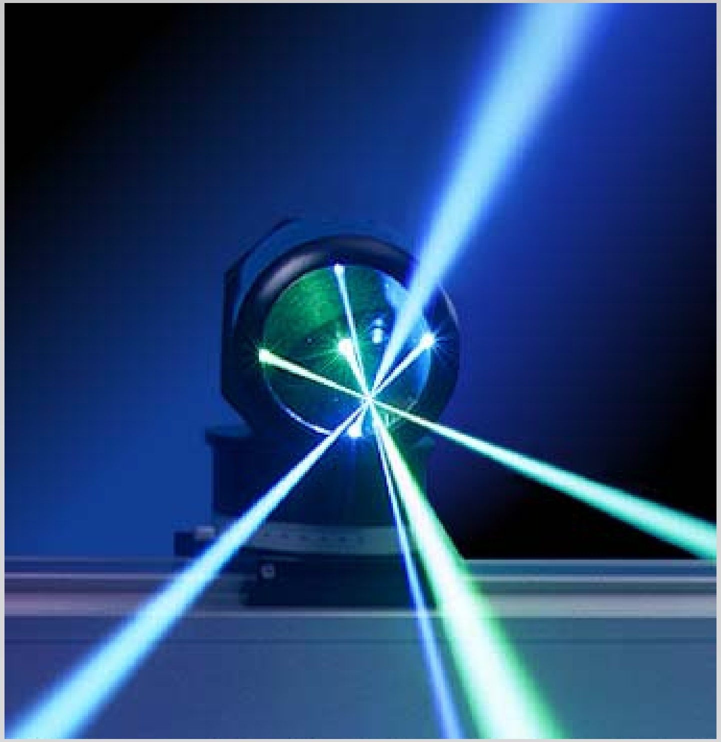
Laser Doppler Anemometry

Introduction to principles and applications



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Contents

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.**

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

Turbulent motion is 3-D, vortical, and diffusive

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

Measurements are easier (easy?)

Why Measure?

• **Industrial:**	**investigate technical problems** **check technical specs** **verify performance** **improve performance**
• **Engineering:**	**determine parameters in turb. mode** **develop, extend, refine models** **investigate model limits**
• **Theoretical fluid mechanics:**	**verify model predictions** **verify theoretical predictions** **verify new concepts**
• **Conceptual ideas:**	**search for new ideas**

Characteristics of LDA

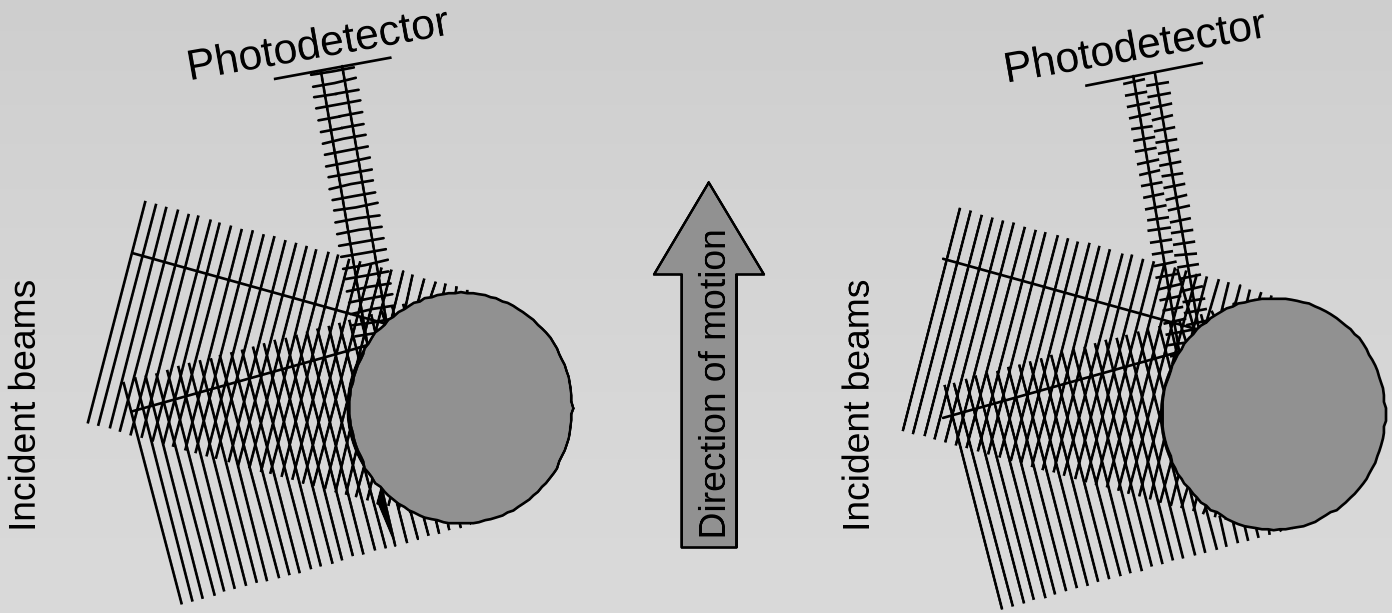
- Invented by Yeh and Cummins in 1964
- Velocity measurements in Fluid Dynamics (gas, liquid)
- Up to 3 velocity components
- Non-intrusive measurements (optical technique)
- Absolute measurement technique (no calibration required)
- Very high accuracy
- Very high spatial resolution due to small measurement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

Applications of LDA

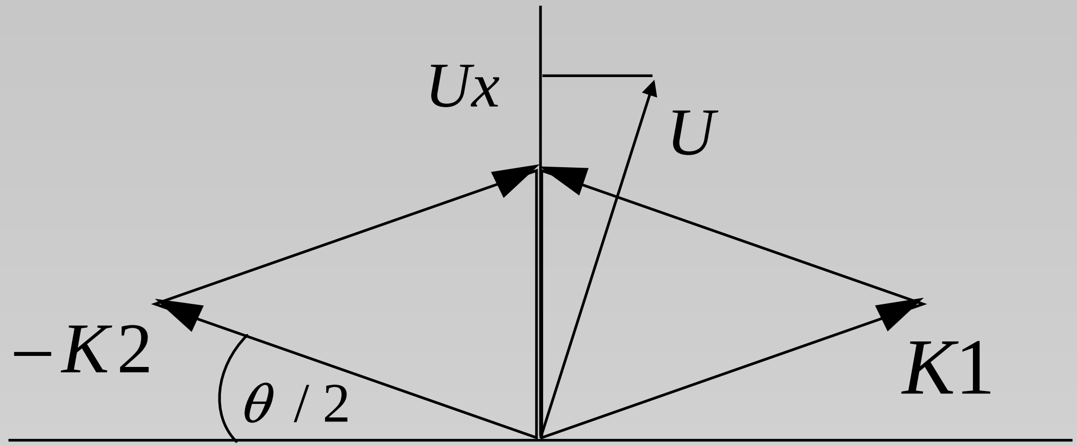
- **Laminar and turbulent flows**
- **Investigations on aerodynamics**
- **Supersonic flows**
- **Turbines, automotive etc.**
- **Liquid flows**
- **Surface velocity and vibration measurement**
- **Hot environments (Flames, Plasma etc.)**
- **Velocity of particles**
- **...... etc, etc, etc.**

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.



Frequency to velocity conversion



$$\omega_D = \omega_{D1} - \omega_{D2} = \vec{U} \cdot (\vec{k}_1 - \vec{k}_2)$$

$$U_x = C f_D$$

$$f_D = \frac{2U_x}{\lambda} \sin \theta / 2$$

$$C = \frac{\lambda}{2 \sin \theta / 2}$$

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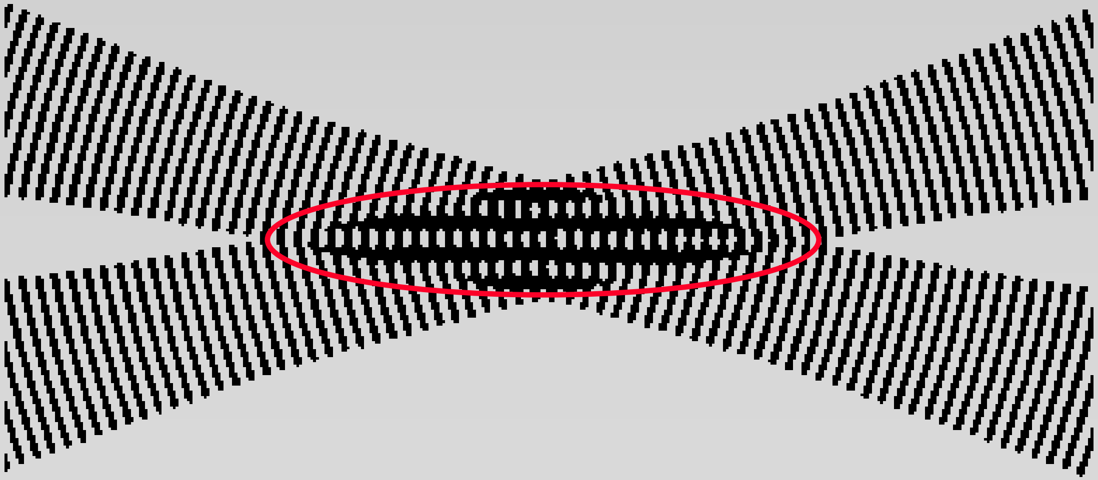
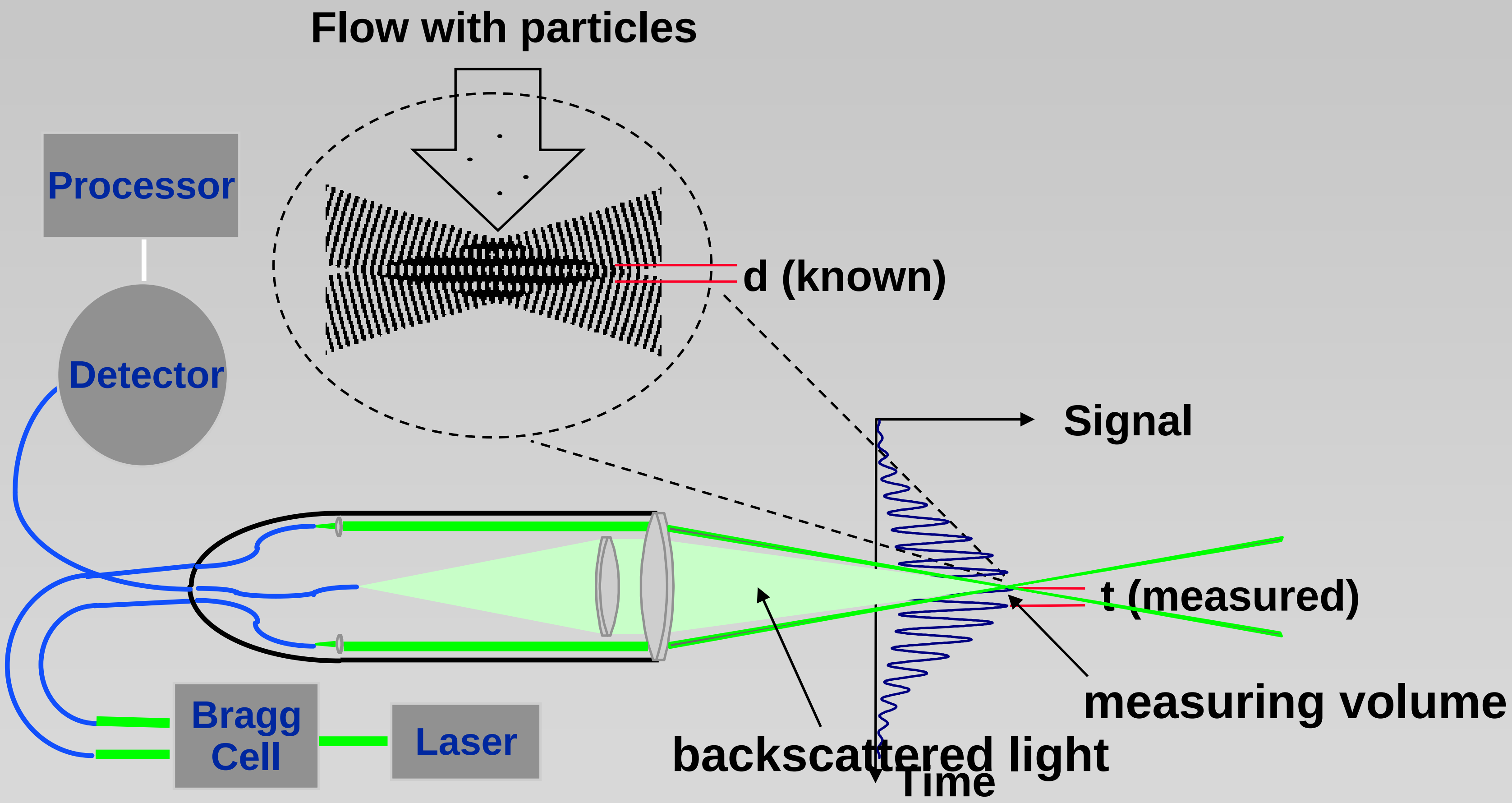
LDA - Fringe Model

- 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



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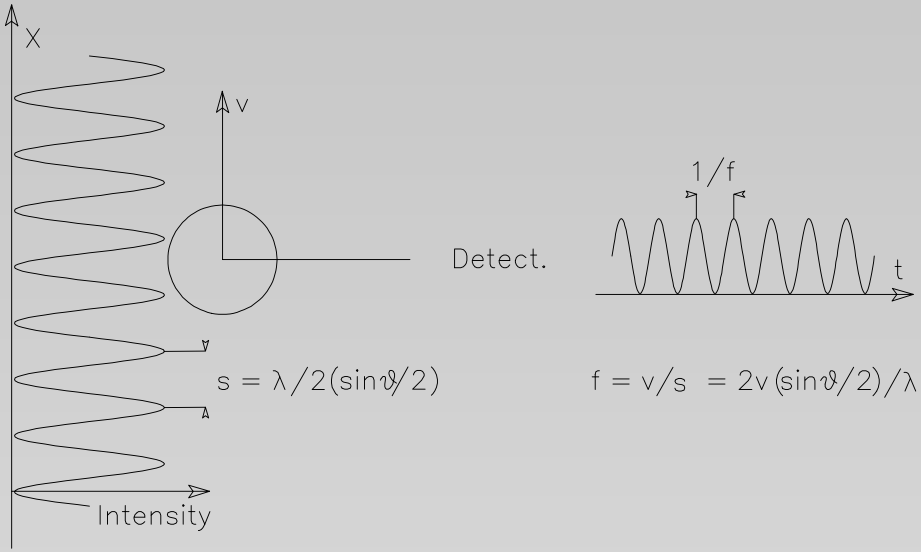
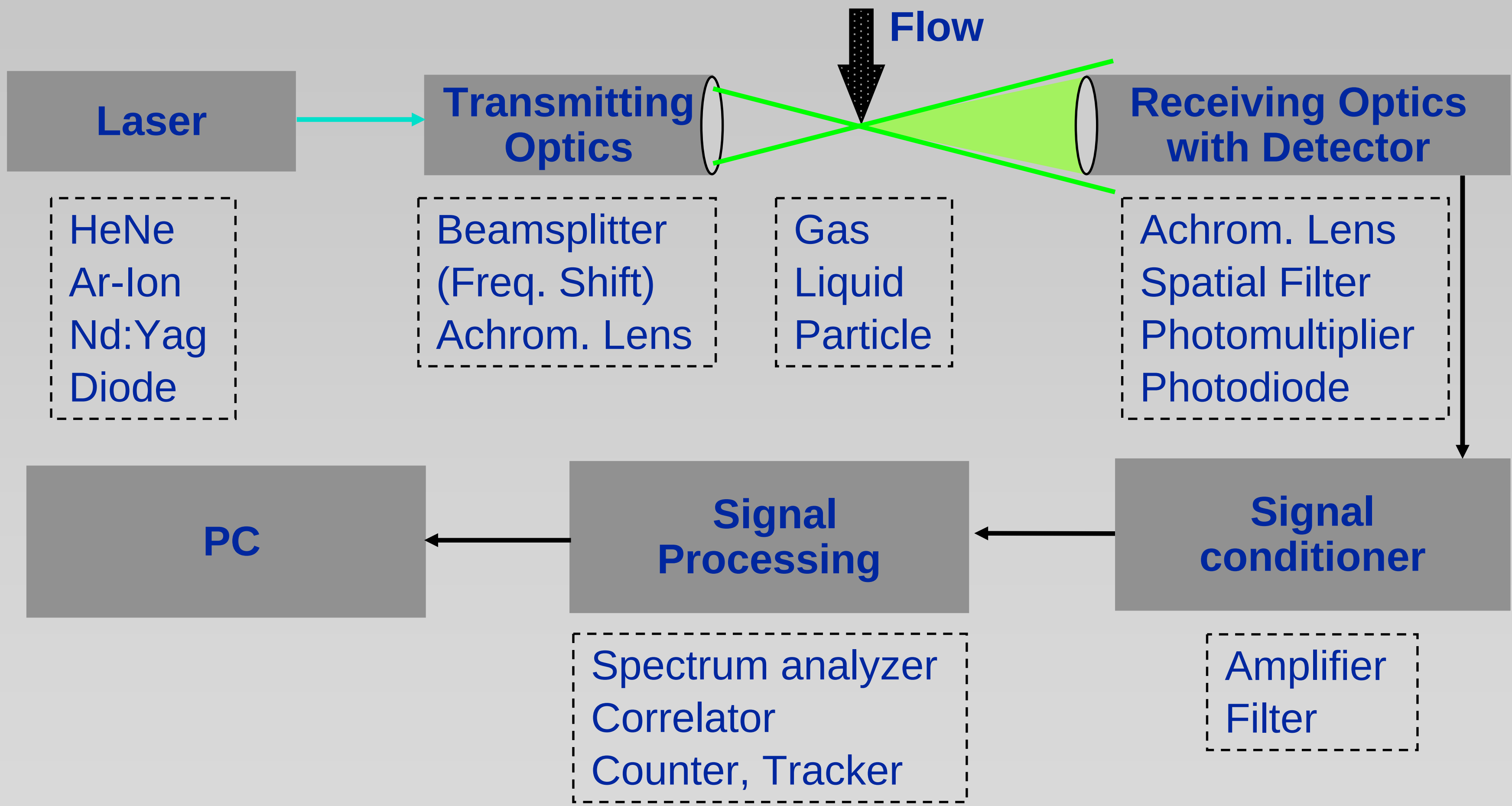
LDA - Fringe Model

- 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.

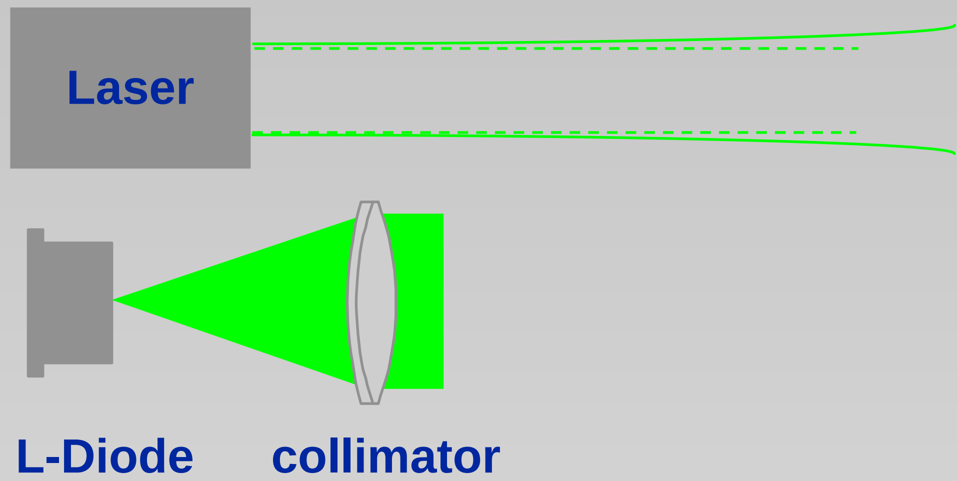


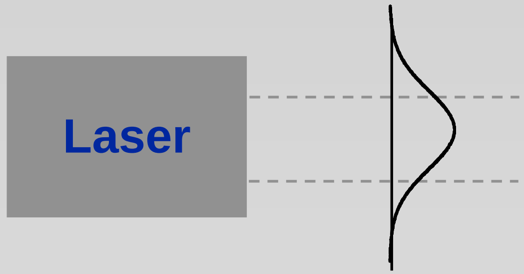
Principle of LDA, differential beam technique



Laser, Characteristics and Requirements

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





- Gaussian intensity distribution

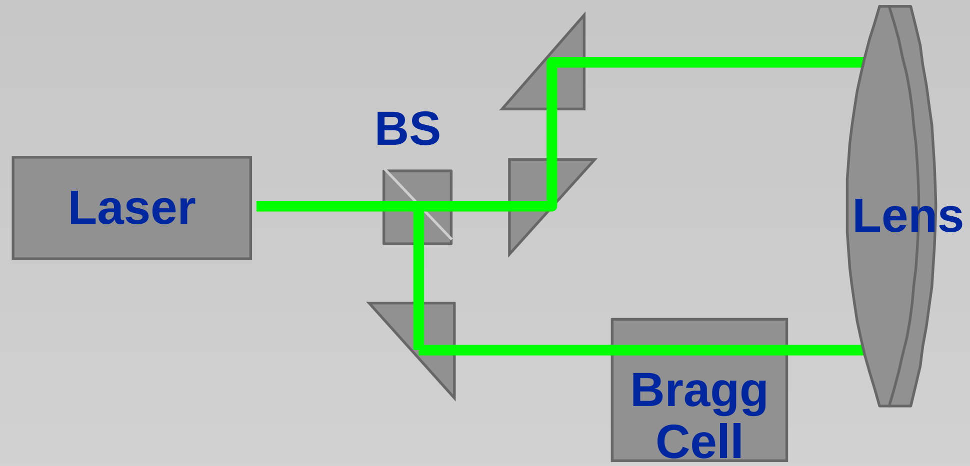
Transmitting Optics

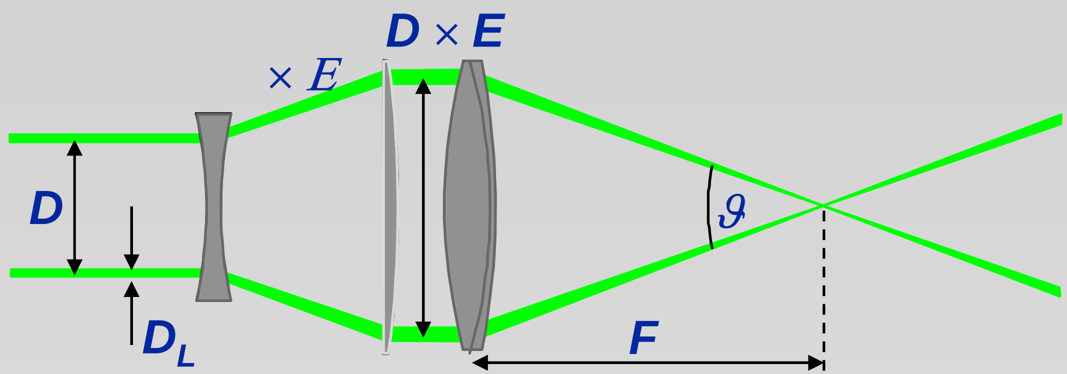
Basic modules:

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

Options:

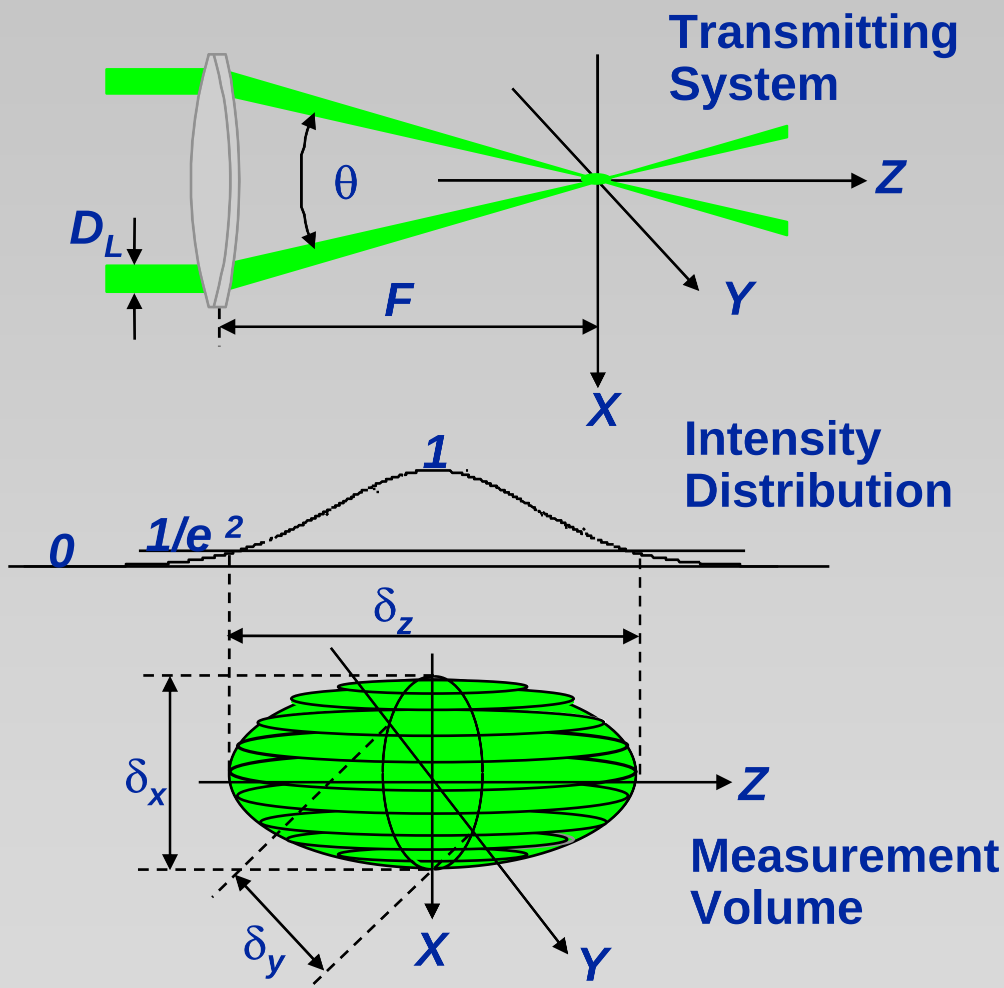
- **Frequency shift (Bragg cell)**
  - – low velocities
  - – flow direction
- **Beam expanders**
  - – reduce measurement volume
  - – increase power density





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:

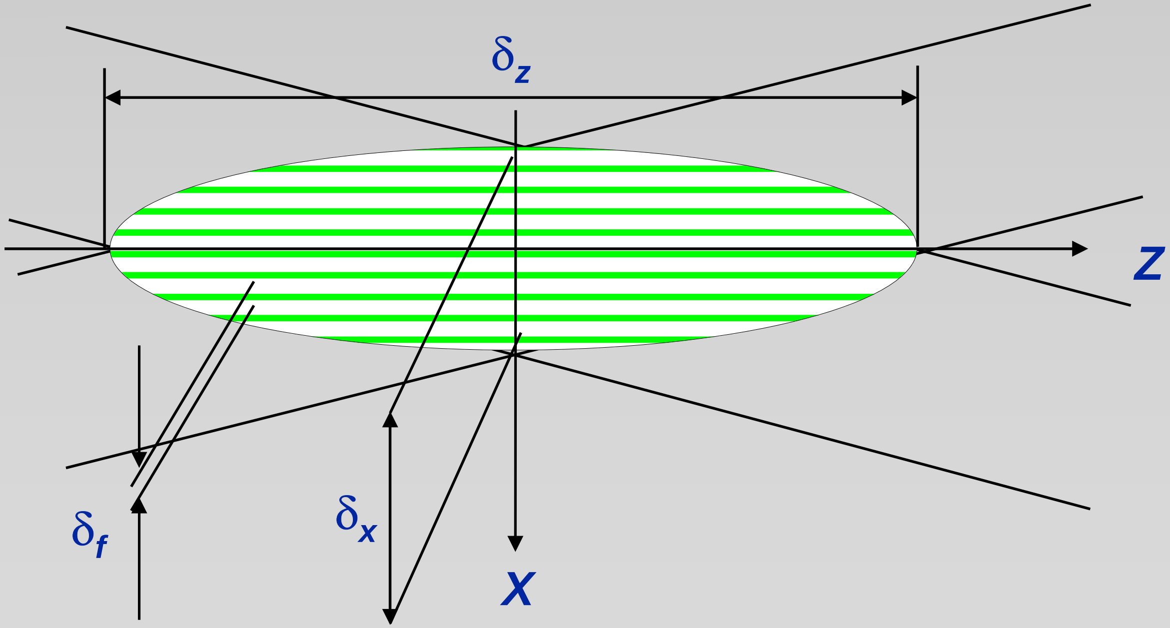
$$\delta_x = \frac{4F\lambda}{\pi E D_L \cos\left(\frac{\theta}{2}\right)}$$

Fringe Separation:

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

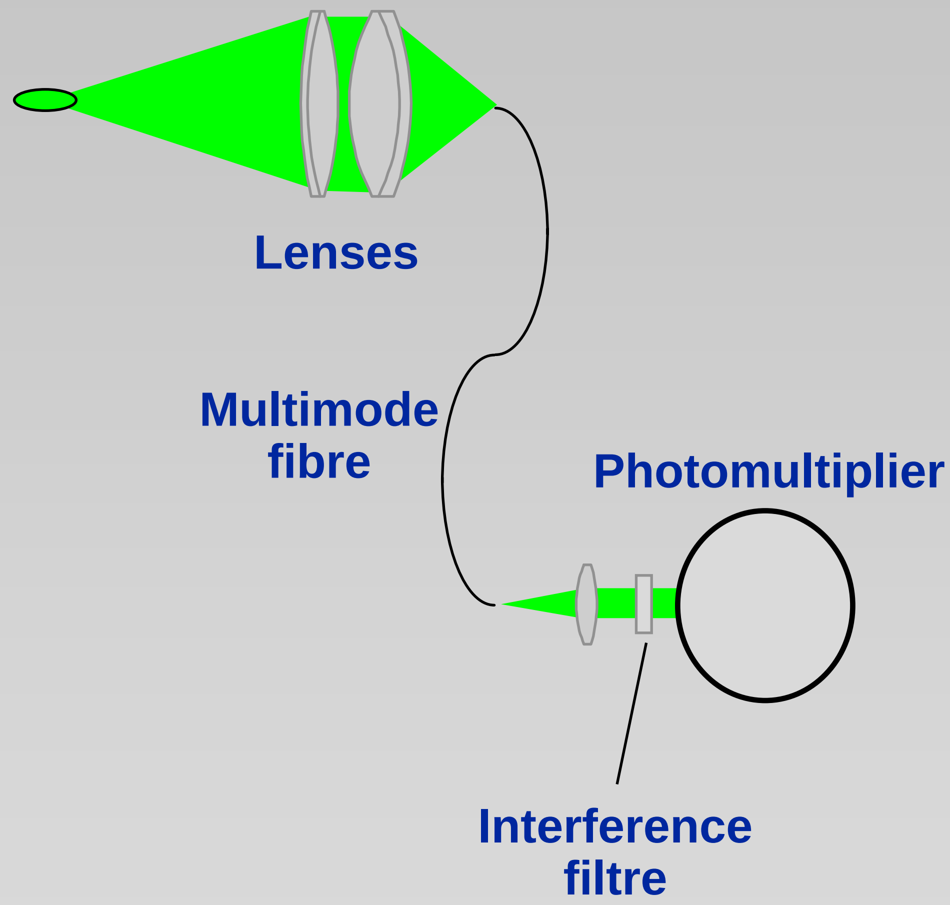
No. of Fringes:

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



Receiving Systems

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



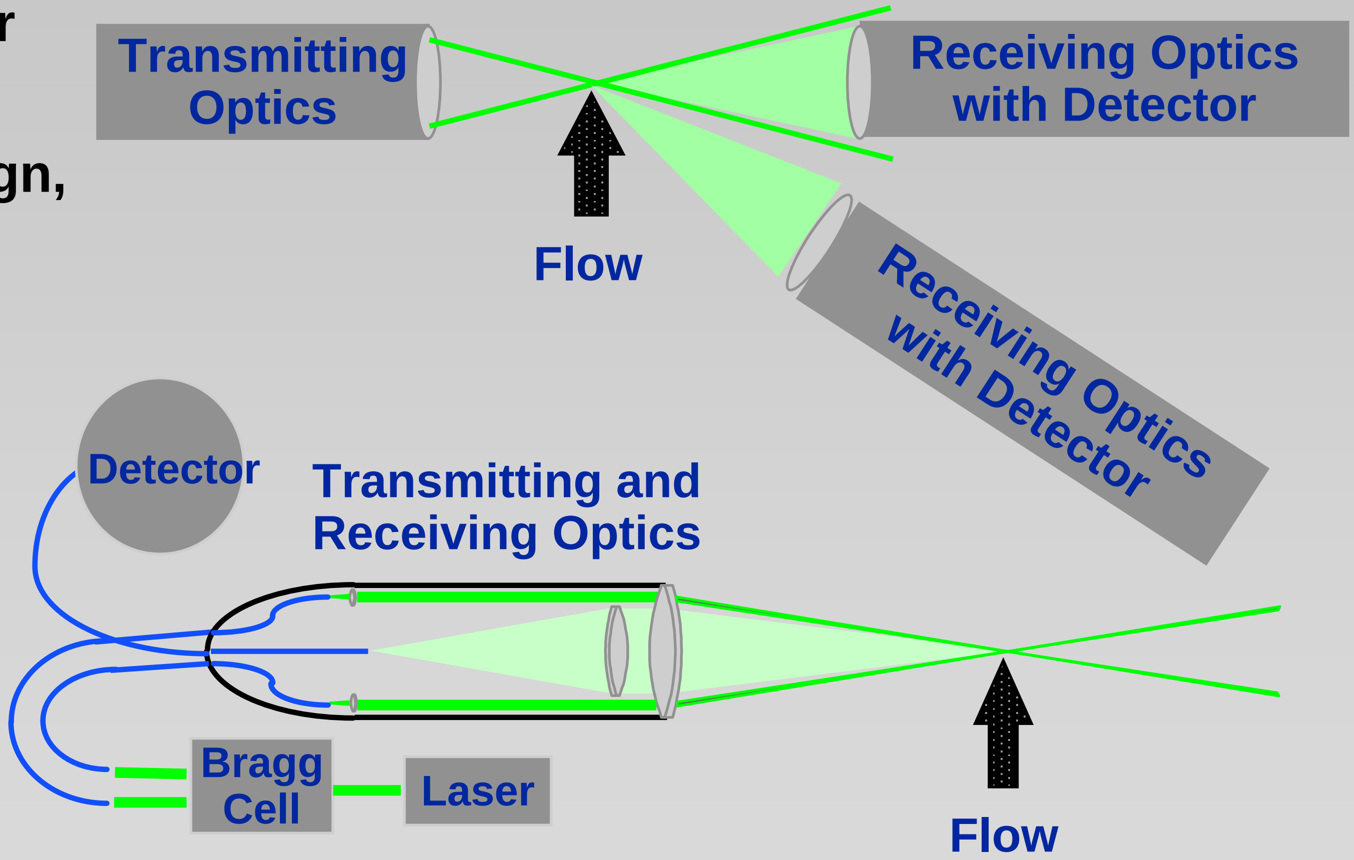
System Configurations

Forward scatter and side scatter (off-axis)

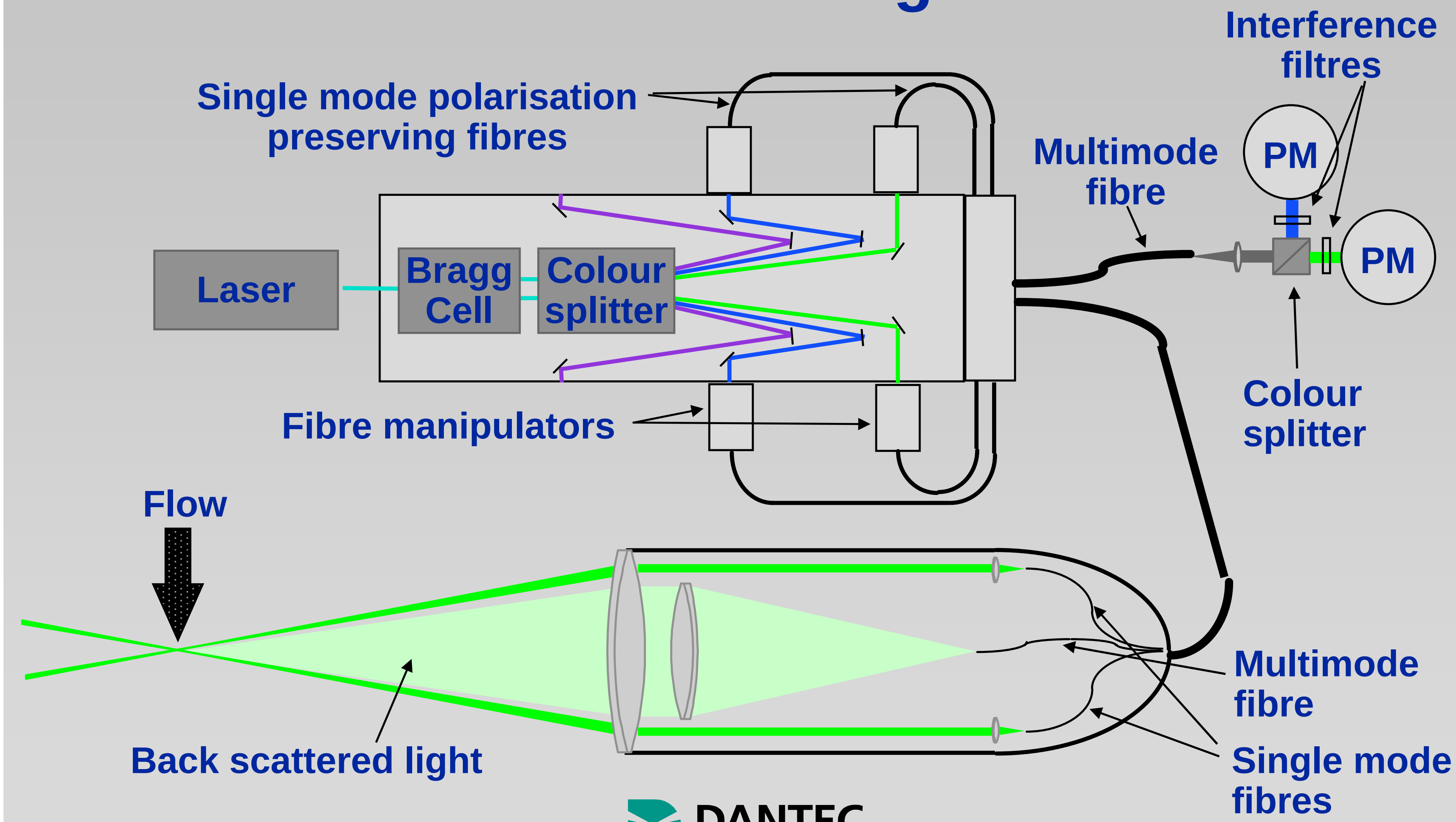
- Difficult to align,
- vibration sensitive

Backscatter

- Easy to align
- User friendly



Backscatter Configuration



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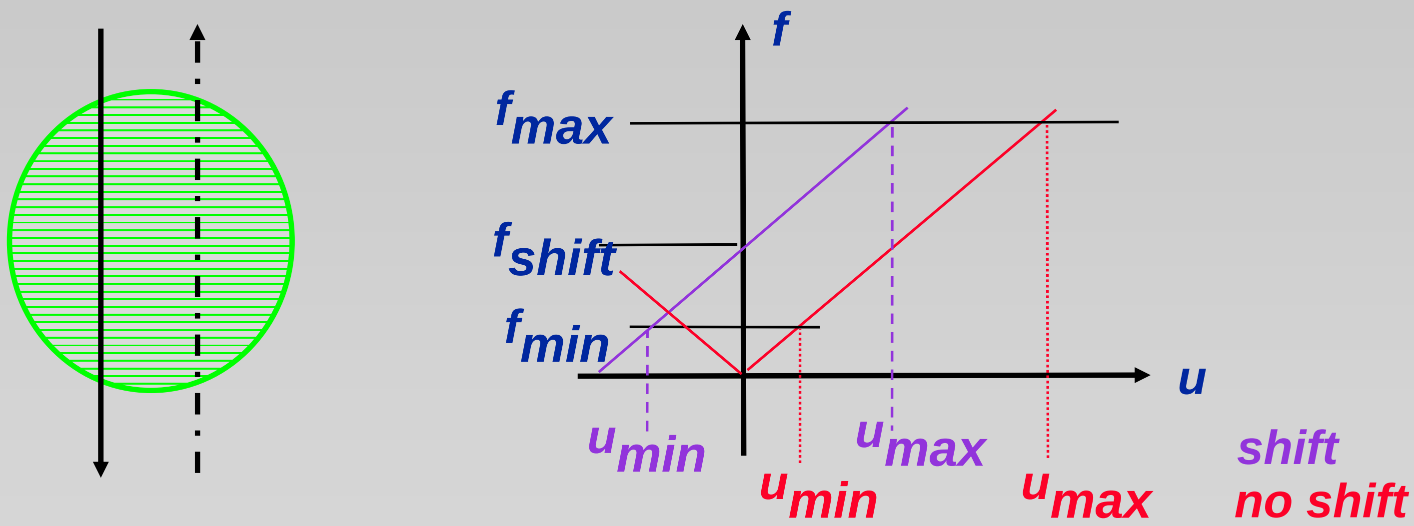
Directional Ambiguity / Frequency Shift

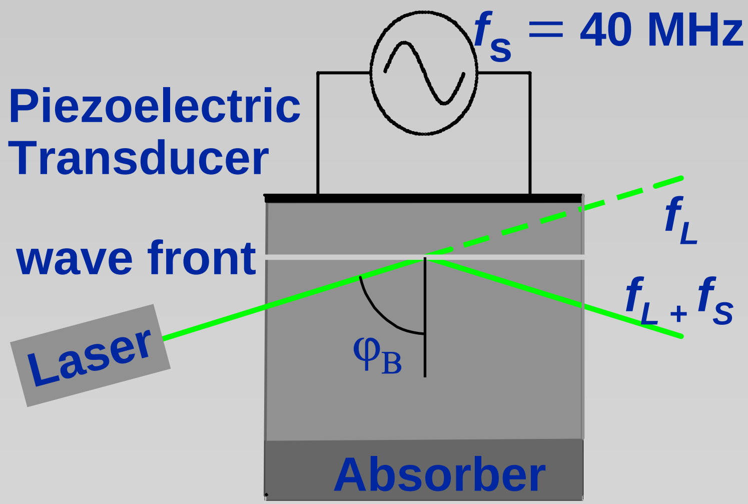
- Particles moving in either the forward or reverse direction will produce identical signals and frequencies.



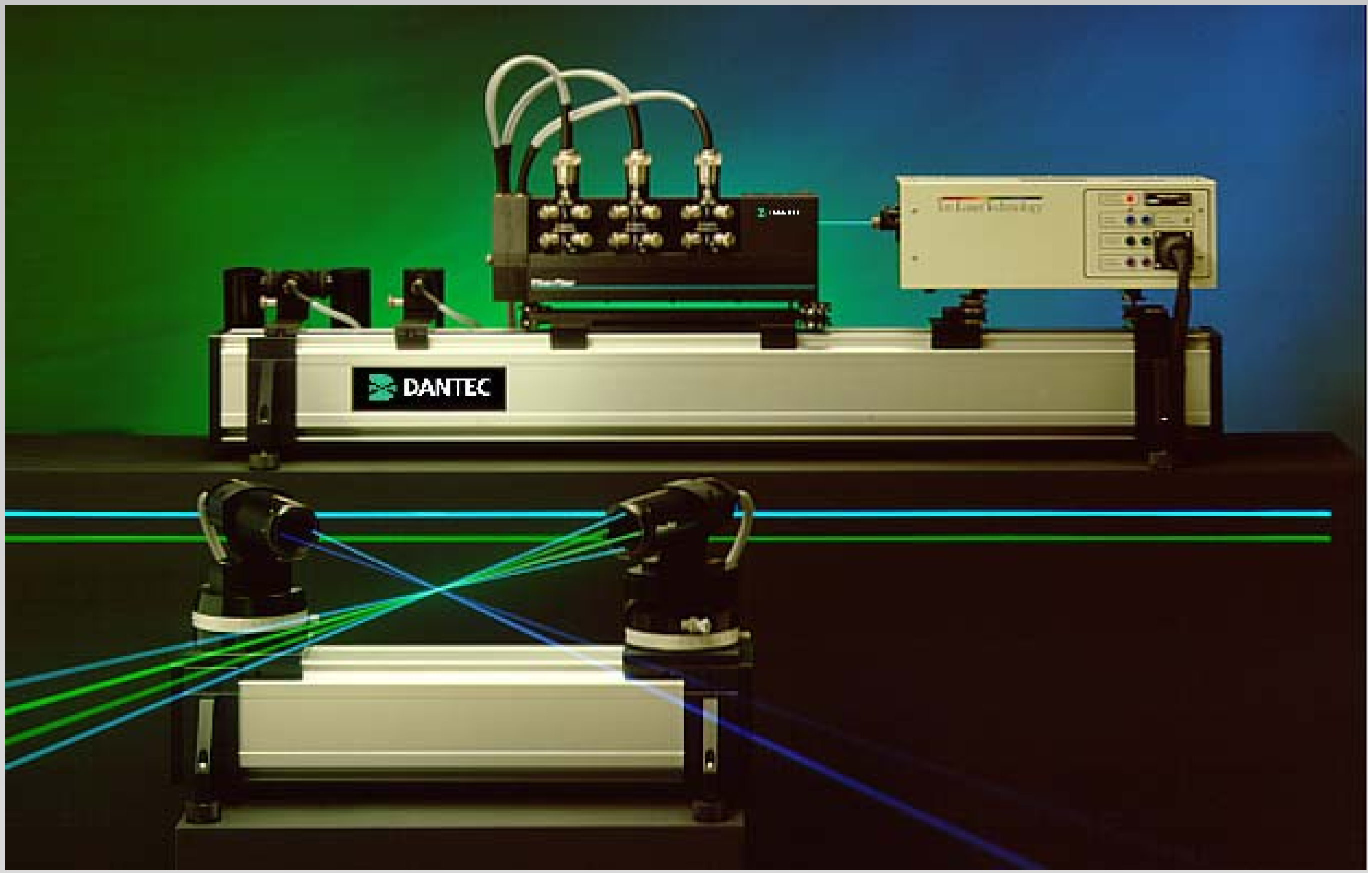
- With frequency shift in one beam relative to the other, the interference fringes appear to move at the shift frequency.
- With frequency shifting, negative velocities can be distinguished.

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



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LDA instrumentation from Dantec

FlowLite

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

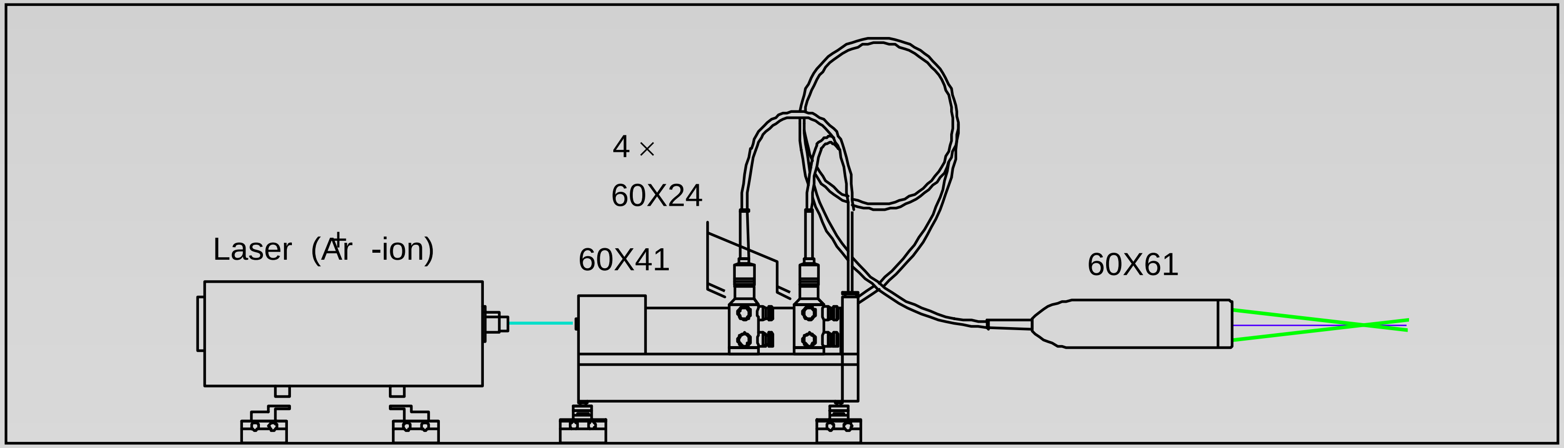
FiberFlow **optics / transmitter**

- 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

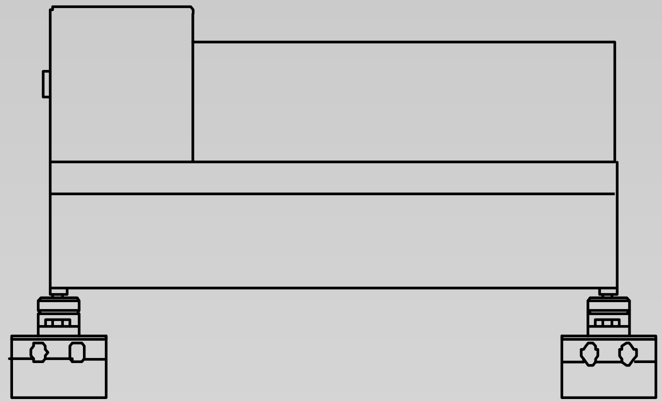
- **Laser: 1D, 2D, 3D: Argon-ion: air or water cooled**
- ***60X41 Transmitter***
- ***60X24 Manipulators***
- ***FiberFlow* series probe**



The *60X41 Transmitter*

The *60X41 Transmitter*

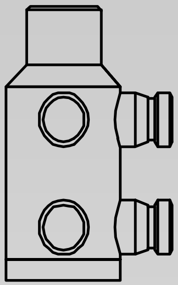
- Divides the laser beam into two:
  - one direct
  - one frequency shifted
- Each beam is then separated into three colors:
  - green λ = 514,5 nm
  - blue λ = 488 nm
  - purple λ = 476,5 nm



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

The *60X24 Manipulator*

- **The manipulator centers 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**

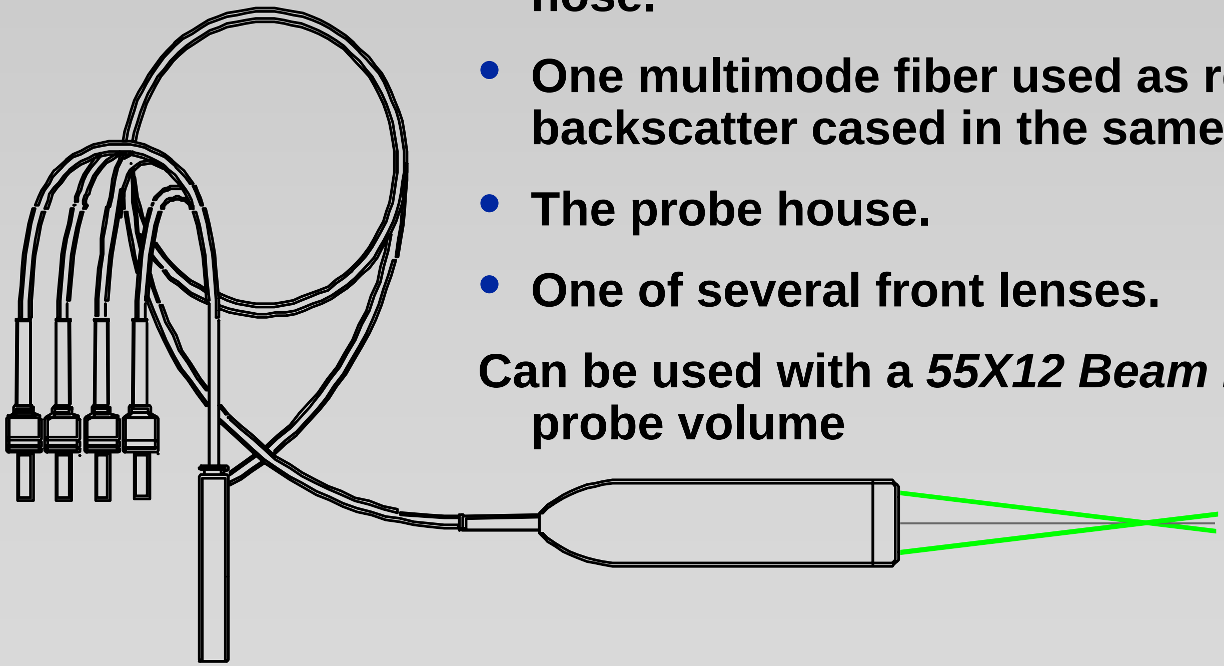


A 60 mm 2D *FiberFlow* probe

The *FiberFlow* probe comprises

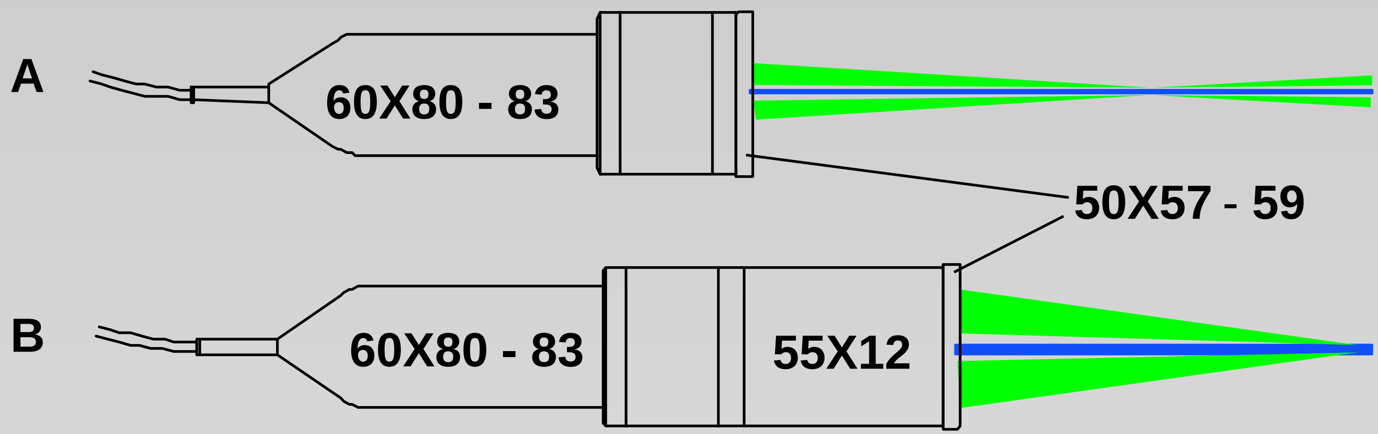
- Four fiber plugs for coupling with the manipulators.
- Four single mode fibers - one for each of the transmitted beams - cased in an enforced cable hose.
- One multimode fiber used as receiving fiber in backscatter cased in the same hose.
- The probe house.
- One of several front lenses.

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

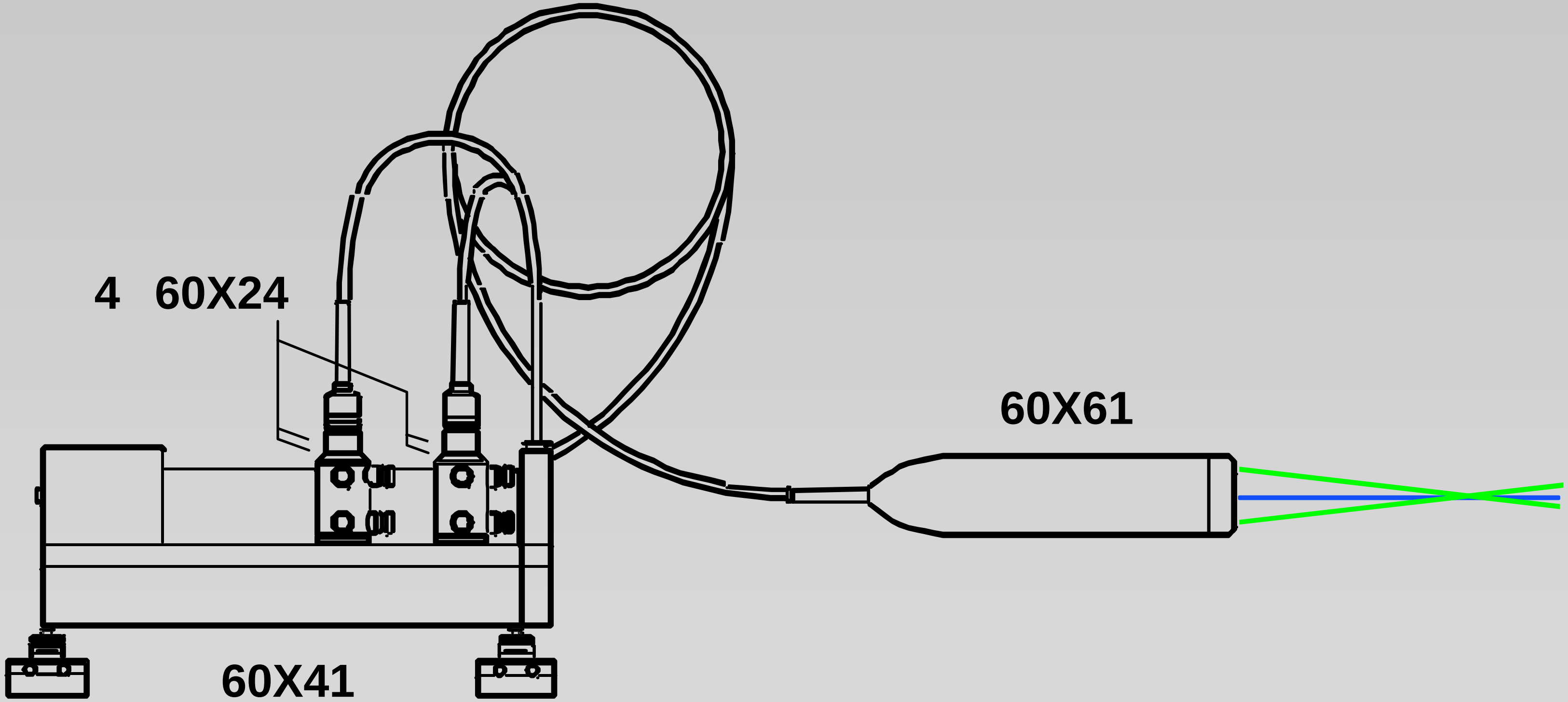


The 85 mm *FiberFlow* probes

- The 85 mm probes provide maximum flexibility for adjustment giving large variation in incident angle of the beams.
- Can be used with a *55X12 Beam Expander* to reduce probe volume



Assembled *FiberFlow* transmitting optics



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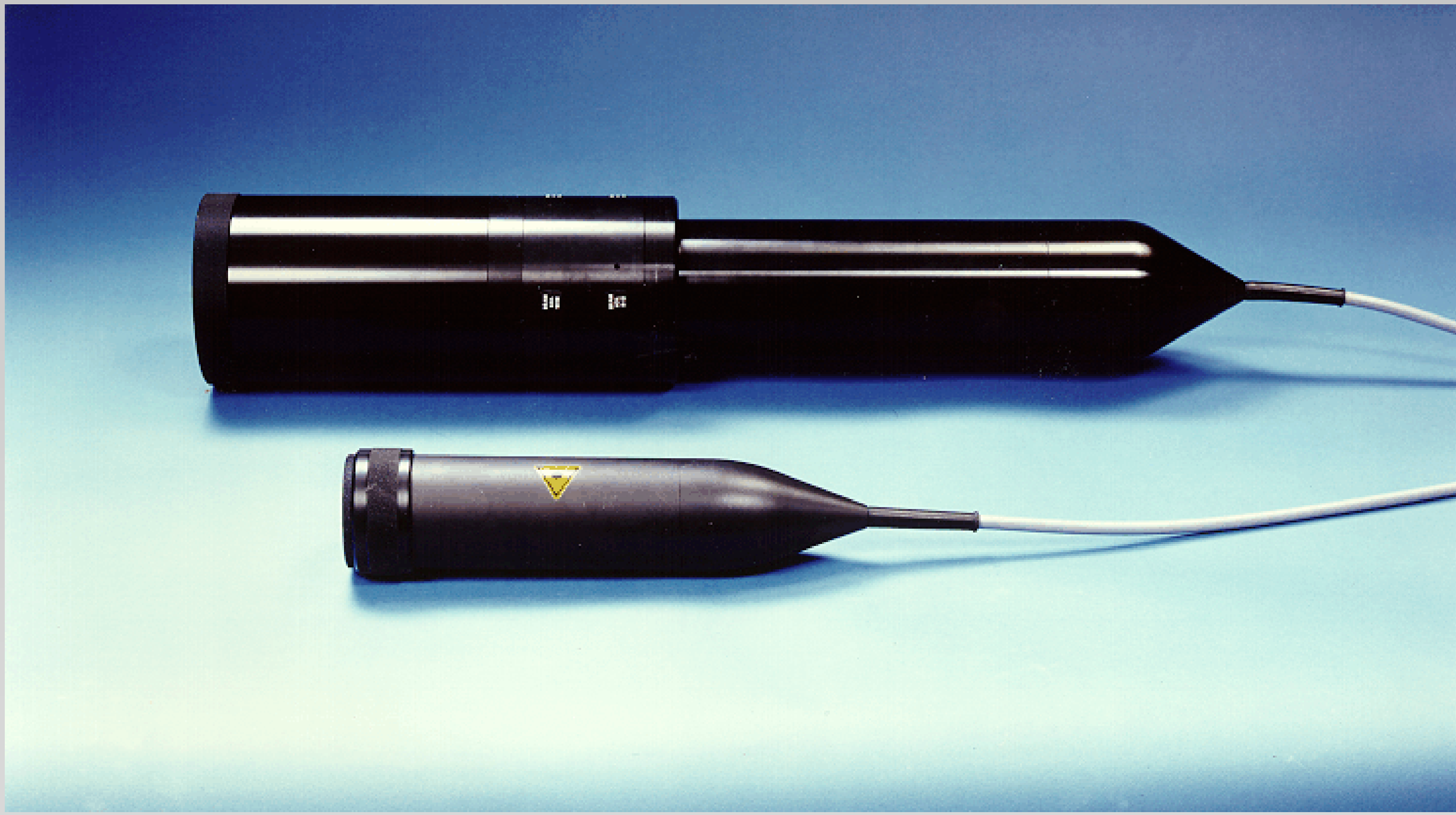
60 mm and 85 mm *FiberFlow* probes



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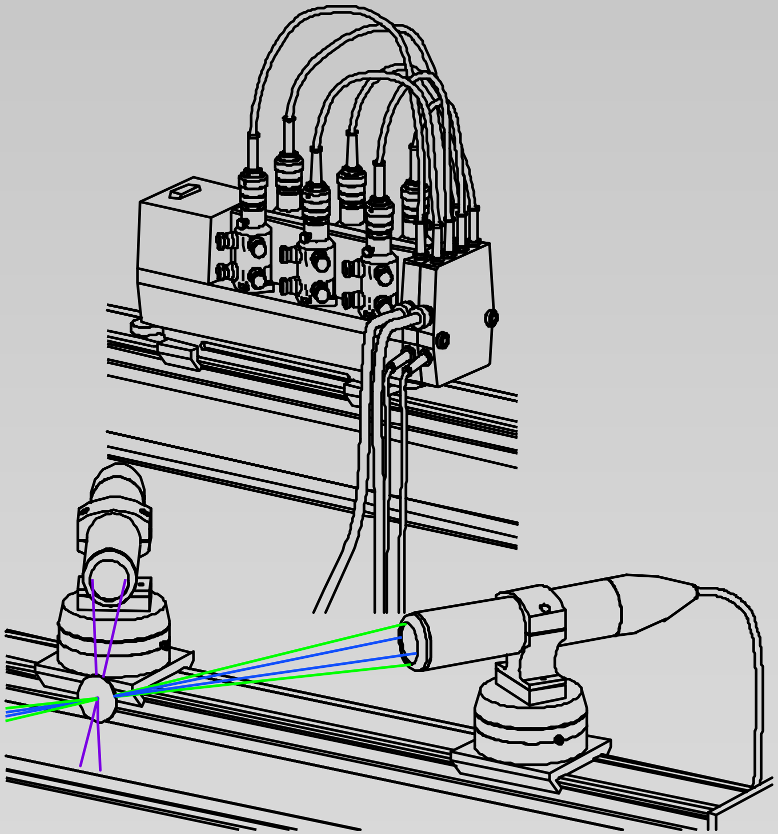
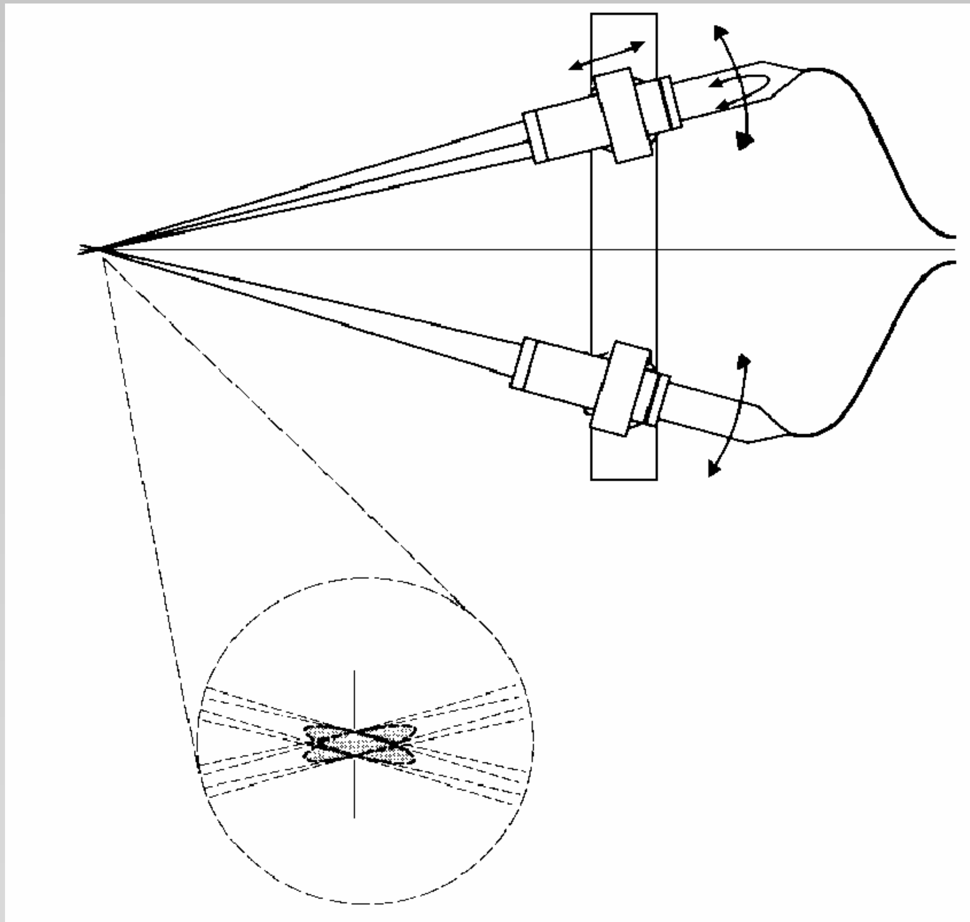
FiberFlow setup for 3-D velocity measurements

- **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.**

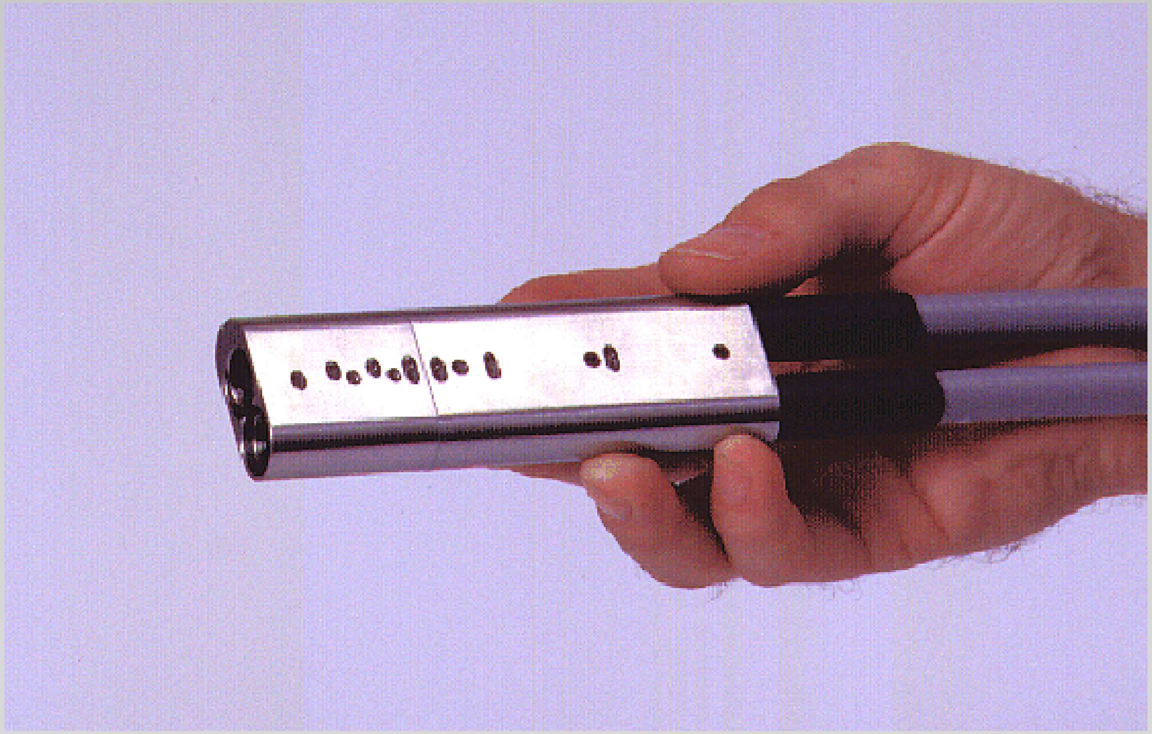


Probe volume alignment for 3-D velocity measurements

- 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 maximizing the power of light passing through the pinhole for each beam.



The small integrated 3D *FiberFlow* probe



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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	Diameter (μm) 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

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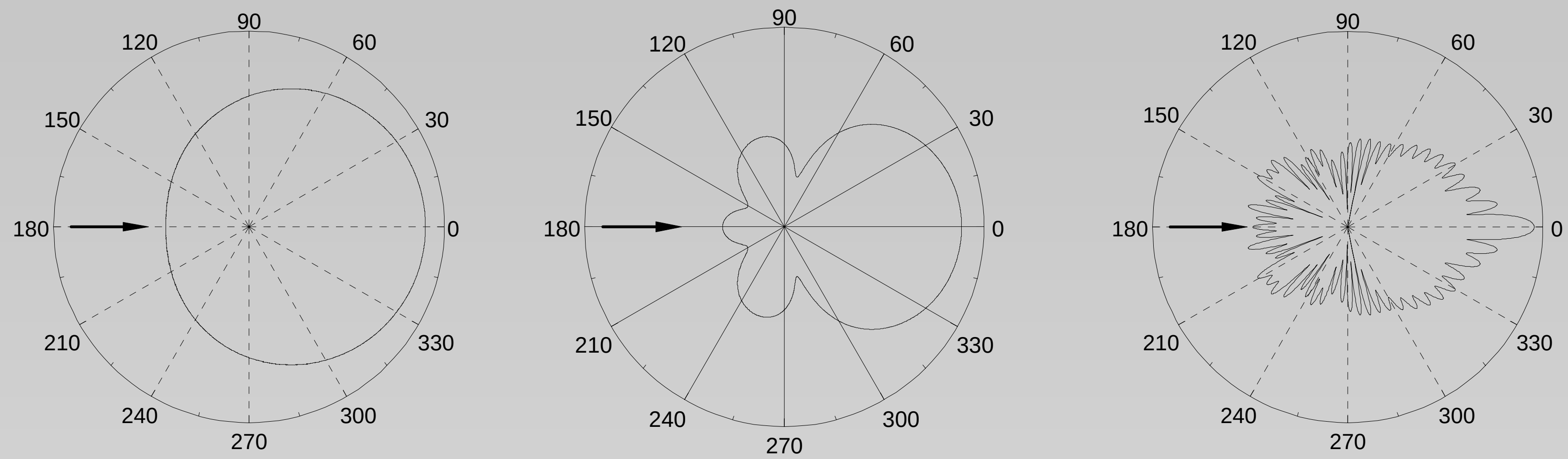
Seeding: scattered light intensity



$d_p \cong 0.2\lambda$ $d_p \cong 1.0\lambda$ $d_p \cong 10\lambda$

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

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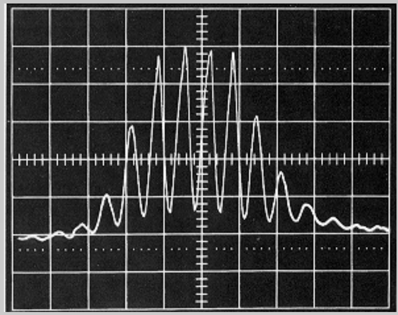
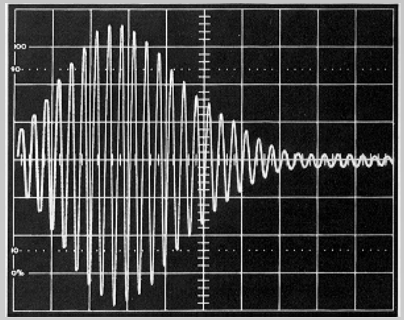
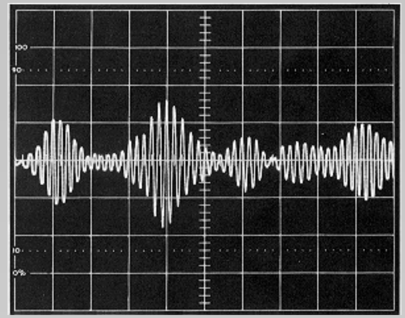
Signal Characteristics







- 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.

Data Processing Specifications

What is important to know about an *LDA software* package?

- **What *functions* does it perform?**
  - **data acquisition?**
  - **instrument control?**
  - **data processing?**
  - **graphics output?**
- **What is the *Input/Output*?**
- **How much *Flexibility* is there?**
  - $S_T(f)_{unbiased}$, $S_T(f)_{biased}$
  - $S_T(f)_{cov}$, $S_T(f)_{FFT}$
- **Is it EASY to use?**

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

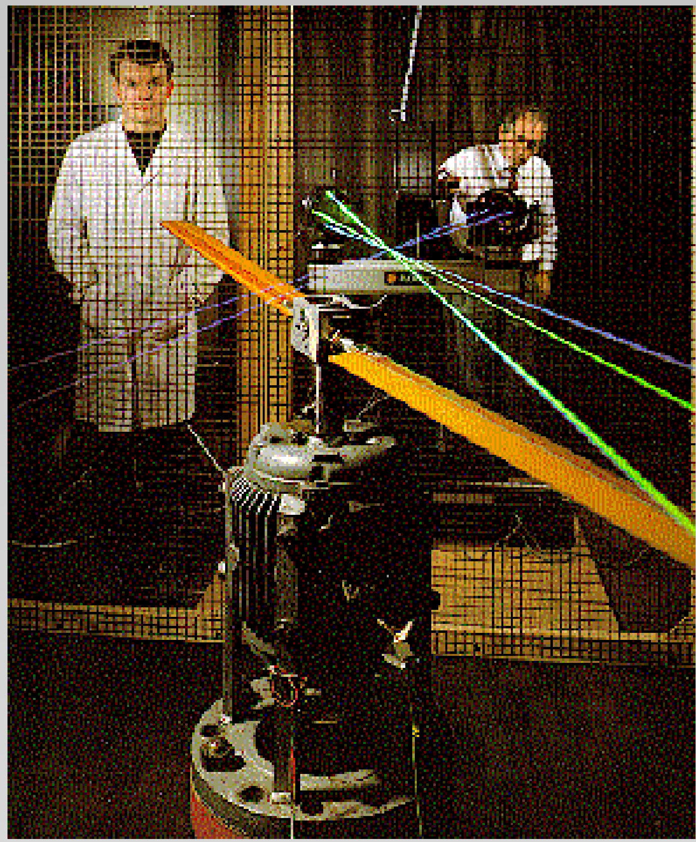


Photo courtesy of University of Bristol, UK

Measurement of water flow inside a pump model

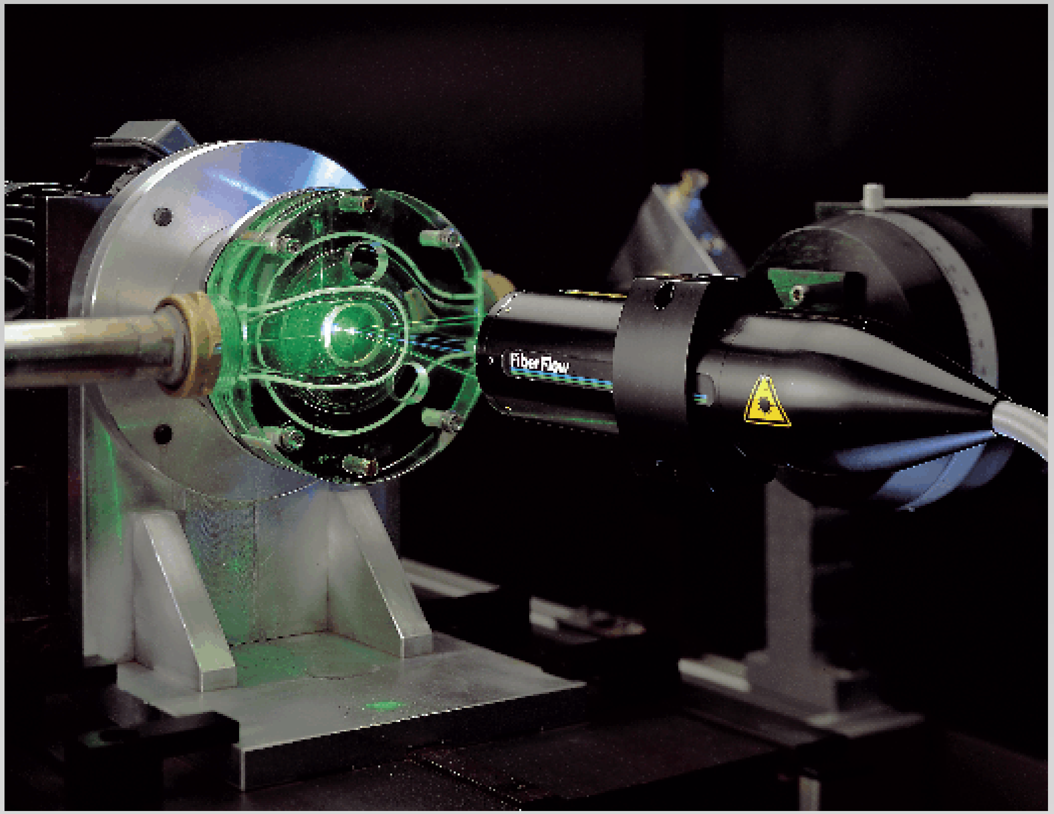
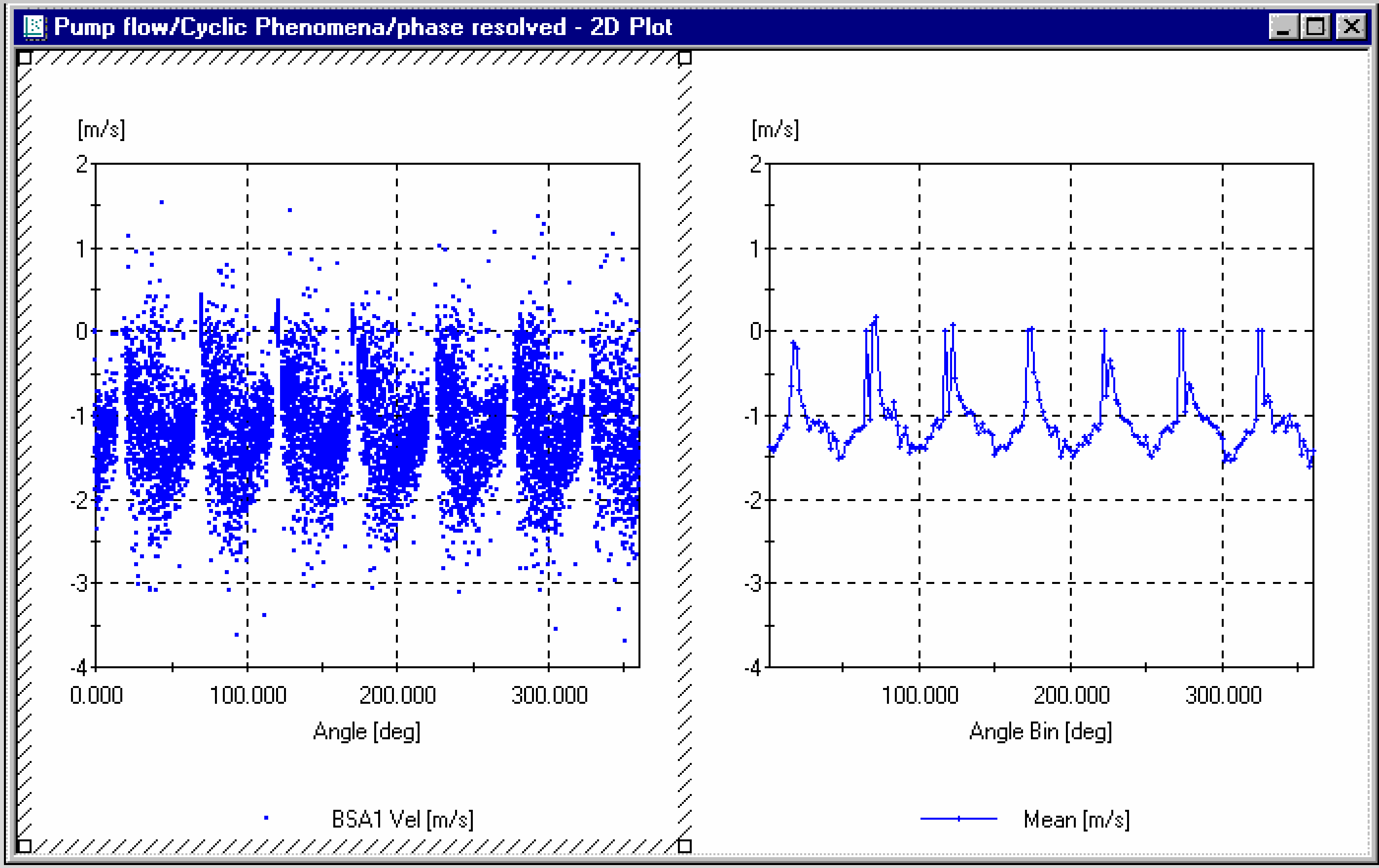
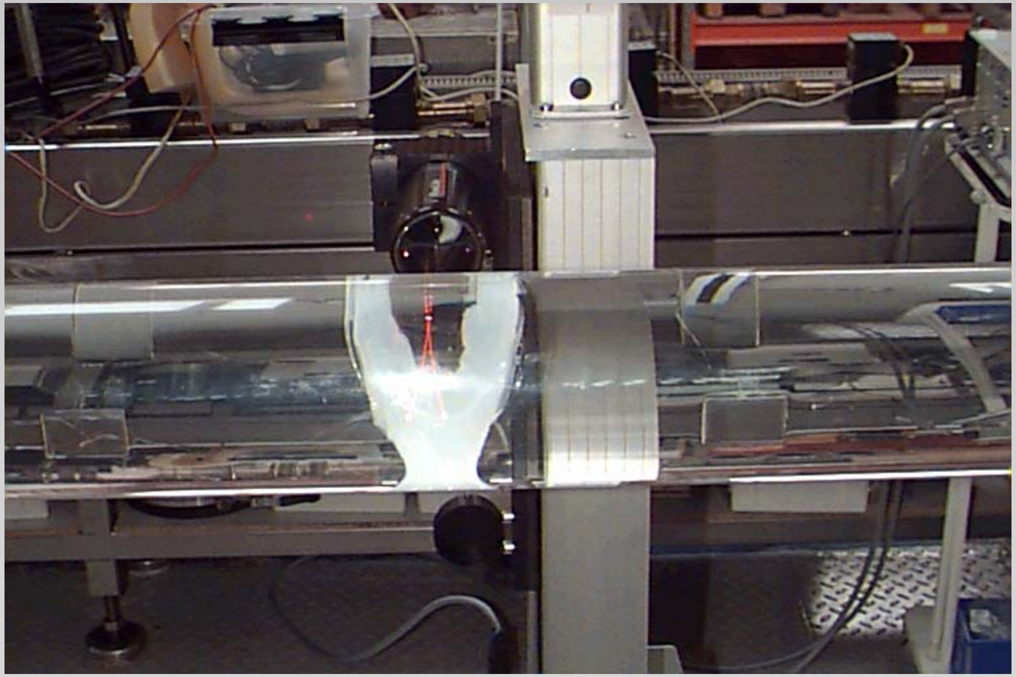


Photo courtesy of Grundfos A/S, DK

Phase resolved and phase averaged data



Measurement of velocity profiles in a water pipe



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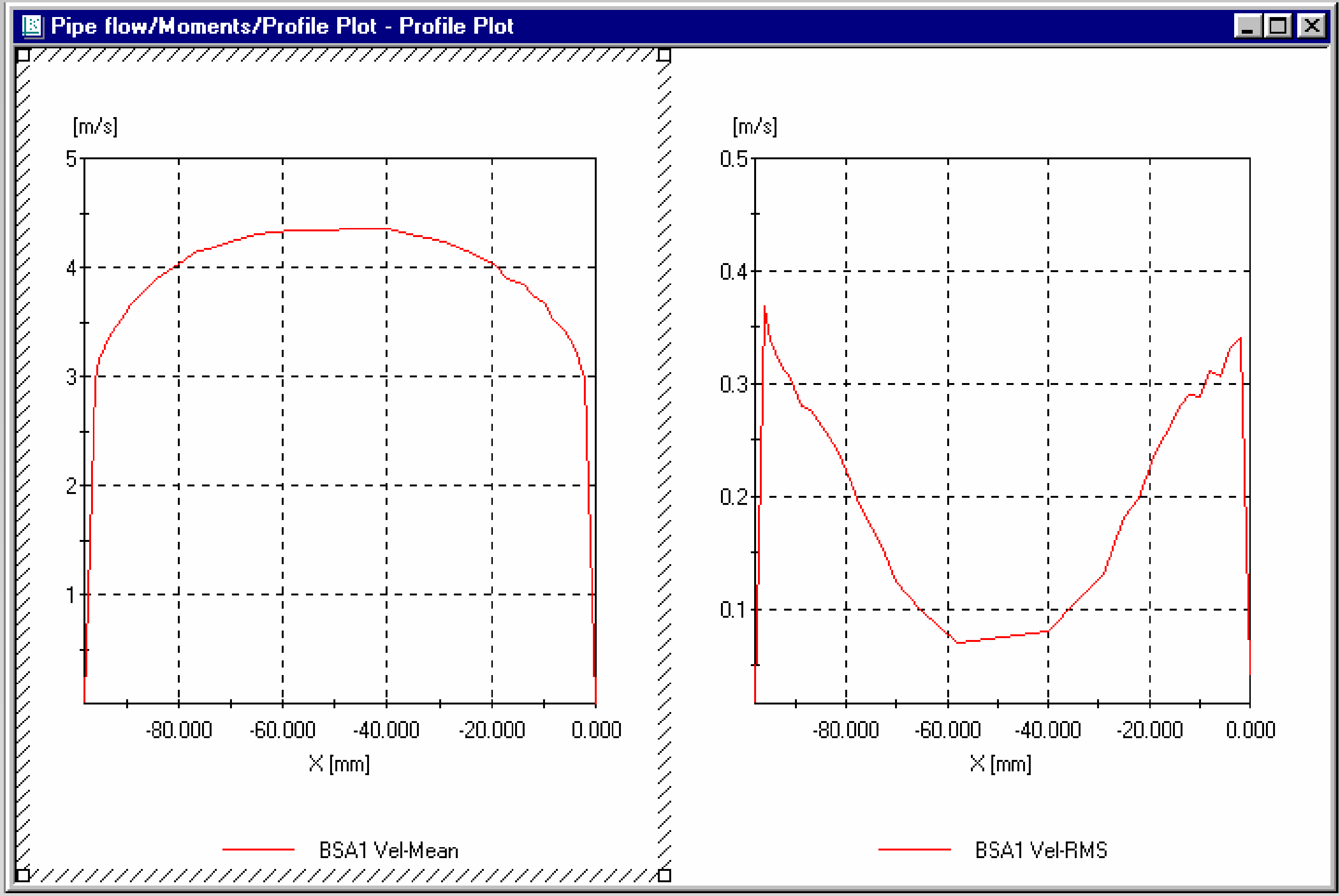
Velocity profile, fully developed turbulent pipe flow



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

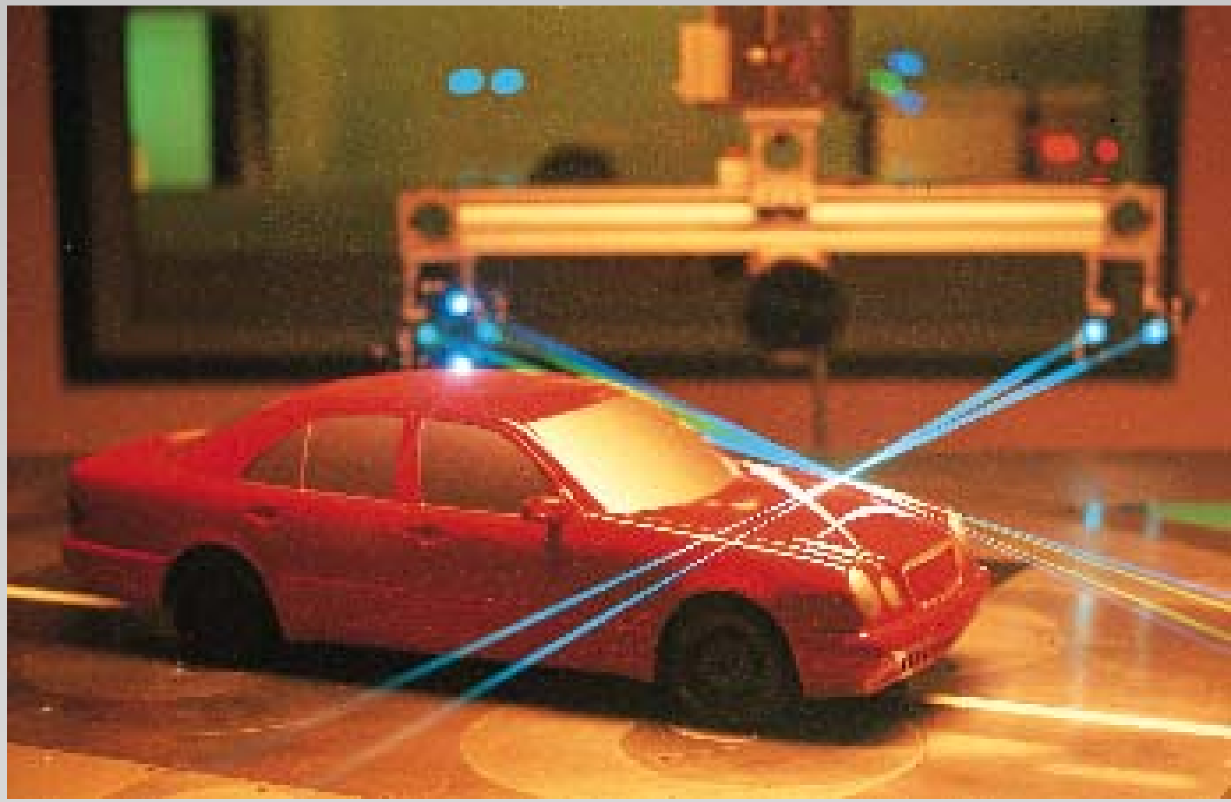

Photo courtesy of Mercedes-Benz, Germany

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

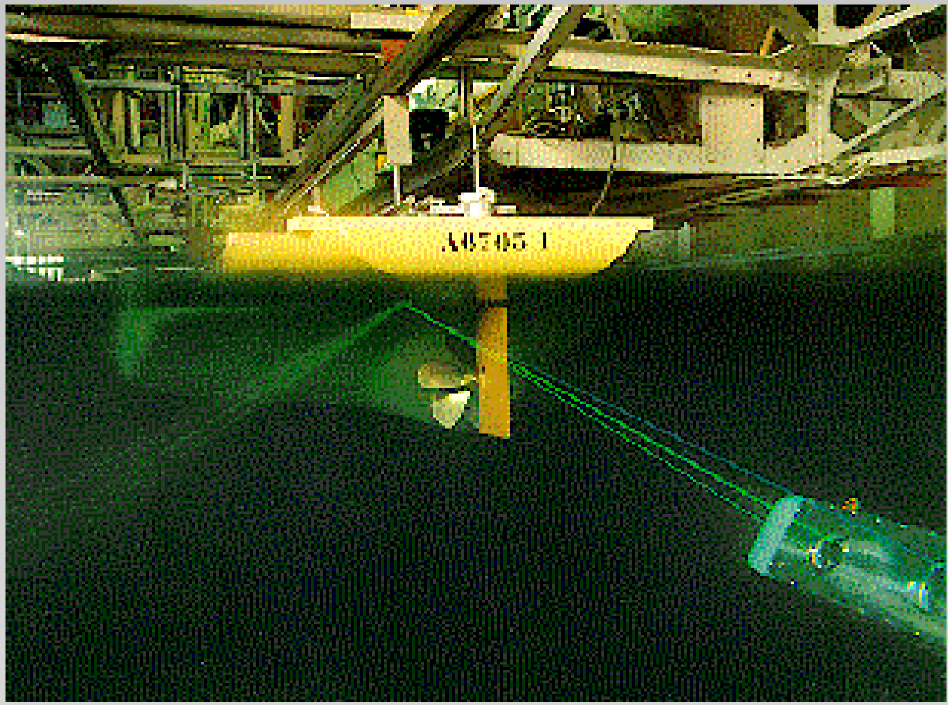

Photo courtesy of Marin, the Netherlands

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

Photo courtesy of University of Bristol, UK

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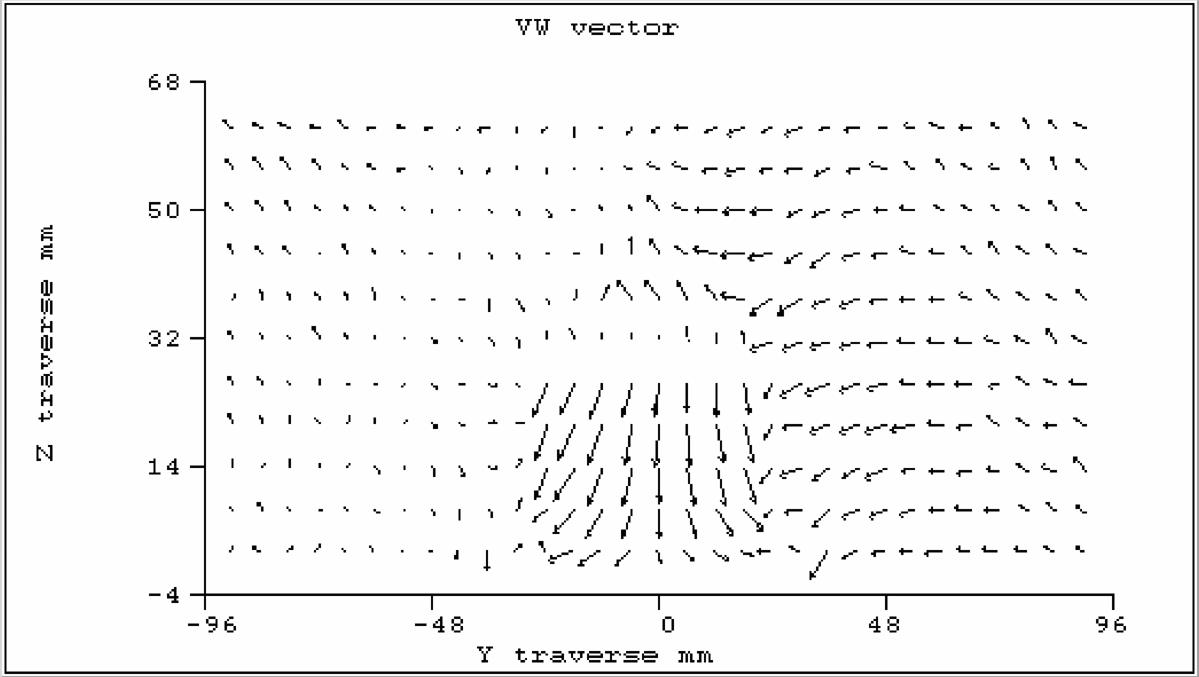
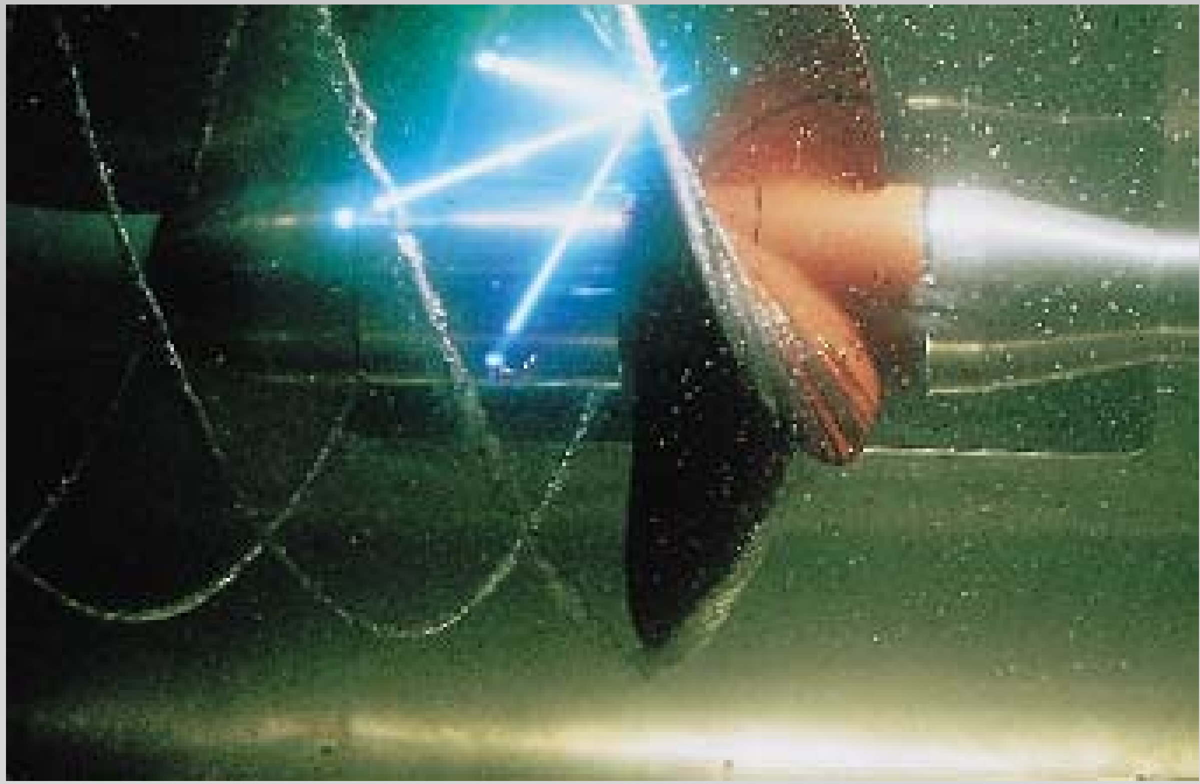
Wake flow field behind hangar



Measurement of flow around a ship propeller in a cavitation tank



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Measurement of flow in a valve model

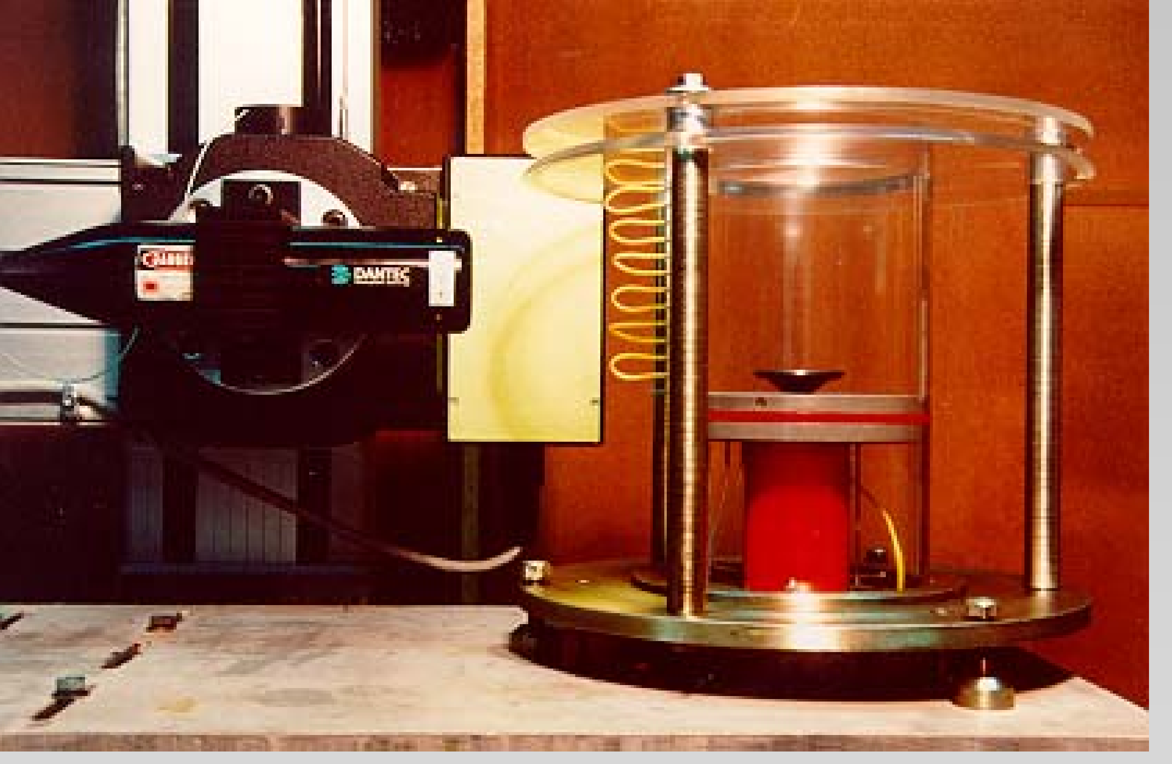

Photo courtesy of Westsächsische Hochschule Zwickau, Germany

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Comparison of EFD and CFD results