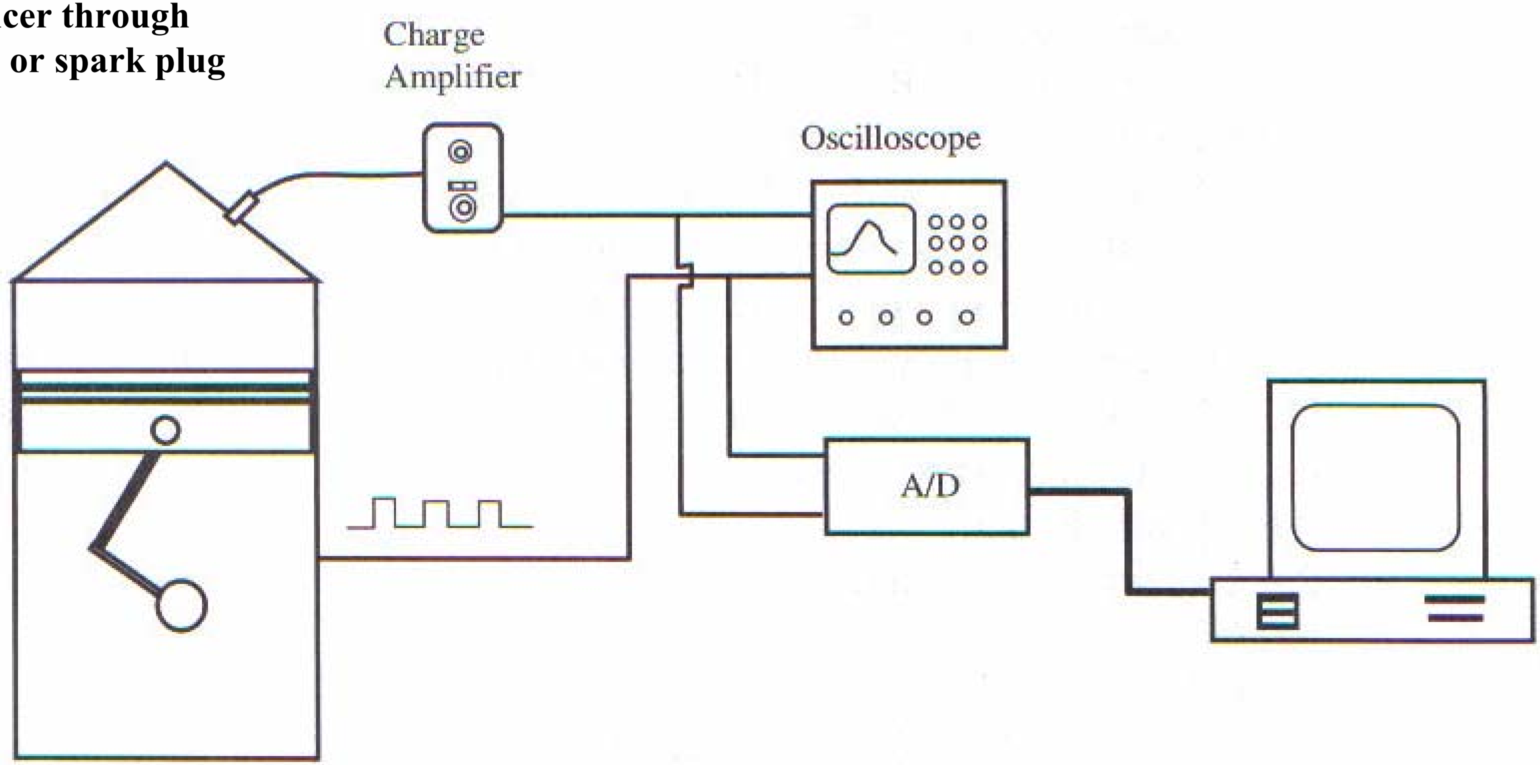
In-Cylinder Pressure Measurement and Analysis

Purposes of In-Cylinder Pressure Measurement

- Monitor max combustion pressure
- IMEP measurement
- Knock analysis
- Cycle-to-cycle variation
- Heat release analysis
- Ignition timing (ignition delay)

In-Cylinder P Measurement

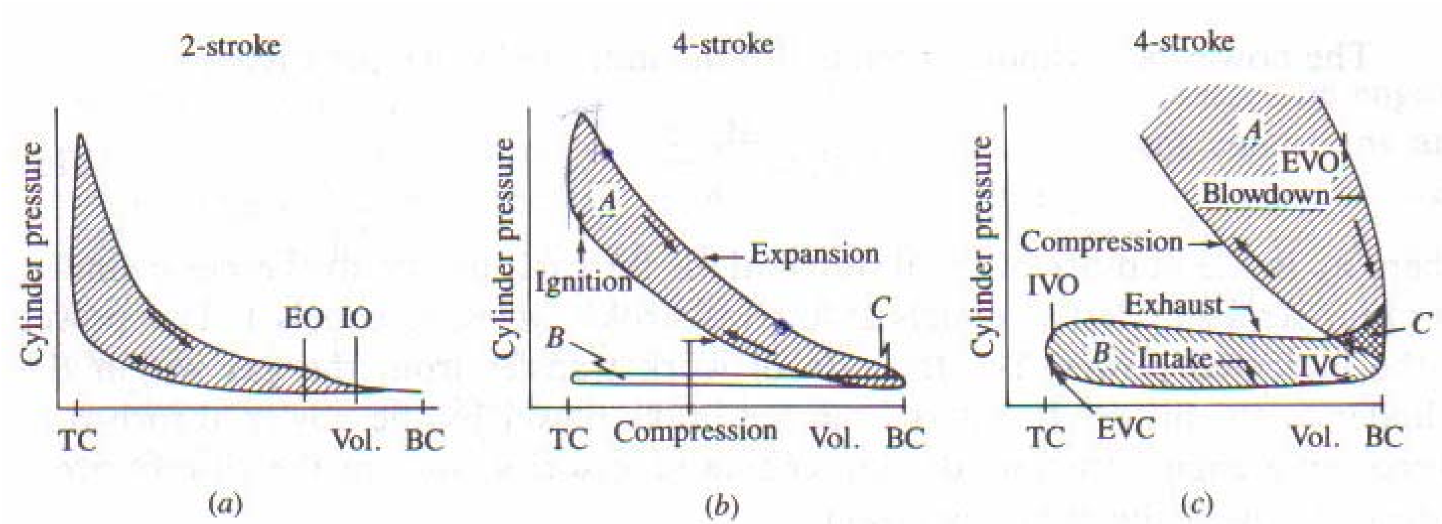
P transducer through glow plug or spark plug adaptor



Max Pressure Monitor

- Design limit
- For total peak power

IMEP-Indicated Mean Effective Pressure



$$W_{c,i} = \oint p\,dV$$

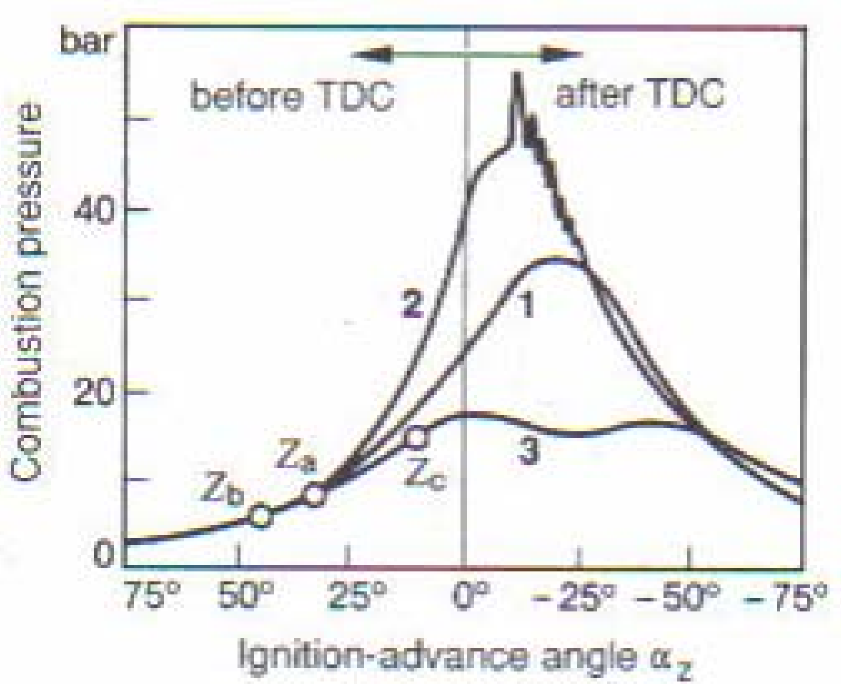
$$p_i = \frac{W_{c,i}}{t} = \frac{W_{c,i}}{n_R \, {}^{1}\!/_{N}} = \frac{W_{c,i} N}{n_R}$$

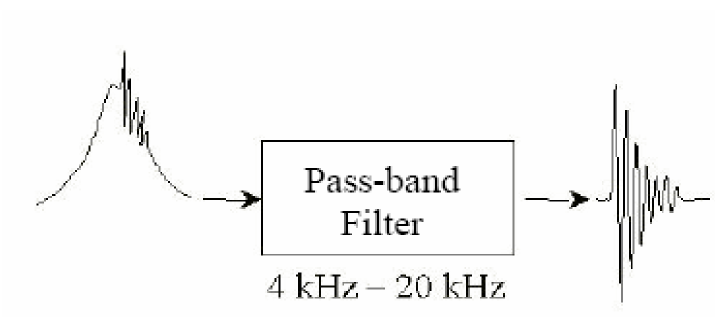
$$IMEP(kpa) = \frac{P_i(KW) \cdot n_R}{V_d(dm^3) \cdot N(rev/s)} \times 10^3$$

n_R – number of crank revolutions for each power stroke

V_d – swept volume

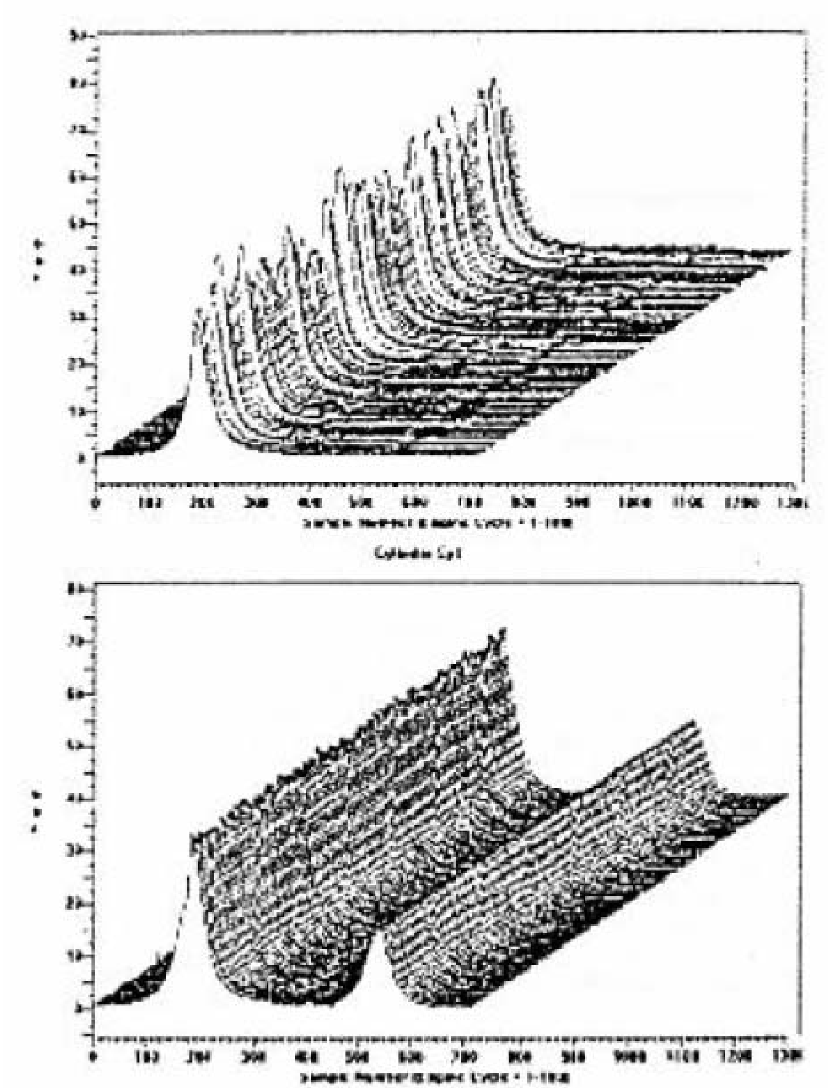
Knock Analysis





- Real-time knock analyses may be carried out from P trace by setting a band-pass filter to single out the characteristic engine knock frequency (~ 8 kHz).
- If the amplitude of the filtered trace is over the predefined threshold (e.g. 0.5bar), the cycle can be defined as knock combustion.

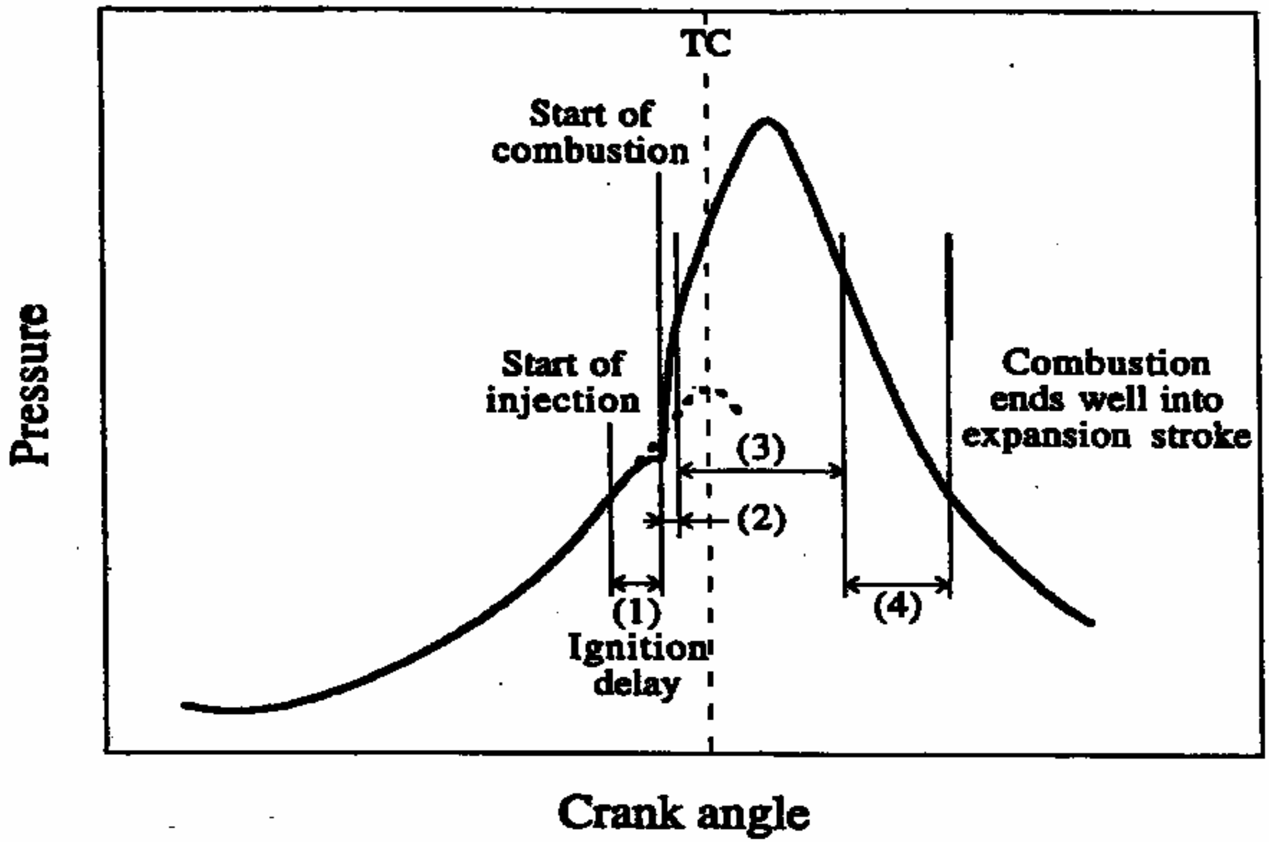
Cycle-to-Cycle Variation



COVimep - the Coefficient of Variation in IMEP

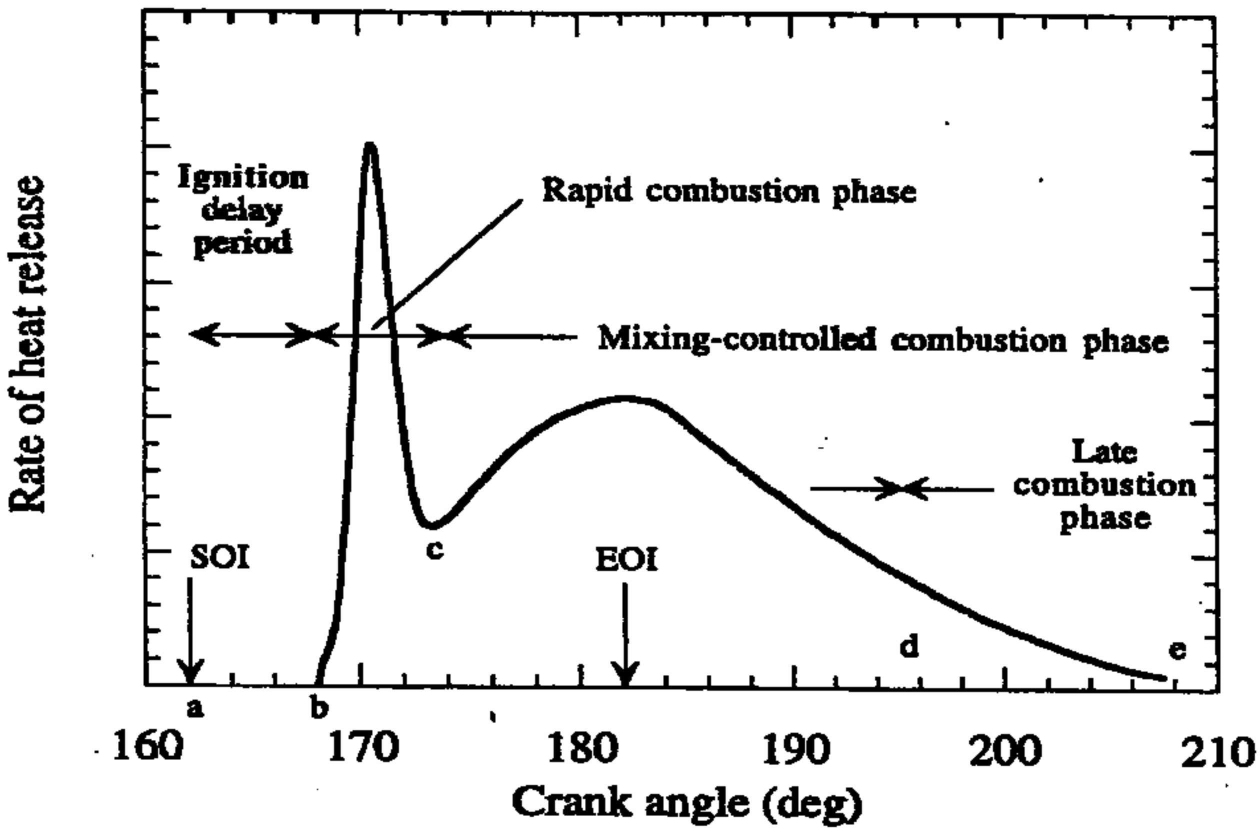
$$COV_{imep} = \frac{\dfrac{\sum_{i=1}^{n}\left|Average_{imep} - IMEP_i\right|}{n}}{Average_{imep}}$$

Heat Release

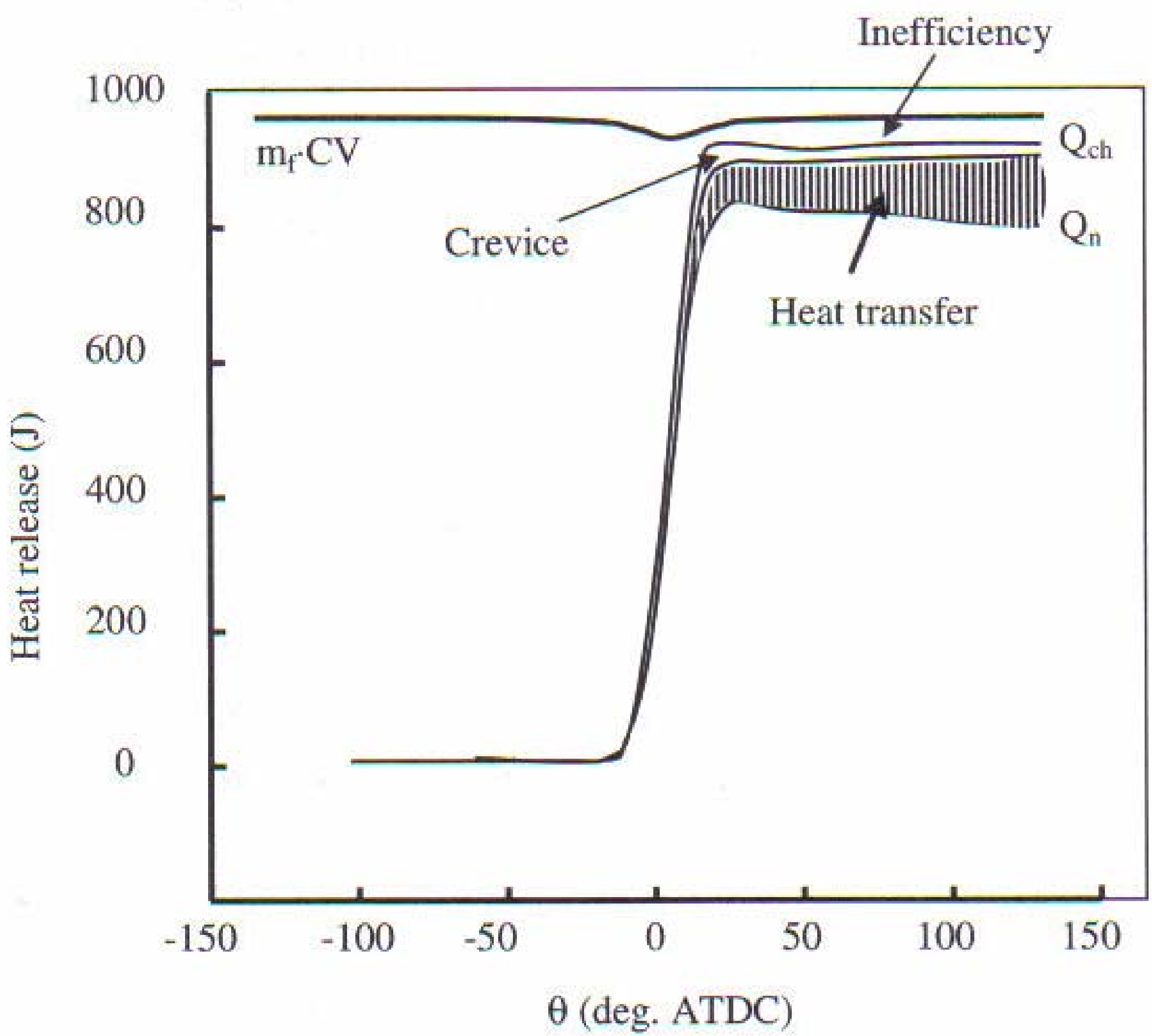


Heat Release

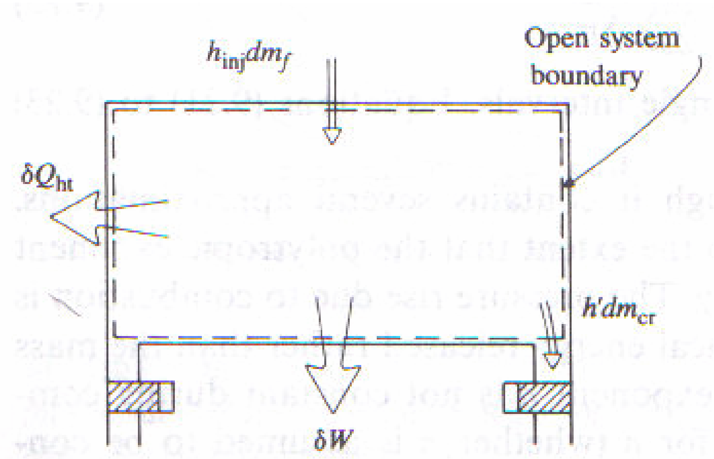
- Four phases of diesel combustion



Heat Release Analysis



Heat Release Formula



$$\delta Q_{ch} = dU_s + \delta Q_{ht} + \delta W + \sum h_i dm_i$$

$$dU_s = mc_v(T)dT + u(T)dm$$

$$\delta Q_{ch} = mc_v dT + (h - u)dm_{cr} + pdV + \delta Q_{ht}$$

m_{cr} – flow mass through crevice

Heat Release Formula

$$PV = mRT$$

$$mdT = \frac{1}{R}Vdp + \frac{1}{R}pdV$$

$$\delta Q_{ch} = \left(\frac{c_v}{R}\right)Vdp + \left(\frac{c_v}{R}+1\right)pdV + (h-u)dm_{cr} + \delta Q_{ht}$$

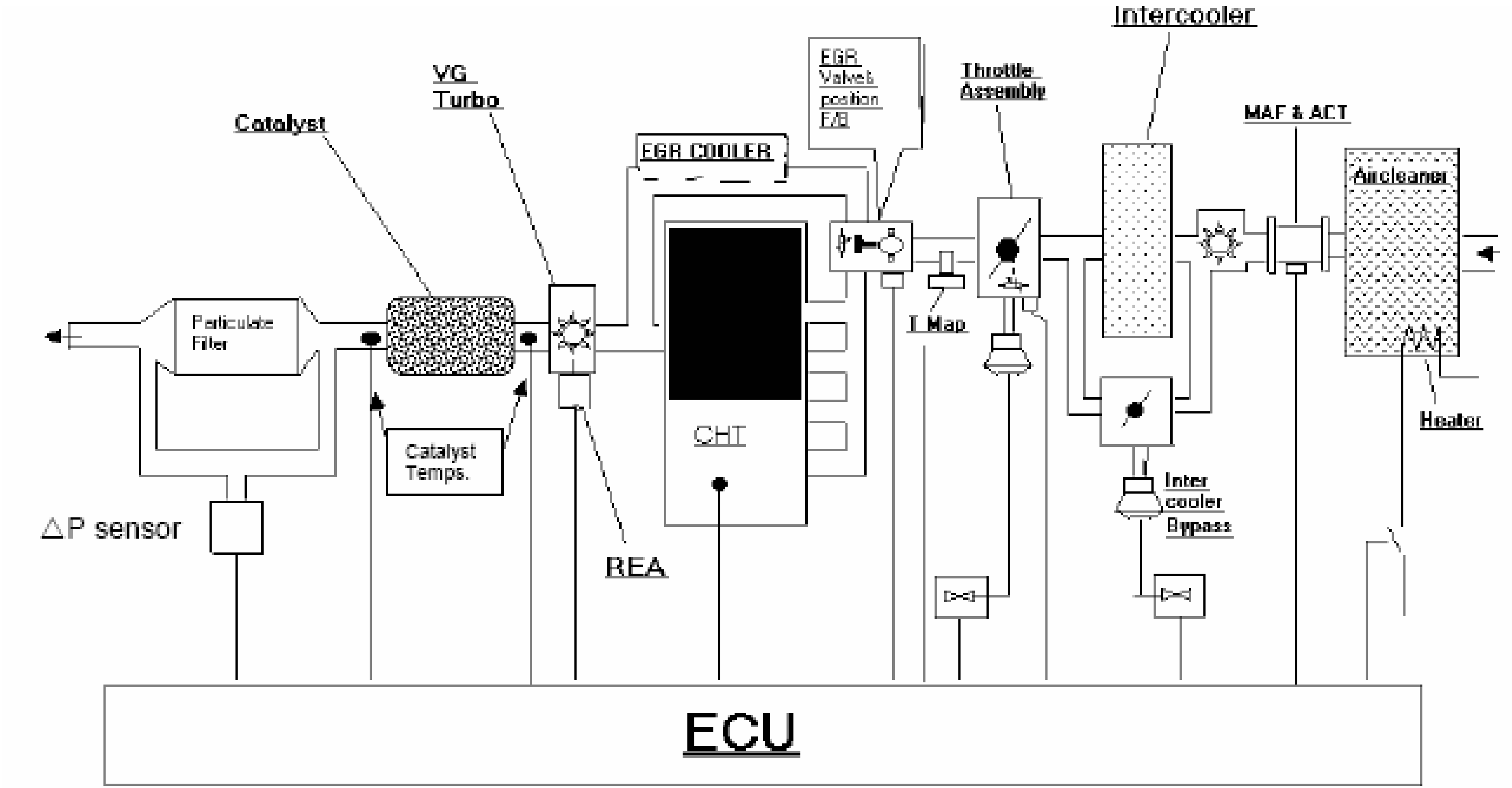
$$\frac{dQ_{ch}}{d\theta} = \frac{\gamma}{\gamma-1}p\frac{dV}{d\theta} + \frac{1}{\gamma-1}V\frac{dp}{d\theta} + V_{cr}\left[\frac{T^1}{T_w} + \frac{T}{T_w(\gamma-1)} + \frac{1}{bT_w}\left(\frac{\gamma-1}{\gamma^1-1}\right)\right]\frac{dp}{d\theta} + \frac{dQ_{ht}}{d\theta}$$

$$\frac{dQ_{ht}}{dt} = Ah_c(T-T_w)$$

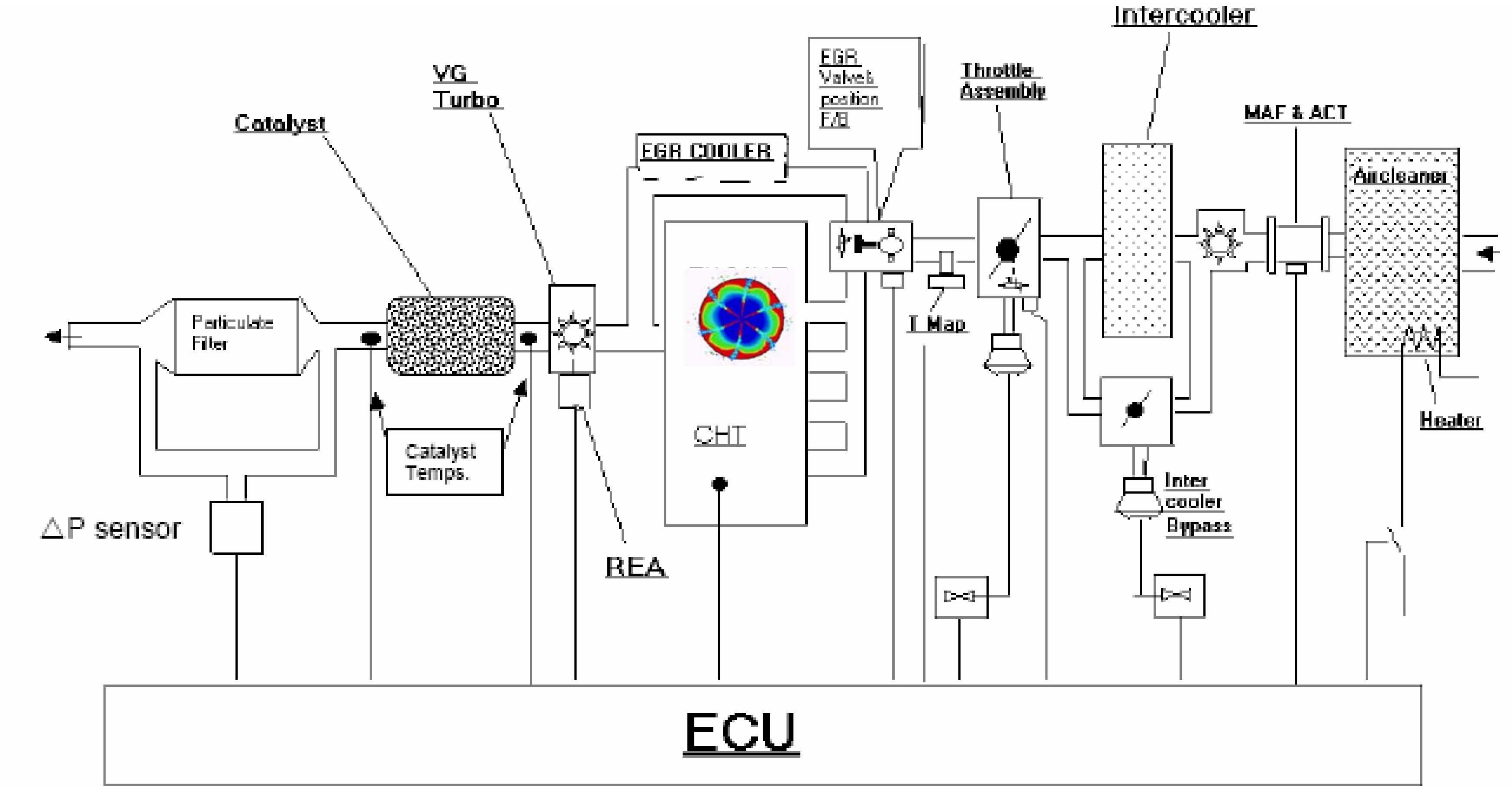
J. B. Heywood <<Internal Combustion Engine Fundamentals>>

Ignition Timing

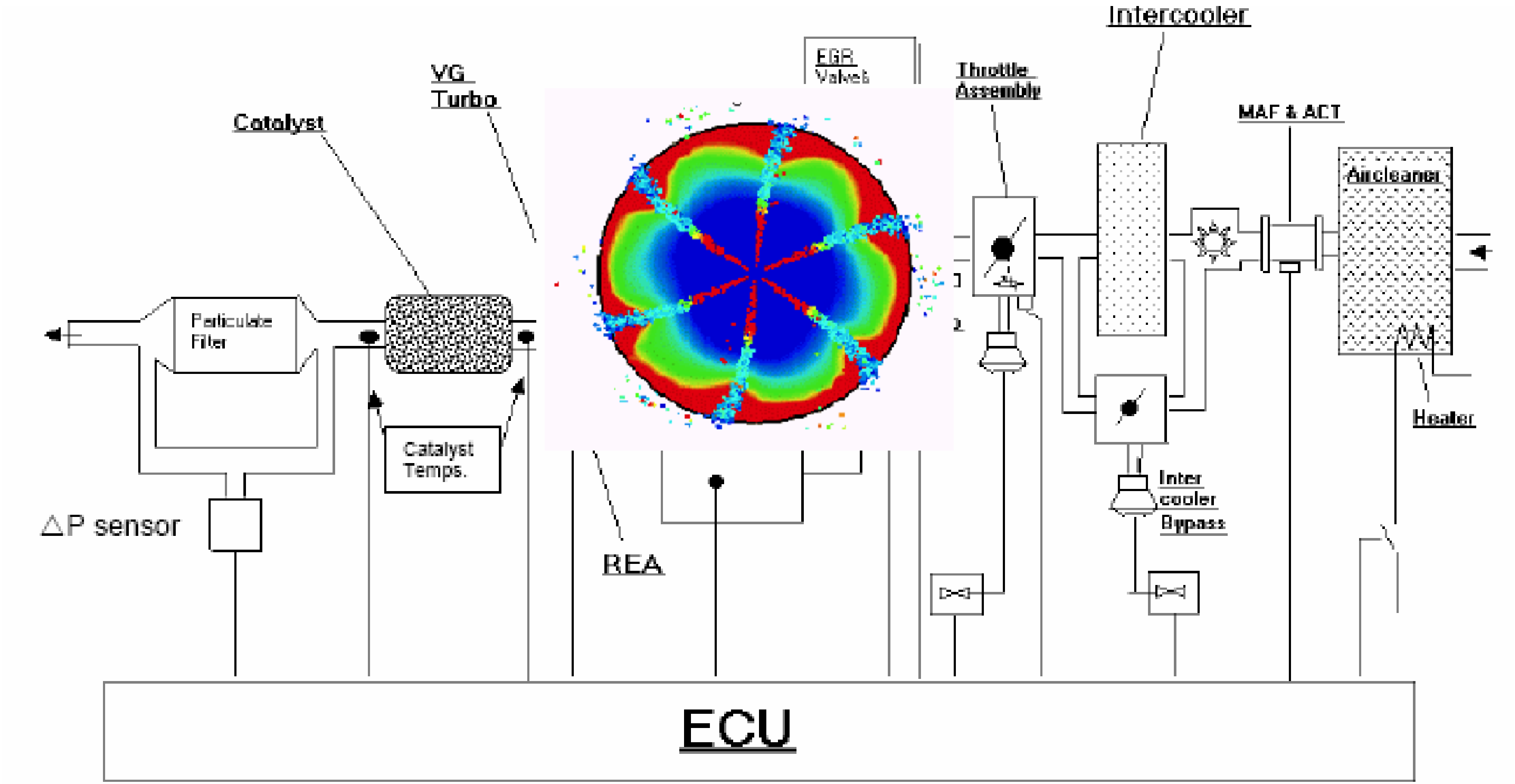
- Ignition delay for diesel and SI ignition engines
- Auto-ignition timing for HCCI



Objectives of in-cylinder combustion measurement

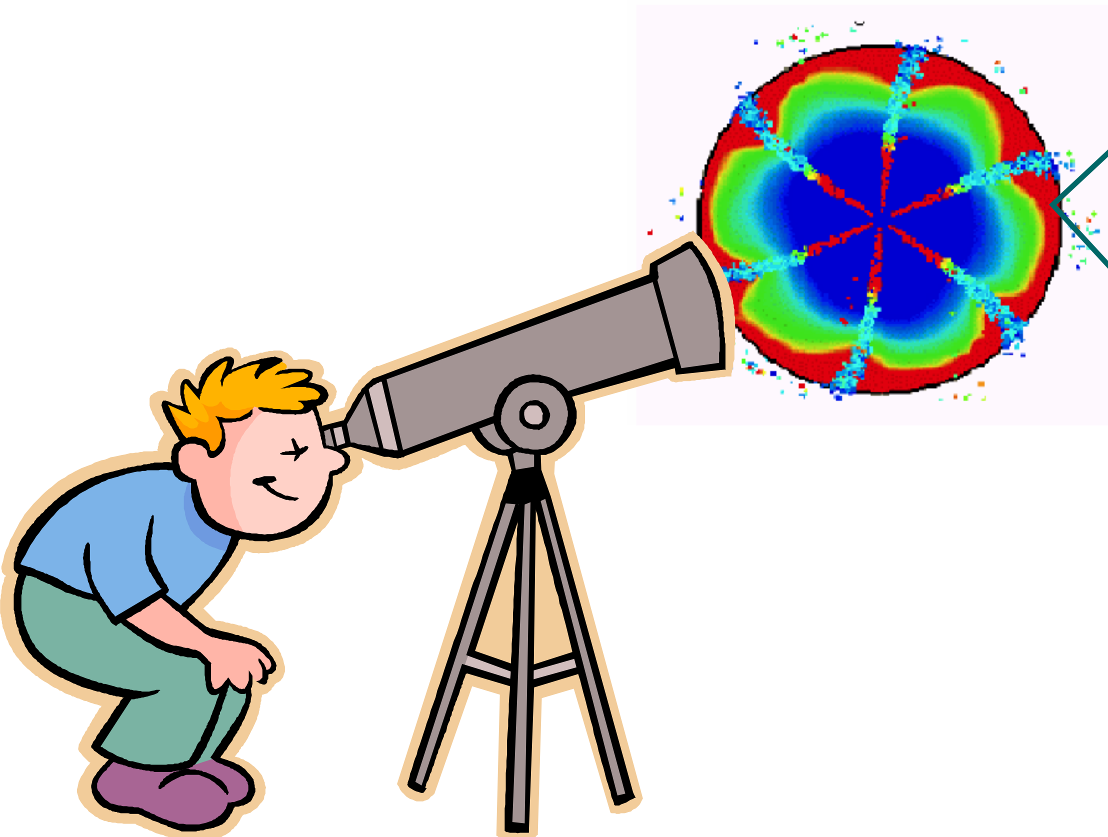


Objectives of in-cylinder combustion measurement



Objectives of in-cylinder combustion measurement

To improve the understanding of combustion and pollutant



- Before, during and after combustion
- Thermodynamic state: T, P, density
- Chemical state: chemica species
- Fluid dynamic: small and large scale structures

Objectives of in-cylinder combustion measurement

Methods of in-cylinder combustion measurement

- Physical probes: in-cyl pressure, fast gas sampling valve, FID
- Optical diagnostics:
  - Classical: direct photography, absorption and emission spectroscopy, schlieren/shadowgraphy
  - Modern diagnostics: LDV, PIV, laser particle sizer, LIF, Raman scattering, Rayleigh Scattering…

In-cylinder flow field measurement

- Introduction
- LDA/LDV – Laser Doppler Anemometry/Velocimetry
- PIV – Particle Image Velocimetry
- Summary

Introduction

- In-cylinder flow plays a vital role for mixture formation and combustion performance, particularly for direct injection engines (GDI, Diesel).
- Both large scale fluid motion (swirl and tumble flows) and small scale turbulent flow field are employed in the optimization of combustion and emissions.
- In-cylinder flow measurement are important for the detailed study of fundamental in-cylinder flow processes and their interaction with combustion.
- The control of in-cylinder flow is achieved primarily through the design inlet ports, the cylinder head and piston crown geometry.
- CFD predictions always require experimental validation in new application.

Possible measurement methods for in-cylinder flow

- Single point:

  Hot-Wire Anemometry (HWA): continuous records, not flow direction, needs careful calibration

  LDA/LDV: non-intrusive, independent of fluid properties, seeding needed

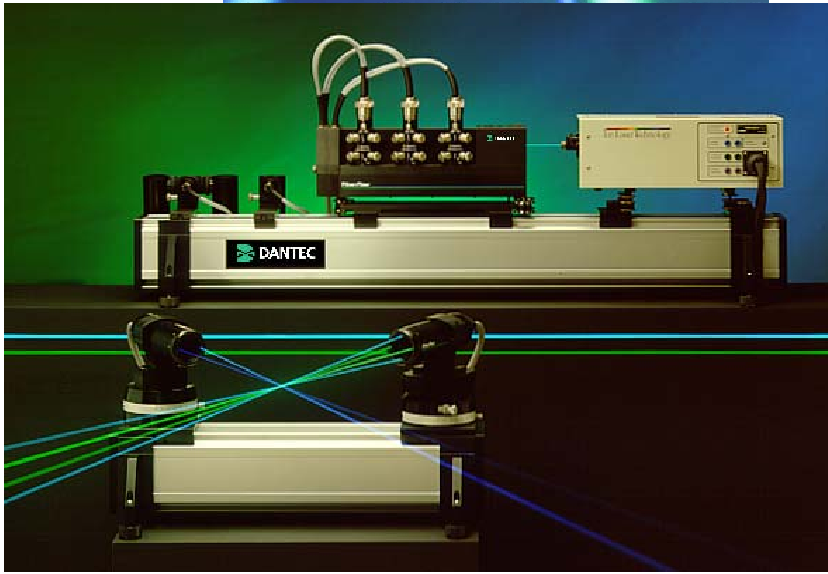
- Whole field (2D, seeding needed, instantaneous record, cycle resolved):

  Particle Tracking Velocimetry (PTW): high speed imaging

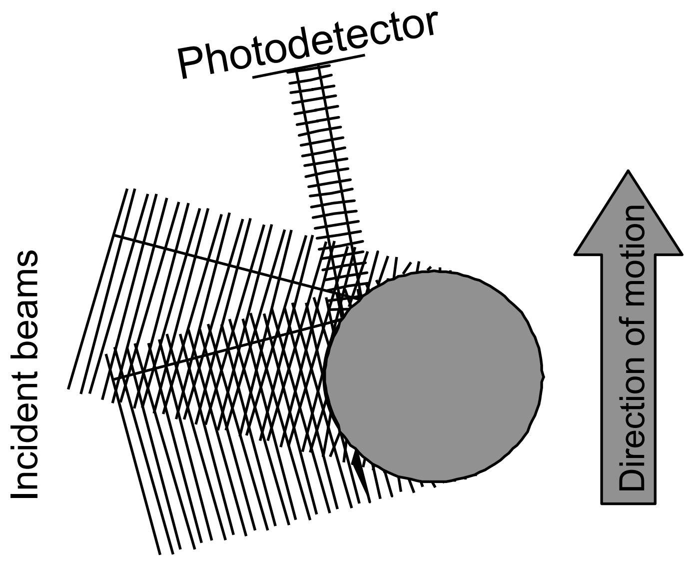
  PIV: high spatial resolution

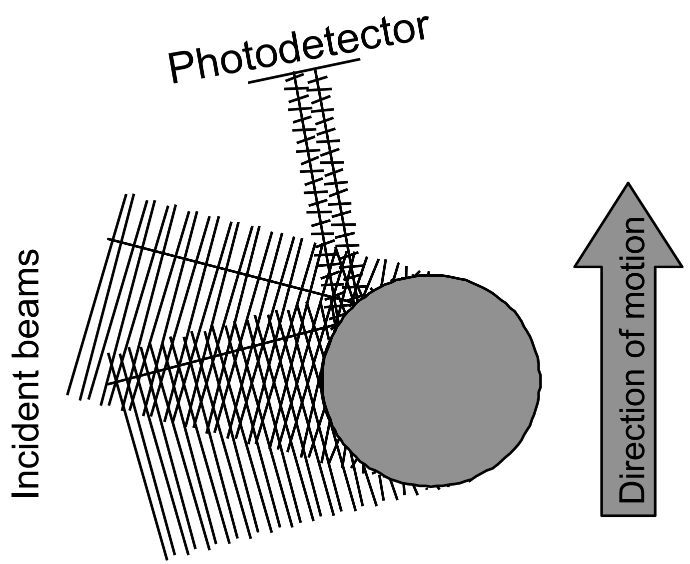
LDA/LDV

- Non intrusive
- Absolute measurement technique - No calibration required
- Velocity range 0 to supersonic
- One, two or three velocity components simultaneously
- Measurement distance from centimeters to meters
- Flow reversals can be measured
- High spatial and temporal resolution
- Instantaneous and time averaged
- Traced particle required

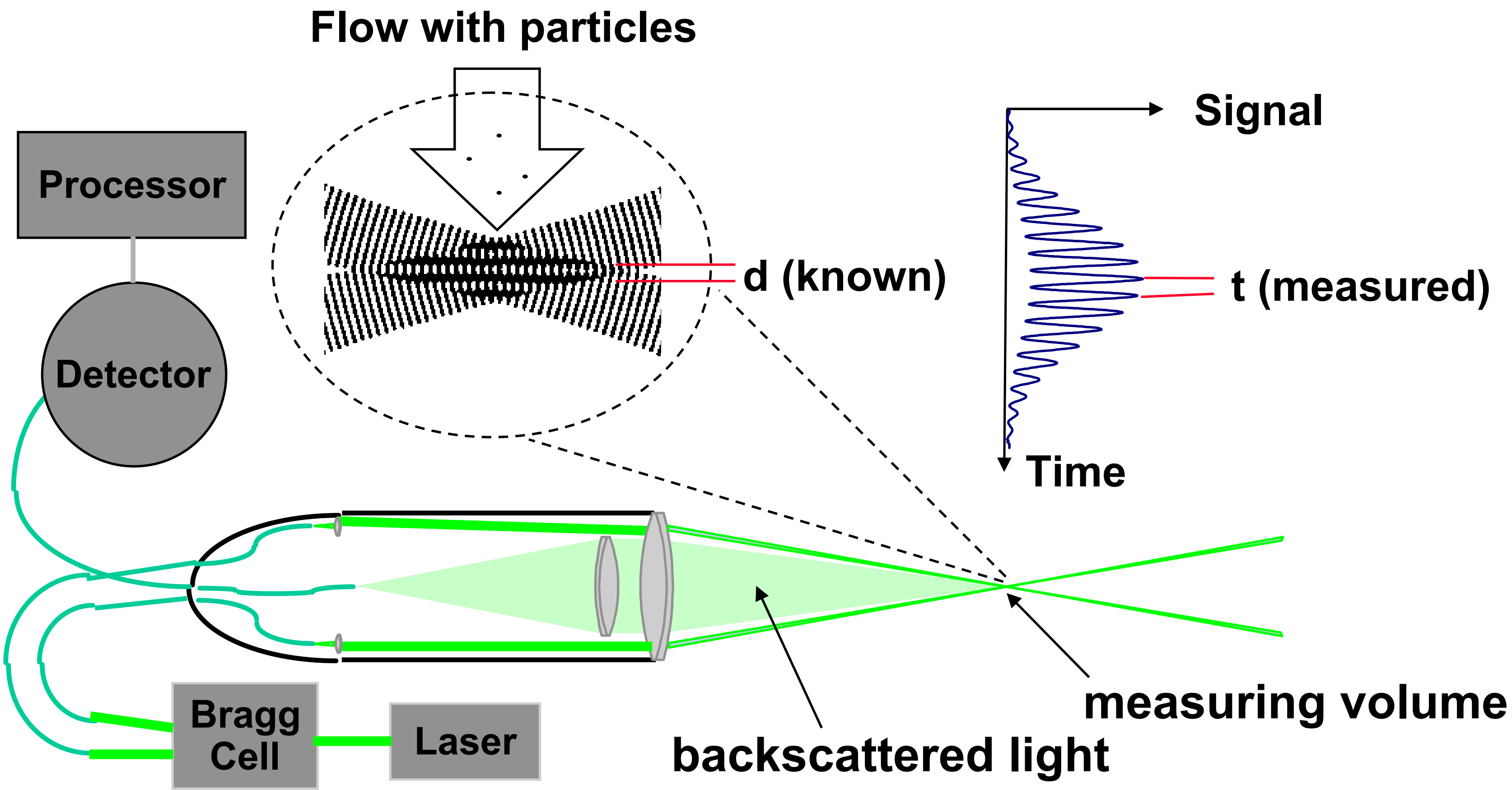


- When a particle passes through the intersection volume formed by the two coherent laser beams, the scattered light, received by a detector, has components from both beams.
- The components interfere on the surface of the detector.
- Due to changes in the difference between the optical path lengths of the two components, this interference produces pulsating light intensity, as the particle moves through the measurement volume.





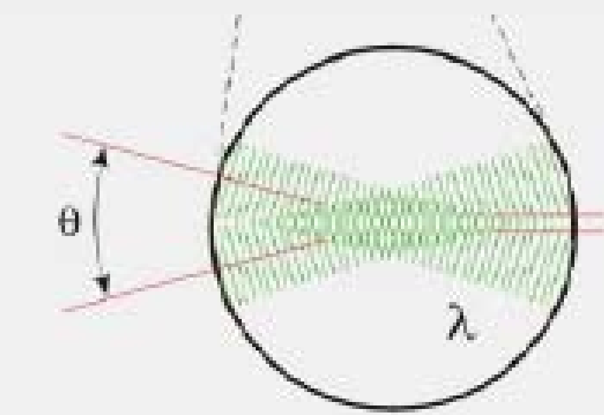
Principle



Velocity = distance/time

LDA

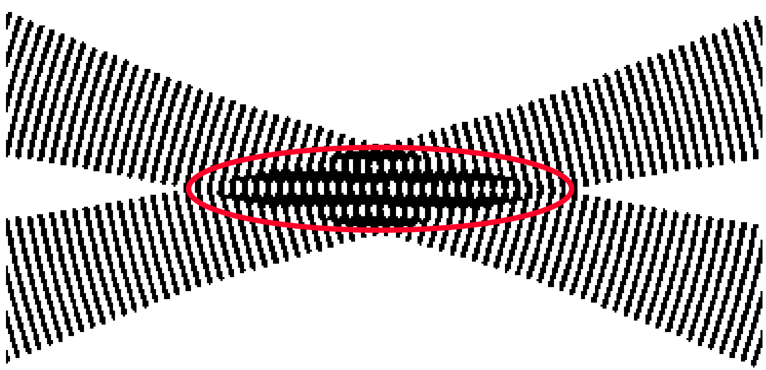
- Focused laser beams intersect and form the measurement volume
- Plane wave fronts: beam waist in the plane of intersection
- Interference in the plane of intersection
- Pattern of bright and dark stripes/planes

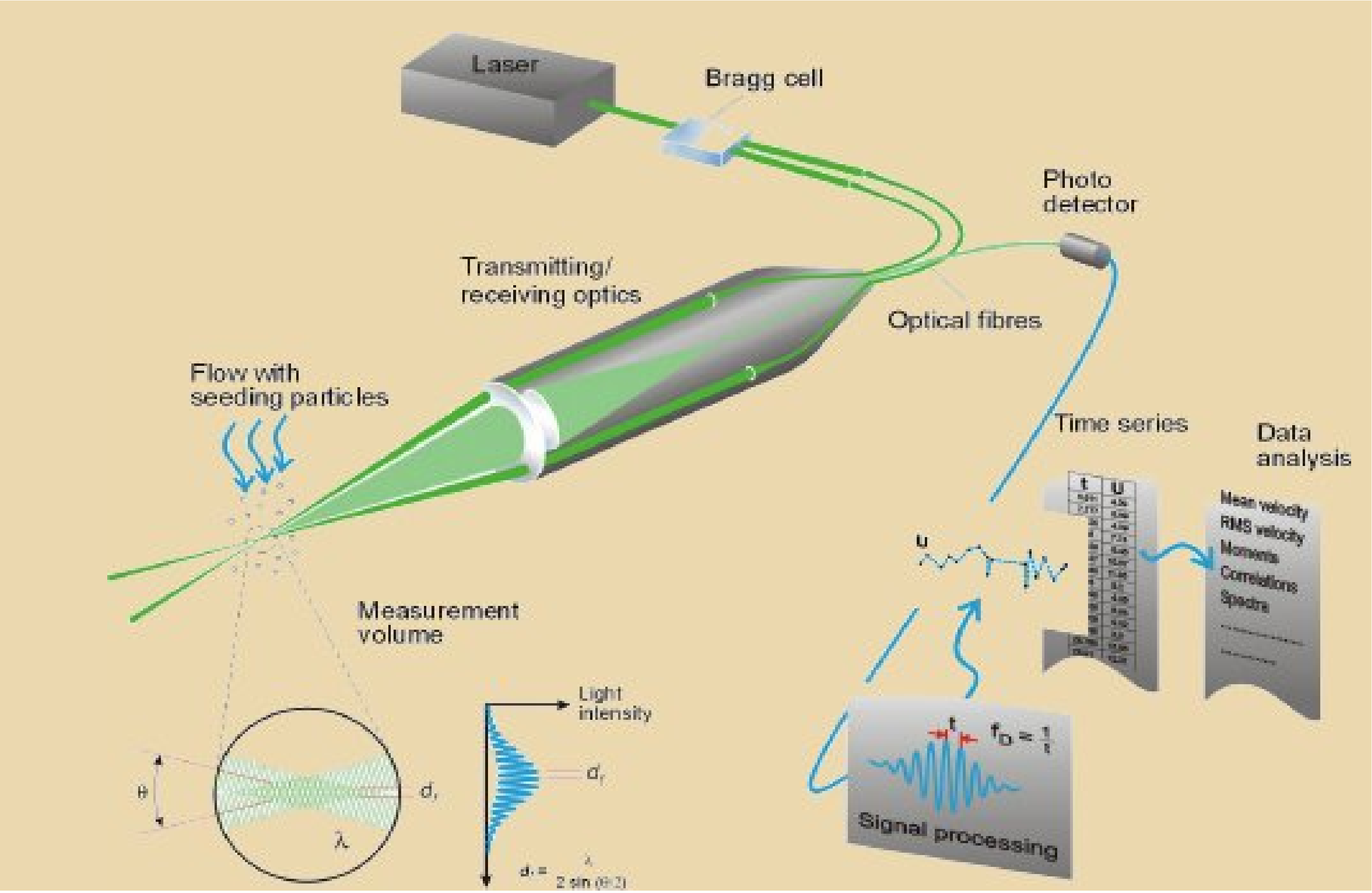


$$d_f = \frac{\lambda}{2 \sin(\theta/2)}$$

$$t = 1/f_D$$

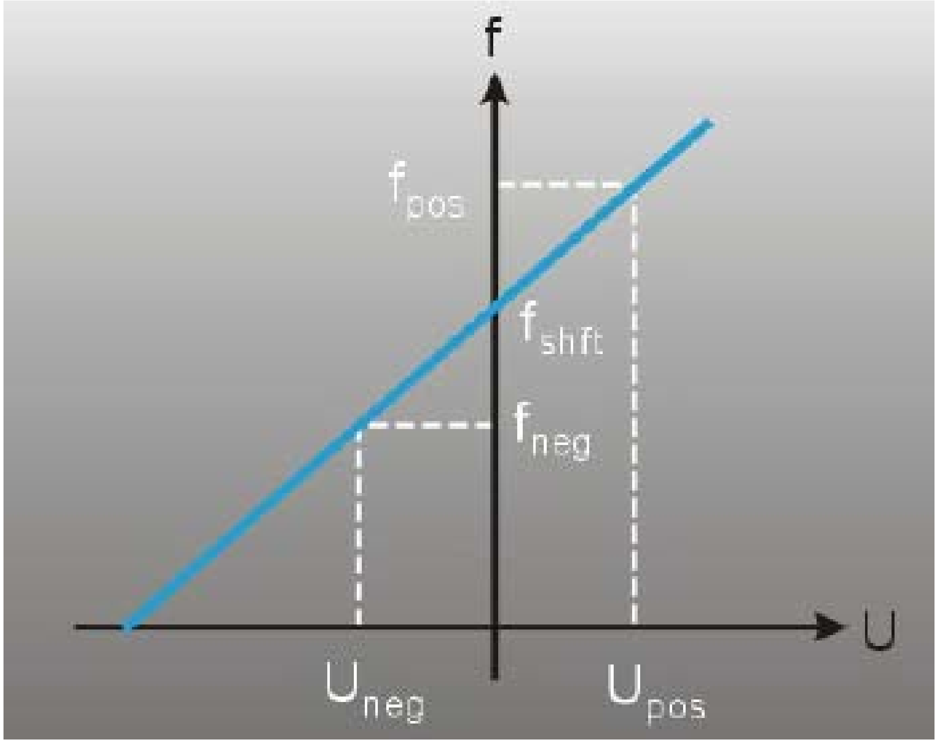
$$\text{Velocity } V = d_f{}^{*} f_D$$

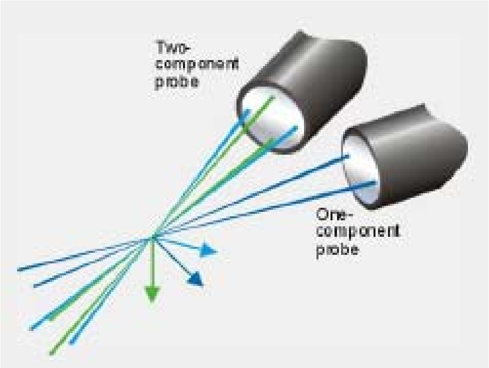




Dantec System

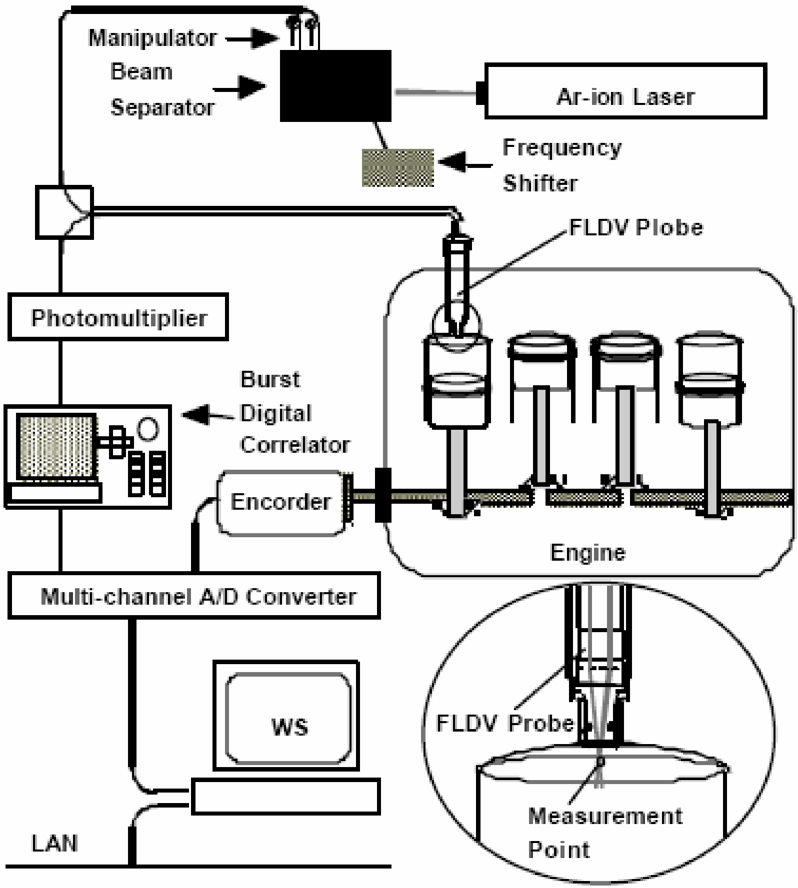
Determination of the sign of the flow direction



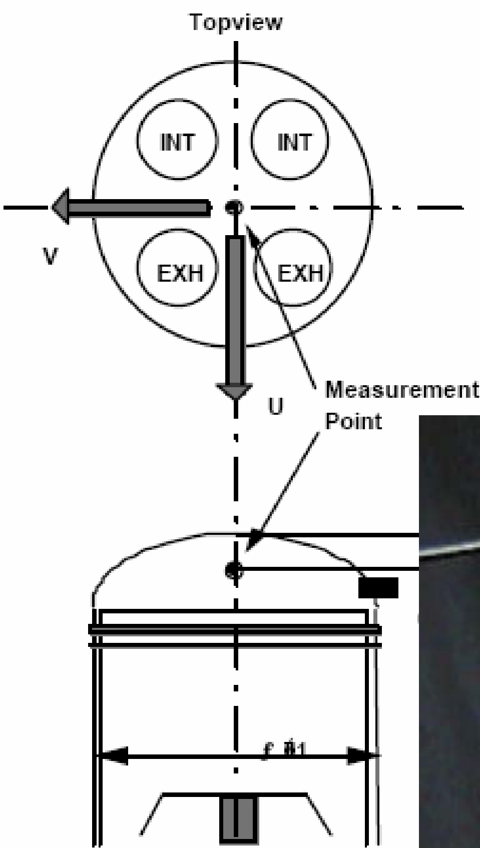


2D or 3D measurement

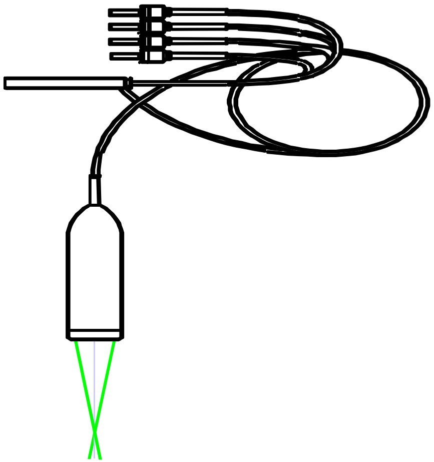
LDV Measurement in a production engine – using fiber probe

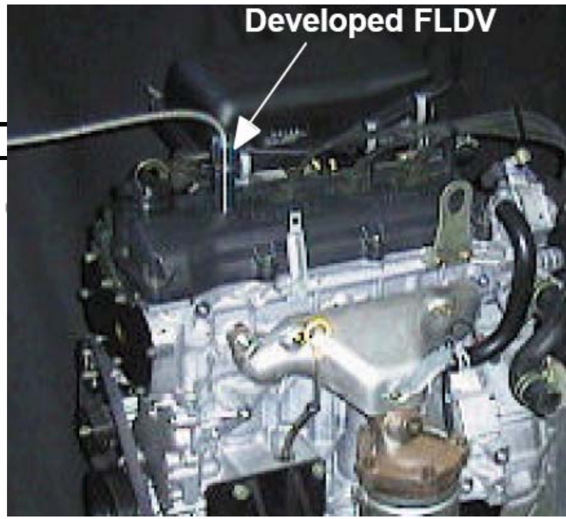


Measurement system



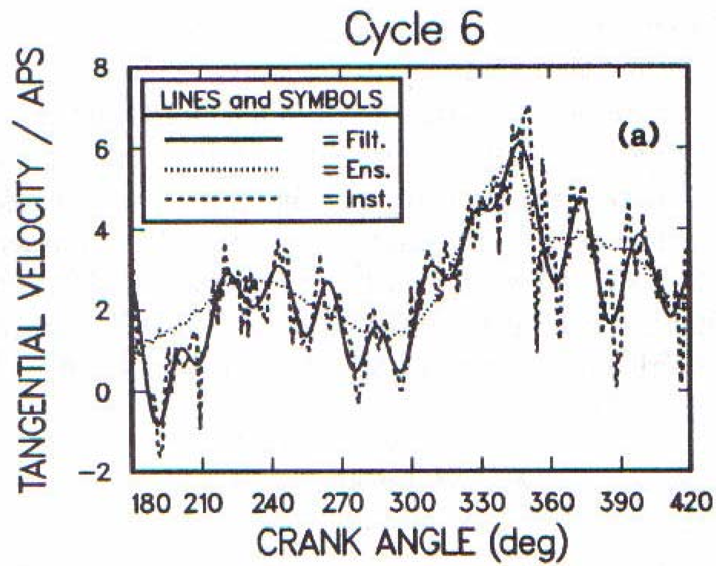
Measurement point

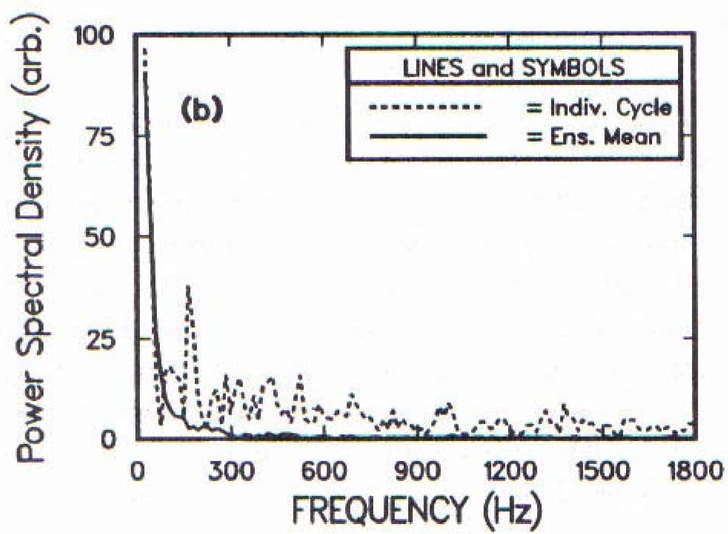




$$U_{B(x,y,\theta,i)} = U_{EA(x,y,\theta)} + u_{LF(x,y,\theta,i)}$$

$$U_{EA(x,y,\theta)} = \frac{1}{N}\sum_{i=1}^{N} U_{(x,y,\theta,i)}$$





Seeding particles

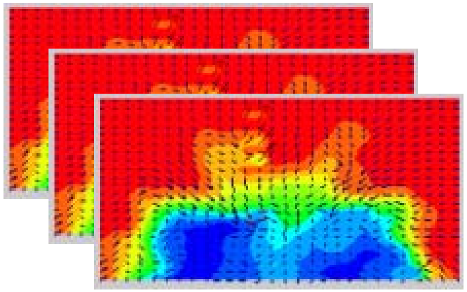
- Liquids often contain sufficient natural seeding, whereas gases must be seeded in most cases.
- Ideally, the particles should be small enough to follow the flow, yet large enough to scatter sufficient light to obtain a good signal-to-noise ratio at the photo-detector output.
- Typically the size range of particles is between 1 um and 10 um. The particle material can be solid (powder) or liquid (droplets).

Measurement considerations

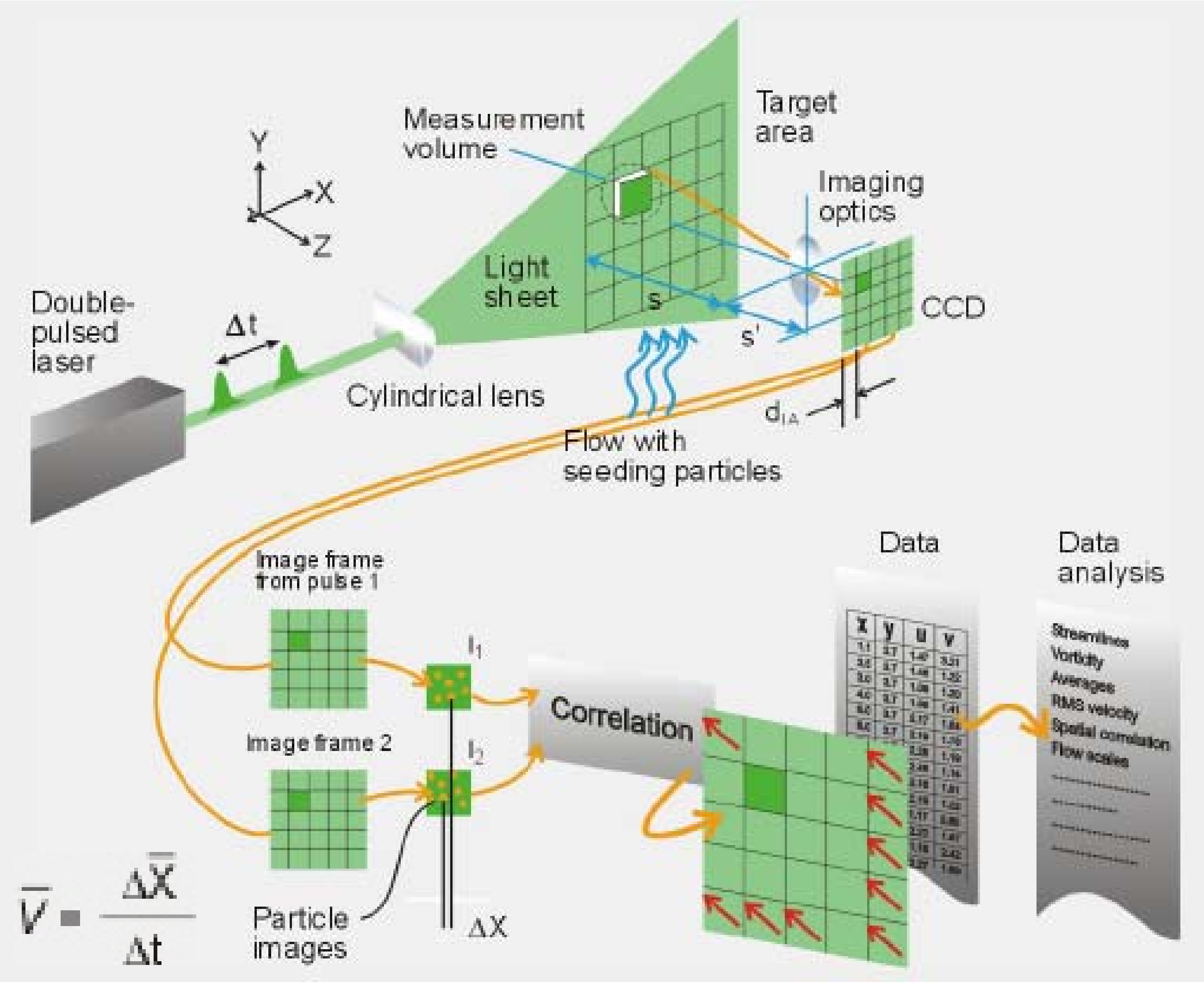
- Seeding
- Laser beam arrangement
- Signal receiving and processing
- Data analysis

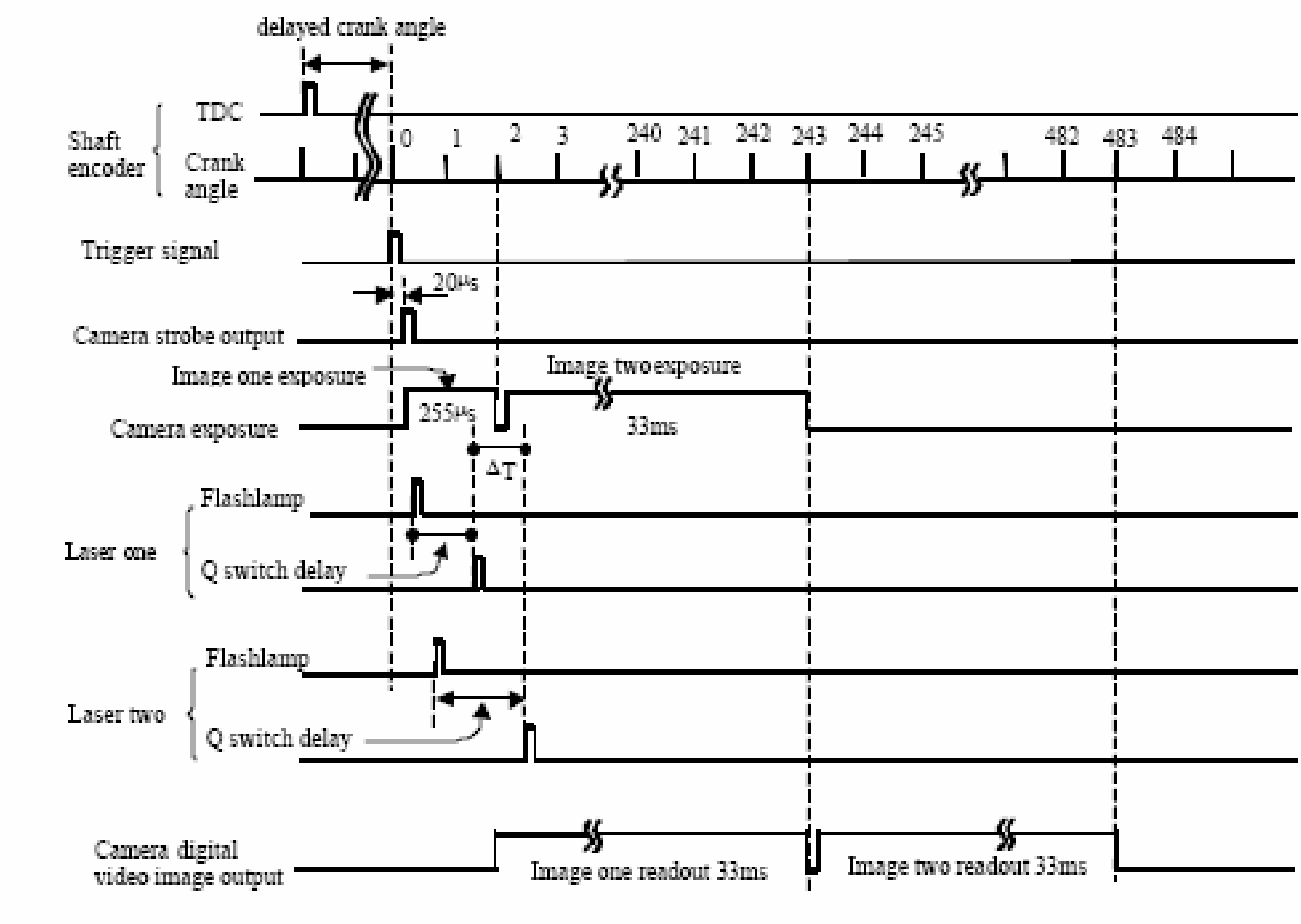
PIV

- The technique is non-intrusive and measures the velocities of micron-sized particles following the flow.
- Velocity range from zero to supersonic.
- Instantaneous velocity vector maps in a cross-section of the flow.
- All three components may be obtained with the use of a stereoscopic arrangement.

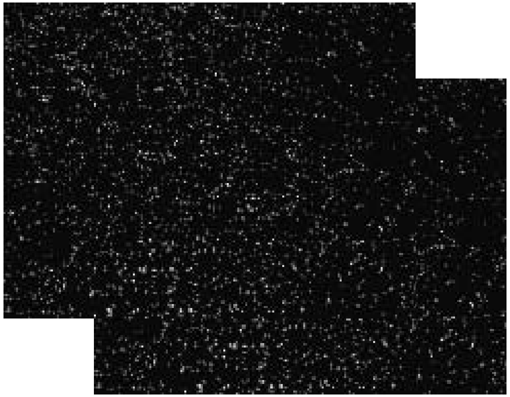


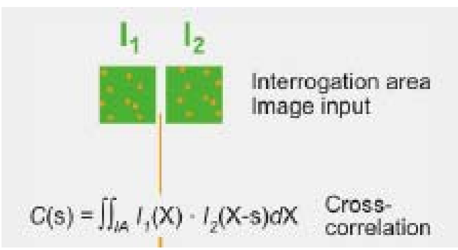
PIV Principle

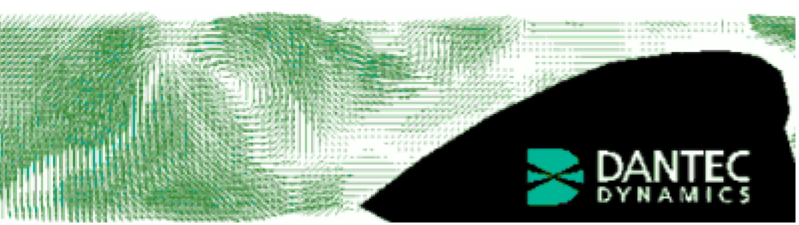




One example of PIV system timing





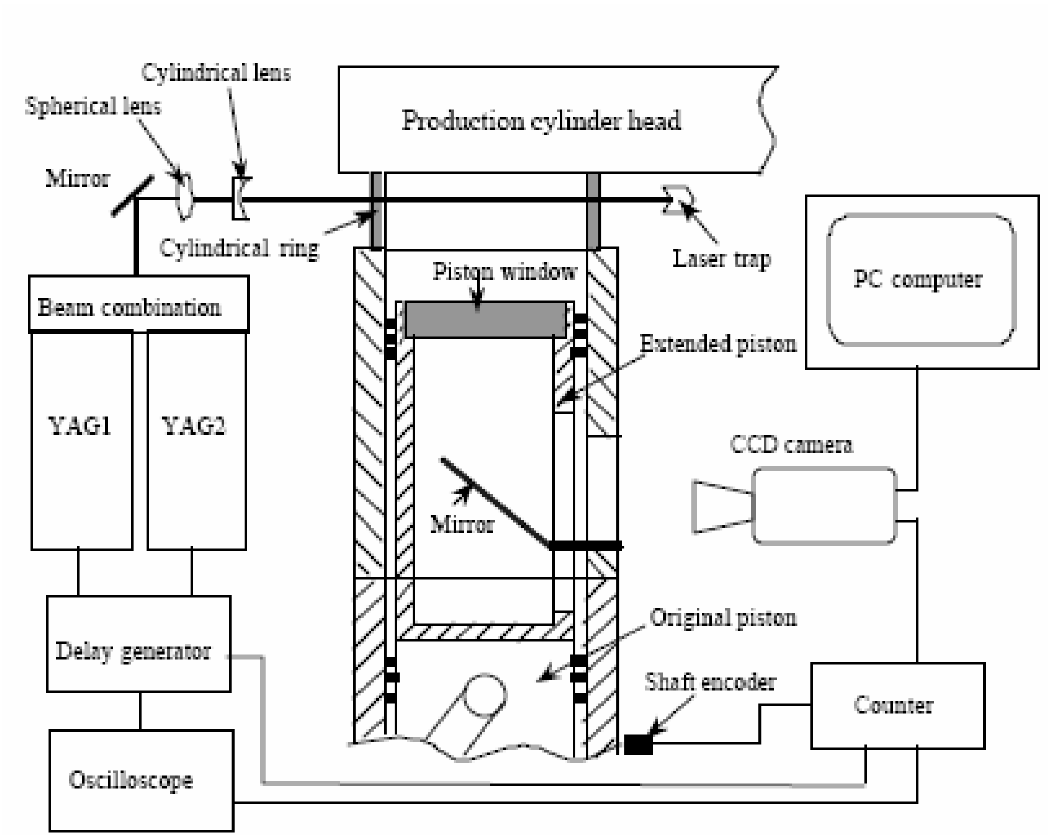


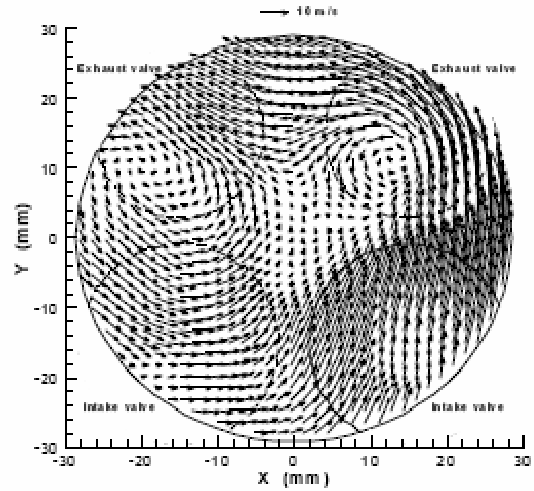
- The velocity vectors are derived from sub-sections of the target area of the particle-seeded flow by measuring the movement of particles between two light pulses
- The flow is illuminated in the target area with a light sheet.

  The camera lens images the target area onto the CCD array of a digital camera. The CCD is able to capture each light pulse in separat image frames.

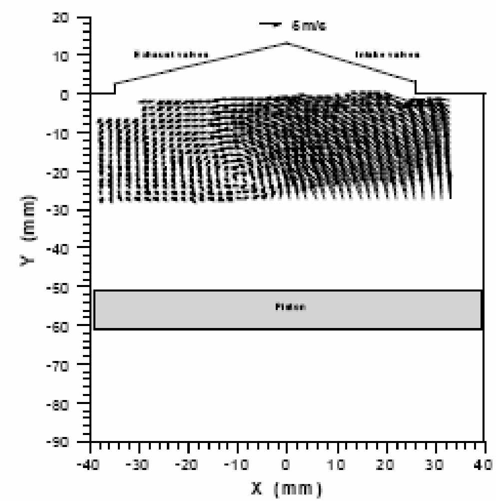
  Once a sequence of two light pulses is recorded, the images are divided into small subsections called inter-rogation areas (IA). The interrogation areas from each image frame, I1 and I2, are cross-correlated with each other, pixel by pixel.
- The correlation produces a signal peak, identifying the common particle displacemen DX. An accurate measure of the displacement - and thus also the velocity - is achieved with sub-pixel interpolation.

In-cylinder measurement

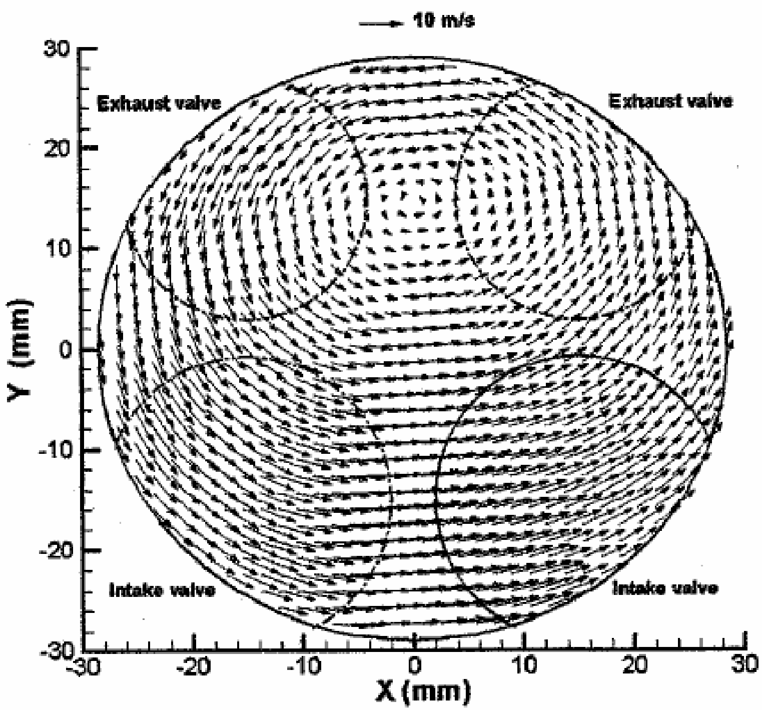




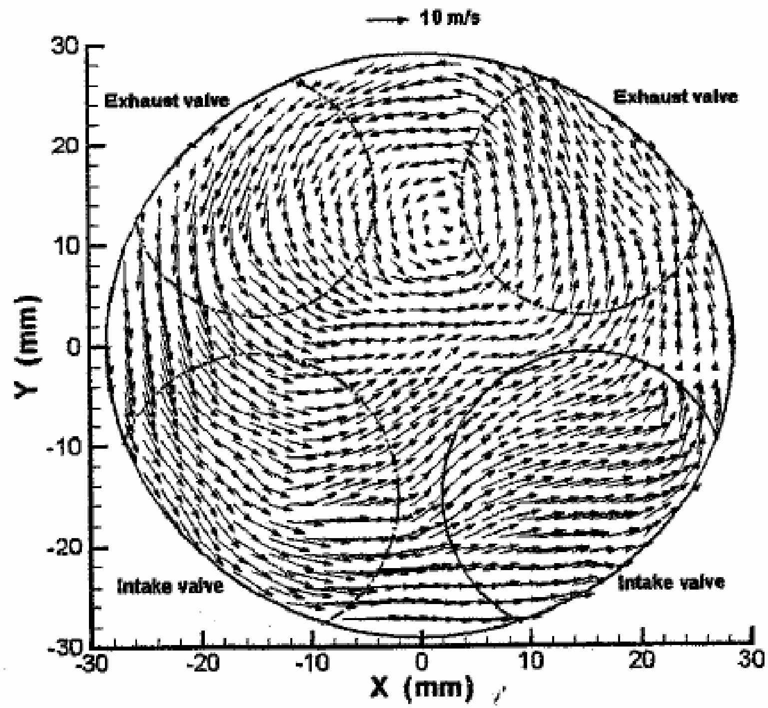
(a) 120°CA ATDC (Intake stroke)



(g) 90°CA BTDC



(a) Ensemble-averaged mean velocity field

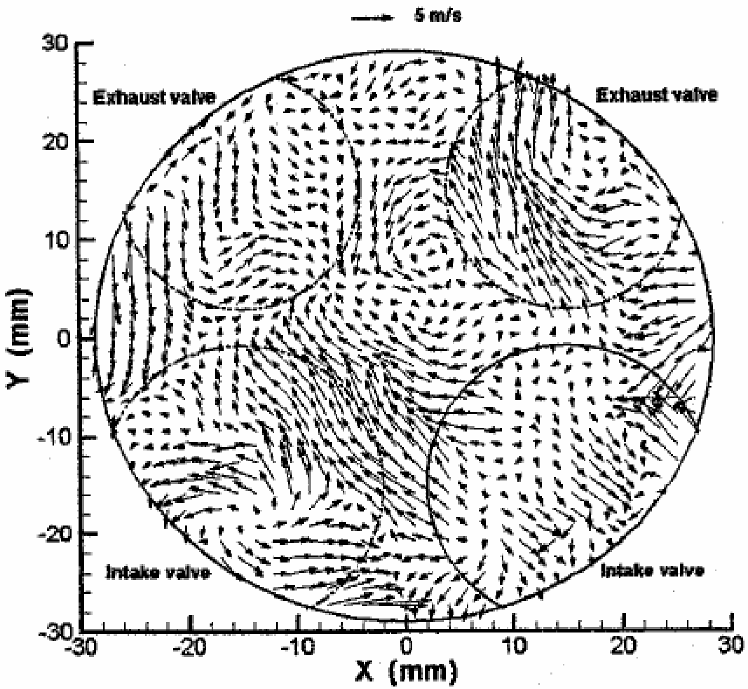


(b) Instantaneous velocity field

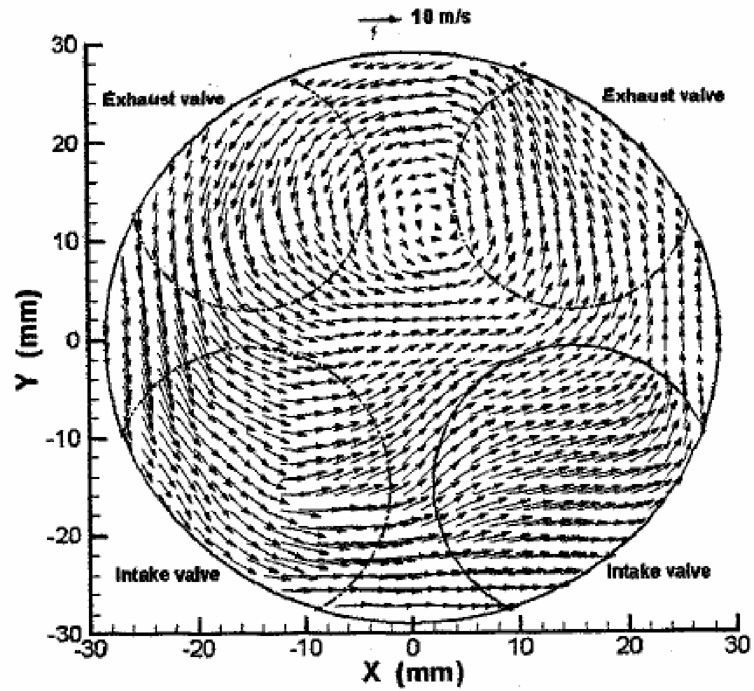
$$U_{EA(x,y,\theta)} = \frac{1}{N} \sum_{i=1}^{N} U_{(x,y,\theta,i)}$$

where N is the total number of cycles in which the velocity vectors at a particular CA θ are measured.

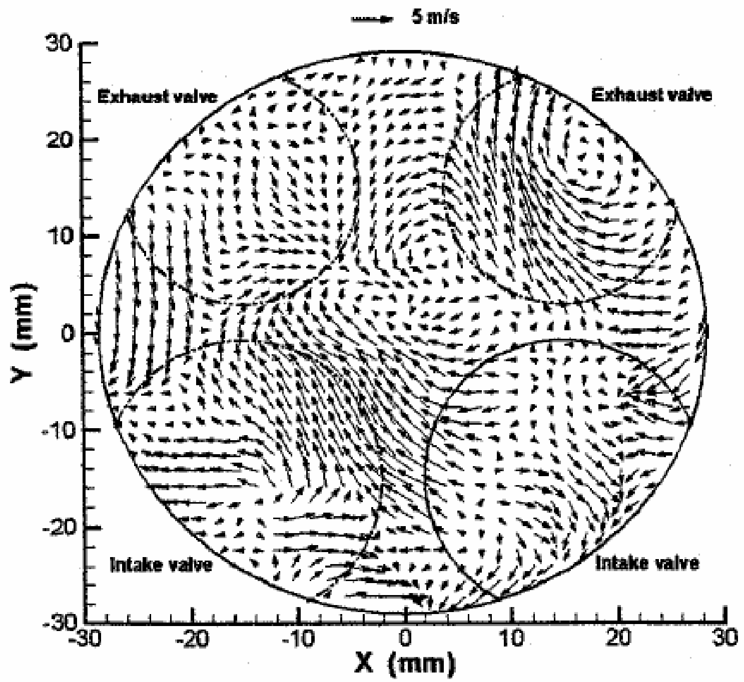
(b)-(a)



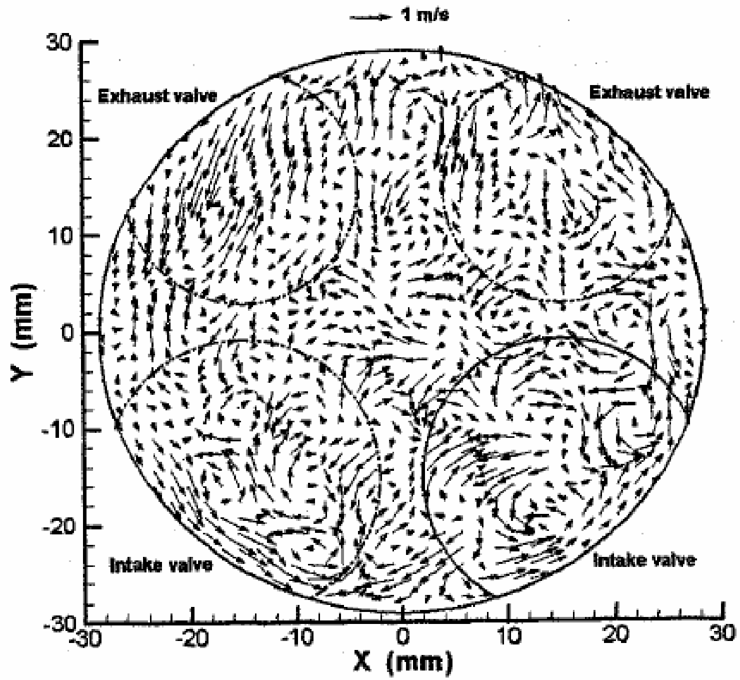
(c) Fluctuating velocity field



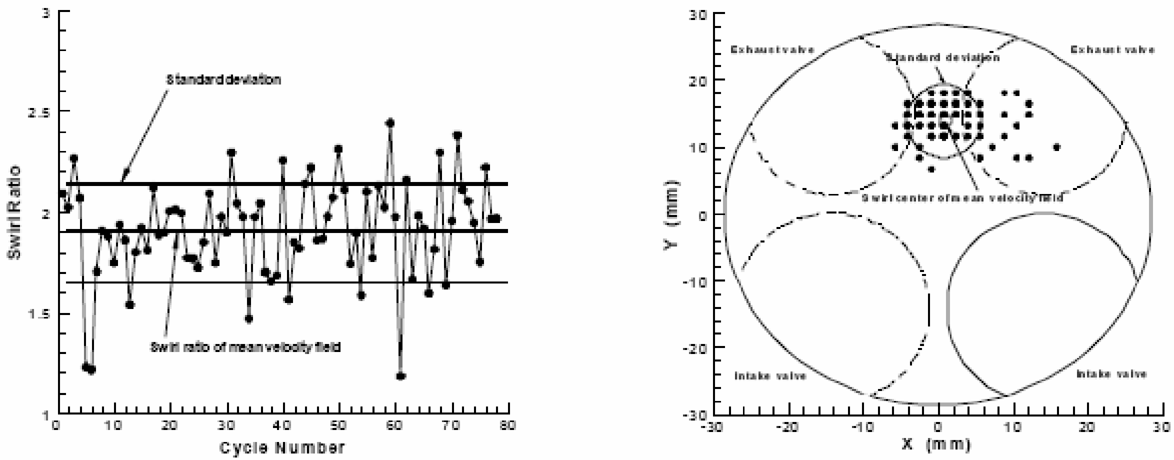
(d) Low-pass filtered velocity (in-cycle mean velocity) field



(e) Low-frequency fluctuating velocity field

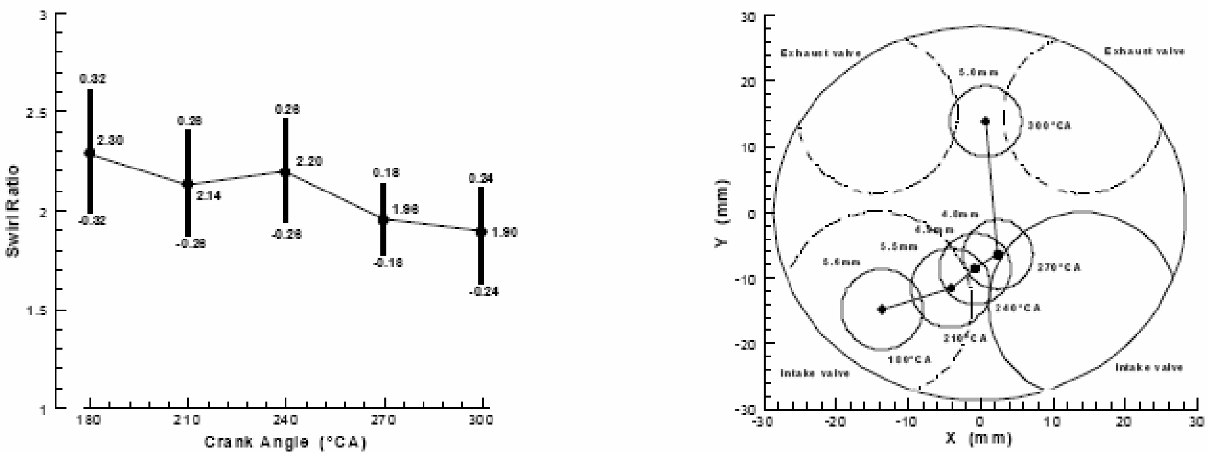


(f) High-frequency fluctuating velocity field



(a) Swirl ratio (b) Swirl center

Cycle-to-cycle variations of swirl ratio and swirl center over 80 cycles at 60°CA BTDC



(a) Swirl ratio (b) Swirl center

Changes in the swirl ratio and swirl center and their cyclic variations during the compression process

Considerations

Optical access

- Laser beam
- Seeding
- Timing – trigger, laser delay, camera timing
- Image process – cross-correlation
- Data analysis

In-cylinder visualization and combustion analysis: before combustion II

- In-cylinder fuel and mixture measurement
- Laser particle sizer based on Fraunhofer Diffraction Method
- Fuel droplet sizing and velocity measurement by a Phase Doppler Analyser (PDA)
- 2D fuel distribution measurement by PLIF
- Simultaneous visualisation of fuel vapour and liquid fuel by LIEF
- summary

* Questionnaire for the course

In-cylinder visualization and combustion analysis: during and after combustion

Before Combustion II
In-cylinder fuel and mixture measurement

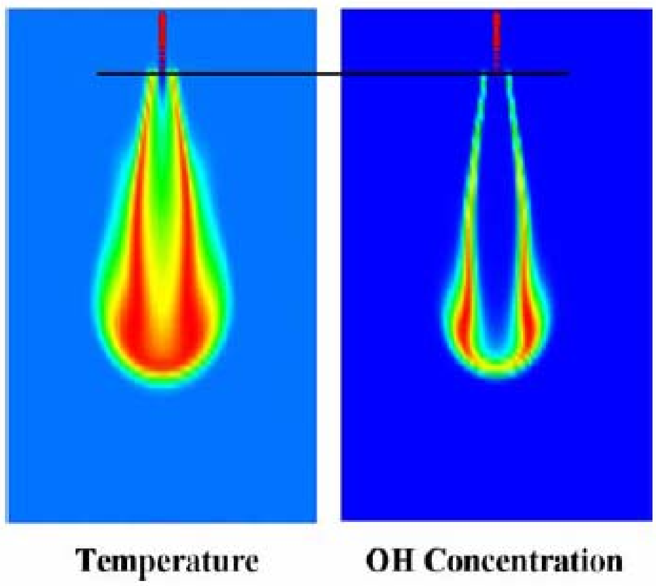
- From liquid fuel to air/fuel mixture which is suitable for combustion, there is a process including injection, automization, vaporization and mixing.
- Fuel atomization, vaporization and mixing process with air directly affect the engine combustion process and performance.
- Mixture preparation and mixture distribution information are important for understanding and optimizing combustion systems, particularly for GDI, diesel combustion, HCCI combustion.
- Fuel/Air ratio is also important for maintaining 3-way catalyst working condition.

Possible methods

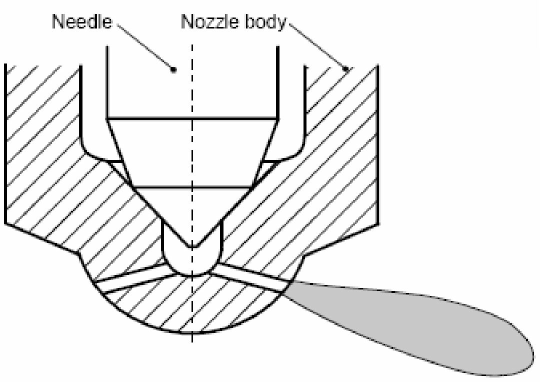
- In-cylinder fuel measurement by FID (Flame Ionization Detector) and high-speed sampling valve
- Spray structure measurement by direct imaging methods or LIF
- Fuel droplet sizing by the Fraunhofer Diffraction Method
- Droplet sizing and velocity measurement by a PDA (Phase Doppler Analyser)
- Fuel droplet velocity measurement by LDV (air entrainment)
- 2D fuel distribution by PLIF (Planar Laser Induced Fluorescence)
- Simultaneous Visualisation of fuel vapour and liquid fuel by LIEF (Laser Induced Exciplex Fluorescence)

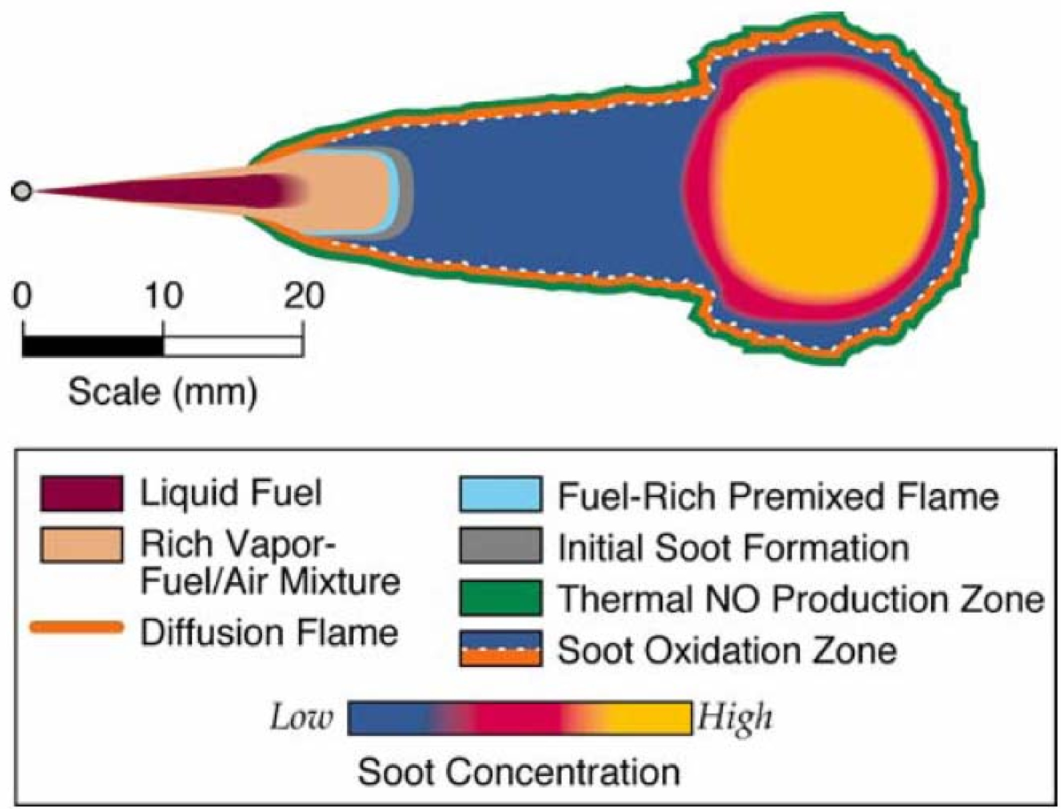
Possible methods

- Air/fuel ratio measurement by Spontaneous Raman Scattering (SRS) and Fuel/Air Ratio LIF (FARLIF)
- Fuel concentration measurement by Laser Rayleigh Scattering (LRS)
- …

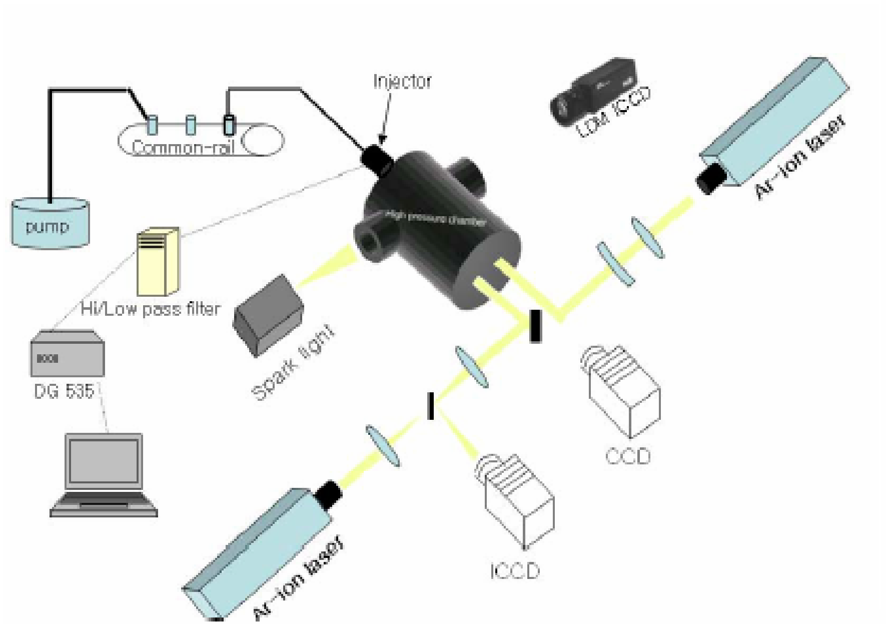


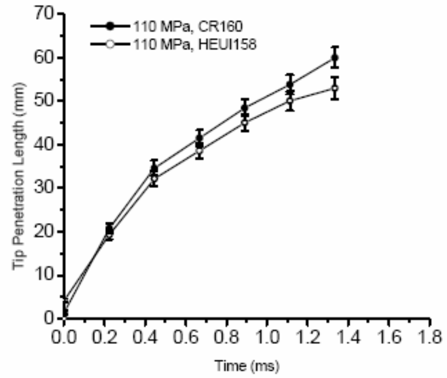
Atomization, vaporization, mixing → combustion and emissions

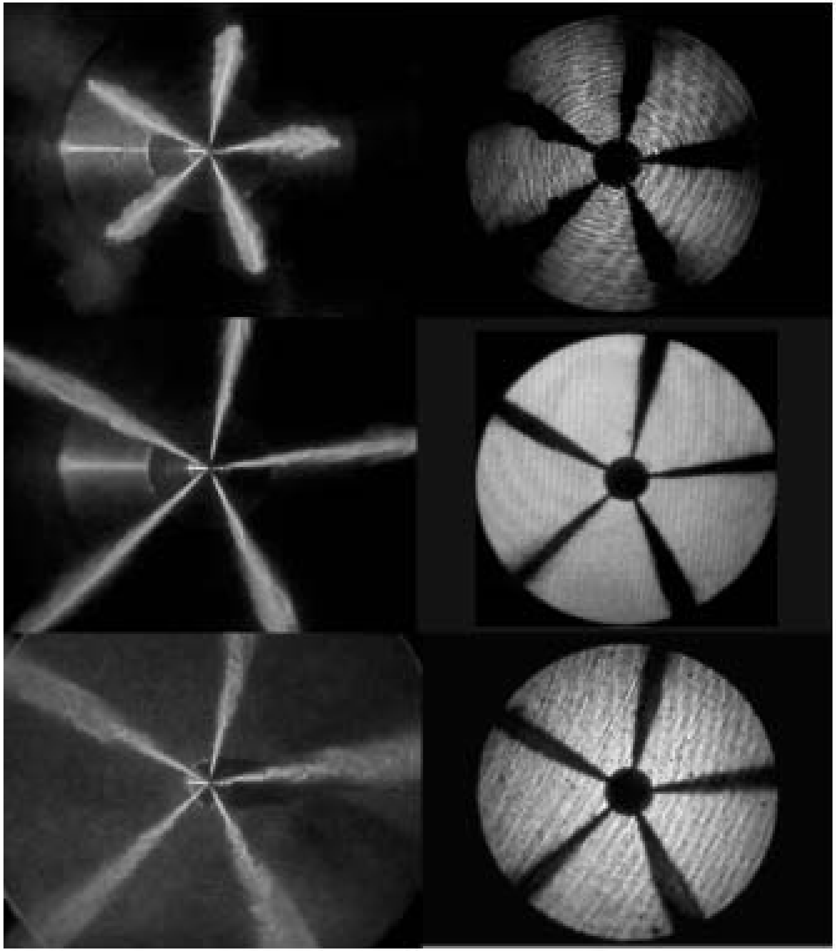




Spray measurement



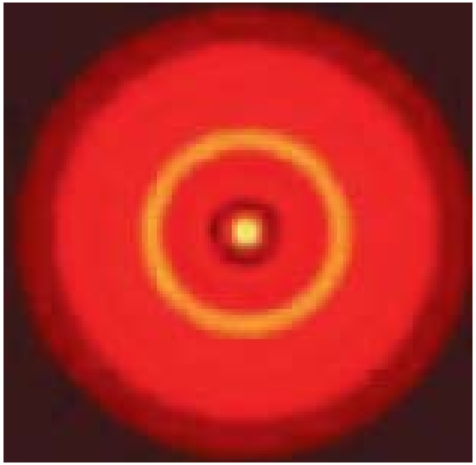




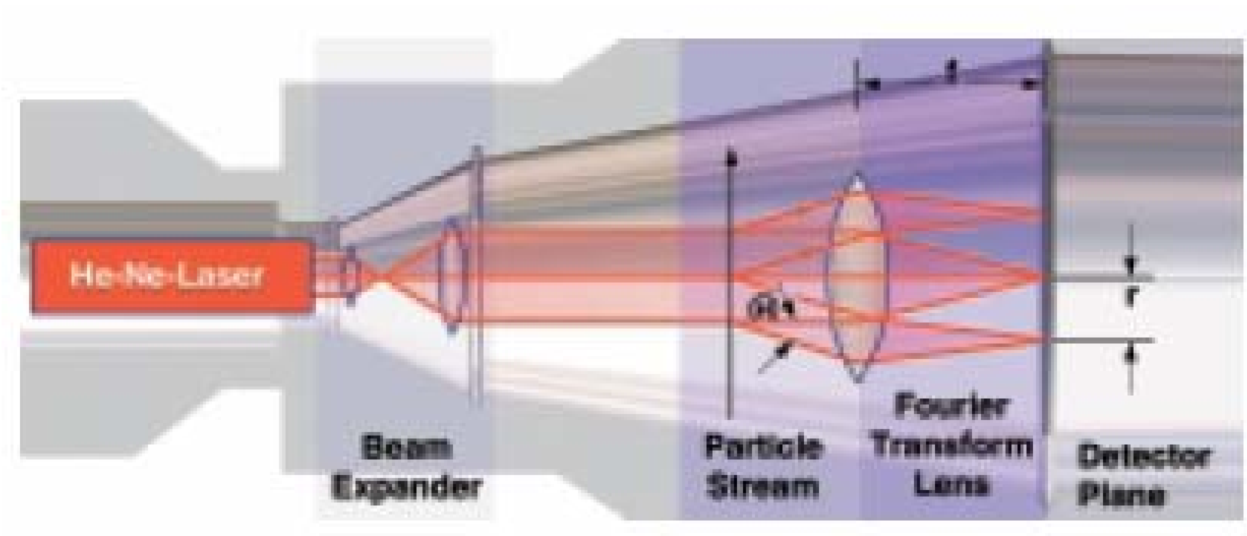
Fraunhofer Laser Sizer for Spray Droplets

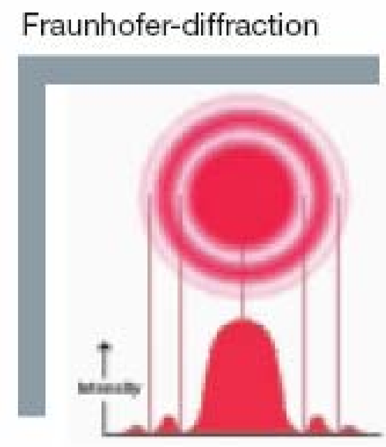
Features

- Based on laser diffraction at the particle edges
- Rapid, automatic droplet or particle size analysis
- Measurement range 0.01-1000um



Fraunhofer Laser Sizer





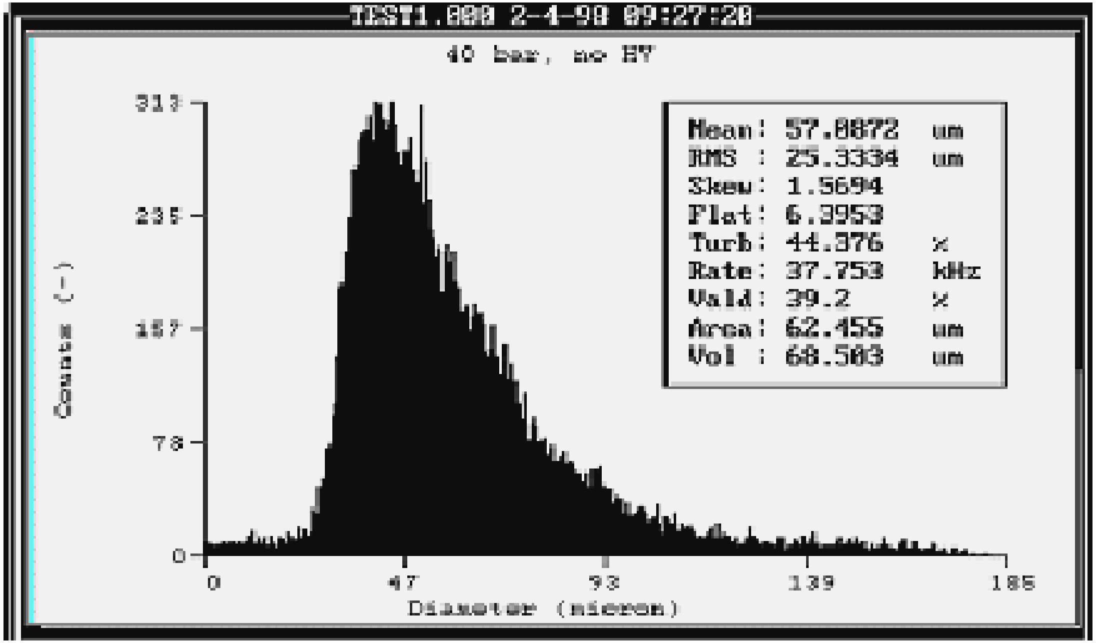
- Particles in a **parallel laser beam** deflect the light in a fixed solid angle that depends on the diameter of the particles.
- A lens focuses the scattered light in a ring on a sensor that is mounted in the focal plane of the lens.
- Undiffracted light converges at the focal point on the optical axis.

Fraunhofer Laser Sizer

- Applies only to fully opaque particles and small diffraction angle.
- If a light beam with a specific wavelength encounters a particle, the particle performs electromagnetic oscillations in the same frequency as the stimulating light – regardless of the relationship of the light wavelength to the particle diameter and the refractive index of the particles and medium.
- The particle is tuned to the reception of specific wavelengths and re-emits the energy like a relay station within a defined spatial angle distribution.
- According to the theory, multiple oscillation states of varying probabilities are possible and there exists a relationship between the optically effective cross section and particle size, light wavelength and the refractive index of the particles and medium.

Fraunhofer Laser Sizer

Result processing



Fraunhofer Laser Sizer

Same volume fuel, the better atomization, the larger surface

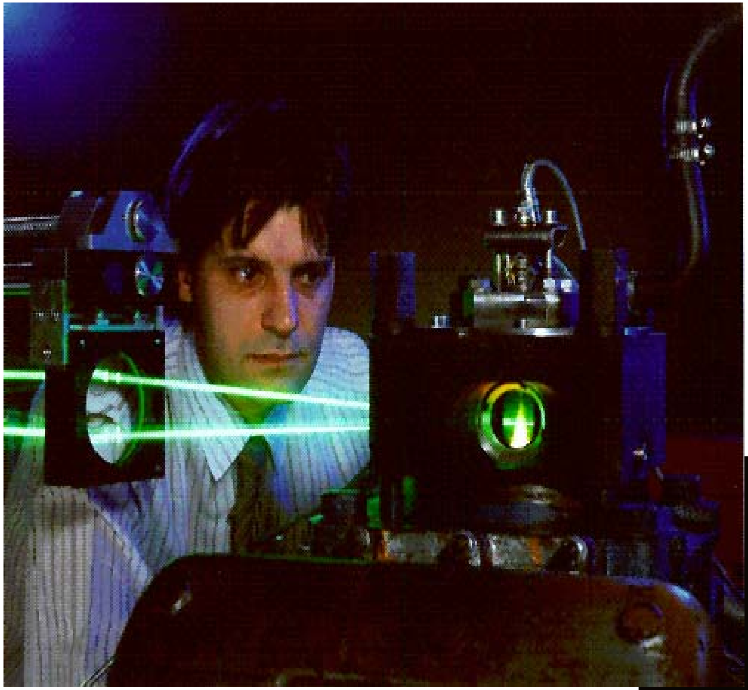
Arithmetic mean diameter, Number – length mean diameter	$d_{10} = \frac{\sum_i n_i d_i}{\sum_i n_i}$
Surface mean diameter (SMD)	$d_{20} = \sqrt{\frac{\sum_i n_i d_i^2}{\sum_i n_i}}$
Volume mean diameter (VMD)	$d_{30} = \sqrt[3]{\frac{\sum_i n_i d_i^3}{\sum_i n_i}}$
Surface – length mean diameter	$d_{21} = \frac{\sum_i n_i d_i^2}{\sum_i n_i d_i}$
Sauter mean diameter (SMD), volume – surface mean diameter	$d_{32} = \frac{\sum_i n_i d_i^3}{\sum_i n_i d_i^2}$

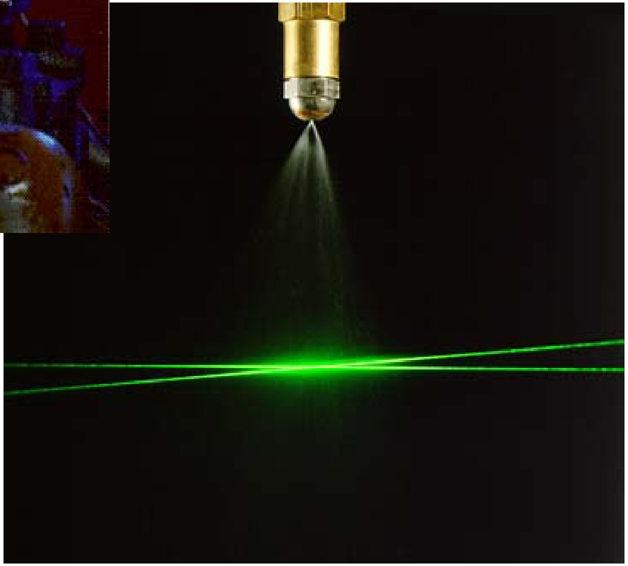
Fraunhofer Laser Sizer

Considerations

- Optical access
- Laser beam
- Timing – trigger and delay
- Data analysis

PDA for Spray Droplet





PDA

General features

- Extension of the LDA principle
- Simultaneous measurement of velocity (up to 3 components) and size of spherical particles as well as mass flux, concentration etc.
- Non-intrusive measurement (optical technique)
- Absolute measurement technique (no calibration required)
- Very high accuracy
- Very high spatial resolution (small measurement volume)

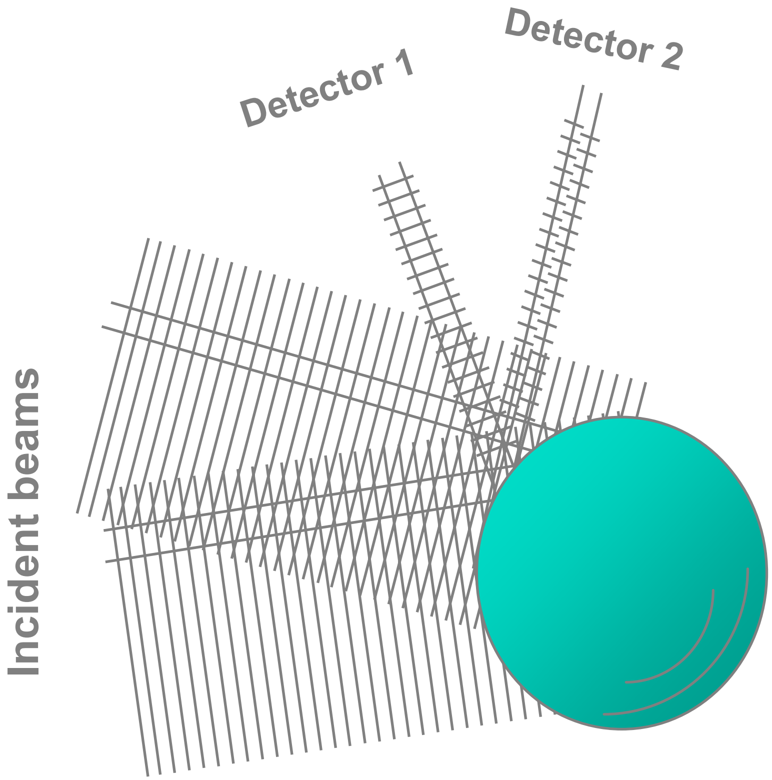
PDA

Preconditions for the application

- Optical access to the measurement area (usually from two directions)
- Sphericity of particles (droplets, bubbles, solids)
- Homogeneity of particle medium
(slight inhomogeneities may be tolerated if the concentration of the inhomogeneities is low and if the size of the inhomogeneities is much smaller than the wavelength used)
- Refractive indices of the particle and the continuous medium must usually be known
- Particle size between ca. 0.5 µm and several millimetres
- Max. particle number concentration is limited

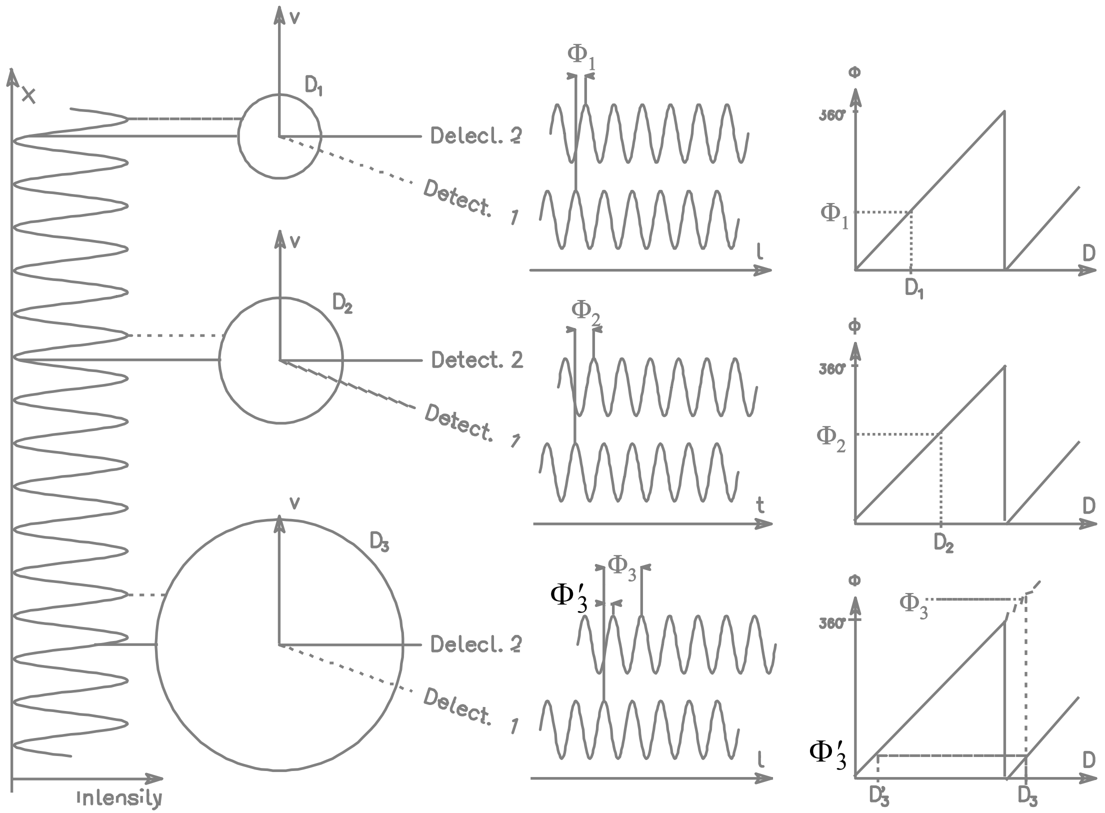
PDA

Optical principle



- A particle scatters light from two incident laser beams
- Both scattered waves interfere in space and create a beat signal with a frequency which is proportional to the velocity of the particle
- Two detectors receive this signal with different phases
- The phase shift between these two signals is proportional to the diameter of the particle

PDA



x
v
D1
Detecl. 2
Detect. 1
v
D2
Detect. 2
Detect. 1
v
D3
Detecl. 2
Detect. 1
Intensity
Φ1
l
Φ2
t
Φ3
Φ'3
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Φ
360°
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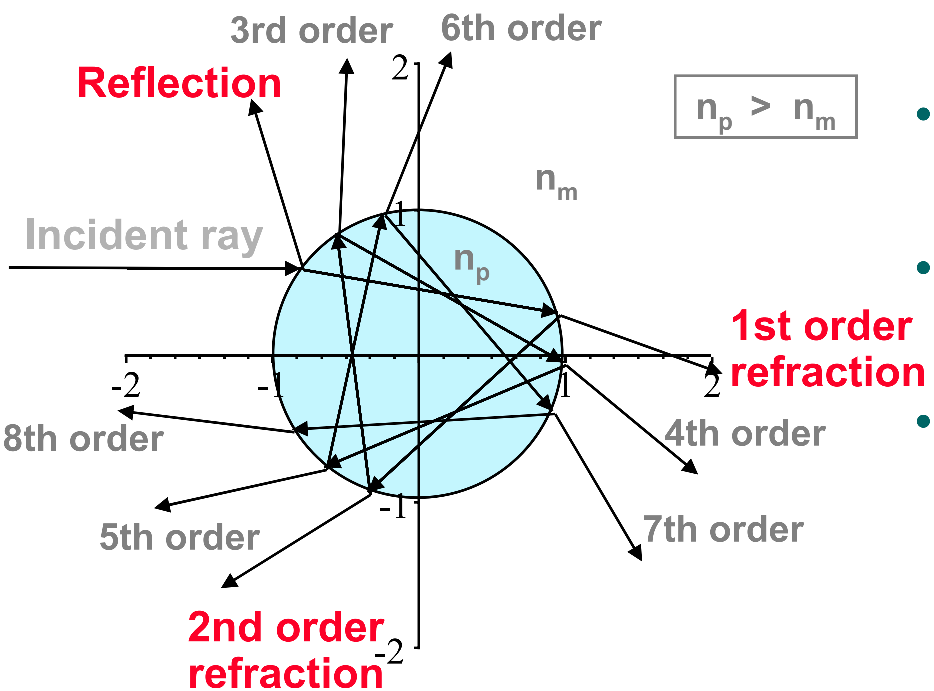
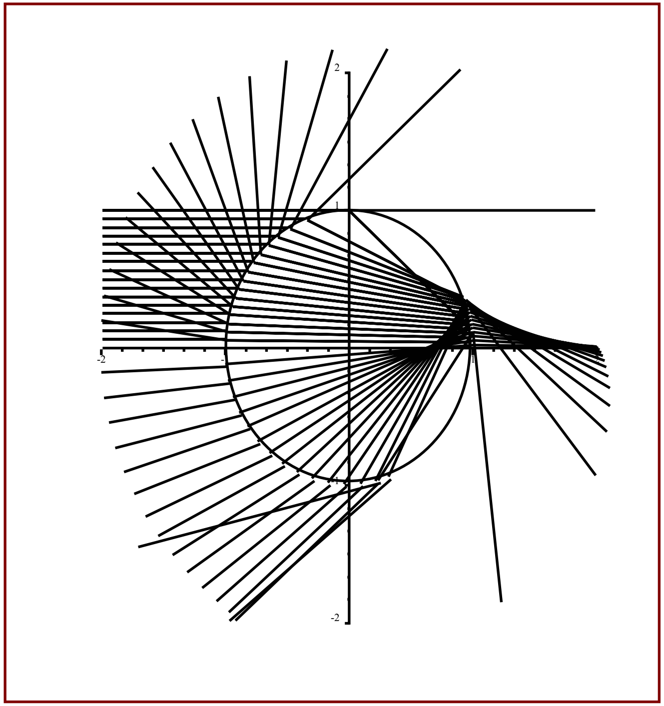
Scattering modes



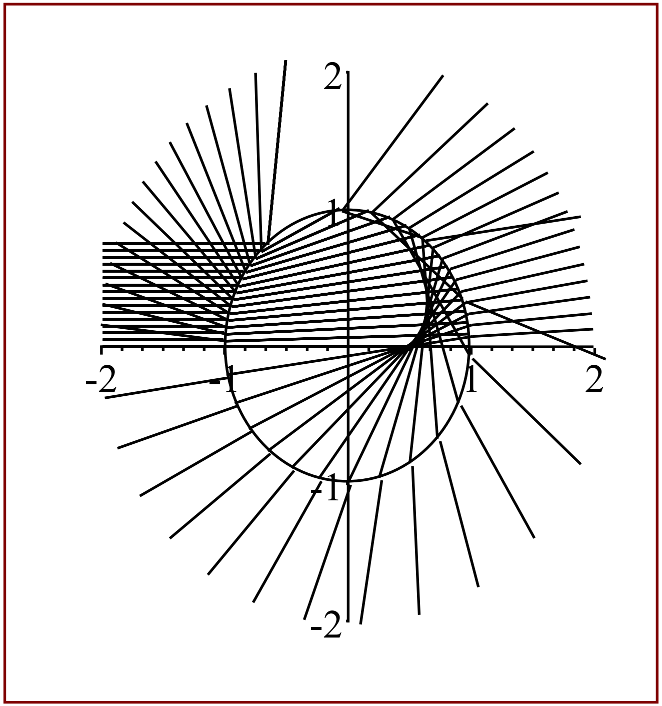
- The intensity of the incident ray is partly reflected and refracted.
- The intensity ratio is given by the Fresnel coefficients and depends on the incident angle, polarization and relative refractive index.
- The scattering angle is given by Snell's law.
- The phase is given by the optical path length of the ray.
- Most of the intensity is contained in the first three scattering modes.

Light scattering by droplets and bubbles

Water droplet in air

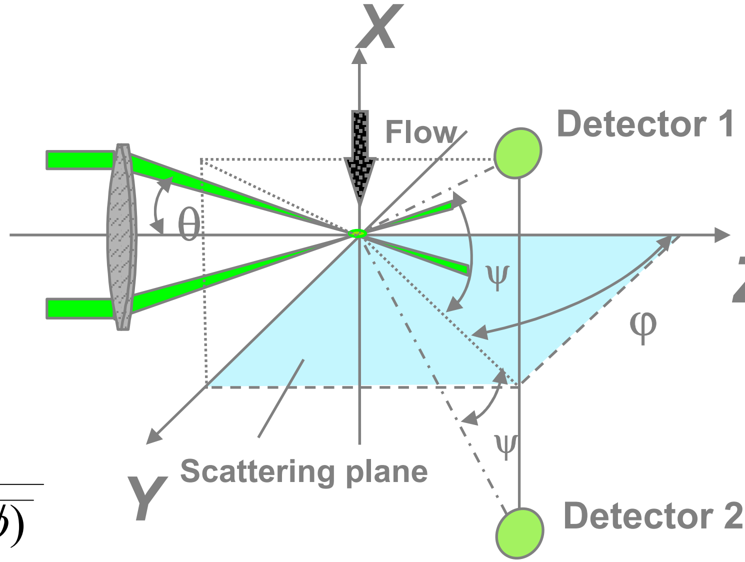


Air bubble in water



PDA

Phase relationships



The phase shift between two detectors is:

For reflection:

$$\Phi = \frac{2\pi\, d_p}{\lambda} \frac{\sin\theta\ \sin\psi}{\sqrt{2(1-\cos\theta\ \cos\psi\ \cos\phi)}}$$

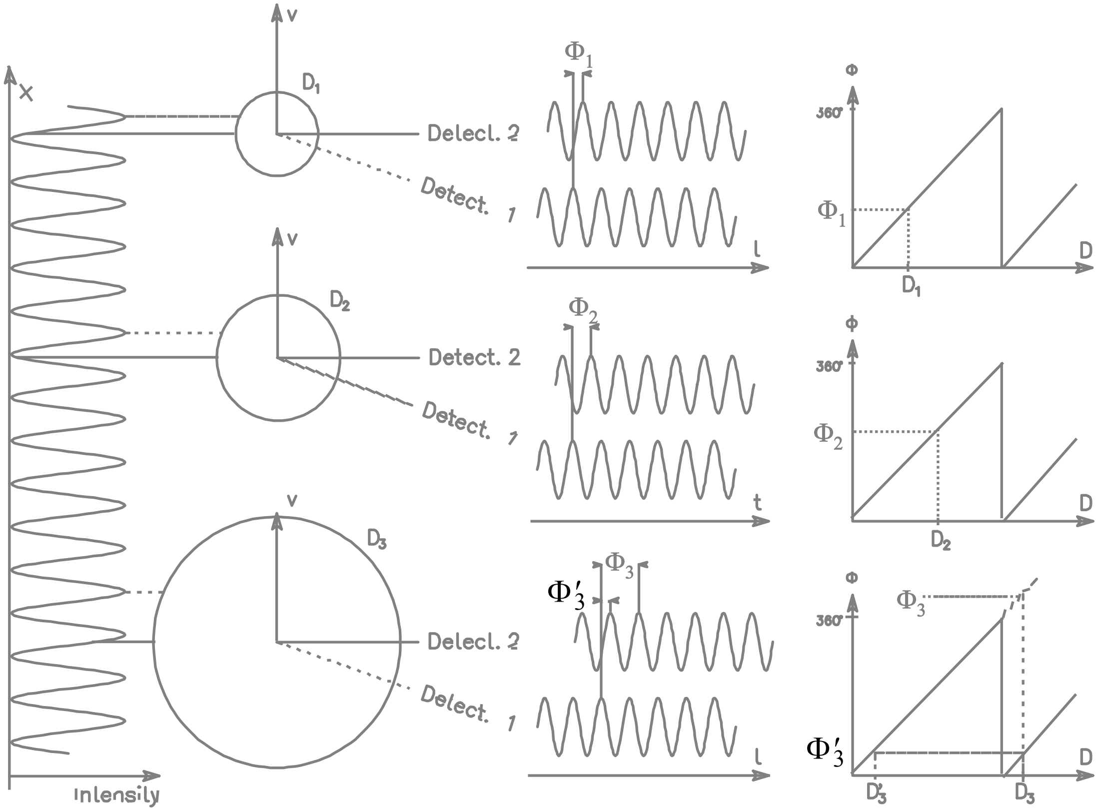
For 1st order refraction:

$$\Phi = \frac{-2\pi\ d_p}{\lambda} \frac{n_{rel}\ \sin\theta\ \sin\psi}{\sqrt{2(1+\cos\theta\ \cos\psi\ \cos\phi)(1+n_{rel}^2 - n_{rel}\sqrt{2(1+\cos\theta\ \cos\psi\ \cos\phi)}}}$$

No calibration constant is contained in these equations

PDA

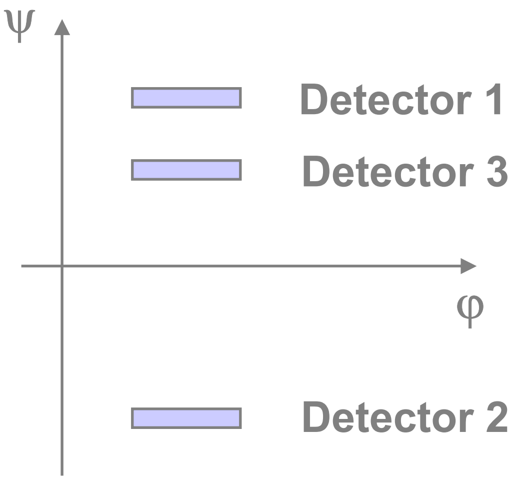
2 π ambiguity in a two-detector system

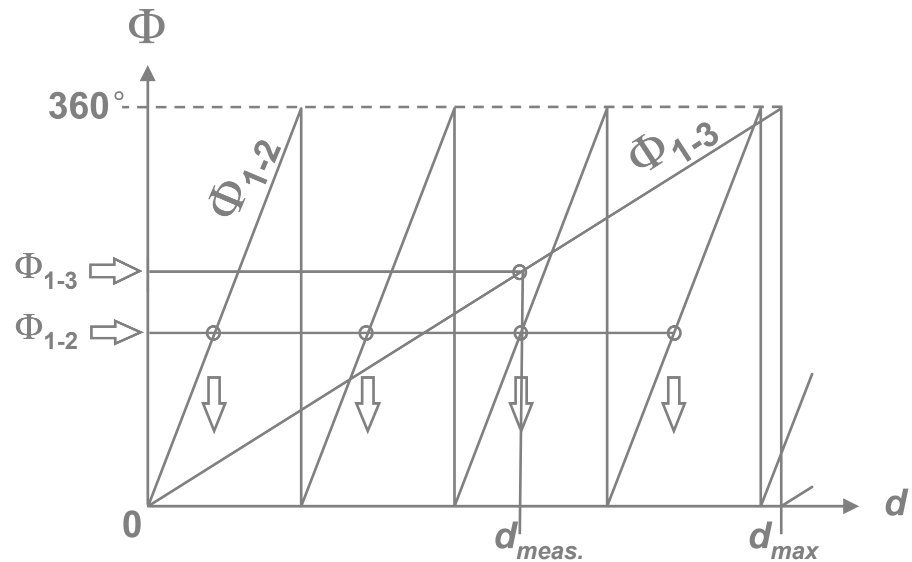


- The phase difference increases with increasing particle size.
- Since phase is a modulo 2π function, it cannot exceed 2π, i.e. 360° .
- Therefore, if a particle has a size that causes the phase to go beyond a 2π jump, a two-detector PDA cannot discriminate between this size and a much smaller particle.

PDA

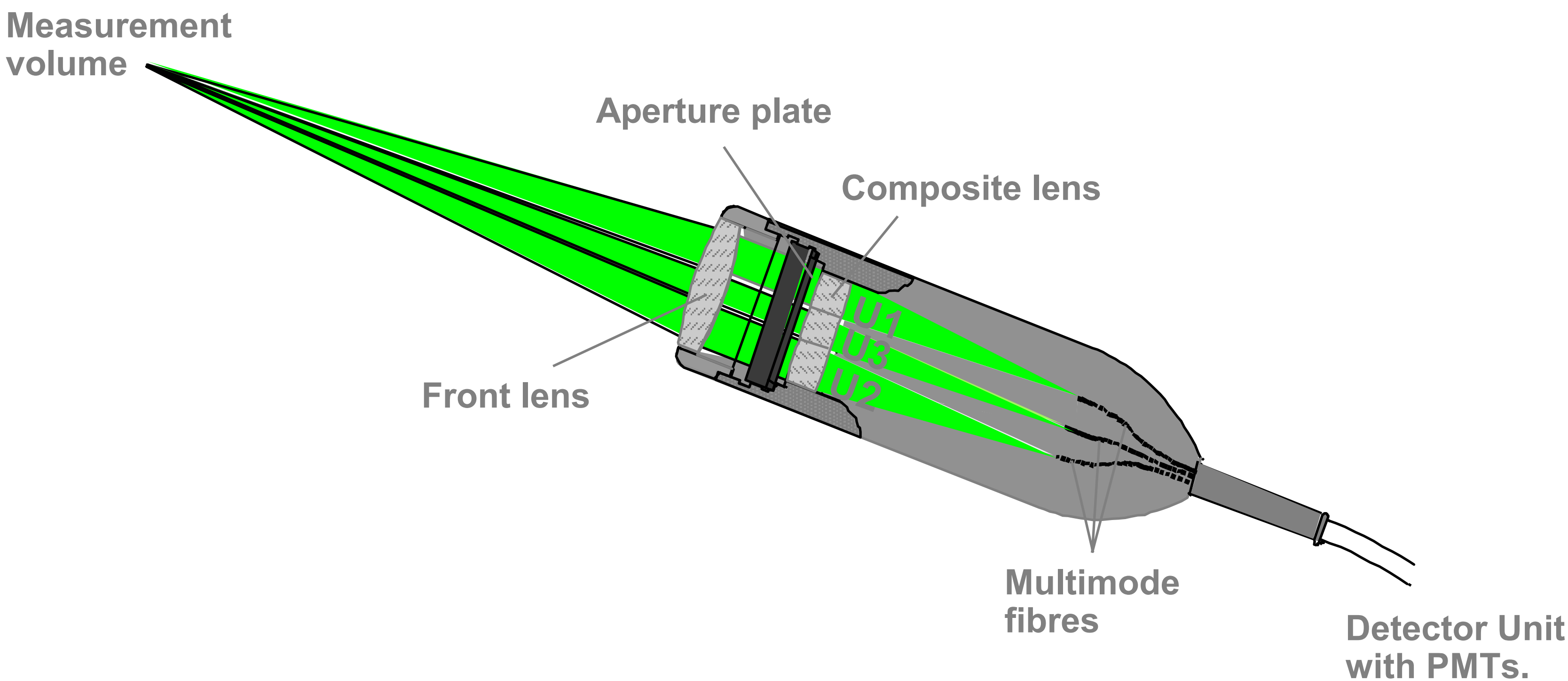
3-detector set-up





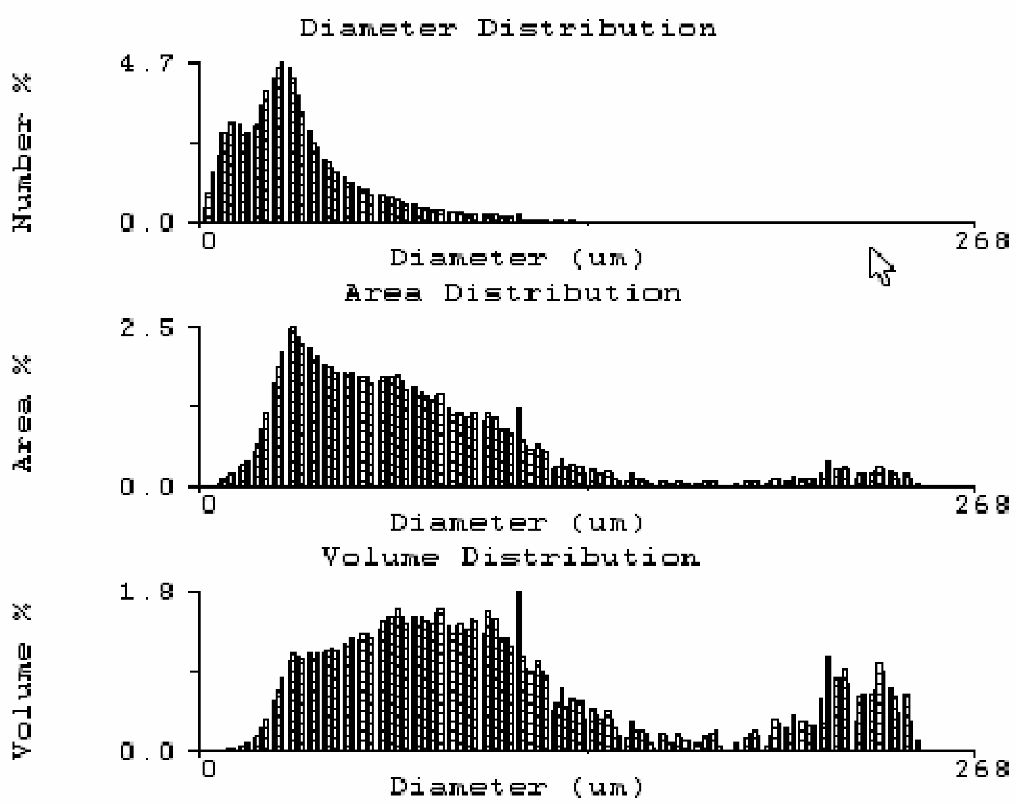
- Overcoming the 2π ambiguity
- Increasing the measurable size range
- Maintaining a high measurement resolution

PDA



- Easy set-up and alignment
- Three receivers in one probe
- Exchangeable aperture masks
- Up to three velocity components

Result display



PDA

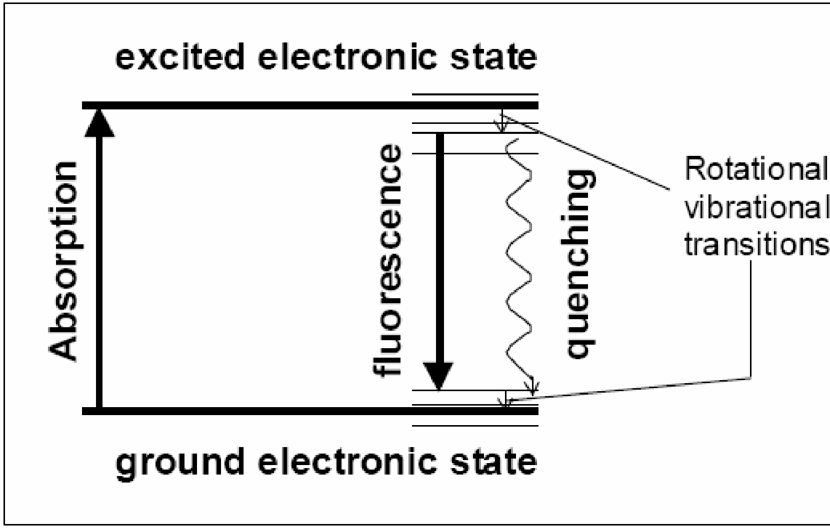
- The temporal modulation is related to the velocity of the droplet, while the spatial frequency is related to the droplet size

LIF for Fuel Concentration

- 2D fuel concentration inside fuel spray or of in-cylinder air/fuel mixture
- Using fluorescence of fuel or fluorescent dopant excited by a laser sheet
- LIF also available for other species concentration (NO, HC, O2…), and also available for in-cylinder temperature
- Specific wavelength laser is required for different measurement

LIF for Fuel Concentration

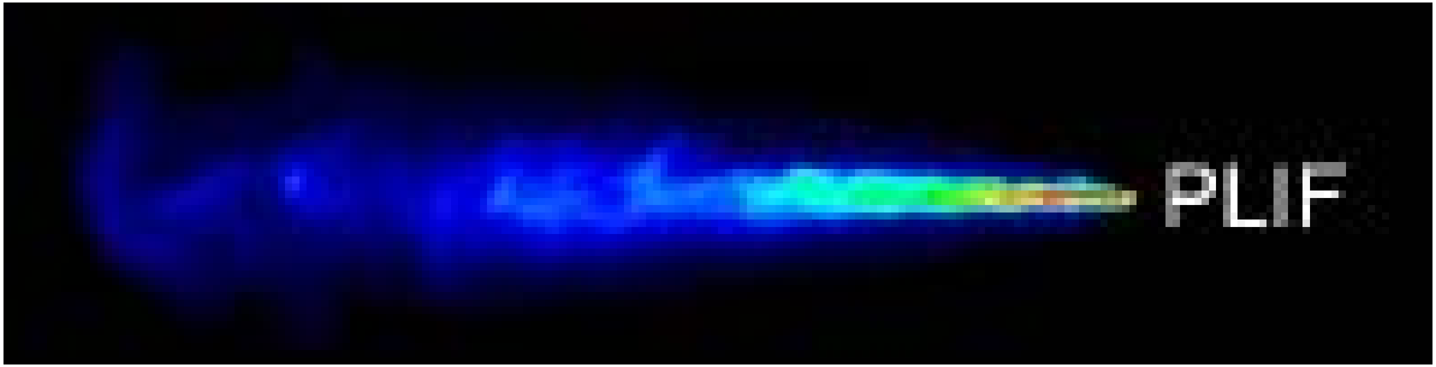
Principle



- The principle of laser-induced fluorescence is to excite a molecule with photons. This raises the molecule from a stable electronic ground state to another short-lived excited electronic state. The molecule can then loose this extra energy by emitting a photon – the fluorescence.
- Since energy is quantised, these emission and absorption phenomena can only occur at given wavelengths. The emission wavelength is usually red-shifted (Stokes shift) compared to the absorption wavelength.
- The number of photons emitted, and hence the fluorescence, is directly proportional to the number of excited molecules, hence to the concentration of the molecule under investigation.

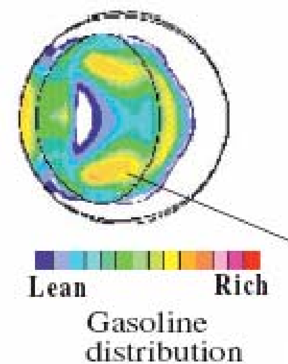
LIF for Fuel Concentration

An example for diesel fuel spray

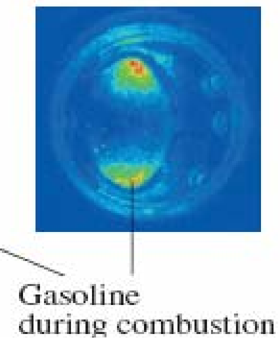


LIF for Fuel Concentration

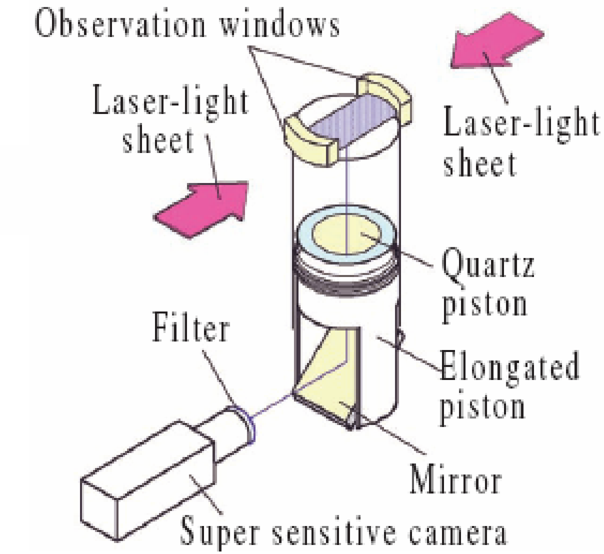
An example in GDI engine

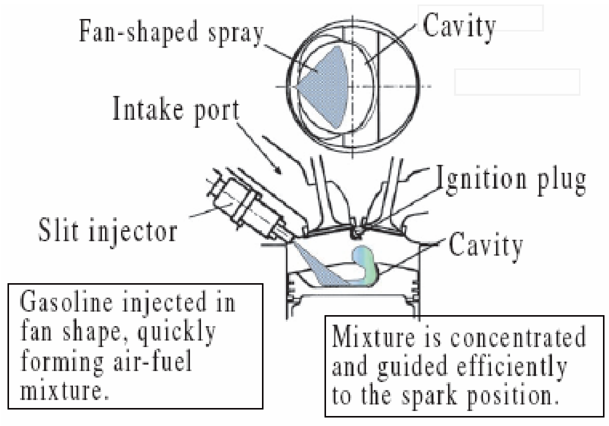


CFD result



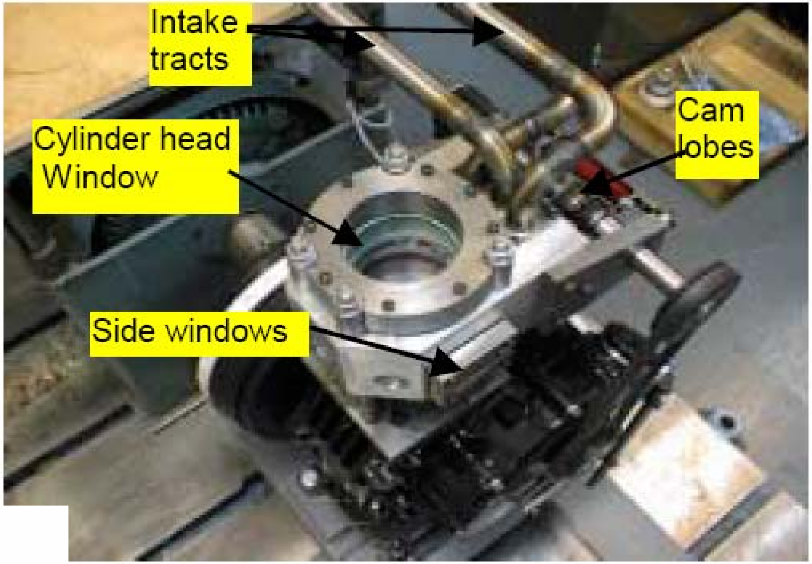
LIF measurement

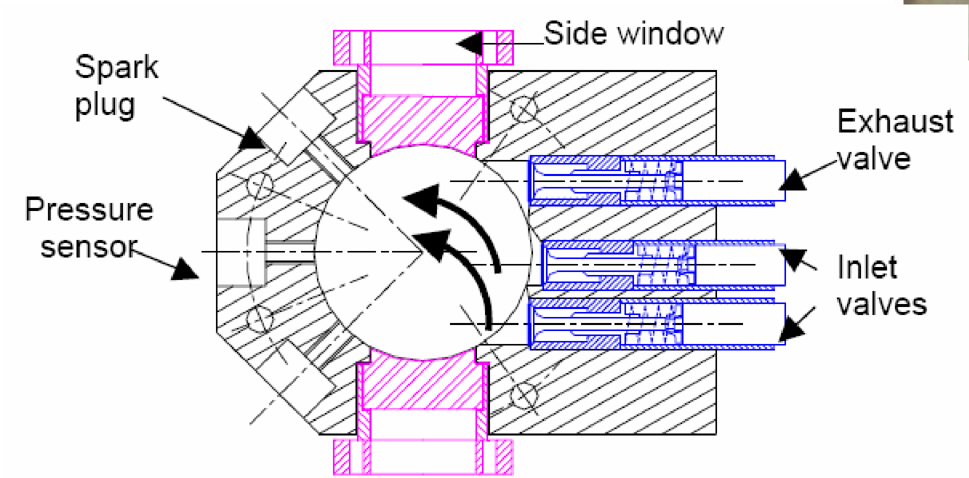




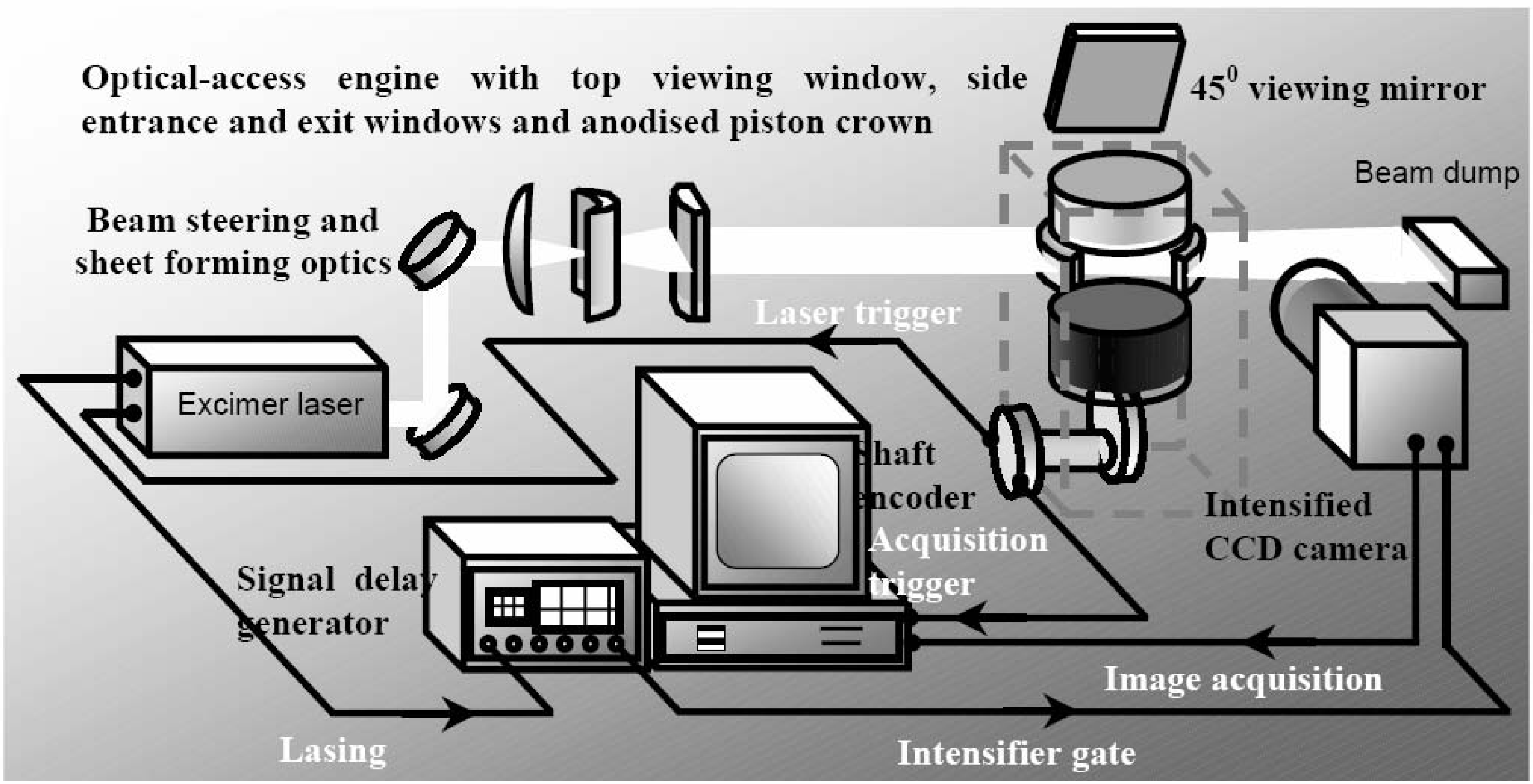
LIF for Fuel Concentration

An example in HCCI combustion





Experimental setup

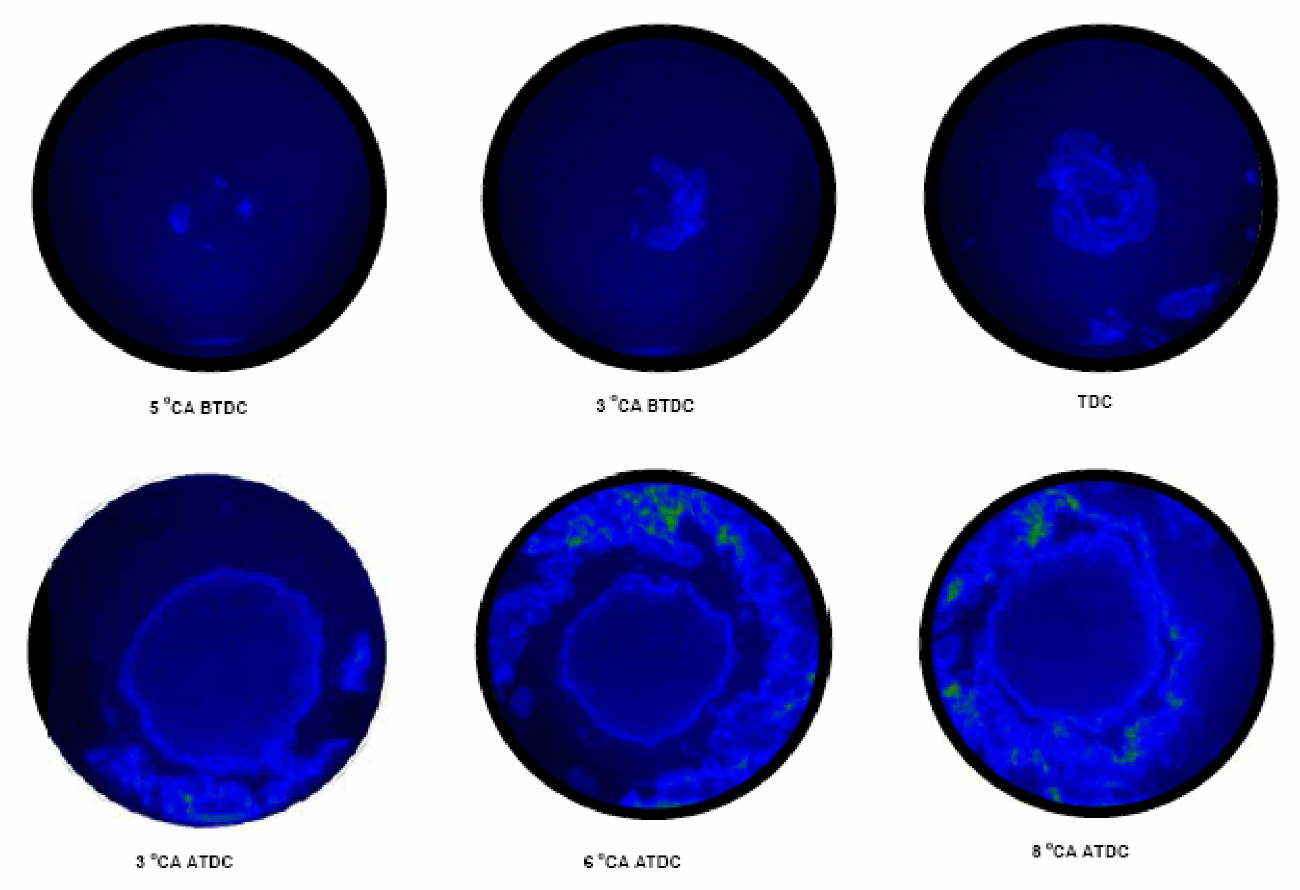


LIF

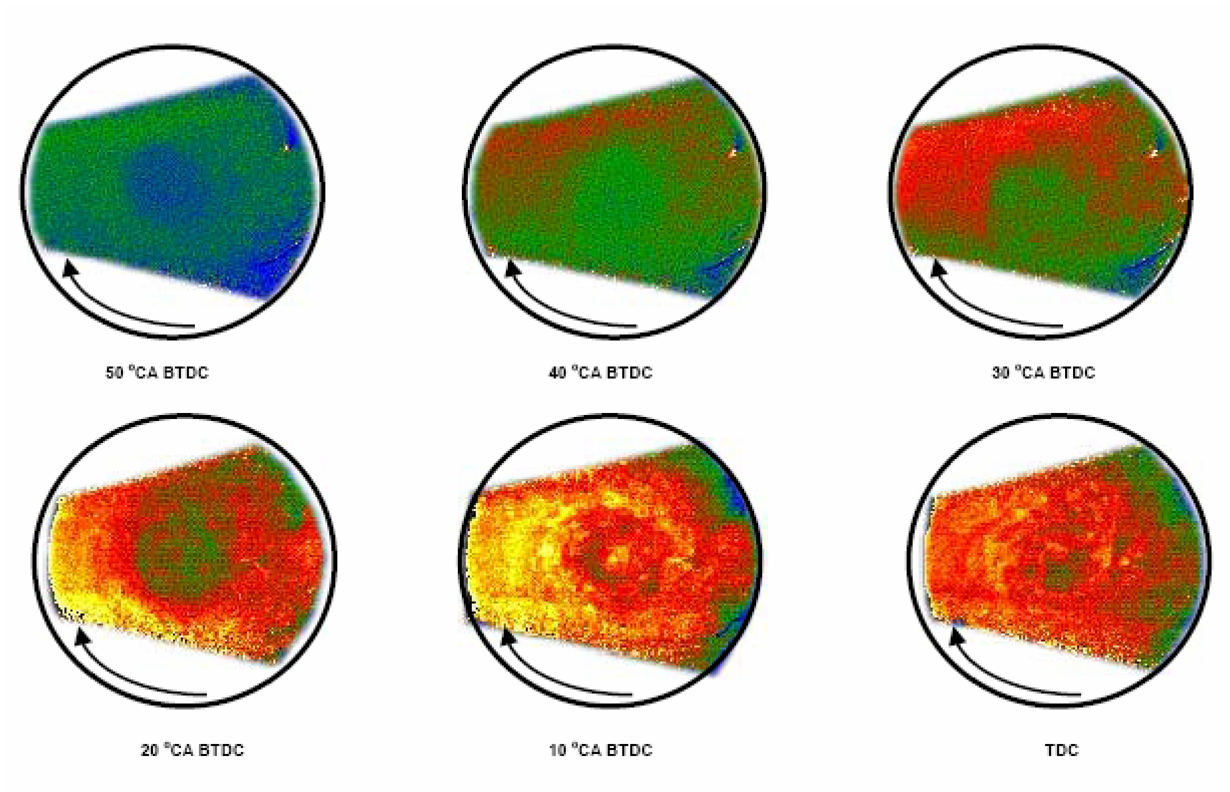
- 3-pentanone (fluorescence dopant) was added to iso-octane fuel and introduced as a premixed charge by means of the PFI injectors.
- A background image was recorded for each PLIF measurement, after the fuel injection had been switched off for a few seconds to allow any remaining fuel in the inlet tract to be completely purged.

LIF

Direct images of auto-ignition combustion

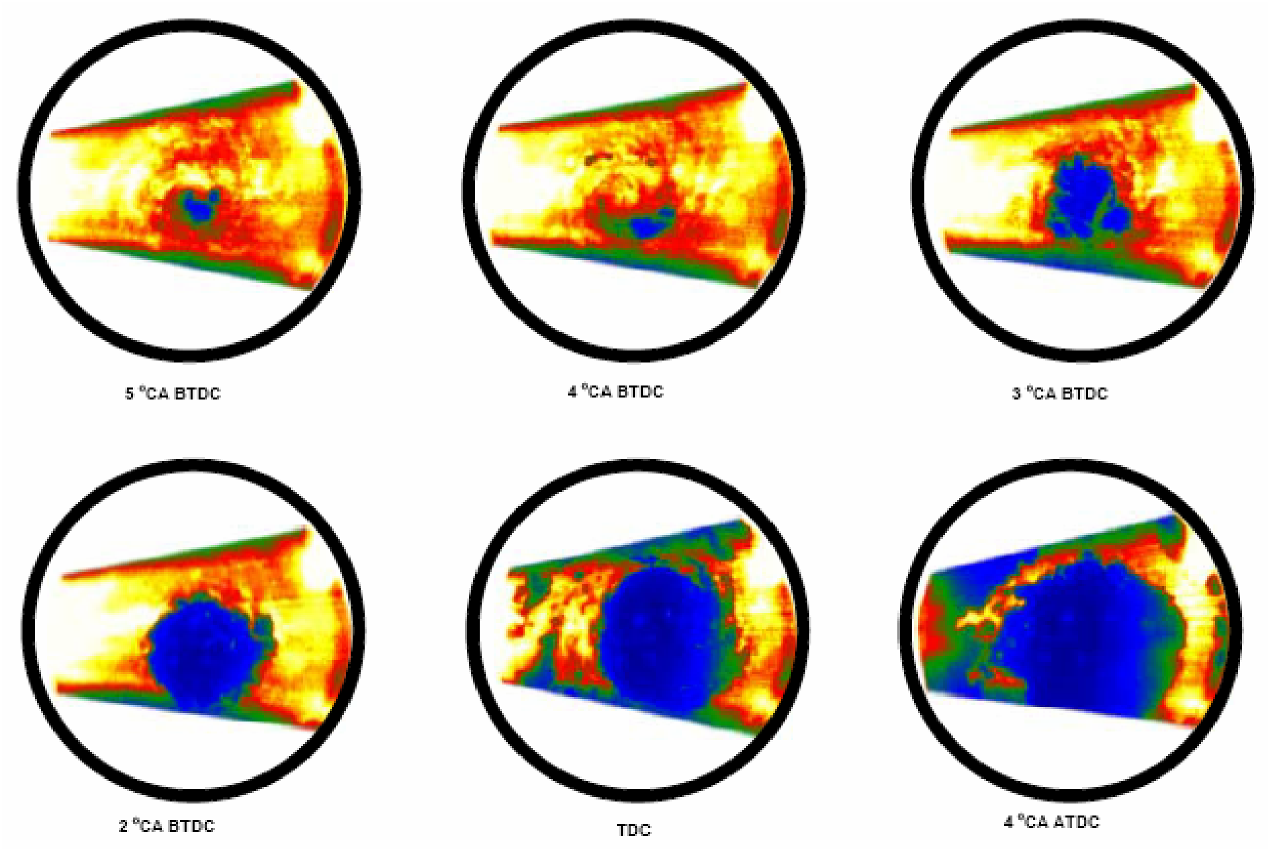


PLIF images of fuel concentration distribution



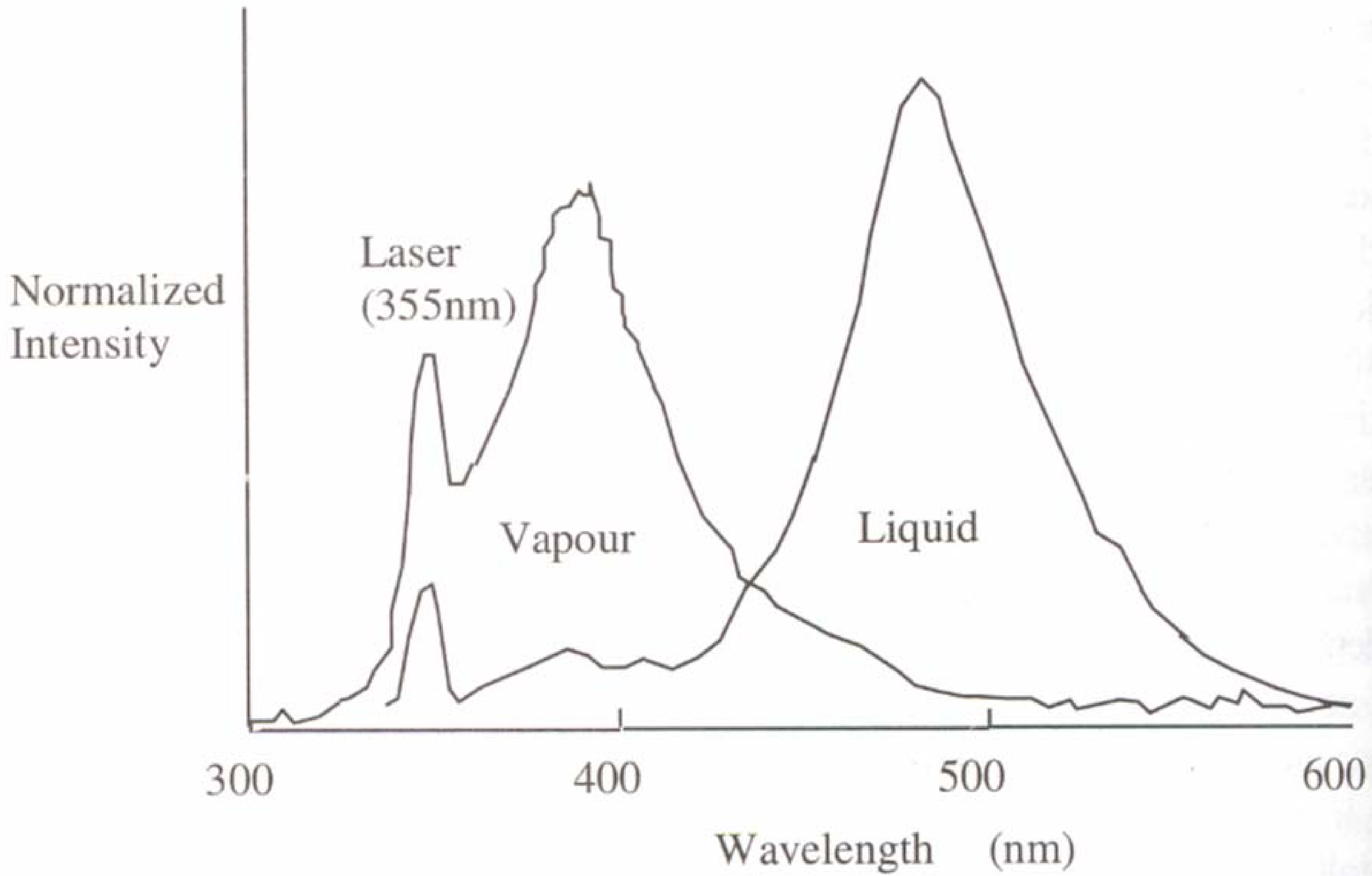
LIF

PLIF images of fuel concentration distribution and auto-ignition combustion



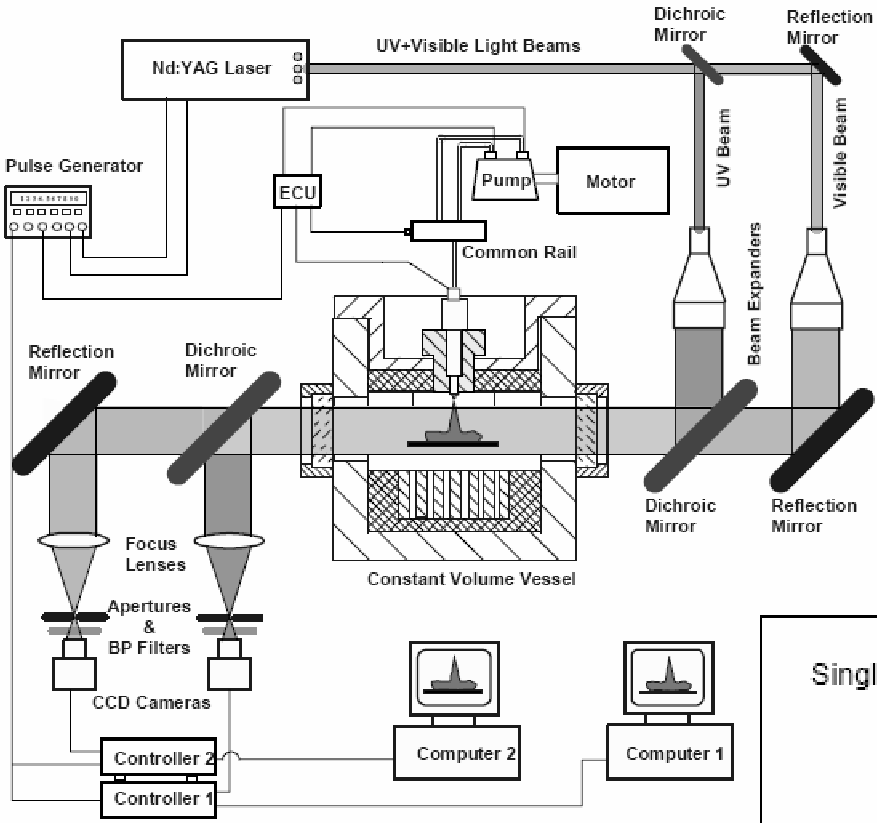
Simultaneous Fuel Vapour and Liquid Fuel Measurement

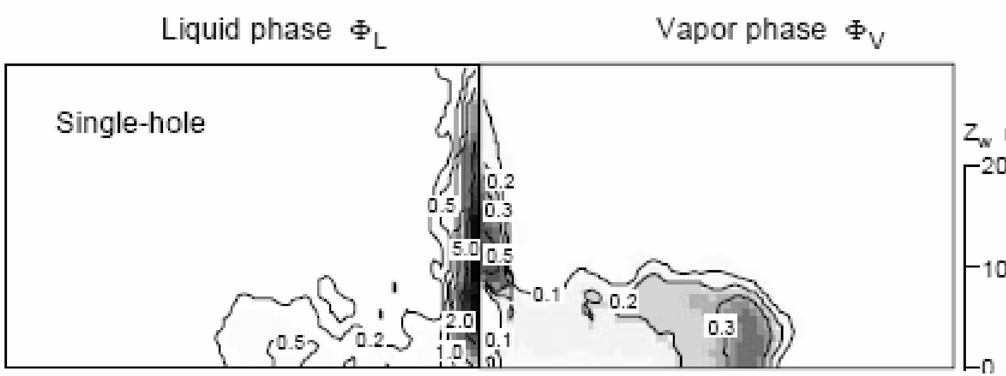
Simultaneous visualization of fuel vapour and liquid fuel by LIEF



LIF for Fuel Concentration

An example for diesel fuel spray

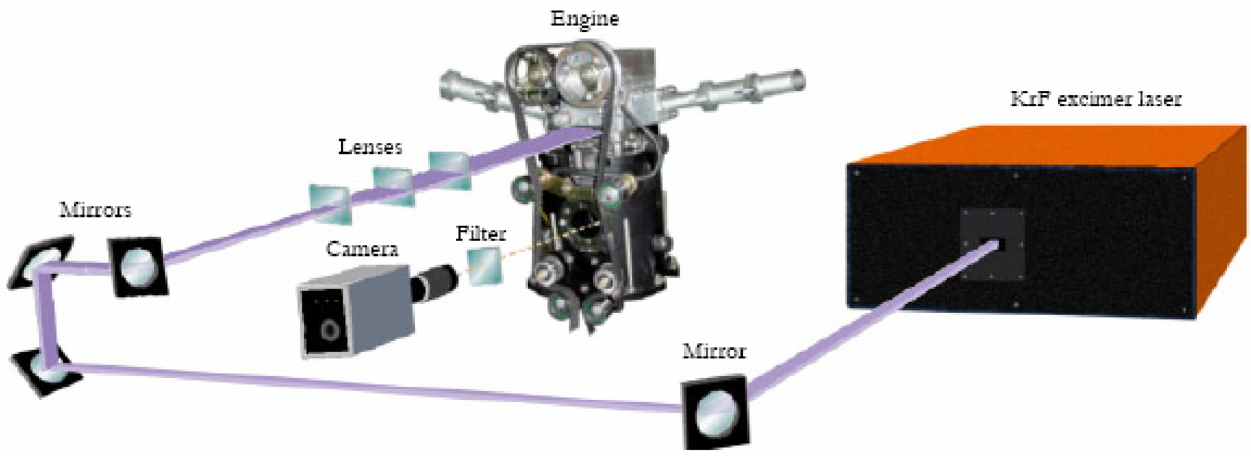




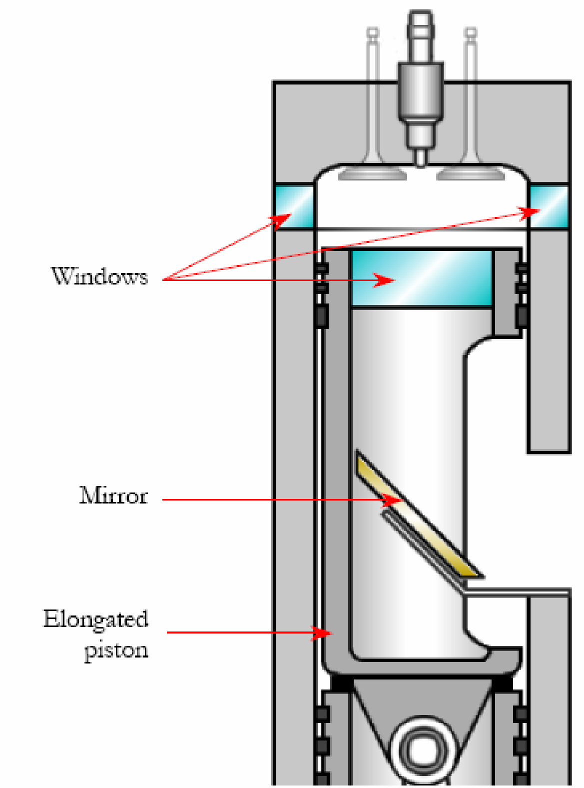
Fuel/Air Ratio by FARLIF

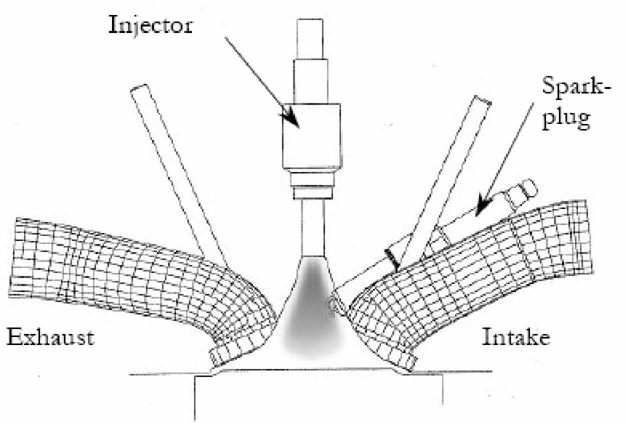
$$LIF\_signal = calibration\_signal \times laser\_intensity \times \frac{fuel\_concentration}{oxygen\_concentration}$$

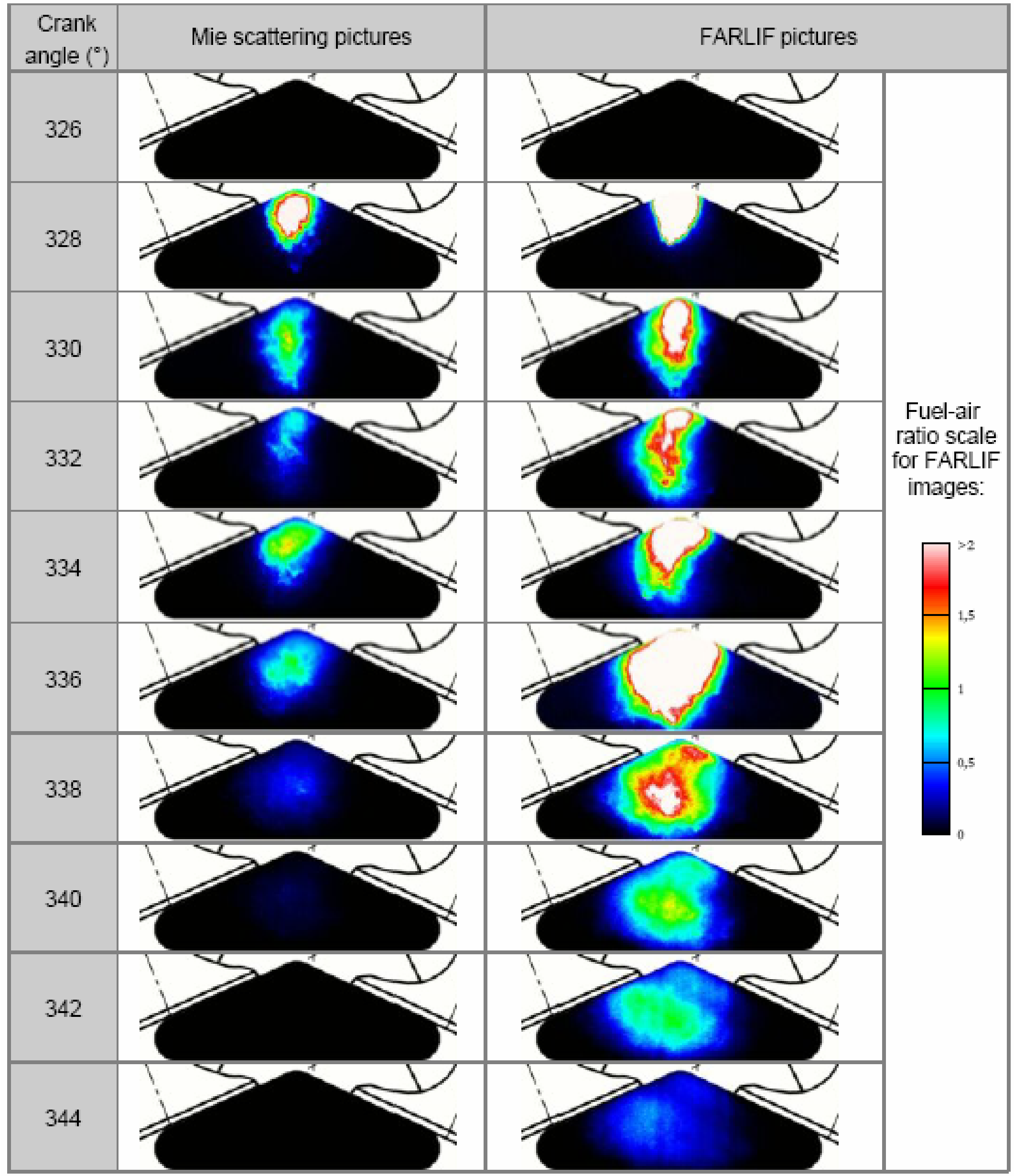
- **Considering the quenching loss of LIF signal by oxygen. This is particularly strong at elevated pressure.**
- **Assuming constant temperature distribution**



Fuel/Air Ratio







Summary

For in-cylinder fuel and mixture measurement

- Some introductions
- Laser droplet sizing by Fraunhofer diffraction method
- Droplet sizing and velocity measurement by PDA
- Fuel concentration by LIF
- Simultaneous fuel vapour and liquid fuel measurement by LIEF
- Fuel/air ratio by LIF

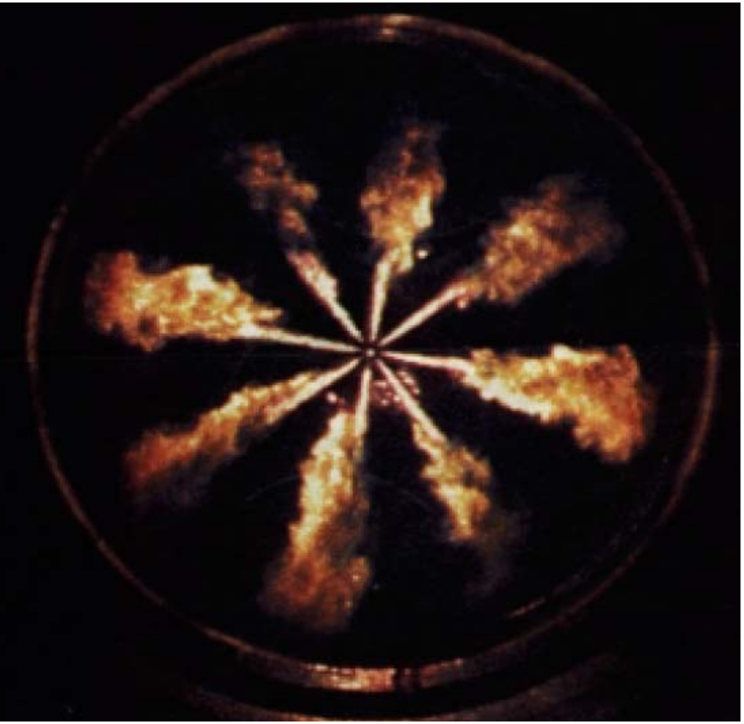
In-cylinder visualization and combustion analysis: during and after combustion

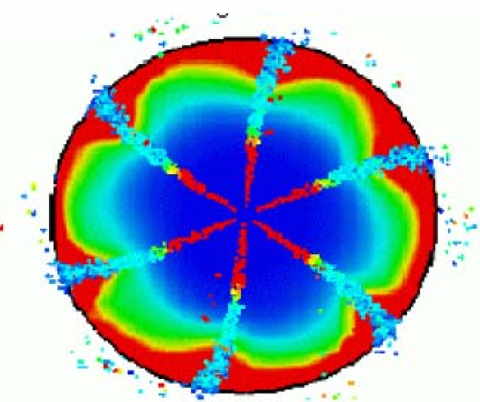
- Introduction
- Combustion and flame visualisation
- Soot measurement (two-colour method)
- Combustion T measurement (PLIF and CARS)
- Visualisation of combustion species
- Summary

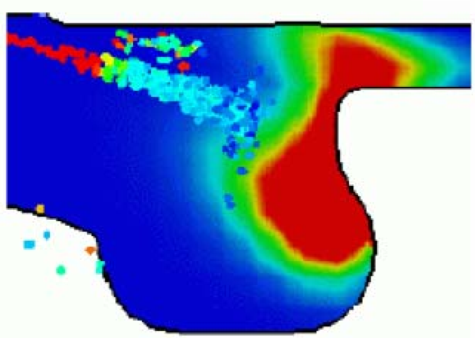
Combustion Visualization

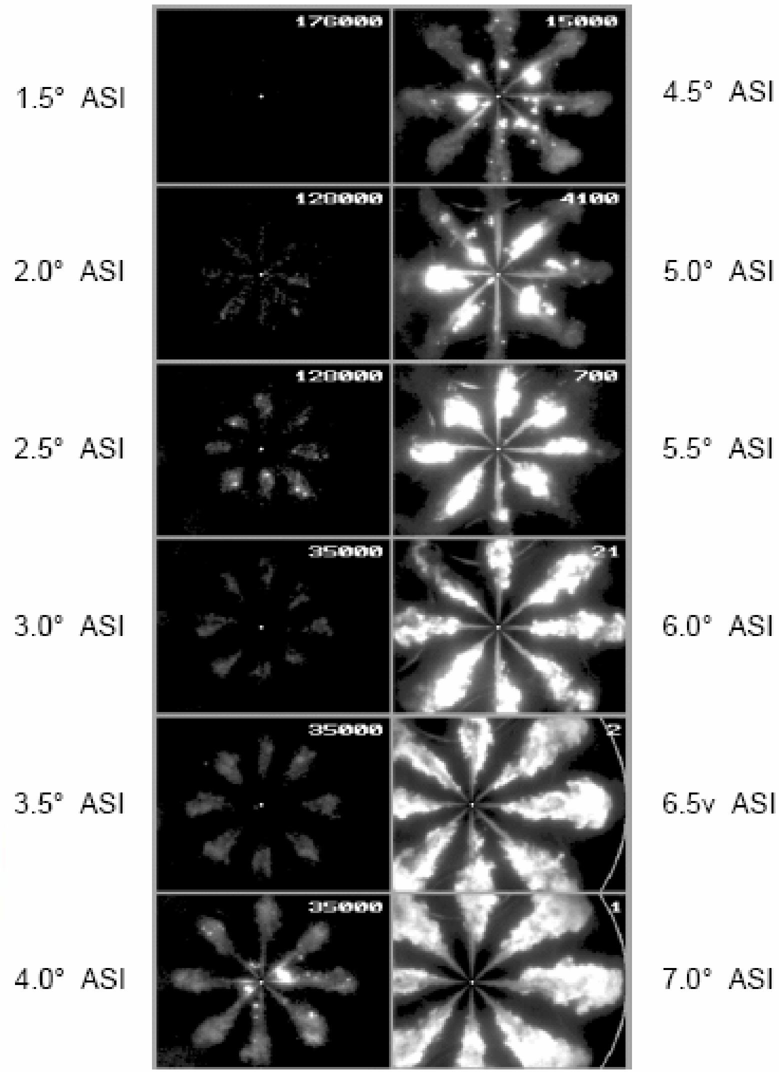
- Direct visualization of combustion and flame propagation if the flame is luminous.
- To observe those non-luminous events (spray, flow field), schlieren/shadowgraph can be used (for density changes) with a high-intensity lamp or a laser as the light source
- High-speed camera (recent year, high-speed video camera, up 20,000 frame/s)
- Optical access is needed on the test engine.

Combustion Visualization



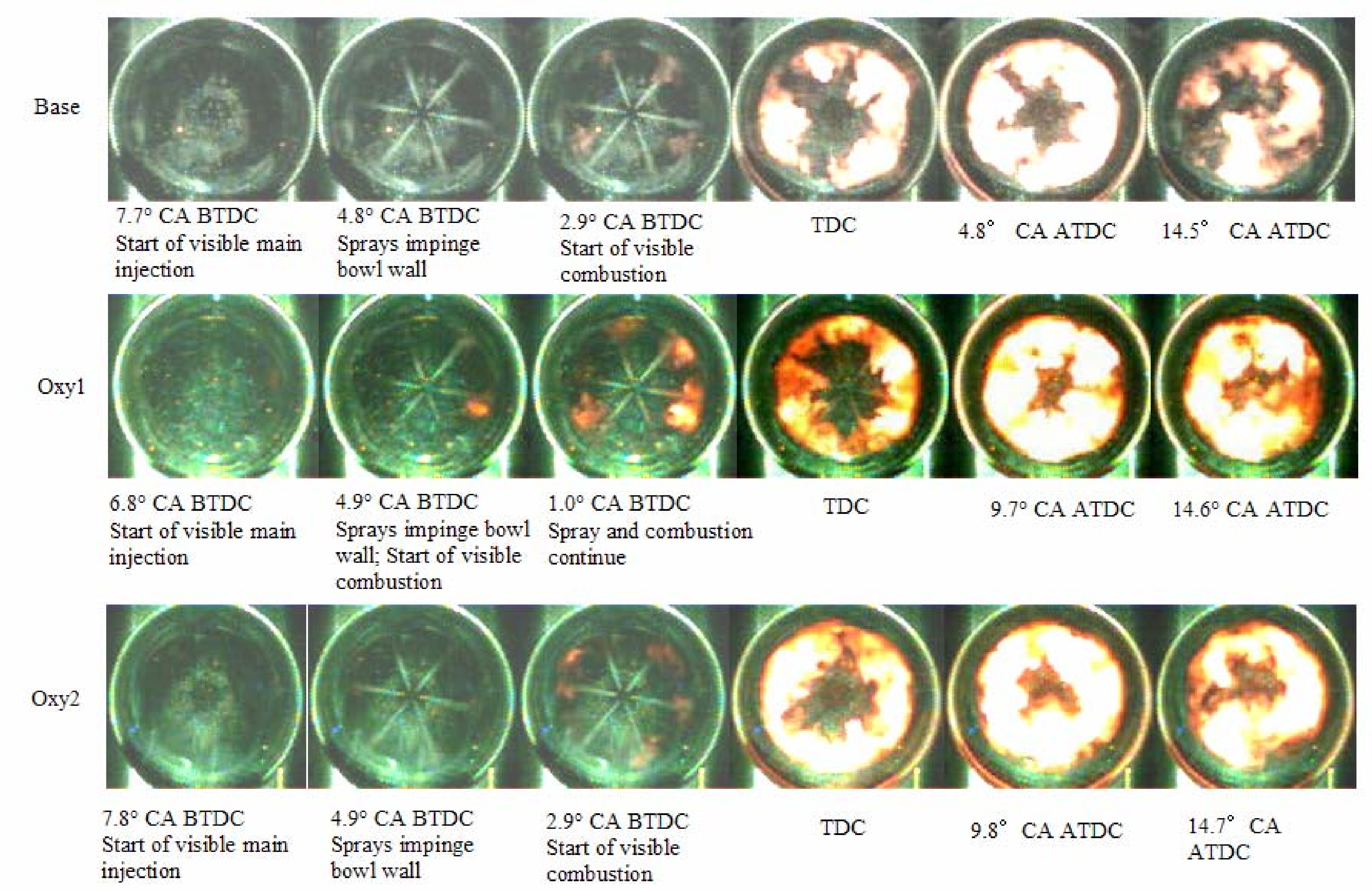






Combustion Visualization

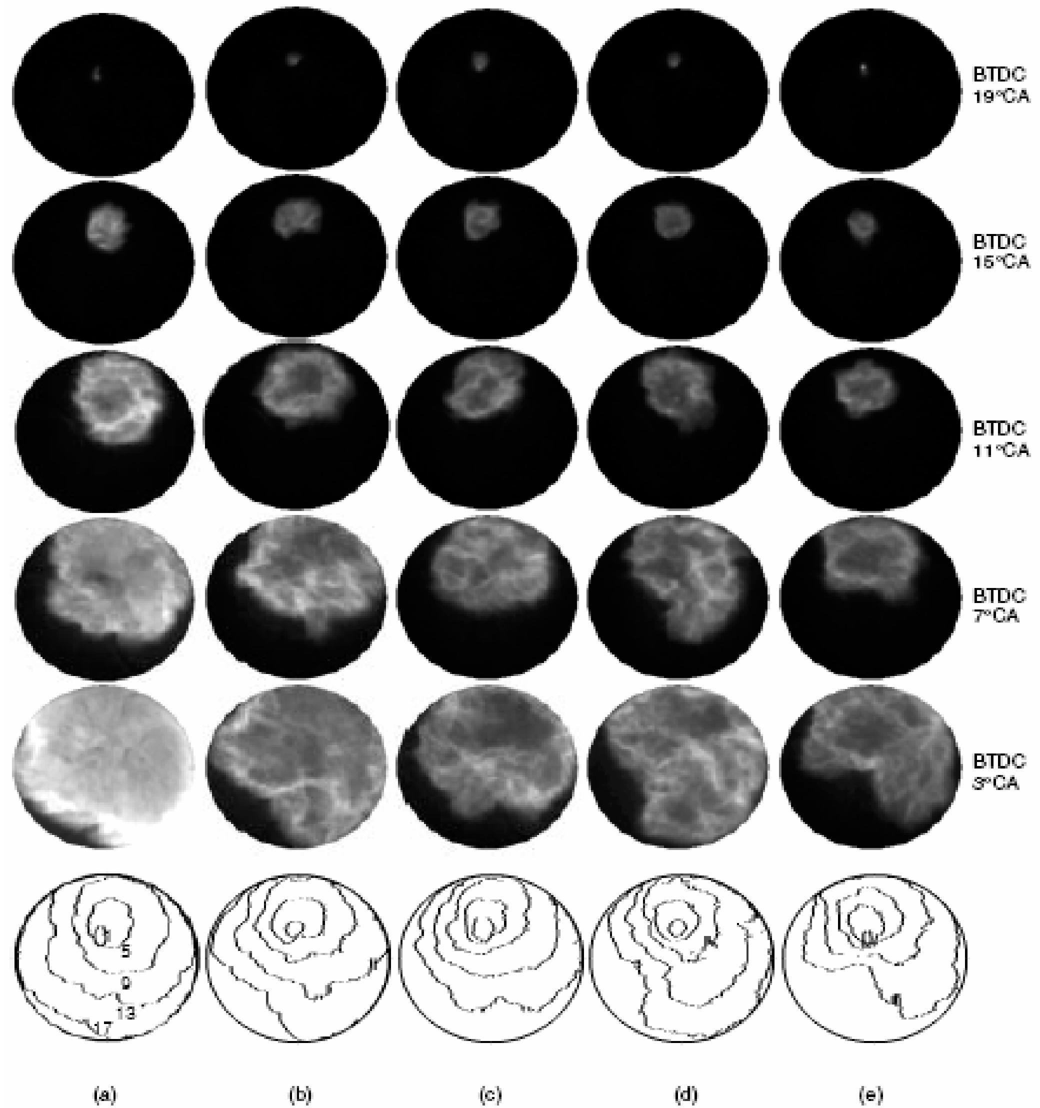
An example of diesel combustion: effect of fuel with swirl



High-speed camera with high frequency laser

Combustion Visualization

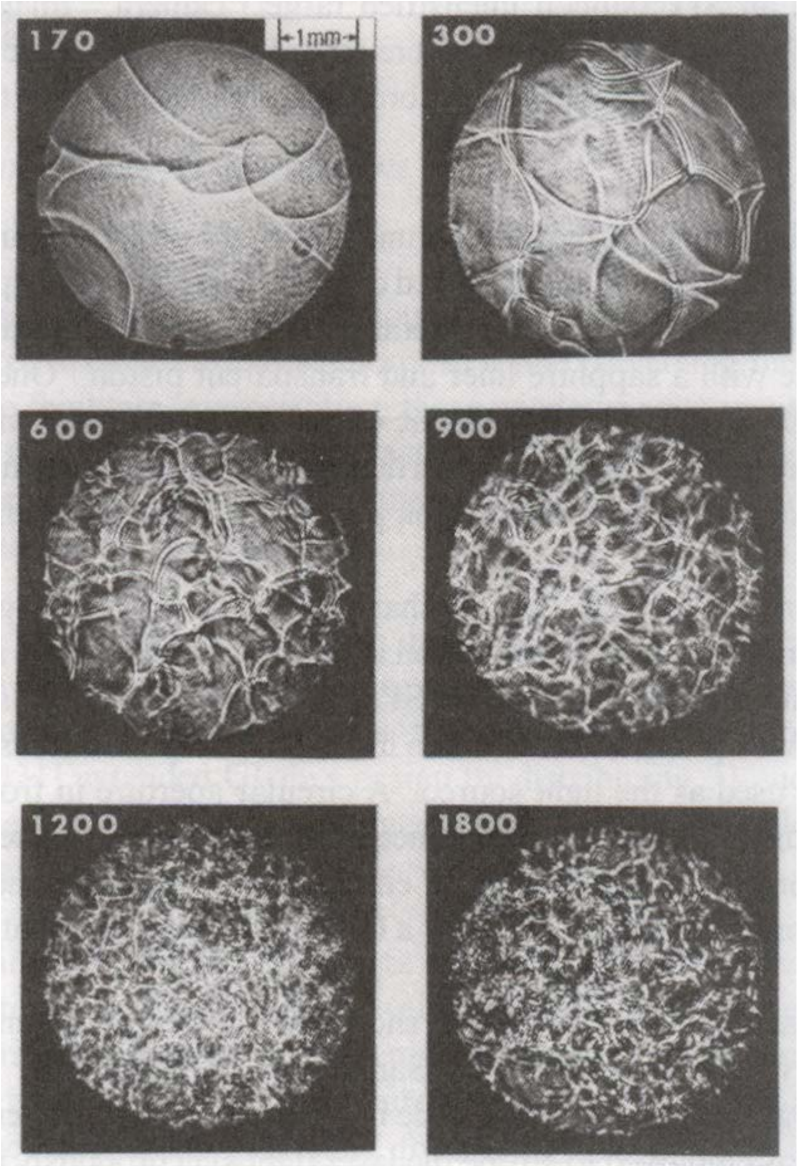
An example of SI engine combustion: Effect of EGR on flame propagation



Typical flame propagation patterns in case of (a) without EGR, (b)EGR#1, (c)EGR#2, (d)EGR#3, (e) EGR#4 (number : crank angle after ignition (°CA))

Combustion Visualization

An example of SI engine combustion: flame surface under different engine speed



Shadowgraph of flames propagating toward the viewer at different engine speed [Smith, 1982)

Two-Colour Method

- The intensity of soot emission, ESl, at wavelength λ is expressed by the relation

$$E_{S\lambda} = \tau * I_{BB}(T,\lambda) * \varepsilon(\lambda, fv)$$

where

- τ is the transmission of the optical system
- I_{BB} is the energy spectral density of a black body, depending on the temperature
- ε is the soot emission coefficient depending on the soot volume fraction fv, and the wavelength

- For the determination of fv is therefore necessary to determine the soot temperature. This can be accomplished by ratioing the emission intensities at two wavelengths, λ_1 and λ_2, and by comparison with a calibrated lamp.

Two-Colour Method

- The soot temperature T_S:

$$T_S = -c_2\left(\frac{1}{\lambda_1}-\frac{1}{\lambda_2}\right)\left[ln\left(\frac{E_{S\lambda 1}}{E_{S\lambda 2}}\frac{E_{L\lambda 2}}{E_{L\lambda 1}}\frac{\varepsilon_L(\lambda_1,T_L)}{\varepsilon_L(\lambda_2,T_L)}\frac{l_{abs1}}{l_{abs2}}\right)+\frac{c_2}{T_L}\left(\frac{1}{\lambda_2}-\frac{1}{\lambda_1}\right)\right]^{-1}$$

where

- S and L stand for soot and lamp, respectively
- c_2 is the second Plank constant
- labs1-2 are the natural length for absorption at wavelength 1 and 2, depending on the refractive index of soot

Two-Colour Method

- The soot volume fraction is then given by the relationship:

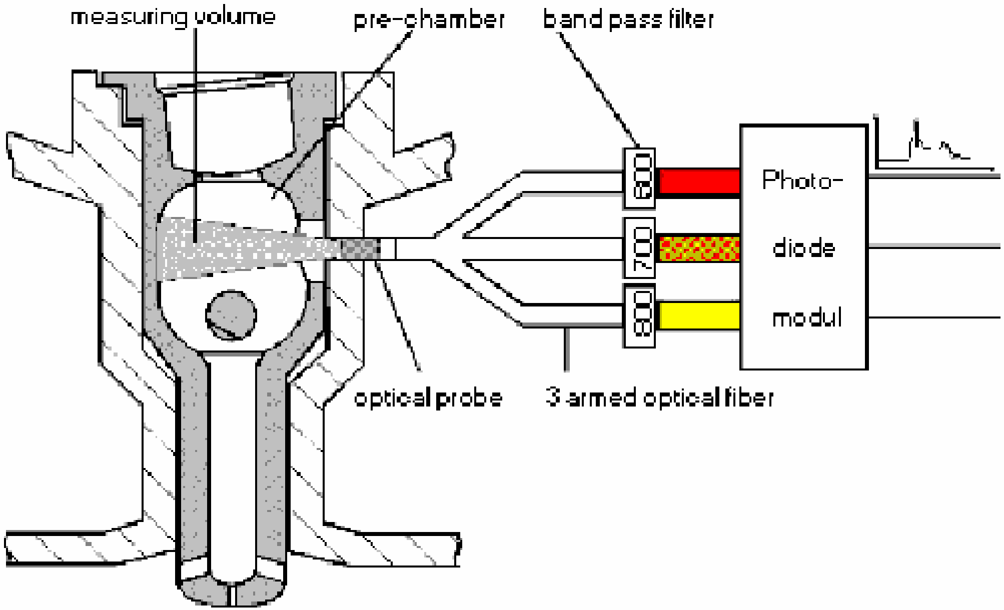
$$fv = -\frac{l_{abs}}{L} ln\left(1 - \varepsilon_L(\lambda, T_L) \frac{\gamma_S}{\gamma_L} \frac{E_S(\lambda)}{E_L(\lambda)} exp\left(-\frac{c_2}{\lambda}\left(\frac{1}{T_L} - \frac{1}{T_S} \right)\right)\right)$$

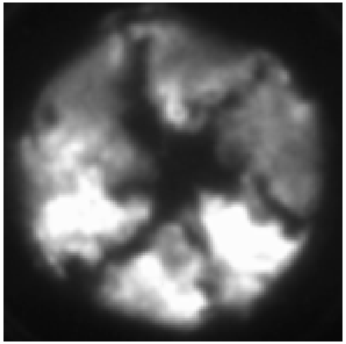
where

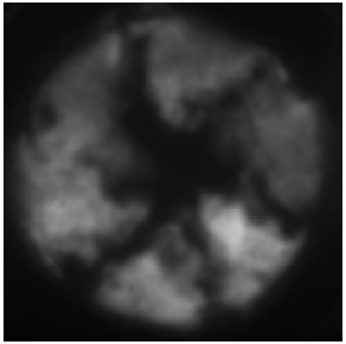
- L is the optical pathlength and the ratio of the g's takes into account possible differences in the optical transmission and detector gain utilized for measuring the soot and the lamp emissions.
- The measurements obtained are, in general, averaged over the optical thickness of the soot layer, as well as for the laser extinction technique.
- However in the case of axial-symmetric flames it is possible to calculate the soot volume fraction and temperature through an Abel inversion procedure of laterally acquired measurements of the soot emission.

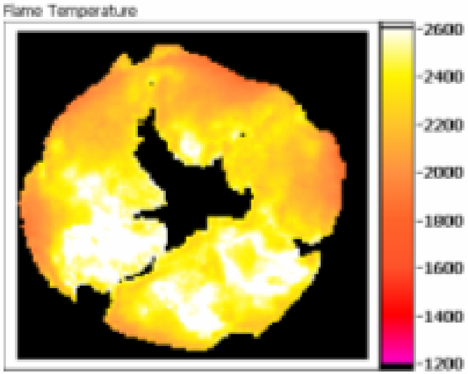
Two-Colour Method

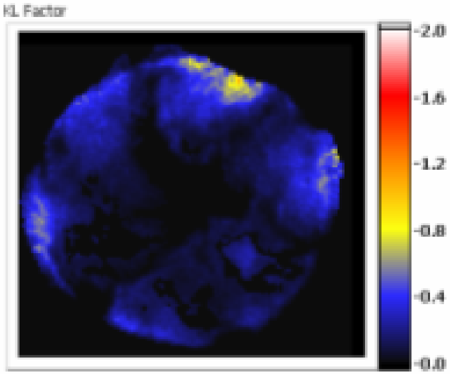
Two-colour measurement











In-Cylinder Combustion T Measurement

- Compared to pressure, the heat transfer is so slow, so the T distribution in the cylinder is always not uniform once the combustion starts. (sharp T gradient between burned and unburned gases)
- The effect of T on NO is significant. (1700K)
- Using in-cylinder pressure traces, the average in-cylinder temperature can be estimated. But it will give a significant error for NO formation information with this estimated average temperature.
- Thermocouples lack the necessary time response, it can not be used for in-cylinder temperature measurement.

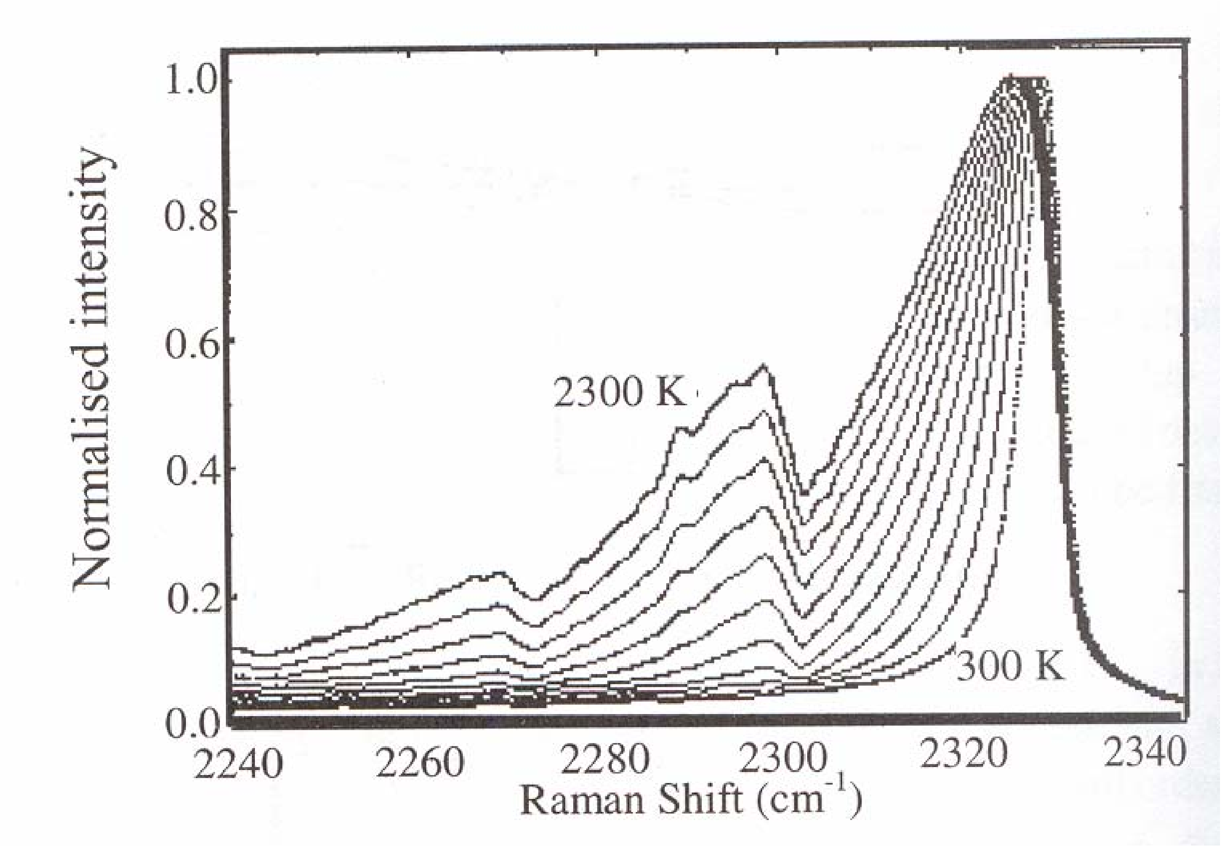
In-Cylinder Combustion T Measurement

Methods

- Velocity-of-sound method
- Spontaneous Raman Scattering (SRS)
- Laser Rayleigh Scattering
- CARS (Coherent Anti-stokes Raman Scattering)
- 2D PLIF

In-Cylinder Combustion T Measurement

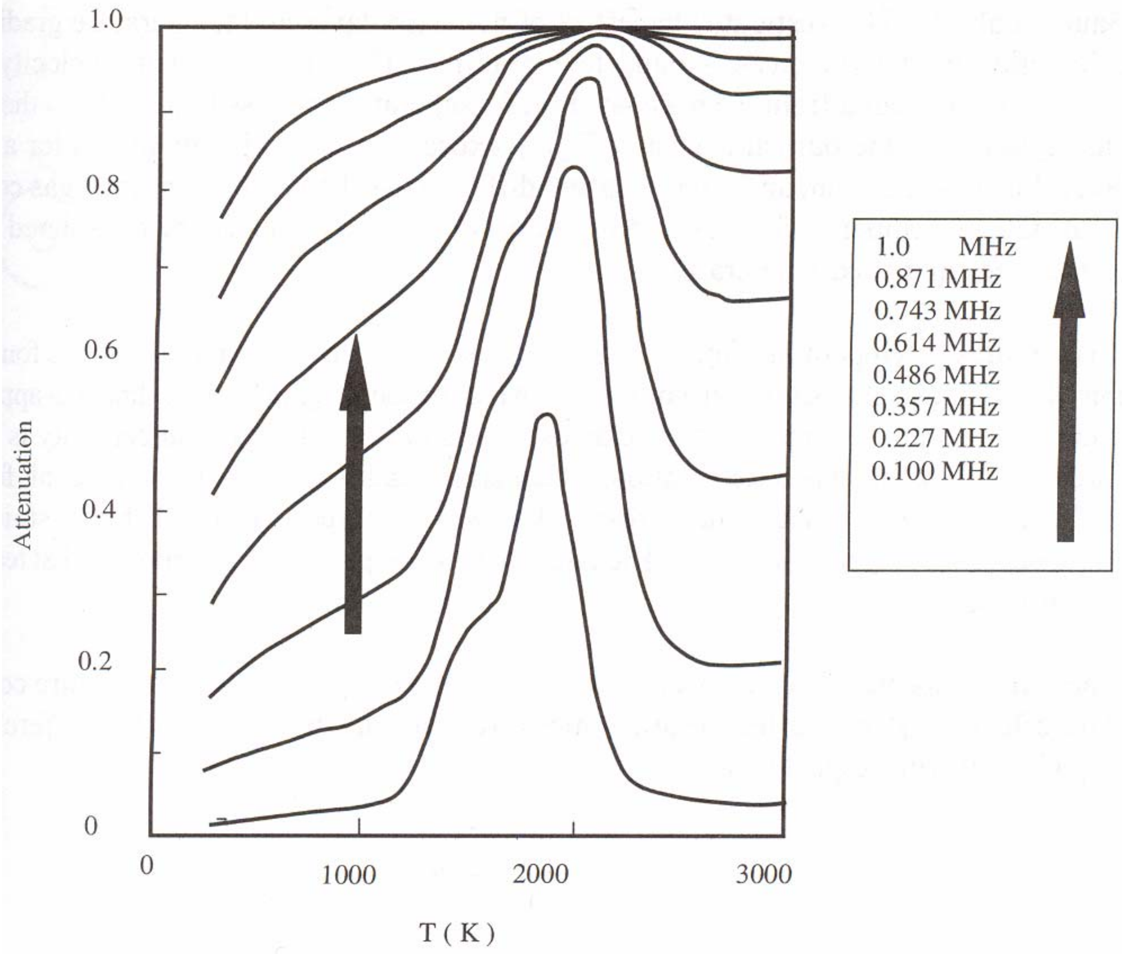
Various laser methods



In-Cylinder Combustion T Measurement

Velocity-of-sound method

$$c = \sqrt{\gamma RT}$$



In-Cylinder Combustion T Measurement

Velocity-of-sound method

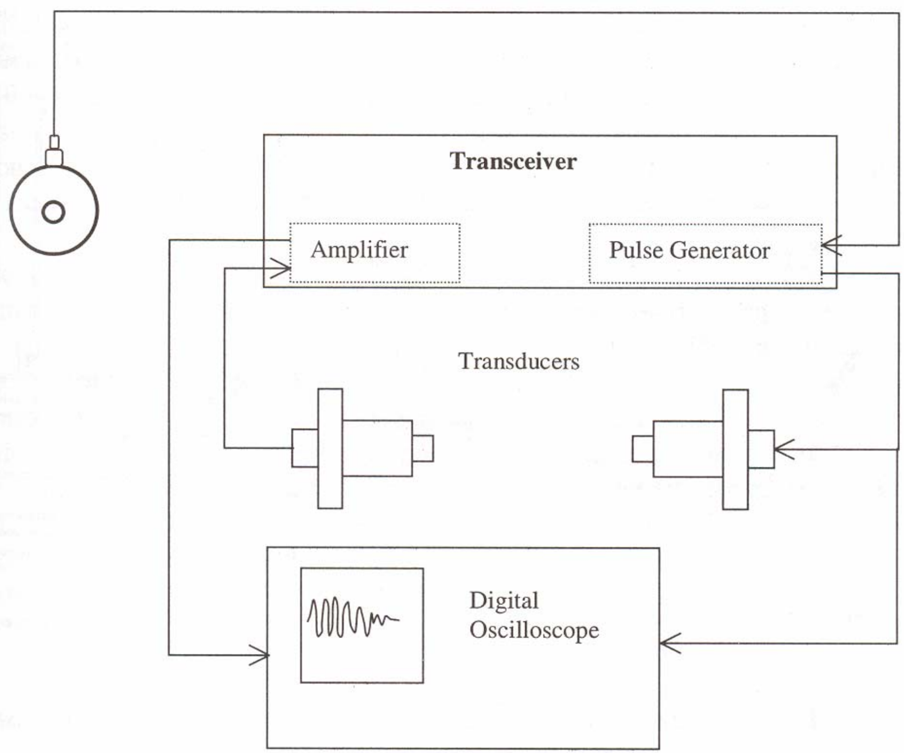


Fig. 12.7 Block diagram of a velocity-of-sound system.

Visualization of Combustion Species

- Before and after ignition, how about EGR rate in the cylinder? after combustion how those reactions take place?
- Reasonable combustion speed: pressure increase rate, combustion temperature for emissions
- To avoid knocking combustion

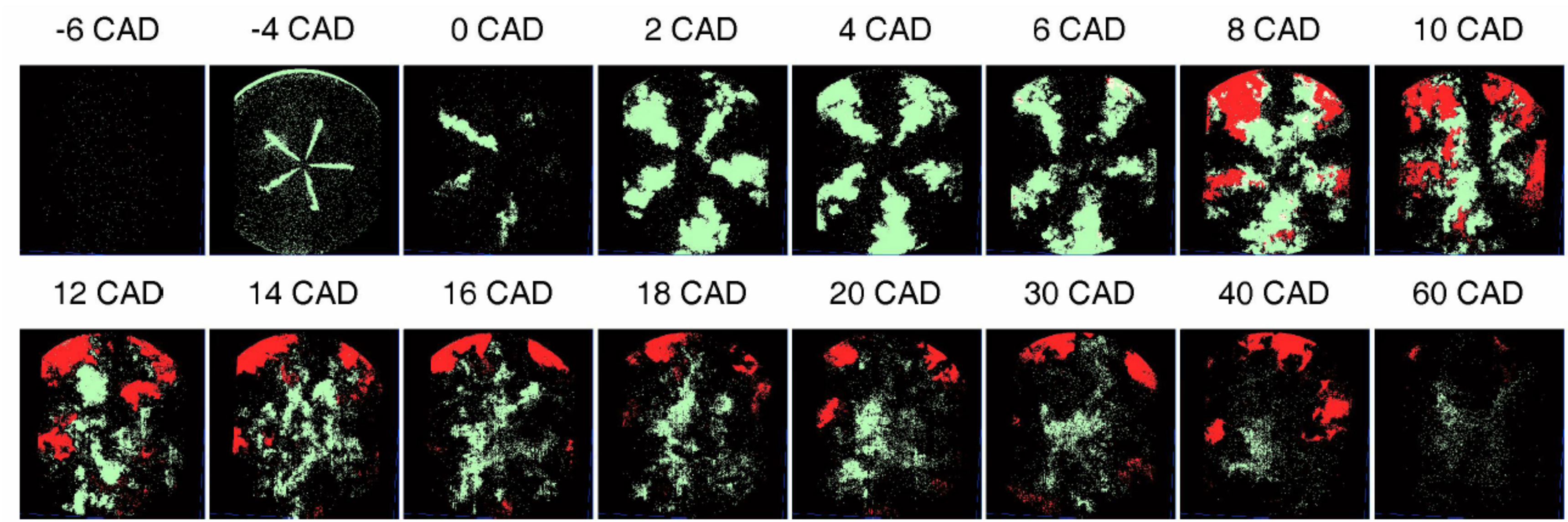
Visualization of Combustion Species

Methods

- Fast FID (HC, residual gas rate)
- Sampling techniques
- Various LIF for combustion species (OH, NO, O_2, CH_2O…)

Visualization of Combustion Species

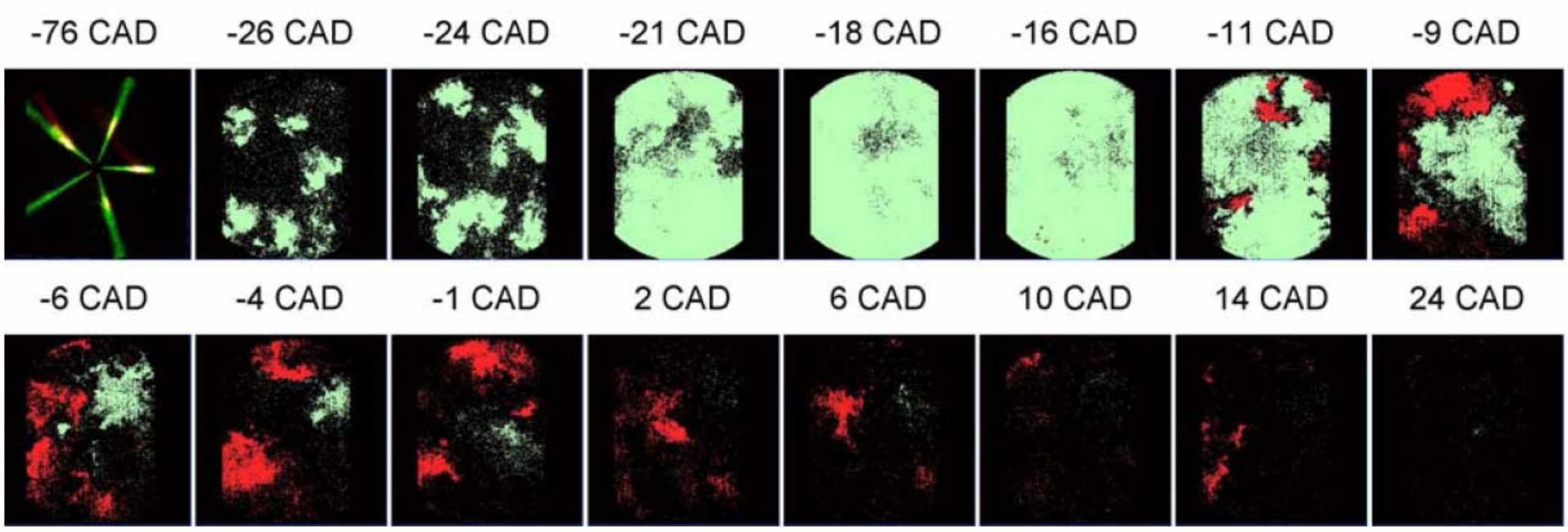
CH_2O and OH in diesel combustion



Single-shot images of formaldehyde and OH

Visualization of Combustion Species

CH_2O and OH in HCCI combustion



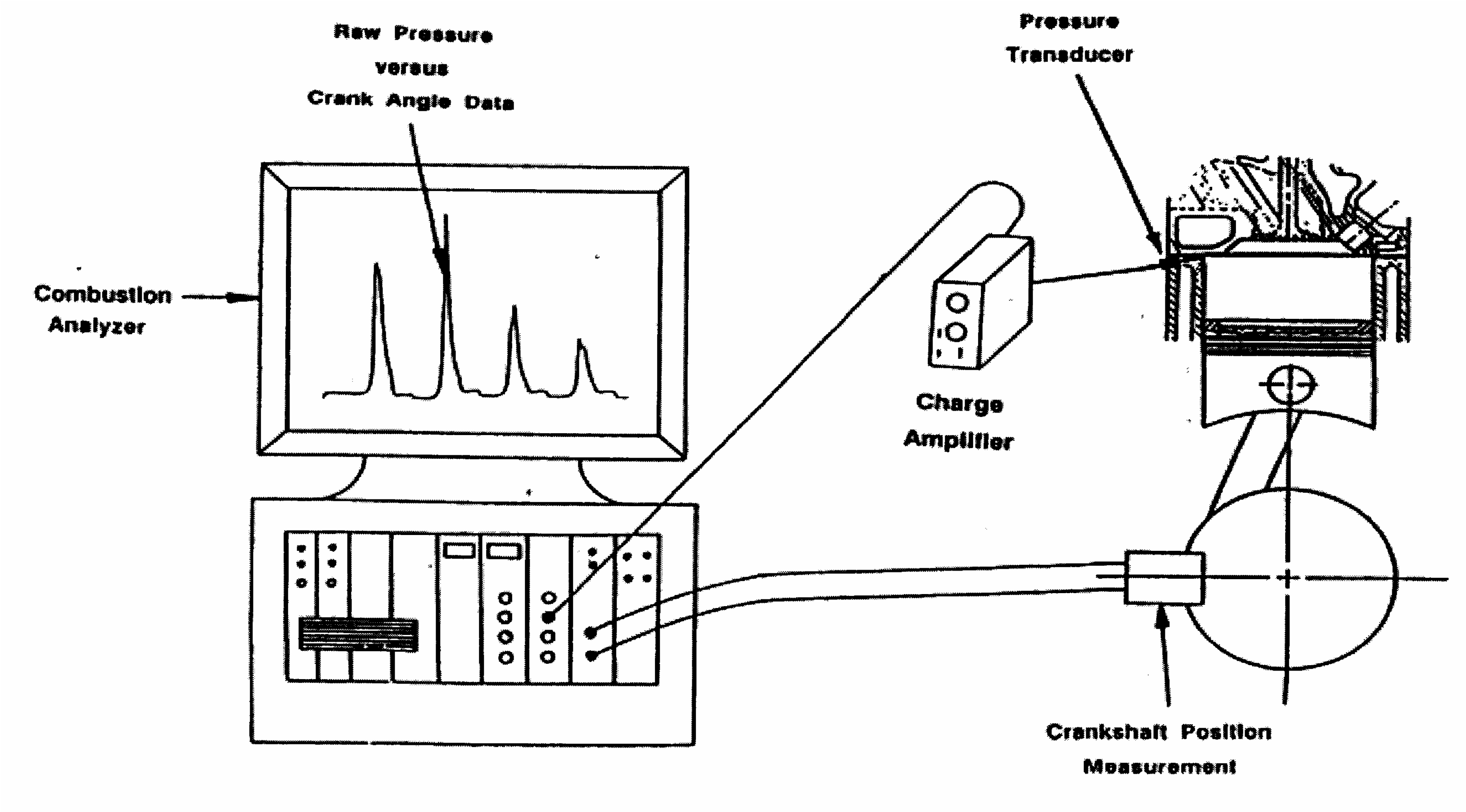
Single-shot images of formaldehyde and OH PLIF

Cylinder Pressure Measurement

Hardware

- Calibrated Transducer
- High Impedance Cable
- Charge Amplifier
- Encoder
- Digitiser

Cylinder Pressure Measurement



Cylinder Pressure Hardware

Piezoelectric Pressure Transducers

Pros

- High temperature and pressure capability
- Fast response

Cons

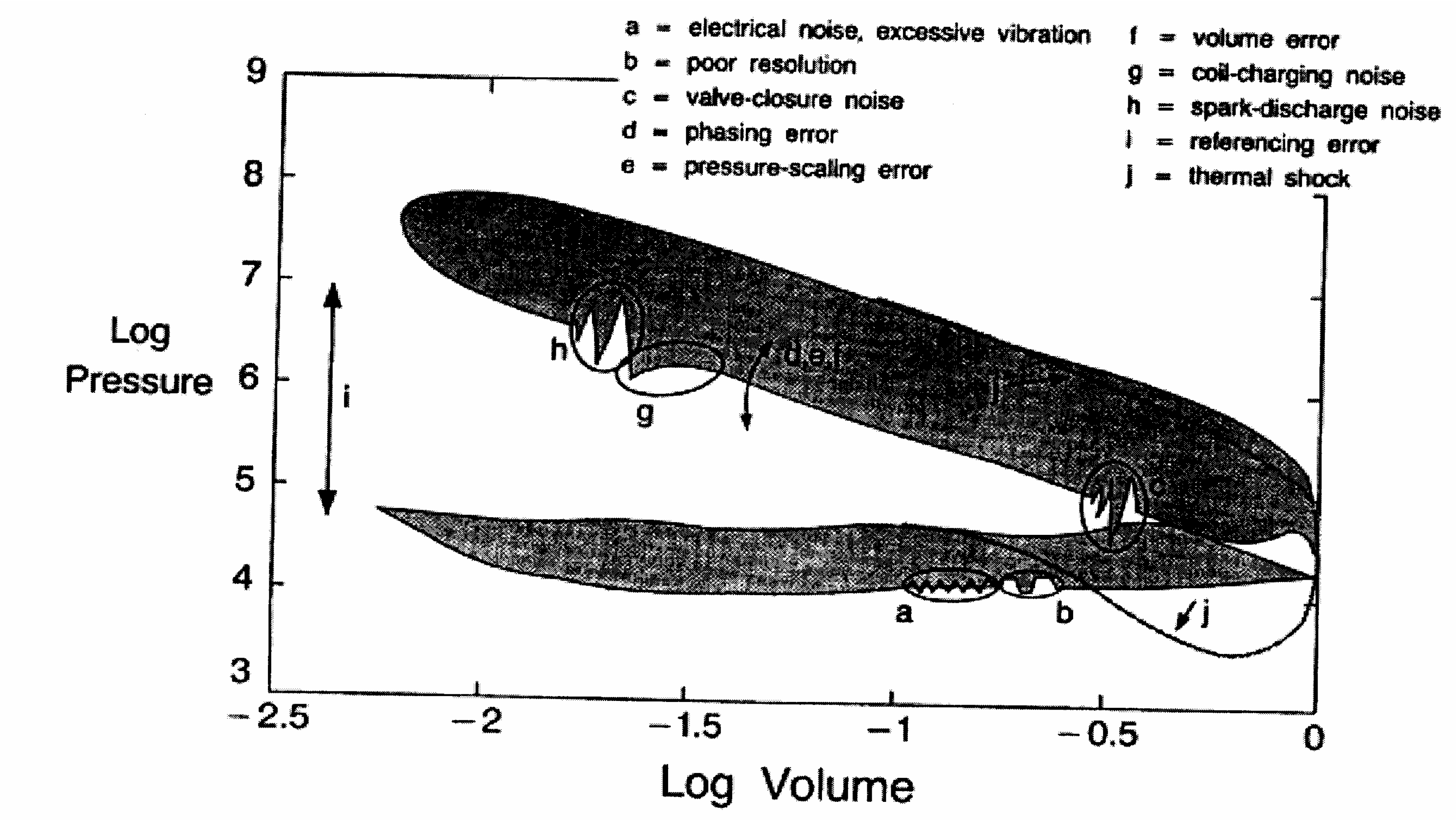
- Expensive
- Only good for fast,transient phenomena
- Output is not absolute– must be ‘pegged’

Cylinder Pressure Hardware

Problems with Piezoelectric Devices

- Sensitivity to electrical and mechanical noise
- Sensitivity to mechanical stress
- Poor calibration
- Moisture in connections
- Carbon accumulation on transducer diaphragm
- Inaccurate referencing
- Thermal shock

Cylinder Pressure Hardware



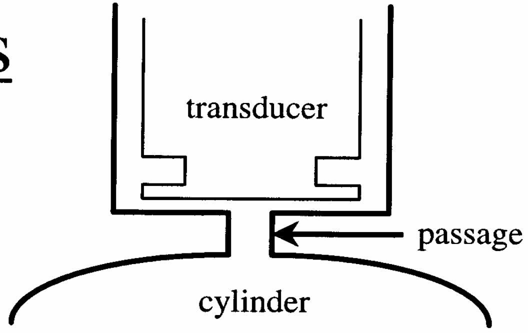
Cylinder Pressure Hardware

Mounting Considerations

- **Mounting:** flush mounting avoids resonance issues associated with passages, but maximises thermal shock, especially at periphery of combustion chamber
- **Torque:** tighten to recommended torque/sensitivity will change if transducer is tightened excessively
- **Leaks:** check for leaks during operation—avoid wetting the connectors
- **Gaskets:** recommend copper material for gaskets (nickel is frequently supplied)

Cylinder Pressure Hardware

Passage Design Considerations



- **Quench** -- prevent flame from propagating into passage.
- **ΔP** -- avoid significant pressure loss and associated phase lag.
- **Resonance** -- maintain passage resonant frequencies at least an order of magnitude above actual combustion phenomena.
- **Volume** -- prevent burned gas from contacting diaphragm, minimize increases in crevice and clearance volumes.

Recommendations:
1 mm diameter
1 to 4 mm length
Minimal clearance between transducer face and inner side of passage (strive of 0.10 mm)

Cylinder Pressure Hardware --Pegging

Referencing Pressure Measurements (pegging)

1. Transducer outputs charge to charge amplifier
2. Charge amplifier outputs voltage to digitiser
3. User must reference voltage to pressure (peg)

Pressure = gain * voltage + bias

$P = G\,\acute{\varepsilon}\,(Ø) + \acute{\varepsilon}_b$

Cylinder Pressure Hardware --Pegging

Is Absolute Pressure Necessary ?

Yes	**No**
Peak Pressure	LPP
Polytropic Coefficients MEP	
Heat Release	COV of MEP

Cylinder Pressure Hardware –Recommended pegging routines

Procedure	Advantage	Disadvantage
IBDC (set cylinder pressure at IBDC equal to MAP)	-Computationally simple	-Accuracy decreases when intake timing occurs. -point measurement highly susceptible to noise
Average Exhaust Pressure (set avg. cylinder pressure firing exhaust stroke equal to measured back pressure	Averaging several measurements minimises susceptibility to experimental noise	-Computationaly intensive --Accuracy deteriorates when exhaust tuning occurs

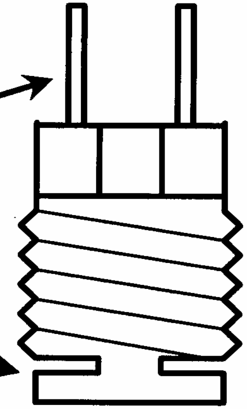
Cylinder Pressure Hardware –Recommended pegging routines cont…

Procedure	Advantage	Disadvantage
Forced Polytropic Compression (force the polytropic compression coefficients of each cycle equal to user-input value)	Effective at all operating conditions	-Computationally insensitive -Eliminates the polytropic coefficient as a data-quality diagnostic -May be highly susceptible to experimental noise

Cylinder Pressure
Hardware - Transducers

<u>Thermal Shock</u> -- change in transducer sensitivity with temperature.

- water cooling
- heat shield
- mounting



Cylinder Pressure
Hardware - Transducers

Recommendations

- Be aware of transducer limitations
- Select a transducer with a good thermal shock resistance
- Mount the transducer precisely
- Keep the heat shield and connectors clean
- Use clean, preferably distilled,water supply
- Examine data for signs of measurement error

Cylinder Pressure Hardware - Cables

High Impedance Cable

Purpose: Conduct charge from the transducer to the charge amplifier

Application: resistance between centre conductor and outer shield must be kept high (.10 ^{13} (Ω)ohms)

--Keep cable length reasonably short

-- Do not allow cable to sit in liquid

-- Keep connector clean and dry (do not use alcohol – based electrical – based electrical contact cleaners)

Cylinder Pressure Hardware – Transducers cont.

Cable Resistance Testing

Tool: Kistler 5491 Insulation tester (circa $1,000)

- Check cable and transducer/cable assembly
- If $< 10^{13}$ (Ω)ohms:
  - **Clean connectors with contact cleaner**
  - **Bake for 2 hours at 125C**
  - **If still low, check cable for damage.**

Cylinder Pressure Hardware – Charge Amplifier

Purpose:

1. Convert charge output from transducer to a voltage (Range capacitor)

   V α charge / capacitance

2. Amplify voltage to produce desired gain

Cylinder Pressure Hardware – Charge Amp.cont…

Charge Amplifier Recommendations

- Use differential amplifier to reduce susceptibility to many types of noise
- Use amplifier which grounds each engine cycle to help keep data from drifting out of digitiser range
- Prefer amplifier with the capability of offsetting ground to allow more efficient use of digitiser range
- Select an amplifier which provides information on intra-cycle drift

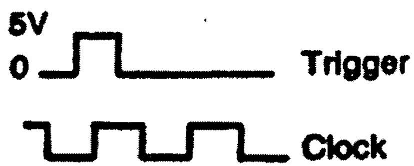
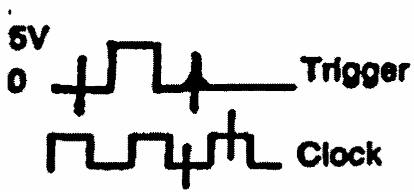
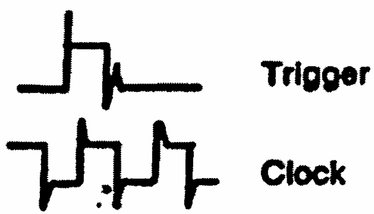
Cylinder Pressure Hardware – Encoders

<u>Crankshaft Position Sensing</u>

- **Optical Encoder-**Light gate and optical pickup indicate crankshaft position
- **Digital Magnetic Pickup (DI-MAG)-**0 to 5v TTL output dependant on magnetic field strength –used for sensing ring gear teeth
- **Magnetic-**Sinewave output corresponding to magnetic field strength-prefer to use zero crossing rather than some arbitrary amplitude threshold
- **Engine Crankshaft Sensor-**Generally insufficient resolution, although 58x systems are adequate for some rudimentary applications (58 pulses per crankshaft revolution)
    - Prefer 360 ppr for general combustion work, 3,600 for knock work

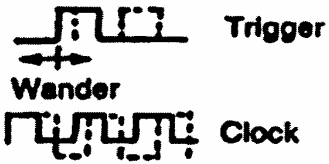
Cylinder Pressure Hardware – Encoders

Encoder Troubleshooting

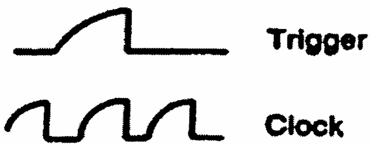
	Condition	Cause
	Good	•Dumb luck
	Noise Spikes Results in false triggers and improperly clocked data	• Poor signal connections • Ground Loops • Noisy instrument power • Signal crosstalk
	Ringing Results in false clocked data	• Excessive system inductance leading to inductive coupling • Noise

Cylinder Pressure Hardware – Encoders

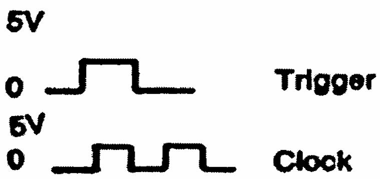
Encoder Troubleshooting, cont.



Condition	Cause
Unsteady Position Results in improperly triggered and clocked data	•Loose encoder disk • Faulty shaft coupling • Faulty encoder electronics



Condition	Cause
Rounding Inaccurate trigger and clock, questionable repeatability	• Excessive system capacitance



Condition	Cause
Low Voltage Improper triggering and clocking	• Poor power supply • Bad connectors • Low impedance input device • Insufficient signal driver in optical encoder

Cylinder Pressure Hardware – Encoders

Encoder Recommendations

- Select an encoder which does not ground to the engine (isolated case)
- Prefer a direct-mount encoder as opposed to one requiring a coupling
- May need to photo-isolate encoder signals in high-noise applications
- Use a quadrature encoder for applications where the engine may rotate backwards (such as cold start tests)