Constructing and Testing of a Picosecond LIDAR system

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Master’s Thesis

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Abstract

Short laser pulses in the picosecond regime can be used as a source in the LIDAR technique to hopefully achieve information of the species locations and concentrations in the investigated area, e.g. a cylinder in a car engine. The first steps towards this approach of the LIDAR technique are presented in this report.

The source of the laser pulses was a mode-locked Nd:YAG laser which could generate pulses of around $30\,\text{ps}$ duration. A streak camera and a detecting system built on a photomultiplier tube were used to collect the information from the short pulses.

The experiments done were focused to seek confirmation that LIDAR method works well in the picosecond regime. The $1/R^2$ relationship is well documented which is predicted by general LIDAR equation. Measurements with different concentration levels in the investigated areas are also presented.

The results show the potential for the LIDAR technique to work well with the picosecond laser pulses. Further experiments and developments must however be made before a total evaluation can be made. Steps toward the DIAL method should be taken to get a well working unit for experiments of scientific value.
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1 Introduction

The LIDAR technique has been used for several decades and is today well used. An area where the method is used is airborne or land surveillance of the atmosphere. It is possible to investigate the location and amount of ozone, which is one of the biggest problems concerning the atmosphere today. For further reading about today’s usage of the LIDAR technique, the homepage of LIDAR research is a good starting point [1].

The source of the LIDAR technique has been laser systems which generate pulses in the nanosecond regime upon today. These systems do not have the spatial resolution that is needed for investigation of smaller areas such as a cylinder in a car engine or a burning flame. Shorter laser pulses are a demand if better spatial resolution should be achieved, e.g. to reach down to a spatial resolution of 1 cm a pulse duration of around 60 ps or lower is needed.

The short laser pulses can be generated by a few different laser systems. It is of course important that the laser intensities are high for the signal-to-noise ratio. The system that is used during the experiment carried out during this work is a Q-switch Nd:YAG laser that uses with both active and passive mode-locking for stability.

By using the Nd:YAG laser a couple of experiments have been done. Measurements on aerosols of water droplets have been done for evaluating the \( 1/R^2 \) relationship that is predicted by the general LIDAR equation. McKenna burners were used to see how well the method responds to concentration variations.

1.1 Objective

This Master Thesis has one primary objective and that is to develop and complement a new picosecond laser technique to study the presence of particles during combustion in real engines or burners. The aim was to combine the Nd:YAG laser, a collecting lens system and the detector into a working unit. This laser-detecting system should allow LIDAR measurement with a resolution of 1 cm. The next step should then be to check how well the LIDAR technique works in the picosecond regime.

A secondary objective was to identify the problems with the setup and possible future problems with the method.

1.2 Overview of presented work

The Master Thesis is presented in a standard way. The second chapter deal with the background and the theory behind the experiment and technique. Chapter three will describe the equipment that was used to perform the experiments. The experimental setup and the result will then be presented in chapter four and discussion of the experimental data will be made in chapter five. In chapter six the conclusions drawn from the result are presented.
2 Background

2.1 Elastic scattering

Even if light is not of a resonant frequency with the atom or molecule, weak scattering affects are still obtained. These scattering processes can be divided into two major categories, elastic- and inelastic scattering. The elastic scattering is the one in which no energy shift takes place regarding the photons. This is mainly the affect that is under study in practically all the experimental setups in this work and so on the only one described a little bit further in the next subchapters.

2.1.1 Rayleigh scattering

The elastic scattering that occurs when the incident light interacts with atoms or small molecules is termed Rayleigh scattering. Small molecules or particles are the ones that can fulfil the Rayleigh criterion; the diameter of the particle divided by the wavelength of the light must be much smaller than one [2].

There are a number of terms that influence the amount of Rayleigh scattering that occurs to the incident light. The wavelength of the light is of importance, $\lambda$, the size and number density of the particles, $d$ and $n$, and the refractive index of them, $m$. The Rayleigh coefficient is then given by:

$$k_s = \frac{2\pi^6}{3}m\left(\frac{m^2 - 1}{m^2 + 1}\right)^2 \frac{d^6}{\lambda^4} \tag{2.1}$$

The angular intensity relationship for Rayleigh scattering is conventionally nearly two lobes. For particles fulfilling the Rayleigh criterion, there is complete symmetry in the probability of scattering with respect to a plane normal to the direction of the incident light. In other words, the forward scattering equals the backward scattering.

2.1.2 Mie scattering

The elastic scattering that occurs from particles, which is considered isotopic spheres, where the Rayleigh criterion is invalid is termed Mie scattering and its cross-section is around ten times larger than for Rayleigh scattering. This theory is much more complex and will not be dealt with further than to say that the angular intensity relationship for Mie scattering is significantly more complex than for Rayleigh scattering. The most probable directions of scattering are of dependence of the size of the particle, with a sharper and more intense forward lobe for larger particles. It can also be mentioned that the Mie scattering does not have the same strong wavelength dependence as Rayleigh scattering has.

2.2 LIDAR technique

LIDAR, stands for Light detection and ranging, is a measurement technique which work as a radar, which until now by far has been used for land-based surveillance of the atmosphere. Pulsed laser radiation, from a laser, is transmitted into the unknown object and the back-scattered light is focused onto the detector by an optical telescope. The time between the transmitted laser pulses until the detection is well determined which makes it possible to calculate the distance to the object with high accuracy. The
principle is illustrated in Fig. 2.1. The back-scattered light comes from a distance $R$ and is detected at a time $t = 2R/c$ after the pulse is transmitted from the laser.

![Figure 2.1: A view over how a Lidar-setup could be applied in a cylinder of an engine.](image)

The best range resolution is given by $\Delta R = t_s c/2$ where the limiting time is either set by the response time of the detector or the duration of the laser pulses. This spatial resolution is not of great importance when studies are made on the atmosphere but is instead one of the major concerns if the measurement is carried out e.g. inside a combustion engine.

The equation of the intensity received of the lidar signal is given by the general lidar equation [3]:

$$P(R, \Delta R) = C \cdot W \cdot N_b(R) \cdot \sigma_b \frac{\Delta R}{R^2} \exp\left(-2 \int_0^R \left[\sigma(\nu) N(r) + K_{ext}(r)\right] dr\right)$$

(2.2)

The parameters of the equation are; $C$ is a system constant, $W$ is the transmitted pulse energy and $N_b(R)$ is the number density of scattering object with back-scattering cross-section $\sigma_b$. The exponential factor describes the attenuation of the laser beam and the back-scattered radiation due to the presence of absorbing molecules of concentration $N(r)$ and absorption cross-section $\sigma(\nu)$, and due to attenuating particles with wavelength-independent extinction coefficient $K_{ext}$. The factor 2 comes from the fact that the light travels both to the object and back.

The general lidar equation has a lot of parameters that are difficult to measure or estimate, which is why it is hard to make concentration measurements. There is a way to get around this problem by recording two lidar curves, and this method is called DIAL (Differential Absorption Lidar). The two curves mentioned above correspond to two recordings performed at slightly different laser frequencies. One of the frequencies is in resonance with an absorption line of the species under investigation and the other one is situated off resonance. Because the two frequencies are closely separated, all the parameters of the general lidar equation are the same except the absorption cross-sections. By dividing the two curves with each other, all the parameters that were difficult to estimate are cancelled out. One of the curves, the non-absorbing, will have an $1/R^2$ intensity fall off and the other one will have intensity reductions where the specie is present, illustrated in Fig. 2.2.a-b. This approach gives a situation with higher signal-to-noise ratio which is clarified in
equation 2.3, where $v_{on}$ is the laser frequency on resonance and $v_{off}$ is the frequency off resonance.

$$\frac{P(v_{on}, R)}{P(v_{off}, R)} = \exp\left(-2\left[\sigma(v_{on}) - \sigma(v_{off})\right] \int_{0}^{R} N(r)dr\right)$$

(2.3)

It is also of interest that this technique gets rid of background effects, since both curves will behave in the same way and the effect will be cancelled out. Equation 2.3 gives the quotient between the two recordings but it is the concentration of the investigated substance, $N(r)$, which is of interest. It is possible to reach this wanted result from equation 2.3, which yields:

$$\frac{d}{dr} \left[ \frac{1}{2} \ln \left( \frac{P(v_{on}, R)}{P(v_{off}, R)} \right) \right]_{0}^{R} = N(r)$$

(1.4)

When the above formula is implemented on the two recordings a final result is received which could look like Fig. 2.2.c.

**Figure 2.2a-c:** The different steps that are taken to get the wanted concentration of the substance in the DIAL method. (a) is the different received signal from the two recordings, (b) is the quotient between the two, (c) is a diagram where the concentration is plotted as a function of the distance.
3 Equipment

3.1 Laser system

A Nd:YAG laser system, which is a four-level solid state laser, was used for experiments throughout this work. Generation of short pulses of about 30 ps pulse duration could be reached by mode-locking, both passive and active. The laser active material, which in this system is pumped by flash lamps, is Neodymium ions (Nd\(^{3+}\)) that are accommodated in a transparent host crystal rod made of yttrium-aluminium-garnet (YAG). From this laser medium a few lasing transitions can be achieved, but the superior most commonly used is the one at 1064 nm.

The ability to generate short pulses is thanks to the mode-locking mechanism. Without this frequency-selective medium in the laser cavity the laser would oscillate simultaneously on the resonator modes within the spectral gain profile. In this state the phases between the oscillating modes will be random which give a laser output equal the sum of the different mode intensities. If instead a coupling between the different oscillating modes can be achieved, a coherent state of the modes amplitude will give intensity of much greater magnitude. Since no more energy is involved, the shape of the peak must be narrowed and the short pulse laser is established.

3.1.1 Active and Passive mode-locking

Active mode-locking is obtained by modulating the gain or losses in the cavity so that it matches the mode separation. This can be done by different methods such as using a Bragg cell or by acusto-optic phenomena. The laser in use had an acousto-optic modulator, AOM, which sends out longitudinal waves through a piezoelectric crystal into the medium. The propagating acoustic wave in the medium, changes the refractive index. These changes can affect the oscillating waves in the cavity in such a way that they are deflected or undeflected. The losses in the cavity are of course then greatly shifting, which is controlled by the electric field applied to the piezoelectric crystal.

Passive mode-locking can be obtained using a saturable absorber. The saturable absorber is usually a dye cuvette with a dye solution of very low concentration. Due to the low concentration, the absorption is easily saturated for high laser intensities. In this regime the absorption has a non-linear dependence on laser intensities. This means that the oscillating modes with the highest power suffer the lowest absorption while the highest absorption is experienced by the modes with the lowest powers. Only the modes with the strongest peak power will survive after a few roundtrips. The non-linear interaction between the absorber and the photons will lead to a mode-locked laser without any other influence. The modes will be locked and separated in time by \(2d/c\), where \(d\) is the effective cavity length and \(c\) the speed of light \([4]\). A very important factor of the absorber is its relaxation time, the time it takes for the absorber, after letting a strong mode pass, until it absorbs with full magnitude again. It is this parameter that will mostly determine the width of the pulses. The absorber must have a relaxation time that is short compared to the roundtrip time for the modes, otherwise there will be a failure in suppressing the weaker modes.

3.1.2 The laser components

The laser in use had both the active and passive mode-locking implemented. These parts of the laser are marked 2 and 1 in the schematic view of the laser components in Fig 3.1. The saturable absorber is directly connected to one of the end mirrors. In this way the oscillating waves has to travel through a dye cuvette that appears to be twice its actual size, which makes it harder for low powered modes to pass through.
Part 3 is a prism arrangement that can make fine adjustments of the cavity length depending on the incoming angle of the wave. The last marked component, part 4, in the cavity is the arrangement of the crystal rod between two flash lamps. From the cavity a pulse train of around eighteen peaks is sent out, can be seen in Fig. 5.1, with a repetition rate closely to 10 Hz. This pulse train then reaches the Q-switch system, part 5, which actually is two polarisers and the Q-switch. First of all the pulse train travels through one polariser, which makes sure every peak has the same polarisation. Then the pulse train enters the Q-switch which triggers on one of the first peaks. The Q-switch then shifts the polarisation of one of the peaks, ideally the same all the time, so that only this peak can pass the last polariser.

When passed through the Q-switch the only surviving part of the pulse train is one peak. This peak carry on to the amplification stage and further on to the doubling or tripling crystal.

3.2 Streak Camera

A streak camera is a detector for measurements of very fast optical transients. It can be used for time resolved measurements down in the picosecond regime. With such a camera it is now days also possible to reach even further, time resolution in the regime of femtoseconds can be achieved [4]. The temporal resolution is achieved by deflection of an electron beam, which to some extent is comparable to how an oscilloscope works.

![Figure 3.1: A schematic view over the laser; 1-Passive mode-locker, 2- AOM for active mode-locking, 3- Prisms for fine adjustment of the cavity length, 4-Pumping arrangement, 5-The Q-switch setup, 6-To amplifier stage.](image)

![Figure 3.2: A schematic design of a streak camera system, where the main parts is pointed out.](image)
The design of a streak camera system is schematically illustrated in Fig. 3.2. Photoelectrons are produced when an optical pulse is imaged onto the photo cathode. These electrons are focused and accelerated towards the anode. Then they are further accelerated and can travel through an amplification stage before they hit the phosphor screen, where an image appears. This image is focused by the lens onto the CCD-chip which sends a digital signal to a data acquisition system, e.g. a computer. When no voltage is applied to the deflection plates, the streak camera is operated in focus mode. This mode will give a replica on the phosphor screen of the object that is imaged onto the photo cathode. If instead a voltage is applied to the deflecting plates, the focus point on the phosphor screen will be shifted sideways. Utilization of the voltage will result in a temporal axis on the phosphor screen. This is done by allowing the voltage profile to follow a rapidly increasing ramp. The focus point of the electrons will then move across the phosphor screen, which implies that the position of the image reflects the time the photons from the object impinged on the photo cathode. The total sweep over the phosphor screen could be over in tens of picoseconds which mean that it would be rather few photons reaching the CCD-chips. This poor situation for signal to noise is improved since the image will remain long after the sweep is over on the phosphor screen. This advantage is reached because of phosphorus rather long decay time [6].

**Figure 3.3a-c**: Streak camera modes. (a) With no applied voltage there will be no temporal information. (b) Temporal information is achieved with the voltage ramp applied. (c) Temporal and spatial information blurred into the same picture.

The difference between the focus mode and the streak mode is depicted in Fig. 3.3. Both operating modes are represented here. In the first part, Fig 3.3a, there is no applied voltage onto the deflecting plates and the two pulses which differ in time but not in one spatial dimension will only be separated by the y-axis. When the voltage ramp is applied the x-axis will be better represented as the time-axis, which will give a result somewhat like Fig 2.3b. An image that has an extension in the horizontal dimension, x-axis, will have its spatial information mixed with the temporal information. The result is an image on the phosphor screen that is blurred. This is what is illustrated in Fig 3.3c.
The speed of the sweep, the time scale, is controlled by the slope of the voltage ramp. Changing time scale will also change the appearance of the result. If the same pulses are viewed with a faster sweep, the pulses will be enlarged as is seen in Fig 3.3c.

3.3 PMT and an oscilloscope

The use of a photomultiplier tube (PMT) can also be used for detection in the picosecond regime. As in the streak camera, the PMT has also a photosensitive cathode where the photons impinge on. The design of one type of PMT is shown in Fig. 3.4.

![Figure 3.4: A typical design of a photomultiplier tube.](image)

When the photon hit the photo cathode a burst of electrons are ejected into the vacuum tube. The emitted electrons then accelerate towards the anode, but they collide with a high number of dynodes before they reach the anode. The dynodes eject several secondary electrons for each electron that hits their surface. These secondary electrons and the primary ones are then directed towards the next dynode. In this way an amplification corresponding to $10^7$ is normally achieved. A PMT is therefore a highly sensitive detector, which can even detect single photons, so called photon counting.

A comparison between the streak camera and the PMT will be made here regarding their properties that are of importance in a LIDAR-measurement. The PMT system has the advantage of being much more movable and easier to handle. Another advantage is that there is no problem with the trigger signal. The oscilloscope will trigger on the incoming signal and no delay line or delay box has to be introduced. It is also possible to detect much weaker signals.

On the other hand there is a huge disadvantage in the lower spatial resolution, since there is a rise- and fall of time on the order of at least 100 ps for PMT:s. This means that the PMT has not the ability to resolve photons that comes from places that lies around 5 cm from each other. The rise time depends mainly on the so called transit-time spread. The transit-time is the time elapsed from the ejection of an electron from the cathode until it impinges on the anode and the spread is then the difference between the first and the last electron in the cascade. This spread is caused by i.e. variations in the voltage between the dynodes and from which point the electron is ejected from the cathode.
4 Experimental setups and Results

The task was to verify that the Lidar-technique works with laser pulses in the picosecond regime and to determine the possible problems. To accomplish this, a few different setups were used. These setups are explained each and one in the following chapters. It can already be pointed out here that the single most destructive problem in all the experiments carried out was the unwanted back scattered light, such as from walls, mirrors and bright surfaces.

4.1 The streak camera setup

The first couple of setups were used to merely get good knowledge and a touch for the streak camera. Two such experiments were carried out; one in which the laser pulses was separated by a beam splitter and travelled different distances towards the streak camera, and one where the lifetime of Rhodamine 590 was studied.

The experiment with the beam splitter, where the laser pulses were divided into two directions, was setup to simulate how a future experiment with the lidar technique could represent back scattered light from two objects. The delay line, which was constructed as a rectangle with mirrors in each corner, was estimated to $76 \text{ cm}$ by a tape measure. The calibration of the transformation between pixels from the CCD-camera to a time scale was first of all carried out. By taking a picture of a ruler placed at the phosphor screen a pixel to $\text{mm}$ conversion factor could be obtained. Then the operator manual for the steak camera suggested a transformation factors between distances and time for different sweep speeds. The final result of the measurement is shown in Fig 4.1, it is an acquisition of 150 accumulated sweeps.

![Figure 4.1: A picture taken by the CCD-camera of the phosphor screen for two laser pulses arriving at different times.](image)

The time difference between the two pulses was measured to 2.3 $\text{ns}$, which corresponds to a path difference of 69 $\text{cm}$. This divergence between the two results of the path difference will be comment in chapter 5.1.1.

Instead of using the delay line, to check the possibilities of the steak camera, a cell of Rhodamine 590 was placed in the propagation direction of the beam. This cell was placed at a straight line from the photo cathode of the streak camera. A lens that focused and collected the fluorescence was positioned between the streak camera and the cell. It was of great importance where the lens was positioned to get a good result. A slight change in position could mean an almost uniform signal all over the phosphor screen, which does not give any valuable information of the depicted object. Another
problem was to find a sweep speed that suited the life time of the fluorescence well, since no delay box for the trigger pulse was at available. This problem will be discussed later. The result of this measurement is presented in Fig. 4.2 and is again an acquisition over 150 accumulated sweeps.

Figure 4.2: A life time measurement of the fluorescence of Rh 590, the upper picture is the picture from the CCD-camera and the lower one is a intensity calculation of each column made in MatLab.

The lifetime of Rh 590 cannot be extracted without problems since it is measured at the point where the intensity has fallen off to 1/e. This point isn’t represented in Fig 4.2 since the time interval didn’t cover this part. An extrapolation of the decay can however be made and this is done in Fig 4.3. The green line represents the extrapolation and gives a hint of the decay beyond the recorded image. The measured lifetime is about 3.6 ns through this approximation. Another method, the sFLIM system, has measured the lifetime of Rh 590 to be around 4.1 ns [7].

Figure 4.3: An extrapolation of the fluorescence decay to achieve a value of the lifetime for Rh 590.
4.2 The photomultiplier tube setup

Since there unfortunately became a major electronically failure in the streak camera after the first couple of weeks, the detecting apparatus had to be switched. Instead of the streak camera, a detecting system based on a PMT was chosen. The PMT\(^1\) had according to the manual a rise time of 199 ps and a slower fall off time about 800 ps. Two different oscilloscopes\(^2\) were used to accumulate the data. The main difference between them was the bandwidth; one had a bandwidth of 500 MHz and the other one of 3 GHz. This means that the laser pulse width no longer set the limit for the spatial resolution, but it was instead the PMT. Peaks that was separated by 250 ps or more could be resolved, which corresponds to a distance of about 37 mm.

To be able to get a good acquisition of the back scattered light a few different telescope system can be used such as a Newton’s or a Cassegrain telescope. The one used during all the experiments carried out, is kind of similar to the Cassegrain telescope. The setup is illustrated in Fig 4.4. The lens, that was collecting the back scattered light, was placed so that its focus agrees with the detecting area of the PMT.

\[ \text{diameter of the collecting lens, } d: 100 \text{ mm} \]
\[ \text{distance to the object, } r: 1500 \text{ mm} \]

\[ \frac{d^2 \cdot \pi}{4 \cdot 4 \pi \cdot r^2} = \frac{d^2}{16 \cdot r^2} \approx 0.0003 \]

It is a very small fragment of the scattered light that is processed for evaluation but nonetheless the signal was strong enough. As described in chapter 2.1 the scattering from particles has not always an isotropic angular distribution, which means that the

---

\(^1\) Hamamatsu MCP PMT R1564U
\(^2\) Tektronix TDS 620 and LeCroy Wavemaster 8300
above calculation is not correct from that point of view but it gives an idea about the collecting efficiency.

4.2.1 Standard deviation of the fluctuations

The first line of experiments was more of a verification and optimisation of the setup. As shown in Fig. 4.4 the laser pulses were directed out towards the measuring area by a small mirror. An unwanted signal from this mirror was recorded by the PMT, even though a lot of work was done to suppress this signal it did have some advantages; first of all these peaks marked the zero point of the distance measurements and second they were used to make a standard deviation of the laser pulse fluctuations in energy.

The first experiment was to measure the standard deviation of the fluctuation of the laser pulse energies. It was not only the fluctuations of the laser energies that were measured but also the fluctuations of an aerosol, which was produced by a device that sprays out droplets of the liquid that it is filled with. These two measurements were made by the LeCroy oscilloscope. This oscilloscope was integrated into a computer which included a large range of options. However it was a little bit tricky to extract the wanted information since the oscilloscope did not have the desired function for standard deviation. Instead the peak value was recorded for 5000 shots and they were then evaluated in MatLab by the following formula:

\[
S = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (I_i - \bar{I})^2}
\]  
(4.1)

where \(N\) is the number of shots, \(I_i\) is the intensity of every shot and \(\bar{I}\) the mean value of the intensity.

The above described path to evaluate the standard deviation was repeated a number of times with different magnitude of the laser pulse energy and the results are listed in Table 4.1.

<table>
<thead>
<tr>
<th>(S_L)</th>
<th>(S_A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.121</td>
<td>0.247</td>
</tr>
<tr>
<td>0.131</td>
<td>0.256</td>
</tr>
<tr>
<td>0.124</td>
<td>0.246</td>
</tr>
<tr>
<td>0.118</td>
<td>0.254</td>
</tr>
</tbody>
</table>

Table 4.1: The standard deviation divided by the peak power for the laser fluctuation \((S_L)\) and for the aerosol \((S_A)\).

As can be seen in Table 4.1 the standard deviation relative to the peak power is of the order of 12% for the laser fluctuations only and around 25% for the aerosol for a single shot measurement. The percentage for the aerosol is a combination of both the laser fluctuations and the fluctuation of the flow stream of droplets.

4.2.2 Investigation of water drops aerosols

After the standard deviation experiments a focus was put into the devices that produced aerosols, which were filled with water throughout the whole time. The main feature was to get an acknowledgment that the \(1/R^2\) relationship was valid, which is a proof that the lidar technique in principle works even in the picosecond regime. The tests that were carried out were fairly straight forward and no larger setup problems were encountered.
An easy way to verify the above assumption is to place two aerosols in the laser propagation direction separated merely in one spatial dimension, illustrated in Fig 4.5. The result is an average of 2500 laser pulses, and it can be seen in Fig 4.6. Diagram a provides information of how the time elapsed after that the pulses left the out coupling mirror until they were recorded. Diagram b is giving the information of the distance of the objects relative to the out coupling mirror. According to the location of the peaks the distance to the aerosols should be 120 cm and 253 cm. The same spaces between the objects were estimated with a tape measure to 119 cm and 252 cm.

![Figure 4.5: The experimental setup for measurements of two aerosols.](image)

![Figure 4.6: The blue curve in both diagrams, intensity as a function of time and intensity as a function of distance, corresponds to the back scattered signal from the two aerosols and the red line corresponds to the fitted $1/R^2$ curve.](image)

Instead of using two fixed positions of the devices that produced the aerosols, one of them can be moved around in the laser pulses’ propagation direction. This was done as the next step for five different positions, which all can be presented in the same
The distances that the peaks were placed at in the diagram were the ones that were measured with a tape measure (98, 111, 123, 138, 163 cm) and the result can be seen in Fig 4.7. A function given by \( const \cdot 1/R^2 \), the red line, was also fitted to the peaks in Fig 4.7. As can be seen the fitted curve is in close agreement with the experimental peaks.

\[
\text{Figure 4.7: The blue curves correspond to the back scattered signal from the aerosol placed at different distances from the out coupling mirror and the red line corresponds to the fitted } 1/R^2 \text{ curve.}
\]

In order for the LIDAR-technique to be applicable in turbulent media it is an absolute necessity that the method can be used for single-shot measurements. Therefore a set of single-shot data was recorded. This was done by using two aerosol devices and again evaluates the \( 1/R^2 \) dependence. The unwanted back-scattered signal from the out-coupling mirror has been edited away to retouch the peaks that are of importance. These unwanted signals were still used to normalise the peaks from the aerosols, so that the laser fluctuations have no affect on the final result. The single-shot measurement is compared to the standard deviation to see how well it is applicable. The standard deviation relative the intensity for the aerosol in table 4.1 is a combination of both the laser and the flow, but since they are uncorrelated it is possible to calculate \( S_f \) according to formula 4.2 [8]. In this way a value of 22\% is given for \( S_f \).

\[
S_f = \sqrt{S_L - S_A}
\]

The result of these measurements can be seen in supplement 1, where four single-shot images are shown. The red line is the same as the one drawn in Fig 3.6. The green lines represent the standard deviations which are centred at the red \( 1/R^2 \) relation curve.
4.2.3 Soot particles measurements

In this line of experiments, water cooled McKenna burners were used instead of the aerosols. A stabilising stainless-steel plug was placed approximately 20 mm above the burner in order to stabilise the flame. It is of importance that the fuel and oxidant is premixed to get a laminar flame. The fuel that was used was ethylene, C₂H₄, which was premixed with air. In order to generate a sooty flame, which is desired here because it leads to a strong signal from elastic scattering, the flame was made fuel-rich. The fuel-air equivalence ratio was set to 2.7. With this setup it was possible to make a somewhat qualitative concentration measurement, since the amount of soot is dependent on the equivalence ratio. To improve the signal to noise ratio a filter, which only was transparent at a small region around 532 nm, was put in front of the PMT. The background radiation due to chemi-luminescence was then significantly suppressed.

The soot formation is directly connected to the equivalence ratio as pointed out above. This can be used to verify that the signal is dependent of the amount of soot in the flame. The result of six separate accumulated series of measurements where the equivalence ratio is changed from approximately 2.55 to 2.95 is shown in Fig. 4.8. There is a slightly difference between the points that are marked with an x and the ones marked with an o, which is a 2 mm displacement in the flame. The points marked with an x are those who respond to the laser pulses that were focused through the centre of the flame.

Axelsson, Collin and Bengtsson have reported results from measurements of soot volume fraction in fuel-rich premixed ethylene-air flames [9]. These results show that the soot concentration increases with increasing height above the burner. Now, this knowledge can be used to verify that the LIDAR-signals are proportional to the soot concentration. The results of three series of measurements are shown in Fig. 4.9. The equivalence ratio was set to 2.7 during the collection of data. This ratio gave rather
stable values during the measurement of the intensity as a function of the equivalence ratio, as can be seen in Fig. 4.8.

A second McKenna burner was introduced in line with the laser pulses to demonstrate the difference between laminar and turbulent flame. The ethylene that was sent into the burner was not premixed with air, which when burnt can symbolise a turbulent state. A number of single-shot measurements for the back-scattered light from these two burners were made which were normalised to the signal from the out-coupling mirror as was described for the single-shot measurements with the aerosols, chap. 4.2.2. The values collected from these measurements were then normalised to 1. The result can be seen in Fig. 4.10, where the red o-marks represent the values for the laminar flame and the x-marks represent the values for the turbulent flame.

Figure 4.9: The intensity of backscattered light for different heights above the burner.

Figure 4.10: Single-shot measurements which are normalised to 1. The red o-marks and the blue x-marks represent the laminar- and the turbulent flame.
5 Discussion

This section will be divided into two main parts to summarise the conclusions that have been drawn from the work that has been made. First of all an evaluation of the results will be done and secondly a discussion will be made for future developments in order to get a good foundation for this laser diagnostic method.

5.1 Evaluation of the results

5.1.1 The streak Camera
To start off with the results from the streak camera it can be seen that the agreement in terms of the delay time between the measured and the calculated value is not that great. The biggest source of error in this measurement did probably come from the transformation factor from mm to ps at the phosphors screen of the streak camera. The value that was used came from the operator manual. Unfortunately there was no time given to investigate this conversion factor further because of the electronically failure. It should be taken under consideration to have a reference signal guided into the streak camera in the future. This reference signal should have been modulated in such a way that it is a pulse train with very well defined time separation between the peaks. This arrangement would then lead to a well calibrated time scale of the streak camera.

When measuring the lifetime of Rhodamine 590 it became clear that a variable delay of the trigger signal would make the system much more flexible. The problem lay in different internal delay times of the streak camera between different sweep speeds. The approach that was used during these experiments was to use coaxial cables of different lengths. Because of a limited set of coaxial cables it was impossible to achieve the optimum delays for the different sweep speeds. The sweep speeds used were therefore determined by weather a match with the coaxial cable could be reached.

The measured lifetime of Rhodamine 590 did not perfectly match the tabulated value. However the discrepancy could be due to the same reason as discussed above for the two pulses. Since the same time scale or sweep speed was used it is possible to make a new time scale from backwards calculations. This is done in the following way:

\[ \tau_c \]

The correct lifetime: \( \tau_c \)

\[ \tau_m \]

The measured lifetime: \( \tau_m \)

The time scale should then be \( \frac{4.1}{3.6} \approx 1.14 \) times greater.

The path difference should then be: \( 2.3 \cdot 1.14 \cdot 30 \text{ cm} \approx 78 \text{ cm} \)

The value that was gotten from the tape measure was 76 cm, which agrees to a higher degree with the new time scale. This indicates that the problem with the deviating results lies in the transformation factor.
5.1.2 The aerosols

The standard deviation evaluation showed that the value for the fluctuation of the laser intensity is in the order of 12 percent of the peak intensity. A part of this fluctuation is believed to arise from the fact that the Q-switch did not choose the same peak out of the pulse train all the time. The chosen peak was most often either the central peak or the one that came directly after. In Fig. 5.1 an accusation is made for a number of pulse trains and the difference in power between the two peaks under investigation is around 10%.

![Image](image.png)

Figure 5.1: The pulse train before it enters the Q-switch. The y-axis is relative intensity.

The fluctuation of the laser pulses will be reduced if the Q-switch would have higher satiability in selecting one peak.

The investigation of the $1/R^2$ relationship with aerosols gave promising results. There are some slight differences between the two experimental results when looking at the agreement with the $1/R^2$ relationship. The agreement seems to less good for the case where two aerosols were used compared to the one where one aerosol was placed at five different places. This difference can arise from the fact that the two aerosols did not have exactly the same amount of water in them which affects the flux of droplets sprayed out. Also the flow of air was probably not exactly the same for the two aerosols.

5.1.3 The McKenna burner

The first task done, the result presented in Fig. 4.8, showed a decrease in the signal for the series of measurements done with a slight sidewise displacement and that the signal increase with the equivalence ratio. This can be explained by the following arguments. The scattering of the photons is mainly due to the soot particles and they are produced by the unburnt fuel. The amount of unburnt fuel increases with higher equivalence ratio, which is also the result of our measurements. The decrease of the signal when the laser pulses are moved sideways is also due to the amount of soot particles, since they are produce in the centre of the flame. A sidewise movement will then investigate an area with fewer soot particles than the central area.

The second experiment, with the measurement points at different heights above the burner will be compared to the similar diagrams found in the article presenting the work done with laser-induced incandescence [9]. Our results match the results
achieved by the LII method rather well. However, the slope of the curves disagrees at higher positions in the flame (from 13 mm height above the burner and above). The slope seems to be decreasing more for our results than for the LII method. A reason for this can be the size of the soot particles. The spatial distribution of the soot particles and the average size of them are of interest. The average size of the particles is growing with the height above the burner [10]. The particles are no longer much smaller than the wavelength which implies that Mie scattering is also included in the calculation of the total amount of back scattered light. Since the spatial distribution of Mie scattering is not homogenous in all direction the affect is hard to predict. It can be so that the scattered light is focused more into the forward direction which means that the recorded signal would be smaller and that could be the explanation for the declining of the slope for the lidar-method.

5.2 The future

5.2.1 Development areas
There are a few areas that need more work for the lidar-technique to really work well in the picoseconds regime.

First of all, the problem with unwanted back scattered stray light from different objects must be solved. The best way to do this is by having a gated detector that is only open during the time when the scattered light from the investigated area is received. If this is not possible there is a solution to the disturbing signal from the out coupling mirror. If the beam path, exactly before and after the out coupling mirror, is welded in black paper there will probably not be any problems. This will of cause also reduce the signal from the investigation area since the beam pipe will block parts of the collecting mirror. This solution is therefore depending on that the signal is strong enough for a reasonable signal-to-noise ratio.

Another area is to achieve a tunable laser frequency, which would make DIAL-method available, see section 2.2. This is merely a problem of getting the DFTL-laser up and running.

The third area and probably the one that needs most work, is to get a working base for the system to handle scanning functions. The out coupling mirror should be able to direct the light towards different directions by remote control, e.g. a computer. Unfortunately this also implies that the collecting mirror has to be changed in the same way so it is in direct line with the outgoing pulses. A detector system, e.g. a streak camera, is ungainly to move and it will therefore probably be fixed. This implies another lens or a mirror has to be introduced to direct the signal into the detector system.

5.2.2 Remarks
A detector system, preferable a streak camera, of high quality will be needed. It is mostly the dynamic range that is of importance for the choice of streak camera, since most of them have good temporal and spatial resolution. The dynamic range is of importance since the scattered light can be of rather strong magnitude and rather weak.

Another remark concerns the laser system. It is of course good for the spatial resolution to have as short laser pulses as possible but from a laser line width point of view this is devastating. If the DIAL-method is used it is important to have a narrow banded laser because of the demand to be on and off the absorption line. The
bandwidth of the laser is in the end limited by the Heisenberg uncertainty principle if all other affects to the bandwidth is suppressed. The Heisenberg uncertainty principle for Gaussian profiles is given by:

\[ \Delta f_p \cdot \tau_p \geq \frac{2 \cdot \ln 2}{\pi} \sqrt{1 + \left( \frac{b}{a} \right)^2} \approx 0.44 \sqrt{1 + \left( \frac{b}{a} \right)^2} \]

\[ \Delta f_p \cdot \tau_p \geq 0.44 \Rightarrow \Delta f_p \geq \frac{0.44}{\tau_p} \quad \text{when } b = 0 \]

\[ \Delta f_p \approx 15 \text{ GHz} \quad \Delta \lambda_p \approx 2.2 \text{ pm} \]

The parameters a and b represent the real and imaginary part in the complex Gaussian parameter \( \Gamma \). If the Gaussian profile is perfect, which in this case means it is not chirped, the imaginary part is zero [11]. A bandwidth of 15 GHz or 2.2 pm is the lowest possible limit if pulses of 30 ps are used.

5.2.3 The next steps towards 2-d pictures

The next major development step should be to go from line measurement to two-dimensional measurement. These measurements should also be applicable to fast changing courses of events, such as turbulent flames. An example of how such a system could work will be described here. First of all there has to be the option of making DIAL-method. Since there are no tunable laser that can shift in wavelength with high frequency, the system will probably be built on two tunable lasers. One for the wavelength with corresponds to the absorption energy and the other one slightly shifted in wavelength. The beam from the pumping laser will then somehow swift between the two tunable lasers and the DIAL-method can be applied. The laser pulses will after the tunable lasers be directed into a lens system which will transform the shape of the pulses from a Gaussian profile into a laser sheet. This laser sheet should then be directed into the investigated area. A schematic view of the 2-d lidar system can be seen in Fig. 5.2.

![Diagram](image)

**Figure 5.2:** A schematic view of how a 2-d lidar setup could look like.

The two-dimensional image that is recorded has limits in both spatial dimensions. The depth that the image covers is dependent on the time sweep of the streak camera and the height of the image is limited by the height of the photosensitive cathode.

It is important to point out that the laser system should have the option to deliver two pulses separated with a very small time. This option is wanted for the use of the
DIAL-technique, because of the fact that this technique needs two pulses to evaluate
the investigated specie. Since most courses of events are unstable, they changes over
time. Therefore the two pulses needed for the DIAL-technique most be closely
together to investigate the same area before its contents is changed.

A further development to the laser in the area of higher pulse frequency would be of
great interest. Then an average of many pulses would be accessible, which would give
a more accurate result than the single-shoot measurement. Especially measurements
from turbulent flame will benefit from acquisition possibility which was demonstrated
in Fig. 4.10. A simple calculation to get some understanding of which frequency is
needed is shown Fig. 5.3.

flame velocity: 10 m/s

![Diagram](image)

\[ \text{frequency of the laser: } f_i = \frac{10 \text{ m/s}}{10 \mu\text{m}} = 1 \text{ MHz} \]

**Figure 5.3:** A simplified calculation of the needed repletion rate for the laser, needed to achieve acquisition measurements in a turbulent flame.

The calculation implies that the laser must have a pulse rate above 1 MHz to achieve
the wanted result. The pulse power of each pulse must of course still be of the same
magnitude as in the case for the single-shoot measurement.

Another question that is substantial for the two-dimensional imaging to work is that
the laser can provided sufficient pulse power. An estimation of rather simple nature
will be made for the laser sheet to work properly. The energy in the pulses that were
used to conduct the experiment during, e.g. the height above burner experiment, was
measured right before the out coupling mirror to be around 7 mJ. The pulse shape
looked somewhat like a flat Gaussian profile with diameter of 3 mm when measured
with a ruler. Most of the energy is concentrated to the centre of the beam where the
peak power is highest. An approximation is that 50% of the total energy concentrated
within a radius of 0.5 mm from the centre and is considered to be even distributed for
simplicity. A laser sheet does not need to be larger than the dimension of the photo
cathode of the streak camera, which seems to be around 2 cm in most cases. The
estimation then comes to a conclusion that the laser must delivers pulse energy of
around 70 mJ to have the same shoot-to-noise ratio. This energy estimation is made
for a back-scatter measurement which is not the case for the above described
technique. Instead the probably much weaker signals of absorption measurement will
be evaluated in this case. To get a better signal-to-noise ratio it is therefore desirable
to have even higher pulse energy.
6 Conclusions

The constructing of a laser-detecting system which can be used for LIDAR measurements with good spatial resolution is not that hard to build, if the necessary laser and detecting apparatus is available. The part that needs attention is the collecting lens system which can be built on different basic ideas, such as a Newton’s or a Cassegrain telescope, depending on what apparatus that is available.

Results, from the experiments made in this work, point in the direction that the LIDAR technique is applicable in the picosecond regime. The $1/R^2$ relationship shows rather good correspondents with the data from the measurements. The result obtained in the present work indicates that our system may be used for qualitative particle density measurements. One criterion is however that the particles are small enough to result in Rayleigh scattering only, i.e. no Mie scattering is generated. For species specific quantitative concentration measurements the current setup must be modified so that Differential Absorption LIDAR (DIAL) measurements can be performed.

The problems that where encountered during the work which did not directly bear reference to the apparatus were mainly of two kinds. The unwanted back-scattering from mirrors and surfaces are a major problem. This problem can probably be solved with gated detection. The second type of problem is the differences in the power of the signals. The dynamic range of the detector used under this work could not handle the different magnitudes of the signals. The major differences were between the back-scattered signal from investigated area and the unwanted back-scattered light. This implies that this problem can be reduced by using a gated detector. However, regarding the future developments of this technique a detector, preferably a streak camera, with as high dynamic range as possible should be used.

The future for this approach of the LIDAR technique do I look optimistic upon. The first line of experiments have shown promising results which indicates that the picosecond regime is open for further improvements. I believe that the improvements should be directed to get a DIAL laser-detecting system to work. With a system of this kind, an option of getting two-dimensional pictures of the presence of species in turbulent flame would be available with the need of only one optical access.
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