Experimental observations of fuel sprays in gasoline engines

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The Sir Harry Ricardo Laboratories
Centre for Automotive Engineering

13th April – Workshop- New mathematical tools for modelling the processes in IC engines: a dialogue between mathematicians and engineers

University of Brighton

Contents of presentation

- Current objectives in gasoline engine research
- Progression in gasoline fuel injection systems
- Key characteristics of fuel sprays
- Optical diagnostics commonly applied to sprays
- The Phase Doppler anemometer
- Conclusions and modelling challenges for fuel sprays

Current objectives in gasoline engine research

- **Significant simultaneous reduction in emissions and consumption**
    - Direct injection, downsizing, boosting, VVA technologies...
- **Fuel injection system optimisation**
    - Metering, variable needle lift, phasing, targeting, atomisation, multi-shot, fuel blends...
- **Engine management system**
    - Crank-angled resolved, poor cycles identified, multi-strike ignition...

Understanding the fuel injection process is key to the mixture preparation... the ‘trial and error’ approach is no longer adequate...

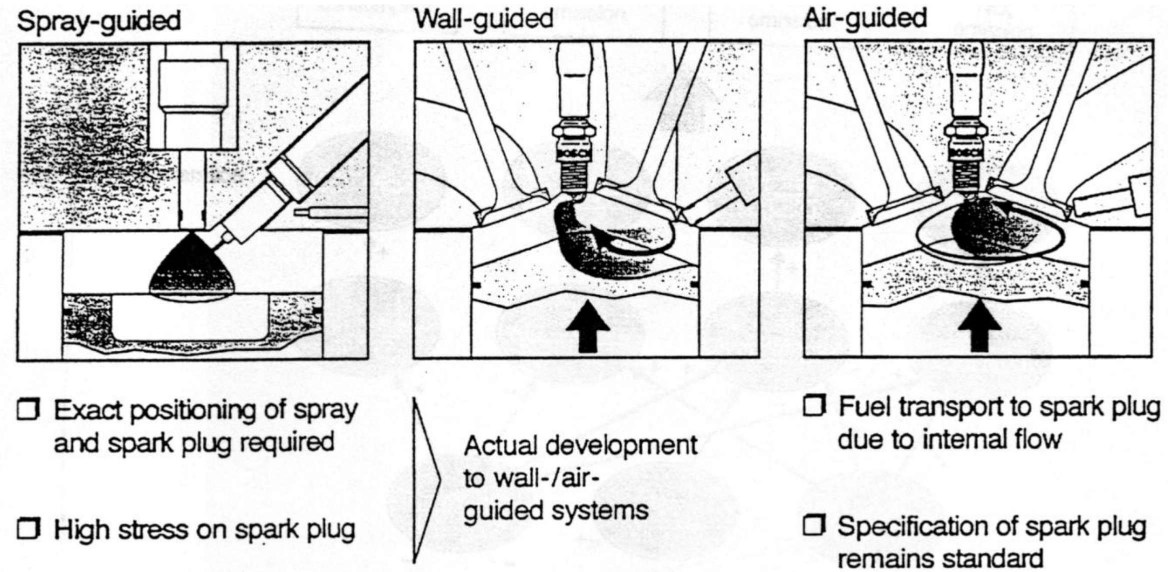
Progression in fuel injection systems

- Single point and multi-point port fuel injection (PFI)
  - 2-12 bar fuel pressure / fixed OVI and CVI injection timing
  - High cyclic variations, poor lean operation, poor tolerance to EGR

- 1st generation direct injection (G-DI)
  - 10-120 bar fuel pressure / range of injection timings
  - Optimised flow structures / stratification of charge
  - Sensitivity to fuel injector location and spray characteristics
  - Relatively high ubHC and NOx emissions

Progression in fuel injection systems

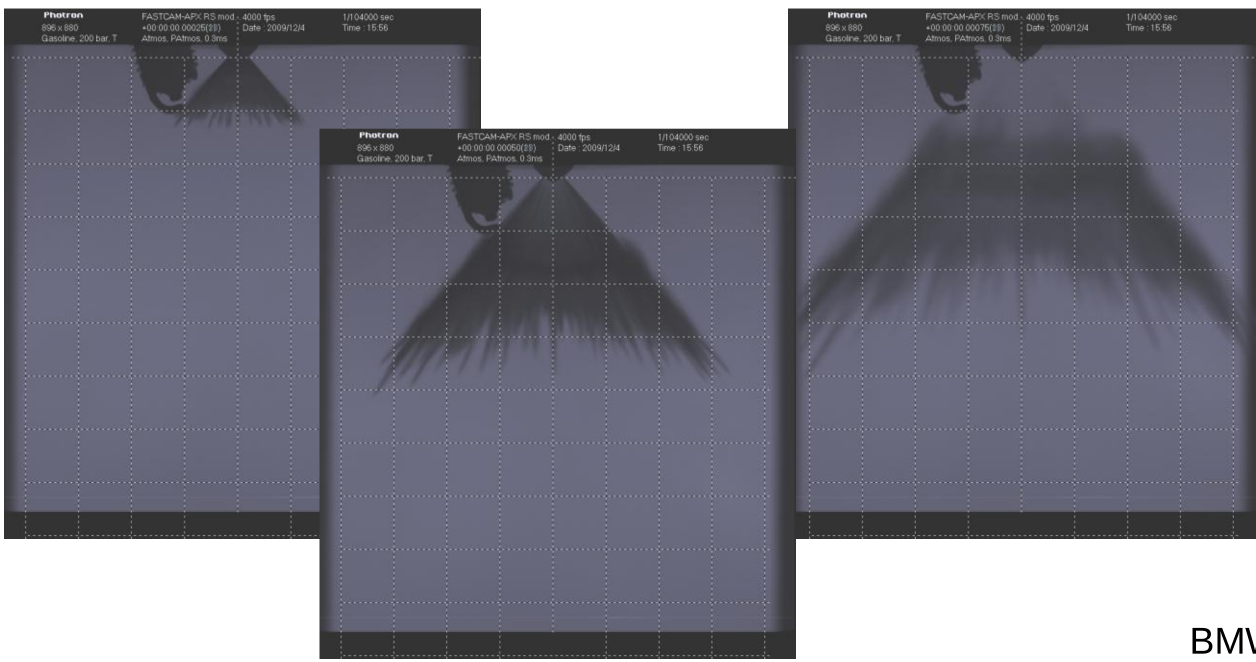
- 1st generation direct injection (G-DI)
  - 10-120 bar fuel pressure / range of injection timings
  - Single and multi-hole solenoid

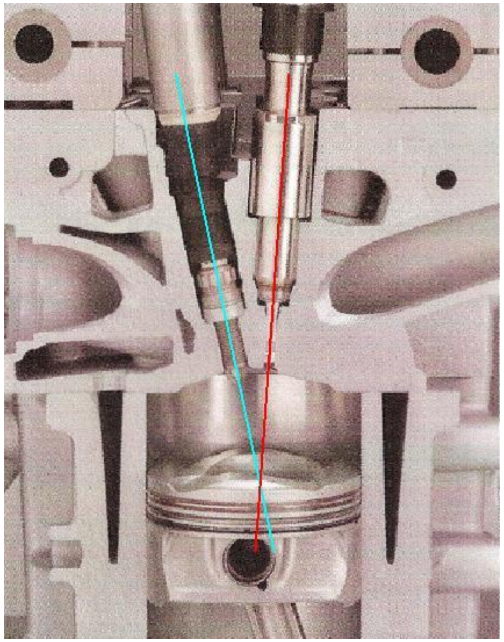


(Preussner et al., (1998))

Progression in fuel injection systems

- 2nd generation direct injection- high degree of specialism
  - 150 - ?? bar fuel injection pressure / variable needle lift / multi-shot
  - Outward pintle or multi-hole, solenoid and piezo



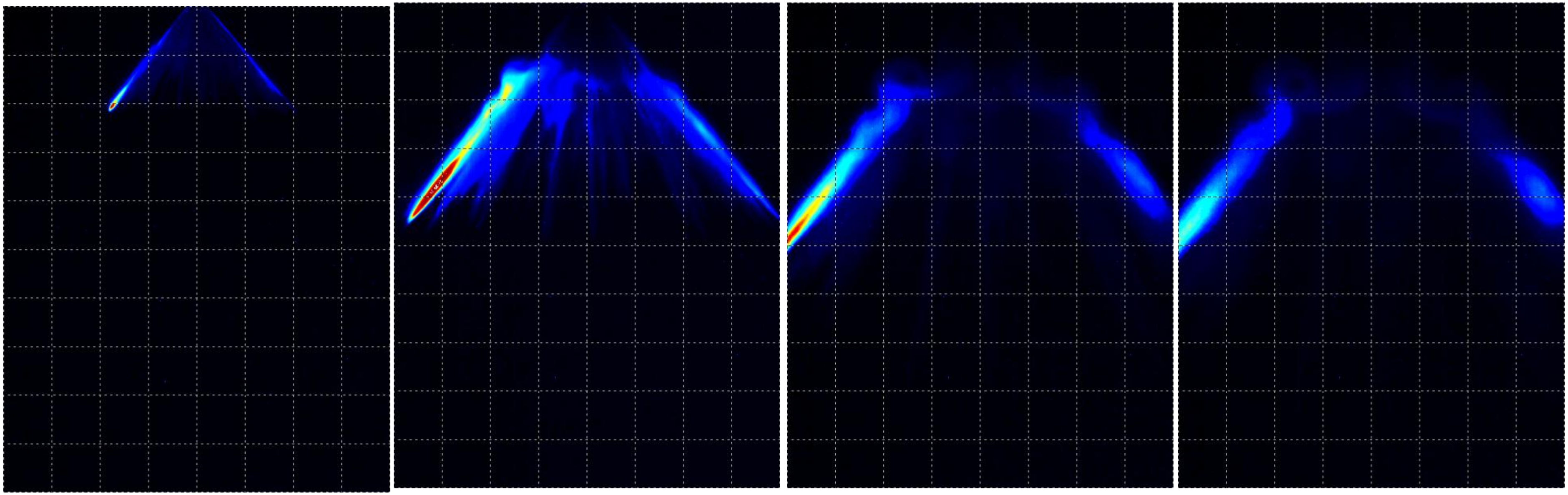


BMW stratified, 16° Spark plug / Injector

Images courtesy of collaborative project with Uni. Of Cardiff and Ricardo, 0.3 to 0.9 ms ASOI, 200 bar, ambient pressure gas

Progression in fuel injection systems

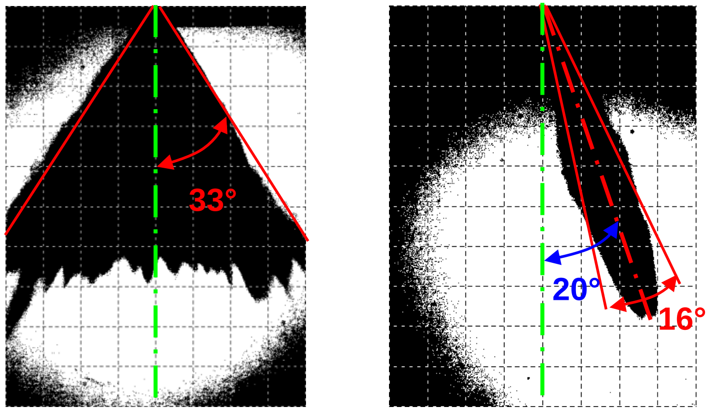
- 2nd generation direct injection
  - 200 bar fuel injection pressure/ outward pintle solenoid injector
  - Laser light-sheet (Mie scattering) highlights head vortex-ring-like structures

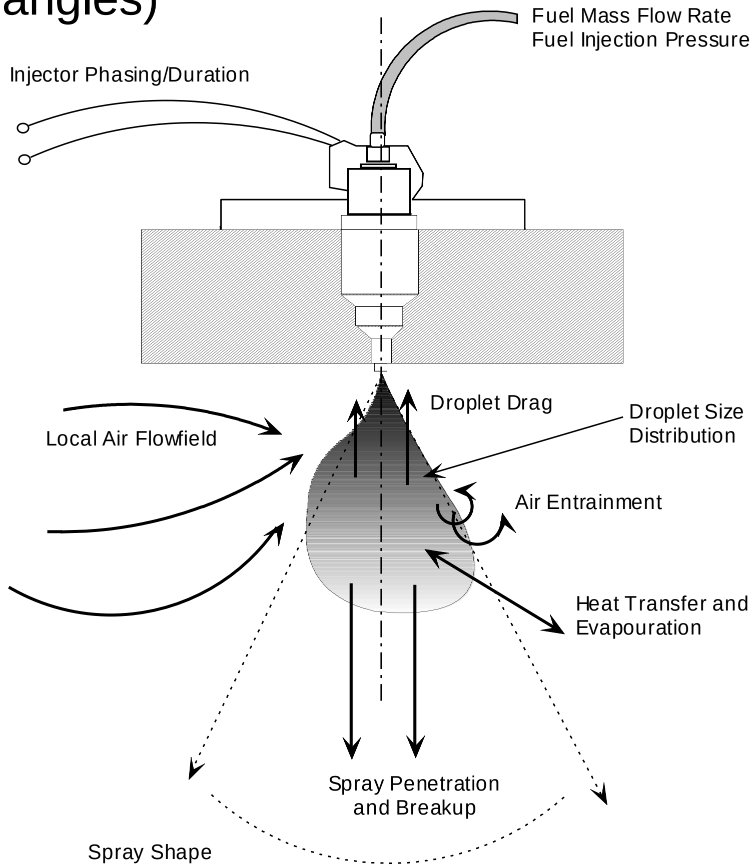


Images courtesy of collaborative project with Uni. Of Cardiff and Ricardo, 0.3 to 1.2 ms ASOI, E85 at 200 bar, ambient pressure gas

Key characteristics of the fuel spray

- Spray geometry (cone, separation, deflection angles)
- Length scales (penetration/impingement)
- Droplet atomisation 'quality'
- Time scales (0.1 to 100 ms range)
- Shot-to-shot repeatability
- Vortex ring-like structures



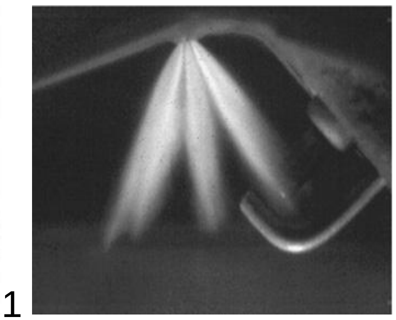


Images courtesy of collaborative project with Uni. Of Cardiff and Ricardo

Optical diagnostics commonly applied to sprays

- Photographic
- Planar Mie techniques
- Planar inelastic scattering techniques
- Phase Doppler Anemometry

1



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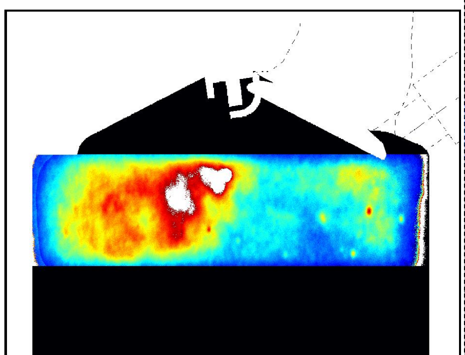
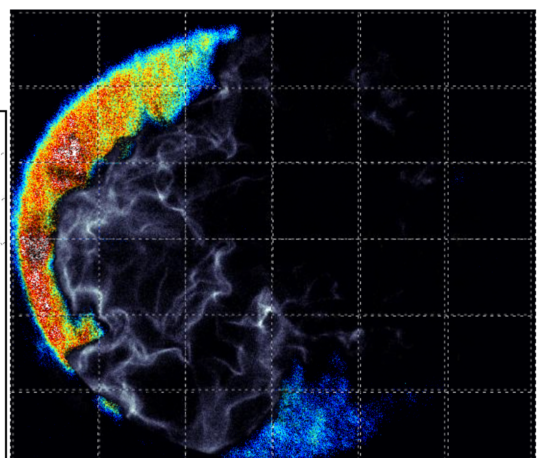
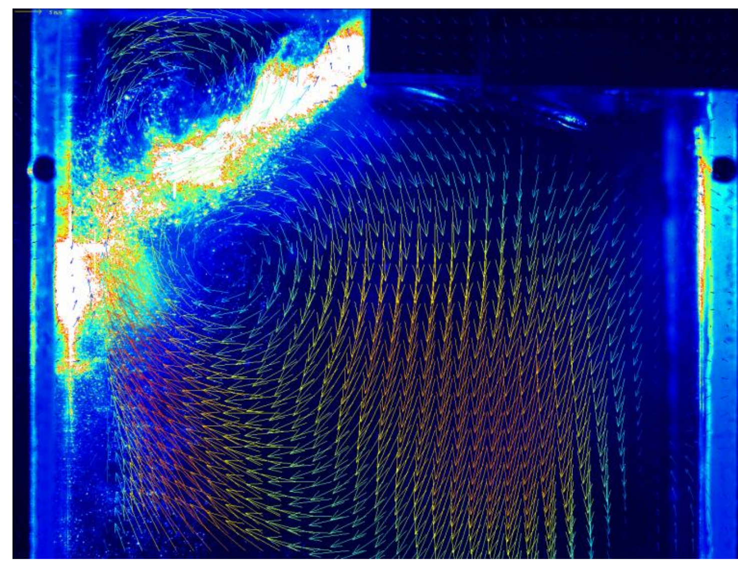


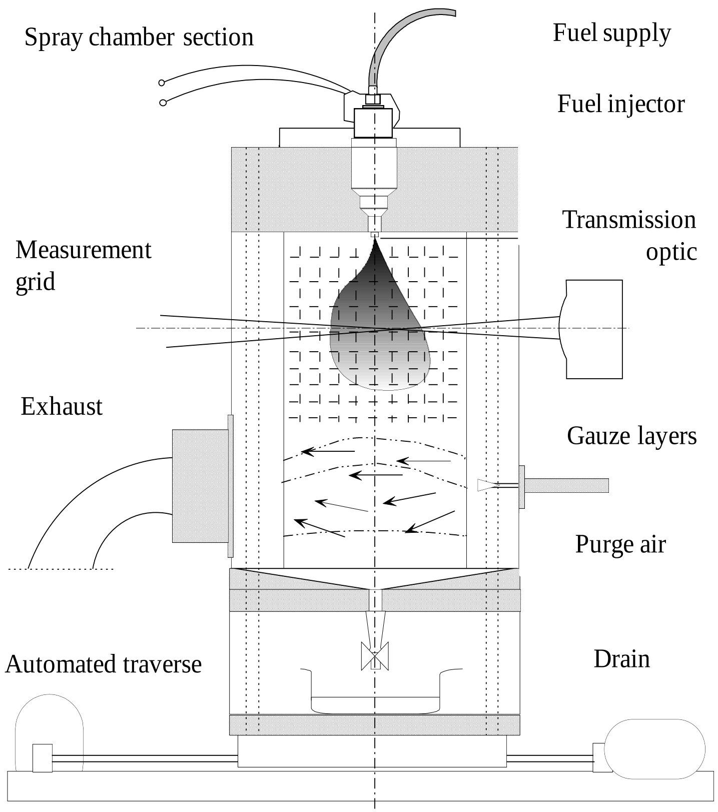


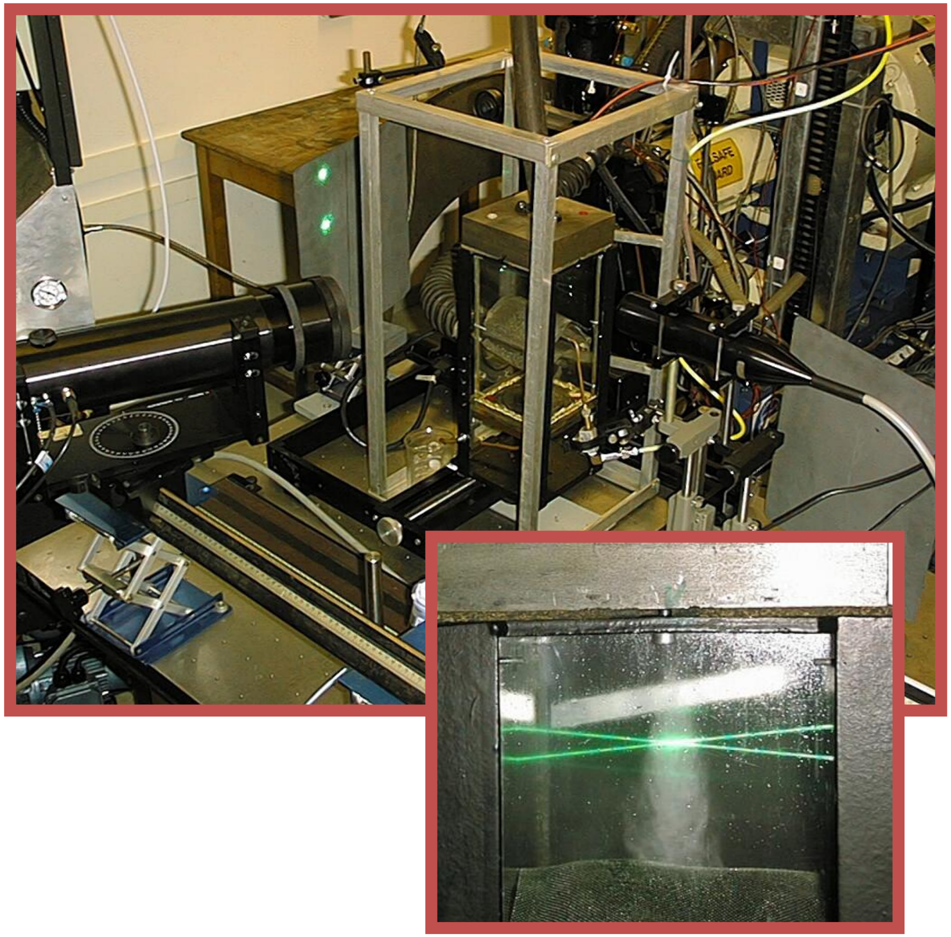


[1] *Nouri et al., 2007,* [2] *(Fansler et al., (2006))*

Optical diagnostics commonly applied to sprays

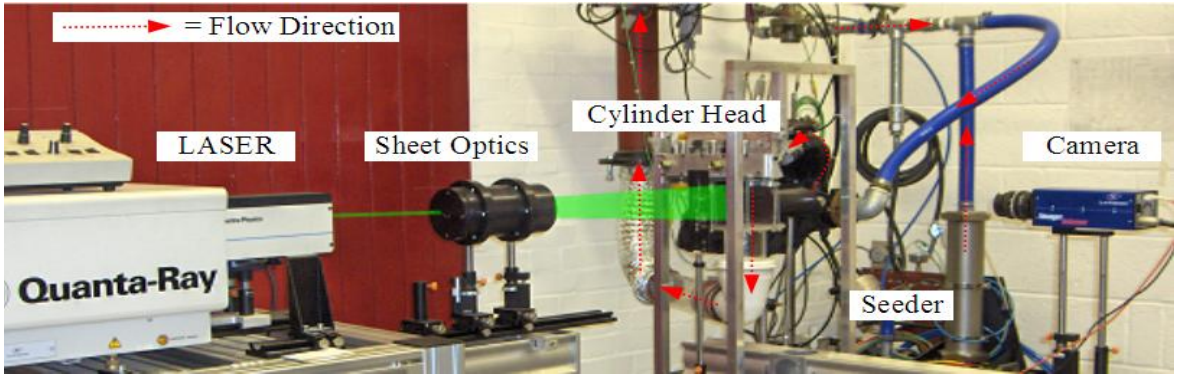
- Simple static chamber

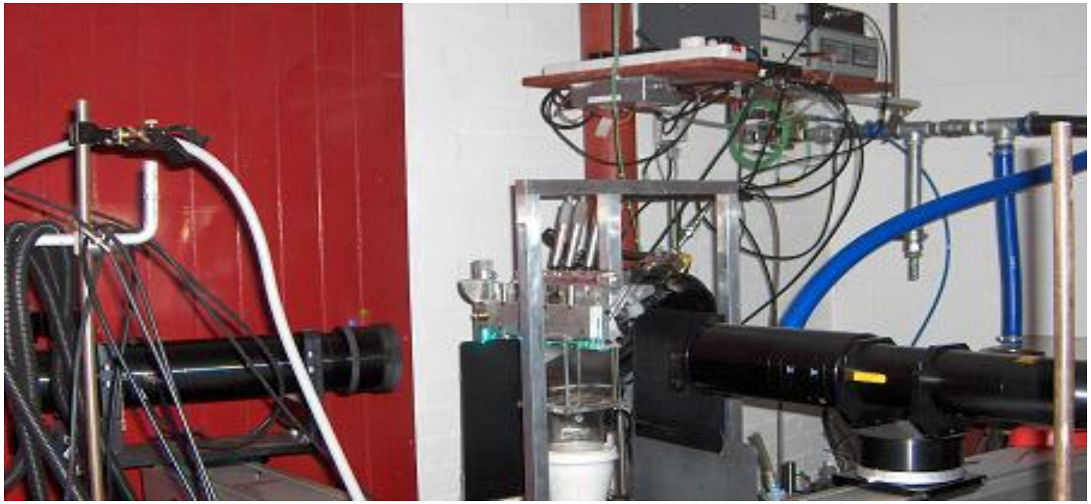


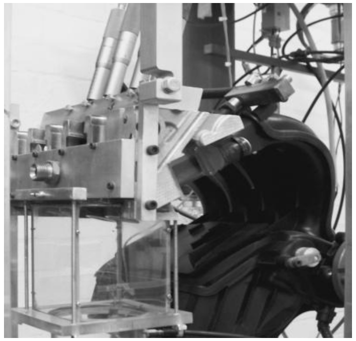


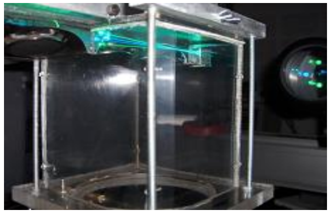
Optical diagnostics commonly applied to sprays

- Steady-flow rig

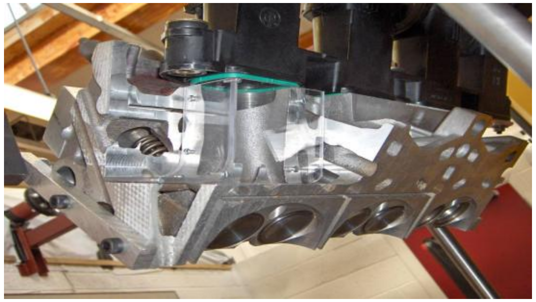






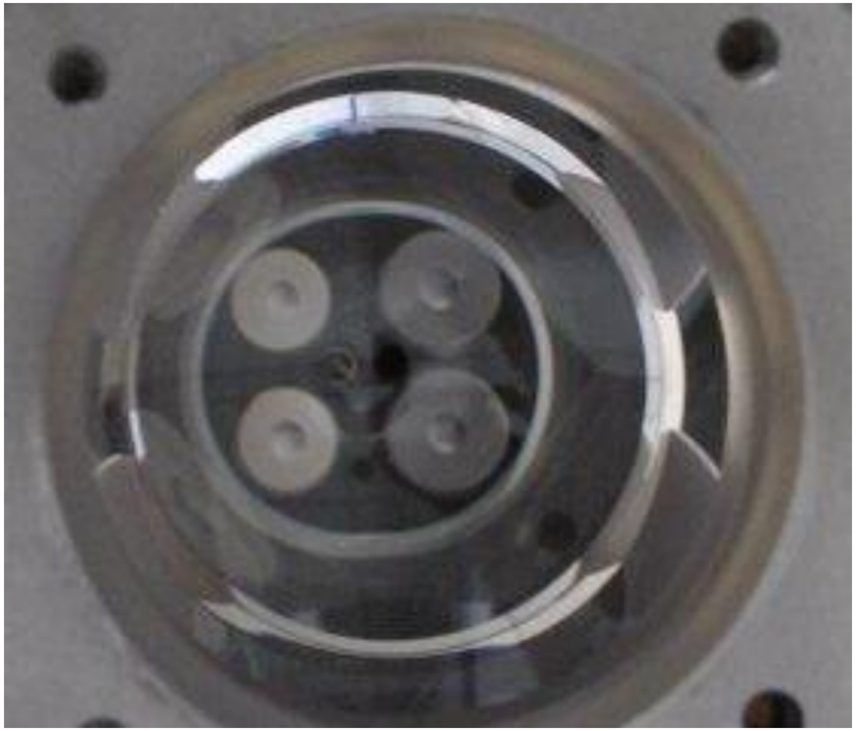


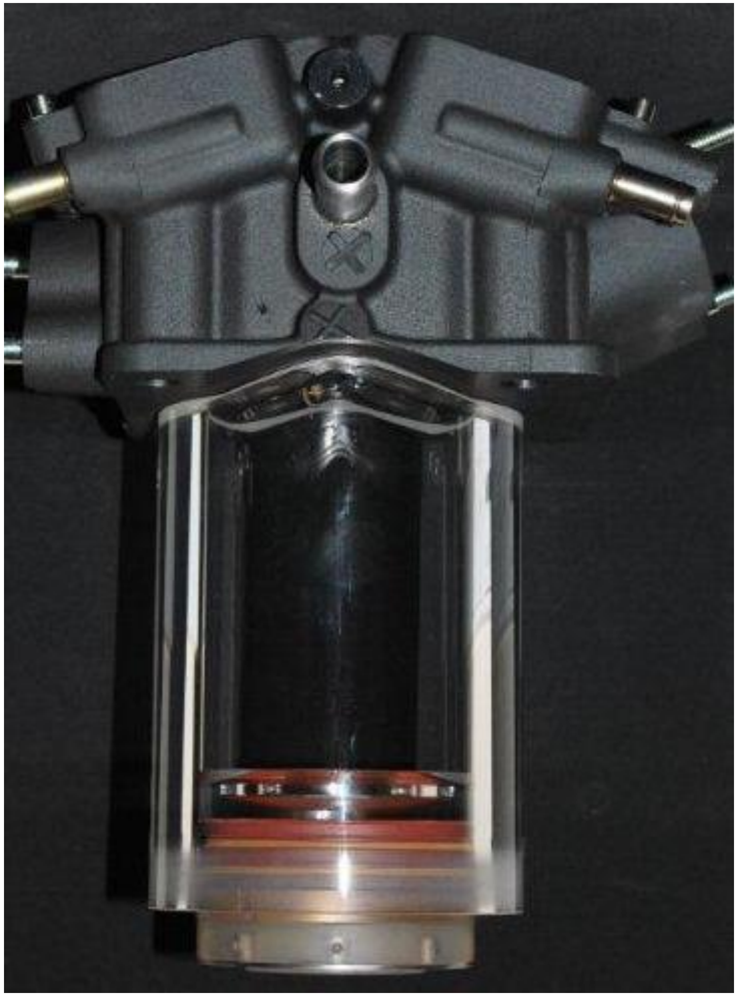
Modified Production
BMW Valvetronic Engine



Optical diagnostics commonly applied to sprays

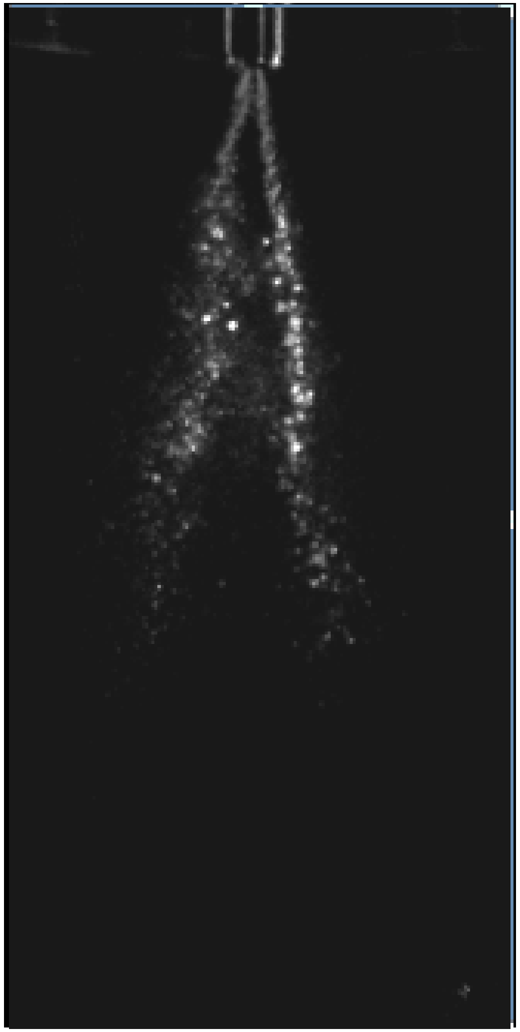
- Fired, optical engine



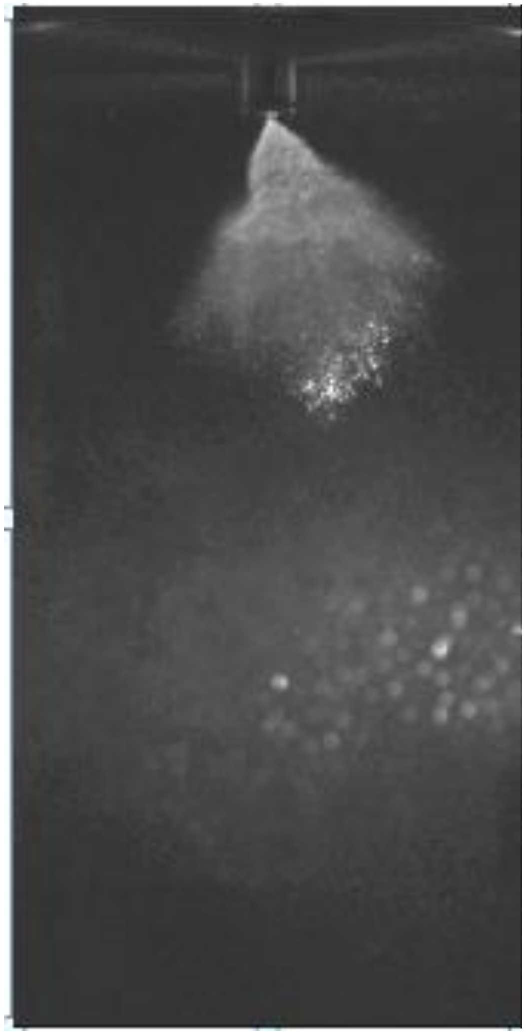


Spray imaging- chamber

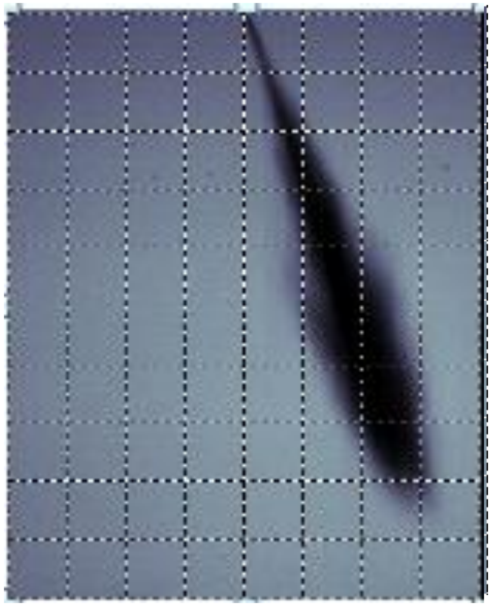
PFI multi-stream



Off-axis pressure-swirl



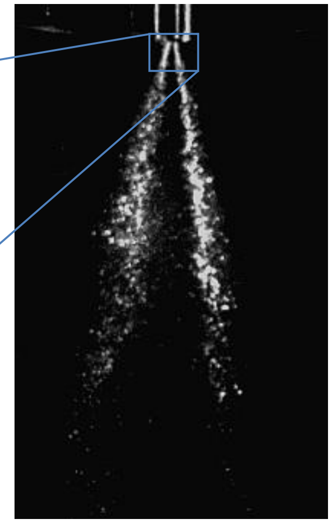
Flat fan

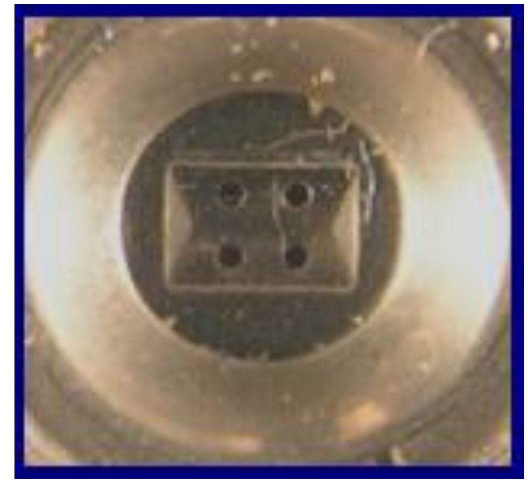


Fan images courtesy of collaborative project with Uni. Of Cardiff and Ricardo

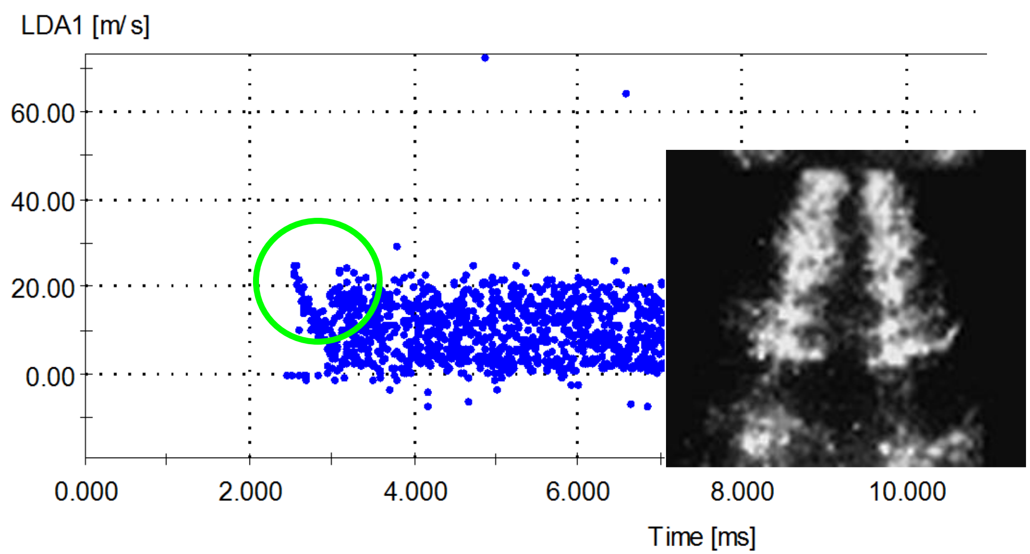
Combining Spray Imaging with PDA

8 mm



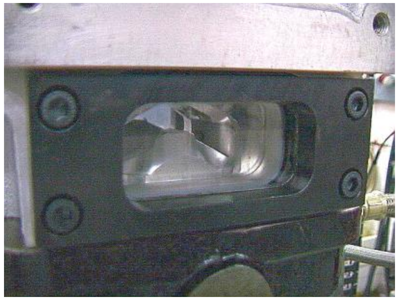


- axial and radial waves
- droplet stripping
- asymmetry
- 'hesitation' due to necking of the liquid stream

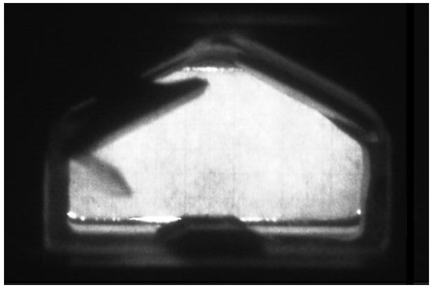


Spray imaging- motored engine

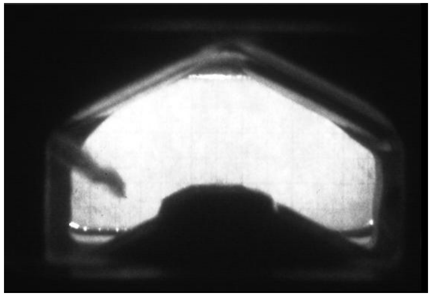
Top-entry G-DI – effect of in-cylinder pressure

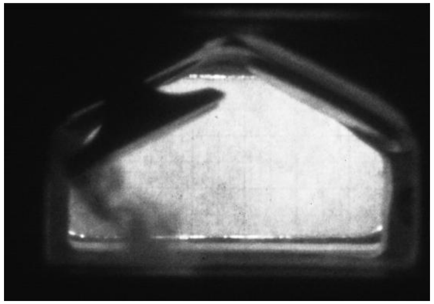


Early Injection		Late Injection
60° - 121°		301°- 318°

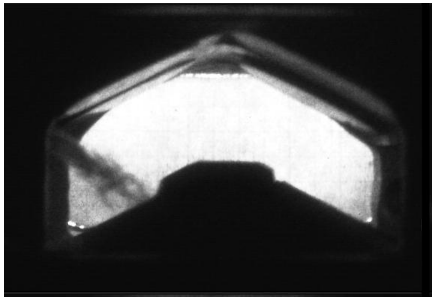


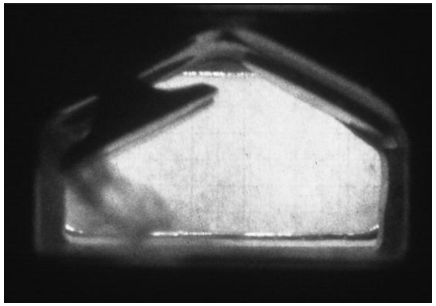
Onset



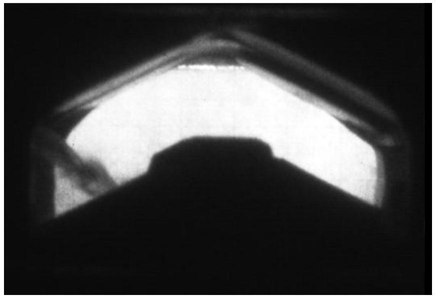


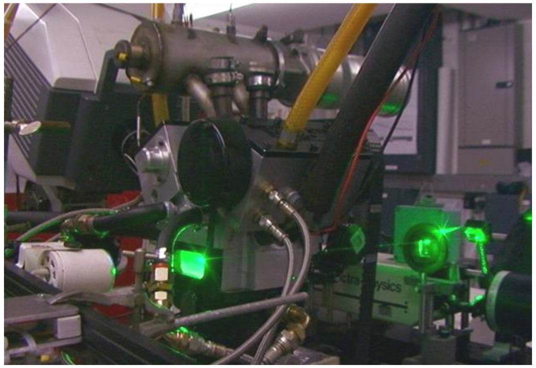
Middle

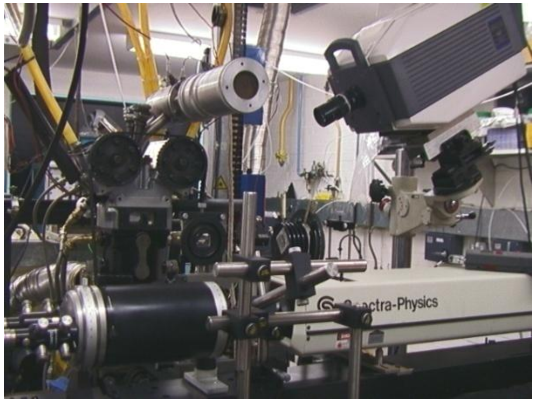




End

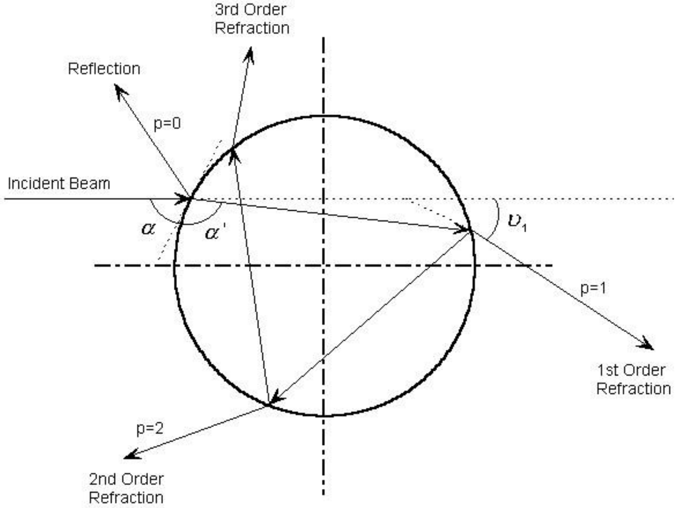


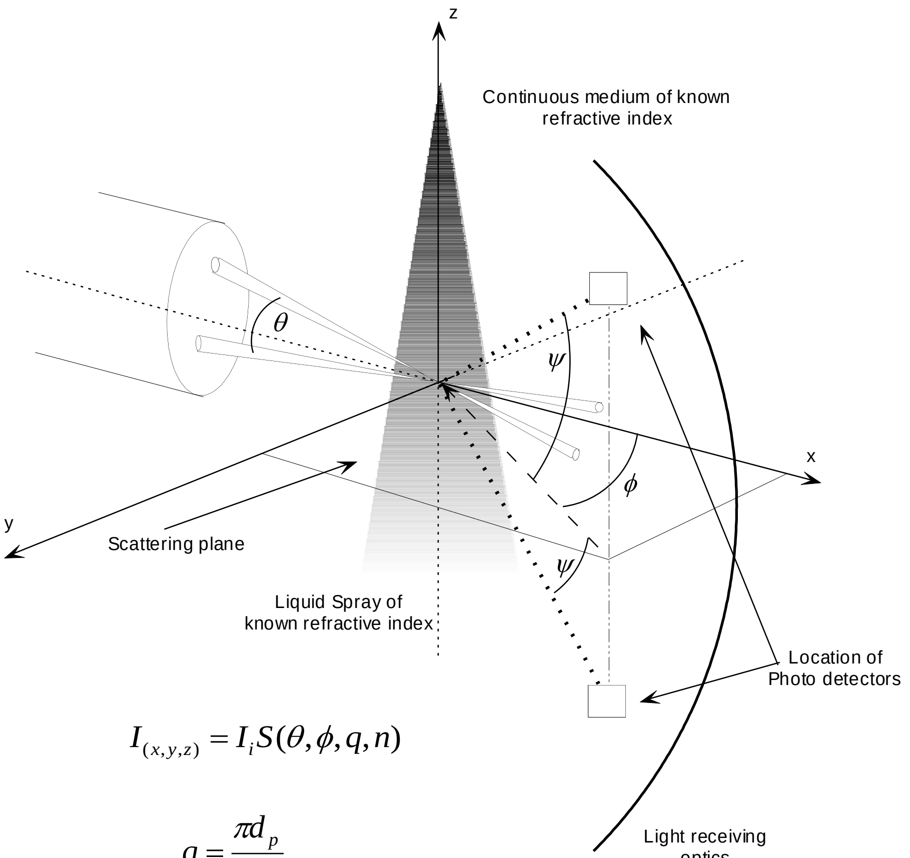




Phase Doppler anemometer (PDA)

- Conventional PDA





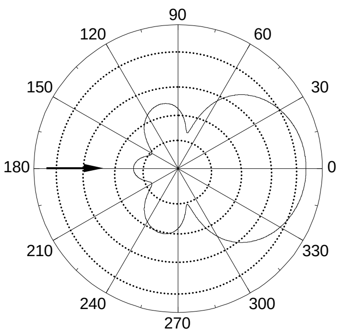
$$I_{(x,y,z)} = I_i S(\theta, \phi, q, n)$$

$$q = \frac{\pi d_p}{\lambda}$$

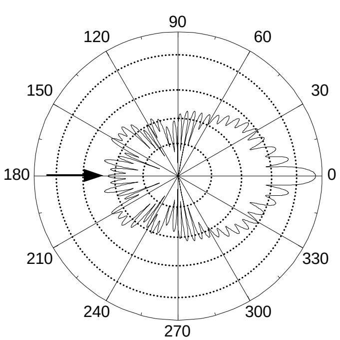
Phase Doppler anemometer (PDA)

- Polar distribution of light intensity

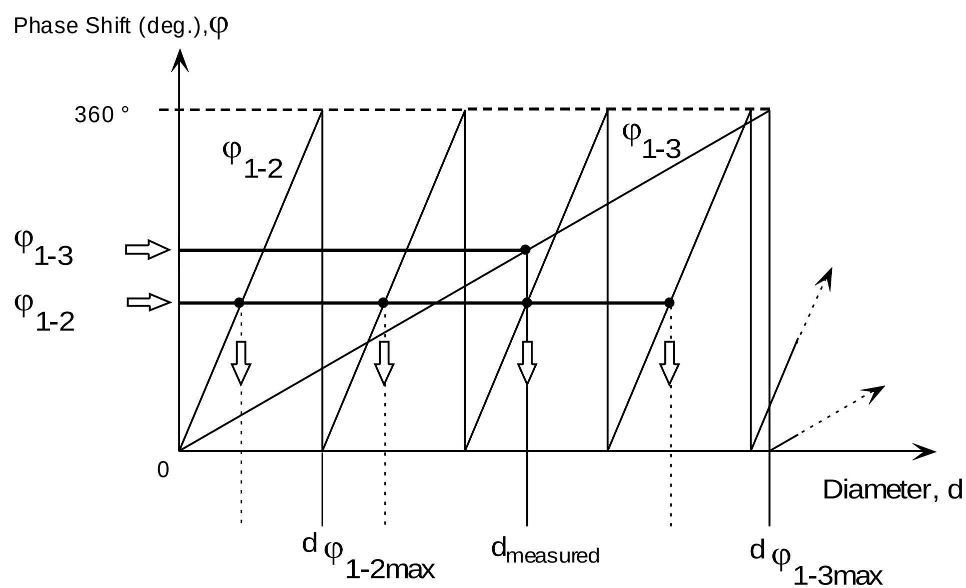
Brewster's angle used to collect first order refraction p=1



$d_p \cong 1.0\lambda$



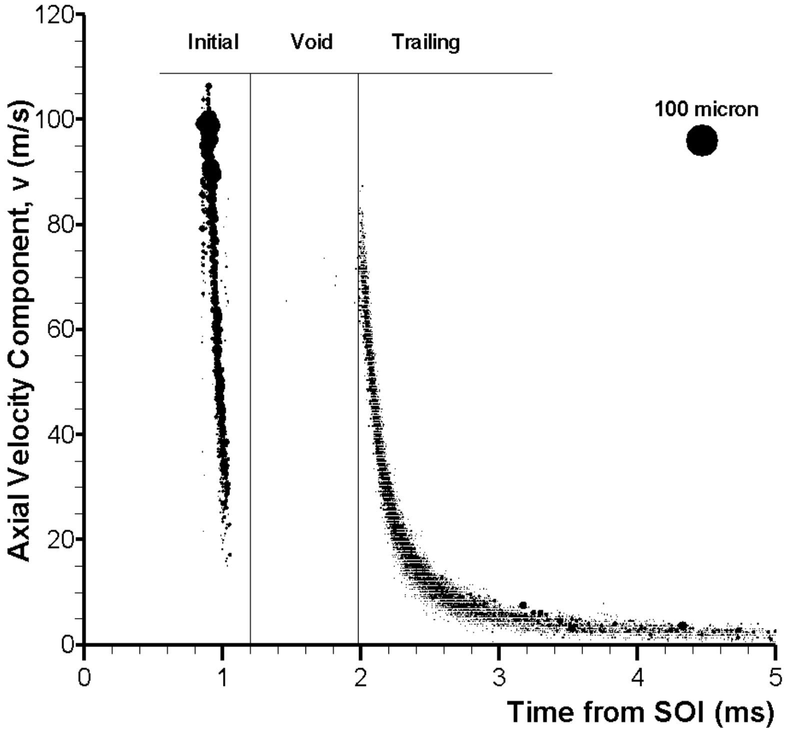
$d_p \cong 10\lambda$



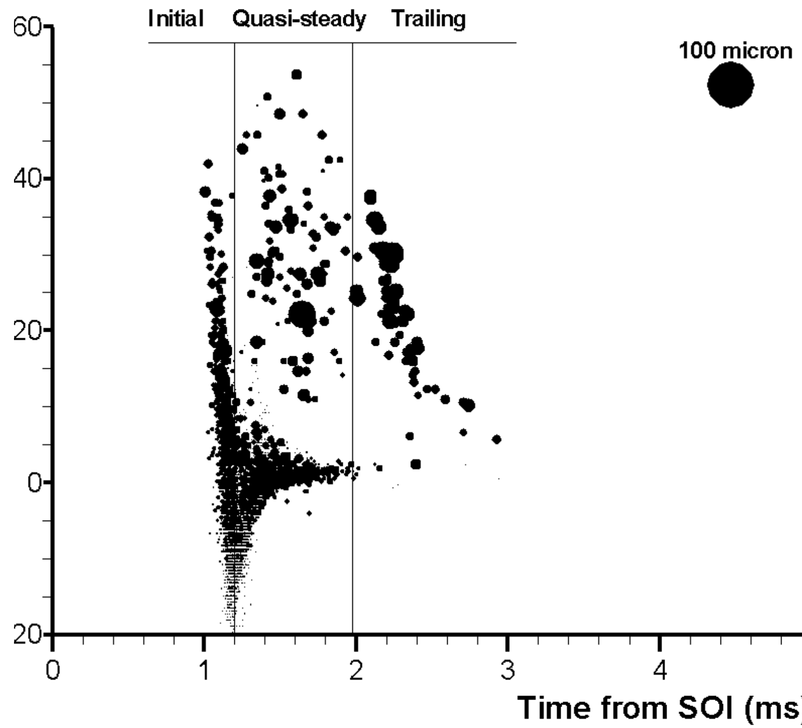
$$d_p = -\Phi\left(\frac{\lambda}{2\pi}\right)\left(\frac{\sqrt{2\left(1+\cos\theta\cos\varphi\cos\phi\right)\left(1+n^2-n\sqrt{2\left(1+\cos\theta\cos\varphi\cos\phi\right)}\right)}}{n\sin\theta\sin\varphi}\right)$$

Phase Doppler anemometer (PDA)

- Typical features of time series at two locations in a high-pressure spray

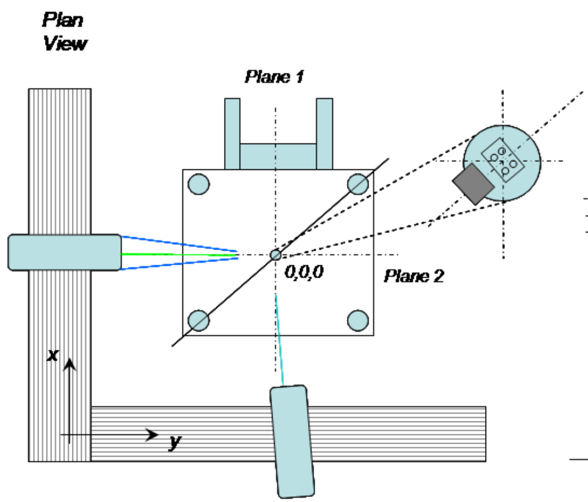


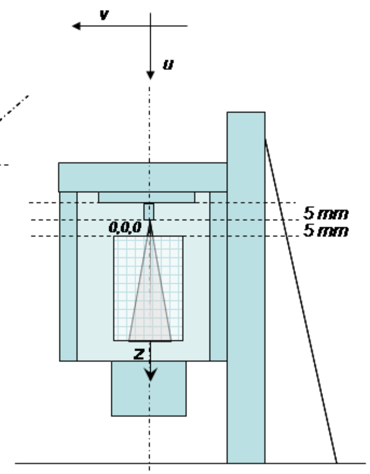
r = 0, x = 15 mm

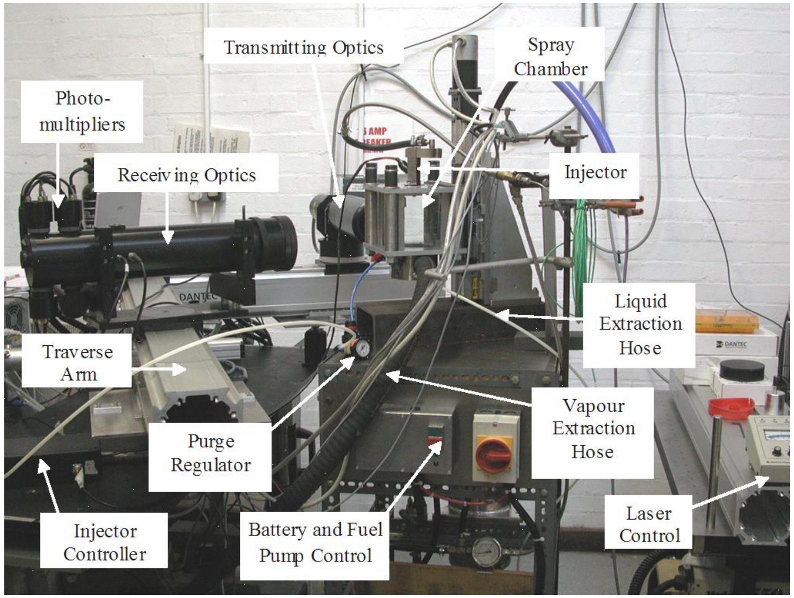


r = 10, x = 15 mm

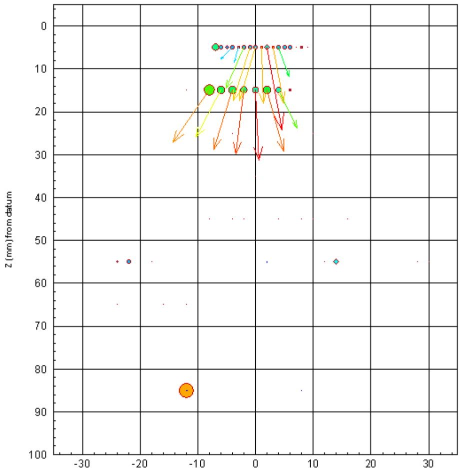
PDA– Spray chamber



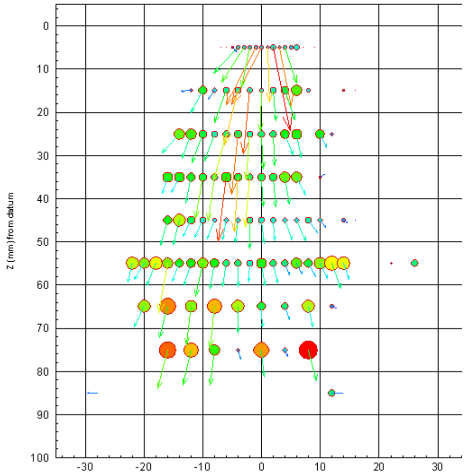




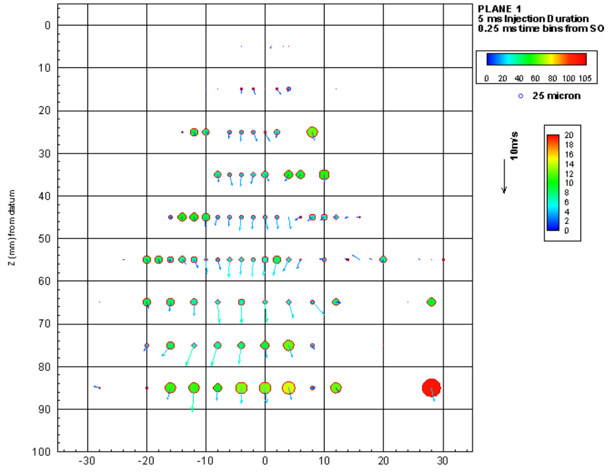
Initial Phase



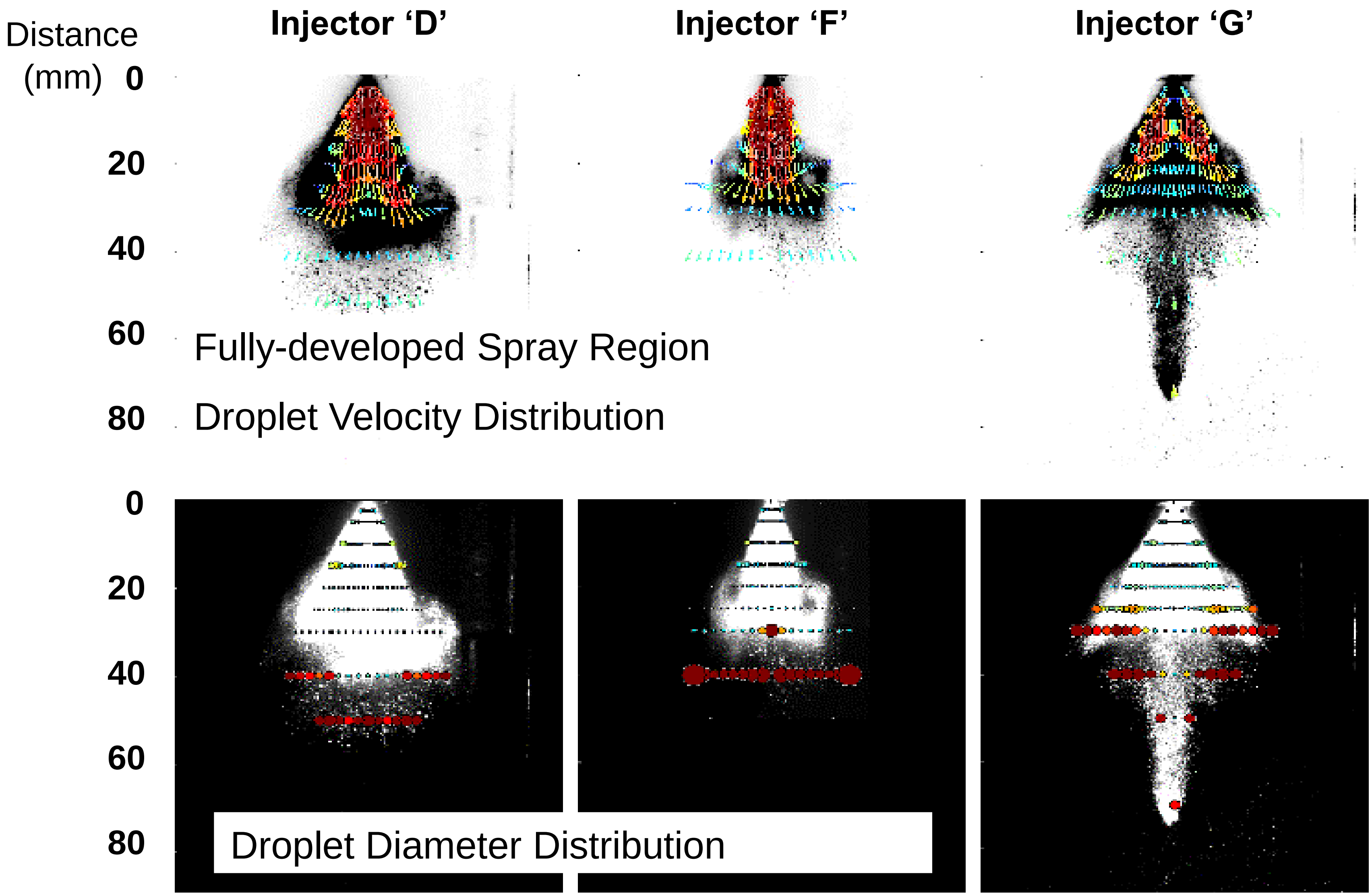
Quasi-steady Phase



Trailing Phase

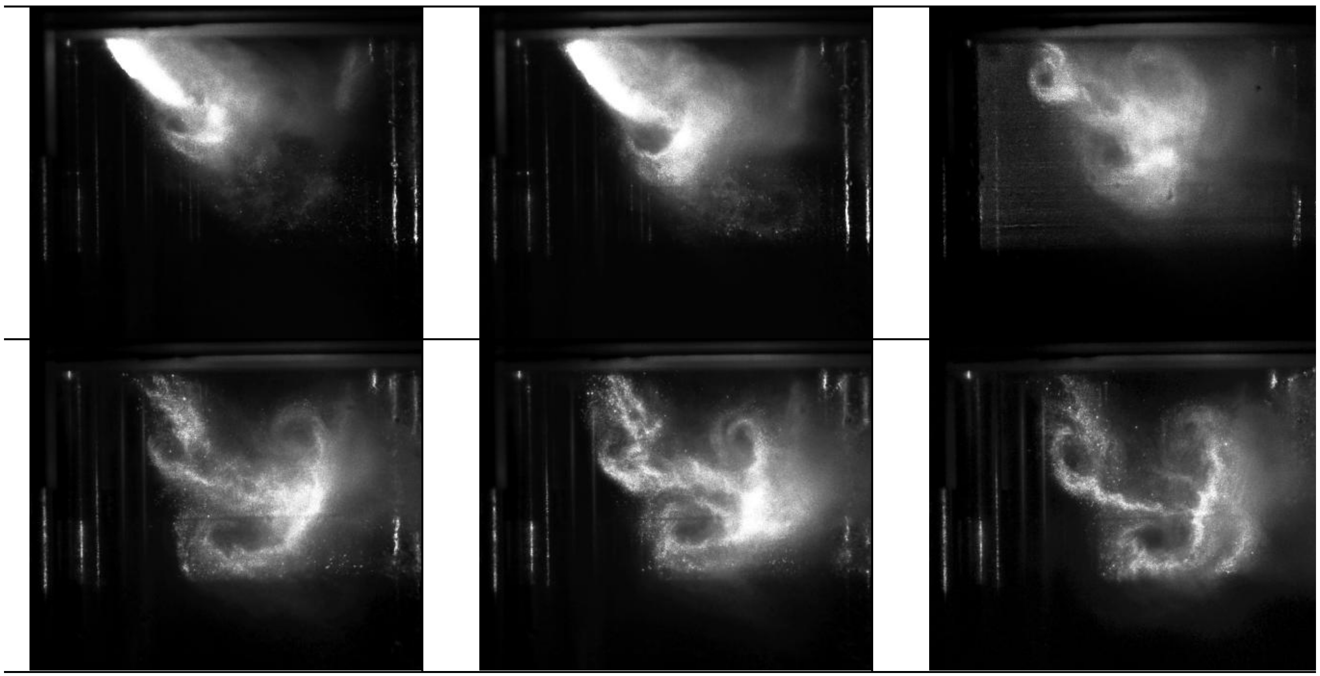


Combining imaging with PDA– Spray chamber

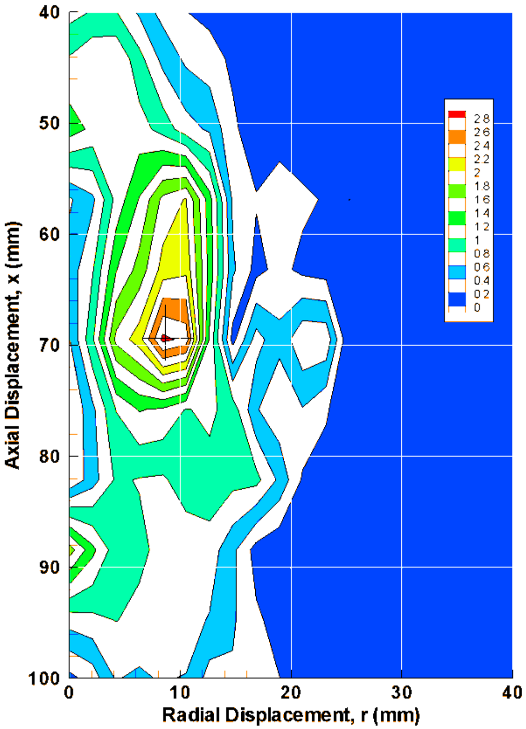


Vortex ring-like structures

- Development of a generalised vortex ring model



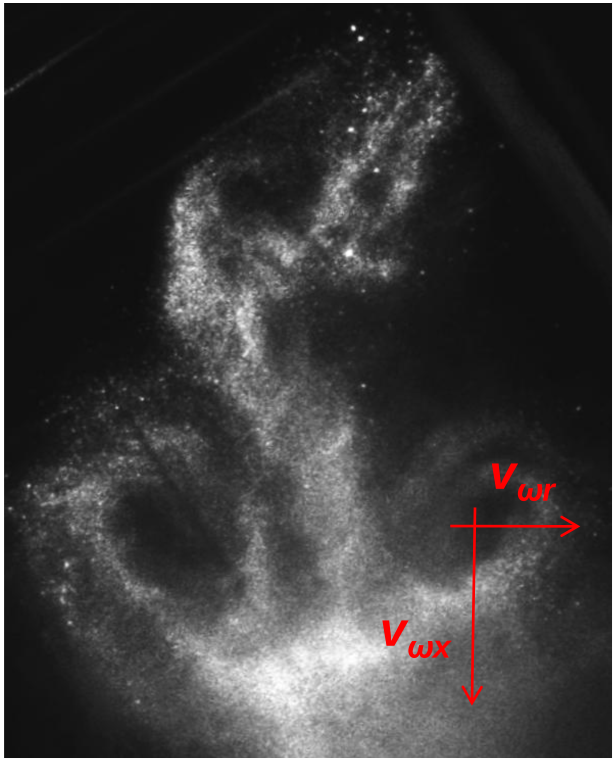
Chronological sequence of high-speed photographs, (left to right) recorded using a laser light sheet, in a G-DI spray in an optical engine with full glass cylinder liner

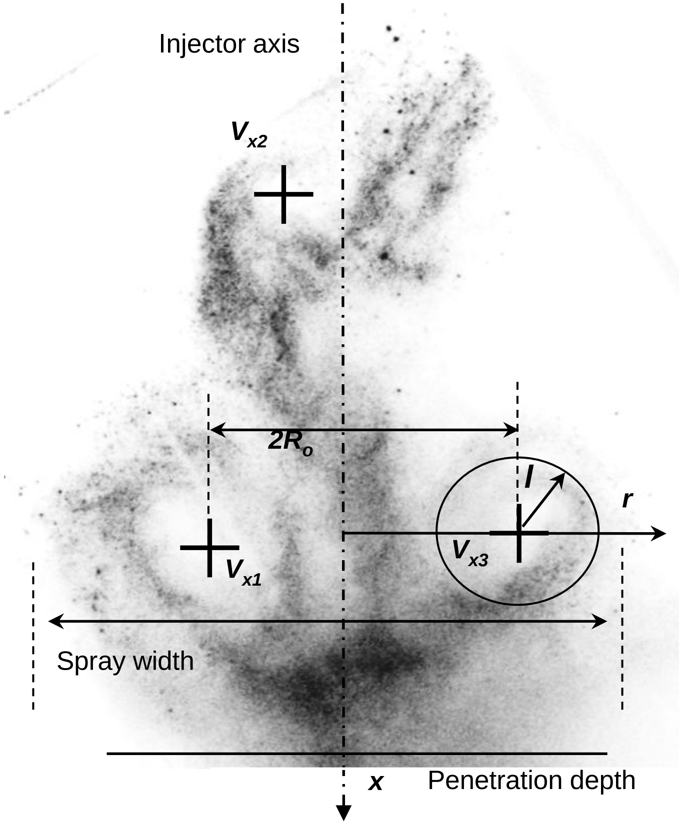


The distribution of the vorticity magnitude for *t*=3.75 ms

Phase Doppler anemometer (PDA)

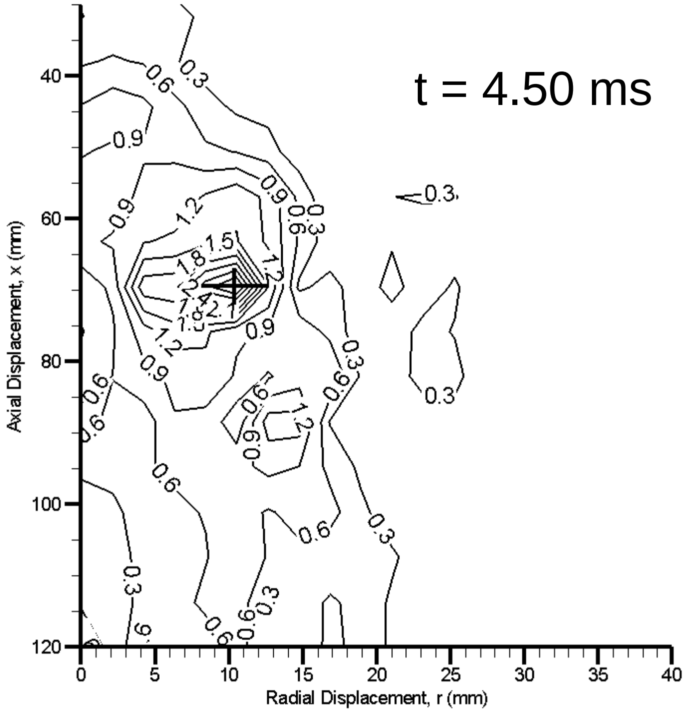
- Vortex-ring like features in a high-pressure spray

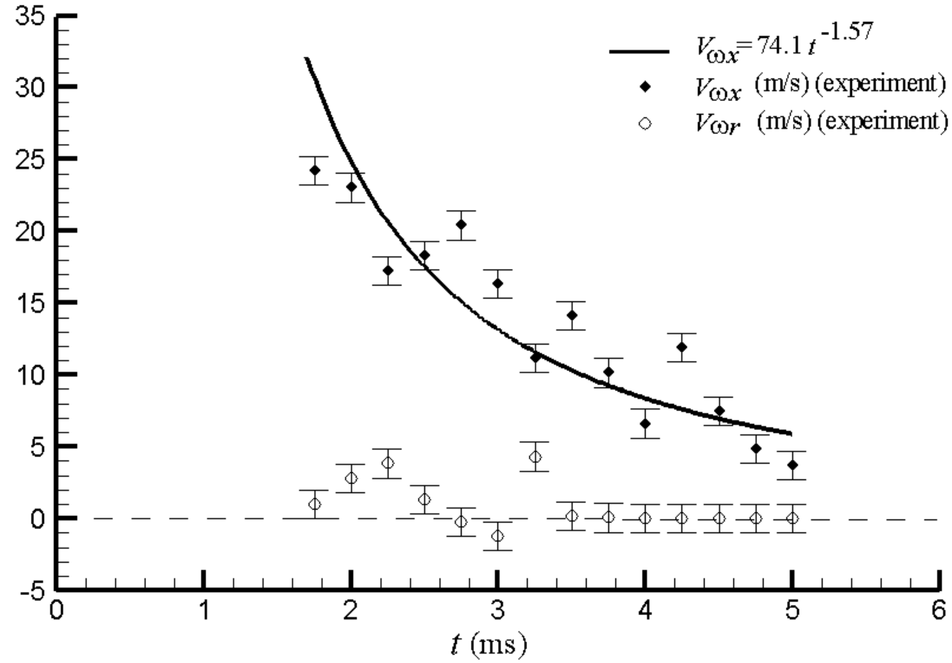




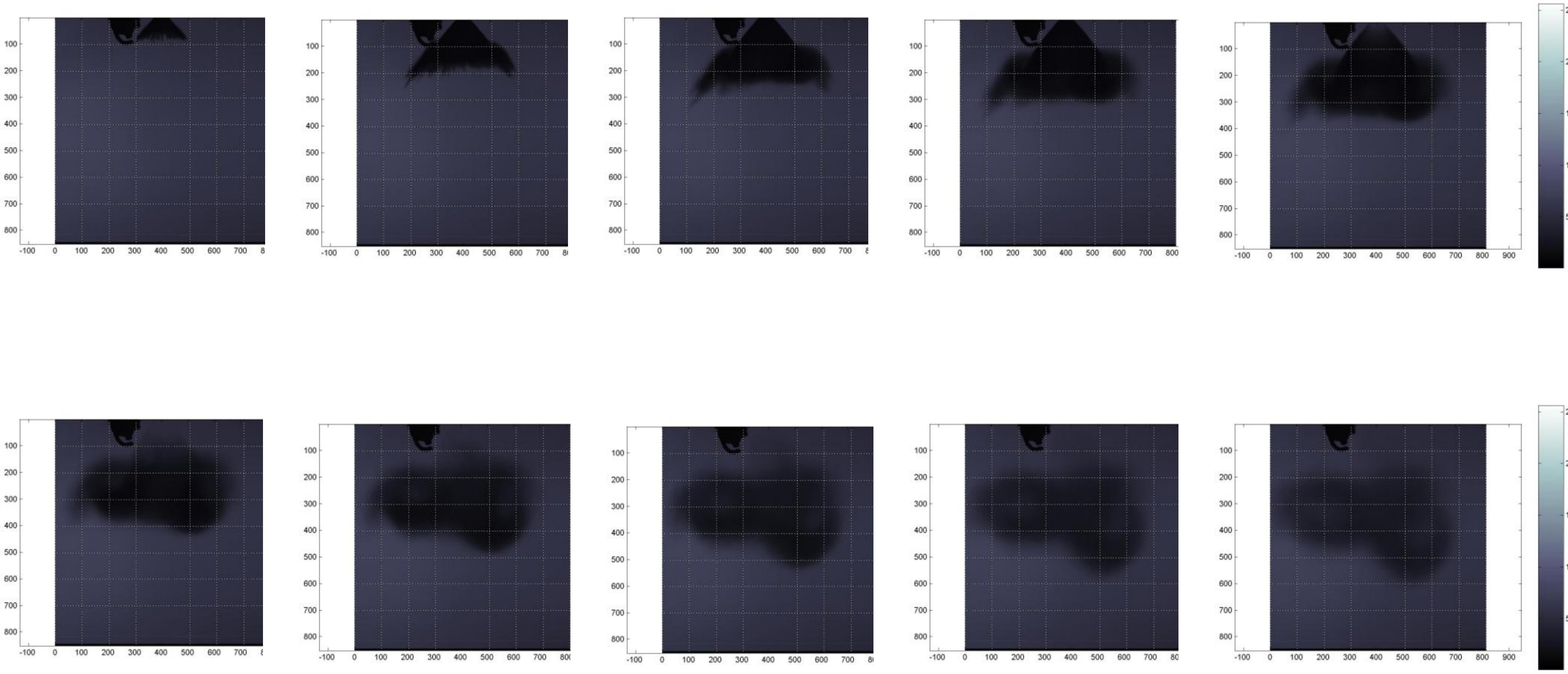
Phase Doppler anemometer (PDA)

- Reconstruction of the spatial distribution of the droplet velocity and size
- Data ensemble-averaged within arbitrary time bins
- Track features (e.g. translation of region of maximal vorticity)





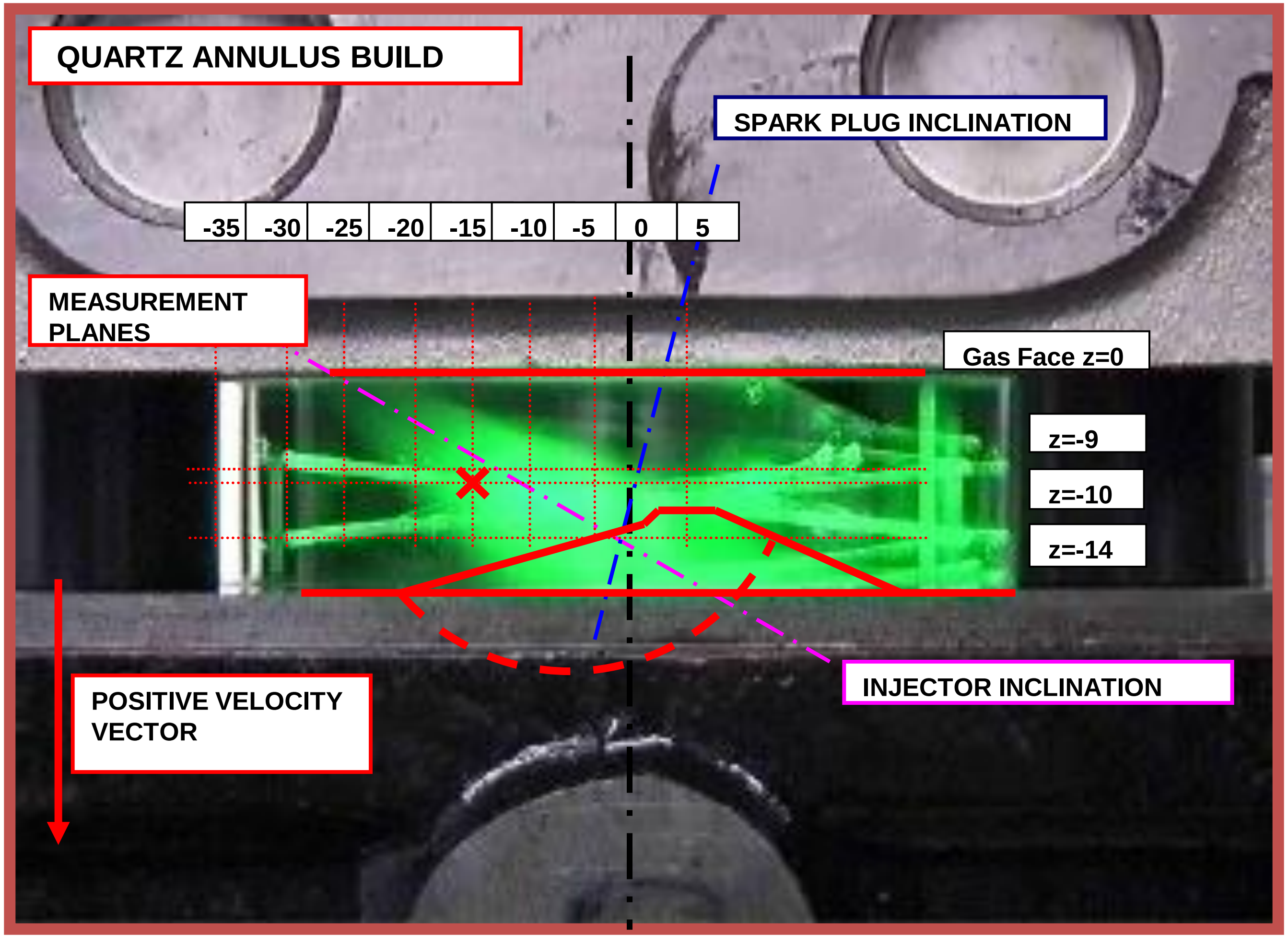
Vortex ring-like structures



Chronological sequence of high-speed photographs, recorded using a laser light sheet, (left to right) in a static spray chamber, 150 bar fuel pressure, 6 barg gas pressure, 1 to 10 ms ASOI, gasoline fuel.

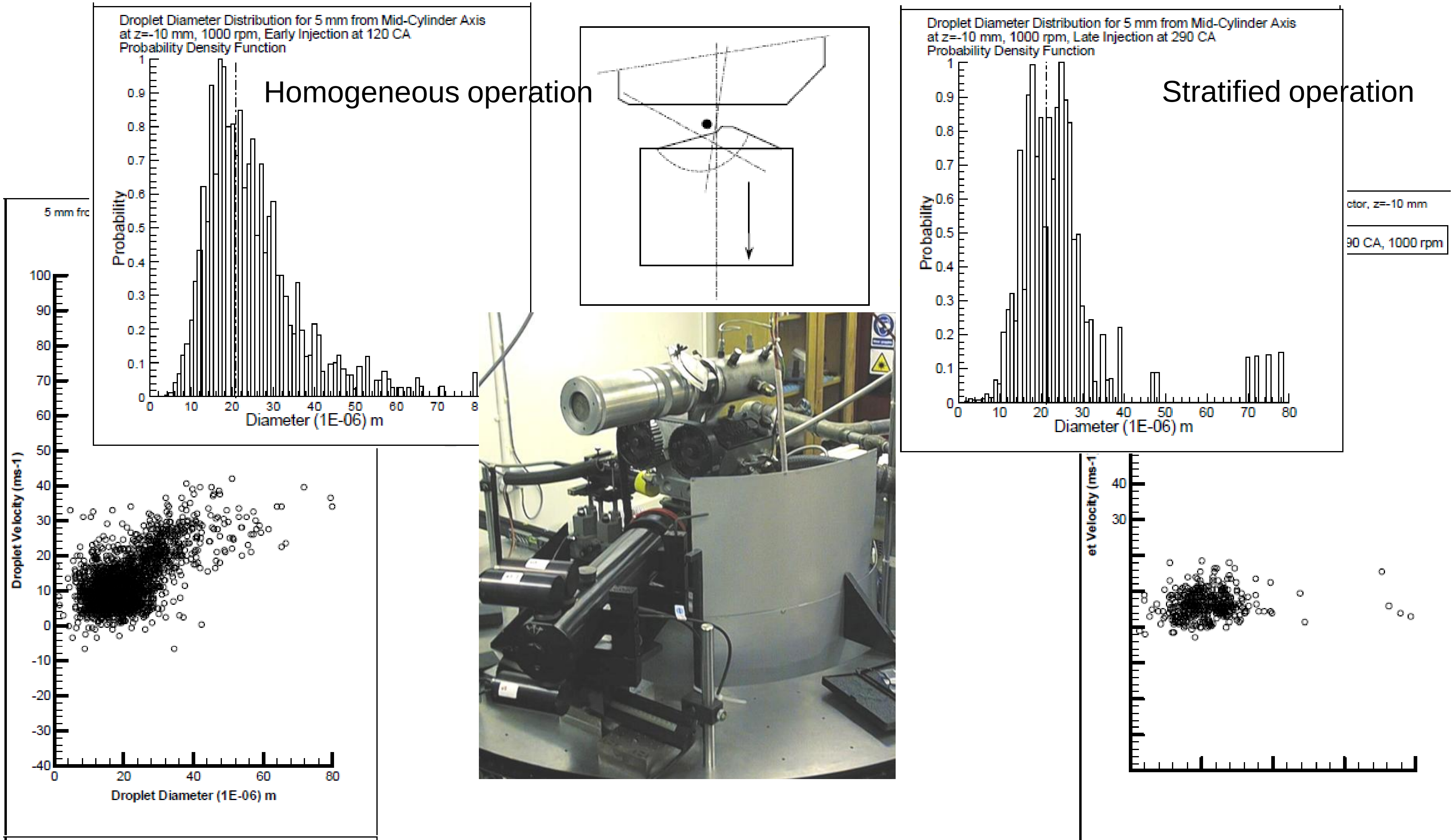
Images courtesy of collaborative project with Uni. Of Cardiff and Ricardo

Phase Doppler anemometer (PDA) – motored engine



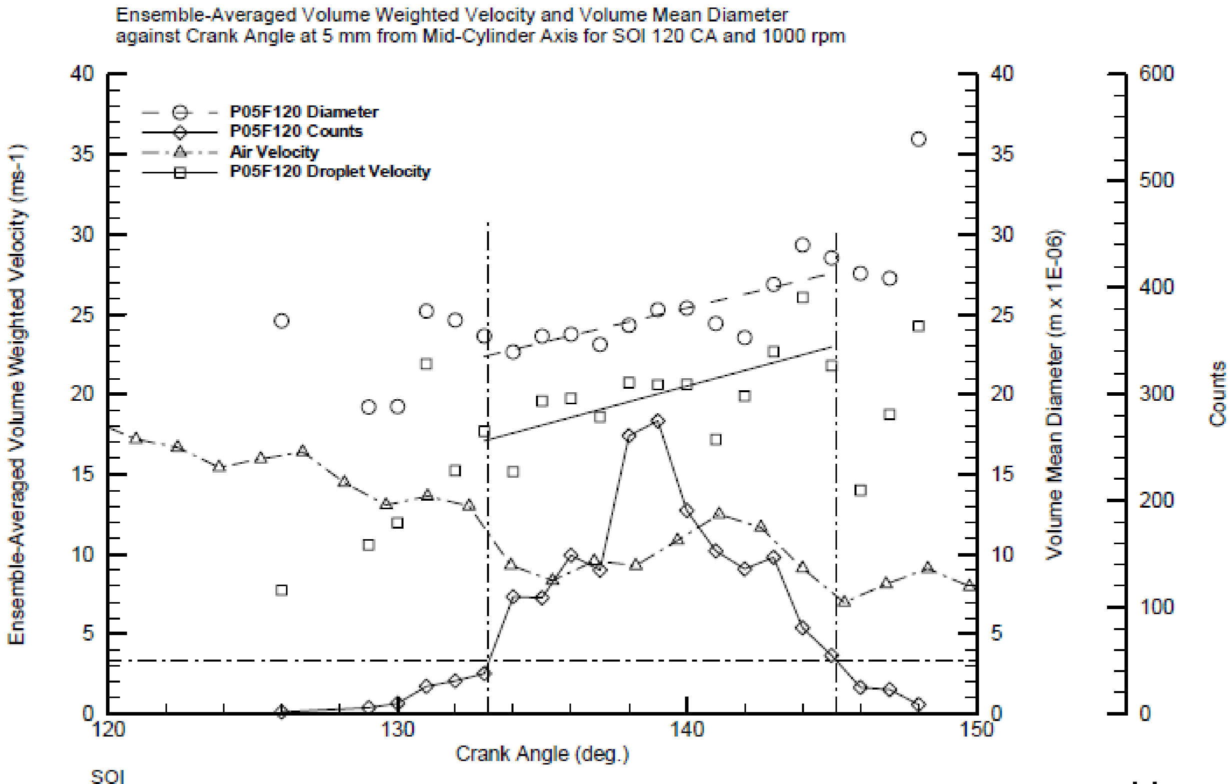
Phase Doppler anemometer (PDA) –motored engine

- Comparison of static chamber results with reciprocating engine



Phase Doppler anemometer (PDA)

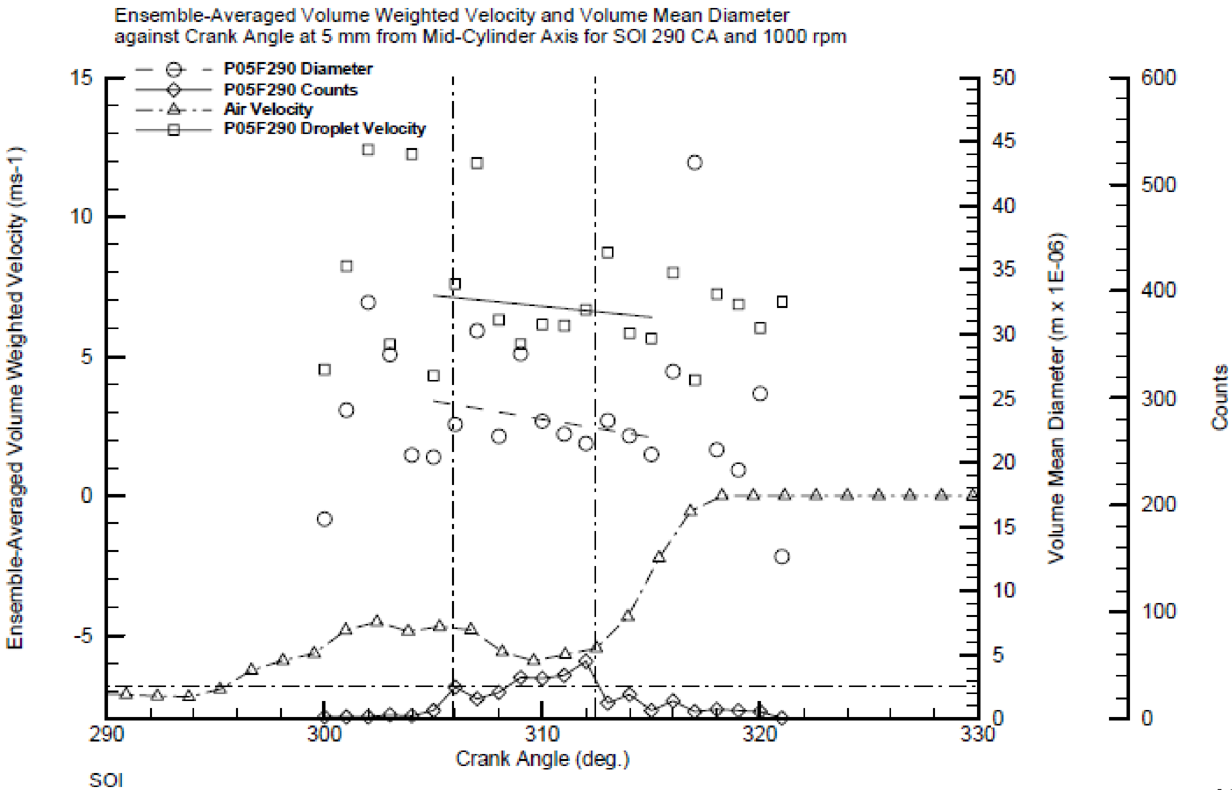
- Comparison of higher order number and moment mean diameters for reciprocating engine (e.g. d_{30})



Homogeneous operation

Phase Doppler anemometer (PDA)

- Comparison of higher order number and moment mean diameters for reciprocating engine (e.g. d_{30})



Stratified operation

Conclusions and modelling challenges for fuel sprays

- Future experiments must address a single injection event
  - to capture the characteristics at crank angle resolution
  - within a single cycle and from one consecutive cycle to the next
  - correlation with poor cycles of combustion
- Modelling must incorporate the finer details
  - evolution of vortex ring models
  - fuel injection and gas flow coupling
  - multi-component fuels and fuel blends
  - integration of chemical kinetic models with physical models

Acknowledgements

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- Ricardo UK Ltd
- DTI/TSB 2/4 SIGHT and 2/4 CAR programmes
- Staff and students of the CAE

Experimental observations of fuel sprays in gasoline engines

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