Droplet velocity and diameter measurements in vortex-ring like structures in a non-evaporating fuel spray

Progress and research directions in the EPSRC Vortex Ring projects

Dr Steven Begg
Experimental Fluid Mechanics Research Group
Centre for Automotive Engineering

1st December – Workshop- Vortex Ring-Like Structures

EPSRC
Engineering and Physical Sciences Research Council

france (manche channel) england interreg

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University of Brighton

Contents of presentation

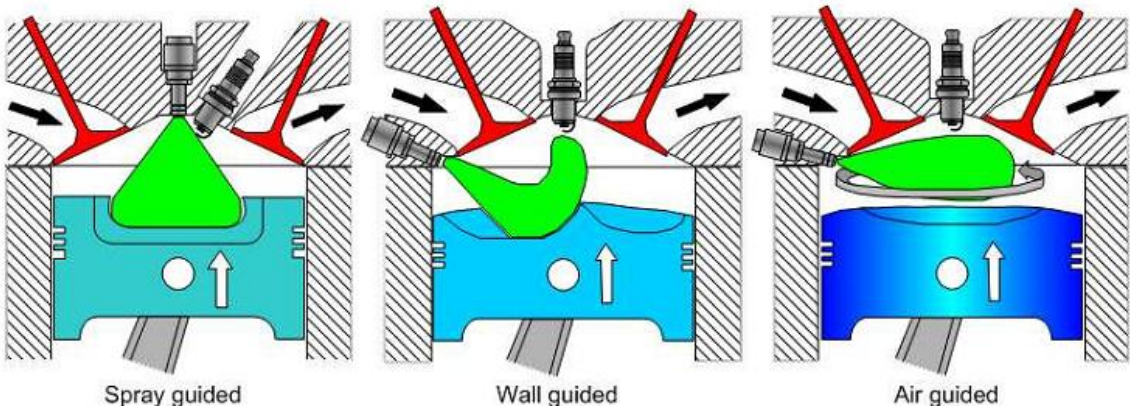
- Context and motivation for research
- Development of vortex projects undertaken by the partners
- Current and future directions
  - Measurement focus
    - Developments in Phase Doppler anemometry
    - Gas phase particle seeding

Gasoline engine – mixture preparation and combustion stability

- **Air handling**
  - Extending unthrottled operation, boosting, VVA, geometry, low cyclic variation, stratified lean control…
- **Fuel injection**
  - Direct (‘piezo’) injection, precision fuel metering, multiple injections, spray repeatability...
- **Engine control**
  - Crank-angled resolved, individual misfired cycles identified, multiple ignitions...

Progression in fuel injection systems

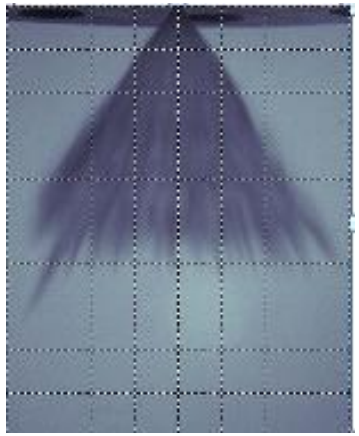
- Single point and multi-point port fuel injection (PFI)
  - 2-12 bar fuel pressure, OVI and CVI injection strategies
  - High cyclic variations, poor lean operation, poor tolerance to EGR
- 1st generation direct injection (G-DI)
  - 10-120 bar fuel pressure / flexible range of injection strategies
  - Optimised flow structures / stratification of charge
  - Sensitivity to fuel injector location and spray characteristics
  - Relatively high ubHC and NOx emissions



Stefan S., Optical Diagnostics on FSI Transparent Engine, FISITA World Automotive Congress, Barcelona Spain, 2004.

Technological progression

1. Flat Fan DI 2. Hollow Cone PFI 3. Multi-hole (10) DI 4. Pressure Swirl DI 5. Hollow Cone DI



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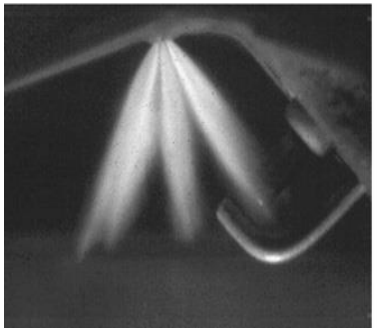

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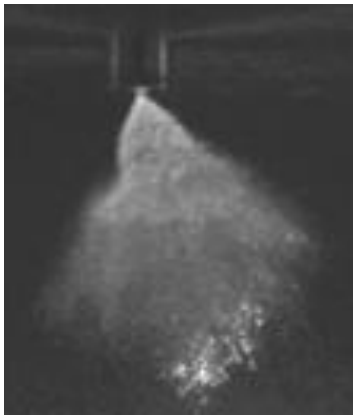
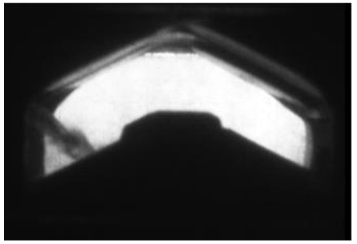
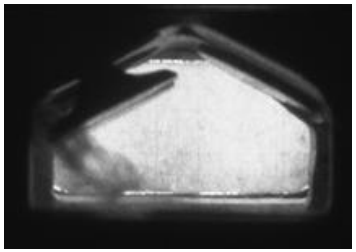
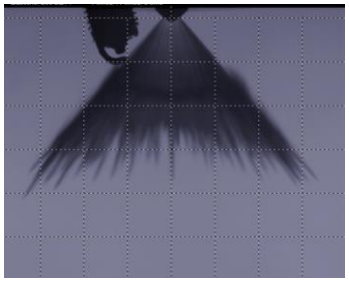
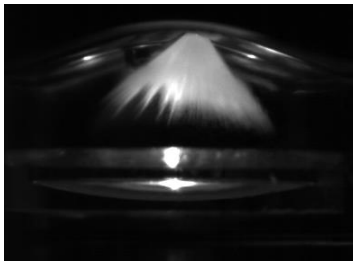
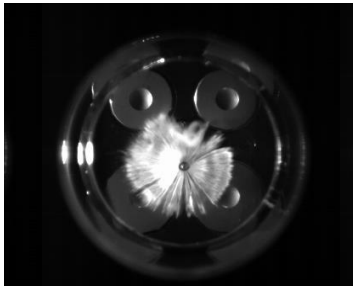


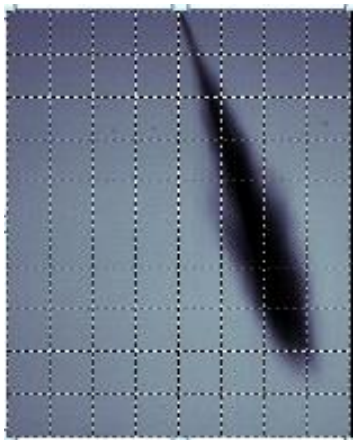










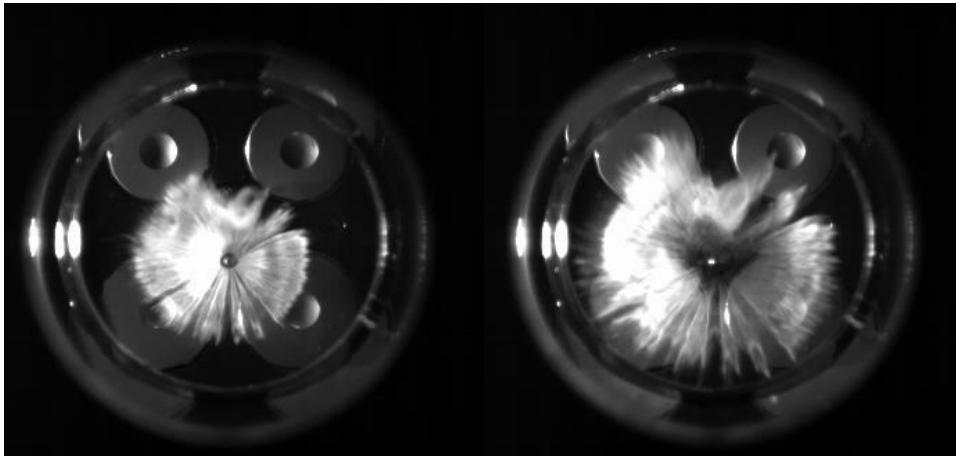


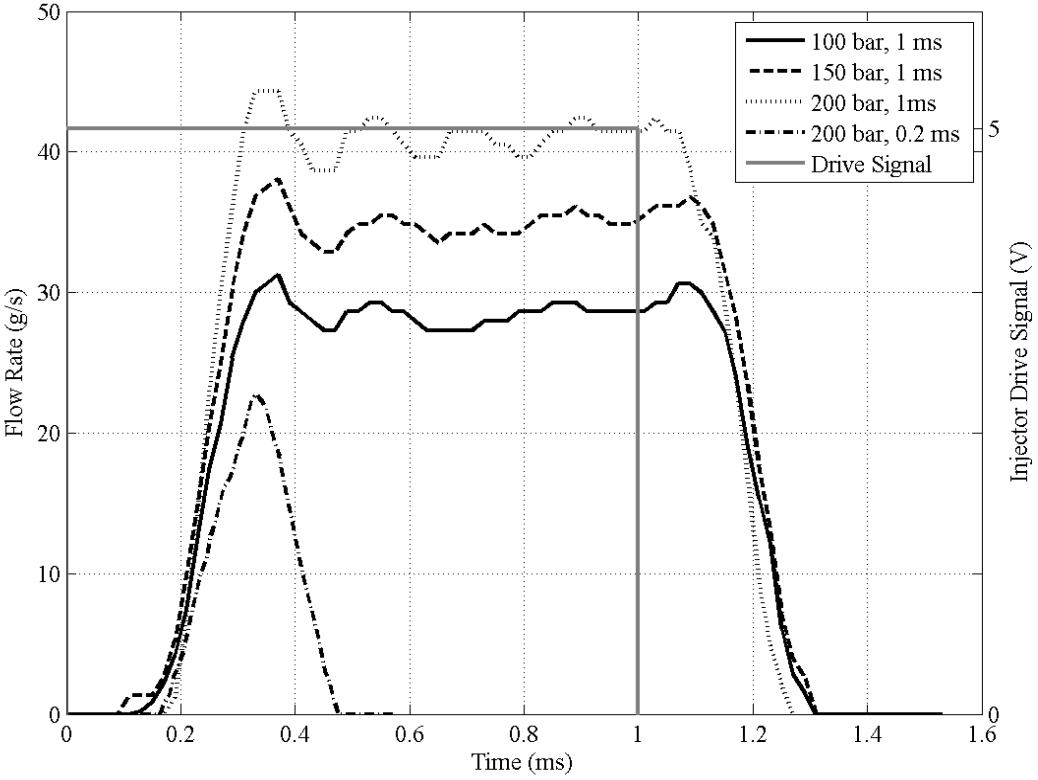
[1] Nouri et al., 2007, [2] Fansler et al., (2006)

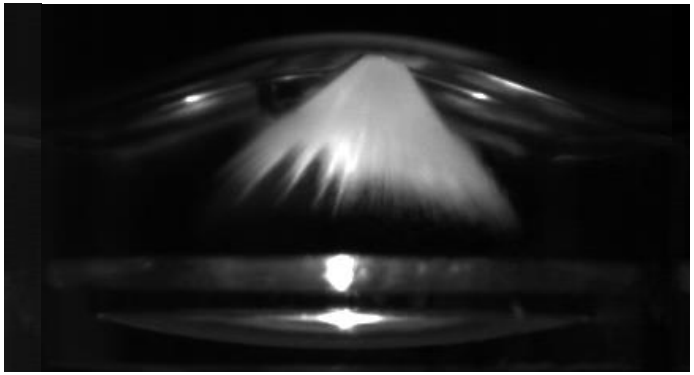
Fan images courtesy of collaborative project with Uni. of Cardiff and Ricardo

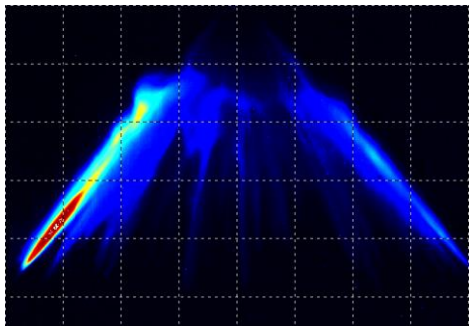
Outwardly opening pintle

- Injector 5: Bosch HDEV Hollow Cone
- DI piezoelectric
- 140-200 bar fuel pressure
- High flow rate 42 mg/ms at 200 bar
- Multiple injection









Current state-of-the-art gasoline fuel injection

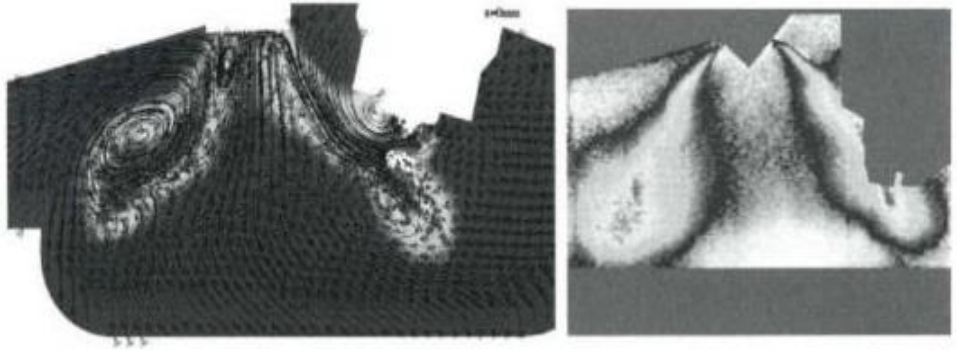
2nd generation direct injection – spray guided combustion systems

Characteristic scales:

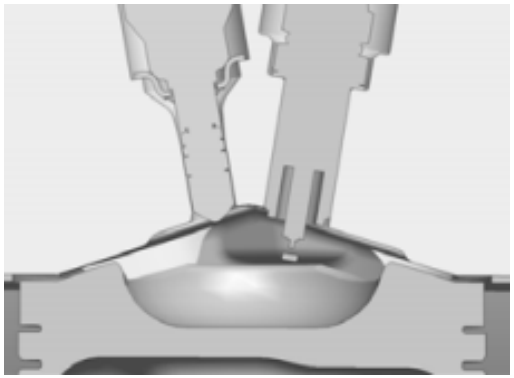
- high fuel pressure (> 200 bar?) for rapid atomisation and evaporation
- reduced penetration from hollow cone compared to multi-hole (wetting)
- piezoelectric rapid multiple injections, 0.08 (<1 mg) to > 4 ms varying duration
- high spatial and temporal repeatability required of spray
- short injections coupled to ignition angle (0.5 to 4.5 ms, injection to ignition)
- in-cylinder gas absolute pressure at injection up to 20 bar
- stoichiometric air to fuel ratio at spark plug gap (globally lean, $\lambda > 4$)
- dependence on geometry of piston and orientation of spark plug and injector

Current state-of-the-art gasoline fuel injection

- Fuel vortex stratification in plug region
  - -stabilises fuel distribution
  - -augments gas turbulence intensity



CFD and LIF (Abdelfattah et al., 2002)



Ricardo Volcano close-spaced combustion chamber layout spray-guided direct injection (Osborne et al., 2013)

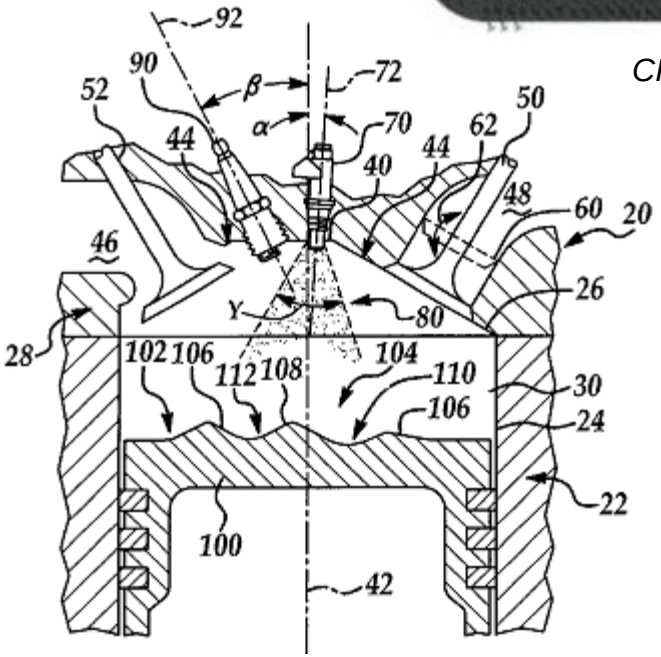


Figure 1

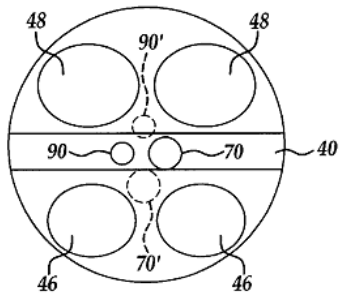


Figure 2

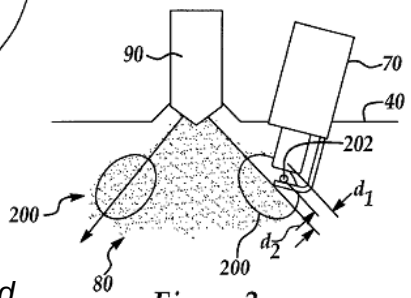


Figure 3

Commercialisation
e.g. Mercedes-Benz 'BlueDIRECT',
Ricardo CCVS

Ford Global Technologies vortex-induced stratification combustion for direct injection spark ignition engines (Han et al., 2004)

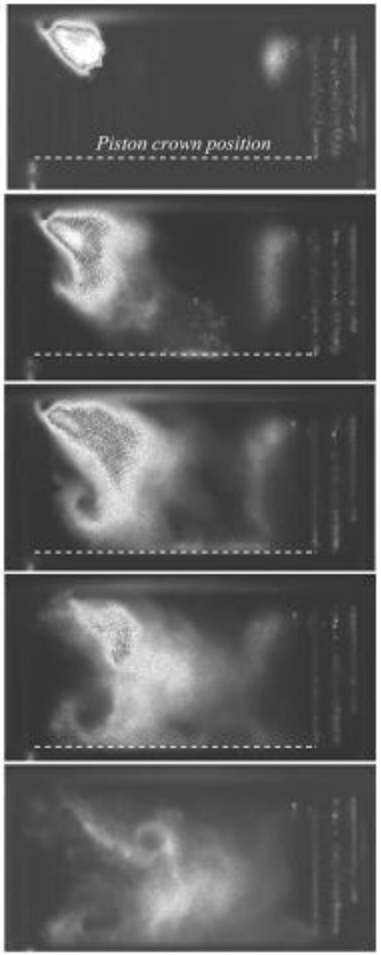
Vortex ring projects – experimental measurements

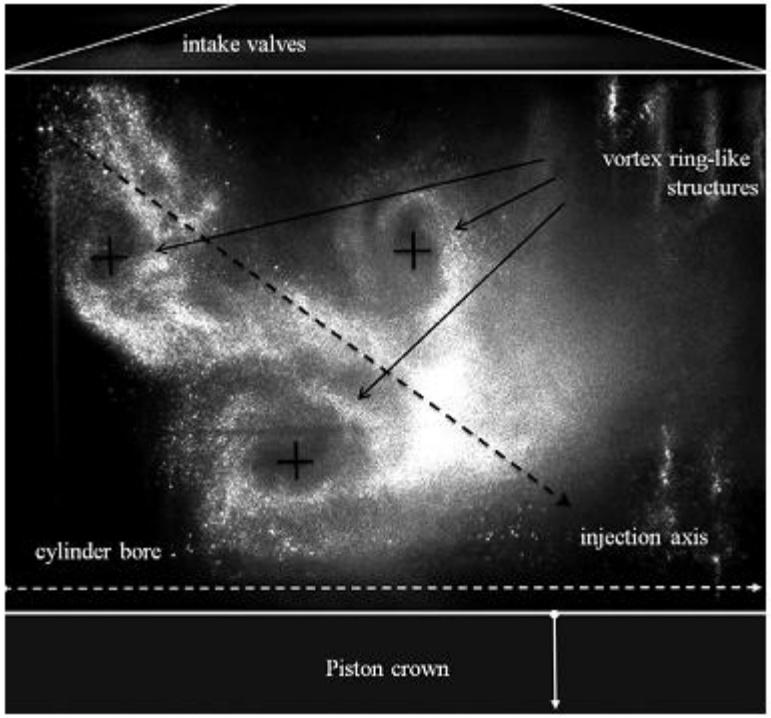
-Visualisation

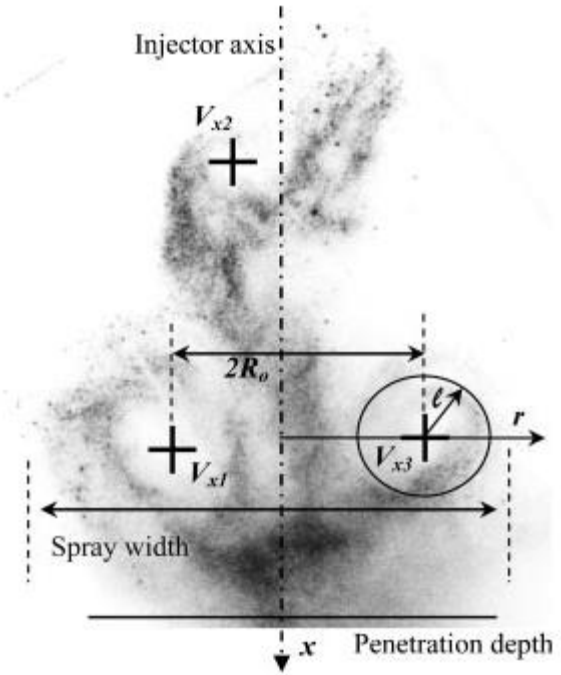
-Droplet size and velocity components

Vortex ring projects – experimental measurements

- Vortex-ring like structures observed in PFI and G-DI engine sprays







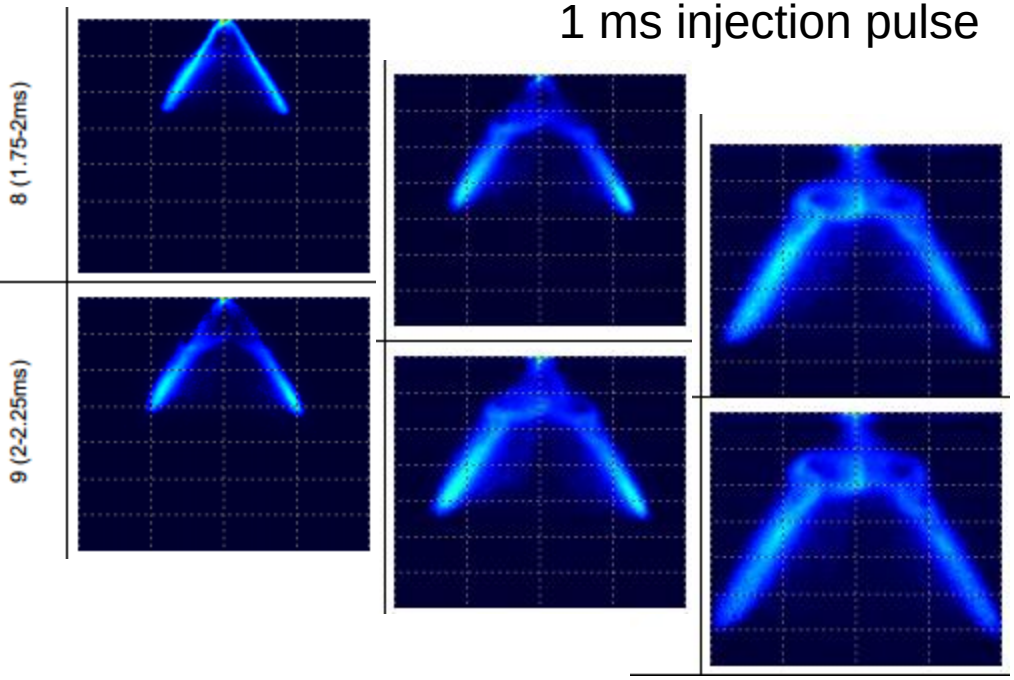
High-speed photographic sequence in optical engine at 1000 rpm (Begg et al., 2009, Kaplanski et al., 2010)

Model parameters; generalised vortex ring model

Vortex ring projects – experimental measurements

- Vortex-ring like structures observed in SGDI engine sprays

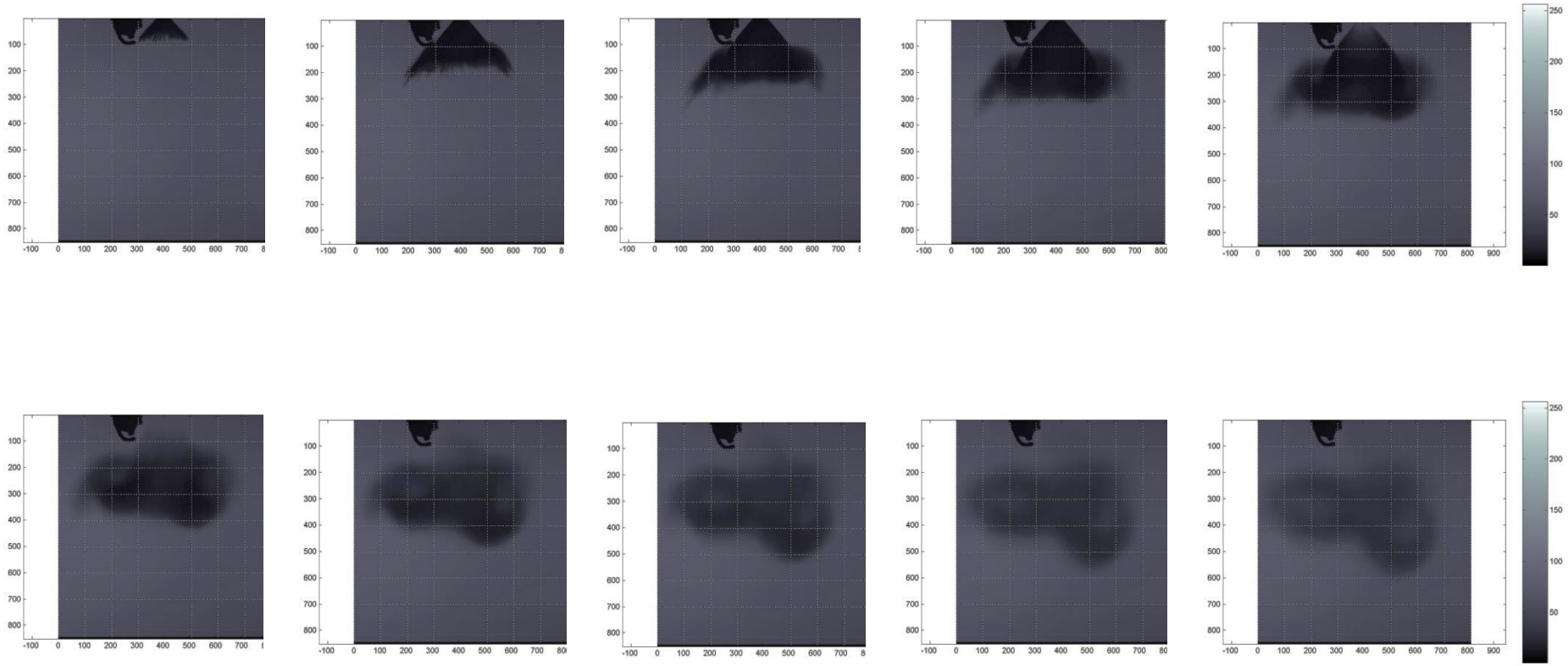
Quiescent chamber- atmospheric pressure
1 ms injection pulse



In-cylinder, motored engine, 1500 rpm
(confinement and thermal effects)

Laser sheet images courtesy of Uni. of Cardiff and Ricardo UK

Vortex ring-like structures - visualisation

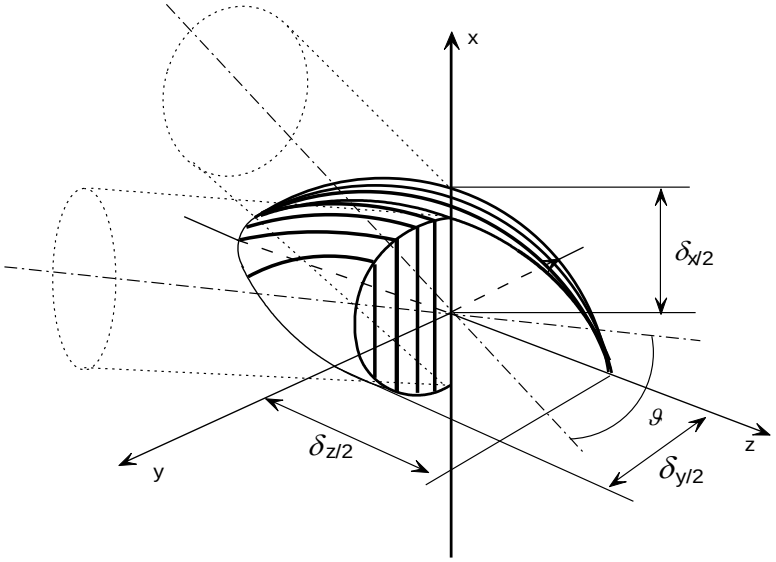


Chronological sequence of high-speed photographs, recorded using a laser light sheet, (left to right) in a static spray chamber, 150 bar fuel pressure, 6 barg gas pressure, 1 to 10 ms ASOI, gasoline fuel.

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

Vortex ring projects – droplet distributions

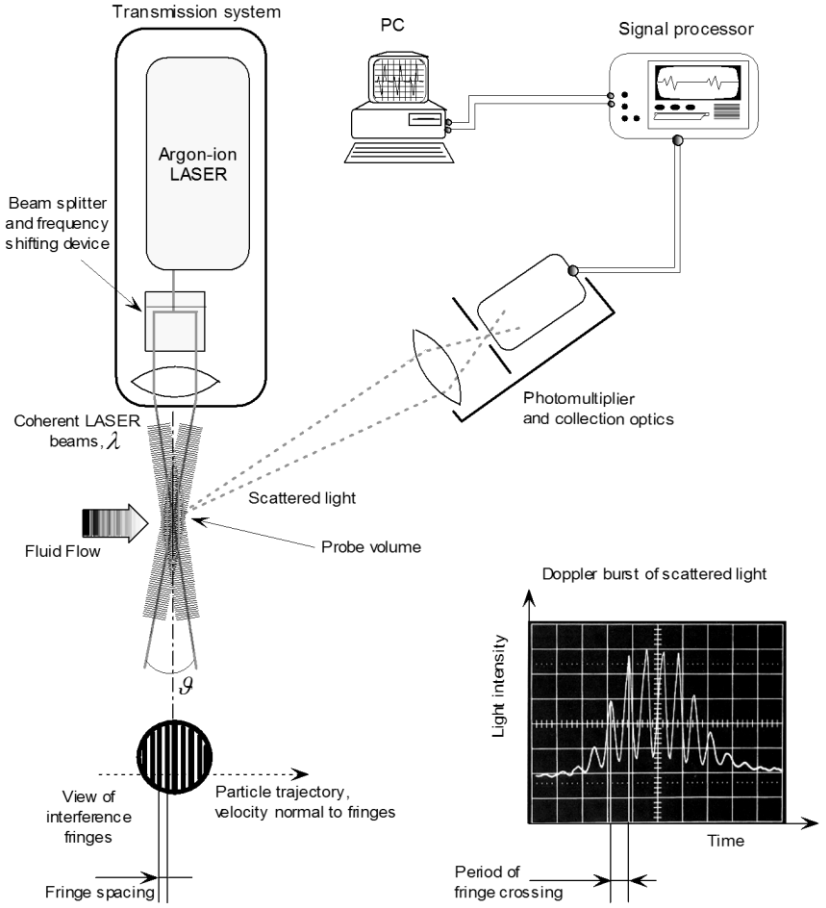
- PDA measurement technique applied to PFI and G-DI sprays
- Droplet size and velocity measurements performed over fine grid



$$\delta_x = \frac{4F\lambda}{\pi E d_g \cos\left(\theta/2\right)} \qquad \delta_y = \frac{4F\lambda}{\pi E d_g s} \qquad \delta_z = \frac{4F\lambda}{\pi E d_g \sin\left(\theta/2\right)}$$

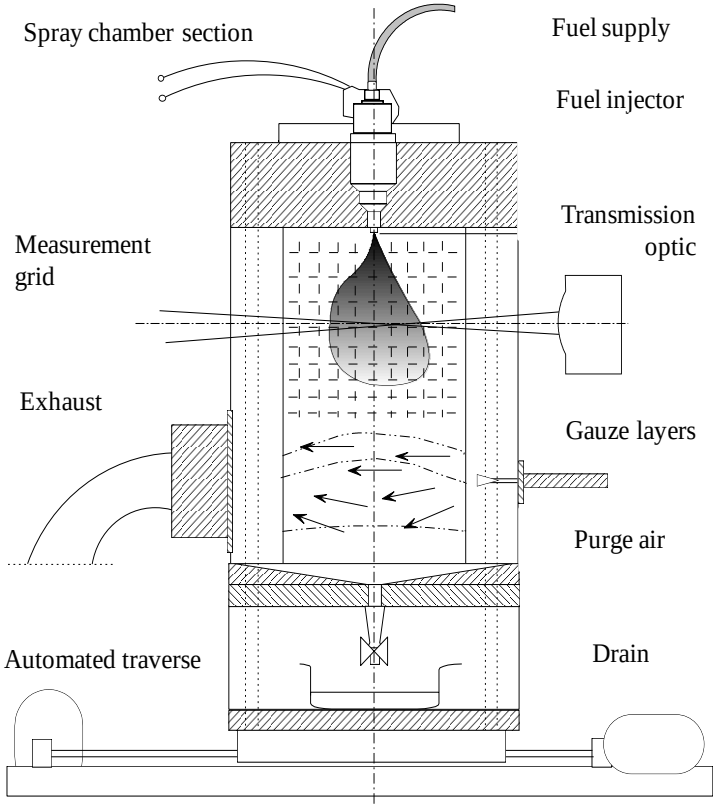
Measurement volume dimensions

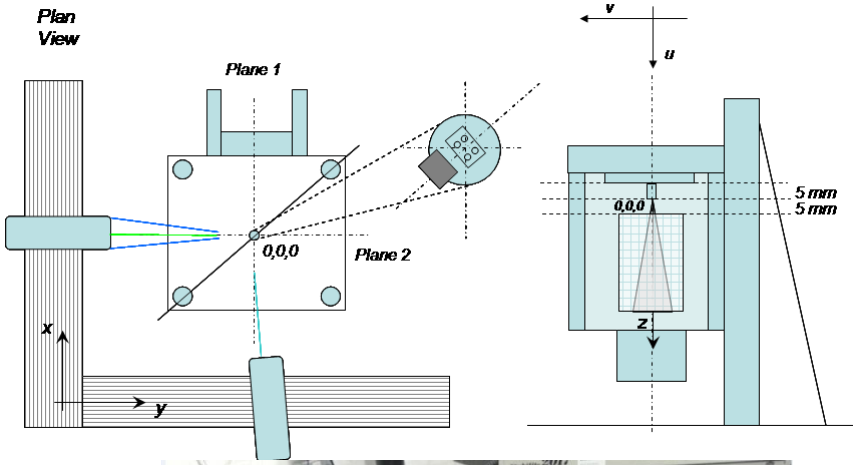
$$f_d = \frac{2U\sin\left(\theta/2\right)}{\lambda}$$

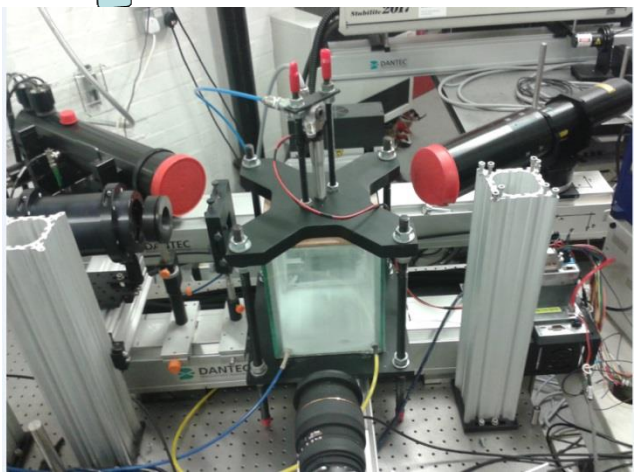


Vortex ring projects

- PDA measurement technique applied to PFI and G-DI sprays
- Droplet size and velocity measurements performed over fine grid

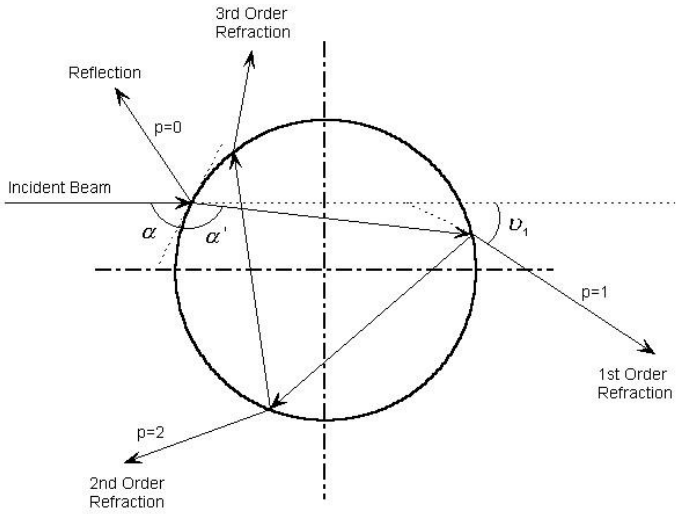


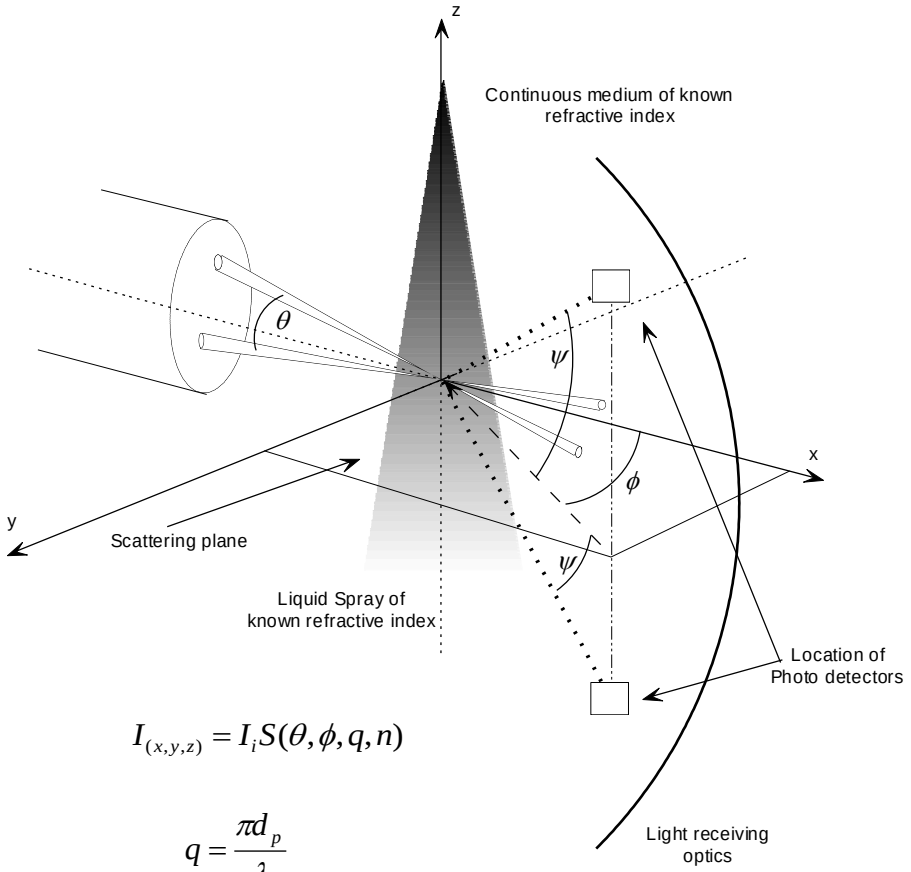




Phase Doppler anemometer (PDA)

- Classical PDA



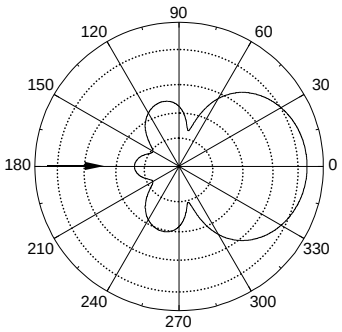


$$I_{(x,y,z)} = I_i S(\theta, \phi, q, n)$$

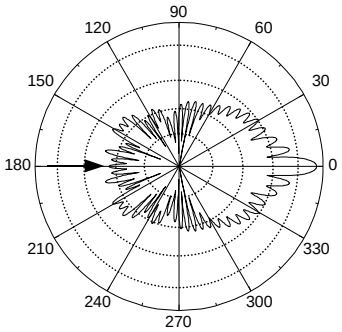
$$q = \frac{\pi d_p}{\lambda}$$

Phase Doppler anemometer (PDA)

- Polar distribution of light intensity

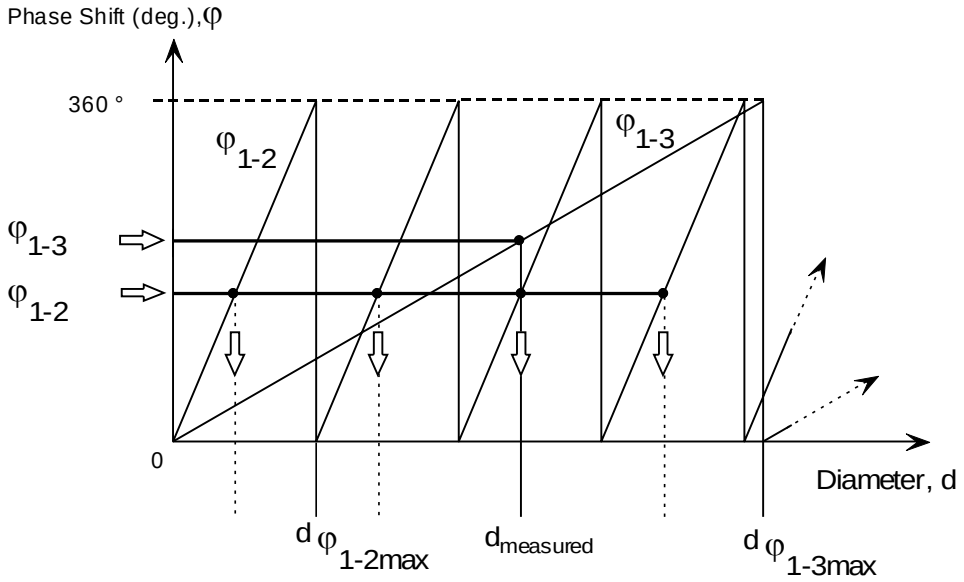


$d_p \cong 1.0\lambda$



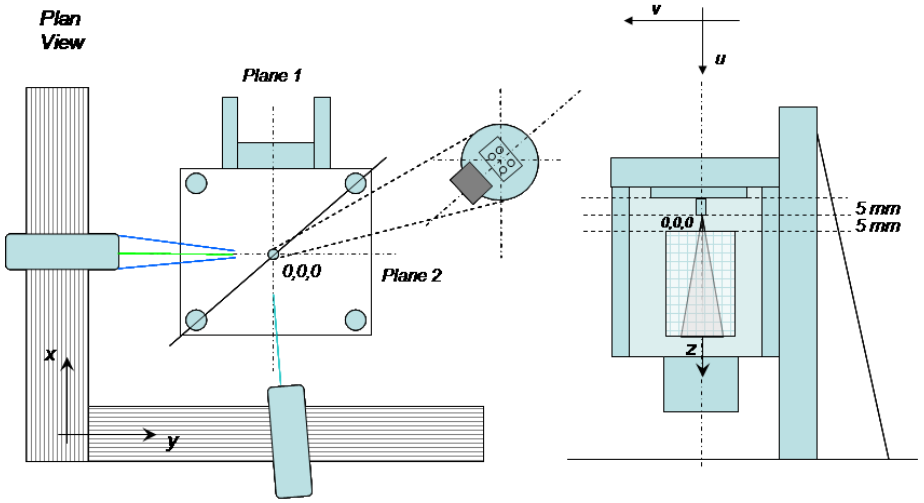
$d_p \cong 10\lambda$

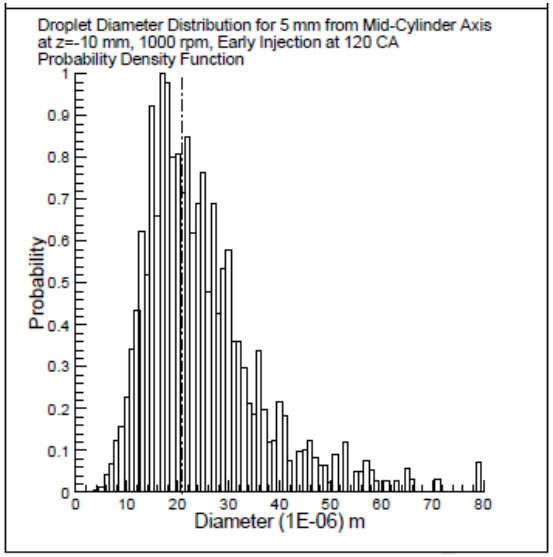
Brewster's angle used to collect first order refraction p=1

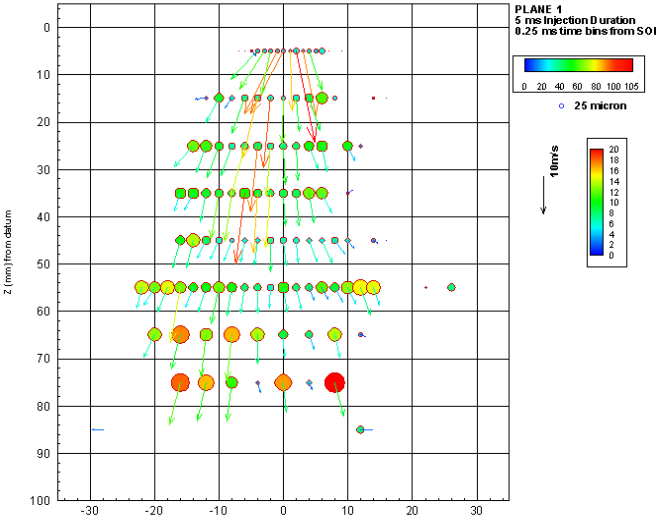


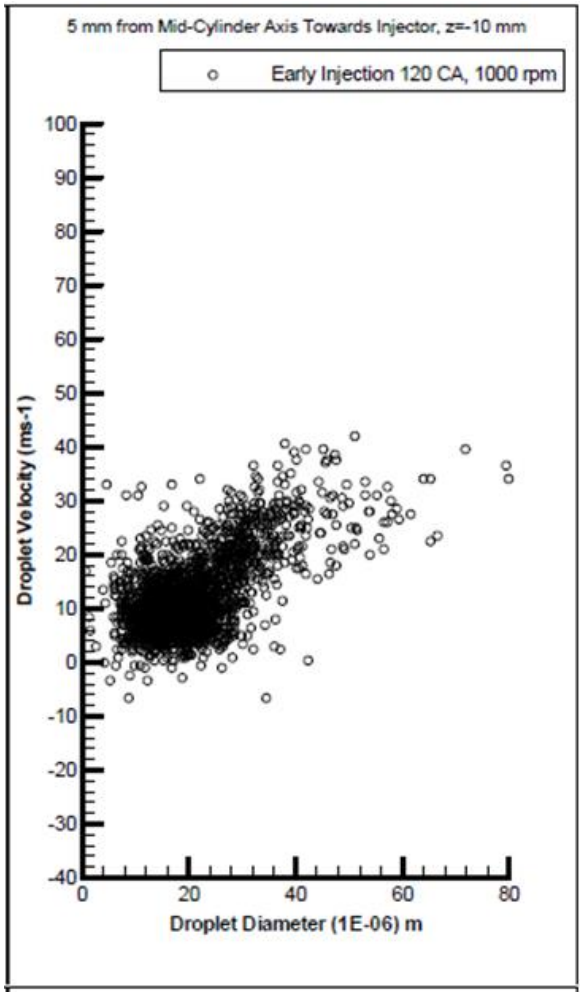
$$d_p = -\Phi\left(\frac{\lambda}{2\pi}\right)\left(\frac{\sqrt{2(1+\cos\theta\cos\varphi\cos\phi)\left(1+n^2-n\sqrt{2(1+\cos\theta\cos\varphi\cos\phi)}\right)}}{n\sin\theta\sin\varphi}\right)$$

PDA– Simultaneous liquid droplet velocity components and diameter



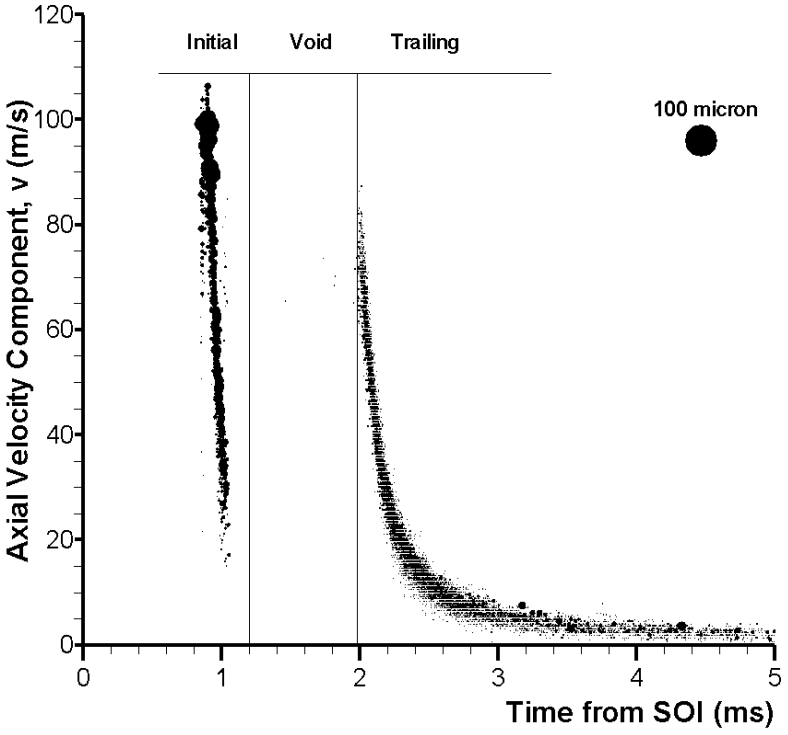




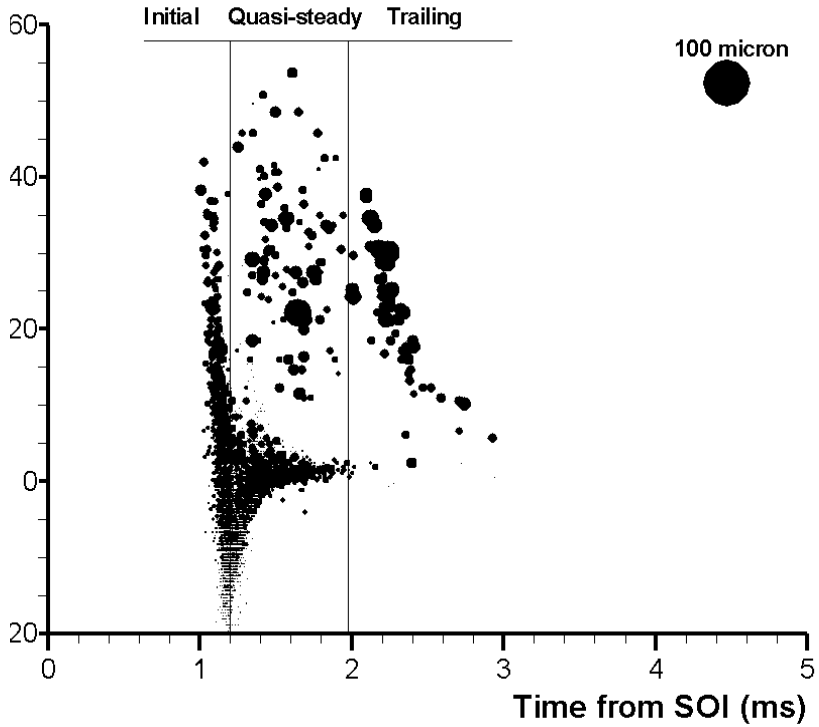


Phase Doppler anemometer (PDA)

- Time series at two locations in a high-pressure spray



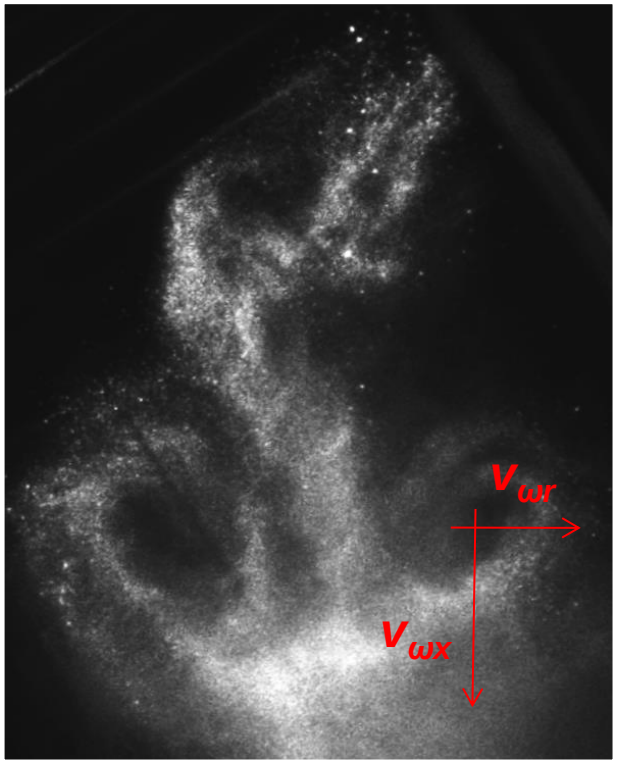
r = 0, x = 15 mm

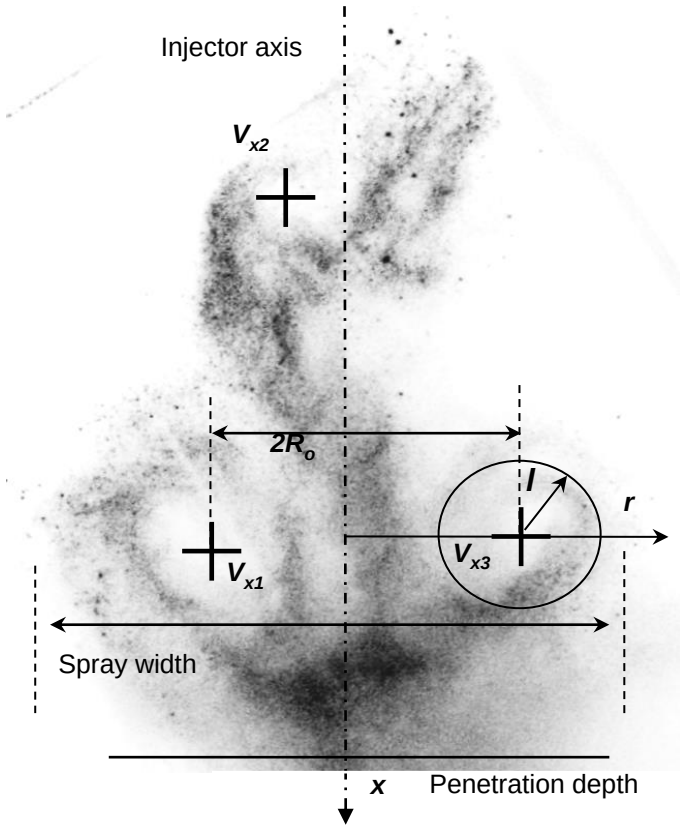


r = 10, x = 15 mm

Phase Doppler anemometer (PDA)

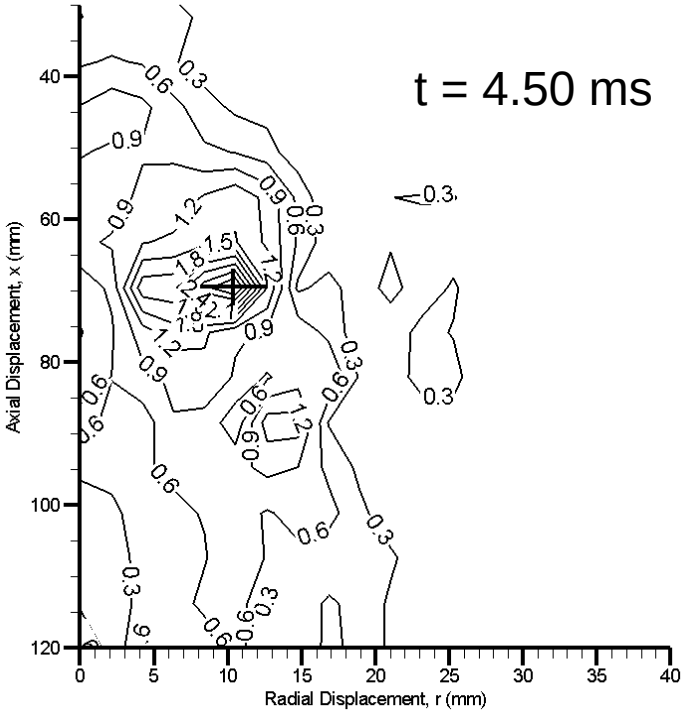
- Vortex-ring like features in a high-pressure spray – regions of maximal vorticity

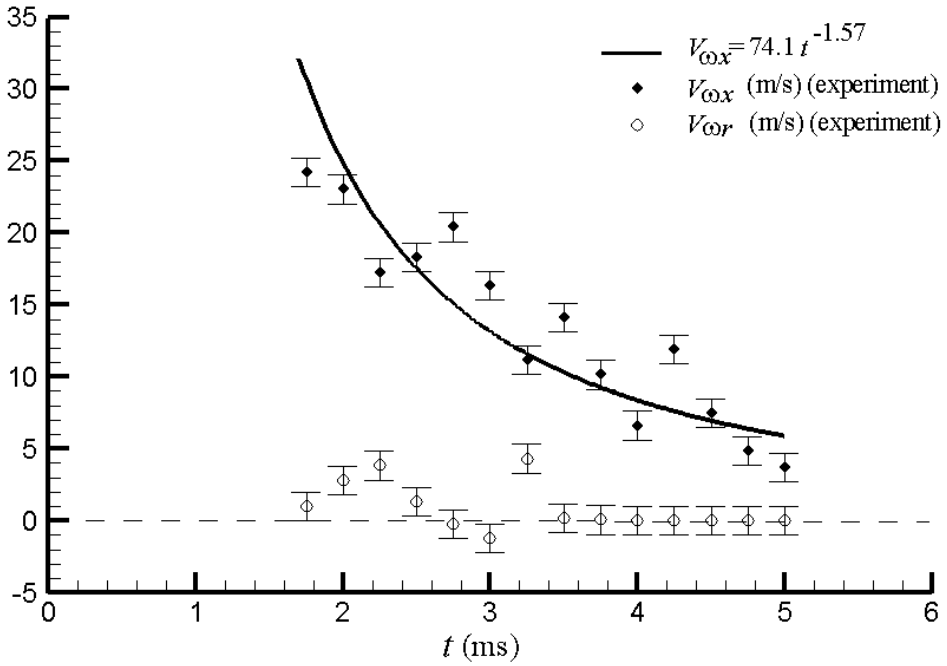




Phase Doppler anemometer (PDA)

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





Current and future directions

Current and future directions – 2 streams

- Increased modelling complexity
  - Development of the full Lagrangian approach for the analysis of vortex ring-like structures – development of a mathematical formalism.
  - Studies of an elliptical core.
  - Investigation of vortex ring-like structures taking into account thermal and confinement effects (DNS, Full Lagrangian and analytical models)
- Measurements focus
  - High-speed photography / injection parameters
  - Phase Doppler Anemometry issues
  - Particle seeding of gas phase

Current and future directions

- Measurement focus
  - Identify impulse parameters for generation of vortex rings with piezo injector using HSP
  - Define finer grid region for PDA measurements in local regions of rings
  - Counter-rotating ring formations observed using LIF in motored engines

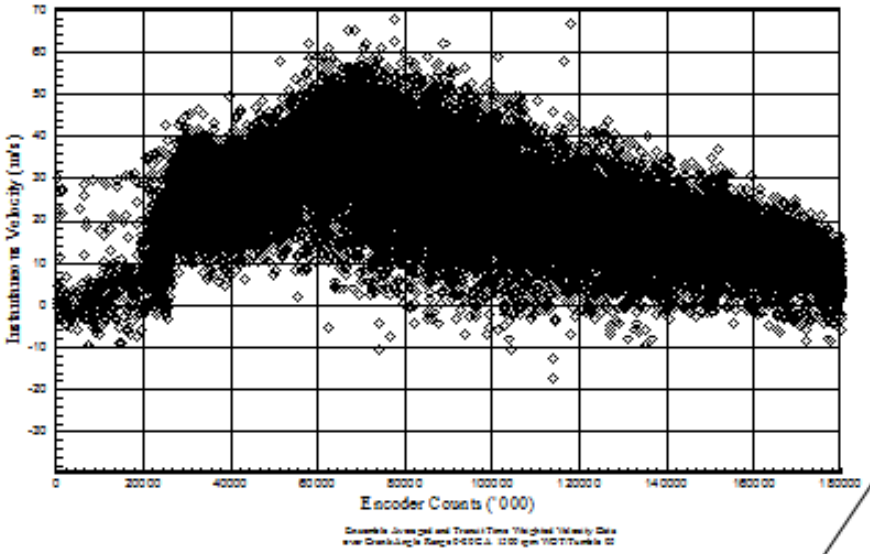
Sequence of consecutive LIF images recorded at a frame rate of 10 kHz, motored engine speed of 1500 rpm

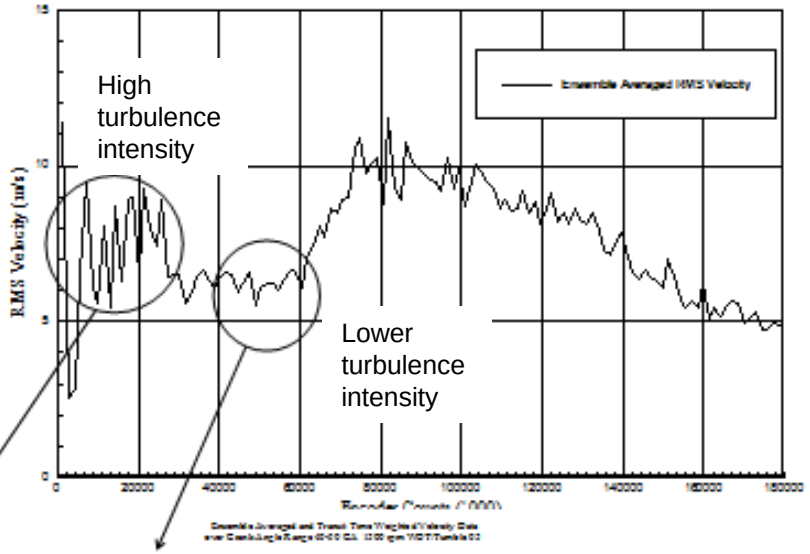
Current and future directions

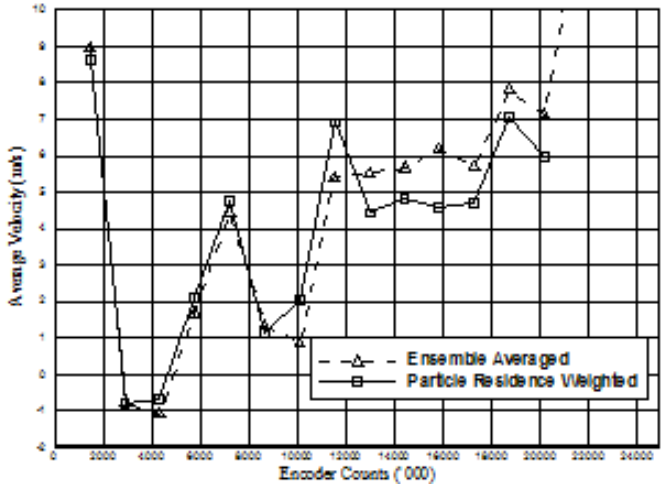
- PDA measurement technique focus
  - Higher data validation rates (<1000 counts/mm^3) – optically dense
  - Signal to noise validation and ‘sphericity’ tolerance
  - Optimise number of fringes and fringe spacing, laser power, SNR
  - Particle number density requires determination of volume of intersection volume projected onto receiver optics (slit mask)
  - Reduction of other errors observed in swirling flows (velocity gradient, finite transit time, trajectory ambiguity, slit effect etc.)
  - Separate reflected from refracted signals running PDA ‘without validation criteria’ and post-processing of raw data?
  - Particle averaging (velocity) bias – turbulent jet (weighted statistics)

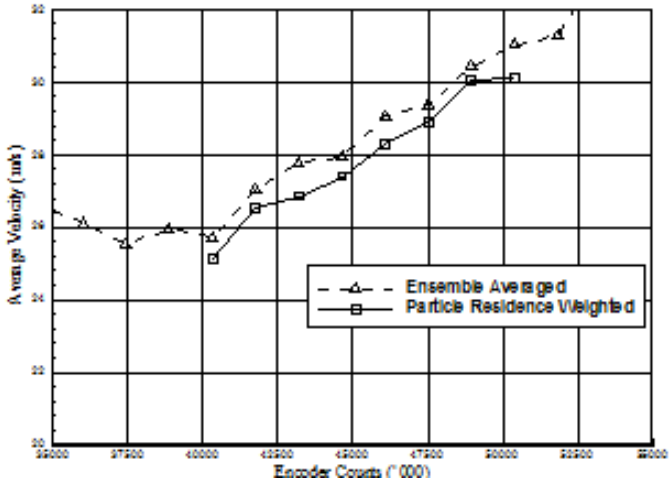
Current and future directions

- PDA particle velocity bias- example in highly turbulent air jet
- Velocity component weighted by particle inter-arrival or residence times







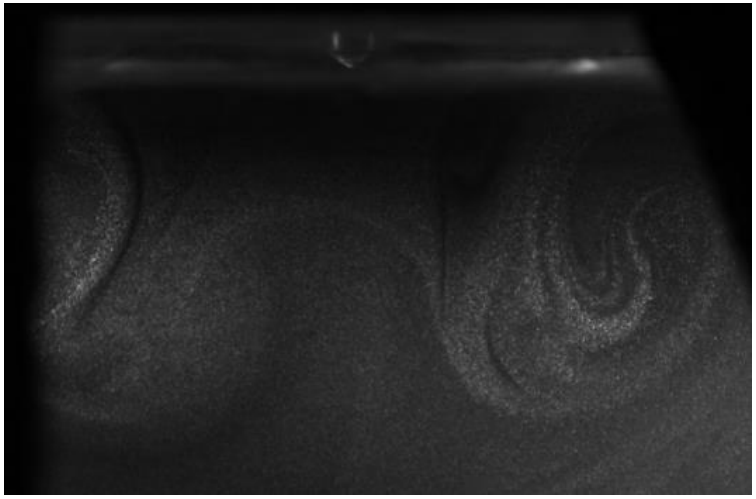


Residence time-weighted mean velocity

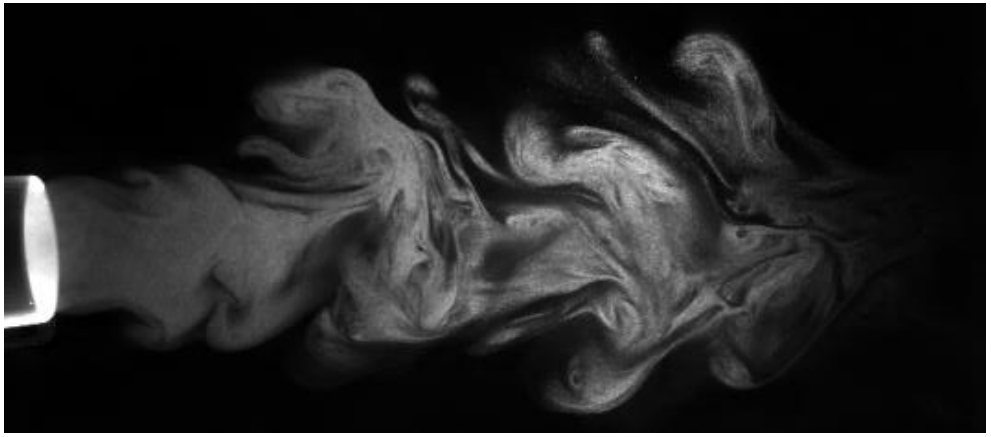
$$\bar{u}_R = \frac{\sum (u_i \Delta t_i)}{\sum \Delta t_i}$$

Current and future directions

- Particle seeding of gas phase technique (and PDA)
  - Solid particles neutral buoyancy / air & water injection / vortex generator
  - UV phosphorescence SNR / image doubler / narrow band filter
  - Homogeneous distribution / variation in seeding density / fluidised bed
  - Momentum exchange between seed and fuel spray.



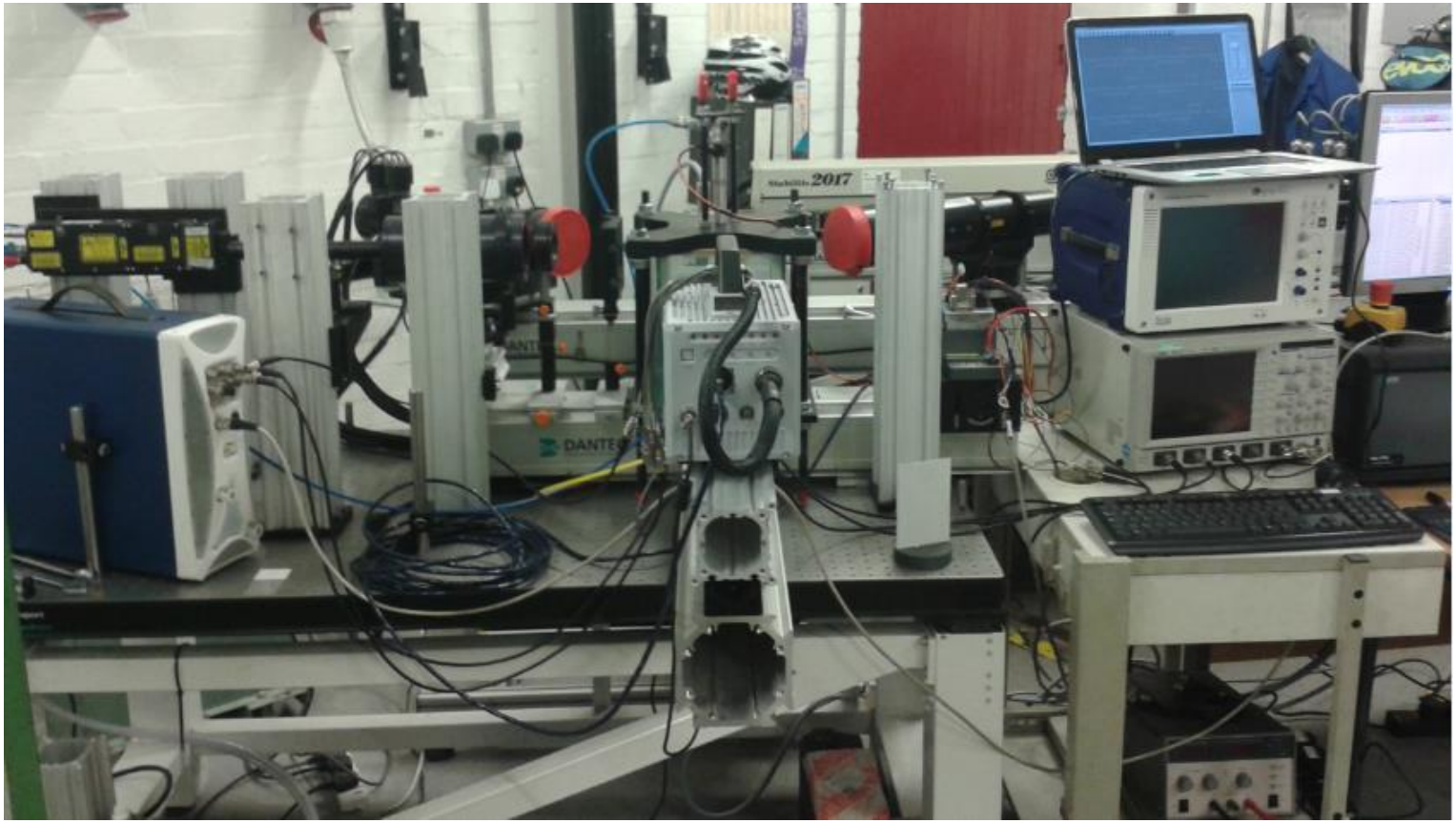
Vortex ring like structures observed in gas phase after air injection impulse



Water droplet continuous stream at ambient gas temperature

Current and future directions

- Particle seeding of gas phase technique (and PDA)- Experimental set-up



Conclusions and modelling challenges for fuel sprays

- Future experiments must address a single injection event (high frame rate)
  - capture the characteristics at crank angle resolution
  - within a single engine cycle and from one consecutive cycle to the next
  - firing operation- correlation with poor cycles of combustion
- Modelling must develop finer details
  - evolution of vortex ring models
  - fuel injection and gas flow coupling
  - droplet heating and evaporation
  - multi-component fuels and fuel blends

Acknowledgements

- Dr Daniel Coren and Dr Guillaume de Sercey
- EPSRC (Vortex, 2-ACE) and equipment loan pool
- EU INTERREG IVA – CEREEV project 4224
- Prof. P. Bowen, University of Cardiff
- Ricardo UK Ltd
- DTI/TSB 2/4 SIGHT and 2/4 CAR programmes
- Technical staff and students of the CAE

Droplet velocity and diameter measurements in vortex-ring like structures in a non-evaporating fuel spray

Progress and research directions in the EPSRC Vortex Ring projects

Dr Steven Begg
Experimental Fluid Mechanics Research Group
Centre for Automotive Engineering

1st December – Workshop- Vortex Ring-Like Structures

EPSRC
Engineering and Physical Sciences Research Council

Interreg IVA France-Manche-England Programme

CEREEV project 4224