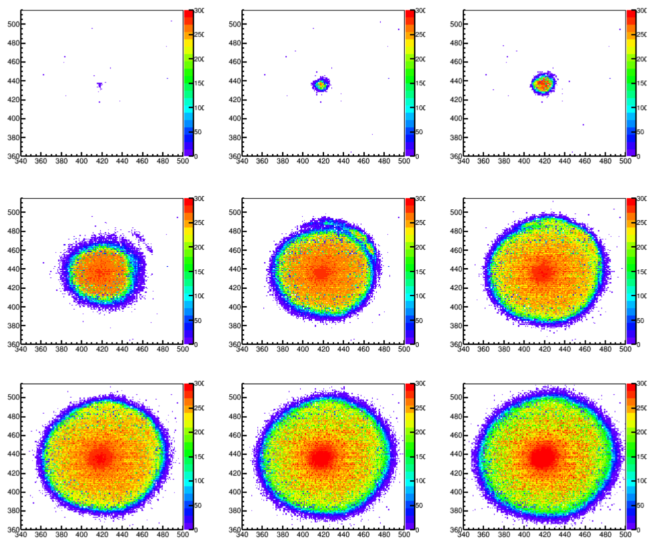
Testing the sensitivity of a Monolithic Active Pixel Sensor using an LED light source

Author: Sarah Kok
Studentnummer: 4021312

Supervisor: dr. ir. G.J.L. Nooren and dr. ir. M. van Leeuwen



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Abstract

The purpose of this experiment is to test the sensitivity of the sensor that is used in the Forward Calorimeter (FoCal). This is a prototype for a new proposed detector that can measure photons in the ALICE experiment, which is located in CERN Switzerland, in the forward region. In this experiment a Light Emitting Diode (LED) was used to send light pulses to the sensor instead of particles. There were two areas on the sensor that the LED was directed to, area A was on the right side of the sensor and area B on the left. The light output of the LED were varied and measurements were made on both areas. The result was that the occupancy at area A was more than area B when the threshold was V_{ref2}=76. The occupancy at area A was less than area B when the threshold was V_{ref2}=85. The noise and signal at different V_{ref2} values suggest that the is a correlation between the two.

Contents

1 Introduction

The ALICE experiment is used to study the QGP (Quark Gluon Plasma) which is produced when two lead nuclei are collided by the LHC (Large Hadron Collider). By studying the behaviour of the QGP, which has a very high energy density, the properties of the strong interaction will be further understood.[1]

A new electromagnetic calorimeter is proposed as an upgrade at the ALICE experiment to detect photons in the very forward angles. This detector can separate close-lying electromagnetic showers and reconstruct their direction with high accuracy. It is expected that the calorimeter can separate direct photons and photons from π^0 decays. The name for this detector is the FoCal (Forward Calorimeter).[1]

This experiment described in this thesis will be about the sensor that is used in the FoCal prototype. The calorimetric energy can be measured by the number of pixels that are above a predefined signal threshold.[3] This experiment tests if the energy measured from the sensor depends on where the particles hit the sensor. This chapter will be an introduction to the experiment.

1.1 The sensor

The sensor used in the FoCal experiment is a PHASE2 Mimosa23 chip which is the only full size MAPS (Monolithic Active Pixels Sensor).[2] The total surface of the sensor is 19.52×20.93 mm^2 and the surface of the pixel matrix of the sensor is 19.2×19.2 mm^2, see figure 1. The pixel matrix of the sensor has 640×640 pixels which are divided in 640 rows and 640 columns. The area of one pixel is 30×30 μm^2. One pixel has a charge collection diode and a built in amplifier.[1] The sensor is a silicon detector which has a band gap of 1.11 eV[3], but to create charge in the sensor particles that hit the sensor need to deposit an energy of 3.67 eV.[3]

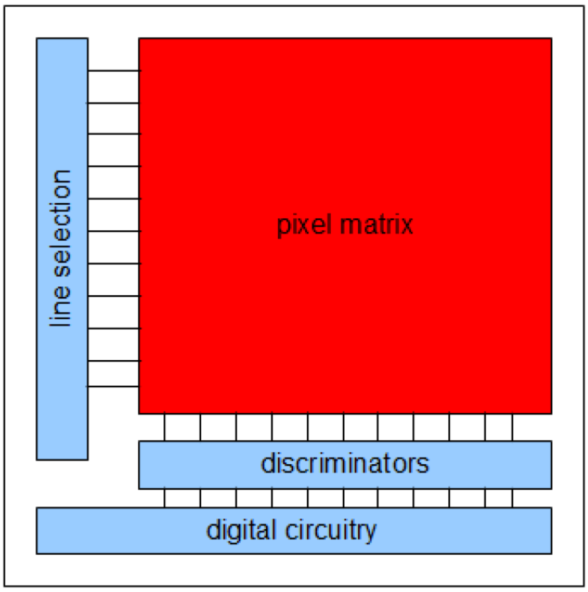

Figure 1: A basic layout of the sensor: The red area is the pixel matrix and at the bottom of the layout the discriminators are connected to the columns in the pixel matrix.[1]

The sensor reads the data, line for line and converts the charges in the pixels to digital signals. This is done by the discriminators that compare the signal to a threshold. The parameter V_{ref1} sets the threshold and V_{ref2} influences the positional dependence of the threshold.[1]

Because all the columns are divided into four outputs at 160 MHz it can be continuously readout. A full readout of all the pixels with 160 MHz$\times$4 takes 642 μs and is called one frame.[1]

1.2 Electromagnetic calorimeter

A calorimeter is a device that can measure the energy of particles. This can be done by measuring the energy loss of particles in the medium of the calorimeter. So the calorimeter does two things, firstly it makes the particle lose energy, the part of the calorimeter responsibly for this interaction is called the absorber, and secondly it measures the energy loss, the part that obtains the energy loss is called the sensor.[1]

There are two types of calorimeters, the hadronic- and electromagnetic calorimeter. The hadronic calorimeter measures mostly by strong nuclear force and the electromagnetic calorimeter mostly by the electromagnetic interaction. The electromagnetic calorimeter measures electrons, positrons and photons.[2]

In figure 2 there is an early example of a calorimeter: a Wilson chamber with lead plates. Cosmic rays enter the chamber and interacts with the absorption layers and creates a particle shower. There are three lead layers, 6 cm apart, the top two are 0.63 cm thick and the lower one is 0.07 cm thick. This arrangement provides a good method of studying the growth of showers. With every layer more particles are created and counted between the layers. The figure shows the tracks of the particle shower.

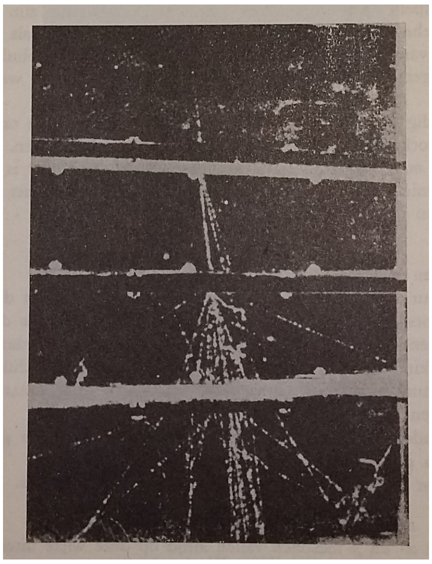

Figure 2: Development of a particle shower in a Wilson chamber with three lead plates.[4]

1.3 The FoCal Prototype

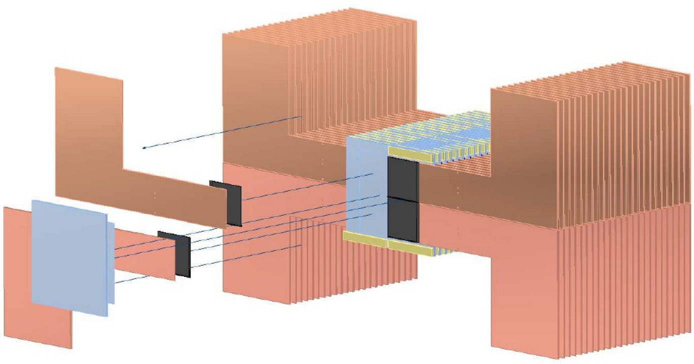

Figure 3: The inner structure of the FoCal prototype. The light grey is the tungsten absorbers, black the sensors and brown/pink the PCB's.[1]

Figure 3 shows a schematic view of the layers inside the prototype of the FoCal. The prototype consist of layers of tungsten were particle showers are created. Tungsten is chosen because of the high density which shows to have a higher chance of interaction with a charged particle than a low density material. Every layer has 2 by 2 sensors. This is because one sensor is too small to effectively show the profile of the showers. The sensors from one layer have 2 tungsten plates, with an area of 50×49.85 mm^2 and thickness of 1.5 mm at both sides.[1] Two of the sensors of one layer are facing upwards and the other two are facing downwards. Every sensor is connected to a PCB (Printed Circuit Board) which are then again connected to the tungsten plates. The PCB's are connected to cables and transfers the data to the Bergen boxes where the data is collected in a memory buffer, this buffer can contain around 814 frames. So the data generated by the sensor is not directly sent to the computer. This would be too much and so there is an interface between the sensor and computer, the data acquisition system. With the data acquisition system the data that is stored in a memory buffer can be collected and a pedestal with hitmaps can be drawn.[2]

2 Measurement method

When particles hit an area on the sensor it is not certain if the total number of hits measured will be the same number of hits if the same particles were to hit the sensor at a different area on the sensor. So for this experiment measurements will be taken for two different areas of the sensor and the results will be compared to each other. The initial threshold over the sensor will then be changed to a different threshold and the same measurements will be made and also these results will be compared to one another.

2.1 Using light instead of particles

To make measurements with the sensor energetic particles are needed. There are two ways to get energetic particles: at a particle accelerator and cosmic rays. The first option is a very expensive option and not practical for a bachelor thesis. So the first option is not a good idea. Then there is the second option, which is moneywise ideal since cosmic rays are free. But a high energetic cosmic particle does not hit the earth surface often, for example a muon hits the earth surface at cm^2 per minute. Since the sensor has an active area of 19.2×19.2 mm^2 the measurements will take a long time. The time that is available for this bachelor thesis makes it impossible to make enough measurements to get a reasonable result. So to do this experiment another way to make measurements has to be found.

Visible light has wavelengths in the range from 380 to 780 nm. In energies this is from 1.59 eV to 3.26 eV. The sensor is a silicon detector and the energy needed to free an electron for this is 1.11 eV. So all visible light will have enough energy to create an electron-hole pair. Also the amount of light sent to the sensor can be regulated and the area on the sensor where the light hits can be easily changed. The light source used is a LED (Light Emitting Diode) which sends light pulses to the sensor. Per measurement the charges through the LED will be changed, the assumption is that this correspond with the amount of light emitted to the sensor.

2.1.1 The electric circuit

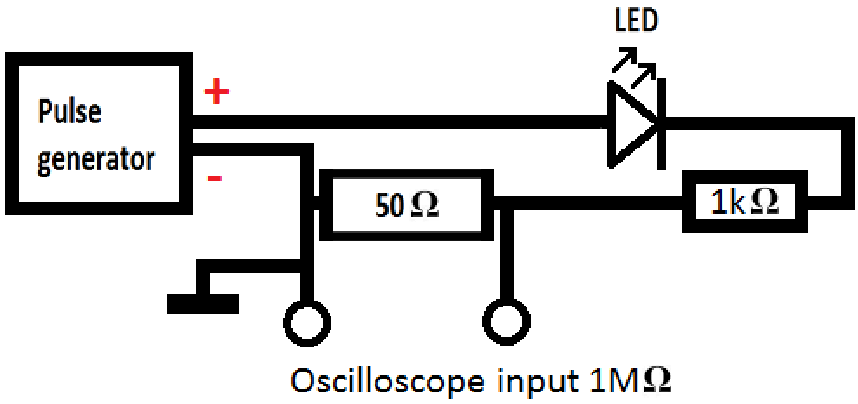

Figure 4: Schematic of the LED circuit

Since the pulse generator sends a signal to the LED every 1920 μs and one frame takes 642 μs, the maximum fraction of hits a pixel can have is: $\frac{642}{1920} = 0.33$.

The reason that there is chosen for 1920 μs is because when a pixel measures a hit and when the same pixel measures another hit the next frame it will then show that the pixel did not get hit. To get rid of this effect the pulses send needs to be at least twice the length of the 642 μs. To be certain that the signal measured is really is a hit or no hit there has been chosen to send a pulse once every three frames.

Figure 5: Screen of oscilloscope: the pulse to LED

To measure the charge through the LED an oscilloscope was used, see figure 5. Since the pulse has a square shape the total charge in the LED is:

$$Q = \frac{V \times T}{R} \tag{1}$$

Where the Q is the charge, V is the voltage, R is the resistance and T the width of the pulse. To change the charge over the LED only the pulse width sent from the pulse generator was changed.

On the screen of the oscilloscope in figure 5 the width of the pulse is T and the height V. The current through the LED is 8.9 ± 0.3 mA. The uncertainty was determined by calculating the largest and smallest possible value for the current.

2.2 Comparing the two positions

Per measurement around 814 frames are taken. After the measurements a hitmap can be drawn, see figure 6. This shows how many times a pixel is hit in that measurement. In total the maximum number a pixel can be hit is 0.33×814. The colour scale on the right of the hitmap shows how many times the pixel was hit in all the 814 frames.

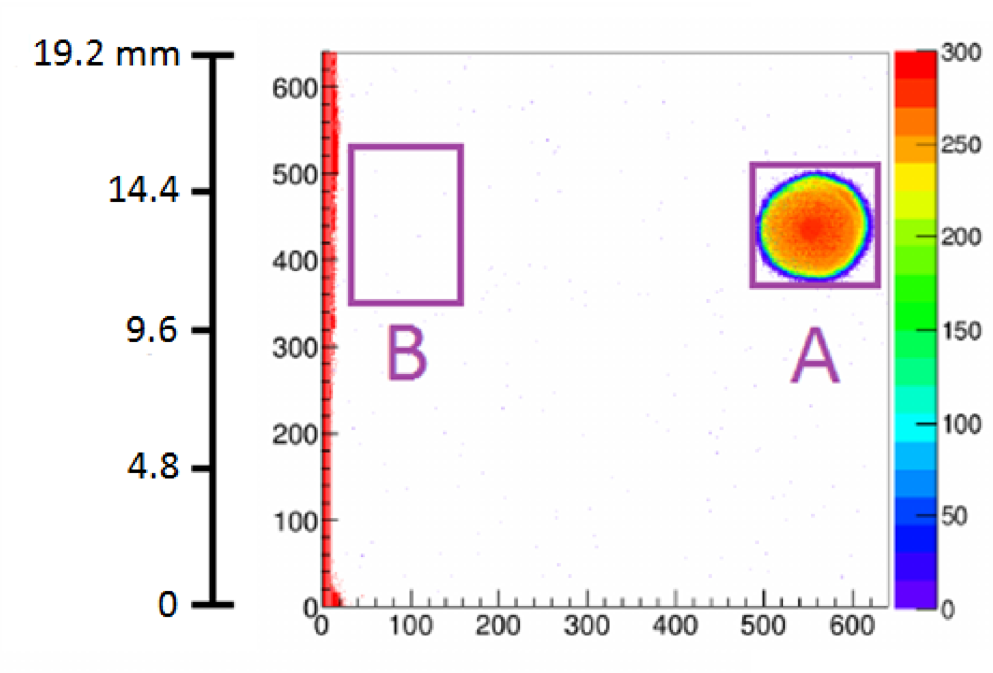

Figure 6: Hitmap at threshold V_{ref1}=170 and V_{ref2}=76 for an LED charge of 1780 nC.

On the left-hand side of the hitmap there is a red line. In every measurement this red line is visible even when no light is emitted to that area. This means these pixels are broken. Since this is an unreliable area it was avoided. The numbers on the horizontal and vertical axis show the position in number of pixels.

Two areas will be compared to one another. This means that the beam of light is directed at two areas on the sensor, area A and B (drawn in figure 6). The pulse generator will send per measurement different pulse widths to the LED so that the total charge in the LED and light that is emitted to the sensor varies. Per area the same series of different charges will be used.

The occupancy of the two areas is given by:

$$occupancy \equiv \frac{N}{0.33 \times 814 \times area} \tag{2}$$

where N are all the hits in area A or B and $area$ all the pixels in area A or B. Now this can be plotted against the different charges in the LED. Also the normalized difference between the two areas are going to be calculated so that the difference in sensitivity in the sensor can be analysed. The normalized difference between the two areas is given by:

$$Normalized \quad difference \equiv \frac{occupancyA - occupancyB}{occupancyA + occupancyB} \tag{3}$$

where $occupancyA$ and $occupancyB$ are the values of the occupancy in those areas.

2.3 Compare V_{ref2} settings

The initial threshold of the sensor is V_{ref1}=170 and V_{ref2}=76. This threshold will be changed to a different V_{ref2} value so that the positional dependence of the sensor changes. The new V_{ref2} value will be decided by making first the measurements of only the noise of the sensor, see figure 7. The initial threshold is the top right of the hitmaps.

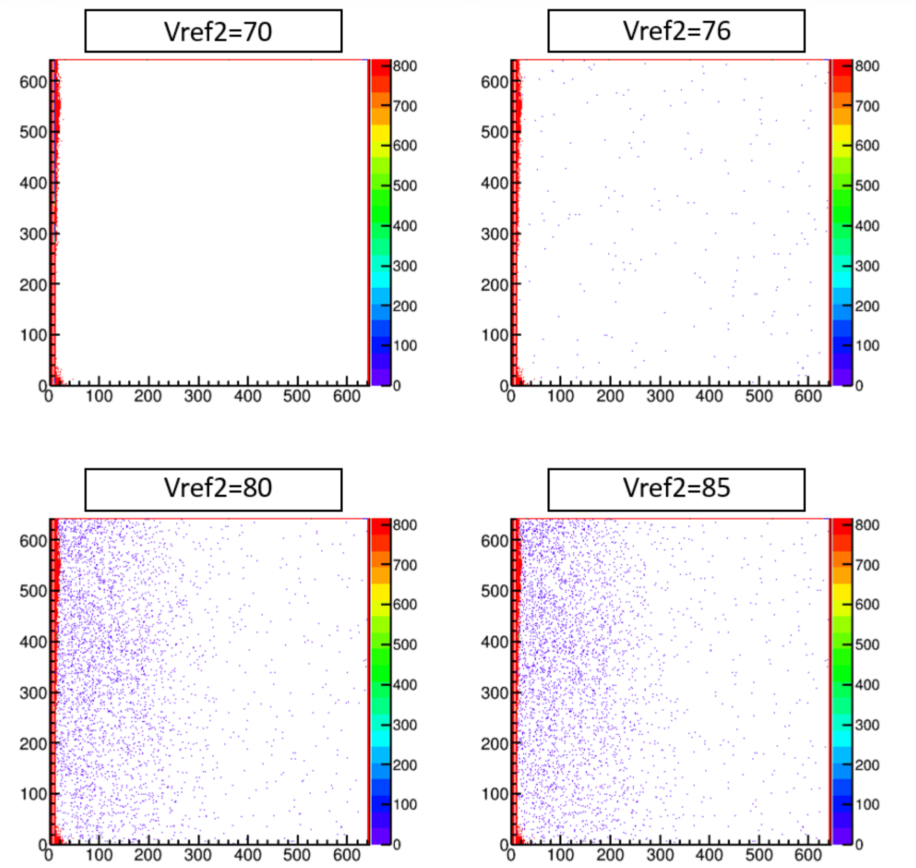

Figure 7: Noise at different threshold values of V_{ref2}

When V_{ref2} is changed the noise will change also, for V_{ref2}=80 and V_{ref2}=85 the noise on the left side of the sensor is more than on the right side.

The thresholds V_{ref2}=76 and V_{ref2}=85 are chosen because of the large positional dependence. The measurements are done over area A and B at both thresholds.

3 Setup of the experiment

3.1 Setup

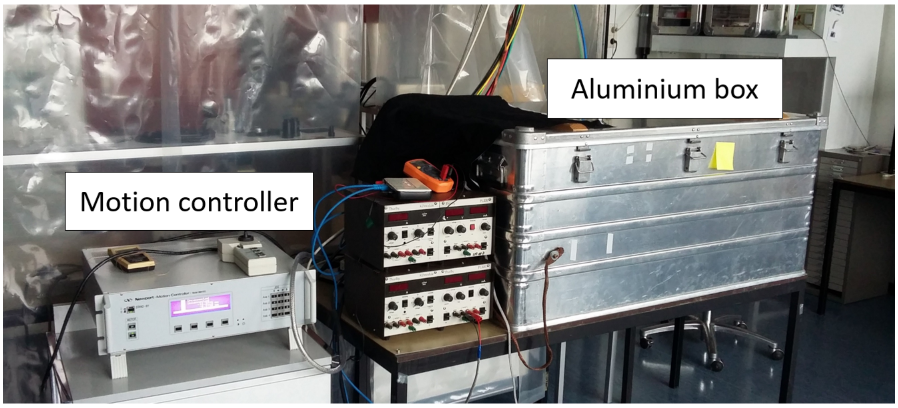

Figure 8: Outside of the setup

Figure 8 is a picture of the outside of the setup. The sensor and LED are inside the aluminium box. When measurements were made the box was closed to prevent external light to interfere with the measurements. The device on the left is the motion controller. This can be used to change the position of the LED with respect to the sensor, in figure 9 this is the x and the y axis.

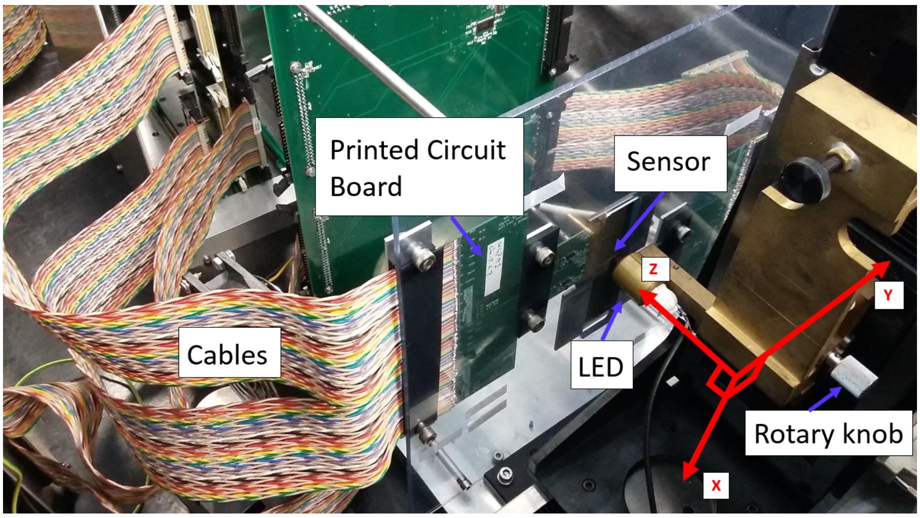

Figure 9: Inside of the aluminium box. The x and y coördinate of the motion controller.

Figure 9 is a picture of the inside of the aluminium box. The LED is placed in a tube and is perpendicular and directed to the sensor. The distance between the LED and sensor, which is in figure 9 the z axis, can be changed by the rotary knob.

3.2 Light Emitting Diode

Different LED's were used for this experiment. It was preferred that the light that hit the sensor is concentrated and has no spurious images. It would be best if the light is concentrated so that the signal from the sensor can be compared to the total light emitted from the LED. The first measurements were made using an LED that emits infra-red light and has a circular top, which works as a lens. The LED was in a plastic collimator, see figure 10.

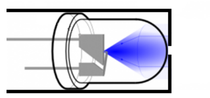

Figure 10: The layout of the LED with collimator

Figure 11 shows a result of two of the measurements that were made with this LED. In the hitmap on the left the LED is around 8 mm closer to the sensor than the hitmap on the right. The distance could not be exactly measured since the LED is in a sort of tube and cannot be seen when the LED is placed in there and the light that is emitted from the light source within the LED has to go through the lens and collimator.

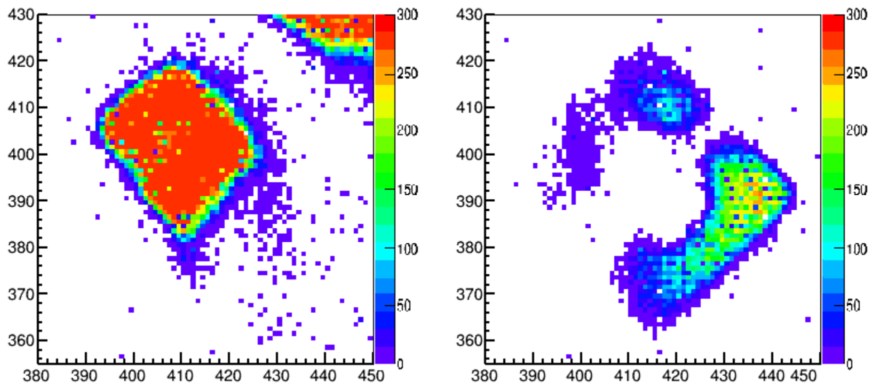

Figure 11: The LED is around 8 mm closer to the sensor in the left hitmap compared to the right hitmap.

The spot on the left hitmap shows a square like shape and in the left upper corner is a refraction from the LED visible. The right hitmap only the square spot is partly visible. When a LED is photographed from the top the light source in the LED also shows a square like shape, see figure 12.

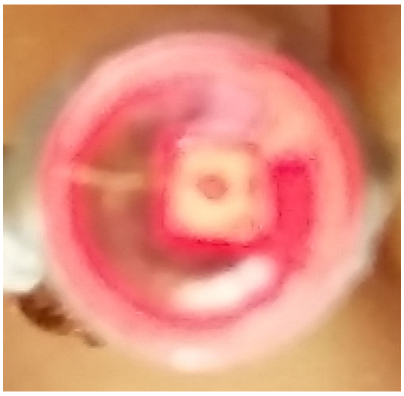

Figure 12: Picture of the top view of an LED that emits red light.

This seems to imply that the shape seen in the hitmap is the inner structure of the LED. It was discovered that the collimator that was used for these measurement had a hole in it that was not completely circular but had a more irregular shape. So a different LED and collimator were used to get rid of this inner structure and refraction.

The LED that emits infra-red light was now replaced with a LED that emits red light. It was discovered that the lens was responsible of the visibility of the inner structure. For this reason the lens was removed. The material of the new collimator is brass, and the hole in the collimator is 0.1 mm. First the hole in the collimator was 0.2 mm but then the refraction was still visible. Figure 13 shows the layout of the new LED with collimator.

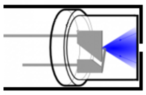

Figure 13: The layout of the LED with collimator

This did give a round spot and no spurious images were visible. In figure 6 in section 2.2 one of the hitmaps made by this LED is shown. So for all further measurements this LED was used.

3.3 Finding the areas on the sensor

Before the measurements are made on two different areas on the sensor the areas need to be determined. First a test measurement was done to see where the spot is located on the sensor. The idea is to find two areas on the sensor that are furthest apart from one another.

The largest possible spot needs to be shifted to one of the edges of the sensor. The edge that is chosen is the right side of the sensor, so the LED needs to be shifted in the x axis by the motion controller. It is known what the length is of one pixel. So from the hitmap it can be calculated how many millimetres the spot needs to shift.

Figure 14 shows the hitmaps of the measurements that were made. Three changes were made: the threshold, charges in LED and position.

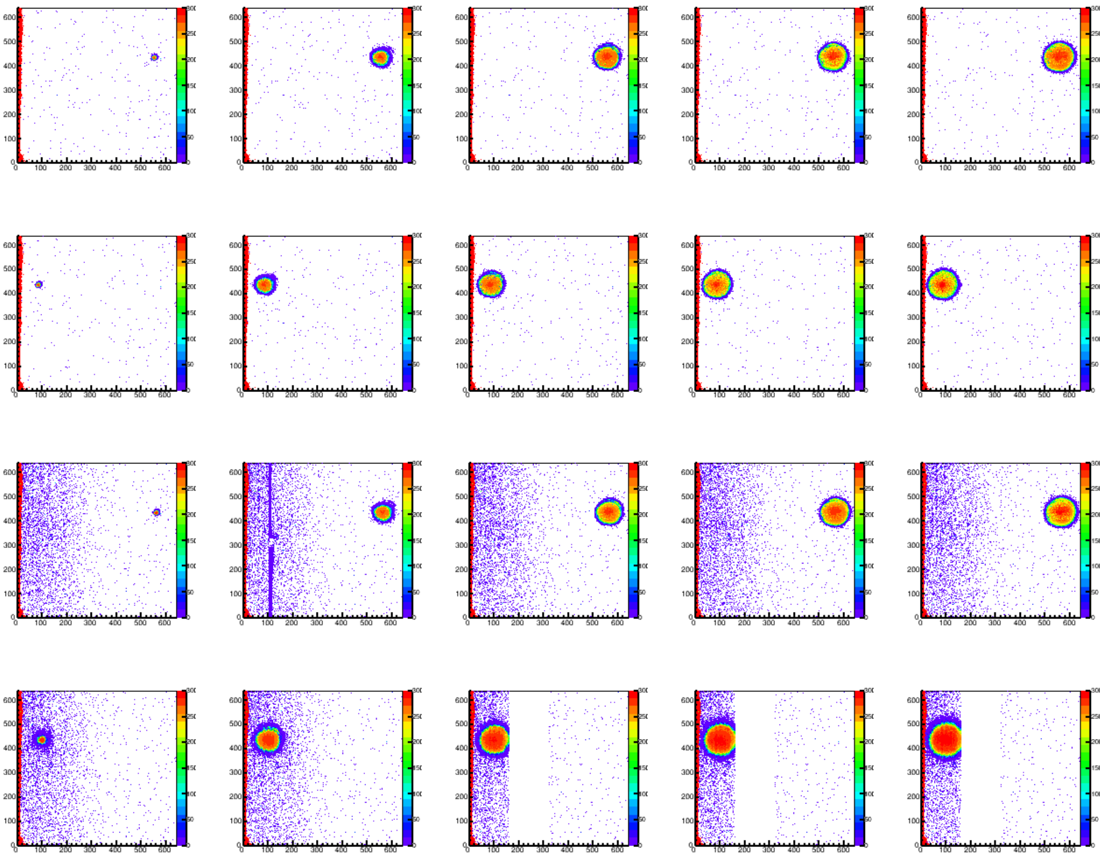

Figure 14: The hitmaps of the measurements of V_{ref2}=76 (upper two rows) and V_{ref2}=85 (lower two rows) over the two areas of charge 89, 445, 890, 1335 and 1780 nC (from left to right).

In figure 14 the upper two rows where at the threshold V_{ref2}=76 and the lower two rows at V_{ref2}=85. Now the two areas can be defined. The first and third lines of the hitmaps, the spot is on the right-hand side of the sensor, this will be called area A. The second and fourth lines of the hitmaps, are directed to the left-hand side of the sensor, this will be called area B.

Now the areas A and B needs to be defined. In figure 14 the last hitmap on every row shows that the spot is the largest of that row. So to determine the areas where all the spots fit in the area, the area of the largest spot has to be determined.

So first the two largest spots of area A at both thresholds is looked at. Figure 15 and 16 shows the two spots on the hitmap at the same region.

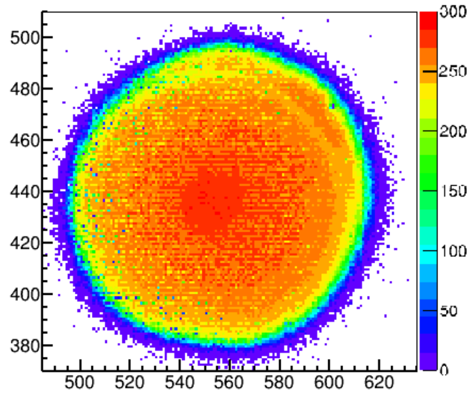

Figure 15: Area A: the region with pixel coördinates at the horizontal axis between 485 and 635, and the vertical axis between 370 and 510 at V_{ref2}=76.

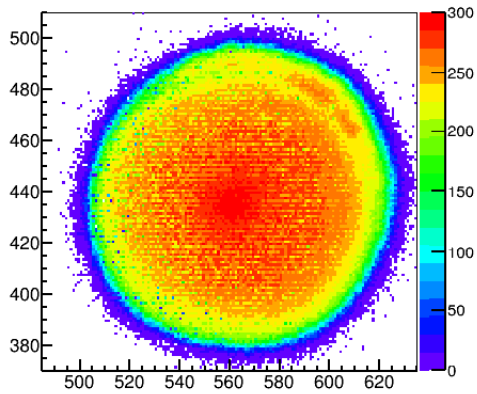

Figure 16: Area A: the region with pixel coördinates at the horizontal axis between 485 and 635, and the vertical axis between 370 and 510 at V_{ref2}=85.

So area A will be in the horizontal axis from 485 to 635 pixels and the vertical axis from 370 to 510 pixels.

Now in figure 17 and 18 the two largest spots of area B at both thresholds are going to be looked at.

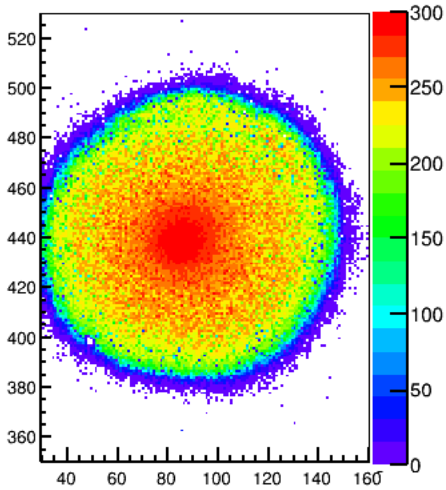

Figure 17: Area B: the region with pixel coördinates at the horizontal axis between 30 and 160, and the vertical axis between 350 and 530 at V_{ref2}=76.

In figure 17 a small part of the spot at the left-hand side is not visible. This was because there were broken pixels in that region so that part was avoided.

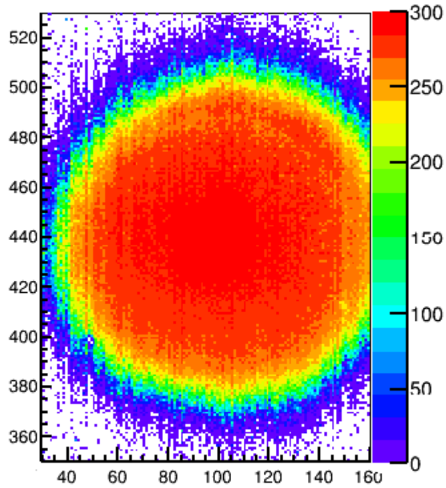

Figure 18: Area B: the region with pixel coördinates at the horizontal axis between 30 and 160, and the vertical axis between 350 and 530 at V_{ref2}=85.

In figure 18 part of the spot on the right-hand side is not visible. This was seen in figure 14 in the last row of the hitmaps. Sometimes that part of the sensor does not work and thus there will be no measurements made over that area.

So area B will be in the horizontal axis from 30 to 160 pixels and the vertical axis from 350 to 530 pixels.

4 Results

4.1 Noise

The noise of area A and B is compared in figure 19 for four threshold settings.

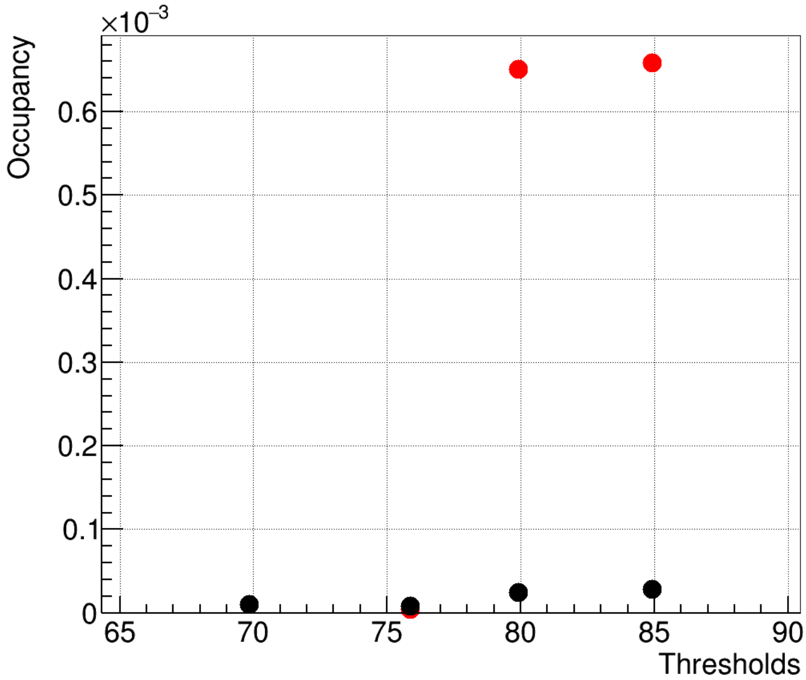

Figure 19: Background noise for threshold V_{ref2} = 70, 76, 80 and 85 of area A (the black dots) and area B (the red dots). The values at V_{ref2}=70 and V_{ref2}=76 coincide.

The occupancy of V_{ref2}=76 and V_{ref2}=85 and uncertainties are shown in table 1:

Table 1: Occupancies at Q=0

	V_{ref2}=76	V_{ref2}=85
Area A	$(8.1 \pm 1.2) \times 10^{-6}$	$(2.8 \pm 0.2) \times 10^{-5}$
Area B	$(4.9 \pm 0.9) \times 10^{-6}$	$(6.6 \pm 0.1) \times 10^{-4}$

The uncertainties are not plotted since it would not be visible in the plot.

4.2 Plots of V_{ref2}=76 and V_{ref2}=85

In figure 20 the plot is made of the occupancy over the different charges in the LED for threshold V_{ref1}=170 and V_{ref2}=76.

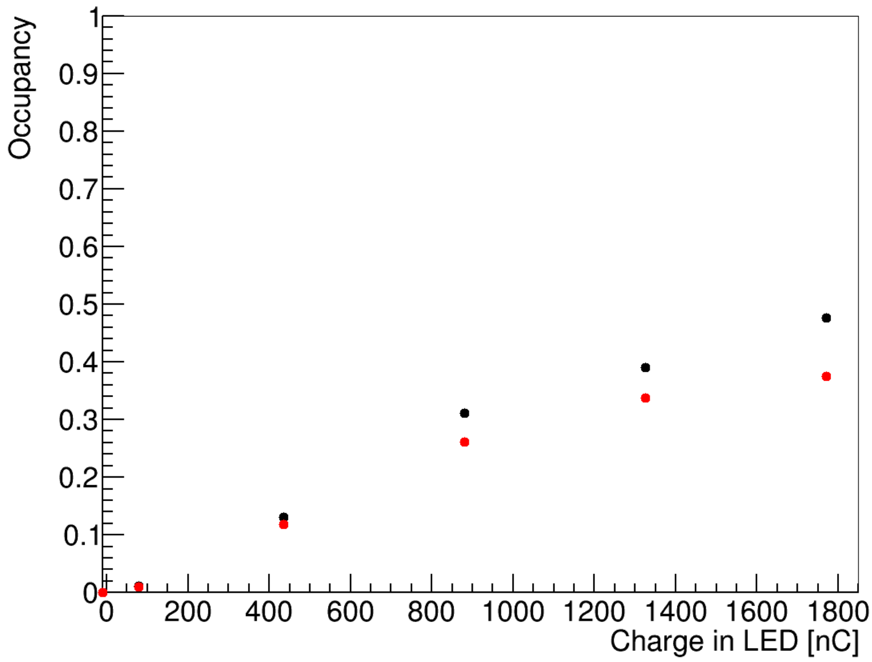

Figure 20: The occupancies of area A (black dots) and area B (red dots) for V_{ref2}=76

Area A has a higher occupancy than area B, especially when the charges in the LED becomes larger.

The different values of the occupancies at V_{ref2}=76 is shown in table 2:

Table 2: Occupancies at area A and B for V_{ref2}=76

Charge [nC]	Area A	Area B
89	0.012	0.010
445	0.13	0.12
890	0.3	0.3
1335	0.4	0.3
1780	0.5	0.4

And figure 21 is the same plot as figure 20 but with a threshold V_{ref1}=170 and V_{ref2}=85.

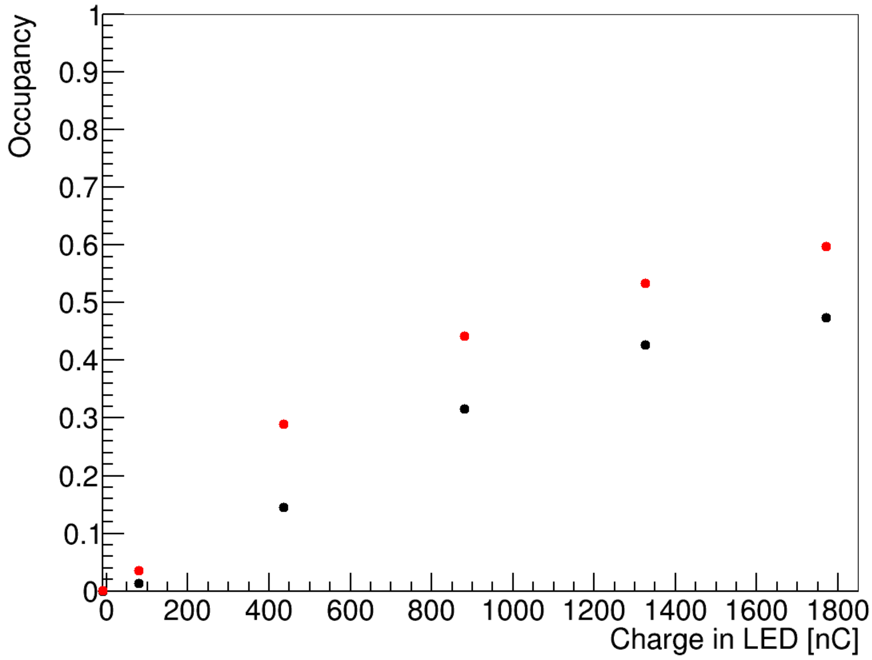

Figure 21: The occupancies of area A (black dots) and area B (red dots) for V_{ref2}=76

Now area A has a lower occupancy than area B. Also the differences between the areas are larger in figure 20.

The different values of the occupancies at V_{ref2}=85 is shown in table 3:

Table 3: Occupancies at area A and B for V_{ref2}=85

Charge [nC]	Area A	Area B
89	0.013	0.04
445	0.14	0.3
890	0.3	0.4
1335	0.4	0.5
1780	0.5	0.6

The occupancy and normalized difference have their uncertainties. Since it is a counting experiment the uncertainty of N is: $\sigma = \sqrt{N}$.

Two measurements were reproduced: area B, V_{ref2}=85, charge 445 nC and at 1780 nC. The results are shown in table 4 and 5:

Table 4: Number of hits at area B, V_{ref2}=85 and charge 445 nC

Measurement	$N \pm \sqrt{N}$
1	4696 ± 69
2	4690 ± 68
3	4705 ± 69
4	4665 ± 68
Average	4689
Standard deviation	17

Table 5: Number of hits at area B, V_{ref2}=85 and charge 1780 nC

Measurement	$N \pm \sqrt{N}$
1	2280 ± 48
2	2258 ± 48
Average	2269
Standard deviation	16

The uncertainty for the occupancy is calculated by:

$$\sigma(occupancy) = \frac{\sqrt{N}}{0.33 \times 814 \times area} \tag{4}$$

The statistical uncertainties of $Q > 0$ are equal or less than 0.05 %. Since the uncertainty is very low this would not be visible in the plots.

The standard deviation compared with the $\sqrt{N}$ is much smaller. This is because the total amount of hits are close to the average. It seems that the real uncertainty is smaller than the $\sqrt{N}$. If this were true then the statistical uncertainty for the occupancy is even smaller than the 0.05 %. But the measurements have not been repeated often so the real uncertainty is not yet determinate.

4.3 Normalized difference

Now the normalized difference between the occupancy of area A and B can be calculated. In figure 22 this is shown for all charges and both V_{ref2} values.

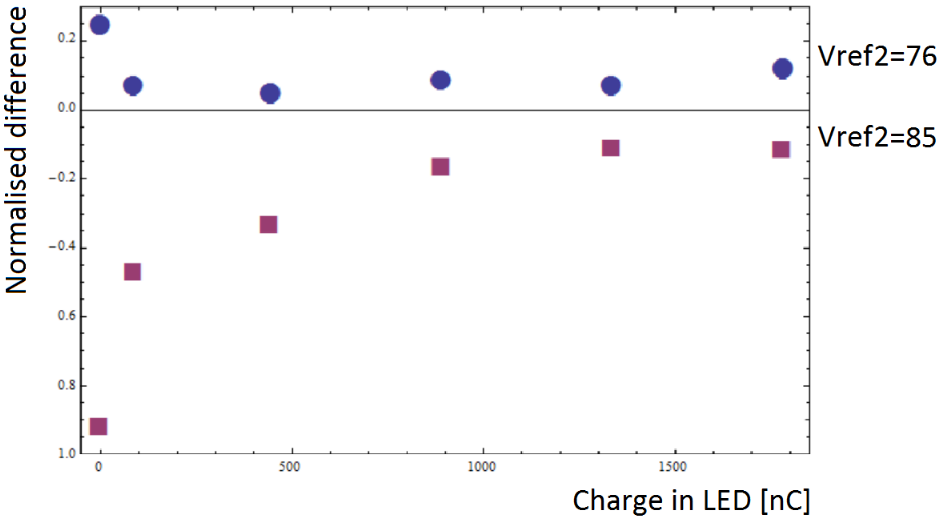

Figure 22: The normalised difference in occupancy for the V_{ref2}=76 and V_{ref2}=85 as a function of charge.

The first point of V_{ref2}=76 and V_{ref2}=85 is the noise. Since the occupancies of the noise levels are very low compared to the rest the normalized difference is higher than the rest.

For V_{ref2}=76 the occupancy of area A was always more than area B. The values for the normalized difference seems to fluctuate around the same number. Perhaps this is because V_{ref2}=76 is independent of the charge.

For V_{ref2}=85 the occupancy of area A was always less than area B. The values for the normalized difference seems to go towards zero.

5 Conclusion

The noise and signal show at different V_{ref2} values that there is a correlation between the two. This suggest that the noise level is a good measure of the sensitivity.

The research question for this experiment was: Does the signal measured from the sensor depend on the particle position on the sensor? From the measurements it seems to depend on where the particle hits the sensor. With both thresholds there is a difference in occupancy at area A and B. But it is still unclear how much the uncertainty is per measurement. To find this out the measurements needs to be reproduced and compared, then there will be a better understanding of the variation in the occupancies.

Also it is not clear how the signal depend on the position. To see how the sensitivity works on the sensor there need to be measurements made at more different thresholds. Not only does V_{ref2} need to change but also V_{ref1}. For this experiment only the difference between two areas are compared. For further measurements even more areas can be chosen and compared to one another. The sensitivity of each sensor is different so to see how the signal depend on position, threshold and charge more measurements needs to be made on the different sensor.

So to get a clearer understanding of the sensitivity of the sensor and uncertainties more measurements needs to be made.

References

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