Optical Experimentation

Technical Basis for Optical Experimentation

<u>The nature of light</u>

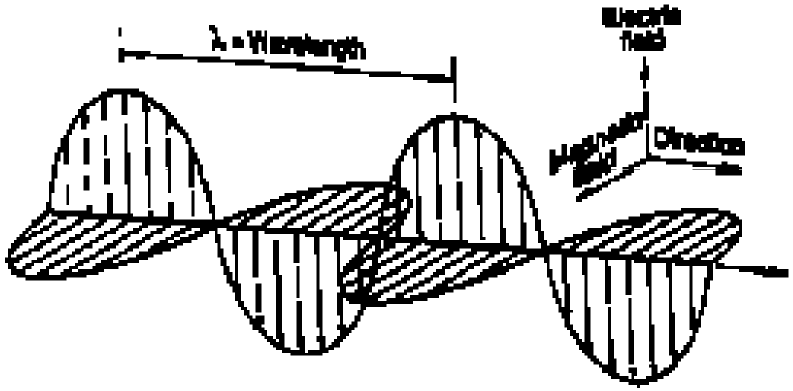
According to classical electromagnetic theory, light is considered to be radiation that propagates through vacuum in the form of electromagnetic waves, both oscillating transversely to the direction of wave propagation and normal to each other.

Electric field

$$E_y(x,t) = E_{y0} \sin 2\pi(\frac{x}{\lambda} - \frac{t}{T})$$

Magnetic field

$$B_Z(x,t) = B_{z0} \sin 2\pi(\frac{x}{\lambda} - \frac{t}{T})$$



λ : *is wavelength*

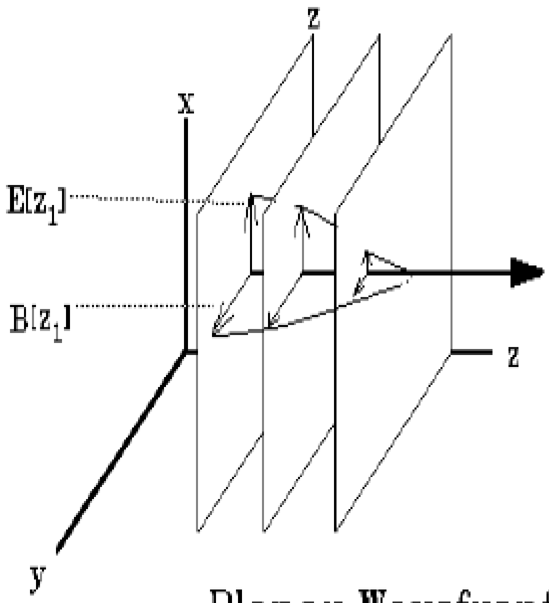
T : *is the period of the oscillation*

ν: *The reciprocal of the period, is called frequency,* $\nu = 1/T$

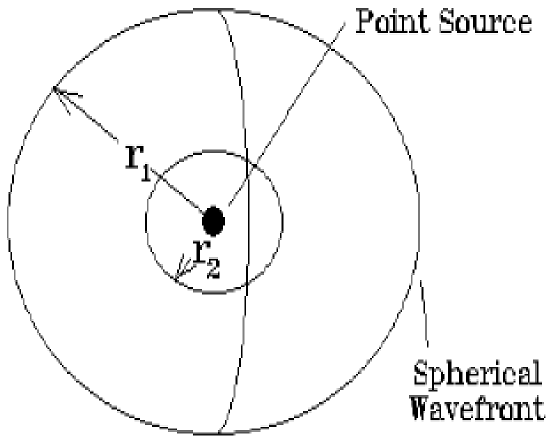
Technical Basis for Optical Experimentation

The nature of light

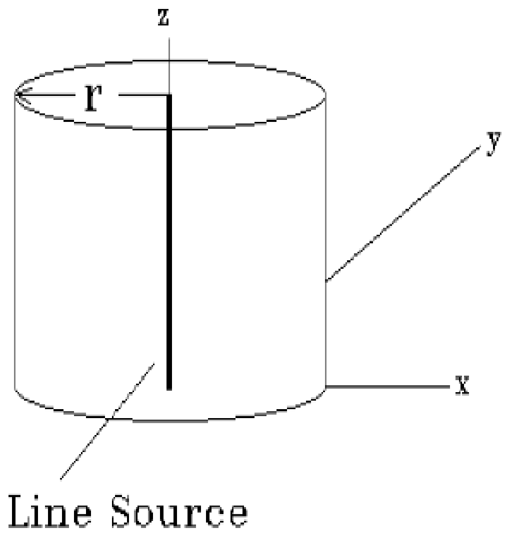
- *Light propagation velocity,* $V = f\lambda$
- *Light propagation velocity in Vacuum,* $C = 2.998\times10^{8}$ *m/s*
- *Wave front: the locus of all points along the different paths that have the same phase.*
- *If all the wave fronts are plane, then, the light is considered to be a plane wave.*
- *If all the wave fronts are spherical or cylindrical, then, the light is considered to be a spherical or cylindrical wave.*
- *Light propagation is associated with electric and magnetic fields. They are in phase and their amplitudes are related as:* $$E_{y_0} = cB_{z0}$$
- *It is usually sufficiently to analyze electromagnetic waves by considering only electric field.*
- *The polarization is associate with the orientation of the plane of the plane of oscillation of the electric field.*



Planar Wavefronts
moving along z−axis



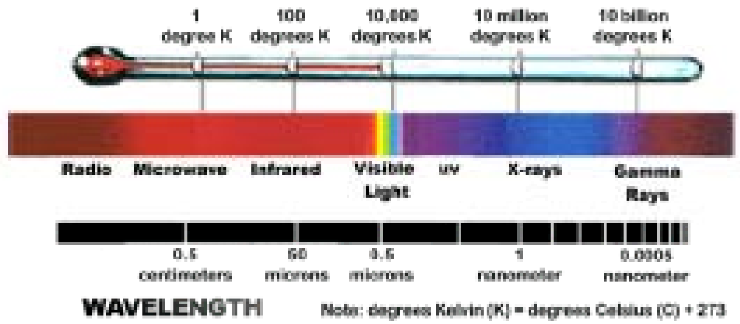
Spherical waves expanding from a point source.



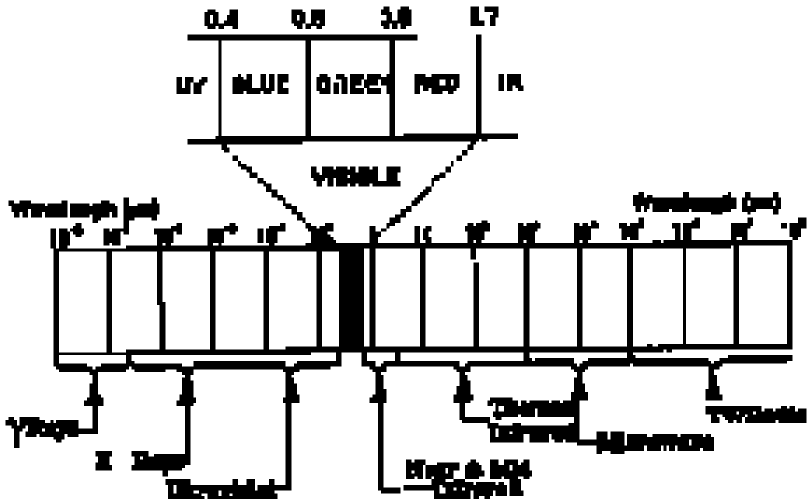
Cylindrical waves expanding from a line source.

Technical Basis for Optical Experimentation

<u>The nature of light</u>



RADIATION TYPE	*WAVELENGTH RANGE*
Cosmic rays	$\lambda < 10^{-4}$ nm
Gamma rays	10^{-4} nm $< \lambda < 10^{-1}$ nm
X-rays	10^{-2} nm $< \lambda < 10^{2}$ nm
Disinfecting radiation	10 nm $< \lambda < 380$ nm
Visible light	380 nm $< \lambda < 750$ nm
Space heating	750 nm $< \lambda < 10^{7}$ nm
Microwaves	10^{6} nm $< \lambda < 10^{9}$ nm
Radar	10^{7} nm $< \lambda < 10^{9}$ nm
Radio and Television	10^{8} nm $< \lambda < 10^{13}$ nm
Electrical power waves	10^{14} nm $< \lambda < 10^{17}$ nm

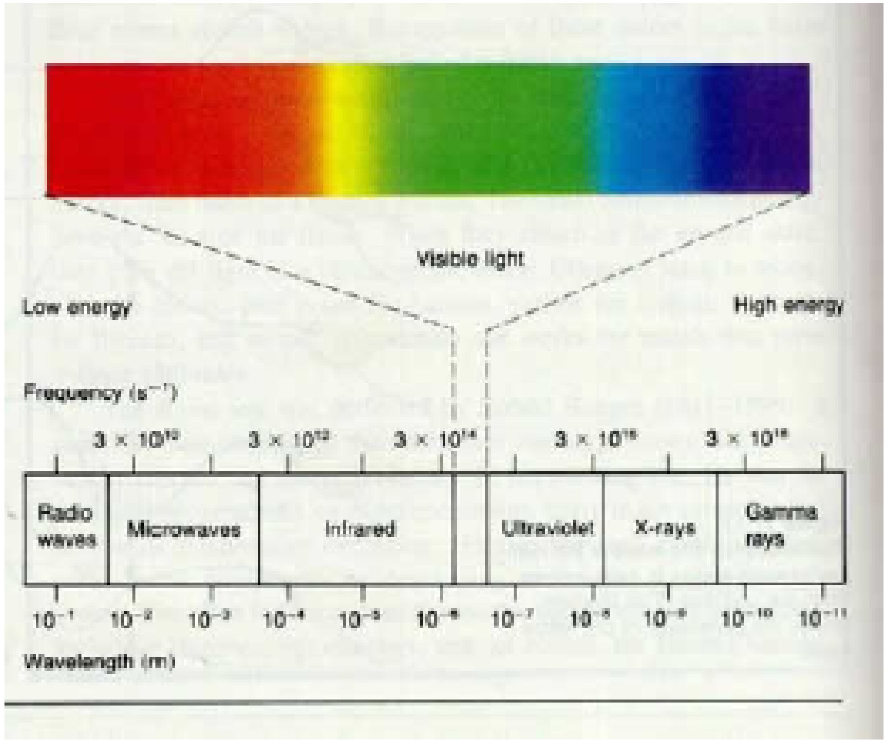


Technical Basis for Optical Experimentation

The nature of light

- *The colors: visible light consists of radiation with wavelength in the range of 380~750nm (1nm=10^{-9}m) which corresponds to the frequency range between 4.0 $\times 10^{15}$ to 7.9 $\times 10^{15}$ Hz.*

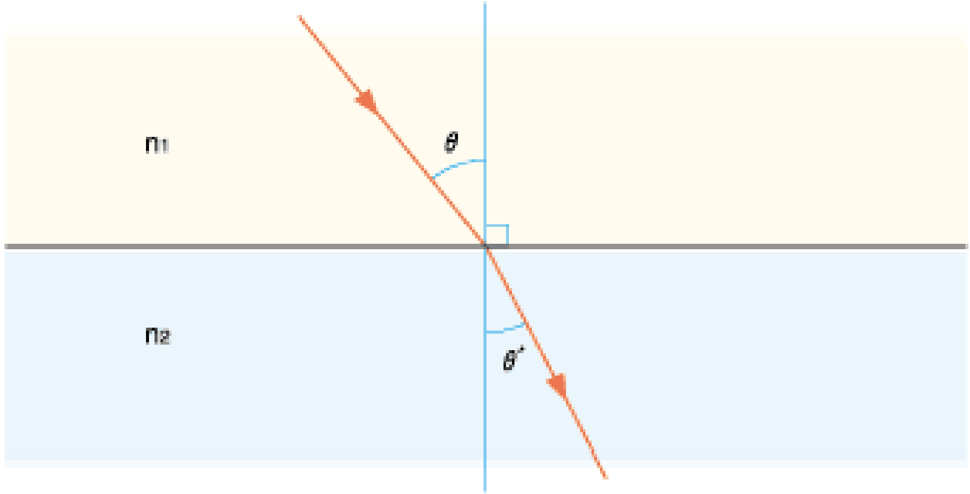
COLOR	*WAVELENGTH RANGE*
Ultraviolet (UV)	*0.85 nm < λ < 380 nm*
Violet	*380 nm < λ < 424 nm*
Blue	*424 nm < λ < 491 nm*
Green	*491 nm < λ < 575 nm*
Yellow	*575 nm < λ < 585 nm*
Orange	*585 nm < λ < 647 nm*
Red	*647 nm < λ < 750 nm*
infrared	*750 nm < λ < 1000 nm*



Technical Basis for Optical Experimentation

Light propagation through a medium

- ***Refraction:***
  - *When light propagates through a homogenous medium, its path would be straight, whereas, if the medium is non-homogeneous or if the light across from one medium to another, the path may change direction gradually or abruptly. The change of light propagation direction is called refraction.*



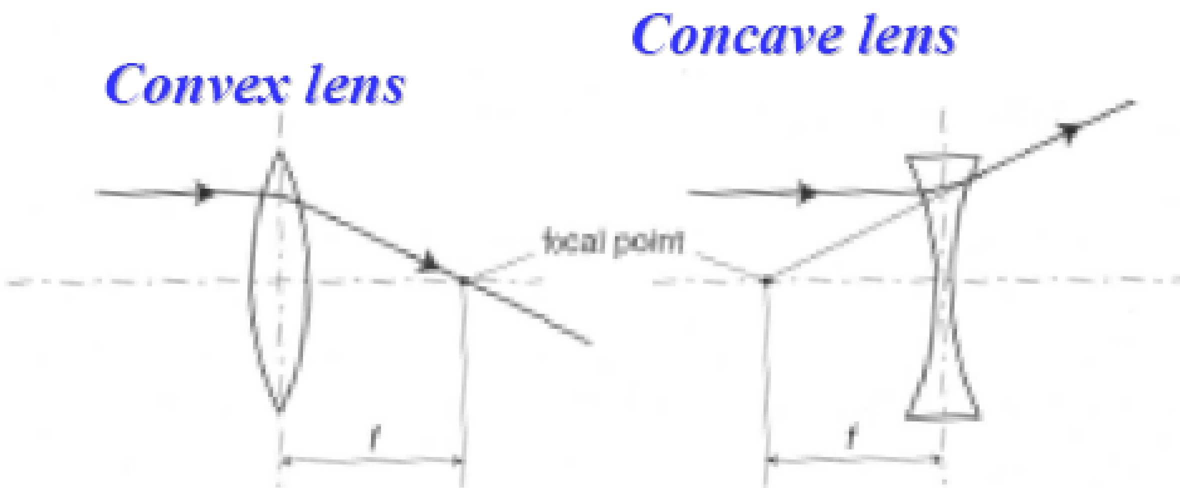
$$\frac{\sin\theta}{\sin\theta'} = \frac{n_2}{n_1}$$

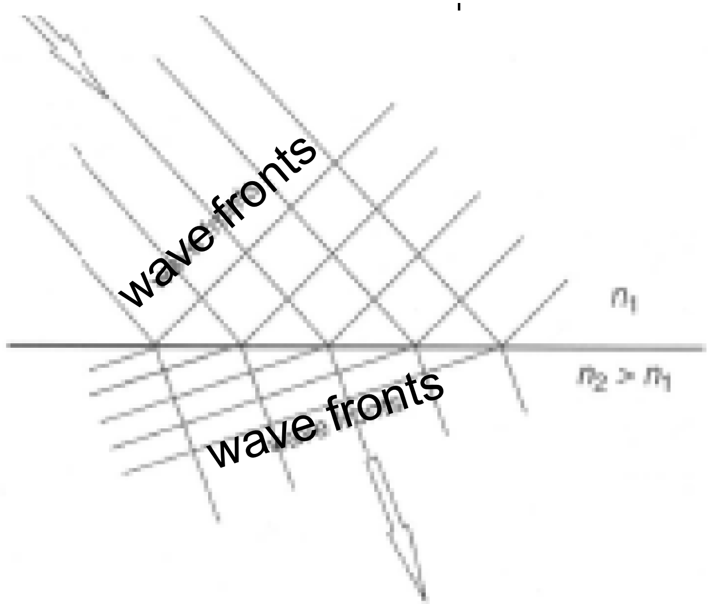
$$(n_1 \sin\theta = n_2 \sin\theta')$$

Technical Basis for Optical Experimentation

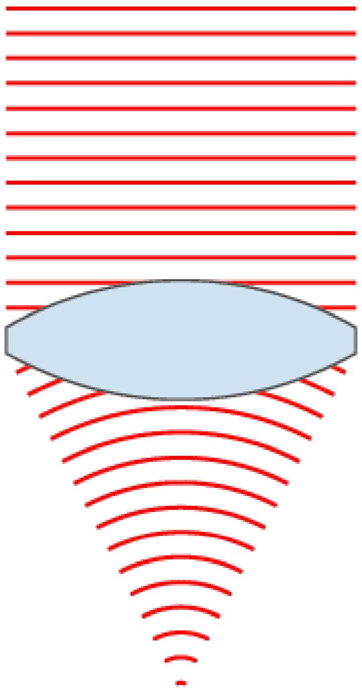
Light propagation through a medium

- *Optical lens*





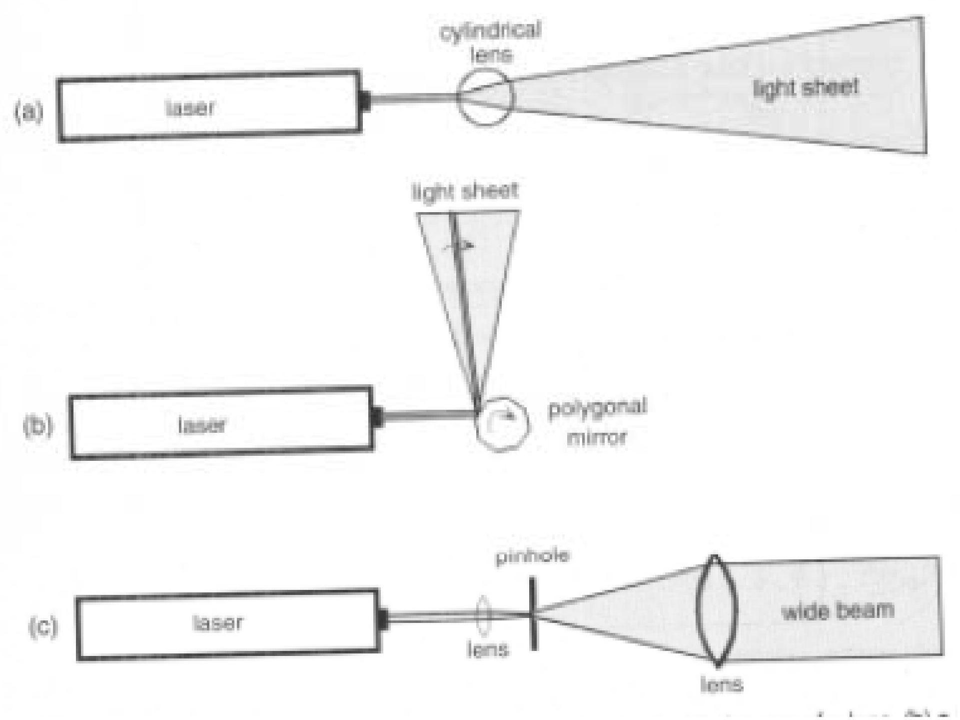
Interpretation of light refraction at the interface between two media as the rotation of wave fronts.



A lens can be used to change the shape of wavefronts. Here, plane wavefronts become spherical after going through the lens.

Illumination

- *Light source*
  - *Thermal source:*
    - *Lamps: Continuous wave (CW)*
  - *Laser sources*
    - *Continuous wave (CW)*
    - *Pulsed laser*
    - *Singe wavelength*
  - *Point source:*
  - *Plane source:*



Color related Terminology

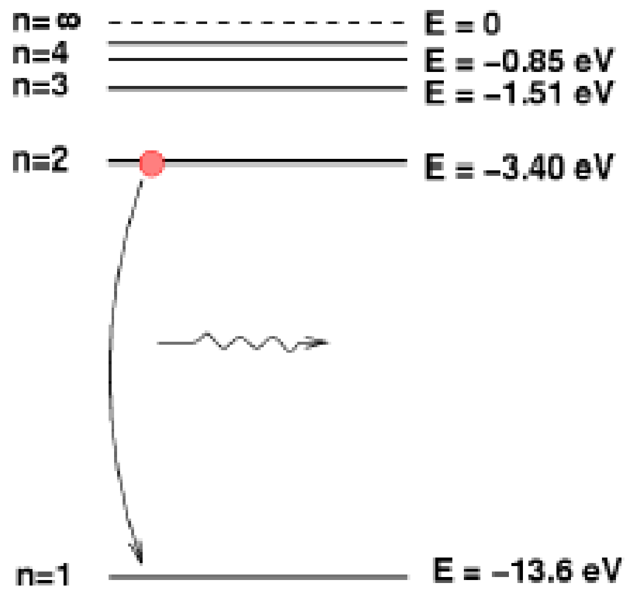
- *International Commission on Standardization (CIE – Comission Internationale de l' Eclairage)*
- *CIE defines colours as an atribute of visual perception consisting of any combination of chromatic and achromatic contents*
- *Chromatic contents: such as yellow, red, blue…*
- *Achromatic contents: such as white, back, gray …*
- *Hue indicates whether an area appears to be similar to one of the receipted colors: red, yellow, green, and blue, or to a combination of two of them*
- *Brightness signifies whether an area appears to emit more or less light.*
- *Lightness is the brightness of an area judged relative to the brightness of a similarlly illuminated area the appears to be white or highly transmitting.*
- *Colorfulness indicates whether the perceived color of an area to be more or less chromatic.*
- *Saturation is the ratio of the colorfulness to the brightness of any area*
- *Vividness of a color is indicated by its saturation, and intensity of a color is indicated by its lightness.*
- *Hue, Saturation and lighness (HSL) has been used as the parameters to determine color perception i.e, HSL model.*
- *RGB model (Red, green and blue is used as primary colors): – widely used for computer and TV monitor.*
- *CMYK (Cyan, Magnenta, Yellow and Black) model: used for high-quality printers*

Laser

Laser: **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation

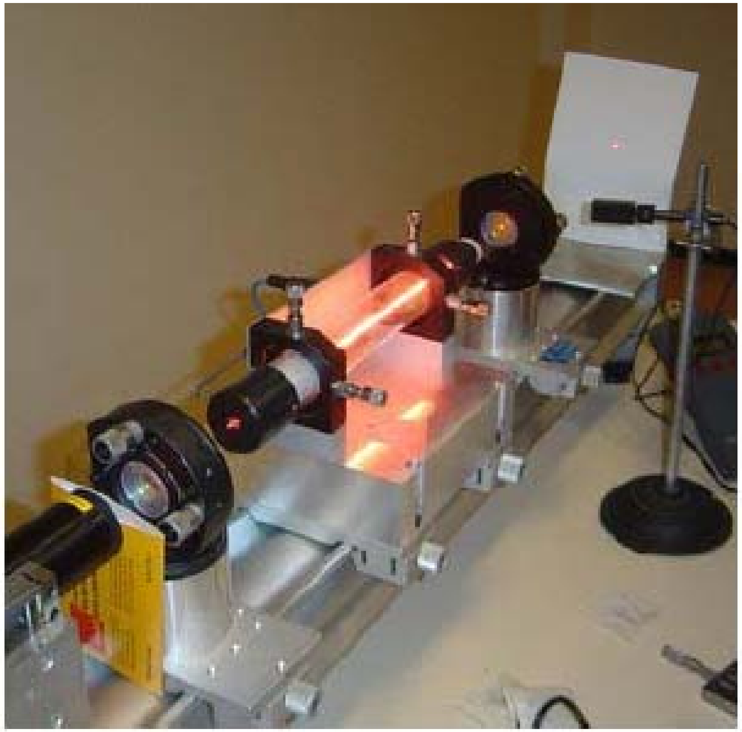
How a laser works:

•Radiation energy is produced by an activated medium (can be gas, crystal, semiconductor or liquid solution)
•When a photon, having energy E=hv, approaches the particle, the photon may be absorbed causing an electron to be raised temporarily to high-energy level.
•When the excited electron return to its ground level, energy emission would take place.



Commonly used Lasers

- Helium-neon (He-Ne) laser
    - Active medium is helium neon atoms
    - Continuous wave laser
    - Power 0.3 ~15 mW
    - λ =633nm (red)



Commonly used Lasers

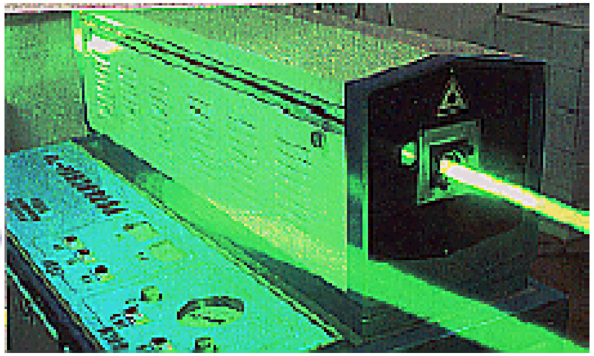
- Argon-ion (Ar-ion) laser
  - Active medium is argon atoms maintained at the ion state.
  - Continuous wave laser
  - Power level: 100 mW ~10 W
  - Have seven wavelengths
  - λ =488nm (blue)
  - λ =514.5nm (green)
  - LDV application
  - LIF in liquid flows

Commonly used Lasers

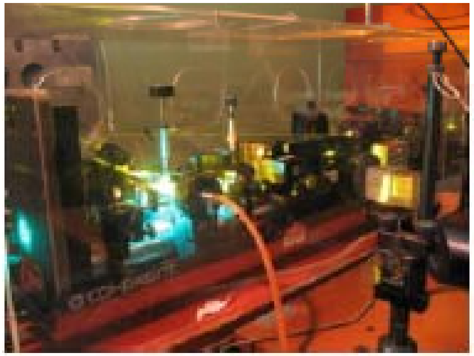
- Nd-YAG laser
  - *Solid-state laser*
  - *Active medium: neodymium (Nd^{+3}) as active medium incorporated as an impurity into a crystal of Yattium-Aluminium-Garnet (YAG) as a host*
  - *Flash lamp is used as external source*
  - *pulsed laser: 10 -400mJ/pulse or more*
  - *Pulse duration: 100ps ~ 10ns*
  - *Wavelenght of tube λ =1064nm (infrared)*
  - *SHG: λ =532nm (green), THG: λ =355nm (UV), FHG: λ =266nm (deepUV)*
  - *PIV, MTV, PLIF*
  - *Repetition rate can be as high as 30 Hz.*

Commonly used Lasers

- Copper Vapor laser
  - Active medium: copper vapor
  - Pulsed laser: 10mJ/pulse or more
  - Pulse duration: 15 ~ 60ns
  - λ =510.6nm (green), λ =578.2nm (yellow)
  - Repetition rate can be as high as f=5,000~15,000 Hz.
  - High-speed PIV, LIF and others



Commonly used Lasers



- Dye laser
  - Active medium: complex multi-atomic organic molecules
  - λ =200nm ~ 1500nm

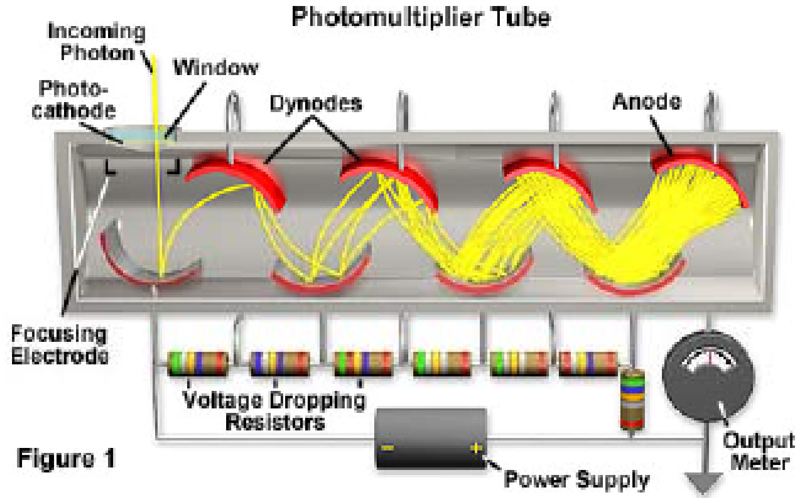
- Excimer laser
  - Gas laser KrF and Xecl
  - High-energy
  - UV wavelength
  - Pulsed laser
  - high repetition frequency

Photodetector

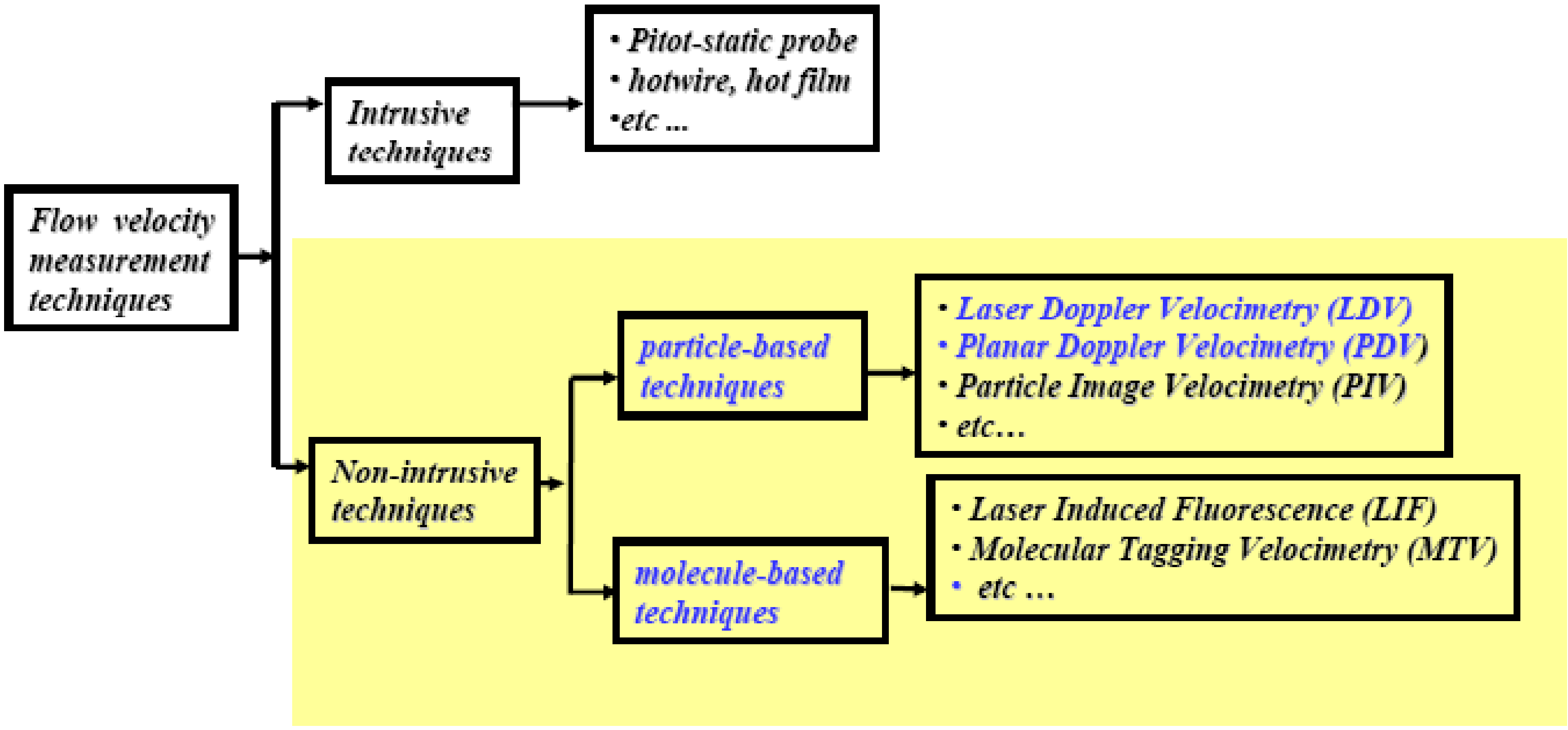
Photo detector is a device to convert light to an electric current through photo electric effect.

Two kinds of photodetector:
-Photomultiplier tubes (PMT)
-Photodiodes (PD) or photo electric cells

- *Photomultiplier tubes (PMT)*
  - *Photocathode: absorbs photons and emits electrons.*
  - *Dynodes: increase number of photons*
  - *Anodes: output*



Flow Velocity Measurement Techniques



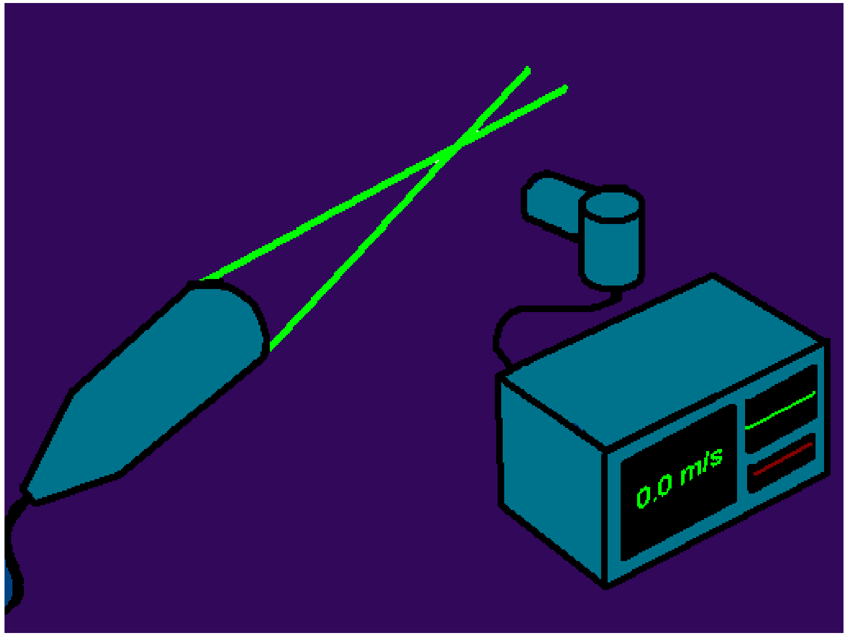
Laser Doppler Velocimetry (LDV)

(Ref. Dantec Dynamics literature)

Why Measure?

- <u>Almost all </u>industrial flows are turbulent.
- <u>Almost all </u>naturally occurring flows on earth, in oceans, and atmosphere are turbulent.

Turbulent motion is 3-D, vortical, and diffusive governing Navier-Stokes equations are <u>very hard</u> (or impossible) to solve.



Characteristics of LDV

The history of laser doppler velocimetry (LDV) started when the first lasers became readily available between 1964-1970.

In the beginning of 70s, an increasing number of people started developing the optical setup as well as electronic devices.

Depending on the laboratory, the same apparatus was called laser doppler anemometer (LDA) or laser doppler velocimeter (LDV).

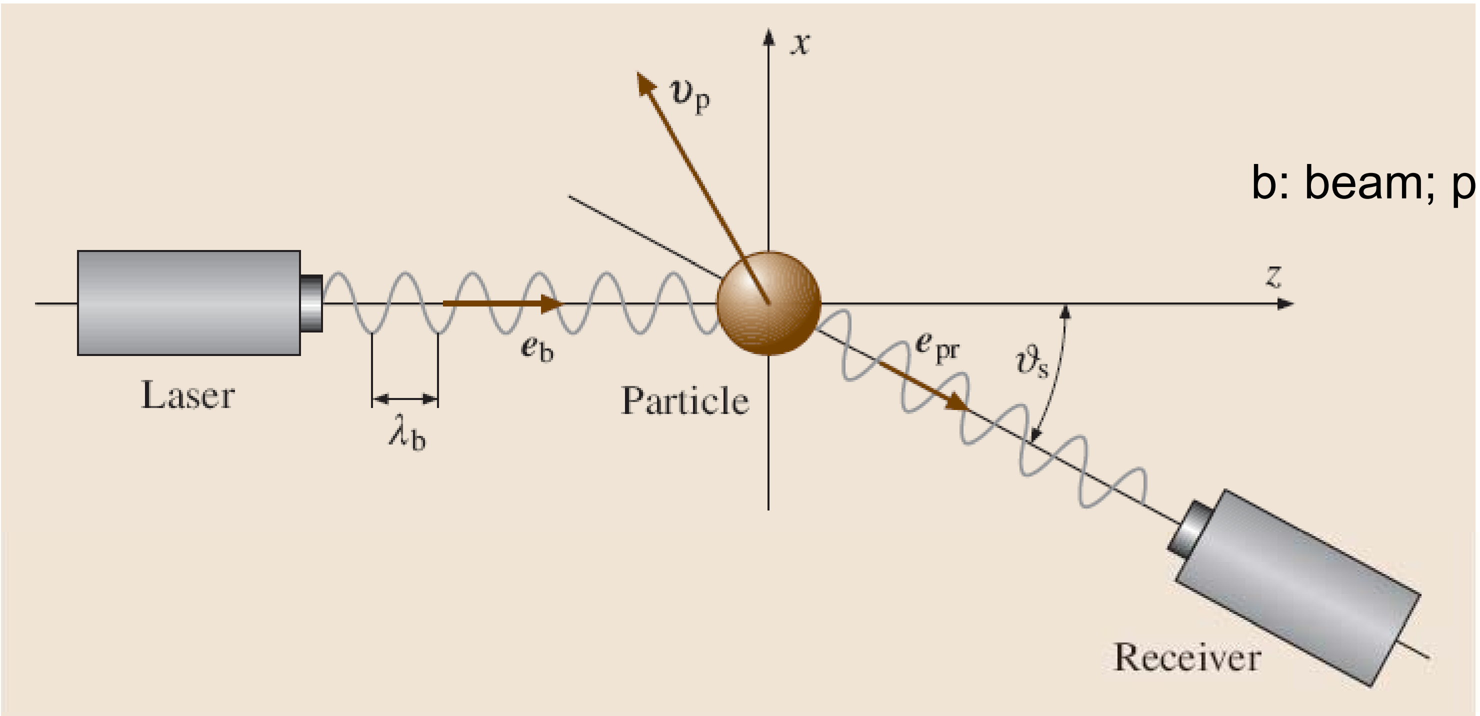
Characteristics of LDA

- Invented by Yeh and Cummins in 1964
- Velocity measurements in Fluid Dynamics (gas, liquid)
- Up to 3 velocity components
- Absolute measurement technique (no calibration required- it depends only to the angle of the lasers)
- Very high accuracy
- Very high spatial resolution due to small measurement volume
- Tracer particles are required

Applications of LDA

- Laminar and turbulent flows
- Investigations on aerodynamics
- Supersonic flows
- Turbines, automotive etc.
- Liquid flows
- Surface velocity and vibration measurement
- Hot environments (flames, plasma etc.)
- Velocity of particles
- ...etc.,

The laser Doppler technique, most frequently referred to as a laser Doppler anemometry (LDA) or laser Doppler Velocimetry (LDV) is a widespread technique for pointwise velocity measurements in a flow with fluid markers.

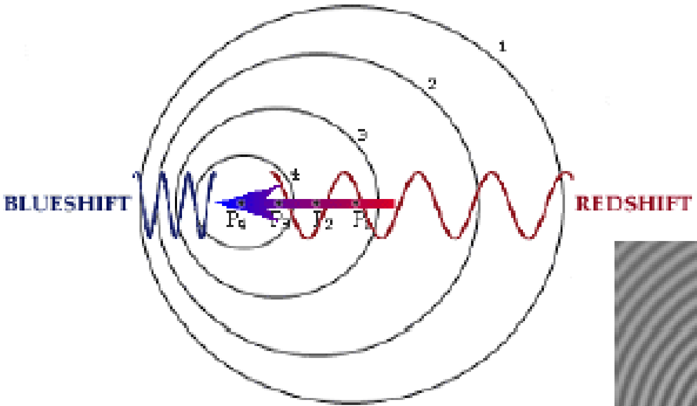


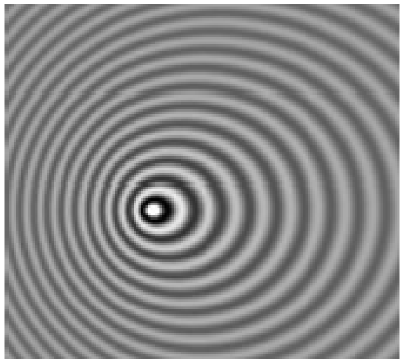
b: beam; p: particle

Defining geometry for applying the Doppler effect in the laser Doppler technique

Doppler Shift

- *The Doppler effect, named after Christian Doppler (an Austrian mathematician and physicist), is the change in frequency and wavelength of a wave that is perceived by an observer moving relative to the source of the waves.*
- *Light from moving objects will appear to have different wavelengths depending on the relative motion of the source and the observer.*
- *Observers looking at an object that is moving away from them see light that has a longer wavelength than it had when it was emitted (a red shift), while observers looking at an approaching source see light that is shifted to shorter wavelength (a blue shift).*

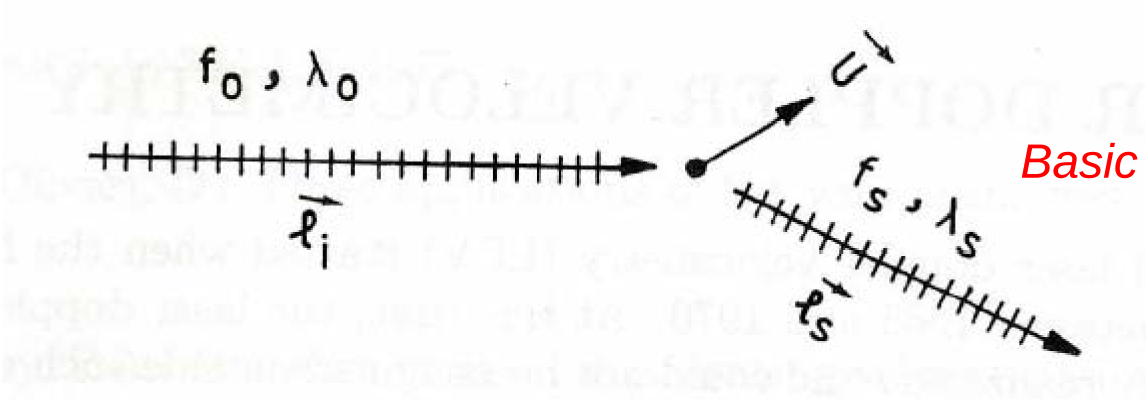




Description of Laser Doppler Velocimeters

Basic Doppler-Fizeau Effect:

The LDV system is an instrument which performs the measurement of the doppler shift of light scattered by a moving particle.



Basic Doppler-Fizeau effect

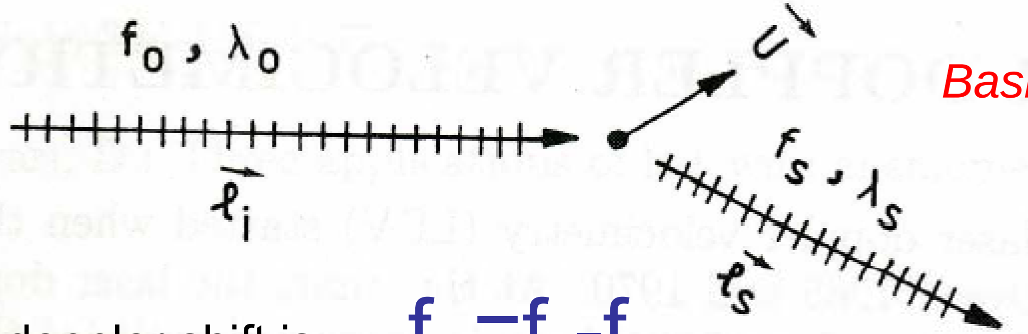
• Let us consider a particle at velocity $\vec{\mathbf{U}}$ illuminated by a laser beam. The laser light is of frequency $\mathbf{f_0}$ and wavelength $\boldsymbol{\lambda_0}$.

$\vec{\mathbf{l}}_i$ is the unit vector corresponding to the propagation direction of the illuminating beam.

The light will be scattered in all directions. Let us consider the light scattered along unit vector $\vec{\mathbf{l}}_s$. It will be of frequency $\mathbf{f_s}$ and wavelength $\boldsymbol{\lambda_s}$.

Description of Laser Doppler Velocimeters

Basic Doppler-Fizeau Effect:



Basic Doppler-Fizeau effect

The doppler shift is: $f_D = f_s - f_0$

The relative speed between the wavefronts of the illuminating beam and the particle is: $c - \vec{U} \cdot \vec{l}_i$ where $c = f_0 \lambda_0$

The rate at which wavefronts are intercepted by the moving particle is

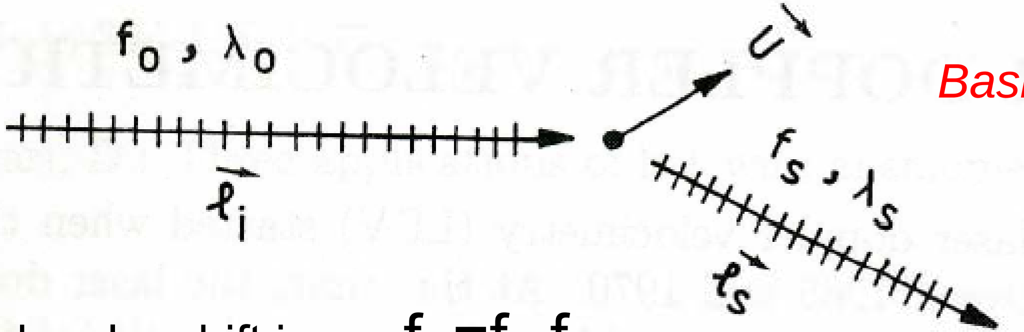
$$f' = \frac{(c - \vec{U} \cdot \vec{l}_i)}{\lambda_0} = f_0 - \frac{\vec{U} \cdot \vec{l}_i}{\lambda_0}$$

The observer intercepting only scattered light along $\mathbf{l_s}$ will intercept wavefronts at rate:

$$f_s = \frac{(c + \vec{U} \cdot \vec{l}_s)}{\lambda_s} = f' + \frac{\vec{U} \cdot \vec{l}_s}{\lambda_s} = f_0 + \vec{U}\left(\frac{\vec{l}_s}{\lambda_s} - \frac{\vec{l}_i}{\lambda_0}\right)$$

Description of Laser Doppler Velocimeters

Basic Doppler-Fizeau Effect:



Basic Doppler-Fizeau effect

The doppler shift is: $f_D = f_s - f_0$

Noting that $\lambda_s \sim \lambda_0$

$$f_s = f_0 + \vec{U}\left(\frac{\vec{l}_s}{\lambda_s} - \frac{\vec{l}_i}{\lambda_0}\right) = f_0 + \frac{\vec{U}}{\lambda_0}(\vec{l}_s - \vec{l}_i)$$

Thus, the net change in frequency or doppler shift, as viewed by a stationary observer, is due to the relative speed and the orientation of the particle trajectory with respect to both the illuminating direction $\vec{\mathbf{l}}_{\mathbf{i}}$ and the scattered light direction $\vec{\mathbf{l}}_{\mathbf{s}}$.

$$f_D = f_s - f_0 = \frac{\vec{U}}{\lambda_0}(\vec{l}_s - \vec{l}_i)$$

f_0 and f_s are on the order of 10^{14}. The doppler shift is on the order of 10^6-10^7.

Different optical modes for LDV

Reference beam system:

This is historically but also fundamentally the basic mode of LDV.
Consider the relationship for f_s:

$$f_s = f_0 + \frac{\vec{U}}{\lambda_0}(\vec{l}_s - \vec{l}_i)$$

The reference beam system is an optical setup which is extracting $\frac{\vec{U}}{\lambda_0}(\vec{l}_s - \vec{l}_i)$ from $\mathbf{f_s}$ by optical heterodyne detection.

Two beams are illuminating the particle assumed to be very small compared to the beam diameter.

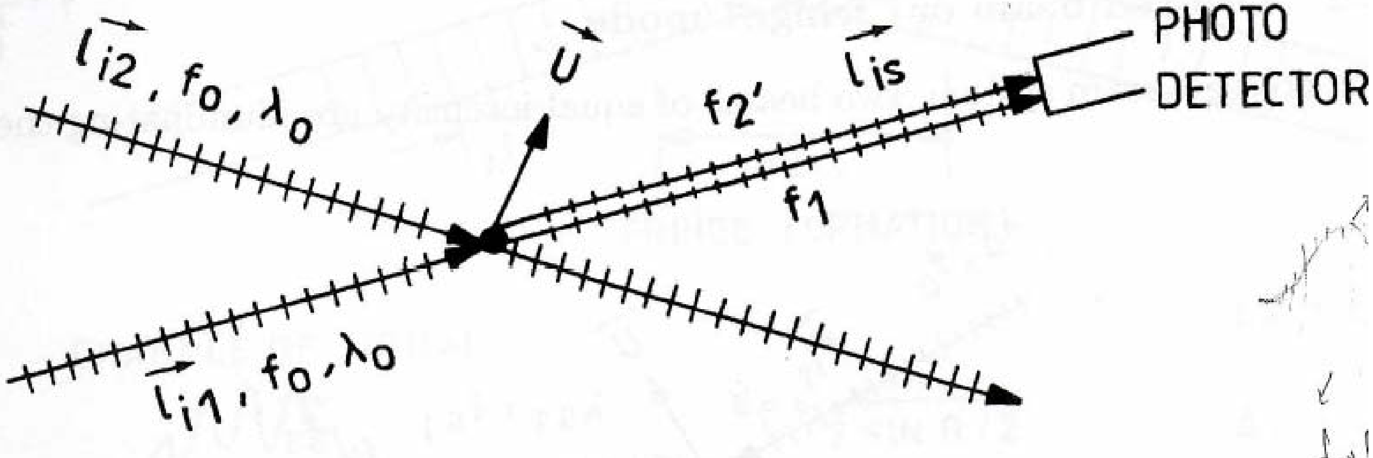


Figure 6.2: Reference beam system

Different optical modes for LDV

Reference beam system:

A photodetector is aligned with the low intensity beam.

The light scattered from the other beam 2 will be mixed with the directly passing light 1.

The photodetector will yield an output current that varies at the doppler frequency f_D. The frequencies are:

$$\left.\begin{aligned} f_1 &= f_0 \\ f_{2'} &= f_0 + \frac{\vec{U}}{\lambda_0}(\vec{l}_s - \vec{l}_{i2}) \end{aligned}\right\} \quad \boxed{f_{2'} - f_1 = f_D = \frac{\vec{U}}{\lambda_0}(\vec{l}_s - \vec{l}_{i2})}$$

This system will give a signal directly proportional to the velocity

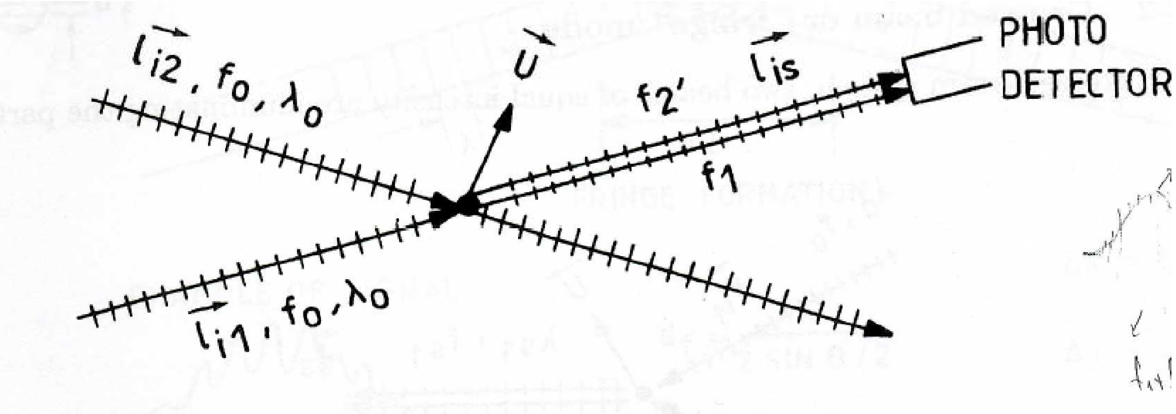


Figure 6.2: Reference beam system

Different optical modes for LDV

Crossed beam or “fringe” mode system:

In the crossed beam system, two beams of equal intensity are illuminating the particles.

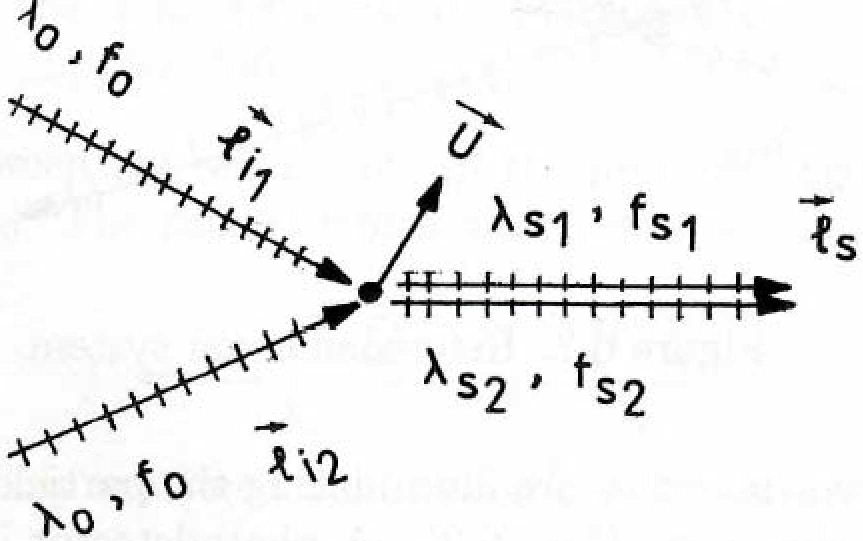


Figure 6.3: Crossed beam or ”fringe” mode

Each beam is scattered; this results into two beams (λ_{s1},f_{s1}) and (λ_{s2},f_{s2}) scattered in $\mathbf{l_s}$ direction.

$$f_{s1} = f_0 + \frac{\vec{U}}{\lambda_0}(\vec{l}_s - \vec{l}_{i1})$$

$$f_{s2} = f_0 + \frac{\vec{U}}{\lambda_0}(\vec{l}_s - \vec{l}_{i2})$$

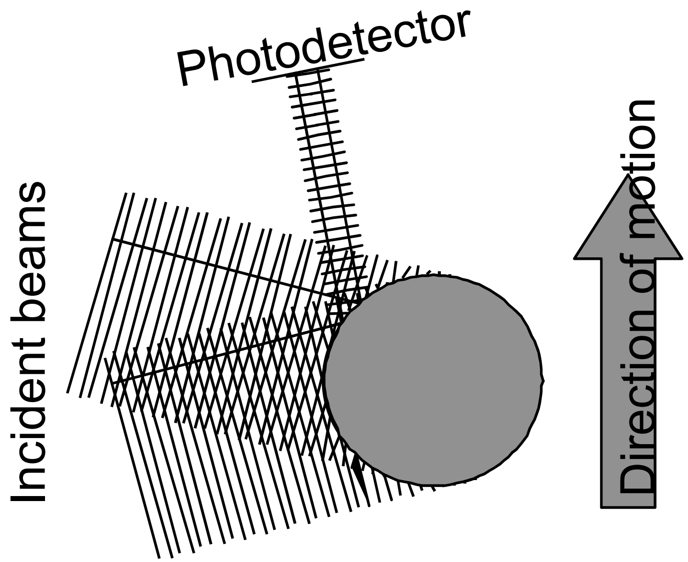
The combination of two beams gives frequency f_D:

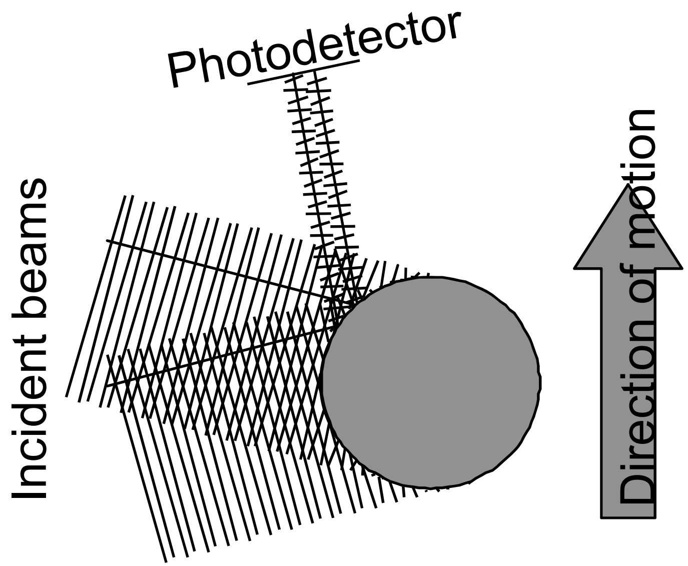
$$f_D = f_{s2} - f_{s1} = \frac{\vec{U}}{\lambda_0}(\vec{l}_{i1} - \vec{l}_{i2})$$

The detected frequency is no longer dependent on the direction of scattering. It is now possible to collect the scattered beams in a wide solid angle with a lens and concentrate them at the surface of the photodector. The detected intensity will thus be much higher.

LDA - Optical principle

- 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.





Different optical modes for LDV

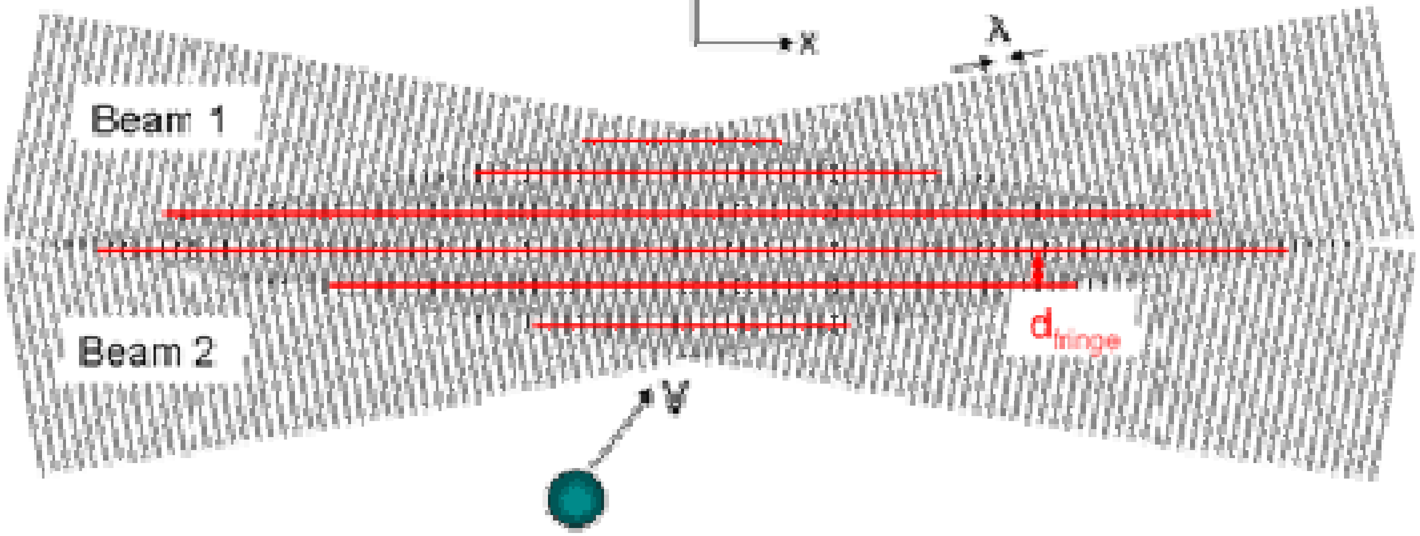
Crossed beam or "fringe" mode system:

The dual beam mode can also be analyze in another way, namely the "fringe" method.

One is considering now two illuminating beams in the absence of particles.

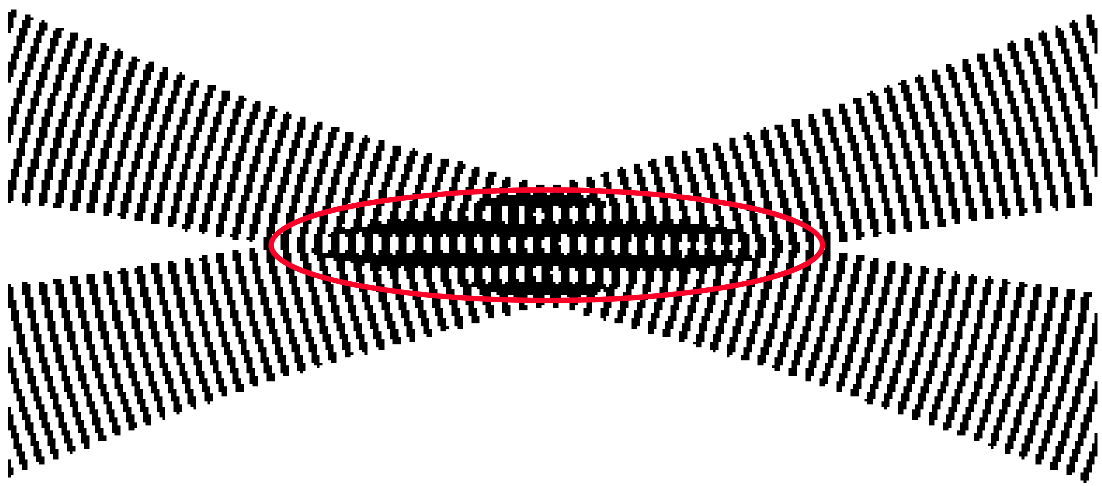
When two laser beams of equal intensity are crossing, there is a formation of interference fringes in the crossing region.

As the frequency of the light is the same in the two beams, these fringes are stationary.



LDA - Fringe Model

- 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



Different optical modes for LDV

Crossed beam or “fringe” mode system:

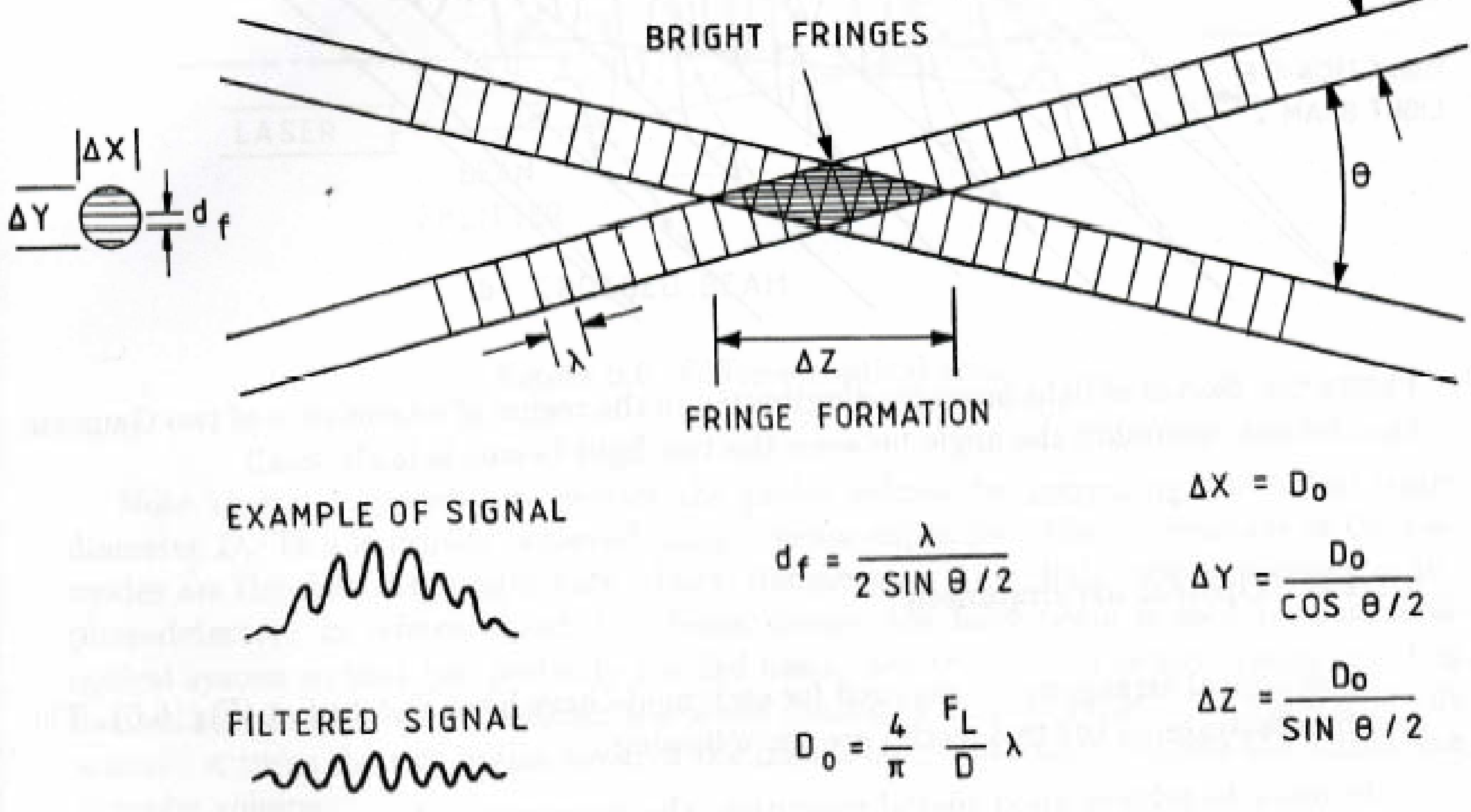


Figure 6.4: Fringe concept and signals

Different optical modes for LDV

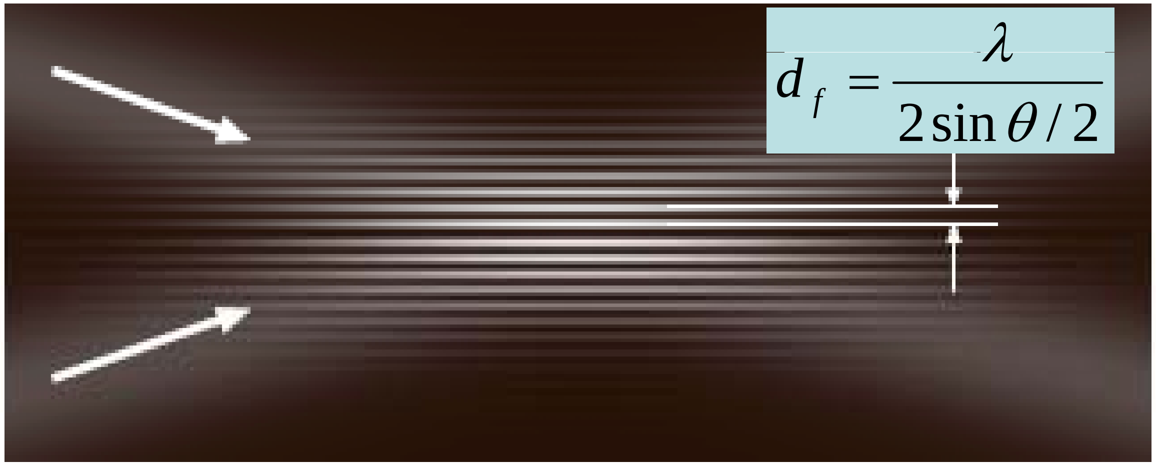
Crossed beam or "fringe" mode system:

If a solid particle is passing through this region, it will cross successively bright and dark fringes.

Light will be scattered only when a bright fringe is crossed. A stationary observer will then "see" the particle only when it is illuminated, i.e., when it is in a bright fringe.

The rate at which the particle is crossing the fringes will thus be proportional to its velocity.

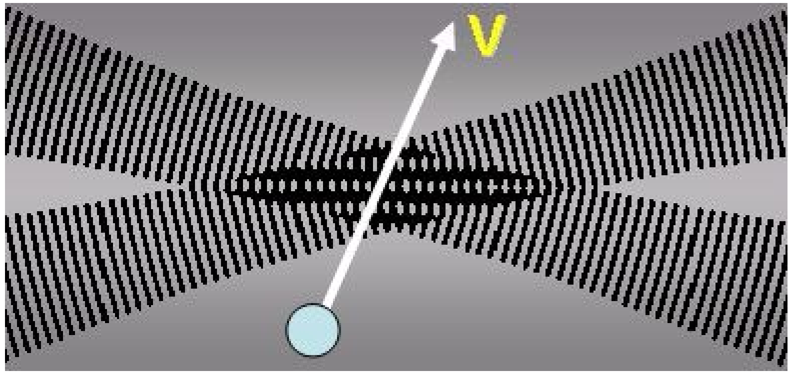
Fringe spacing is d_f with $d_f = \dfrac{\lambda}{2\sin\theta/2}$, λ being the laser wavelength and θ the beam angle.

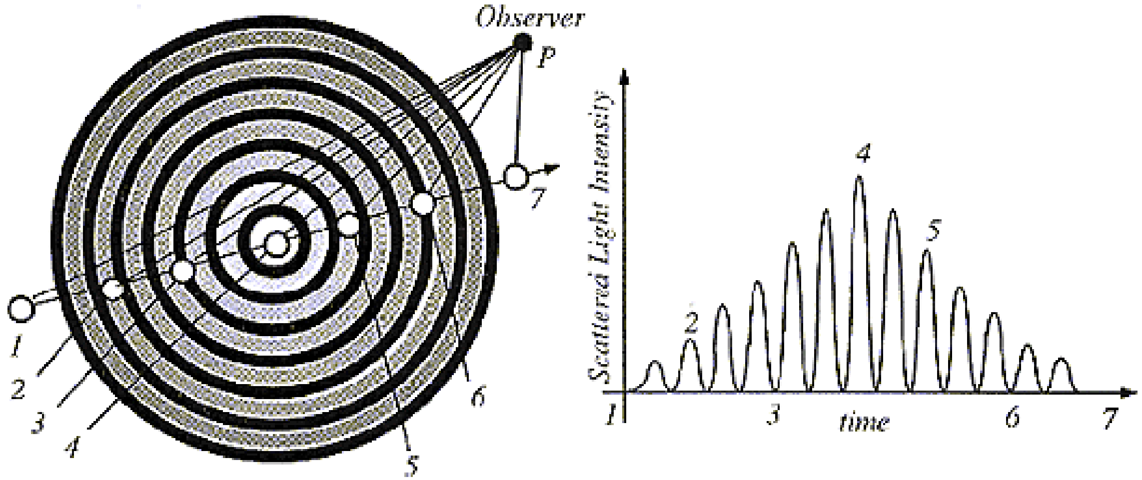


Interference pattern in the measurement volume – fringe model

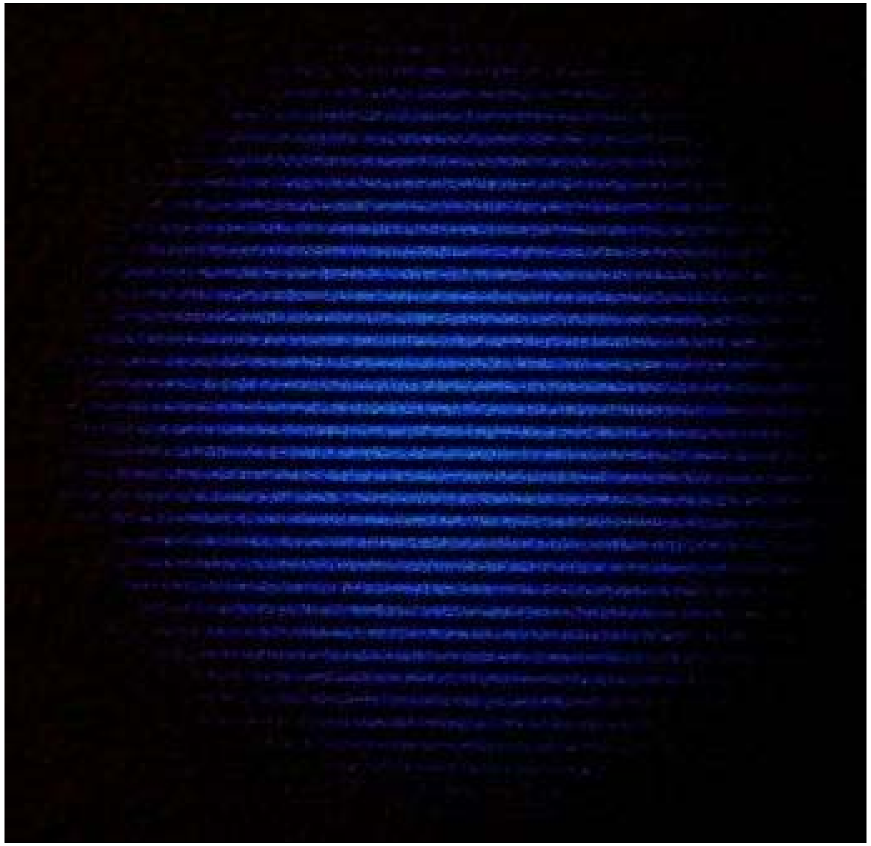
LDA - Fringe model

- The fringe model assumes as a way of visualisation that the two intersecting beams form a fringe pattern of high and low intensity.
- When the particle traverses this fringe pattern, the scattered light fluctuates in intensity with a frequency equal to the velocity of the particle divided by the fringe spacing.





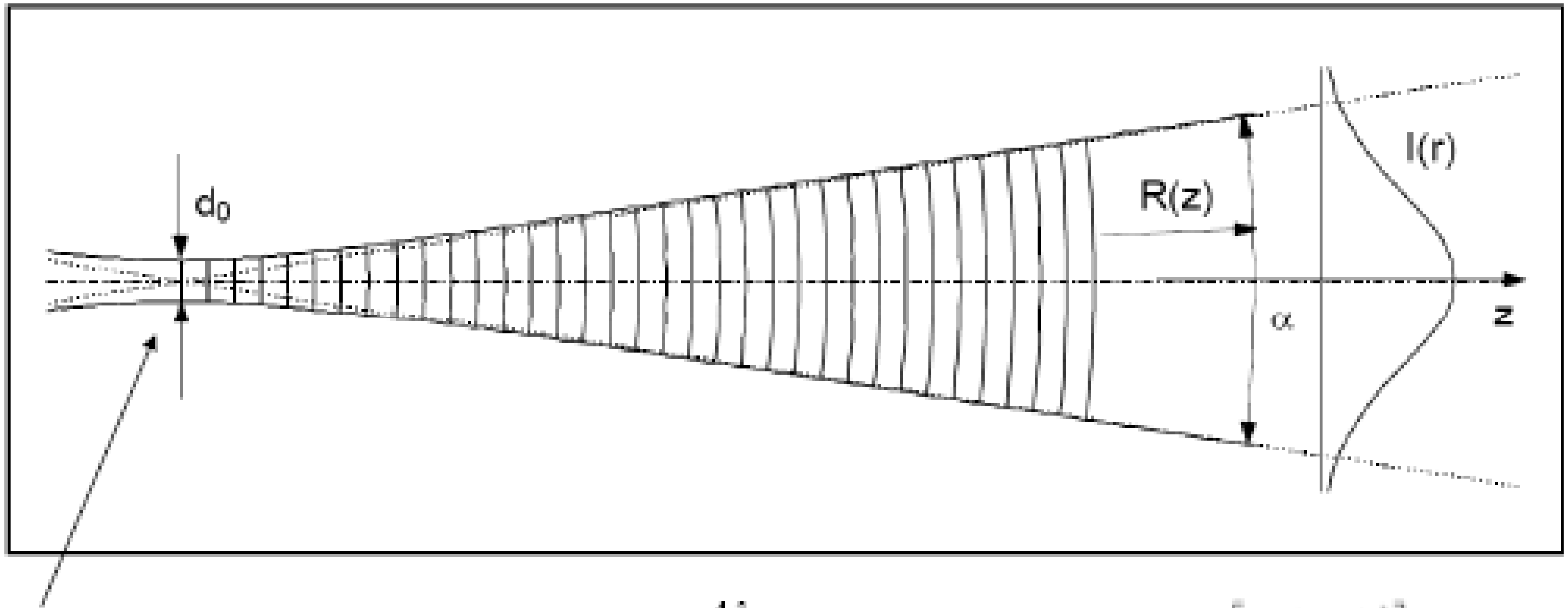
The interference pattern, known as a 'fringe' pattern is composed of planar layers of high and low intensity light. Velocity measurements are made when particles 'seeded' in the flow pass through the fringe pattern created by the intersection of a pair of laser beams.



This is an actual cross-sectional view of the beam crossing of two pairs of beams which illustrates a two component fringe pattern produced by an Argon-Ion Laser.

Gaussian laser beam

Actually the laser beam has a Gaussian intensity distribution.



Beam waist: d_0 Beam divergence: $\alpha = \dfrac{4\lambda}{\pi d_0}$

Wave front radius $R(z) = z\left[1+\left(\dfrac{\pi d_0^2}{4\lambda z}\right)^2\right]$ $\begin{cases} \to \infty \text{ for } z \to 0 \\ \to z \text{ for } z \to \infty \end{cases}$

Different optical modes for LDV

Crossed beam or “fringe” mode system:

Therefore, the fringe pattern is also presenting a Gaussian intensity distribution.

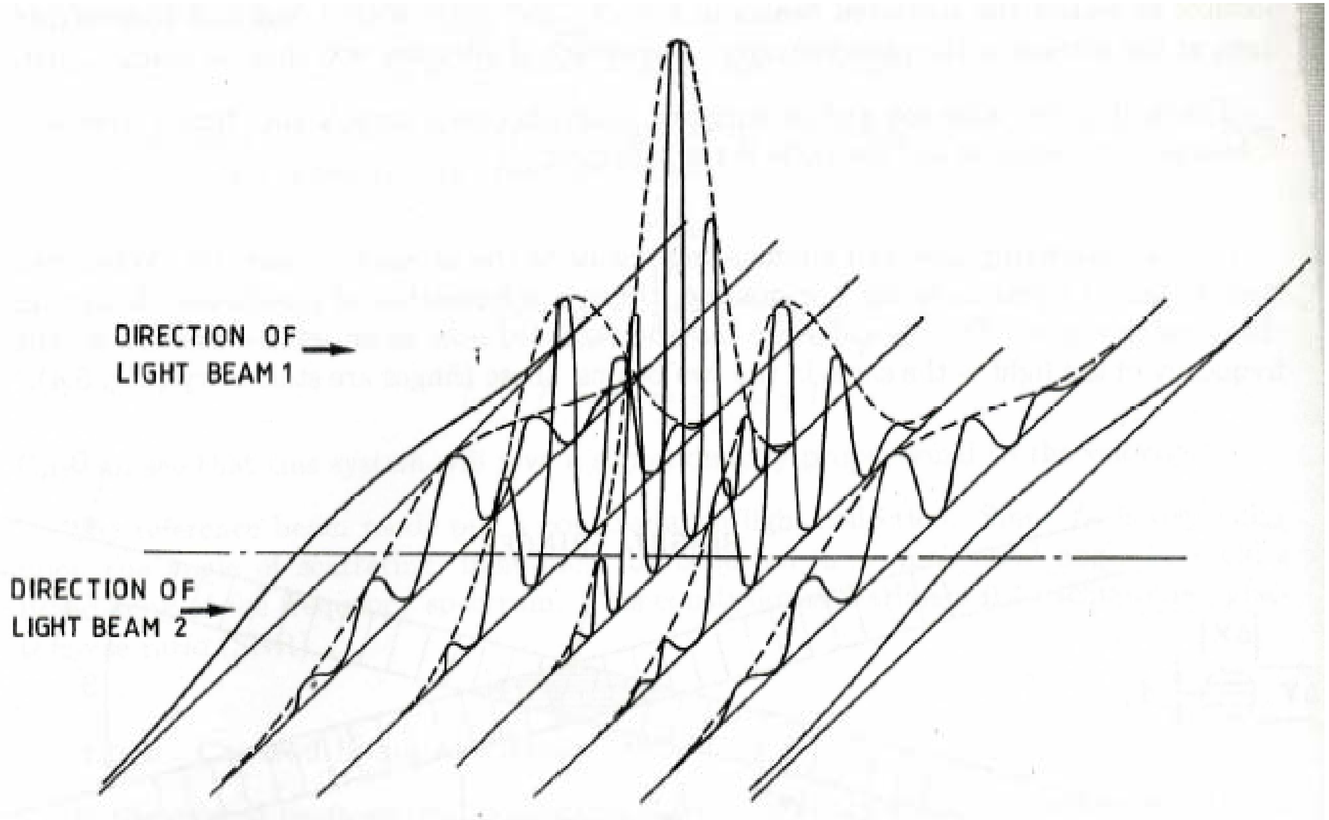
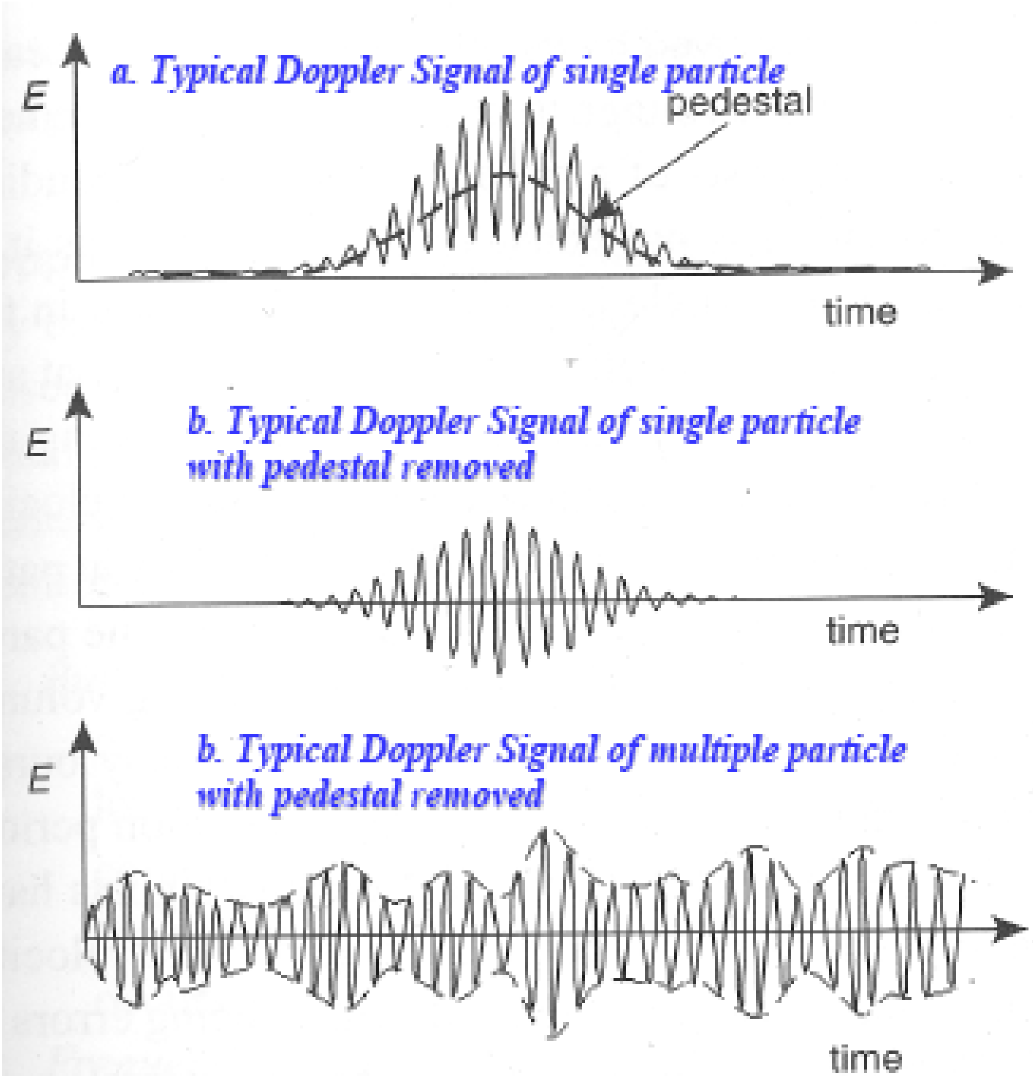


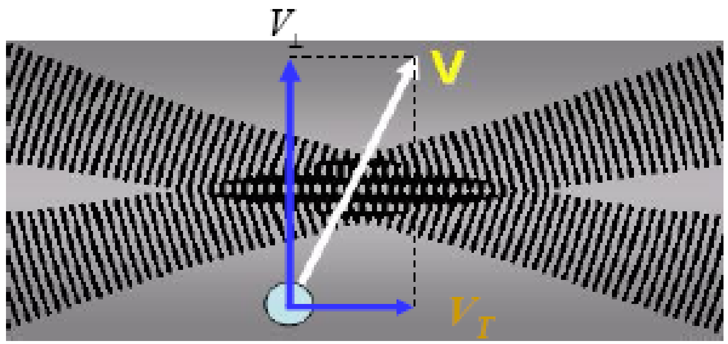
Figure 6.5: Sketch of light intensity distribution in the region of interference of two Gaussian light beams, assuming the angle between the two light beams is fairly small

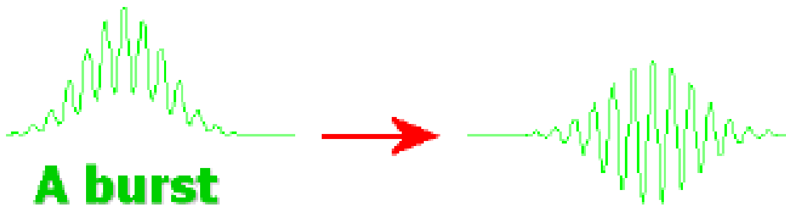
Frequency of the burst signal

$$f = \frac{V_\perp}{\delta} = \frac{2\sin(\theta/2)}{\lambda} V_\perp$$

$$V_\perp = \frac{f\lambda}{2\sin(\theta/2)}$$

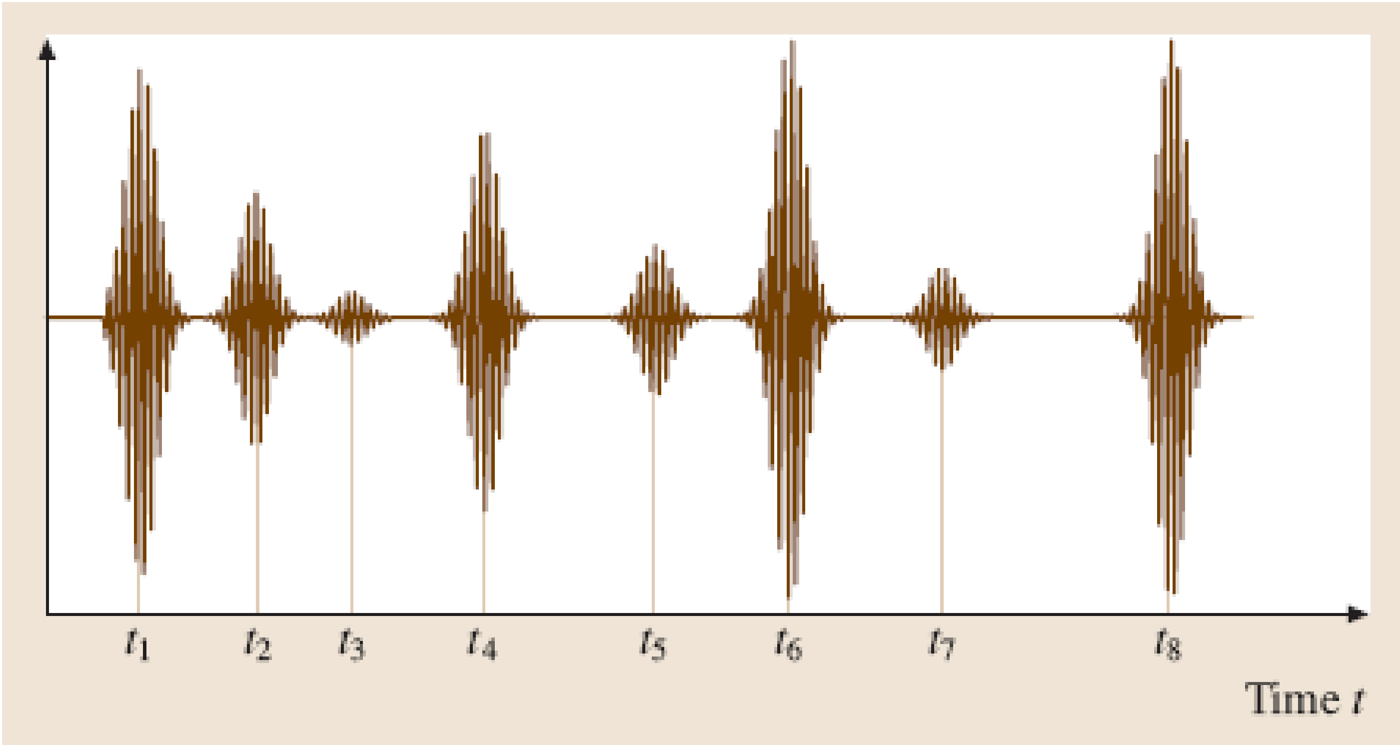




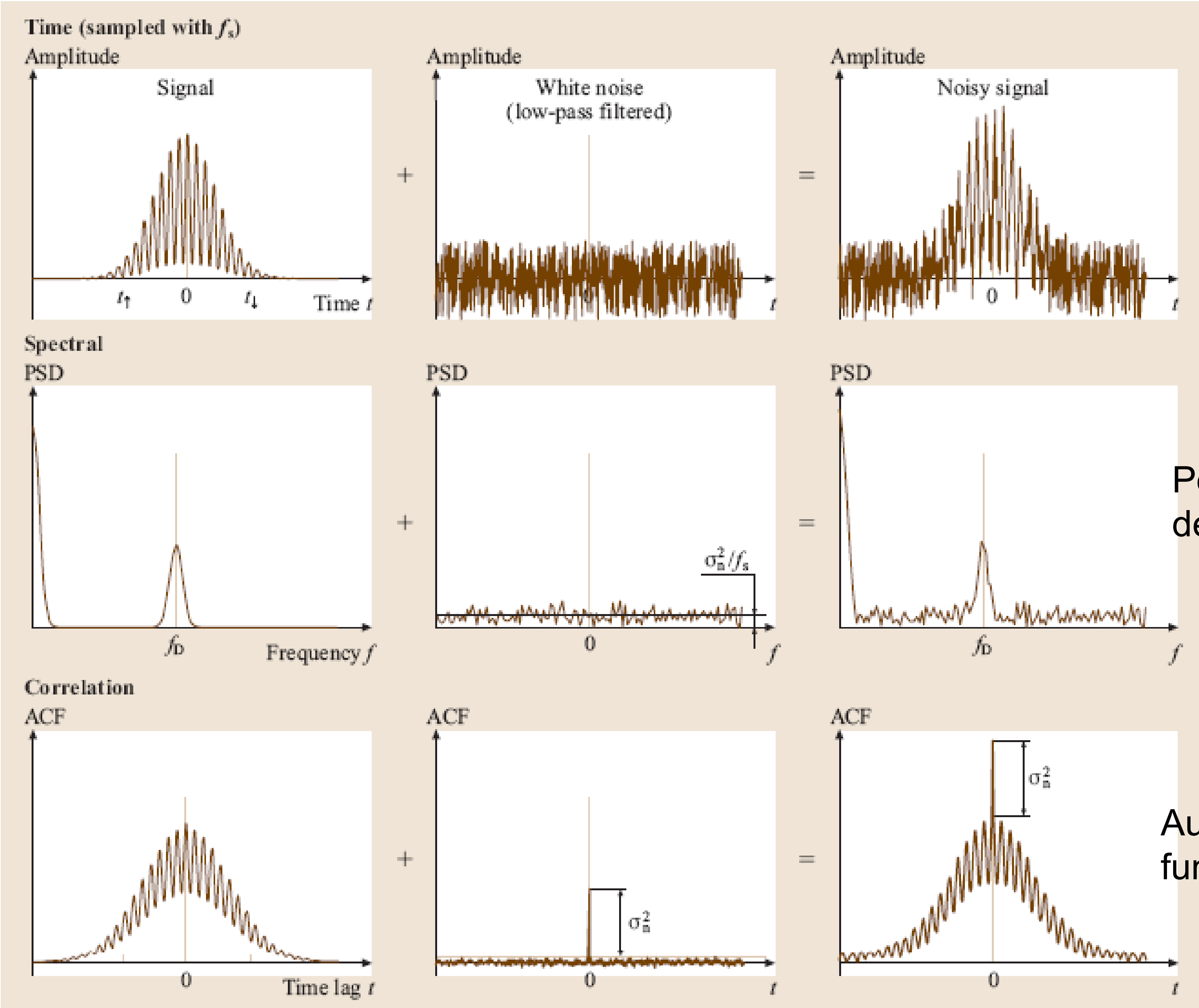


The **pedestal** is due to the intensity of the laser beam and usually has a Gaussian Distribution.

Burst intensity: the number of particles crossing the measuring volume.



Irregular arrival of burst signals in time



Power spectral density

Autocorrelation function

Representation of a laser Doppler signal, a noise signa,l and a combination of the two in the time, spectral, and correlation domains

Different optical modes for LDV

Optical Arrangement:

The optical arrangements required for each mode:

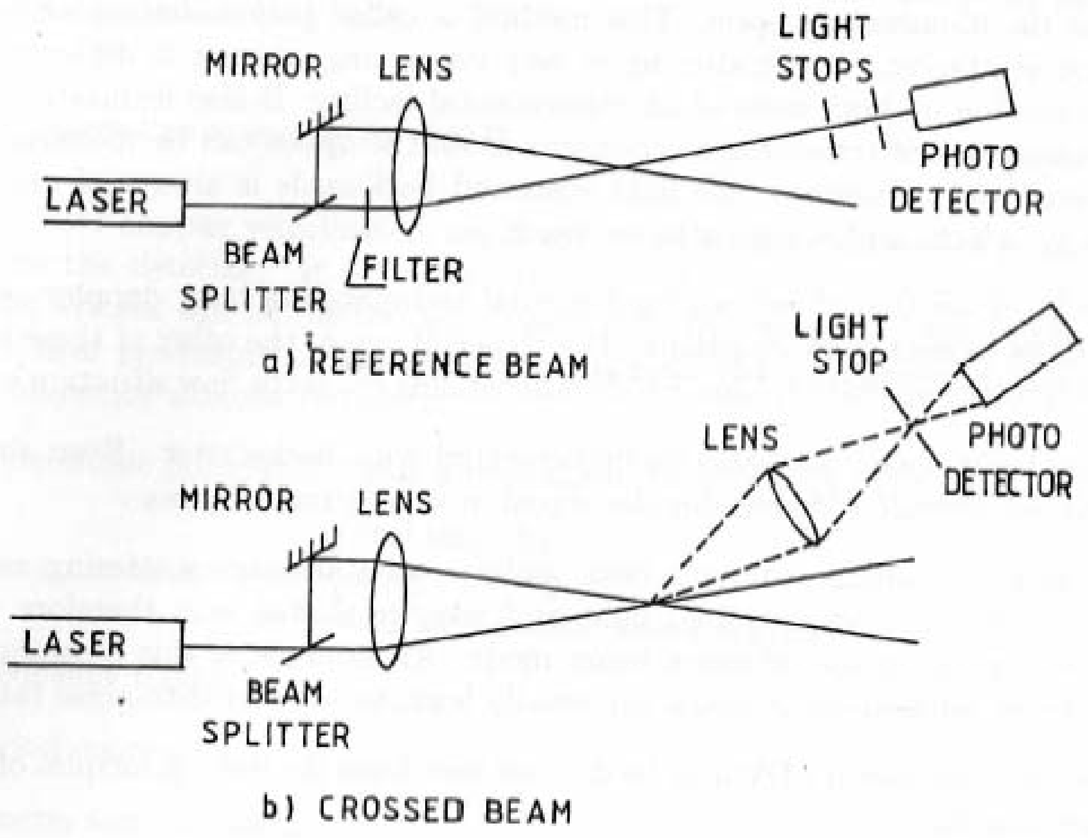


Figure 6.6: Different optical setup

In reference and dual beam modes, the laser beam is split by a suitable optical system so that two perfect parallel beams are obtained.

The two beams are then focused to a common point defining the probe volume.

The *focusing lens* has a double action

1. It turns the two beams towards the measuring point
2. It reduces the actual size of the probe volume.

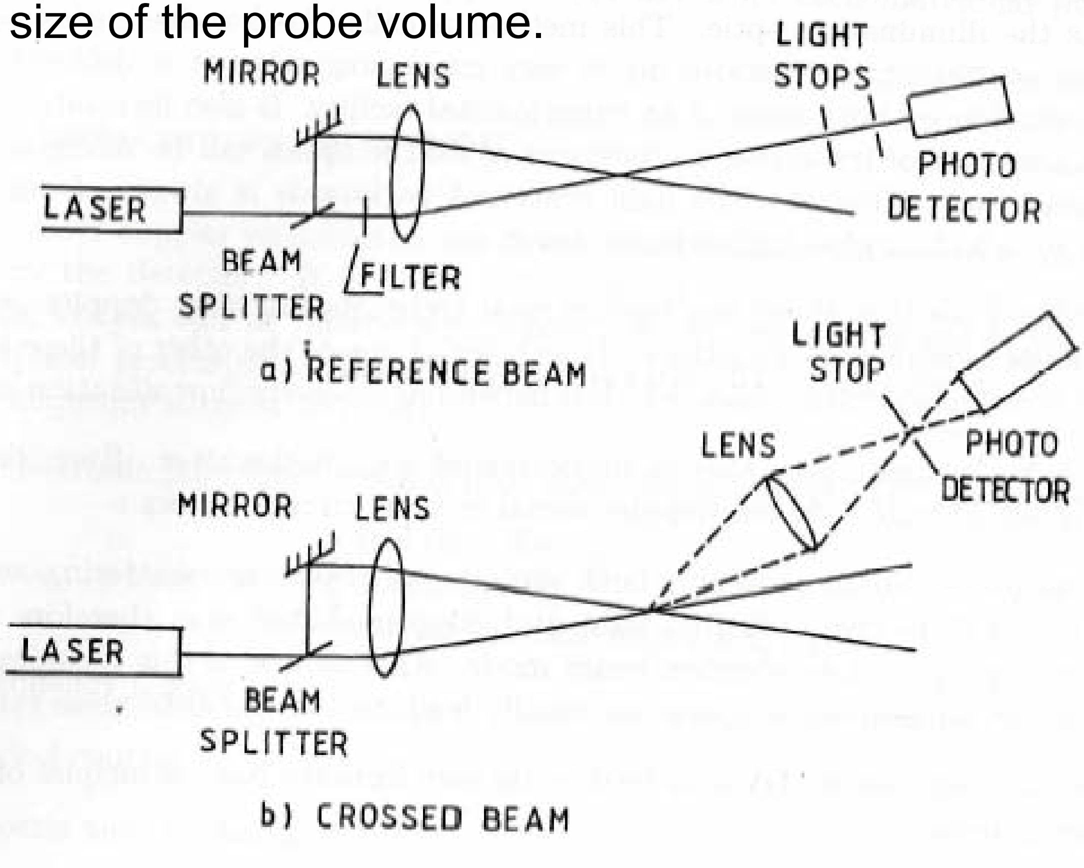


Figure 6.6: Different optical setup

The receiving optic is the one which collects the scattered light to the photodetector.

In reference beam, it consists only of two light stops defining a very narrow beam and excluding all undesirable radiations.

In dual beam, a lens collects scattered light in a wide angle and concentrates it to a photodetector. Between lens and photodetector, a light stop is places. It prevents light scattered from other points than the probe volume.

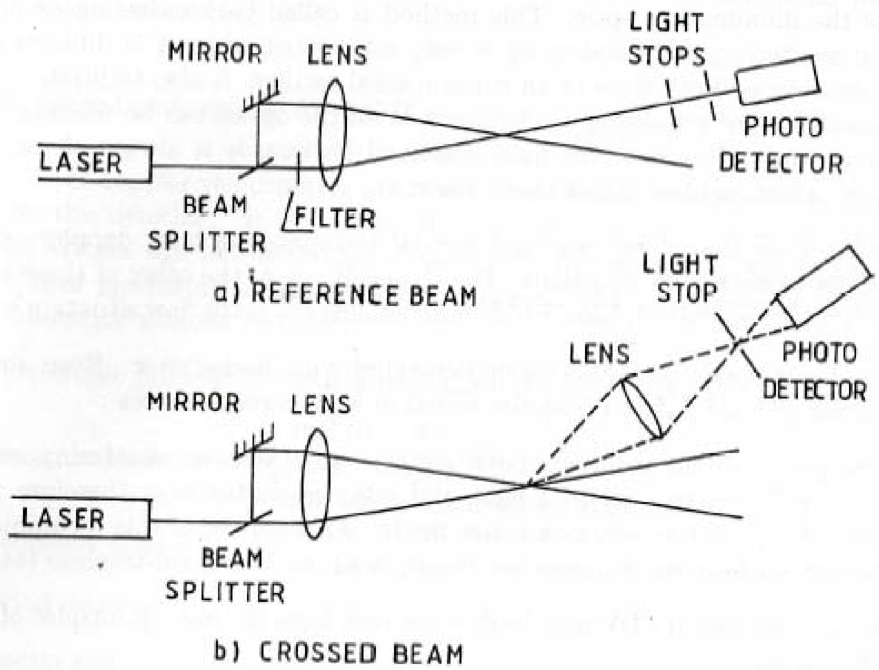


Figure 6.6: Different optical setup

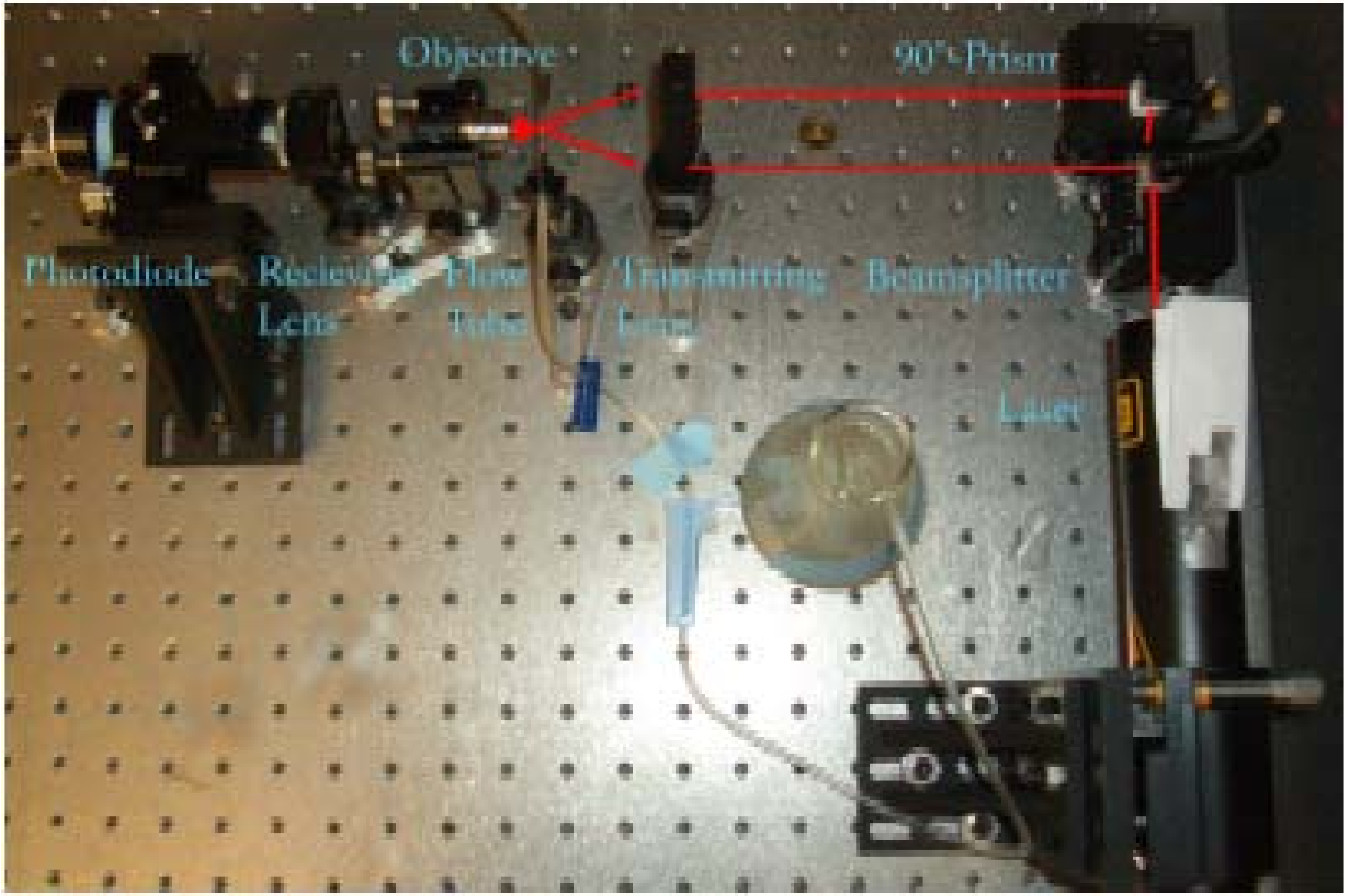


Figure 2: Experimental setup

Different optical modes for LDV

Optical Arrangement:

In order to achieve good spatial resolution, the measuring volume must be as small as possible.

The probe volume is reduced by focusing the illuminating beams. The size of the probe volume is function of the initial beam diameter D; beam angle θ; focal length of lens F_L and laser wavelength λ.

D_0 is the waist diameter of the focused beam:

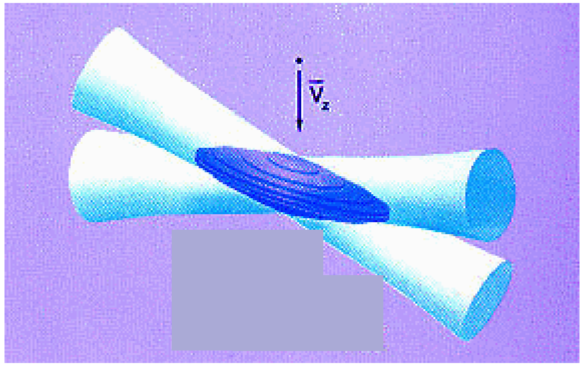
$$D_0 = \frac{4}{\pi}\frac{F_L}{D}\lambda$$

Dimensions of the probe are:

$$\Delta x = D_0$$

$$\Delta y = \frac{D_0}{\cos\theta/2}$$

$$\Delta z = \frac{D_0}{\sin\theta/2}$$



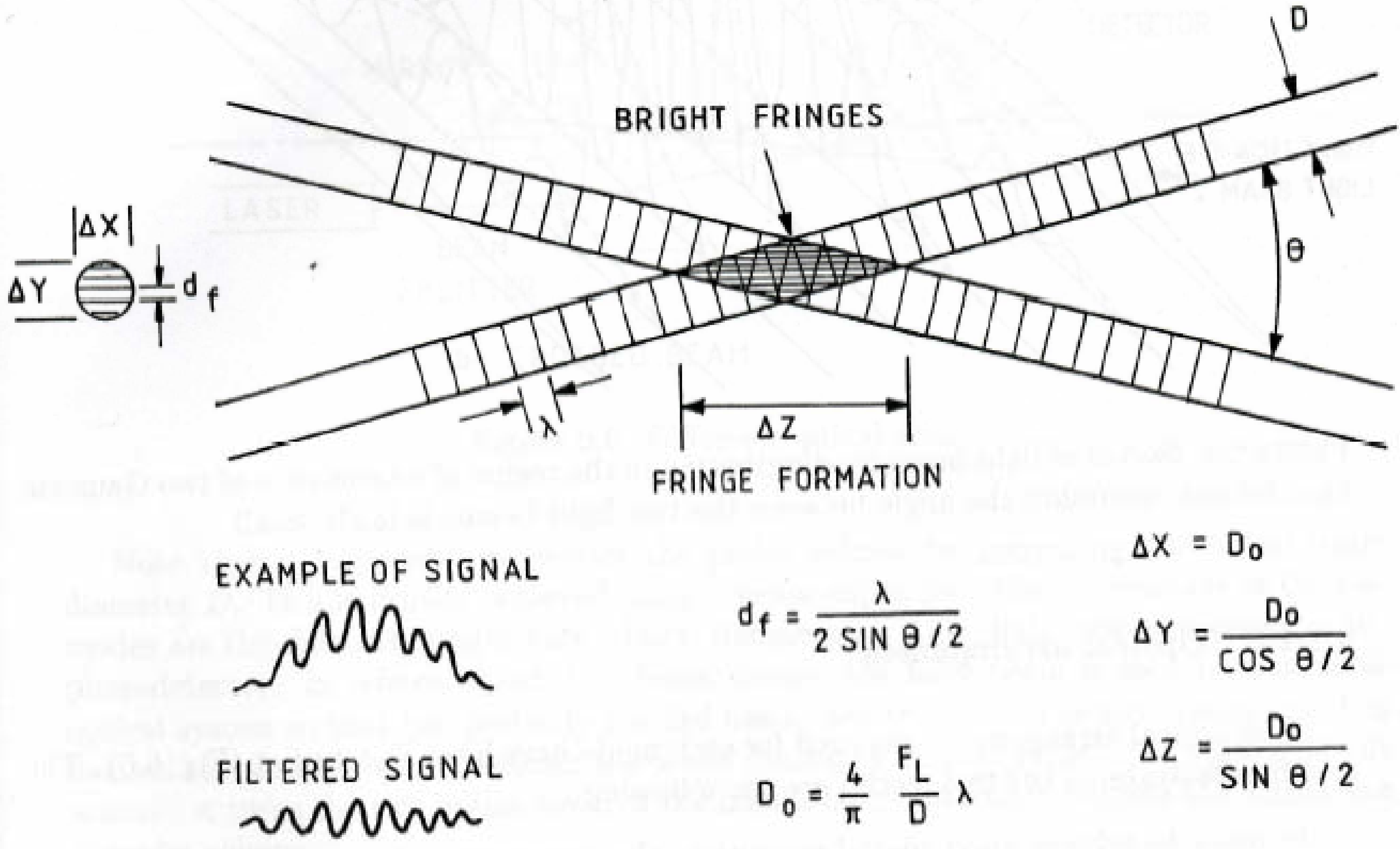
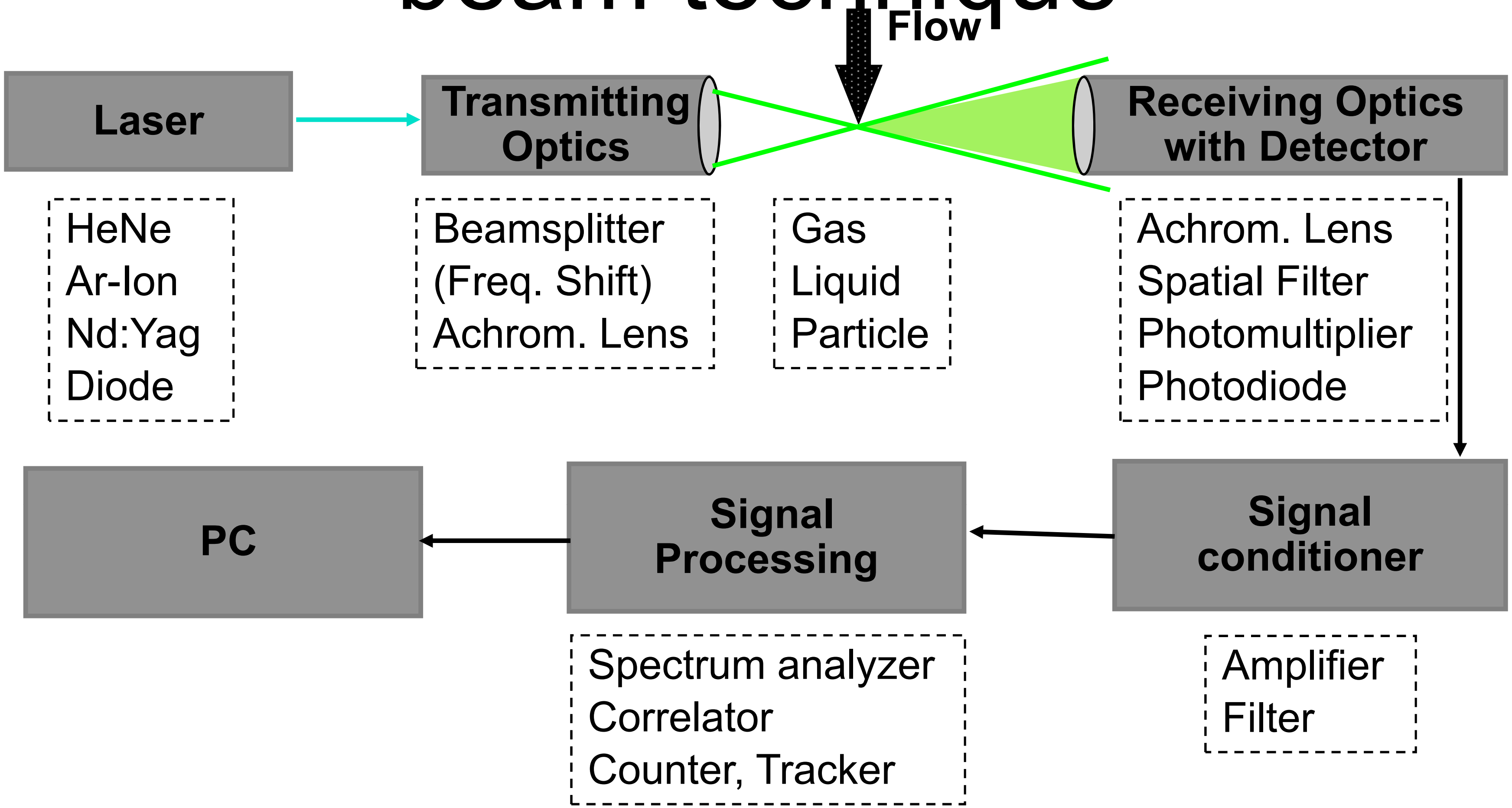
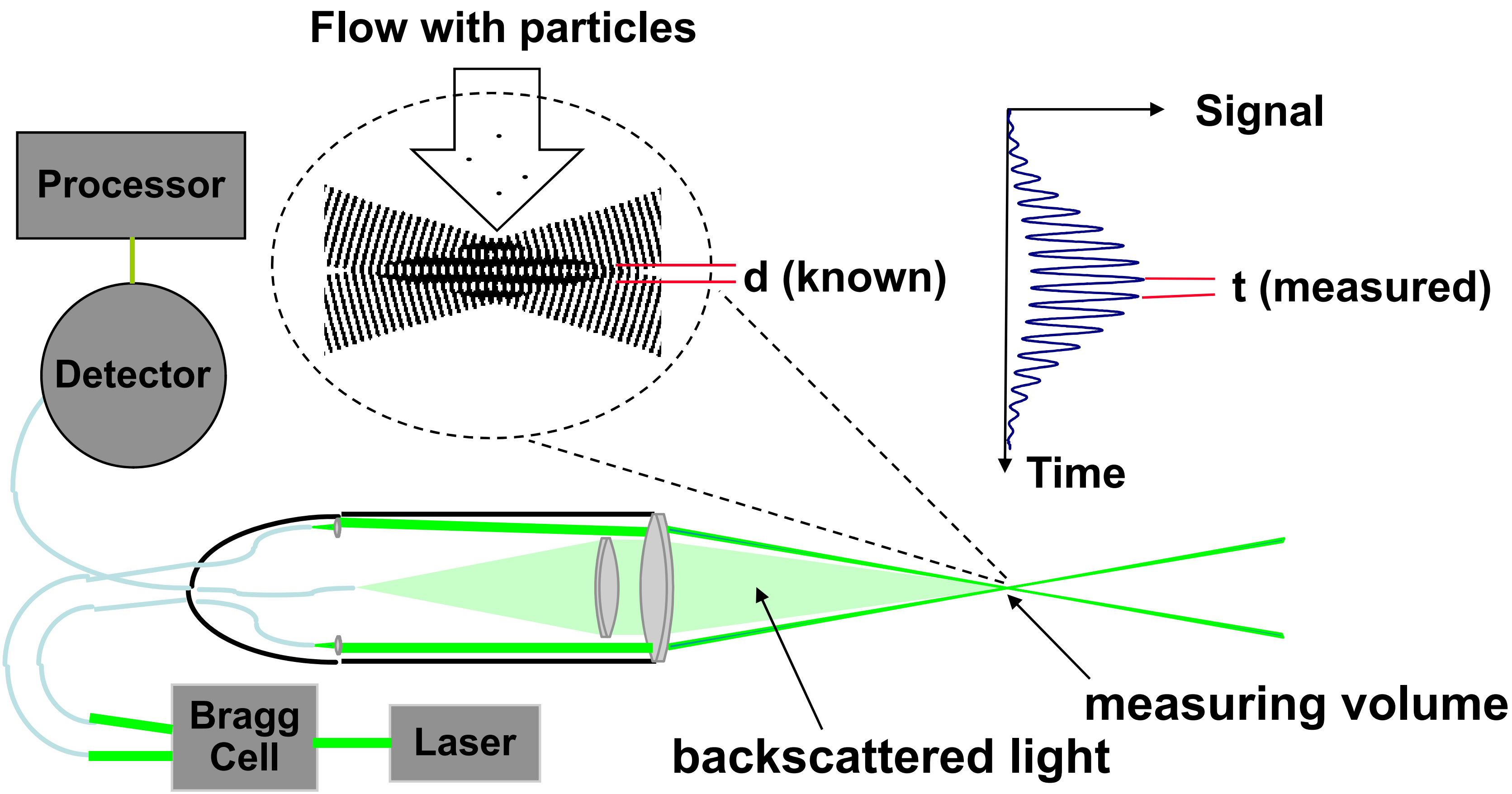


Figure 6.4: Fringe concept and signals

Principle of LDA, differential beam technique

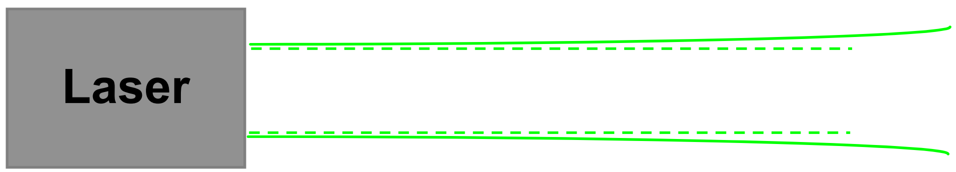


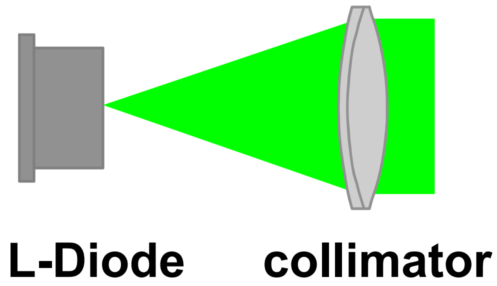
Velocity = distance/time



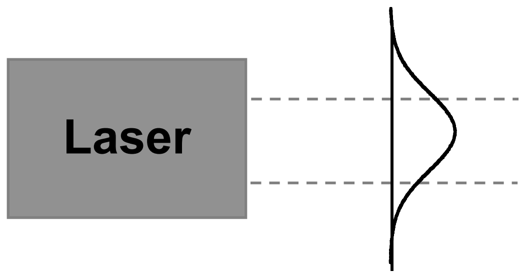
Laser, Characteristics and Requirements

- Monochrome
- Coherent
- Linearly polarized
- Low divergence (collimator)





- Gaussian intensity distribution



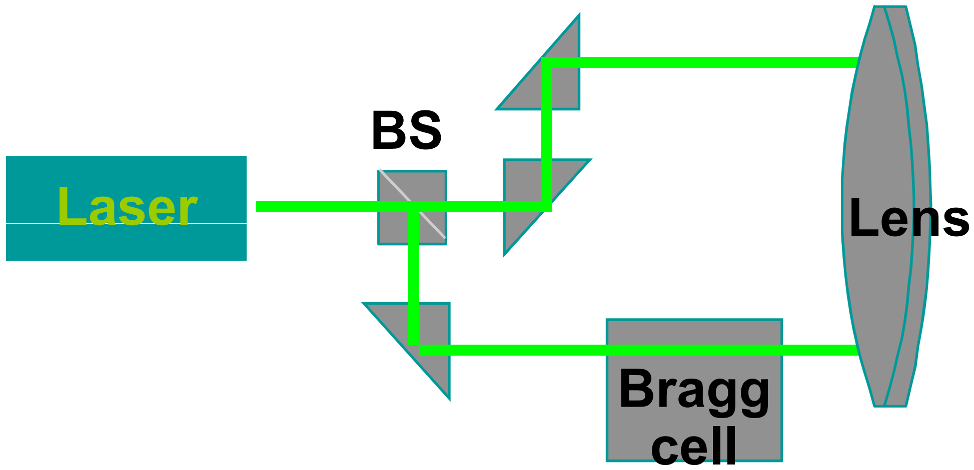
Transmitting optics

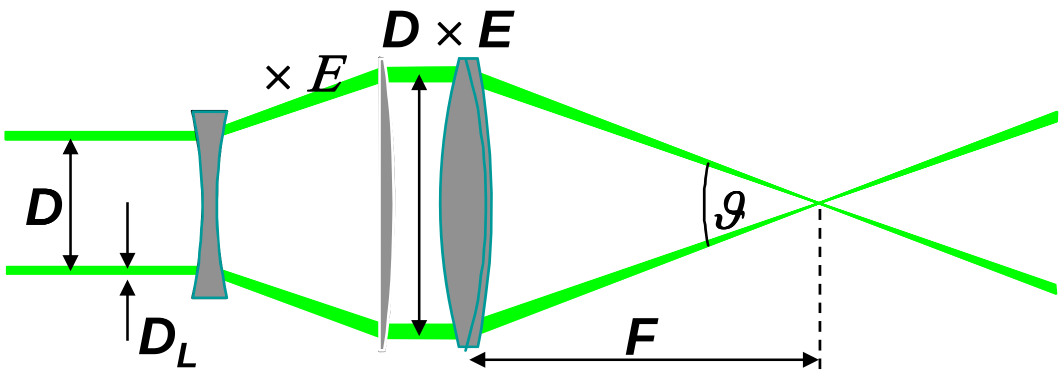
Basic modules:

- Beam splitter
- Achromatic lens

Options:

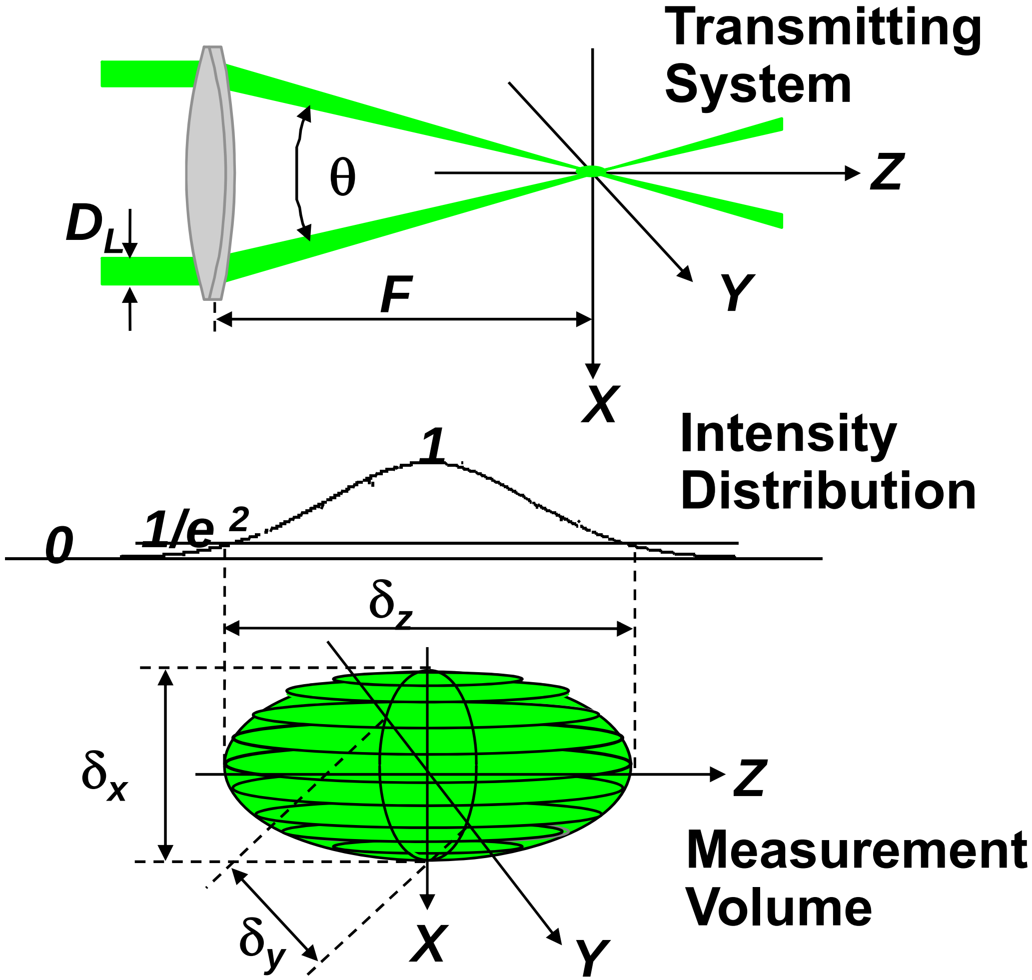
- Frequency shift (Bragg cell)
  - low velocities
  - flow direction
- Beam expanders
  - reduce measurement volume
  - increase power density





Measurement Volume

- The transmitting system generates the measurement volume
- The measurement volume has a Gaussian intensity distribution in all 3 dimensions
- The measurement volume is an ellipsoid
- Dimensions/diameters δ_x, δ_y and δ_z are given by the $1/e^2$ intensity points



Measurement volume

Length:

$$\delta_z = \frac{4F\lambda}{\pi E D_L \sin\left(\frac{\theta}{2}\right)}$$

Width:

$$\delta_y = \frac{4F\lambda}{\pi E D_L}$$

Height:

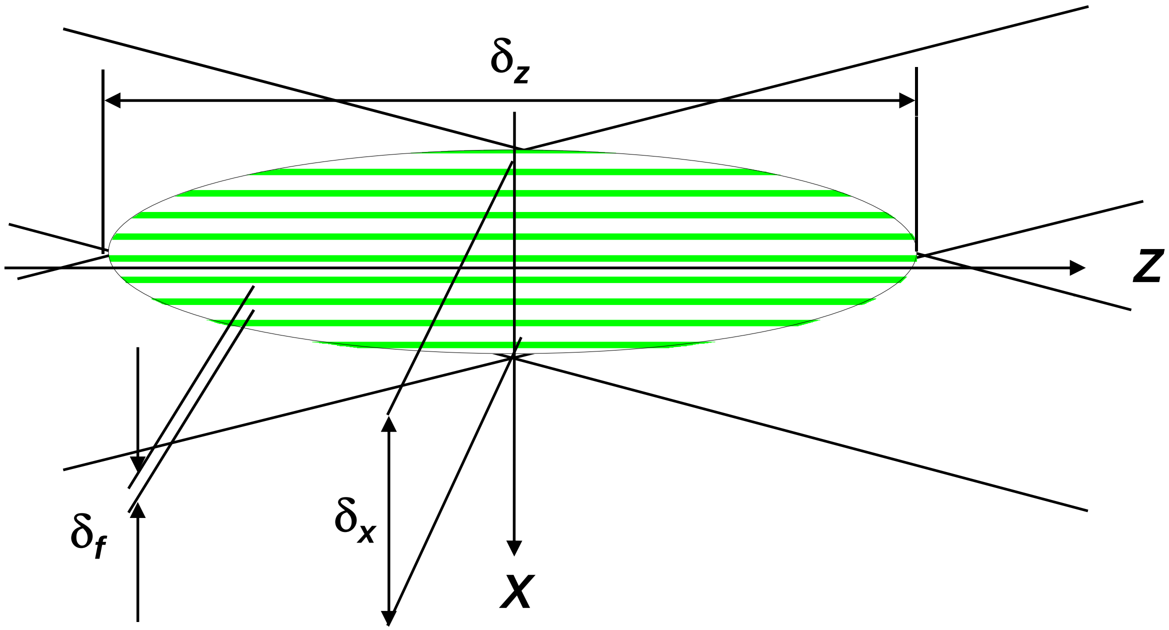
$$\delta_x = \frac{4F\lambda}{\pi E D_L \cos\left(\frac{\theta}{2}\right)}$$

Fringe spacing:

$$\delta_f = \frac{\lambda}{2\sin\left(\frac{\theta}{2}\right)}$$

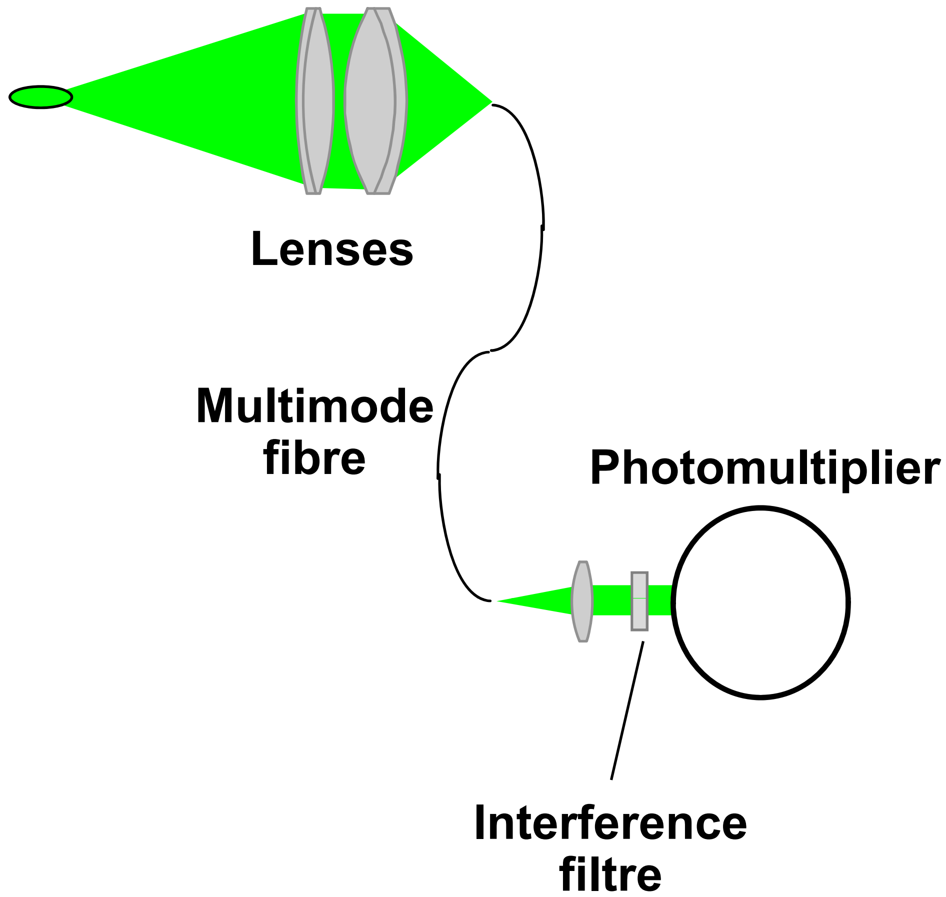
No. of fringes:

$$N_f = \frac{8F\tan\left(\frac{\theta}{2}\right)}{\pi E D_L}$$



Receiving Systems

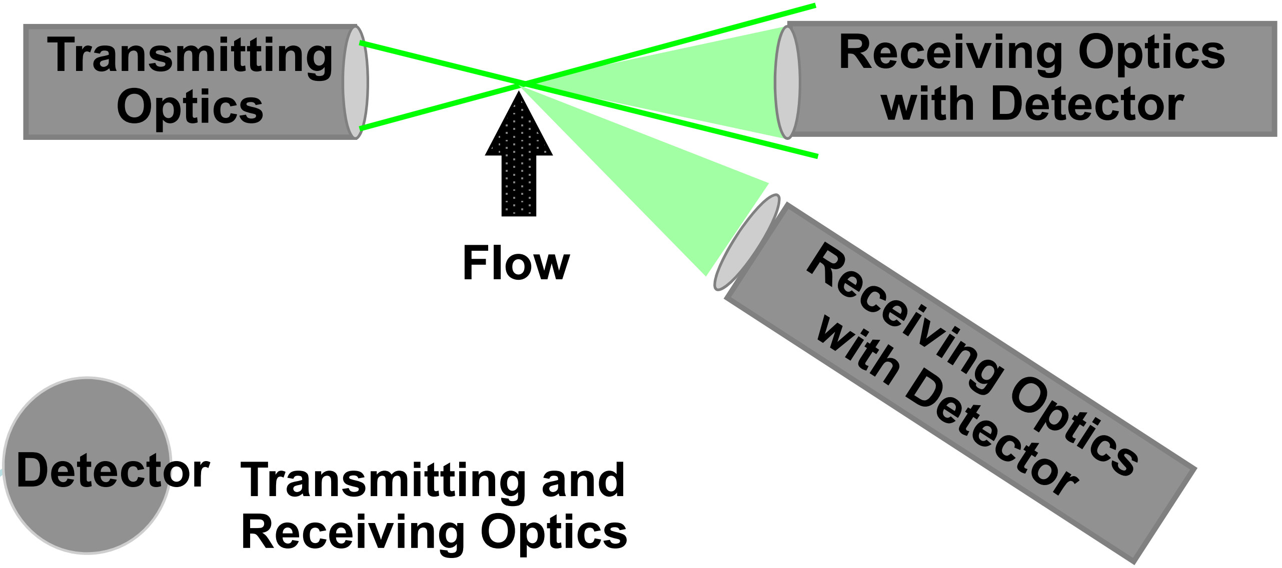
- Receiving Optics
  - Receiving optics
  - Multimode fibre acting as spatial filtre
  - Interference filtre
- Detector
  - Photomultiplier
  - Photodiode



System Configurations

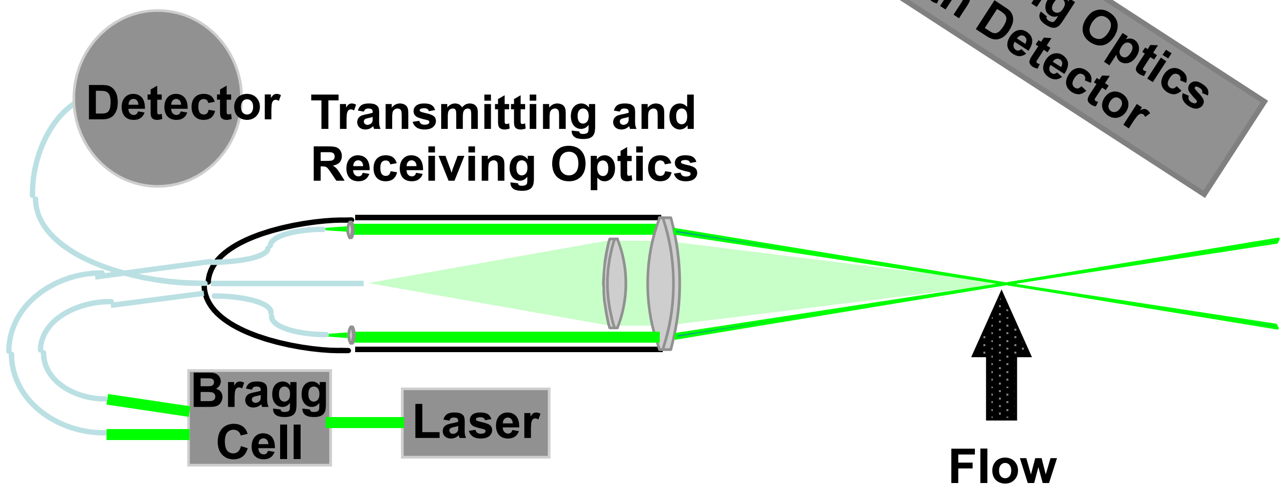
Forward scatter and side scatter (off-axis)

- Difficult to align,
- vibration sensitive

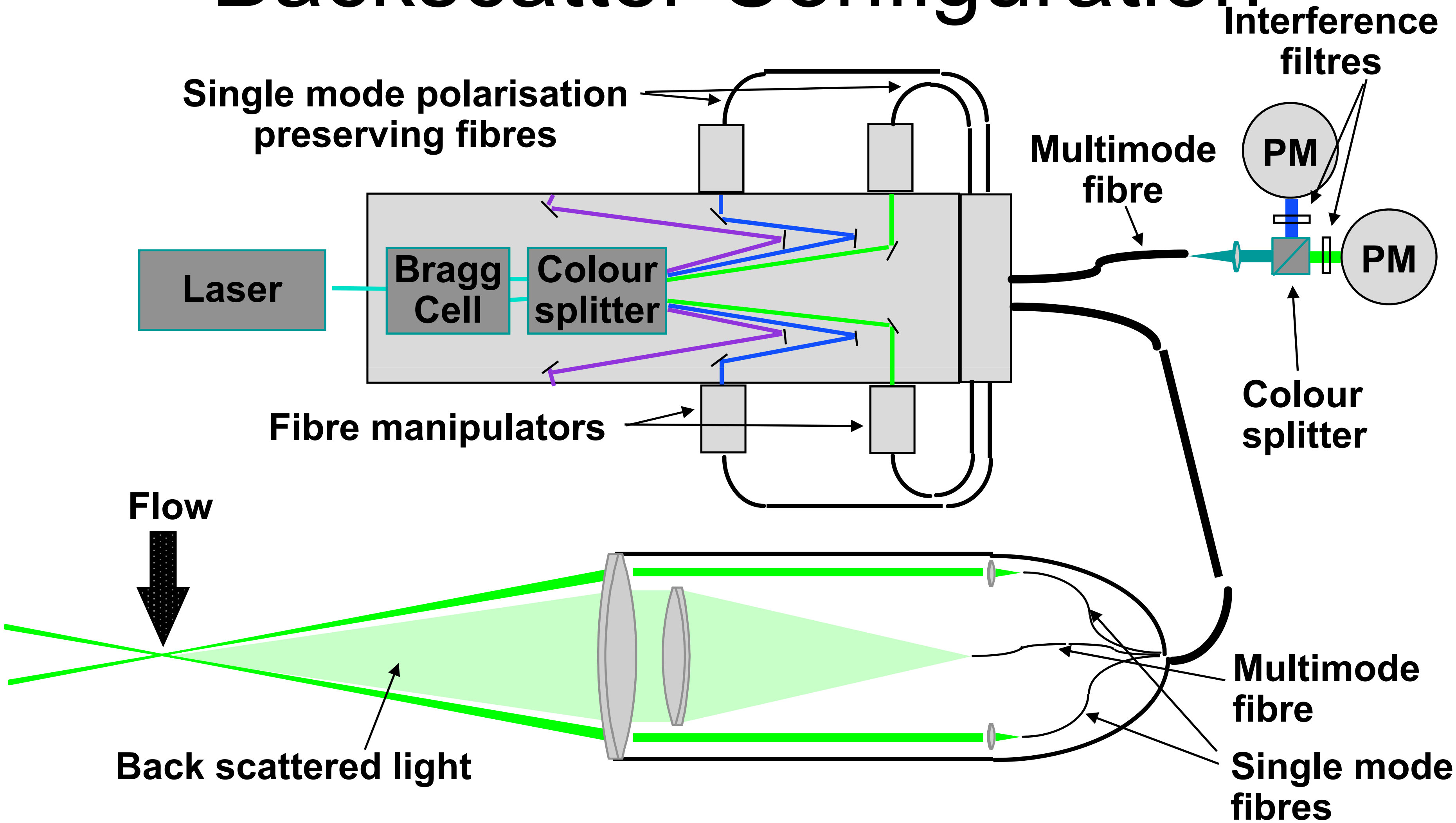


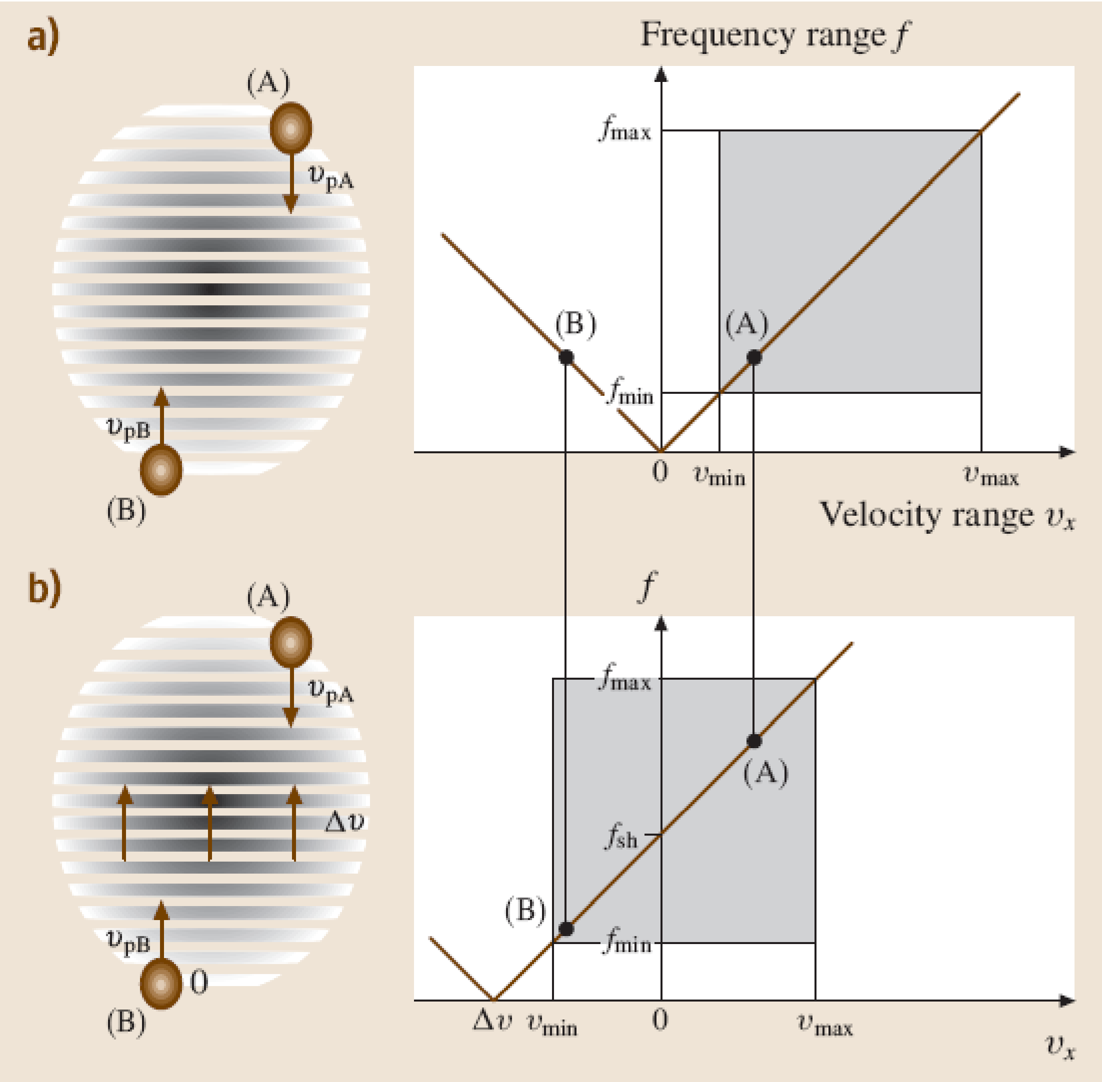
Backscatter

- Easy to align
- User friendly



Backscatter Configuration





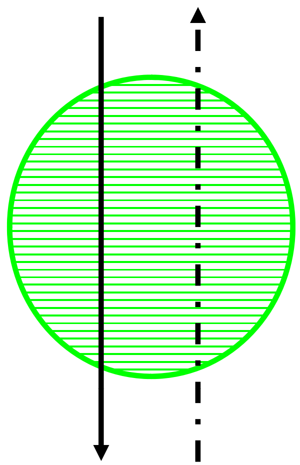
Measured frequencies for particles crossing the measurement volume in positive (A) and negative (B) x directions: **(a)** without frequency shift; and **(b)** with frequency shift

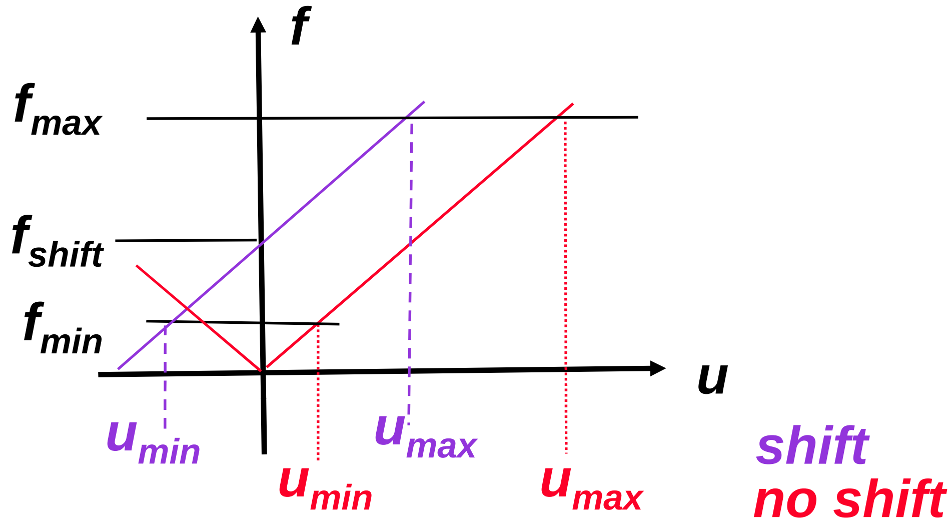
One further requirement is to distinguish the sign of the particle velocity, since the Doppler frequency alone does not contain this information as shown in **Figure (a).** The same signal will be obtained for a particle crossing the fringes in either direction.

To achieve directional sensitivity the frequency of one of the incident beams is shifted by an amount f_s compared to the other beam, which results in a moving fringe pattern. A tracer particle with zero velocity in the measurement volume will result in a received frequency of f_s, while any movement of the particle will result in a frequency larger or smaller than f_s, depending on the direction relative to the fringe motion **Figure (b)**.

Directional Ambiguity / Frequency Shift

- Particles moving in either the forward or reverse direction will produce identical signals and frequencies.

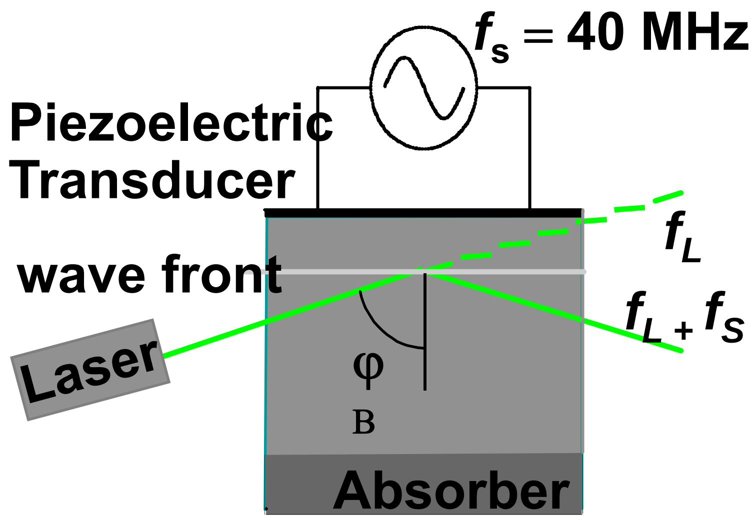




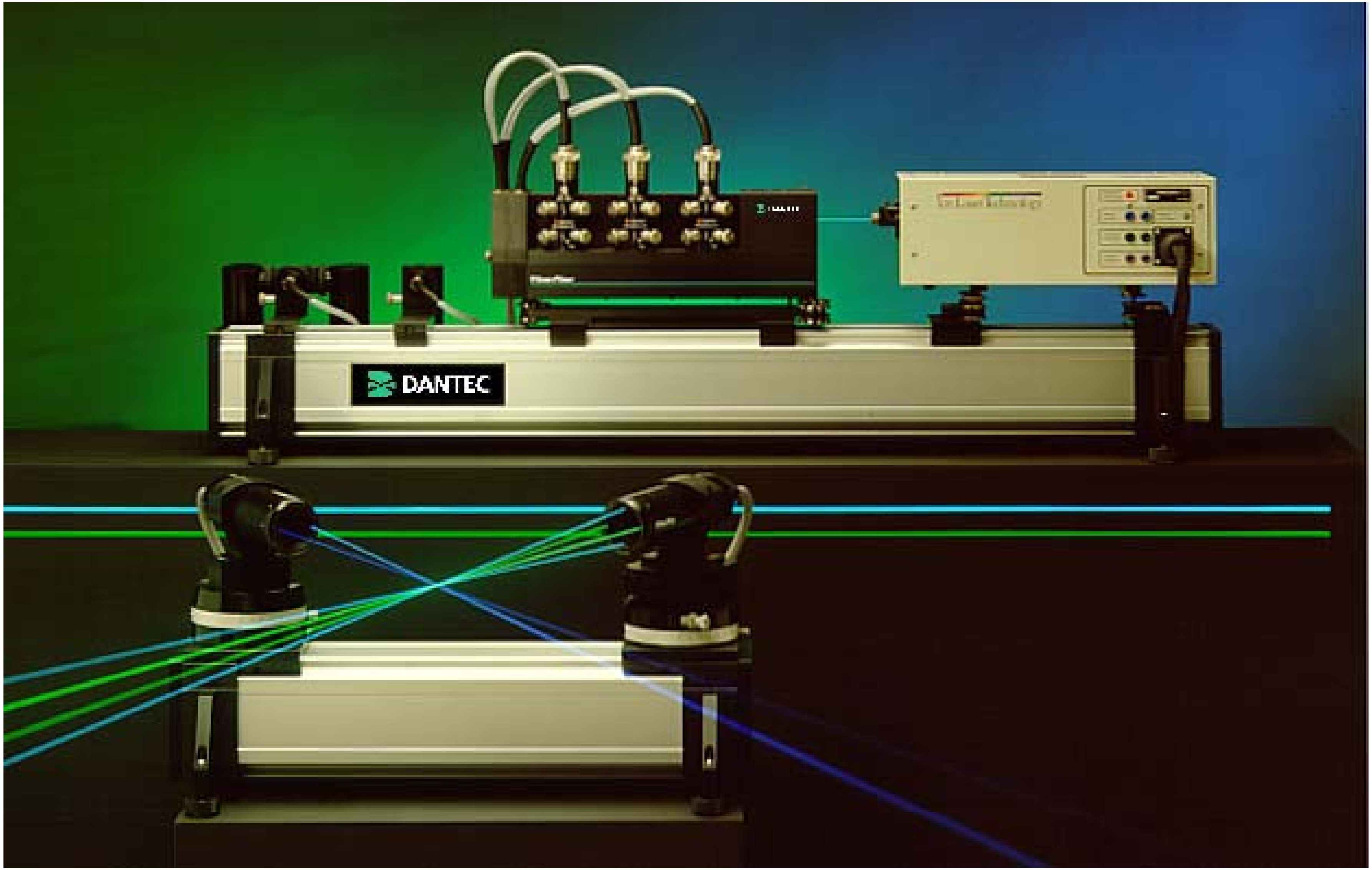
- **With frequency shift in one beam relative to the other, the interference fringes appear to move at the shift frequency.**
- **With frequency shifting, negative velocities can be distinguished.**

Frequency Shift / Bragg Cell

- Acousto-optical Modulator
- Bragg cell requires a signal generator (typically: 40 MHz)
- Frequency of laser light is increased by the shift frequency
- Beam correction by means of additional prisms



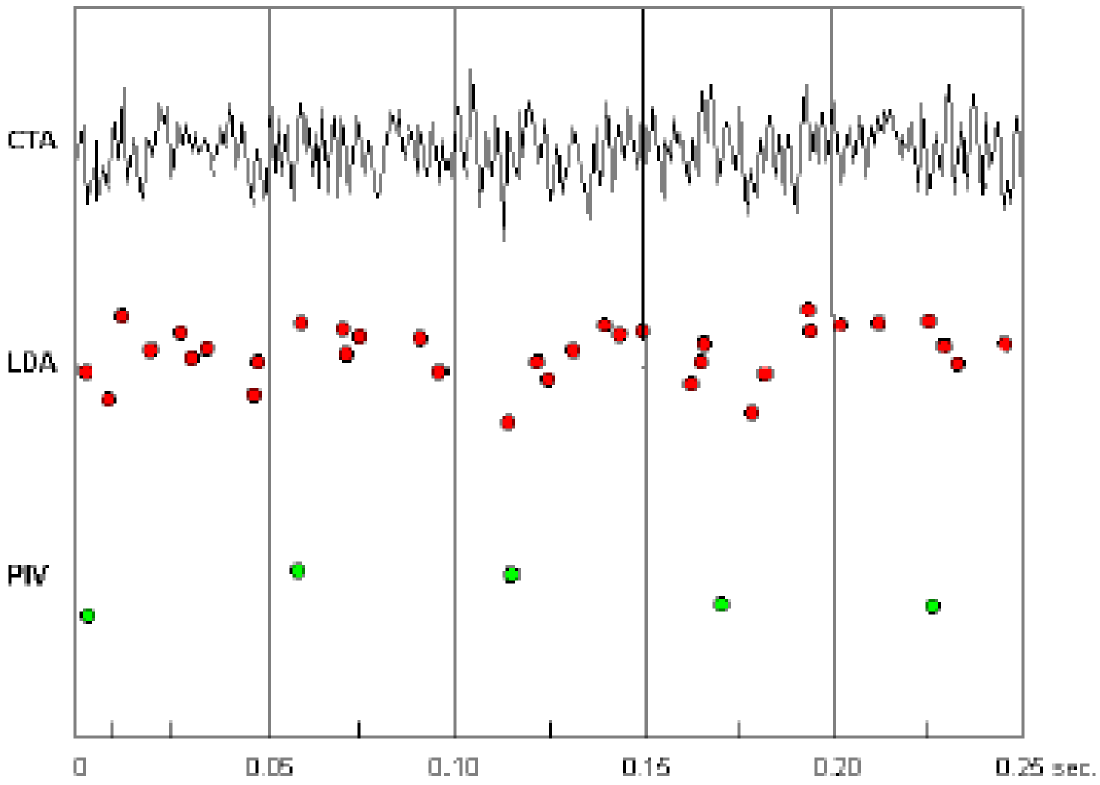
LDA Fibre optical system



Comparison with other techniques

The thermal anemometer provides an analogue output which represents the velocity in a point. A velocity information is thus available anytime.

Note that LDA signals occur at random, while PIV signals are timed with the frame grapping of illuminated particles.



LDA instrumentation from Dantec Dynamics

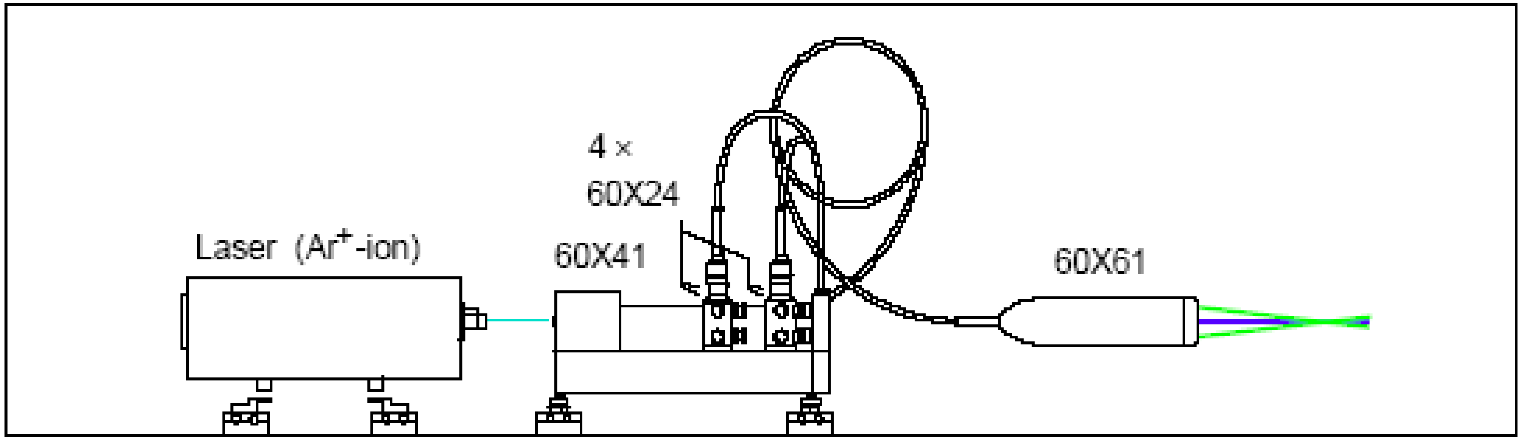
- FlowLite
  - HeNe laser
  - 1 velocity component
  - With frequency shift
  - Wide selection of accessories

- FiberFlow optics/transmitter
  - Ar-Ion laser required
  - 1, 2 or 3 velocity components
  - With frequency shift
  - Wide selection of probes and accessories

Components on the transmitting side

Overview

- Laser: 1D, 2D, 3D: Argon-ion: air or water cooled
- *60X41 Transmitter*
- *60X24 Manipulators*
- *FiberFlow* series probe



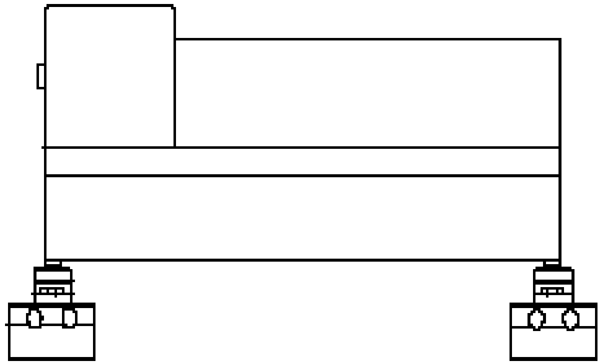
The *60X41 Transmitter*

The *60X41 Transmitter*

- Divides the laser beam into two:
  - one direct
  - one frequency shifted

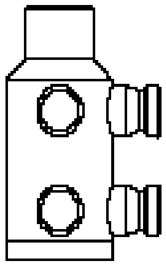
- Each beam is then separated into three colours:
  - green λ = 514,5 nm
  - blue λ = 488 nm
  - purple λ = 476,5 nm

- Each colour is used for measuring one velocity component. Thus the transmitter can be used for 1D, 2D and 3D measurements.



The *60X24 Manipulator*

- The manipulator centres and directs the laser beam to get the maximum amount of light coupled into the thin single mode optical fibers of the fiber flow probe.
- For each output beam from the transmitter one *60X24 Manipulator* is needed.
- Thus, for a 3D system 6 manipulators are needed.

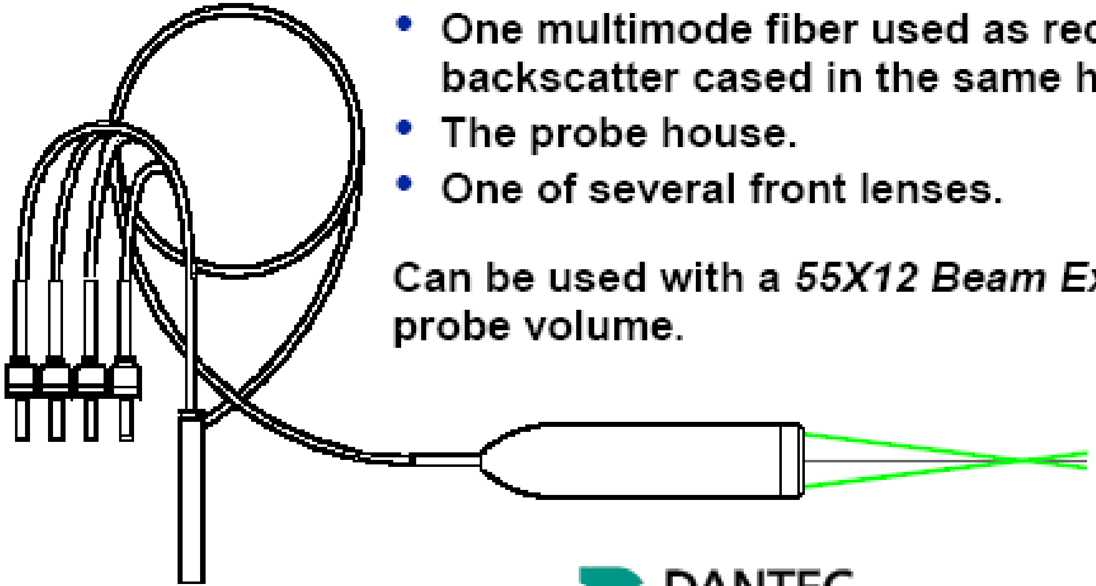


A 60 mm 2D *FiberFlow* probe

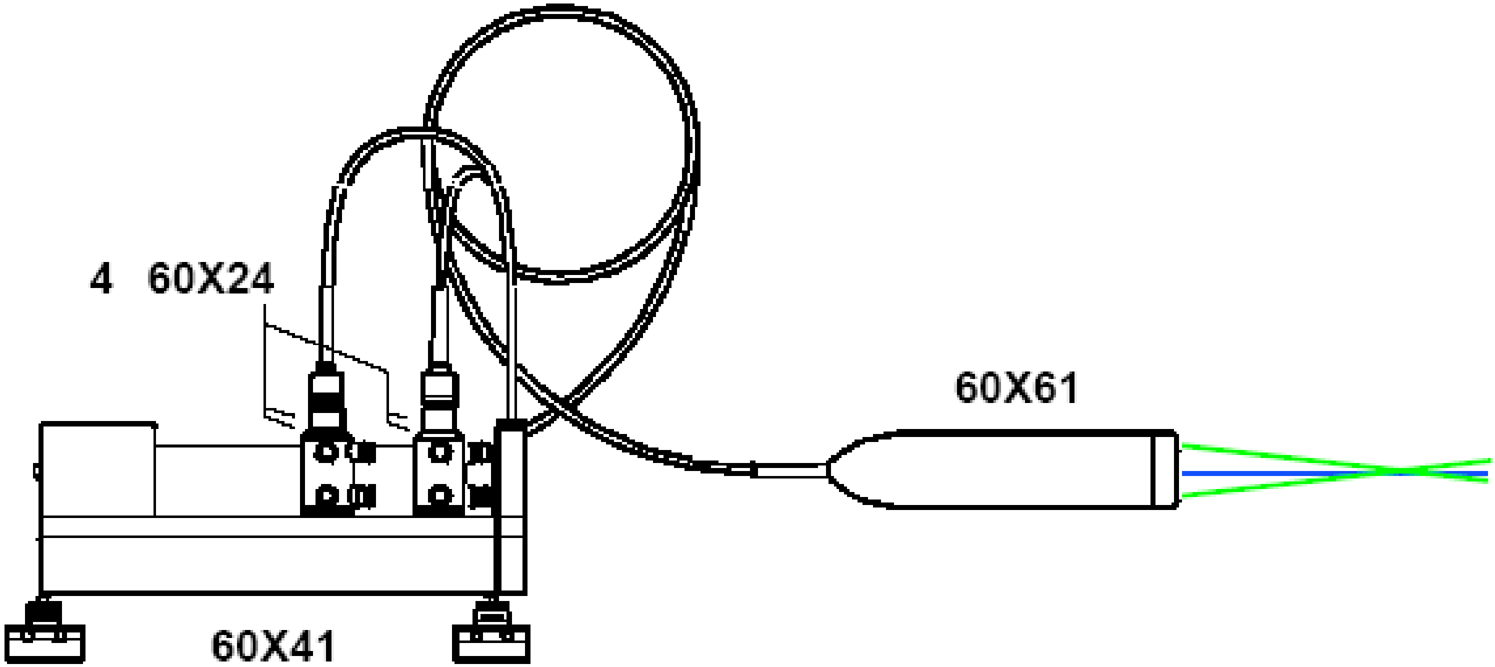
The *FiberFlow* probe comprises

- Four fiber plugs for coupling with the manipulators.
- Four single mode fibers - one for each of the transmitted beams - cased in an enforced cable hose.
- One multimode fiber used as receiving fiber in backscatter cased in the same hose.
- The probe house.
- One of several front lenses.

Can be used with a *55X12 Beam Expander* to reduce probe volume.



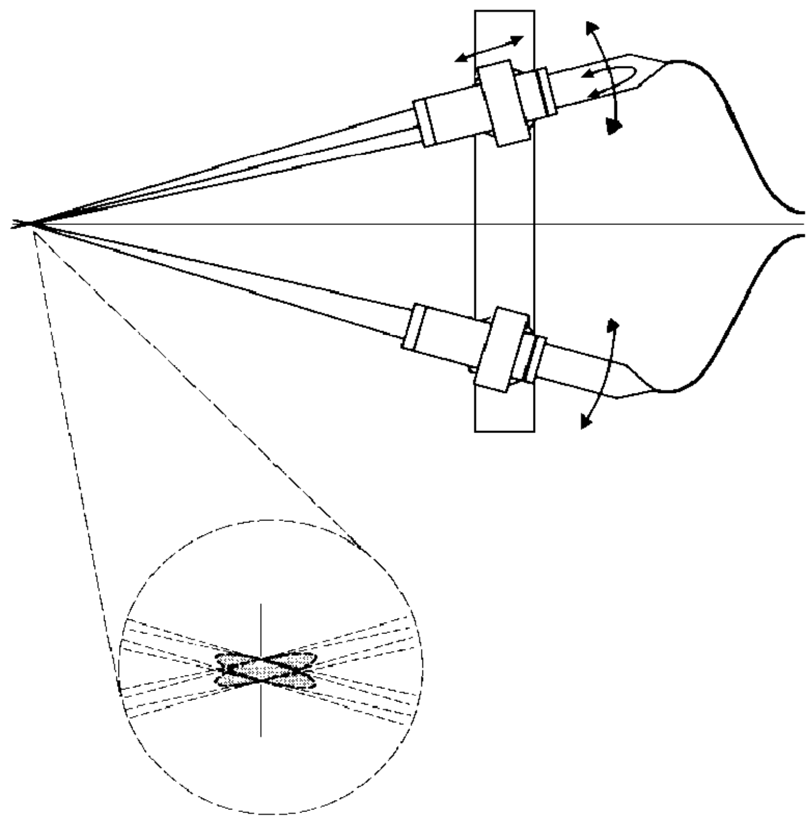
Assembled *FiberFlow* transmitting optics



60 mm and 85 mm *FiberFlow* probes

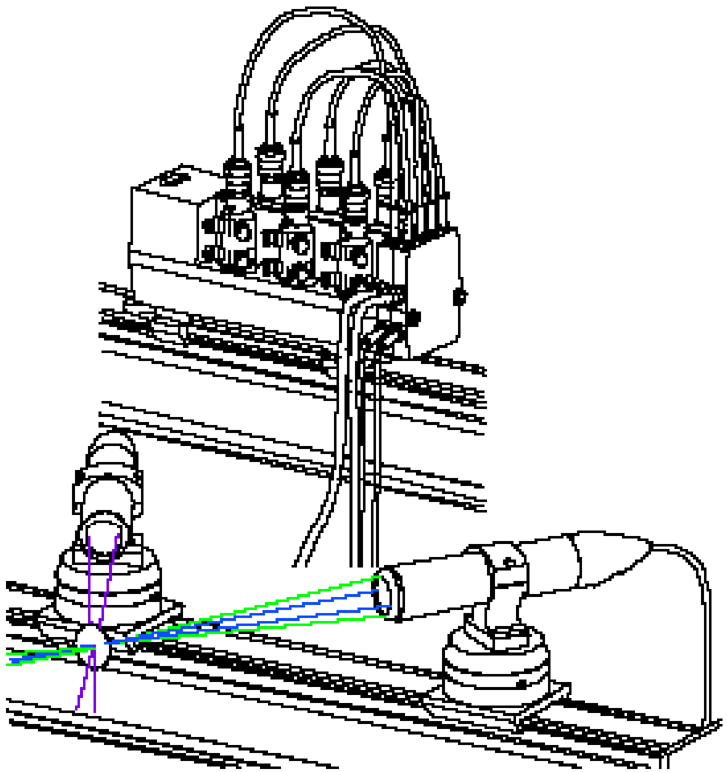
Probe volume alignment for 3D velocity measurements

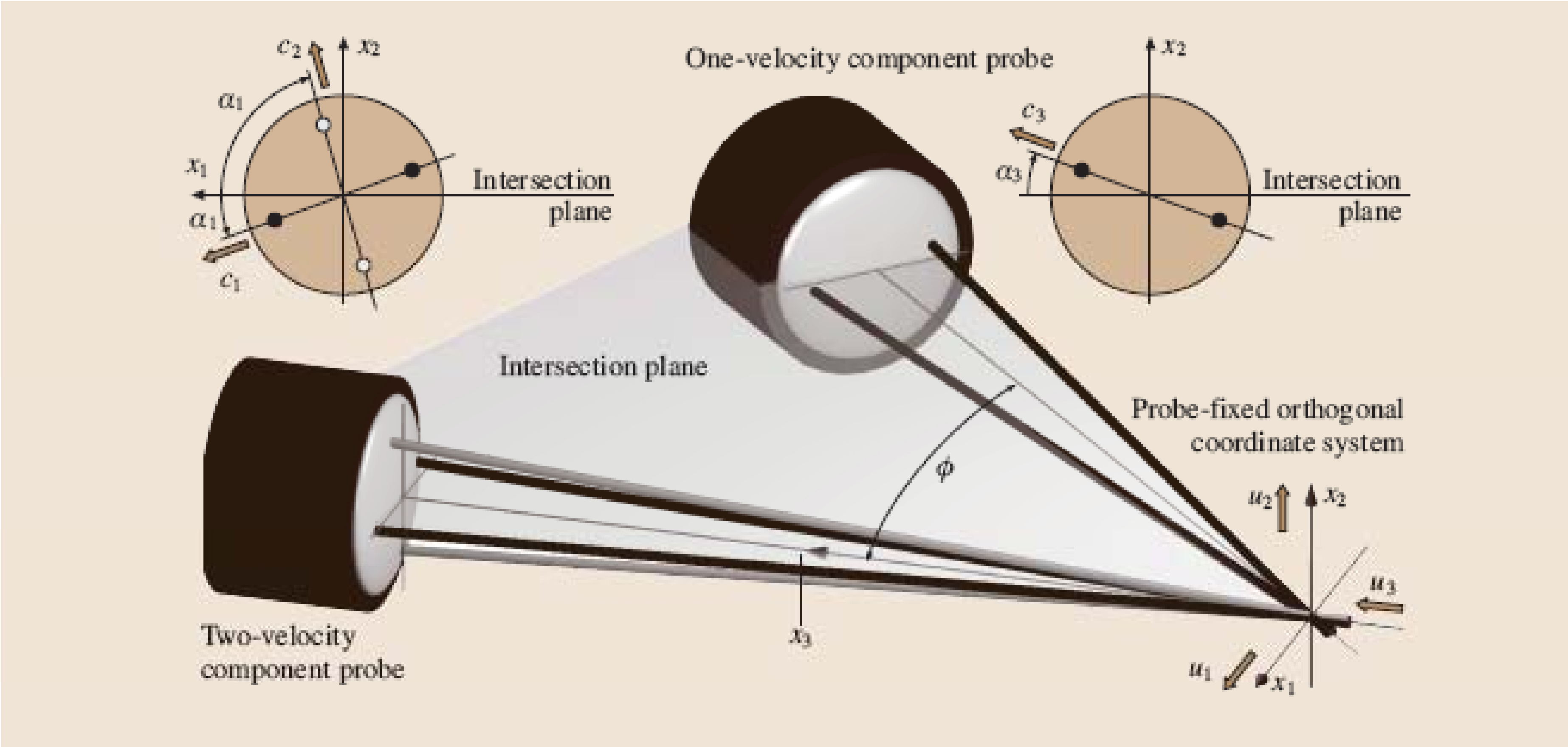
- To measure three velocity components requires careful alignment.
- The simplest method is by using a fine pinhole with an opening just large enough that the focused beam can pass through.
- Fine adjustment can be made using a power meter behind the pinhole maximising the power of light passing through the pinhole for each beam.



FiberFlow set-up for 3D velocity measurements

- Measuring three velocity components requires three beam pairs.
  - Two pairs are emitted from a 2D probe
  - One pair from a 1D probe
- The two probes are aligned so their intersection volumes coincide.
- The velocity components measured by the beams from the 2D probe are orthogonal.
- The third velocity component can be orthogonalized by software.



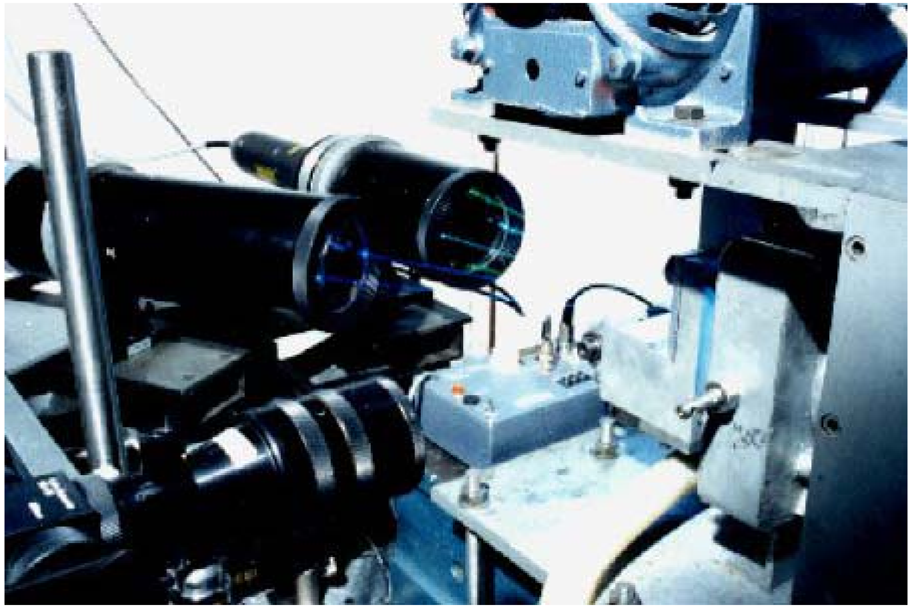


Three-velocity component laser Doppler system, showing measured velocity components and probe-fixed, orthogonal coordinate system

Using three different colors of a laser source, two or three measurement volumes can be overlaid but with differing fringe orientation. By distinguishing the signas from the different beam pairs through color filtering in the receiving optics, two or three velocity components can be simultaneously acquired.

3-D LDA Applications

- Measurements of boundary layer separation in wind tunnels
- Turbulent mixing and flame investigations in combustors
- Studies of boundary layer-wake interactions and instabilities in turbines
- Investigations of flow structure, heat transfer, and instabilities in heat exchangers
- Studies of convection and forced cooling in nuclear reactor models
- Measurements around ship models in towing tanks



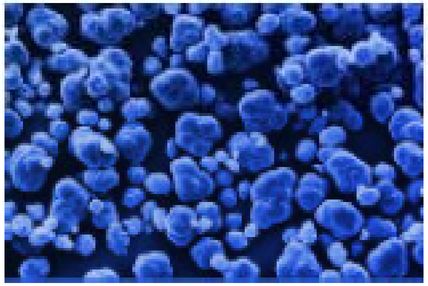
A three-component LDA system

Seeding and Tracer Particles

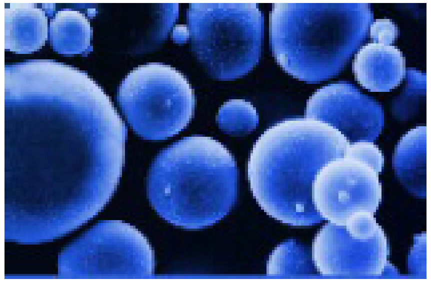
- Main properties

  - **Flow tracking:** The particle should follow the fluid flow as accurately as possible. Therefore the particle should be as small as possible and have a density close the fluids density.

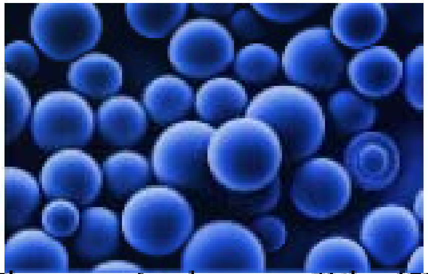
  - **Light scattering:** The particle should scatter light efficiently. Therefore the particle should be as large as possible and there should be a large difference in refractive index between particle and fluid.



Polyamide seeding particles (PSP)



Hollow glass spheres and silver-coated hollow glass spheres (HGS & S-HGS)



Fluorescent polymer particles (FPP)

Seeding and Tracer Particles

- Desired properties
  - Conveniently generated.
  - Cheap.
  - Non-toxic, non-corrosive
  - Non-volatile, or slow to evaporate.
  - Chemically inactive.
  - Clean.
  - Uniform seeding
  - Spherical particles
  - Long lived

Diameter d_p	Scattering cross section C_s	
Molecule		$\simeq 10^{-33}$ m^2
1 μm	$C_s \simeq (d_p/\lambda)^4$	$\simeq 10^{-12}$ m^2
10 μm	$C_s \simeq (d_p/\lambda)^2$	$\simeq 10^{-9}$ m^2

Seeding: ability to follow flow

Particle Frequency Response

$$\frac{d}{dt}U_p = -18\frac{\nu}{d_p^2}\frac{U_p - U_f}{\rho_p / \rho_f}$$

Particle	Fluid	Diameter (μm) f = 1 kHz	f = 10 kHz
Silicone oil	atmospheric air	2.6	0.8
TiO_2	atmospheric air	1.3	0.4
MgO	methane-air flame (1800 K)	2.6	0.8
TiO_2	oxygen plasma (2800 K)	3.2	0.8

Seeding and Tracer Particles

- Turbulence

Particle response in turbulent flow (η = 0.99)

Particle	ρ_p (kg m^{-3})	Gas (10^5 Pa)	Density ratio s	Viscosity ν (m^2 s^{-1})	f_c (kHz)	Sk_c	d_p (μm)
TiO_2	3500	Air (300 K)	2950	1.50×10^{-5}	1	0.0295	1.44
					10		0.45
Al_2O_3	3970	Flame (1800 K)	20250	3.00×10^{-4}	1	0.0113	2.46
					10		0.78
Glass	2600	Air (300 K)	2190	1.50×10^{-5}	1	0.0342	1.67
					10		0.53
Olive oil	970	Air (220 K)	617	1.45×10^{-5}	1	0.0645	3.09
					10		0.98
Microballoon	100	Air (300 K)	84.5	1.50×10^{-5}	1	0.1742	8.50
					10		2.69

Particle selection (Air flow)

Material	Particle Diameter [μm]	Comments
Al_2O_3	< 8	Generated by fluidisation. Useful for seeding flames on account of a high melting point.
Glycerine	0.1 - 5	Usually generated using an atomiser.
Silicone oil	1 - 3	Very satisfactory.
SiO_2 Particles	1 - 5	Spherical particles with a very narrow size distribution. Better light scatterer than TiO_2, but not as good as glycerine.
TiO_2 Powder	From submicron to tens of microns	Good light scatterer and stable in flames up to 2500°C. Very wide size distribution and lumped particle shapes.
Water	1 - 2	Generated by atomisation. Evaporation inhibitor must be added.
MgO		Generated by combustion of magnesium powder giving a dirty unsteady supply of seeding.

- Particle selection (water flow)

Material	Particle Diameter [μm]	Comments
Aluminium powder	< 10	Preserves polarisation by scattering.
Bubbles	5 - 500	Can only be used if two-phase flow is acceptable.
Glass balloons	10 - 150	Cheap even in large volumes, but with a large spread in particle size.
Latex beads	0.5 - 90	Can be delivered with relatively narrow size distribution, but quite expensive.
Milk	0.3 - 3	Cheap and efficient.
Pine Pollen	30 - 50	Egg-shaped and swell somewhat after some time in water. Can be supplied in large volumes.

Seeding: ability to follow flow

In order to measure fluid velocity using the technique of laser anemometry, it is necessary for the fluid to contain “tracer particles” or “scattering centers.”

The characteristics of these particles are important for two reasons:

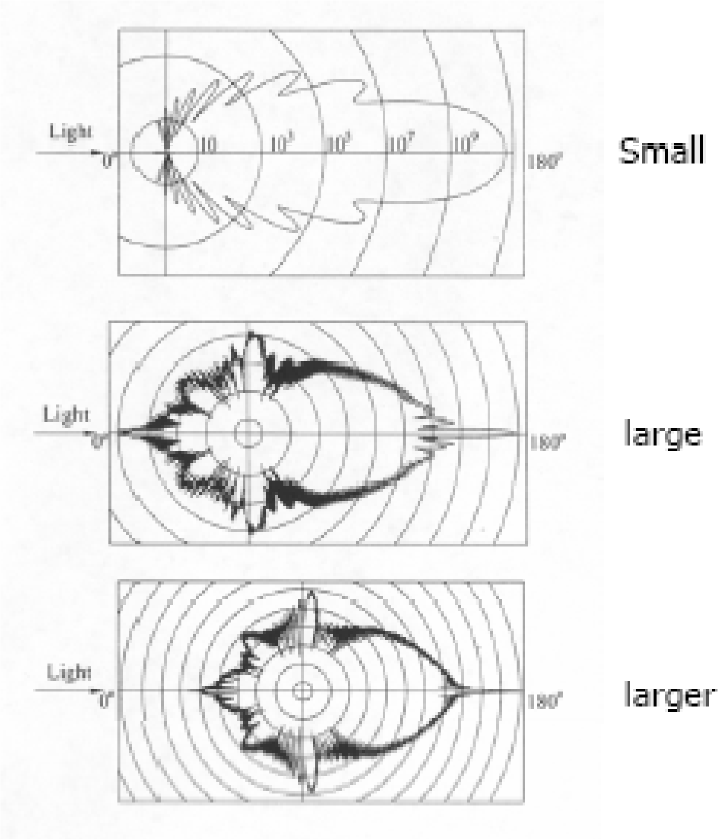
i) if the particles *do not* follow the flow, the interpretation of the measurement result is subject to error,

ii) the signal obtained from particles is a function of many parameters including: particle size, scattering direction, index of refraction, etc.

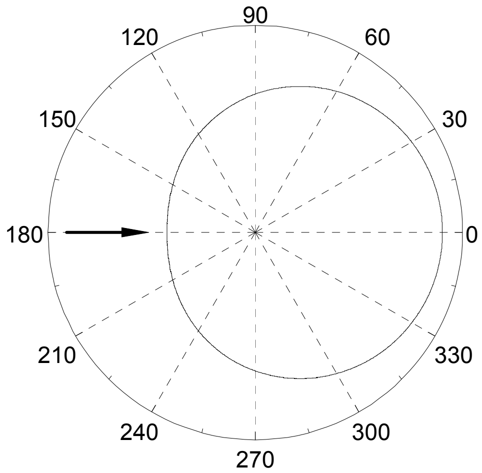
Seeding and Tracer Particles

- Lorentz-Mie light scattering

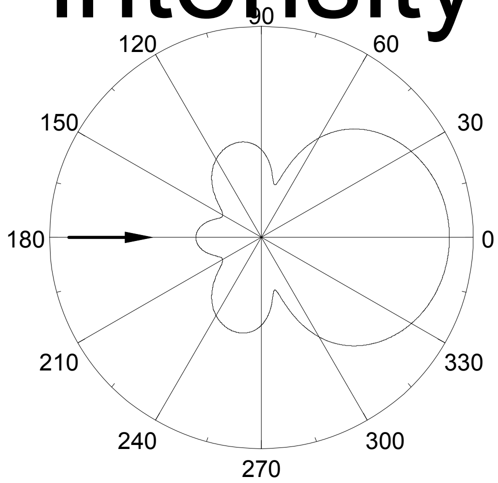
  - The seeding particles have a diameters ranging from 0.1μm to 50μm, depending on the flow.
  - Small particles have quick response – but poor light scattering
  - Large particles have slow response but good light scattering
  - Strong directional dependency of scattered light



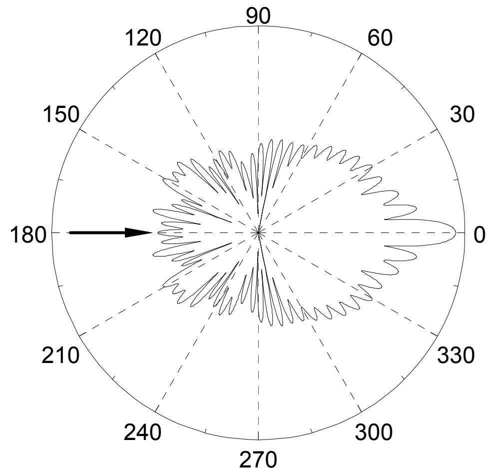
Seeding: scattered light intensity



$d_p \cong 0.2\lambda$



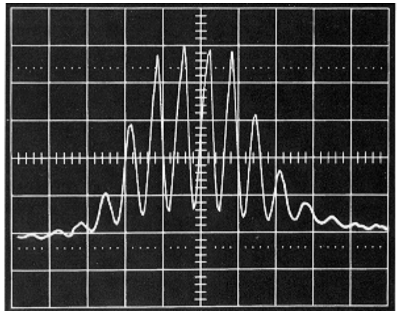
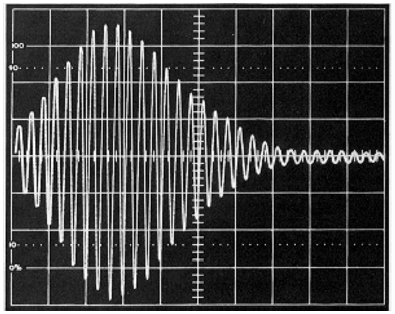
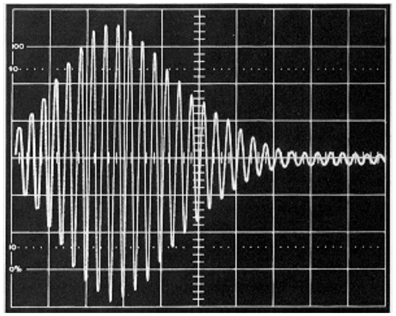
$d_p \cong 1.0\lambda$



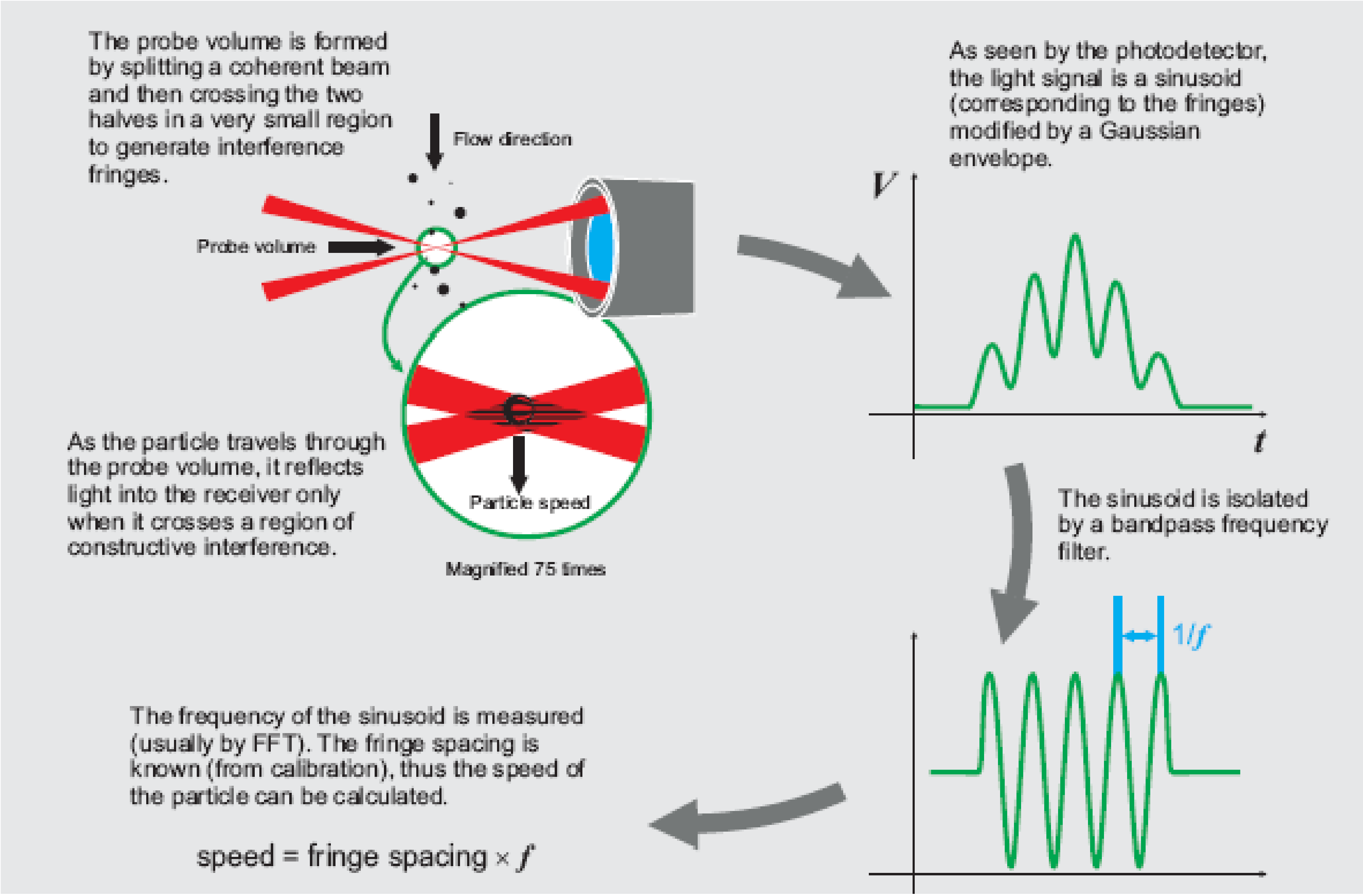
$d_p \cong 10\lambda$

- **Polar plot of scattered light intensity versus scattering angle**
- **The intensity is shown on a logarithmic scale**

Signal characteristics

- Sources of noise in the LDA signal:
  - Photo detection shot noise.
  - Secondary electronic noise, thermal noise from preamplifier circuit
  - Higher order laser modes (optical noise).
  - Light scattered from outside the measurement volume, dirt, scratched windows, ambient light, multiple particles, etc.
  - Unwanted reflections (windows, lenses, mirrors, etc).
- Goal: Select laser power, seeding, optical parameters, etc. to maximise the SNR.


The probe volume is formed by splitting a coherent beam and then crossing the two halves in a very small region to generate interference fringes.
Flow direction
Probe volume
As the particle travels through the probe volume, it reflects light into the receiver only when it crosses a region of constructive interference.
Particle speed
Magnified 75 times
As seen by the photodetector, the light signal is a sinusoid (corresponding to the fringes) modified by a Gaussian envelope.
V
t
The sinusoid is isolated by a bandpass frequency filter.
1/f
The frequency of the sinusoid is measured (usually by FFT). The fringe spacing is known (from calibration), thus the speed of the particle can be calculated.
speed = fringe spacing × f

DATA PROCESSING

What is a Signal Processor?

A signal processor is a device designed to measure the instantaneous Doppler frequency and convert it into a velocity measurement.

System Requirements:

Accurate discrimination of burst.
High dynamic range.
Large frequency range.
High data rate capacity.
Can discriminate signal in low SNR.

Signal Processor Types:

Spectrum Analyzers.
Photon Correlators.
Trackers.
Counters.
Covariance processor.
Digital Signal processor.

System Requirements:

Accurate discrimination of burst: Measuring individual burst as opposed to a mean burst averaged over several bursts is important, particularly in turbulent flows. It is very important to be able to measure this burst accurately.

High dynamic range: High dynamic range means the processor can measure velocities over a wide range from high speed flow to flow reversal with minimal change to system parameters.

Large frequency range: Large frequency range implies that the processor does not have an inadequate floor or ceiling on the range of velocities that it can process. In other words, velocities ranging from mm/s to km/s can be processed.

High data rate capacity: Some flows have characteristically high data rates. In addition, high data rates are needed for spectral analysis.

Can discriminate signal in low SNR Must be able to identify and measure a burst in high background noise.

Processor Types:

Spectrum Analyzers: FFT to get power spectrum, then determine Doppler frequency. Good for average frequency but not for instantaneous frequency measurement.

Photon correlators: similar to spectrum analyzer but could be used for lower SNR.

Trackers: Good for high burst density (high data rate) signals. Did not work well in low data density situations (low data rate) due to the trackers inability to track large velocity changes with large time between data bursts.

Counters: used a high speed clock and logic circuits to measure the time between a fixed number of fringe crossings or cycles in the burst signal. The counter could not measure signals well in low SNR situations.

Covariance processor: poor accuracy.

Digital Signal Processors: Digitally sample the burst with a high frequency and then perform a variety of signal processing techniques to determine the Doppler frequency

DIGITAL SIGNAL PROCESSORS

Digitally sample the burst with a high frequency and then perform a variety of signal processing techniques to determine the Doppler frequency.

These processors combine:

- High pass filters to remove low frequency components such as low frequency noise.
- Low pass filters to limit high frequency noise components.
- High speed A/D converter.
- Burst detection algorithms to help identify burst from background signal. Digital signal analyzer to estimate the frequency.

LDV SIGNAL BIAS

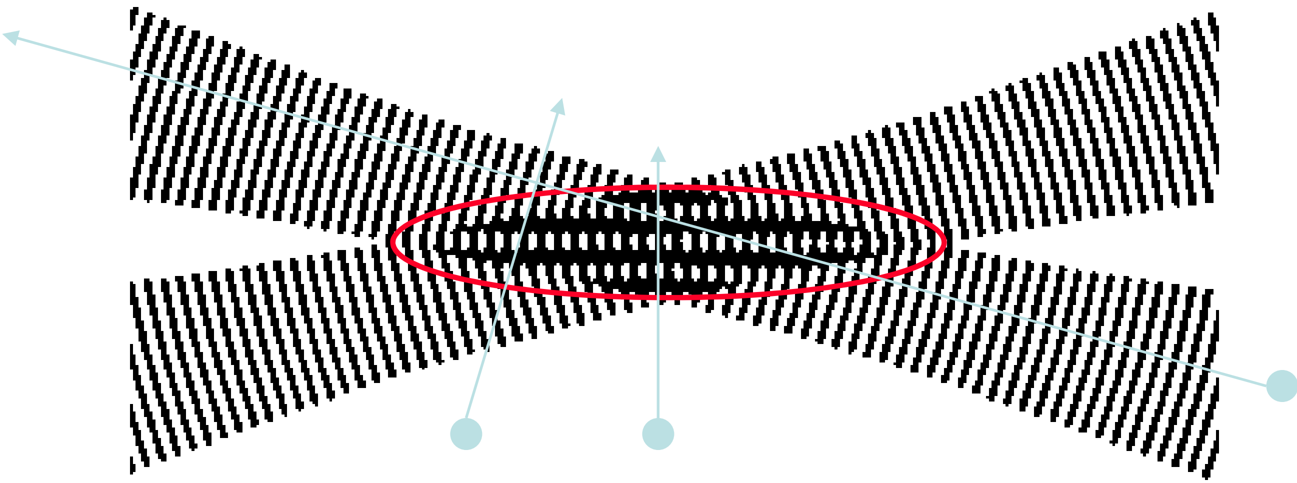
Bias: An one way error in the calculation of a statistic caused by an identifiable but uncontrollable source causing an unrealistically high or low measure of that statistical quantity.

Types of bias in LDV signals:

1) Velocity bias.

2) Fringe bias.

3) Gradient bias.



LDV SIGNAL BIAS

Type of bias in LDV signals:

Velocity bias – the statistics for LDV measured data are random arrival in time with a higher probability of getting more particles with a high velocity component crossing the probe volume in a given sampling time than particle with a lower velocity component. As a result, standard statistical methods such as ensemble averaging produces an averaged that is bias towards the higher velocities.

Fringe Bias: The LDV probe volume has a limited size and limited number of fringes. Most processors require a fixed number of fringes be crossed to validate the burst detectors. Particles moving through the outside edges of the measurement volume will cross fewer fringes than those crossing near the center. Thus, these particles may not get validated due insufficient fringe crossings. Also, particles crossing at a sharp angle to the fringe direction may not cross enough fringes. They may have crossed through the center but if their flow direction angle is too sharp compare to the fringe direction, they will not cross enough fringes. This is often called an angle bias.

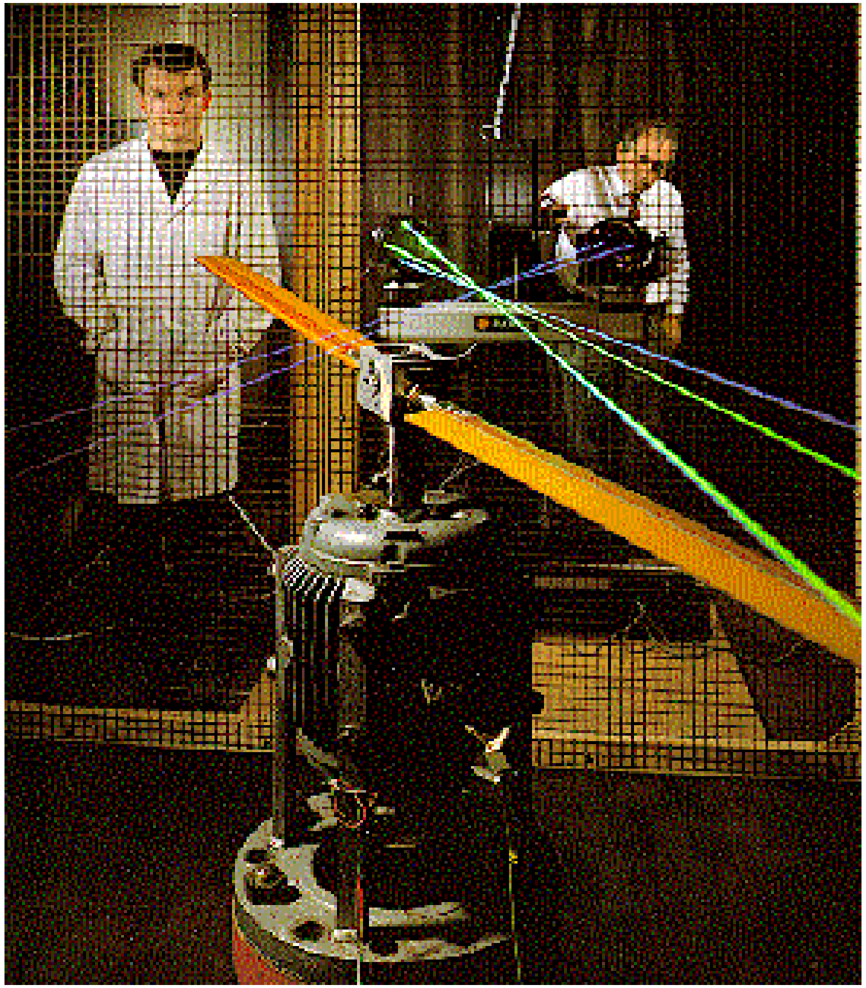
Gradient bias: Since the LDV probe volume is a finite size with a length that is typically much longer than its diameter, it is not possible to accurately resolve velocity scales that are smaller than the length of the probe volume. This implies that sharp spatial gradients in the velocity field cannot be resolved. This results in an averaging over the length of the probe volume, and produces a resolution bias in the data.

Advantages and disadvantages of LDV technique

- *Advantages:*
  - *Non-intrusive*
  - *High resolution*
  - *High accuracy*
  - *Wide dynamic range for velocity measurements*

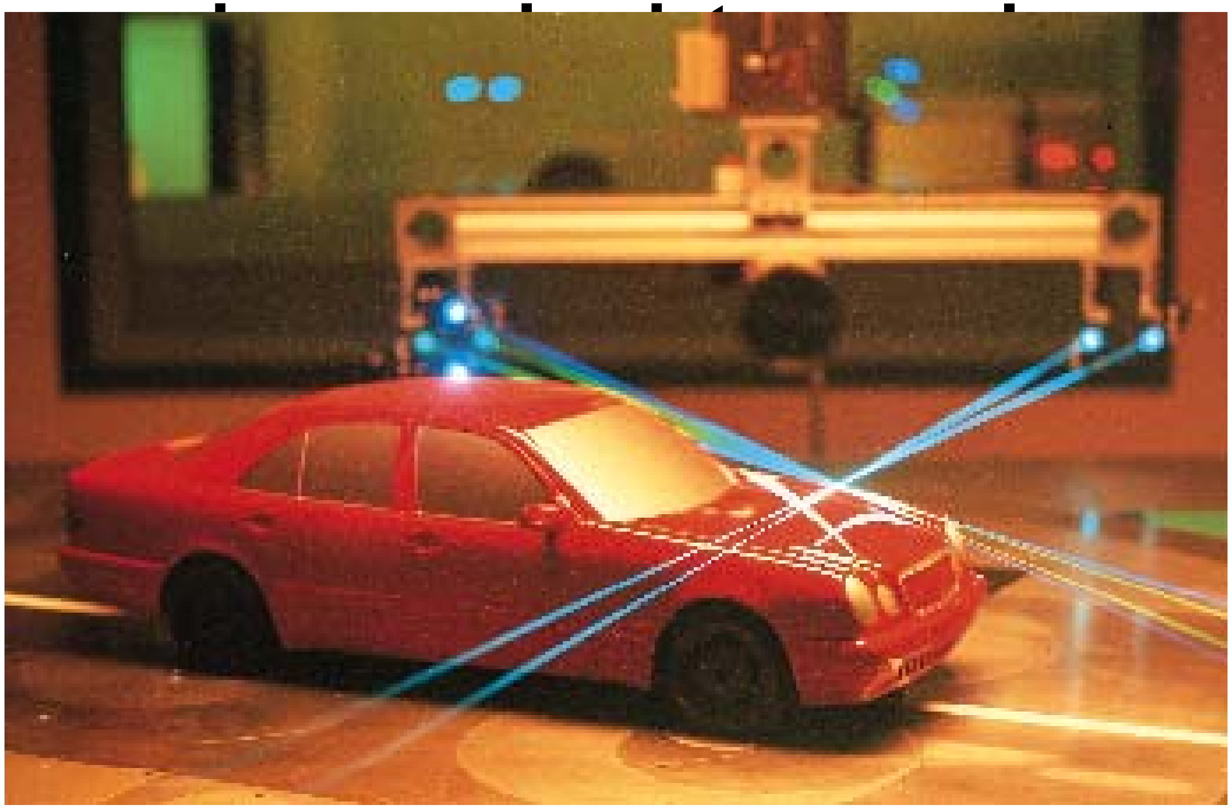
- *Disadvantages*
  - *Single point measurements*
  - *Expansive in instrumentation*

Measurement of air flow around a helicopter rotor model in a wind tunnel



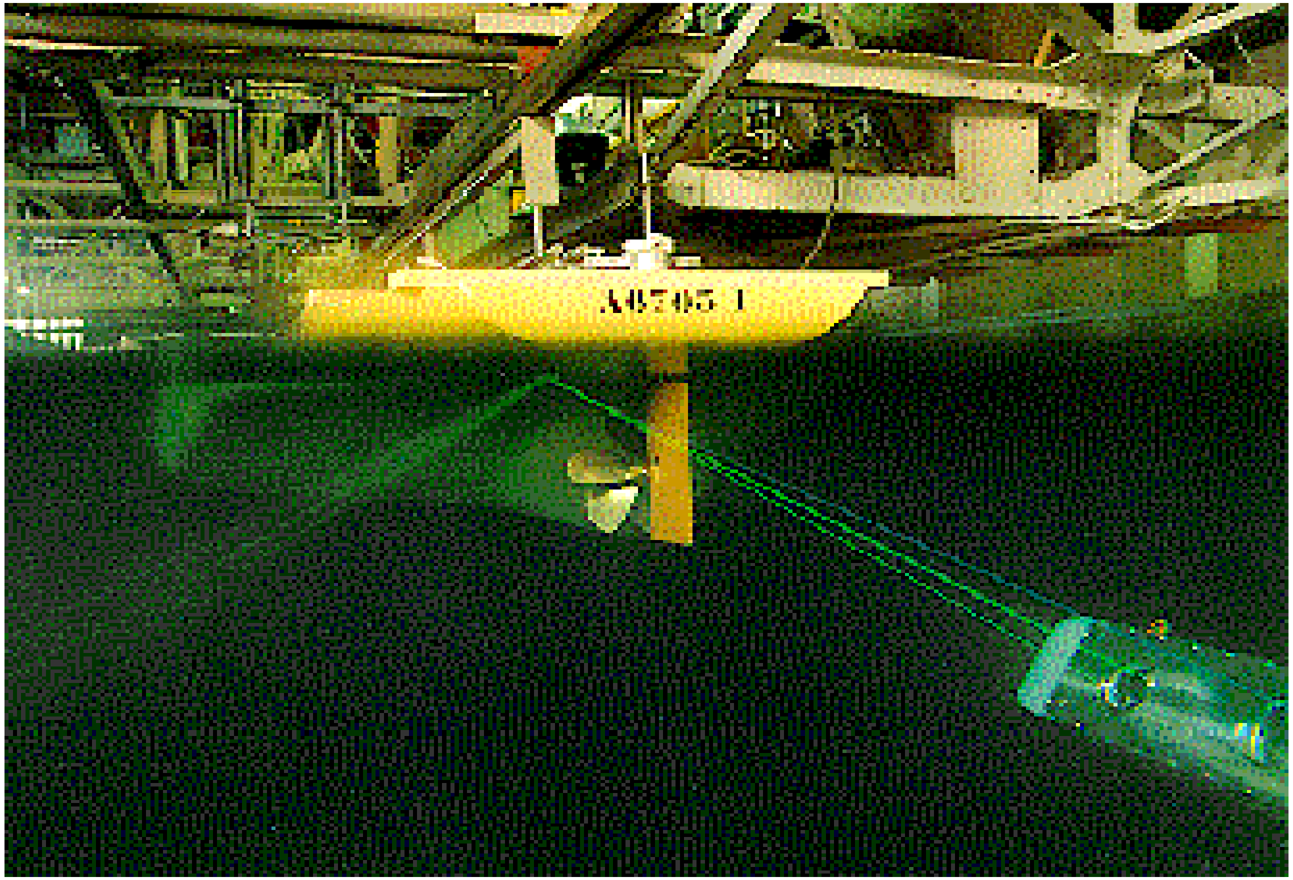
University of Bristol, UK

Measurement of flow field around a 1:5 scale car model



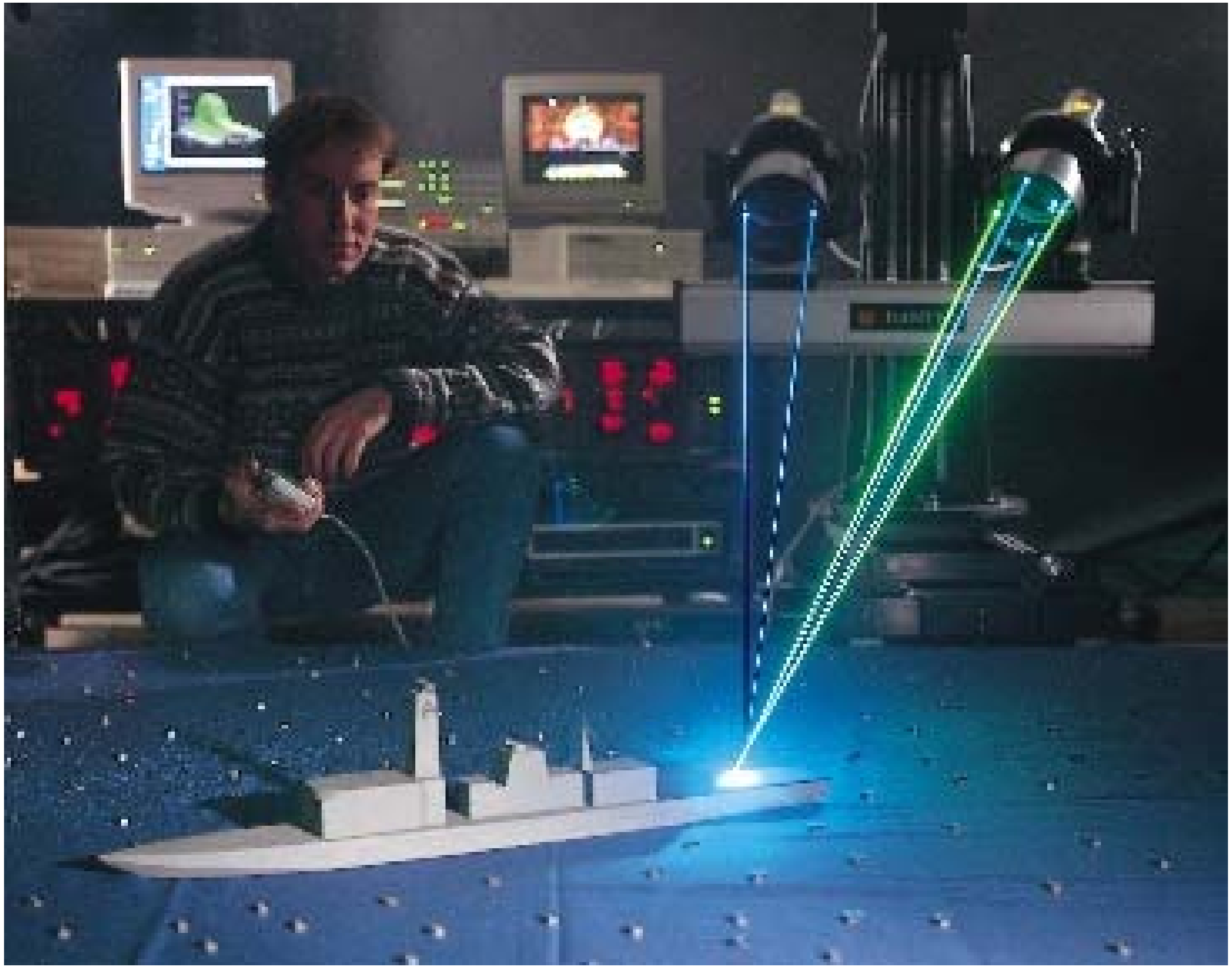
Mercedes-Benz, Germany

Measurement of wake flow around a ship model in a towing tank



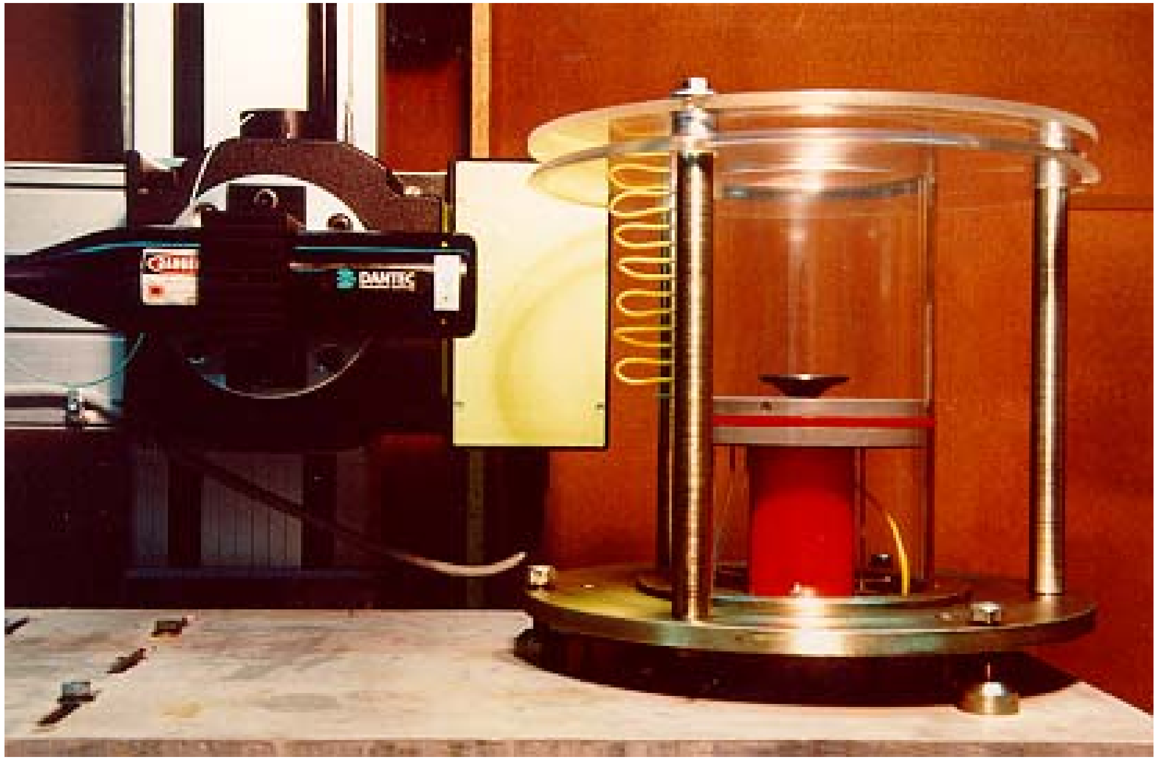
Marin, the Netherlands

Measurement of air flow field around a ship model



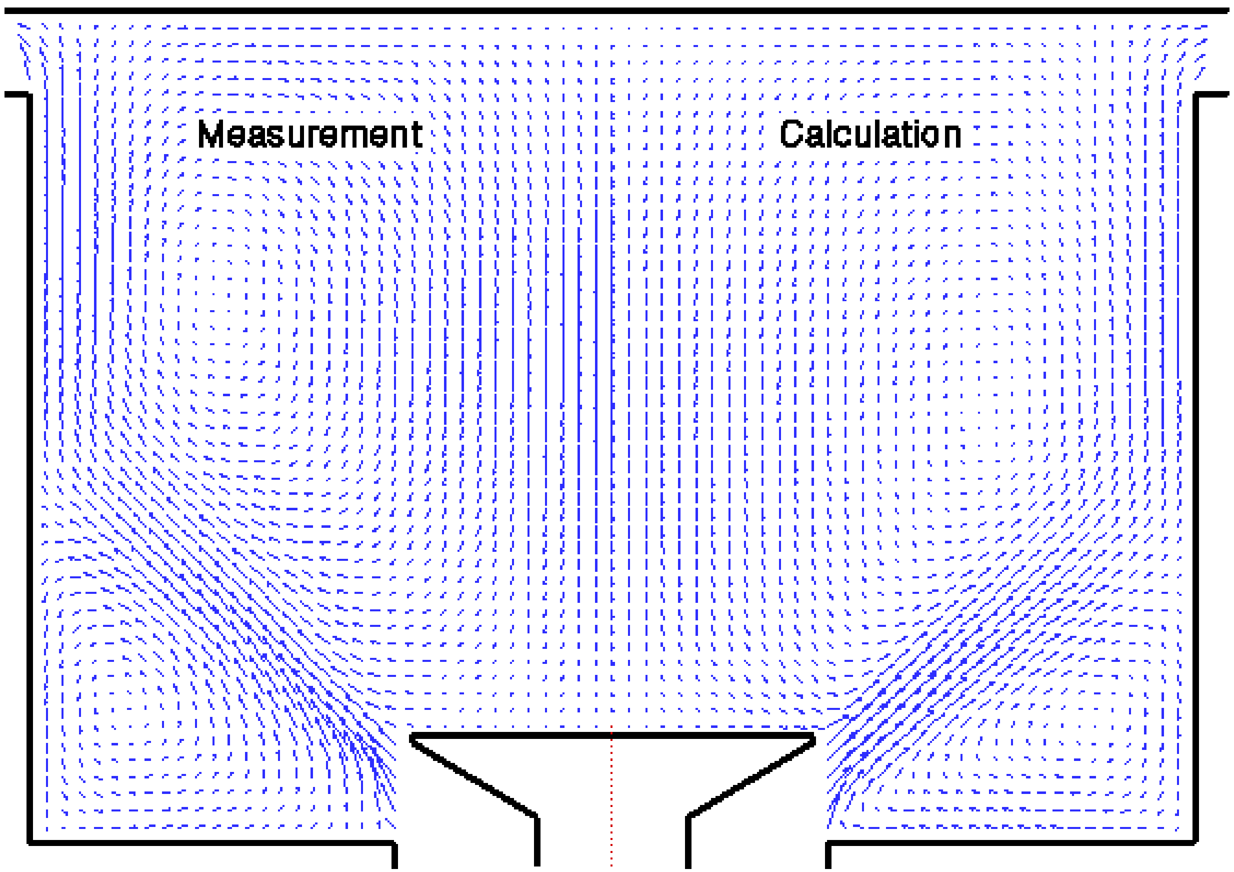
University of Bristol, UK

Measurement of flow in a valve model



Westsächsische Hochschule Zwickau, Germany

Comparison of EFD and CFD results



Planar Doppler Velocimetry (PDV) or Doppler Global Velocimetry (DGV) technique

- *Planar Doppler Velocimetry (PDV) or Doppler Global Velocimetry (DGV) is capable of determining instantaneous, three-dimensional velocity vectors of moving particles or solid material in a laser light sheet everywhere in the field of view.*