Novel Spray Measurements in Support of Modeling Advancements

Presented to the 4th Workshop on Measurement and Computation of Turbulent Spray Combustion (TCS4)

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TSC3 – invited lecture:

Atomization and Spray: Link to Turbulence, Vaporization and Combustion

by Francois-Xavier Demoulin from CORIA

He discussed many interesting approaches to modeling, but also mentioned a lack of information about the spray formation region.

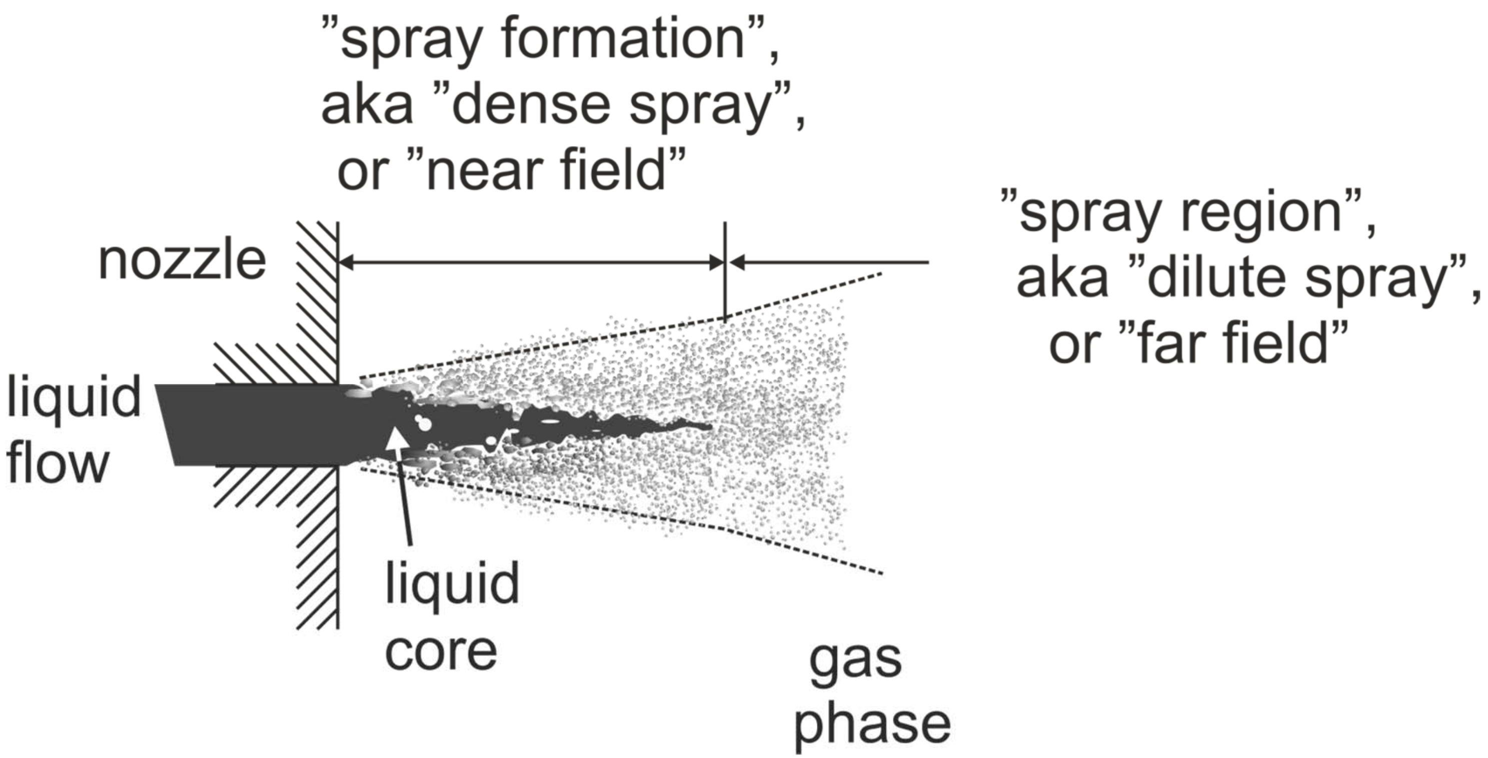
Also, from Baumgarten's book: "experimental investigation is extremely complicated because of the dense spray and small dimensions … it is difficult to understand the relevant processes and verify primary breakup models."

Some of us are trying to help

Topics

- Sprays and nomenclature
- Measurements across the spray
- Measurements in the spray formation region
- What is possible
- Discussion

Sprays and nomenclature



SPRAY: 1) water or other liquid broken up into minute droplets and blown, ejected into, or falling through air (or a more complex gas); 2) a jet of fine particles of liquid, as medicine, insecticide, paint, perfume, etc., discharged from an atomizer or other device

Topics

- Sprays and nomenclature
- **Measurements across the spray**
- Measurements in the spray formation region
- What is possible
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Measurements across a liquid jet/spray

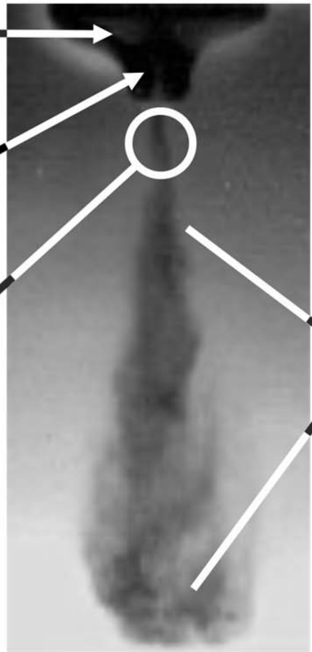
Dissolved O_2 in fuel
pyrene LIF decay

Surface temp.
Thermographic phosphors

Inside nozzle
- optical tip + microscope
- x-ray pci

Spray formation
- ballistic imaging
- x-ray radiography

Gas phase
PIV

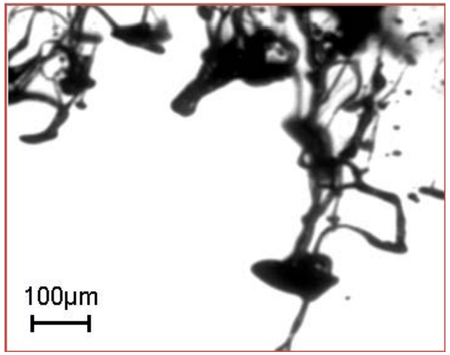


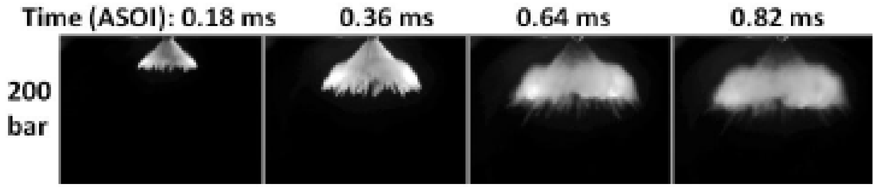
Spray region
Spray imaging: high speed Shadow/Schlieren, Mie/LIF
Droplets: PDI, LSD
Combustion species & temperature: LIF/Raman
Soot: thermal emission, LII
SLIPI

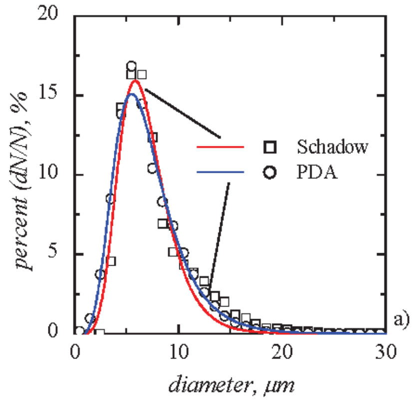
Most spray researchers are familiar with the more common measurements

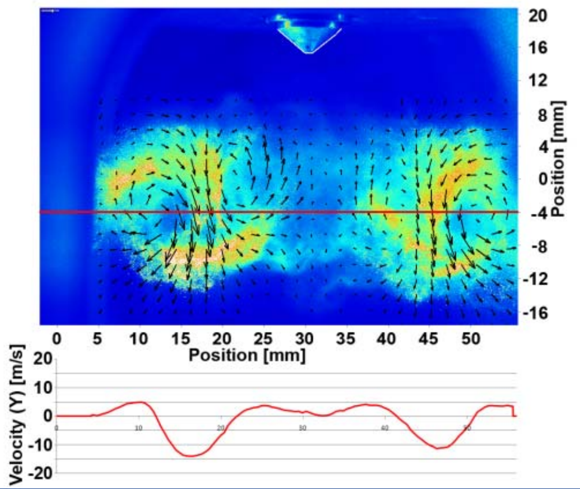
Typical experimental tools

- Shadowgraphy
- High speed imaging
- Planar laser imaging
  - o PIV (images of 3-D velocity)
  - o Laser induced exciplex imaging for drops/vapor and T
  - o Mie/LIF imaging of droplets & vapor
  - o LII (soot)
- Phase Doppler interferometry



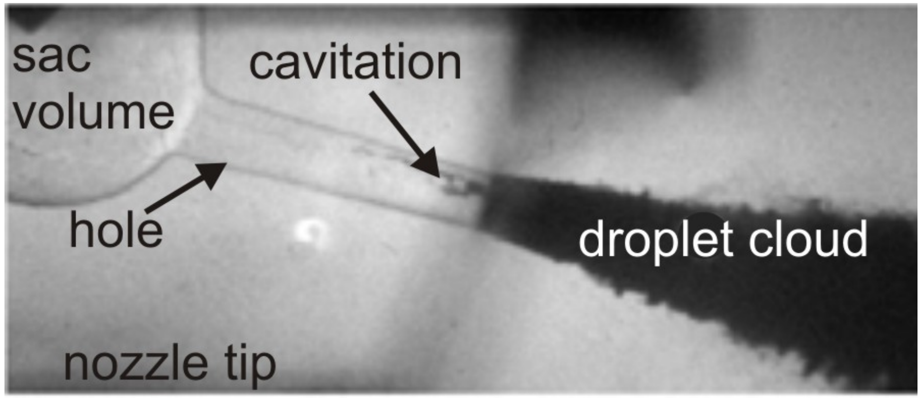






What has been missing?

- Upstream - optically transmissive Diesel injector tip shows us that the liquid cavitates inside the nozzle[1]:



- Until recently it has been impossible to see what happens when the liquid leaves the nozzle (in the spray formation region) because a dense droplet cloud hides what is happening
- The optical depth in a Diesel spray issuing into 1 atm is about 10 – 13 (human tissue is 11)

1. M. Blessing, G. König, C. Krüger, U. Michels, V. Schwarz, SAE paper no. 2003-01-1358 (2003)

Topics

- Sprays and nomenclature
- Measurements across the spray
- **Measurements in the spray formation region**[2]
- What is possible
- Discussion

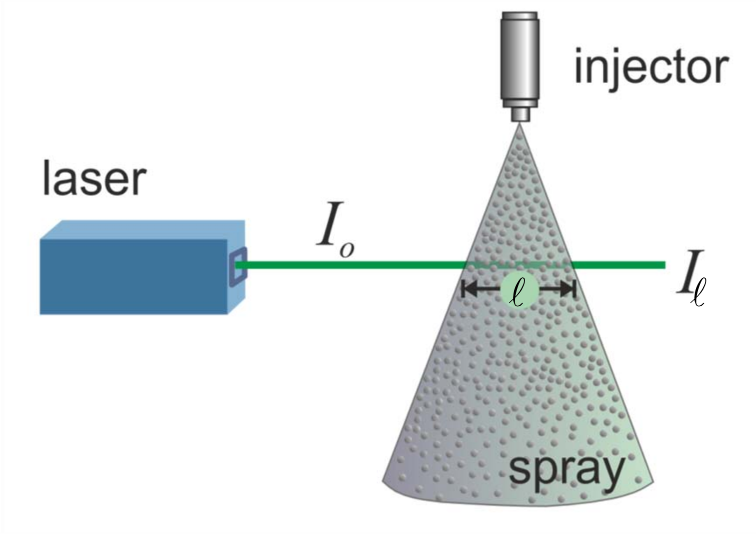
2. M. Linne, Progress in Energy and Combustion Sciences, Vol. 39, No. 5, 403 - 440, (2013).

Optical depth

- What is an optically dense spray anyway?
- Lambert-Beer law:

$$\tau = \frac{I_\ell}{I_\circ} = e^{-OD}$$

$$OD \equiv N\sigma_e \ell$$

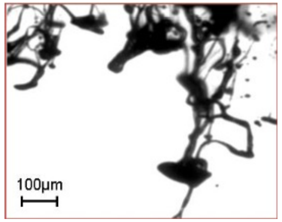


N = no. density of drops in this case, σ_e = extinction cross section for the drops & ℓ = path length through the spray

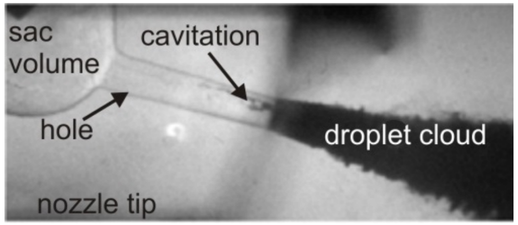
- For sprays, $1 \leq OD \leq 12$

Optical depth

- For OD ~ 1 – 2 no special techniques are required, one can use classical optical shadowgraphy (but use a fast shutter to freeze motion)



- When OD ~ 2 – 5 optical measurement becomes more difficult and it is necessary to use specialized techniques (SLIPI, PDI works also)
- When OD > 5 optical measurement becomes very difficult, and for OD ~ 10 one can make measurements but they will never be entirely free of corruption

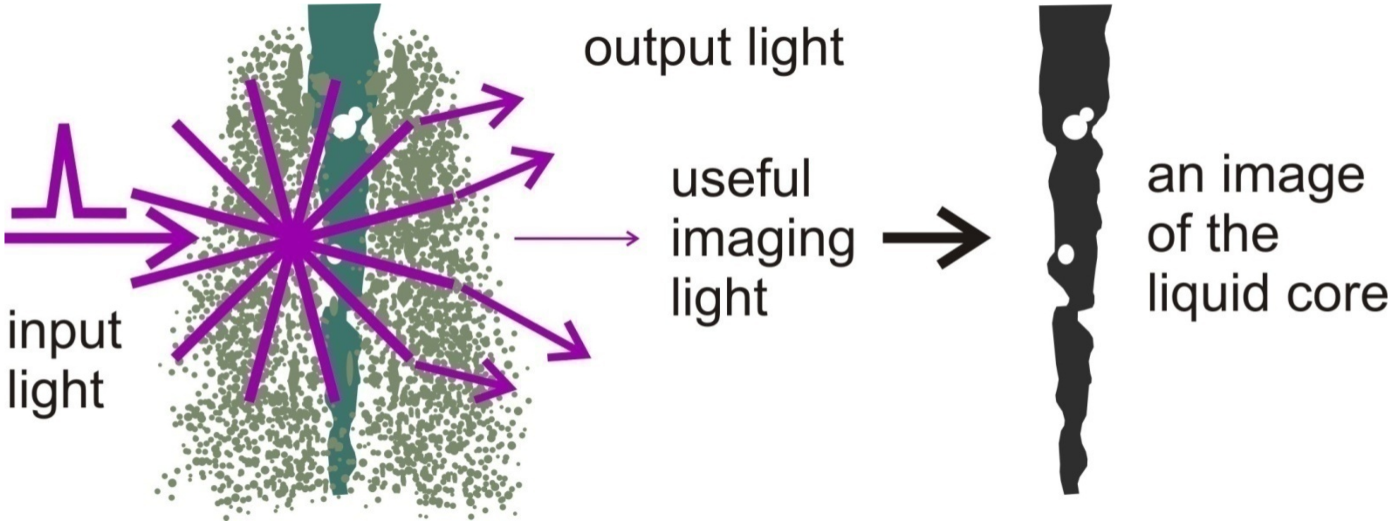


- X-rays have OD effectively = 0 in sprays unless absorption is strong, which is why x-ray techniques are discussed so much – but they can have problems
- The name "dense region" applies just to optical wavelengths

New techniques for the spray formation region

- Ballistic imaging (a trans-illumination laser technique)
- Structured laser illumination planar imaging (SLIPI, a planar laser technique)
- X-ray phase contrast imaging (a trans-illumination x-ray technique)
- X-ray radiography (a trans-illumination x-ray technique)

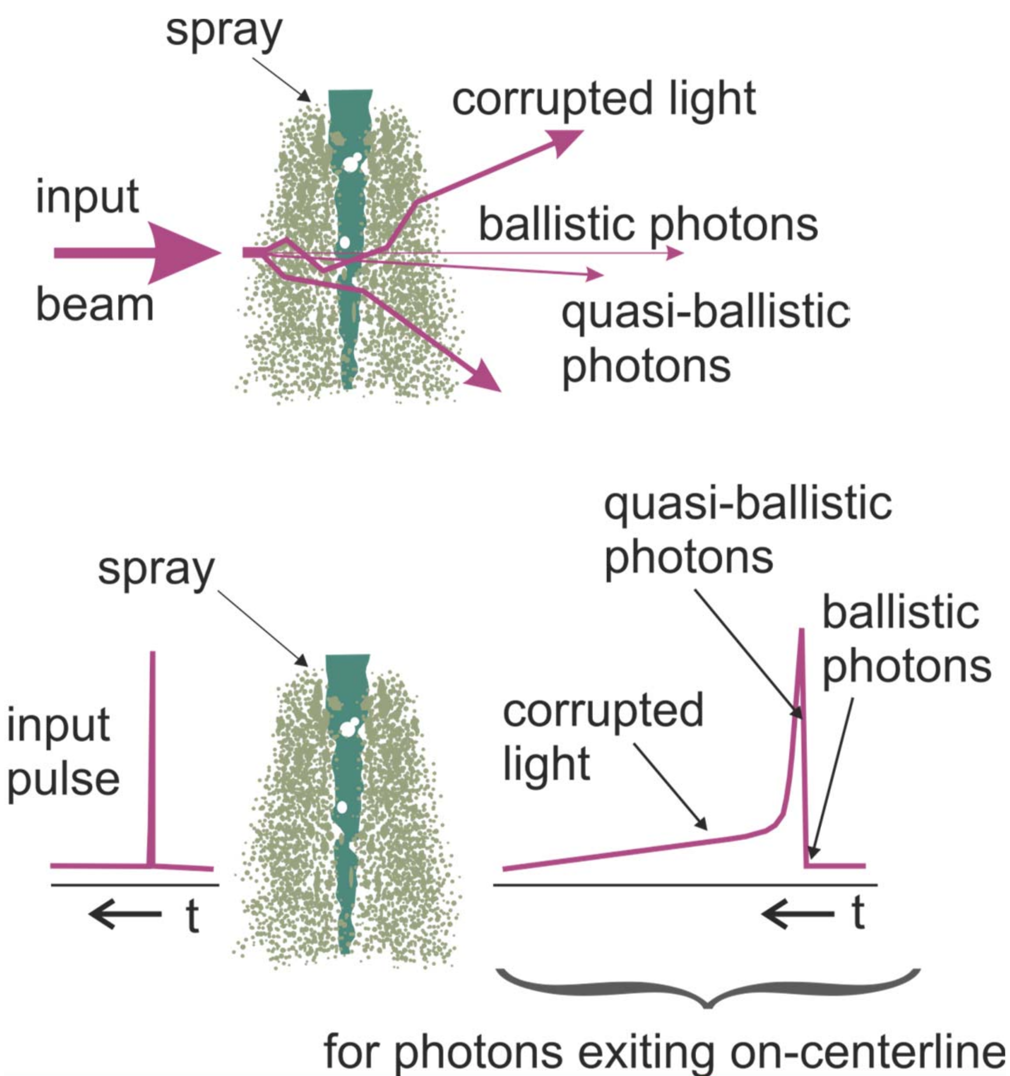
Introduction to ballistic imaging[3]



- Use what we know about light traversing a turbid medium:
  - Most of it is just spatial noise caused by **scattering off-axis** that corrupts the image
  - A very small amount of it contains useful image information about structures (e.g. intact liquid) buried inside – via **refraction**
  - The useful imaging light has not been corrupted with spatial noise
- Collect just useful imaging light; rejecting most of the light exiting the spray, and turn up the camera gain

3. M. Paciaroni, M. Linne, Appl. Opt. 43, 5100-5109, (2004)

Introduction to ballistic imaging



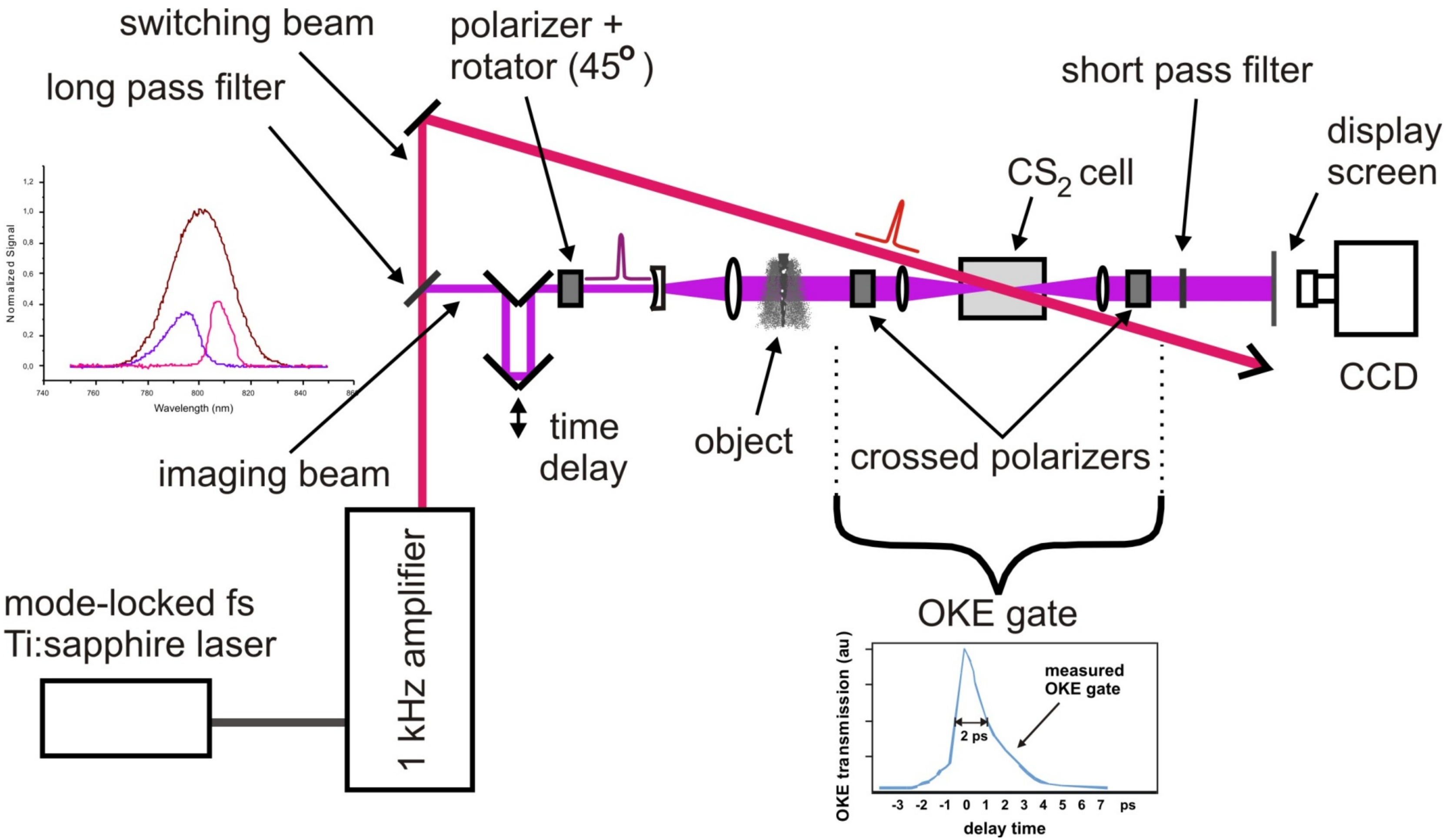
Even in turbid media, some photons do not scatter, passing directly through the medium – called “ballistic photons”. Forward scattered photons can behave almost exactly the same way – all of them together are called useful imaging light

Because they do not scatter at significant angles, useful imaging photons have the shortest path length and exit first

Introduction to ballistic imaging

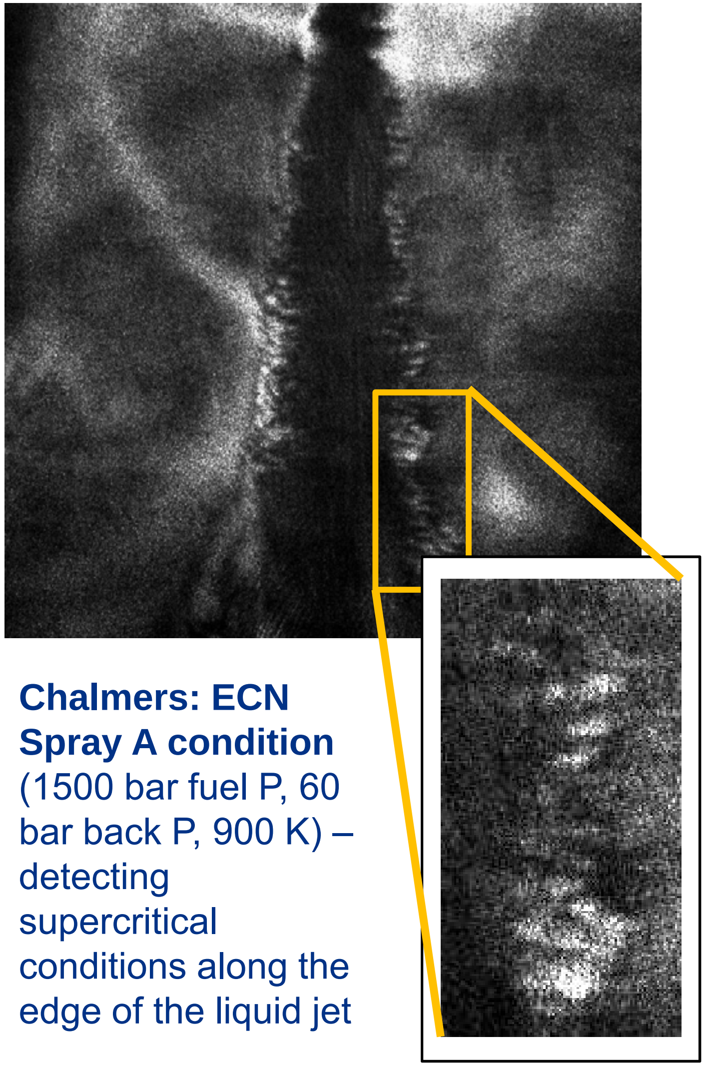
- Useful imaging photons can be used to image the liquid core via refraction (like a shadowgram) – if separated from the much more prevalent corrupted light
- This can be done by seeking their signature:
  - Directional orientation (spatial filtering)
  - Preservation of polarization (polarization filtering)
  - First to exit (time gating)
  - Ballistic photons are coherent with the input beam (coherence gating – interferometry, DFWM)
- We use the first 3

Two-band transient ballistic imaging



Ballistic imaging system at Chalmers

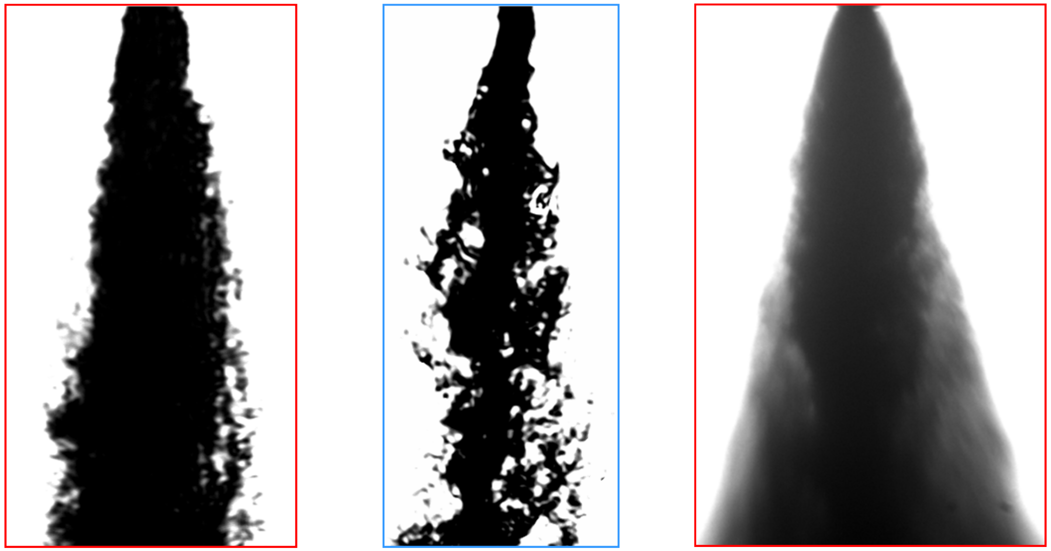
Diesel sprays by 2 different groups:



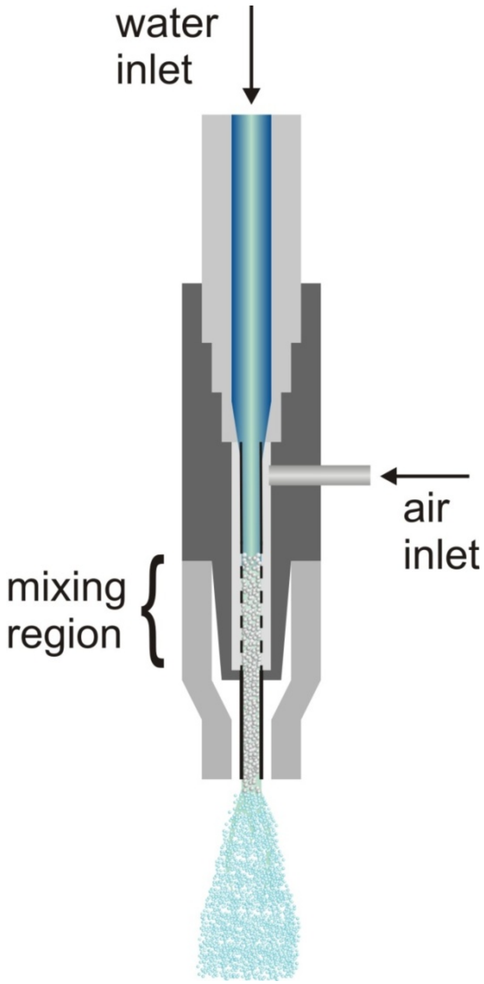
Chalmers: ECN Spray A condition (1500 bar fuel P, 60 bar back P, 900 K) – detecting supercritical conditions along the edge of the liquid jet

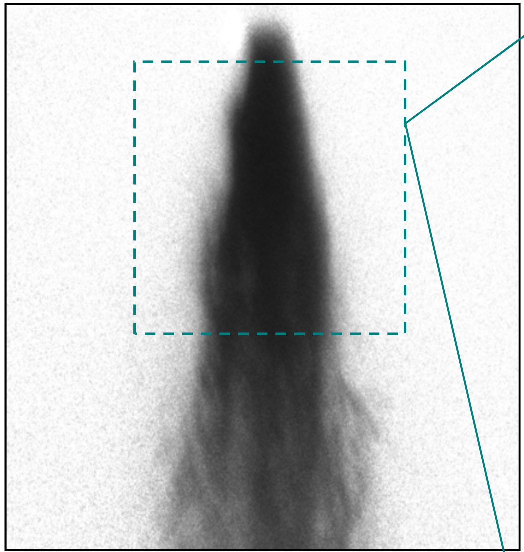
CNRS/CORIA
Diesel spray into 1 bar, room T

steady period | late in injection | shadowgram of spray

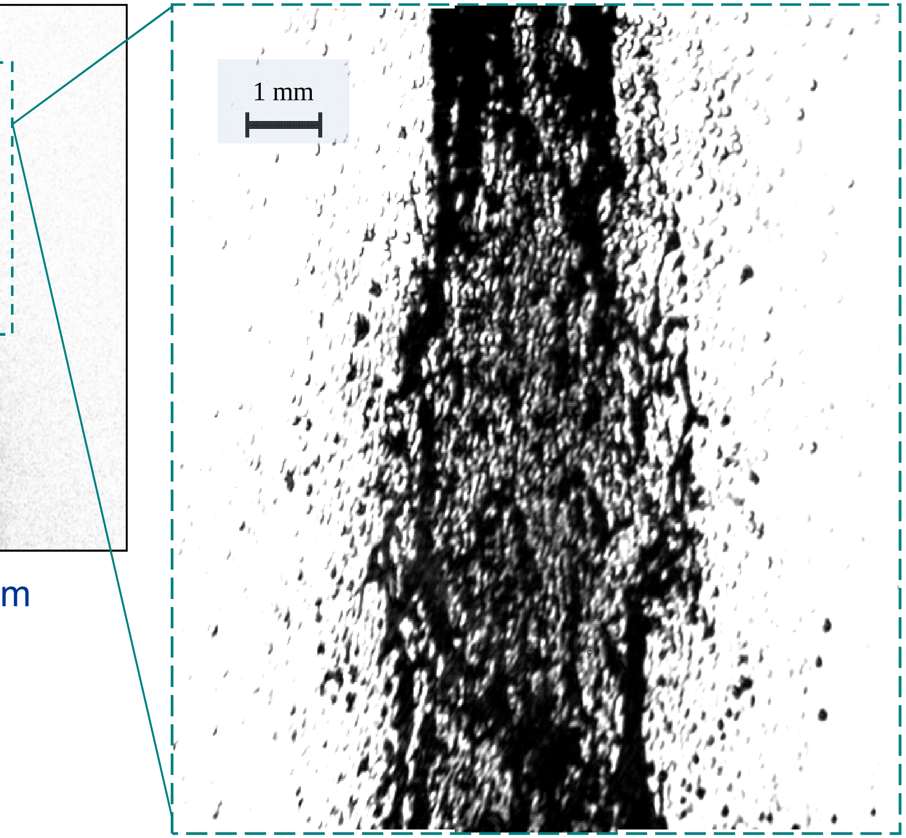


Effervescent spray developed and studied by Cam Carter (AFRL):





White light shadowgram

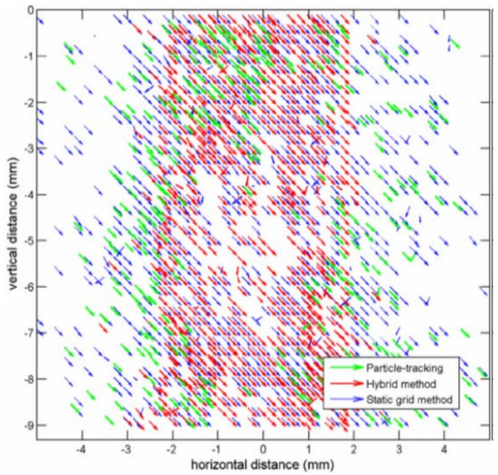


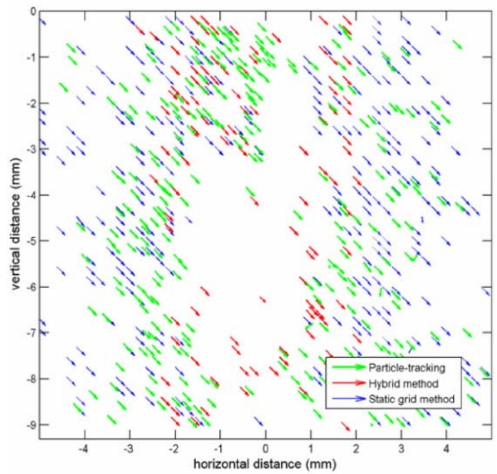
Time gated ballistic image

Two images taken in rapid succession (e.g. 10 μs) can be correlated to extract velocities

- Distinct droplets correlate similar to PTV
- Can also correlate structures and edges ("grid technique") to get the velocity of the liquid/gas interface
- Can characterize & minimize errors:

60% correlation coefficient





95% correlation coefficient

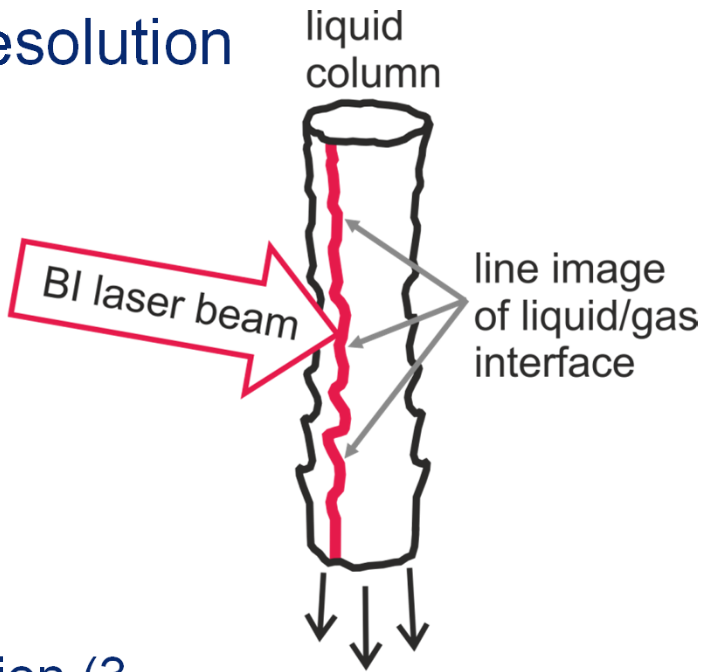
Error results:

	PT	Hybrid	Grid
60% correlation	3/313 < 1%	23/713 ~ 3%	42/928 ~ 4.5%
95% correlation	3/279 ~ 1%	0/109 0%	4/327 ~ 1%

Consider a third amplifier

Ballistic imaging attributes

- The fs lasers are not cheap
- A line-of-sight technique, but it captures the liquid/gas interface with good spatial resolution (from 20 – 30 μm)
- Not a drop size technique
- Can go up to OD = 14
- Can extract statistics on:
  - Ligament size distributions
  - Void size distributions
  - Surface curvature distribution
  - Surface wave spectra
  - Velocity (2-pulse system) and/or acceleration (3-pulse system)
- Does not detect liquid mass

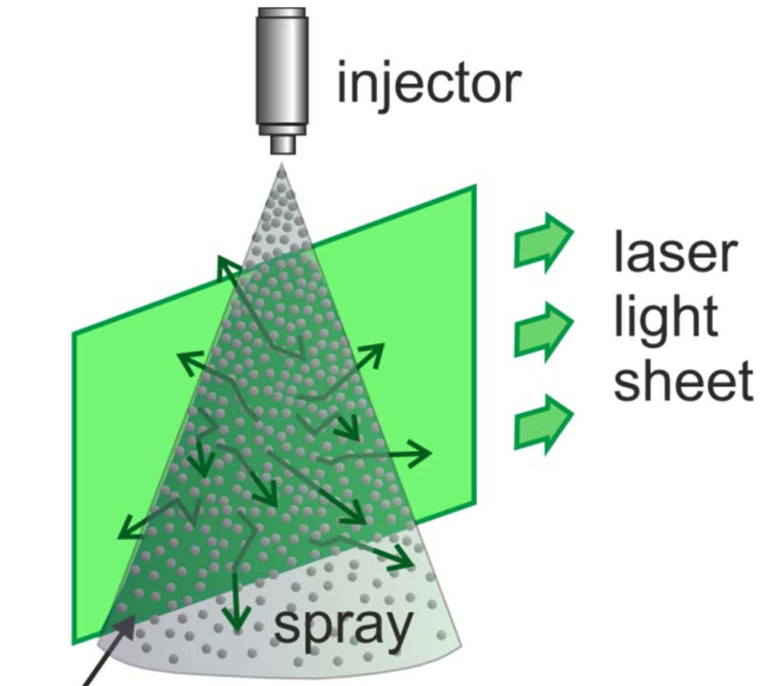


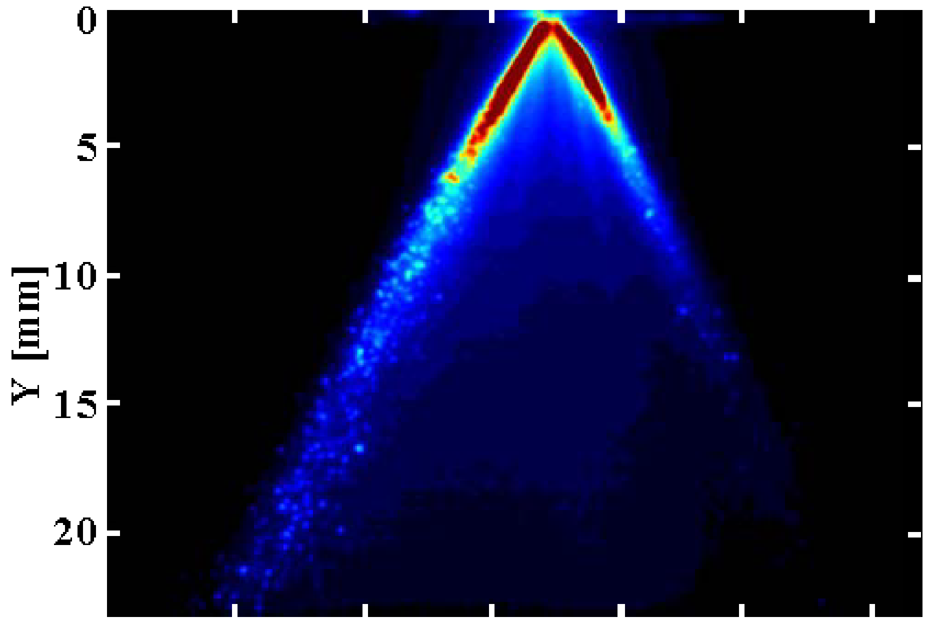
New techniques for the spray formation region

- Ballistic imaging (a trans-illumination laser technique)
- **Structured laser illumination planar imaging (SLIPI, a planar laser technique)**
- X-ray phase contrast imaging (a trans-illumination x-ray technique)
- X-ray radiography (a trans-illumination x-ray technique)

SLIPI[4]

- The problem – multiple scattering from a planar imaging format

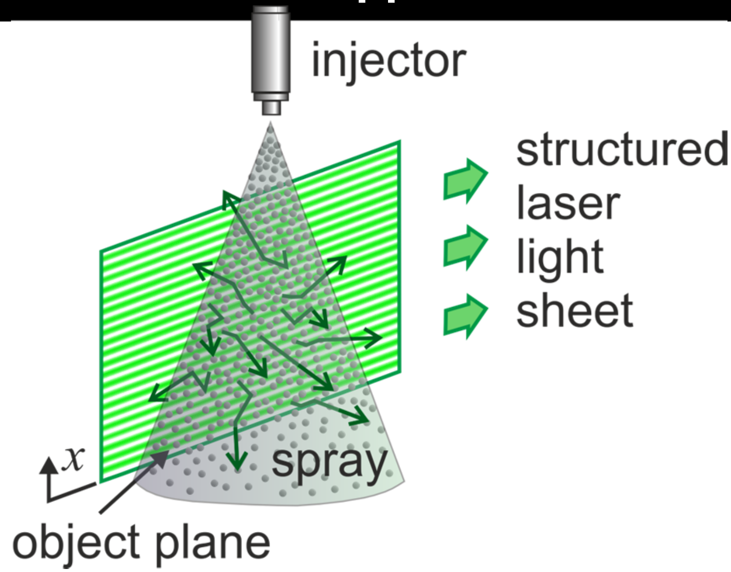




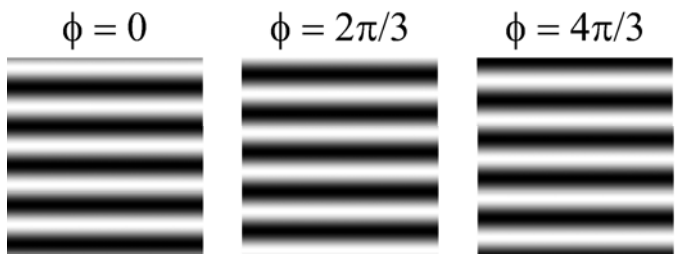
- A hollow cone spray has very few drops in the center but this planar image shows a lot of structure in the center – caused by multiple scattering

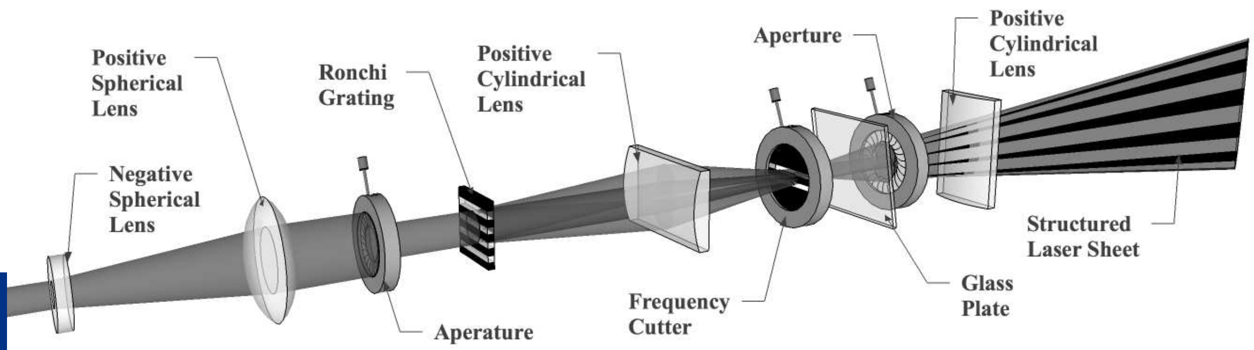
4. E. Berrocal, E. Kristensson, M. Richter, M. Linne, M. Aldén, . Opt Express 16 (22) 17870-17881, (2008)

SLIPI



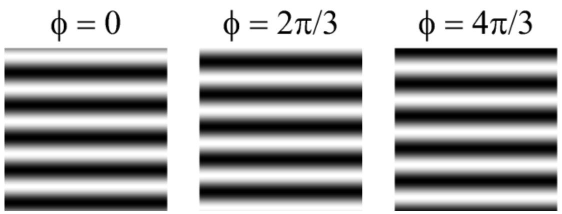
- The solution:
  - Imprint the light that originates from the object plane (with a spatial sinusoid)
  - Multiple scattering will remove the imprint
  - Use image processing to reject light that lost the imprint
  - Need to fill in the gaps – use 3 such planes shifted up (in x) – have to take 3 images
  - System uses 1-3 pulsed Nd:YAG laser(s)
  - Whole setup:



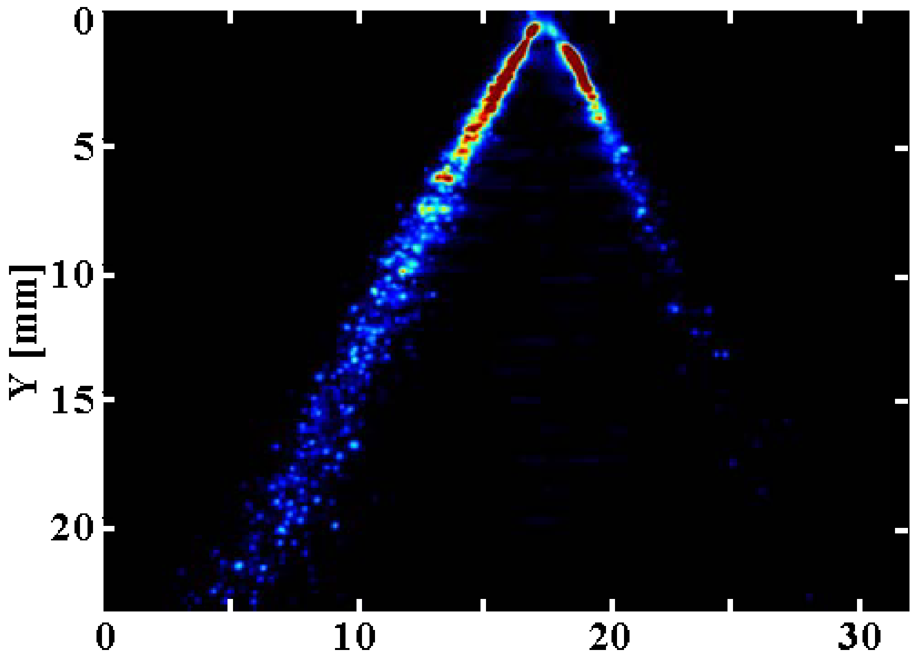


SLIPI

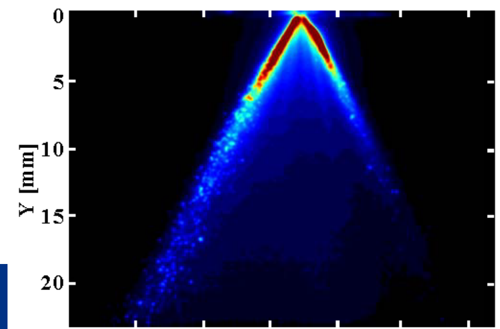
- The rms of the three images is taken:



$$I_s = \frac{\sqrt{2}}{3}[\left(I_0 - I_{2\pi/3}\right)^2 + \left(I_0 - I_{4\pi/3}\right)^2 + \left(I_{2\pi/3} - I_{4\pi/3}\right)^2]^{1/2}$$



- The same hollow cone spray acquired via SLIPI, v.s. this

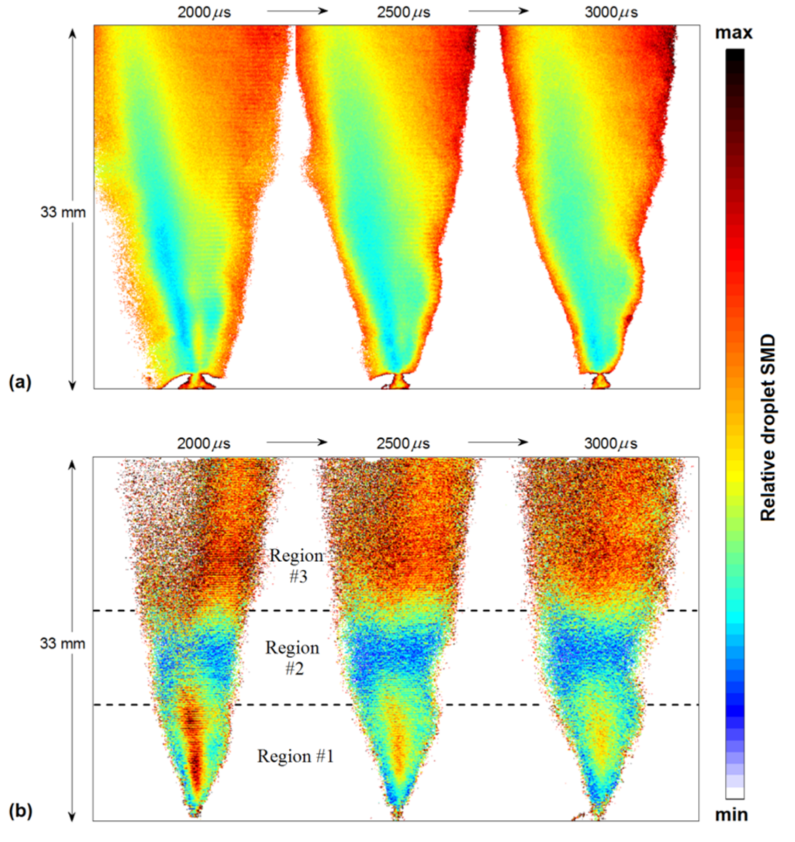


SLIPI attributes

- SLIPI works for droplet scattering (Mie) and LIF imaging
- Can take 3 images with 1 laser in an averaged-image format, manipulate the 3 images and get an averaged SLIPI image (commercially available from LaVision)
- Can get 3 small Ng:YAG lasers with an imaging system that can capture 3 images very quickly and capture an instantaneous SLIPI image
- SLIPI works up to an OD < 6
- NEW – “Two-pulse SLIPI” by Elias Kristensson, presented at ILASS last week – could use a modified PIV system

SLIPI applied to LSD

- Laser sheet dropsizing: the ratio of two images (LIF/Mie) gives an image of droplet SMD – but there are many problems – and one of them is multiple scattering



- Relative drop size from conventional LIF/Mie images

- Relative drop size from SLIPI LIF/Mie images

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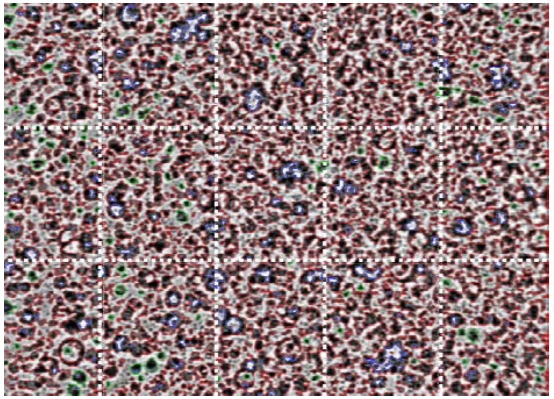
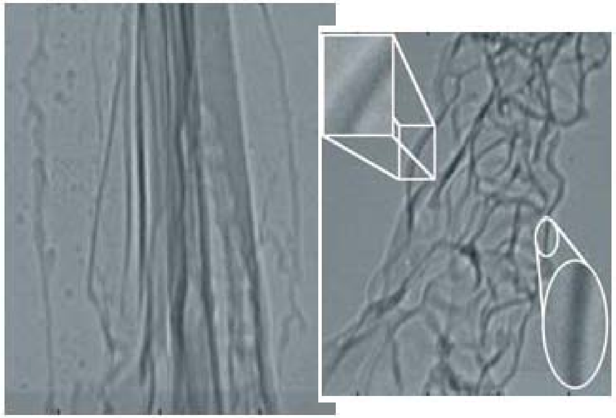
- X-ray radiography (a trans-illumination x-ray technique)

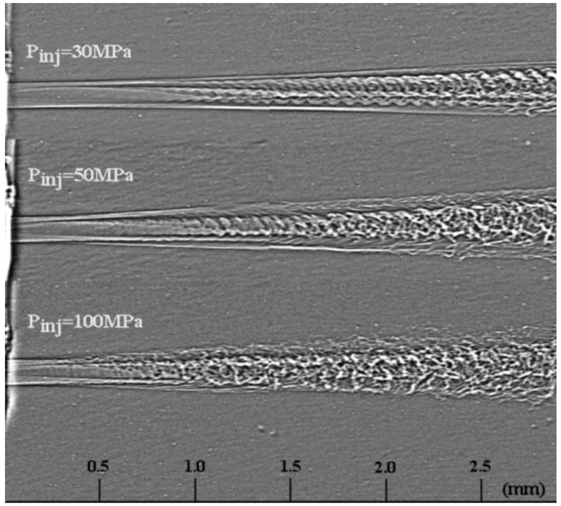
X-ray phase contrast spray imaging



Effervescent water spray producing large drops[5]

Gasoline injector producing many small drops[6]





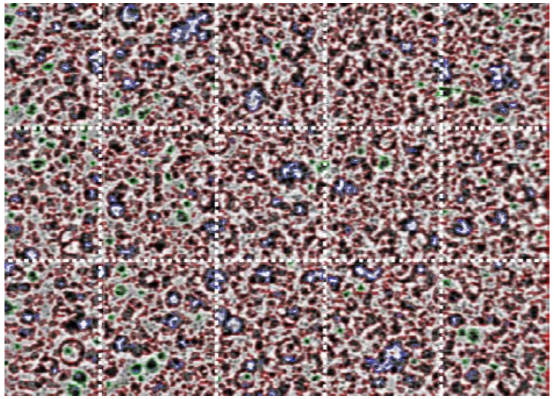
Bio-Diesel spray with hydro-ground nozzle[7]

5. K.-C. Lin, C. Rajnicek, J. McCall, C. Carter, K. Fezzaa, ILASS Americas, (2010).

6.- Y. Wang, X. Liu, K.S. Im, W.K. Lee, J. Wang, K. Fezza, D.L.S. Hung, J.R. Winkelman, Nature Physics 4, 305 (2008).

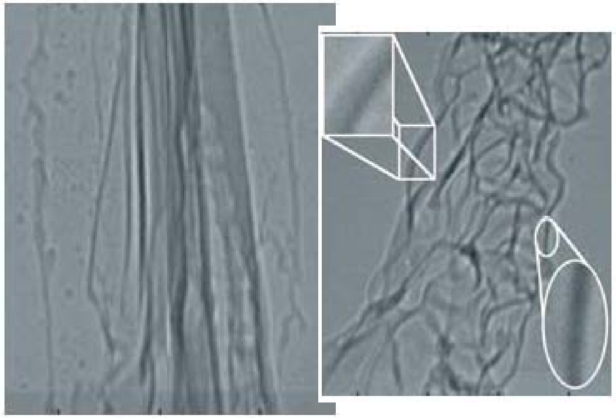
7. J. Gao, Z. Liu, S. Moon, X. Xie, E. Dufresne, K. Fezzaa, M. c. Lai, J. Wang, R.D. Reitz, ILASS Americas, (2010)

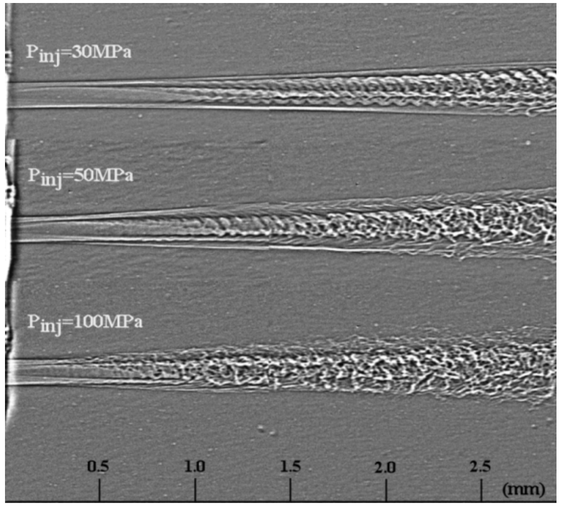
X-ray phase contrast spray imaging



Effervescent water spray producing large drops

Gasoline injector producing many small drops



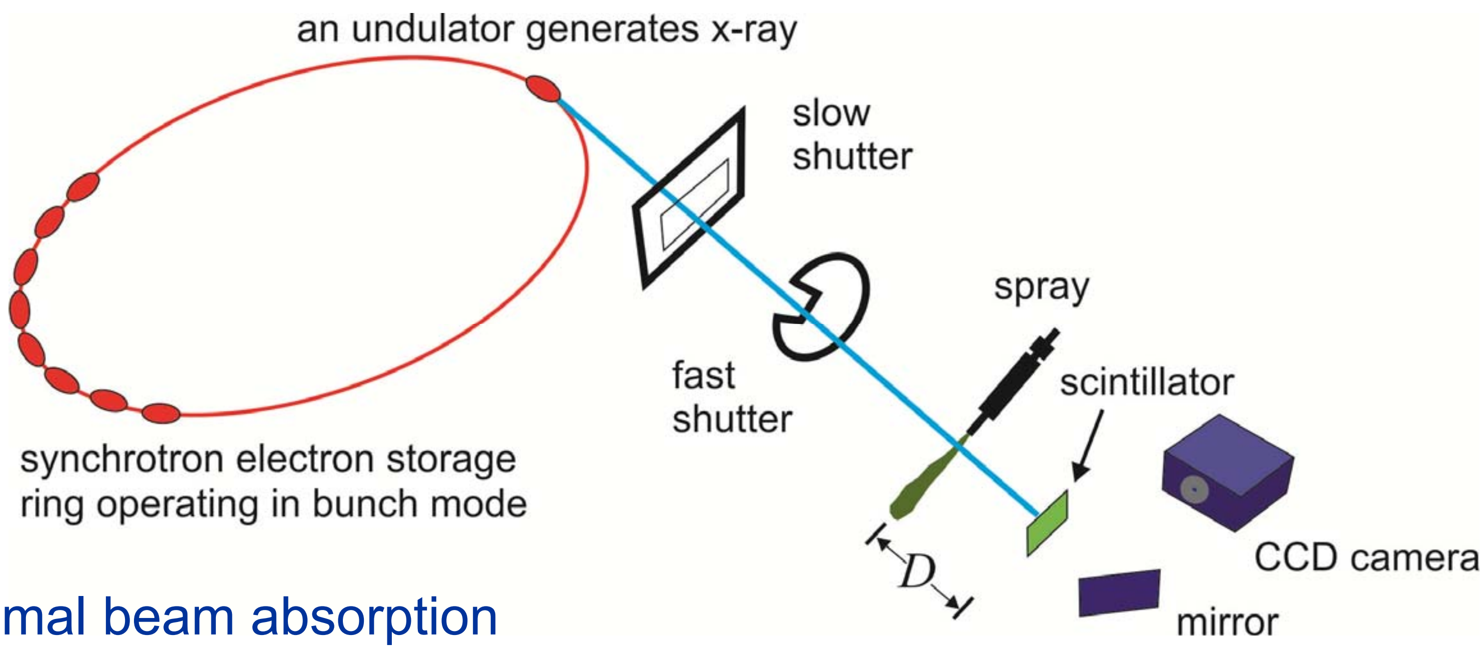


Bio-Diesel spray with hydro-ground nozzle

Two questions:

- How are we to understand these images - what do they depict?
- Can x-ray PCI image intact structures inside drop clouds?

X-ray PCI at APS/ANL



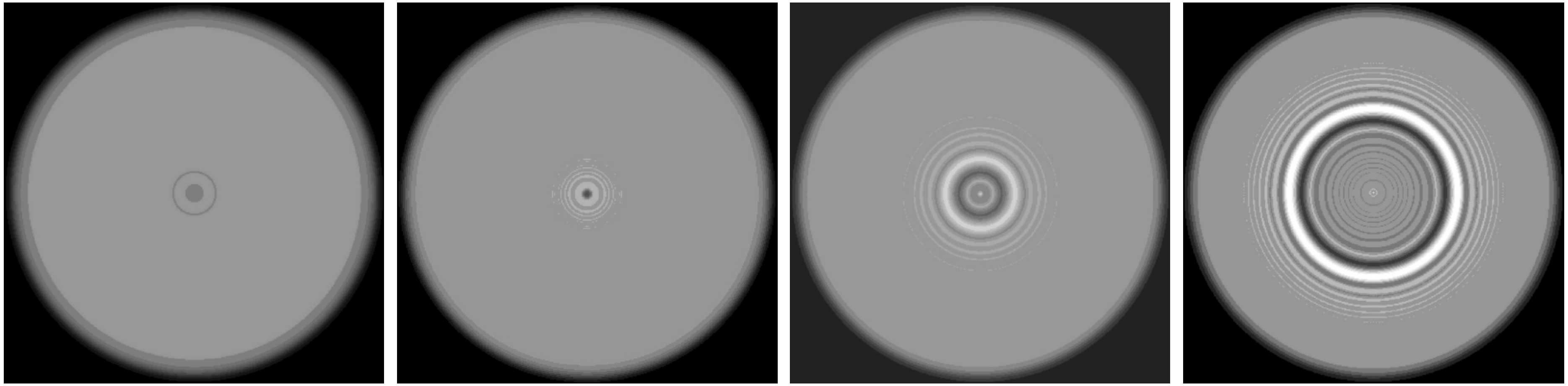
- Minimal beam absorption
- Similar to optical shadowgraphy but with x-rays - the image is formed by refraction, but just from edges now (steep gradients in the index of refraction)
- No lens, use Fresnel diffraction to form the image
- X-ray PCI is converted to visible light in the scintillator crystal & imaged with a normal CCD

Simulations[8]

- Propagate an electromagnetic wave by solving the full e&m problem
- X-ray beam modeled as a super-Gaussian beam
- X-ray radiation at 13.3 keV (0.09 nm)
- Simulate x-ray bandwidth by propagating 5 separate beams with different wavelengths (within the x-ray spectrum) & add them incoherently
- Distance from sample to scintillator (*D*) is usually 70 cm
- Simulate spatial resolution by applying a Gaussian filter to the synthetic images, with filter width that matches the quoted resolution – important only for small drops

8. Linne, Experiments in Fluids, Vol. 52, no. 5, 1201-1218, (2012)

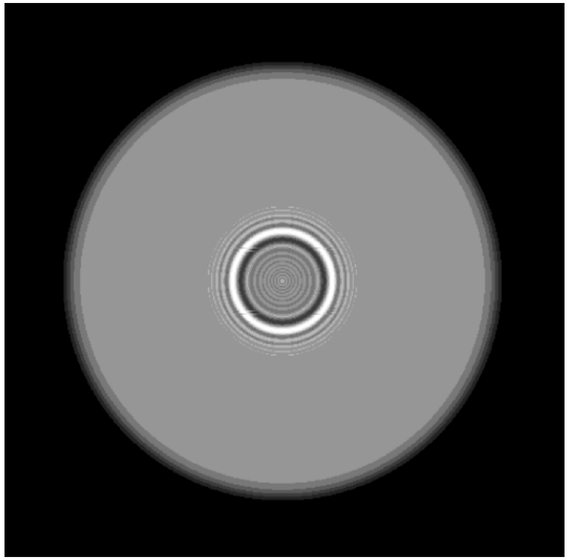
Size dependence

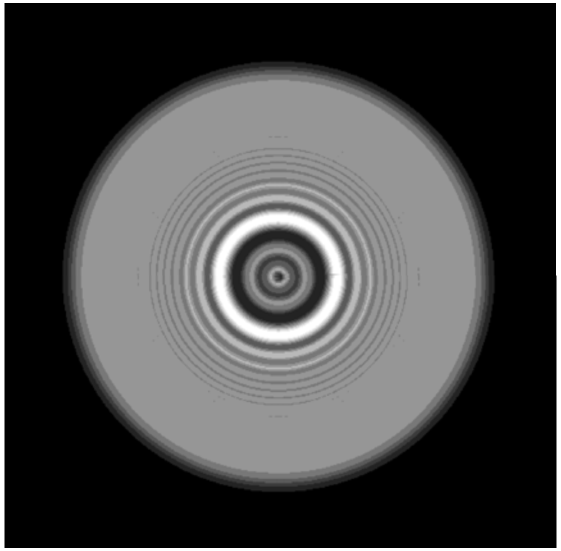


5 μm 10 μm 30 μm 80 μm

Observation: Large drops produce a complex ring structure & small drops produce a single gray pixel. Spatial resolution would matter a lot for small drops.

The pattern does not leave the beam



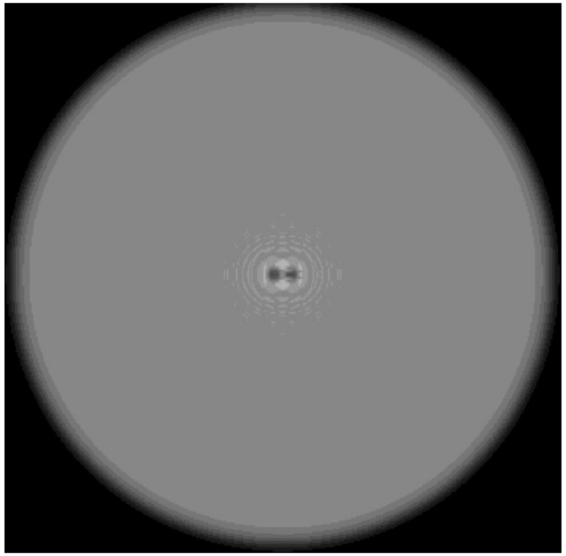


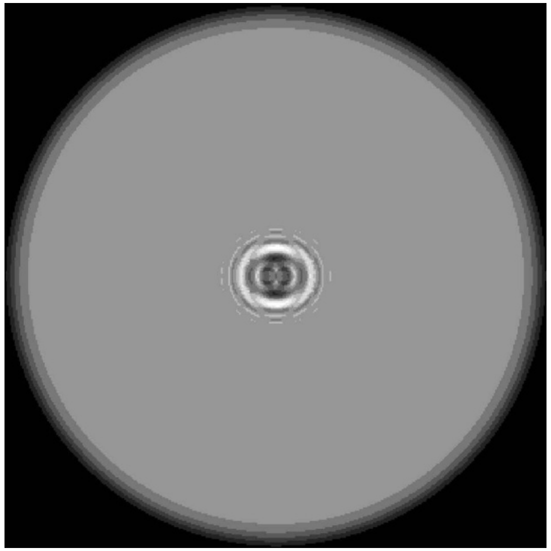
80 μm drop in a 200 mm beam

D = 1 m *D* = 5 m

Observation: The imprint of a drop on the beam does not change much with distance, it <u>does not leave the beam</u>.

Two drops spaced downstream from each other


10 μm drops


30 μm drops

Observation: The drop images overlap and form a structure – very different for small and large drops.

Effervescent spray simulation

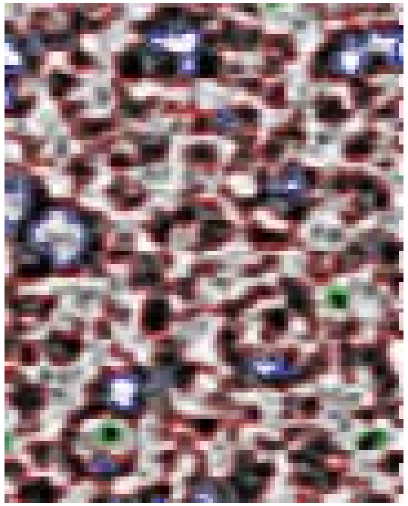
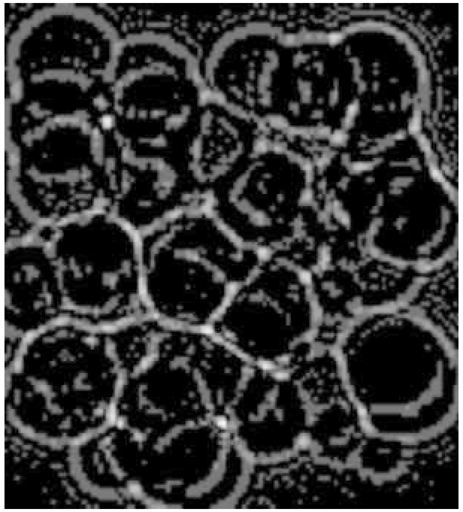
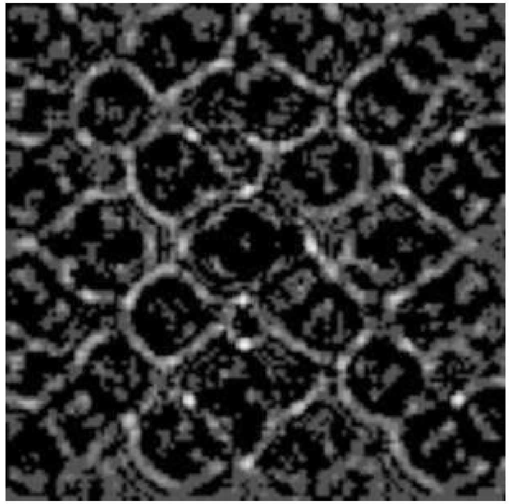


Image extracted from larger expt. image



Simulation using randomly sized (20 – 50 μm) & placed drops



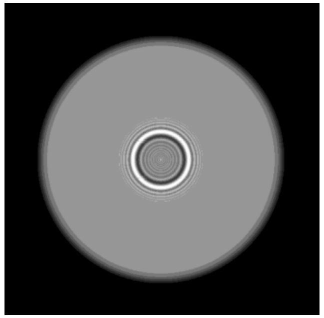
Simulation using 30 μm drops in randomly placed grids

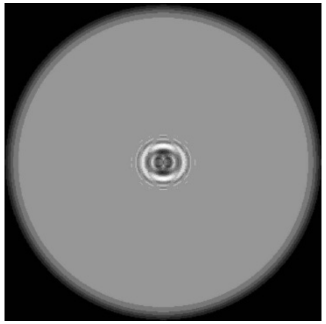
Observation: Persistence of the drop signatures means the final image includes overlapping signatures of every interface encountered, from the input to the output planes, producing a deeply modulated image that can not be interpreted.

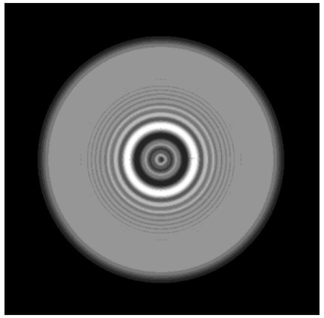
Effervescent spray simulation

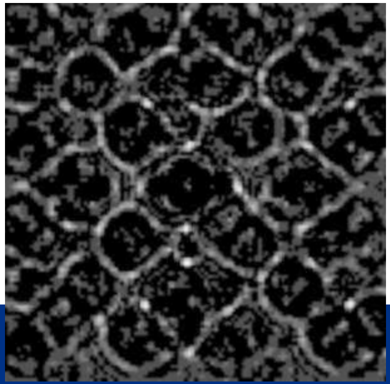
Recap:

- PCI are constructed by interfaces – every interface produces a diffraction signature
- Nothing leaves the beam
- Multiple drops will produce many diffraction signatures that overlap and never leave the beam
- Large drops - produces a complex modulated structure that can be impossible to interpret

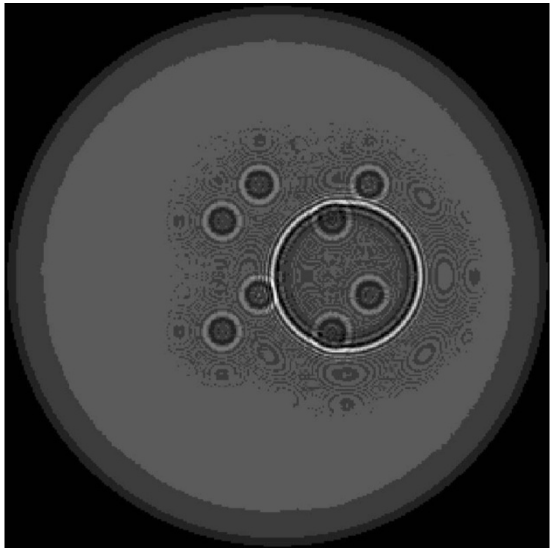




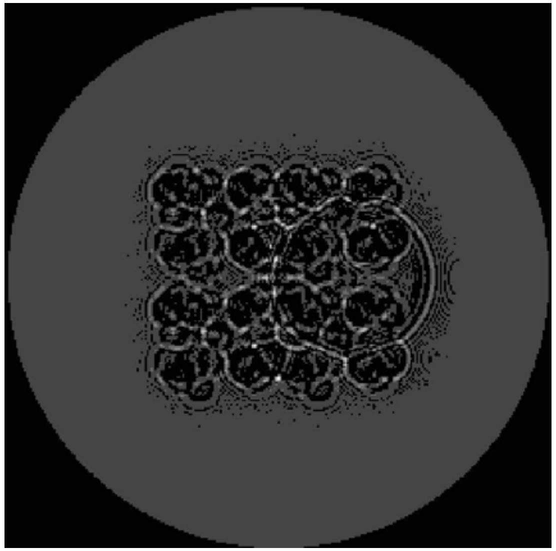




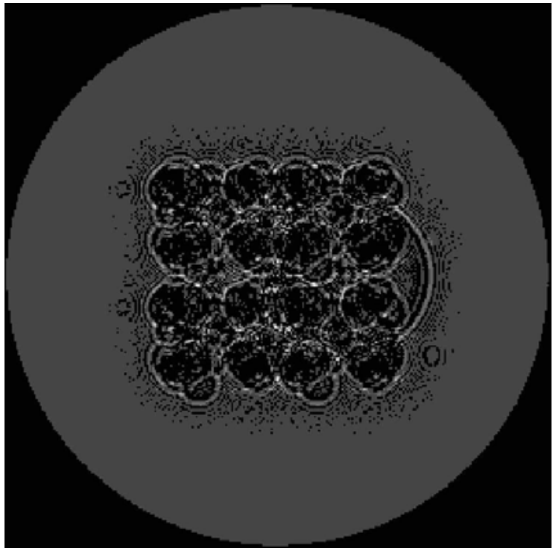
Can PCI see intact liquid behind drops?



150 μm drop behind 2 arrays of 30 μm drops



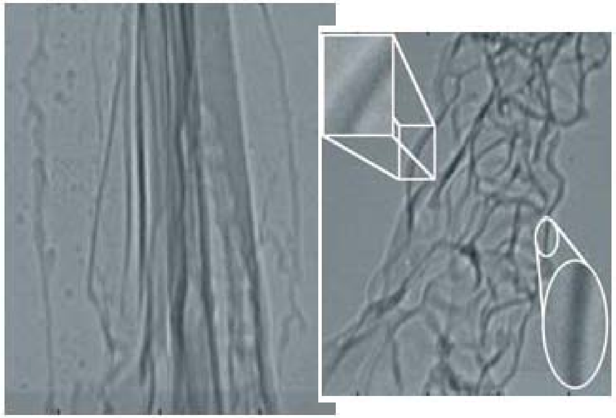
150 μm drop behind 50 arrays of 30 μm drops



150 μm drop behind 100 arrays of 30 μm drops

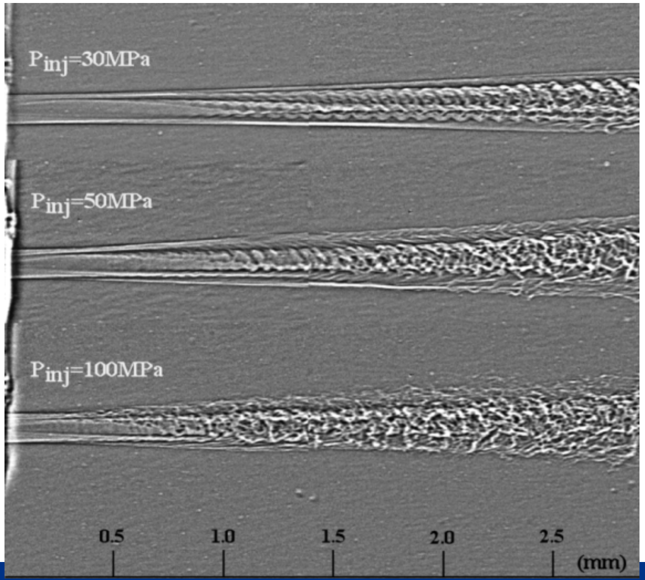
Observation: Once there are drops standing between large intact structures and the scintillator, the image of the intact structure has been corrupted. Moving the scintillator doesn't help.
<u>X-ray PCI can't be used to image interior structures in sprays</u>.

sGDI spray



- Use GLAD to model a cloud of small drops:
  - Discovered that the images look different than the effervescent spray because of the drop size difference
  - Reach the same set of conclusions

Bio-Diesel jet



- No drops were present
- This was not a spray

X-ray phase contrast spray imaging

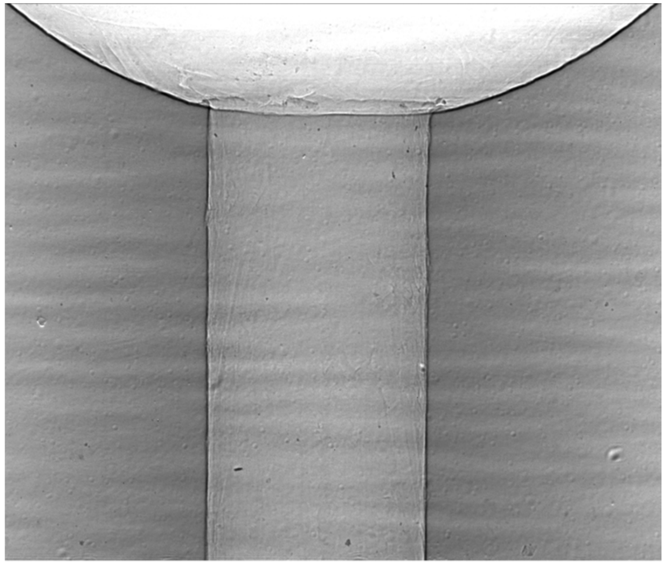
- X-ray phase contrast imaging suffers from:
  - There is no scattering – everything stays in the beam (including interferences)
  - All interfaces cause structures that add up at the exit plane
  - These patterns obscure the details of any structures that may be inside the spray

My own opinion: X-ray phase contrast imaging can not be used to study sprays

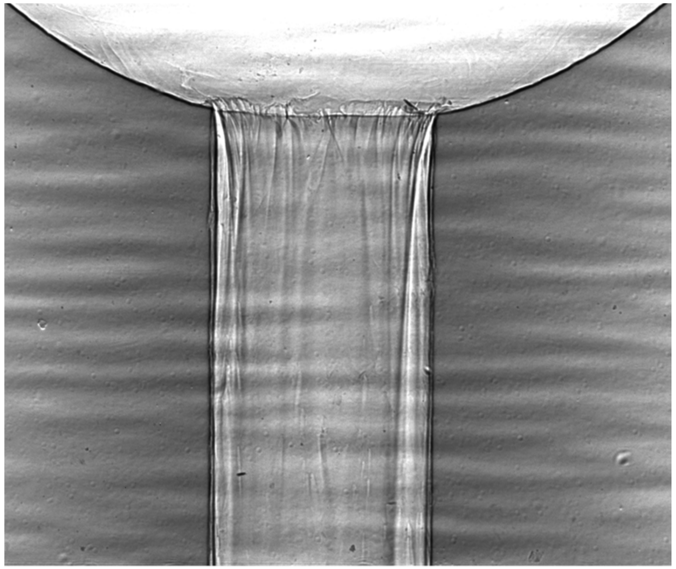
- X-ray PCI can be used to study flows with few or no drops
  - Not a spray
  - The simulations indicate the optical OD is so low in such cases that one can observe the same fluid physics using classical optical techniques

X-ray phase contrast imaging

- **BUT**: X-ray phase contrast imaging with very hard X-rays can be used **to see inside nozzles**, and they have imaged cavitation[9]:



without cavitation



with cavitation

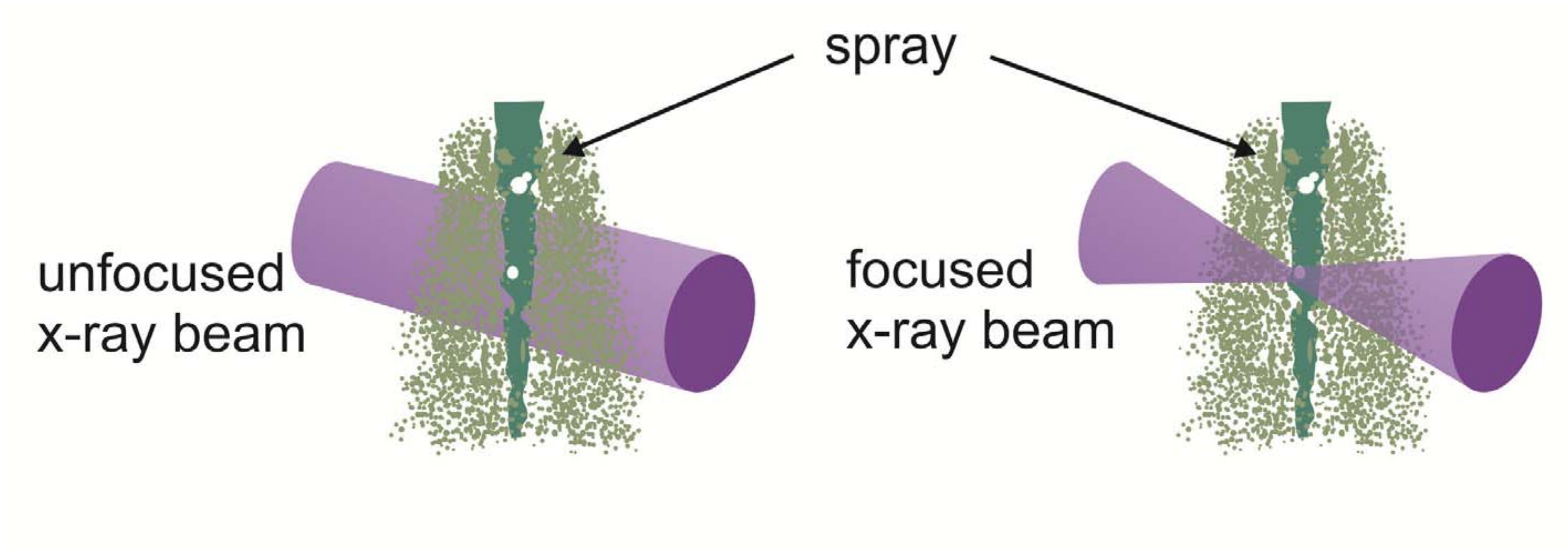
- A very promising technique

9. D.J. Duke, A.L. Kastengren, F. Z. Tilocco, C.F. Powell, ILASS-Americas, Pittsburgh, PA, (2013)

New techniques for the spray formation region

- Ballistic imaging (a trans-illumination laser technique)
- Structured laser illumination planar imaging (SLIPI, a planar laser technique)
- X-ray phase contrast imaging (a trans-illumination x-ray technique)
- **X-ray radiography (a trans-illumination x-ray technique)**

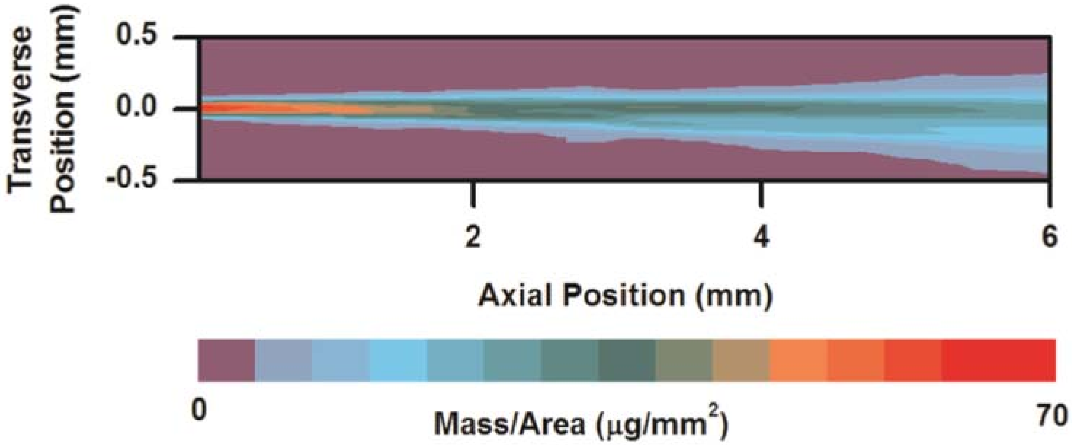
X-ray radiography



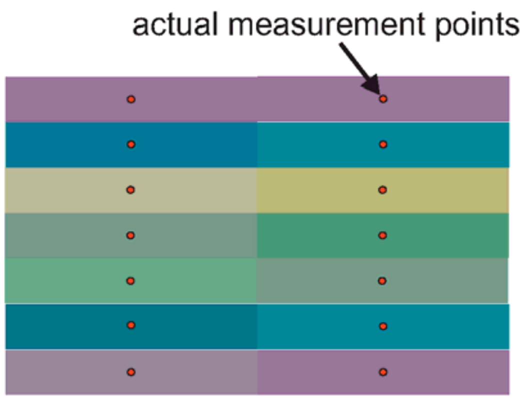
- Absorption can be imaged or measured at single point

X-ray radiography

- Recent result at single point[10]:



- They claim 8 - 10 μm spatial resolution, but that's only at the measurement points:



10. A. Kastengren, C. F. Powell, K. Fezzaa, Z. Liu, S. Moon, X. Zhang, SAE paper no. 2011-01-0383, (2011)

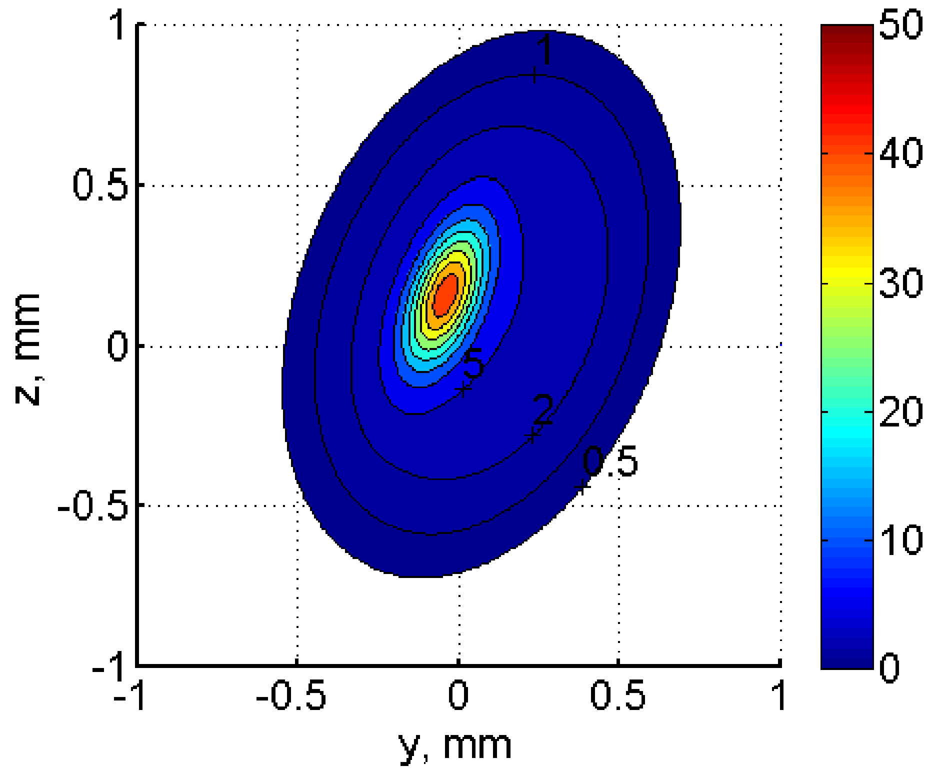
X-ray radiography

- Performed modeling using GLAD again – added absorption[11]
- Result is:
  - Radiography mages line-of-sight-averaged liquid mass/area
  - Technique detects all mass – liquid core, ligaments, and drops → easily converted to mass fraction → entrainment
  - Tomography is somewhat complex, requiring reasonable assumptions for model based reconstruction but very promising as a way to detect spatial distribution of mass (within the spatial resolution of the system)
  - If vapor existed it would also absorb, air also absorbs, but the contribution is a background
- Technique is not single shot – measurements are made over thousands of shots
- Done at max 20 bar, room temperature

11. M. Linne, Experiments in Fluids, Vol. 53, no. 3, 655-671, (2012)

X-ray radiography

- Recent pseudo-tomographic result:



The spray formation region

- Ballistic imaging, SLIPI, and radiography provide different, complementary results
- Can be used to characterize the spray formation region
- When coupled to other techniques the entire spray can now be described experimentally

Topics

- Sprays and nomenclature
- Measurements across the spray
- Measurements in the spray formation region
- **What is possible**
- Discussion

Example project at Chalmers

- Experiments funded by the Knut and Alice Wallenberg foundation
- Measurements across the spray
- Start with studies of various basic steady sprays with water, water/glycerin & water/acetone (interior flow and breakup): non-vaporizing and vaporizing
  - Turbulent primary breakup
  - Cavitating breakup
  - Shear
  - Mixed modes
- Then a single hole pressure atomized fuel spray in the steady region (e.g. the ECN injector)
- Transient multi-hole sprays

Example project at Chalmers

spray supply

transparent nozzle, for turbulent sprays

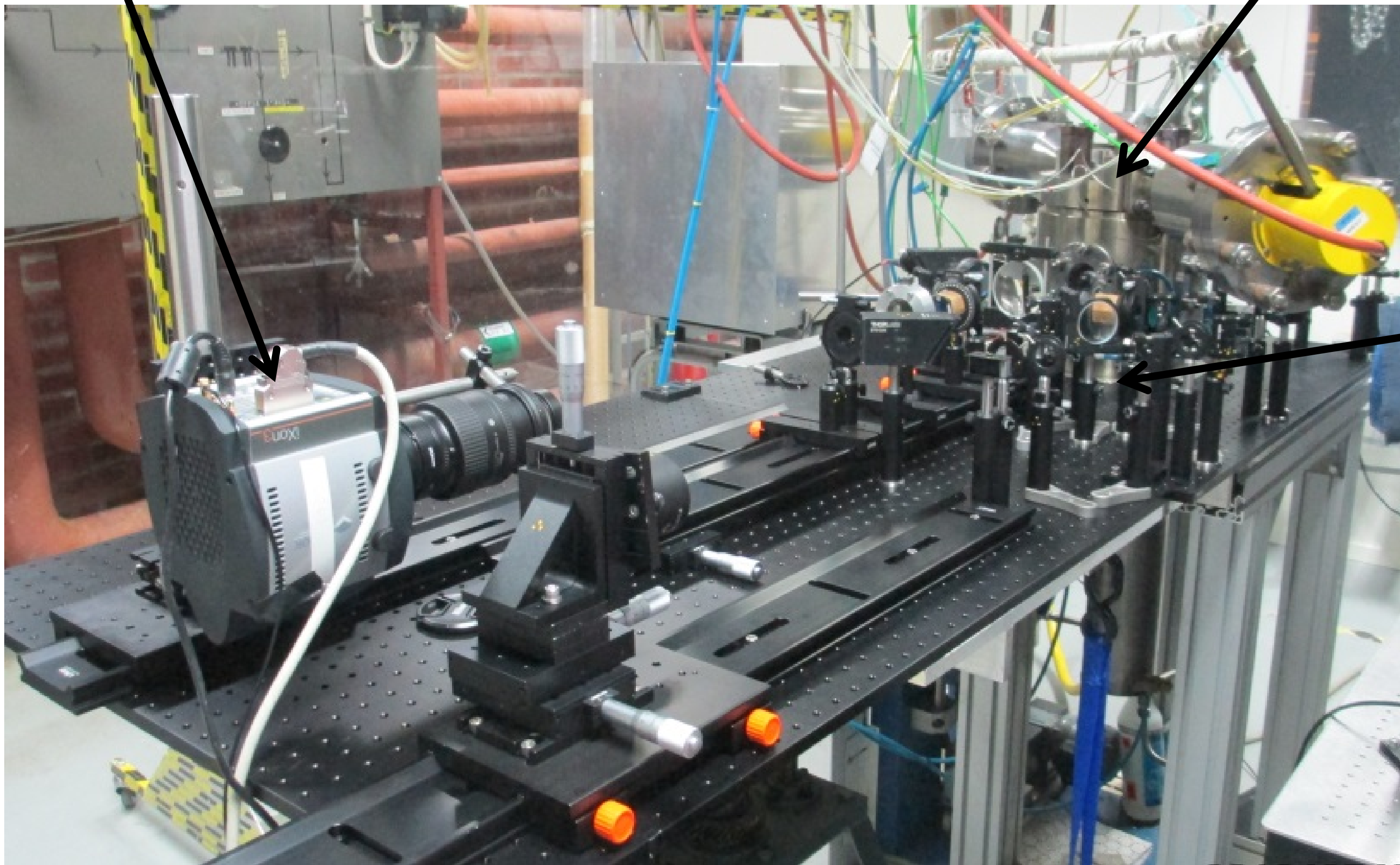
fs lasers

initial beam -steering optics for ballistic imaging

Example project at Chalmers

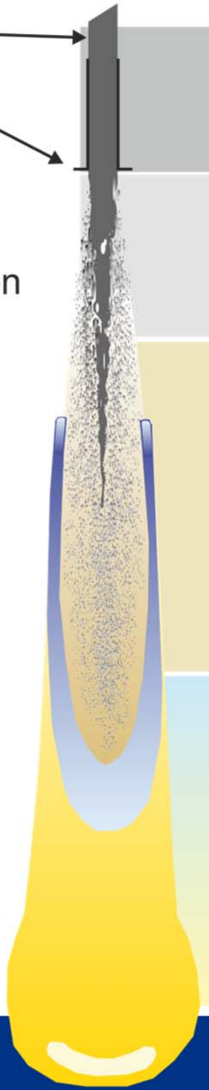
high P & T spray chamber

ballistic imaging camera



ballistic imaging optics

Spray strategy



Spray region	Techniques	Models
liquid flow / nozzle	- high-speed shadowgraphy - micro-PIV	- URANS/LES - cavitation
spray formation	- 3-pulse ballistic imaging - h.s. shadowgraphy	- DNS - std. "blob" models - stochastic breakup - ODT
spray	- h.s. shadowgraphy - PIV - Mie/PLIF/PLIEF - SLIPI/LSD	- Lagrangian spray models
combustion	- chemiluminescence - PLIF - thermal emission - LII	- URANS/LES with: stirred reactor models flamelets LEM - Chalmers mechanisms - others

Topics

- Sprays and nomenclature
- Measurements across the spray
- Measurements in the spray formation region
- What is possible
- **Discussion**

Thanks for your attention

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