State-of-the-art measurements of primary atomisation and spray characteristics

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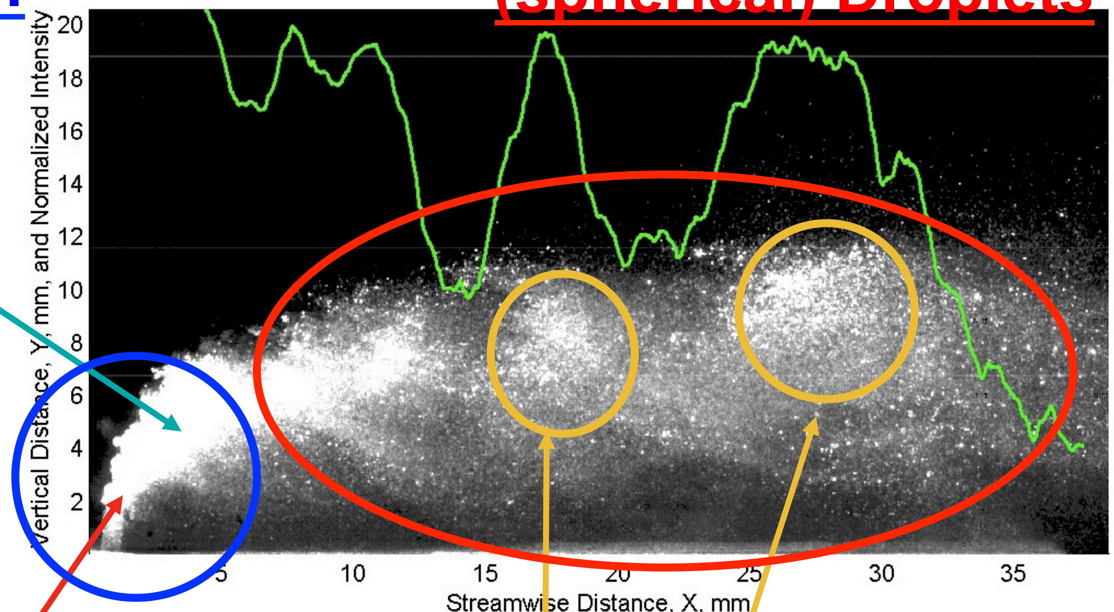
Example: Spray formation from liquid Jet in cross-flow of air

Near Nozzle region (non-spherical droplets)

Ligament break-up & dense spray region

- What is the ligament size and velocity?
- Are droplet collisions common?
- How does liquid evaporation evolve?

Spray region with Stable (spherical) Droplets



Liquid Jet Intact Length

- Where does it end?
- Does it matter?

- What is the spatial and temporal droplet size, velocity and concentration distributions?
- Why are *droplet clusters* formed?
- Are droplet clusters important for droplet evaporation and droplet collisions?

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Photo from: "Liquid jet in Cross Flow of air"
S.M. Thawley 2006, MSc thesis, Virginia State University

Outline

- ✓ Near Nozzle spray characterisation (i.e. ligaments, non-spherical droplets)
  - Optical Connectivity Technique
  - Ballistic Imaging
  - X-Ray Imaging

- ✓ Characterisation of Sprays in the stable droplet region (i.e. spherical droplets)
  - LIF/Mie Intensity Ratio for planar characterisation of droplet SMD and droplet cluster velocity (not individual droplets)
  - SLIPI: a method for correcting LIF/Mie intensity ratio for multiple scattering effects in dense sprays
  - Interferometric Laser Imaging Droplet Sizing (ILIDS) for planar measurements of individual droplet size, velocity and concentration

- ✓ Liquid Film Thickness on surfaces

Near Nozzle spray characterisation

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Optical Connectivity for liquid breakup and liquid interface instabilities

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Optical Connectivity technique for 'studies' of liquid jet breakup

- Idea from illumination of water fountains
- Note that source of the illumination is immersed within the source of the liquid jet

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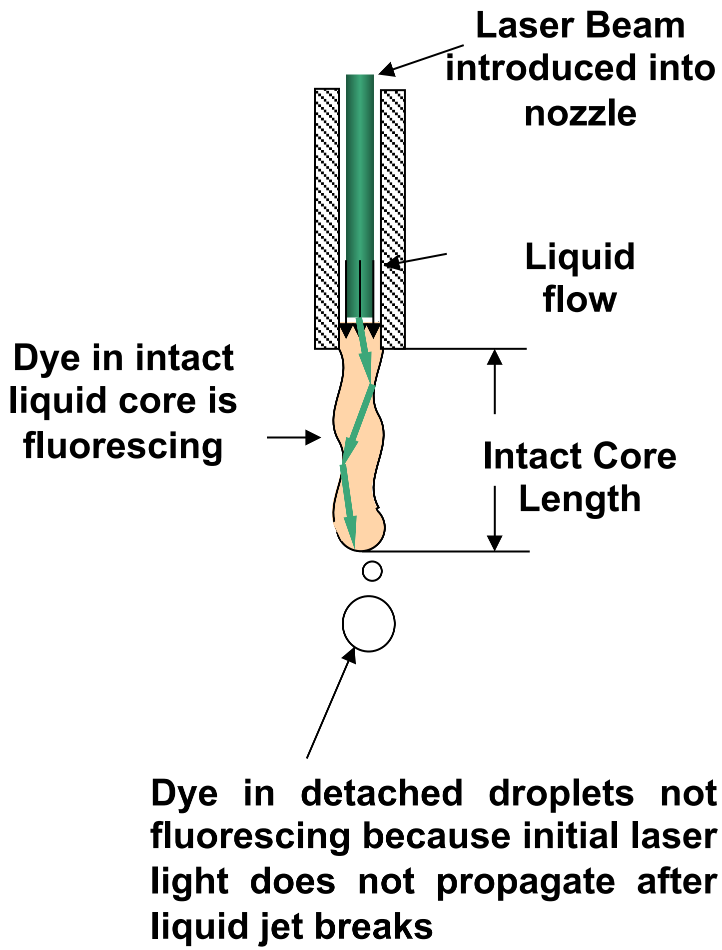
Optical Connectivity of Liquid jet

- Introduction of the laser beam through liquid injection nozzle
- Propagation of laser beam along intact liquid jet core, which acts as an optical fiber
- Break-up of liquid jet interrupts light propagation, so light intensity change identifies the intact core length
- Addition of fluorescing dye in the atomizing liquid, so that all the liquid volume is observed
- Addition of optical filter to collect fluorescent intensity eliminates scattered light from droplets

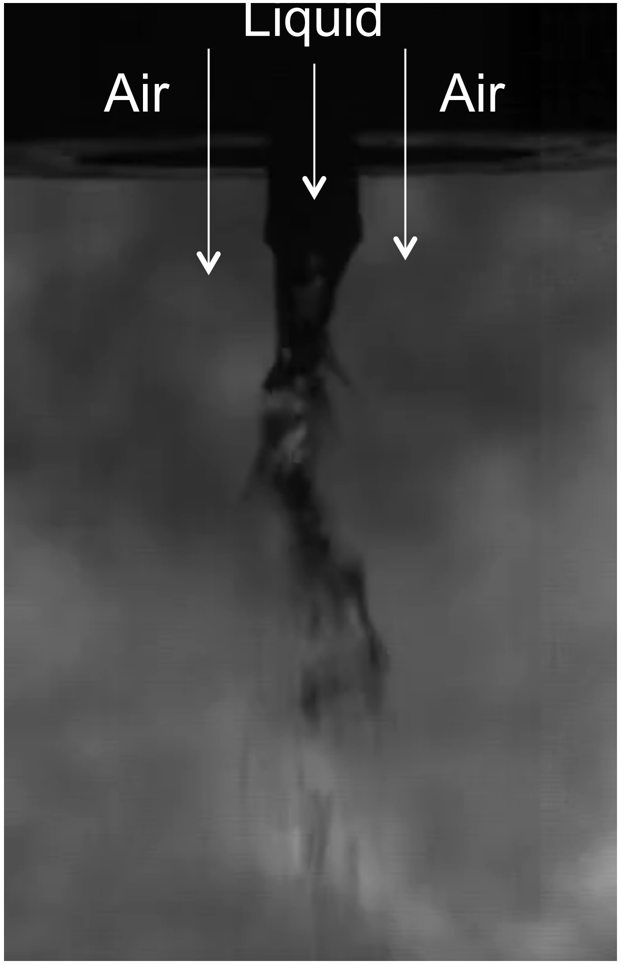


- Charalampous G., Hardalupas Y. and Taylor A.M.K.P. "A novel technique for measurements of the intact liquid jet core in a coaxial air-blast atomizer". AIAA J. 47, Number 11, (2009), 2605-2615.
- Charalampous G., Hardalupas Y. and Taylor A.M.K.P. "3-Dimensional structure of the intact liquid jet core during coaxial air-blast atomisation". Intern. Journal of Spray and Combustion Dynamics (IJSCD) 1, (2009), 389-415.

High speed visualisation of primary liquid breakup in coaxial airblast atomiser

Optical Connectivity

Shadowgraphy



- Charalampous G. and Hardalupas Y. "Application of Proper Orthogonal Decomposition to the morphological analysis of confined co-axial jets of immiscible liquids with comparable densities". Physics of Fluids 26, (2014), 113301.

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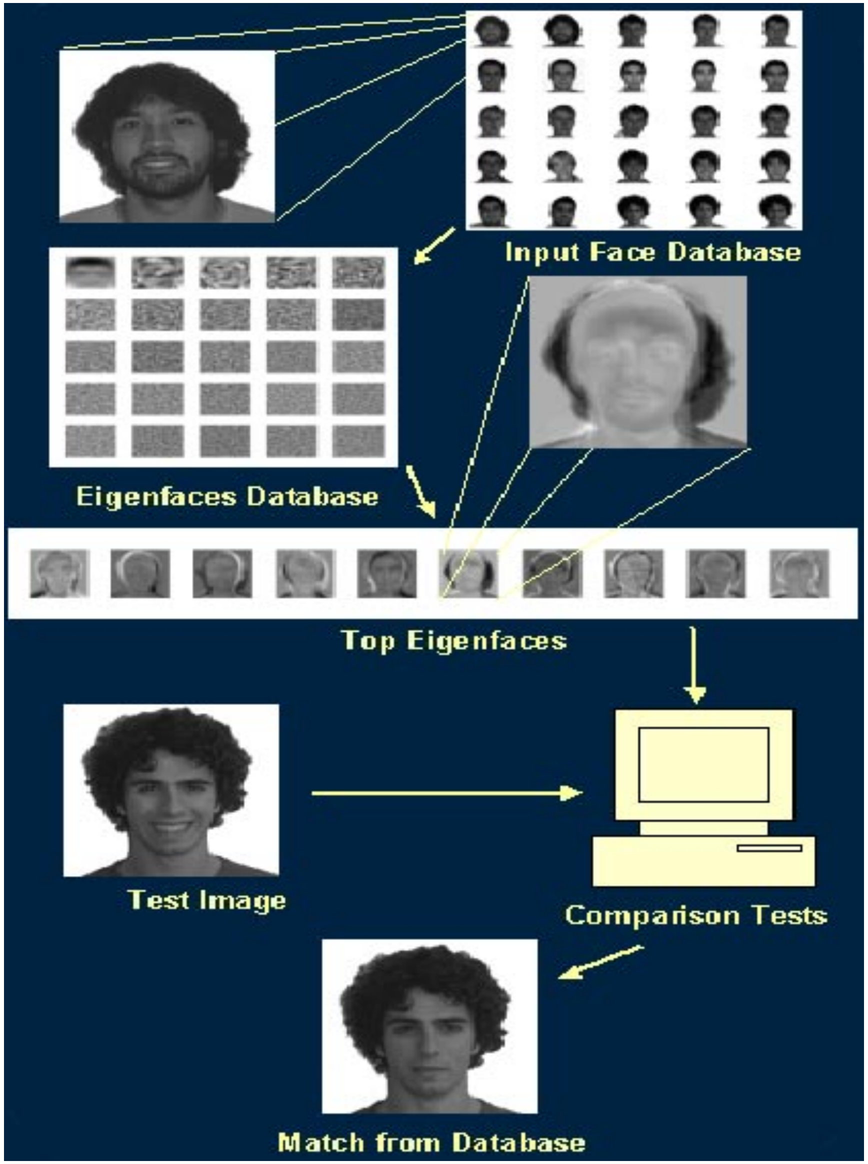
- Charalampous G., Hardalupas Y. "How do liquid fuel physical properties affect liquid jet development in atomisers?". Physics of Fluids 28, (2016), 102106.

Proper Orthogonal Decomposition (POD): Example for Face Recognition

- ✓ Recording of main features of the face. POD analysis provides information on contributions of large scales (e.g. head dimension, distance between eyes) to smaller scales (e.g. wrinkles) on the overall image
- ✓ Recording of a few larger scales (POD Eigen-modes) is enough to recognise the face of a person
- ✓ Can yield correct matches whether the person is feeling happy or sad !!!!

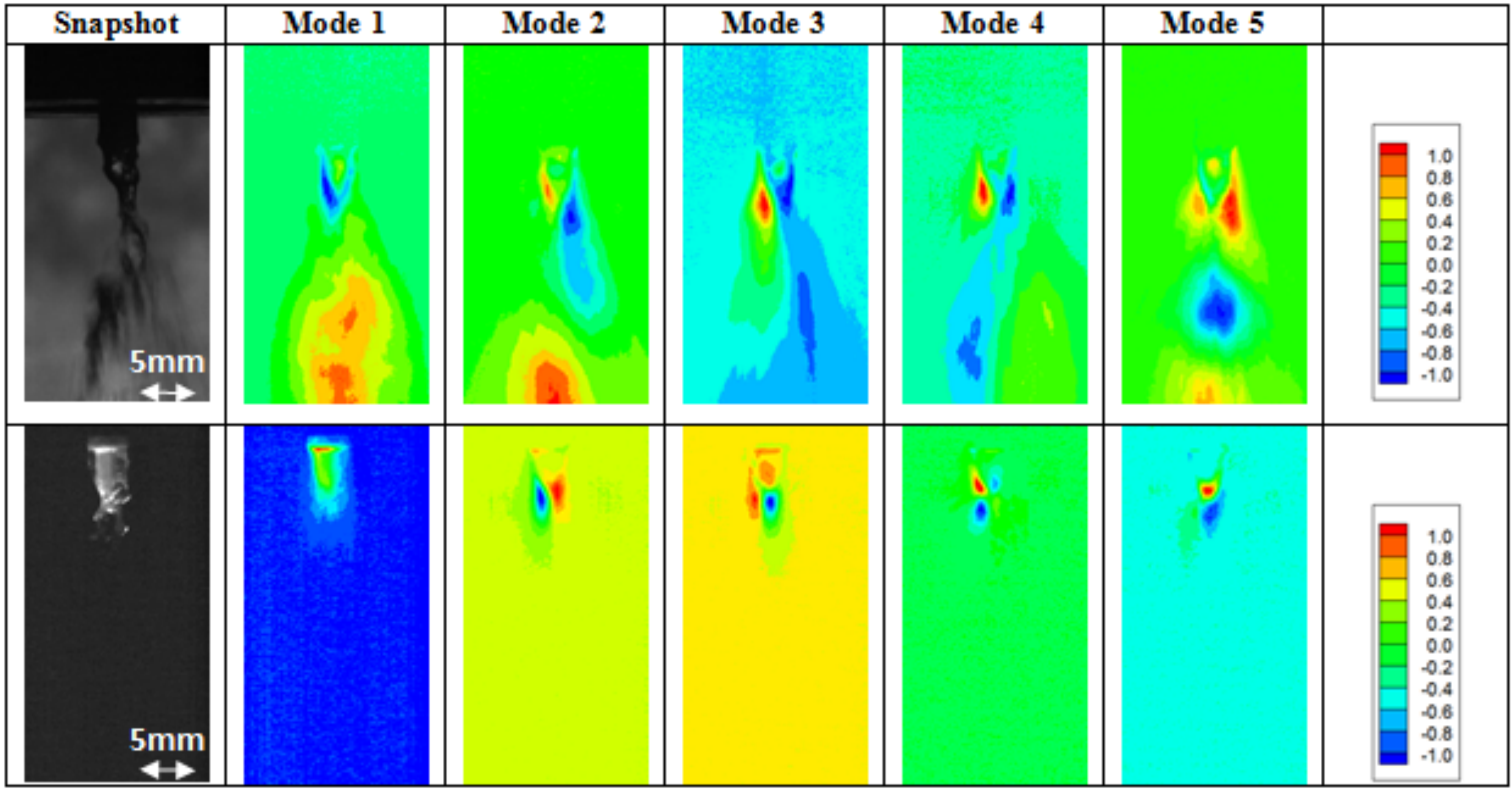


http://cnx.org/content/m12531/latest/

Proper Orthogonal Decomposition Modes (POMs) of liquid jet during breakup

High speed Shadowgraphy

High speed optical connectivity



- At more intense atomisation conditions, in the photographic measurements, the spray droplets account for the greater part of the spatial extent of the POMs
- In optical connectivity, the POMs demonstrate the development of the liquid core
- No dominant POM found in either technique

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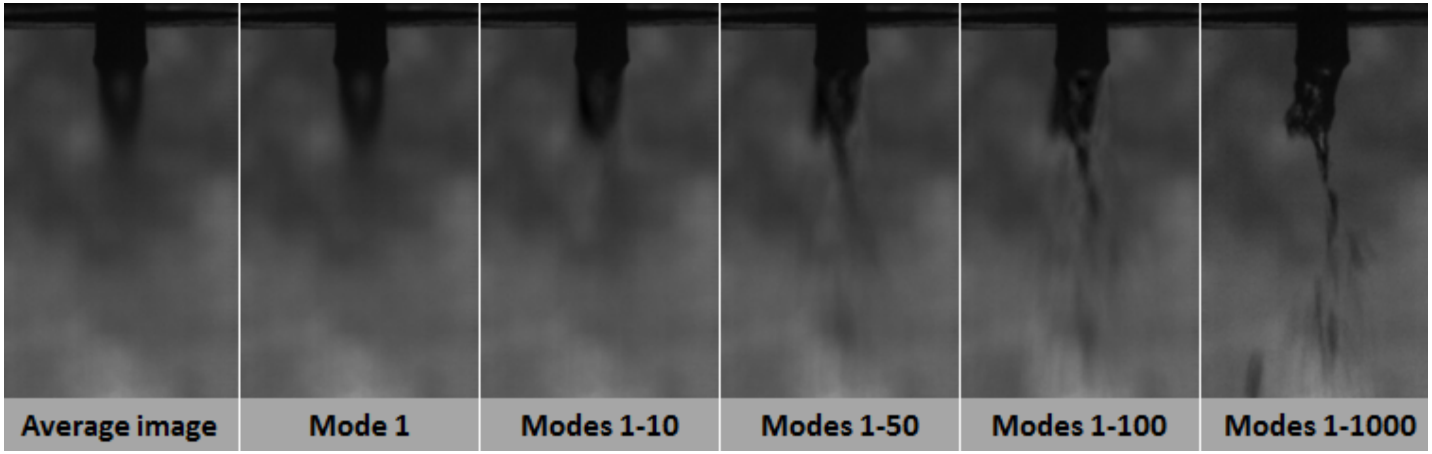
Charalampous G., Hadjiyiannis C. and Hardalupas Y. "Proper Orthogonal Decomposition analysis of photographic and optical connectivity time resolved images of an atomising liquid jet". In "Proceedings of 24th Annual Conference on Liquid Atomization and Spray Systems, ILASS – Europe 2011", Estoril, Portugal, 5-7 September 2011.

Reconstruction of original liquid jet based on limited number of POMs

High speed Shadowgraphy



High speed optical connectivity

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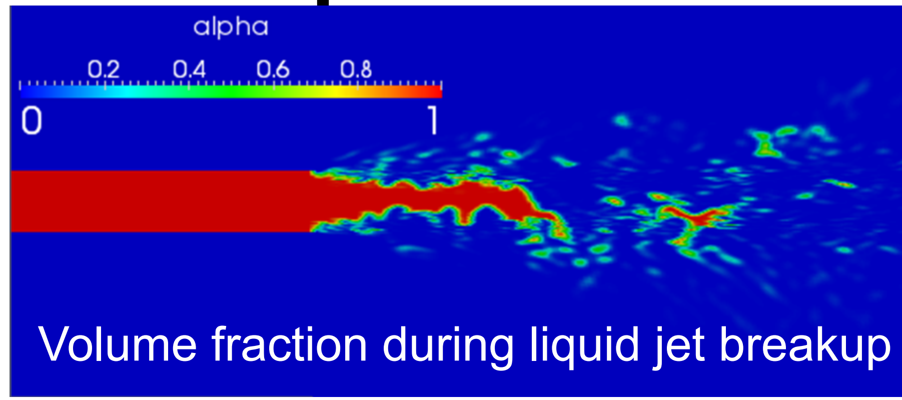
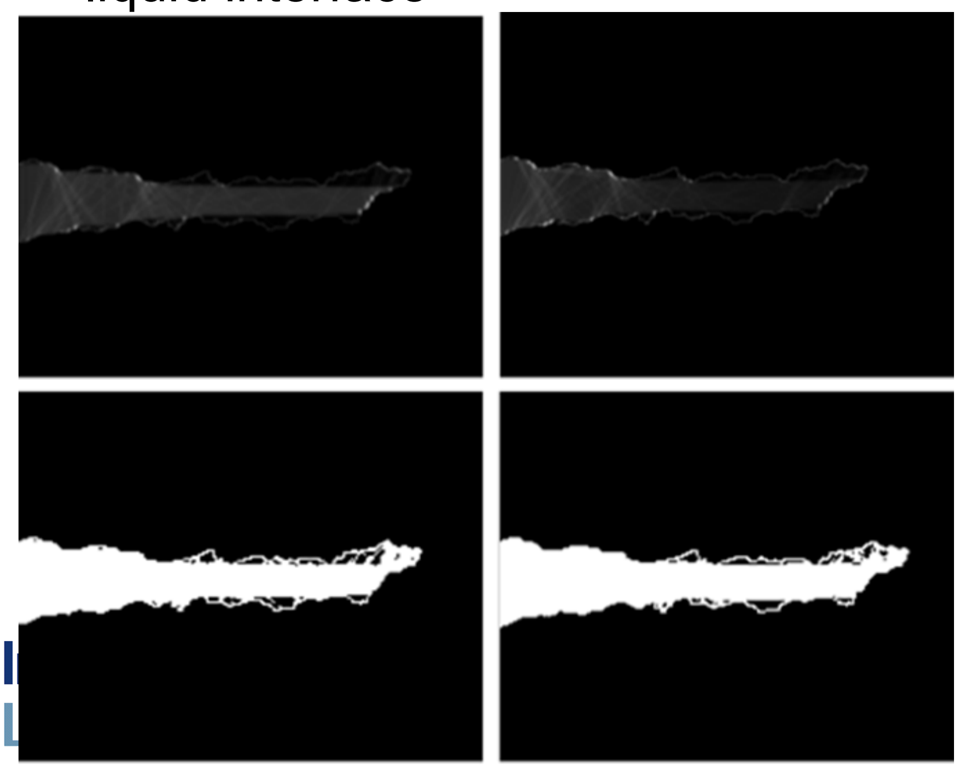
Evaluation of Large Eddy Simulations of liquid jet breakup

OpenFOAM Simulation of coaxial jet atomisation for

- Weber of 1040
- Gas-to-liquid momentum ratio of 336
- Liquid volume fraction indicates gas liquid interface



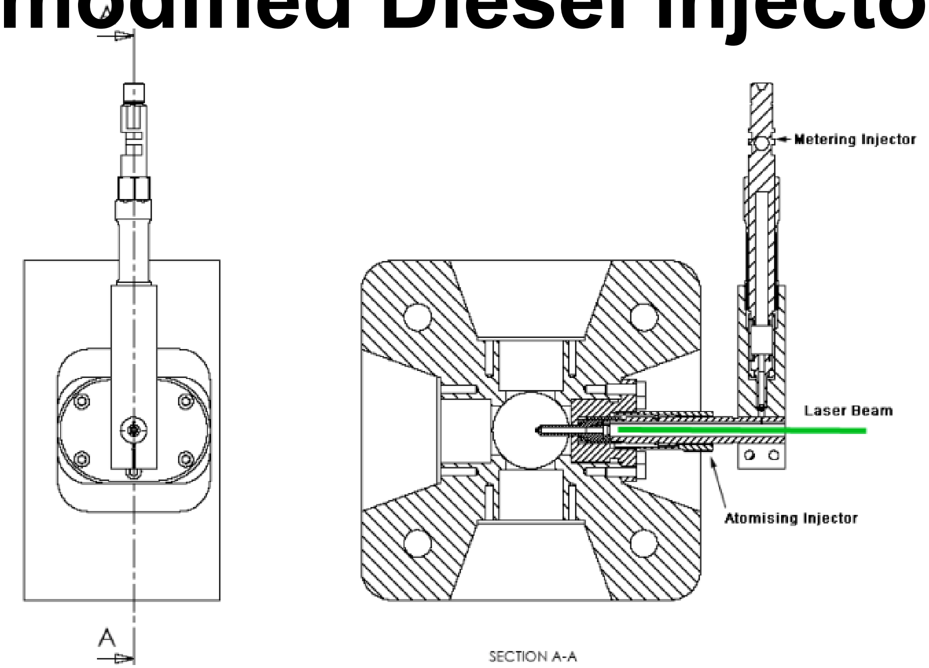
Volume fraction during liquid jet breakup



* Threshold of 10% intensity applied to identify liquid jet surface
* Most of the liquid jet volume is sufficiently illuminated
* Regions of the contour where the geometry changes abruptly are not fully illuminated with some loss of detail
  * Possibly increase of number of rays is required.

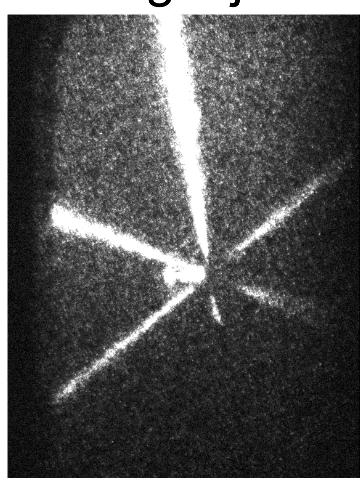
Charalampous G., Soulopoulos N. and Hardalupas Y. "Ray tracing analysis of realistic atomizing jet geometries for optical connectivity applications". In "Proceedings 53rd Aerospace Sciences Meeting & Exhibit", AIAA paper 2015-0164, AIAA, Washington, 2015.

Demonstration of Optical Connectivity in modified Diesel injector



Metering injector operated at 80 MPa, 0.6 ms injection duration corresponding to 1.8 CAD at 500 rpm, atomising injector duration 1.92 ms corrresponding to 5.76 CAD at 500 rpm

View along the injector axis of the scattered visible light image, when illuminated by flashlamp



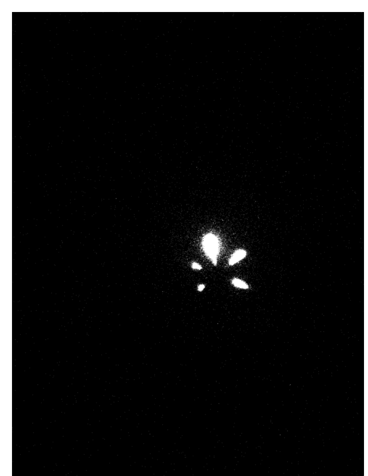


Image measured with optical connectivity through laser beam illumination through the nozzle

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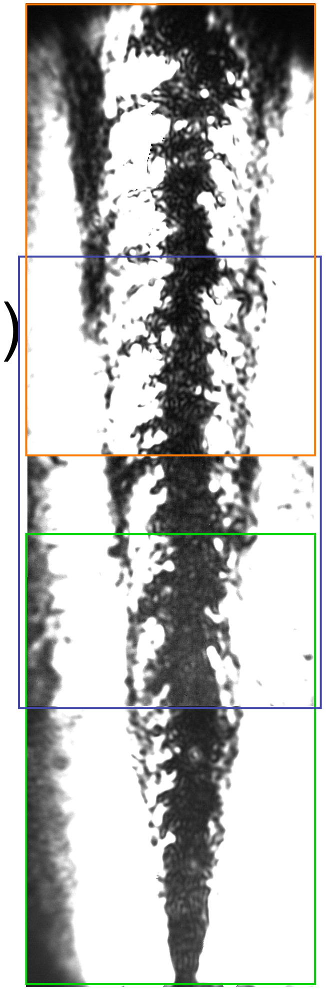
Ballistic Imaging

Based on information from Loic Méès, Ecole Centrale de Lyon, France

Principle

- Time selection of ballistic or single scattered light
- Shadowgraphy through Strongly scattering Medium



(built from 3 raw images)

Applications:
Imaging of dense sprays (car engine, aeronautical, …)

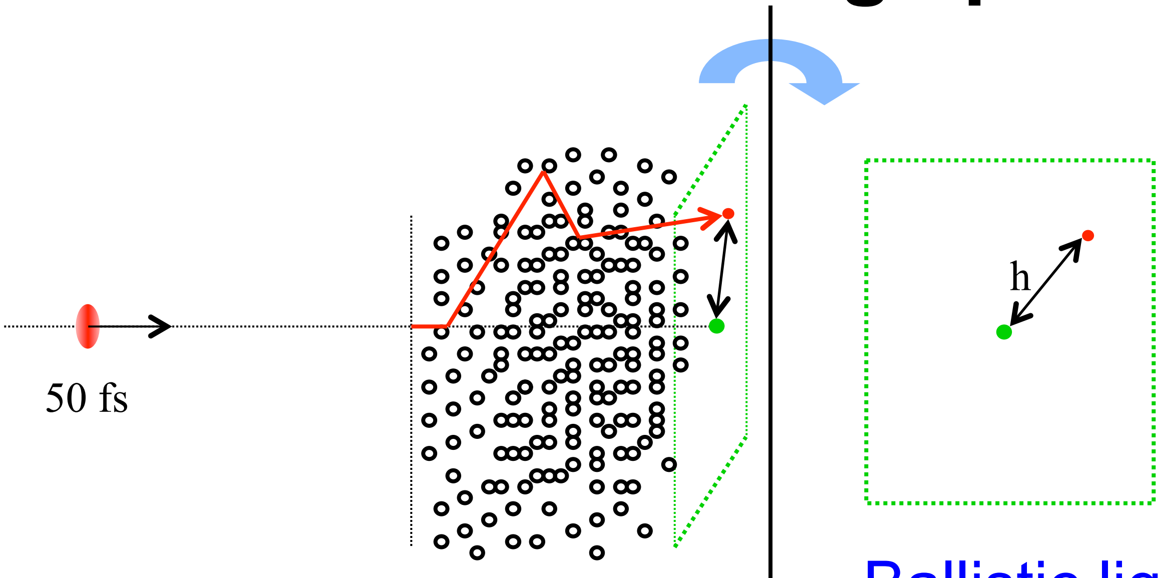
Y. XIANG et al Applied Optics Vol. 36 No. 5 1997

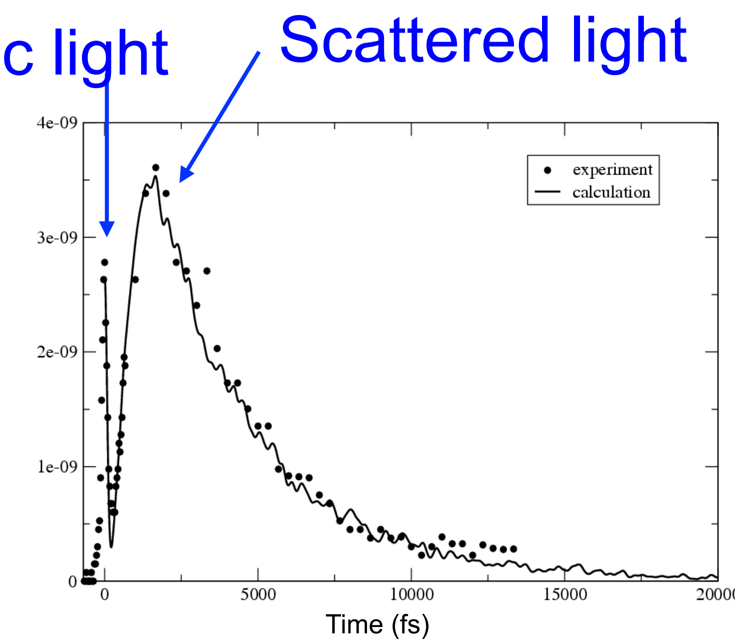
M. PECIARONNI, M. LINNE Applied Optics Vol. 43 No. 26 2004

Some groups working on :

- Sandia : Mark Linne & Hope Michelsen
- LTH : Megan Paciaroni, David Sedarsky, & EdouardBerrocal
- AFRL : Jim Gord & Joe Zelina
- UC Davis : Jean-Pierre Delplanque
- Iowa State U : Terry Meyer
- Cranfield U : Igor Meglinski
- CSM : Terry Parker

Multiple and Single scattered light: Example with large particles





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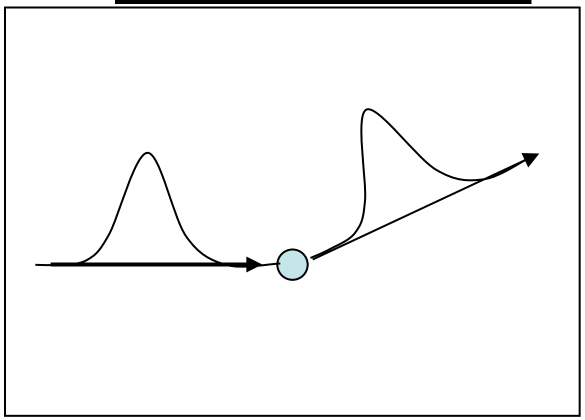
Difference between small and large particles: Time-resolved Monte Carlo

Small particles

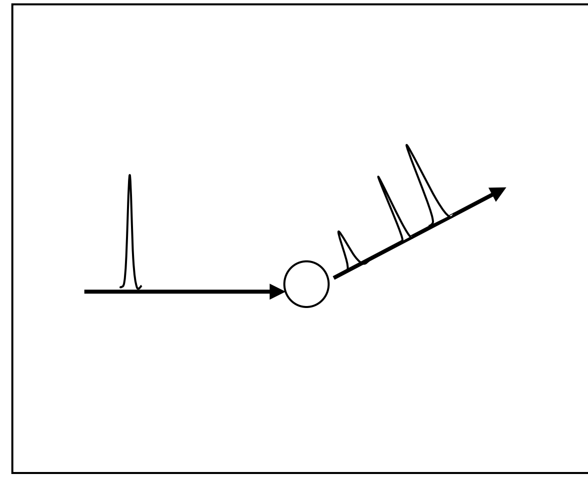


Time of flight is a direct function of optical path between scattering particles

→ + polarisation

→ + Semi analytical MC scheme computation time gain

Large particles



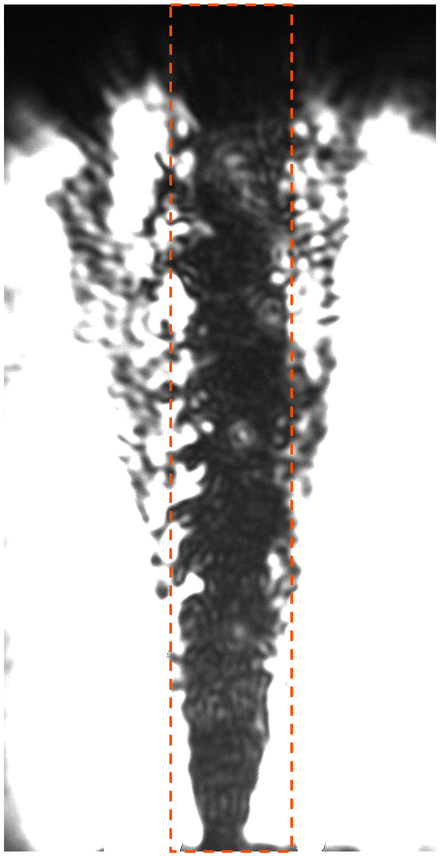
Need to consider :
- interaction time
- time spreading of pulses

1 “photon” = series of pulses (couples amplitude/time delay)

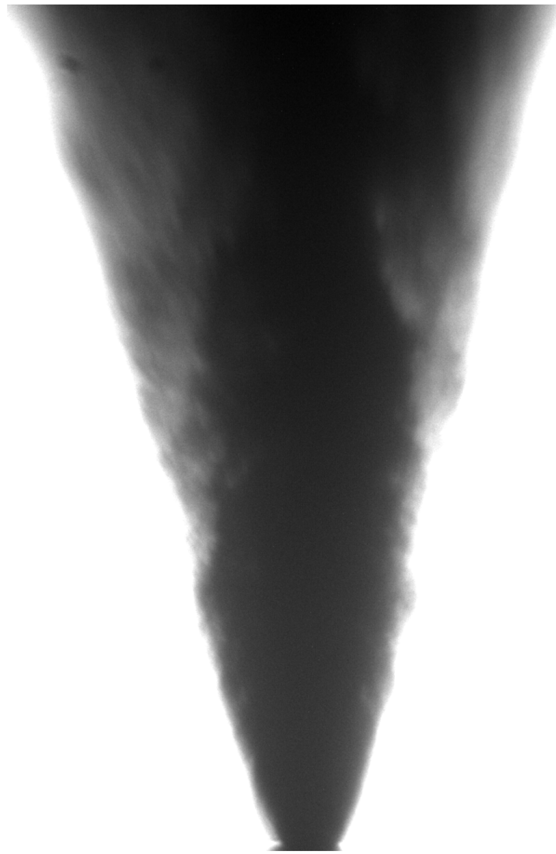
C. Calba, C. Rozé, T. Girasole and L. Méès. Optics communications 265 (2006) 373-382.

Ballistic vs Classical shadography

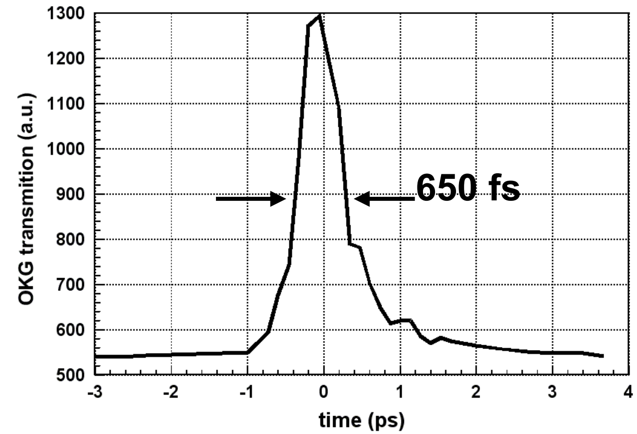
Ballistic Imaging: Femtosecond + gate

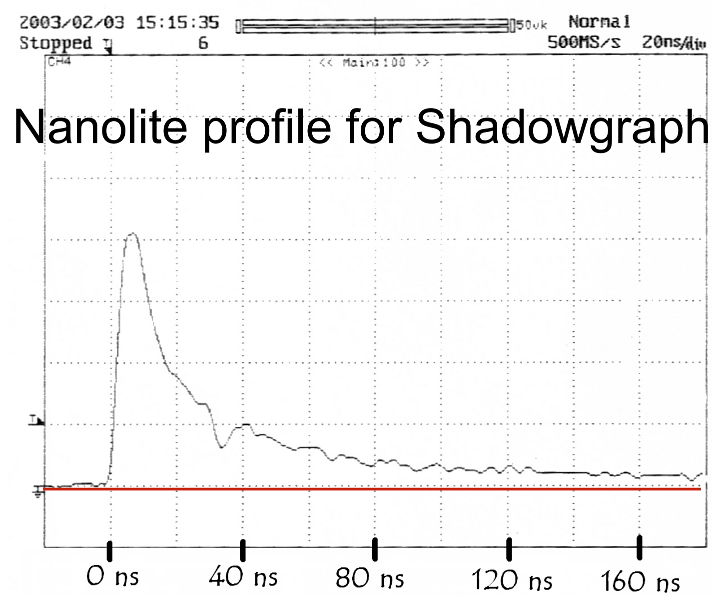


Shadowgraphy: Nanolite



Optical Kerr Gate





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Perspectives

Ballistic Imaging

Hidden Structures are visible with fs illumination

Time gating interest/necessity is growing with **optical and physical** depth

Application domain to be precisely defined (qualitative ≠ quantitative ?)

Spatial resolution enhancement (two colours set-up) → Spatial filtering removal
→ Necessity of time gating

Quantitative information

Particle sizing :
- Time resolved scattering : single shot technique
- Multi wavelength extinction / ballistic photons

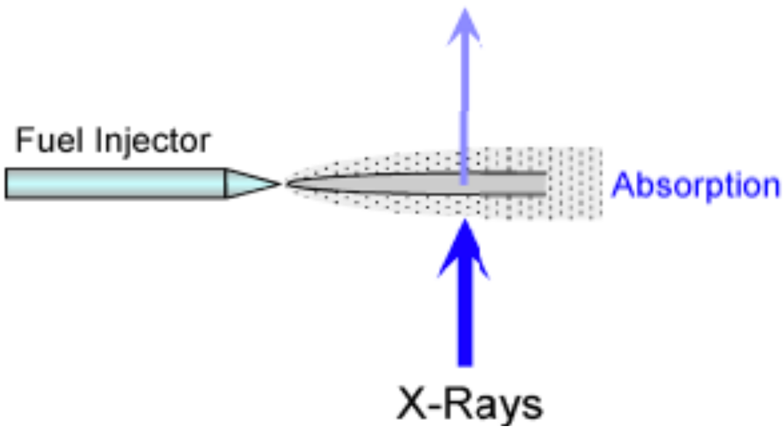
Images Sprays : Quantitative Interpretation

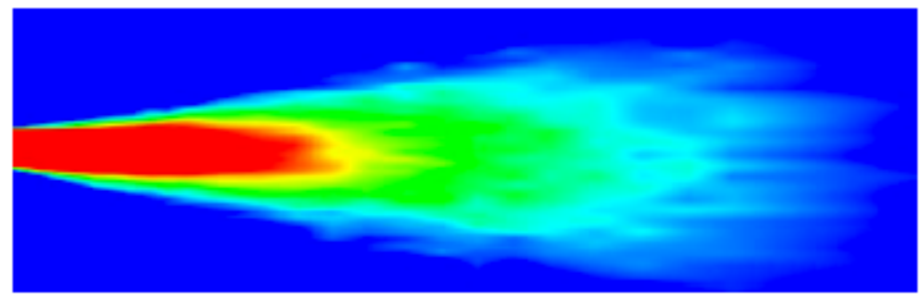
Main difficulties : to link the light transmission measurements and pertinent parameters from numerical fluid mechanics point of view
: Line of sight information

X-RAY Imaging

X-Ray imaging for spray measurements

X-Ray absorption

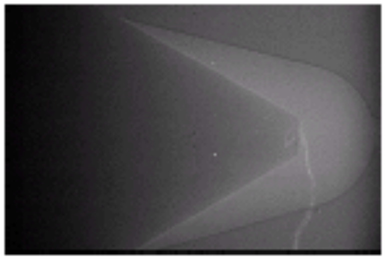




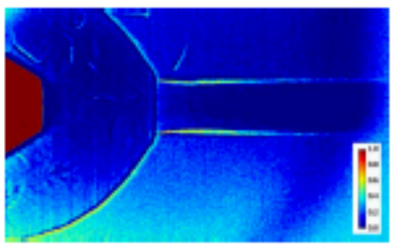
Also, X-Ray fluorescence for detection of two phases in aerated sprays

Different applications

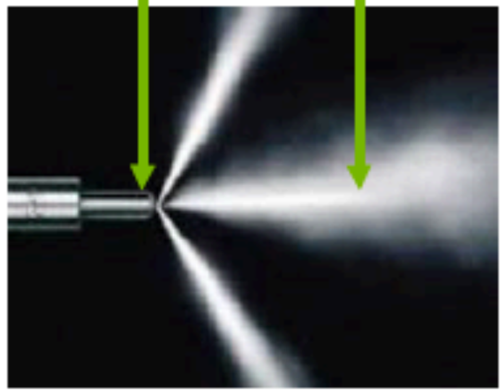
Needle Motion



Nozzle Cavitation



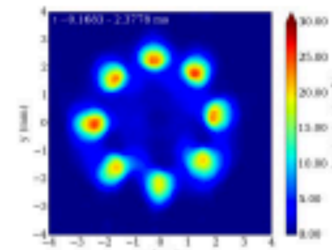
High Precision Nozzle Geometry



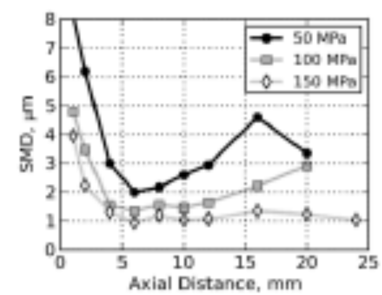
X-rays enable unique capabilities, both *inside* and *outside* the nozzle

Near-Nozzle Fuel Density

Spray Tomogaphy



Near-Nozzle Drop Sizing



Example results

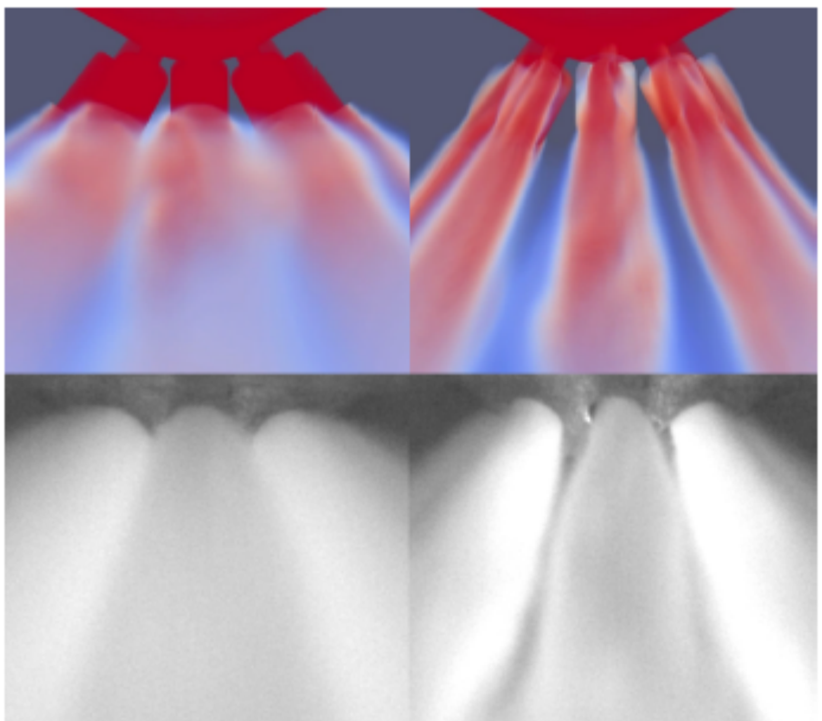
X-rays enable unique diagnostics

- Mass-based measurements of the fuel distribution
- Penetrate through steel to measure geometry, flow, motion
- Can quantify shot-to-shot variation
- Fast time resolution (<5 μs)
- Fine spatial resolution (5 μm)

Flashing spray   Non-Flashing spray

CFD

X-Ray

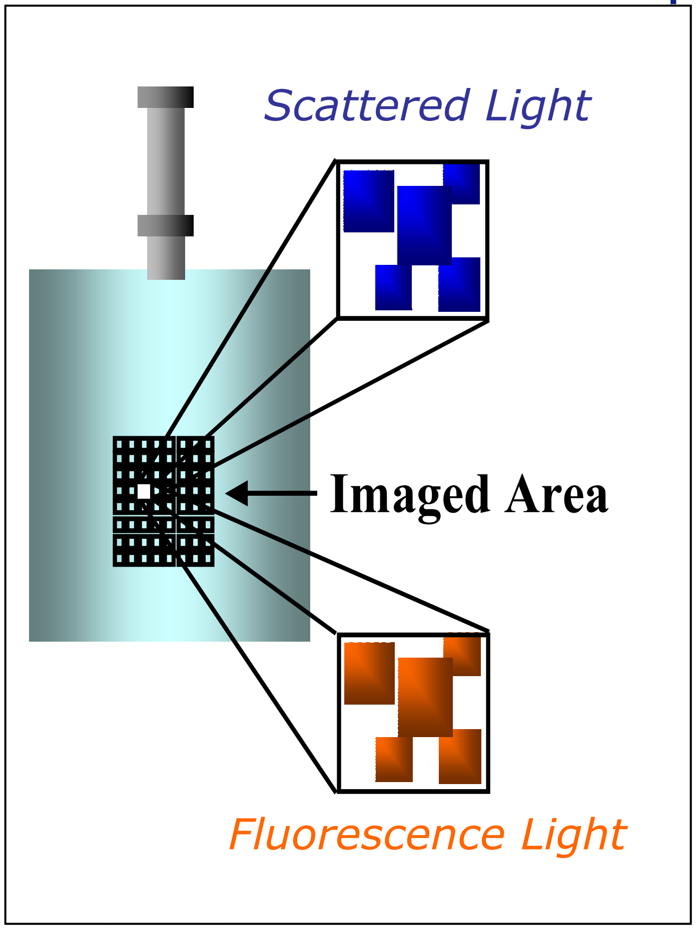


E.T. Baldwin, R.O. Grover, Jr, D.J. Duke, K.E. Matusik, A.L. Kastengren, C.F. Powell, S.E. Parrish and D.P. Schmidt “String Flash-Boiling in Flashing and Non-Flashing Gasoline Direct Injection Simulations with Transient Needle Motion”. ILASS Americas 28th Annual Conference on Liquid Atomization and Spray Systems, Dearborn, MI, May 2016

Planar characterisation of Sprays in the stable droplet region (i.e. spherical droplets)

Optical Spray Patternation using LIF/Mie intensity ratio

Measurements of spherical droplet clouds NOT individual droplets



- *Fluorescence Intensity from dye in liquid droplet cloud*

$$\boxed{i_{fluorescence} = a_f D^3}$$

<u>proportional to liquid volume</u>

- *Scattered light Intensity from droplet cloud*

$$\boxed{i_{scattered} = a_s D^2}$$

<u>proportional to liquid surface area</u>

- *Ratio of fluorescence to scattered light intensities*

$$\boxed{SMD = \frac{\sum_{j=1}^{m} D_j^3}{\sum_{j=1}^{m} D_j^2} = \frac{1}{K} \frac{\sum_{j=1}^{m} i_{fluorescence}(D_j)}{\sum_{j=1}^{m} i_{j,scattered}(D_j)}}$$

<u>proportional to Sauter Mean Diameter of droplet cloud</u>

Calibration constant required!!

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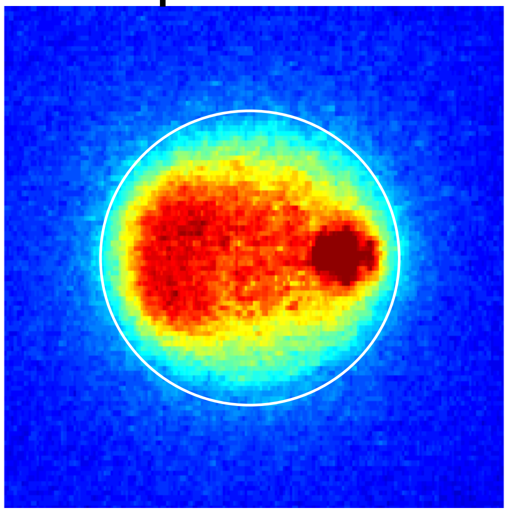
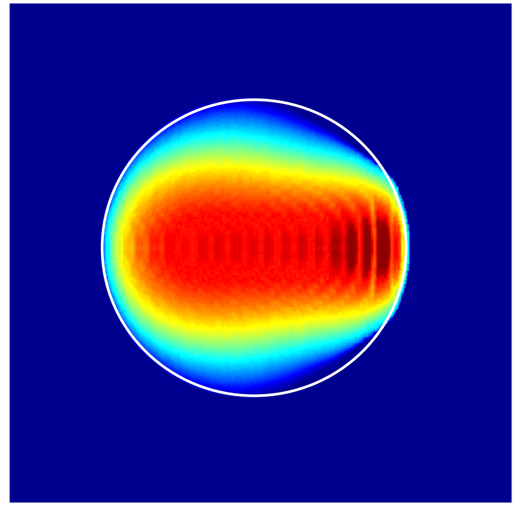
Calibration parameter is not Constant

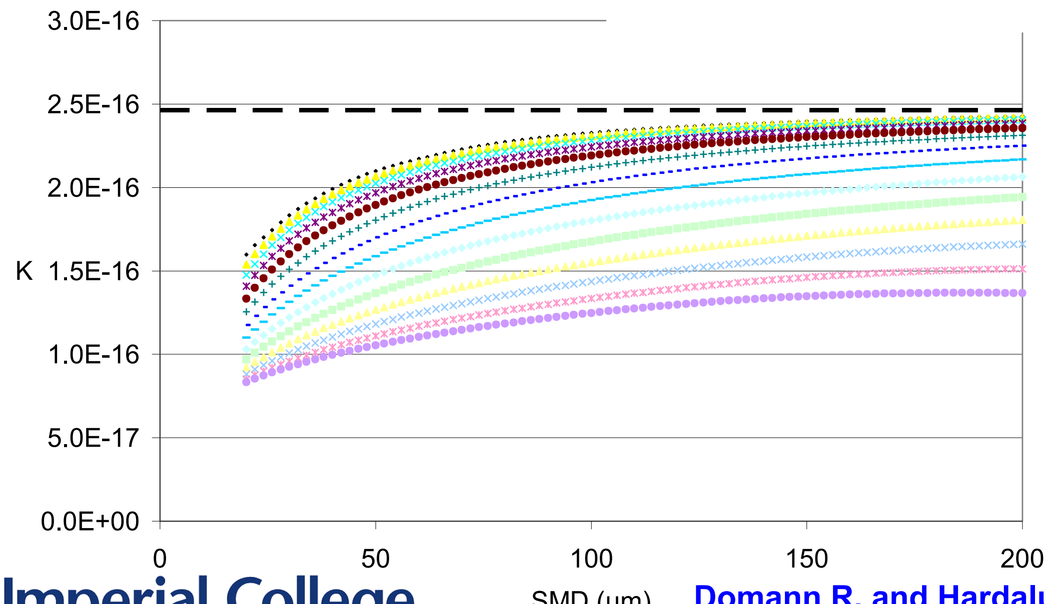
Experiment



Light Scattering Calculation



Internal droplet fluorescent intensity distribution.
Dye concentration 0.001 g/l



The calibration parameter K varies with

- Droplet size
- Scattering angle
- Dye concentration

Domann R. and Hardalupas Y. "Quantitative Measurements of planar Droplet Sauter Mean Diameter in Sprays using Planar Droplet Sizing" Part. Part. Syst. Charact. 20, (2003), 209 - 218.

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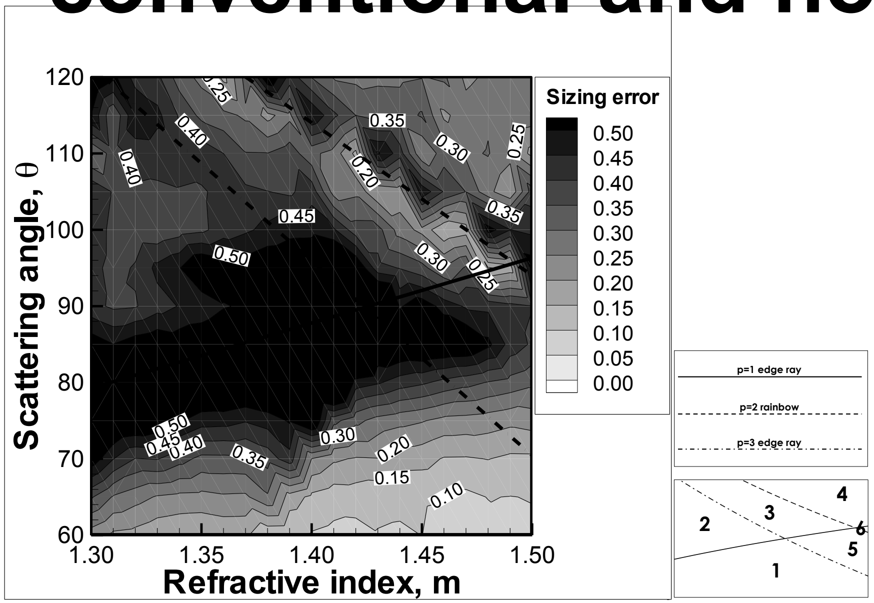
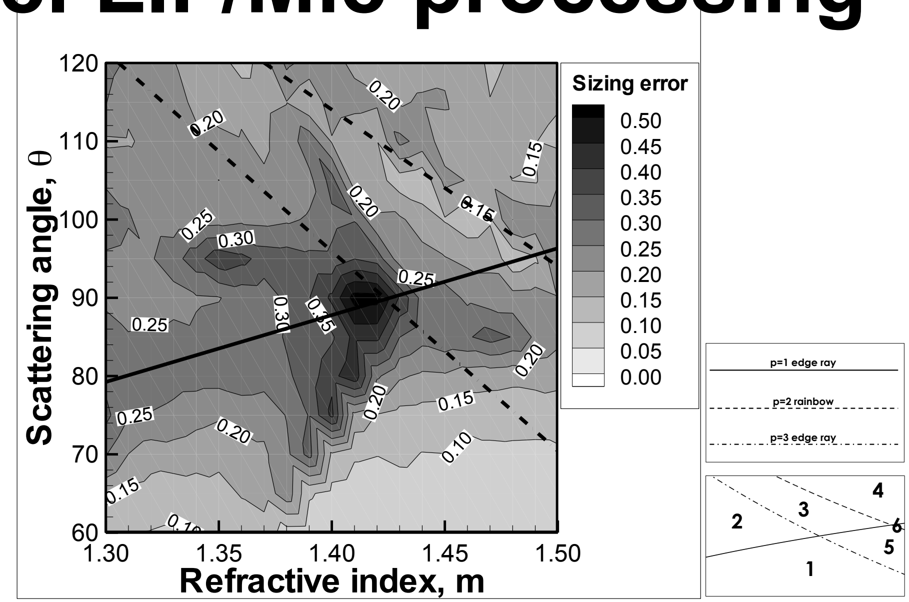
Comparison of sizing uncertainty between conventional and novel LIF/Mie processing





Example showing sizing error for droplet size range of 20-70μm and LIF/Mie calibration with 100μm droplets

Conventional LIF/Mie processing

- Sizing error can exceed 50%
- Imaging at 90° is unsuitable for accurate sizing measurements
- Better sizing accuracy with measurements at 60°
- Best case uncertainty ~10%

Proposed LIF/Mie processing

- Sizing accuracy always better than conventional approach
- Sizing uncertainty improvements by over 25%
- Optimal sizing accuracy at ~60°
- Best case uncertainty ~5%

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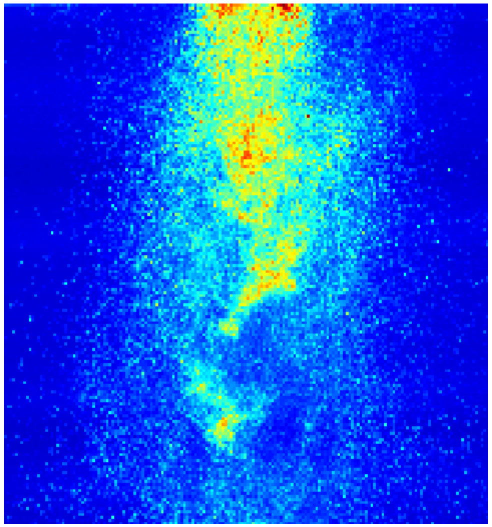
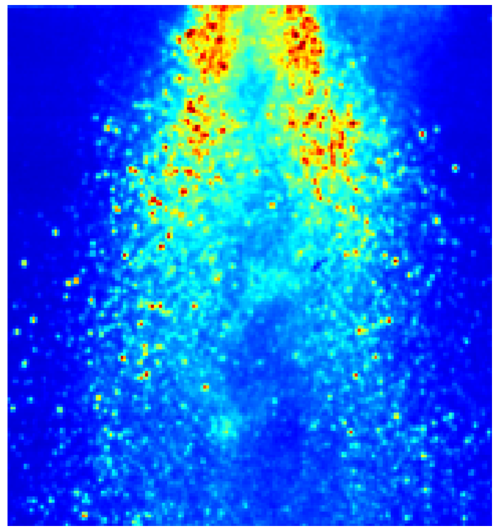
Charalampous G. and Hardalupas Y. "A novel method to reduce errors of droplet sizing based on the ratio of fluorescent and scattered light intensities (LIF/Mie technique)". Applied Optics 50, (2011), 3622-3637.

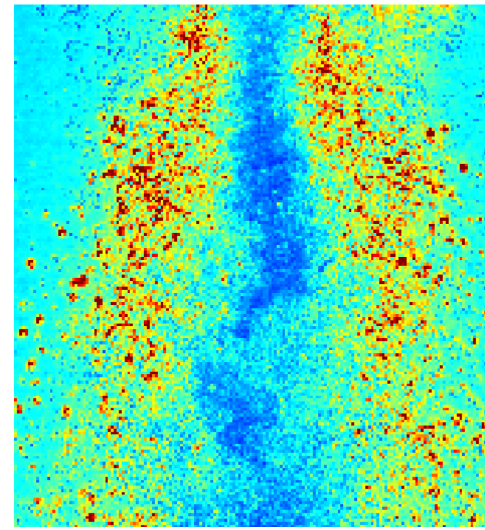
Instantaneous Spray Characteristics



Surface area (Scattered Light, Mie)



Liquid volume (Fluorescent Light, LIF)



SMD (quantitative) (ratio LIF/Mie)

- Droplet Clusters are visible and can be quantified

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Zimmer L., Domann R., Hardalupas Y. and Ikeda Y. "Simultaneous Laser Induced Fluorescence and Mie scattering for droplet cluster measurements". AIAA J. 41, (2003), 2170-2178.

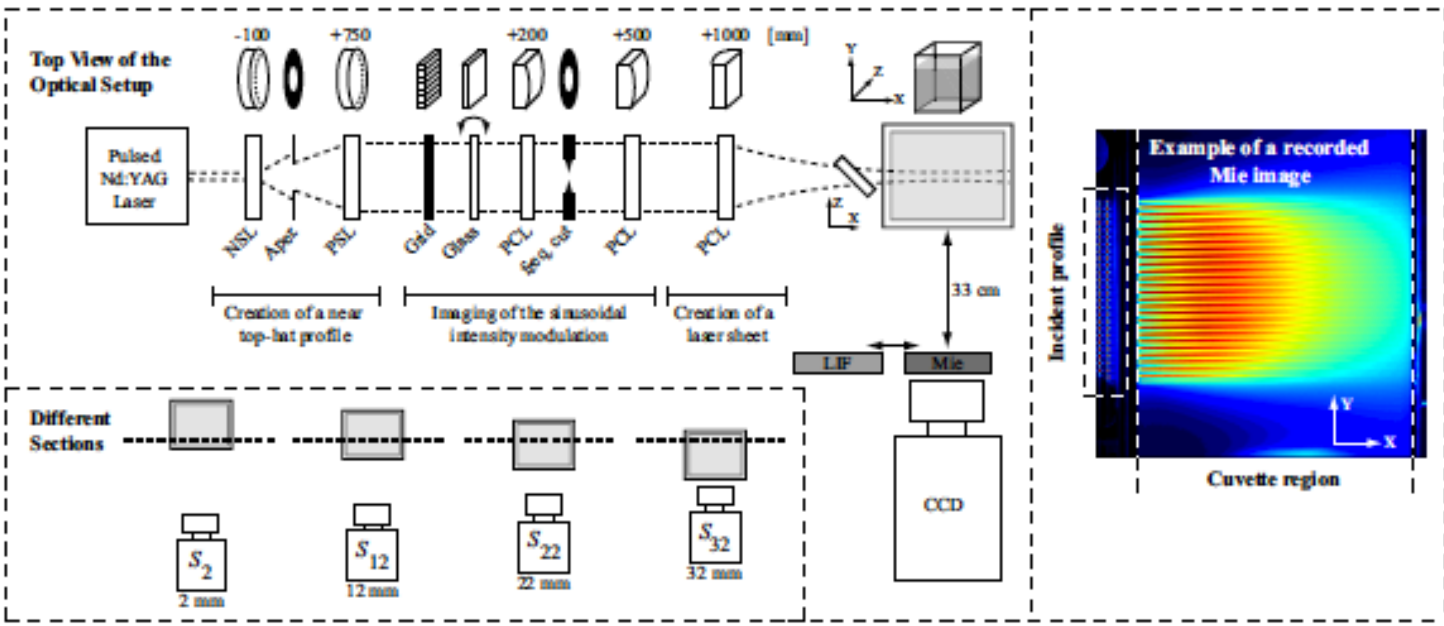
Structured Laser Illumination Planar Imaging (SLIPI)

Purpose:

- Remove light due to multiple-scattering on spray droplets from recorded intensity distribution.
- Then, use more accurate LIF/Mie intensity ratio to obtain Sauter Mean Diameter in dense sprays.

Principle and optical arrangement

- An intensity modulated laser sheet, using a Ronchi grating, is created with thickness ~100 µm.
- To acquire a near top-hat intensity profile only the central part of the quasi Gaussian beam was selected.
- Phase shifting was achieved by tilting a glass plate situated directly after the Ronchi grating.
- To account for even minimal laser fluctuations, the incident profile was monitored and used as a normalization factor in image post-processing.



E. Kristensson, L. Araneo, E. Berrocal, J. Manin, M. Richter, M. Alden and M. Linne. "Analysis of multiple scattering suppression using structured laser illumination planar imaging in scattering and fluorescing media". OPTICS EXPRESS, Vol. 19, No. 14, 4 July 2011

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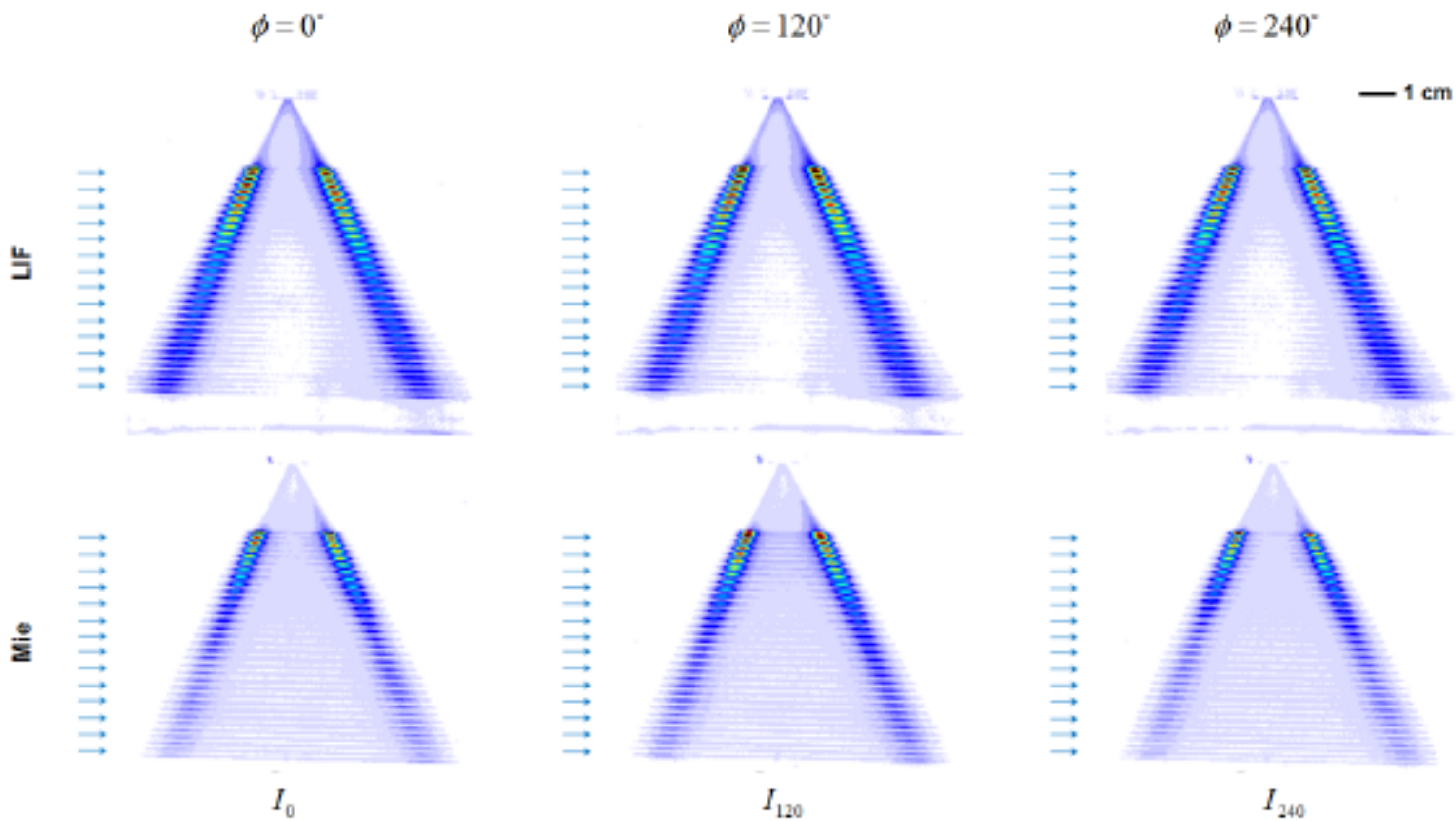
Spatial distributions of LIF and Mie intensities at 3 phases of the structured laser sheet



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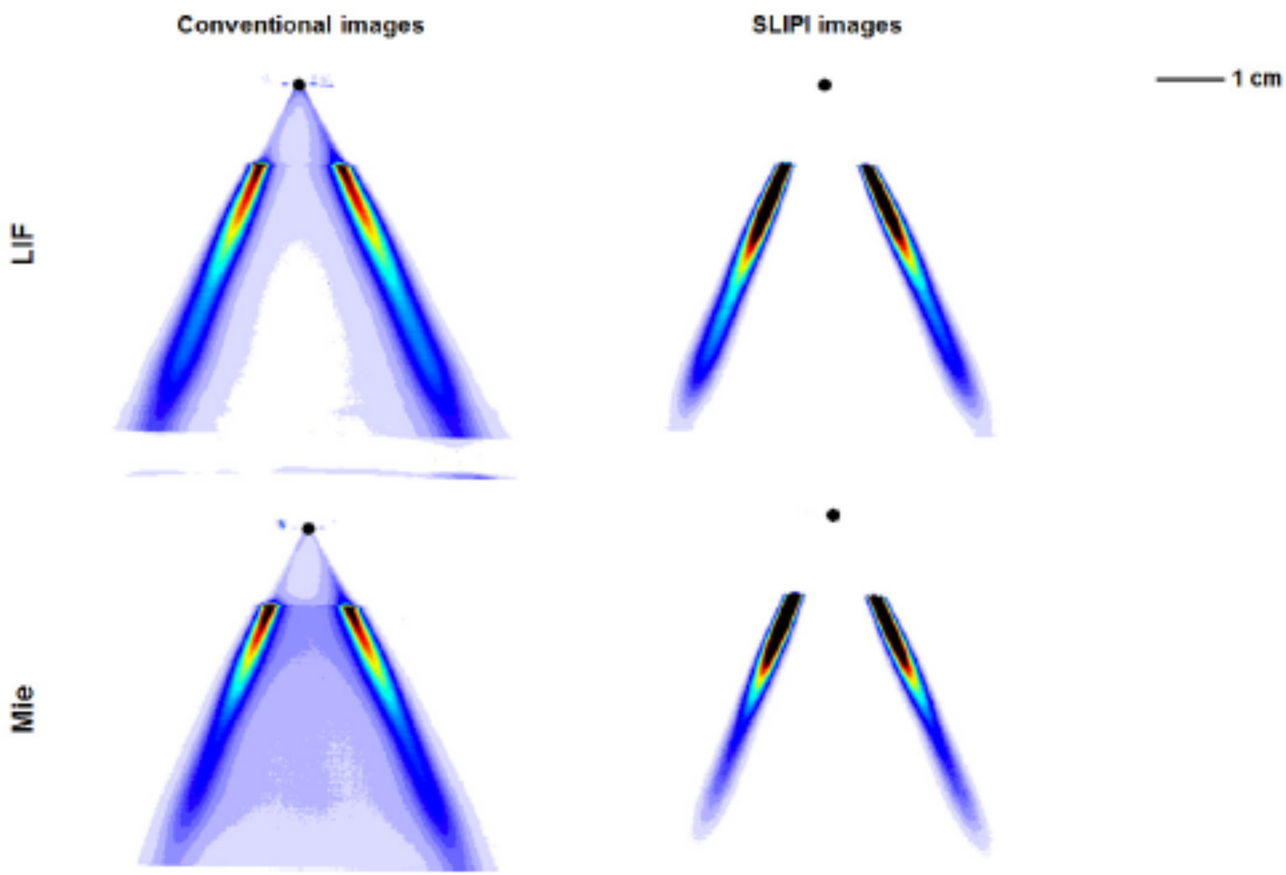
Y.N. Mishra, E. Kristensson, E. Berrocal. "Reliable LIF/Mie droplet sizing in sprays using structured laser illumination planar imaging". OPTICS EXPRESS, Vol. 22, No. 4, 24 February 2014

Spatial distributions of LIF and Mie intensities without and with SLIPI correction



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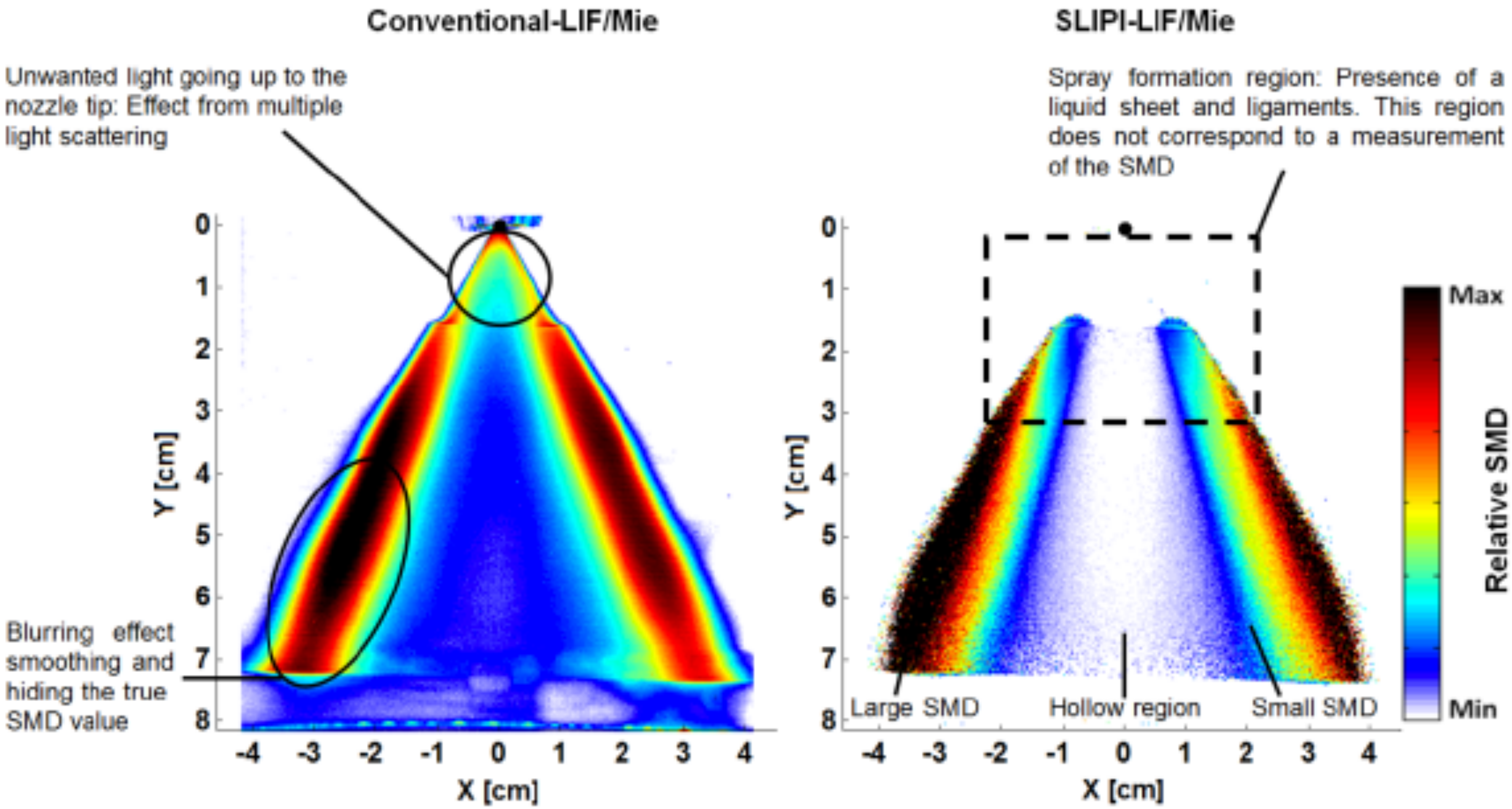
Y.N. Mishra, E. Kristensson, E. Berrocal. "Reliable LIF/Mie droplet sizing in sprays using structured laser illumination planar imaging". OPTICS EXPRESS, Vol. 22, No. 4, 24 February 2014

SMD spatial distributions from LIF/Mie intensity ratio without and with SLIPI correction



Y.N. Mishra, E. Kristensson, E. Berrocal. "Reliable LIF/Mie droplet sizing in sprays using structured laser illumination planar imaging". OPTICS EXPRESS, Vol. 22, No. 4, 24 February 2014

Interferometric Laser Imaging Droplet Sizing (ILIDS)

Planar Droplet Size, Velocity and concentration of individual droplets

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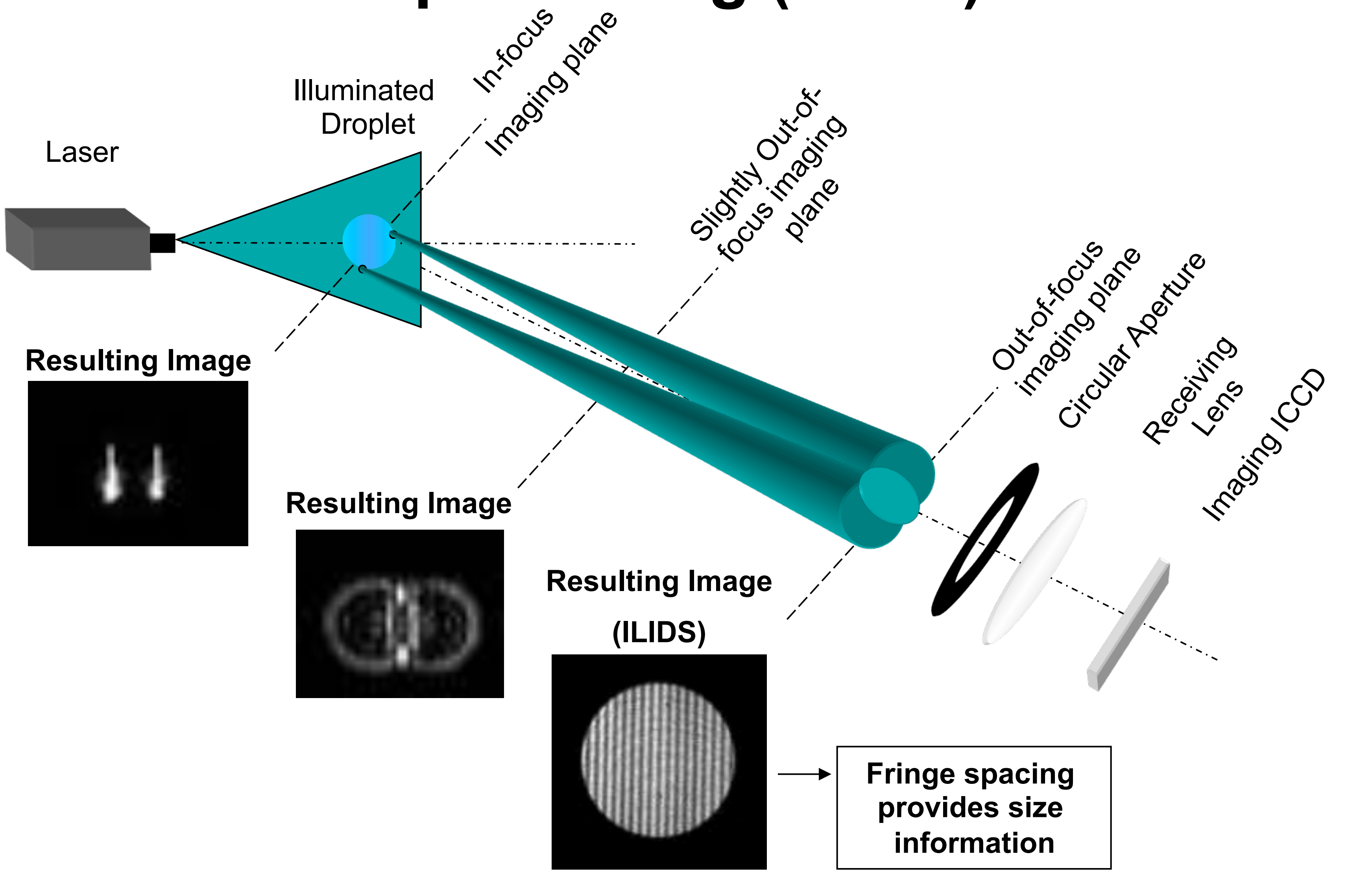
Principle of Interferometric Laser Imaging Droplet Sizing (ILIDS)



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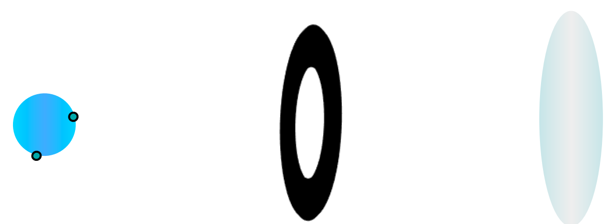
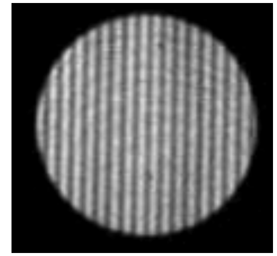
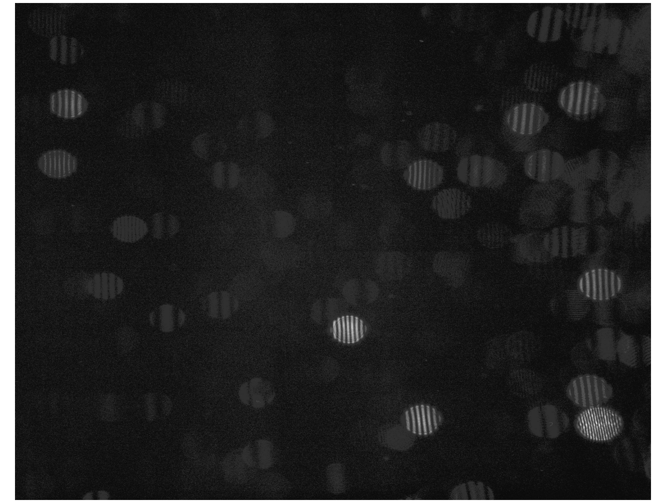
Note: Fringe spacing represents the frequency of scattered light intensity fluctuations

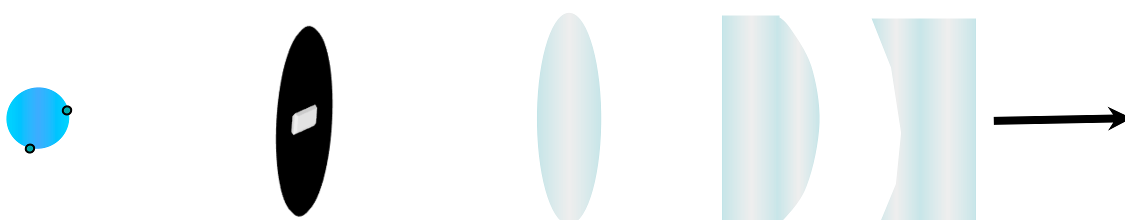
ILIDS for dense sprays: Image Compression

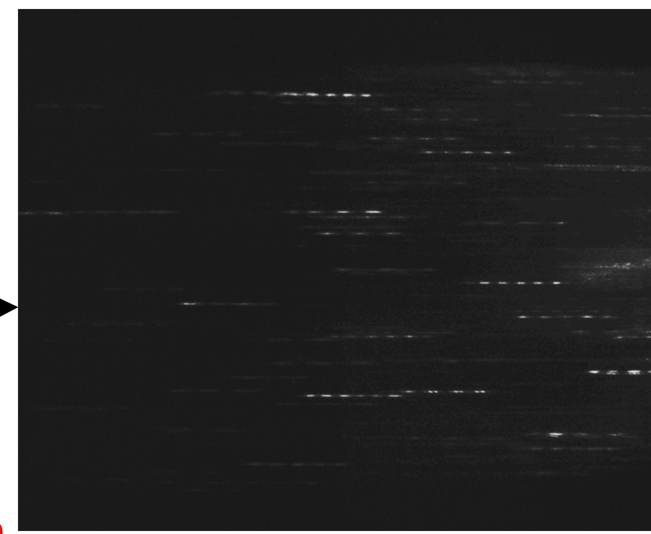






Without Compression





With Compression

- **Kawagushi et al (2002) "Size measurements of droplets and bubbles by advanced interferometric laser imaging technique" Meas. Sci. Technol. 13, 308–316.**
- **Hardalupas Y., Taylor A.M.K.P. and Zarogoulidis K. "Detection and evaluation of droplet and bubble fringe patterns in images of planar interferometric measurement techniques using the Wavelet Transform". Int. Conf. Optical Particle Characterisation (OPC 2014); Book Series: In Proceedings of SPIE, Vol. 9232, UNSP 92320E, (2014); doi:10.1117/12.2065482.**

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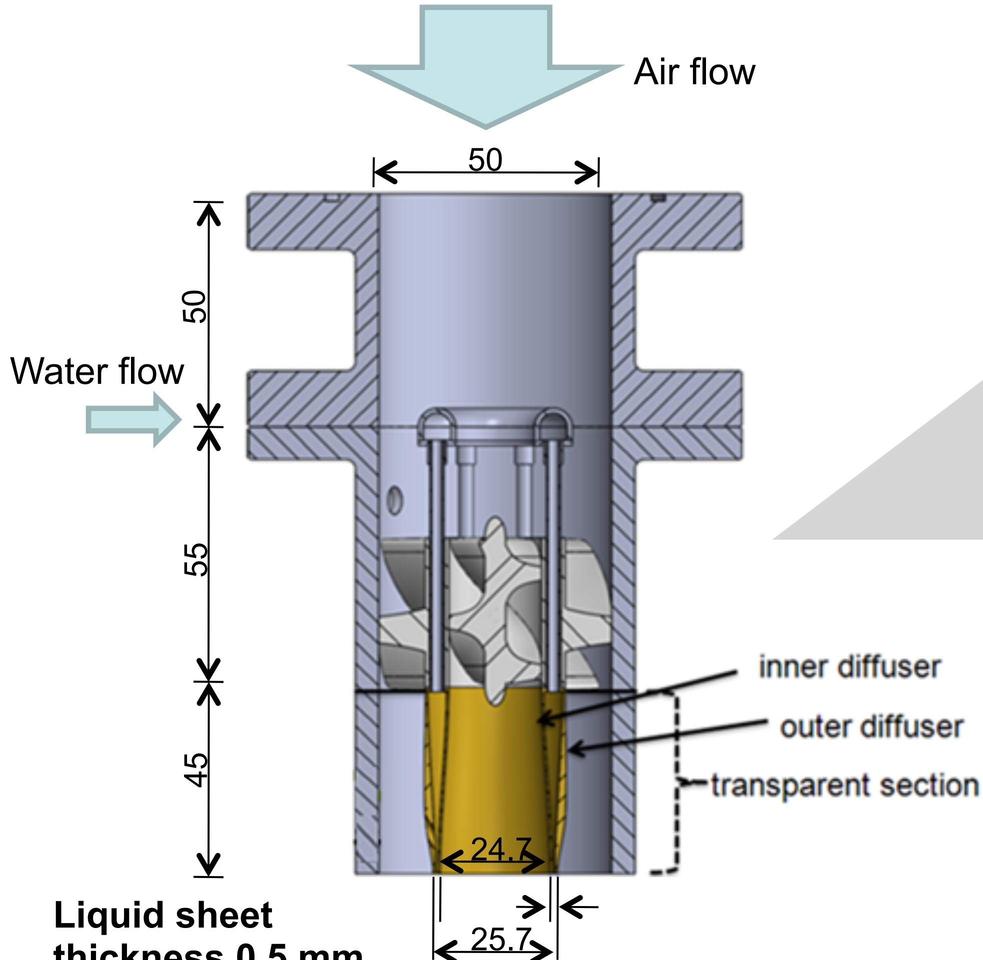
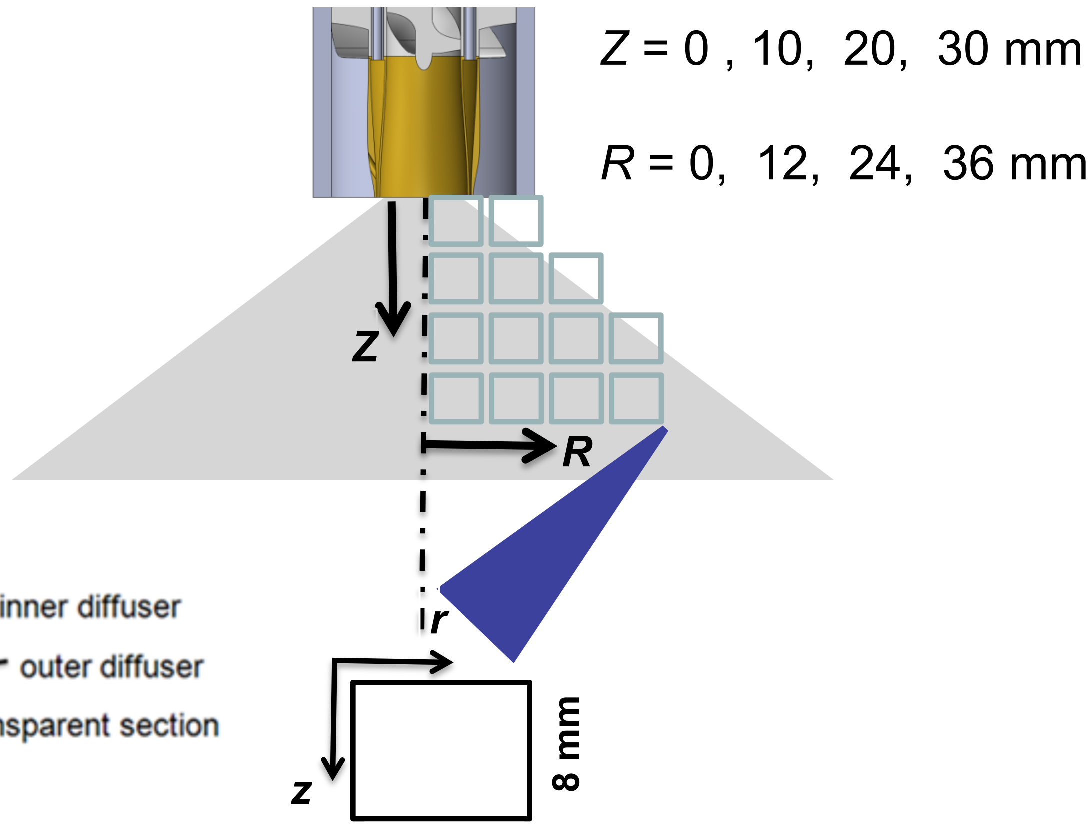
Planar Droplet Sizing in sprays from gas turbine prefilming atomisers



Liquid sheet thickness 0.5 mm



Measurement area: 8 mm × 12 mm

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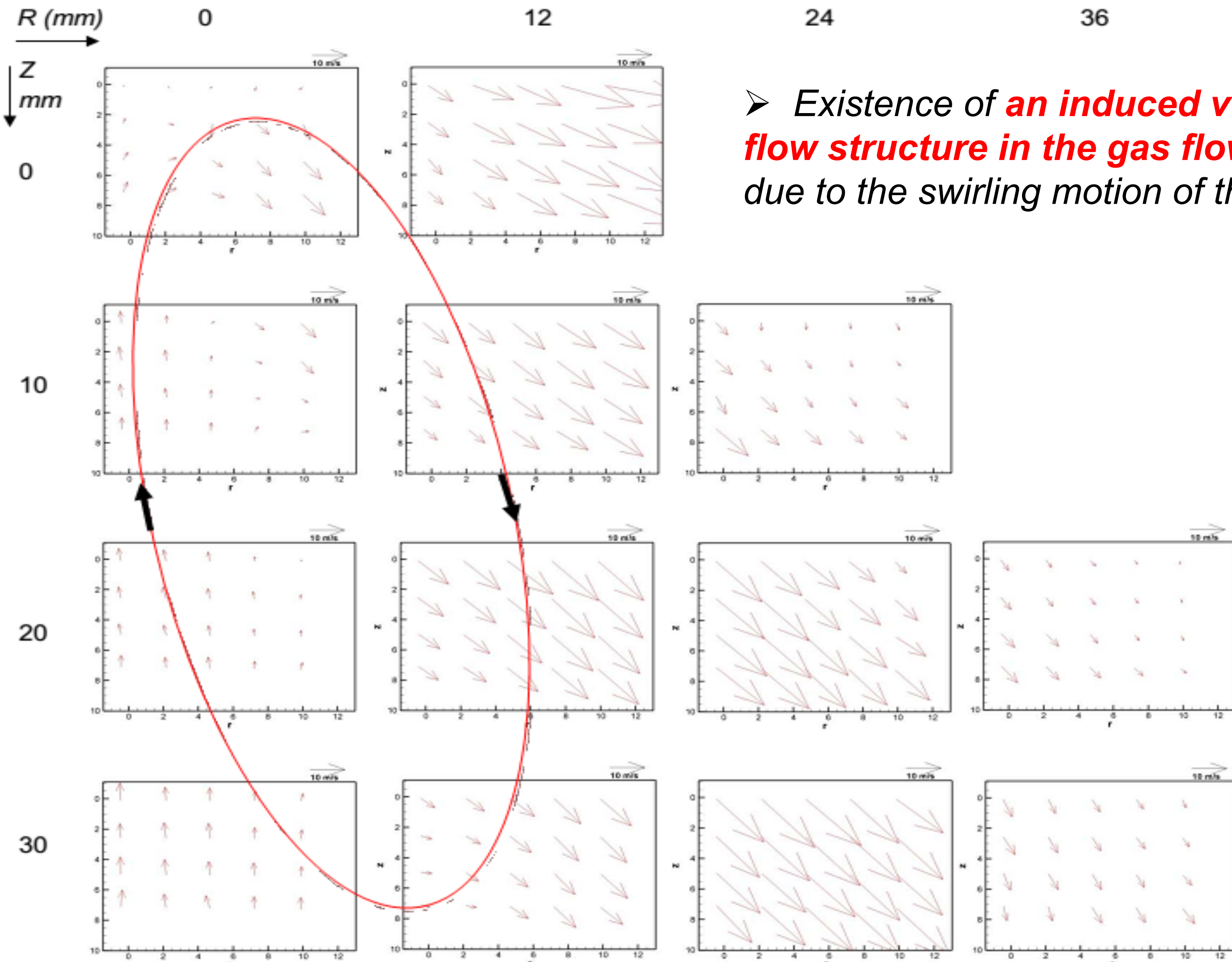
Mean droplet velocity (15-30 μm)



- *Existence of* ***an induced vortical reverse flow structure in the gas flow****, which arises due to the swirling motion of the air.*

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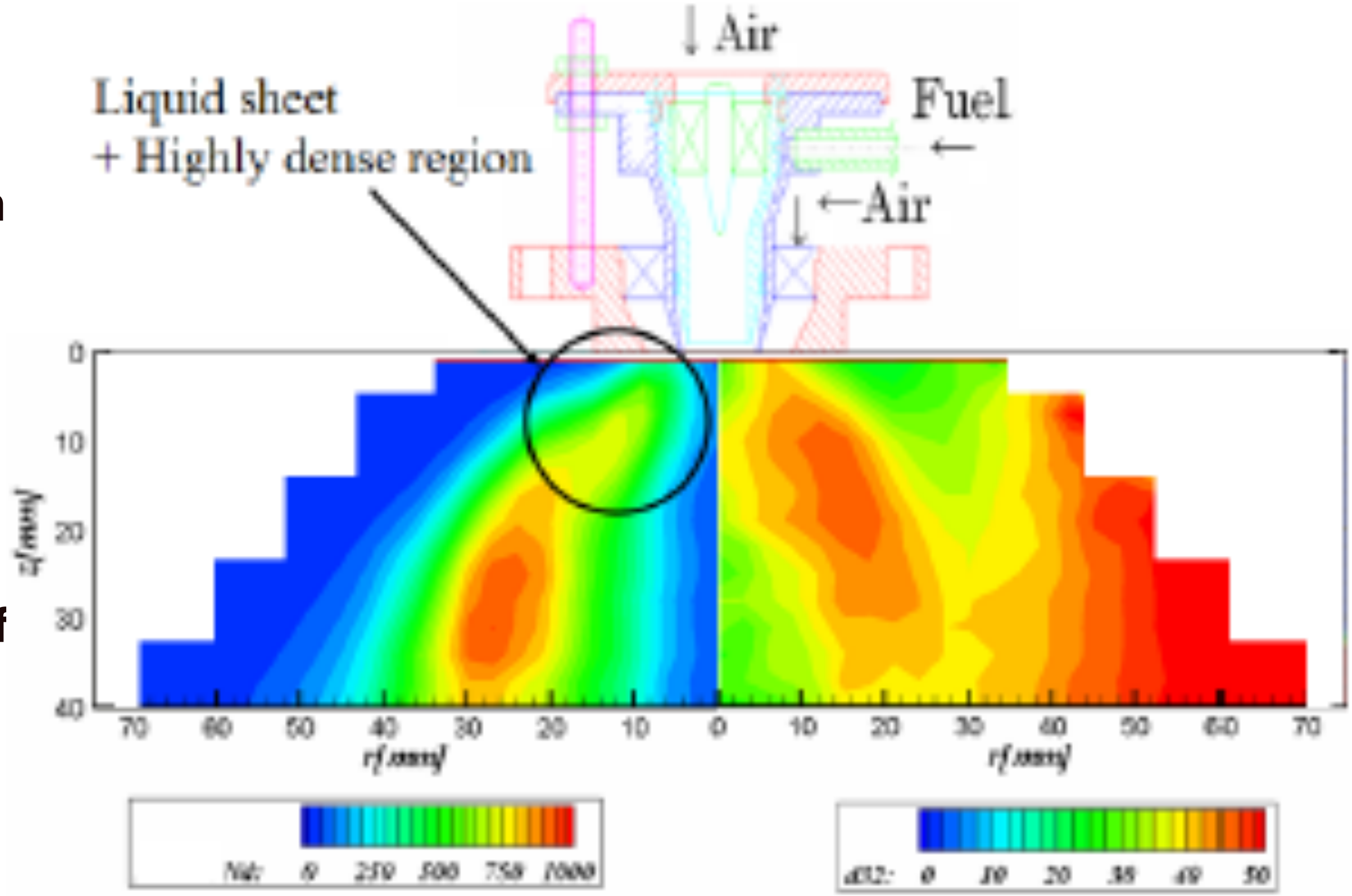
Sahu S., Hardalupas Y. and Taylor A.M.K.P., "Experimental spray characterization for a double swirl coaxial air blast atomizer". In "Proceedings of the 13th Triennial International Conference on Liquid Atomization and Spray Systems (ICLASS 2015)", Tainan, Taiwan, 23-27 August 2015.

ILIDS in sprays from Aero-Engines prefilming atomisers

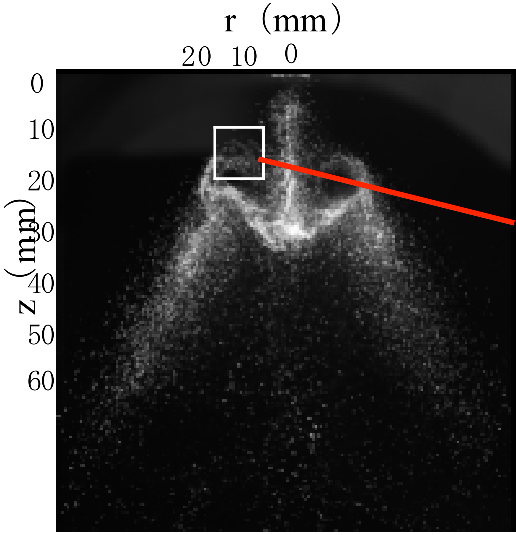
- **Parker Hannifin prefilming atomiser**
- **Operating condition with ALR=9.5 and Pressure Drop in Nozzle 4% of Back pressure**



Droplet number density [/cc] ***Sauter Mean Diameter [μm]***

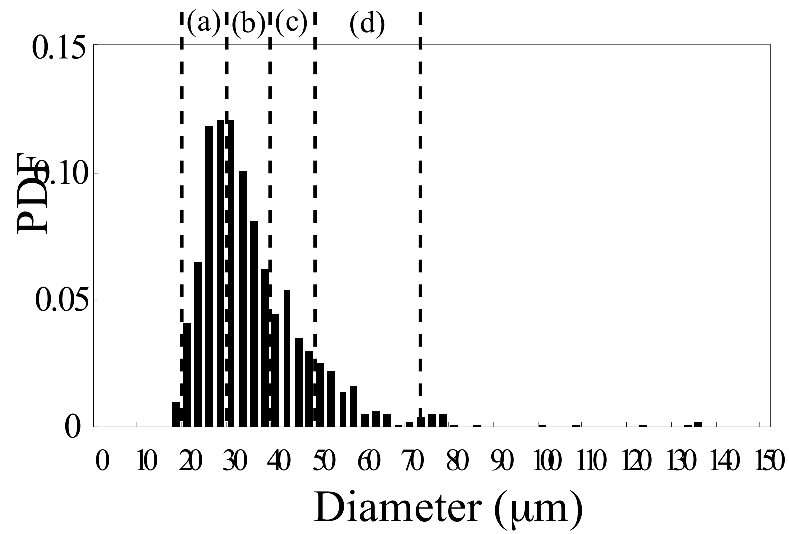
Matsuura K., Zarogoulidis K., Hardalupas Y., Taylor A.M.K.P., Kawaguchi T., Sugimoto D., Hishida K. Simultaneous planar measurement of size and three-component velocity of droplets in an aero-engine airblast fuel spray by stereoscopic interferometric laser imaging technique. In Proc of 10th Int. Conf. on Liquid Atomisation and Spraying Systems (ICLASS-2006), Kyoto, Japan, August 2006.

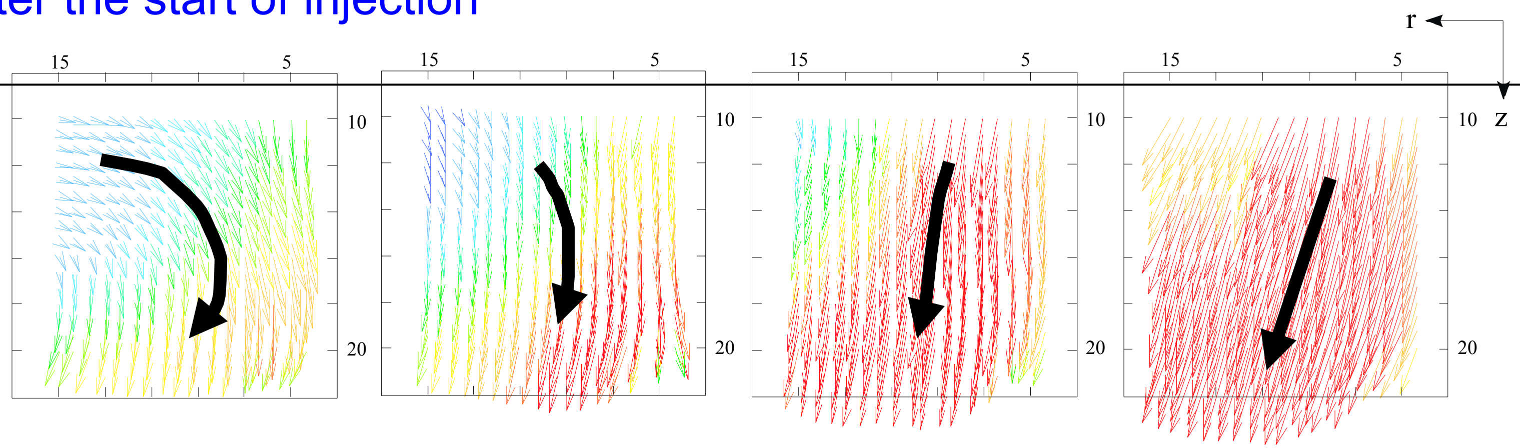
ILIDS measurements of transient spray from gasoline direct injector



A transient spray picture at **4.2ms** after the start of injection

Transient spray





(a) $20 < d < 30$ μm (b) $30 < d < 40$ μm (c) $40 < d < 50$ μm (d) $50 < d < 75$ μm

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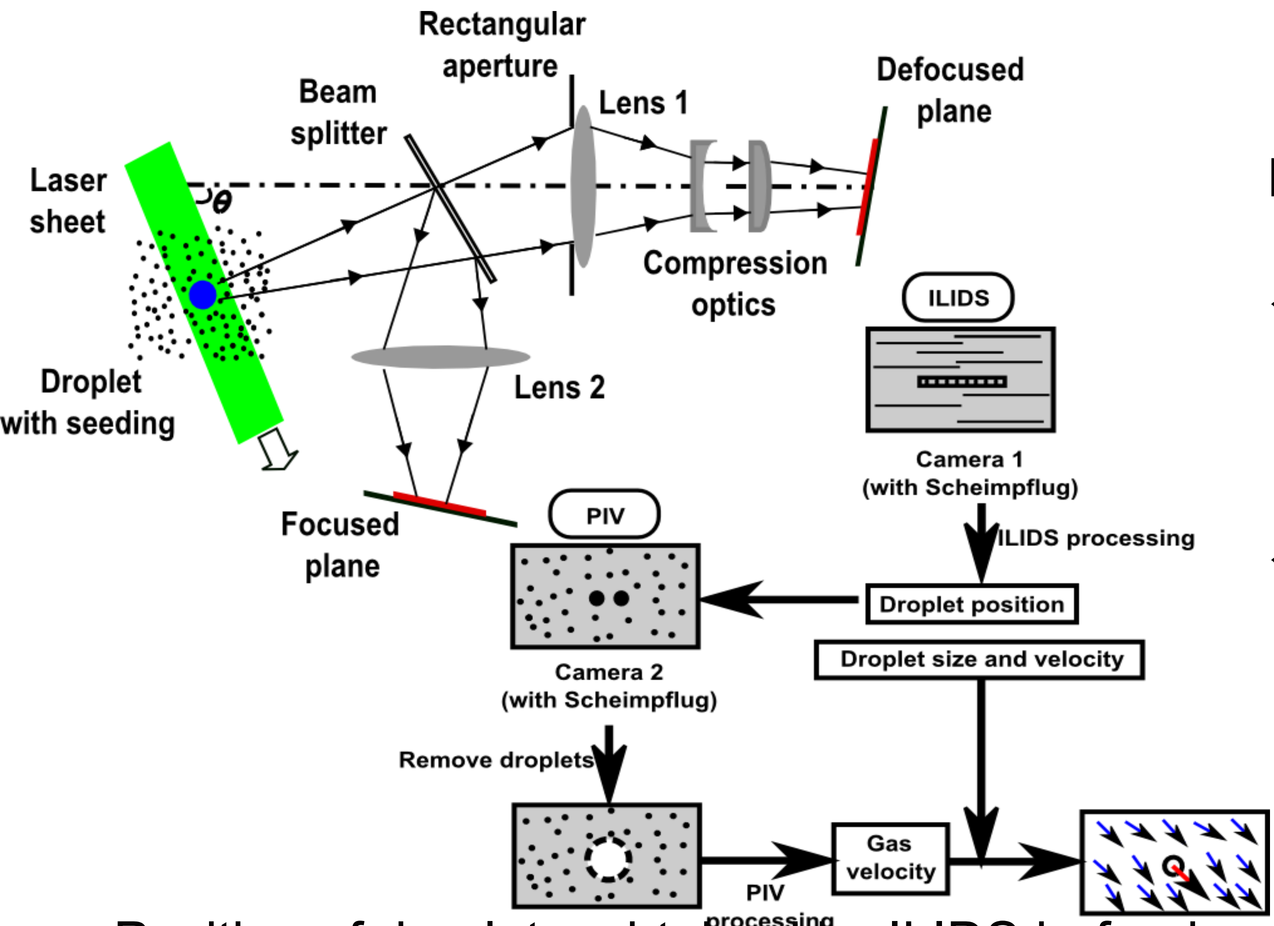
Simultaneous droplet and air flow velocity measurements by ILIDS and PIV



Each droplet is viewed as:

- ✓ a set of fringes at defocused plane of ILIDS camera
- ✓ two glare points at focal plane of PIV camera

- Position of droplets, obtained by ILIDS beforehand, helps in identifying the images of the same droplets in the focused PIV image, thus making it possible to associate the droplet size to the glare-points.

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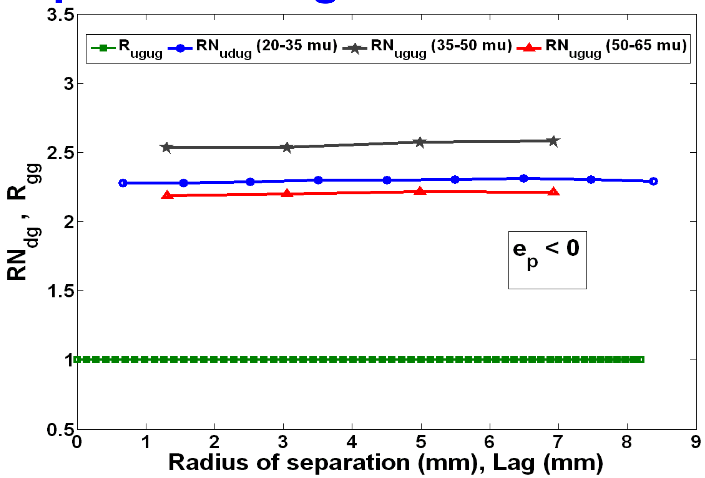
Hardalupas Y., Sahu S., Taylor A.M.K.P. and Zarogoulidis K. "Simultaneous planar measurement of droplet velocity and size with gas phase velocities in a spray by combined ILIDS and PIV techniques". Experiments in Fluids 49, (2010) 417-434.

TKE Modification of various gas flow structures (POD modes) by droplets

Same droplet size augments turbulence for Mode 1 and attenuates it for Mode 4

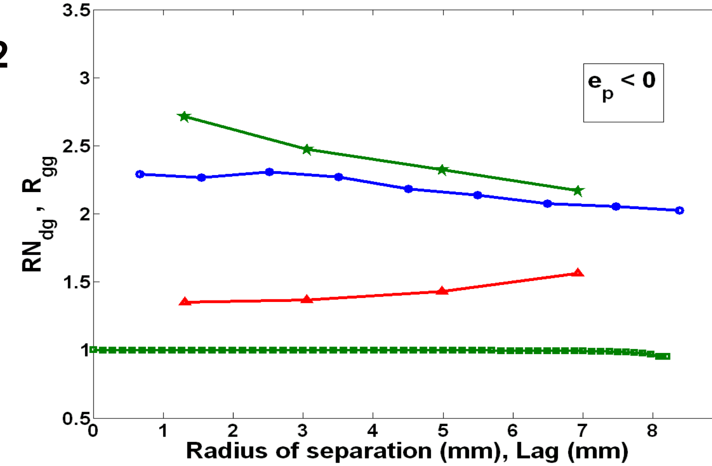
Mode 1

TKE



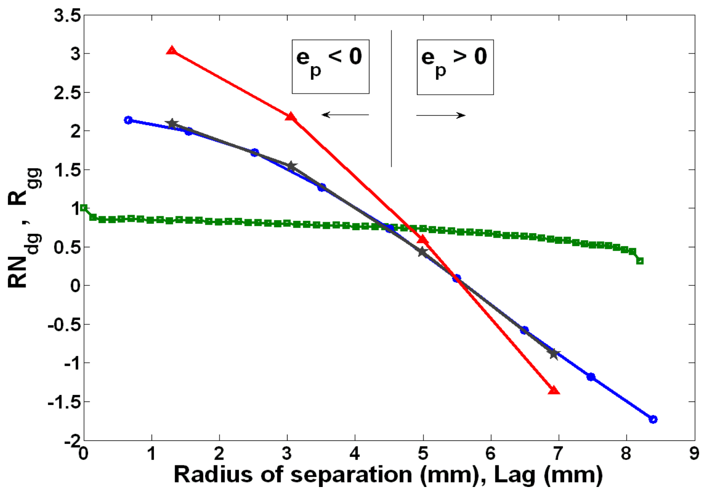
Mode 2

TKE



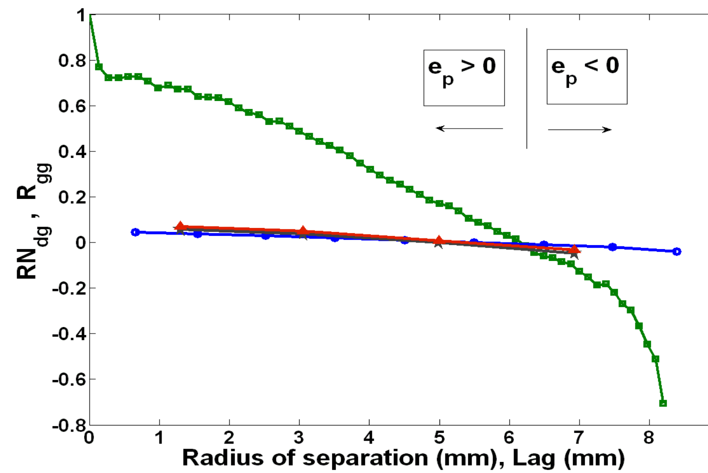
Mode 3

TKE



Mode 4

TKE



Sahu S., Hardalupas Y. & Taylor A.M.K.P.

- "Droplet-turbulence interaction in a confined polydispersed spray: Effect of droplet size and flow length scales on spatial droplet-gas velocity correlations". J. Fluid Mech. 741, 98-138, (2014)
- "Droplet-turbulence interaction in a confined polydispersed spray: Effect of turbulence on droplet dispersion". J. Fluid Mech. 794, 267-309, (2016)

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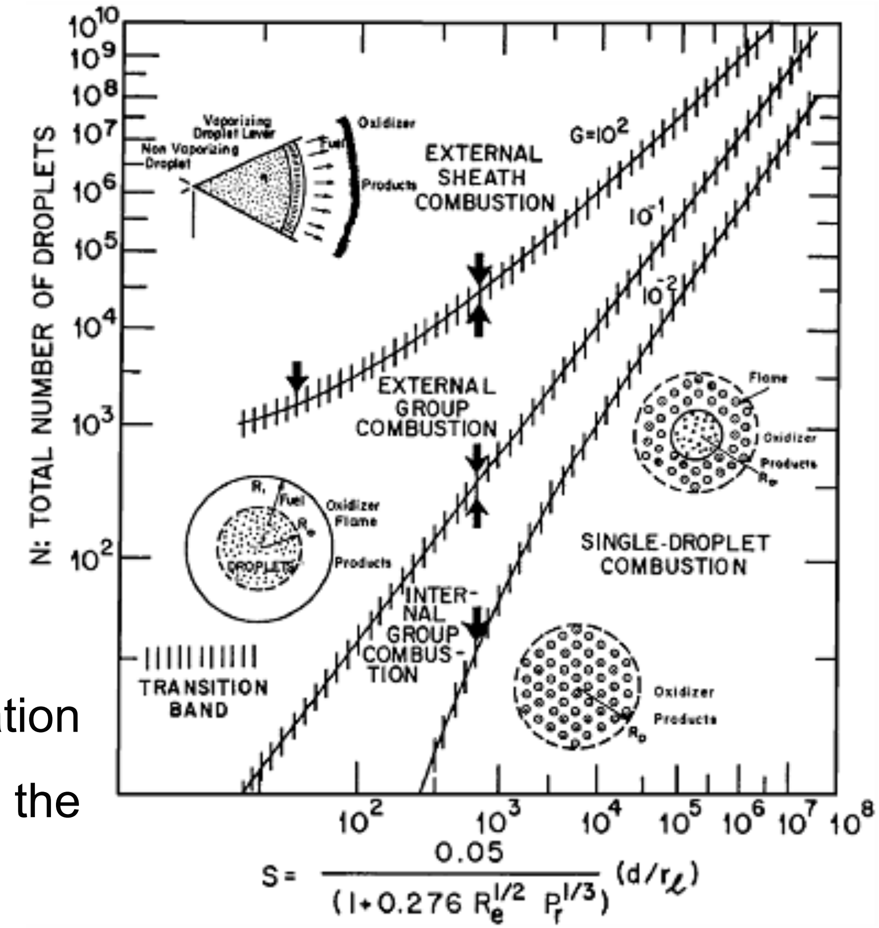
Does instantaneous droplet group ('cluster') evaporation occur?
Does the lengthscale of clusters matter?

- Depending on number of droplets, droplet size and inter-droplet spacing, droplets may evaporate and, eventually, burn, as a group leading to Group Combustion/ Evaporation of droplets, [Chiu & Liu, CST (1977)]



- Group evaporation number

$$G = 1.5(1 + 0.276\mathrm{Re}^{0.5} Sc^{0.33}) Le N^{2/3} \frac{D}{l_d}$$

- It is essential to identify the group evaporation regimes in an evaporative spray and the spatial and temporal variations

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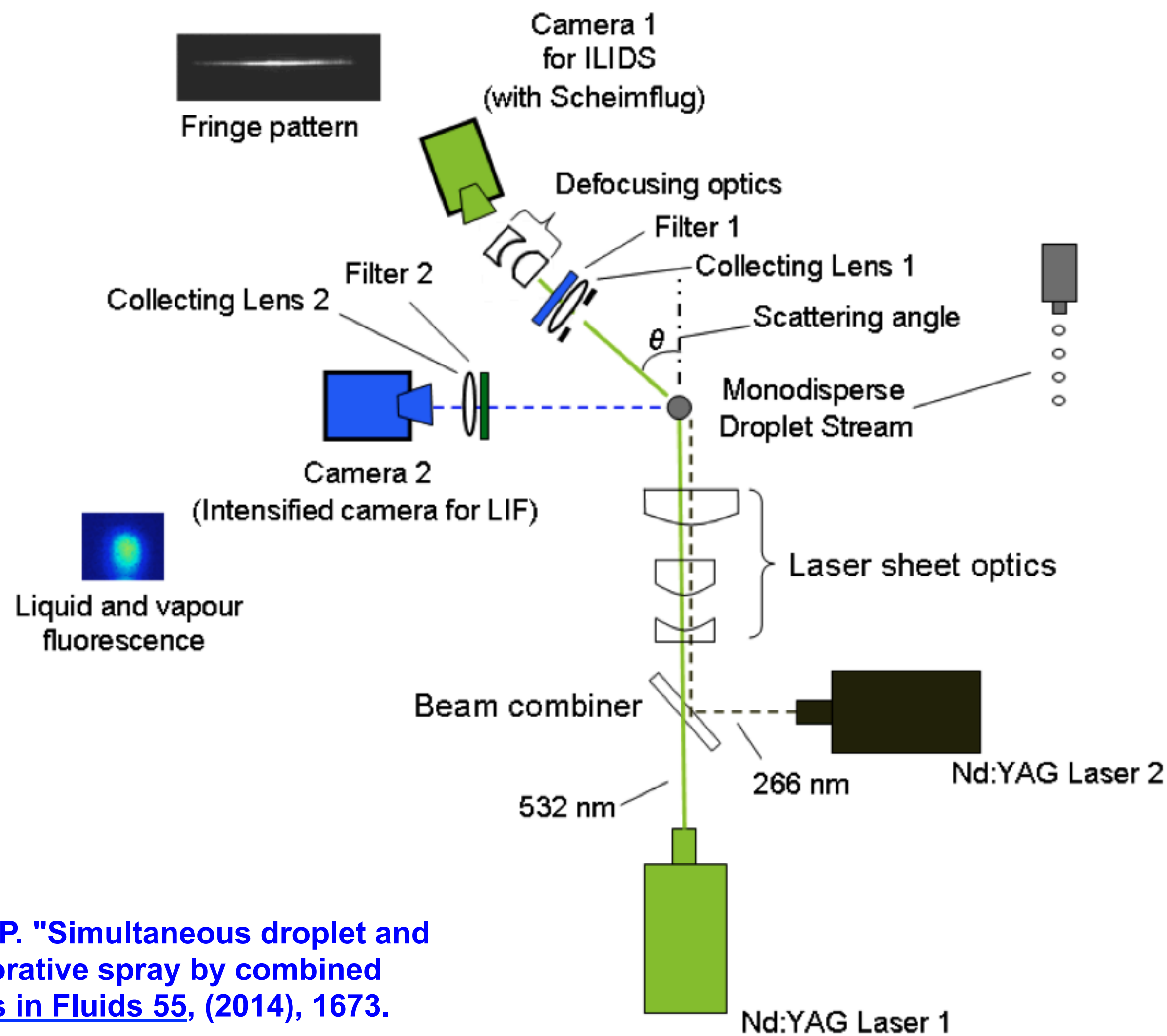
Simultaneous ILIDS and vapour Laser Induced Fluorescence

Simultaneous planar measurements of droplet size, velocity and concentration and vapour concentration measurements



Sahu S., Hardalupas Y. and Taylor A.M.K.P. "Simultaneous droplet and vapour phase measurements in an evaporative spray by combined ILIDS and PLIF techniques". Experiments in Fluids 55, (2014), 1673.

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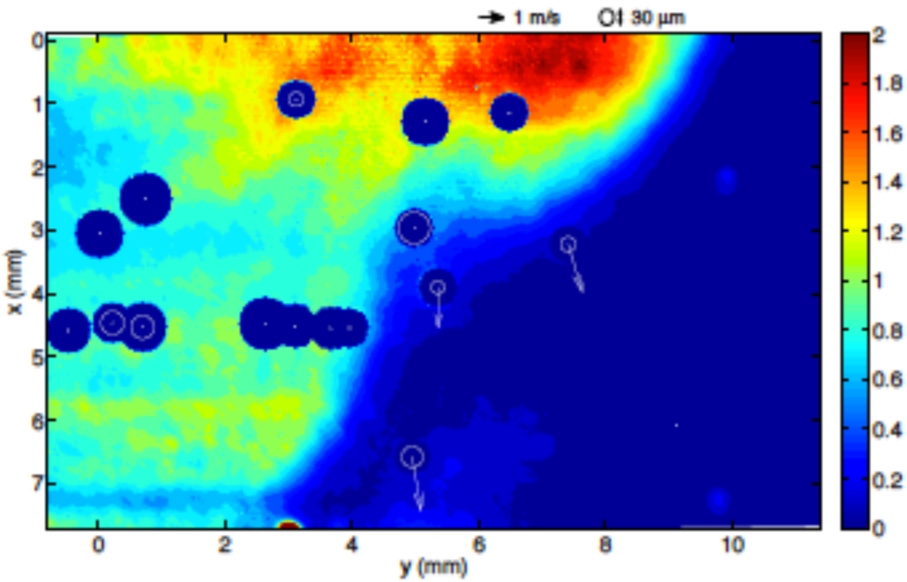
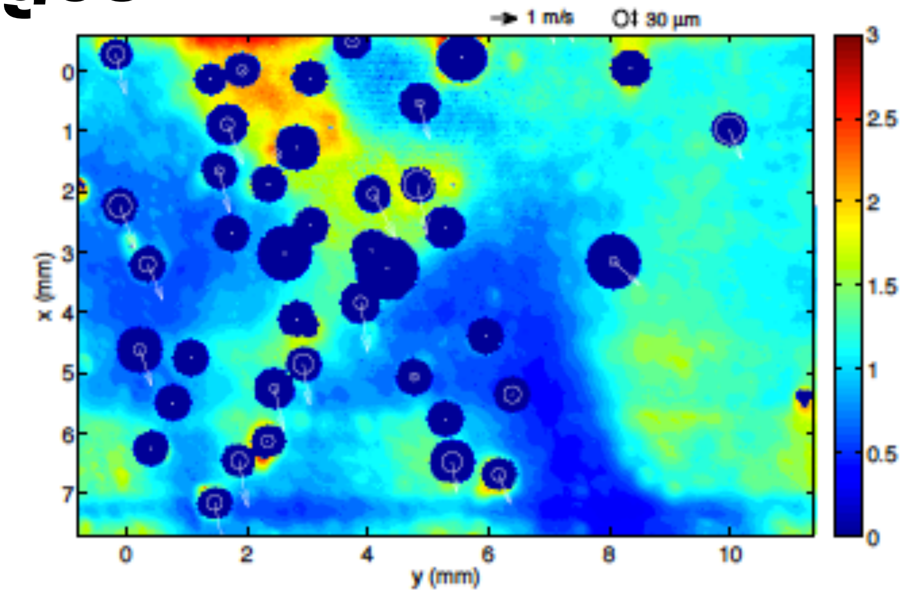
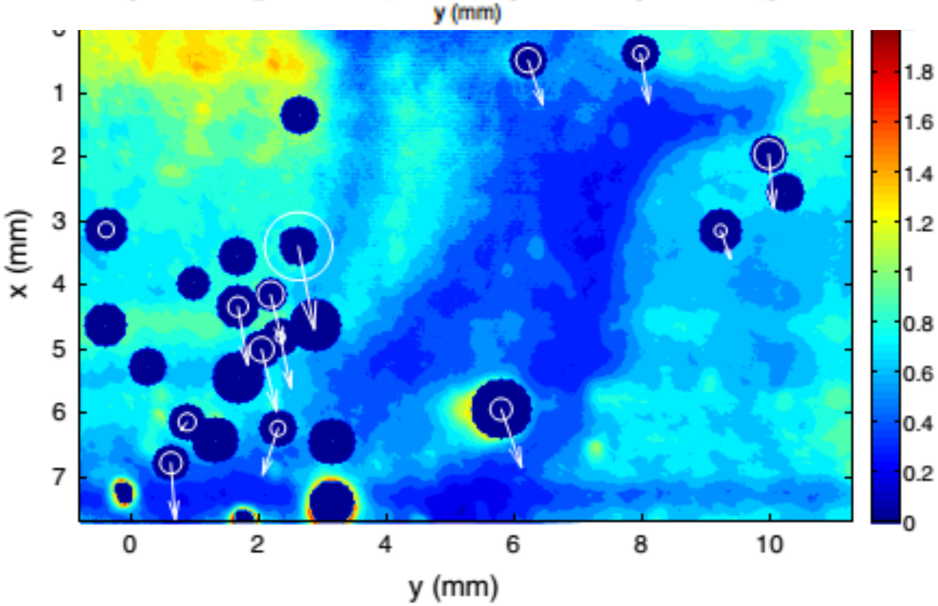
Examples of simultaneous droplet/vapour images

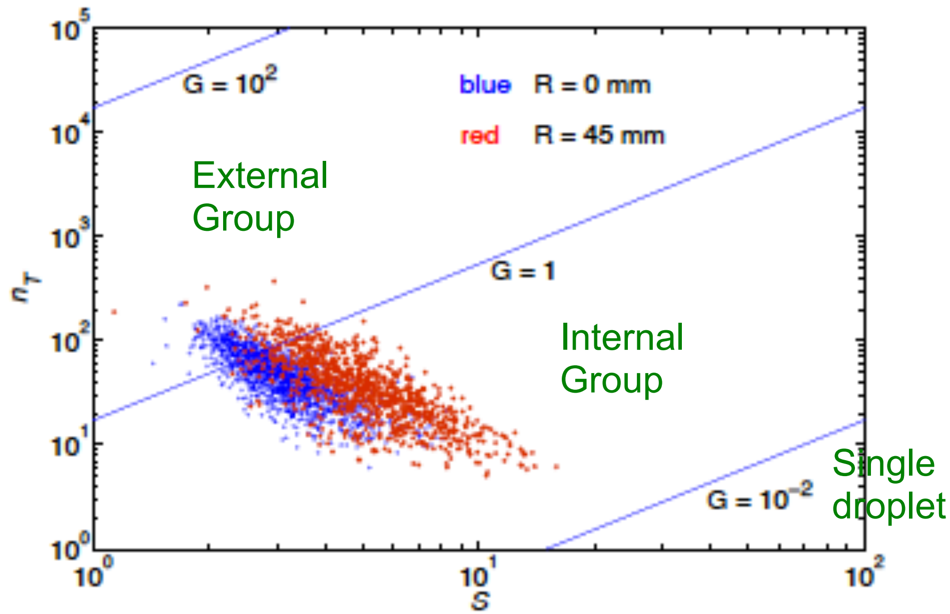






- ✓ Important to know the slip velocity between between droplets and gas flow.
- ✓ In the current spray, slip velocity is small. So correlation between vapour mass fraction and droplet number density fluctuations should exist.

Instantaneous Values of Group evaporation number



- ➢ Instantaneous values indicate some external group evaporation and mainly internal group evaporation. Few cases of single droplet evaporation are present.
- ➢ Very larger variation of the droplet evaporation regime occurs in the spray
- ➢ The observation justifies the behaviour of the cross-correlation coefficient R_{n^*y}

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Sahu S., Hardalupas Y. and Taylor A.M.K.P. (2017), under review

Liquid Film Thickness measurements

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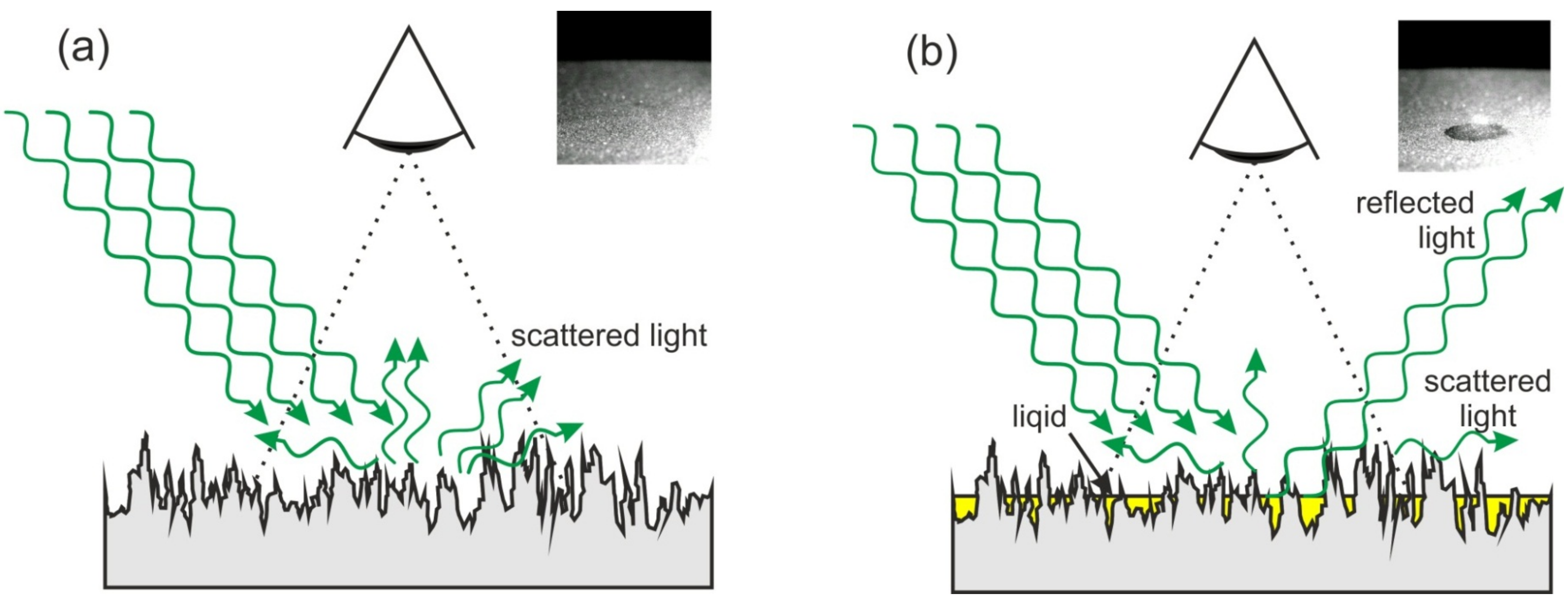
Novel Method for liquid film thickness measurements

Applied to investigate fuel deposit on hot surfaces

– based on “Refractive Index Matching” technique (**RIM**)

–“Diffuse Scattered Light Ratio” (**DSLR**)



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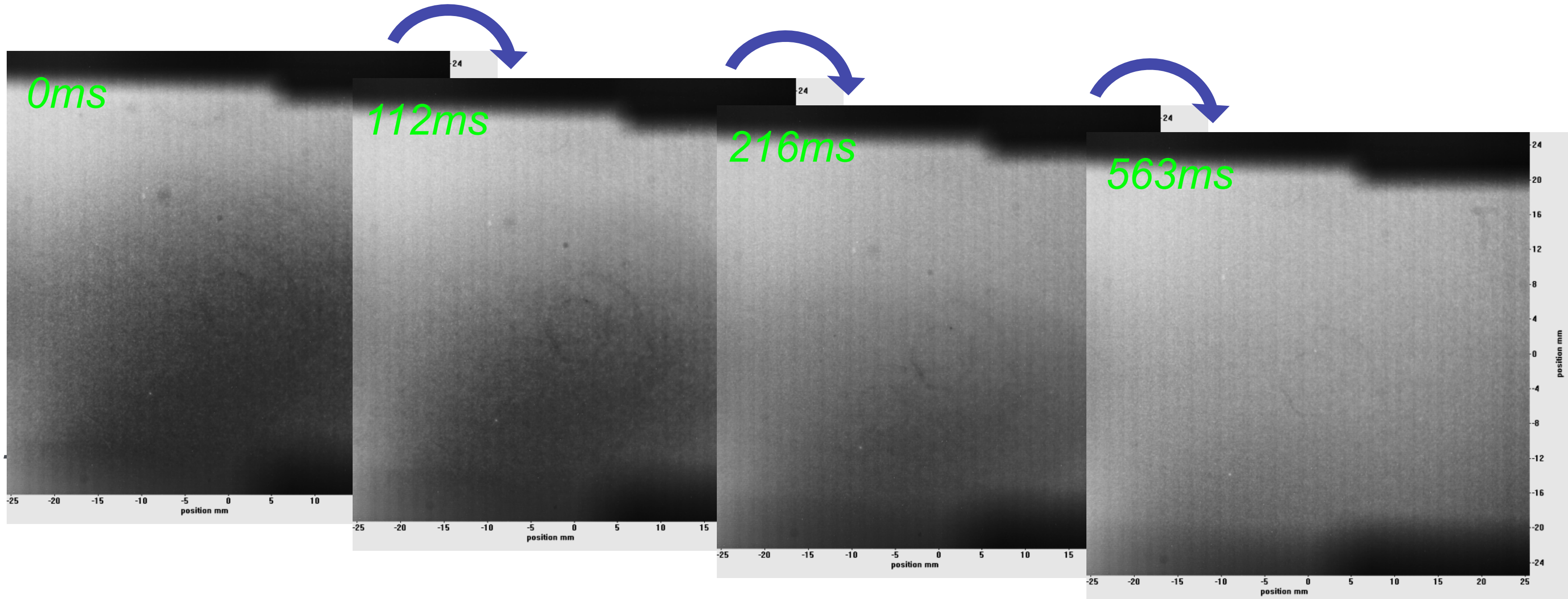
Henkel S., Beyrau F., Hardalupas Y., Taylor A.M.K.P. “A novel method for the measurement of liquid film thickness during fuel spray impingement on surfaces”. Optics Express 24, (2016), 2542-2561.

Fuel Deposit and Evaporation



- *Condensation due to breathing on a plate is sufficient to change intensity significantly and measure micron size film thickness*

  → *Technique is very sensitive*

  → *No requirement of addition of fluorescent dye*

  → *Requires calibration with known liquid volume on surface*

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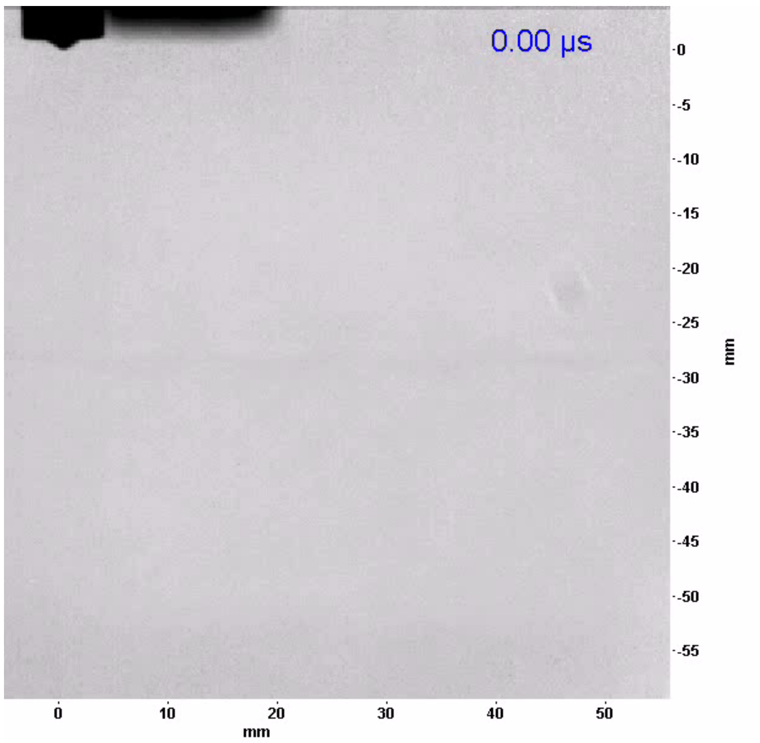
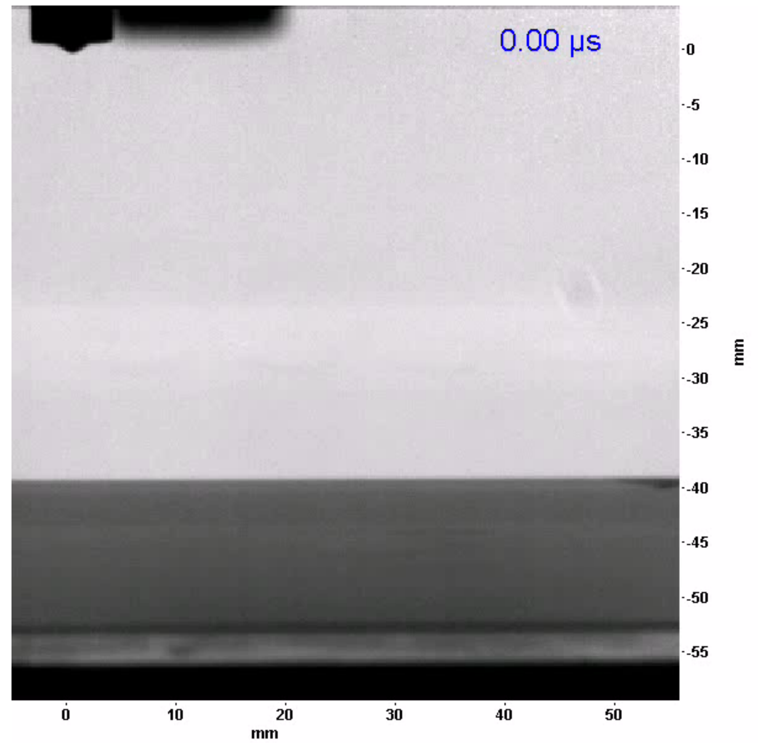
Gasoline Direct Injection Spray

High speed recordings of the spray



Free spray configuration



Impinging spray configuration

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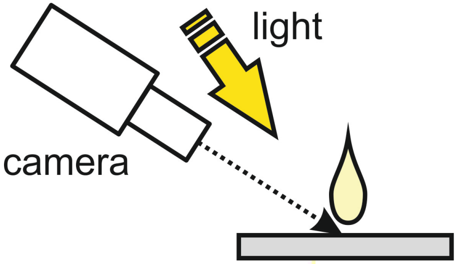
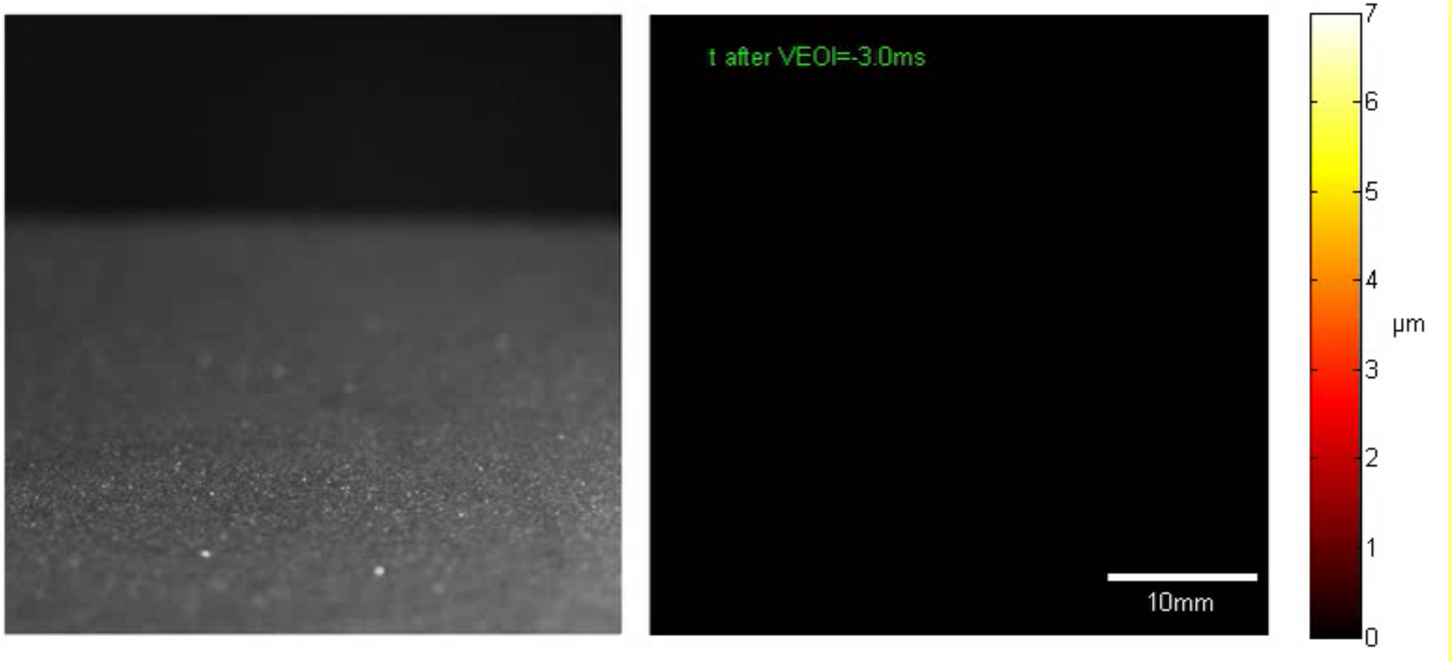
Fuel Deposit and Evaporation

Data acquisition and post processing

→ correction for optical distortion

→calibration method





→2D information of fuel deposit over time

Tanaka D., Uchida R., Noda T., Kolbeck A., Henkel S., Hardalupas Y. and Taylor A.M.K.P. "Effects of Fuel Properties Associated with In-Cylinder Behavior on Particulate Number from a Direct Injection Gasoline Engine". SAE Technical Paper 2017-01-1002, 2017

Summary

- Planar optical methods for characterisation of the near nozzle region and the downstream spray chracteristics are necessary for new physical understanding

- Planar, instantaneous measurements in space are required for evaluation of current LES computational approaches

- It is important to understand the physical meaning of the experimental data and try to compute the same quantity

- Volume-based, as opposed to planar, optical diagnostics represent a useful development

Thank you