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Optical diagnostic techniques for spray systems

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Centre for Automotive Engineering, University of Brighton

Workshop: Utilisation and valorisation of CO₂ for green chemistry

Chemical reactor, Optic methods and Catalyst

19th and 20th February 2015

Saint-Etienne-du-Rouvray, France

Bâtiment Dumont d'Urville, amphi DU BRJ 02



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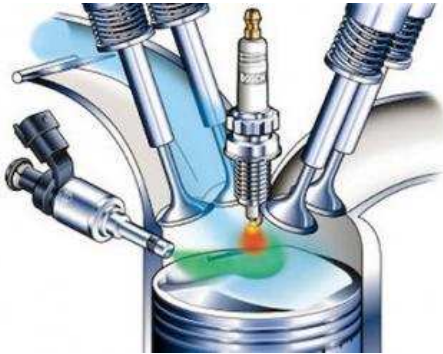
Contents

- ❑ Spray systems and spray technology
- ❑ Data needed to develop a spray system
- ❑ Common optical diagnostic techniques
- ❑ Hardware/components to study spray characteristics
- ❑ Digital image processing (introduction into typical problems)
- ❑ Conclusions



Spray systems and spray technology

Internal combustion engines



Picture: <http://www.climatetechwiki.org/>

Vessels cleaning systems



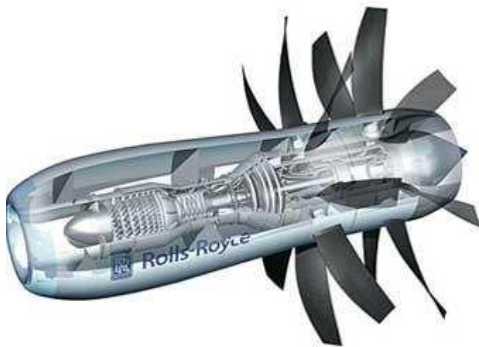
Picture: <http://chemacinc.com>

Water mist fire protection systems



Picture: <http://www.enggcyclopedia.com/>

Jet engines/gas turbines



Picture: <https://www.asme.org>

Agriculture



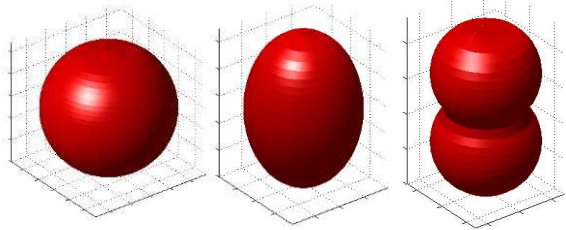
Picture: <http://www.growthproducts.com/>

Other

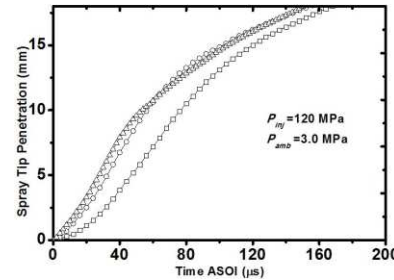
- Food industry
 - Vitamin spraying
 - Product moisturizing
 - Spraying of sugar solutions
- Disinfection
 - Hygiene applications

Data needed to develop a spray system

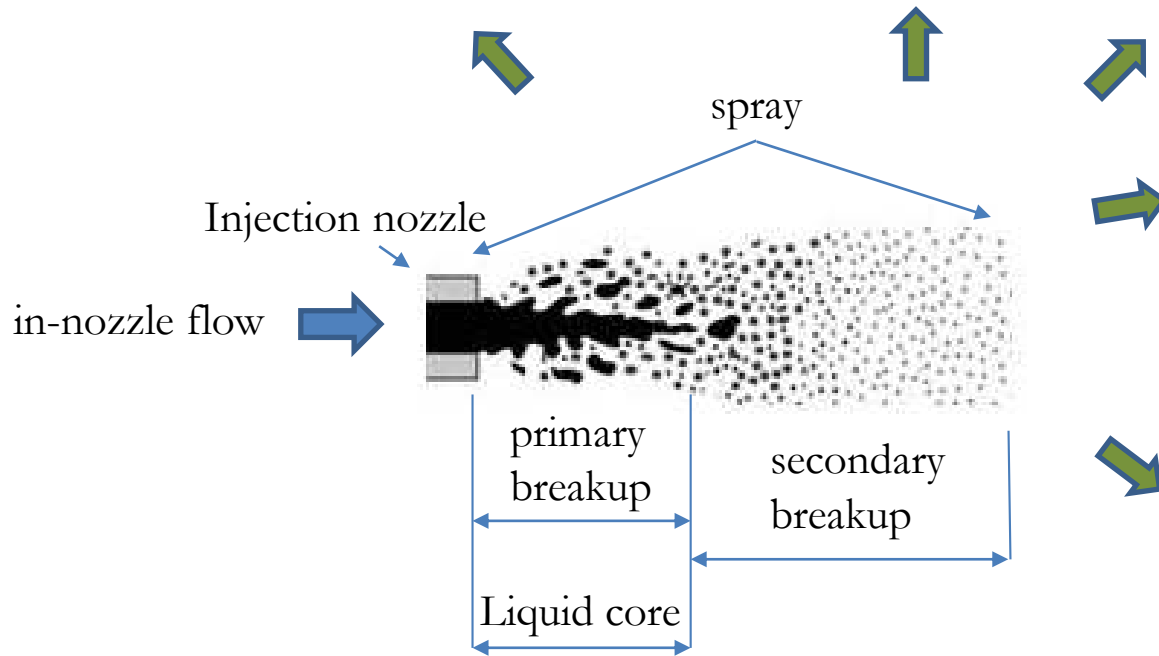
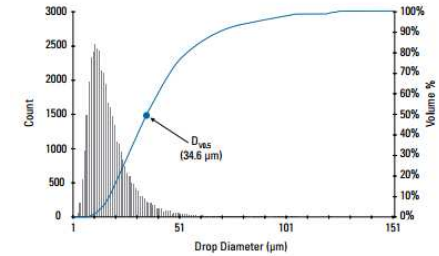
Droplet shape (volume, surface)



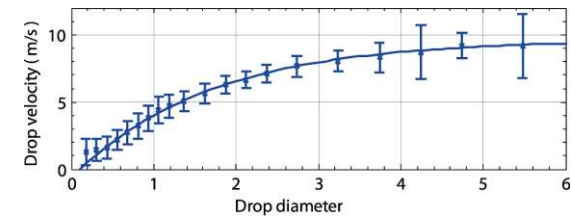
Tip penetration



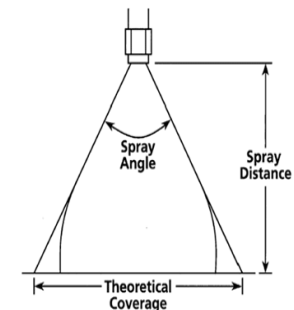
Drop size distribution



Drop velocity distribution



Spray geometries



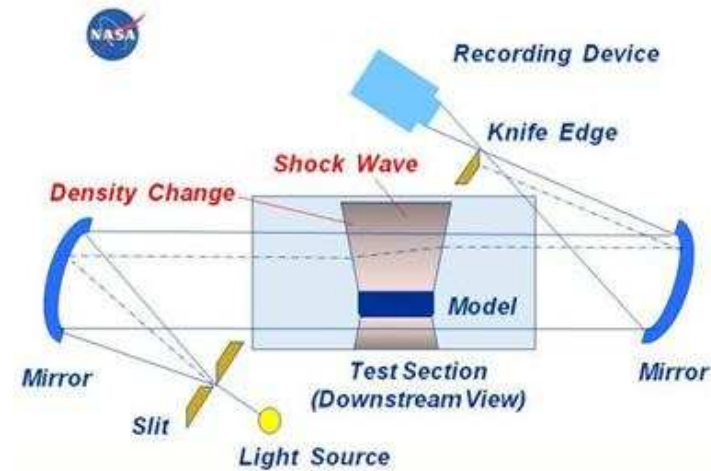
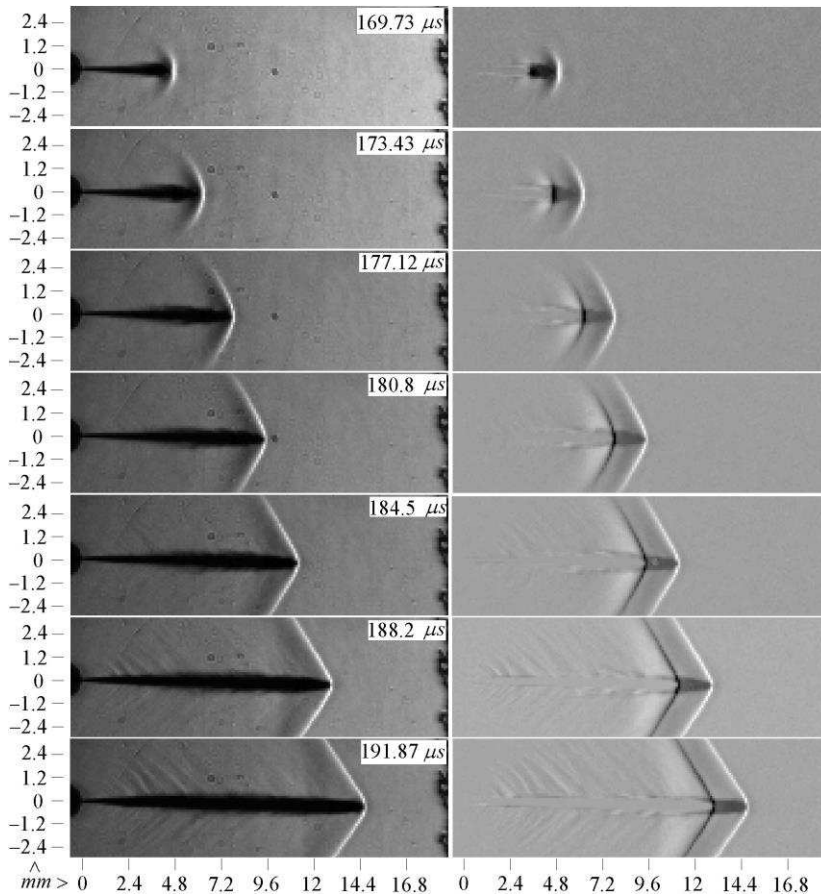
Common optical diagnostic techniques

- Particle image velocimetry (velocity)
 - Schlieren imaging
- } flow visualisation techniques
-
- High-speed video imaging (size and velocity)
 - Direct imaging (size and velocity)
 - Phase Doppler anemometry (size and velocity)
 - Interferometric laser imaging for droplet sizing (size and velocity)
 - Microscopic Imaging (size and velocity)
 - Rainbow thermometry (size and temperature)
 - Planar laser-induced fluorescence (size and velocity)
- } not covered in this presentation

Schlieren imaging

[Foucault, 1859 and Toepler, 1864]

- Flow visualisation [density gradients]
- Spray visualisation [tip penetration]



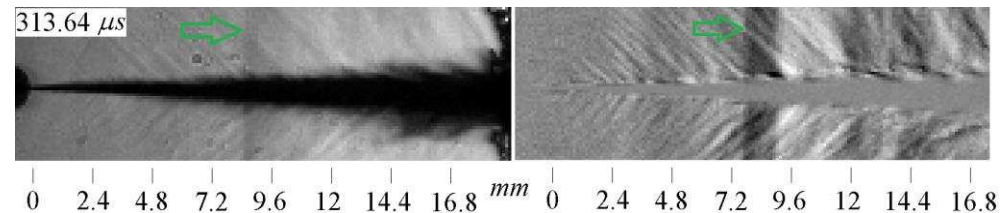
Picture: <http://www.grc.nasa.gov/WWW/k-12/airplane/tunvschlrn.html>



Evolution of n-dodecane spray as a function of time after the start of the trigger.

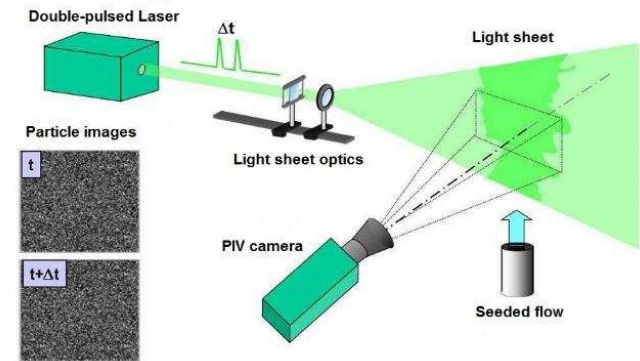
Injection pressure is 1500 bar, ambient is 1 bar

Reflected pressure wave [local speed of sound]

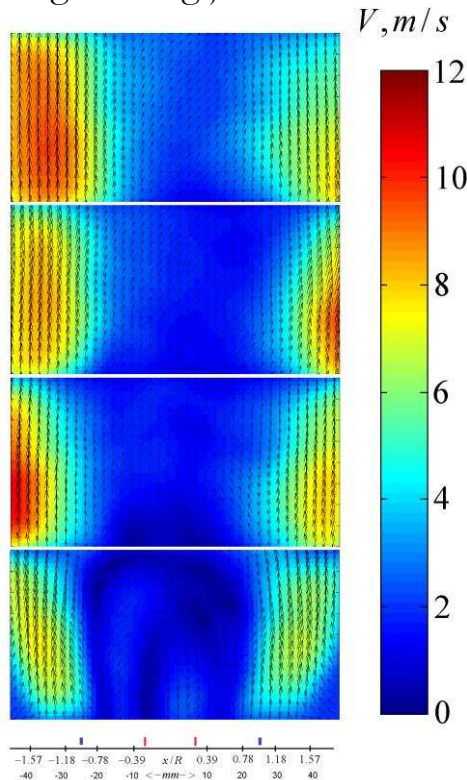


Particle image velocimetry (PIV)

- Flow or droplet velocity can be measured
- Flow must be seeded with small particles or droplets must present
- Double pulse lasers and double frame cameras are needed

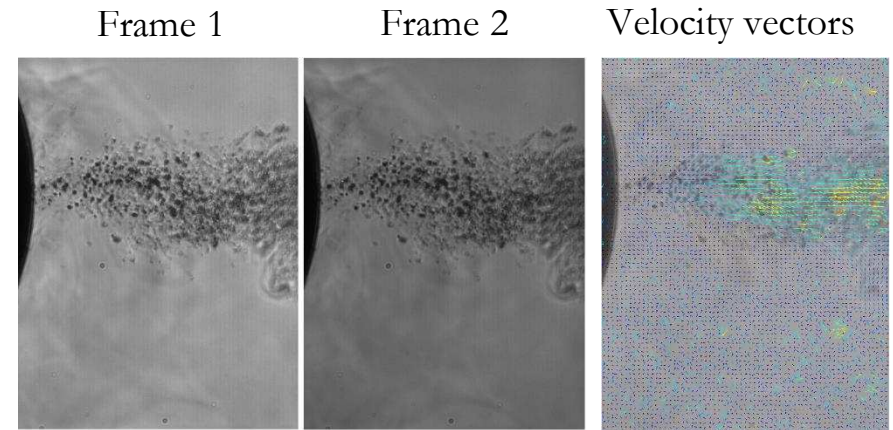


PIV image of swirling burning jet



Flow was seeded with Al_2O_3 particles

PIV image of diesel fuel spray [no seeding]

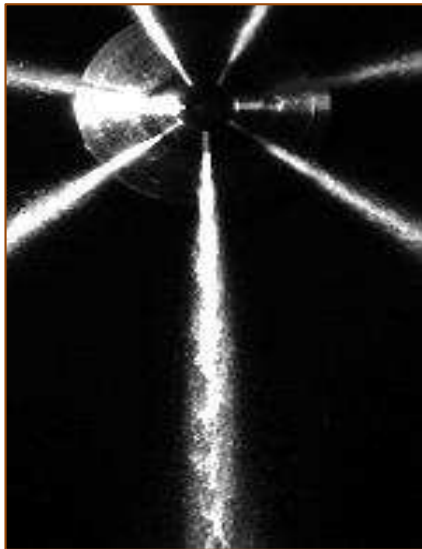


Direct imaging

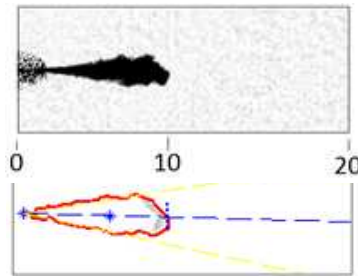
[Dombrowski and Fraser 1954; Chigier, 1976]

- Requirement for high magnification to resolve small droplets
- Spatial resolution issues (high-speed video)

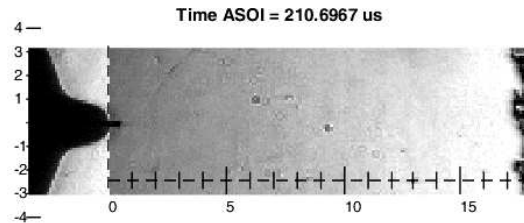
7-hole injector spray



Processed frames



High-speed video of supersonic diesel spray

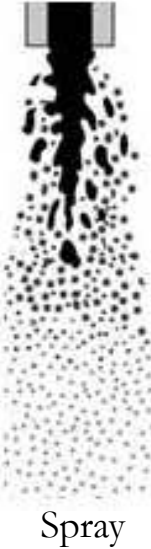


Mach number = 1.35
Fuel: n-dodecane

CCD camera



Injector



Spray

Diffusing screen



Light source



High-speed video of diesel spray [1500 bar into 48 bar ambient]

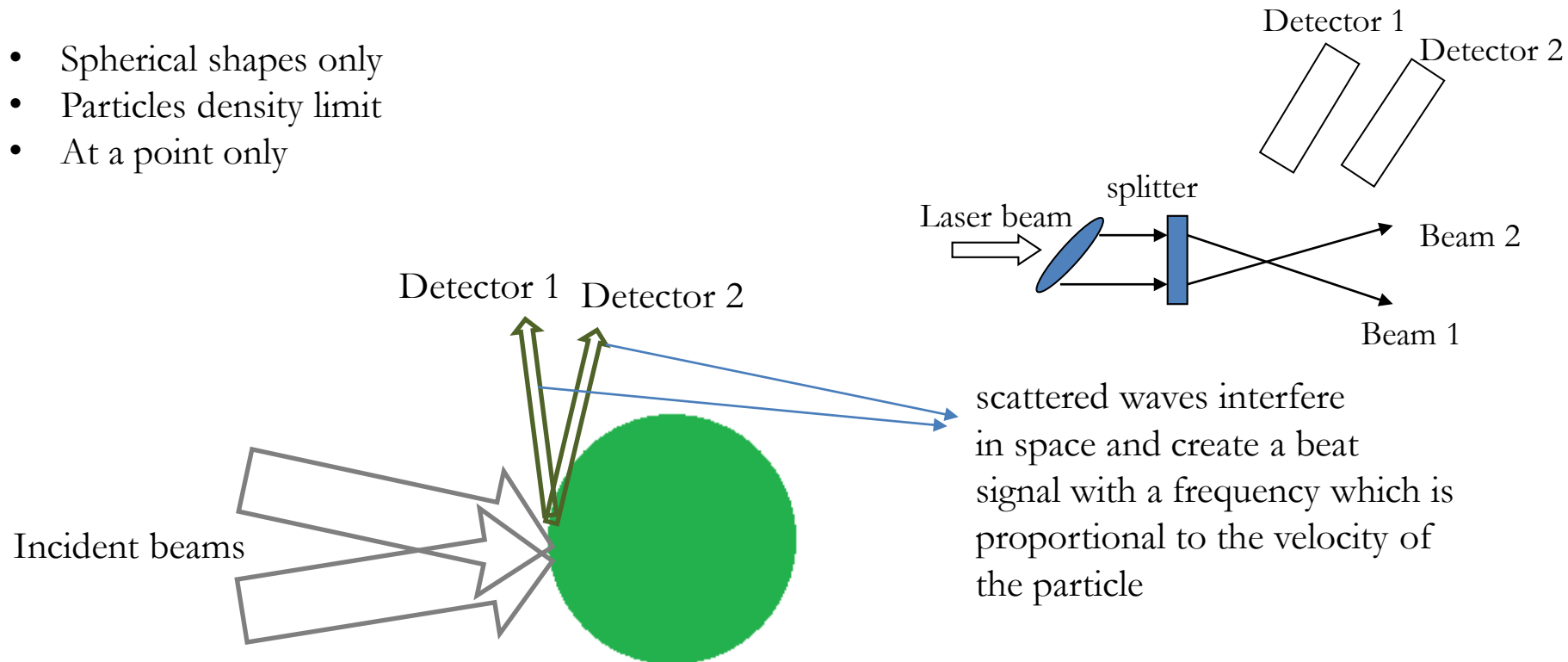


Phase Doppler Anemometry (PDA)

[Bachalo & Houser 1984; Saffman et al. 1984; Bauckhage et al. 1987]

- ❑ Velocity is computed from Doppler shift (beat frequency)
- ❑ Size is computed from the phase difference between two detectors
- ❑ Three detectors provide greater resolution and a large measurable size range

- Spherical shapes only
- Particles density limit
- At a point only



Why 2 beams?

$$\Delta f_{\%} = v/c = 100\% \cdot 10 / 299700000 = 3.3367e-06$$

Interferometric Laser Imaging for Droplet Sizing (ILIDS)

- 2D spatial droplets distribution
- Instantaneous size and velocity (two cameras or a single double frame)
- Spherical droplets only
- Fundamental limit of geometrical optics
- Minimum droplet diameter $2 \times k$.
- Maximum droplet diameter $N_{max} = L/4$

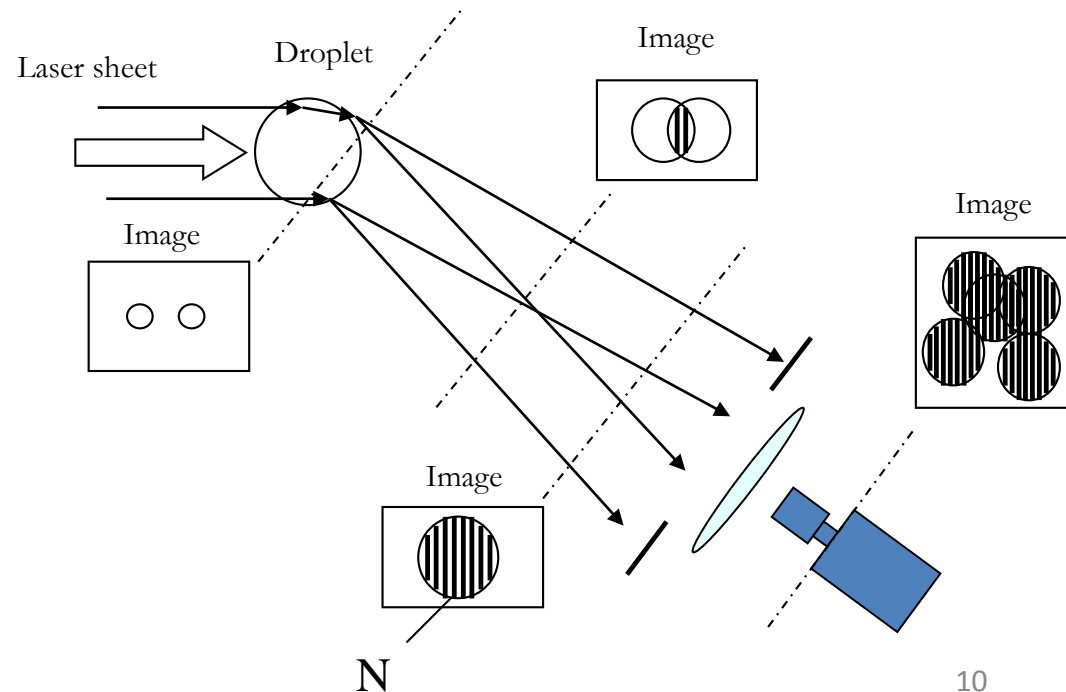
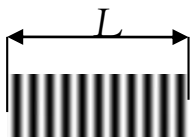
conventional ILIDS technique [Glover *et al.* 1995]

[Golombok *et al.*, 1998]

$$d = N \cdot k$$

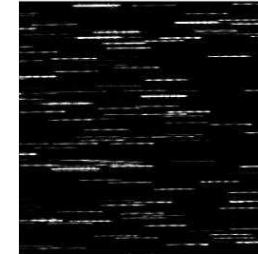
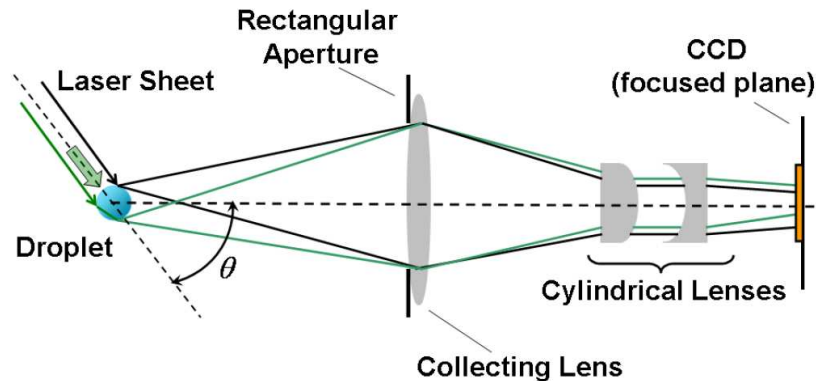
N - Fringe count

k - Diameter per fringe



Interferometric Laser Imaging for Droplet Sizing (ILIDS)

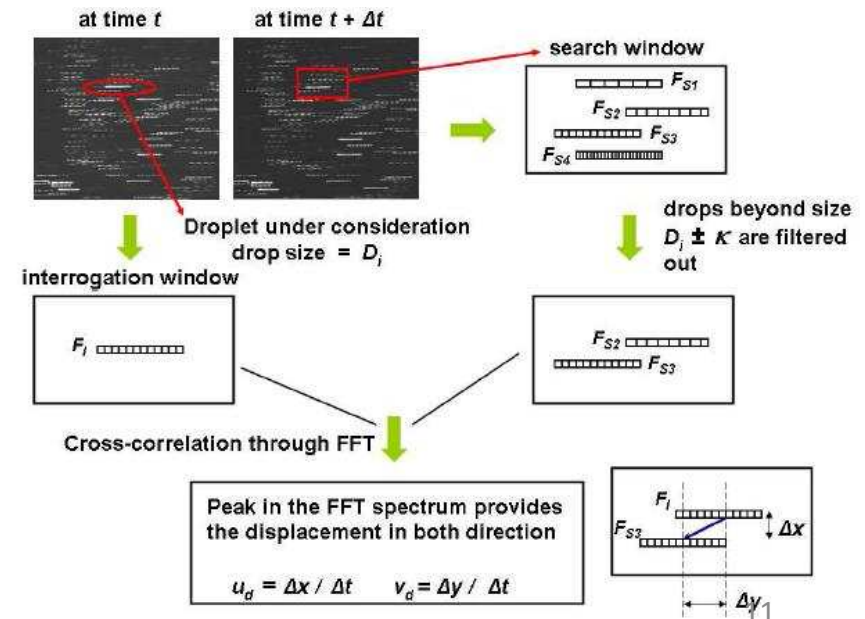
Typical compressed ILIDS image



Schematic of the optical configuration of ILIDS including the optical compression unit introduced by Maeda et al., 2000

❑ Optical compression unit is used to prevent droplets overlapping on screen

droplet velocity estimation in ILIDS processing



S. Sahu, Experimental Study of Isothermal and Evaporative Sprays (PhD thesis), Imperial College London, 2011.

Microscopic Imaging

[Crua *et al.* 2010; Bae *et al.* 2002; Badock *et al.* 1999; Sjöberg *et al.* 1996]

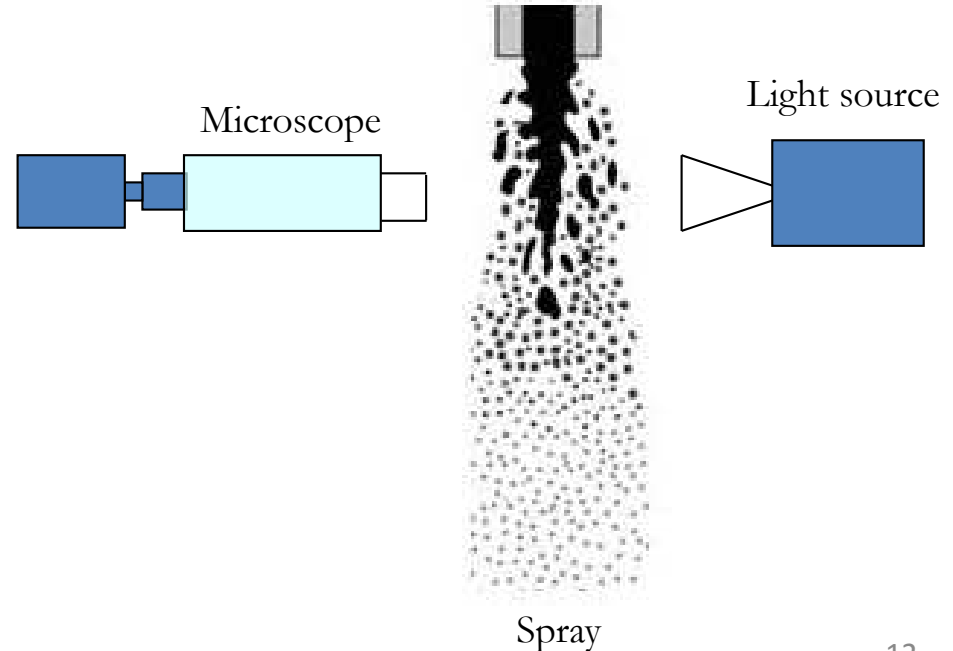
- High spatial resolution ($d < 10 \mu\text{m}$)
- Spherical and non-spherical droplets including partially formed (ligaments) can be measured
- Velocity of individual droplets can be estimated

- Difficulty with lighting at microscopic level
- Diffraction limit [fundamental limit]

colour of light used to illuminate

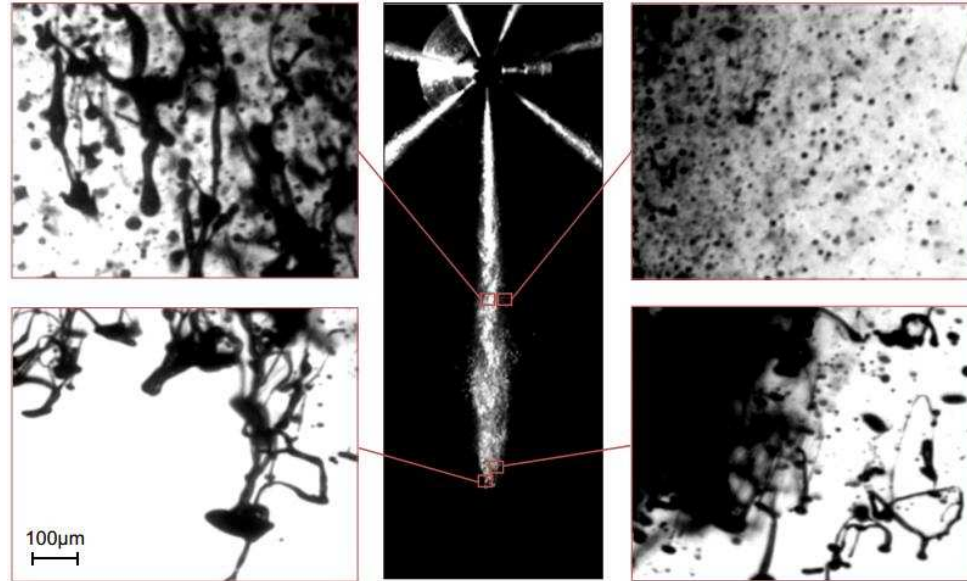
$$\text{Limit of resolution} = \frac{0.61\lambda}{\text{NA}}$$

numerical aperture



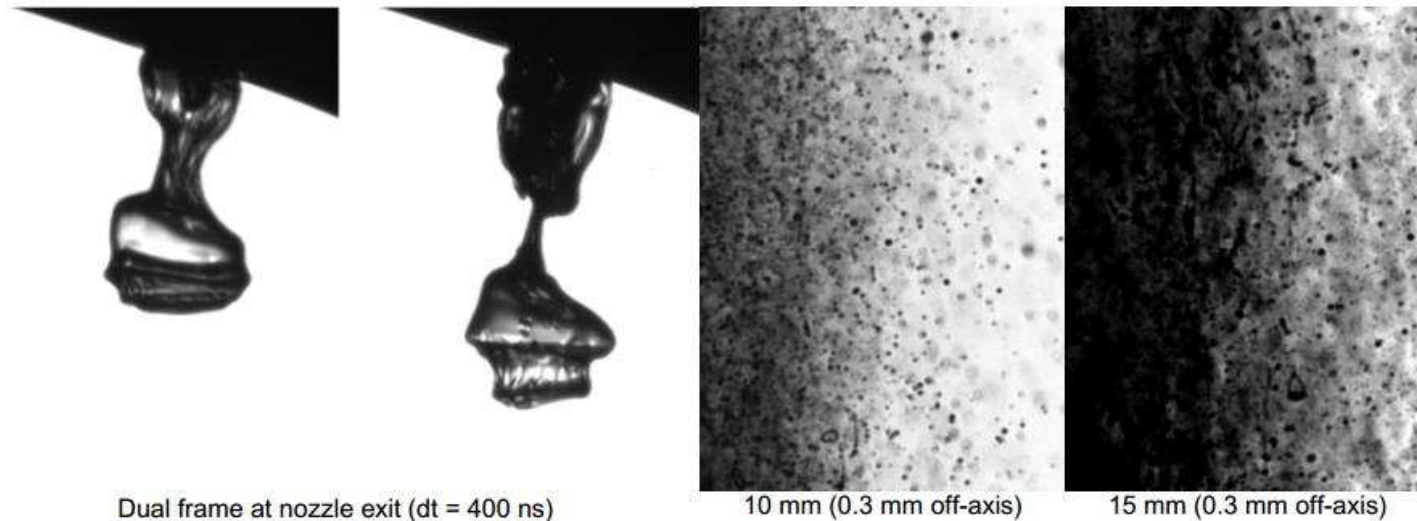
Microscopic Imaging (cont.)

7-hole DFI-1.3 injector; nozzle diameter of 135 μm



← Shadowgraphs of diesel sprays with sub-micron resolution
Injection at 40 MPa into atmospheric conditions.

- Small droplets are visible
- Initial jet structure is visible
- Detailed spray structure is scanned



Dual frame at nozzle exit (dt = 400 ns)

10 mm (0.3 mm off-axis)

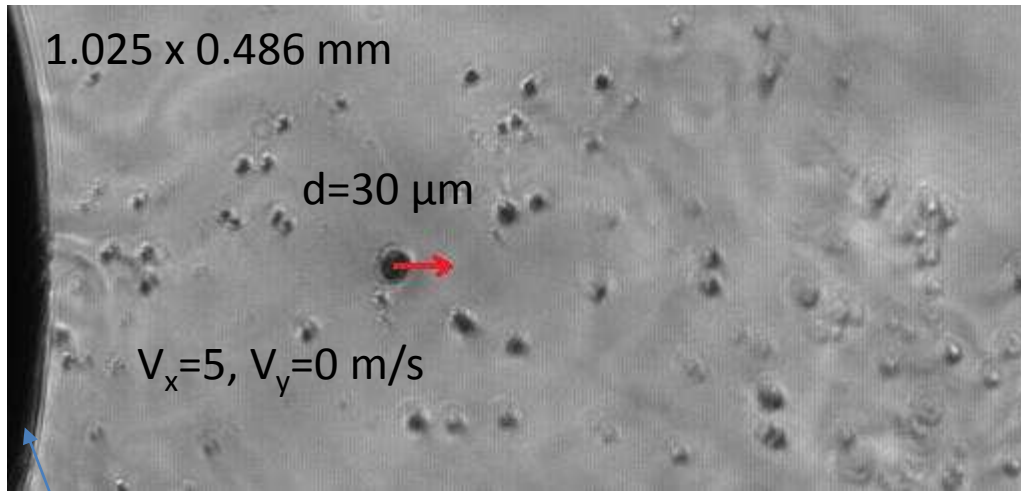
15 mm (0.3 mm off-axis)

Crua et al., ICLASS 2012,
Heidelberg, Germany,
September 2-6, 2012

Microscopic Imaging (cont.)

Shadowgraphs of diesel sprays with sub-micron resolution

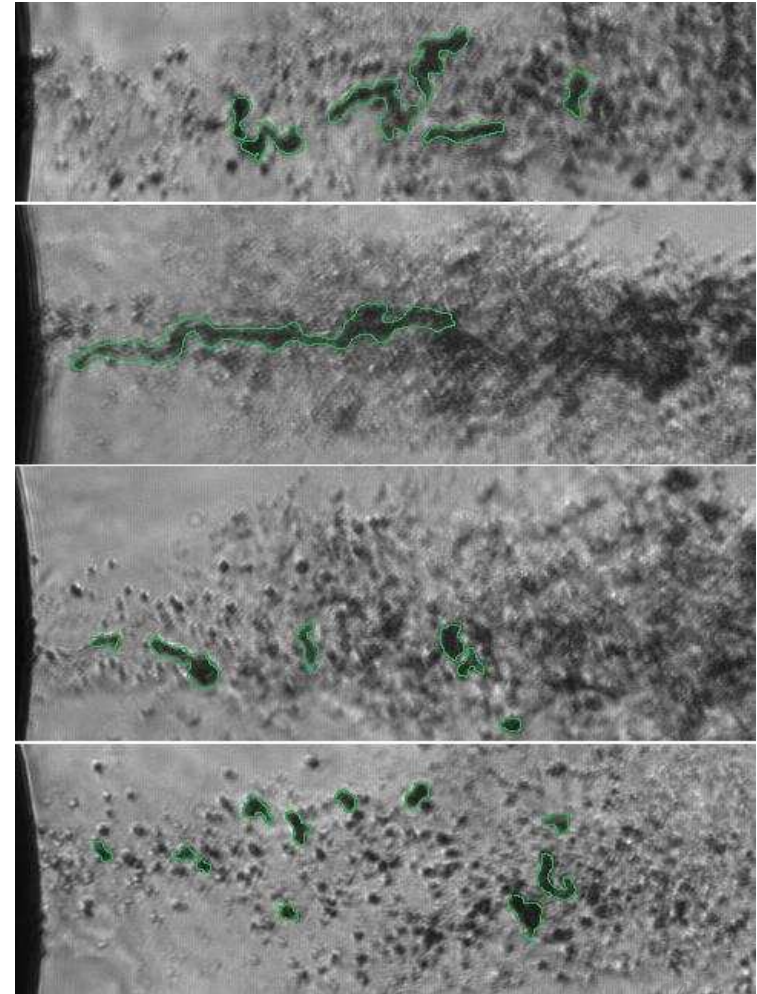
Injection at 100 MPa into high pressure and temperature environment



Tip of injector

Injection direction

- Spherical and nearly spherical droplets
- Highly deformed structures [shown in green]



Microscopic Imaging (cont.)

❖ When microscopic imaging is considered?

- Initial stage of jet formation
- Primary breakup
- Near nozzle effects, e.g. thermal boundary layer

- Diffraction issues (low resolution)
- Significant rejection rate (out of focus) during engine tests



Ambient 1 bar, Injection 500 bar, n-dodecane

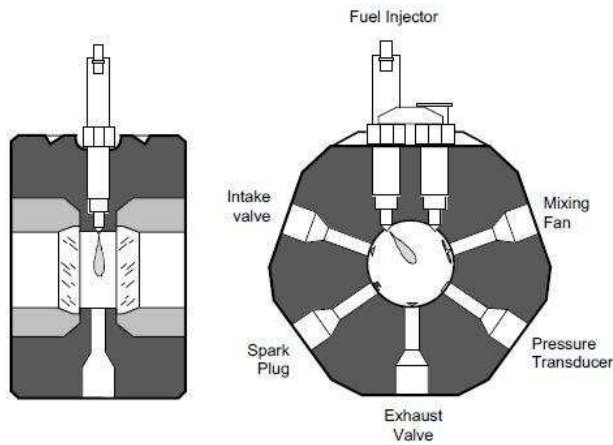


Ambient 40 bar, Injection 500 bar, n-dodecane



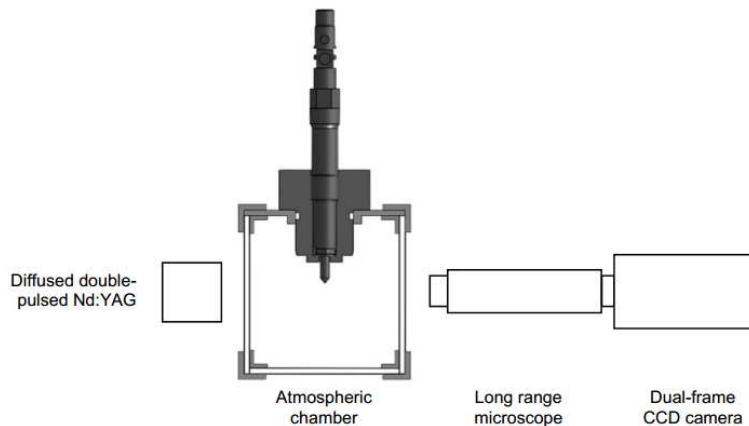
Hardware/components to study spray characteristics

Constant volume chamber [P<350 bar]

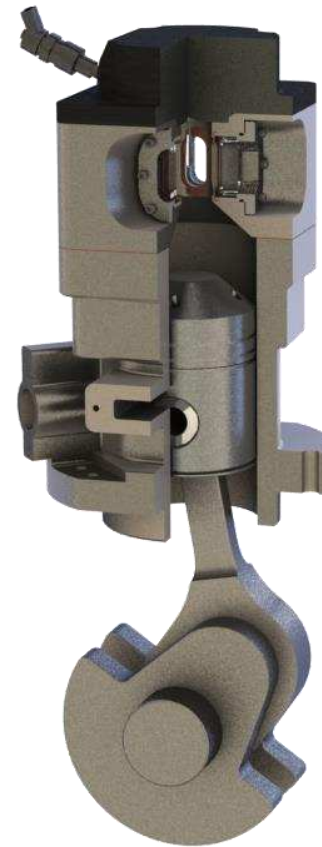


Picture: <http://www.sandia.gov/ecn/cvdata/sandiaCV/vesselGeometry-pc.php>

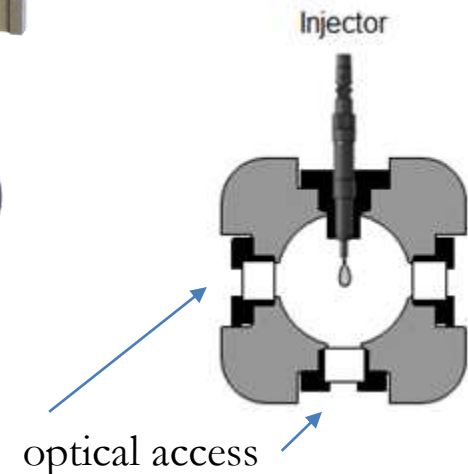
Atmospheric chamber [P=1 bar]



Rapid compression machine [P<120 bar]



- Bore: 135 mm
- Stroke: 150 mm
- Displacement: 2.2 l
- RPM: 500
- T = 540-850 K



Hardware/components to study spray characteristics

Long-distance microscopes



Picture: <https://www.infinity-usa.com/products/instruments/K-Series.aspx>

Lenses



Pulsed diode laser light source



High-speed cameras



Picture: <http://www.visionresearch.com/Products/High-Speed-Cameras/v710/>

Low-speed cameras



Picture: <http://www.photonics.com/>

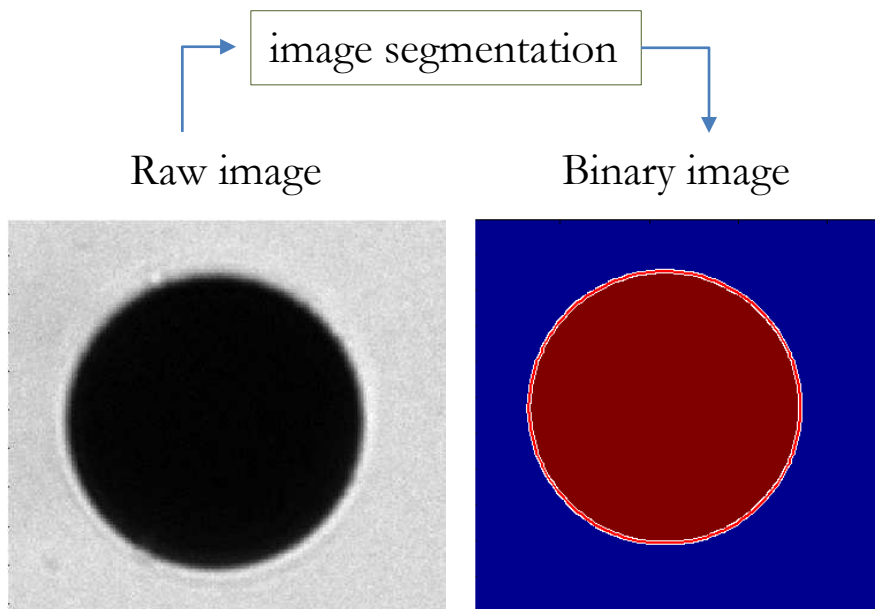
LED pulsing systems



Picture: <http://www.ila.de/piv/piv-systems/lps.html>

Image processing

- ❑ There is a need to automatically identify drops in images
- ❑ Spherical droplets are relatively easy to account for
- ❑ Several optical techniques work well with spherical non-deformed droplets
- ❑ Classical approach: Find all pixels, assume sphericity, compute equivalent diameter



Typical questions

- How to get from raw images to binary images?
- What happens if a droplet is not spherical?
- Volume and surface area for deformed droplet?
- Small droplets (pixilation)?
- Measured droplet size/real size?

Conclusions

Key elements in selection of optical diagnostic techniques

- Access into a test section
- Signal acquisition and interpretation
- Specific method and conditions are defined by research tasks

- Particle image velocimetry (velocity)
- Schlieren imaging

- High-speed video imaging (size and velocity)
- Direct imaging (size and velocity)
- Phase Doppler anemometry (size and velocity)
- Interferometric laser imaging for droplet sizing (size and velocity)
- Microscopic Imaging (size and velocity)

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