Optics

Laser optics

Optical applications

LD Physics Leaflets

P5.8.8.4

Laser Doppler anemometry

Objects of the experiment

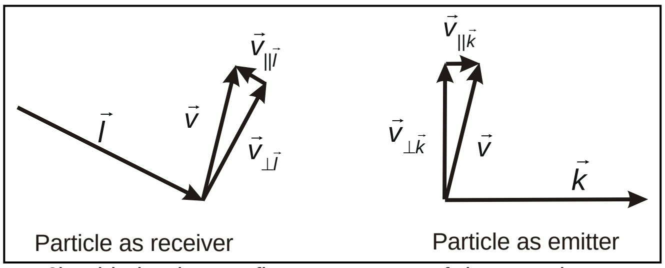
- To detect interference at the intersection of two coherent rays
- To measure the frequency shift for two light rays which are being scattered by moving particles

Principles

Laser Doppler anemometry (LDA for short) is a contact-free, optical measuring method for determining the flow rate of a liquid or gas by determining the velocity of small particles in that flow. If the particles flow through the measuring volume of the LDA they scatter light whose frequency is shifted on account of the Doppler effect. The magnitude of the frequency shift is determined and this is used to calculate the particle velocity and therefore the flow rate.

There are two models for describing laser Doppler anemometry:

a) In the first case the Doppler shift is considered as is experienced by the light from the small particles moving at a velocity $\vec{v}$. For this the particle is first considered as a moving receiver which is illuminated by a stationary source. For the Doppler shift in this case only the speed component in the direction of the light spread $\vec{l}$ makes a contribution (see figure 2). This leads to a first component of the complete Doppler shift of



$$\nu = \nu_0 \left(1 - \frac{\vec{v} \circ \vec{l}}{c \cdot l}\right) \quad \text{for } (v \ll c). \qquad \text{(I)}$$

For the scattered light, the particle then represents a moving emitter and the photo detector a stationary receiver. This leads to a further factor in the Doppler shift. Only the velocity component in the direction that the scattered light spreads $\vec{k}$ contributes to the Doppler shift of this velocity component.

Fig. 1: Diagram showing light scattering by small moving particles

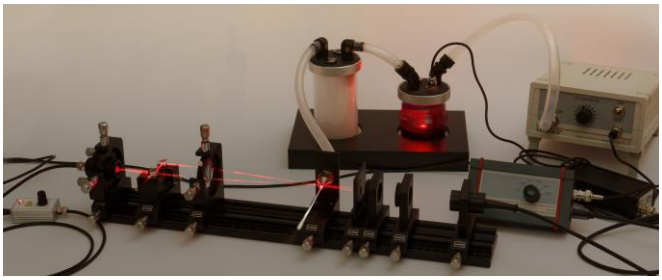


Fig. 2: Experimental setup

$$\nu = \nu_0 \frac{1}{1 - \frac{\vec{v} \circ \vec{k}}{c \cdot k}} \cdot \quad \text{for } (v \ll c). \qquad \text{(II)}$$

The frequency measured at the photo detector determined by both processes is:

$$\nu = \nu_0 \frac{1 - \frac{\vec{v} \circ \vec{l}}{c \cdot l}}{1 - \frac{\vec{v} \circ \vec{k}}{c \cdot k}}. \qquad \text{(III)}$$

In this application the observed frequency shift is very small and is therefore difficult to observe. For this reason methods are used which avoid direct optical frequency measurements.

In the setup for this experiment the laser beam is split into two partial beams of equal intensity which are then superimposed inside the measuring volume (see figure 3). Particles passing through this zone scatter the light from both beams.

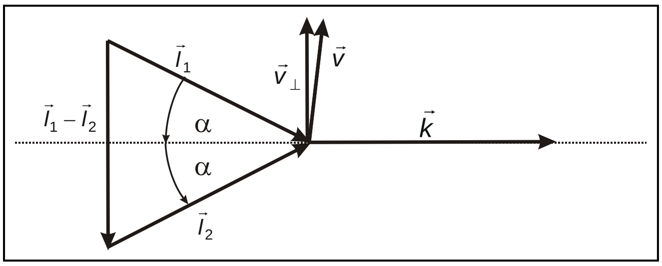


Fig. 3: Scattering with two superimposed light beams

The Doppler shift is in this case different for the two beams because they enter from different directions, but the scattered

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light is observed from the same direction (different vectors $\vec{l}$, identical vector $\vec{k}$, see figure 3).

The difference in the two frequencies, which is generally known as the interference frequency, is in this case called the Doppler frequency and is much smaller than the frequency of the light source, and furthermore it has a much smaller bandwidth. For this reason it is relatively easy to measure it electronically.

The dependency of the Doppler frequency on the velocity of the particles is determined as follows. According to equation (III) the frequency of the scattered light of the two partial beams is given by

$$\nu_1 = \nu_0 \frac{1-\frac{\vec{v}\circ\vec{l}_1}{c\cdot l_1}}{1-\frac{\vec{v}\circ\vec{k}}{c\cdot k}} \text{ and } \nu_2 = \nu_0 \frac{1-\frac{\vec{v}\circ\vec{l}_2}{c\cdot l_2}}{1+\frac{\vec{v}\circ\vec{k}}{c\cdot k}}. \quad \text{(IV)}$$

The difference is then

$$\nu_D = \nu_1 - \nu_2 = \frac{\nu_0}{c\cdot|\vec{l}_1-\vec{l}_2|}\frac{\vec{v}\circ\left(\vec{l}_1-\vec{l}_2\right)}{1-\frac{\vec{v}\circ\vec{k}}{c\cdot k}}. \quad \text{(V)}$$

The vector $\vec{l}_1-\vec{l}_2$ is perpendicular to the median line between the two beam directions (see figure 3); for this reason in this experiment only the speed component $\vec{v}_\perp$ can be determined along this vector. Therefore, in our experiment the glass tube containing the flowing liquid is oriented parallel to this direction. Then, by measuring $\vec{v}_\perp$ the flow rate v is detected directly.

If only the scattering in the direction of the median line between the two beams is considered and only the velocity component $\vec{v}_\perp$, the denominator is $1-\frac{\vec{v}\circ\vec{k}}{c\cdot k}$ = 1. If, in addition, the angle between the two beams is 2α, one obtains:

$$\nu_D = \nu_1 - \nu_2 = \frac{\nu_0}{c}\, v_\perp \cdot 2\sin\alpha = \frac{v_\perp \cdot 2\sin\alpha}{\lambda}. \quad \text{(VI)}$$

In the measurement ν_D is determined, the wavelength of the laser $\lambda = \frac{\upsilon_0}{c}$ is known and the angle between the two beams 2α is determined by the geometric dimensions of the setup. This allows us to determine the velocity component $v_\perp$ of the particle by measuring the Doppler frequency ν_D.

$$v_\perp = \frac{\nu_D \cdot \lambda}{2\sin\alpha} \quad \text{(VII)}$$

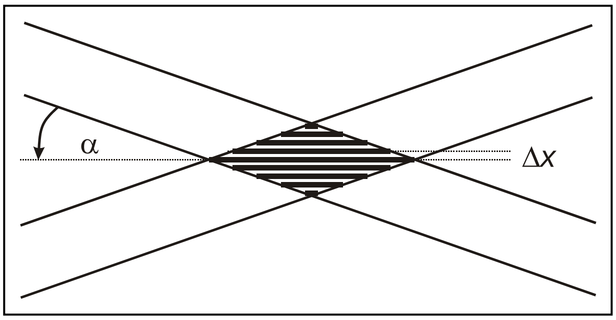

Fig. 4: Interference pattern in the superposition zone of two beams

b) The LDA principle can also be considered as an interference phenomenon. In the zone where the two laser beams cross, an interference pattern forms. If the superposition zone coincides with the foci of the beams, the wave fronts are straight and the zones of constructive and destructive interference are parallel and have a spacing Δx (see figure 4). This spacing depends only on the wavelength λ of the light used and the angle 2α between the two beams:

$$\Delta x = \frac{\lambda}{2\sin\alpha} \quad \text{(VIII)}$$

If a particle moves through this interference pattern, it scatters light in the light areas but not in the dark ones. At the detector therefore a temporal variation in the intensity is measured; the temporal spacing Δt and therefore the frequency ν_D of the variation depends on the distance between the interference strips Δx and the velocity component $v_\perp$ of the particle perpendicular to it:

$$\frac{1}{\Delta t} = \nu_D = \frac{v_\perp}{\Delta x} = \frac{v_\perp \cdot 2\sin\alpha}{\lambda}. \quad \text{(IX)}$$

This equation is identical to equation (VI). Thus when considering it both ways, the same result is obtained for the dependence of the Doppler frequency on the velocity of the moving particles.

<u>Summary</u>

With both ways of considering the phenomenon therefore, the temporal variation of the signal at the photodiode depends only on the wavelength of the laser used, on the angle 2α between the two beams and on the velocity component $v_\perp$ of the particle perpendicular to the median of the two beams. If, therefore, the frequency ν_D of the variation is measured, the velocity component of the particles $v_\perp$ can be determined.

Apparatus

2	Focussing Optics, f = 60 mm	474 104
1	LDA Beam Splitting Assembly	474 187
1	LDA Beam Deflection and Focussing	474 1876
1	Ultrasonic particle seeder	474 188
1	Ultrasonic Particle Nebuliser	474 315
1	Photodetector, Ultrafast with Amplifier	474 331
1	Photodetector signal conditioning box	474 306
1	Oscilloscope, Dual Channel, Digital	474 5464
1	HF-Cable, BNC-BNC, 1.5 m	501 06
1	HF-Cable, BNC-Mini BNC, 1.5 m	501 061
1	Adaptive Power Supply	474 301
1	Diode laser module, 532 nm (green)	474 128
1	Profile rail, 500 mm	474 5442

Safety notes

The laser conforms to class 3B. Class 3B lasers are potentially dangerous if a direct or reflected beam impinges on the unprotected eye (direct view into the beam). As long as the appropriate information in the operating instructions is observed, experimentation with the laser is not dangerous.

- Do not look into the direct or reflected laser beam!
- Wear suitable laser protection goggles.
- Avoid unintended mirror reflections (e.g. from watches, jewellery, tools with metal surfaces etc.)!
- All laser beams should be blocked at the end of the path by diffusely scattering material set up for this purpose.
- Before introducing new optical components into the setup (mirrors, beam splitters, lenses etc.) cover the laser beam or switch it off!
- View diffuse reflexes at a distance of at least 15 cm from the reflecting surface!

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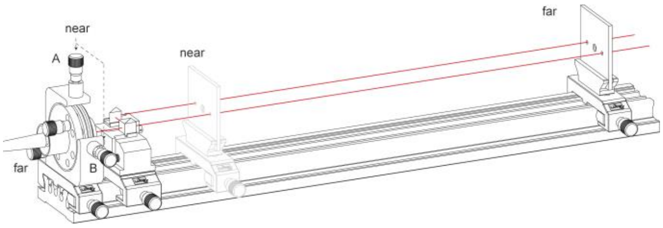
Setup and method

<u>Setup of the optical components</u>

1. Adjust the laser beam to be parallel to the optical bench:

- Attach the laser to the laser holder and attach it to one end of the optical bench. Put the beamsplitter close to the laser, it will be aligned later.
- The laser Diode will be supplied by the 5 V DC USB power supply.



- Adjust the undeflected, straight laser beam to be parallel to the optical bench, but offset by a few mm. The second beam will be adjusted later.:
  a) Attach the iris aperture on the optics rider directly upstream of the laser (“near”) and adjust the laser position to the right hole in the aperture.
  b) Move the iris aperture as far away from the laser as possible (“far”). Tilt the laser beam until it passes through the centre of the aperture.
- Repeat actions a and b until the beam passes through the centre of the aperture in both positions.

Note:

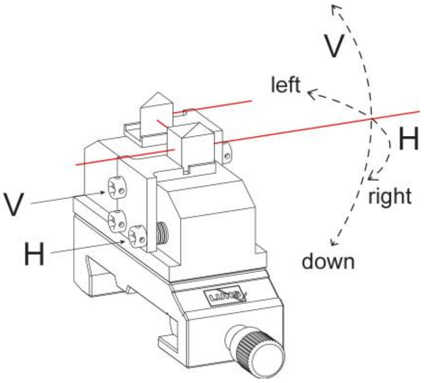
By introducing a new optical element into the path of the beam, uncontrolled reflections can occur which may be dangerous for the observer:

- *Cover the laser beam upstream of the new element or switch off laser.*

Only uncover the path of the beam after the new element has been introduced.

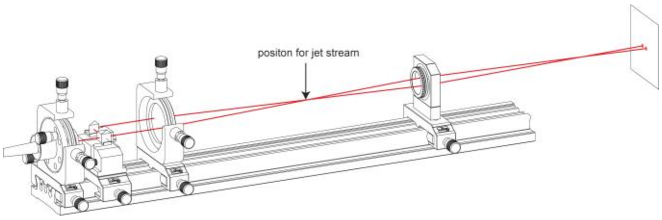
2. Adjust the split beam to be parallel to the optical bench:

- The two glass parts of the beamsplitter assembly create a second laser beam. To make this beam parallel to the first and the bench we align these optical parts.

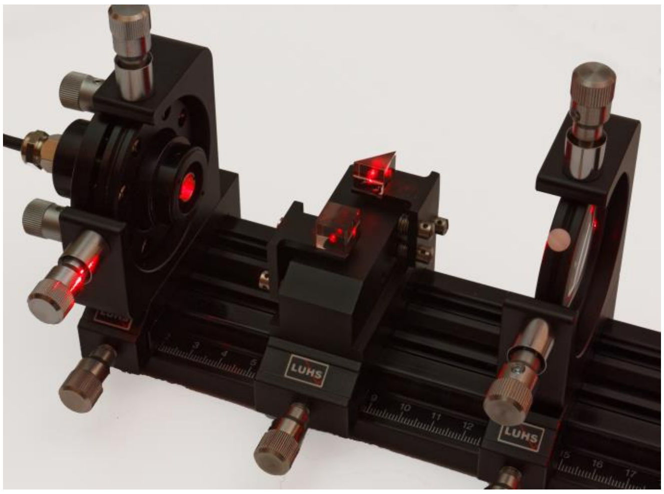


- With the help of the tool provided, the 6 screws can be adjusted in a way that the second beam passes similarly through the aperture in the “near” and “far” positions.
- Both adjustments are interlocked a bit, so it might take several successive adjustements until the laser beam passes throught the iris. Do not spend too much time, we will come back to this adjustment later.
- The undeflected beam cannot be aligned with these screws.

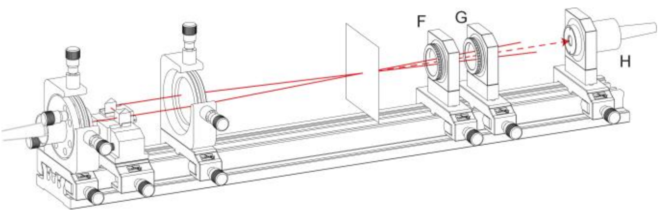
3. Put in the focussing lens



- Place the 150 mm lens on the bench close to the beamsplitter. Both laser beams will be focused to one point in a distance approximately the focal length of 150 mm apart.
- Use one of the 60 mm lenses to create two dots on a distant wall (Take care nobody walks through the beam).
- Move the big lens in XY direction until both rays hit the small lens symmetrically and in the middle
- Re-align the beamsplitter in such a way that both red dots on the wall are at the same height over ground.



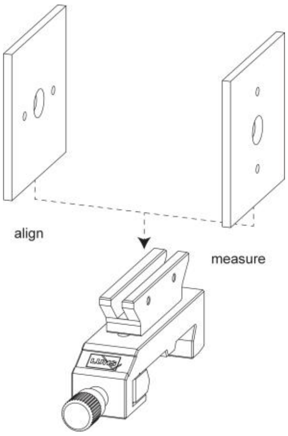
4.Align the Detector with lenses



- Both small lenses F ang G are used to focus the scattering light from the particles onto the detector. Without the aperture, we can use the two laser beams coming from the same point to adjust the position of the lenses.
- Put only lens F on the bench and move it until the two laser beams come out more or less parallel.
- Put lens G on the bench together with the photodetector, with G close to F and position the photodetector at the point where the two laser beams meet on the surface of the photodiode.

5. Assemble beam stop

- Note that the Iris can be used in two different orientations

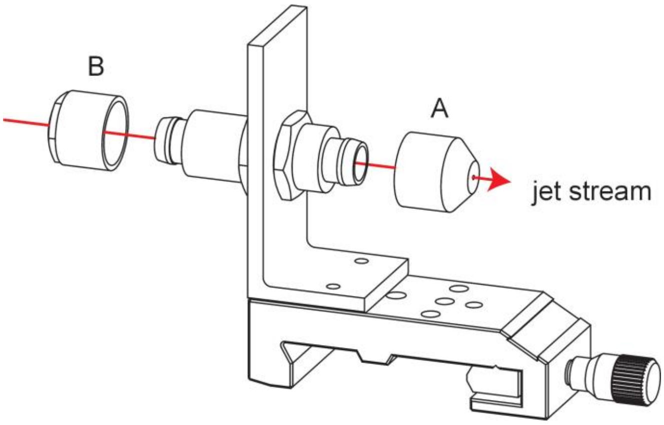


- During alignment, the two holes were horizontally, now we use this as a beam stop for the two laser beams after the scattering point and turn the plate by 90°.
- Place the beam stop in front of lens F

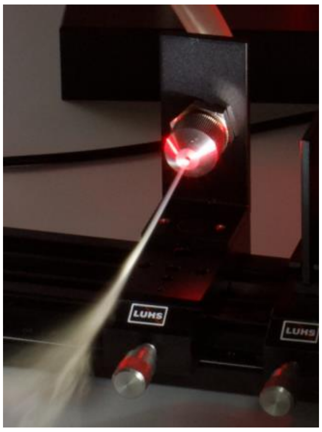
6. Assemble the particle seeder and nozzle.

- We use a stream of water droplets in air as the scattering particles. These are created by an ultrasonic nebulizer.
- Assemble the setup like shown in the photo:

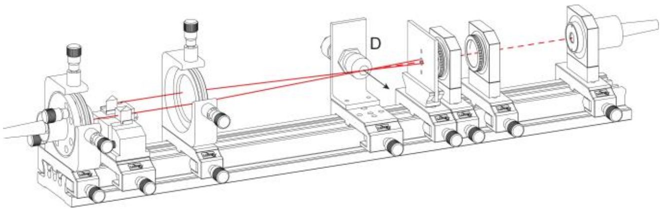
- The white box serves as a supply unit, delivering electrical power to the nebulizer and an adjustable flow of air to the system.
- Two Perspex tubes are mounted onto the base plate, the right one, looking blueish in the photo, contains the nebulizer. This tube has to be filled with distilled water up to a level about 2 cm below the upper cap. Note that the nebulizer has a fluid level sensor. When the water is below the resistor the nebulizer will switch off. Ultrasound waves created inside will force water droplets to emerge from the water surface. These will be taken away by the air stream.
- On the left side of the base plate is a hollow Perspex tube. This one is used to “dry” the mist created by the nebulizer. Large droplets will touch the wall and stay there. Only the smaller droplets will pass through. During the experiment some water will “condense” inside this tube and needs to be removed from time to time.
- The mist is “dry”, because the remaining water droplets are small. Whenever such a droplet touches a surface, surface tension will make it bounce of instead of wetting it.
- A longer tube brings this air stream to the nozzle. There are four different diameter nozzles. The big ones are better for aligning the beam aroung the focus point, the smallest one gives better signals in the end, as the flow is restricted to the laser interference pattern only.



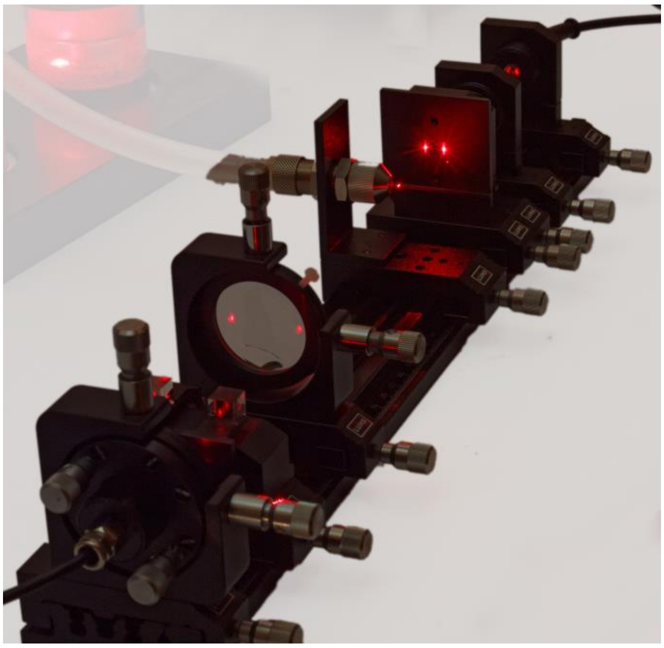
- The tubes are simply plugged onto the connections and secured by a nut. The nozzle is put on the other end without any tube inside.
- Do a test run of the mist generator outside the optics setup. There should be a clearly visible “steam jet” coming out of the nozzle.



- Place the nozzle on the optical bench and align the position



- Both laser beams have to meet inside the steam jet. It can be clearly seen using the largest nozzle if the two beams are separate before or after the focus.



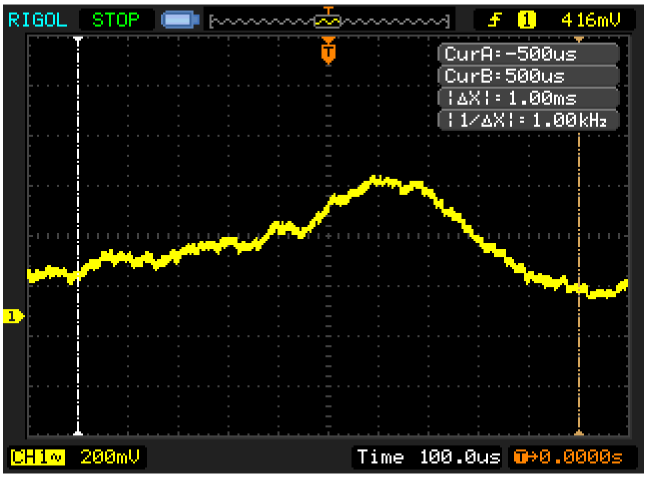
7. Electrical

- Finish the electrical connections by connecting the photo-detector to the 474 306 box and the BNC output to the amplifier box. The 474 306 has a built in battery, which is the most noiseless way of supplying energy. The amplifier is supplied with 5V DC from the same USB power supply that is used to power the laser diode.
- The output can be recorded with an oscilloscope.
- Expecting frequencies from 50 kHz to 200 kHz set the oscilloscope to 50 µs per division or more, depending on the oscilloscopes memory. A Signal amplitude of several 100 mV is to be expected, so we can use a trigger at 50 mV to select only the good events.

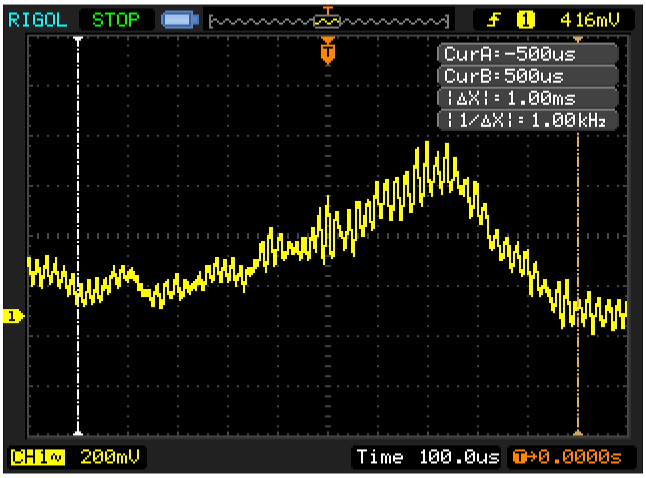
Carrying out the experiment

Although some adjustment of the optical beams has been done it is rather unlikely that both laser beam focus really meet inside the steam jet. Usually, there is a tiny height variation and both laser beams will not cross at all.

A particle moving through one laser beam only will give a slow scattering signal like this:



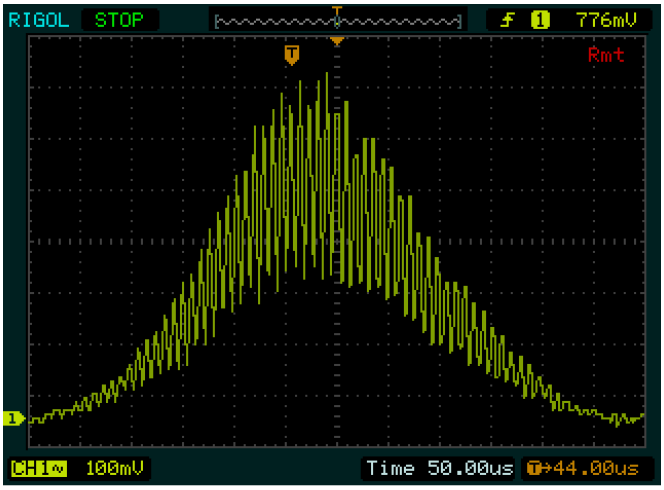
A particle moving through the interference fringes of two correctly crossing laserbeams will additionally show the high frequency modulation of the spatial interference pattern.



- Usually the signals will start without the high frequency features. Slowly align the height (upper screw) of the beam spitter.
- If necessary, redo the initial alignment.

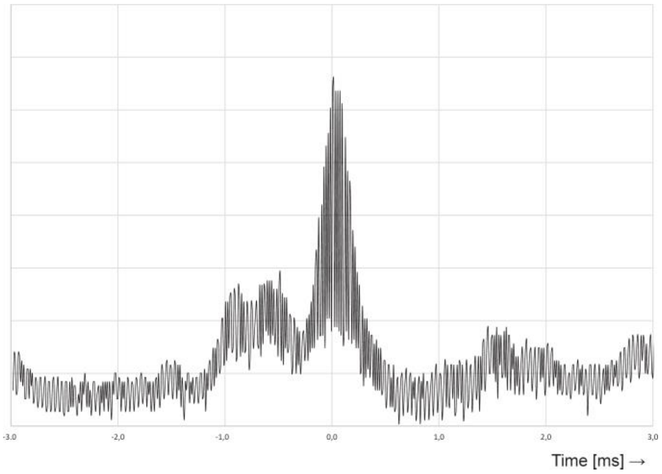
Measuring example and evaluation

A good signal would look like this:

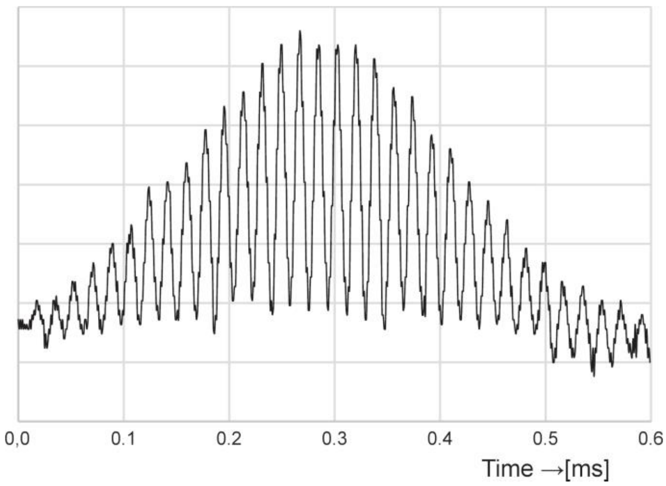


We see a strong scattering signal while the particle passes through the laser beams and there is a fast modulation due to the interference pattern.

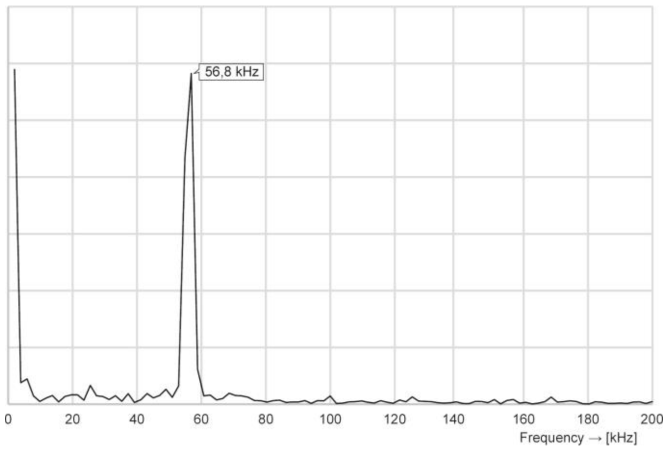
If the particle density is rather high, there might even be an overlapping signal of successive particles.



Zooming in to such a signal will give the sinusoidal modulation:



We can see that there are about 5.5 oscillations in a 100 µs time, corresponding to a frequency of 55 kHz.



A modern oscilloscope is able to calculate the Fourier transform frequency spectrum of the measurement, usually by using a FFT. The result is shown above. The exact frequency is 56.8 kHz in this example.

Of course, faster particles will show a higher frequency, while slower particles will have lower frequencies. Even inside the beam there is some turbulence, so there will be a variation of particle speeds.

Use different settings of air flow and nozzle diameters to show the variations in particle speed.

To calculate the spped of the particles from the frequencies, we need to go back to theory.

Laser wavelength: 630 nm

The angle α is determined by the focal length if the lens and the beam distance. The Iris has two holes located 27 mm apart and the focal length of the lens is 150 mm.

$$\tan\alpha = \frac{d}{2\cdot(f)}$$

α = 5,14°

For a more precise measurement of the angle, remove the detector with the lenses and let both laser beams hit a distant wall. Measure the distance between both spots and the distance to the lens and do some trigonometry.

Equation VII tells us the 56,8 kHz particle had a speed of 0.20 m/s.

This was a rather slow one.