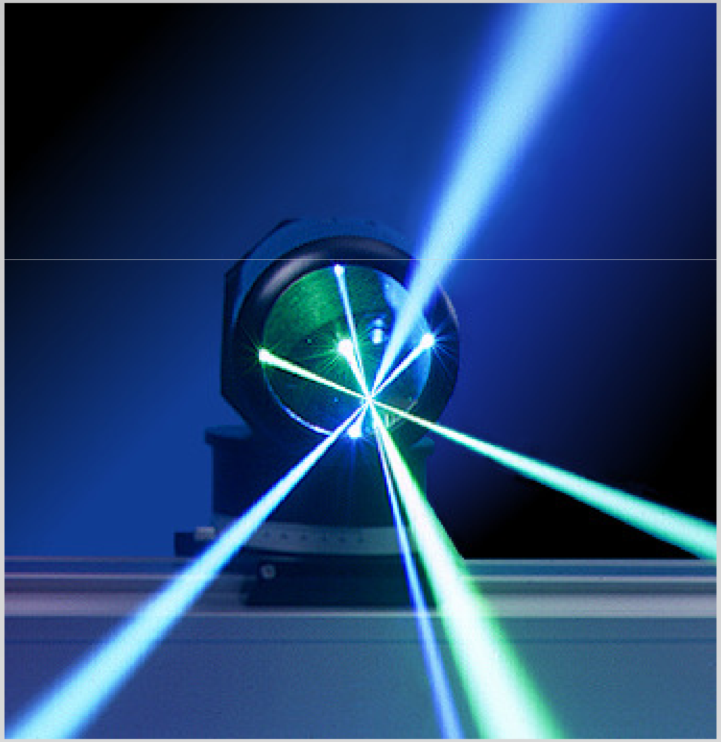
Laser Doppler Anemometry

Introduction to principles and applications



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Measurement Technology

Characteristics of LDA

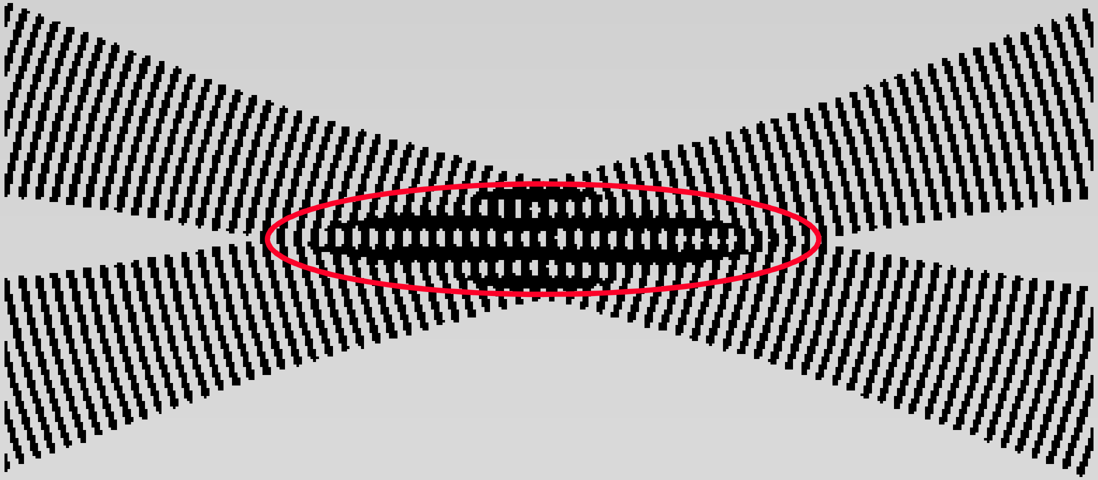
- Invented by Yeh and Cummins in 1964
- Velocity measurements in Fluid Dynamics (gas, liquid)
- Up to 3 velocity components
- Non-intrusive measurements (optical technique)
- Absolute measurement technique (no calibration required)
- Very high accuracy
- Very high spatial resolution due to small measurement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

Applications of LDA

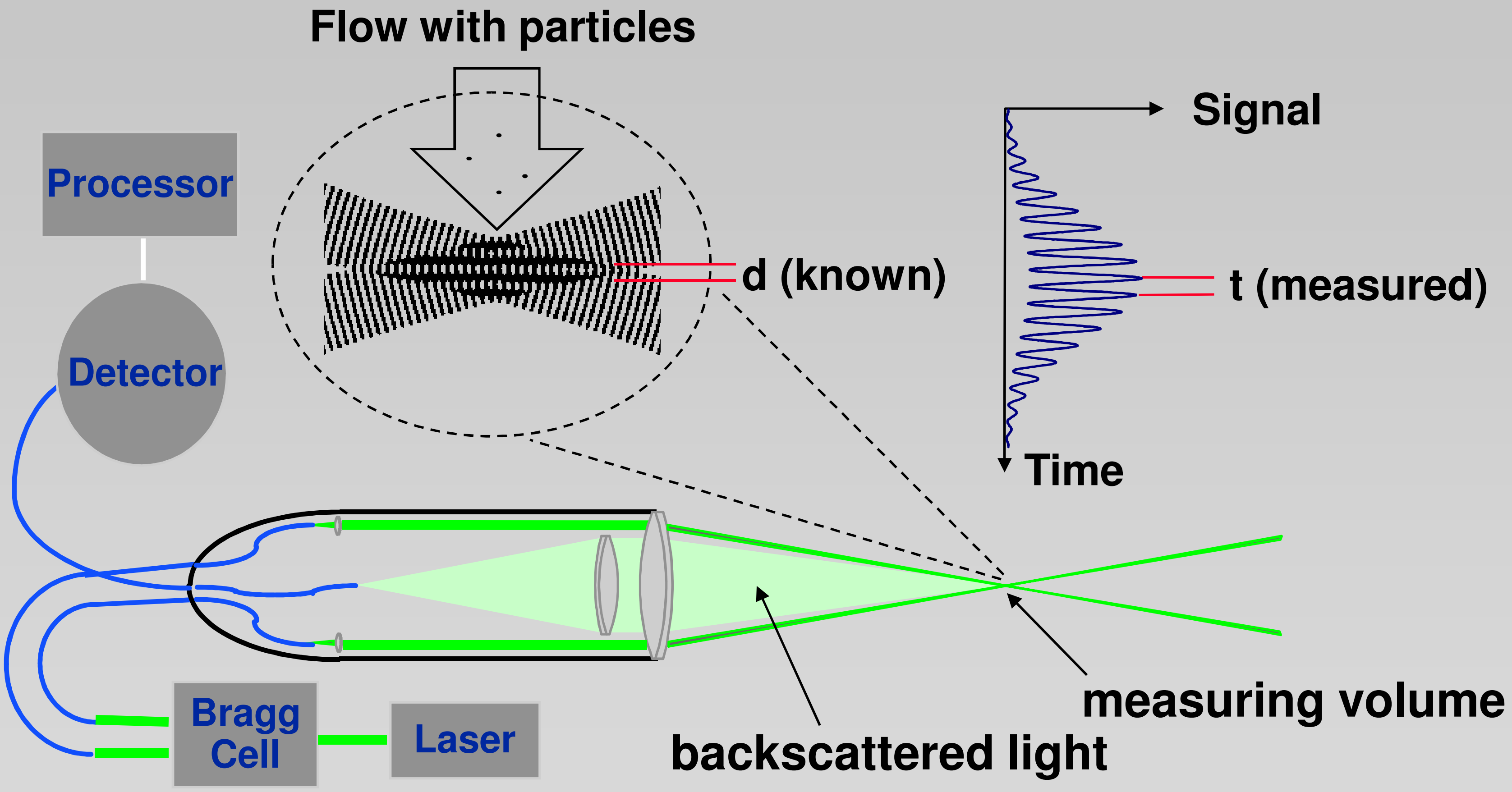
- Laminar and turbulent flows
- Investigations on aerodynamics
- Supersonic flows
- Turbines, automotive etc.
- Liquid flows
- Surface velocity and vibration measurement
- Hot environments (Flames, Plasma etc.)
- Velocity of particles
- ...... etc, etc, etc.

LDA - 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

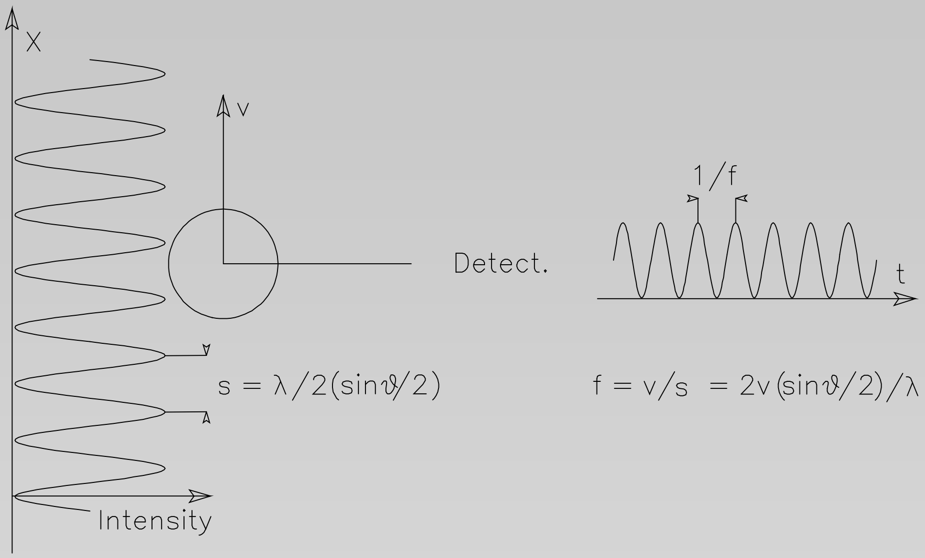


Velocity = distance/time

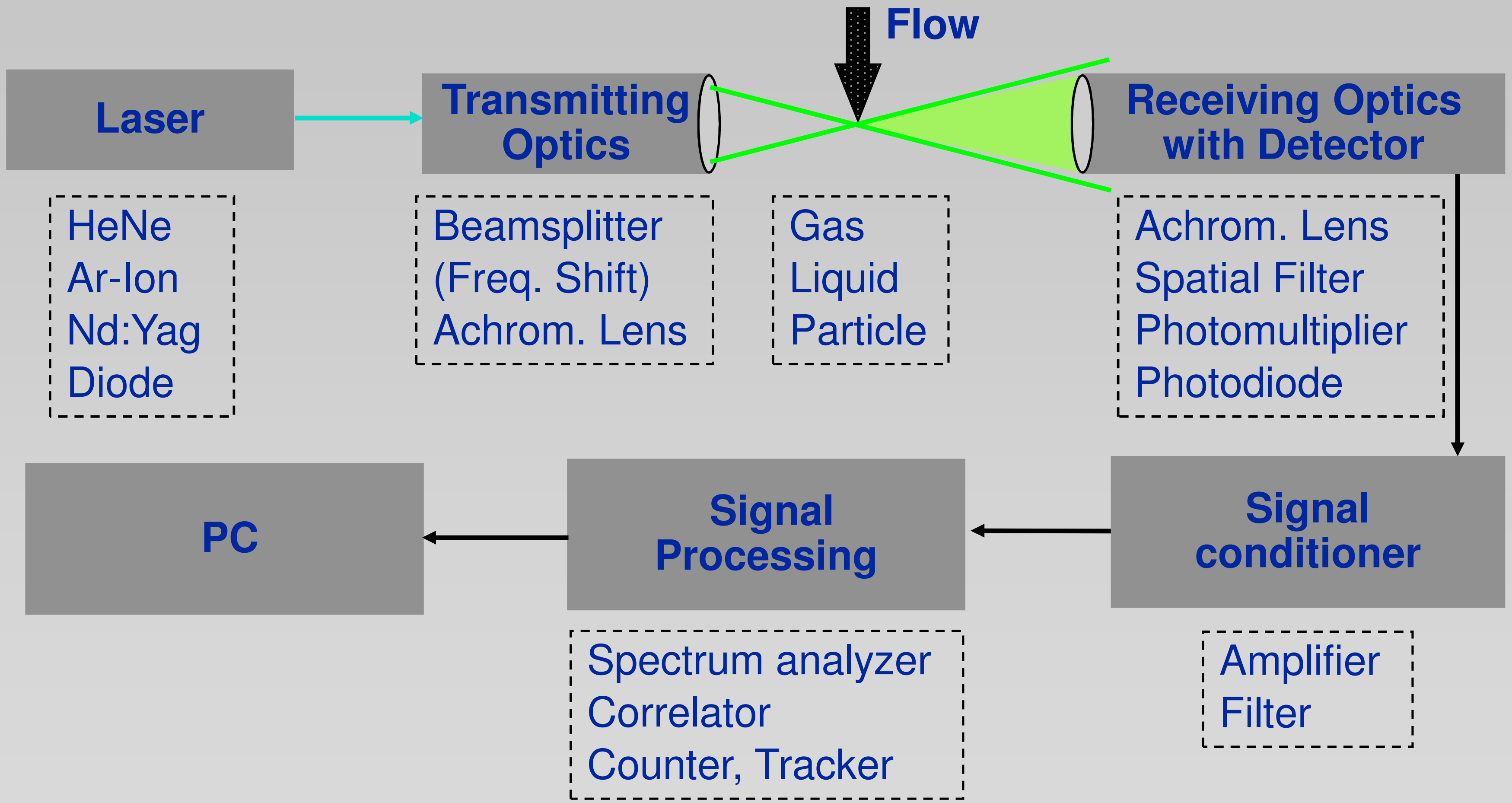


LDA - Fringe Model

- **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.**



Principle of LDA



Flow

Laser

- HeNe
- Ar-Ion
- Nd:Yag
- Diode

Transmitting Optics

- Beamsplitter
- (Freq. Shift)
- Achrom. Lens

- Gas
- Liquid
- Particle

Receiving Optics with Detector

- Achrom. Lens
- Spatial Filter
- Photomultiplier
- Photodiode

Signal conditioner

- Amplifier
- Filter

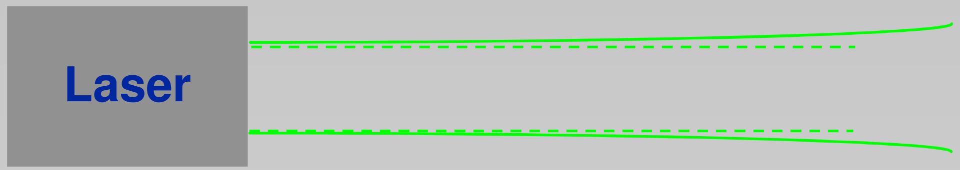
Signal Processing

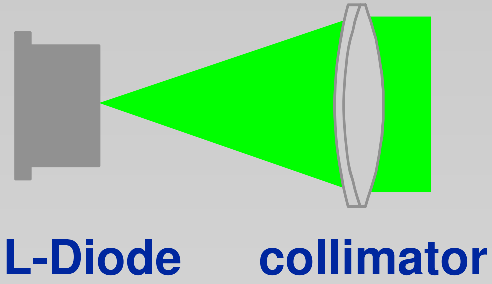
- Spectrum analyzer
- Correlator
- Counter, Tracker

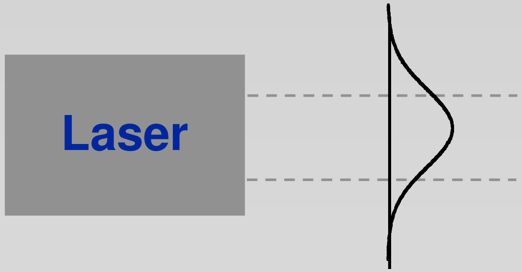
PC

Laser, Characteristics and Requirements

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







- Gaussian intensity distribution

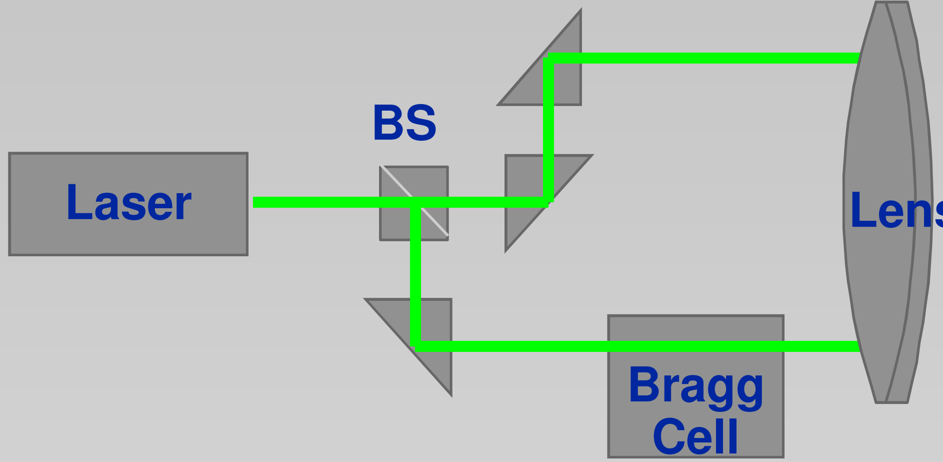
Transmitting Optics

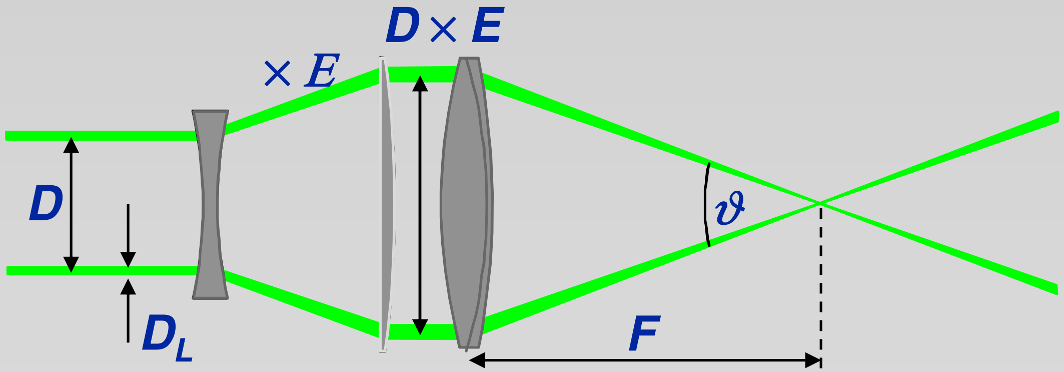
Basic modules:

- Beam splitter
- Achromatic lens

Options:

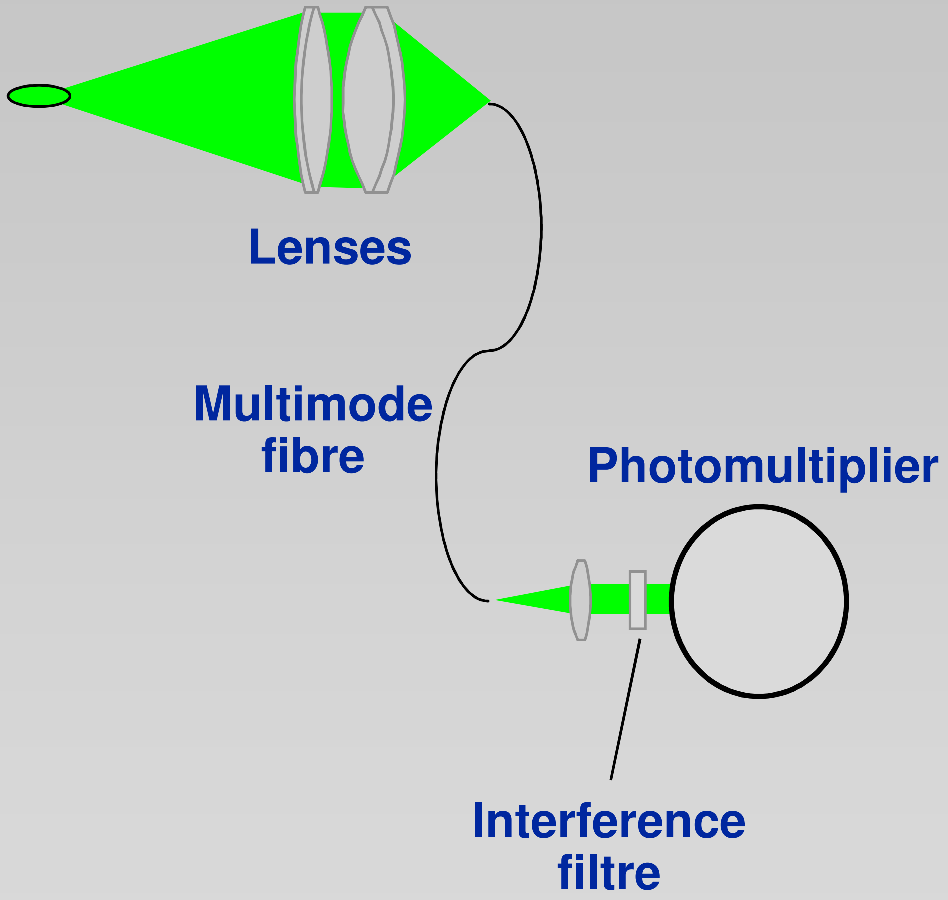
- Frequency shift (Bragg cell)
  - low velocities
  - flow direction
- Beam expanders
  - reduce measurement volume
  - increase power density





Receiving Systems

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



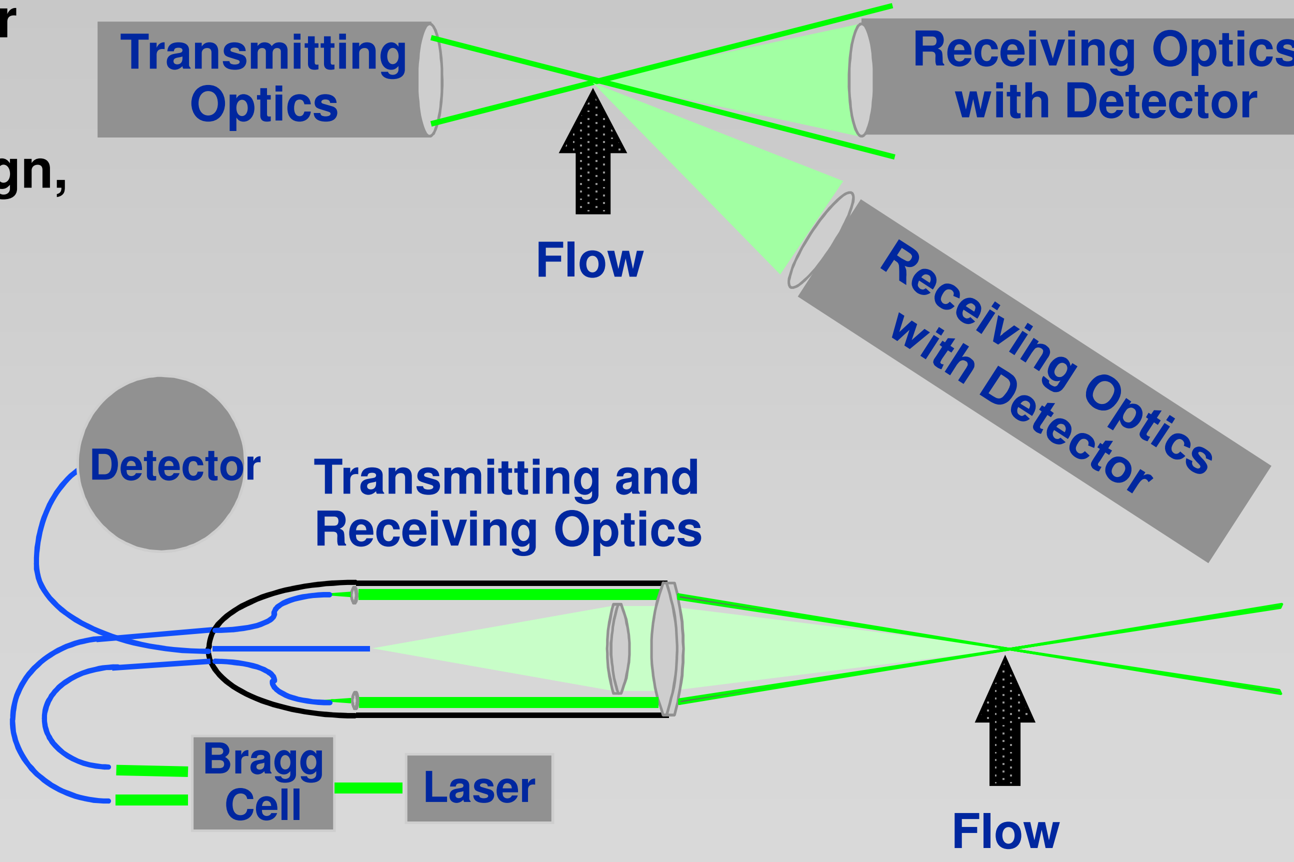
System Configurations

Forward scatter and side scatter (off-axis)

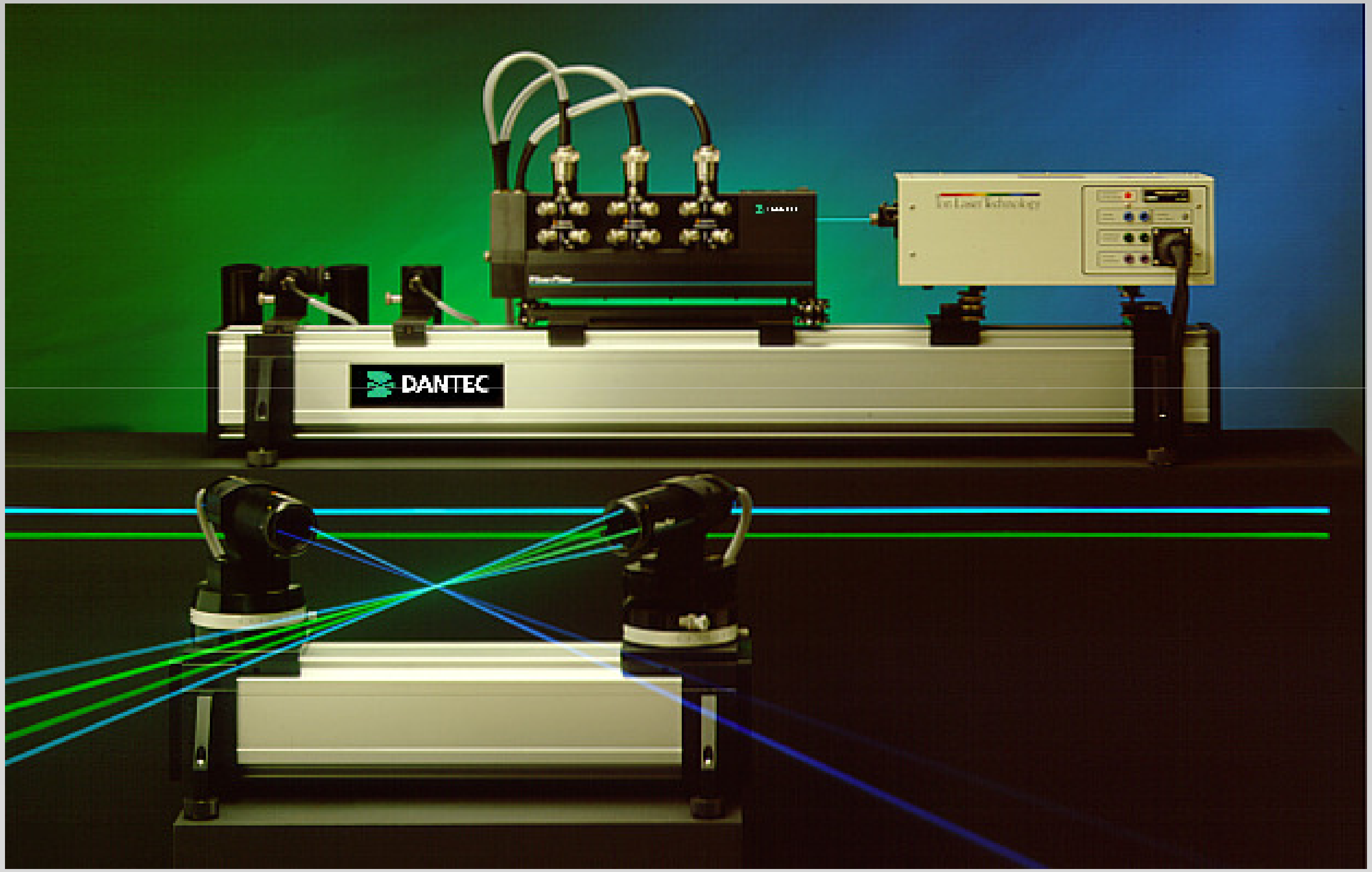
- Difficult to align,
- vibration sensitive

Backscatter

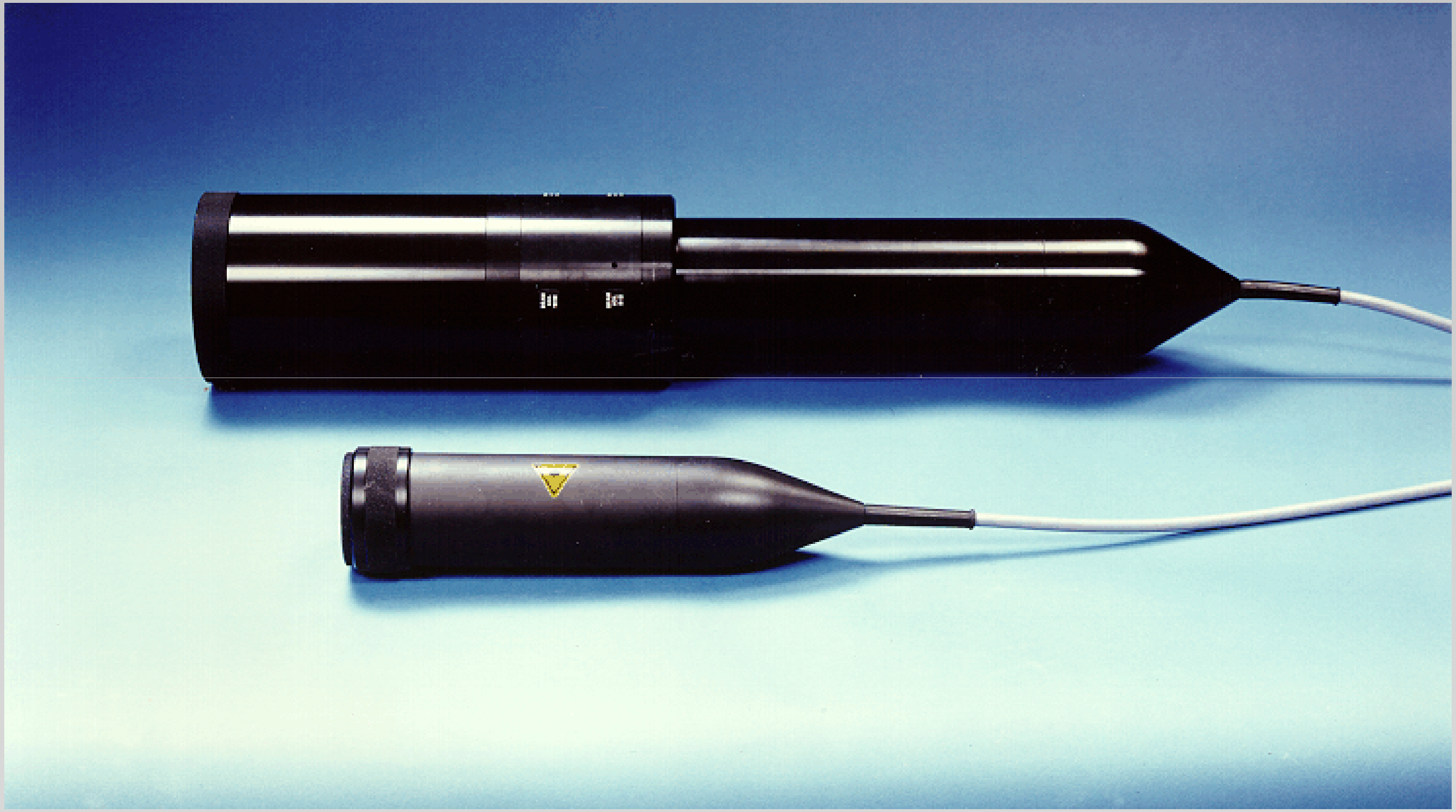
- Easy to align
- User friendly



LDA Fibre Optical System



60 mm and 85 mm *FiberFlow* probes



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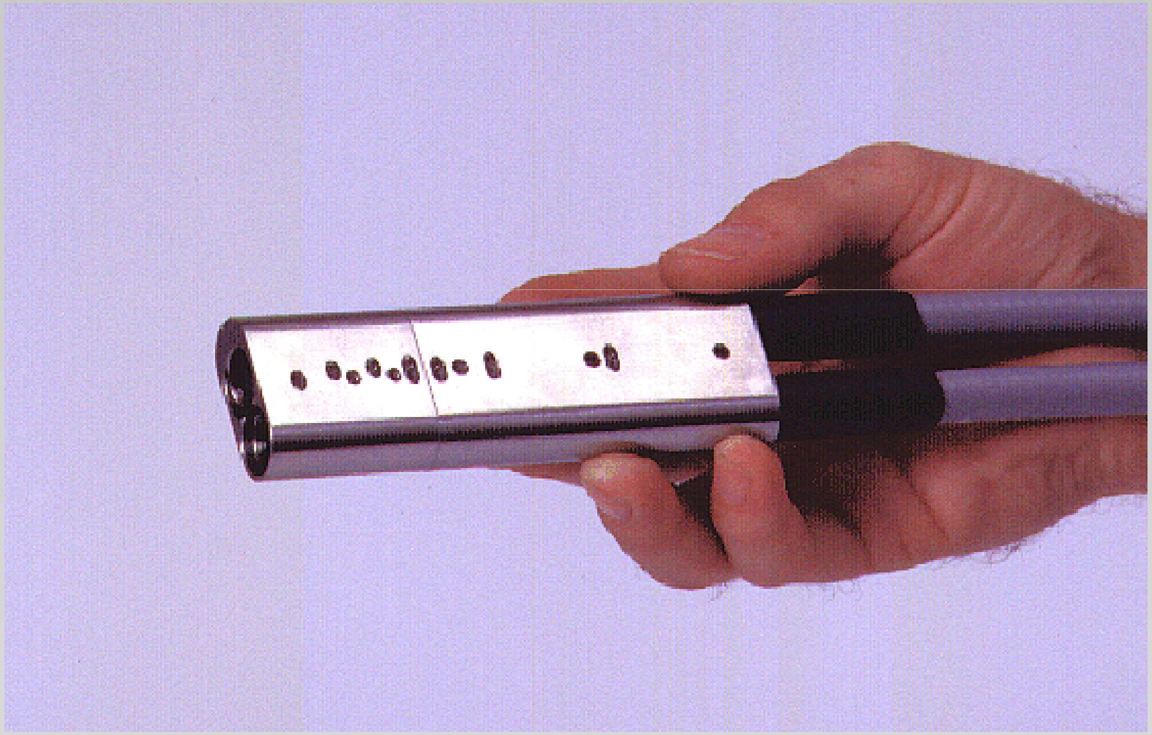
The small integrated 3D *FiberFlow* probe



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

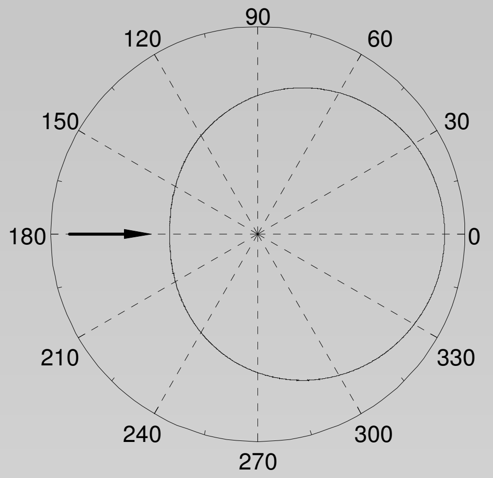
Seeding: ability to follow flow

Particle Frequency Response

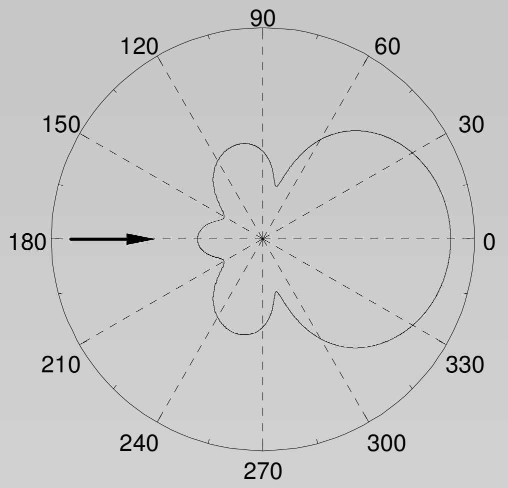
$$\frac{\mathrm{d}}{\mathrm{dt}} U_p = -18 \frac{\nu}{d_p^2} \frac{U_p - U_f}{\rho_p / \rho_f}$$

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 0.8	methane-air flame (1800 K)	2.6	
TiO_2	oxygen plasma (2800 K)	3.2	0.8

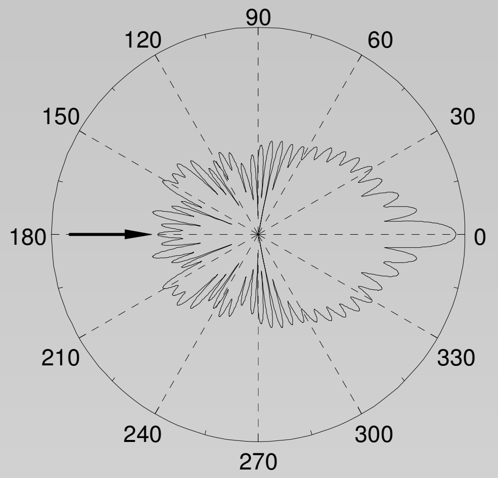
Seeding: scattered light intensity



$d_p \cong 0.2\lambda$



$d_p \cong 1.0\lambda$



$d_p \cong 10\lambda$

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

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

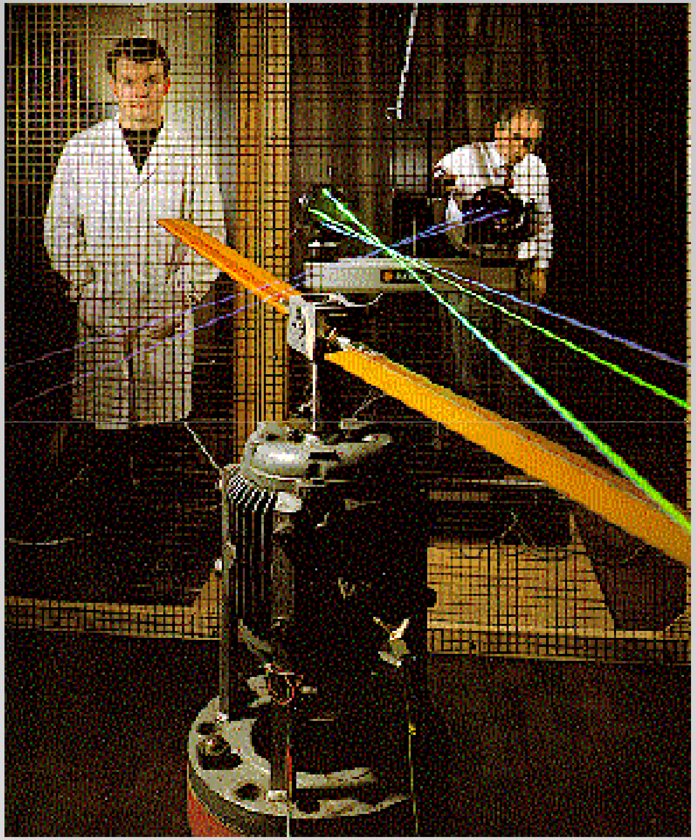


Photo courtesy of University of Bristol, UK

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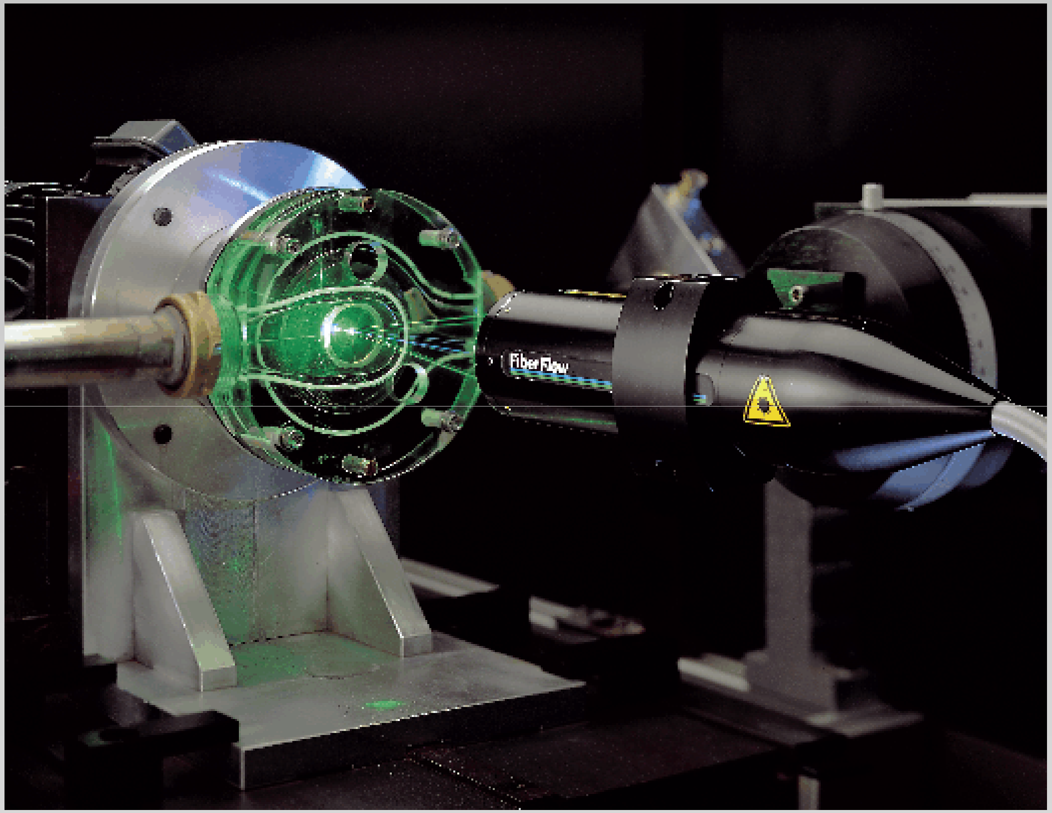
Measurement of water flow inside a pump model



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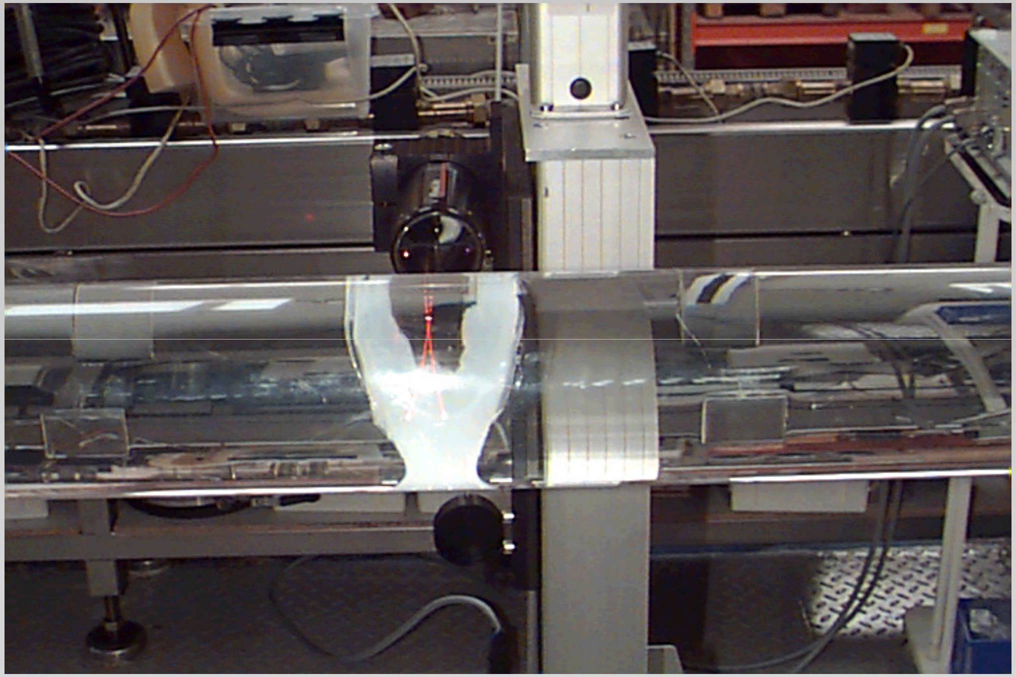
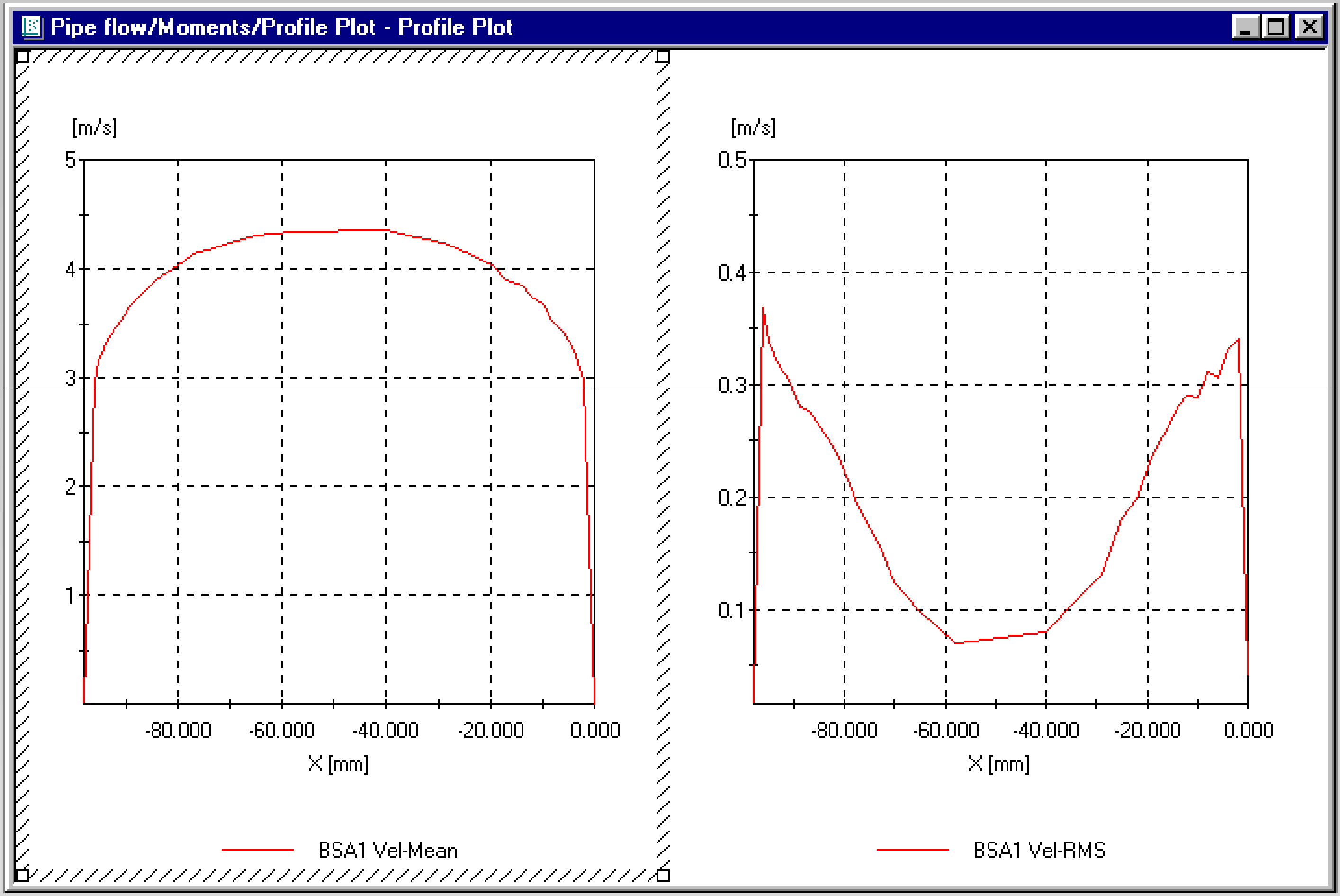
Measurement of velocity profiles in a water pipe



Velocity profile, fully developed turbulent pipe flow



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

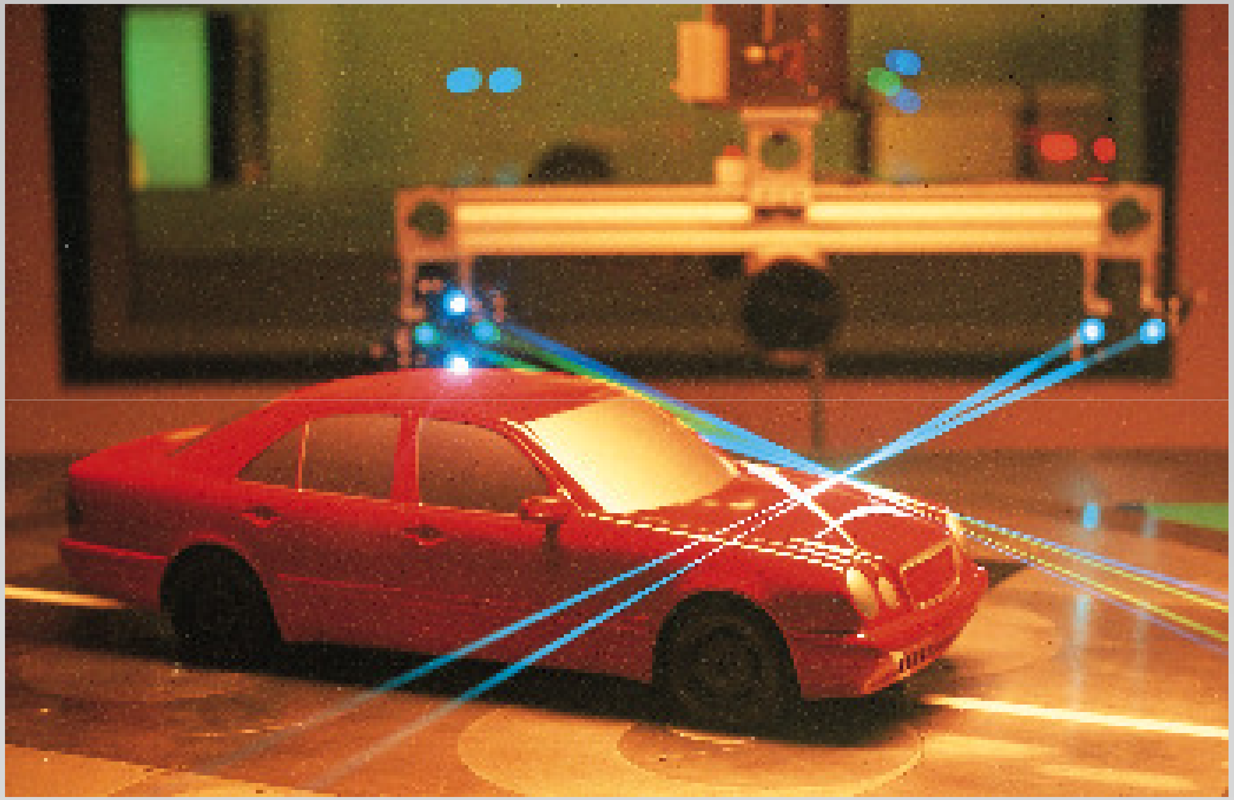


Photo courtesy of Mercedes-Benz, Germany

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

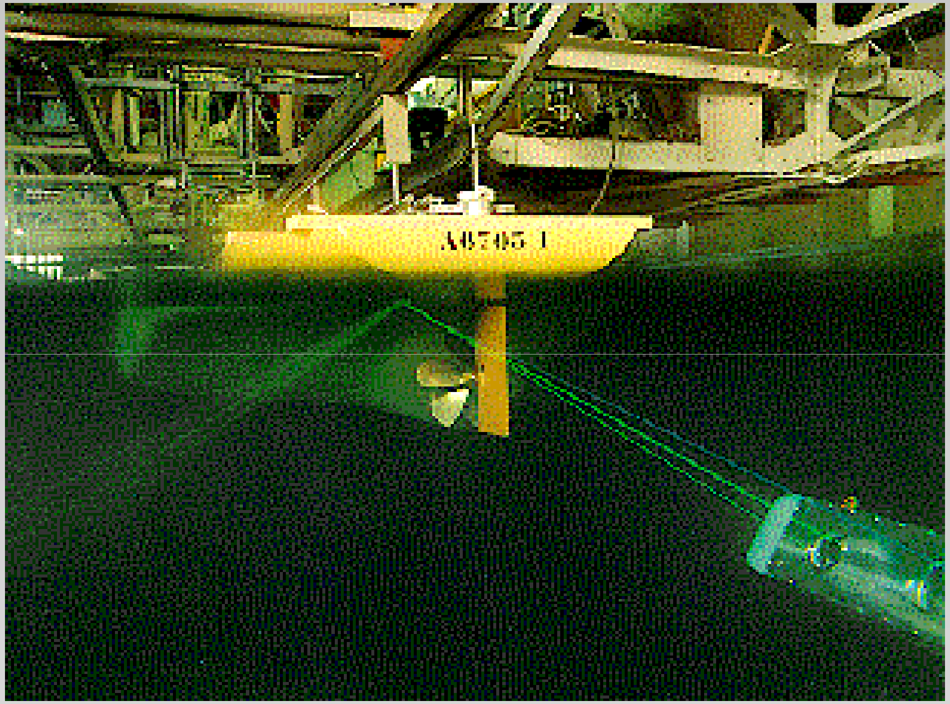
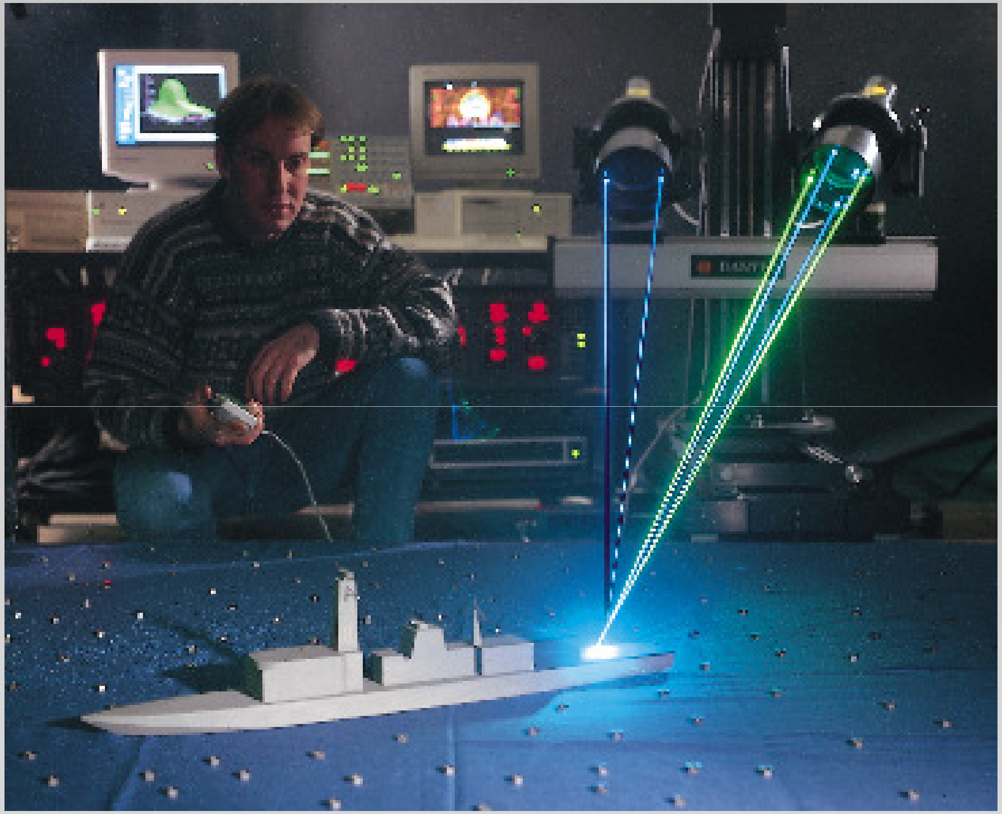


Photo courtesy of Marin, the Netherlands

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



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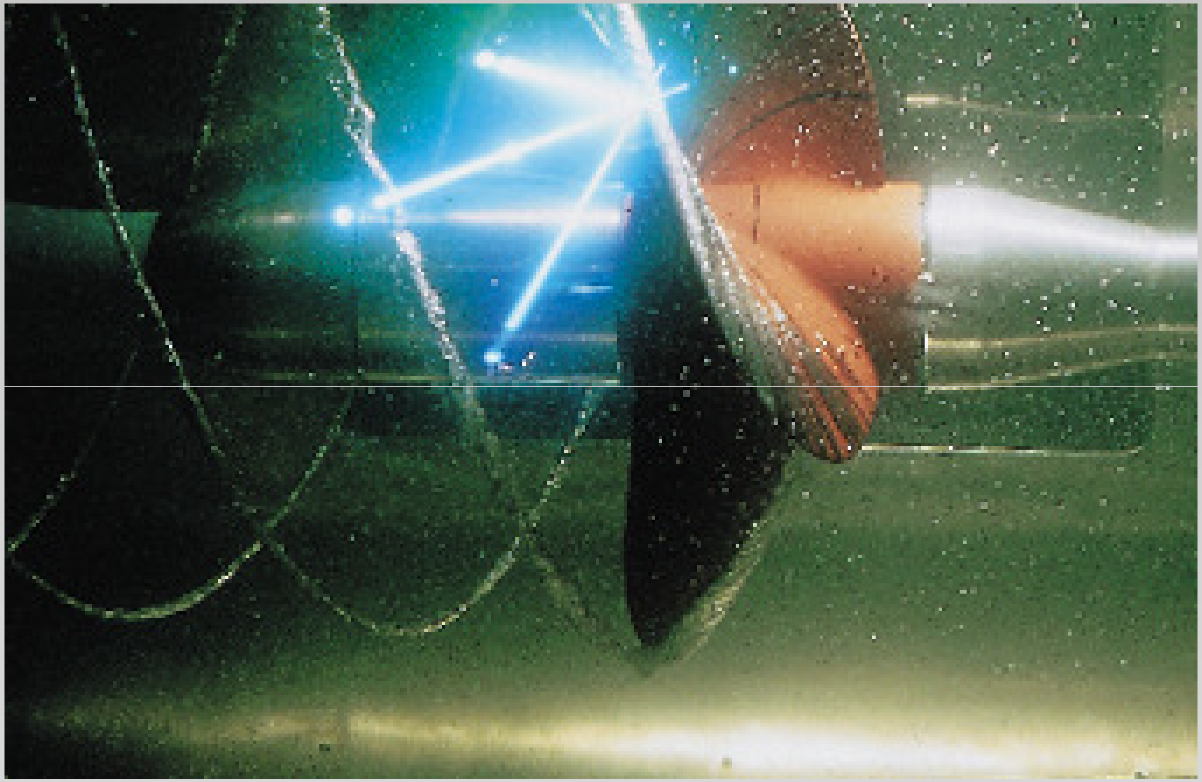
Measurement of flow around a ship propeller in a cavitation tank



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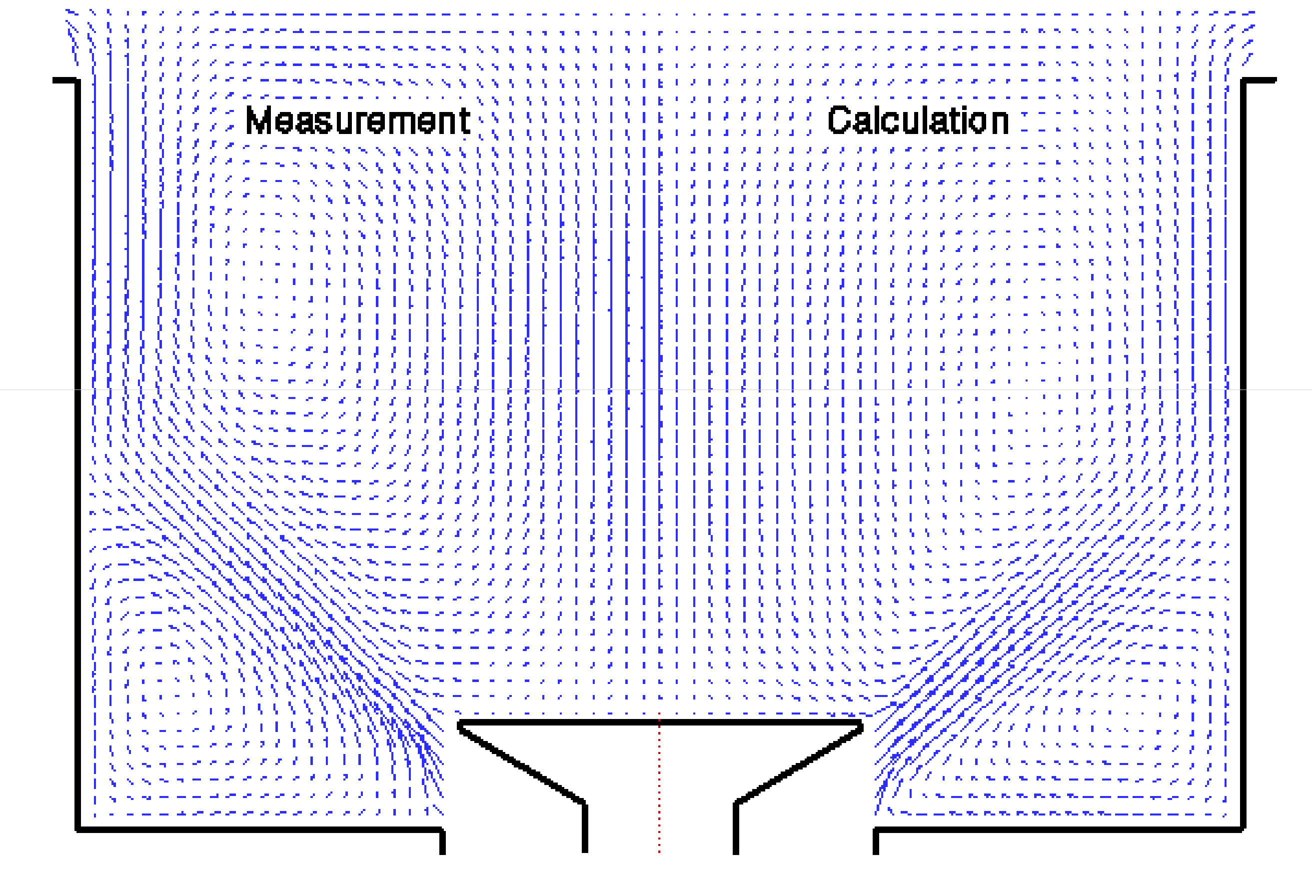
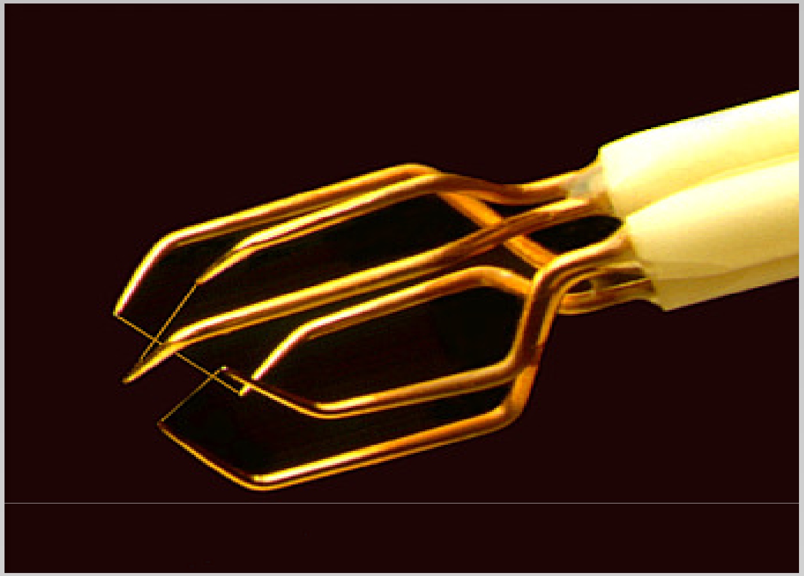
Comparison of EFD and CFD results



Hot-Wire Anemometry



- **Purpose:**

  to measure mean and fluctuating variables in fluid flows (velocity, temperature, etc.): mean velocity, turbulence characteristics

CTA Application

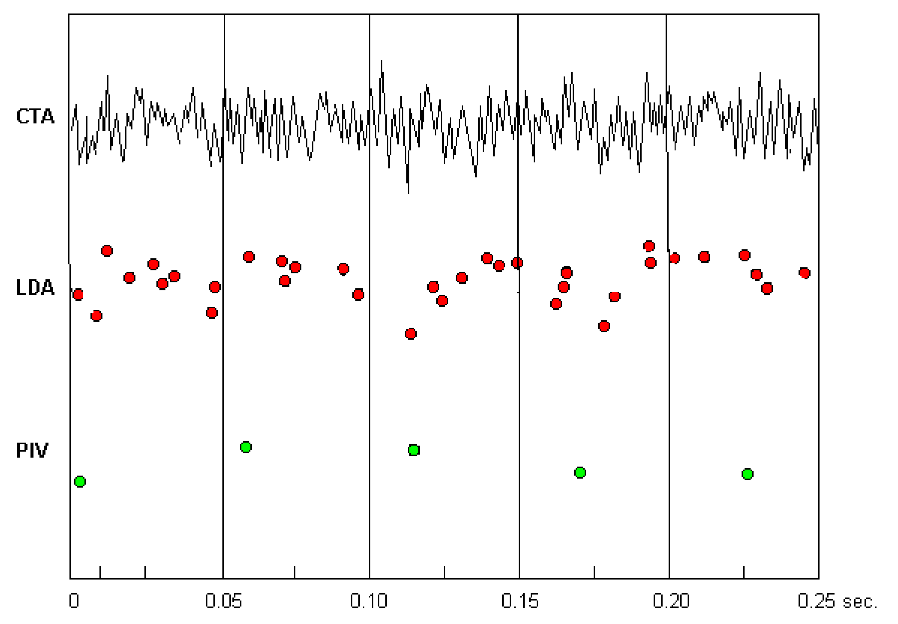
Flow field over helicopter landing pad

(Danish Maritime Institute, Lyngby Denmark)

Anemometer signal output

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.

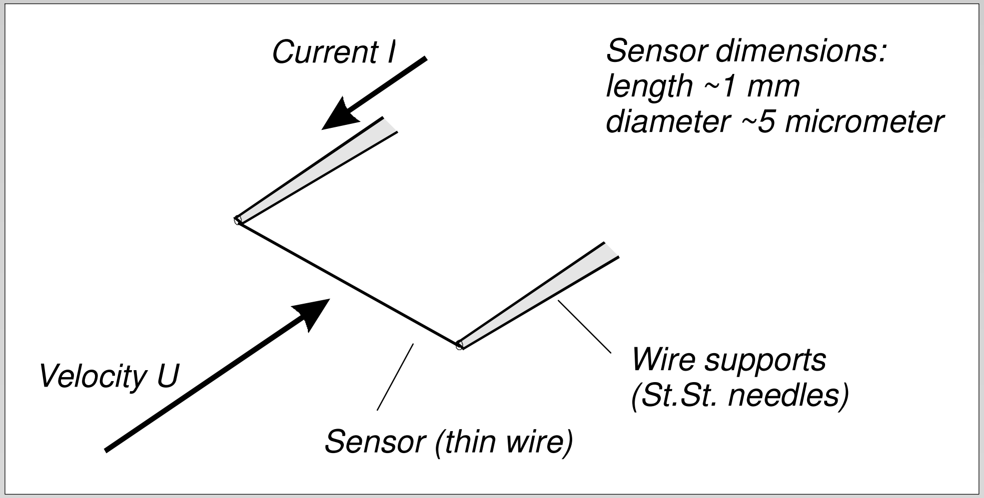


Principles of operation

- Consider a thin wire mounted to supports and exposed to a velocity *U*.

  When a current is passed through wire, heat is generated (I^2R_w). In equilibrium, this must be balanced by heat loss (primarily convective) to the surroundings.

- If velocity changes, convective heat transfer coefficient will change, wire temperature will change and eventually reach a new equilibrium.



Governing equation

- **Governing Equation:** $\frac{dE}{dt} = W - H$

E = thermal energy stored in wire

$E = CwTw$

Cw = heat capacity of wire

W = power generated by Joule heating

$W = I^2 Rw$

recall $Rw = Rw(Tw)$

H = heat transferred to surroundings

Simplified static analysis I

- For equilibrium conditions the heat storage is zero:

$$\frac{dE}{dt}=O \quad \therefore W=H$$

and the Joule heating W equals the convective heat transfer H

- Assumptions

- Radiation losses small
- Conduction to wire supports small
- *Tw* uniform over length of sensor
- Velocity impinges normally on wire, and is uniform over its entire length, and also small compared to sonic speed.
- Fluid temperature and density constant

Simplified static analysis II

Static heat transfer:

$$W = H \Longrightarrow I^2Rw = hA(Tw - Ta) \Longrightarrow I^2Rw = Nukf/dA(Tw - Ta)$$

h = film coefficient of heat transfer
A = heat transfer area
d = wire diameter
kf = heat conductivity of fluid
Nu = dimensionless heat transfer coefficient

Forced convection regime, i.e. $Re > Gr^{1/3}$ (0.02 in air) and $Re < 140 \Longrightarrow$

$$Nu = A_1 + B_1 \cdot Re^n = A_2 + B_2 \cdot U^n$$

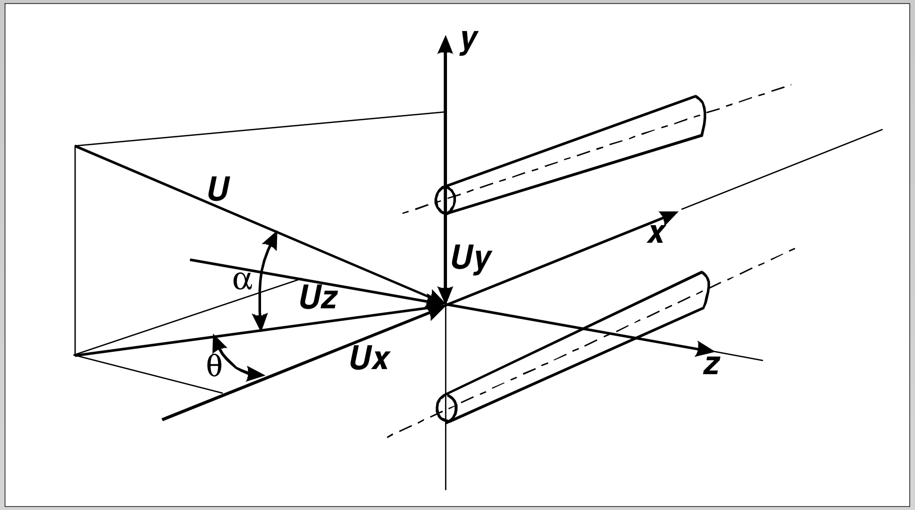
$$I^2Rw^2 = E^2 = (Tw - Ta)(A + B \cdot U^n)$$ "King's law"

The voltage drop is used as a measure of velocity ⇒ data acquisition, processing

A, B, n: BY CALIBRATION

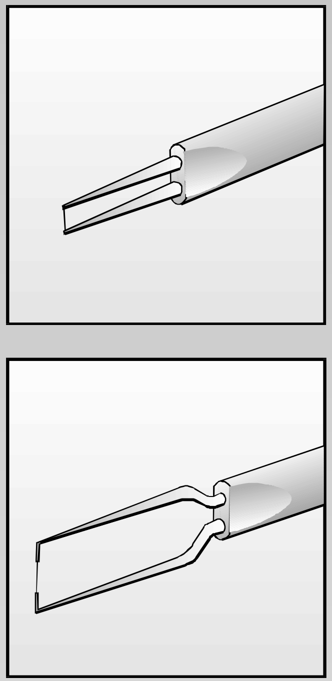
Directional response

Probe coordinate system



Velocity vector *U* is decomposed into normal *Ux*, tangential *Uy* and binormal *Uz* components.

Probe types I



- **Miniature Wire Probes**

  Platinum-plated tungsten,
  5 µm diameter, 1.2 mm length

- **Gold-Plated Probes**

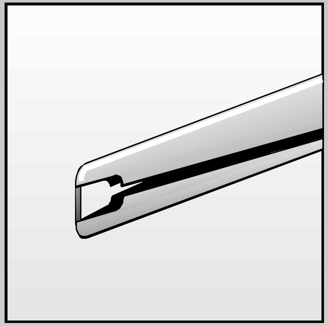
  3 mm total wire length,
  1.25 mm active sensor
  copper ends, gold-plated

__Advantages:
__- accurately defined sensing length
- reduced heat dissipation by the prongs
- more uniform temperature distribution along wire
- less probe interference to the flow field

Probe types II

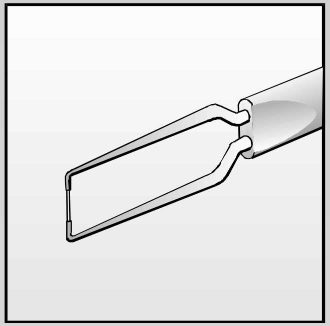
- **Film Probes**

  Thin metal film (nickel) deposited on quartz body. Thin quartz layer protects metal film against corrosion, wear, physical damage, electrical action



- **Fiber-Film Probes**

  “Hybrid” - film deposited on a thin wire-like quartz rod (fiber) “split fiber-film probes.”



Probe types III

- **X-probes for 2D flows**

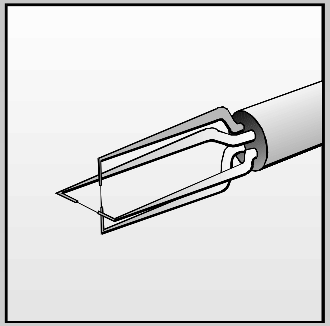
  2 sensors perpendicular to each other. Measures within ±45°.

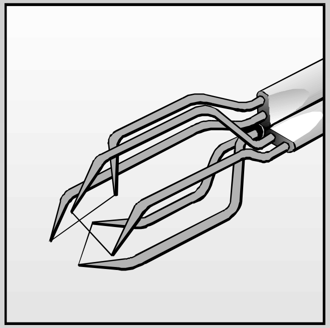
- **Split-fiber probes for 2D flows**

  2 film sensors opposite each other on a quartz cylinder. Measures within ±90°.

- **Tri-axial probes for 3D flows**

  3 sensors in an orthogonal system. Measures within 70° cone.





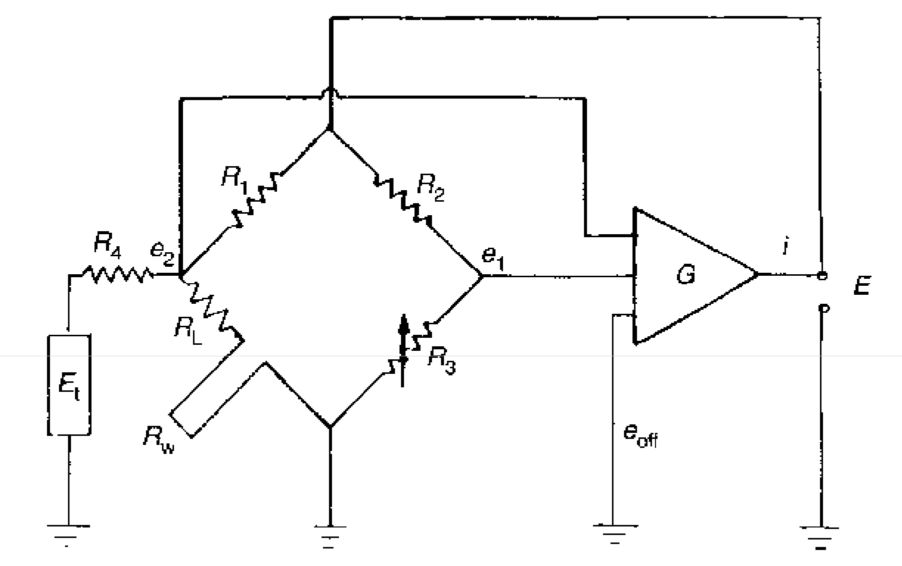
Constant Temperature Anemometer CTA

- **Principle:**

  Sensor resistance is kept constant by servo amplifier

- **Advantages:**
  - Easy to use
  - High frequency response
  - Low noise
  - Accepted standard

- **Disadvantages:**
  - More complex circuit



Velocity calibration (Static cal.)

- Despite extensive work, no universal expression to describe heat transfer from hot wires and films exist.
- For all actual measurements, direct calibration of the anemometer is necessary.

Dynamic calibration

- To calibrate the internal dynamics of the instrumentation (electronics etc.)

Problem Sources
Temperature Variations

- **Fluctuating fluid temperature**

__Heat transfer from the probe is proportional to the temperature difference between fluid and sensor.

$$E^2 = (T_w - T_a)(A + B \cdot U^n)$$

As *Ta* varies:

- heat transfer changes
- fluid properties change

TO BE HANDLED