Velocity & Particle size Measurement

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Velocity & Particle size Measurement

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- Aerosol generation
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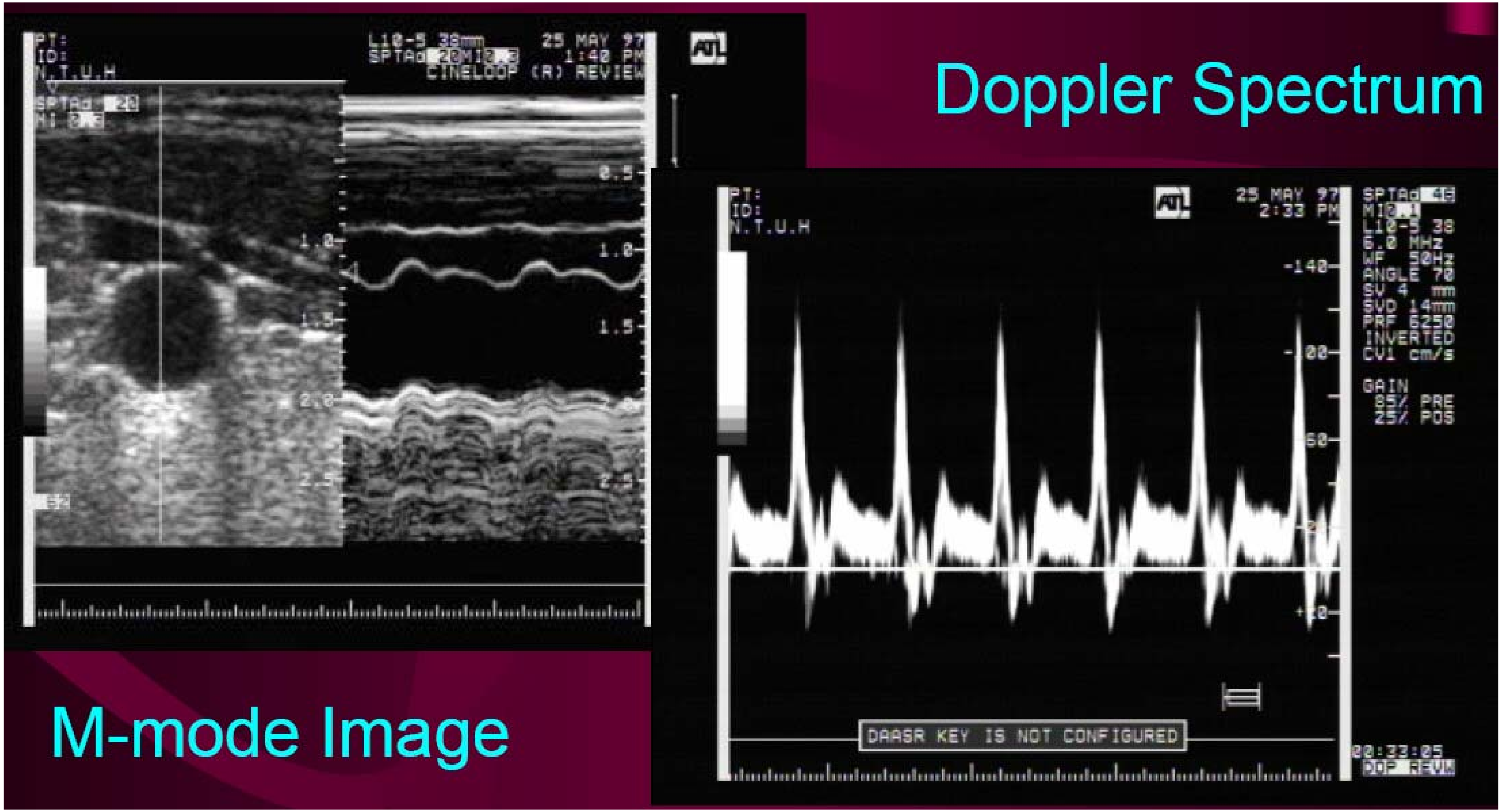
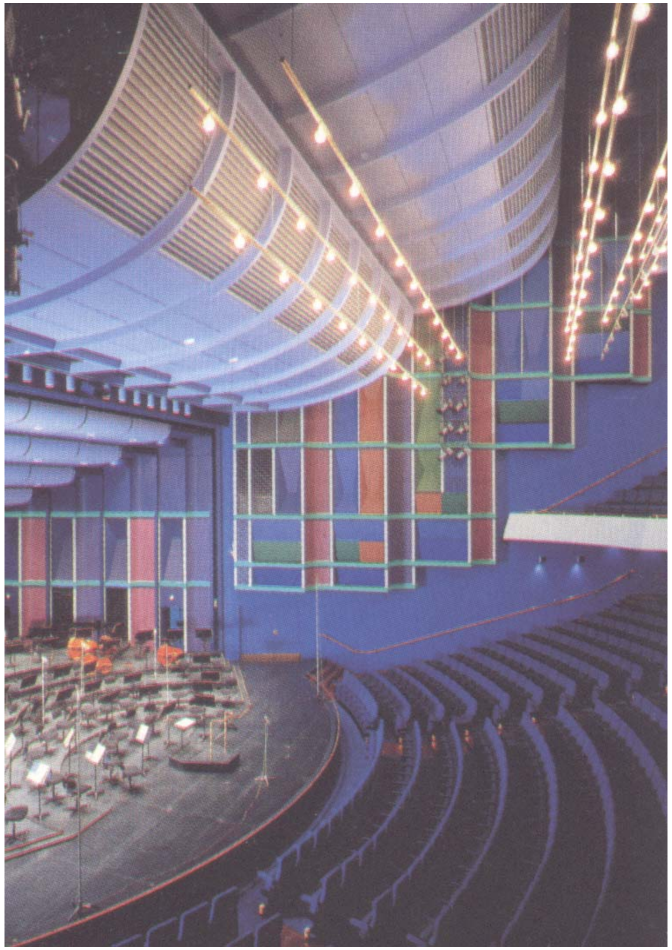
Ultrasound Flow measurement



(From Y.H. Shau)

Velocity measurements in daily Life



Traditional velocity Measurements

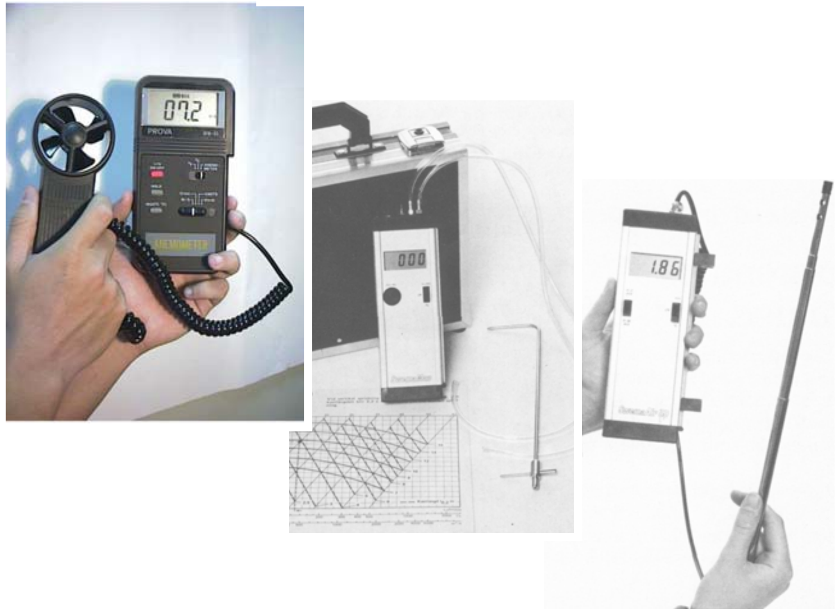
- (flow rate ⇨) Average velocity
  Q = U A
- Local velocity measurement:

  - mechanical rotation*($)
  - Pitot-static tube ($$)
  - Hot-wire/-film*($$$)

  (* regular calibration needed)

Bernoulli's Equation

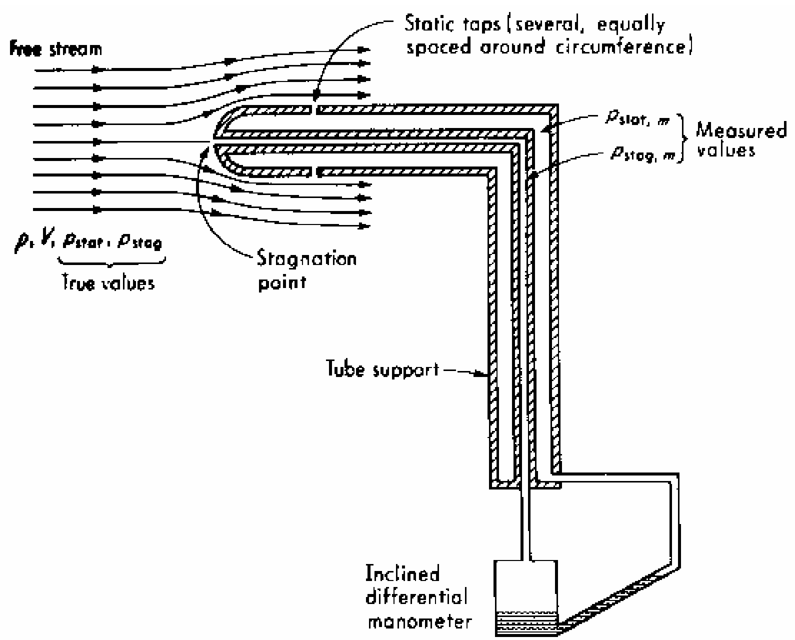
$$\frac{p_0}{\rho_0} = \frac{p}{\rho} + \frac{V^2}{2}$$

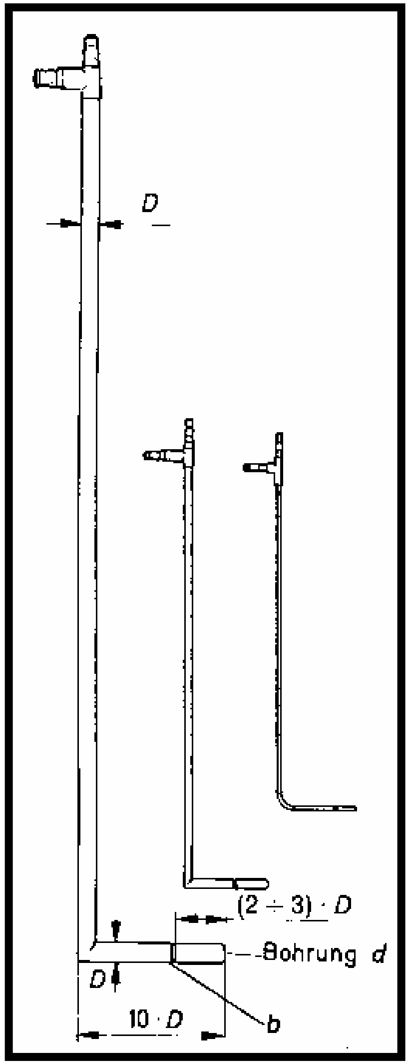


Dynamic pressure measurement

Measurement of dynamic pressure

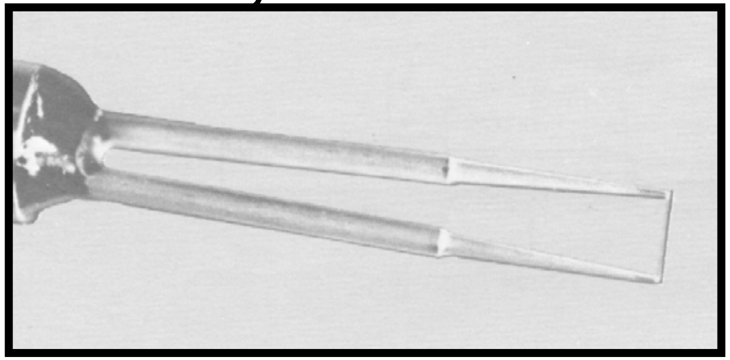
- Pitot-static tube (or Prandtl tube) is used to measure dynamic pressure and hence flow velocity.
- It should not be used at too low Reynolds numbers or too close to a wall.
- Advantages: robust, cheap
- **Limitation**: low dynamic response

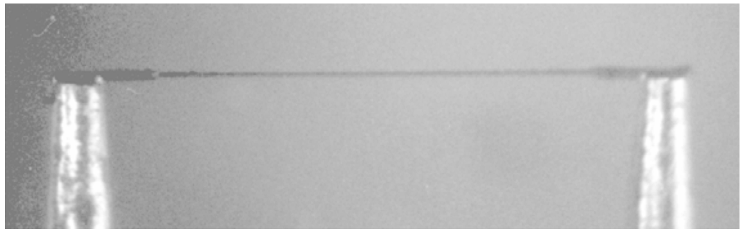




Thermal Anemometer

Hot wire and hot film are most commonly used sensor of thermal anemometers.





⊙**Advantages:**

- **convenient usage**
- **fast response**

⊙**Disadvantages of thermal anemometer**:

- intrusive
- calibration-required
- fragile
- blind to direction
- thermo-sensitive
- regular cleaning needed

Principle of thermal anemometers (I)

- Thermal anemometer is an indirect measuring technique (not the velocity but the heat loss from a thin, heated wire is measured and related to the flow velocity.)
- The heat loss of a hot wire (or hot film) is dependent on a number of factors:
  - relative velocity between sensor and fluid medium. (magnitude and direction)
  - temperature difference between sensor and medium.
  - material properties of sensor and medium.(e.g. thermal conductivity, film coefficient,…etc.)
  - dimensions of the sensor.
- If the last three factors are kept constant, a calibration can be given the relation between the heat loss and the flow velocity

Principle of thermal anemometers (II)

- The basic circuitry for hot-wire and hot-film anemometry is identical.
- The heated wire, whose resistance is dependent on the temperature.
- Temperature changes due to velocity fluctuations (⇨resistance changes) are detected by means of a bridge circuit.
- For the sensor by Joule heating:

heat loss

$$Q = IE = I^2 R = \frac{E^2}{R}$$

Constant current ⇨***R*** changes ⇨ wire temperature changes

constant temperature ⇨ ***R*** remains constant ⇨ ***E*** changes

CCA & CTA

Basically two methods of operation are possible.

- CCA : (Constant current Anemometer)

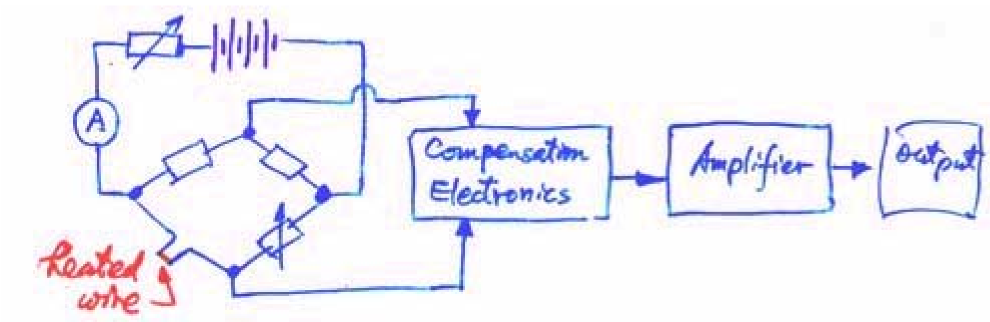
  The heating current ***I*** is held constant.

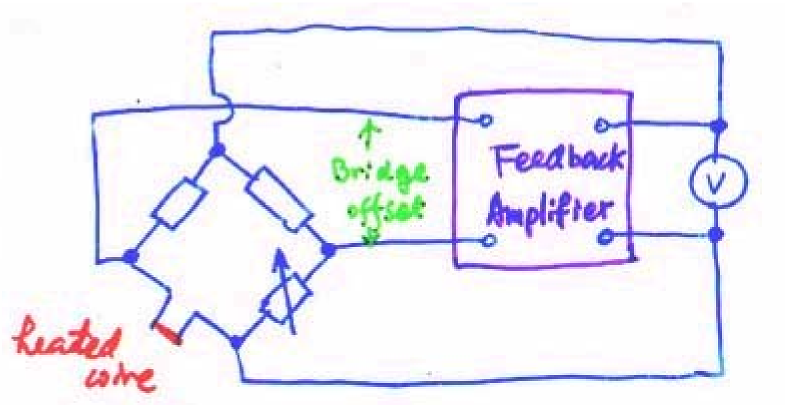
  ⇨ ***R*** is then a measure for heat loss ***Q***.

- CTA: (Constant temperature anemometer)

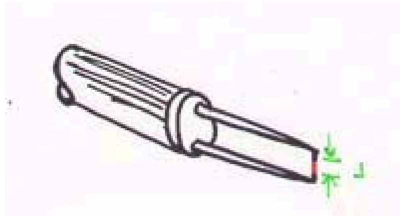
  The resistance R, and hence the temperature of the sensor is held constant.

  ⇨ The bridge voltage ***E*** is then a measure for Q.





Hot-wire probe



- Hot-wire (***HW***) probe

  ϕ : 1~10μm, L : ~200 ϕ
- Wire materials are chosen mainly according to their temperature sensitivity

  $$R = R_0 [1 + \alpha_1(T-T_0) + \alpha_2(T-T_0)^2 + \ldots]$$

  for platinum: α_1 =3.5 x 10^{-3} /ºC, α_2 = -5.5 x 10^{-7} /(ºC)^2

  for tungsten: α_1 =5.2 x 10^{-3} /ºC, α_2 = 7.0 x 10^{-7} /(ºC)^2
- In addition, the material must be mechanically robust.
- Comparison of different materials according to various criteria (1.- highest ranking):

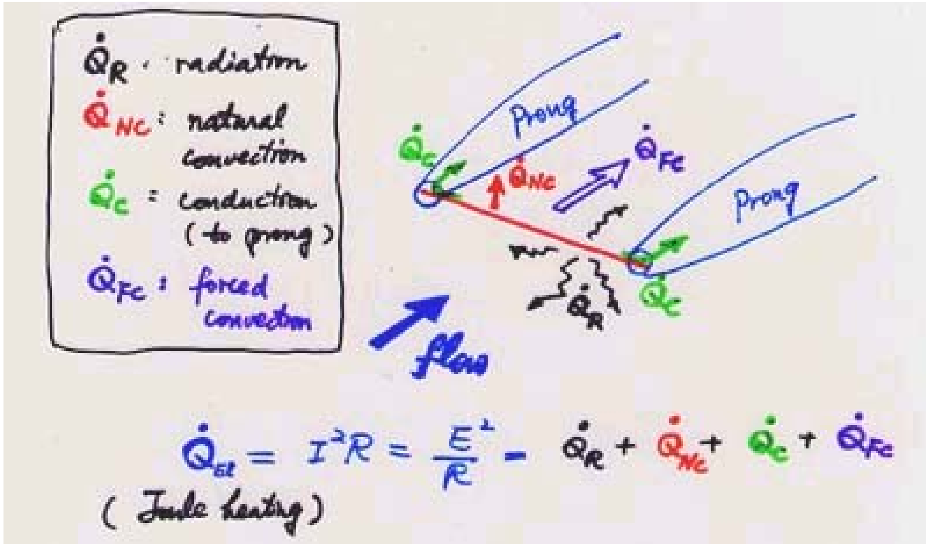
Material	α_1	Mech. strength	Time constant
Tungsten	2	1	1
Platinum	3	4	3
Nickel-Platinum	1	3	4
Iridium(80%Pt)	4	2	2

Heat transfer of a Hot-wire probe (I)

- Radiation and natural convection losses are negligible for most operating conditions.
- Conduction to the prongs can be up to 20% of Q_{FC} , and is given by Fourier as:

$$Q_C = -2k\left(\frac{dT}{dx}\right)_{sensorend} \frac{\pi d^2}{4}$$

- Forced convection (of a cylinder in parallel flow):



Nu = Nu(Re, Pr, Gr, Ma, l/d, ΔT,…)

$$Q_{FC} = Nu\ \pi\ l\ k(Tw - Ta); \quad Nu = \frac{hd}{k}$$

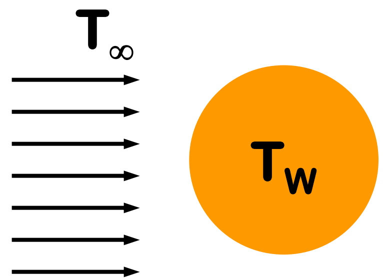
Heat transfer of a Hot-wire probe (II)

- Many influentral parameters can be neglected under certain conditions.

  $$Nu = Nu(Pr, Re)$$

  (by constant reference temperature, fixed operation condition, excluding low velocities.)
- Most commonly used reference temperature is the film temperature

  $$T_m = 0.5(T_w + T_a)$$



- The first theoretical solution, based on potential flow theory, for the heat transfer from circular cylinder was given by King(1914):

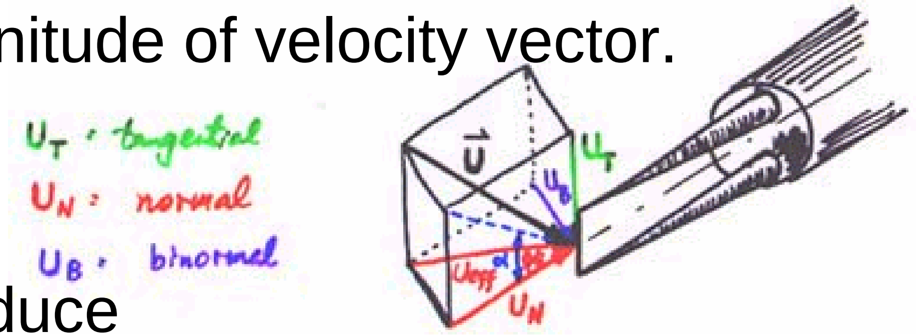
$$Nu = \frac{1}{\pi} + \sqrt{\frac{2}{\pi} \operatorname{Re} \operatorname{Pr}}$$

For Re×Pr >0.08

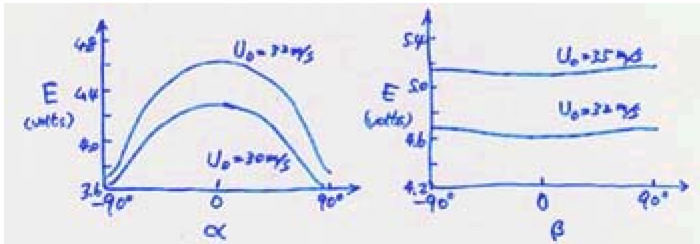
Directional sensitivity of HW

- The heat loss due to force convection is dependent on direction as well as the magnitude of velocity vector.

  U_T: tangential
  U_N: normal
  U_B: binormal

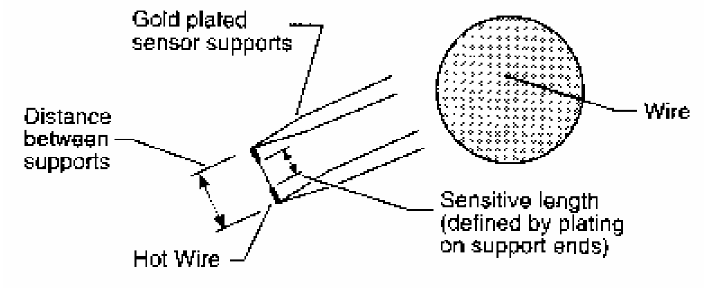


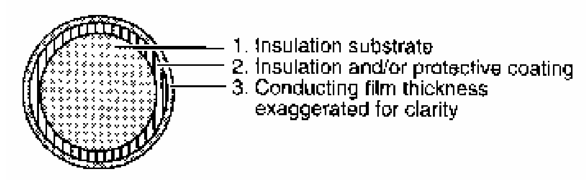
- Common practice is to introduce the effective cooling velocity $U_{eff} = f(\alpha, \beta)|U|$ where α and β are the yaw and pitch angles respectively.
- It is customarily assuming $E^2 = A + BU_{eff}^n = A + B\ f(a,b)^n |U|^n$
  i.e., the yaw and pitch influence can be separated from the speed influence.



Hot wire and hot film

Comparison of hot-wire to hot-film probes:



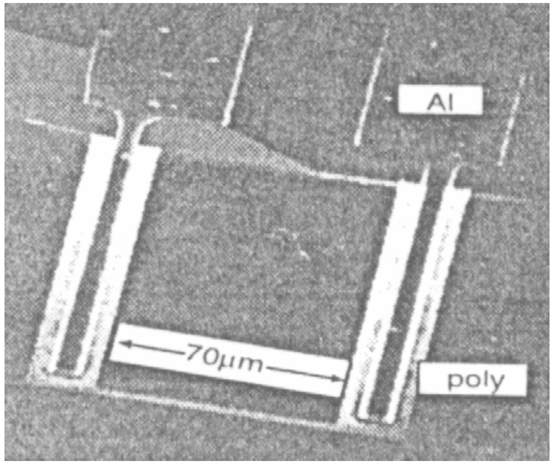


- **Advantages of hot-wire probes:**
  - low thermal inertia
  - high bandwidth
  - high sensitivity
- **Advantages of hot-film probes:**
  - long time stability
  - uniform production possible (constant calibration coefficients for the same type of sensors)
  - very robust mechanically, not sensitive to contamination
  - can be easily insulated with quartz film (useful for conducting liquids)

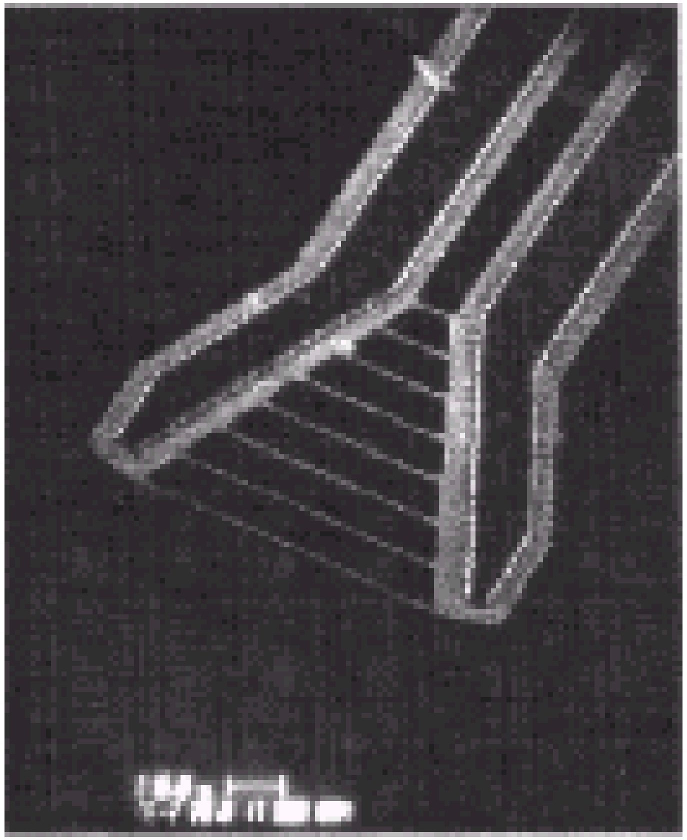
Hot-wire by IC-technology

(from Jiang et al. [1994])

- **Advantages:**
  high spacial resolution,
  high response (~MHz),
  disposable, cheap

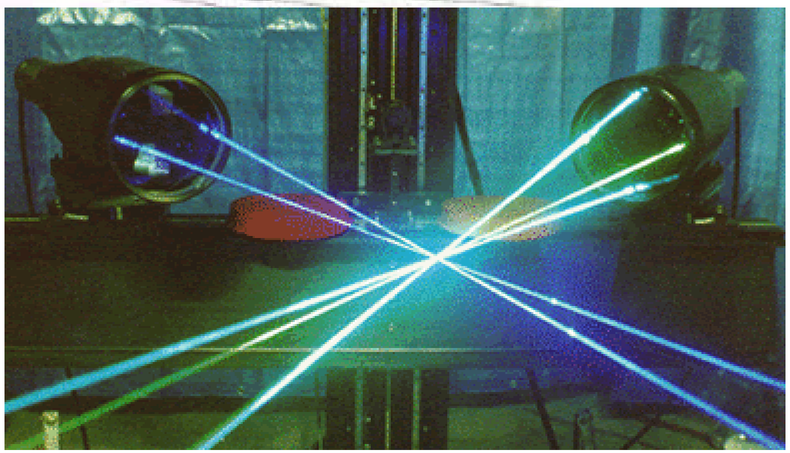


(1um x 70 um single hot wire)



(hot- wire array)

Introduction to Laser Doppler Anemometry (LDA)



Characteristics of LDA (I)

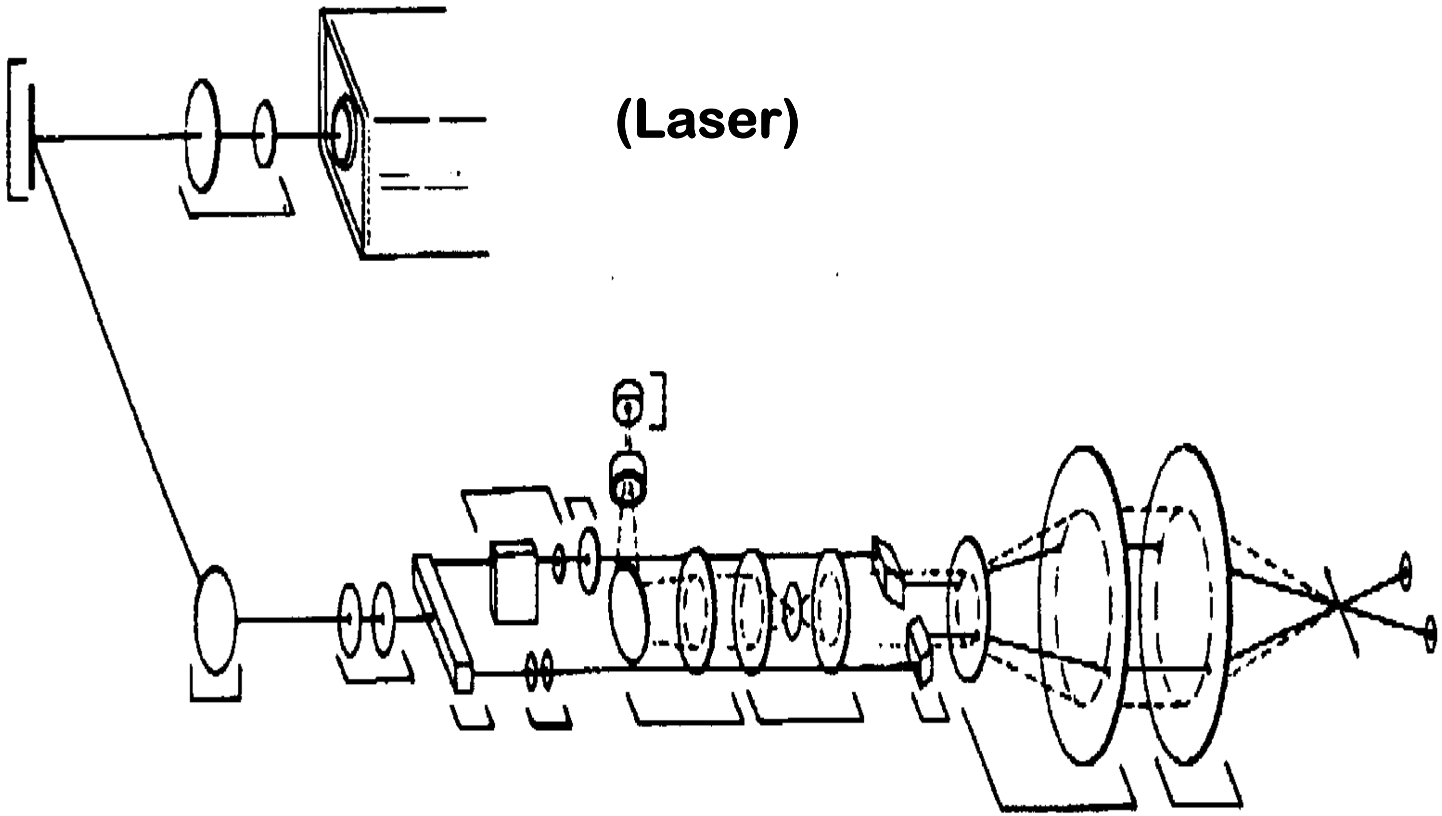
⊙ <u>**Advantages**</u>:

- ***Non-intrusive***
- ***no calibration*** required (not strongly dependent on the temperature, density, composition of the flows)
- sensitive to ***velocity*** magnitude and ***direction***
- ***linear transfer function*** for velocity measurements
- measures a ***single*** desired velocity component directly
- ***high accuracy*** obtainable
- ***very high frequency response***
- very ***small*** measuring volume
- ***high dynamic range*** (from μm/s to 1000 *m/s*)

Characteristics of LDA (II)

- **<u>Disadvantages</u>**:
  - relatively ***expensive*** for set-up and maintenance
  - ***seeding particles*** in the flow required
  - ***optical access*** to measuring point required
  - flow medium must be ***transparent***
  - ***experienced*** man-power recommended
  - ***spherical*** particles based
  - relatively huge and heavy for traditional LDA system

Principle and configuration of LDA



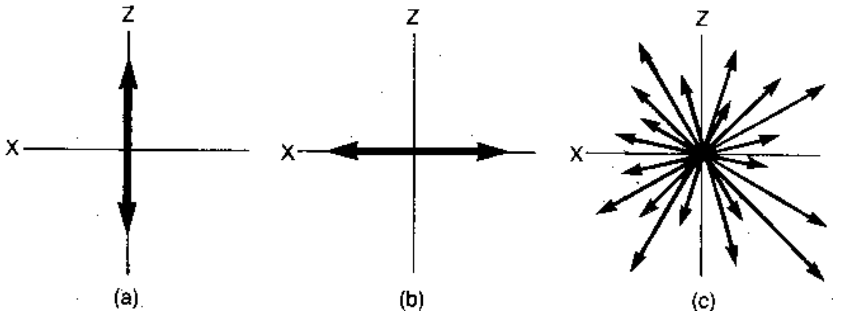
Introduction to Laser

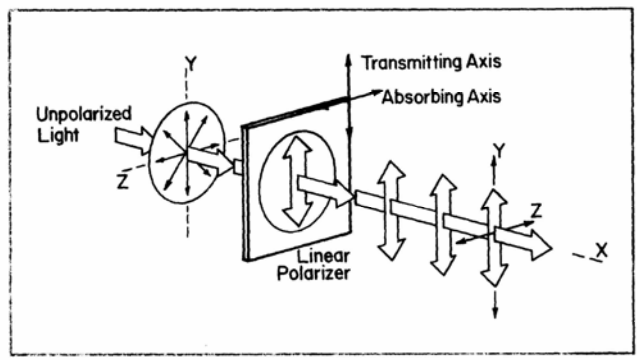
- ***Laser*** (雷射、激光、鐳射) :
  Light Amplification by Simulated Emission of Radiation
- **Characteristics of Laser:**
  - **high light intensity**
  - **narrow monochromaticity**
  - **high coherence (temporal & spatial)**
  - **low divergence angle (0.1º: 360º)**
  - **short pulse time(*ns* ~ *ps*)**

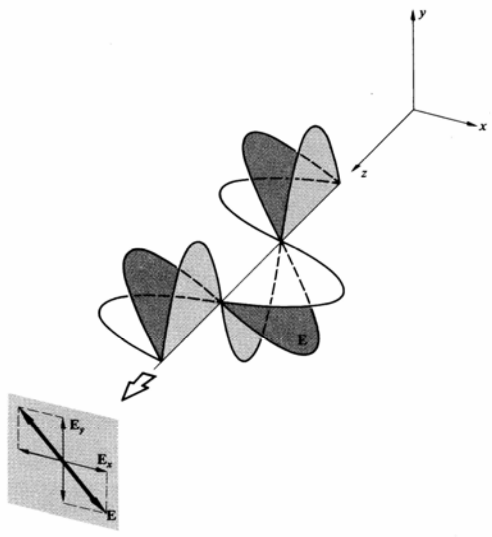
Development of LASER

1900 Planck's quantum theory
1905 Einstein's photon theory
1917 Einstein's stimulated radiation theory
1954 Townes produced the 1st Maser
1960/5 Maiman produced the 1st rubby Laser
1960/11 1st gas Laser (He-Ne)
1962 1st semi-conductor Laser(GaAs)
1964 CO_2-Laser, Ar^+-Laser, YAG-Laser, Dye-Laser
1970 Excimer Laser

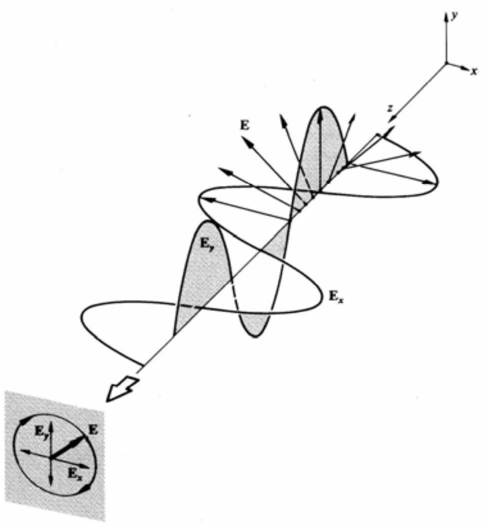
Polarization Light & Laser modes



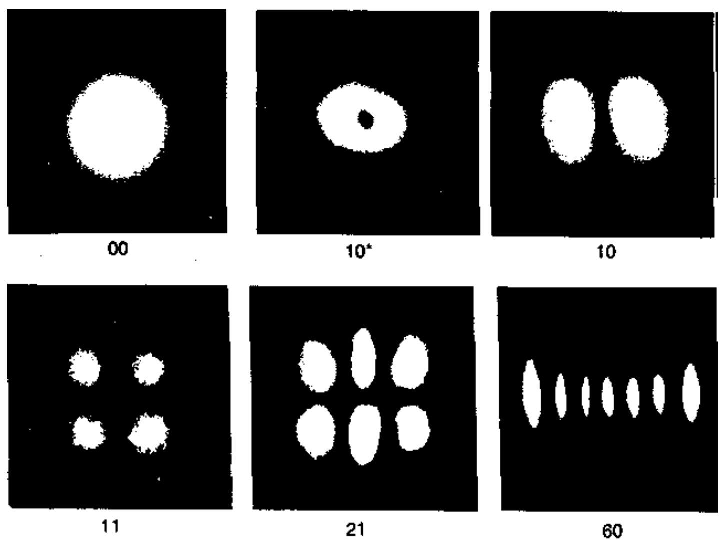




Linear light.

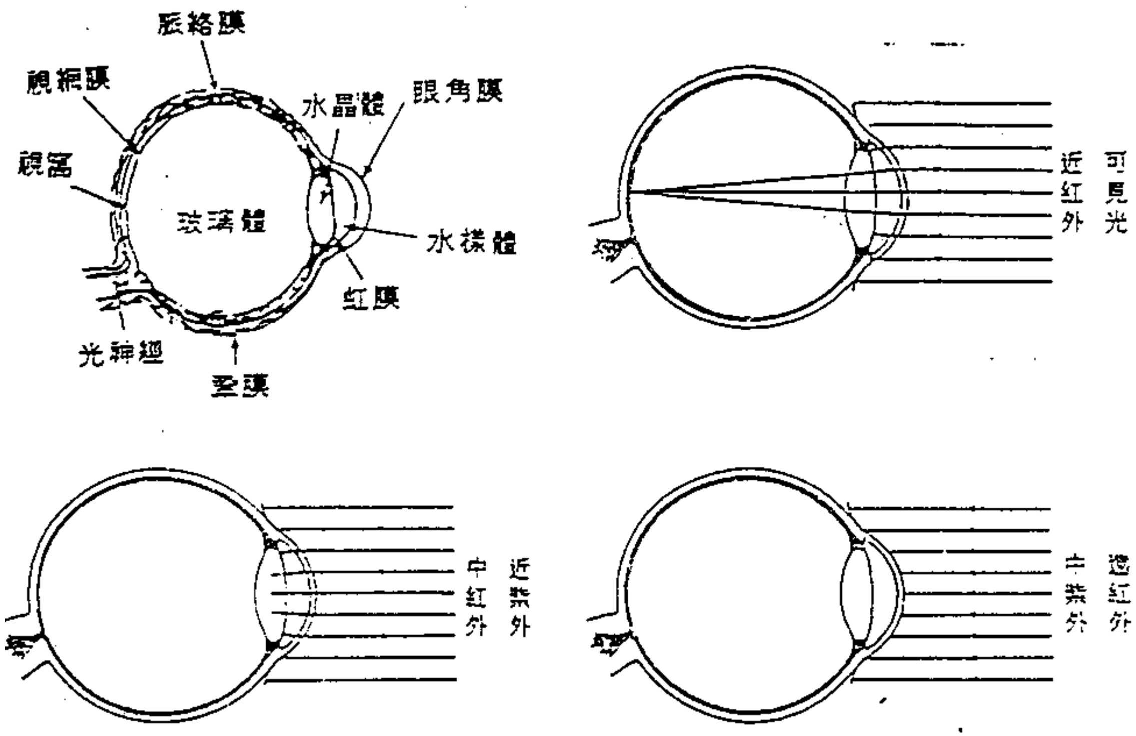


Right-circular light.

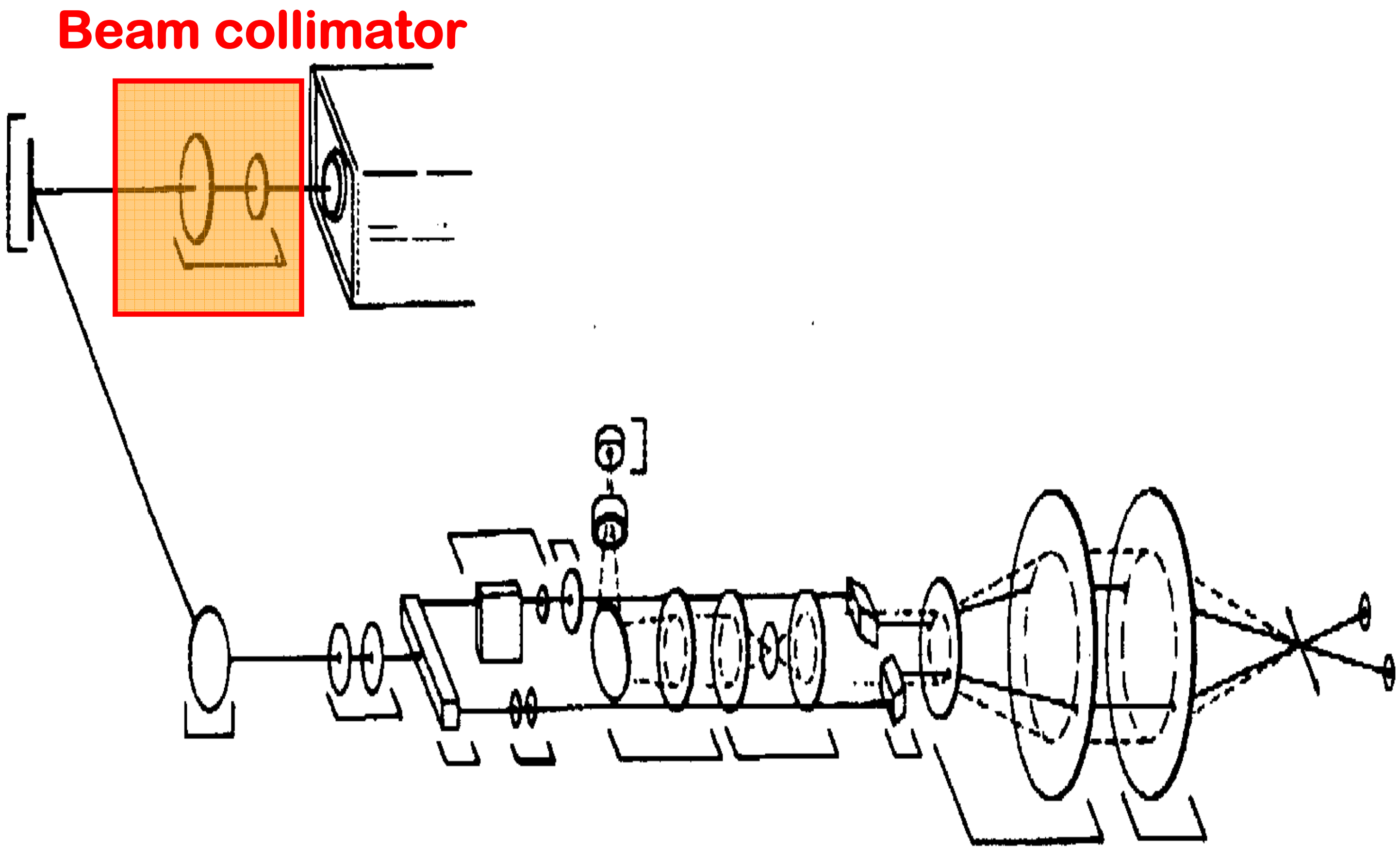


Laser safety

- **Class I:**
  no gangeous, <0.4mW
- **Class II:**
  dangeous for direct observation, < 1mW
- **Class III:**
  1~500mW
- **Class IV:**
  >500 mW

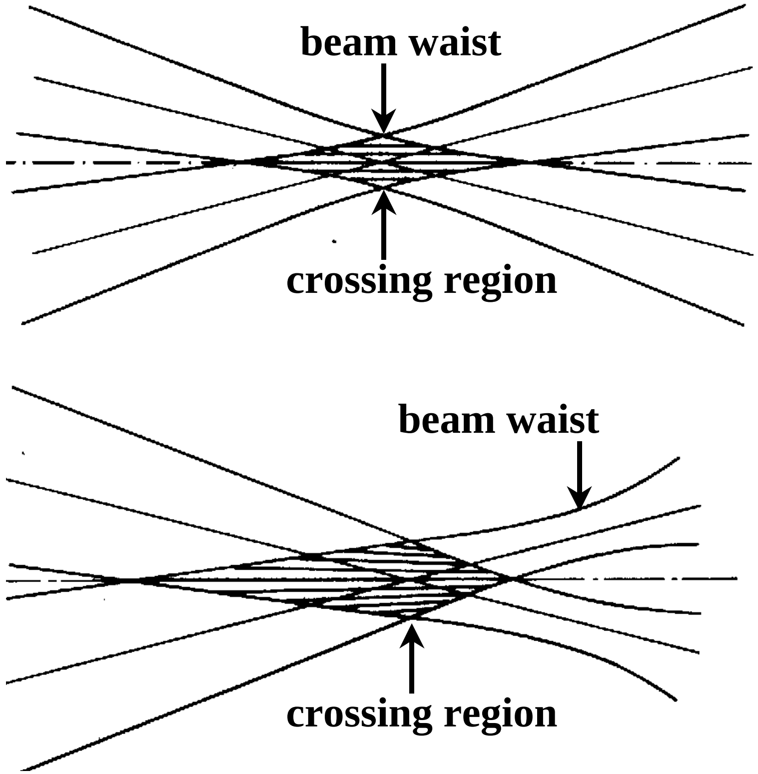


Principle and configuration of LDA

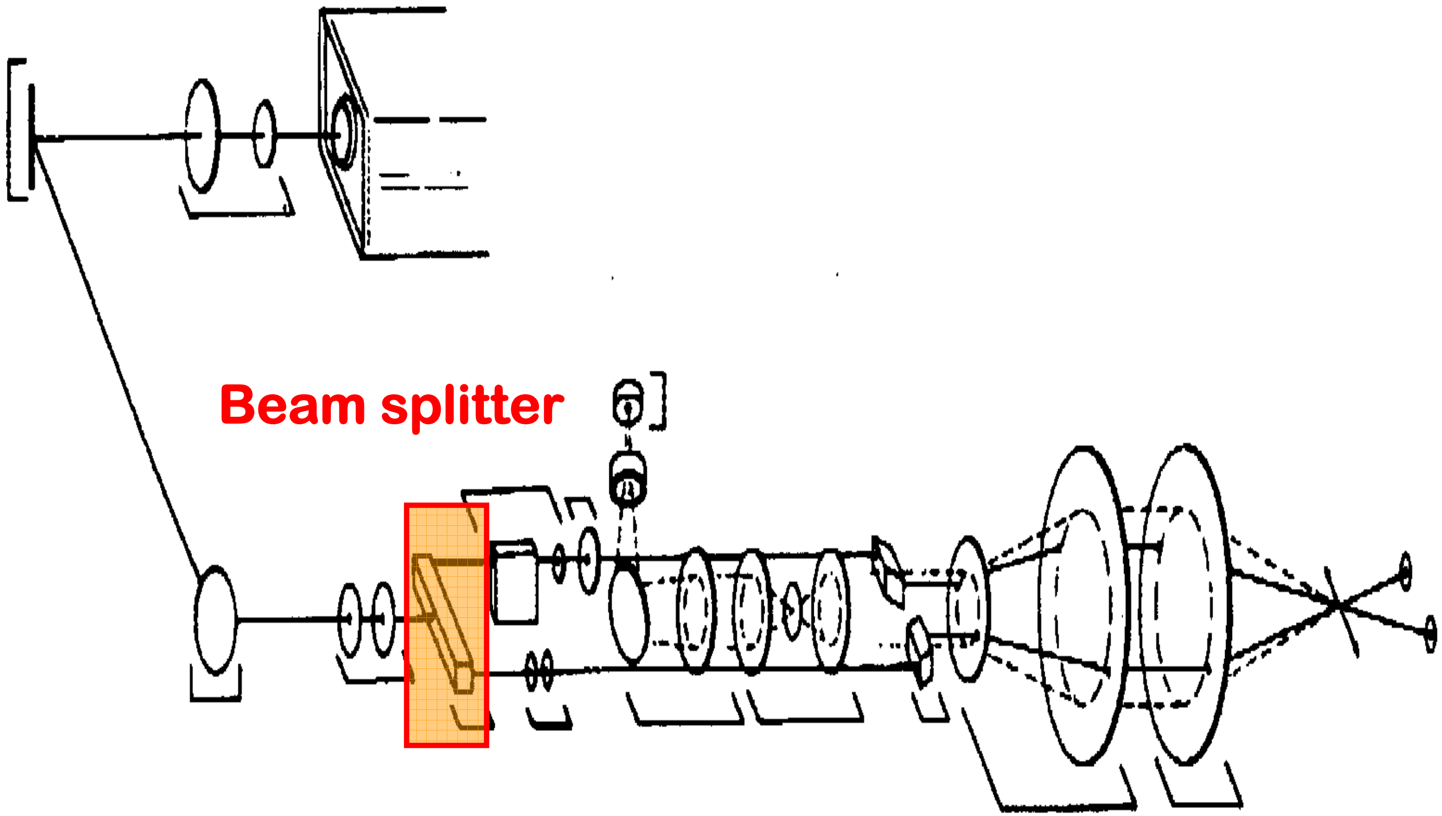


Beam Collimator

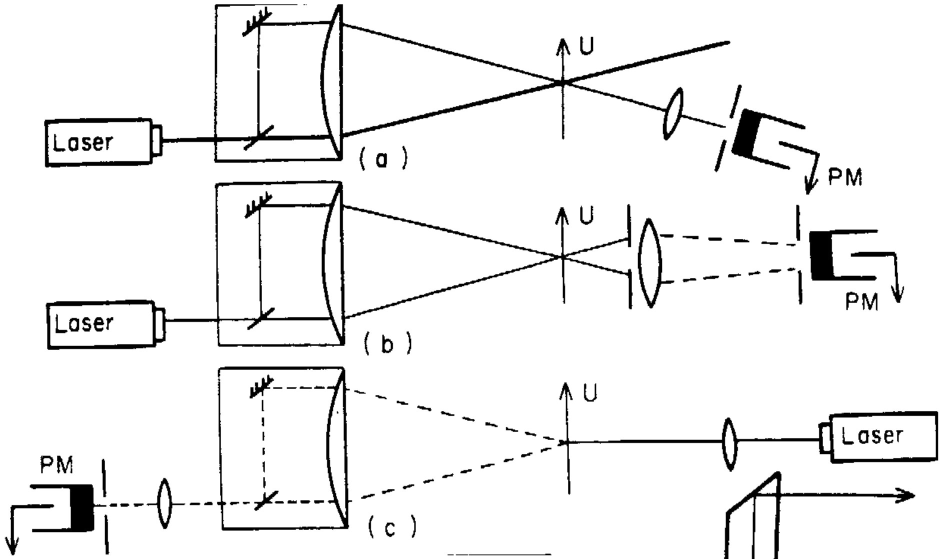
- **Beam collimator** is basically a pair of positive and negative lens, which is used to control the beam divergence of a given laser.
- Collimator is used to adjust the positions of both **laser-beam waists** located at the same place, to avoid **artificial turbulence** caused by fringe-spacing variations.
- The need of collimator increases as the optics become more complex.



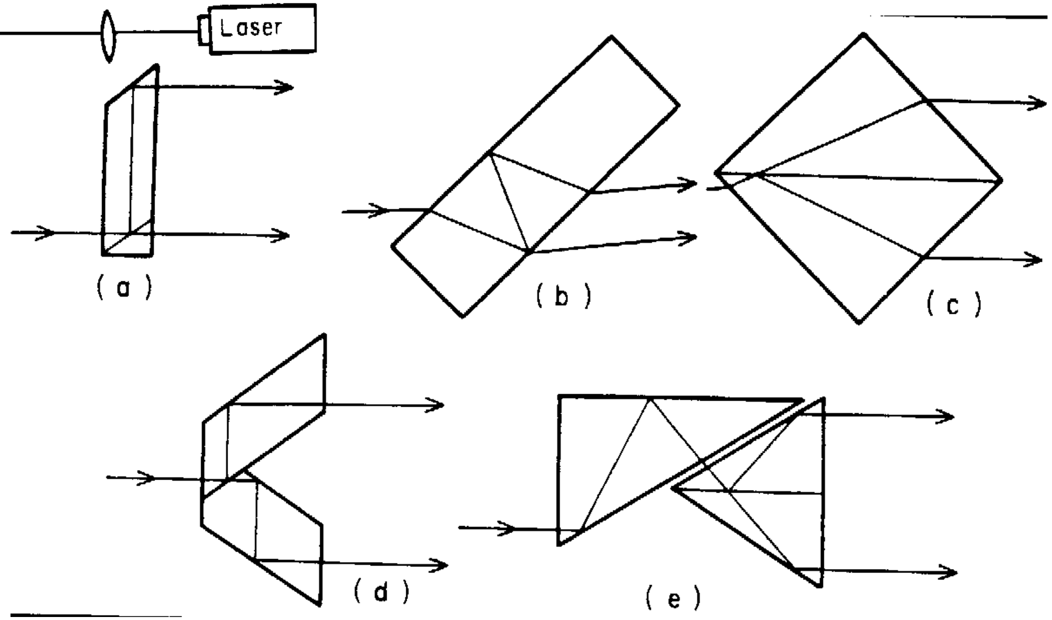
Principle and configuration of LDA



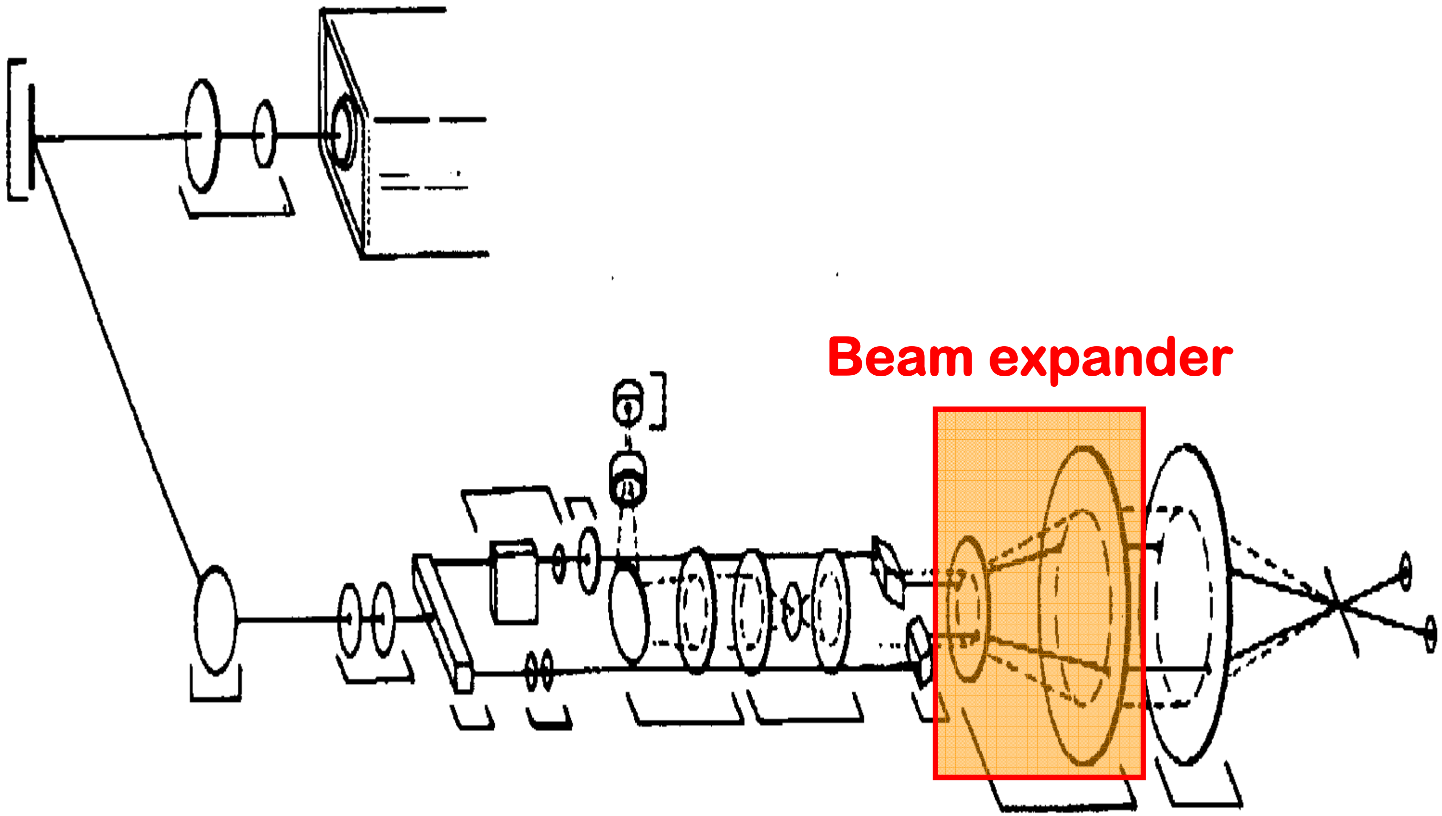
Beam Splitter



The integrated beamsplitters:

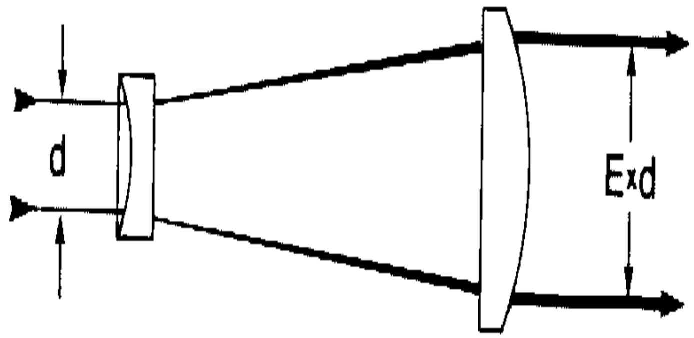


Principle and configuration of LDA



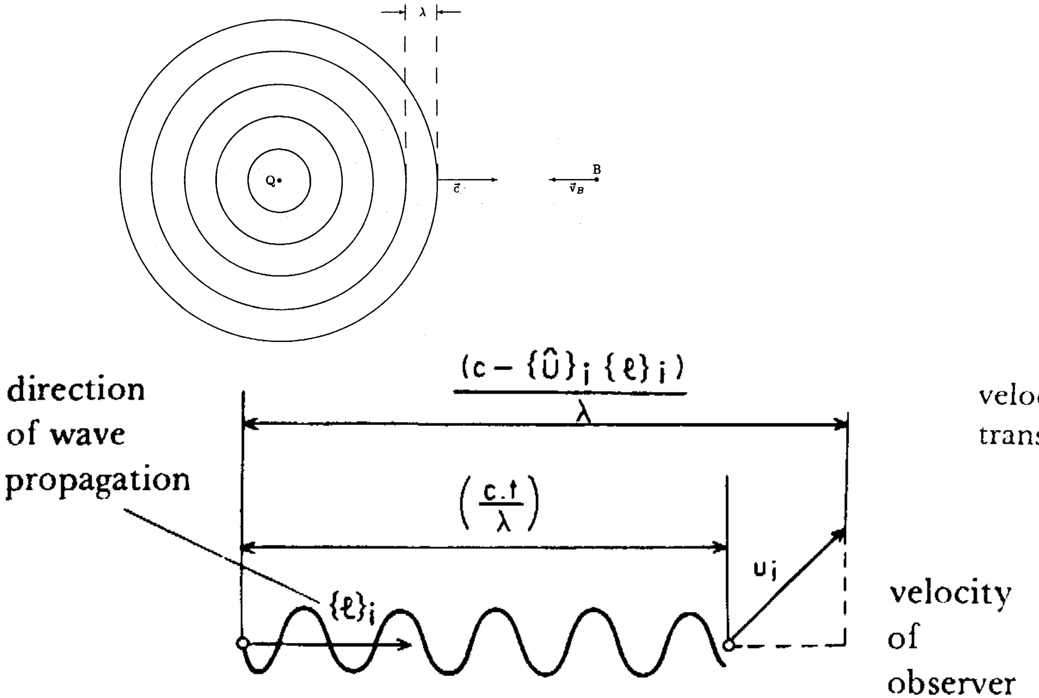
Beam Expander

- Beam expander is recommended when measuring for the case of large distance, or high velocity gradient or low SNR.
- Beam expanders are designed to increase (a) the input beam diameter and (b) the collection aperture (for backscatter). This results in a smaller mcv and better signal quality.
- A beam expander with expansion ratio E may decrease diameter of mcv ($d_m = \frac{4f\lambda}{\pi D_{e^{-2}} \cos\varphi}$) by a factor of E, decrease measuring length by a factor of E^2, and improves estimated SNR.
- Commerial available: E = 2 ~ 8.5



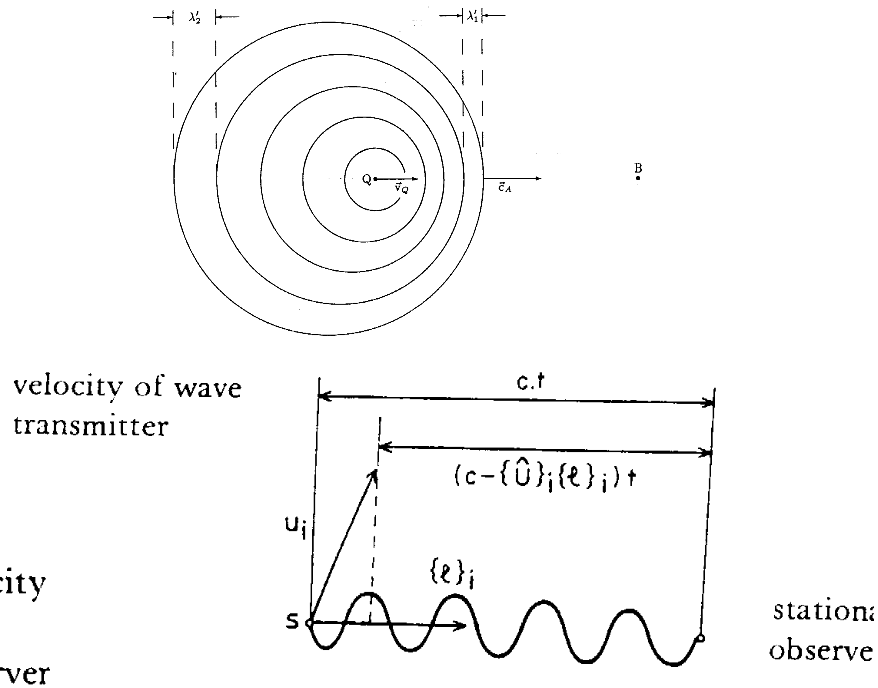
Doppler principle (I)

The measuring principle of LDA is the ***Doppler shift*** of light scattered from small particles.



$$\nu' = \nu \left[1 - \frac{1}{c} \{\hat{U}\}_i \{\ell\}_i \right]$$

Doppler effect caused by moving observer.

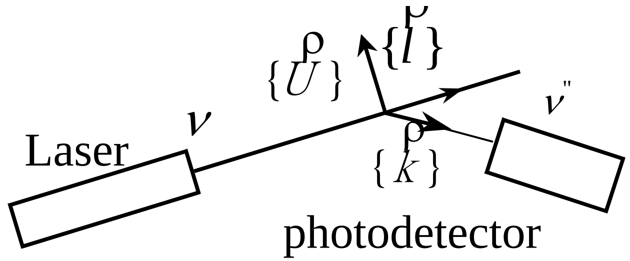


$$\nu' = \frac{\nu}{1 - \frac{1}{c} \{\hat{U}\}_i \{\ell\}_i}$$

Doppler effect caused by moving source.

Doppler principle (II)

- The two expressions above can be combined to describe the optical arrangement as shown.



- The frequency detected by the photodetector becomes

$$\nu'' = \nu \left(\frac{1 - \{\vec{U}\}\{\vec{l}\}}{1 - \{\vec{U}\}\{\vec{k}\}} \right)$$

- Direct detection of this Doppler shift as a velocity measure is ***not feasible*** for the example of backscatter.

$$\nu'' = \nu \left(\frac{1 - \{\vec{U}\}\{\vec{l}\}/c}{1 - \{\vec{U}\}\{\vec{k}\}/c} \right) \approx \nu \left(\frac{1-\varepsilon}{1+\varepsilon} \right)$$

$$\sim \nu(1 - 2\varepsilon)$$

For $\{\vec{U}\} = 300\text{m/s}, \quad \varepsilon = 10^{-6}$
This accuracy of measurement **cannot** be achieved.

Doppler principle (III)

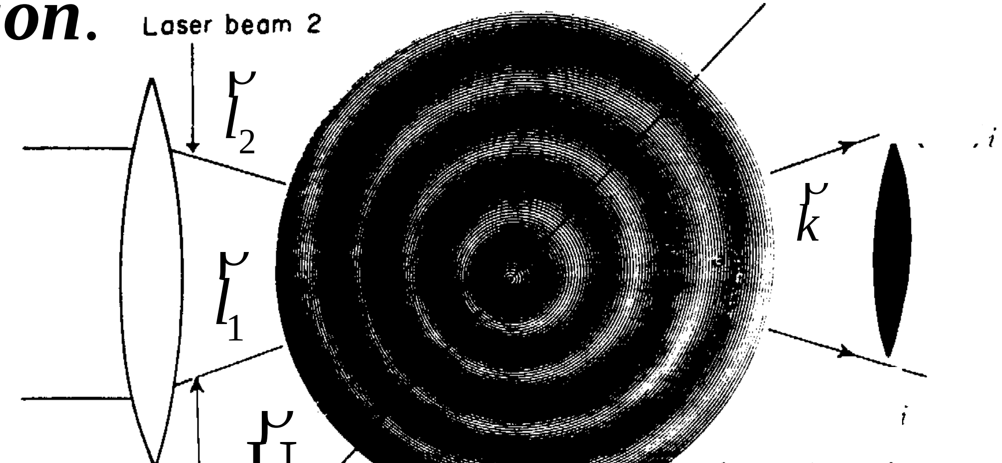
- One solution to utilize the Doppler effect is the ***optical heterodyne detection***.

For beam 1

$$\nu_{D1} = \nu\left[\frac{c - \vec{U}\cdot\vec{l}_1}{c - \vec{U}\cdot\vec{k}}\right]$$

For beam 2

$$\nu_{D2} = \nu\left[\frac{c - \vec{U}\cdot\vec{l}_2}{c - \vec{U}\cdot\vec{k}}\right]$$

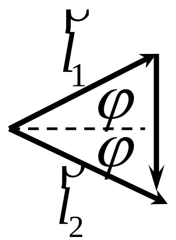


Simulations of laser-Doppler signals as described by Durst and Stevenson (1974)

The frequency difference is given by

$$\nu_D = \nu_{D1} - \nu_{D2} = \frac{1}{\lambda}\vec{U}\cdot(\vec{l}_2 - \vec{l}_1) = \frac{2U_\perp \sin\varphi}{\lambda}$$

$$\vec{U}\cdot\vec{n} = U_\perp$$



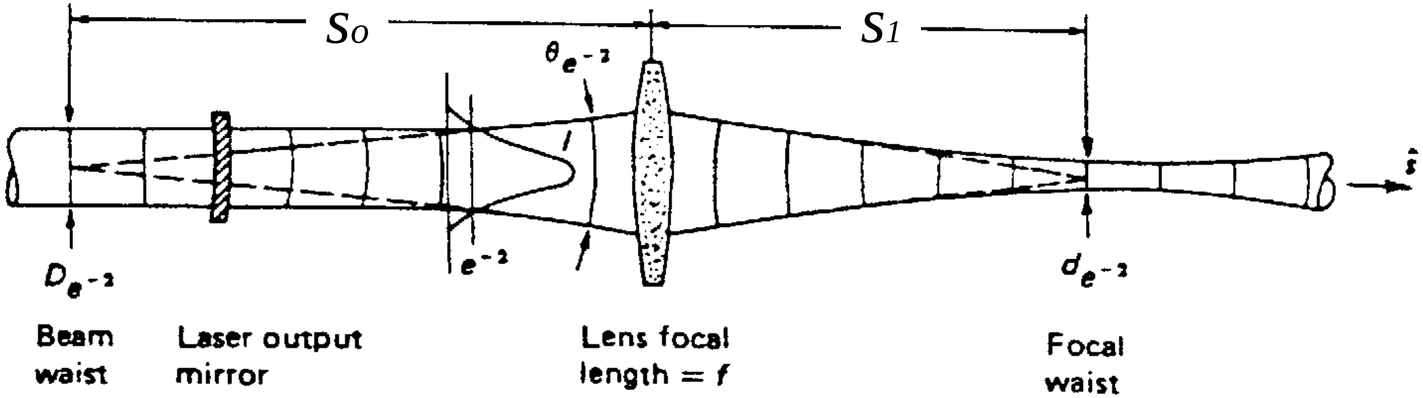
For instance:

(measurable!)

$$\lambda = 632.8nm, 2\varphi = 6°, U_\perp = 300m/s \Rightarrow \nu_D = 49.6\,MHz$$

Measuring Control Volume (I)

⊙ In describing the measuring control volume, the properties of ***Gaussian beams*** must be considered.



$$s_1 = f + \frac{s_0 - f}{(s_0 / f - 1)^2 + (\pi D_{e^{-2}} / 4 f\lambda)^2}$$

$$\frac{1}{d_{e^{-2}}^2} = \frac{1}{D_{e^{-2}}^2}(1 - \frac{S_0}{f})^2 + (\frac{\pi D_{e^{-2}}}{4 f\lambda})^2$$

For $s_o = f$,
then $s_1 = f$ and $d_{e^{-2}} = \frac{4 f\lambda}{\pi D_{e^{-2}}}$

Measuring Control Volume (II)

- The measuring control volume (mcv) is ellipsoidal in shape

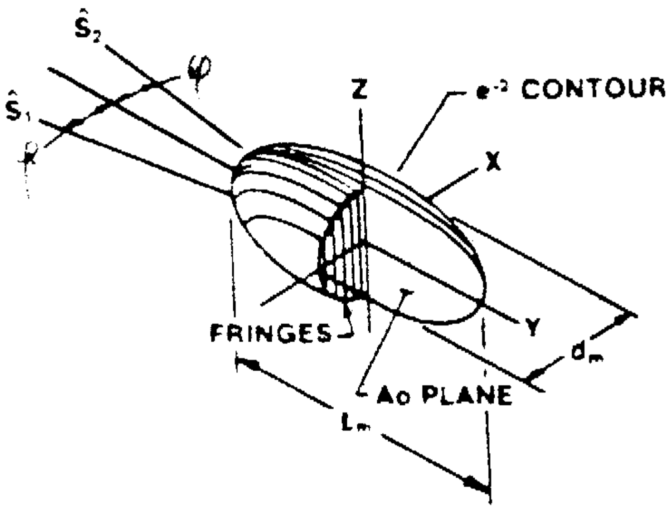
  diameter of mcv: $d_m = d_{e^{-2}} / \cos\varphi$

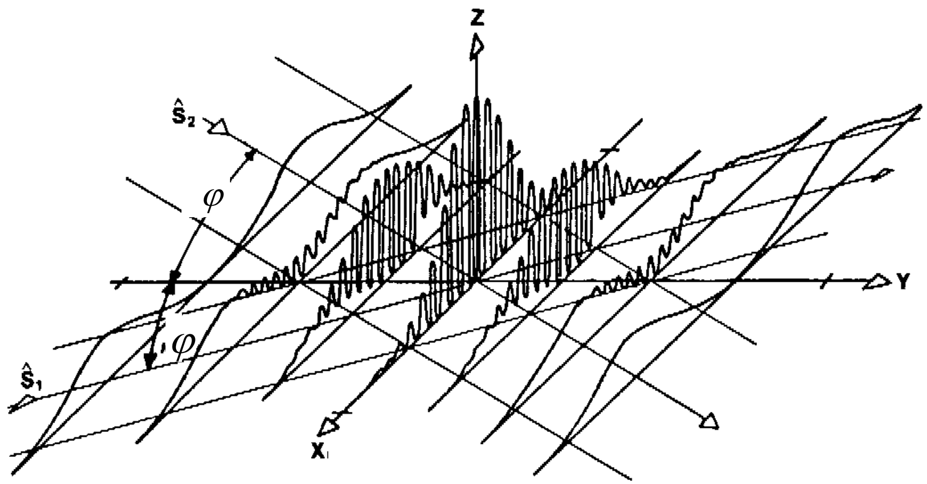
  length of mcv: $l_m = d_{e^{-2}} / \sin\varphi$

  no. of fringes: $N_{fr} = 1.27 d / D_{e^{-2}}$

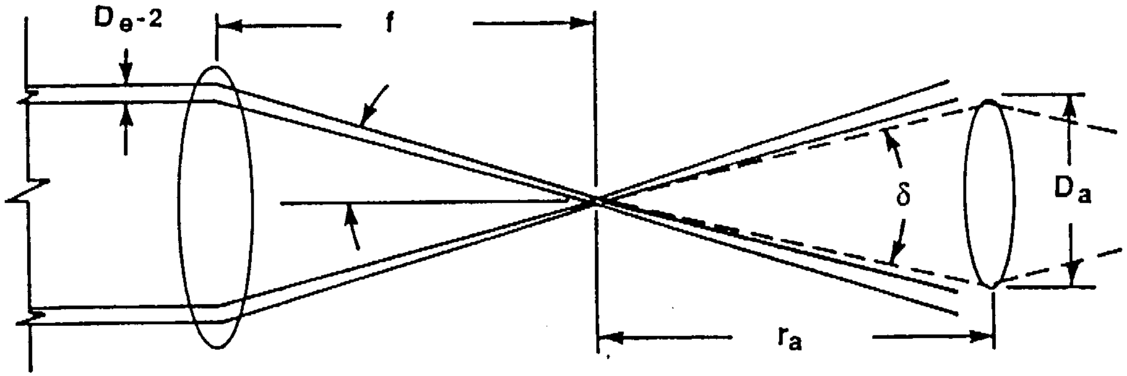
d: beam spacing before lens

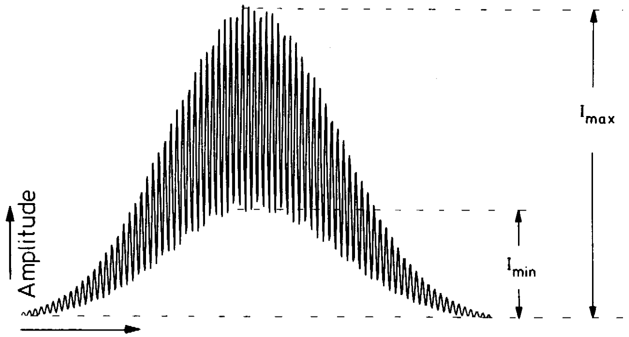
φ : intersection half-angle





Signal-to-Noise Ratio





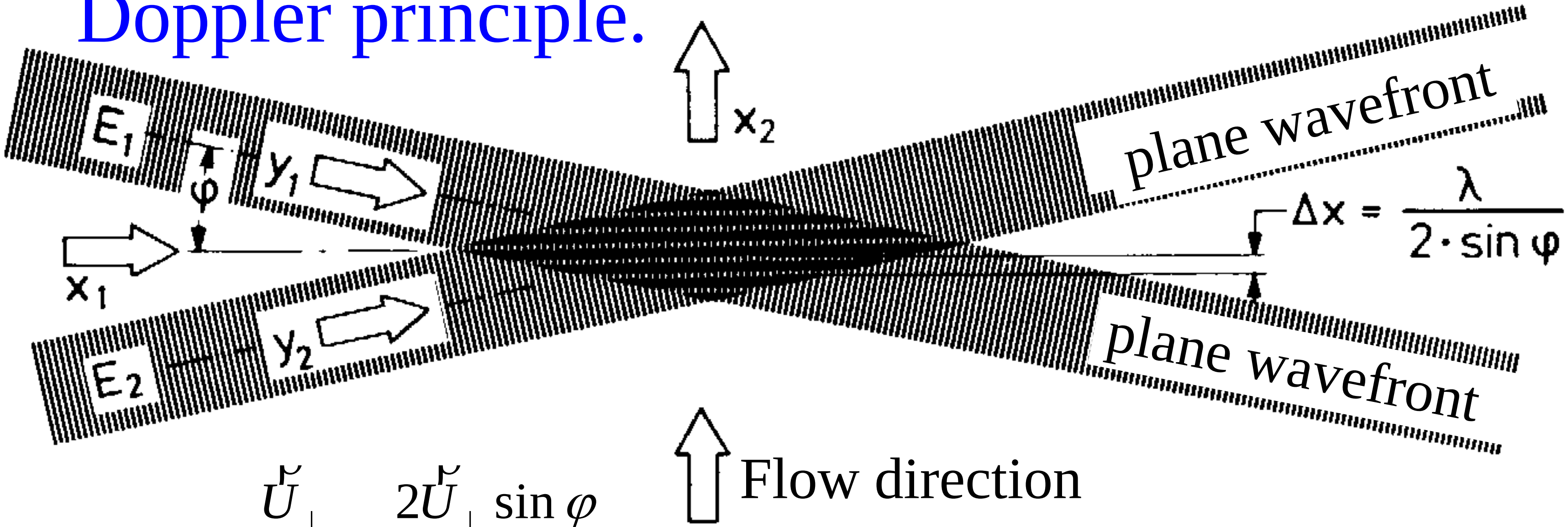
SNR	= signal to noise ratio (Power)	d_p	= particle diameter, µm
η_q	= quantum efficiency of photodetector	$\bar{G}$	= scattering parameter
P_o	= power in each beam, watts	$\bar{V}$	= visibility
Δf	= bandwidth, MHz		

$$\bar{V} = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

$$SNR = 4 \times 10^{11} \frac{\eta_q P_o}{\Delta f} \left[\frac{D_a}{r_a} \frac{D_{e^{-2}}}{f} \right]^2 d_p^2 \bar{G} \bar{V}^2$$

Fringe Model (I)

- ***Moire fringes*** can be used to illustrate the basic characteristics of an LDA. The ***resulting frequency*** agrees with that derived using the Doppler principle.



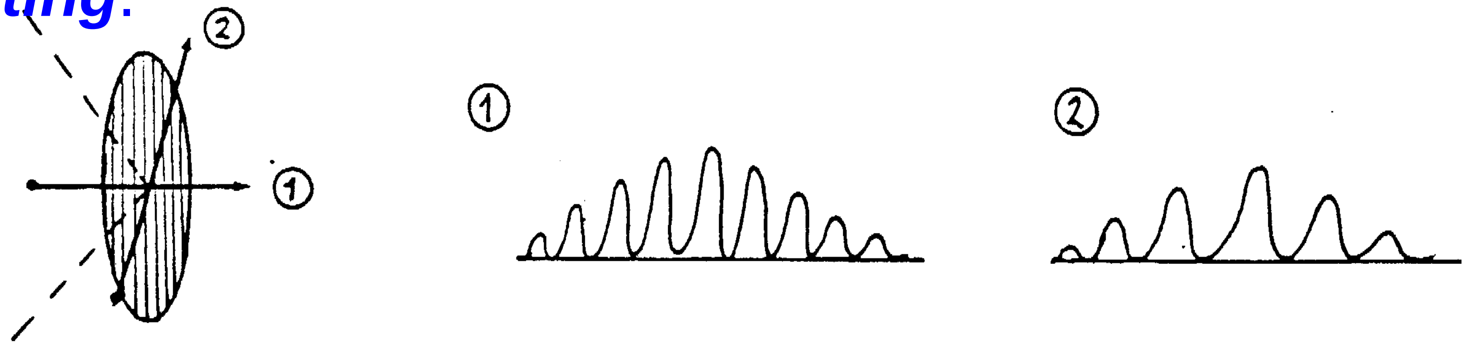
$$\nu = \frac{\vec{U}_\perp}{\Delta x} = \frac{2\vec{U}_\perp \sin\varphi}{\lambda}$$

Fringe Model (II)

- However, this model yields an ***incomplete*** and physically ***incorrect*** description of the resultant LDA-signal properties because the ***shape of particles***, the ***optical properties of the particle material***, the ***intensity distribution inside the measuring volume***, and the complex ***spatial light scattering mechanisms*** are ***not*** taken into account.

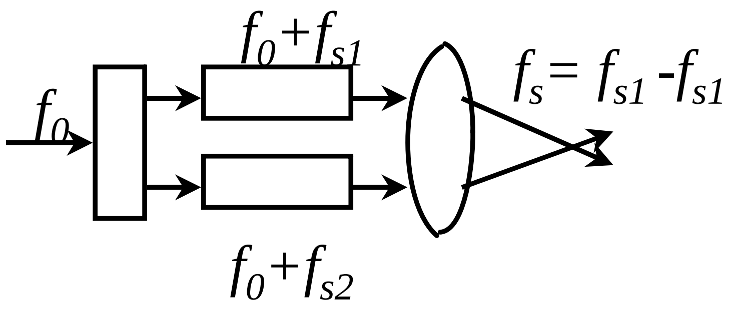
Directional Sensitivity

- The ***simple*** dual-beam LDA does ***not*** allow the direction of the particle to be determined. In addition the ***measurable turbulence level*** is very ***low***.
- The signal processor may require a ***minimum number of Doppler periods for validation***, thus restricting particle trajectories to a certain range of angles. This leads to a biased velocity.
- Both the directional sensitivity and the problem of measuring high turbulence levels can be resolved using ***frequency shifting***.



Frequency Shifting

- The concept of frequency shifting involves producing a ***frequency difference*** between two LDA beams. This can be achieved by shifting the frequency of one beam or of both but different amounts.
- The detected frequency will be larger or smaller than f_s depending on the sign of the velocity.

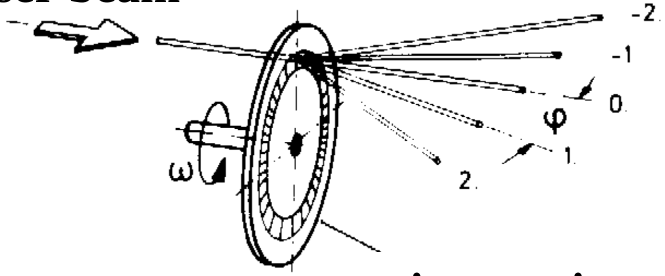


the detector sees

$$f = \frac{2\sin\varphi}{\lambda} U_{\perp} + f_s \frac{1 - \frac{\vec{U}\cdot\vec{l}_1}{c}}{1 - \frac{\vec{U}\cdot\vec{l}_2}{c}} \approx 1$$

Frequency Shifting

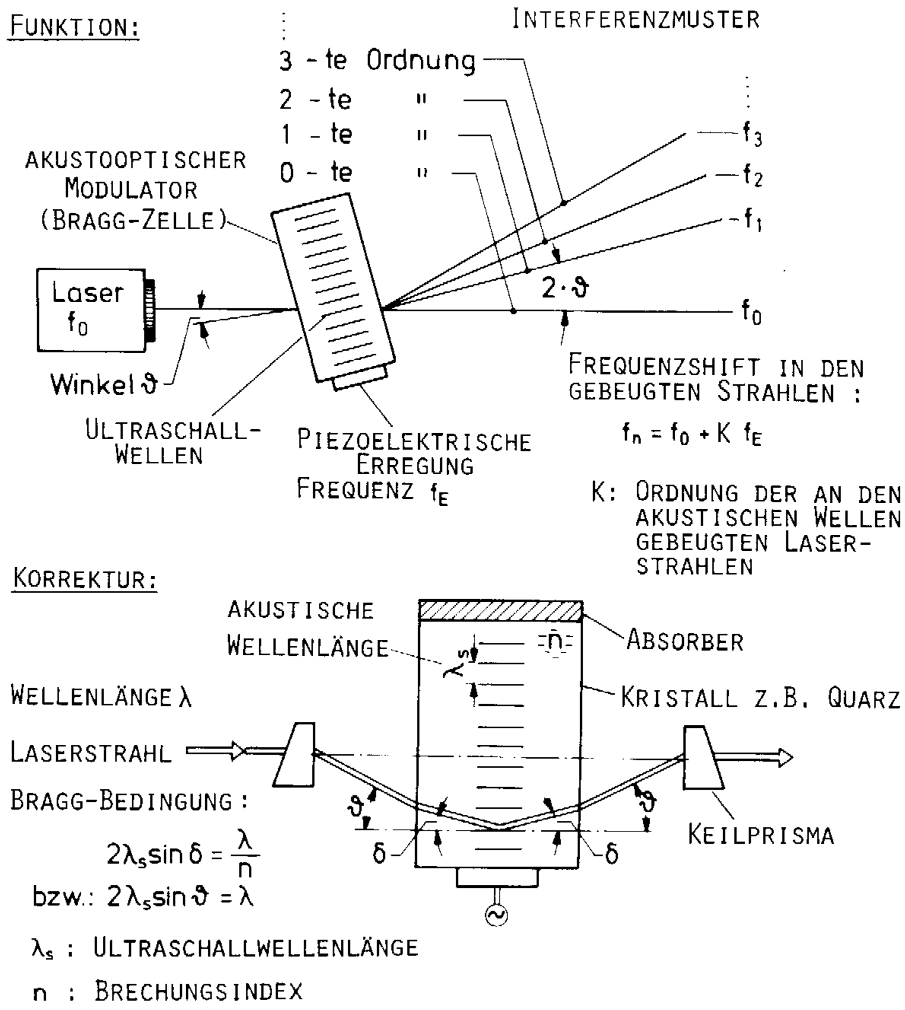
- Particle with $U_{\perp}$=0 still produce signals. By choosing f_s correctly there will be sufficient Doppler periods to allow validation by the processor.
- **Methods of frequency shifting**:
  - **rotating grating** (mechanical): simple, inexpensive, moderate accurate,$f_s = n\ \ N$ <15MHz



  - **Pockel's cell**: produces transient shift magnitude
  - **Kerr cell** (electro-optical): processing complex
  - **Bragg cell** (AOM): highly stable, accurate, relative high shift frequency

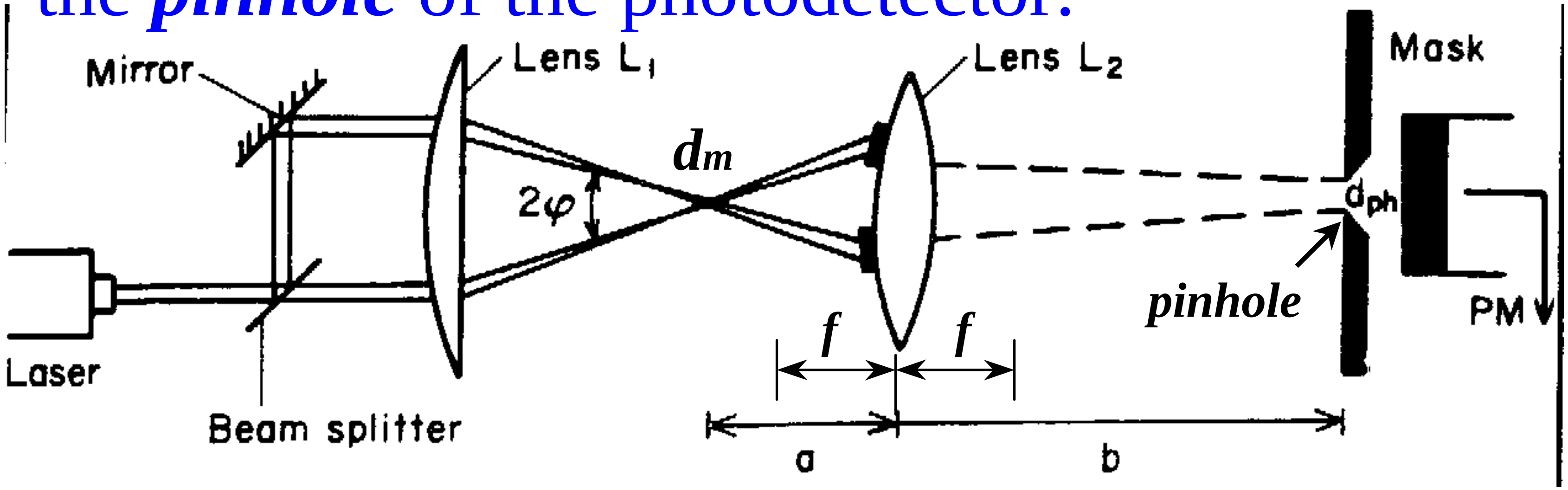
Bragg Cell

- The most widespread approach of frequency shifting is the single or double Bragg cell module.
- The single Bragg cell requires use of electronic downmixer.
- 90% of the incident light intensity for the 1st-order beam is achievable.



Receiving Optics (I)

- The ***effective mcv*** is the volume imaged onto the ***pinhole*** of the photodetector.



Magnification factor : ***M= b/a***

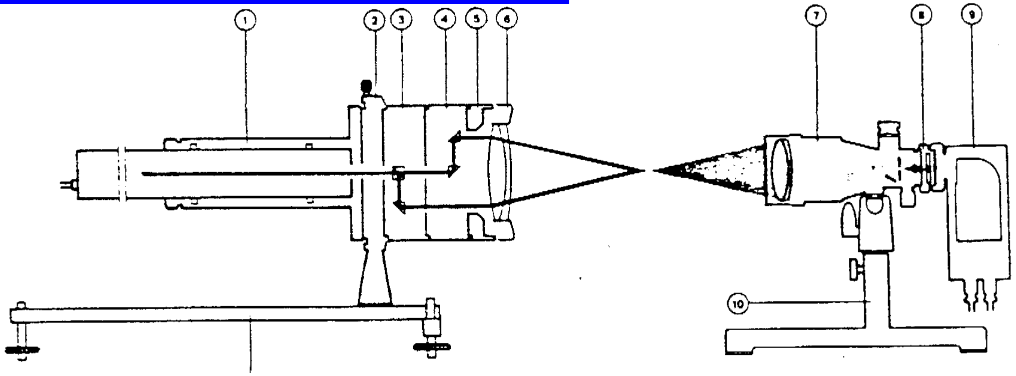
Effective no. of fringes :

$$N_{fr}' = N_{fr}\, d_{ph} / (M\, d_m)$$

$$\frac{1}{a}+\frac{1}{b}=\frac{1}{f}$$

Receiving Optics (II)

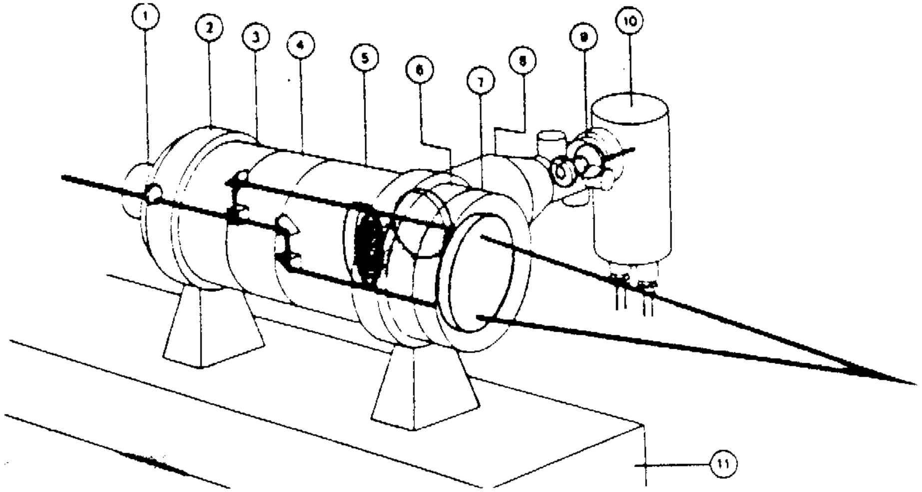
⦿ Forward Scattering



- Good ***SNR***
- Low laser power is needed
- more complex traversing rig

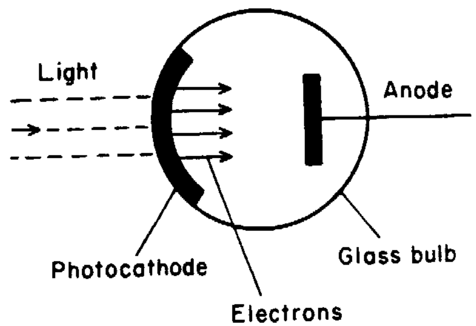
⦿ Backward scattering

- Only one optical acess necessary
- Self-adjusting
- more laser power needed

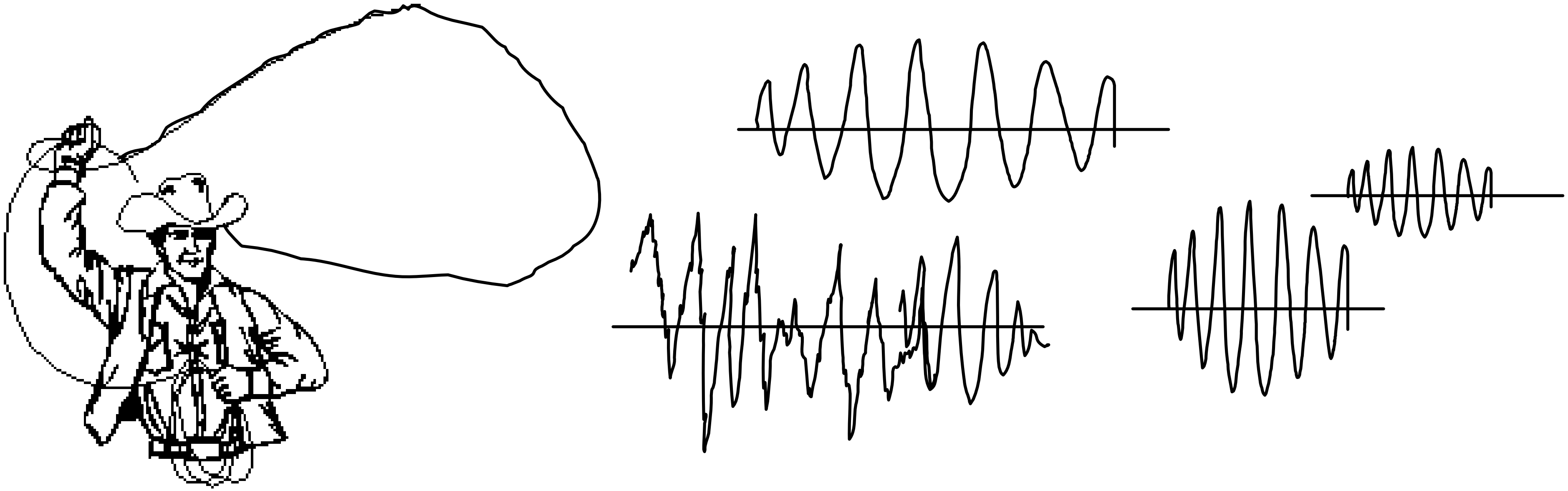


Photodetector

- The photodetector convert light intensity to a voltage. Three types of devices are commonly used in LDA systems: ***Photodiode, Avalanche diode, Photomultiplier***.
- For ***photodiode***: high resistence is desirable to give sufficient amplification and to minimise the thermal noise, but a low resistance leads to better frequency response. The ***compromise*** limits the use of diodes to use with ***strong scattering*** and ***low Doppler frequency***.
- The ***avalanche effect*** takes place when the photodiode is reverse-biased near its breakdown voltage.



Light scattering
&
signal processing



Required Properties of Particles

Suitable tracer particles used for LDA measurements should have the following properties:

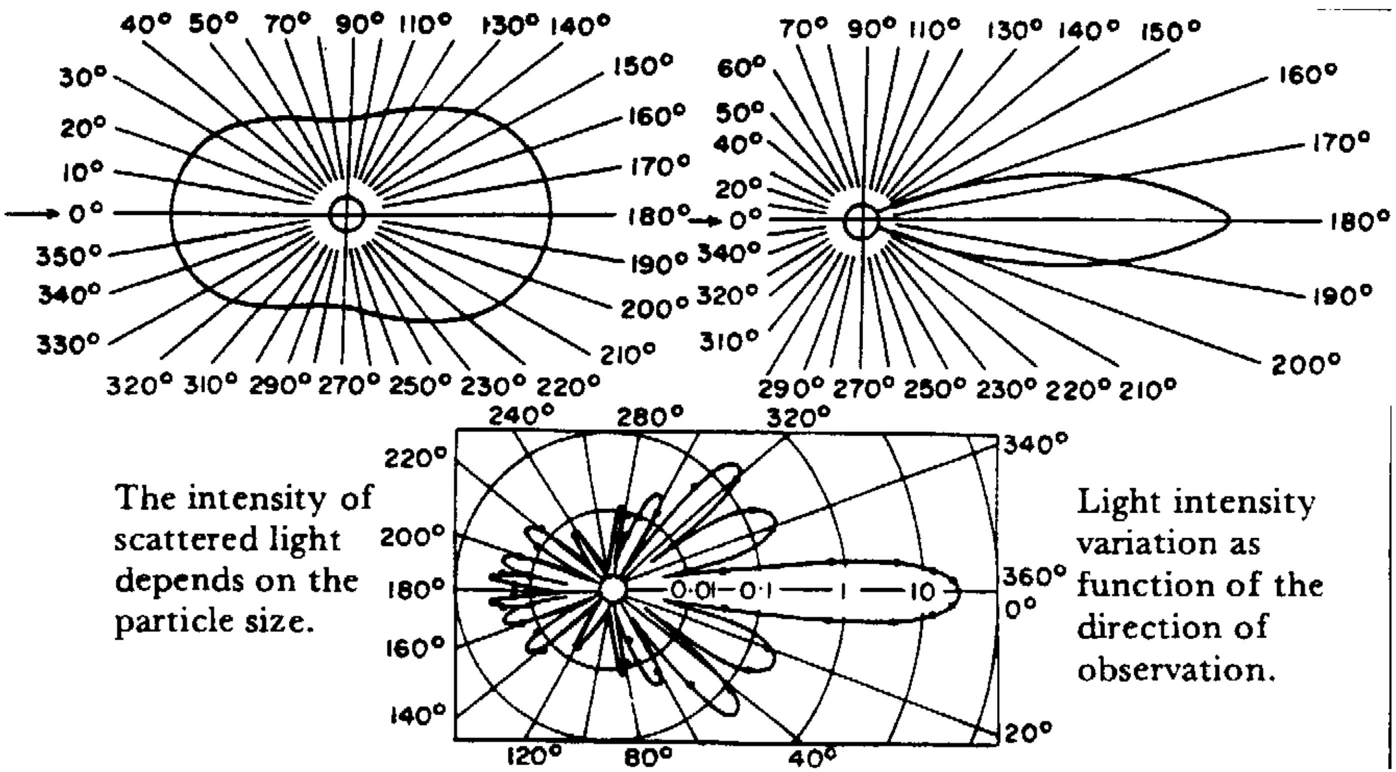
- small slip velocity
- good scattering properties to yield high signal strength
- good produceability of particles
- cheap
- chemically inactive
- non-toxic

Light Scattering from particles (I)

- The light scattering phenomena is described by the *Mie-scattering theory* for spherical particles.
- *Mie parameter:* $q = \dfrac{2r_p\pi}{\lambda}$ and *m* (refractive index)
- The *intensity of scattered light* depends on:
  - incident intensity
  - wavelength (λ)
  - particle shape , particle size (r_p), particle concentration and particle distributions
  - index of refraction of particle
  - scattering angle

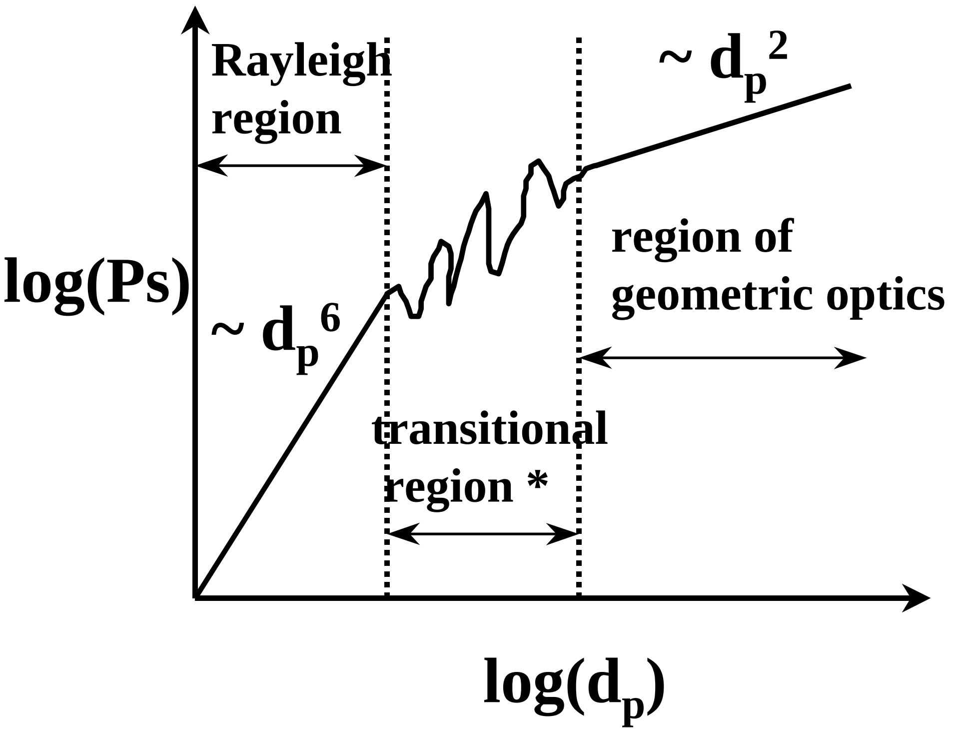
Light Scattering from particles (II)

$$q = \frac{2r_p\pi}{\lambda}$$

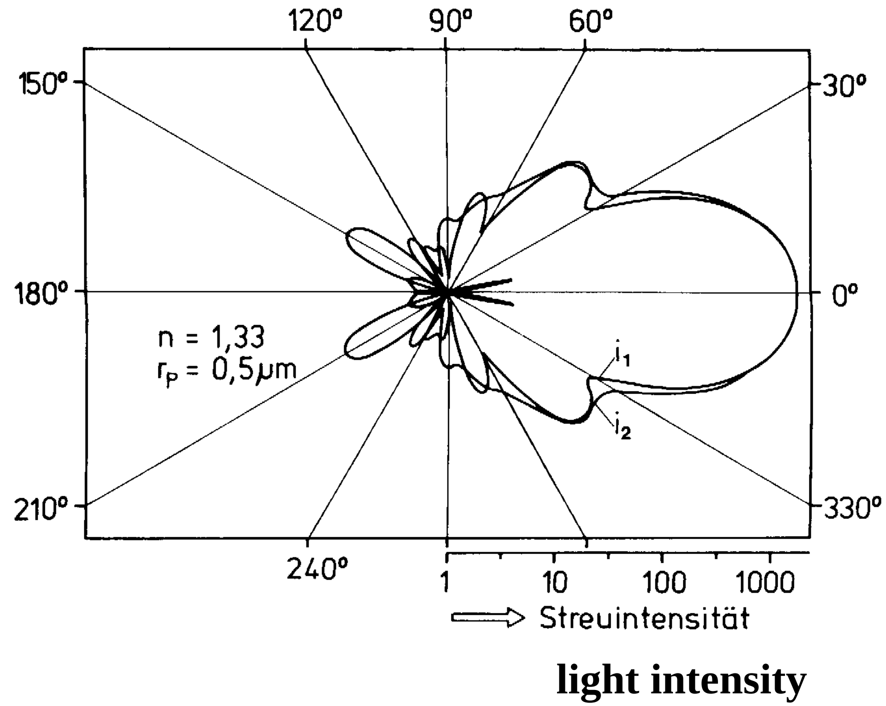


For a given system, the signal intensity is several orders of magnitude larger in forward scattering arrangement.

Light Scattering from particles (III)



(* for water $\mathbf{d_p}$ ~ 0.5 - 3μm)



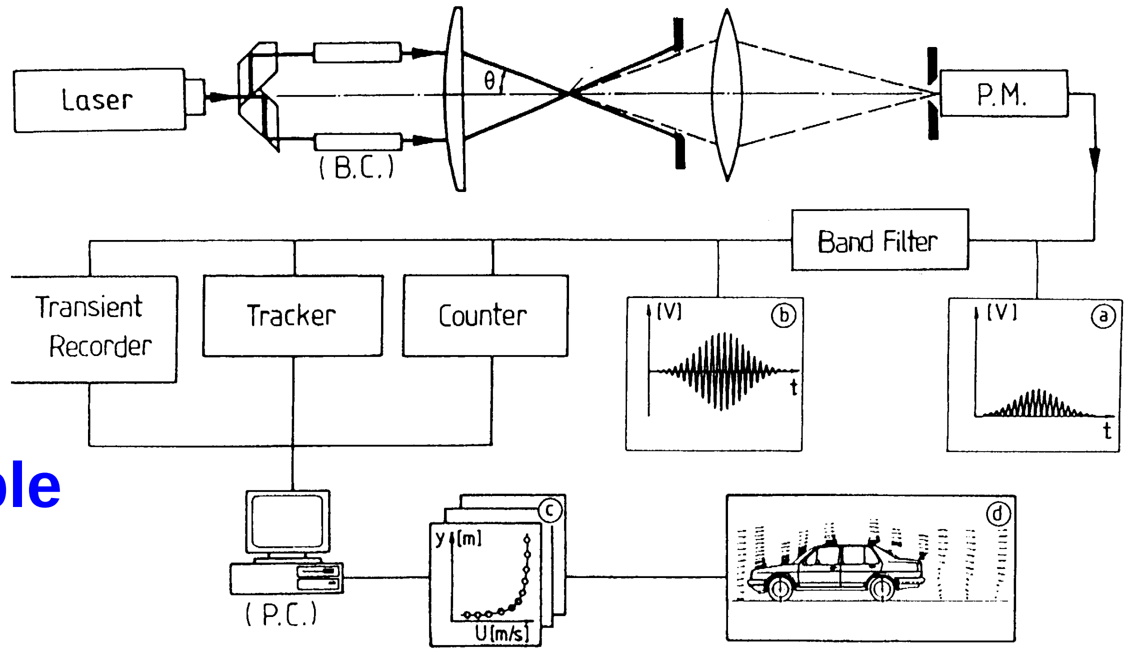
(for water droplet $\mathbf{d_p}$ =1 μm)

Signal Processing Tasks (I)

- The signal processing has the broad task of extracting fluid mechanics information from the Doppler signals. This entails
  - signal conditioning
  - determination of Doppler frequency

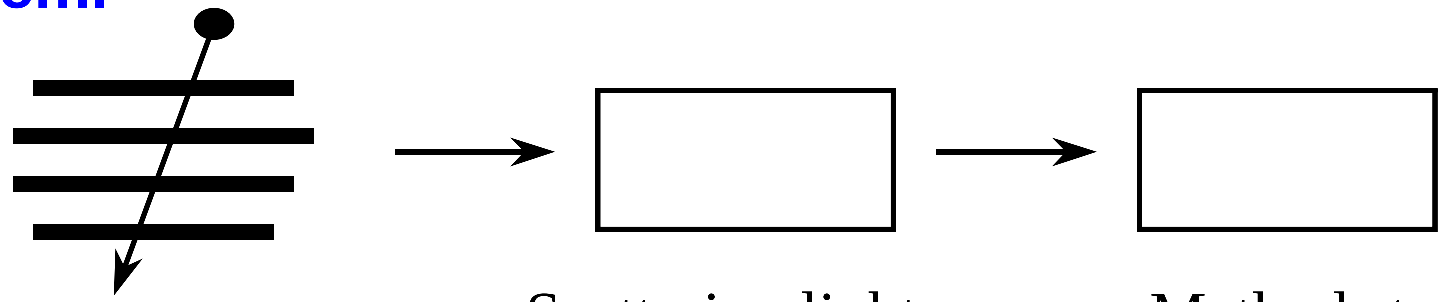
$$U_{\perp} = \frac{\nu_D \lambda}{2\sin\varphi}$$

  - computation of statistics and possible coordinate transformations.



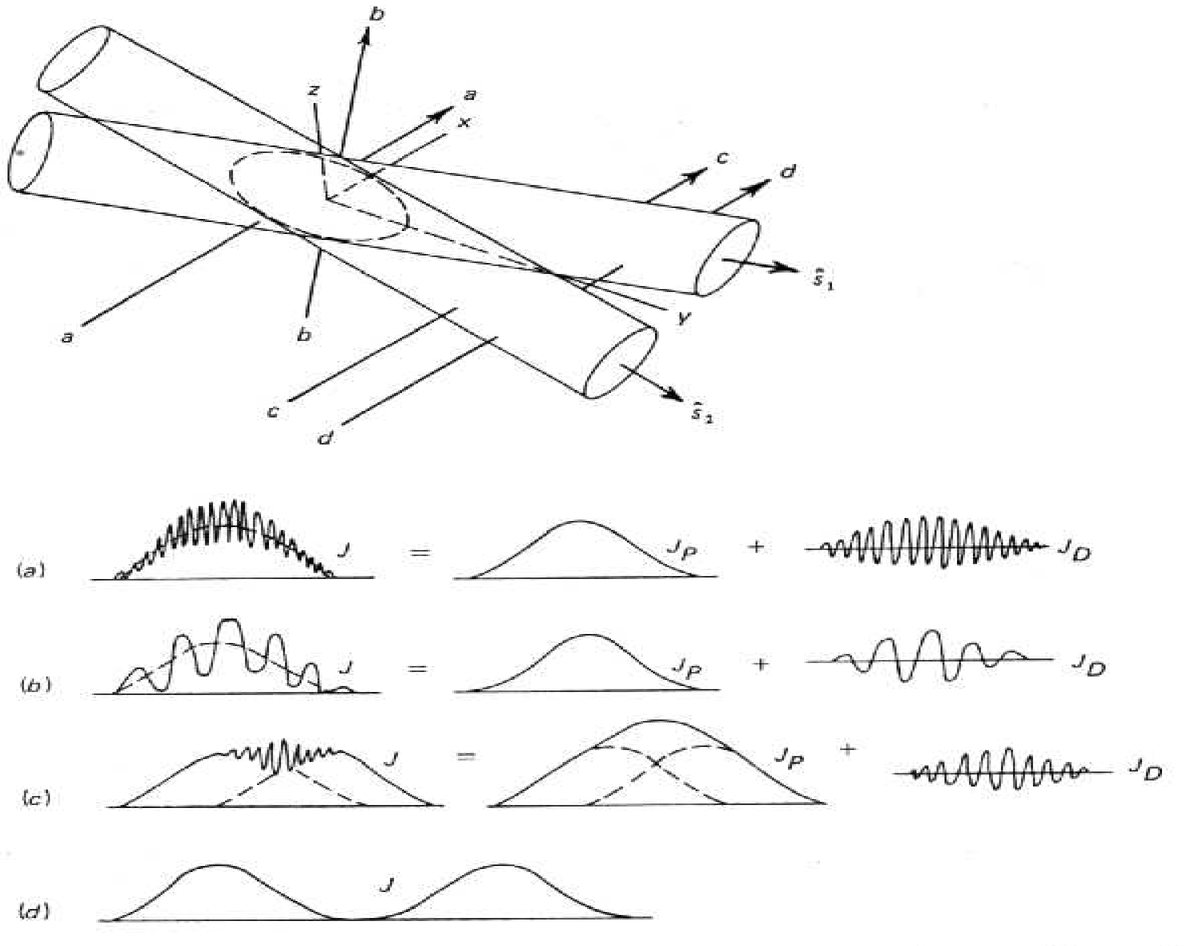
Signal Processing Tasks (II)

- **The signal processor is *not* an *independent* part of a LDA system.**



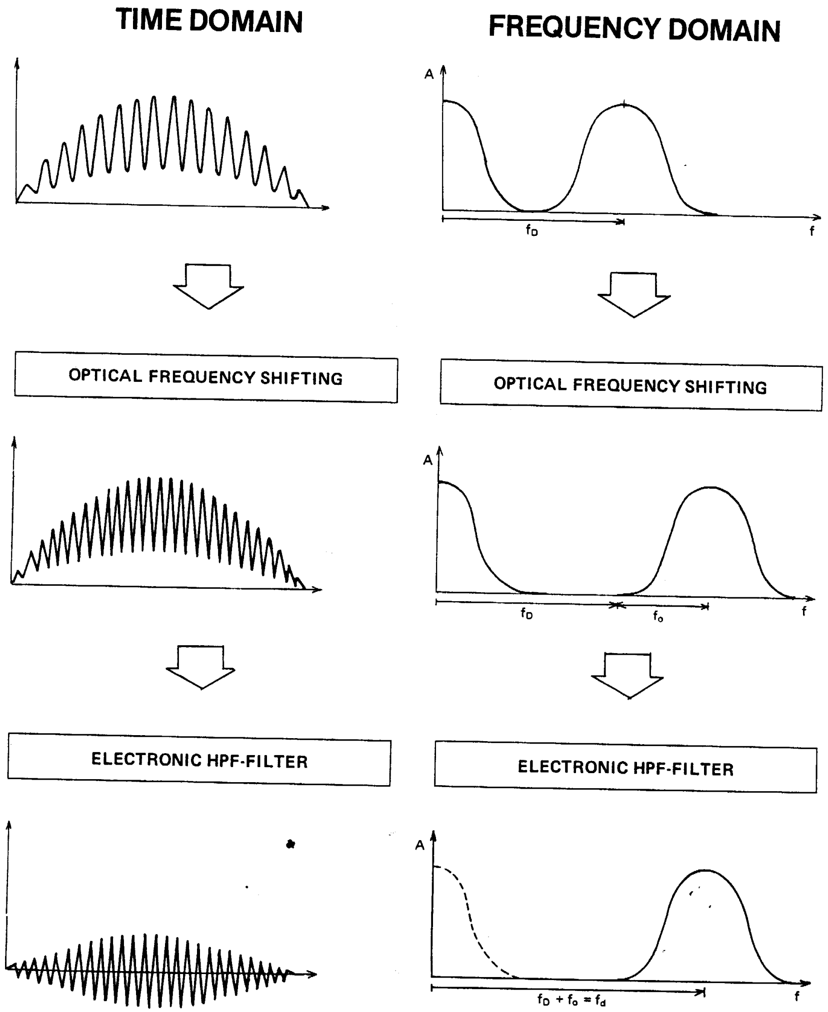
- ***Don't* expect to *improve* your signal by signal processor.**
- **There are several (either time domain-based or frequency domain-based) instruments available to process the LDA-signal.**

Characteristics of LDA Signals



Signal Conditioning

- **Signal conditioning improves signal quantity considerably.**
- **A *high pass filter* is used to remove the signal pedestal and make it symmetric. (If necessary, *frequency shifting* can be used to insure good separation of pedeatal and Doppler frequencies.)**
- **A *low pass filter* is used to remove high frequency noise content in signal.**



Signal Processor

- The signal processor has the task of determining the signal frequency.

$$U_{\perp} = \frac{\nu_D \lambda}{2 \sin \varphi}$$

- There are several instruments available to do this,

<u>Frequency domain</u>

– filter bank

– spectrum analyzer

– tracker

– Fabry-Perot interferometer

<u>Time Domain</u>

–counter

–photo correlator

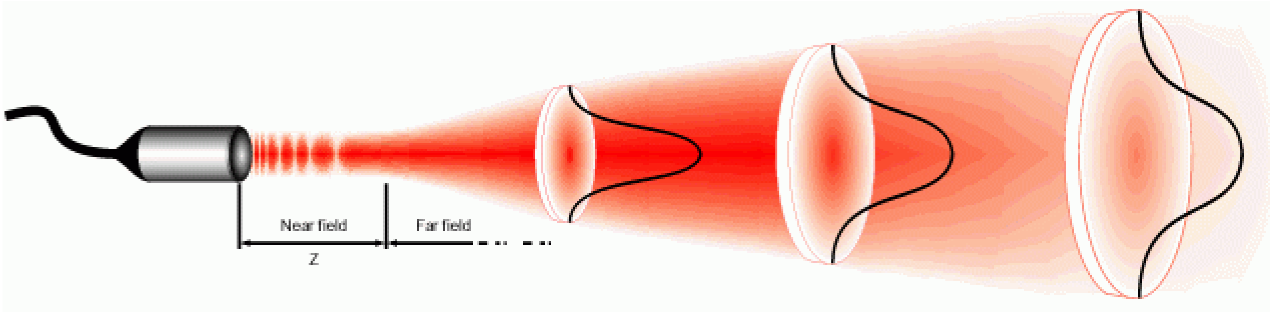
–transient recorde

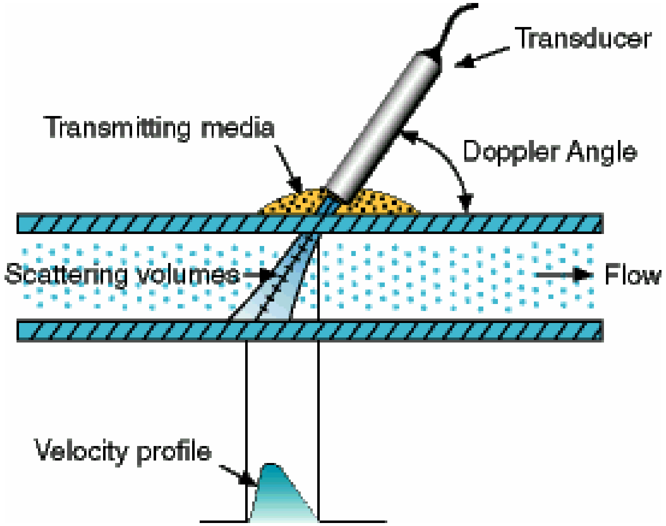
Choice of Signal Processor

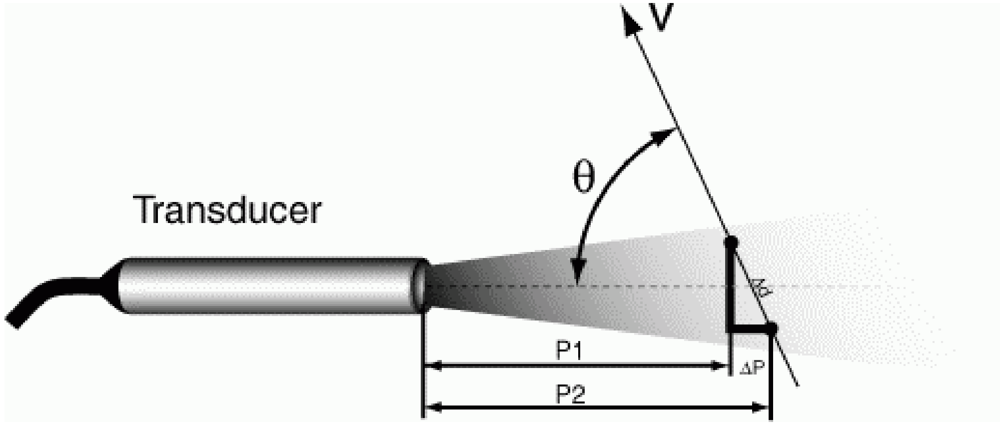
- The choice of signal processor depends on:
  – particle density (= particles / integral time scale)
  – digital or analog results
  – signal quality (SNR)
  – required accuracy
  – dynamic range and signal amplitude (bandwidth)
  – stationary or transient flowfield
  – sample processing speed
  – user-friendliness
  – cost

Pulsed Doppler Ultrasonic technique

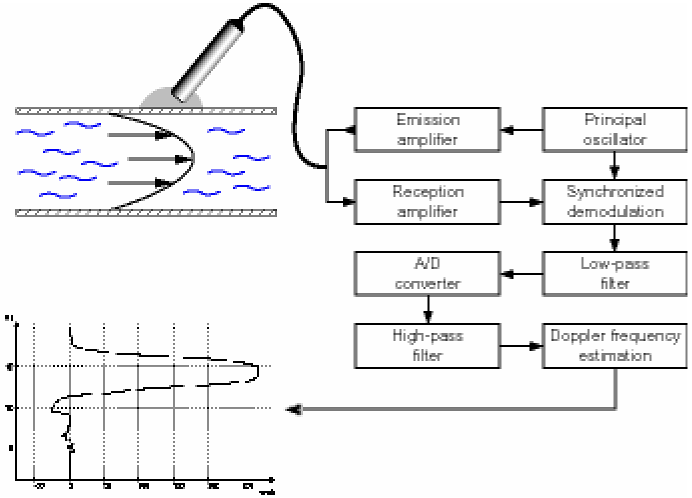
⦿ Pulsed Doppler Ultrasonic technique

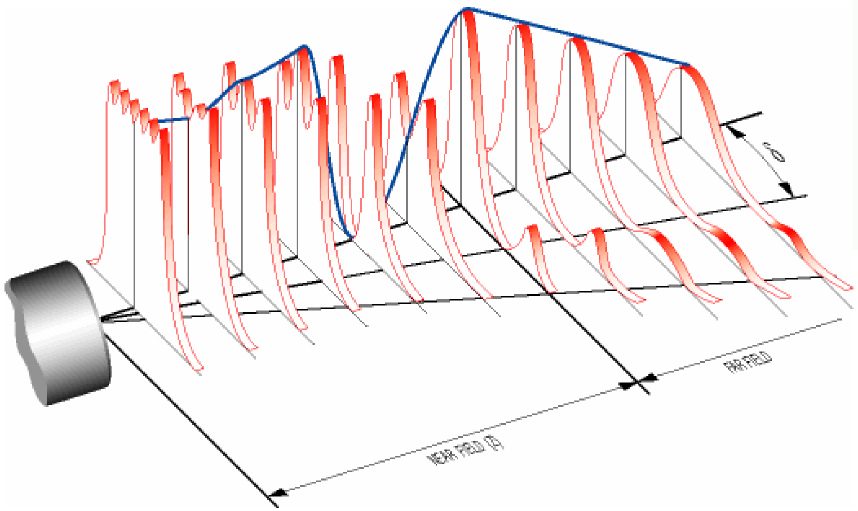


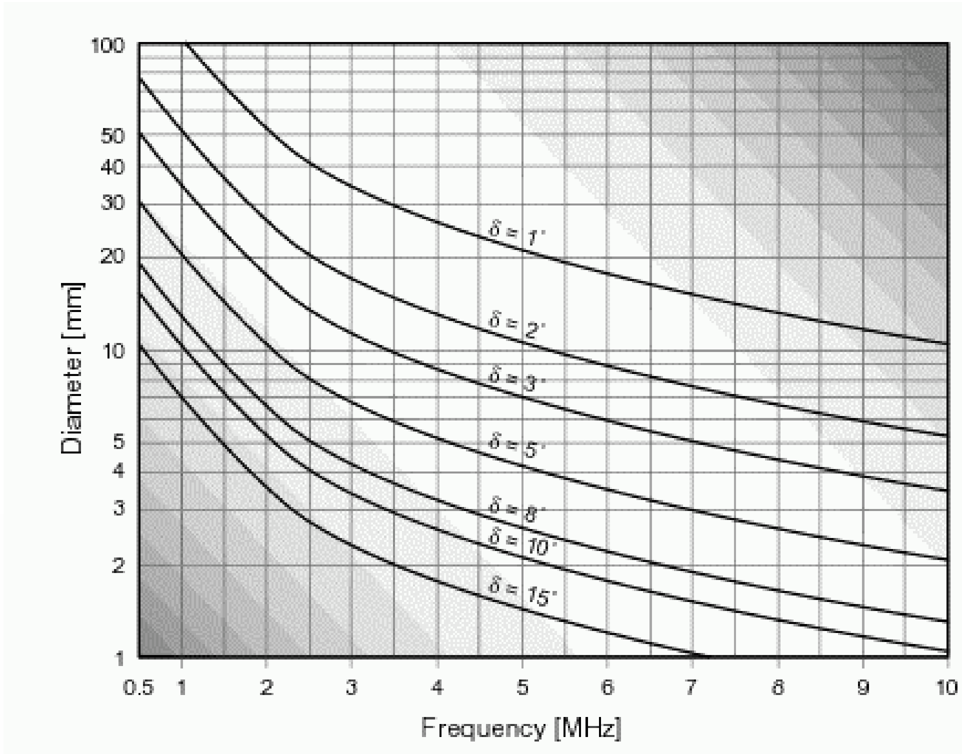




Pulsed Doppler Ultrasonic technique







Introduction to
Particle Image Velocimetry
(PIV)

Introduction to PIV

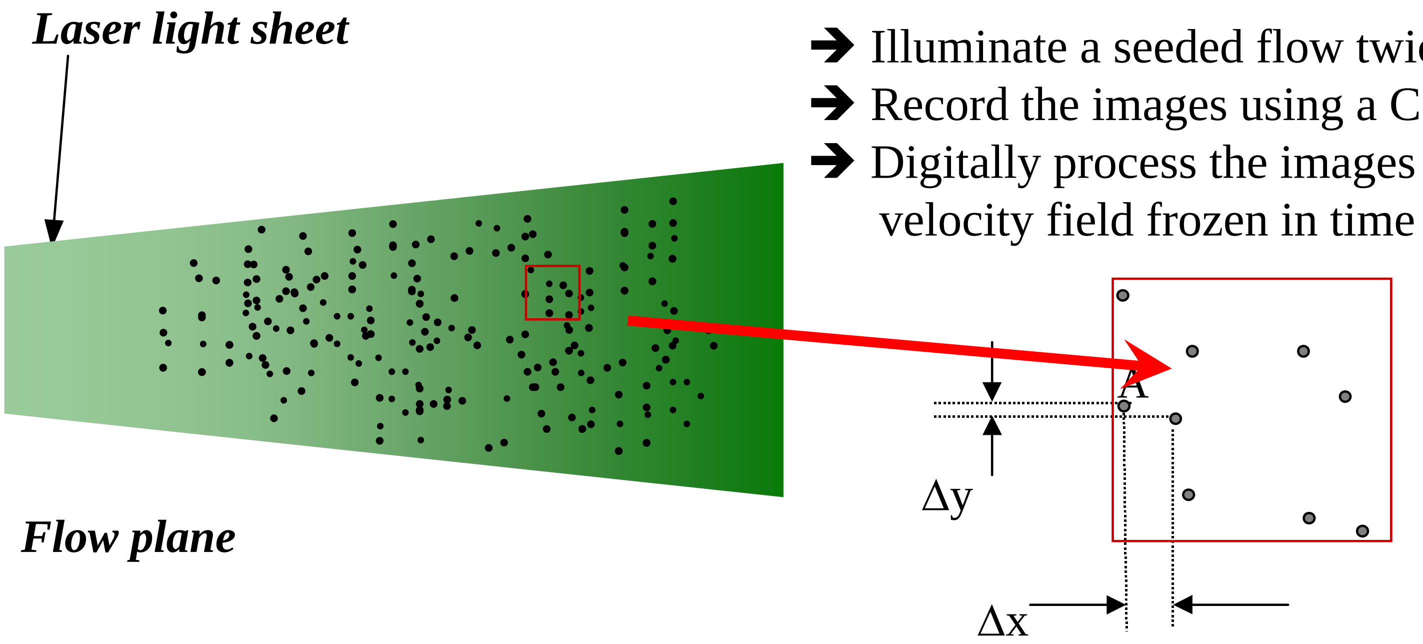
- **First commercial PIV in 1988**
- **PIV is a quantitative flow visualization by using an optical method to measure fluid velocity at many points in a flow field simultaneously.**
- **Similar techniques:**
  PTV: particle tracking velocimetry, offers lower accuracy and resolution for low seeding density.
  LSV: laser speckle velocimetry,

Characteristics of PIV

- **Advantages:**
  - provides instantaneous velocity vectors in detail (for flow structure, especially for turbulence).
  - provides spatial gradients of instantaneous and average flow properties for many points
  - Ideal for unsteady or periodic flows
  - obtain global nature of flows

- **Disadvantages of PIV:**
  - expensive cost
  - seeding
  - small measuring region

Principle of PIV



- Illuminate a seeded flow twice in succession
- Record the images using a CCD or film camera
- Digitally process the images to obtain a 2D velocity field frozen in time

Δt - time between two pulses
Δx - particle displacement in x direction
Δy - particle displacement in y direction

Velocity of particle A

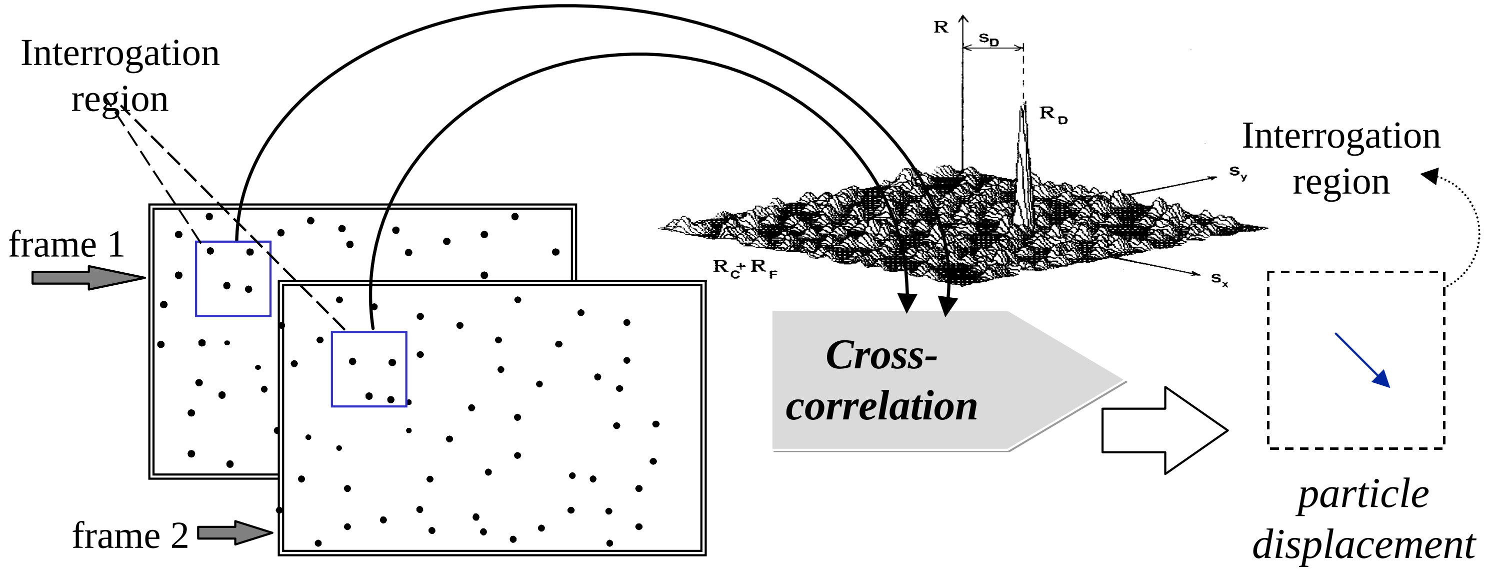
$$u_x = \Delta x/\Delta t \quad \text{as } \Delta t \rightarrow 0$$

$$u_y = \Delta y/\Delta t \quad \text{as } \Delta t \rightarrow 0$$

Data processing of PIV

- **The image displacements are obtained by doing the spatial crosscorrection or spatial autocorrection of the image intensity field.**
- **Spatial cross-correlation:**
  - **- Particle images from each laser pulse is on separate frames**
  - **- No directional ambiguity (because sequence of frames is known)**
  - **- Dynamic range can be greater than 100 to 1**
  - **-** Robust algorithm - can detect lower signal quality
- **Spatial Autocorrelation**
  - **- Double or multiple pulses on each frame**
  - **- Directional ambiguity**
  - **- Dynamic range may be up to 10 to 1**

Crosscorrelation Processing



Each frame contains particle images from one laser pulse.

Analysis by correlating the two image fields from separate video frames.

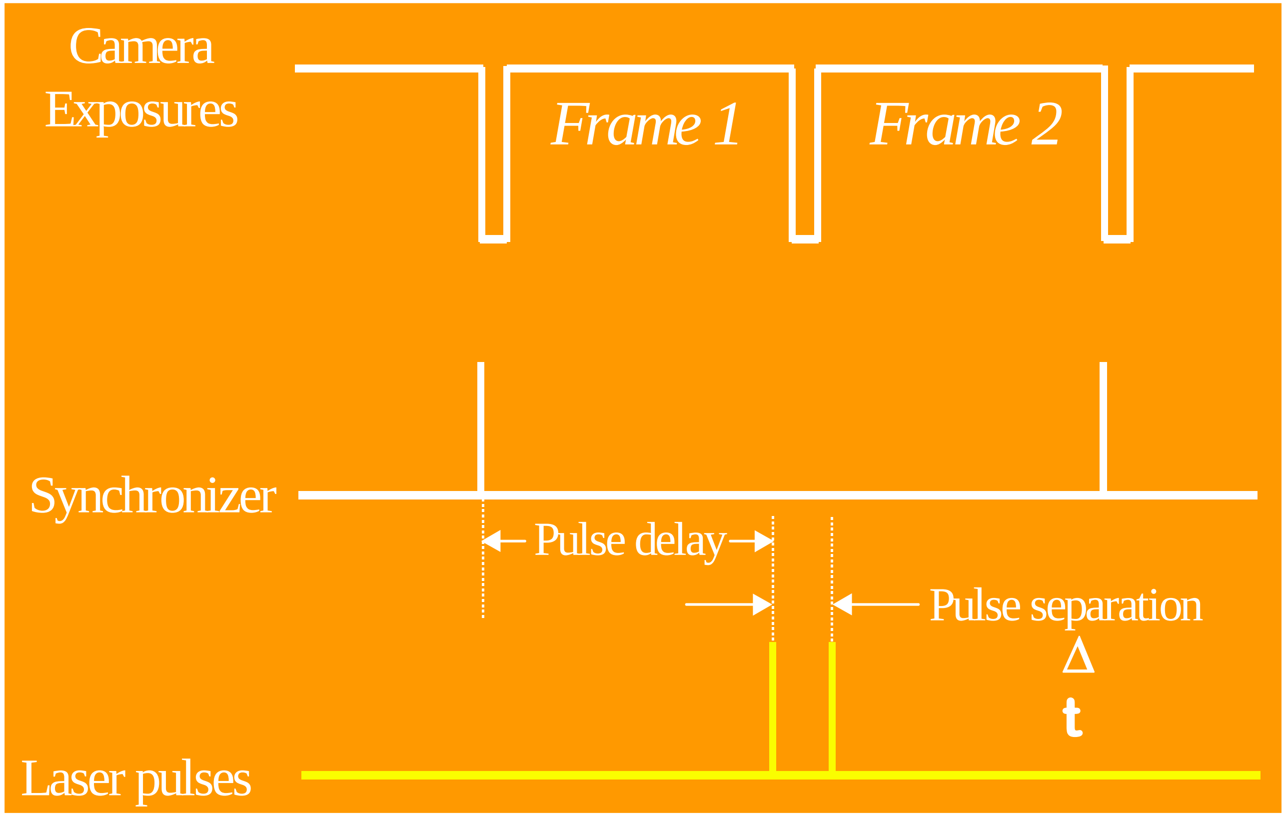
Advantages:

works very well to >400 m/sec (with specially developed cameras and frame straddling technique)

no additional hardware required to resolve flow direction

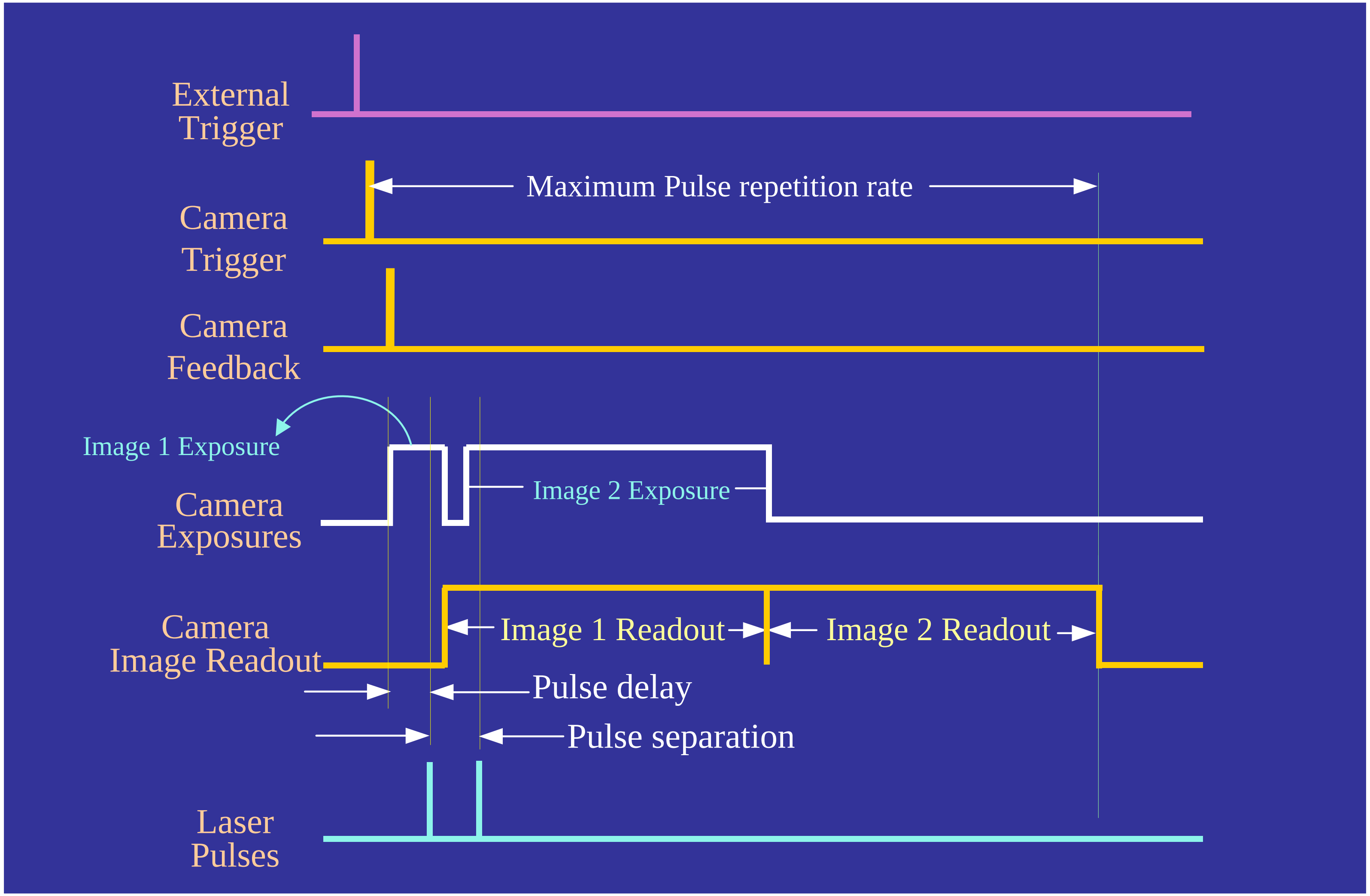
frames need not be successive (especially for measuring very low speed flows)

Frame straddle with free-run camera

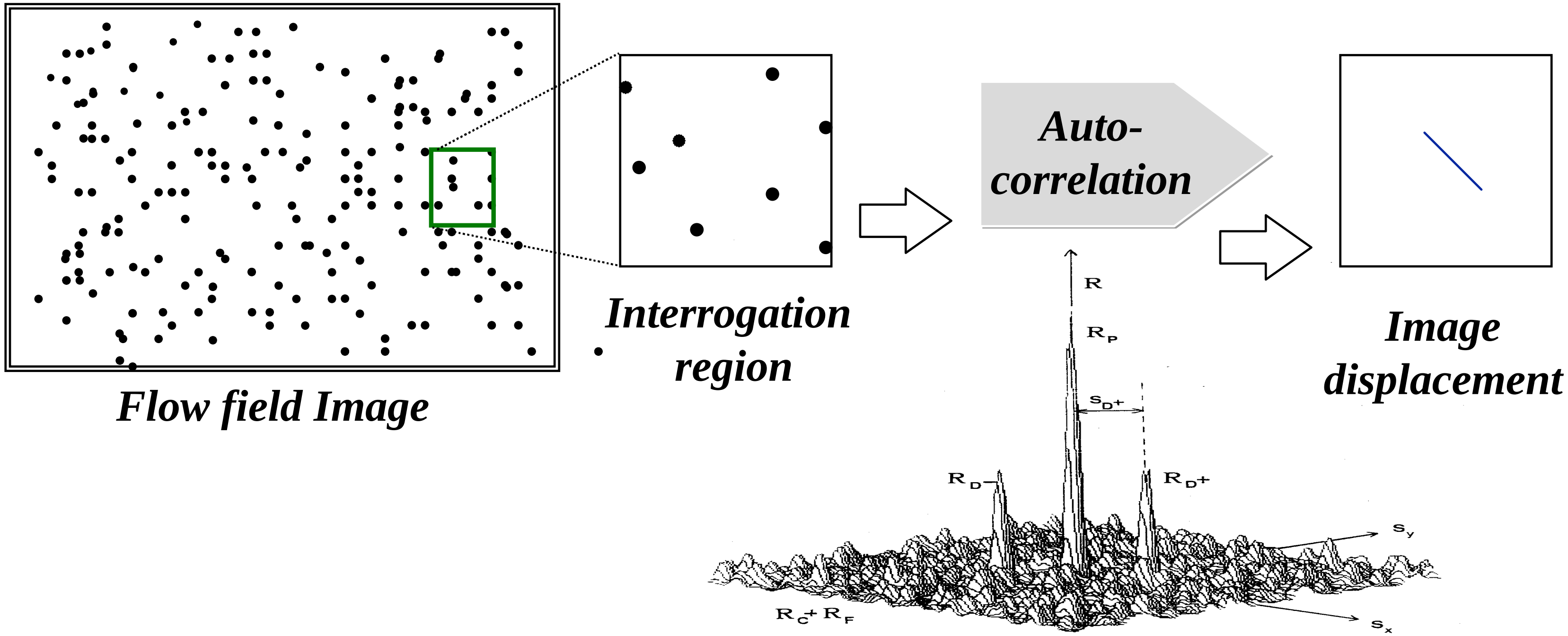


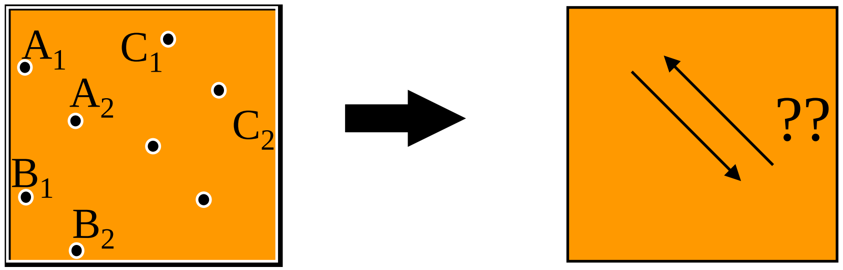
max. measuring velocity is function of image size and camera type

Frame straddle with controlled camera



Autocorrelation Processing (I)





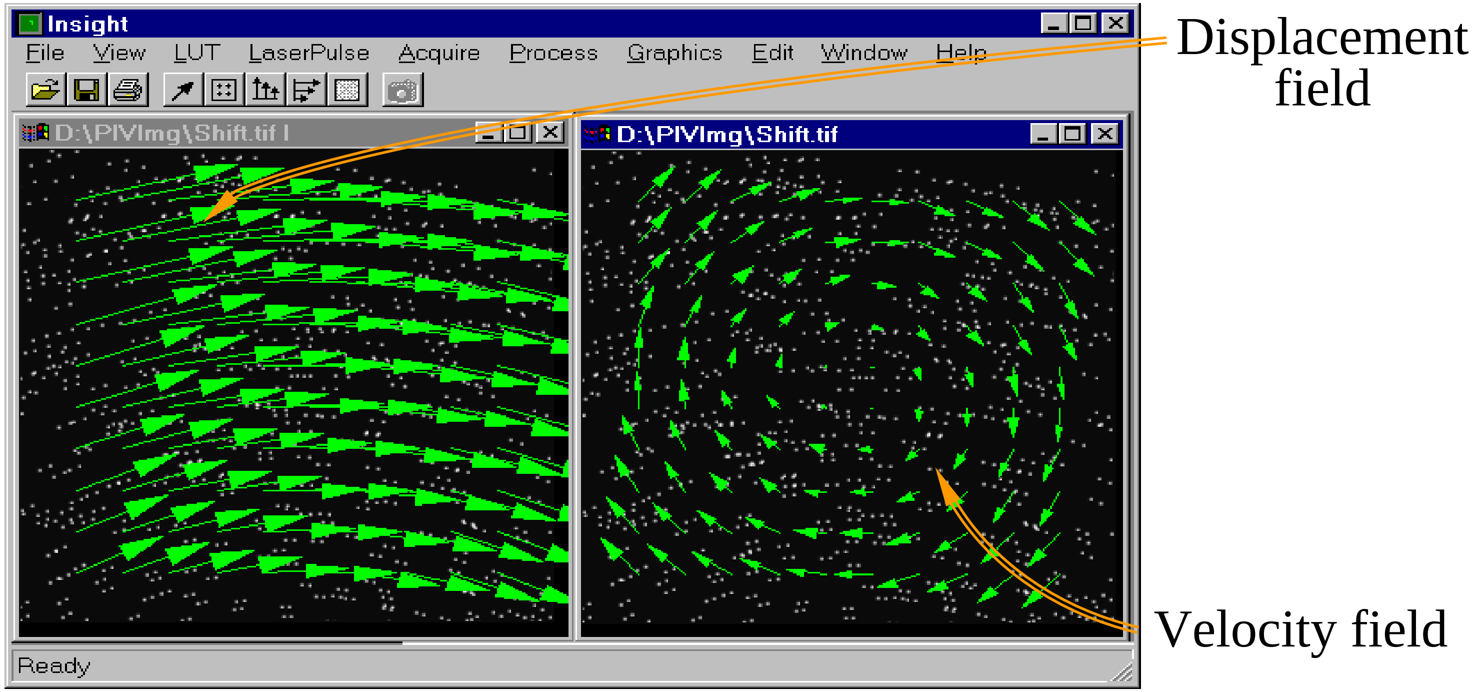
Directional ambiguity:

Is the flow direction from C_1 to C_2 or from C_2 to C_1 ?

Autocorrelation Processing (II)

Solution: using Image shifting to make all displacements to be positive

$$\text{Velocity} = \frac{\text{image displacement} - \text{image shift}}{\Delta t}$$



Components of PIV system

A complete PIV system combines three sub-systems:

- Illumination Subsystem (Laser, Beam delivery system, light optics)
  - Illuminate a plane in the flow (seeded) using a pulsed laser
- Image Capture Subsystem (CCD Camera, Camera Interface, Synchronizer-Master control unit)
  - Capture the particle images and record them
- Analysis and Display Subsystem
  - Calculates and displays a two dimensional vector field from the particle image fields
  - can be done on-line or off-line

Introduction to Aerosol generation & Particle Size Measurement

Aerosol/Powder in Daily Life

Powder: Particle size less than 1000 μm (British Standard 2955); most often encountered powder size between 0.01 μm and 1000 μm

Allergy, Lung disease
Food (ice cream, Coffee, tooth paste, ketchup, …etc.)
Medical treatment
Safety (Dust explosion …etc.)

Producing powder

Chemical process

raw components

A → B

↓

reaction

↓

crystallization

↓

filtration

↓

drying

↓

product

Mechanical process

Melting

↓

Atomization

↓

Cooling of Spray

↓

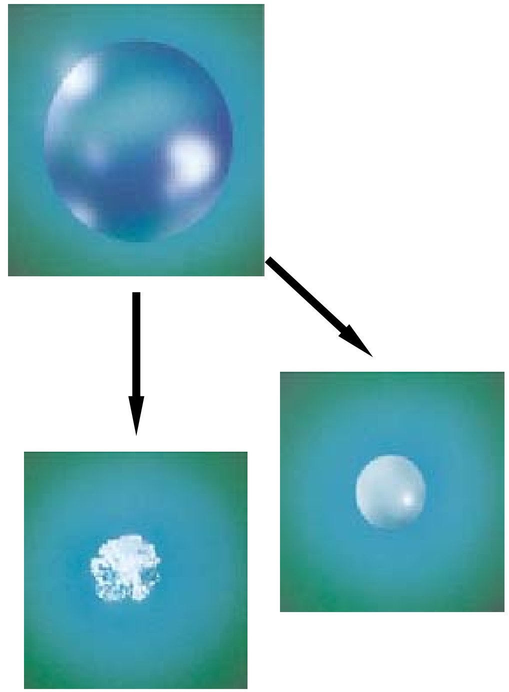
Powder Collection

↓

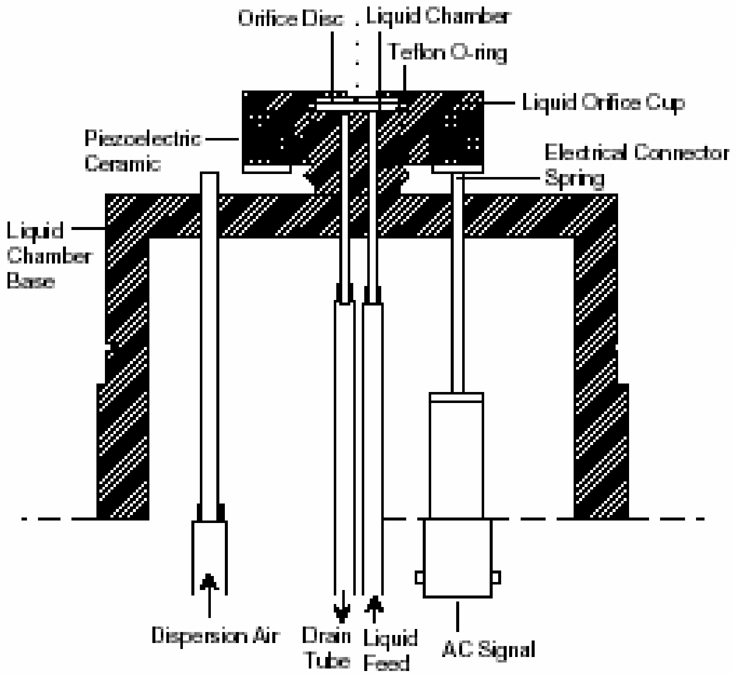
Powder Classification

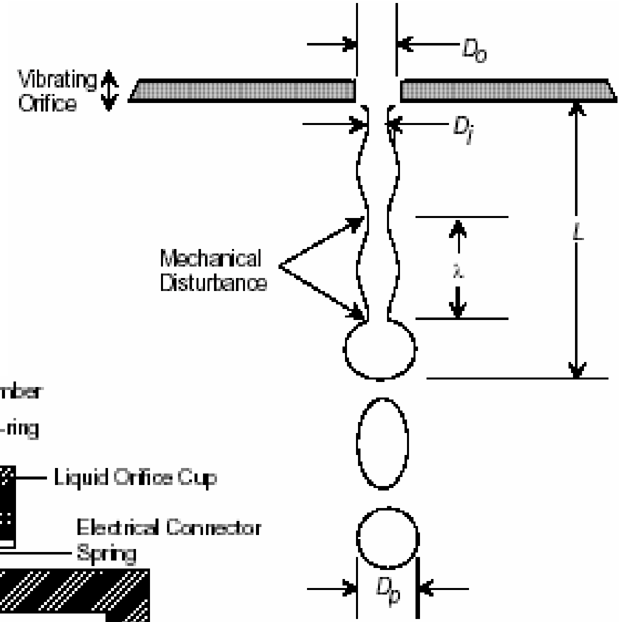
Grinding

…



Vibrating Orifice Aerosol Generator





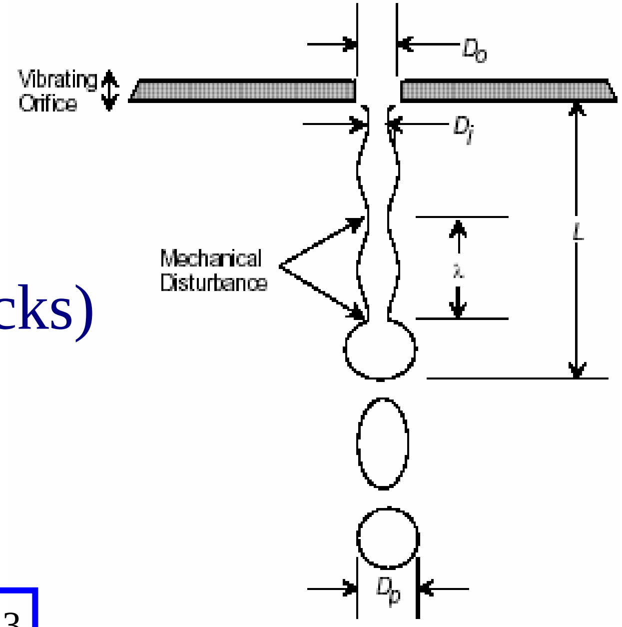
Vibrating Orifice Aerosol Generator

$\lambda_{min} = \pi D_j$

$\lambda_{Rayleigh} = 4.508 D_j$

$3.5D_j > \lambda > 7 D_j$ (Schneider & Hendricks)

$$V_j > V_{j,\min} = \left(\frac{8\sigma}{\rho D_j}\right)^{1/2}$$



$$D_p = \left(\frac{6QC}{\pi f}\right)^{1/3} \quad \text{or} \quad D_p = \left(\frac{6Q}{\pi f}\right)^{1/3}$$

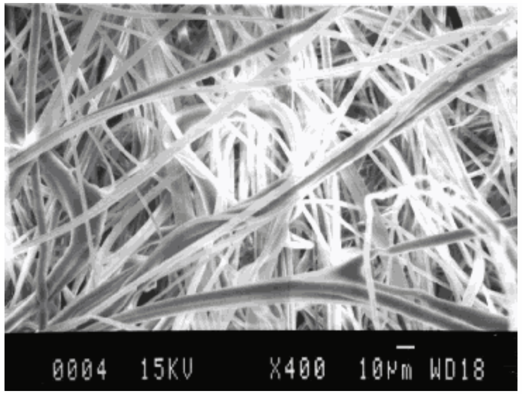
Q: liquid flow rate

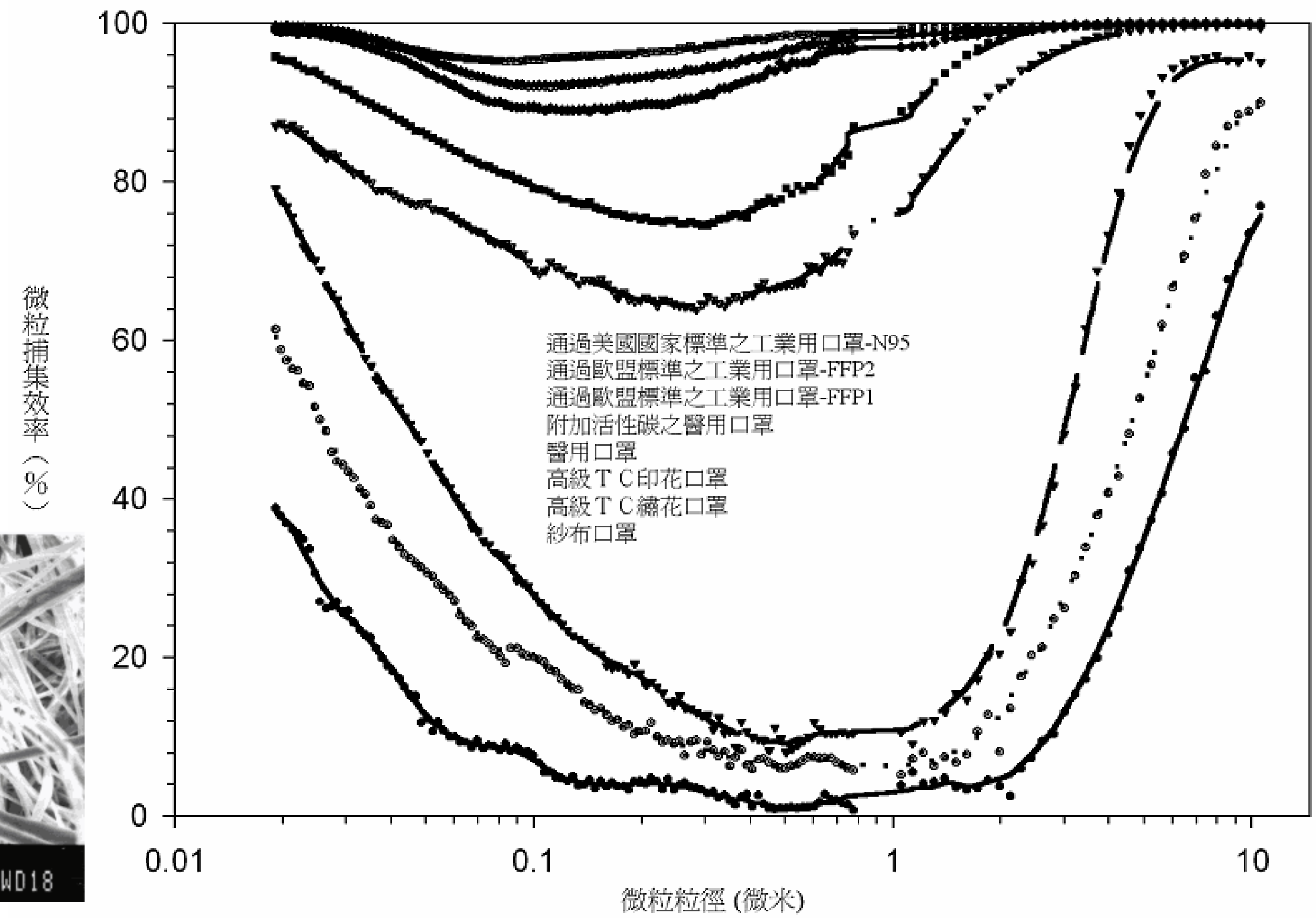
f: oscillation frequency.

C: volumetric concentration of the nonvolatile portion.

Filtration Technology

纖維直徑5微米, 間距約16微米
（填充密度10%)





(http://www.iosh.gov.tw/data/f5/news920521.htm)

Optical Measuring Principle

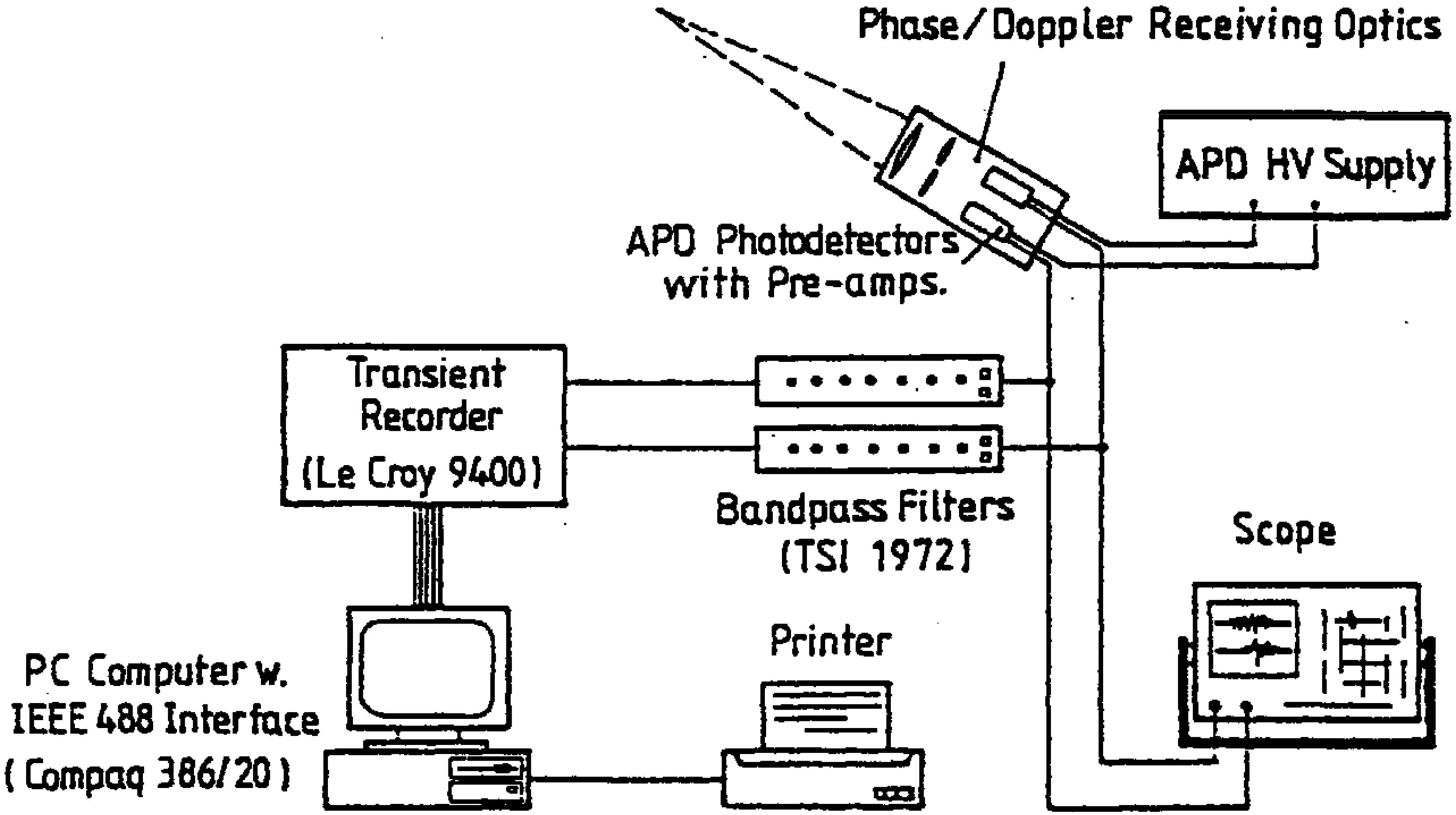
Image Analysis

Non-image analysis

- **blockage**
  - (a) $X = mD/\lambda >> 1$
    - D : particle diameter
    - λ :wave length of light
    - The light is blocked completely
- **diffraction**
  - (b) $x \geqq 1$, Fraunhofer diffraction
    - Using Airy's formula
    - $I(\theta)=(r/2)\alpha^2[2J_1(\alpha\theta)/\alpha\theta]^2$
    - $I(\theta)$:light intensity
    - r : particle radius
    - α : particle size parameter
    - J_1: Bessel function of order unity
- **scattering**
  - (c) $x \leqq 1$, Mie's scattering theory
    - $I(\theta)=(\lambda^2/8\theta r^2)(i_1+i_2)$

(from Y.-D. Tai)

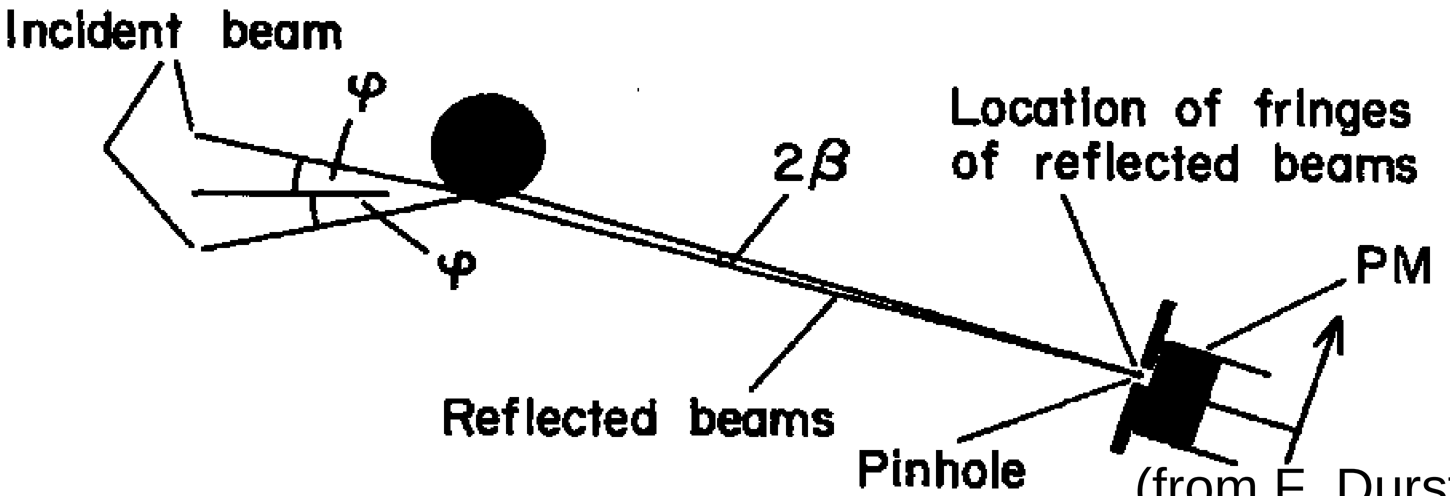
Hardware of Phase-Doppler System



(from F. Durst)

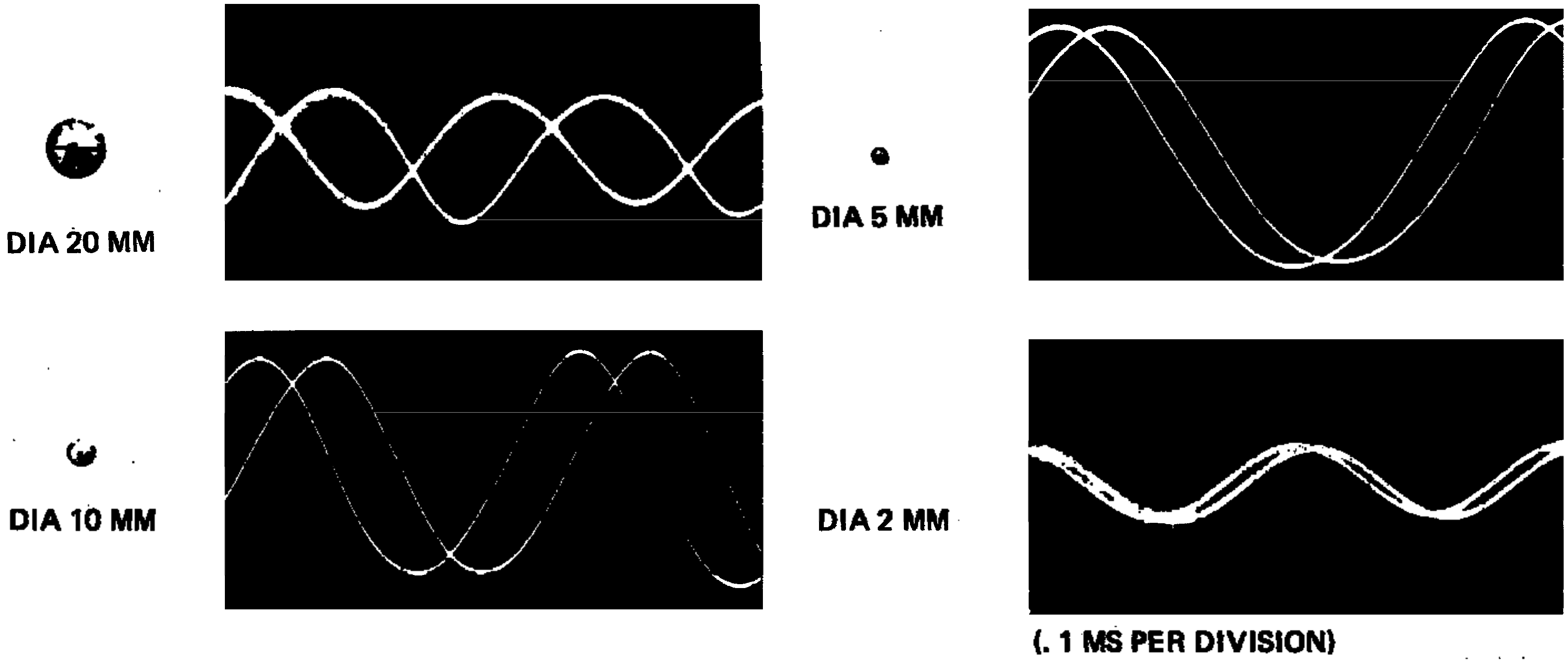
Fringes in Space from Reflected Beams

- In single phase flows, the Doppler signals can be explained as created by small scattering particles penetrating a fringe system in the crossing region of two light beams. The particles should be small with respect to the fringe spacing.
- To measure the velocity of large particles the two incident beams of an anemometer are reflected to produce a fringe pattern on the photodetector mask.



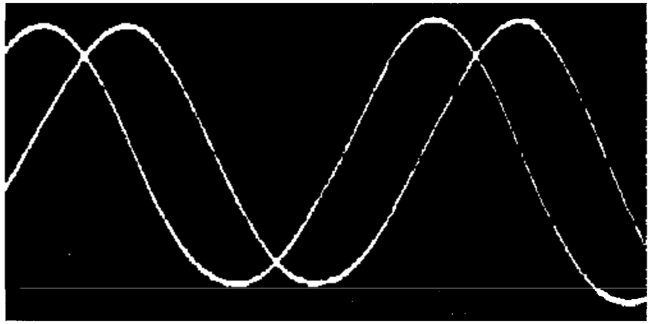
(from F. Durst)

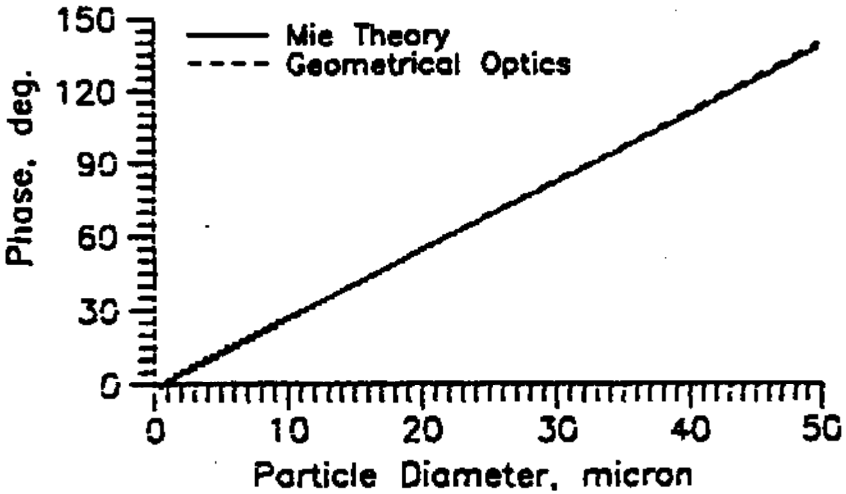
Phase Difference and Particle Size

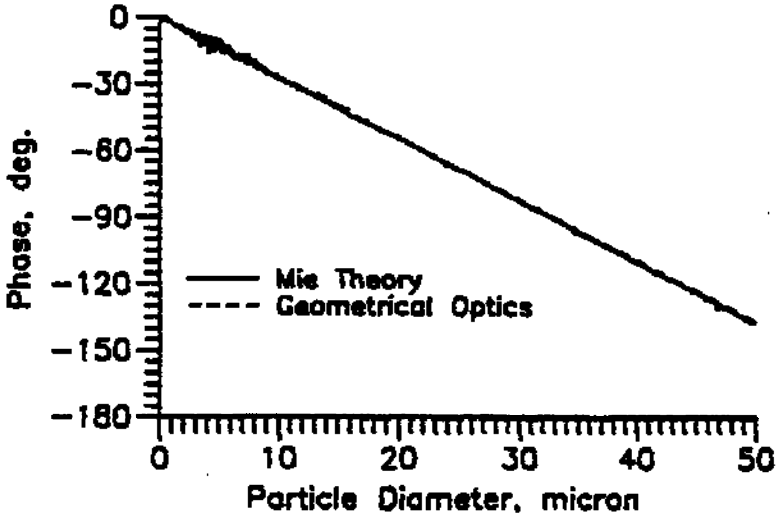


(from F. Durst)

PDA-Phase Relationships







(from F. Durst)

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