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Report

Ultrasound

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Contents

1 Introduction

In this experiment we measure the diffraction pictures of a phase and amplitude gratings. The following describes the basics of the experiment, compare [3]

1.1 Diffraction

If a beam of light hits an element and changes its direction although there occurs no reflection nor refraction one speaks of diffraction. Following to the principles of Huygen one can model the broadening of the light behind the obstacle as sphere. Does this happens in a periodic setting as a grating, many of this sphere will overlap. At the directions where the spheres cross within the propagation we find positive interference, between those negative. With other words we have interference maximums at the points there wavepackets go along with each other. For this to happen the distance of their origin at the grate must differ only by a whole-number multiple of the beams wavelength. This happens at the angles described by the law:

$$m\lambda = K \sin\theta. \tag{1}$$

Here m names the order λ the wavelength and K the grating constant. Θ is the angle of change of direction. In this experiment we will analyse two different types of gratings. The *Amplitude Grating* and the *Phase Grating*.

1.2 Amplitude Grating

An Amplitude Grating differs the transmittivity at different positions. This is easily described with the *Aperaturfunction*. So the apertur function of a simple grating is

$$g(x) = \begin{cases} 1 & 2n \cdot b < x < (2n+1)b \quad n = 1, 2, ...N \\ 0 & else \end{cases} \tag{2}$$

$g(x) = 1$ means full transmission and $g(x) = 0$ no transmission. With the Fresnel-Kirchhoffschen integral relation one can show that the square of the absolute value of the Fouriertransformed equates the intensity on a screen.

$$|I| = |\int g(x, y) \cdot e^{iKr} dA|^2 \tag{3}$$

So we found a transformation from the apertur function to the distribution of intensity at a screen which is for reasons of symmetry reversible. Is the exact function of intensity at the screen is unknown one can use the Fourier-Row to approximate the apertur function.

$$g(x) = \sum_{i=0}^{\infty} \sqrt{I_i} \cdot \cos\left(2\pi i \frac{x}{K}\right) \tag{4}$$

In reality one can not determine all orders so we end with a finite sum. So we estimate $g(x)$ as

$$g(x) \approx \frac{1}{\sum_{i=-N}^{N} \sqrt{I_i}} \sum_{i=-N}^{N} \sqrt{I_i} \cdot \cos\left(2\pi \frac{x}{k}\right). \tag{5}$$

The factor at the beginning will norm the function to 1. The changes of the sum parameters allows us to include both, negative and positive, sides of the orders. With the apertur function one can find the gap width.

1.3 Phase Grating

In contrast to the prior named Amplitude Gratings stands the Phase Grating. A ideal Phase Grating is totally transparent and assigns it self through a non-constant refraction index. Through ultrasonic a phase grating is produced in isooctan. The acoustic wave propagates with compressing and depressing its carrier. The different degrees of compressing lead to different refraction indices.

Coherent waves that insert the grate will loose their equiphase because their velocities differ with the different refraction indices. The outcoming light is out phase again and can interfere as seen before. The refraction index within the ultrasonic cell is described as

$$n(x) = n_0 + \Delta n \sin(2\pi x/\Lambda). \tag{6}$$

Here n_0 names the refraction index without sonic waves. Δn is the amplitude and Λ the ultrasonic wave length. One can see that Λ corresponds with the Grating constant k. The intensity S of the ultrasonic is proportional to the square of the applied current U and the relative change of density ρ.

$$S \propto U^2 \propto \left(\frac{\Delta\rho}{\rho_0}\right)^2 = \left(\frac{\Delta n}{n-1}\right)^2. \tag{7}$$

we find a proportional connection between $U \propto \Delta n$.

1.4 Raman-Nath-Theorie

The Raman-Nath-Theorie gives information to the intensity maximums of a grating. For the A angle Θ of the m^{th} order it gives the relation

$$\sin(\Theta) = \pm m \frac{\lambda}{\Lambda} \tag{8}$$

with λ the lights- and Λ the ultrasonics wavelength. Further it states the intensity of the ${m_1}^{\text{th}}$ and the ${m_2}^{\text{th}}$ order behave like the square of the ${J_1}^{\text{th}}$ and the ${J_2}^{\text{th}}$ order

Bessel functions.

$$\frac{I_m}{I_{m'}} = \frac{J_m^2(\Delta n D 2\pi/\lambda)}{J_{m'}^2(\Delta n D 2\pi/\lambda)}. \tag{9}$$

D is the length of the ultrasonic cell. To verify this we need to find the relation between the measured time t and the Bessel functions.

1.5 Resolving Power

The power of resolving a is defined for light of the wave length λ as

$$a = \frac{\lambda}{\Delta\lambda}. \tag{10}$$

$\Delta\lambda$ is the smallest distinction of two maximums which one can perceive separately. An other way to find the resolving power is given in the manual [3].

$$a = N \cdot m \tag{11}$$

N is the number of illuminated bars and m the highest visible order. Does the laser has the diameter w and the grating the constant K we can write

$$a = N \cdot m = \frac{w}{K} \cdot m \tag{12}$$

2 Setup and Measurement Procedure

2.1 Setup

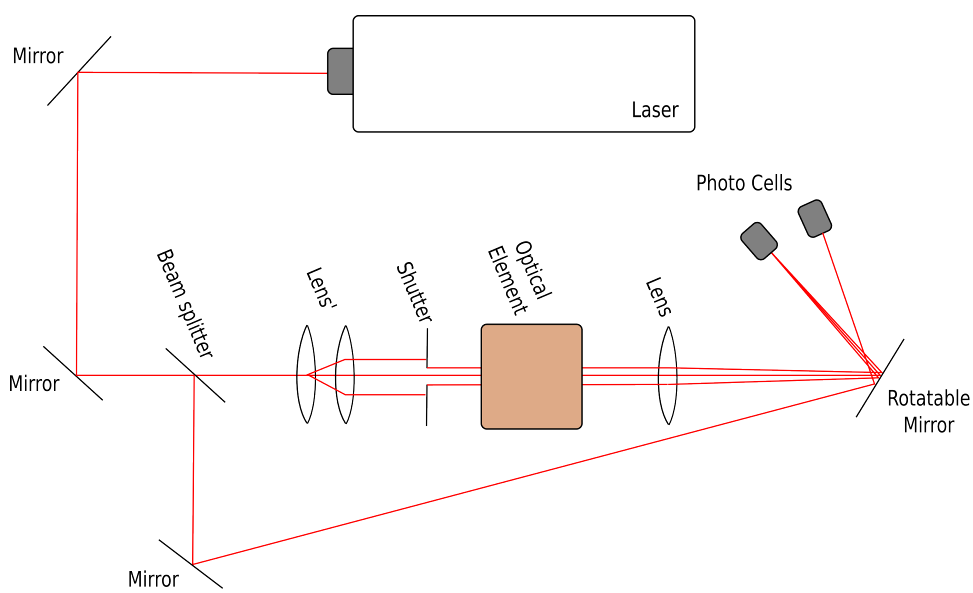

Figure 1: Schematic Setup

A class 3B laser provides the necessary light for the experiment. We use two mirrors to adjust hight and angle of the beam. A beam splitter demerges the beam in two. The straight part strikes a lens set which expands the width of the beam. A following shutter sharpens the edges. Now the beam hits the optical element which will be the different gratings in the experiment. Another lens focuses the expanded beam on a photocell that is located behind a rotatable mirror. This mirror is attached to a motor. The rotation will drive the in the optical element splitted beams over the first photo cell. Back to the beam splitter. The other part of the demerged beam leaves the inner setup and is reflected through another mirror onto the rotatable mirror and further on the second photocell. The mirror allows to adjust the hight of the beam in a way that it does not hit the first photo cell. The signals from the photo cells is passed on to an oscilloscope. The first photocell provides the signal we want to analyse the second is connected to the trigger.

2.2 Measurement Procedure

2.2.1 Alignment

We took some time to figure out an effective way to set a nice alignment. We found it useful to use the shutter in a very small adjustment to determine hight and angle of the beam to the optical elements parameter. We put the shutter at the very beginning of the rack to find a rough alignment an slided it back to the very end to do the fine alignment. Repeating this several times we were able to adjust the beam perfectly. Now we could put in the first lens and adjust it again on the small hole of the shutter which we placed at the very end of the rack. For the second lens we calculated its distance from the first to get a parallel beam again and aligned it to the shutter at the end as the first lens. Afterwards we located the shutter in its final position right behind the second lens. Behind this we located the S-grating for the first measurement. For the position of the third lens we calculated its focal distance and subtracted the distance between photo cell and rotatable mirror to get its position on the rack measured from the end. Finally we locked the second photo cell in a high position so there will not be any nuisance with the first and adjusted the second beam at its mirror to the second photocell.

2.2.2 Sinus Grating

First we put the grating labeled with an "S" at the position described before. With a screen placed between grating and lens we determined the position of the first order of diffraction and its distance to the grating. The values for all measurements we compiled in section 3.

2.2.3 Gauge

Herefore we replaced the S- with the R-grating into the mount which we attached on the rack at the position of the previous used R-grating and took the screen away.

We captured the dispartment with the oscilloscope.

2.2.4 Five Different Gratings

One after the other we put the grates labeled 1 to 5 into the mount and captured the data with the oscilloscope.

2.2.5 Laser Beam Width

Measuring the diameter of the beam was not easy. The best way we thought of was using again the screen without grate and metering its width with the imprinted scale. We measured it several times to decrease the error.

2.2.6 Ultrasonic Phase Grating

Now we came to the mean part of the Experiment. Carefully we switched the mount of the gratings before with the isooctane tank and drove through the different charges making a measurement every 0.5V.

Peak	x-Position	y-Position/mm
0^{th} Order	6.5	-1
1^{st} Order, left	-47	6
1^{st} Order, right	59	-6

3 Measurement Values

3.1 Sinus Grating

As described in section 2.2.2, we have measured the diffraction maximums created by the sinus grating. The screen was crooked, so we measured x an y positions.

The distance between grating an screen was $d = 64.5$mm. We estimated statistical uncertainty of these measurements as follows: $s_x = s_y = s_d = 1$mm.

3.2 Amplitude Grating

3.2.1 Gauge

Grating:	R
File:	`gauge.csv`

3.2.2 The Grates

Grating No.	File	visible Orders m
1	`grating1.csv`	9
2	`grating2.csv`	3
3	`grating3.csv`	4
4	`grating4.csv`	4
5	`grating5.csv`	4

Table 1: Values of measurement of the five amplitude gratings

3.2.3 Laser Width

We each measured the width of the laser several times with the screen we used in the previous measurement 3.1.

w_i/mm	3; 4; 3; 4; 3; 4
s_{w_i}	1mm

3.3 Phase grating

f	2130kHz
s_f	0,5kHz

s_U	0,01V

U	File
0	`rm1.csv`
1,00	`rm2.csv`
1,51	`rm3.csv`
2,00	`rm4.csv`
2,50	`rm5.csv`
3,00	`rm6.csv`
3,50	`rm7.csv`
4,00	`rm8.csv`
4,51	`rm9.csv`
5,00	`rm10.csv`
5,48	`rm11.csv`
6,00	`rm12.csv`
6,50	`rm13.csv`
6,99	`rm14.csv`
7,51	`rm15.csv`
8,00	`rm16.csv`
8,50	`rm17.csv`
9,00	`rm18.csv`
9,50	`rm19.csv`

Table 2: Files of the phase grating for different charges

4 Evaluation

4.1 Sinus Grating

We can use equation (1) to calculate the grating constant from our measurement 3.1. So we have to calculate the distances on the screen of the left an right maximum of first order.

Let $\boldsymbol{x}_0$ be the position vector of the central maximum (0^{th} order), and $\boldsymbol{x}_{1r}$ and $\boldsymbol{x}_{1l}$ the position vector of the left and right maxima (1^{th} order) respectively. The distances can the expressed by

$$d_r = |\boldsymbol{x}_0 - \boldsymbol{x}_{1r}| = (54.0 \pm 1,7)\text{mm} \tag{13}$$

$$d_l = |\boldsymbol{x}_0 - \boldsymbol{x}_{1l}| = (53.0 \pm 1,7)\text{mm}, \tag{14}$$

where the error was calculated using Gaussian error propagation of s_x and s_y.

From the geometry of the experiment we know that $\tan \Theta_{l/r} = \frac{d_{l/r}}{d}$. To remember $d = (64.5 \pm 1)$mm and $\lambda = 632,8$nm[3]. So using the relation $\sin(\arctan(x)) = x/\sqrt{x^2+1}$ and (1) we get

$$K_{l/r} = \frac{m\lambda}{\sin \theta_{l/r}} = \sqrt{\frac{d_{r/l}}{d}^2 + 1} \cdot \frac{m\lambda}{\frac{d_{r/l}}{d}} \tag{15}$$

where $m = 1$ because we have measured the maxima of first order. So we get the two values for K

$$K_r = 985,8 \cdot 10^{-9}\text{m}$$

$$K_l = 996,7 \cdot 10^{-9}\text{m}$$

The error came from

$$s_K = \sqrt{\left(\left(\frac{m\lambda}{d\sqrt{\left(\frac{d_r}{d}\right)^2 + 1}} - \frac{\sqrt{\left(\frac{d_r}{d}\right)^2 + 1} \cdot dm\lambda}{d_r^2}\right) s_{d_r}\right)^2 + \left(\frac{\lambda m}{d_r \cdot \sqrt{\left(\frac{d_r}{d}\right)^2 + 1}} s_d\right)^2} \tag{16}$$

$$s_{K_{r/l}} = 19 \cdot 10^{-9}\text{m} \tag{17}$$

If we take the average and its well known error we come to the result of K

$$K = (991 \pm 13) \cdot 10^{-9}\text{m}$$

4.2 Gauge

In the setup for the measurment of the five amplitude gratings we have to much uncertenties – as the position of the third lens or the speed of rotation – to calculate the relation between t and Θ. So we use a grating with well known parameters to get the relation through a linear fit. We are interested at the relation

$$at + b = \sin\Theta \tag{18}$$

to avoid errors in x directions we permuted the equation to

$$t = \frac{\sin(\Theta) - b}{a}. \tag{19}$$

Figure 2 shows the fit and the results So we come to the result for the calibration

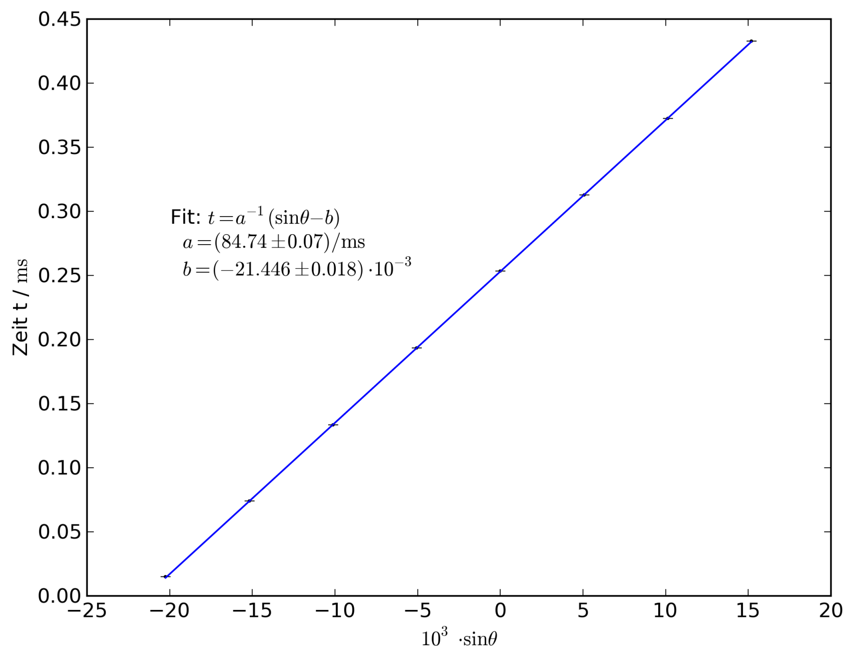

Figure 2: Gauge of the time t and the angle Θ

$$(84,74 \pm 0,07)/ms \cdot t - (21,446 \pm 0,018) \cdot 10^3 = \sin\Theta \tag{20}$$

4.3 Amplitude Gratings

4.3.1 Grating Parameter K

Now with the calibrated setup we are able to measure the grating 1 to 5. One by one we pluged them in the mount and captured the data with the oszilloskop. We fitted the peaks with a gaussian and got their positions and errors. In figure

3 we show exemplarily the fits of grating 1. The other grates can be found in the appendix. With equation (20) we extracted the angles Θ from the data. Further

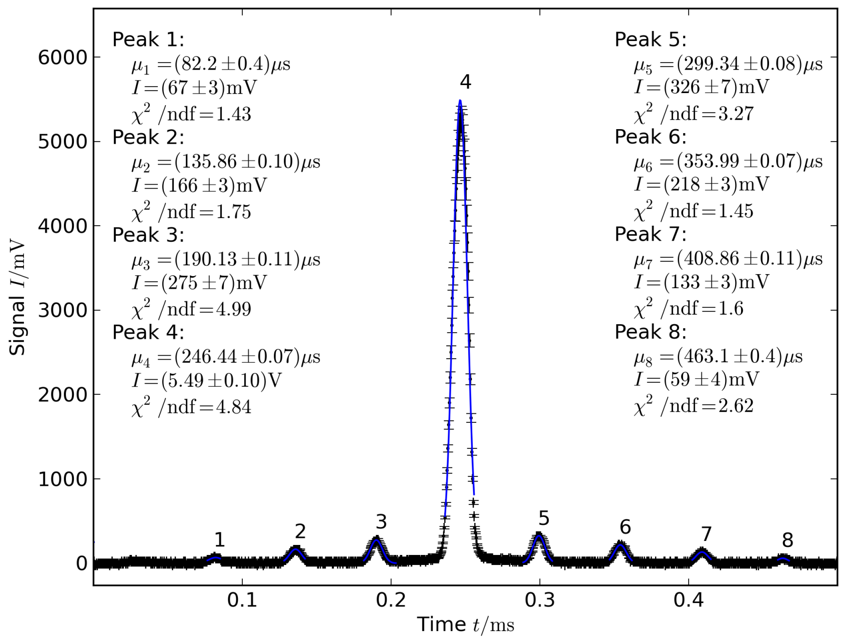

Figure 3: Captured data of grating 1. Fitted with 8 gaussians.

we used equation (1) to recive all the K values

$$K_1 = (138.87 \pm 0.18)\mu\text{m}$$
$$K_2 = (36.44 \pm 0.03)\mu\text{m}$$
$$K_3 = (107.17 \pm 0.14)\mu\text{m}$$
$$K_4 = (108.91 \pm 0.11)\mu\text{m}$$
$$K_5 = (54.44 \pm 0.05)\mu\text{m}$$

The errors for equation (1) and the weighted mean comes from

$$s_{K_i} = \frac{\cos(\Theta) \cdot m\lambda}{\sin^2(\Theta)} \cdot s_\Theta \qquad \text{and} \tag{21}$$

$$s_x = \sqrt{\frac{1}{\sum \frac{1}{\sigma_i^2}}}. \tag{22}$$

4.3.2 Power of Resolving

With the ansatz (12) we found a way to estimate the resolving power of a grate. This we want to determine for the 5 former gratings. Therefore we need the width of the laser and the previous calculated grating constants. In measurment 3.2.3 we find all the needed data. Taking the mean of the measured laser widths w_i we come to the value $w = 3,5\text{mm}$ and its error $s_w s_{w_i}/\sqrt{6} = 0,4\text{mm}$. We come to the results

$$a_1 = (230 \pm 30)$$
$$a_2 = (290 \pm 30)$$
$$a_3 = (200 \pm 20)$$
$$a_4 = (161 \pm 19)$$
$$a_5 = (260 \pm 30)$$

As usual we used Gauss law to determine the error

$$s_a = \sqrt{\left(\frac{m}{K} \cdot s_w\right)^2 + \left(\frac{wm}{K^2} \cdot s_K\right)^2}. \tag{23}$$

4.3.3 Apertur Function of Grating No. 1

We use the Fourier-Series from equation (5) to calculate the apertur function. With the data from figure 3 we got a sum with 8 terms. We relinquish to print the explicit term here because we do not see any use in it. Much more intresting is the plot of exactly this shown in figure 4

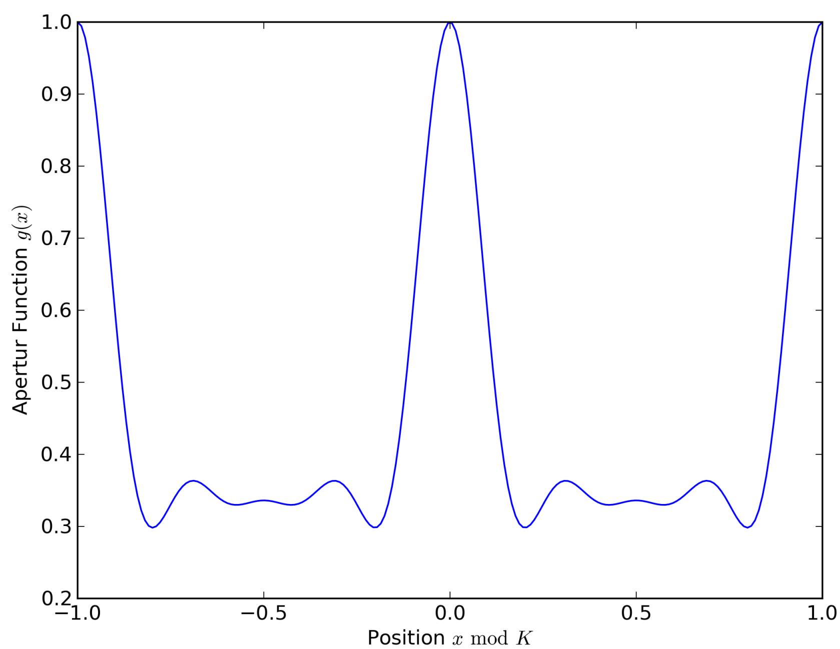

Figure 4: Plot of the aproximated apertur function for the grating no 1.

4.3.4 Proportion of Grating 1

To figure out the proportion of bar and gap in grating 1 we took some data from the plot shown in figure 5 We measured for $x_{width/2} = 0,11 \cdot K$ with the error

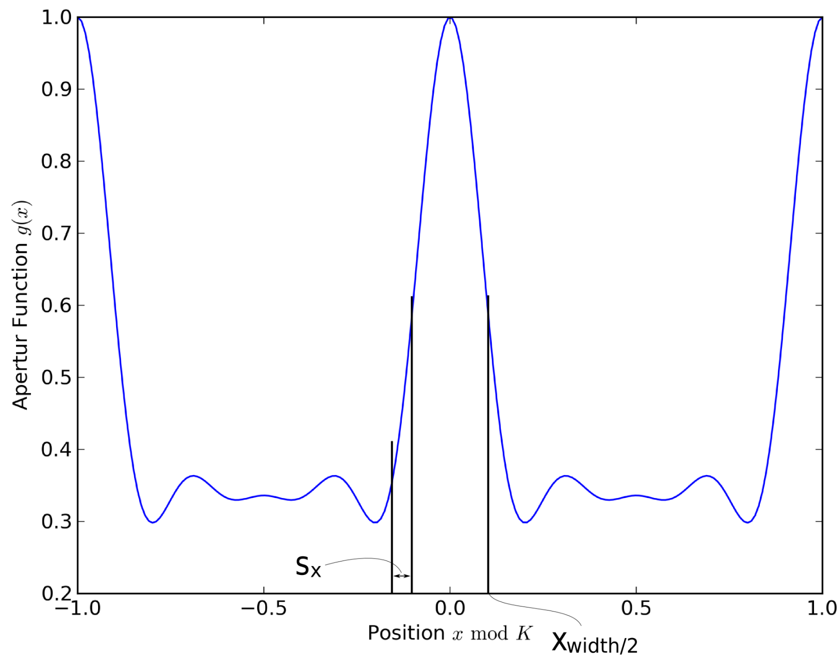

Figure 5: Aproximation of the proportion of bar and gap in grating 1

$s_x = 0,05 \cdot K$. Hence we find the proportion via

$$P = \frac{2 \cdot x_{width/2}}{K} = (0,11 \pm 0,05) \tag{24}$$

The error of K can be negilected.

4.4 Phase Grating

4.4.1 Raman-Nath-Theory

As stated in 2.2.6 we have measured the diffraction picture for different amplitudes of the piezo oscillation. One of these pictures is shown exemplarily in figure 6. The other fits can be found in the appendix. The peaks in figure 6 are fitted with Gaussians

$$U(t) = Ie^{-\frac{1}{2}\frac{(t-\mu)^2}{\sigma^2}}. \tag{25}$$

From these fits we get a set of intensities $\{I_{\pm m}\}$ (= peak heights) where m numbers the interference order and the $\pm$ sign specifies the side (left/right) of the peak. For every voltage U_p (and therefore every picture like figure 6) we obtain a whole set of peaks.

When we rearrange these data points, and plot the intensities as a function of the voltage U_p for a fixed diffraction order $m = 0, 1, 2, 3$, we obtain the figures shown in 7, 8, 9 and 10. We did not plots higher diffraction orders because there were too

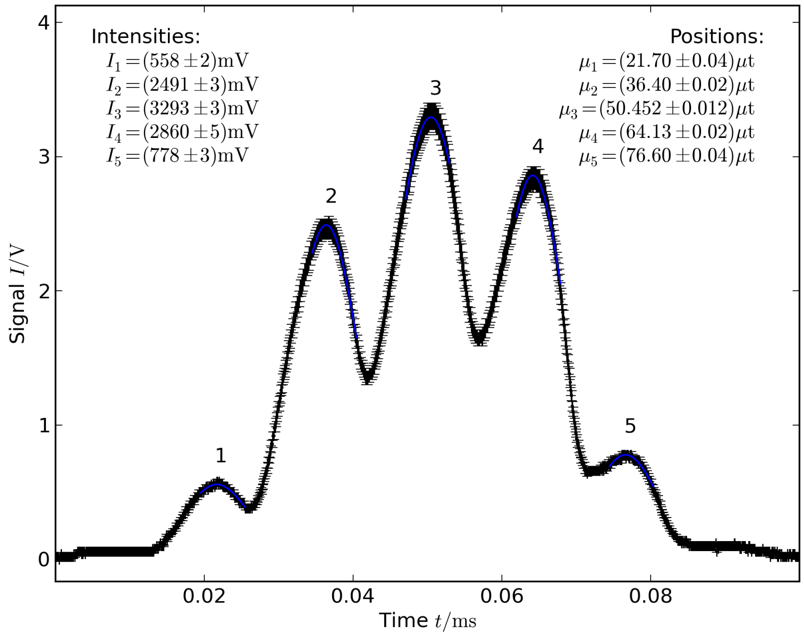

Figure 6: Measured diffraction picture with the piezo voltage $U_p = 5.48$V. Peaks fitted with a Gaussian.

few data points (< 5).

The error bars in y direction s_y in these figures shows the statistical error of the fitted intensities s_I and the systematic error of oscilloscope $\tilde{s}_I = 0.03 \cdot I$:

$$s_y = \sqrt{s_I^2 + \tilde{s}_I^2} \tag{26}$$

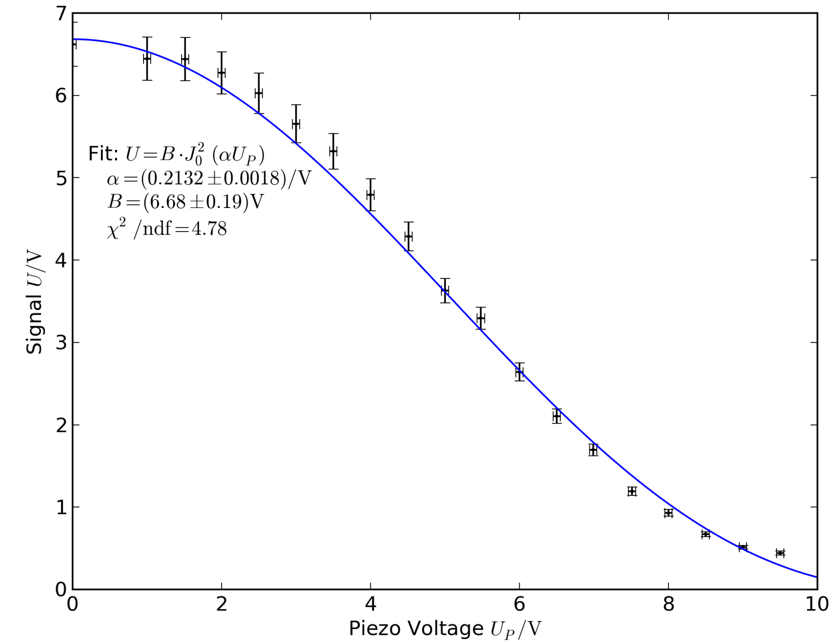

Figure 7: Intensities as a function of U_p for diffraction order $m = 0$ fitted with the Bessel function $B \cdot J_0^2(\alpha U_p)$

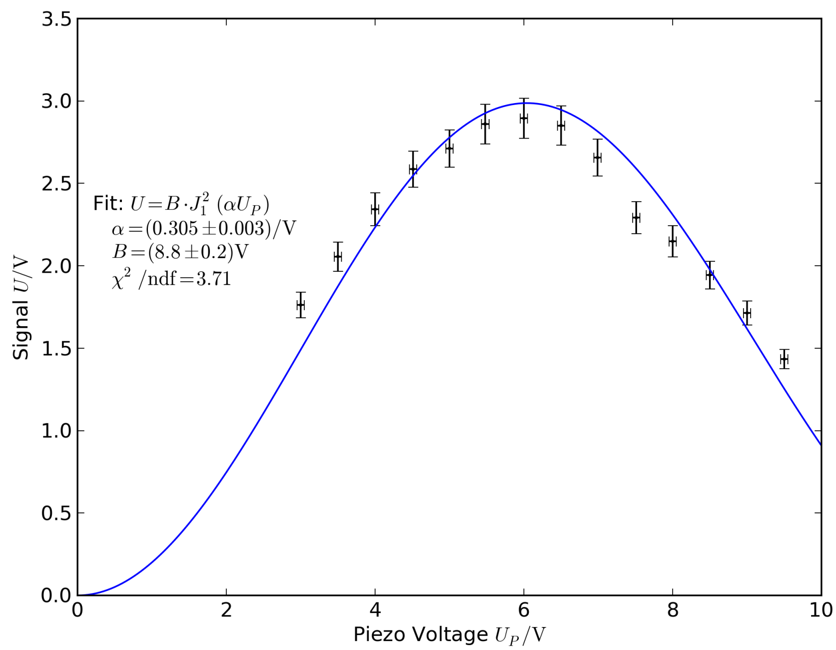

Figure 8: Intensities as a function of U_p for diffraction order $m = 1$ fitted with the Bessel function $B \cdot J_1^2(\alpha U_p)$

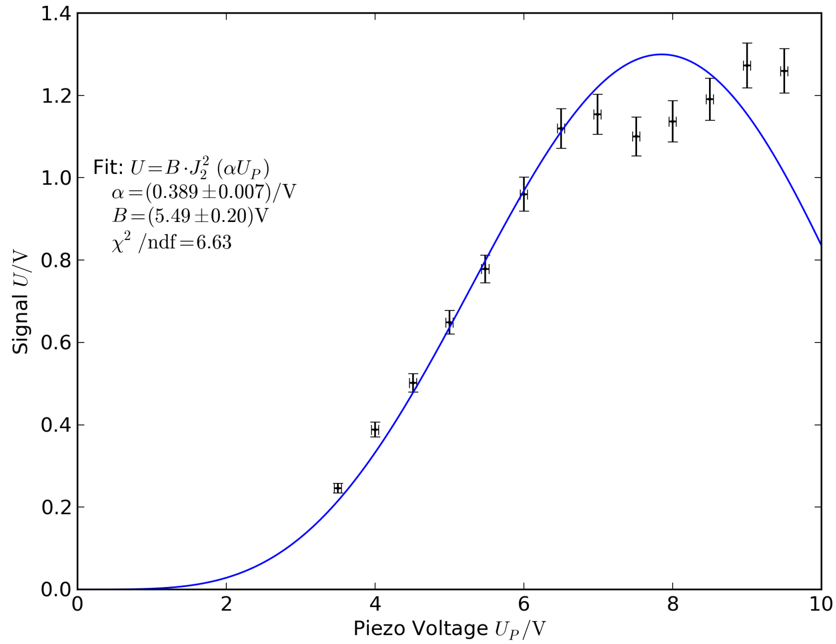

Figure 9: Intensities as a function of U_p for diffraction order $m = 2$ fitted with the Bessel function $B \cdot J_2^2(\alpha U_p)$

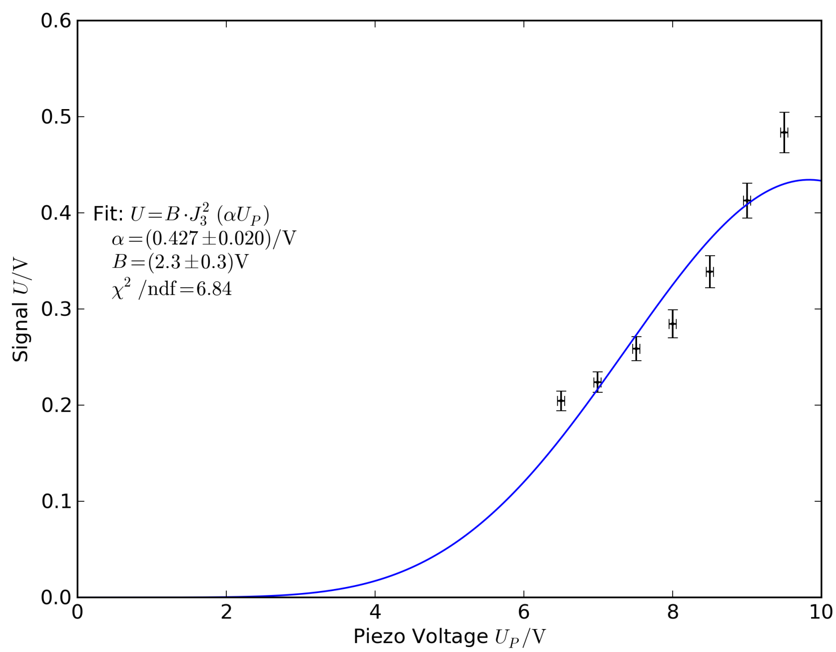

Figure 10: Intensities as a function of U_p for diffraction order $m = 3$ fitted with the Bessel function $B \cdot J_3^2(\alpha U_p)$

The fits reproduce the tendency of the data points, but a χ^2/ndf up to 6.84 indicated that there are untreated systematic errors. Indeed we did neglect a large amount of potential sources of errors, but we can not measured their effect quantitatively. Potential sources of errors are as follows.

- Heating of the Isoocatne due to the heat dissipation in the crystal, which causes density fluctuations and schlieren.
- The laser beam is not perfectly monochrome.
- Maybe we did not adjust the laser beam perfectly leveled and aligned.
- The trigger beam could interfere with the photo diode.

Except for the first source, these source apply to all other measurements, too.

4.4.2 Sonic Wave Length

The fits (25) also generated a set of the timely positions $\{\mu_{\pm m}\}$. From this we calculate distances $d = \mu_{+1} - \mu_{-1}$ for every diffraction picture. The error of d is

$$s_d = \sqrt{s_{\mu_{+1}}^2 + s_{\mu_{-1}}^2 + 0.03^2\mu_{+1}^2 + 0.03^2\mu_{-1}^2} \tag{27}$$

where we included the error of the fit parameter and a systematic error of 3% of oscilloscope.

Using the gauge function $\sin\theta = a\Delta t$ (20) with $\Delta t = d$ we can calculate the wave length

$$\Lambda = \frac{2\lambda}{\sin\theta} = (540 \pm 40)\mu\mathrm{m} \tag{28}$$

$$\text{with} \quad s_\Lambda = \frac{2\lambda}{\sin^2\theta} s_\theta. \tag{29}$$

The error of the gauge function can be neglected.

We can also calculate the wave length using the sonic speed $c = 1111\mathrm{m/s}$ in Isooctane [4] and the frequency $f = (2130 \pm 0.5)\mathrm{kHz}$ of the piezo crystal:

$$\Lambda = \frac{c}{f} = (521.60 \pm 0.12)\mu\mathrm{m} \tag{30}$$

$$\text{with} \quad s_\Lambda = \frac{c}{f^2} s_f. \tag{31}$$

This means the two wave length are in agreement within their standard deviation.

5 Conclusion

We have measured the grating constant of the sinus grating. The result is

$$\boxed{K = (991 \pm 13)\mathrm{nm}.} \tag{32}$$

The gauge function, to calculate the angle Θ from a measured time t, is

$$\boxed{(84,74 \pm 0,07)/ms \cdot t - (21,446 \pm 0,018) \cdot 10^3 = \sin\Theta.} \tag{33}$$

By applying the arcsin to this equation, we get the angle θ.

From the diffraction picture of five different gratings we calculated the grating constants K_i and the resolving power a_i. The results are listed in table 3

Grating No	Grating Constant K	Resolving Power a
1	$(138.87 \pm 0.18)\mu$m	(230 ± 30)
2	$(36.44 \pm 0.03)\mu$m	(290 ± 30)
3	$(107.17 \pm 0.14)\mu$m	(200 ± 20)
4	$(108.91 \pm 0.11)\mu$m	(161 ± 19)
5	$(54.44 \pm 0.05)\mu$m	(260 ± 30)

Table 3: Grating constants and resolving powers.

For grating 1 we estimated the apertur function and concluded therefrom the proportion P of bar and gap.

$$\boxed{P = (0,11 \pm 0,05).} \tag{34}$$

From the diffraction picture we have calculated the wave length in Isooctane

$$\boxed{\Lambda = (540 \pm 40)\mu\text{m}.} \tag{35}$$

In comparison we have calculated the wave length from the frequency of the piezo crystal. The result is

$$\boxed{\Lambda = (521.60 \pm 0.12)\mu\text{m}.} \tag{36}$$

The two values are in agreement within their standard deviations.

A Amplitude Grating Fits

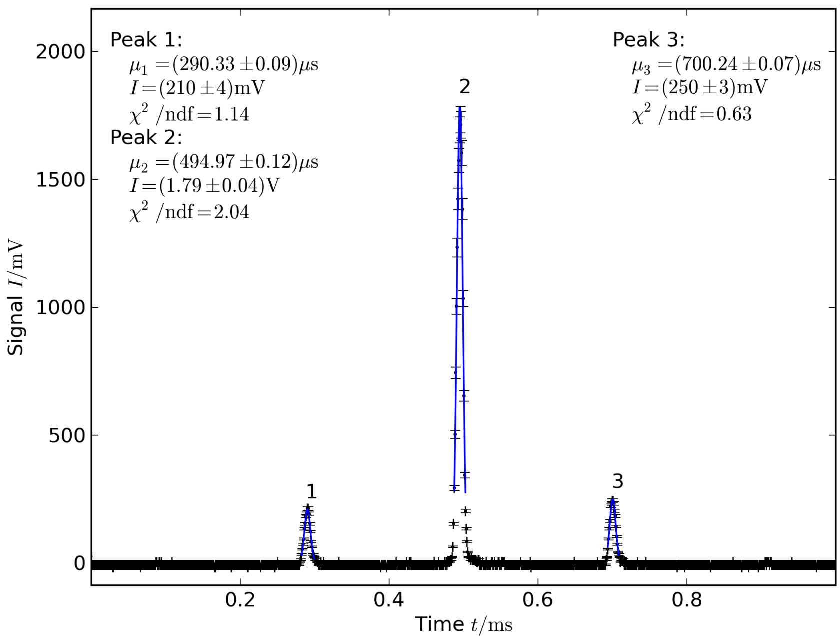

Figure 11: Captured data of grating 2. Fitted with Gaussians.

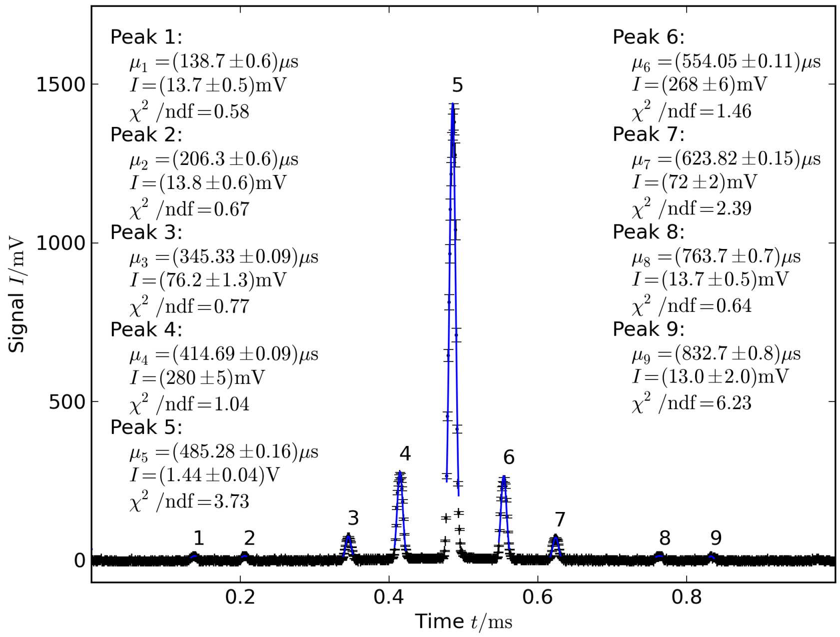

Figure 12: Captured data of grating 3. Fitted with Gaussians.

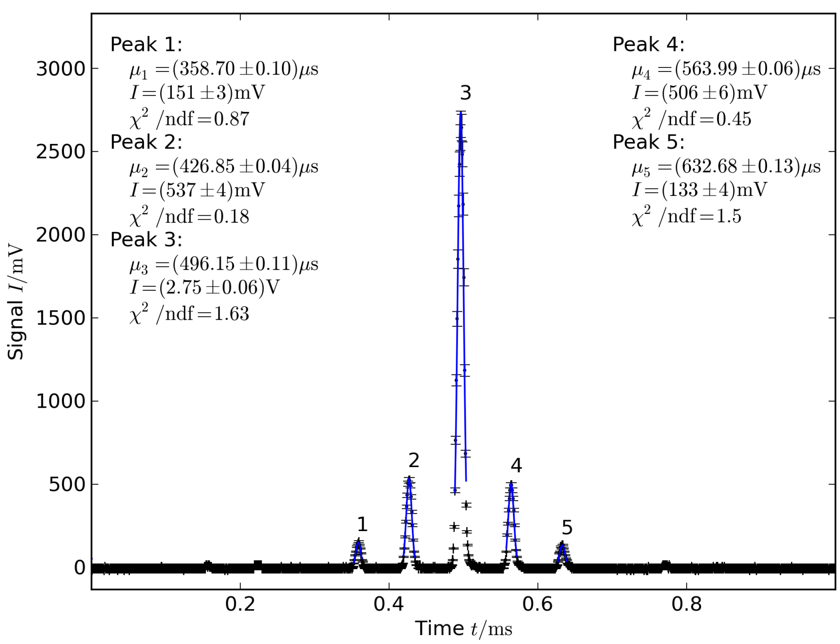

Figure 13: Captured data of grating 4. Fitted with Gaussians.

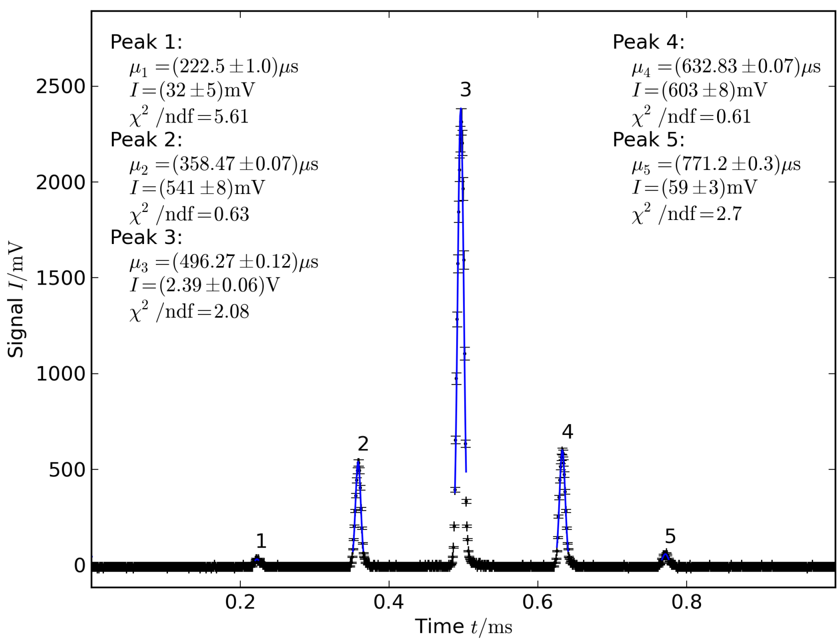

Figure 14: Captured data of grating 5. Fitted with Gaussians.

B Phase Grating Fits

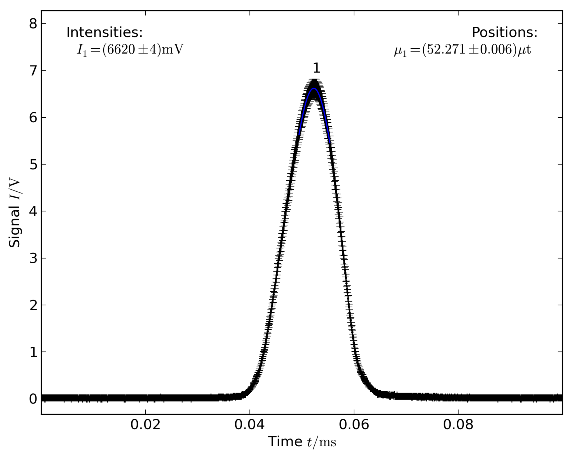

Figure 15: Measured diffraction picture with the piezo voltage $U_p = 0\mathrm{V}$. Peaks fitted with a Gaussian.

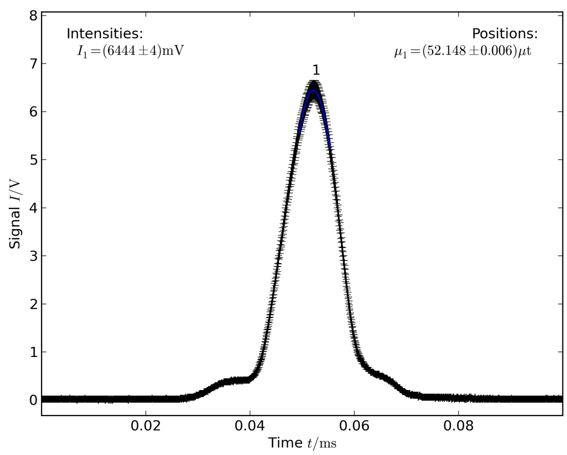

Figure 16: Measured diffraction picture with the piezo voltage $U_p = 1.00$V. Peaks fitted with a Gaussian.

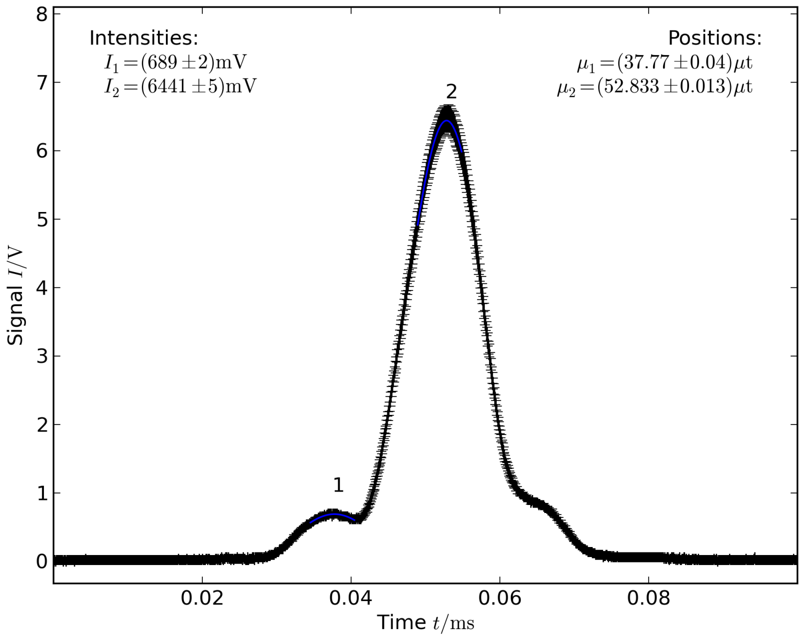

Figure 17: Measured diffraction picture with the piezo voltage $U_p = 1.51$V. Peaks fitted with a Gaussian.

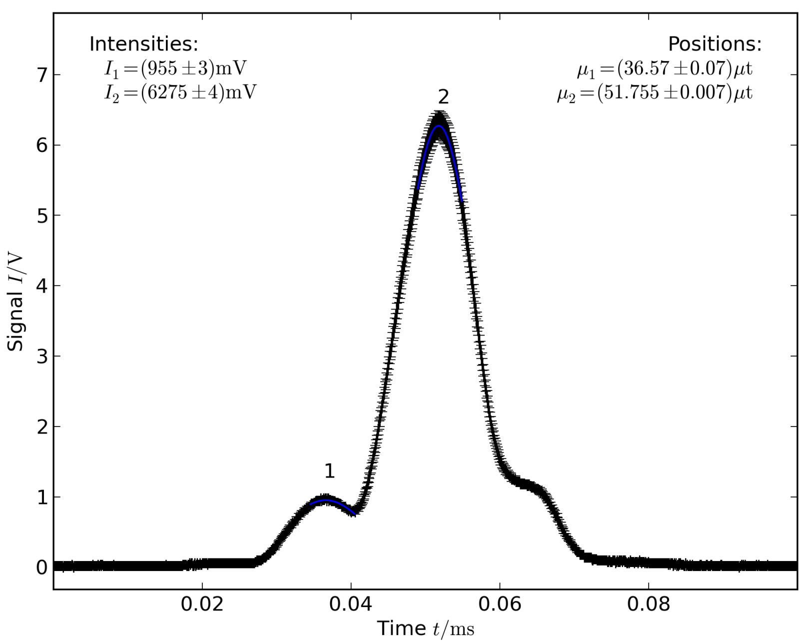

Figure 18: Measured diffraction picture with the piezo voltage $U_p = 2.00$V. Peaks fitted with a Gaussian.

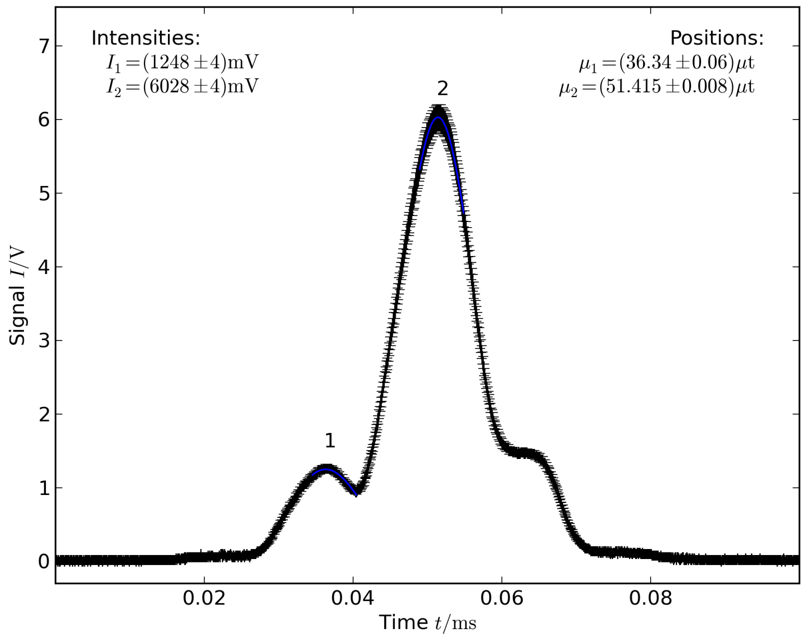

Figure 19: Measured diffraction picture with the piezo voltage $U_p = 2.50$V. Peaks fitted with a Gaussian.

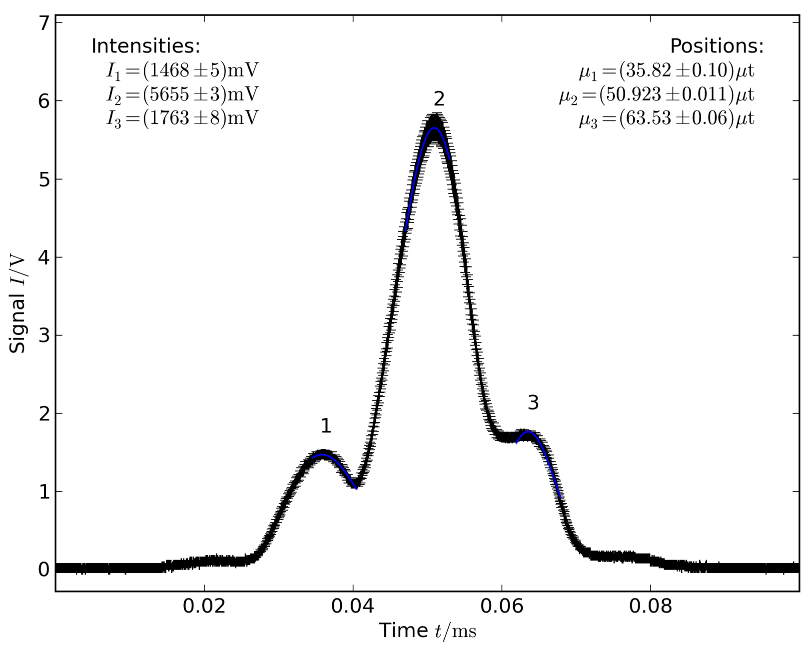

Figure 20: Measured diffraction picture with the piezo voltage $U_p = 3.00$V. Peaks fitted with a Gaussian.

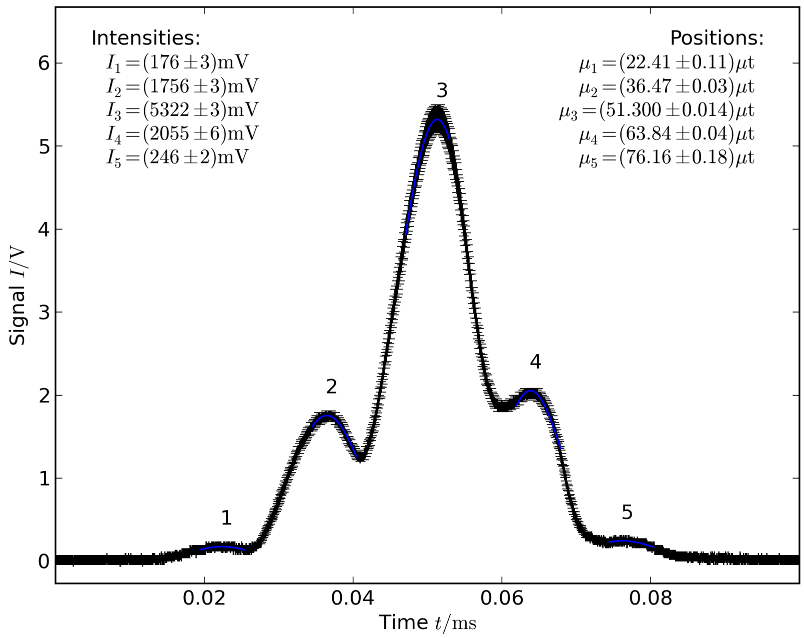

Figure 21: Measured diffraction picture with the piezo voltage $U_p = 3.50$V. Peaks fitted with a Gaussian.

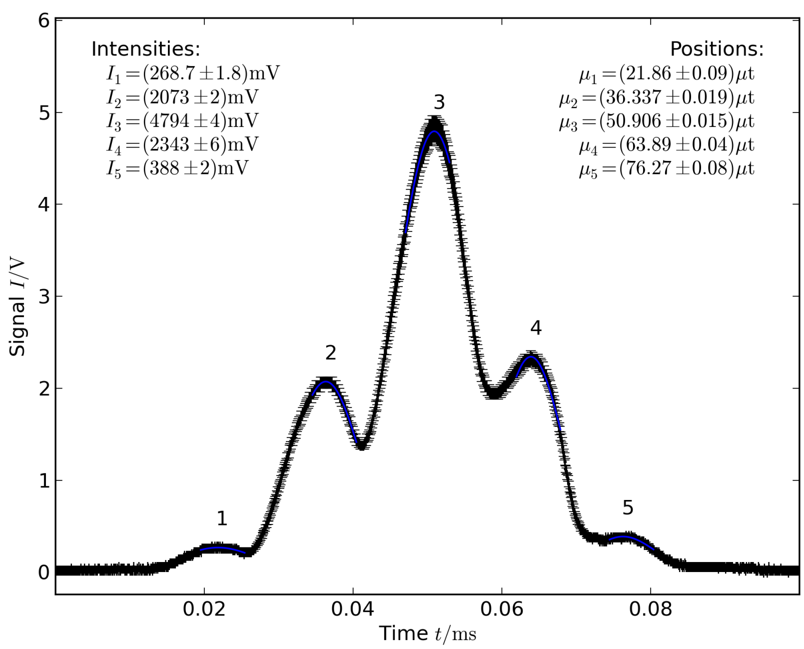

Figure 22: Measured diffraction picture with the piezo voltage $U_p = 4.00$V. Peaks fitted with a Gaussian.

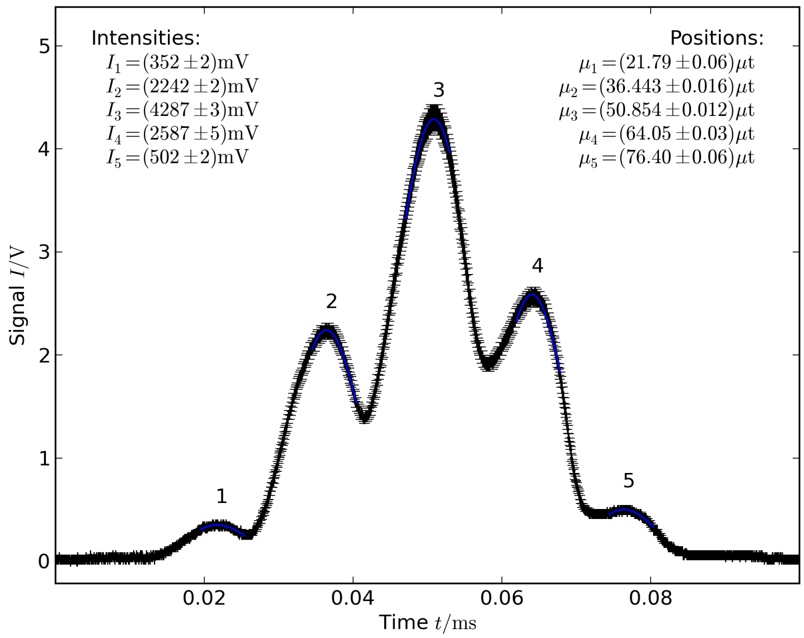

Figure 23: Measured diffraction picture with the piezo voltage $U_p = 4.51$V. Peaks fitted with a Gaussian.

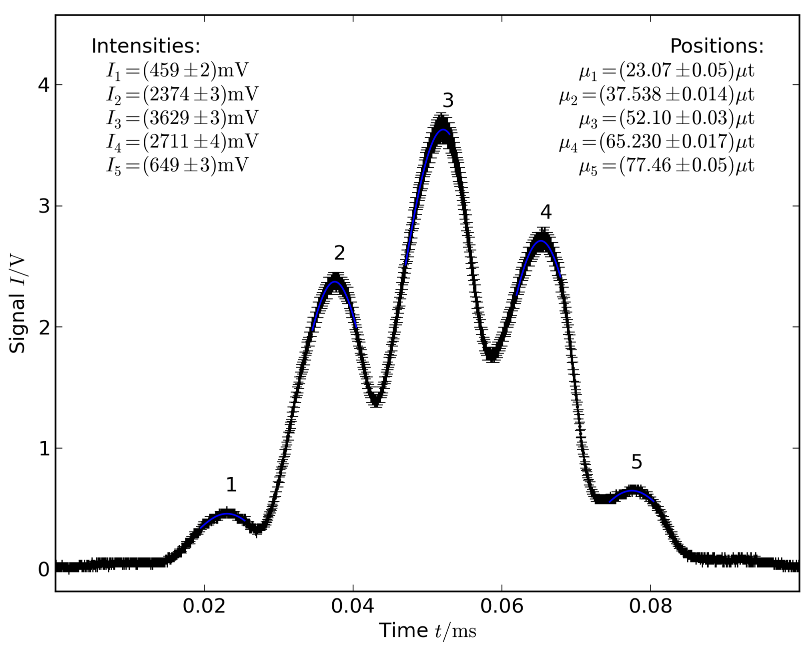

Figure 24: Measured diffraction picture with the piezo voltage $U_p = 5.00$V. Peaks fitted with a Gaussian.

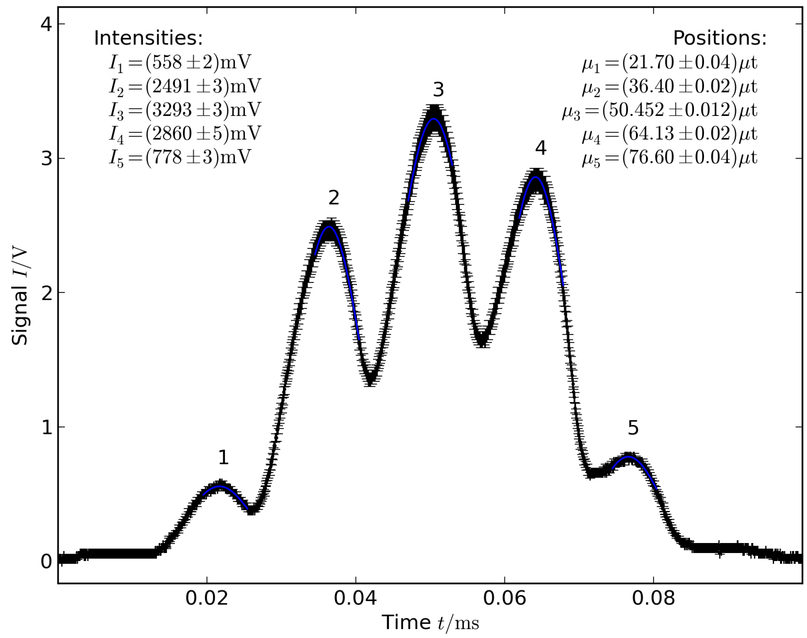

Figure 25: Measured diffraction picture with the piezo voltage $U_p = 5.48$V. Peaks fitted with a Gaussian.

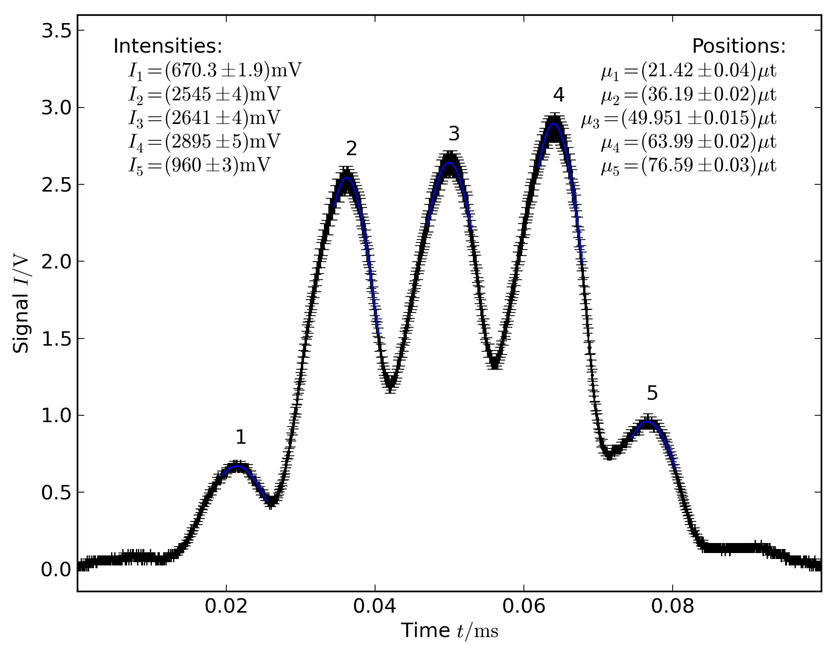

Figure 26: Measured diffraction picture with the piezo voltage $U_p = 6.00$V. Peaks fitted with a Gaussian.

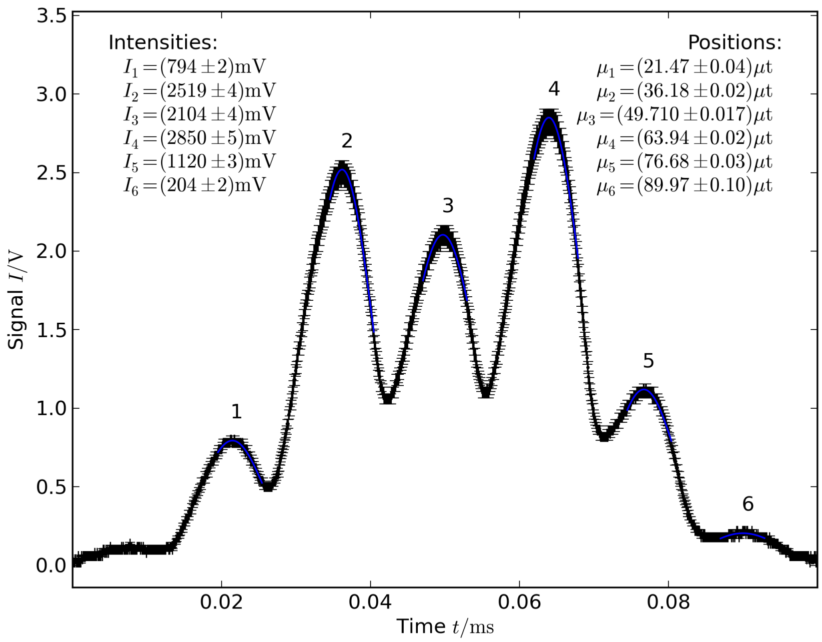

Figure 27: Measured diffraction picture with the piezo voltage $U_p = 6.50$V. Peaks fitted with a Gaussian.

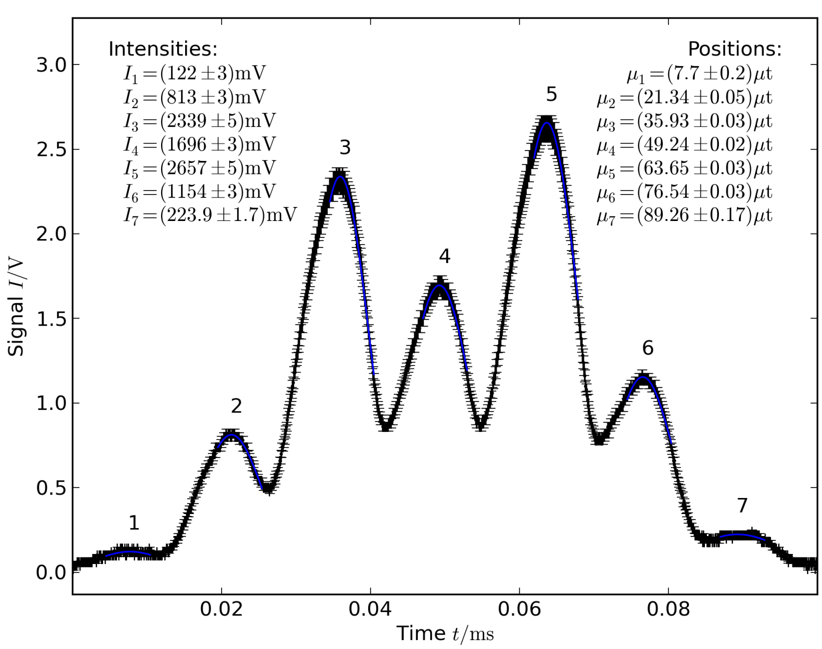

Figure 28: Measured diffraction picture with the piezo voltage $U_p = 6.99$V. Peaks fitted with a Gaussian.

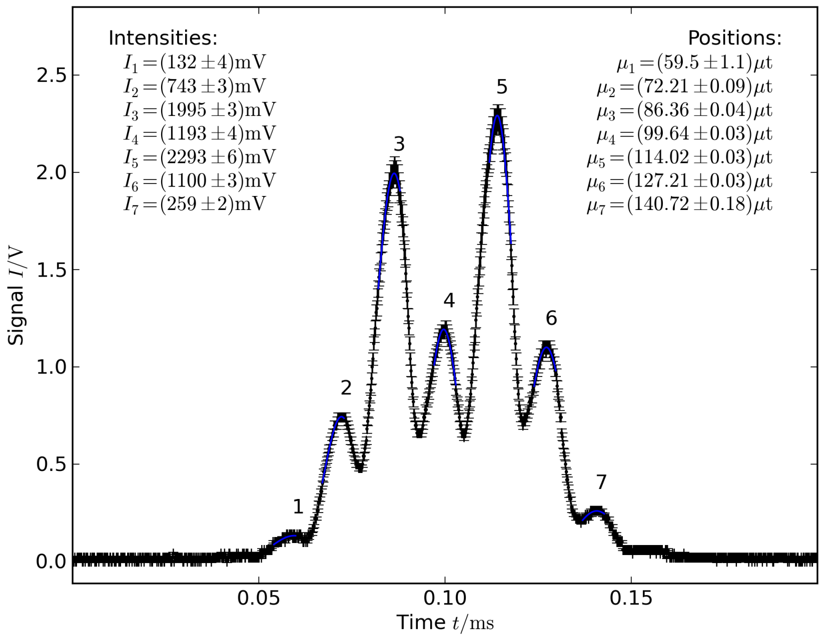

Figure 29: Measured diffraction picture with the piezo voltage $U_p = 7.51$V. Peaks fitted with a Gaussian.

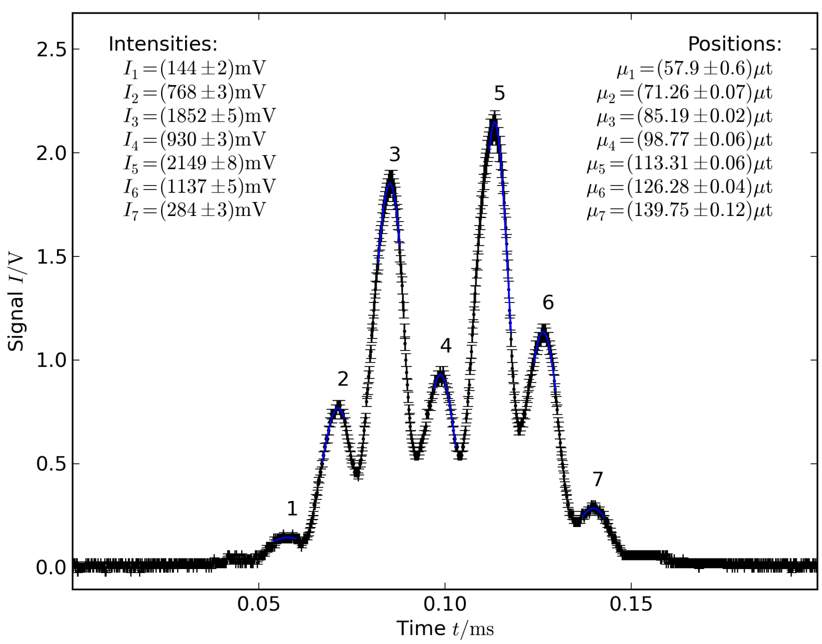

Figure 30: Measured diffraction picture with the piezo voltage $U_p = 8.00$V. Peaks fitted with a Gaussian.

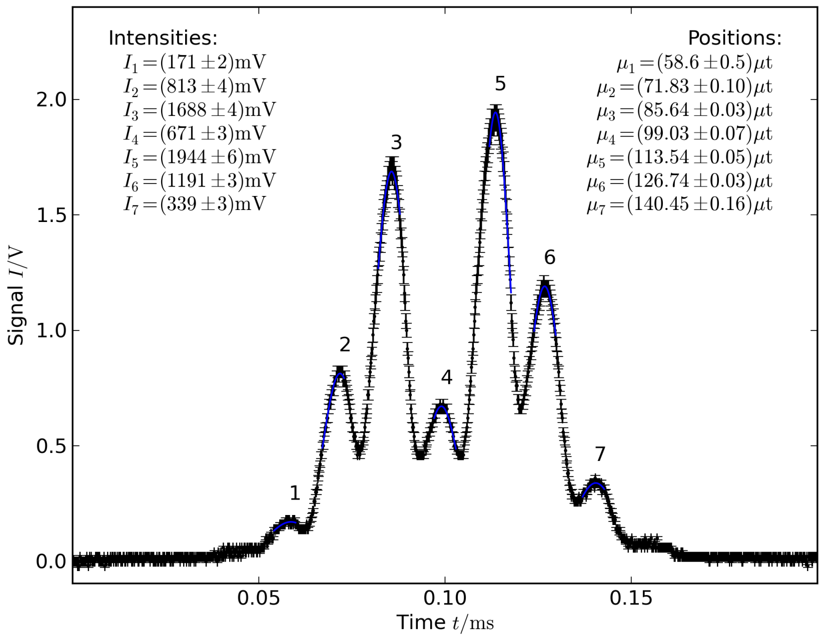

Figure 31: Measured diffraction picture with the piezo voltage $U_p = 8.50$V. Peaks fitted with a Gaussian.

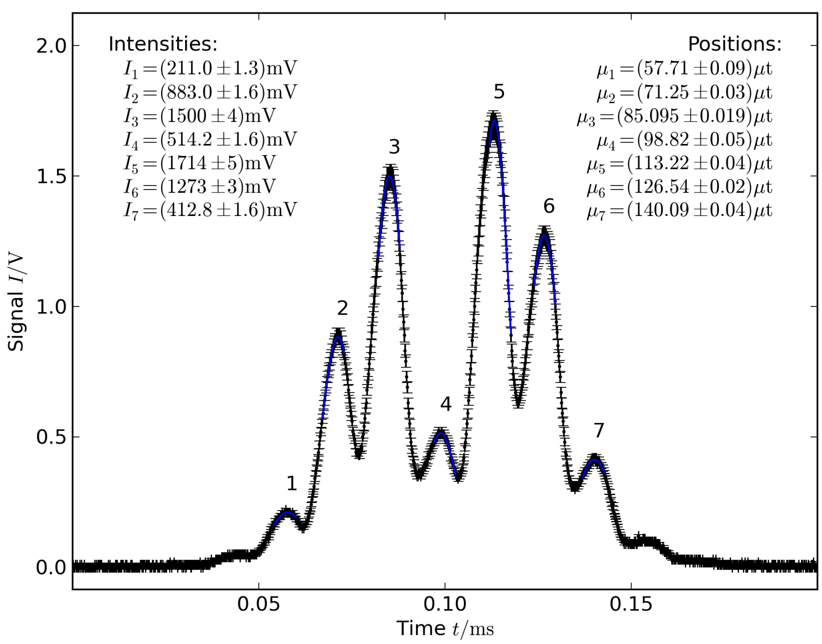

Figure 32: Measured diffraction picture with the piezo voltage $U_p = 9.00$V. Peaks fitted with a Gaussian.

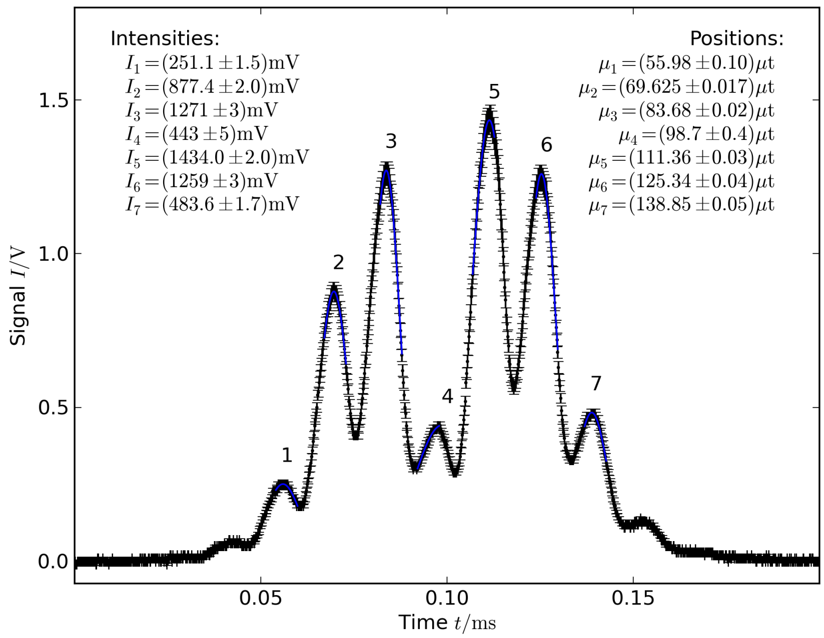

Figure 33: Measured diffraction picture with the piezo voltage $U_p = 9.50\mathrm{V}$. Peaks fitted with a Gaussian.

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