Characterization of a modular design for a Cherenkov telescope camera

Master’s Thesis in Physics

by

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1 Introduction

Gamma ray astronomy is one of the most powerful tools to understand our cosmos. Indeed, gamma ray production is related to a whole collection of highly energetic celestial objects and events such as active galactic nuclei, supernovae remnants, quasars and gamma ray bursts (GRBs). Most of these objects were discovered relatively recently (GRBs were first detected in 1967), and the principles underlying their nature are not yet fully understood. Gamma ray astronomy has not only a huge potential in high energy astrophysics but also in particle physics, since it appeals to the fundamental interactions related to electromagnetic radiation (pair production, radioactive decay, bremsstrahlung,...etc), and cosmology, for such high energy objects are detected even with high redshift. The understanding of the different gamma ray sources and processes related to them is thus primordial for the comprehension of our universe.

Since gamma rays are absorbed by our atmosphere, the first evidence of their existence was proven by spatial telescopes, and for several years gamma ray astronomy was confined to spatial experiments only. However, relatively recent discoveries and techniques allowed ground based laboratories to contribute to this field of research throughout the last 25 years, with the rise of imaging atmospheric Cherenkov telescopes. This was a major breakthrough in gamma ray astronomy, since it opened the spectrum of observable energies beyond a few tens of GeV.

The Cherenkov Telescope Array (CTA) is the new generation project for ground based gamma ray astronomy. One of the considered design for the small size telescopes of the array is using silicon photomultiplier (SiPM) based detectors. Indeed, the success of the FACT experiment (First APD Cherenkov Telescope) highlighted the possibility of using avalanche photodiodes as photodetectors for Cherenkov telescopes, it is thus natural to consider it as a lead to investigate for the CTA design.

In this paper, we will thus be interested in a SiPM camera prototype for a possible use in CTA. We will test the different features of the modular design developed by the laboratory in order to improve our knowledge of its different components, and confirm the usage validity of such a device. Finally, we will use the camera module to detect muons via Cherenkov radiation.

2 Theoretical considerations

2.1 Imaging Atmospheric Cherenkov Technique (IACT)

Even if our atmosphere is not transparent to gamma rays, it is possible to use ground based telescopes in order to detect and characterize high energy gamma rays (above ~ 30GeV). Since the flux of photons is low at these energies, we need a big collection area for the detector, which, for obvious practical reasons, is not feasible in space. Imaging atmospheric Cherenkov technique (IACT) is the ground-based method used to detect these photons, where the earth atmosphere is used as a
calorimeter. Indeed, when a gamma ray hits the atmosphere, its interaction with a nucleus of the atmosphere creates a cascade of relativistic charged particles that will emit Cherenkov radiation detectable at ground level as flashes of light. A typical electromagnetic shower can be seen in fig (1). Electrons and positrons are produced by pair production, while photons are produced by Brehmstrahlung.

![Figure 1: A typical electromagnetic shower. The incident γ ray interacts with the atmosphere and creates a first pair of electron/positron. The two particles then emit photons by Brehmstrahlung. These newly created photons will then create other electron/positron pairs, and so forth. What we intend to detect at ground level are photons produced by Cherenkov radiation of the electrons and positrons. Note that these photons are not represented on the figure and should not been confused with the Brehmstrahlung photons, which don’t reach the ground for most of them since they first decay in $e^+/e^-$ pairs.](image)

On the ground, the light area will illuminate several hectares. Therefore, a telescope will have a comparable effective collection area (it is enough for the telescope to be in the light pool, see fig 2). In order to detect the showers efficiently, but also to have a better angular and energy resolution, large telescope arrays are used. Notable examples of such existing arrays are MAGIC in the Canaries [1] or HESS in Namibia [2]. CTA (Cherenkov telescope array), the new generation project of array [3], intends to improve the detection methods used in the current telescope arrays in order to have a better flux sensitivity. The camera we will test in this paper is a prototype for this next generation project (see details section 2.4). Let us first recap some of the basic phenomenons involved in Cherenkov radiation.

*Cherenkov radiation:*

Cherenkov radiation is produced when a charged particle travels faster than the speed of light in the traversed dielectric medium ($v > c/n$). The charged particle polarizes the molecules of the medium,
which turn then back to their ground state and emit light by doing so. In normal circumstances, the produced photons destructively interfere with each other and no radiation is detected. However, when a disruption which travels faster than light is propagating through the medium, the photons constructively interfere and intensify the observed radiation. The particle creates this way some kind of "photonic shock wave" which is detected as the Cherenkov cone of light (see fig 3). The opening angle of the Cherenkov cone is defined by $\cos(\theta) = \frac{1}{n\beta}$ where $\beta = v/c$. The frequency spectrum of Cherenkov light is given by Frank-Tamm formula, which gives (in the following form), the number of photons emitted per track length $dx$ and for a wavelength $\lambda$:

$$\frac{d^2N}{dx d\lambda} = \frac{2\pi\alpha}{\lambda^2} \left(1 - \frac{1}{n^2\beta^2}\right) = \frac{2\pi\alpha}{\lambda^2} \sin^2 \theta_c$$  \hspace{1cm} (1)
Figure 3: The charged particle emits a wavefront of Cherenkov light at an angle $\theta$, which is the angle of the Cherenkov cone.

where $\alpha = \frac{2\pi e^2}{\hbar c}$ is the fine structure constant, and $n$ the refraction angle of the medium. For the second equality, we used the fact that the Cherenkov angle is defined by $\cos(\theta) = \frac{1}{n}$. Since intensity is proportional to $1/\lambda^2$, short wavelengths dominate the spectrum (this is why Cherenkov radiation always appears as a blueish glow for the naked eye). We will have to take this into account when choosing the materials for our camera module since a material which is non transparent to UV for example would deprive us of most of the detection. It is interesting to see that the more relativistic the emitting particle is, the bigger are the intensity and angle of Cherenkov emission. Note also that the dependance on the refraction index of equation (1) indicates that we can expect an increase of Cherenkov emission intensity with atmospheric depth since n decreases with altitude.

2.2 Cosmic muons

The final purpose of the camera is to detect Cherenkov light emitted in the upper layers of the atmosphere, but in order to test the basic features of the camera module, we will first do simple tests using cosmic muons which are easier to detect directly at ground level. When a cosmic ray (mostly protons) hits the atmosphere, it interacts with the nucleons of the medium which produces a shower of particles containing, among other species, muons. In the particular case of the proton
cosmic ray impacting an atomic nuclei in the upper atmosphere, charged pions are created, which
decay then rapidly into muons and neutrinos.

\[ \pi^\pm \rightarrow \mu^\pm + \nu_\mu (\bar{\nu}_\mu) \] (2)

This is the principal source of muons at ground level and their different properties, which we will
present in this section, make them a perfect candidate for simple detection. In our final experiment,
they will produce Cherenkov light by passing through a medium, and we will detect this Cherenkov
light with our camera (see section 4 for all the details about the experiment).

Muons are the most numerous energetic charged particles at sea level. This is due to the fact
that they interact very little with matter except by ionization, their decay being mediated by weak
interaction. The average muon flux at sea level is about 1 muon per minute per square centimeter.
Note that the flux depends on the arrival angle of the muons, which is easily explained by the fact
that a muon coming with a non-zero angle to the ground will have to go through a bigger layer
of air than a muon arriving vertically. Typically, the angular distribution that can be observed is
proportional to the square of the cosine of the zenith angle: \[ I(\theta) = I(0^\circ) \cos^2 \theta. \] The average lifetime
of a muon is around 2.2 \( \mu \)s, which would not be sufficient to reach the ground classically, but, due
to relativistic effects, the influence of disintegration on muon flux at ground level is negligible above
\( \sim 10 \) GeV.

2.3 Geometry of Cherenkov telescope

When designing a telescope, there are many parameters that need to be taken into account, and
many types of design we can choose in order to fill the particular requirements of the project. In
the case of Cherenkov astronomy, we observe showers of particles with different energies that imply
different opening angles of the Cherenkov cone. Since a single telescope design cannot satisfy the
conditions for the optimal observation of every event in the whole energy spectrum, we have to sepa-
rate the work between different classes of telescopes of different sizes and sub-arrays, corresponding
to different ranges of energies. In the case of CTA and the camera module we want to characterize,
we focus on the class of small-size telescope (SST) that will probe the very high energies, over a few
TeV. Knowing that at these energies the ground image of the shower extends over a few degrees and
that we still want to satisfy a certain precision in the image resolution, we can determine that we
need the telescope to cover a quite wide field of view (FoV), while the characteristic field of view of
a pixel should be constrained (0.15°-0.35°) in order to diminish noise and to keep a high resolution
(the pixel should not exceed the typical angular size of the fluctuations of the shower). The solution
that seems to be the most promising for both a wide field of view and a relative precision of the
image on the focal plane is the Davies-Cotton design.

Let’s first resume in broad outline the main possible designs for a reflector.

The spherical design:
The spherical reflector presents the advantage of having the same focal distance at any point of the
mirror, but due to its shape and the direction of its normal vector, rays are not focused to the focal point (light striking the inner part of the mirror focuses farther from the mirror than light striking the outer part). This phenomenon is known as "spherical aberration" and is particularly present in the case of distant light sources, which explains why this design is often rejected when building a telescope. The spherical design is not used in Cherenkov astronomy due to spherical aberration, but spherical mirrors are used in tessellated Davies-Cotton design, as we will see below.

The parabolic design:
Contrary to the spherical one, the parabolic reflector will focus any parallel ray hitting the telescope to the focal point but, due to its non-spherical shape, will not provide the same focal distance at any point. Note that the rays are perfectly focused only if they are parallel to the parabola axis. Any angular deviation from this axis will result in another type of aberration called "coma", which de-centers the image, making it look wedge shaped. In the case of stars, it creates the illusion of a cometary coma, hence the name of the effect.

The Davies-Cotton design:

![Figure 4: Davies-Cotton design using tessellation. Small spherical mirrors of focal length f are displayed on the sphere of radius f. We can see that both on and off axis incident rays are focused on the focal plane. A secondary mirror is then placed on this focal plane to bring all the light to the detectors.](image-url)
According to what we learned, it appears that the ideal reflector should be a mix of spherical and parabolic design, and this is exactly what the Davies-Cotton reflector is about. The ideal Davies-Cotton (DC) reflector is a purely theoretical construction that is spherically shaped but that focuses light hitting any point of the mirror to the focal point. In other terms, an ideal DC reflector is a spherical mirror that is not locally spherical. It is obvious that such an object cannot be built, however, it is possible to approach the behavior of the ideal DC reflector using tessellation. Practically, we separate the reflector in multiple hexagonal spherical mirrors that are oriented in order to focus their light on the main focal point. The higher the tessellation of the mirror, the closer we get to the situation of the ideal DC reflector. A schematic of the DC design using tessellation is shown on fig (4).

The SST in CTA may use a tessellated DC reflector, the main advantage of this design being that it is a single reflector design. The light is thus directly sent to the cameras. The important parameters that will define the performance of our telescope are light collection efficiency, resolution, and screening of the night sky background, which is obtained by means of the Winston cones discussed below.

**Winston cones:**

In order to concentrate light on the light sensors and to restrict the angular acceptance of the camera (i.e. filter out the light not coming from the primary reflector), we are going to use Winston cones that will be glued on the sensors. A Winston cone is a transparent parabolic shaped solid of revolution with two flat surfaces, a big one collecting the light, and a small one releasing it on the other side. Inside the cone, rays are reflected by the inner surface in order to reach the small "exit" surface, thus concentrating light. The ideal Winston cone is drawn on fig (5). The limit of

![Figure 5: The profile of a Winston cone. Rays until a certain incident angle will be reflected on the side surfaces of the cone and will leave the cone by the exit area.](image)
light concentration reachable with a Winston cone is directly dictated by Liouville’s theorem, which states that the phase space distribution of the flux is conserved. In other words, what happens is that we trade angle acceptance against area contraction. It was proven by Winston [4] that the maximal concentration factor for such a light concentrator is

\[ C_{\text{max}} = \frac{A}{A'} = \left( \frac{n'}{n} \right)^2 \frac{1}{\sin^2 \phi} \]  

(3)

where \( A \) and \( A' \) are respectively the entrance and exit surfaces, \( n \) and \( n' \) are the refractive indexes of the media around the cone (in our case, \( n = n_{\text{air}} \approx 1 \)) and of the cone, and \( \phi \) is the maximum angle at which a ray can enter the cone (\( \phi \approx \frac{1}{2f} \)). The area ratio of the two surfaces is then constrained by the angle acceptance we want to obtain on the incident surface. It is interesting to note that once the photo-sensor size, the Winston cone material, the pixel angular size and the FoV are chosen, the remaining parameters of the telescope (pixel FoV and linear size, diameter of the primary detector \( D \) and focal distance \( F \)) are fully constrained (see fig 6 and 7).

![Figure 6: Tangential (left) and sagittal (right) PSF (point spread function, which is approximately the square root of the sum of the squared RMS in the two directions: \( \sqrt{\Delta \xi^2 + \Delta \eta^2} \)) contours of the ideal DC design. Here, \( f \) denotes the ratio of the focal distance with the diameter of the telescope \( (f = F/D) \). The PSF improves with increasing \( f \) and \( \Delta \eta \) is better than \( \Delta \xi \).](image_url)
\[ \theta_{\text{pixel}} = 4 \text{RMS} \]

Figure 7: Optimal Cherenkov telescope parameter design: A relationship can be established among the parameters of a telescope:

- Size of the primary reflector \( D \), focal distance \( F \) and f-number \( f = F/D \);
- Physical pixel size \( l \) and pixel FoV \( \phi \);
- Winston cone geometry: cones, which lie on top of photo-sensors are expanding the physical size of the sensitive pixel area and at the same time screen a fraction of the background light (i.e. not coming from the direction of the reflector);
- Tessellation of the primary reflector;

in order to obtain an optimal design, once the FoV of the telescope and the technology fixed and a condition on the point spread function (PSF) set, reducing the telescope design parameter space. (ref: private communication).

Note that in our case, we are not going to use strictly speaking Winston cones. We want to bring light from a plane surface tessellated in hexagons, to light detectors that are square shaped. Our
cones will therefore not have a circular section like Winston ones, but a hexagonal shaped entering area and a square shaped exit area (see fig 8). As one can imagine, the properties of such an object are more complicated and not fully understood. Typically, one should not assume the same angle acceptance from our cones than from the ideal Winston cones: the symmetry of the object is not the same and light reflections inside it are not easy to describe. The simulation for the angular acceptance of a parabolic cone, which is a cone with a round section but with parabolic shape which is not similar to Winston cones but closer to the cones we are using, are displayed in fig (9).

Figure 8: The cone we will use to concentrate light to our camera. The profile is the same as a Winston cone (parabolic shaped), but the section is not circular. The area of the entering surface is given by \( \frac{\sqrt{3}}{2} (16.28)^2 = 229.53 \text{ mm}^2 \), and the area of the exit surface is \( 4.8^2 = 23.04 \text{ mm}^2 \). The compression factor is then \( \sim 10 \), and we can assume that such a light concentrator will bring a gain of around 10 without considering any absorption by the medium. Eq. 3 then gives us a maximum angle of \( \sim 28.11^\circ \) which can give us an idea on what we should expect for the angle acceptance of the cone. Note that this value is valid for a Winston cone, and should therefore not be taken as an absolute reference for our cone. The cone is made of PMMA (plexiglas), as the transparent window we will use to cover the camera. Plexiglas offers the advantage of being one of the most UV-transparent material we can use, which is of prime importance in the transmission of Cherenkov light, since the spectrum tends to be more and more intense at shorter wavelengths (see section 2.1)
Figure 9: A numerical simulation for the angular acceptance of a parabolic cone. Note that the cutoff is not extremely sharp, as it would be for a Winston cone which theoretically has a vertical cutoff.

2.4 SiPM’s

Silicon photomultipliers (SiPM) are single photon sensitive sensors that can be used as a replacement of the traditional photomultiplier tubes (PMTs) in the light detection experiment such as the ones we are interested in. SiPMs are made of an array of thousands of avalanche photodiodes (APD) in geiger mode (see below) generally disposed on a silicon substrate. Every cell acts in a binary manner: either the cell is "at rest", either it detects a photon and emits a fixed electrical pulse. The SiPM is obtained by parallel cumulation of every cell’s signal. We then obtain an analog signal corresponding to a number of photons from 1 to a few thousands. SiPMs present a lot of advantages that motivates their use counter to PMTs:

- **Quality and price:** the quantum efficiency of the SiPM integrated over the Cherenkov spectrum (~ 300 to 650 nm) is ~ 20% and the gain of the order of $10^6$, which allows SiPMs to
compete with standard PMTs at a lower price.

- **Low bias voltage**: contrary to PMTs, SiPMs don’t need a high voltage supply and are operable at bias voltages below 100 volts. This is due to the fact that the dependency of bias voltage against gain is linear in the case of the SiPM, while ruled by a power law for the PMT.

- **Magnetic field independence**: contrary to PMTs which are strongly affected by external magnetic fields, a SiPM can still do measurements when exposed to magnetic fields of several Teslas, without being influenced by it.

- **Better resistance to time**: Due to long time illumination PMT’s dynodes become "tired" which affects the gain of the PMT. This does not happen with SiPMs which do not age. A direct consequence of this is that SiPMs can work with moonlight without fearing premature aging or destruction, contrary to PMTs.

Let’s now describe in a more detailed manner the different components of a SiPM, the physical principles involved, and the features we will have to deal with when using this sensor.

*Avalanche Photodiodes and Geiger mode:*

Silicon photodiodes use the photoelectric effect to convert light to an electrical signal. When a photon hits the diode with more energy than the bandgap energy, an electron of the valence band is promoted to the conduction band, where it can be read out as a signal. In the case of APDs, we use the avalanche effect to create gain. The avalanche effect is obtained by applying a voltage to the diode, in order to create a strong electrical field that will accelerate the electrons in the conduction band. If one electron is sufficiently accelerated, it will cause impact ionization and liberate another electron which will be accelerated as well causing a chain reaction (the avalanche), and increase the number of electrons in the conduction band. The signal will therefore be higher and it is possible to reach a gain of the order of a few hundreds. If we want to increase the gain even more, we need to apply a stronger electrical field by increasing the applied voltage. At some point, when the applied voltage is higher than the "breakdown voltage", the semiconductor junction will break down and the APD will start acting like a conductor, producing suddenly a large current flow. This is known as the Geiger-mode operation. When an APD is in Geiger mode, it is actually stable (acting like a semiconductor) until an electron enters the avalanche region: at this moment, the avalanche region breaks down and the APD becomes a conductor (Geiger discharge). A single electron produces then a really high current flow, leading to a large gain (above $10^5$). APDs used in Geiger-mode (Geiger-mode APDs, or GAPDs) are the only way to detect single photons. The issue is that this device triggers only once, which is not interesting. A GAPD needs thus to be reset after an avalanche, by reapplying a voltage below the breakdown voltage. This is usually done by placing a resistor in series with the APD that will cause a voltage drop after each large
current flows. Of course, it takes some time to the system to go through the whole process of discharge and reset, and a cycle takes usually around 20 nanoseconds to be complete (recovery time).

**PM use of the diode:**
Since a single GAPD only allows to have a binary output signal, it is not sufficient as a photon counter. A full SiPM is constituted of a full array of GAPDs connected in parallel, allowing to distinguish multiple-photons to single-photon events. When more than one photon hit the array at the same time, the signals produced by the pixels (the single GAPDs) is added up and the amplitude of the electrical output pulse is directly related to the number of photons. In this sense, the multipixel photon counter (MPPC) formed by the array returns a pseudo-analog signal since it can measure the number of photons per pulse. Note that we will often count photons in P.Es which is the abbreviation for "photon equivalent", 1 p.e. pulse is the voltage pulse with amplitude equivalent to one detected photon. An example of MPPC can be seen on figure (10).

![Image of MPPC](image)

**Figure 10:** A simple example of MPPC. The dimensions for the SiPM we will use are slightly different and will be specified below.

**Photon detection efficiency:**
The photon detection efficiency (PDE) measures the percentage of incident photons that are detected. It is described by the following equation.

\[ \text{PDE} = \text{QE} \times \text{Fg} \times \text{Pa} \]  

(4)

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where "QE" is the quantum efficiency, a value showing the number of electrons or holes created as photocurrent divided by the number of incident photons, $F_g$ is a geometric factor (the "fill factor'', $F_g = \frac{\text{effective pixel size}}{\text{pixel size}}$) and $P_a$ is the avalanche probability ($P_a = \frac{\text{Number of excited pixels}}{\text{Number of photon incident pixels}}$). PDE increases as the reverse voltage is increased. PDE is dependent on the wavelength of the incident photon as we can see in fig (11).

Figure 11: The PDE of a 3x3 mm$^2$ SiPM, as predicted by the constructor [6]. Note that below a certain wavelength, the SiPM does not detect anything. Contrary to a classic PMT, there is no sharp cutoff in the large wavelengths, this is actually a problem in the case of Cherenkov astronomy since visible light coming from all kind of sources is also detected by the SiPM and introduces a strong noise in the measurements. One of the solutions to this issue is to select frequencies earlier in the detection process, by using the mirrors of the telescope.
**Crosstalk:**
During the avalanche process, secondary photons might be generated which are not the incident photons detected in the first place. If these photons propagate throughout the chip and are then detected by another pixel of the MPPC (see fig. 12), the output will be higher than the number of P.Es that were primarily detected by the MPPC. This phenomenon is the cause of crosstalk in the MPPC. Note that by increasing the voltage, we increase the crosstalk effects since light emission during an avalanche is proportional to the number of electrons in the discharge. At some point, when crosstalk is too high, the device cannot give proper results anymore. When using a SiPM one might think that having the biggest possible gain is the best thing to do, but actually, reducing the crosstalk as much as possible might even be more important. It is therefore important to optimize the applied voltage in order to have a sufficiently good PDE with reasonably low crosstalk effects. Crosstalk is the main obstacle that projects using SiPMs will have to face, there is still a lot of research to be done in crosstalk suppression, including improvements in the SiPM structure and having a better understanding in the phenomenon of light production in avalanche discharges.

![Figure 12: Crosstalk in a MPPC](image)

**Figure 12:** Crosstalk in a MPPC: In red, the first incident photon activates the first APD. During the avalanche, other photons are produced (in blue on the figure), and some of them might propagate sufficiently far to activate another APD and falsify the output.

**Dark count:**
Output pulses can also be produced by thermally-generated dark current carriers. These dark current pulses are measured as dark count (# of dark pulses per second) and are responsible for imprecisions in the measurements. Once again, the fine balance for the applied reverse voltage is constrained by the fact that increasing the voltage also increases the dark count since dark current is amplified as well. However, since these carriers are thermally-generated, it is possible to decrease the dark current by lowering the temperature. Note also that a dark pulse in the MPPC is output as a pulse of 1 p.e. Dark pulses of more than 1 p.e. are very unlikely to be detected. However, dark
pulses produce crosstalk as normal incident photons, which can raise the final number of P.Es to more than one.

After-Pulse:
After-pulses take the shape of a jolt in the voltage peak formed by the pulse, a few nanoseconds after the initial peak. They are believed to be generated by electrons of the avalanche that are trapped and released with a small delay with regard to the avalanche. These pulses corrupt the photon counting resolution of the device. Random dark pulses occurring just after the detection can also have the same effect on the voltage peaks.

Temperature dependent behavior:
The SiPM is a solid state device which implies a strong temperature dependency. Indeed, an augmentation of temperature increases the strength of the vibrations in the crystal lattice. The direct consequence is that the ionization by the carriers is more difficult since they have a bigger probability to hit the crystal before having acquired enough energy to ionize the medium. Therefore, the gain at fixed reversed voltage drops with the increase of temperature. If we want to keep the gain constant, which is obviously preferable, we will have to adapt the applied reversed voltage on the SiPM in function of the temperature.

Other specifications:
The SiPMs we use in our experiments are produced by Hamamatsu, one of the world leader in the market of photonics. The particular model of SiPM we use is the 2x2 channel array, type no. S10985-050C, which is constituted of 4 MPPC arrays with active areas of 3x3 mm each.
3 Characterizing the elements of the camera module

Structure of the camera module:
One pixel of the camera is characterized by several elements that all have an influence on the detection efficiency (see all the elements in fig 13). Naturally, the SiPM itself has a photon detection efficiency (described in section 2.4), but the overall efficiency of the setup is also controlled by the different absorption factors of the cone, the window, the glue layer between the latter and the optical gel we will use temporarily to connect the cone and the SiPM (fig 13). In the final camera module, the cones will be glued to the SiPM but for obvious reasons of convenience, we use the gel that allows us to remove and put back the cone whenever we need to. The efficiency of the system is also depending on the angle of the incident photons, which is monitored by the angle acceptance of the cone. Finally, note that the behavior of the SiPM is sensitive to temperature changes. We will quantify all these effects in the following section.

Figure 13: An exploded view of the camera module. From upper left to lower right: the PMMA window on which are glued the seven cones bringing the light to the SiPMs. The whole setup is placed in a shell and the SiPMs are plugged on a printed board (in green) from which is controlled bias and channels outputs. The remaining lower part of the camera module is of less importance for this paper, since we are not going to use the final connection design for our experiment.
3.1 The "Catafalque" setup

The "Catafalque" setup is what we are going to use for all the measurements described in this section, that is to say all the measurements related to the distinct elements of the camera module and their influence on the detection. Basically, the Catafalque is constituted of a dark box (isolating its content from external light) inside of which is contained a pulsing light source (a LED plugged on a pulse generator, pulsing at 10kHz), an optical rail on which the tested setup (the SiPM in our case) is placed, and a photomultiplier tube (PMT) used for calibration means. The beam created by the LED goes through two diaphragms and one diffuser that are used to parallelize the beam and make its intensity distribution flatter. The beam can be send to both the PMT or the SiPM using a mirror. A pneumatic system allows the user to switch the position of the mirror or to place elements in the path of the beam from the exterior of the box without changing anything on the system. We will use this last feature to measure the absorption coefficients of the different materials.

The tested setup is constituted of a SiPM mounted on a preamplifier plate along with an amplifier (40dB, 50 Ω) and a temperature control setup, controlled from outside of the box. The SiPM is plugged to the amplifier and the output is sent to an oscilloscope we use to analyze the signals. The oscilloscope is triggered on the pulse sent to the LED, and we can clearly see traces of P.E's (see an example of trace on fig 14). The oscilloscope allows us to measure parameters directly on the traces. We will often use this feature to plot histograms of peak amplitude, area, etc... directly on the oscilloscope. We can then save this data into text files, which can be easily read with root, the data analysis tool developed at CERN [7].

3.2 Poisson statistics

In many cases, we will use the same method to determine the influence of a material on the beam (absorption or gain). This method is based on Poisson statistics. We know that a discrete stochastic variable $X$ meets a Poisson distribution with parameter $\mu > 0$, if its probability of being equal to $k = 0, 1, 2, ...$ is defined by:

$$f(k; \mu) = Pr(X = k) = \frac{\mu^k e^{-\mu}}{k!}$$

(5)

where $\mu = E(X) = var(X)$. We can then easily measure the expected value of $X$ by knowing its probability to be equal to zero since $Pr(X = 0) = e^{-\mu}$.

$$\mu = -ln(Pr(X = 0))$$

(6)

In our particular case, $X$ is the variable describing the number of p.e's, $\mu$ is the most probable value of $X$, which is directly related to the average number of photons per trigger, and $Pr(X = 0)$ is the probability of a zero p.e state, which is described by the ratio of the number of events in the zero p.e peak with the total number of events (in a peak amplitude histogram for example). By taking simple histograms of our measurements without changing the pulse, we can thus compare...
the average number of p.e’s for two sets of events in order to determine a gain or an absorption coefficient.

This method for determining the average number of p.e also presents the advantage of not being corrupted by crosstalk, unlike the result we would obtain by simply computing the average of our histogram, since crosstalk leaves only the zero p.e peak untouched (the system needs at least one photon to produce crosstalk). The value of $\mu$ we will find will then be always slightly lower than the corrupted one.
3.3 Photodiode channels

The SiPMs we are using are made of 4 main channels (4 sub-SiPMs in a sense), every channel is a square array of GAPDs of 3x3 mm$^2$, which makes the whole SiPM 6x6 mm$^2$, this is called the 2x2 channel configuration. Note that these 4 channels each have an anode but share a common cathode. Previous experiments done by the lab in the catafalque tended to indicate that if the full SiPM (i.e. all 4 channels) was connected, the output signal was too noisy for precise measurements. We will briefly study the difference of using a configuration with only one of the four channels connected, with using 2 channels connected in parallel. This will lead to differences in the amplitude and width of the P.E peaks. Note that in this section, instead of only record histograms as we will do in the next sections, we write every trace we measure on a different file, in order to have full liberty on the parameters we want to measure. This method has the disadvantage of being heavy time and space wise, and this is why we will use it only when the oscilloscope does not provide the tools we need.

**Width of the single P.E. pulse:**

![Peak width histogram](image)

Figure 15: Here is the width histogram measured on a set of pulses in the catafalque, using only one of the four channels of the SiPM. Note that there is no clear distinction between the number of P.Es

We want to measure the width of the single P.E. peak. The first problem we encounter is that it is not really easy to discriminate single P.E from the rest of the signals just looking at the width histogram of the pulses as we can see on figure (15). This is due to the fact that width doesn’t nec-
essarily change a lot with the number of P.Es. Moreover, width is strongly corrupted by after-pulse, which explains the continuous shape of the histogram.

In order to restrain our histogram only to the single P.E peaks that are not corrupted by after-pulse, we will have to use others variables measurable on the pulses, i.e. amplitude and area. By measuring the amplitudes and areas of the pulses, we can plot a two-dimensional histogram of the pulses, where the distinction between the different number of P.Es is way more apparent (fig 16). We then can use this histogram to restrict the events to a circular zone around the single P.E. peak. If we plot the peak width histogram corresponding to the events selected in the two dimensional histogram, we obtain what we were looking for, that is to say a distribution of the widths for the single P.E. peaks that is not (or less) corrupted by after-pulse (fig 17).

![Figure 16: A 2d histogram of both amplitude and integral (area) of the pulses with only one channel of the SiPM plugged to the output. The peaks correspond to the different number of P.E's, zero on the lower left, then 1, 2, ...etc.](image)

By using the same methods with measurements taken with two channels, we can now plot both single and two channels histograms of the peak width, in order to see the evolution of the latter (fig 18). We observe an increase of the peak width, which is due to the increase of capacitance. That has the effect to reduce the amplitude of the peaks which is bad for PE discrimination since the peaks level is getting closer to noise level.
Figure 17: This histogram is basically another version of the previous one (fig 17), where only the events corresponding to a one P.E. pulse are considered. These were selected by using the 2d area-amplitude histogram (fig 16), where the separation between the number of pulses is way more apparent. The more restrictive the selection was (that is to say the smaller the area around the peak was taken), the smaller is corruption of the results by after-pulse.

Note that the plots and results presented in this section were accurate when taking the measurements, that is to say before we shielded more strongly the SiPM. With the new shielding, it is actually possible to use all 4 channels at a time without being drowned by the level of noise. Besides, we will use in some cases the 4 channels configuration for some measurements that demand the whole SiPM to be reactive to light detection. However, our standard configuration of the SiPM will be the two channels configuration, which has a satisfying peak level to noise ratio.
Figure 18: In red, the histogram for the peak width of the single P.E. pulses measured with only one channel of the SiPM. In blue, the same measurement made with a two channels configuration. As we can see, the width of the P.Es increases with the use of more than one channel.
3.4 Temperature dependent behavior of the SiPM

In the case of a telescope running measurements over a whole night, it is primordial for the gain of the SiPM's to be as constant as possible, in order to have valid and consistent results. We saw in section 2.4 that the gain of a SiPM is strongly dependent on temperature, and that changes of a few degrees can already have a non negligible influence on the results. In order to keep the gain constant through a night of data taking, the final system will have to adapt the applied voltage of every SiPM regarding to temperature. The other solution would be to control the temperature of the SiPM in order to keep it constant, but a temperature control system takes up a lot of space, especially if we have to install one for every pixel of the final camera. This last solution is therefore not considered. In this section, we will try to find the relation between voltage and temperature at constant gain.

The gain of the SiPM is directly determined by the number of carriers in a Geiger discharge. When a photon hits the SiPM, one electron is promoted to the conduction band (see section 2.4), but after the avalanche and the Geiger discharge the observed current is made of a way bigger number of carriers ($10^5$-$10^6$). In order to compute the value of the gain of our SiPM, we thus need to measure the charge contained in the P.E. peaks we observe. In the end, keeping the gain constant amounts to keeping the charge contained in one P.E constant.

How do we measure the charge with the system at our disposal? We can convince ourselves by a simple dimensional analysis that the area of a one P.E. peak and the impedance of the system are all we need to compute that charge:

\[
\frac{\text{area of 1 P.E peak}}{\Omega} = \frac{V \times s}{V \times A^{-1}} = \frac{V \times s}{V \times s \times \text{[charge]}}^{-1} = \text{[charge]} \tag{7}
\]

This actually computes the charge at the output of the amplifier, in order to have the real charge involved in the Geiger discharge, we will have to divide the measured charge by the gain of the amplifier (which is dimensionless): $q_{\text{geiger}} = \frac{\text{area of 1 P.E peak}}{\text{impedance} \times \text{gain of the amplifier}}$. In our case, we use a 40dB amplifier, which implies a gain of x100, and the impedance of the system is 50Ω. We therefore divide the area by a factor 5000 in order to have the charge contained in a single P.E peak (in Coulombs).

Next step is to measure the area of a single P.E peak for different temperatures and bias voltages. Using, as usual, the catafalque setup linked to an oscilloscope, it is quite easy to record the area of detected pulses in a histogram, measured between two arbitrary gate values. Using a simple routine in root, we can then fit the first and second peaks of the histogram (corresponding to the 0 and 1 P.E peaks) with gaussian functions, which allows us to extract the average areas of the 0 and 1 P.E traces. We then can extract the particular value we are looking for by subtracting the average value of the 0 P.E area from the 1 P.E area, in order to get rid of the noise. We then repeat this
operation many times, each time with different values of bias voltage and temperature, both being easily set up with our installation. We then come out with a list of values corresponding to the charges matching the different combinations of temperatures and biases. The whole list is plotted in a 3d graph on fig (19). We write a code in root that allows us to read this list and plot every couple of values (charge, temperature or bias) with the third one kept constant. As we can see in fig (20), these variables depend linearly on each other. Since the charge is different for every

![Figure 19: The full set of points C(T, V). For reasons of legibility, error bars are not plotted in this figure.](image)

(T, V) pair, we have to interpolate the value of temperature and voltage corresponding to a charge kept constant. A more visual way to see it is the following: finding \( V(T)\big|_{C=\text{const}} \) is equivalent to slice horizontally the surface formed by the points in figure (19). In order to do this, we write a routine that interpolates linearly all the sets \( T(C)\big|_{V=\text{const}} \) and \( V(C)\big|_{T=\text{const}} \) (i.e. the plots in fig 20). Given a reference \((V_{\text{ref}}, T_{\text{ref}})\) pair corresponding to a charge value of \( C_{\text{ref}} \), it is now easy to plot \( V(T)\big|_{C=C_{\text{ref}}} \) using the previously interpolated values of \( T \) and \( V \) (fig 21). Fitting linearly once
Figure 20: First two lines: $V(C)|_{T=const}$ measured with different values of T. Last three lines: $T(C)|_{V=const}$ with different values of V. Note the linear dependence of the values.
again this last plot gives us the linear relation between $T$ and $V$ that keeps the gain constant, given an initial $(T_{ref}, V_{ref})$ pair. In the particular case of the SiPM we were testing, with the nominal values given by the constructor as reference values $((V_{ref}, T_{ref}) = (71.4 \text{ Volts, } 25^\circ C))$, we find the relation $V(T)|_{gain=const} = 0.0593 * T + 69.922$ (with $T$ in celsius and $V$ in volts), which is quite similar to the reference Hamamatsu prediction (see fig 21).

Figure 21: $V(T)$ at constant gain (corresponding to an initial reference pair $(V_{ref}, T_{ref}) = (71.4 \text{ Volts, } 25^\circ C)$), interpolated from the $V(\text{Charge})$ and $T(\text{Charge})$ plots (fig 20). The error bars come from the uncertainty of the interpolation. The blue line represents the Hamamatsu prediction (56mV per $^\circ C$). As we can see, it fits the measurements well.
3.5 Choice of the materials

As mentioned before, the materials we will have to deal with all have absorption factors we need to characterize in order to validate their use in the final design of the camera module. We focus on the wavelength dependance of these absorptions factors, particularly the capacity of the materials to be transparent to UV light since the spectrum of Cherenkov light is more intense in these wavelengths (see section 2.1). By using the Catafalque as explained in (3.1), we measure histograms of peak amplitude and compute the ratio of absorbed photons by using the method described in section (3.2).

Glue:
We want first to know what is the absorption induced by the glue we are going to use between the cone and the window (and also between the cone and the SiPM in the final camera module). We know that this glue is supposed to absorb quite dramatically light below a certain wavelength but we need to quantify this effect in order to determine if it is sufficient to invalidate its use on the camera. In order to compute this absorption coefficient, we glue a cylinder to a window (the window is the same that will be used on the camera module, and the cylinder is made of the same material as the cones: we thus already know both of their absorption coefficients). We put this device on the beam path and compare the number of photons arriving to the SiPM with and without the obstacle. Transmission in function of wavelength is displayed on fig (22).

Optical gel:
As said before, we are going to use optical gel to couple the parts of the device that we need to be separable at any time, that is to say between the cone and the SiPM. In order to test the absorption coefficient of the gel, we place a layer of the gel on a window made of the same material than the window of the camera module, and use the usual method to compute the absorption at different wavelengths. We did not measure a lot of different wavelengths, since we just needed to know qualitatively if there was no dramatic absorption, the results are displayed in table (1). As we can see, this gel doesn’t seem to be a bad candidate, even if it clearly has an effect on the light transmission. Since this gel is not going to be used in the final design, its relatively bad performances are of lesser importance.

<table>
<thead>
<tr>
<th>Wavelength [nm]</th>
<th>Absorption coefficient [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>5%</td>
</tr>
<tr>
<td>360</td>
<td>15.4%</td>
</tr>
<tr>
<td>325</td>
<td>18.7%</td>
</tr>
</tbody>
</table>

Table 1: Absorption coefficient of the optical gel for a few different wavelengths. Its use should not affect the results too much since the absorption never goes beyond 20%. However, even if these coefficient can seem not negligible, we have to take into account the fact that the layer of gel between the cone and the SiPM is going to be thinner.
Figure 22: Here is displayed the transmission coefficient of the glue we are going to use. As we can see, there is a clear cutoff below wavelengths around 350nm. Since the absorption is not dramatic (below $\sim 20\%$) at low wavelengths ($\sim 320\text{nm}$), we can still validate the use of this glue.

**Cylinder test:**
We know the absorption for each part of the camera module separately but in the final camera, each element will be linked to the next one without any air interface in between. This might change the value of the total attenuation factor. We then use again the device we used when measuring the absorption coefficient of the glue (cylinder+glue+window) and fix it against the SiPM, with some gel in between. This allows us to simulate the attenuation of the full camera module, without perturbations coming from the geometrical characteristics of the cone (e.g. without light deviation due to the surfaces of the cone). There are some difficulties: we need first to measure the light coming to the "naked" SiPM, then dismount the SiPM support, apply a layer of optical gel on the SiPM,
fix the new montage on it, then put the whole thing back in the catafalque but displaced such as the position of the incident surface of the window is where the surface of the SiPM was when taking the "naked" measurements and...measure the amount of photons coming through the materials, to the SiPM. This is exactly the same process we will use when measuring overall gain of the device in section (3.6). Of course, this measurement is not perfect and there are some uncertainty sources: between the two measurements the bias voltage of the SiPM might not be exactly the same (we can expect an imprecision of ±0.05 Volts due to the power supply), the distance might change as well from a few millimeters (this should not affect the measurement too much, since the detector is placed at a large distance from the source with regard to an imprecision of a few millimeters. We also measured that at this distance, a removal of 1 cm from the initial position implies a decrease of the intensity of only 5%), etc. Note however that the light source should not change in the process since we don’t touch anything on this side of the experiment. By using this method, we find an absorption for a wavelength of 400nm of $Absorption_{cylinder+glue+window,400nm} = (14.5 \pm 0.6)\%$, that is to say a transmission coefficient of $\sim 85\%$. This is the result we will use when estimating the overall gain brought by the cone on the SiPM at 400nm (see next section).

3.6 Gain

We bring light to the SiPMs using cones for two main purposes: angular selection (we restrict the field of view of the light reaching the detector) and gain (the compression factor of the cones increases the number of photons reaching the SiPM). In order to quantify the magnitude of the latter, we take some measurements in the Catafalque with the setup we used before. We connect this time the whole set of materials to the SiPM in order to simulate the behavior of a pixel of the camera. We glue a cone to a window that has the same characteristics as the one used on the camera module, and cover the area of the window that is not directly in contact with the cone with black tape in order to select only the light coming in the cone through the window. Finally, we mount this structure on a support which can be attached to the SiPM plate and removed freely when necessary.

We will now measure the gain obtained by adding the cone on the SiPM. We measure the histograms of the amplitude of the P.E. peaks in two cases: once with the SiPM "naked" that is to say with nothing in the path of the beam between the source and the detector, and once with the cone-glue-window structure connected to the SiPM with optical gel. When placing the cone on the SiPM, we translate the whole setup in order to have the same distance between the source and the incident surface in both cases. The method we will use to compare those histograms is the same method we used when measuring the absorption coefficients of the materials except this time the coefficient will be higher than 1 (gain). We arbitrarily choose a LED with a 400nm wavelength for the pulse. As for previous experiments, only two channels out of four of the SiPM are connected.
What gain should we expect? As a first naive approximation, we can consider that the gain is simply the product of the compression factor of the cone (the ratio of the surfaces of the cone $A_1/A_2$) with the transmission coefficient of the materials placed in the path of the photon (at 400 nm, we measured an absorption of $\sim 15\%$, which implies a transmission coefficient of $\alpha_{400\text{nm}} \sim 85\%$). We also have to consider the fact that the small surface of the cone (the one connected to the SiPM) is smaller than the surface of the SiPM. When taking measurements without the cone, the whole surface of the SiPM is exposed to light which is not the case anymore when connecting the cone to it (or at least it should not be, but it is not impossible that some photons escaping the cone reach the outer parts of the SiPM surface). We should then expect our gain to be reduced by a factor which is the area ratio of the two surfaces in contact ($A_2/A_{\text{SiPM}}$). Combining all these factors gives us:

$$\text{Gain} = \frac{A_1}{A_2} \frac{A_2}{A_{\text{SiPM}}} \alpha_{400\text{nm}} = \frac{A_1}{A_{\text{SiPM}}} \alpha_{400\text{nm}} \approx \frac{229.53 \text{mm}^2}{36 \text{mm}^2} \times 0.85 \approx 6.38$$

We measure a first gain of 4.80. This is lower than expected. There are several factors that could explain this discrepancy. First, the absorption factor we used is the one found when we took measurements with the whole set of cylinder+window+glue. But the glue used is not the same in both cases: since we only had one cone at our disposal, we could not glue another cone with the new glue. The absorption factor is then not exactly the same. This does not however suffice to explain the difference we observe. What could also be possible is that the beam could be not equally intense everywhere. We explore this possibility below. Finally, the cone itself might not be as efficient as we expected. Obviously, some of the light is escaping from the cone even when coming perpendicularly and trying to describe the gain without attenuation only by taking the ratio of the two surfaces of the cone is a rough and naive approximation that may not be sufficient in our case since we are not using real Winston cones.

**Profile of the beam:**

We want to test the intensity profile of the beam we are sending to the SiPM and to the cone in order to see if there is an eventual rapid decrease of the intensity away from central axis, which could be one of the causes of the discrepancy between the measured and the theoretical gain. As we will see later, this result will also have its importance when considering the angle acceptance of the cone (section 3.7). In order to measure this profile, we simply compare the average number of photons detected by the SiPM at different distances off axis. In order to have the best possible resolution, we connect only one of the channels to the amplifier, and we displace the system off axis by steps of 3 mm, which is the size of one channel on the SiPM. By doing so, we manage to cover the whole beam profile. Results are displayed in fig (23). As we can see, the intensity profile of the beam is extremely flat until 1 cm. Since our cone has a radius of less than 0.9 cm, we can clearly conclude that the beam is not a strong error source in our gain and angle acceptance measurements.
3.7 Angle acceptance of the cone

When discussing the geometric characteristics of the telescope (section 2.3), we saw that the angle acceptance of the cones used on the camera module were of primary importance in order to select exclusively the light coming from the mirror of the telescope. Having such a constraint on angle acceptance allows us to reduce the noise coming from other directions, such as star light.

In order to measure this acceptance, we will use the catafalque with small modifications on the setup we used until now. We add a rotary stage (Edmund Optics) on the translation rail and adapt the disposition of the SiPM support, in order to be able to translate the rotation axis. In our case, we will take measurements with the rotation axis positioned on the surface of the window. This allows us to rotate the system without changing the distance separating the cone from the light source.
We use a LED with a 400 nanometers wavelength for the light pulse. At this wavelength the absorption of all materials is still relatively low which will help us to show the effect of angle acceptance.

We use the same method described in (3.2) to determine the relative intensity of the light with respect to the angle of rotation. Note that we observed some noise which is probably the result of light reflections inside the box coming from both the LED and eventual "leaks" on the box reaching the SiPM from the side. After having subtracted the part of the intensity due to the noise (measured by covering the cone with some adhesive tape), we normalize the observed intensity to the one at 0°. The result is presented in figure (24). Note that we also plotted the acceptance with a \( \cos(\theta) \) correction, which takes into account the fact that the incident surface gets smaller by a factor \( \cos(\theta) \) when rotating the system, since the incident rays are strictly parallel.

As we can observe, the angle acceptance is not as selective as we might have hoped, with regard to a Winston cone. This could be due to several reasons such as a bad intensity profile of the beam. If the center of the beam was to be considerably more intense than the sides of it, it would increase the slope of the angle acceptance since as the angle gets bigger, the cone receives more photons from the center of the beam and gets therefore more "illuminated". We nevertheless already considered this problem in section (3.6), and arrived at the conclusion that the profile should play a negligible role on the measurements if any, since it is very flat in the area of the cone. Another factor might of course be some additional noise we did not get rid of, even if that should not affect the slope a lot since most of the noise were eliminated by the method we used. Finally, the cones we are using are not strictly speaking Winston cones, their characteristics are therefore less predictable and maybe some geometrical effects and internal reflections we don’t know about happen in the cone when the light gets in with large angles. Note however that if we compare our results with the simulations that were made by the lab for a parabolic cone (fig 9), we get somewhat closer to the prediction. Note also that we tested the angular acceptance of the cone only for one rotation axis, maybe another axis would be more selective, but since we did not have other cones at our disposal, we did not go further in our investigations.
Figure 24: In blue, the angle acceptance of the cone. In red, the same corrected by a factor $\cos(\text{angle})$ in order to take into account the decrease of the incident surface. We did not draw error bars on the latter for reasons of legibility. We can observe the expected cutoff, and see that the slope is smaller than the Winston cone one (see fig 9). We thus cannot expect the same angle selection properties for our cones than for the Winston cones.
4  Muon detection with the camera module

4.1 Primary design

We want to design an experiment that will productively test the newly assembled camera module. One source of Cherenkov photons we have easily at our disposition is cosmic muons. We will thus design an experiment where muons passing through a radiator emit Cherenkov light in the direction of our camera. We will record the outputs of every pixel of the camera (7 SiPMs) on an oscilloscope at first, then with the DRS, which is an acquisition device we will detail later. In order to take these measurements, we will have to trigger on the muons coming through the right angle and direction in our radiator. We will use two scintillators triggers to do so. Our radiator will be made of stacked sheets of plexiglas. This material is the same used for the window and cone of the camera module: it proved its utility for the transmission of short wavelength photons which we are interested in. Finally, the whole setup will be placed in a dark box to isolate it from daylight. The disposition and dimensions of the elements of our experiment (camera module, radiator, scintillators) will be the first problem we will have to solve.

A natural guess for the positioning of the elements would be to select vertical muons and place every part of the experiment in the same vertical axis (fig 25). The problem comes from the fact that the Cherenkov angle in plexiglas is too big, which makes the produced photon internally reflect on the plexi-air interface. Indeed, the Cherenkov angle (see section 2.1) is given by

\[ \theta = \arccos \left( \frac{1}{n_{PMMA}} \right) = 47.84^\circ \]

in our case (we took \( \beta = 1 \) which is a valid approximation since the muons arriving at ground level travel at a speed near \( c \), and \( n_{PMMA} = 1.49 \)). While the angle of total reflection is given by \( \theta_{\text{lim}} = \arcsin \left( \frac{n_{\text{Air}}}{n_{PMMA}} \right) = 42.15^\circ \). One solution to avoid this situation would of course to get rid of the air interface between the radiator and the camera module by stacking the two together but this solution is not really convenient since we might have to remove the camera module often. Moreover, in the case we want to add other cameras to the experiment it would be better not to have such a layout. Finally, we want to avoid as much as possible triggering on muons passing through the camera module itself and producing photons inside the cones, it is then better to considerate a non vertical solution.

We thus choose the second most natural choice for our setup: instead of triggering on vertical muons, we will trigger on vertical Cherenkov photons, that is to say we will trigger on muons arriving on the radiator with the Cherenkov angle as the incident angle (fig 26). Of course, the case presented in fig (26) is the particular "perfect" case where the muon arrives with the right angle. In reality, we will select a flux of muons coming with different angles and points of impact on the radiator around this perfect case. We can impose, as a condition on the maximum angle of incidence of the photons on the camera module, that only the muons producing photons coming with an angle
Figure 25: A vertical muon entering the radiator (crystal) and emitting Cherenkov photons with an angle $\theta$. Since $\theta$ is bigger than the total reflection angle of the radiator, Cherenkov photons internally reflect.

$\angle < 20^\circ$ on the camera module should be selected, in order to stay in a relatively ideal detection case (see fig 24). This will give us a constraint on the placement and size of the scintillators we are going to use as triggers. A maximum angle of $\pm 20^\circ$ on the camera module, that is to say post-refraction, implies an incident angle inside the radiator, before the refraction, of $\phi_{in} = \pm \arcsin(\frac{1}{n}\sin(\phi_{out}))$, where $\phi_{out} = 20^\circ$. This angle also describes the maximum deviation for the muons, coming thus with angles from $\theta - \arcsin(\frac{1}{n}\sin(\phi_{out}))$ to $\theta + \arcsin(\frac{1}{n}\sin(\phi_{out}))$. Practically, it makes the muon arrive on the radiator with an incident angle in the interval $[\theta - 13.3^\circ, \theta + 13.3^\circ] = [34.56, 61.12]$. Since the scintillators we have at our disposition have a length of $\sim 20cm$ it implies that we will have to place them $\sim 85cm$ from each other, which is easy to do. We will not stick exactly to these numbers, but will keep them in mind when doing the assembly of our experiment and try to approach them as much as space constraints let us do so.
Figure 26: The basic idea of the final experiment. We trigger muons arriving with an incident angle equal to the Cherenkov angle ($\theta = 47.84^\circ$) in order to detect mostly vertical photons arriving to the camera module. Since the photon arrives at the PMMA-air interface with a zero incident angle, there is no deviation due to refraction.
4.2 Assembling the final experiment

The camera module:
In the final design of the camera, biases of the SiPMs will be controlled independently. However, at the time we are doing this experiment, the control test board of the camera module is not yet designed to do that, and the same bias is applied to all the SiPM's. Since we want the SiPMs to be used at their optimal bias voltage, we have to use SiPMs that all have close optimal biases. We thus selected 7 SiPMs in the stock at our disposition with similar characteristics (see the list of selected SiPMs in the Annex). The 7 SiPM that are now used in the first prototype camera module have a nominal bias of 72 Volts at 25°C.

The control board of the camera module was designed to match the electronics characteristics of the board used for the FACT experiment. It basically allows to have access to the outputs signals of every pixel (i.e. every SiPM) of the camera, and to a sum signal that displays the voltage sum of the seven pixels. A scheme of the test board is displayed on fig (27).

![Test Board Diagram](image)

Figure 27: The test board where the camera module is connected. "J1" and "J2" are the connectors to the camera module, "out1" to "out7" are the outputs for every pixel of the camera, "sum" is the output of the sum of all the outputs signals and "bias" is the input where is set the reversed voltage of the SiPMs of the camera.
**Trigger:**
We will use two scintillators to trigger on the events that have the wanted angle and direction. We plug these two scintillators into NIM discriminators in order to have a normalized logical signal. We then use a coincidence module to output a signal when both scintillators detect something. We send the coincidence signal in a counter, in order to have records of the counting rate of the muons, and in the trigger of our readout setup, whether it is the oscilloscope or the DRS. Note that there is a strong difference (a factor 10) between the detection rate of our two scintillators that remains unexplained. We did not have other scintillators at our disposal at the time and not enough time to build new ones. We however observe coincidences with our scintillators: when placed in a configuration similar than the one described in section 4.1, we obtain a coincidence rate of the order of 2-3 muons per minute. We optimized this rate as well as we could, using the oscilloscope and setting the thresholds and signal widths of the different used modules.

**Coincidence rate:**
Accidental coincidences are random events occurring when both of the scintillators trigger at the same time for two unrelated events. Let’s estimate the accidental coincidence rate of our system, in order to see if we should expect a strong influence of this effect on our measurements. This rate is simply defined by:

\[ \tau_{acc} = \tau_1 \tau_2 \Delta t \]  

where \( \tau_1 \) and \( \tau_2 \) are the detection rates of the two scintillators, and where \( \Delta t \) is the resolving time that is to say the sum of the trigger signals widths. Using a counter and an oscilloscope, we can easily measure these variables. We find rates of 138 Hz and 15 Hz (this difference has already been discussed), and a signal width of 80 ns for both triggers, which implies a resolving time of 160 ns. The accidental coincidence rate is thus extremely low, as expected when dealing with low trigger rates: \( \tau_{acc} = 3.312 \times 10^{-4} \) Hz, which is 4 orders of magnitude smaller than the coincidence rate we observe. This confirms that accidental coincidences should not have any measurable influence on our experiment.

4.3 Traces analysis
At first, we have to do some measurements characterizing the camera module and the signals we receive from it. We will use an oscilloscope as we want to have a first idea of the signals we are receiving, before having to deal with the DRS setup. Since the oscilloscope doesn’t allow us to record traces for more than one source at the same time, we will focus mainly on the sum output. We record every trace of the sum, in order to be able to do take some measurements a posteriori. We do observe peaks that always have the same delay with regard to the trigger, those are our muons (see an example of a muon trace on fig 28). Unfortunately, the triggering rate is low (during our first round of measurements, the scintillators were triggering with a rate of 0.069Hz which represents
Figure 28: The trace produced by the Cherenkov light emitted by a muon going through the radiator, as seen on the sum output.

~ 4 trigger per minute) and muons are not even detected every time the scintillators trigger. Since this detection rate is quite low, we let measurements run in rounds of 24h, typically. With the help of a root code, we then analyze the traces taken and can deduce the ratio of the number of actual detections with the number of times the system triggers, with regard to an arbitrary threshold voltage above which we consider a voltage peak in the right time opening as a detection. Since the noise we observe has a measured amplitude of 1 mV, we choose the threshold of detection to be twice as big, that is to say 2 mV. With this threshold, we determine that only 12.5% of our events correspond to a muon detected in the camera (this represents approximately one detection every two minutes). This can be understood if we consider the fact that the surface covered by the camera module is considerably smaller than the surface of the scintillators (the camera module has a surface of ~ 18 cm² while the scintillators cover an area of 300-400 cm² which is more or less 20 times bigger). This is probably the main cause of this low detection rate, most of the muons don’t emit light on the camera, or at least too few to be distinguishable from the noise. We would need to cover a bigger surface with more than one camera in order to have a better detection rate. Accidental coincidences could have been another factor but as we saw in the previous section, the
accidental rate is too small to play any role in our experiment. Note that some of the muons we detect actually go through the camera module itself. This was proven by taking another round of measurement with the exact same configuration except with no radiator. In this case, we observe a proportion of $\sim 3\%$ of the triggers corresponding to a muon detection. The main part of the muons we trigger on though, produce light through the radiator when taking measurements with it.

We plot the amplitude histogram of a round of measurement (fig 29), and the "zoomed in" version where only the events considered as muons appear (fig 30). Note that there are no clear peaks in our histogram: it is continuous. This was to be expected since there is a whole spectrum of possible configurations in terms of energy of the detected muon, angle and point of incidence, illumination of the camera module, etc.

![Amplitude Histogram](image)

Figure 29: The amplitude histogram for the sum signal of triggered events. Note that the noise peak (on the right) is clearly dominating. A "zoomed in" version displaying only the events linked with the actual detection of a muon is shown on fig (30).
Figure 30: Here we display the amplitude histogram of the events with an amplitude above 2mV (for the sum signal), that is to say the events that are believed to be due to an actual muon detection.

**Expected number of photons:**
Let’s try to determine the number of photons emitted by a muon passing through our radiator. This is done by using the Frank-Tamm formula (1), applied on our system. If we integrate the formula between two wavelengths we obtain:

$$\frac{dN_{\gamma}}{dx} = \int_{\lambda_1}^{\lambda_2} \frac{d\lambda}{\lambda^2} 2\pi \alpha \sin^2 \theta_c = 2\pi \alpha \sin^2 \theta_c \left( \frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right)$$

(10)

where we did the approximation that the refraction index does not depend on the wavelength (a valid approximation since this dependance is really negligible on such small differences of wavelength). In our case, we integrate on the part of the Cherenkov spectrum where our instruments are sensitive (from 350 to 600 nm) and we take the Cherenkov angle we used before ($\theta_c = 47.84^\circ$). We find that a muon passing through a layer of PMMA at a speed $\beta \sim 1$ produces 300 Cherenkov photons per cm, in the integrated wavelength range. These photons are emitted in all the directions of the Cherenkov cone, if we want to know how many of these photons reach the surface of the camera module (i.e. the window), we now have to know the disposition of the latter with regard to the muon trajectory. In our assembly, the camera module is situated $\sim 5$ centimeters below the
radiator, and the diameter of the camera module can be reasonably approximated by 3 times the
diameter of one cone ($d_{\text{camera}} \approx 4.88$ cm). We can now compute the angular size of the camera
module for the muon. Since the module is close to the radiator, we cannot neglect the variation of
the angular size from when the muon enters the radiator to when it goes out. We will however do
the approximation that the angular opening is constant through the whole process, with an average
value corresponding to when the muon is halfway in the radiator (we then find an angular size of
$\sim 42^\circ$). Since the cone is spread out on 360$^\circ$, the angular size of the camera module represents
$\sim 12\%$ of the cone opening, that is to say only $12\%$ of the Cherenkov photons reach the camera. Our
triggered muons enter the radiator with an incident angle included in the interval [34.56$^\circ$, 61.12$^\circ$]
(see section 4.1). Knowing the height of our radiator (3.6 cm), we can compute the corresponding
traveled distances in the radiator ([1.74 cm, 2.96 cm]). We can then compute the number of photons
reaching the camera: travelled distance $\times 12\% \times 300$ photons/cm $\approx 60 - 100$ photons.

**Expected number of P.E.s:**

Let’s try to estimate the number of P.Es we should see every time a muon passes through our device.
We just computed the number of photons reaching the window, we need to deduce the number of
photons reaching the SiPM, and the proportion of the latter that will trigger an avalanche, that
is to say, the number of actual P.E’s. Since this will depend on the transmission coefficients of
the materials, as well as on the PDE of the SiPMs, and since all these parameters are wavelength
dependent, we have to take a step back and re-consider our integral. We have thus:

$$\frac{d^2 N_{\text{P.E.}}}{dx d\lambda} = p_{12\%} \frac{d^2 N_\gamma}{dx d\lambda} PDE(\lambda) \beta(\lambda)$$  \hspace{1cm} (11)

where $p_{12\%}$ is the $12\%$ factor found before corresponding to the proportion of the Cherenkov cone
illuminating the camera module and $\beta(\lambda)$ the transmission coefficient of the materials of the camera
module. Integrating over distance and wavelength and using equation (1) we find:

$$N_{\text{P.E.}} = p_{12\%} 2\pi \alpha L \sin^2 \theta_c \int_{\lambda_1=350nm}^{\lambda_2=600nm} \frac{PDE(\lambda) \beta(\lambda)}{\lambda^2} d\lambda$$  \hspace{1cm} (12)

where $L$ is the travelled distance through the radiator. By fitting the transmission coefficients of all
the materials and numerically integrate the equation above, we find that the whole camera module
should detect $\sim 18 - 32$ P.Es per detected muon (we used again the length interval computed
before). Of course, this is a very naive approximation limited to the case of a muon traversing the
radiator with one particular point of incidence and we should not take this result as an absolute
truth. It does however provide a rough idea of the kind of signals we should expect from these
muons detections. We will now measure the amplitude of the P.E. peak and see that this prediction
is somewhat close to what we observe.
In order to see if our module and test board are able to provide a signal big enough to be detected in the DRS, we need to determine the amplitude of the single P.E. peak. Since the setup we have in our box is not suited for this purpose, we are going to use parts of the catafalque (see section 3.1) in our experiment. We thus add in our box the LED connected to the pulse generator (see details in section 3.1), and use the pulse to trigger the detection on the oscilloscope. We also use the pulse amplifier on the output signal in order to see the P.Es. As for a classical catafalque experiment, we plot the amplitude histograms of the detected pulses directly on the oscilloscope, and use a root code to analyze them. We can plot the histogram for a specific channel of the test board (i.e. one pixel of the module), or for the sum output of the board. These histograms are shown on figs (31) and (32). By fitting the first and second peaks of the 1-channel histogram, corresponding to the 0 and 1 P.E. peaks, we can deduce the amplitude of the single P.E. We find a P.E. of ~0.24 mV. This is lower by a factor ten with regard to the FACT value of the P.E. peak. This is actually explained by the fact that the electronics used on the test board is not exactly similar to the one used in the FACT experiment.

Figure 31: The peak amplitude histogram of one of the channels. Note that we can clearly distinguish P.Es. These measurements were taken with the pulse amplifier.
Figure 32: The peak amplitude histogram for the sum channel. P.Es are not distinguishable. This comes from the fact that the big number of different combinations between the 7 channels make the spectrum continuous.
4.4 DRS system

The Domino Ring Sampler (DRS) is a waveform digitizing system that will be used to read out the data from the camera module in the final version. Basically, the DRS board is separated in two parts: the analog part is used for the signal sampling of the 32 input channels, while the digital part is used for control and multiplexing. When an analog signal is sent to the DRS, it is stored in a bank of 1024 cells that is organized as a ring buffer. Every time a trigger signal is picked up by the DRS, the buffer is "frozen" and digitalized. The high frequency of the system is what makes it attractive to experiments in IACT. The DRS system is actually already used in telescopes like MAGIC II in La Palma [1].

The last part of our experiment is to try to read out the camera module using the DRS board. Contrary to the oscilloscope we were using in the previous section, the DRS board will allow to read out and record the 7 pixels of the camera and the sum signal at the same time. Our first reflex was to simply connect the exact same setup used in section (4.3) in the DRS board instead of the oscilloscope. The trigger worked without flaws, but the noise level of the DRS was covering the signal we were sending to it. We need to compare the signal amplitude we can expect from the camera+test board system to the noise level in order to understand if it is readable or not.

With the P.E. level we measured before (\(\sim 0.24\) mV), we are assured that we will not be able to detect any single P.Es on the DRS (noise level is \(\sim 3\) mV) and it is unlikely that even the sum will be detected as well (if we want a signal at least twice as big as the noise level, we need a peak of more than 25 P.Es). Since we want to be able to read every channel separately, we have to modify the system a little bit. Modifications were then brought to the board in order to boost the level of the P.E. peaks (we removed some of the resistances on the circuit). By the same method used in the previous section, we can measure the value of the new single P.E. level. We now have a P.E. at \(\sim 1\) mV

With its new performances, the output signal from every pixel of the module is now seeable on the DRS. We plotted three examples of a muon trace, as detected by the seven channels of the camera module (tables 2, 3 and 4 in the Annex). We did not have time to do further analysis with the DRS, however, we proved that it was a convenient and perfectly useable readout device for our camera module. We also proved that the seven channels of our module worked and that the test board is a good starting point for future design of the final camera.
5 Conclusion

Our different tests made on both the components of the camera module, and the module itself, allowed us to widen our knowledge of the different features of such a device. We showed that the project was engaged on a good path and that the choices of design made until now were justified. The components of the camera module fill their role well and there are no striking surprises about their behavior. However, there still are some questions that will need to be answered in the future.

We did not manage to explain completely why there is such a discrepancy between the measured value of the gain induced by the cone on the SiPM, and the predicted one, which seems yet to take into account all the principal factors playing a role the compression and transmission of light. There are probably some unknown effects happening in the cone, and it would probably be interesting to run measurements with other types of light source like laser diodes in order to have a better understanding of the internal reflections of the cone. It would also be profitable to numerically simulate the behavior of the cone even if its shape makes this last operation arduous. The optical gel we used could be another source of light losses. In the final design, there will be no use of optical gel since all the elements will be linked with glue. It will be interesting then to recalculate the gain in order to observe possible changes.

We also measured the angular acceptance of the cone and, while the acceptance profile shape is relatively close to the simulated one for a parabolic cone, it is drastically different than the behavior of a typical Winston cone. When optimizing the physical parameters of the telescope, it might be interesting to estimate how these differences affect the telescope design and the detection.

We also proved by direct measurement than the module was fully capable of detecting photons emitted by Cherenkov radiation and that the DRS was an adapted readout device for the camera module. The next step of the characterization would be to take more measurements with the DRS in order to run some statistical analysis and validate the results. This would also lead to the calibration of the camera module, which is an important stage of the development. Another priority is to improve the gain of the test board on which the module is connected, in order be able to detect single P.Es with the DRS. Another board is actually in production to achieve this aim. Finally, it would be a good validation of the camera module if we managed to detect an actual muon ring (or at least a part of it) with the module. It is however probable than more than one module will be needed for this measurement.

The new opportunities offered by SiPMs in the field of Cherenkov telescopes are numerous. It is a new technology that just reached its maturity, but didn’t stop its growth so we can expect more from it in the future. FACT opened the way of the collaboration between Cherenkov astronomy and SiPMs detector, CTA could be the next one to follow its lead, with the aim of exploring, with even more sensitivity than all the current gamma ray telescopes, the depths of our Universe.
References

[7] ROOT analysis tool, on the CERN website: root.cern.ch/
[8] CTA Consortium original article, "Design concepts for the Cherenkov Telescope Array CTA: an advanced facility for ground-based high-energy gamma-ray astronomy", 2010
6 Annex

List of the SiPMs used in the prototype camera:

<table>
<thead>
<tr>
<th>Serial no</th>
<th>Nominal Voltage [V]</th>
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<tr>
<td>338</td>
<td>72.01</td>
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</table>
Table 2: The trace produced on every pixel of the camera by a muon, recorded with the DRS, example 1.
Table 3: The trace produced on every pixel of the camera by a muon, recorded with the DRS, example 2.
Table 4: The trace produced on every pixel of the camera by a muon, recorded with the DRS, example 3.