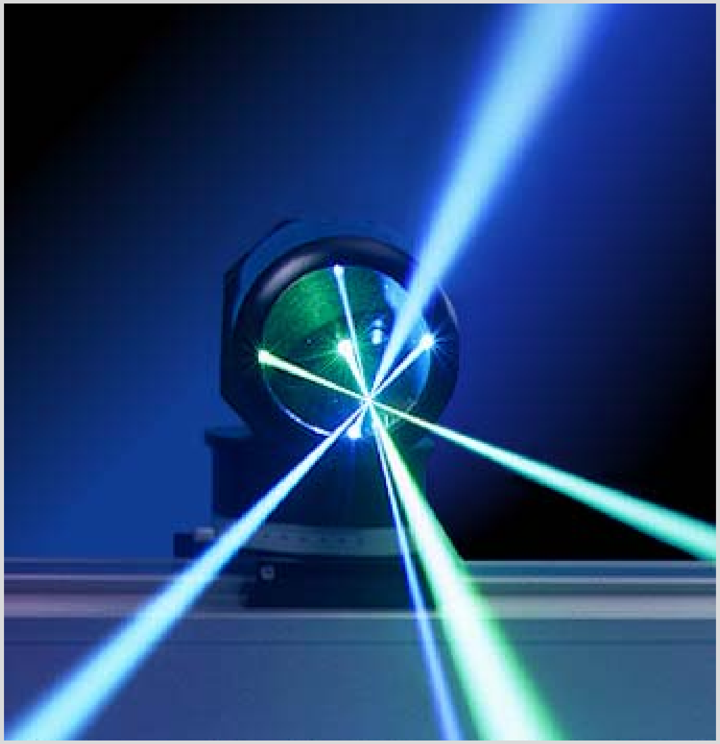
Laser Doppler Anemometry

Introduction to principles and applications

adapted from DANTEC literature by John Sullivan, Purdue AAE. Edited by S.P. Schneider, Purdue AAE.



Why Measure?

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

$$\rho \frac{Du_i}{Dt} = \frac{\partial \tau_{ij}}{\partial X_j} + \rho f_i - \frac{\partial p}{\partial X_j}$$

Turbulent motion is 3-D, vortical, and diffusive

⇨ governing Navier-Stokes equations are very hard (or impossible) to solve.

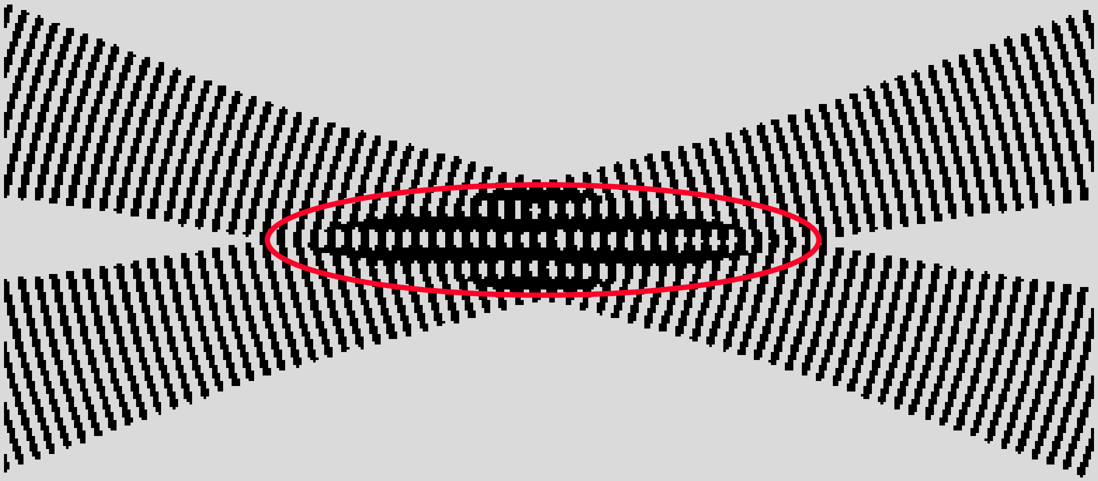
Measurements are easier (easy?)

Characteristics of LDA

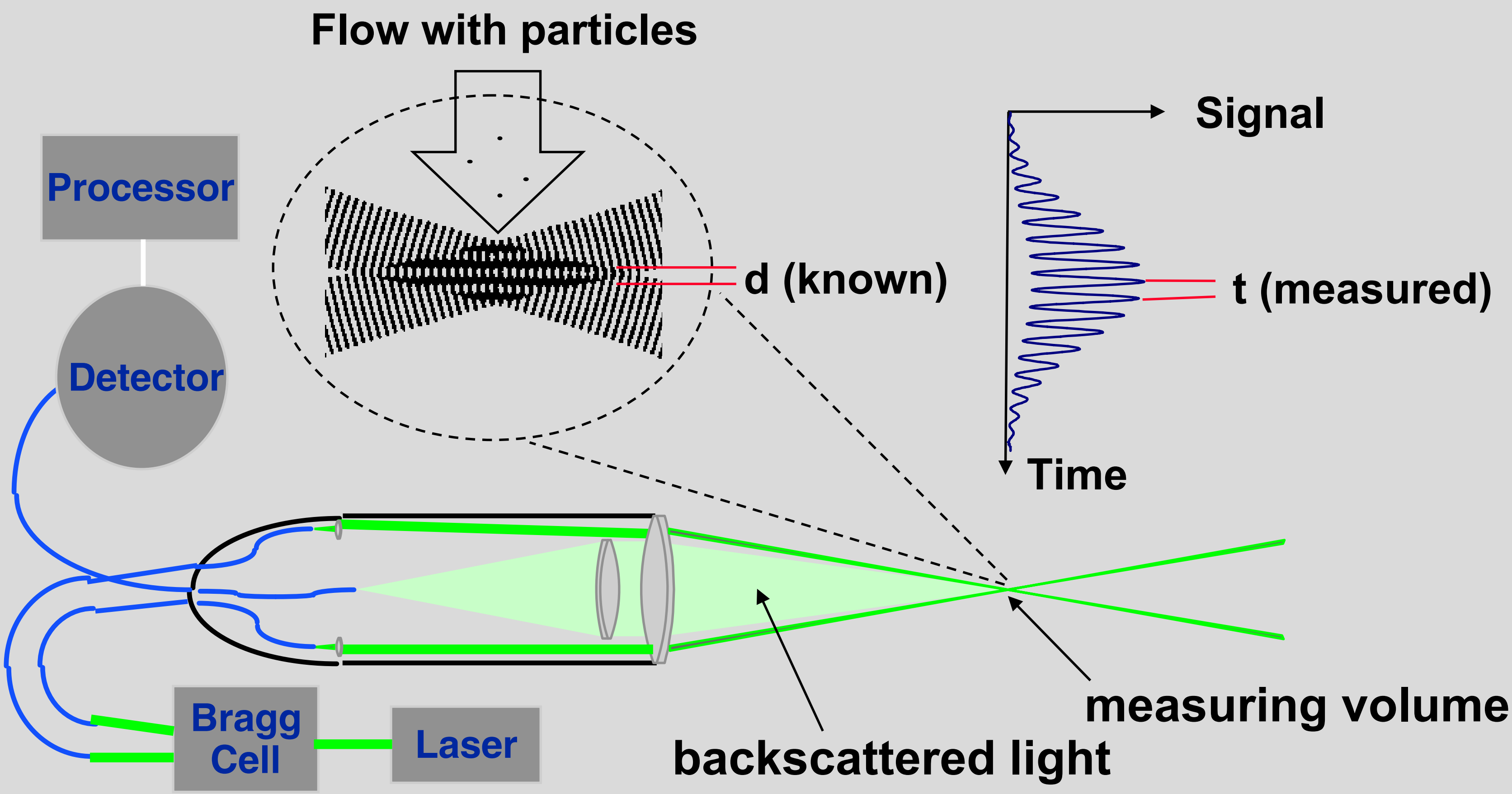
- Invented by Yeh and Cummins in 1964
- Velocity measurements in Fluid Dynamics (gas, liquid)
- Up to 3 velocity components
- Non-intrusive measurements (optical technique)
- Absolute measurement technique (no calibration required)
- Very high accuracy
- Very high spatial resolution due to small measurement volume
- Tracer particles are required

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

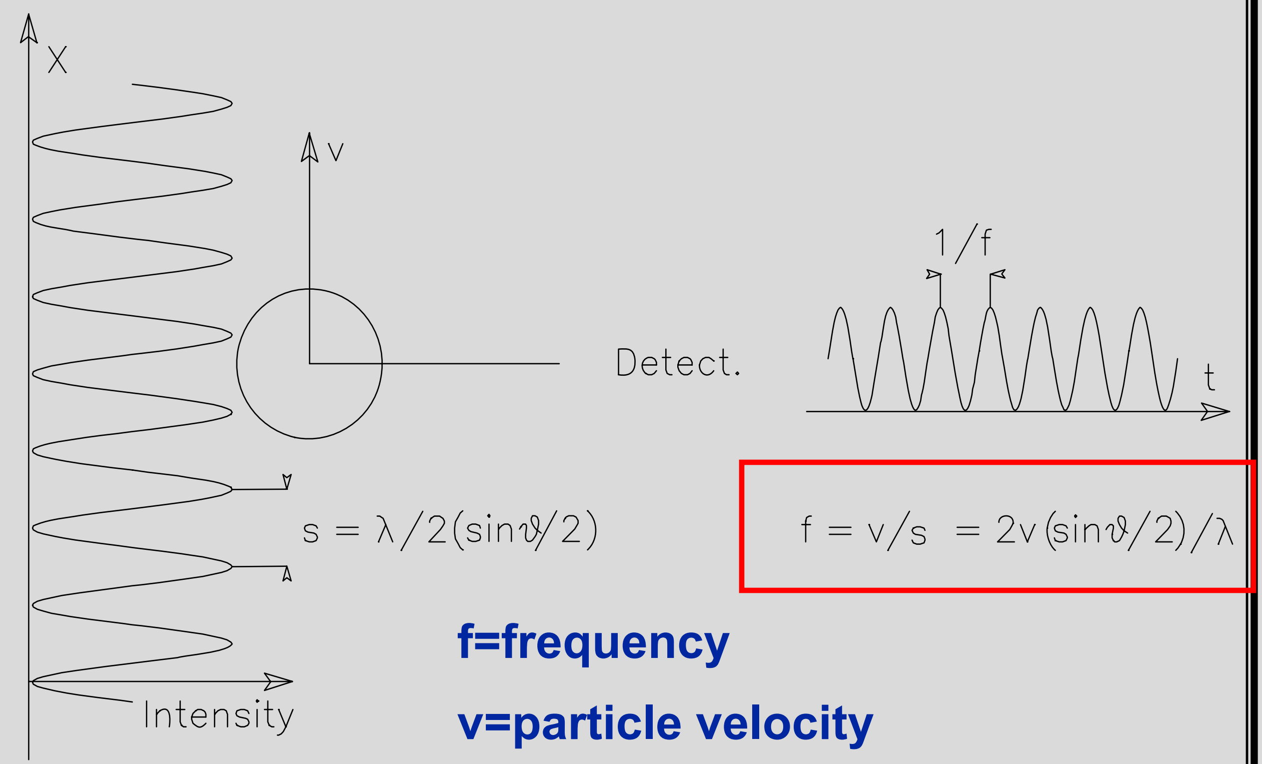


Velocity = distance/time



LDA - Fringe Model

- **The fringe model assumes as a way of visualization 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.**



f=frequency

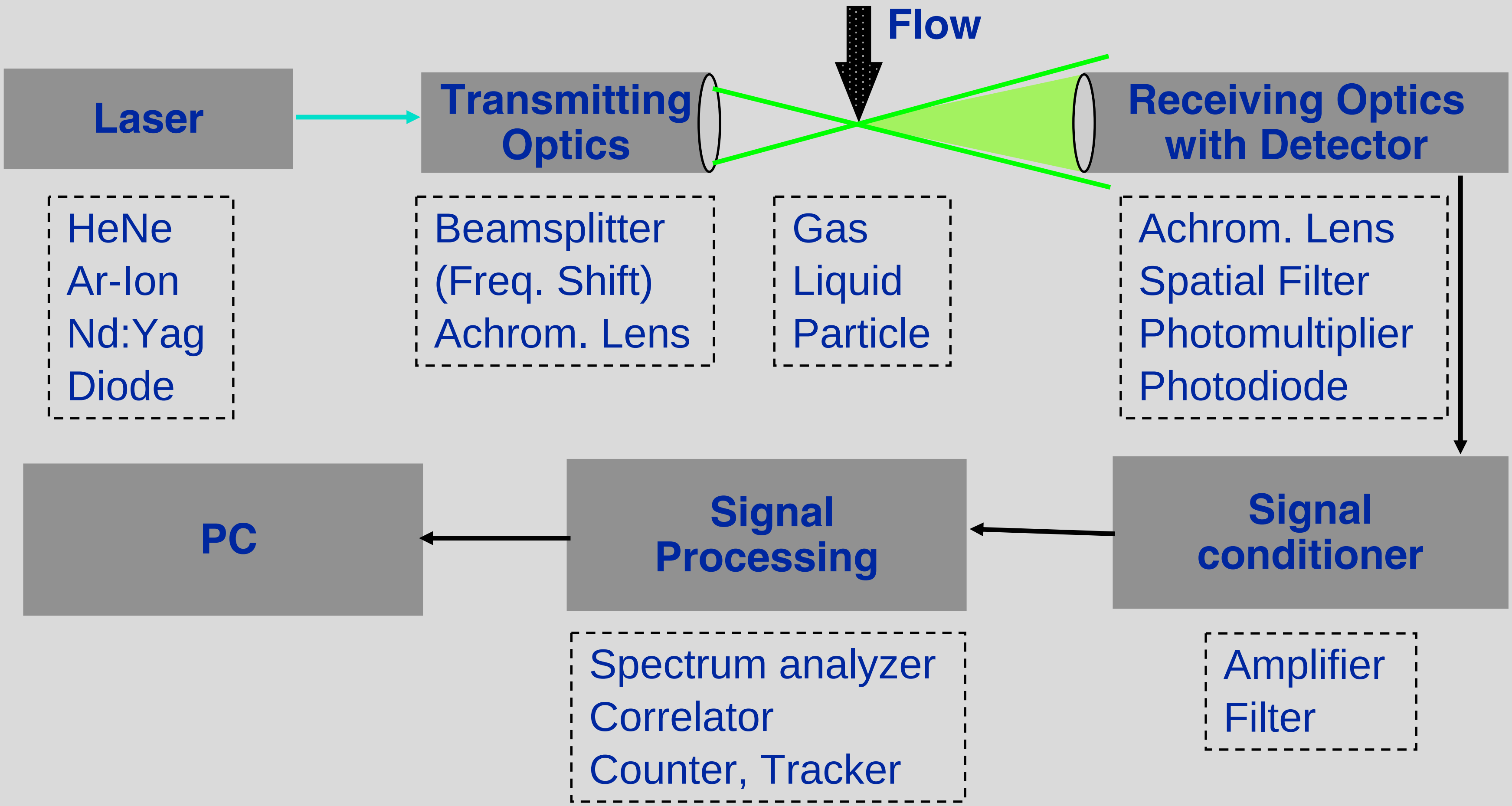
v=particle velocity

θ=angle between laser beams

λ=wavelength of laser light

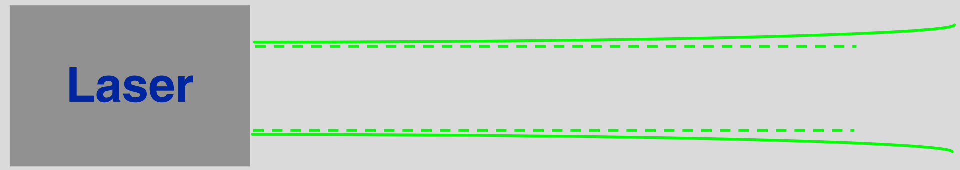
See Adrian paper in Goldstein

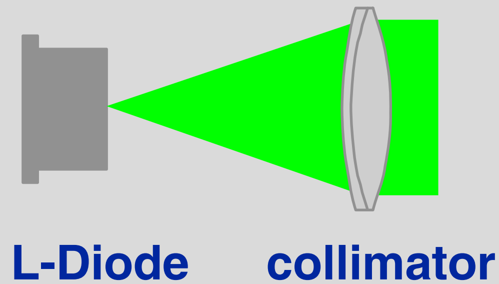
Principle of LDA, differential beam technique



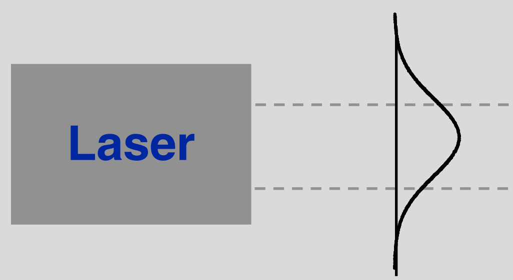
Laser, Characteristics and Requirements

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





- **Gaussian intensity distribution**



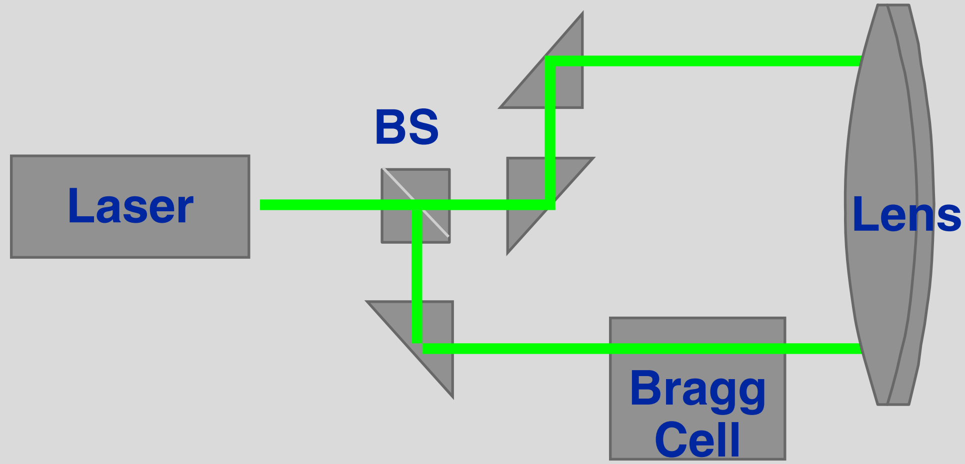
Transmitting Optics

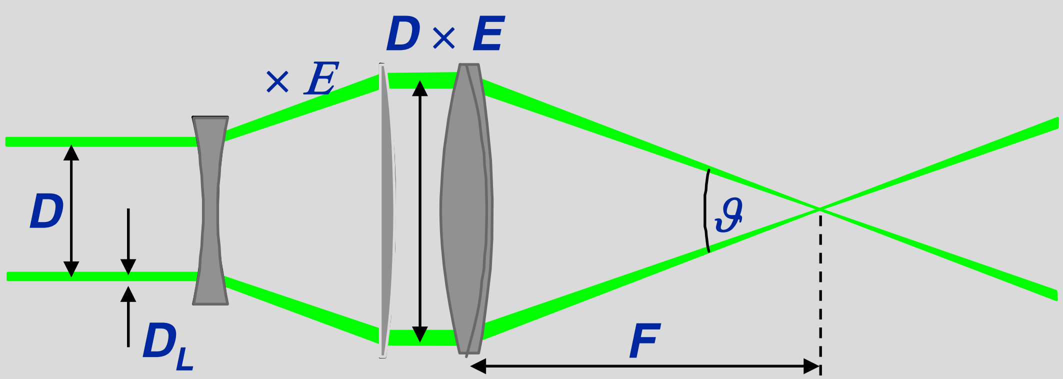
Basic modules:

- **Beam splitter**
- **Achromatic lens**

Options:

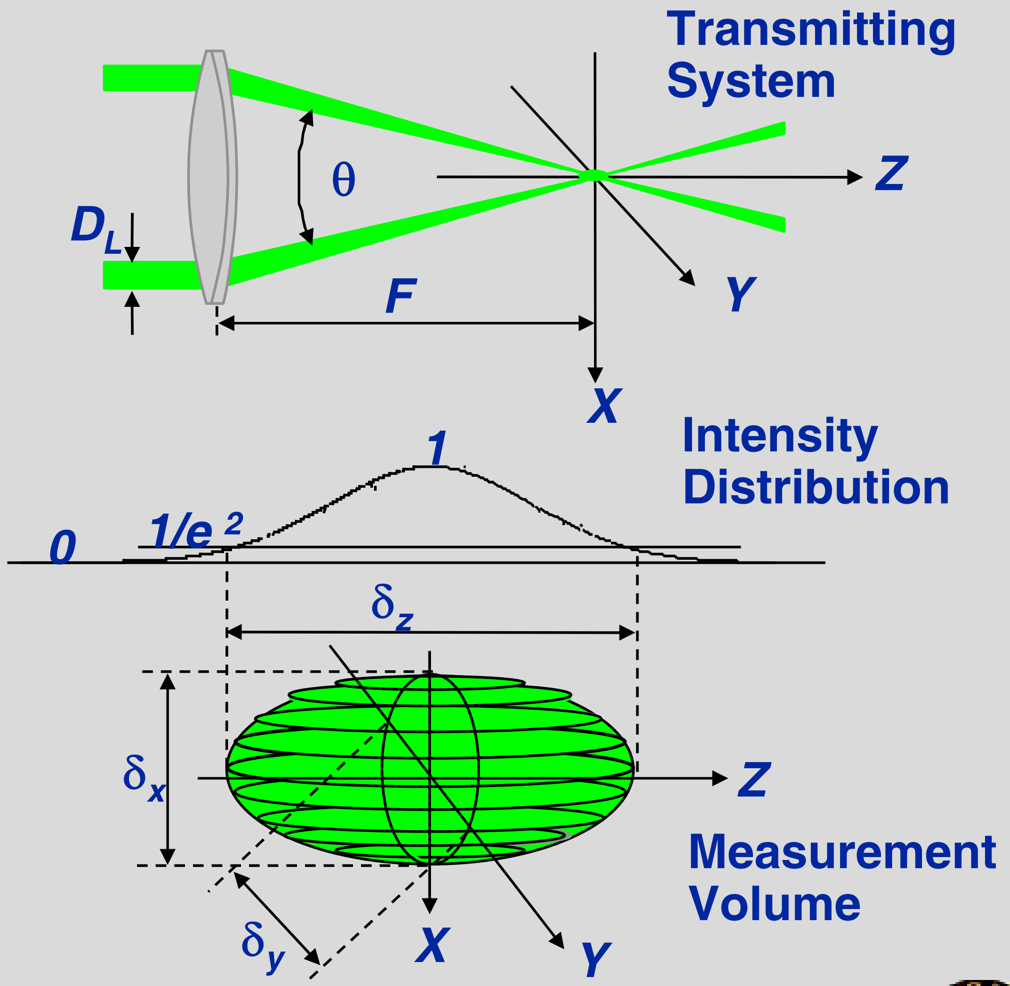
- **Frequency shift (Bragg cell)**
  - low velocities
  - flow direction
- **Beam expanders**
  - reduce measurement volume
  - increase power density





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:

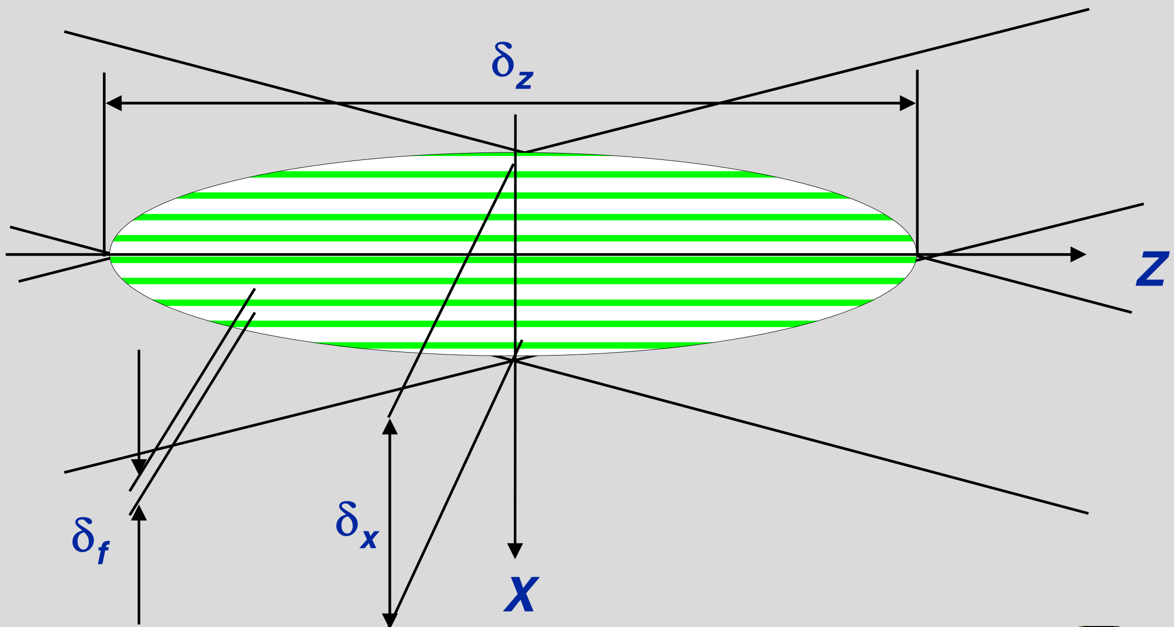
$$\delta_x = \frac{4F\lambda}{\pi E D_L \cos\left(\frac{\theta}{2}\right)}$$

Fringe Separation:

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

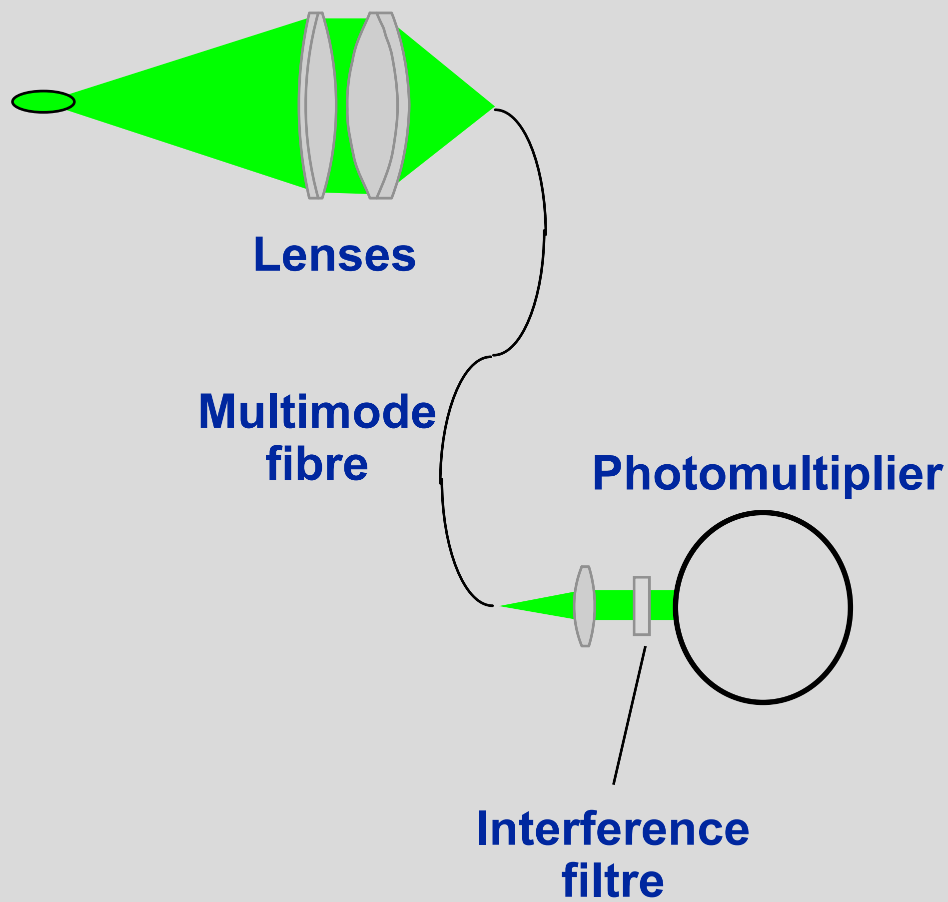
No. of Fringes:

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



Receiving Systems

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



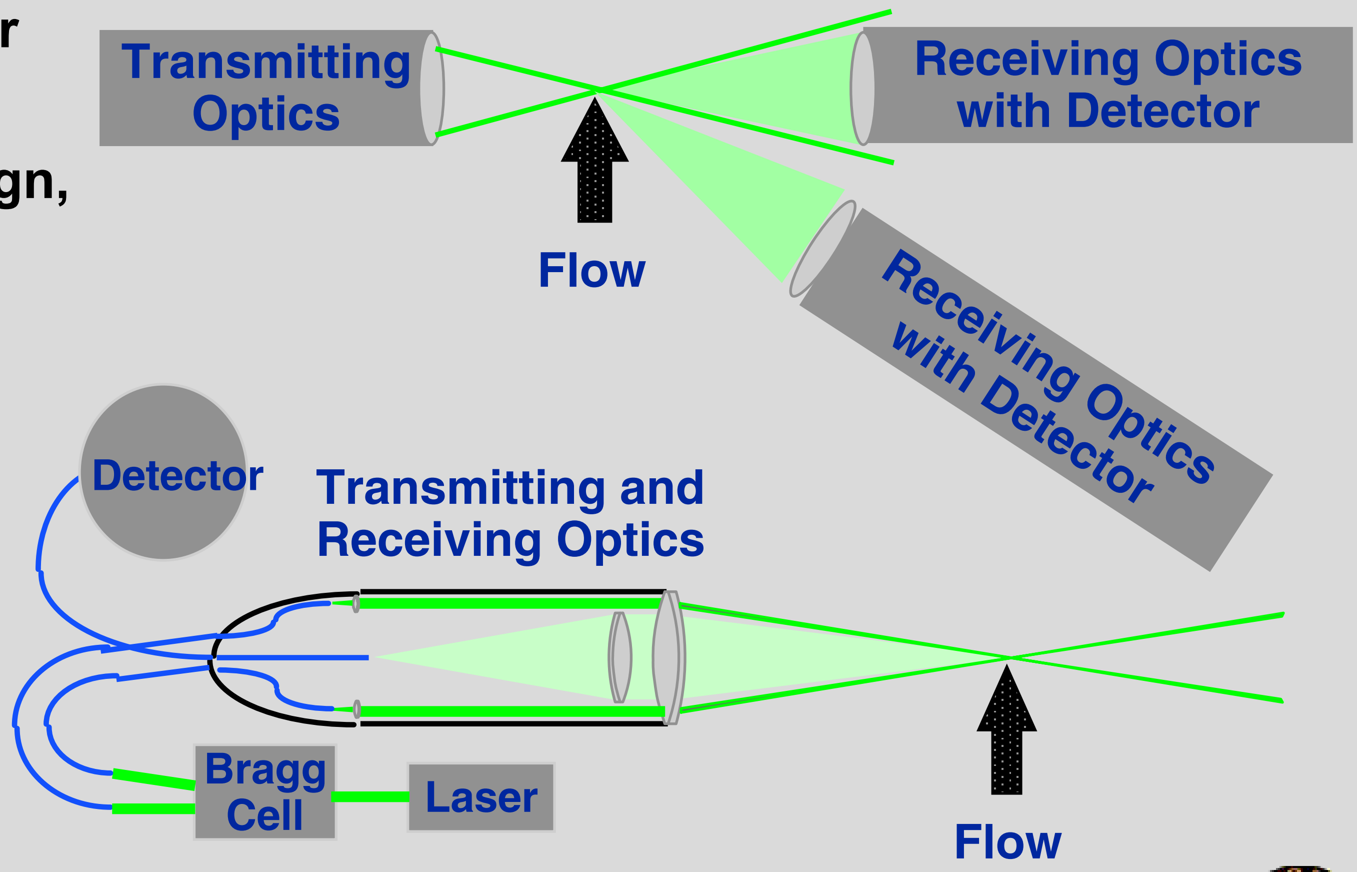
System Configurations

Forward scatter and side scatter (off-axis)

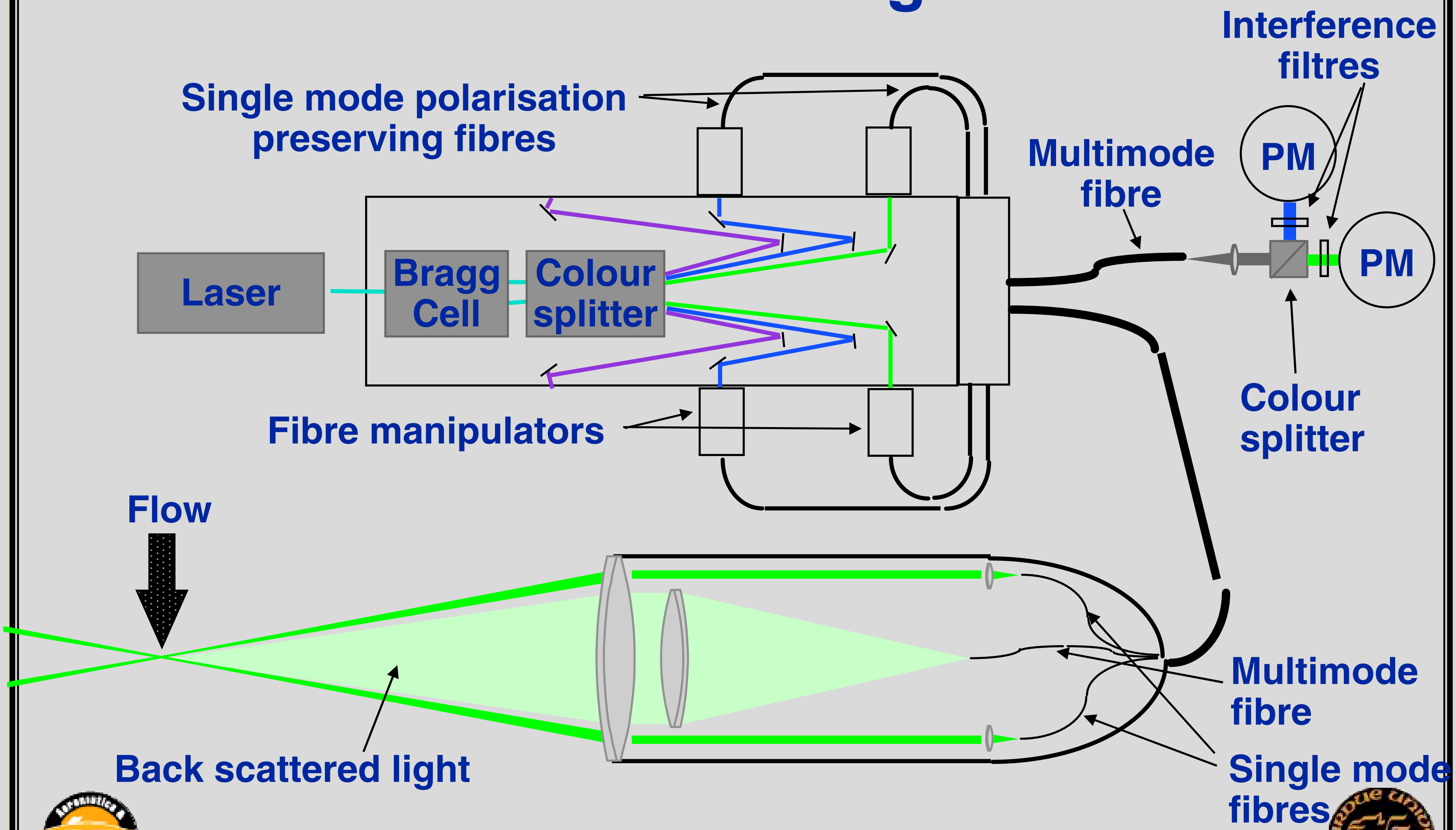
- Difficult to align,
- vibration sensitive

Backscatter

- Easy to align
- User friendly

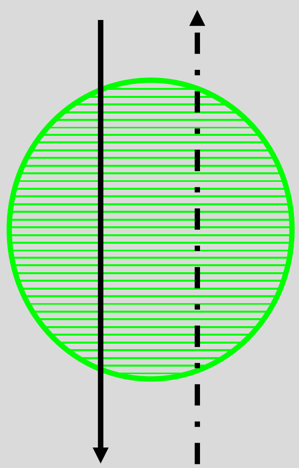


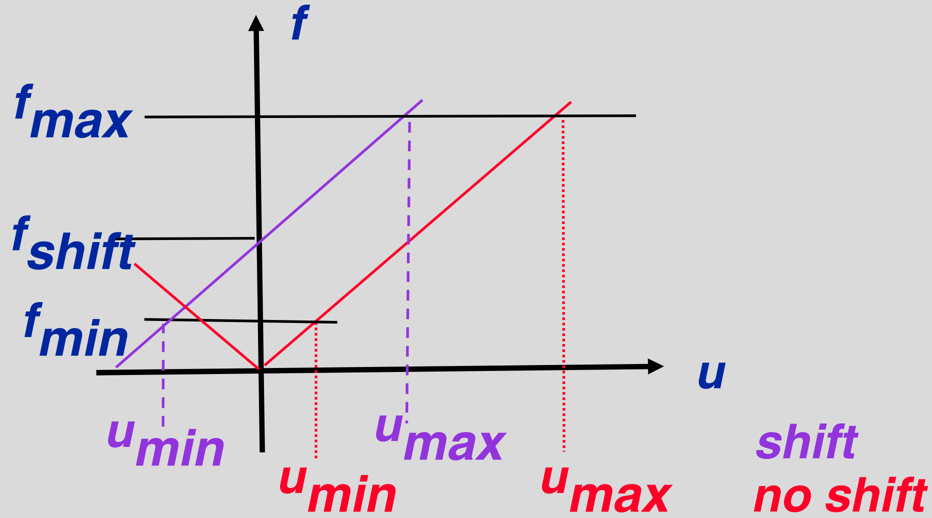
Backscatter Configuration



Directional Ambiguity / Frequency Shift

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

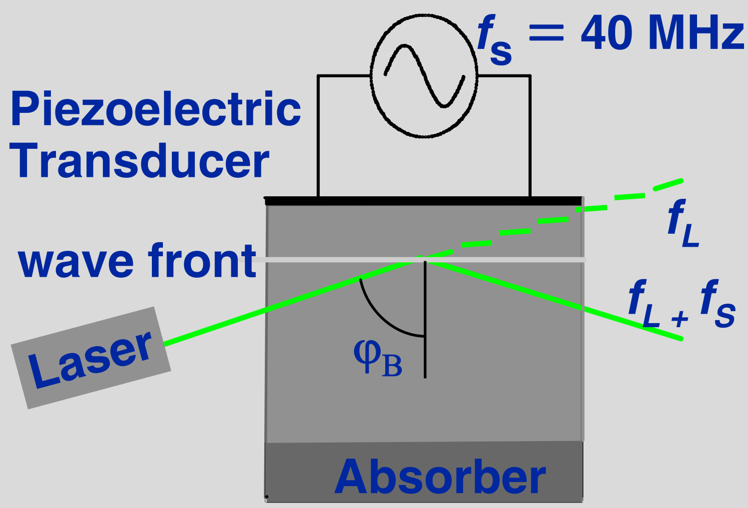




- With frequency shift in one beam relative to the other, the interference fringes appear to move at the shift frequency.
- With frequency shifting, negative velocities can be distinguished.

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



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

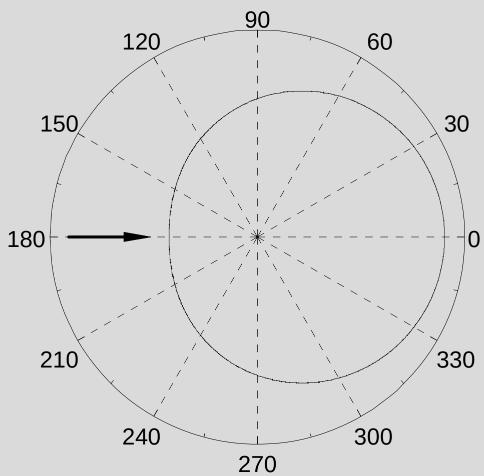
Seeding: ability to follow flow

Particle Frequency Response

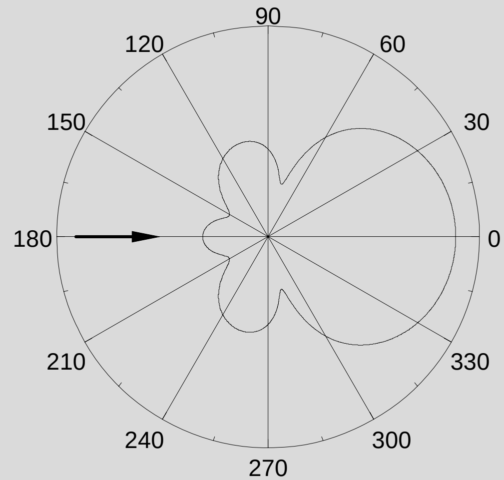
$$\frac{\mathrm{d}}{\mathrm{dt}}U_p = -18\frac{\nu}{d_p^2}\frac{U_p - U_f}{\rho_p / \rho_f}$$

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

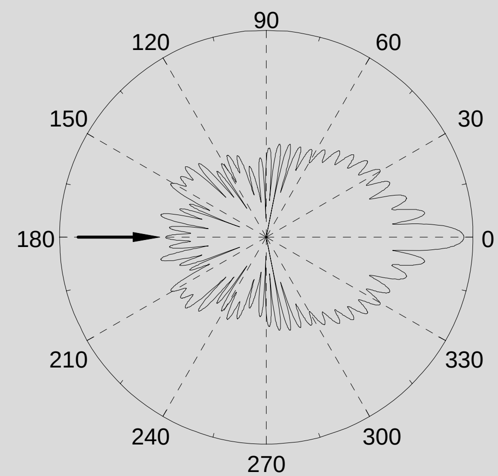
Seeding: scattered light intensity



$d_p \cong 0.2\lambda$



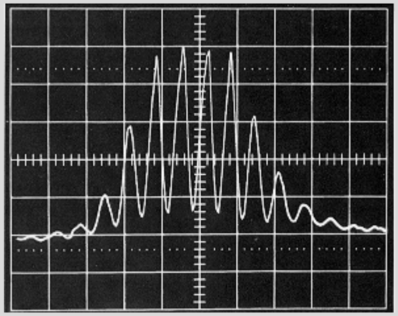
$d_p \cong 1.0\lambda$

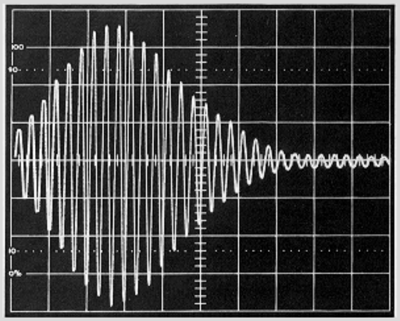


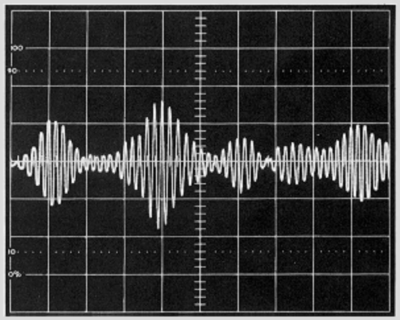
$d_p \cong 10\lambda$

- **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:**
  - **Photodetection 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 maximize the SNR.**

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

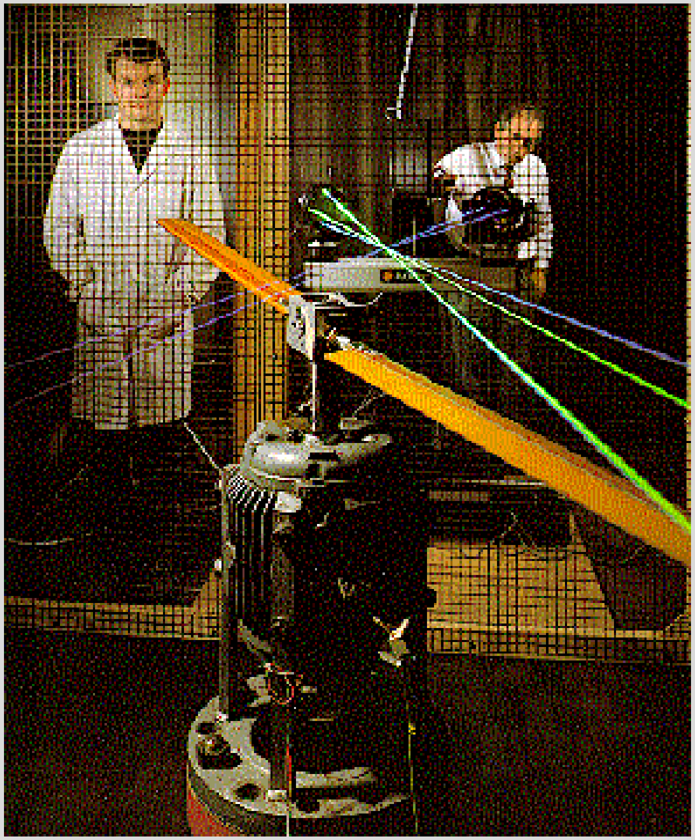


Photo courtesy of University of Bristol, UK

AAE 520 Experimental Aerodynamics

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

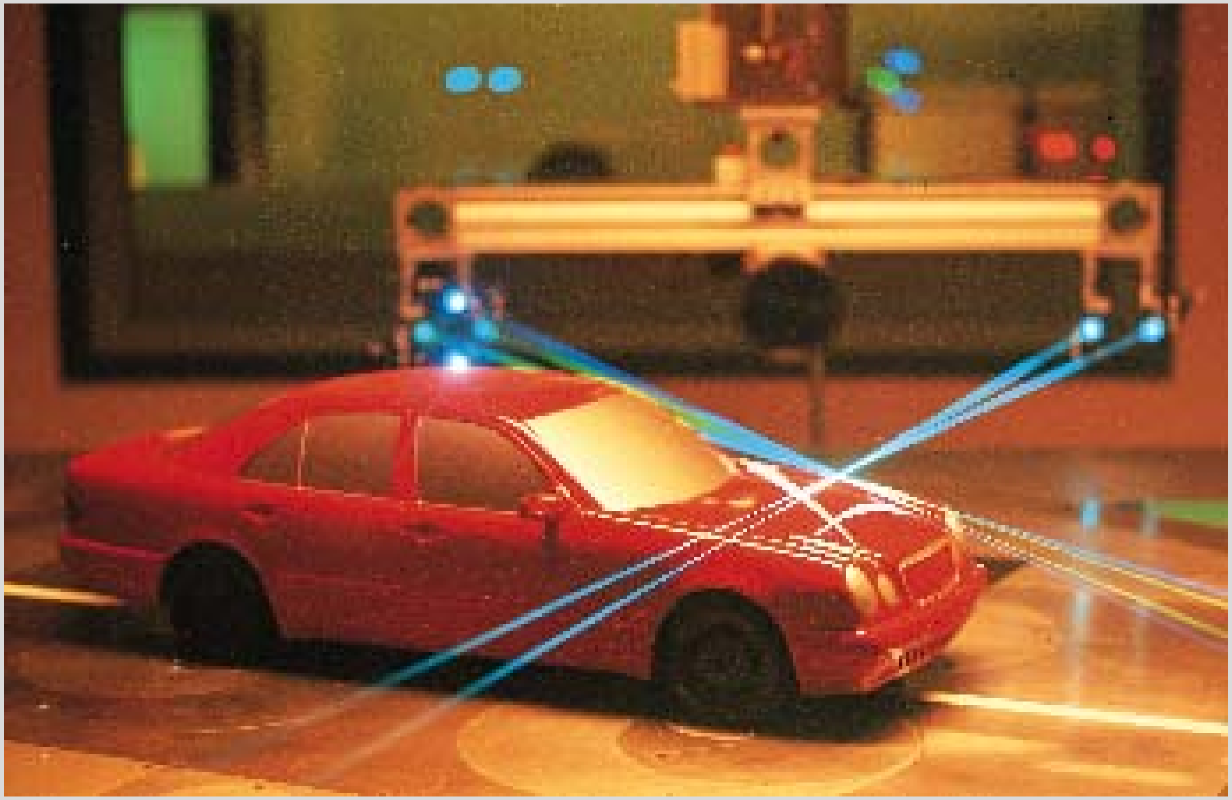


Photo courtesy of Mercedes-Benz, Germany

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

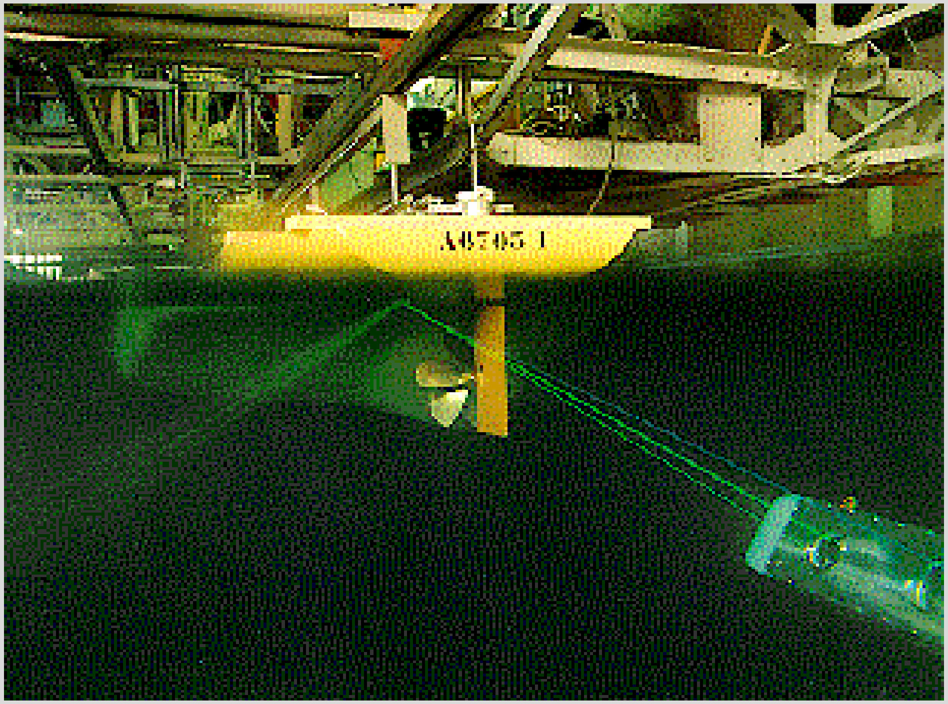


Photo courtesy of Marin, the Netherlands

Measurement of air flow field around a ship model in a wind tunnel

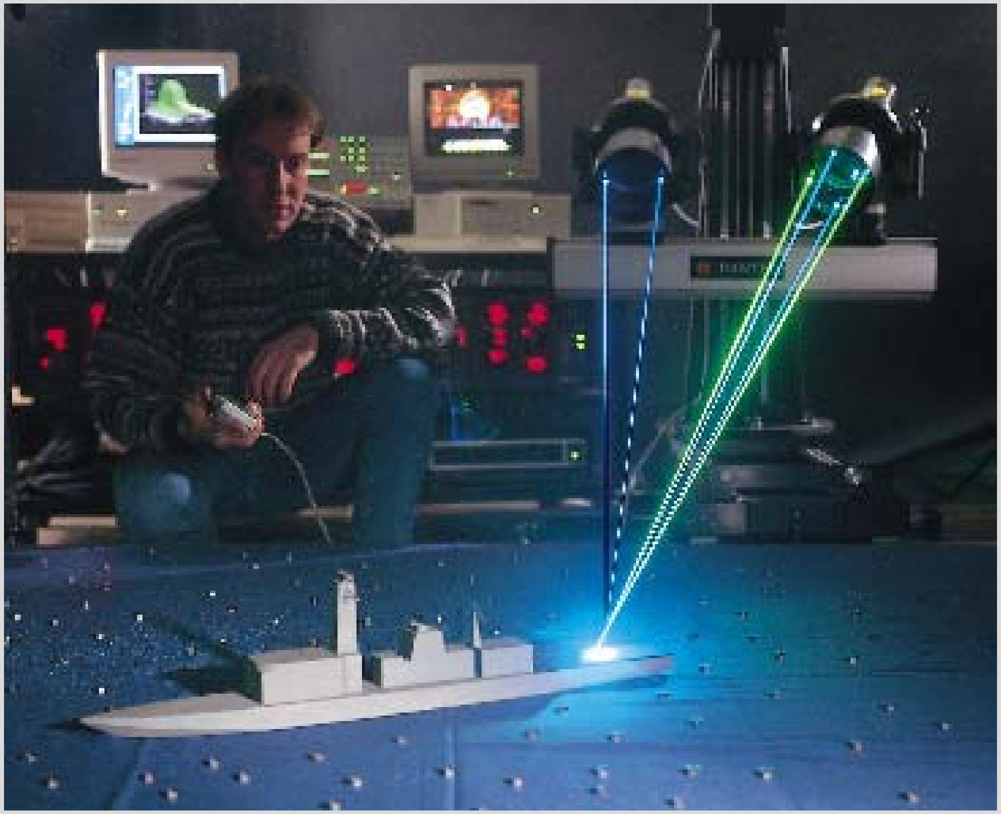
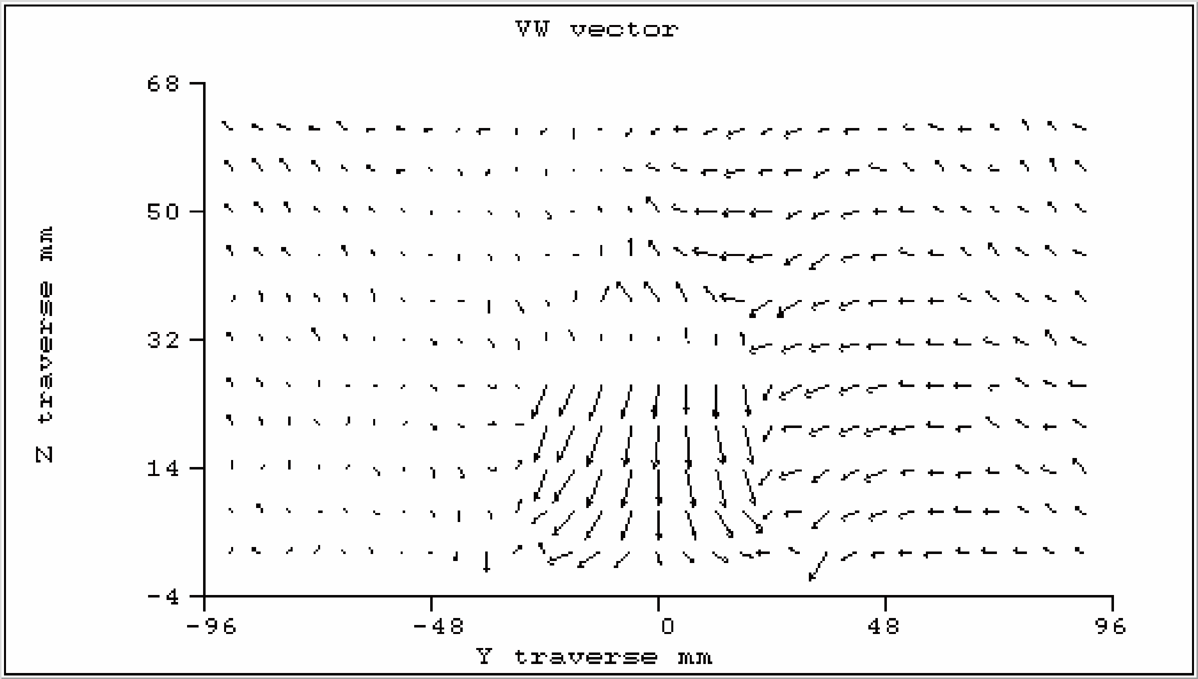


Photo courtesy of University of Bristol, UK

Wake flow field behind hangar



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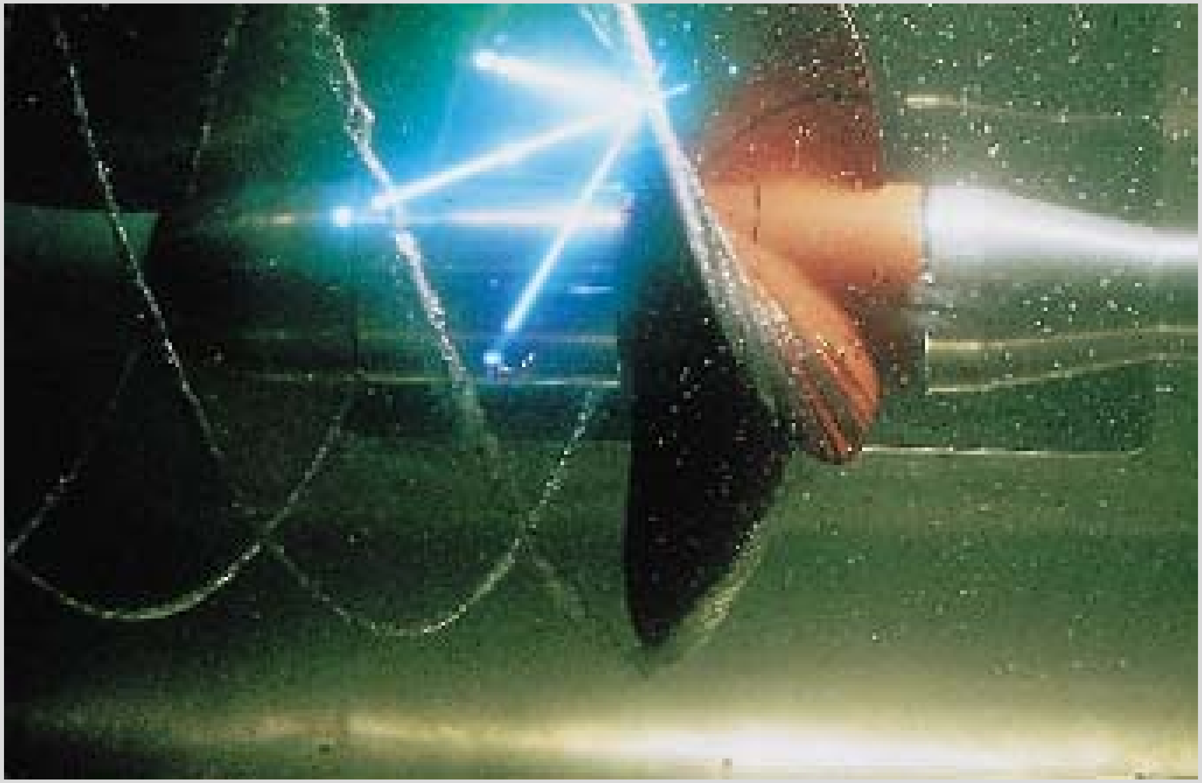
Measurement of flow around a ship propeller in a cavitation tank



Measurement of flow in a valve model

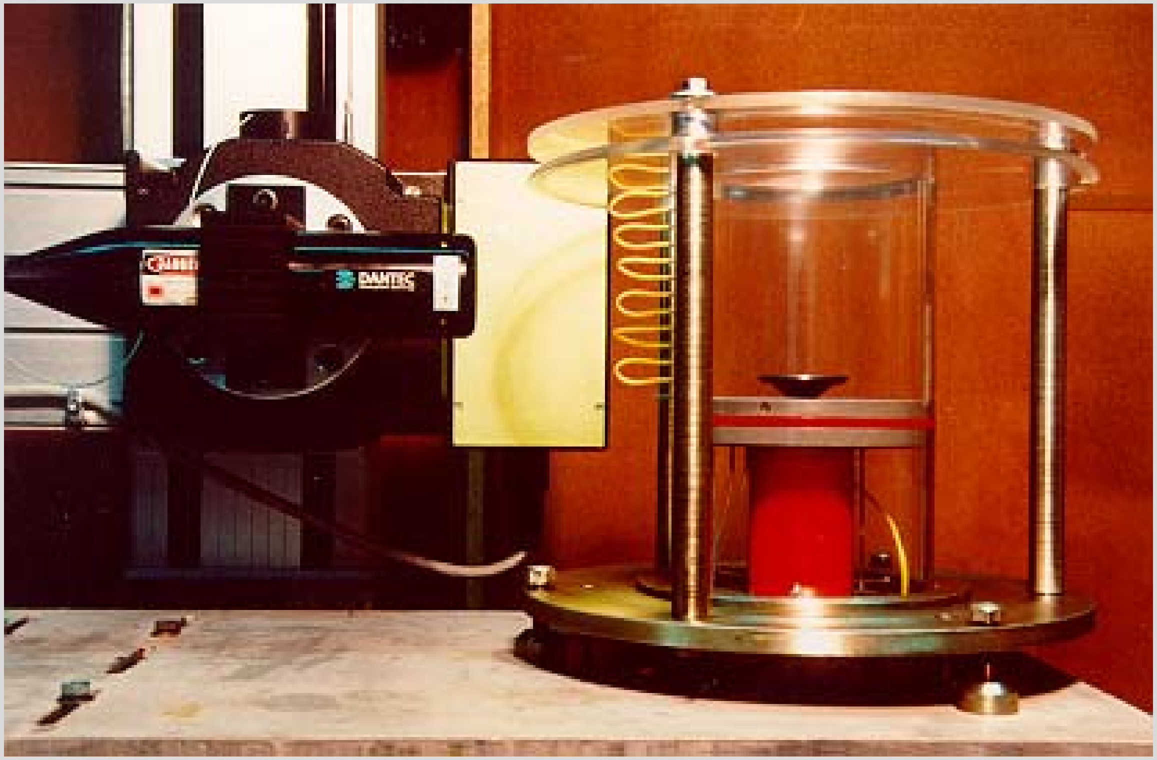


Photo courtesy of Westsächsische Hochschule Zwickau, Germany

Comparison of EFD and CFD results