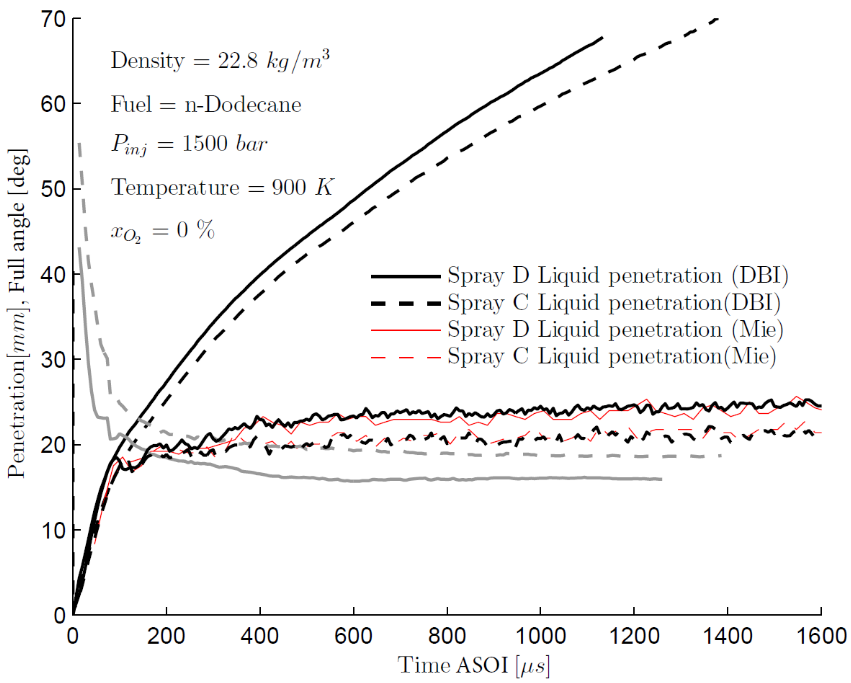


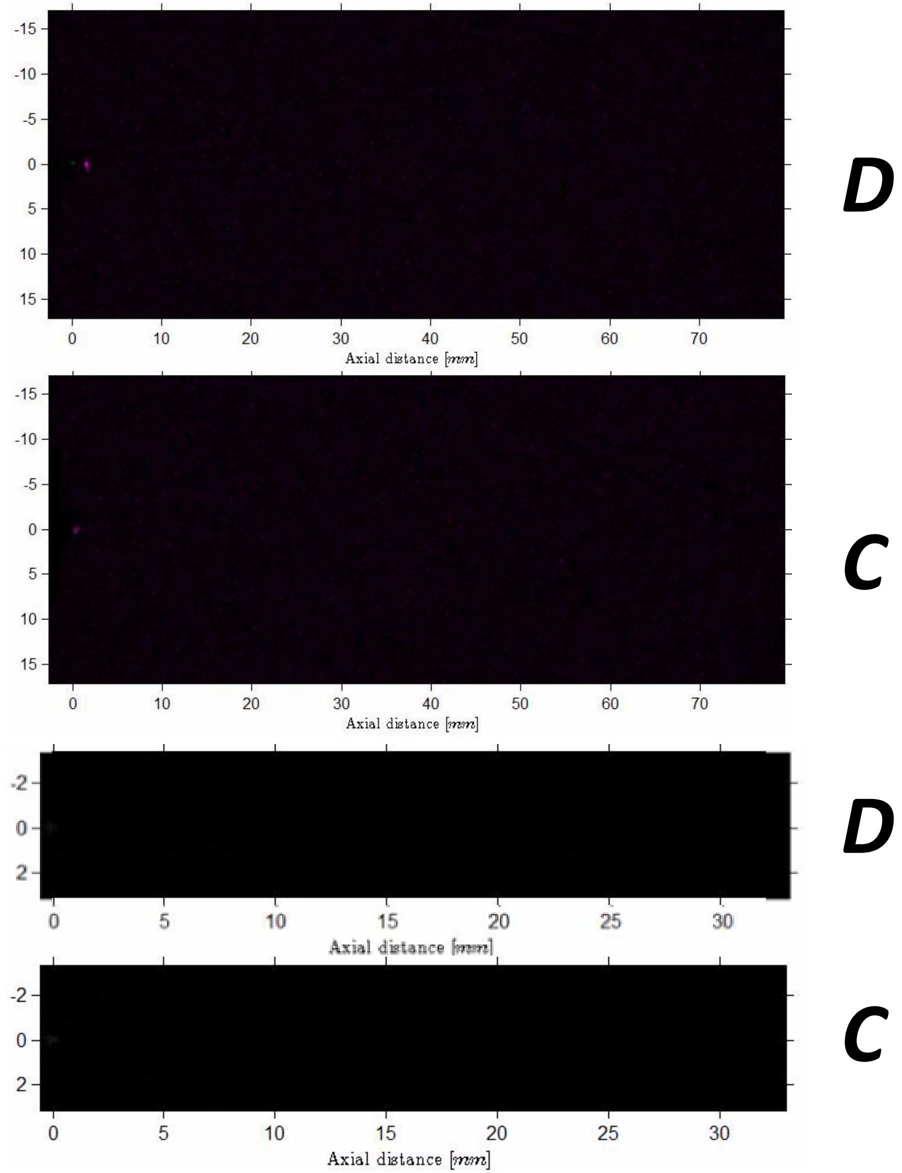


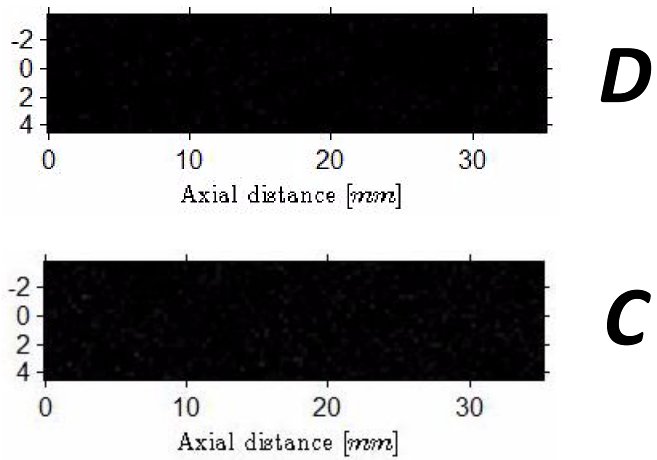




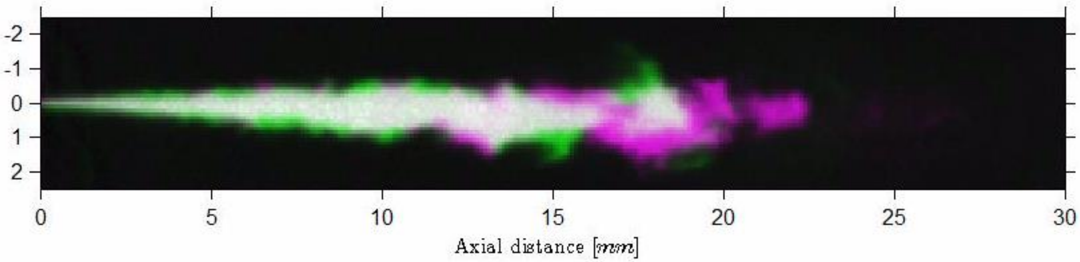
Results Non-reacting

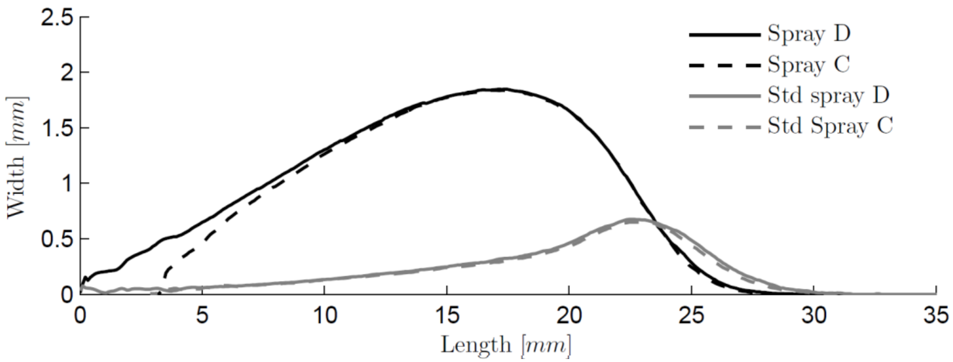






Width of liquid spray



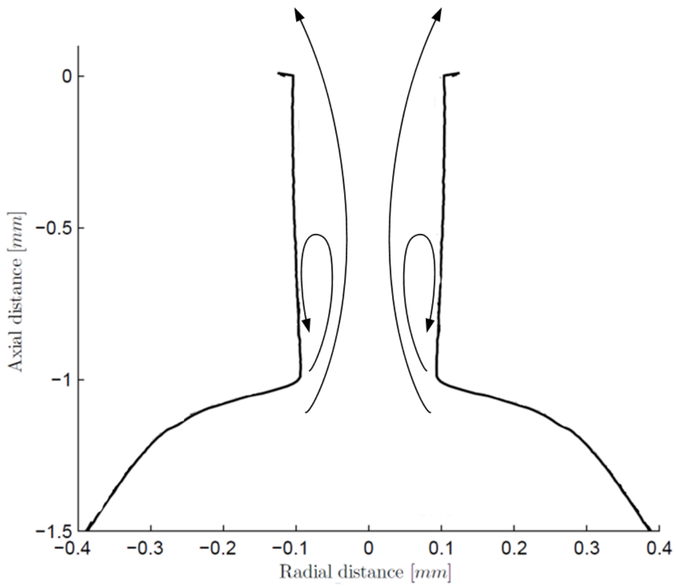


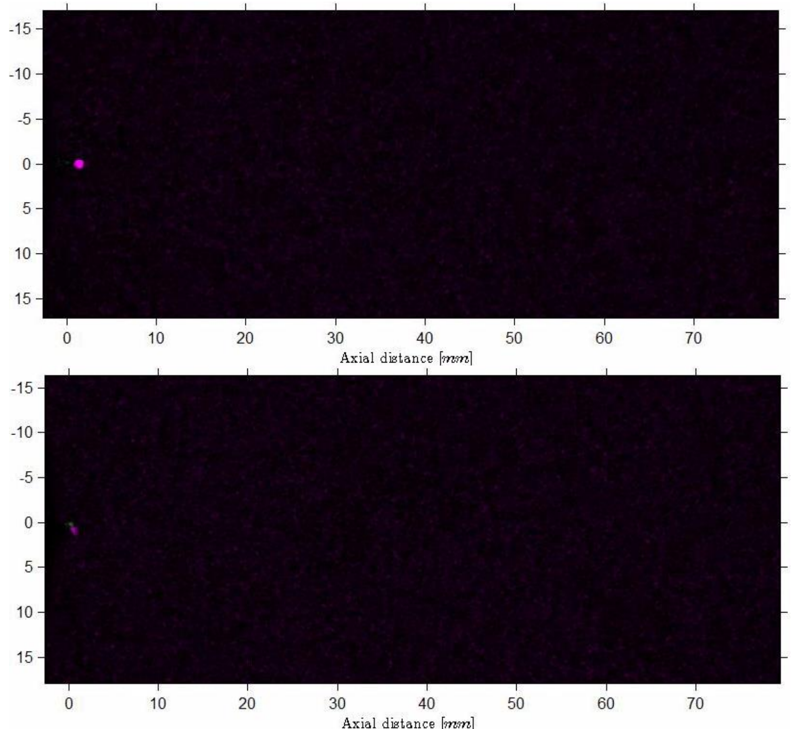
- Onset of boundary instability closer to the nozzle for Spray C
- Spray C looks to have a virtual origin further from the nozzle

- Liquid/vapor boundary is wider and more deformed closer to the nozzle for Spray C
- Oscillations of the boundary are stochastic and show no distinct frequency
- Width of spray correlates with magnitude of oscillations at the boundary

Effect of cavitation

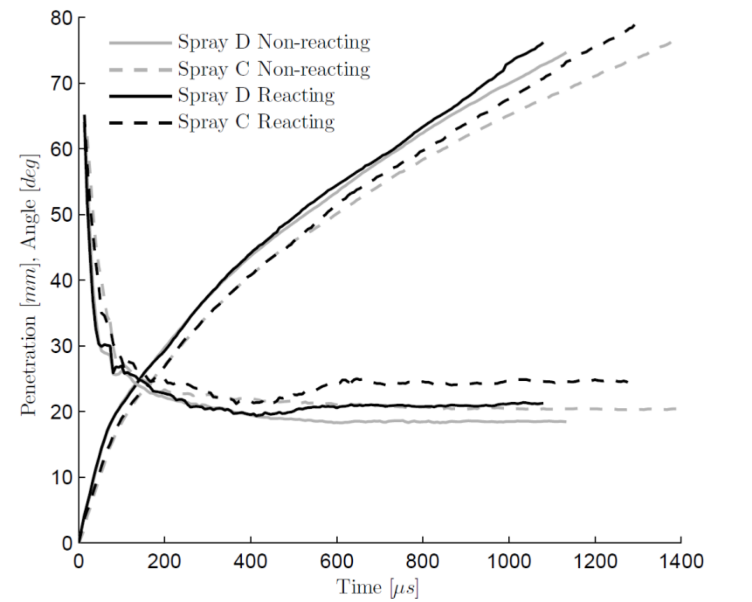
- Mixing based liquid length model accurately predicts the difference in liquid length
- Spray angle and contraction area source of difference in liquid penetration
- Is the difference cavitation related?
- Spray C geometry is slightly diverging
- Lower effective diameter also promotes divergent flow
- Difference may be due to mismatched mass flow
- CFD modelling of internal flow and liquid penetration can help answer these questions

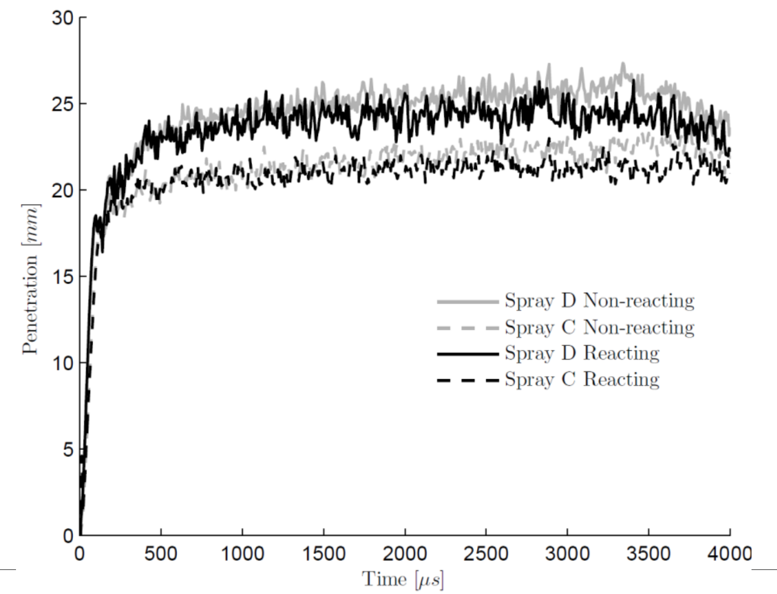




D

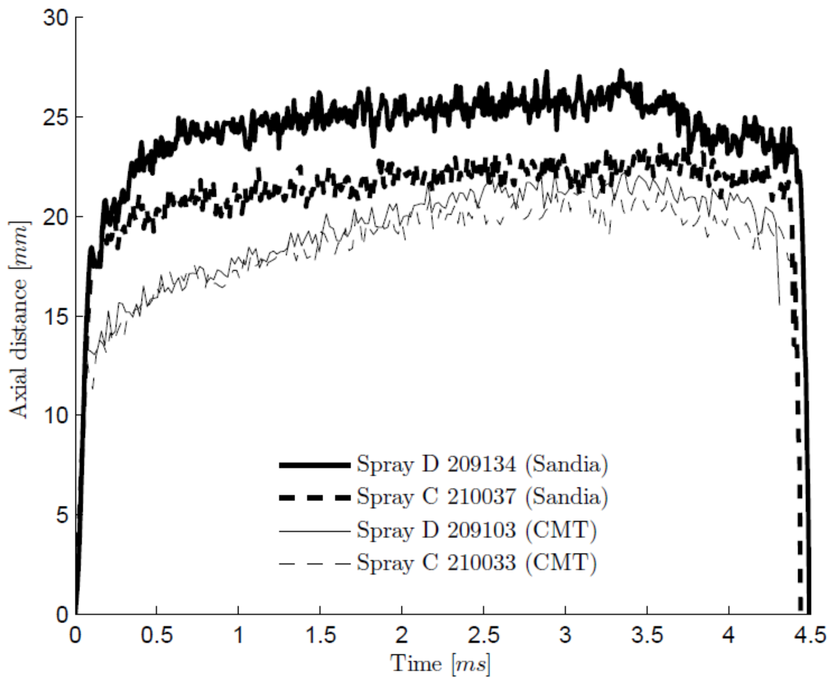
C

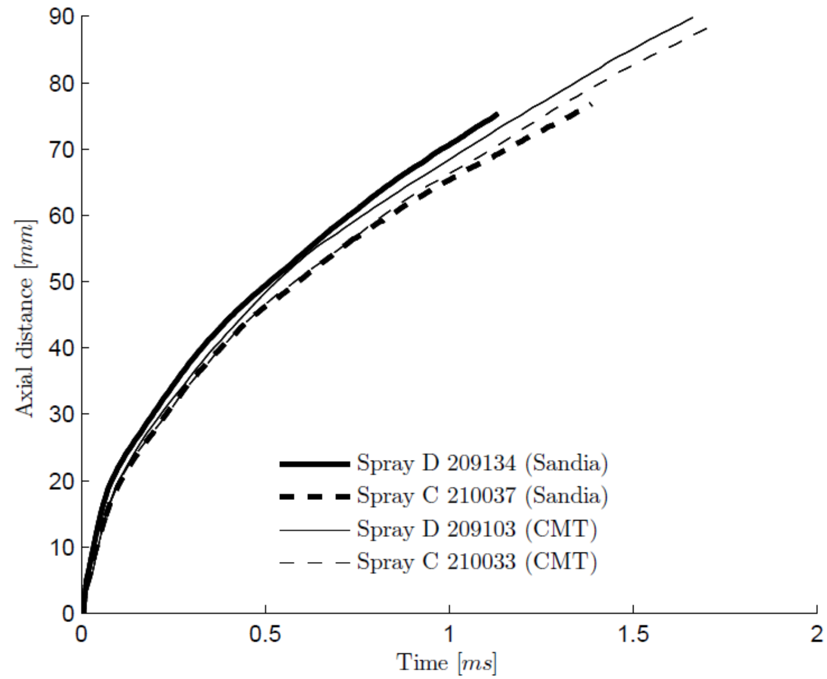




- Vapor penetrates at a slightly higher rate after ignition
- Spray angle becomes wider after ignition
- Liquid length has less tendency to increase over time

Sandia & CMT data



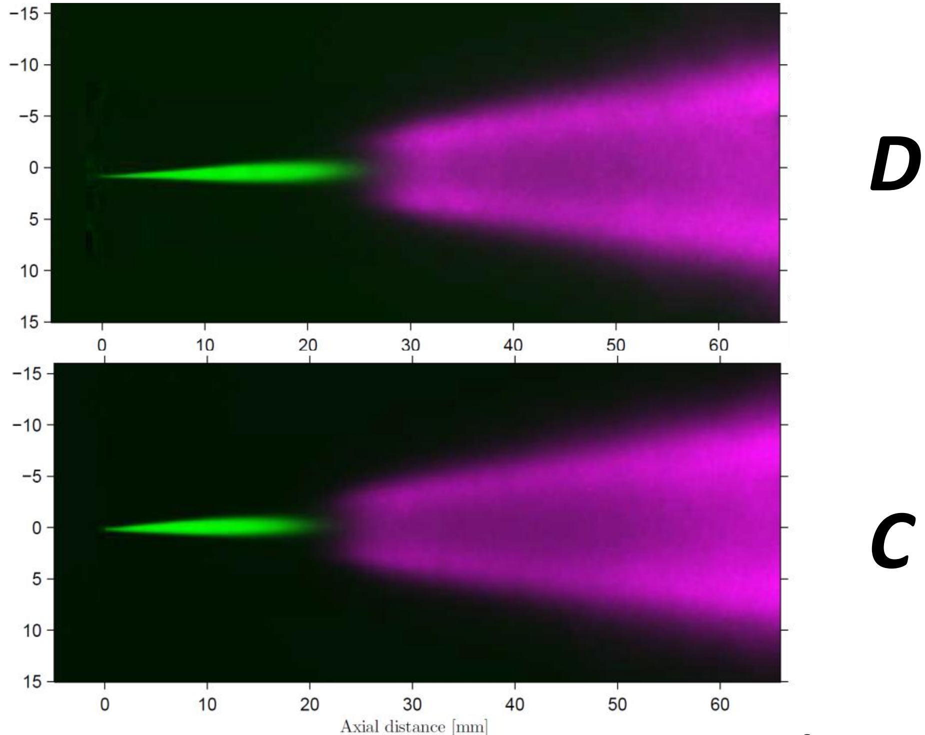


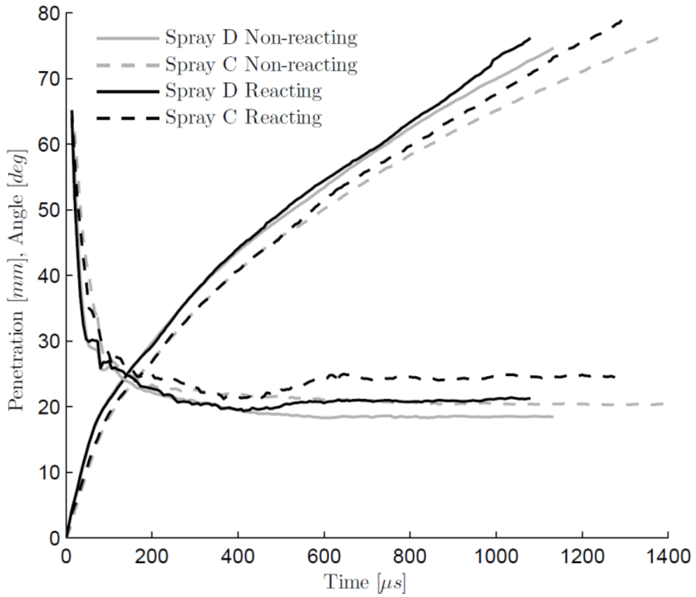
- Large deviation between liquid penetration for both C and D nozzles
- Liquid length increases more with time for CMT measurements
- Vapor penetration measurements are similar

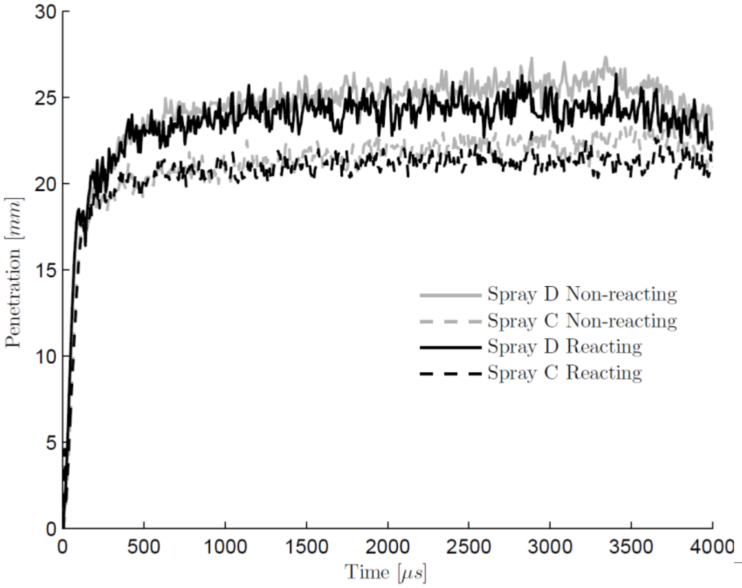
Summary

- Liquid and vapor penetration measurements have been performed simultaneously with Spray C and D.
- Good agreement between DBI and Mie liquid penetration measurements.
- Differences between Spray C and D are mostly caused by difference in spray angle, and it is uncertain as to why Spray C is wider.
- Reacting measurements show that thermal expansion slightly accelerates vapor penetration and liquid penetration does not increase over time due to hotter entrained gases
- More work needed in the comparison between institutions as large deviations seem to stem from differences in nozzles

Results reacting







- Vapor penetrates at a slightly higher rate after ignition
- Spray angle becomes wider after ignition
- Liquid length has less tendency to increase over time

Components and function

- High speed camera

Photron SA-X2

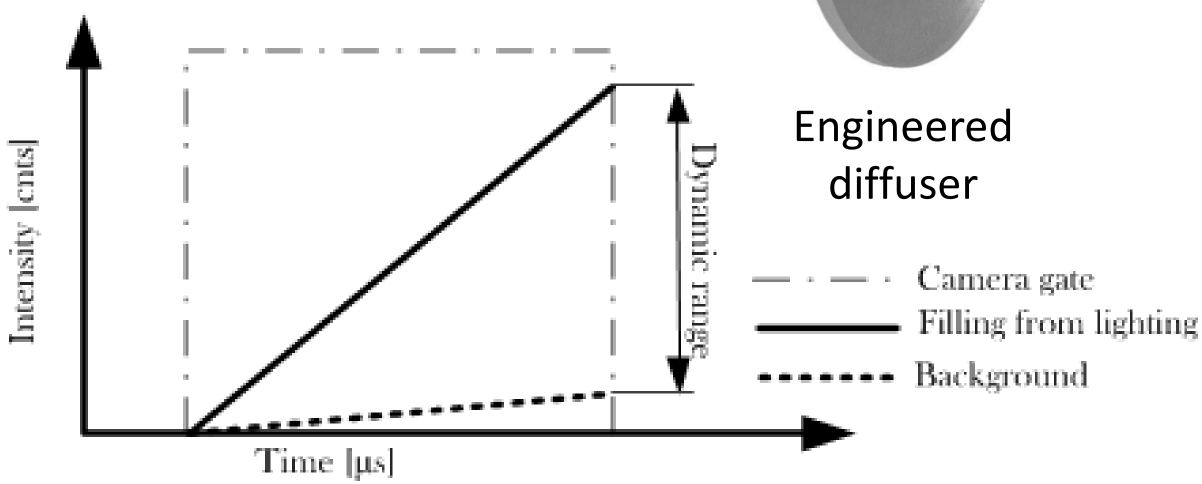
- State of the art LED driver technology

Sandia 614 LED driver

TIR LED collimator

- Optics promoting high collection efficiency

Engineered diffuser



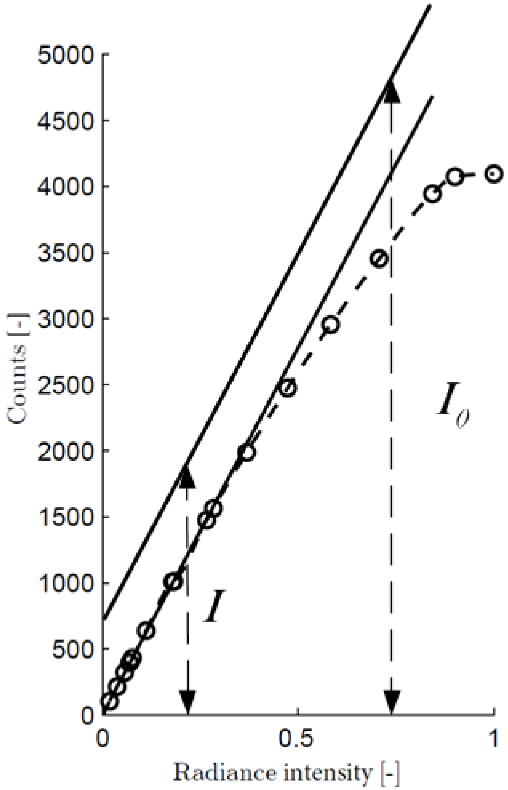
- Filtering

Band-pass filter

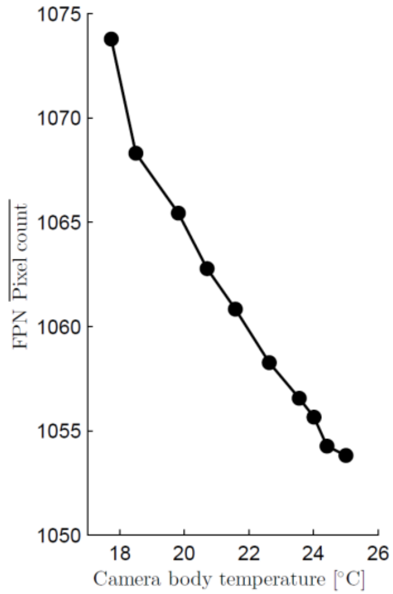
Neutral density filter

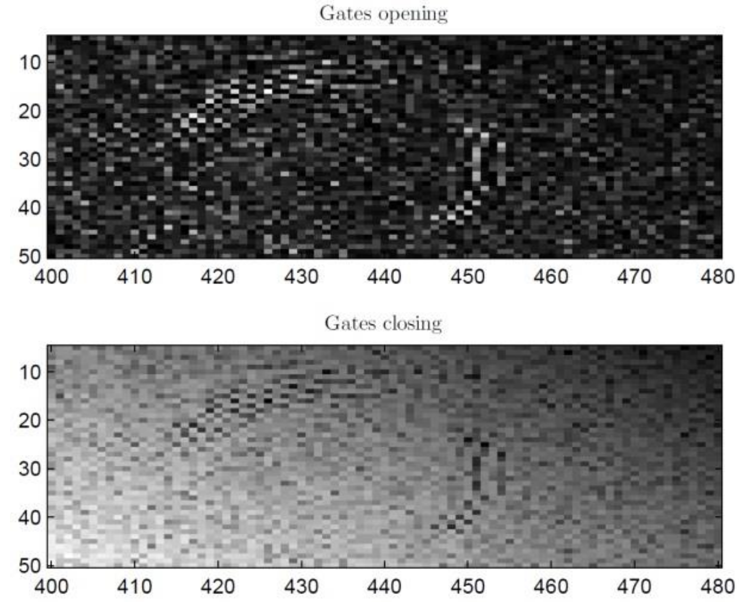
Camera characterization

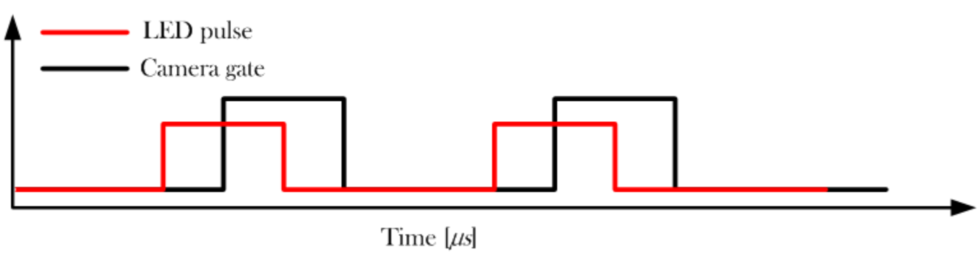
- High speed camera sensors are sensitive to ambient conditions and operation characteristics



$$KL = -\ln\left(\frac{I}{I_0}\right)$$







- Pixel response curve needs to be corrected for

Dimensioning DBI setup

- Collection efficiency is important to promote high temporal resolution capabilities
- Diffusing angle should be chosen so as to not overfill the Fresnel lens
- Spreading angle of final diffuser should be as narrow as possible