Improving light collection at the eEDM experiment

Author: G.G. Wiersema (S2952238)

November 2021

Primary supervisor: Lorenz Willmann

Secondary supervisor: Kristof de Bruyn

University of Groningen - Bachelor research project physics

Abstract

In this report the goal is to find a way to improve the light collection at the experiment concerning the electron electronic dipole moment (eEDM). The main signal in this atomic physics experiment is based on resonant photon scattering of several optical transitions in the barium monofluoride (BaF) molecule. Improving the light collection has been done by designing a light collection system which fits the spatial requirements of the already existing part of the experiment. The light collection is quantified with a Thorlabs' FDS1010 photodiode as a detector and an LED as a light source. An important aspect is that the fluorescence light of the BaF-EDM experiment is not originating from a single point, but from an extended region of about 1 cm^3. Therefore, the designed system has been tested for a number of geometries. By doing this, the light collection has been fully characterized with respect to the volume of the light source. The improvement has been determined reading up to 340 $\pm$ 10 times more than without the light collection system.

Contents

1 Introduction

The aim of the eEDM experiment is to provide a stringent limit on a permanent electric dipole moment (EDM) on the electron. An eEDM can be observed by an interaction of the electron with the electric field, where the parity (P) and time-reversal symmetries (T) are violated. According to the Standard Model, the eEDM is below the level of $d_e < 10^{-38}$ e cm [1]. Finding an eEDM above this level would mean that an extension of the Standard Model is needed.

By the CPT theorem, a T violation is equivalent to a CP violation [2]. Therefore, measuring an eEDM implies a CP violation which can contribute to the search for an explanation of the matter-antimatter asymmetry in the universe [3]. The eEDM can provide a possible explanation for the understanding of dark matter [4]. The search for an eEDM is important to improve the Standard Model and to possibly give further insight into phenomena like these.

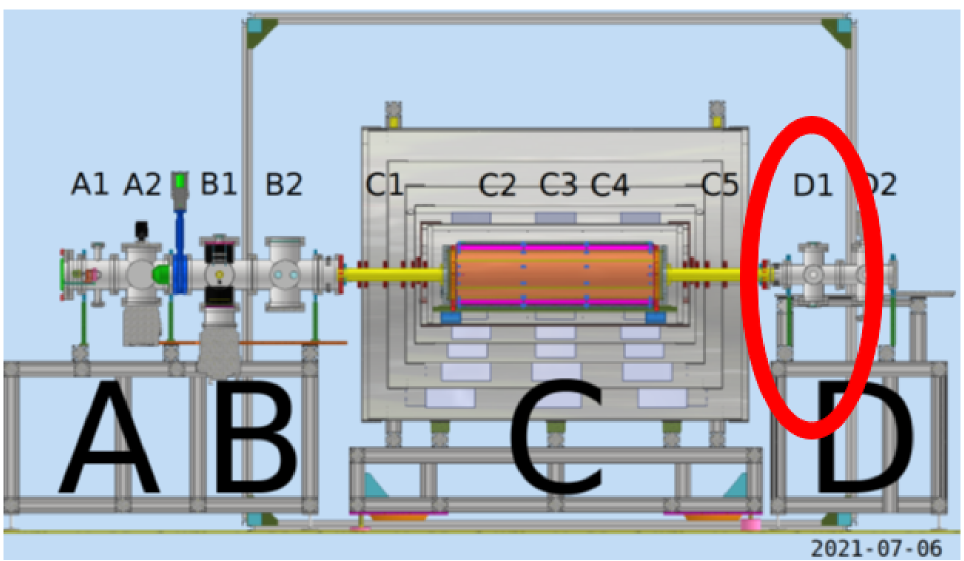

Figure 1: Schematic of the eEDM experiment, schematic made by Thomas Meijknecht. The research in this report takes place in the D1 section of the experiment as indicated by the red circle

A schematic of the eEDM experiment can be seen in figure 1. The different sections can be characterized as follows: In section A is a source for a molecular beam of BaF, section B allows for optical manipulation of the BaF beam, in section C the EDM interaction takes place and in section D the properties of the molecules are measured which allows to discern the limit on the eEDM. The details of this experiment are described in the paper: "Measuring the electric dipole moment of the electron in BaF" [2]. The goal of this report is to improve the detection of light, which takes place in the D1 section of the experiment.

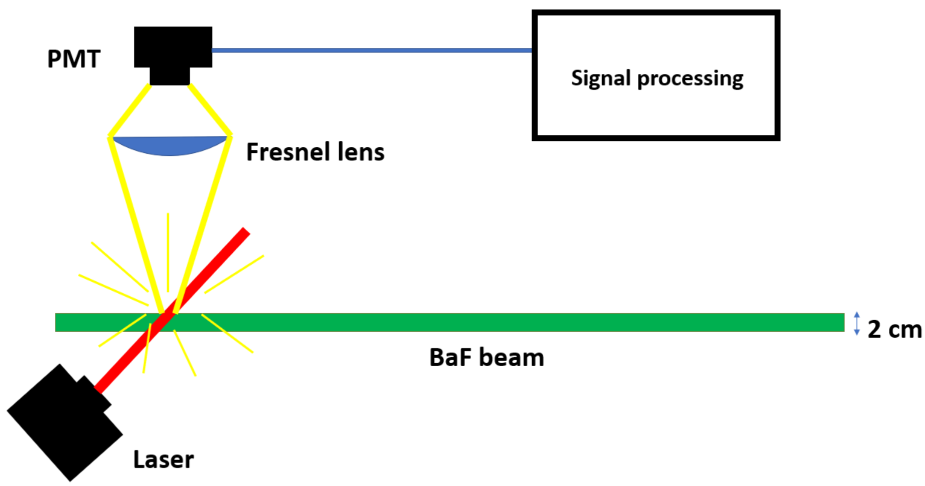

Figure 2: Detection of the eEDM experiment. The laser crosses the BaF beam orthogonally

The working of the detection can be seen in figure 2. In this it can be seen that a barium monofluoride (BaF) beam is coming in and that a probe laser beam crosses the BaF beam orthogonally. The laser induced fluorescence is the spontaneous emission of the molecule due to the excitation with the probing laser. Photons are emitted from the excited molecule and if all individual transitions can be seen, the spectrum is called the fluorescence spectrum [5]. A picture of the detection part of the experiment can be seen in figure 3.

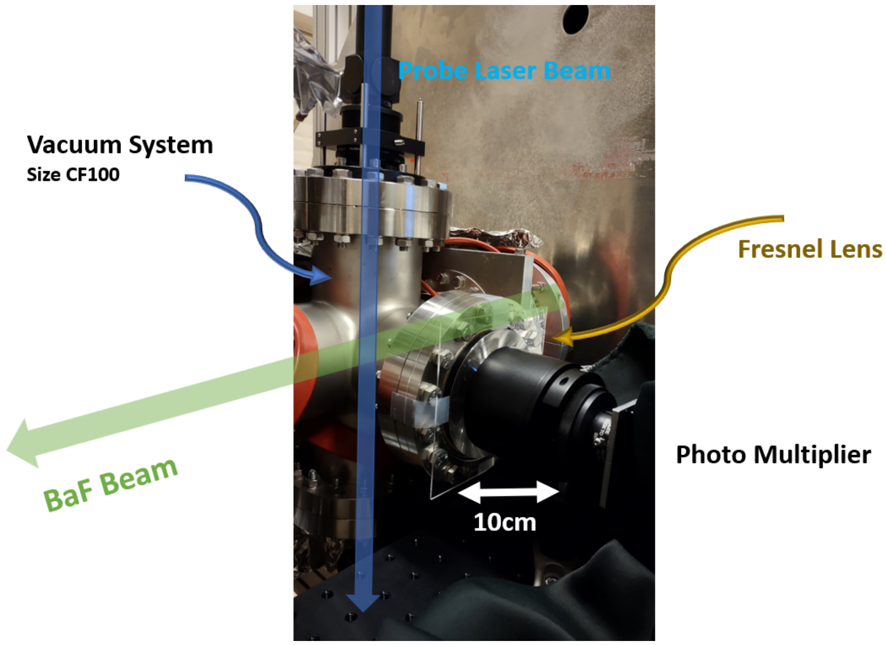

Figure 3: Photo of the detection section of the eEDM experiment

The fluorescence light is scattered in all directions. With the help of a Fresnel lens some of this light is collected onto a photo multiplier tube (PMT), which is connected to several signal processing electronics. The PMT is used in photon counting mode. The laser induced fluorescence takes place in a cross 6-way CF100 vacuum chamber, thus resulting in limited space. The Fresnel lens and PMT are placed outside the vacuum as can be seen in figure 3. A schematic of the vacuum chamber can be found in the appendix in figure 15.

The Fresnel lens only converges a small fraction of the fluorescence light onto the PMT. The goal of this report is to make this light collection more efficient in order to get a better result from the PMT.

2 Experimental setup

In order to improve the light collection several setups have been made on an optical table to measure whether it is possible to improve the light collection using different optical elements.

First of all a Thorlabs' FDS1010 photodiode [6] was used to measure the light intensity, the circuitry can be found in the appendix in figure 14. The detection area of the photodiode has a diameter of 6.9$\pm$0.2 mm. The output of the photodiode is given by the following formula:

$$V_o = P \times S \times R_L \tag{1}$$

Where V_o is the output voltage, S is the responsivity and R_L is the load resistor. From the data sheet found on the product site [6] it can be seen that the responsivity is about S=0.5 A/W for 675 nm wavelength, which is approximately the wavelength of the light coming from the LED. A load resistance of 30k Ω was chosen, because this gave approximately a 1 V voltage when the light was collected onto the photodiode with the lenses. Since the battery has a 1.5 V voltage this still gives plenty of range to measure different amounts of light intensities.

The light coming from the fluorescence in the eEDM experiment can be approximated as a spherical light source. In order to test the light collection and to improve it, a light source is needed that has an isotropic emission pattern. In this case, a red LED was used as a light source. The LED emits light in a forward direction, which is different from the fluorescence light. Therefore, the LED's light emission was determined. The LED's emission would is sufficiently isotropic to use in the experiment. The setup of this measurement can be seen in figure 4.

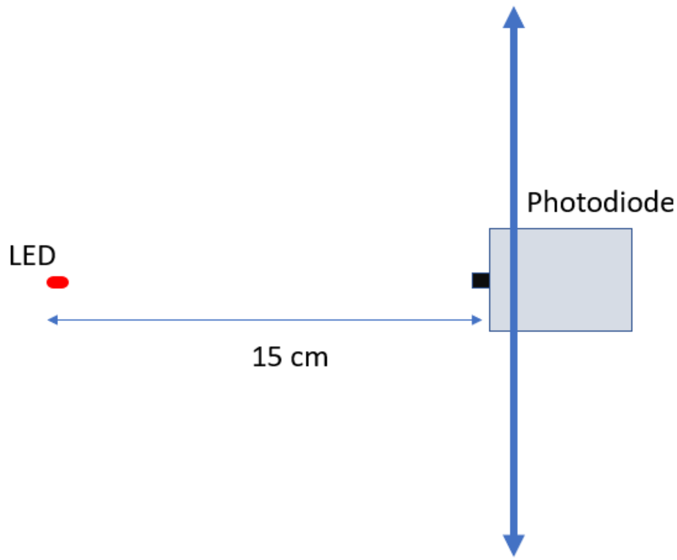

Figure 4: Measuring the angular distribution of the light emission of the LED

The horizontal distance between the LED and the photodiode was kept constant at 15.0 ± 0.1 cm. This was done because this is also the distance between the LED and the first lens in the setup used later on. The vertical position of the photodiode with respect to the light emission of the LED is then varied. This resulted in figure 5.

In the measurement with the lenses the LED was displaced by a maximum of 1 ± 0.1 cm and the lenses have a radius of 0.375 cm. This means that the maximum vertical distance from the LED to the edge of the lens will be 1.4 ± 0.1 cm.

Looking at figure 5 this means that the light intensity of the LED will be homogeneous on a level of about 2-10 percent.

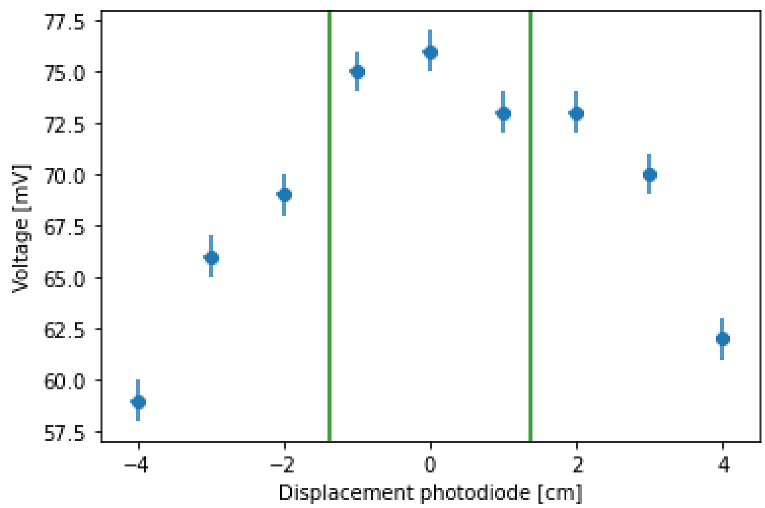

Figure 5: Light intensity distribution of the LED. Uncertainty in the voltage is about 1 mV. The green lines indicate the maximum displacement in the setup used in figure 6

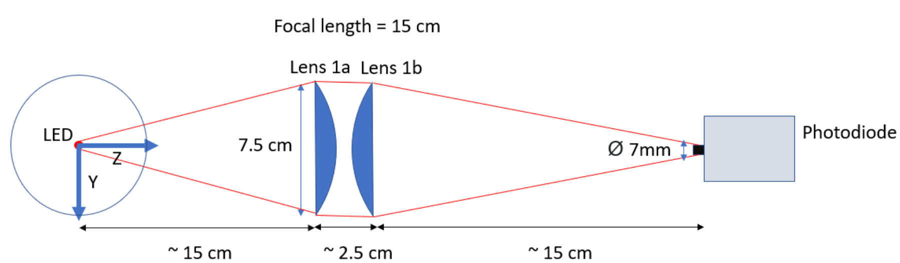

Figure 6: Setup plan: The blue circle around the LED indicates that the actual light coming from the laser induced fluorescence is much larger then the detection area of the photodiode.

The idea behind the setup can be seen in figure 6. A red LED is used as a light source. Then two plano-convex lenses are placed after it (indicated by lens 1a and 1b), both with a 150 mm focal length and a diameter of 7.5 cm. The lenses have a thickness of 11.45 mm. The lenses are coated with a visible-near infrared coating, in order to improve the transmission. This results in a reflection of about 0.5 percent for both of the lenses [7]. By using these lenses at these distances the light from the LED gets collimated by the first lens and then focused onto the photodiode with the second lens. The LED is pointed towards the lenses (along the Z direction). Then after the lenses, a photodiode is placed to measure the light intensity. The aperture of the photodiode is a circle with a diameter of 6.9 ± 0.2 mm. The aperture area is much smaller than the cross sectional area of the fluorescence light in the eEDM experiment. This is one of the major challenges and why the light improvement is measured for different positions of the LED. The photodiode is then connected to an oscilloscope in order to read out the voltage.

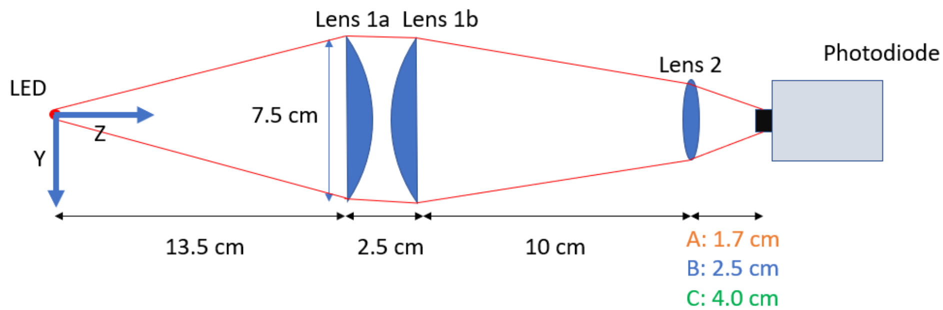

Figure 7: Setup used. The distance between the LED and lens 1a is 13.5±0.3 cm. The distance between lens 1b and lens 2 is 10.0 ± 0.3 cm. The distance between the two lenses is 2 ± 0.1 cm at the top and 2.5 ± 0.1 cm at the bottom of the lenses and the distance between lens 2 and the photodiode is 1.7/2.5/4.0 ±0.2 cm

The actual setup used can be seen in figure 7. An additional lens reduces the distance between the two large lenses and the photodiode. Lens 2 converges the beam even more for optimum light collection. The measurements are done for different positions of the photodiode as indicated in figure 7. They are done for 1.7 cm, 2.5 cm and 4.0 cm between lens 2 and the photodiode. The mounting of lens 1a and 1b was done in an unconventional way, due to no proper mounting components being available. The lenses were clamped with several components in combination with slabs of rubber. This resulted in the bottom of the two lenses being 2.5 cm apart whilst the top of the lenses were 2.0 cm apart. In figure 8 a photograph of the setup can be seen and to see how much the relative positions of the different elements influence the light collection.

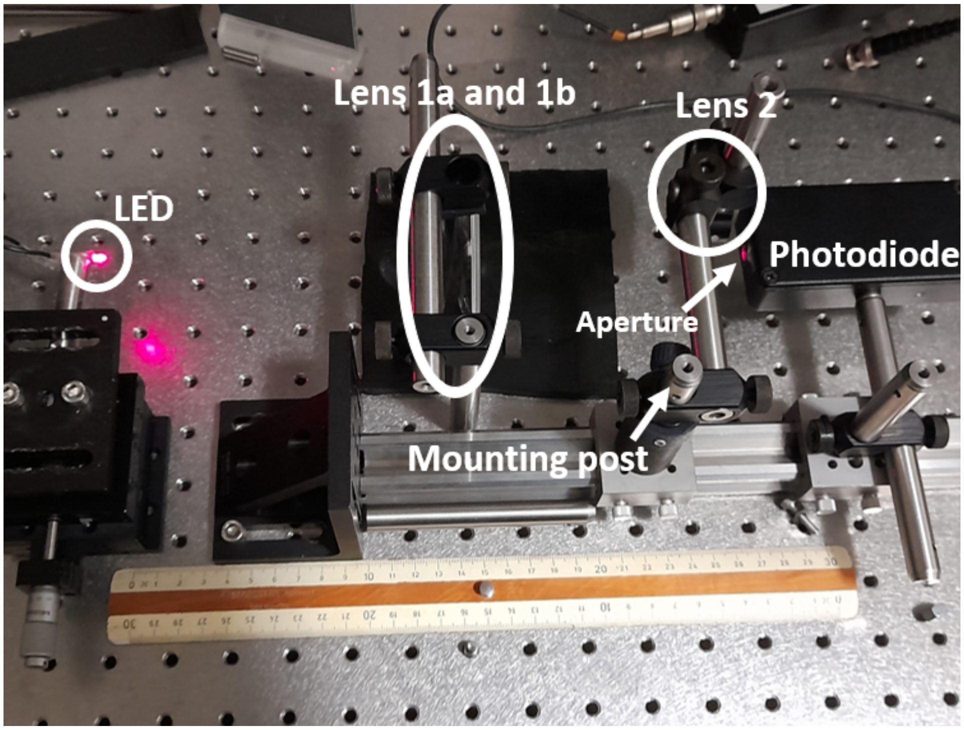

Figure 8: photograph of the setup shown in figure 7

The light intensity was measured with just the LED and the photodiode. In addition the background was measured, this background light has been subtracted from the other measured values. After this the LED's position was varied using the two translational stages which allows the LED to be moved along the Y and the Z direction as depicted in figure 7, the translational stages both had a micrometer knob which allowed for small displacements of the LED. Measurements of the light intensity were done with 1 mm intervals up to a maximum of 1 cm displacement, because this is the range that the translational stages allowed for. This is done because the light in the actual experiment also isn't a perfect point source, but a light source of about 2 centimeters wide. This set of measurements has been done 3 times, one time for each of the different distances between lens 2 and the photodiode as shown in figure 7.

By using the lenses and the setup as shown in 7, the solid angle is increased and therefore the amount of light collected upon the photodiode. The ratio of the solid angle with and without the lenses has been calculated. The solid angle of the setup in figure 7 can be compared to the solid angle when having no lenses at all. This is done using the following formula:

$$\Omega = \frac{Area}{r^2} \tag{2}$$

When calculating the solid angle when having no lenses at all, the area is the area of the photodiode aperture and r is the distance from the LED to the photodiode. For the case with the lenses, the area is the area of the lens and r is the distance from the LED to the lens.

The diameter of the aperture of the photodiode was estimated based on figure 8, the aperture is visible on the figure as an area illuminated by the red LED. The size in pixels has been compared to the size of pixels of a known object. In figure 8 the mounting posts are known to have a diameter of 12.7 mm, thus this is chosen as the reference object. Using this method the diameter of the aperture was calculated to be $\frac{12.7*37}{68} = 6.9\pm$ 2 mm, so an error of about 3 %.

Using this result and equation 2 results in a solid angle for just the LED and the photodiode at a total distance of 28 cm of:

$$\Omega_0 = \frac{\pi 3.5^2}{280^2} = 4.9 * 10^{-4} \text{ Sr} \pm 6\% \tag{3}$$

The radius of the plano-convex lens is given by the manufacturer as 75.00 +0.0/-0.025 mm, so an error of about 0.04 %. Therefore the solid angle for the setup as seen in figure 7 is:

$$\Omega_{setup} = \frac{\pi 37.5^2}{135^2} = 0.24 \text{ Sr} \pm 0.08\% \tag{4}$$

This means that the solid angle is increased by a factor of $\frac{0.24}{4.9*10^{-4}} = 500\pm30$ times.

3 Results

First of all when setting up the setup, it could be seen that different patterns appeared for different distances between lens 2 and the photodiode. This can be seen in figure 9. In front of the focal point ($<$ 2.5 cm) a bright outer edge was formed with a more dim middle part, around the focus point (2.5

cm) a bright dot formed and after the focal point (> 2.5 cm) a bright middle part with a dim outer edge was formed.

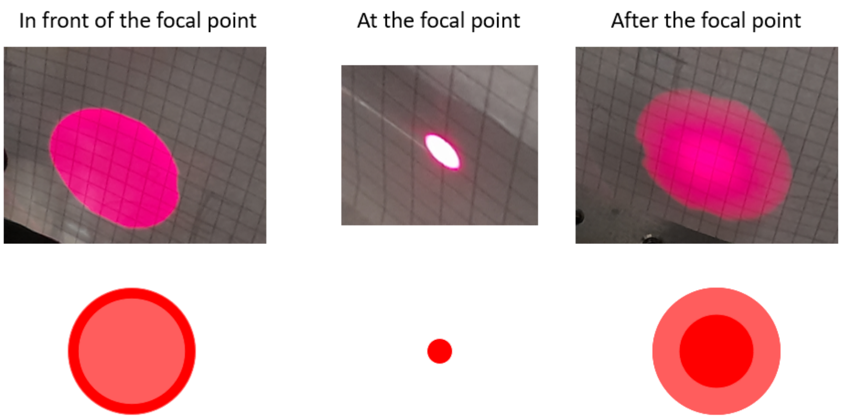

Figure 9: Above: pictures taken in the lab. Below: Schematic of what can be seen on the pictures to emphasize the differences

Next, the light was measured without adding any of the lenses, just the light from the LED reaching the photodiode. This was done for the different placements of the photodiode as indicated in figure 7. This was measured to be 4.6 ± 0.4 mV for distances A and B and 4.3 ± 0.4 mV for C. Also the background light was measured, this was found to be 1.5 ± 0.4 mV for all different distances.

Finally, the light intensity was measured for different positions of the LED with the lenses as indicated in figure 7. The LED was moved using it's translation stages. In figure 10 it can be seen which graph belong to which movement of the LED. The actual graphs can be seen in figure 11 and 12. The graph numbers correspond to the numbers in figure 10. The horizontal axis indicates the displacement distance along the corresponding arrows in figure 10, for example in graph 2 the LED starts out in the top right corner and is displaced towards the bottom right corner with steps of 1 mm up to a total displacement of 1 cm. The vertical axis in the graphs indicate the light improvement in comparison to having no lenses at all. The errors in the graphs are too small to be visible. The background light was subtracted from all data.

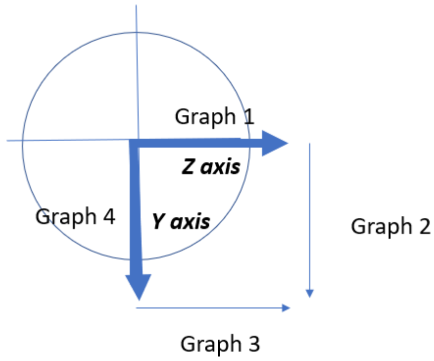

Figure 10: Measurement directions, each graph is a measurement where the LED is displaced along the corresponding arrow

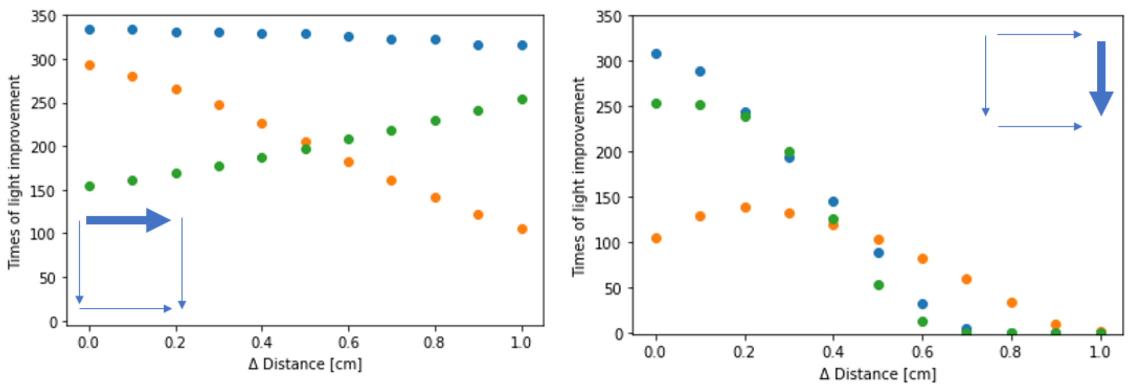

Figure 11: Graph 1 and 2 . Corresponding to figure 10. The different colors correspond to the distances between lens 2 and the photodiode as indicated in figure 7. Orange = 1.7 cm, blue = 2.5 cm and green = 4.0 cm

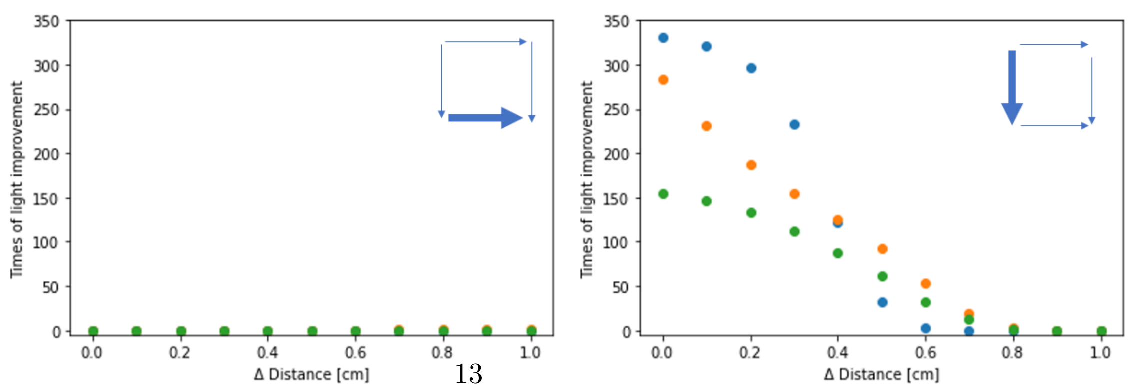

Figure 12: Graph 3 and 4. Corresponding to figure 10 The different colors correspond to the distances between lens 2 and the photodiode as indicated in figure 7. Orange = 1.7 cm, blue = 2.5 cm and green = 4.0 cm

4 Discussion

The patterns in figure 9 are likely to be caused by spherical aberration. This is due to flaws in the lenses where not all incoming light rays are converged to a single point. The rays close to the center are more or less converged in comparison to those closer to the edge of the lens. This results in multiple focus points. Figure 13 shows this schematically. In our case, the rays on the edge of the lenses seem to get more converged, thus resulting in a bright outer edge for the pattern in front of the focal point. Part of this might also occur because lens 1a and 1b are not perfectly parallel. Due to the unconventional mounting it was difficult to get the lenses properly aligned. In the end the bottom part of the lenses were separated by 2.5 cm and the top part by 2 cm.

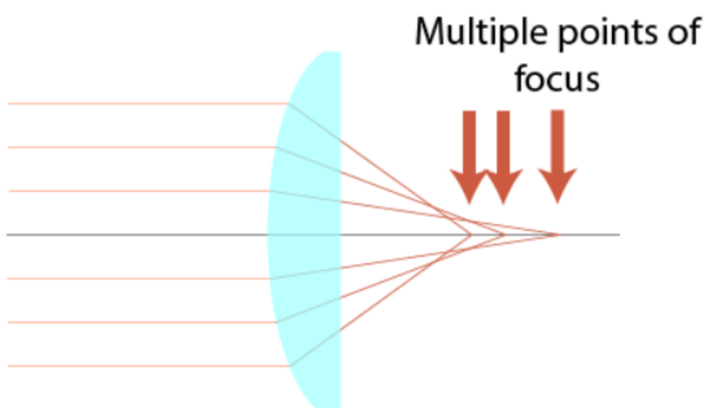

Figure 13: Spherical aberration [8]

Considering the graphs in figure 11 and 12 it can be seen that the light collection is indeed improved quite much, although not for all positions of the LED. In graph 1 all positions seem to have a great light improvement with this setup. For the blue line this goes up to a light improvement of 340 $\pm$ 10 times. The green line is increasing because this is the position after the focal point where the center is really bright and the outer edge more dim. The orange line is decreasing, because this is in front of the focal point where the outer edge is more bright. In graph 2 a bump in the orange line can be seen, this is due to one of the rings moving in front of the photodiode and then moving past it.

Graph 3 shows a really low signal for all three measurements. This means that light coming from this direction is barely captured at all with this setup. In order to increase this, perhaps a larger lens can be used in order to increase the solid angle or a photodiode with a larger detection area can be used to capture more of the light, although this may also increase the amount of noise. Graph 4 also shows a steep decline for all three measurements.

All in all the graphs show very different results in terms of light improvement, whilst graph 1 shows a light improvement of up to 340 $\pm$ 10 times, graph 3 shows no improvement at all. With the solid angle being improved by a factor of 500 $\pm$ 30 times by using the lenses as shown in equation 3 and 4, and the light improvement getting better by a factor of 340 $\pm$ 10 times in the ideal position, this means that the setup has an efficiency of about $\frac{340}{500} * 100 = 68 \pm 5$ %, which is more than is expected from the currently used Fresnel lens in the eEDM experiment.

5 Conclusions

The lenses used cause spherical aberration to occur. Better lenses can be used in order to minimise this. Better alignment of the lenses might already improve this, but in order to test this the lenses will need to be mounted in a different way.

The light collection can indeed be greatly improved with this setup. Although it will not improve the light coming from all directions. In graph 3 it can be seen that light detection coming from this direction is not improved at all. Light coming from a different parts of the light volume may hold different valuable information for the experiment, thus it may be needed to also increase the light capture of the light coming from the direction as measured in graph 3. This may be done in several different ways. A different photodiode can be used which has a larger detection area, the disadvantage of this will probably be that also more background light will be captured, resulting in a more noise in the signal. Another solution might be using larger lenses in order to increase the solid angle even further, although this is limited by the window where the BaF beam passes through which has a diameter of about 85 mm. All in all, light collection has been fully characterized by using the method in this report and the lenses show a promising light improvement of up to 340 $\pm$ 10 times.

6 Future perspective

For implementation into the real experiment, several more things can be done. First of all testing could be done with a Fresnel lens which is currently used in the eEDM experiment. Then it would be possible to compare those results to the results denoted in this report and to see whether the lenses used here are an improvement over the Fresnel lens that is currently being used in the eEDM experiment.

Another part that can be improved is the amount of light collected, this can be done be getting larger lenses that will increase the solid angle or be using a photodiode with a larger detection area, although this might also increase the amount of unwanted background light measured. Finally, proper mounting and alignment of the different lenses may improve the measurements done in order to test the light collection and proper mounting is needed in order to implement the lenses into the eEDM experiment.

7 Acknowledgements

I would like to thank Lorenz Willmann and Kristof de Bruyn for supervising me throughout this bachelor project. Furthermore, I would like to thank Olliver Böll, Ginny Marshall and Thomas Meijknecht for helping me around the lab and Thomas also for providing the schematic of the eEDM experiment. Finally, I would like to thank the entire eEDM team.

References

[1] A. Ritz M. Pospelov. "Electric dipole moments as probes of new physics". In: *European Physical Journal D* 318.119 (2005). DOI: 10.1016/j.aop.2005.04.002.

[2] The NL-eEDM collaboration. "Measuring the electric dipole moment of the electron in BaF". In: *European Physical Journal D* 72.197 (2018). DOI: https://doi.org/10.1140/epjd/e2018-90192-9.

[3] K. Jungmann L. Willmann. "Matter-antimatter asymmetry - aspects at low energy". In: *ANNALEN DER PHYSIK* 528 (2016), pp. 108–114. DOI: https://doi.org/10.1002/andp.201500008.

[4] Lars Bergström. "Dark matter evidence, particle physics candidates anddetection methods". In: *ANNALEN DER PHYSIK* 524.9-10 (2012), pp. 479–496. DOI: https://doi.org/10.1002/andp.201200116.

[5] John W. Daily. "Laser induced fluorescence spectroscopy in flames". In: *Progress in Energy and Combustion Science* 23.2 (1997), pp. 133–199. ISSN: 0360-1285. DOI: https://doi.org/10.1016/S0360-1285(97)00008-7. URL: https://www.sciencedirect.com/science/article/pii/S0360128597000087.

[6] Thorlabs. *FDS1010 - Si Photodiode*. 2021. URL: https://www.thorlabs.com/thorproduct.cfm?partnumber=FDS1010 (visited on 11/07/2021).

[7] Edmund optics. *Product page plano-convex lenses*. 2021. URL: https://www.edmundoptics.com/p/750mm-dia-x-1500mm-fl-vis-nir-coated-plano-convex-lens/29335/ (visited on 11/01/2021).

[8] Teledyne Lumenera. *minimizing spherical aberration: make the right lens choice for your imaging system*. 2021. URL: https://www.lumenera.com/blog/minimizing-spherical-aberration-make-the-right-lens-choice-for-your-imaging-system (visited on 11/01/2021).

8 Appendices

8.1 Schematics

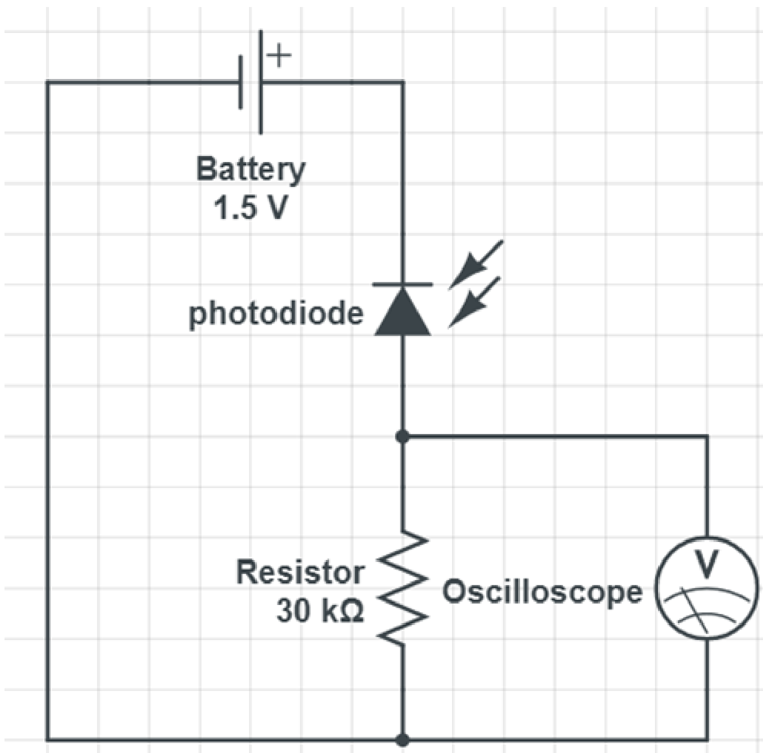

Figure 14: Circuitry of photodiode. The 3 resistors used were a resistor of 50k Ω, 10k Ω and 330k Ω all placed in parallel. For simplicity the schematic depicts a single resistor with a resistance equivalent to the 3 parallel resistors

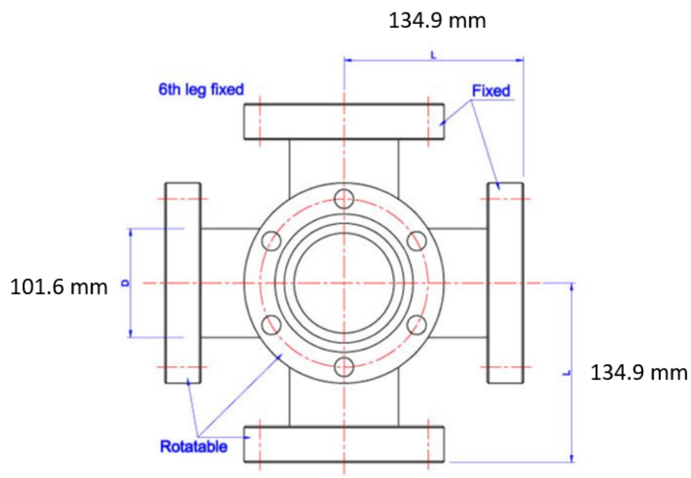

Figure 15: CF100 vacuum chamber, picture taken from URL: https://www.hositrad.com/