Silicon Photomultiplier Characterization

Peter Lyle Rossiter

28/9/2015

Master Thesis

Supervisor: David Berge
Examiners: David Berge and Niels van Bakel
Abstract

The Cherenkov Telescope Array (CTA) is a next generation Imaging Air Cherenkov Telescope (IACT) and is being built to examine cosmic gamma-rays from below $\sim 100$ GeV to above $\sim 100$ TeV. Within this array a Small Size Telescope (SST) is being developed to look specifically at gamma-rays in the range of $\sim 10$ TeV to $\sim 100$ TeV (VHE gamma-rays). In order to record gamma-ray events the SST will collect Cherenkov light from the relativistic secondary particles generated by the extended air shower seen when VHE gamma-rays interact in our atmosphere. This will require a camera sensitive to blue and ultra violet light characteristic of Cherenkov radiation; a role which will be filled by the Compact High Energy Camera (CHEC).

One of the targets of the CHEC collaboration is to develop a prototype camera with a photosensitive layer comprised of Silicon Photomultipliers (SiPMs); a relatively new technology developed to replace the role of PMTs in the current generation of IACTs. SiPMs are an attractive option as they have an improved photo-sensitivity and time resolution compared to PMTs, and deliver this at a cheaper cost in a more robust unit. The size of SiPMs in particular will afford CTA never before seen resolution leading to potentially $\sim 1000$ TeV sources being pinpointed on the night sky. In order to facilitate this, the experimental setup at NIKHEF will be developed to characterize SiPMs. This development will allow devices to be assessed and compared for suitability within CHEC.

The goal of this thesis was to develop the existing experimental setup for SiPM characterization at NIKHEF. By ensuring the apparatus was light tight, and that sensor temperature could be controlled, the setup ought to become appropriate for assessing dark count rate (DCR), dynamic range (DR), photon detection efficiency (PDE), single photo-equivalent pulse (1 PE) level and crosstalk probability. With this setup in hand, two potential SiPM arrays, the Philips Digital Photon Counting kit (PDP C) and the Excelitas C30742-66 Series SiPM, were tested and compared for suitability in CHEC.

The results of this analysis showed that after developing the apparatus, it went from not being light tight, to light tight with a confidence of $\alpha = 0.01$, and temperature controlled to within $2.22 \times 10^{-4} \pm 1.11 \times 10^{-4}$. This allowed for the determination of several SiPM characteristics for comparison. The results also showed that the DCR and crosstalk probability for both devices under test were comparable. However, the Excelitas sample crucially outperforms the PDPC with respect to its dynamic range. While the PDPC dynamic range peaks at a cell breakdown rate of $\sim 44$ MHz/cm$^2$, the Excelitas sample showed no sign of saturation at the same light level. This measure rules out the PDPC for use in CHEC as the expected background cell breakdown rate from the current HESS data is $\sim 100$ MHz/cm$^2$. 
5.2.3 Conclusion .................................................. 30
5.3 LED Attenuation ............................................. 30
5.4 Updated Apparatus ......................................... 31
  5.4.1 Excelitas C30742-66 Series ......................... 32

6 Silicon Photomultiplier Characterization ................. 32
  6.1 Dark Count Map ........................................... 32
     6.1.1 Procedure ........................................... 33
     6.1.2 Discussion .......................................... 33
     6.1.3 Conclusion .......................................... 34
  6.2 Temperature vs. Dark Count Rate ........................ 34
     6.2.1 Procedure ........................................... 36
     6.2.2 Discussion .......................................... 36
     6.2.3 Conclusion .......................................... 38
  6.3 Dynamic Range ........................................... 38
     6.3.1 Apparatus ........................................... 39
     6.3.2 Procedure ........................................... 40
     6.3.3 Discussion .......................................... 41
     6.3.4 Conclusion .......................................... 44
  6.4 Wavelength vs. Photon Detection Efficiency ............ 45
     6.4.1 Procedure ........................................... 46
     6.4.2 Discussion .......................................... 49
     6.4.3 Conclusion .......................................... 51
  6.5 Multi Photo-Equivalent Peak Spectrum ................. 51
     6.5.1 Apparatus ........................................... 52
     6.5.2 Procedure ........................................... 53
     6.5.3 Discussion .......................................... 53
     6.5.4 Conclusion .......................................... 54

7 Conclusion .................................................. 55
  7.1 Silicon Photomultiplier Comparison ...................... 55
  7.2 Setup Development and Recommendations .................. 56

8 Acknowledgements ........................................... 59
1 Introduction

This thesis will explore silicon photomultiplier characterization and the development of the experimental setup to perform said characterization. This study is being done in conjunction with the Cherenkov Telescope Array (CTA) collaboration; a next generation Imagine Air Cherenkov Telescope (IACT). As part of this telescope array will be Small Sized Telescopes (SSTs) used to sensitively measure cosmic gamma-ray fluxes above $\sim$10 TeV. An essential component to the SST is the Compact High Energy Camera (CHEC) which will be used to detect photons. It is the goal of the CHEC project to develop a camera which utilises the new technology of Silicon Photomultipliers (SiPMs). It is hoped these devices will improved collection rates. [1] [3].

What is of particular focus for this thesis is the development of the experimental setup at NIKHEF to characterize SiPMs. Several characteristics are of specific attention to this study; these are; dark count rate, dynamic range, photon detection efficiency, the single photo-equivalent peak and crosstalk probability. To do this it will first be necessary to ensure that the apparatus has sufficient temperature control, is light tight and that the optical power of light emitting diode used to test the devices is operating in a range appropriate to the devices under test. All three of these variables can affect cell break down rates, making them confounding variables when determining true photon count rates.

With this improved experimental apparatus, characterization of two devices was conducted. Specifically the devices examined were the Philips Digital Photon Counting Kit [16], and the Excelitas C30742-66 Series SiPM [27]. In the end these two devices were compared for their suitability for use within the CHEC camera.

Chapter 2 of this thesis will begin by discussing very high energy astronomy. Chapter 3 will go on to discuss silicon photomultipliers. Chapter 4 will examine the existing setup at NIKHEF and motivate any developments which need to be made. Chapter 5 will explain setup developments which needed to occur. Chapter 6 will detail the SiPM characterization which was performed. To conclude characteristics of both SiPMs under test will be examined and compared, followed by a recommendation for which of the two will be the better option for the CHEC camera.

2 Very High Energy Gamma-Ray Astronomy

In this section I will introduce Very High Energy (VHE) Gamma-Ray Astronomy, Imaging Atmospheric Cherenkov Telescopes (IACTs), the Cherenkov Telescope Array (CTA) and the Compact High Energy Camera (CHEC). This section will conclude by focusing on the photo-sensors of the CHEC. Unless otherwise specified, all material is based on [1], [2] and [3].
2.1 Very High Energy Gamma-Ray Astronomy

A relatively recent development in the field of astronomy is the study of very high energy gamma-rays. By observing VHE gamma-rays (i.e. with energy > 10 GeV) we are given a window into the most extreme astrophysical processes in the Universe. A more exciting notion comes from the fact there is no known way for thermal radiation to have the actual energy observed in VHE gamma-rays. These gamma-rays are thought to be the result acceleration of relativistic charged particles, for example by a magnetic field or a plasma shock. Thus the powerful processes behind their origins could provide a window to examine theories beyond the standard model. The list of possible candidates for sources of VHE gamma-rays is wide open but includes collapsed stars and super massive black holes.

Furthermore VHE gamma-ray astronomy will continue to find itself at the forefront of physics for some time as it is theorized that gamma-rays could be by-products of new physical processes, such as neutralino annihilation. Thus detection of gamma-rays by specialised instruments such as the upcoming Cherenkov Telescope Array has the potential to confirm the existence of such processes.

2.2 Gamma-Ray Production

Stars are able to emit light because they have very high temperatures; this type of light is known as thermal radiation. Thermal radiation has a signature spectrum whereby the temperature of an object entirely determines its thermal radiation output. But regardless of an object’s temperature it will never produce a large number of gamma-rays. The abundance of gamma-rays detected in our Universe can only be accounted for by non-thermal processes such as synchrotron radiation, bremsstrahlung radiation, inverse Compton scattering, neutral pion decay, matter/anti-matter annihilation, and nuclear transformations.

These effects are thought to occur at sources such as supernovae remnants (SNR), fast rotational objects such as neutron stars and pulsars, active galactic nuclei (AGN), and matter accreting black holes.

Synchrotron Radiation

When a charged particle changes direction in a magnetic field an acceleration occurs resulting in a radiated electromagnetic (EM) wave. This EM wave is known as Synchrotron radiation (figure 1). Synchrotron photons have a continuous energy spectrum. Electrons with energy E in a magnetic field of strength B radiate a power P. This relationship is reflected in equation 1.

\[ P \sim E^2 B^2 \]  (1)
Bremsstrahlung Radiation

Similar to synchrotron radiation, when charged particles are deflected in a Coulomb field of another charge (be it an atomic nucleus or an electron) the result is the emission of bremsstrahlung photons (figure 2). The probability of bremsstrahlung ($\phi$) depends in both the square of the projectile charge ($z$) and the square of the target charge ($Z$). $\phi$ is proportional to the particle energy, and inversely proportional to square mass of the deflected particle. This can be seen in equation 2.

$$\phi \sim \frac{z^2 Z^2 E}{m^2}$$  \hspace{1cm} (2)

Since electrons have a tiny mass compared to even the smallest atomic nuclei, they are the predominant source of bremsstrahlung photons. The bremsstrahlung photon energy spectrum is continuous and decreases by $1/E_\gamma$ to high energies.

Inverse Compton Scattering

Compton scattering occurs in a collision between a free electron and an energetic photon, and is defined by the photon losing a percentage of its energy to the electron. The reverse is also possible and is a significant effect in astrophysics (figure 3). Energetic electrons have the opportunity to collide with many photons from blackbody radiation ($E_\gamma \approx 250 \mu\text{eV}$, photon density $N_\gamma \approx 400/\text{cm}^3$) or starlight photons ($E_\gamma \approx 1 \text{eV}$, $N_\gamma \approx 1/\text{cm}^3$) transferring it’s energy to the
photon.

Figure 3: Collision of an energetic electron and a low energy photon. The electron transfers energy to the photon and subsequently slows down. The photon on the other hand gains energy and becomes blue-shifted.

**Neutral Pion Decay**

Accelerated protons can produce charged and neutral pions in proton-proton or proton-nucleus interactions (figure 4). A possible process for this is given in equation 3.

\[
p + \text{nucleus} \rightarrow p' + \text{nucleus}' + \pi^+ + \pi^- + \pi^0 \quad (3)
\]

The charged pions quickly decay \((\tau = 26 \text{ ns})\) into muons and neutrinos while the neutral pion decays \((\tau = 8.4 \times 10^{-17} \text{ s})\) into two photons. The division of energy between these two photons depends on the pion’s motion. If it is at rest, the photons are produced back-to-back with each receiving half the rest mass of the pion. \((\sim 135 \text{ MeV})\). In other cases it will depend on the direction of photon emission with respect to pion direction.

Figure 4: Neutral pion production via proton interactions, followed by pion decay into photons.
Photons from matter / anti-matter annihilation
Charged particles can annihilate with their antiparticles into energy. This primarily occurs via electron-positron and proton-antiproton annihilations (figure 5). A minimum of two photons must be created in this process in order to conserve momentum. In the rest frame of $e^+e^-$ annihilation each photon receives 511 keV; equivalent to the rest mass of the electron and positron respectively. This process can also occur between a proton and anti-proton to produce a neutral pion. This process can be seen in equation 4, where the neutral pion subsequently decays into two photons.

$$p^+ + p^- \rightarrow \pi^+ + \pi^- + \pi^0$$  \hspace{1cm} (4)

Figure 5: $e^+e^-$ annihilation into two photons.

Photons from Nuclear Transformations
Supernova explosions result in the production of heavy elements, leading to both stable elements and radioactive isotopes. As a result of beta decay these isotopes emit photons in the MeV range. An example of this can be seen in equation 5.

$$\Rightarrow^{60}C_o \rightarrow ^{60}N_i^{**} + e^- + \nu_e$$
$$\Rightarrow^{60}N_i^{**} \rightarrow ^{60}N_i^* + \gamma \ (1.17 \ MeV)$$
$$\Rightarrow^{60}N_i^* \rightarrow ^{60}N_i + \gamma \ (1.33 \ MeV)$$  \hspace{1cm} (5)

Neutralino Annihilation
Neutralinos are an exotic particle from beyond the standard model. They exist as the super-symmetric partner to neutrinos. In certain situations it is theorized that the annihilation of neutralinos could result in the production of photons. This annihilation can be seen in equation 6.

$$\chi + \bar{\chi} = \gamma + \gamma$$  \hspace{1cm} (6)
2.3 Imaging Atmospheric Cherenkov Telescopes

With the exceptions of radio waves and visible light, electromagnetic (EM) radiation arriving at Earth will not be able to pass through our atmosphere to ground level (see Figure 6). In order to observe radiation of other wavelength it has traditionally been required to take measurements at high altitudes with the aid of balloons and other aircraft. More recently, mounting instruments on satellites has been possible. But such techniques present another problem for VHE gamma-ray astronomy as there are typically very low fluxes (~ a few photons per m² per year) coming from objects of astro-physical interest. Thus any sensor mounted on a satellite, hampered with a low collection area, cannot be expected to provide much data.

Figure 6: Earth’s atmosphere stops most EM radiation from reaching the surface. This illustration shows the atmospheric penetration depth of different parts of the EM spectrum before absorption. [4]

However when VHE gamma-rays interact with nuclei in the atmosphere they create particle cascades (a.k.a. extensive air showers), and in this we find a solution to our detection problem. Detection becomes possible because the relativistic secondary particles in air showers move faster than the local speed of light, resulting in the emission of Cherenkov light. This light can be thought of as the counterpart to the shock wave created by objects moving at supersonic speeds. This Cherenkov radiation appears as blue or UV light, emanating in a narrow cone around the path of the original gamma-rays. This allows the Cherenkov light to be used to "reconstruct" the direction and energy of the original gamma-ray (figure 7).

In Imaging Atmospheric Cherenkov Telescopes (IACTs), collected Cherenkov light is focused into a camera consisting of an array of light sensitive photomul-
tipliers, facilitating the generation of an image of the air shower (see Figure 7). Because the "light pool" of these showers is large at ground level, the energy of shower is spread out over a wider area. Thus the detection surface must also be large (of order $10^5$ m$^2$).

Figure 7: An extended air shower where a primary gamma-ray produces many secondary particles. Illustration also includes the associated Cherenkov light when the charged relativistic secondary particles are travelling faster than the local speed of light, specifically showing how this Cherenkov light cone falls around a given detection area. Finally the illustration shows how a given photon detection from a Cherenkov cone is recorded on the pixels of a telescope camera.

2.4 The Cherenkov Telescope Array

The soon to be built Cherenkov Telescope Array (CTA) is an example of a next generation IACT. The CTA is designed to observe VHE gamma-rays from astrophysical sources. It is envisaged as an open observatory made up of two arrays of IACTs, one in each hemisphere, for full sky coverage. The northern site will be located in La Palma (consisting of $\sim$19 dishes) and will focus on low energy extra-galactic objects only. The southern site will be located in Paranal Chile ($\sim$99 dishes), and will focus on galactic and extra-galactic objects across the full energy range. Both sites will be jointly constructed and operated by one international consortium.

While Modern IACTs (HESS, MAGIC and VERITAS) have taken great strides in ground based gamma-ray astronomy above $\sim$10 GeV and the investigation of cosmic non-thermal processes, CTA will be building on this work in ways not previously possible. The current accessible energy range by modern IACTs is $\sim$50 GeV to $\sim$50 TeV. Not only will CTA extend this accessible energy range (from below $\sim$50 GeV to above $\sim$100 TeV), it will also increasing the sensitivity in the energy range of $\sim$100 GeV to $\sim$10 TeV by an expected factor of 5-10. Furthermore, current IACTs typically use no more than 5 telescopes; resulting
in most showers only being viewed by 2 or 3 telescopes. This limits the ability to distinguish between showers that have a gamma-ray origin from those with a cosmic-ray origin\(^1\). CTA will improve on this dramatically by increasing the observed area. This will also provide the added benefit of improved angular resolution due to the larger number of views of each cascade. The improved angular resolution of CTA will for the first time allow us to resolve between structures of Galactic emission regions on parsec scales. It is expected that CTA will pin-point more than 1000 TeV, galactic, and extragalactic gamma-ray sources. This would increase previous levels of detection by a factor of > 10.

2.5 The Compact High Energy Camera

CTA is envisaged as employing three types of telescopes; Large-Sized Telescopes (LSTs), Medium-Sized Telescopes (MSTs) and Small-Sized Telescopes (SSTs). The SSTs are intended to be sparsely arrayed with large fields of view. Their purpose is to detect the highest energy gamma-rays, which are typically bright, and spread over a large area but are relatively rare events. The Compact High Energy Camera (CHEC) project has been specifically set up to meet these demands.

Figure 8: The CHEC. This version is equipped with MAPMs instead of SiPMs. Different pre-amplifiers are used with each sensor type to allow the use of the subsequent electronics chain.

CHEC is to be the camera used by the SST. Two CHEC prototypes, based on different photo-sensors, are underway. CHEC-M, the first prototype will be

\(^1\)Cherenkov showers from a cosmic-ray origin are the primary background events for VHE gamma-ray astronomy.
based on multi-anode photomultipliers and CHEC-S, on silicon photomultipliers. CHEC will be built to provide a reliable, inexpensive, quality assured solution to the SST. It is to have a curved focal plane to meet the SST optical needs, and will be fitted with $32 \times 64$ pixel photo-sensor modules (figure 8). Photo-sensor signals will be fed to a low noise shaping pre-amplifier and then, to a $1 \text{ GS/s}$ (i.e. 1 ns time-bin) digitising application-specific integrated circuit (called TARGET). Camera level trigger decisions will be made on a black-plane printed circuit board (PCB) with programmable trigger algorithms implemented on a field programmable gate array. CHEC will give full waveforms for each camera pixel in every event.

The photo-sensors to be used in this device are the focus of this thesis, specifically the testing of silicon photomultipliers for the CHEC-S. In the next section I will describe the silicon photomultiplier, and explain what qualities make it is a good fit for the CHEC camera.

Figure 9: The PMT is a decommissioned Hamamatsu R580 formerly from the ZEUS experiment, it is 13 cm long and has a diameter of 4 cm. The SiPM array is the Philips DPC-6400-22 consisting of over $\sim 400,000$ individual SiPM cells. The SiPM array has an outer dimension of $3.26 \text{ cm} \times 3.26 \text{ cm}$, with individual cells being $59.4 \mu \text{m} \times 32 \mu \text{m}$.

3 The Silicon Photomultiplier

Section 2 explained the need for a light sensitive device in CHEC, this chapter will look at a device that is capable of doing that; the Silicon Photomultiplier (SiPM). SiPMs represent the next step in avalanche photodiode (APD) technology [5-10]. At low temperatures SiPMs typically have an improved gain and response to PMTs. SiPMs also have the advantage in their compact size (figure 9) and ruggedness [11]. It is these characteristics which have led to their potential use not only by VHE gamma-ray astronomy [3] but also medium en-
ergy physics, high energy physics and medical applications [12, 13].

Similar to a PMT, an SiPM provides high gain and a fast response when detecting radiation. What is particularly interesting about both these devices is their ability to detect low levels of light, even single photons. What’s more, both devices achieve this low level light detection, with high photo-sensitivity and time resolution. However SiPMs typically deliver a higher photon sensitivity at a lower cost and in a more robust unit. The SiPM has a lower voltage operation, a lower power consumption requirement, and also offers insensitivity to magnetic fields. It is mechanically robust and gives highly uniform responses to homogeneous light sources. For these reasons the SiPM is quickly becoming the detection tool of choice in high energy physics.

In this section I will discuss how an SiPM detects photons, possible sources of noise and important characteristics. I will finish by discussing what these parameters need to be for the CHEC camera.

3.1 Photon Detection

As a photon travels through silicon there is a certain probability of it transferring energy to a valence electron, thus pushing it into the conduction band. This process is also known as creating an electron-hole pair. As shown in figure 10, a photon’s absorption depth in silicon is dependent on its energy/wavelength. This tells us that silicon is an excellent material for photon detection in the range from 350 nm up to 1000 nm. Below 350 nm the absorption length is so short that silicon is too thin and above 1000 nm it is too bulky.

This effect can be used to detect incident light. The force which would usually pull electrons and holes back together can be suppressed by applying a reverse bias across the diode in the depleted region of a p-n junction. Such an arrangement will lead to a flow of electrons to the n-type side and holes to the p-type side of the device when the respective charge carriers are created by a photon. To understand how a depleted region in a p-n junction leads to the detection of photons consider the case of an energetic photon passing through the region which has been reversed biased. Assuming this photon’s energy is greater than the band gap energy of the material it is passing through (1.1 eV for silicon), there is a certain probability of the creation of an electron-hole (e-h) pair. In this case the field will cause the electron to move towards the n side and the hole towards the p side. In the circuit around the photodiode this will lead to the flow of a photo-electron. These two newly created charge carriers are accelerated until they have enough kinetic energy to create secondary pairs of electrons and holes. This occurs via a process known as impact ionization. Here, one photo-electron can start an ionization cascade that spreads through the whole silicon where ever the field is applied. At this point we see the silicon break down and become conductive, which amplifies the original photo-electron into a much larger current. This is called a Geiger discharge, and is illustrated in figure 11 (a).

The gain of photodiodes in Geiger mode can be improved with the use of this
Figure 10: The effect of wavelength on photon absorption depth in silicon [14]. A notable feature omitted from this plot is a cut-off at $\sim 1155\text{ nm}$ as the wavelength drops below the band gap energy. This occurs because the photon is no longer energetic enough to create an electron-hole-pair.

Figure 11: Illustrations from [14]

(a) A Geiger discharge in an APD. It causes an ionisation cascade in which a single photon begins a chain of impact ionizations spreading through the whole depleted region

(b) Cycle of cell breakdown, avalanche, quenching and bias reset.
breakdown. The p-n junction region is designed so that it is able to maintain a reverse voltage bias beyond its nominal breakdown voltage, creating the large field gradients across the junction. Once a current is flowing then it needs to be stopped (a.k.a. quenched). This can be done by using what is called passive quenching, (i.e. without using active circuitry). Here a series resistor (RQ) restricts the current taken by the diode as it breaks down. Subsequently, there is a reduction in the reverse voltage seen by the diode to a value below its breakdown voltage. From here the APD recharges and is ready to breakdown again upon photo-excitation in its depleted region. This cycle of breakdown, avalanche, quench and bias reset to a value above the breakdown voltage is illustrated in figure 11 (b).

3.2 The Silicon Photomultiplier

Silicon Photomultipliers (SiPMs) integrate a dense array of small, photodiodes in Geiger mode which have been electrically isolated. The photodiodes in the array, (aka microcells) typically have a dedicated quenching resistor. The output of the SiPM is the summation of all of these diodes, as shown in figure 12 (a). All microcells detect photons in identical but independent ways. The discharge current from each detector is summed to give the devices output, providing information on the magnitude of an incident photon flux.

3.3 Over Voltage

When adjusting the voltage to generate the electric field over the depleted region, a point is reached where Geiger discharges will occur. This point is called the breakdown voltage ($V_{br}$). This point is clearly seen on an I-V plot by a sudden jump in the current (as shown in figure 12 (b)). This tipping point is an important characteristic of SiPMs and typically goes hand in hand with two others; bias voltage and over voltage. Over voltage is ideally set to the optimal voltage above the breakdown voltage for which the SiPM operates. Bias voltage is the sum of the other two:

$$V_{bias} = V_{over} + V_{breakdown}$$  \hspace{1cm} (7)

Of these three variables, only two are critical performance parameters of SiPMs as the third is easily resolved from the others.

3.4 Noise

A fired cell is not invariably referable to an incoming photon. There are several noise effects which mimic the response of an absorbed photon. Because these effects enlarge the measured number of cell breakdowns, it is inevitable to take
them into account. The combined rate of these types of signals is called the dark count rate (DCR).

3.4.1 Thermal Noise

Thermal excitation can generate an e-h pair which is able to induce an avalanche. A typical noise rate of an SiPM cell is in the order of magnitude of 10 kHz at room temperature, with an increase of 7.5°C leading to this rate doubling [16]. Since the noise rate is proportional to the number of cells, the rate of a whole SiPM can easily exceed a few MHz. The probability of a cell breakdown due to thermal excitations is described by the well known equation [19]:

\[
Pr(T) = CT^{3/2} \exp\left(\frac{E_g}{2k_BT}\right)
\]  

Where \(T\) is the absolute temperature, \(E_g\) is the bandgap energy, \(k_B\) is the Boltzmann constant and \(C\) is a proportionality constant dependent on the material and the technological parameters.

3.4.2 Optical Crosstalk

If an e-h pair created during an avalanche recombines, a photon will be emitted which in turn is able to start a new avalanche in a neighbouring cell. Alternatively the photon can transmit directly into another cell or can first be reflected on the coating. This will see the photon enter the n-substrate of another cell creating a new e-h pair. These charge carriers can subsequently drift into the avalanche region causing a breakdown. The precise crosstalk probability can vary widely between devices, but are typically accepted to be between 5% to 35% [17].
3.4.3 After Pulses

Charge carriers from an avalanche can be trapped by impurities of the silicon. After a few tens of nanoseconds, their release can induce a cell breakdown. Here too the probability can vary, for instance the Hamamatsu S10361 series SiPM can vary from 5% to almost 50% [17].

3.5 Gain

Every microcell in an SiPM consists of a Geiger-mode photodiode in series with a quenching resistor. Every time microcells undergo Geiger breakdown they produce a quantized, uniform charge. A microcell gain, hence the detector gain ($G$), is given by ratio of the output charge ($CV_{\text{over}}$) to the electron charge ($e$). The output charge can be found by the product of the over-voltage and the microcell capacitance:

$$ G = \frac{CV_{\text{over}}}{e} \quad (9) $$

If the quantized pulses from several Geiger discharges (as seen in figure 13 (b)) are integrated over, a charge spectrum can be formed. In this charge spectrum peaks due to successive numbers of detections stand out and are clearly seen. The constant spacing between the peaks can be used to find the gain via the equation above.

3.6 Dynamic Range

Although individual cells of an SiPM array are sensitive to individual photons, the entire array typically has a trigger setting requiring more than one photon to begin recording an event. This value typically defines the lower limit of the SiPM sensitivity. There is also a point at which the device "saturates" and cannot process any more photons. Between this minimum threshold and the saturation point exists a region in which the SiPM response can be mapped to the incoming photon flux. This region is known as the dynamic range and is the optimal region for device operation.

3.7 Quantum Efficiency

Quantum efficiency (QE) is a key measure of the effectiveness of an APD to detect light. It is defined as the number of e-h pairs generated per incident photon and is dependent on wavelength. For a perfect detector the QE = 1, but losses from photons being absorbed by silicon outside of the depleted region and photonic reflections will lower this value.

3.8 Photon Detection Efficiency

PDE in SiPMs is not simply the QE due to the device being built out of microcells. PDE typically refers to the probability of an incoming photon generating
a detectable Geiger pulse in one of its microcells. The PDE is a function of wavelength and bias:

\[ PDE(\lambda, V) = QE(\lambda)\varepsilon(V)F \]  

(10)

Here, \( QE(\lambda) \) is the quantum efficiency of silicon, \( \varepsilon(V) \) is the avalanche initiation probability and \( F \) is the fill factor of the device. Not every photoelectron will result in an avalanche, this is taken into account by the avalanche initiation probability. Because there are gaps between microcells for electronic or to limit optical cross talk, the entire surface area of the SiPM does not record photon hits. This is taken into consideration by the fill factor. The currently achievable fill factor is 40% to 60%.

The detector responsivity \( (R) \), defined as the mean photocurrent per optical power unit (Amps / Watt), is usually needed to find the PDE. The detector responsivity can be calculated as:

\[ R = \frac{I_P}{P_{OP}} \]  

(11)

\( I_P \) = photocurrent measured, \( P_{OP} \) = detected incident optical power for photons of a specified wavelength. Once SiPM responsivity is found the PDE can be found with the relation:

\[ PDE = \frac{R hc}{G \lambda e} \]  

(12)

\( G \) = SiPM microcell gain, \( h \) = Planck constant, \( c \) = speed of light, \( \lambda \) = wavelength of incident photons, \( e \) = electron charge. For this relation to be accurate it is crucial that the SiPM is being operated in its linear region. It must also be kept in mind this relation will over estimate the actual PDE as it does not account for optical cross talk or after pulsing.

### 3.9 Pulse Shape

The signal produced by an SiPM when exposed to a photon is characteristic to that sensor. There are three parameters which define the pulse; the rise time, the maximum, and the recovery time. For any number photo-equivalent (PE) pulses the rise time will always be the same, as too will the recovery time. However, the peak maximum will be a multiple of the 1 PE peak, thus a 2 PE peak will be double, and a 3 PE peak triple and so on. This feature is illustrated in figure 13 (a).

### 3.10 CHEC Requirements

In order to successfully record Cherenkov flashes the SiPMs used in the CHEC camera will need to have maximum PDE sensitivity in the 300 nm to 550 nm range. They will also need to produce minimal DCR and have a dynamic range which can handle an expected night sky background rate of 100 MHz /cm$^2$, whilst still triggering on low level Cherenkov flashes which may be as low as
a few photons [15]. The determination of these requirements will be the focus of this thesis. This will begin in the next section with an assessment of the preliminary experimental apparatus to determine these parameters.

4 Preliminary Setup Analysis

Before beginning this experiment an apparatus already existed for SiPM characterization. However it had never been used before and it needed to be tested for light tightness, if temperature could indeed be controlled as expected and to see if a dynamic range could be found. The outer chamber was thought to be light tight from its design, but it had not been thoroughly examined. Furthermore, there was no mechanism in place to control the sensors temperature. This was not considered an issue as varying ambient temperature ought to provide temperature fluctuations that could be compared. Finally no dynamic range measurements had been taken yet, but there was a concern that the most incremental increase in light intensity would quickly lead to SiPM saturation. This is an issue when wanting to precisely know the relationship between these two quantities. In short, a number of questions hung over the basic apparatus, and needed to be answered before an informed approach to SiPM characterization could begin.

Aim: Check if the chamber is light tight, check if temperature can be controlled for, and check the dynamic range of the apparatus.

4.1 The Kolmogorov Smirnov Test

The Kolmogorov Smirnov (KS) test was used to compare two sets of cell breakdown data recorded by the PDPC in the dark chamber under varying lighting conditions. This was essential for the light tightness test. The KS test is a
nonparametric statistical tool used to judge the equality of two continuous one
dimensional probability distributions. While it can be used by taking a sam-
ple probability distribution and comparing it to a reference distribution (a.k.a.
one sample test), for our purposes it was used to compare two samples to one
another. In this two sample case the KS statistic calculates a distance between
the empirical distribution functions (EDF) of the two samples. What makes the
KS test such a powerful tool is its sensitivity to both the location and shape of
the empirical cumulative distribution functions of the two samples [20].
When testing if two one dimensional probability distributions come from the
same sample, the KS statistic is [20]:

\[ D_{n,n'} = \sup (|F_{1,n}(x) - F_{2,n'}(x)|) \] (13)

Where \( F_{1,n}(x) \) and \( F_{2,n'}(x) \) are the EDFs of the sample distributions, and \( \sup \) is
the supremum function. The supremum function is defined as the smallest
number which is still greater than the given functions maximum. Here \( n \) rep-
resents one distribution, \( n' \) the other and \( x \) is the data being compared across
distributions. The two distributions are considered different at confidence level
\( \alpha \) if [2]:

\[ D_{n,n'} > c(\alpha) \sqrt{\frac{n+n'}{nn'}} \] (14)

Where the value of \( c(\alpha) \) is given in table 1:

<table>
<thead>
<tr>
<th>( \alpha )</th>
<th>0.10</th>
<th>0.05</th>
<th>0.025</th>
<th>0.01</th>
<th>0.005</th>
<th>0.001</th>
</tr>
</thead>
<tbody>
<tr>
<td>( c(\alpha) )</td>
<td>1.22</td>
<td>1.36</td>
<td>1.48</td>
<td>1.63</td>
<td>1.73</td>
<td>1.95</td>
</tr>
</tbody>
</table>

Table 1: Confidence levels and corresponding \( C(\alpha) \) constants for the KS test [21].

4.2 Apparatus

The existing experimental setup consisted of a dark chamber, housing the Philips
Digital Photon Counting Kit (PDPC). The PDPC was powered by a TTi PL115
Voltage supply set to an output of 5V. It was readout by a dedicated PC with
firmware provided by Philips [16]. The LED used to illuminate the PDPC
was Bridgelux ES Star Array Series BXRA-30G0540-A-00, which has a recom-
mended input voltage of 18.8 V and a variable input current of 0 mA to 500
mA. It was powered by TTI TSP3222 fully remote controlled power supply [24].

What is described here is simply the apparatus applicable to this section
of the analysis. It excludes much including the Excelitas sample, the peltier
element and various cooling fans to name a few. More will be said about these
other components as they become applicable.
The chamber under test is a 330 cm long, 230 cm wide and 160 cm deep iron
box with removable lid. It seals with 6 spaced bolts and a rubber seal. Several
holes exist where items have been installed in the box, which are sealed after
cOMPONENT installation. It was expected to keep out all ambient light. Any light
generated in the box via thermal excitations of the box itself will be in the deep IR range and undetectable by the SiPMs under test.

4.2.1 The Philips Digital Photon Counter

The PDPC is sensitive to a steady light source, was able to count individual photons. This device utilised an active quenching circuit which suppressed after pulsing effects. The kit itself came as a complete unit, which acted like a black box preventing the inner workings from being probed. But what it was capable of was counting the number of photons it detected for a given time frame. The PDPC also came with an internal temperature sensor, and would read out temperature measurements with each photon count. This device has a recommended operating temperature of 0°C to 45°C; however it should also be kept away from the local dew point to avoid condensation on the detector. Operation outside of this range can lead to unexpected behaviour, and perhaps permanent damage [16].

For the PDPC two types of data acquisition were built into its firmware; a frame count and a dark count map. The frame count would quite literally count the number of photons detected for a given number of frames (where 1 frame ~ 33 ms). Within this mode 4 different trigger thresholds were pre-programmed into the devices firmware [16]. The second data acquisition for collecting dark count maps (DCM) turns on cells individually, slowly working its way through the entire device. This mode had poorer temperature control, but eliminated cross talk from the data measurement. For this portion of the analysis only the first data acquisition type was used, but in several later sections this second method was preferable.
4.3 procedure

4.3.1 Light tightness and temperature control

When determining the physical environment which would lead to light tightness, three conditions for light tight chamber were initially considered:\(^2\):

- **Condition D**: Box was closed, room lights were on and daylight filled the room. A small hole behind the detector was left open. This was done to ensure data existed in a condition known to not be light tight, so it could be compared to the other data as a test of our statistical certainty.

- **Condition B**: Same as condition D, but the box was covered with a woollen blanket, also blocking the small hole behind the sensor. This condition was thought to be light tight prior to this analysis.

- **Condition N**: Same as condition B, but lights were out, blinds were down and was done at night to ensure a lower ambient light level.

Prior to this analysis condition B was assumed to prove light tight. Later when it was not, the woollen blanket was replaced by a thick black plastic covering which was taped over the light tight chamber. This arrangement became known as condition U, which also blocked the small hole behind the chamber.

Data was collected by taking the total number of photons detected per event. Events were triggered on the die level when one pixel had its configured trigger scheme satisfied. This was followed by a 45 ns integration window in which all four pixels in the given die were active. Events were expected to follow a Poisson distribution when grouped together by common temperature. These sets of data were compared across conditions, with temperature held constant. On these data sets, a KS Test was run. This was done by taking the condition N data to represent the parent population, and the data to be tested (D, B or U) as the sample data.

Prior to the analysis itself it was found that the KS test could give trivial solutions if the number of event counts in either group was too low. Naively one may assume this is easily dealt with by setting the required level of data above a fixed threshold. However there is a co-dependence on the sample population's influence on this threshold; as one population increases the necessary threshold in the other decreases. For instance, assume we have a population distribution P and a sample distribution S. If this sample does not represent a sample from the parent population, but from another set of data, (i.e. true sample mean \[\mu_S\] \neq true population mean \[\mu_P\]) we would expect a KS test to show this. But as \(|\mu_S - \mu_P| = 0\) the size of each population required to show that these distributions are different will increase. This observation motivated the need for two statistical validity checks on the data about to be analysed.

The first involved taking the mean and count of the two groups of data about to be compared, using a toy Monte Carlo to generate new data randomly sampled from a Poisson distribution with the same mean and count number. Since

\(^2\)For this portion of the analysis the LED was left off.
Condition D and Condition N were known to have different means (on account of the small hole in the box), if the KS test could not tell that the generated condition D data did not come from the generated condition N data 1000 times, the N data was disregarded.

The second validity check was to see if conditions B or U had a high enough count when they were being tested. Here the mean of the corresponding D data was taken with the count of the test data (B or U) to generate data for validity testing. Again, if the generated distributions could not be told apart they were disregarded as having too low a count.

If the data passed these two validity checks, they were run through a KS Test providing an $\alpha = 0.01$.

4.3.2 Dynamic Range Test

No temperature control or additional light tightness conditions were used in this section of the analysis. All that was done was to incrementally increase the input current to the LED (with input voltage of 18.8 V as recommended by the manufacturer) from 0 mA to 4 mA. At this point the light source was visible, and thought to put the PDPC into saturation. For each LED input current 10,000 frames were captured.
4.4 Discussion

In figure 15, we see that the D datasets are consistently the highest, N the lowest and the B data somewhere in between. The KS test also shows that the B condition is not light tight to a confidence of $\alpha = 0.01$ given the consistent failure of the data points to pass the KS test (figure 17). This is not to assume that condition N is light tight, it merely shows that the comparison of two different ambient light levels has an influence on the light levels within the chamber.

Figure 15: Temperature vs. detections for 17 different temperature bins. This plot should be considered a condensation of 17 different sets of distributions to be compared, where the data points represent the means of the distributions for the 3 conditions. One of the individual sets of distributions is shown at 26.38°C.
Figure 16: Temperature vs. detections for 23 different temperature bins. This plot should be considered a condensation of 23 different sets of distributions to be compared, where the data points represent the means of the distributions for the 3 conditions. One of the individual sets of distributions is shown at 26.81°C.

In figure 16 we see the same plot as figure 15, but with condition U instead of condition B being represented. Here we see that the data points for condition U appear nearly indistinguishable from condition N. However, some continue to fail the KS test (figure 18). Given the KS test can only show two distributions do not match to a certain confidence, or that there is not enough evidence to show they do not match to a certain confidence, this means this condition too is not light tight. However we have cause to think that we are on the right track to sealing the chamber, given the noticeable closeness of conditions N and U with respect to N and B.

A great source of uncertainty in this analysis comes from the variation in temperature across the measurement. The methodology here employed no temperature
Figure 17: The B condition KS test result (from figure 15). If the KS statistic is greater than the critical statistic for any particular temperature bin, then the distributions do not match with a confidence of $\alpha = 0.01$.

control. Without it there is a simple reliance on operating the device at various ambient temperatures with the hope that the PDPC will eventually plateau, with different plateaus occurring at different ambient temperature. The first noticeable problem with this approach is that aside from condition N, none of the other data series actually plateau. Each of them seems to have a "wobble" which must be better controlled for. The second noticeable problem is the sharp rise in temperature at the beginning of the run. The issue here is there will be a bigger variation in the temperature between the SiPM layer and the temperature sensor, leading to the sensor behaving in a manner that would not be expected by its given temperature.

While it is possible in principle to deal with this sharp rise by only considering the plateau of the data series, such an approach is problematic for two reasons. First, it still relies on hoping that two plateaus will overlap. Several runs were completed and such a coincidence was never found. It is reasonable to expect that continuing in this fashion will lengthen data runs to unwieldy lengths later in SiPM characterization. Secondly this still does not account for the "wobble" in the plateau, which motivates the need to quantify the uncertainty for each temperature measurement. These two effects will combine to give a greater systematic uncertainty in converting cell breakdowns to photon detections. Given the lack of access to the PDPC’s internal firmware, specifically how it determines photon counts from cell breakdowns, it is hard to say what effect this is
Figure 18: The U condition KS test result (from Figure 16). If the KS statistic is greater than the critical statistic for any particular temperature bin, then the distributions do not match with a confidence of $\alpha = 0.01$.

Additionally in conducting this analysis without temperature control it became clear that the data selected for comparison via a KS test, could very easily have misrepresented temperature information. This is due to the lack of temperature coincidences for entire data series and the steep gradients in both the fast rise and wobbly plateau sections. Because the temperature sensor in the PDPC is separated from the photosensitive layer by a plastic circuit board, there will be a temperature gradient across between the SiPM cells and the temperature sensor. This gradient will only become worse as the cells warm up during data acquisition. What is required is not only to collect data with a temperature coincidence and to exclude the fast rise portion of the data, but to also use a temperature probe in better thermal contact with the SiPM cells. Ideally this would be done with an IR temperature sensor (using photons with a wavelength outside of the SiPM sensitive region), and the protective glass layer removed.

Finally, the dynamic range shown in Figure 20 indicates that the PDPC saturates far too quickly. The issue here is that the power source can only increase its input current by increments of 1 mA. Thus with a saturation point of 6 mA there are only six data points before saturation. This is far too few to allow for a successful determination of the PDPC dynamic range. The curve beyond the saturation point is also quite interesting. Typically we would expect any entries beyond the saturation point to remain at the level of saturation; however we see
it drop well below this point. This is due to the way the data is saved to disk. Before it is read to the PC it enters a buffer which requires a minimum amount of time to process the data before leaving the buffer. When new data is read to an already full buffer, the old data is lost if it has not already been saved to disk. It seems likely that at high enough illumination levels data is reaching the buffer faster than it is being saved to disk. This creates a bottleneck in which no data actually makes it beyond the buffer.

There are two possibilities to reduce the light level emitted by the LED. One would be to attach a resistor in series with the LED, reducing the voltage drop across the LED. However without a calibrated light sensor inside the chamber, this will prevent us from estimating the produced light level.

A second and immediately more promising possibility in the absence of a calibrated sensor is to use neutral density filters to attenuate the LED. With a known spectral response curve for the filters the light levels can be reduced in a predictable way. While this will not provide a definitive answer as to whether the SiPM under test can handle the expected night sky background, it will allow for the determination of the dynamic range.

4.5 Conclusion and Recommendations

This result shows the chamber under test is not light tight and also requires improved temperature control in order to determine the level of light tightness. Furthermore, it shows that not using any kind of temperature control will lead to greater systematic uncertainty in linking cell breakdown rate to photon detection. Finally, it shows that the current setup is not appropriate for determining the dynamic range of the PDPC.

The conclusions from this analysis motivate several developments to the current
experimental setup. First is for better temperature control over the sensor. Secondly, for a level of light tightness which ensures light levels within the chamber are not influenced by ambient light levels. Third, it demands that the light levels from the LED are attenuated, and if possible a calibrated light sensor be installed in the chamber. Only once this has been established can SiPM characterization hope to be done.

5 Setup Development

5.1 Temperature Control

As explained in section 4 temperature control will need to be established in order to determine chamber light tightness and perform characterization of the PDPC. Later when doing further SiPM characterization a tested temperature control methodology will be required. Thus it is an essential first step in this analysis and will be useful for some time to come.

**Aim:** To establish temperature control over the PDPC to within 1°C per ~900 second collection window.

5.1.1 Apparatus

The apparatus is unchanged from section 4 with the exception of a Peltier element fastened to a back plate on the rear of the chamber. The element is in thermal contact with the PDPC sensor. The heated side of the element had its heat dissipated by a cooling fan. It was powered by a Tii MX100TP fully
remote controlled power supply.

**Peltier Element** The Peltier element uses the thermoelectric effect to induce a heat flux between of two different types of materials. It acts as a thermoelectric heat pump, consuming electrical energy to move heat from one side of the device to the other. The direction of heat movement depends on the direction of current flow [22]. In principle this device can be used for heating or cooling, however in order to keep the PDPC within its recommended operating temperature, heating was not used.

![Image of Peltier element mounted on rear of chamber. It is in thermal contact with the PDPC via a metal backboard.](image)

5.1.2 Procedure

Using a Peltier element in thermal contact with the rear of the sensor via a metal back plate, some control over the sensor temperature could be maintained by altering the current in the Peltier. The recommended operating range for the Peltier was 0 A to 2.5 A. Unfortunately there was a steep temperature gradient in the PDPC between the temperature sensor and the photosensitive cells, and a greater gradient between these cells and the Peltier element. This meant that before data could be acquired a $\sim$3500 second thermal equilibrium period needed to take place in which the cooling effect of the Peltier and the warming effect of the sensors could stabilize. To acquire data a $\sim$1735 second data acquisition cycle was run, immediately thrown away then another $\sim$1735 second cycle was done for which the data was saved.

5.1.3 Discussion

Figure 22 show how temperature varies with time for several temperature controlled data series. Each series has two distinct sections, a fast rise and a plateau. Although this fast rise is cut off in figure 22, it can be clearly seen in 19. Here in figure 22, 5 different Peltier input currents were chosen to show the relationship between the current and the plateau temperature. Some of these currents are
shown twice (hence the 9 different data series), with different lines indicating different ambient temperatures. Table 2 shows the temperature range for each data series in its plateau region, the mean and uncertainty of these collective values.

![Temperature Trend](image)

Figure 22: Variation of temperature with time for 9 different runs. Each run was done with temperature control at a different level ranging from 0 A to 2 A.

As can be seen in figure 22, increasing the current on the Peltier element affects the temperature in the PDPC. However it is also clear this is not the only factor influencing the sensor temperature with repeated measurements with the same peltier input current yielding different plateau temperatures. With ambient temperature the next most likely candidate to be influencing the plateau temperature, it seems to be the determining factor here. Nevertheless temperature control is possible by only considering the last ~900 seconds of data. For the data series in figure 22 this led to a stable temperature in the plateau region without the unpredictable "wobble" seen in section 4. This temperature control is essential in minimising and keeping constant the temperature gradient between the SiPM cells and the temperature sensor internal to the PDPC. This stabilization time of ~3500 seconds was longer than expected from the results in figure 19, and the setup as a whole would benefit from an improved temperature control system. However in the context of this study it represents a great improvement and will serve our purposes.

5.1.4 Conclusion

By employing a temperature stabilization period of ~3500 seconds, and a data acquisition period of ~900 seconds a temperature stability of 0.2°C ±0.1°C can be achieved. Due to the continued influence of ambient temperature this procedure does not provide precise control over where the stable plateau will lay. However this can be dealt with by taking successive measurements, increasing or decreasing the Peltier current according to what temperature is read out.
<table>
<thead>
<tr>
<th>Current (A)</th>
<th>Mean</th>
<th>Max.</th>
<th>Min.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>33.7</td>
<td>33.7</td>
<td>33.6</td>
</tr>
<tr>
<td>0.0</td>
<td>30.6</td>
<td>30.8</td>
<td>30.5</td>
</tr>
<tr>
<td>0.5</td>
<td>25.1</td>
<td>25.2</td>
<td>25.0</td>
</tr>
<tr>
<td>1.0</td>
<td>21.9</td>
<td>21.0</td>
<td>20.9</td>
</tr>
<tr>
<td>1.0</td>
<td>19.4</td>
<td>19.6</td>
<td>19.4</td>
</tr>
<tr>
<td>1.5</td>
<td>17.7</td>
<td>17.8</td>
<td>17.6</td>
</tr>
<tr>
<td>1.5</td>
<td>18.6</td>
<td>18.6</td>
<td>18.5</td>
</tr>
<tr>
<td>2.0</td>
<td>18.7</td>
<td>18.9</td>
<td>18.6</td>
</tr>
<tr>
<td>2.0</td>
<td>18.3</td>
<td>18.4</td>
<td>18.3</td>
</tr>
</tbody>
</table>

Table 2: Mean, maximum and minimum for the plateau region of each data series in figure 22. Also includes the expected temperature range with uncertainties for this method of temperature control.

This will of course lead to longer than ideal data acquisition times, but will satisfy the needs of this study so long as the chamber is light tight to the point where ambient light levels do not measurably influence the light levels within the chamber.

5.2 Light Tightness

In order to ensure light levels in the box are not influenced by ambient light levels, the entire chamber must be made light tight.

**Aim:** To establish light tightness within the chamber.

5.2.1 Procedure

In order to test the light tightness of the chamber, temperature controlled measurements were taken for different ambient light levels. One measurement would be taken during the day with a lamp focused on the box, another at night with all precautions taken to minimise ambient light. Data was collected by the PDPC with a frame counting data acquisition cycle. This recorded the total number of cell breakdowns per trigger event. Events were triggered on the die level when one pixel had its configured trigger scheme satisfied. This was followed by a 45 ns integration window in which all four pixels in the given die were active.

Given the limits on temperature control it was necessary to take several measurements for each light condition (i.e. day and night) under various temperature conditions. Temperature was controlled in the same manner as in section 5.1, with data taken at various Peltier current levels. For each ambient light condition 21 light distributions were taken, each corresponding to a different Peltier
input current. The Peltier input currents used ranges from 0 A to 2.5 A with 0.125 A increments. For the data collected, a quality cut was imposed based on the variation in the temperatures. For any ~900 second collection window, if the temperature fluctuated by more than 0.5°C, the data was discarded.

Unlike the previous test of light tightness, several chamber conditions were not tested here. This time the only condition used was to take the black plastic sheet, cover the chamber with it, and tape down the sides. This condition is similar to condition U from section 4; however a thicker sheet was used. Ventilation for the various fans was provided with bent tubing with a 90° twist applied to it.

The reason for no condition D data being collected is due to the plateau region of the temperature trend curve being flatter. This allows for more data to be acquired per data series, and eliminates the concern of there not being enough data to distinguish between two sets of data collected at the same temperature. The old condition N was also omitted in favour of testing the same condition at day and at night then comparing the two. When a temperature coincidence existed between data points of different light levels, a KS test was run between them.

5.2.2 Discussion

All data which could be temperature controlled passes the KS test with a confidence of \( \alpha = 0.01 \). However of the 20 distributions taken for day and night there were only 5 temperature coincidences. Although only 1 was actually needed, this represents 40 hours of collection time and highlights the awkwardness of the current temperature control system when it comes to comparing data. For future analyses requiring the comparison of temperature controlled data this result stresses the importance of determining the ambient temperature and properly characterising its affect on the sensor. Additionally as stressed in section 4, better thermal contact needs to be established between the temperature sensor and the SiPM cells.

Nevertheless the datasets compared represent a random selection of the operating temperature range. Given each of them passes the KS test, this is enough to say that the setup is light tight for our purposes.

5.2.3 Conclusion

The chamber is light tight when covered in black plastic and sealed with tape to a confidence of \( \alpha = 0.01 \).

5.3 LED Attenuation

As motivated in section 4 the light source used to determine the dynamic range of the PDPC has too large incremental steps in its output power. Thus the light will have to be attenuated with the use of neutral density (ND) filters. However, first the ND filters needed to be selected and tested with a trusted device which
Figure 23: Day vs. night cell breakdown distributions. All distributions are temperature controlled.

is not itself under test. The analysis for determining the best attenuation for the LED depended quite heavily on the detected dynamic range of the devices being used. If the light was filtered too much the full range wouldn’t be seen, if not enough the peak would be cut off. For this reason the bulk of the analysis was done in conjunction with the dynamic range analysis. For full details on the LED attenuation read section 6.3.

5.4 Updated Apparatus

Modification to the setup made as a result of the analysis conducted in this section can be seen in figure 25. This figure also reflects that a second SiPM was installed beside the PDPC; the Excelitas C30742-66 Series SiPM.
5.4.1 Excelitas C30742-66 Series

The Excelitas C30742-66 Series Silicon Photomultiplier (henceforth Excelitas sample) is designed for photon detection in the 350 nm to 850 nm range. It is an APD designed for low timing resolution (400 ps FWHM), low dark count, low cross talk and high PDE. It is a 6 mm $\times$ 6 mm array made up of 14,400 microcells. Each microcell is 50 $\mu$m $\times$ 50 $\mu$m. The device has a 95 V breakdown voltage with a recommended over voltage of 5 V to 10 V [27]. Two Excelitas samples were used, one on a DC coupled PCB to be sensitive to continuous light, and one on an AC coupled PCB to be sensitive to flashing light. The sample on the DC coupled board will be used in determining dynamic range, and the sample on the AC coupled board to determine the 1 PE peak and crosstalk probability.

6 Silicon Photomultiplier Characterization

6.1 Dark Count Map

In order to understand the non uniform nature of a typical SiPM array a dark count map was produced. Given access to individual cells is easily accessible on the PDPC, this device was chosen to perform the analysis on. This information was not accessible to the Excelitas sample, subsequently it has been omitted.

Figure 24: KS test results for the data in figure 23. If the KS statistic is greater than the critical statistic for any particular temperature bin, then the distributions do not match with $\alpha = 0.01$. 

![KS Test Result](image-url)
from this portion of the analysis.

**Aim:** Determine the level of similarity in SiPM cell dark count rates for the PDPC.

### 6.1.1 Procedure

The PDPC has a data acquisition mode which allows for the construction of a DCM. This acquisition mode involves activating cells individually for 100 frames (∼33 ms), after which the total cell breakdown count is recorded along with a temperature measurement. This acquisition mode is also useful for determining the probability of thermal excitations causing a cell breakdown as a function of temperature; so long sufficient temperature control can be established. The data for this DCM was captured with the temperature ranging between the values of 15.8°C and 16.4°C. Temperature was controlled with the Peltier element described in section 5.1.

### 6.1.2 Discussion

As can be seen in figure 27, some cells are overactive. Under normal operating conditions these cells will provide a disproportional signal to noise ratio. To improve the signal to noise ratio for the entire device these cells are disabled during normal operating conditions. To best balance the need to have maximum photon collection and minimum DCR, Philips advises that the top 10% of overactive cells be disabled [16]. The reasoning for this can clearly be seen in figure 26, where the DCR can be seen to begin to steepen at ∼90% to ∼95% mark. Quantitatively this corresponds to a reduction in cell breakdown rates of ∼8 × 10^6 Hz and ∼5 × 10^6 Hz respectively.
6.1.3 Conclusion

The PDPC is relatively homogenous, however manufactural limitations will lead to some cells having a higher DCR than others. For optimal operation the top 10% of cells will be deactivated for analysis purposes. This has been done retrospectively, so that prior results with the PDPC have had over active cells deactivated.

6.2 Temperature vs. Dark Count Rate

In order to properly understand the output of the PDPC we must first understand how the PDPC dark count rate is affected by changing temperature. The rate at which thermally induced cell breakdowns (TCBR) occur will have a direct impact on cross talk events and supposed photon counts from the device. To this end two measurements were conducted in this section; first was to determine the pure thermally induced cell breakdown rate, second was to empirically determine an effective model for dark count rate. The first measurement will help determine if the TCBR is typical for an SiPM, the second measurement will allow for effective noise subtraction from cell breakdown counts to determine photon counts.

Aim: To determine the DCR dependence on temperature and determine a functional relationship for noise subtraction.

Figure 26: Cumulative dark count rate of the full sensor die [16]
Figure 27: Dark count map for full DPC-6400 sensor. Each die has its own colour map scheme reflecting the variability between dies. Red cells have the greatest dark count activity.
6.2.1 Procedure

To determine the pure TCBR, data was collected with the DCM data acquisition method with the LED turned off within the light tight chamber. This was done to ensure cross talk was not contributing to the dark count, which only leaves thermal excitations as a source of noise. Temperature was controlled by altering the current on the peltier element from 0 A to 2.5 A by .25 A increments. Before each data collection a thermal equilibrium period existed to allow the temperature sensor and light sensitive panel time to stabilize. The relationship between peltier input current and temperature is not well defined, with ambient temperature still playing a major role in determining the specific temperature reached.

From the collected data the top 10% of overactive cells were removed from further analysis, the rationale for this is detailed in [16]. The remaining data was used to generate six versions of the model defined by equation 2, each with a different temperature offset. Included in the model versions was one without a temperature offset, one with a minimised Chi Square temperature offset, and various offsets at regular intervals in between these two. The only parameter that needed to be determined experimentally (apart from the offset for the final model version) was the proportionality constant $C$. This was done with a Chi Square minimisation algorithm. To determine the effective DCR the same procedure was followed as above. However instead of using DCM data acquisition, the frame counting data acquisition cycle was used.

Uncertainty Analysis: The internal PDPC temperature sensor has a systematic uncertainty attributed to the sharp rise in temperature experienced in the short 100 frame ($\sim 33$ ms) capture time per cell. Although a temperature stabilization cycle is run, the process of activating cells individually does not allow proper thermal equilibrium. This is represented by the horizontal uncertainty bars used in figure 28. The statistical and systematic uncertainty in each TCBR bin is of order $\sim 10^6$ which is low enough to not visible with respect to the data points themselves. Each model in figure 28 has an associated residual analysis in figure 29.

6.2.2 Discussion

The DCM data acquisition cycle turns on individual cells for a period of 100 frames ($\sim 33$ ms). Given this short time there exists a greater thermal gradient between temperature sensor and SiPM cell than would be expected for a frame counting cycle. To account for this a temperature offset needs to be included in the model described by equation 2. Various offsets for our model were included in figure 28, however the model which best described the data was for an offset of $5.33 \pm 0.01$°C. This value comes from a reduced Chi Square analysis and is slightly higher than expected by Philips, which only quotes a maximal temperature offset of 4°C [16]. However there is a clear systematic effect for model versions at offsets less than 4°C, as illustrated in figure 29. This systematic effect appears to weaken and eventually disappear as the offset is raised from
Figure 28: Temperature vs. Thermal Cell Breakdown Rate including several models with various temperature offsets to improve curve shape. Each model has the form of equation 2, with respective differences in $C$ and $T_{OFFSET}$.

0°C to 5.33°C. However this discrepancy between Philips expectations and the results will be best resolved by further experimentation. Specifically, it is recommended a calibrated temperature probe be attached to the PDPC in better thermal contact with the light sensitive panel. Another option is to use an IR thermometer utilising photons outside of the SiPM cells photo-sensitive range. The temperature offset used in DCM data acquisition will be different to the frame counter data acquisition. The offset is influenced by the amount of current running through the cell while it is activated to collect data; this amount and the frequency of current activations are different leading to a different effective temperature.

While a full model construction for noise (thermal + cross talk) would be interesting in providing a full description of the device, all which is required is a functional relationship to describe the noise within a specific operating temperature. This will be needed for analysis where noise must be subtracted, thus making the TCBR model inadequate. The functional relationship is loosely based on the TCBR model, as this was expected to closely mimic the shape. However an extra parameter was included and physical restrictions on the offset constant were removed to improve the fit. It should be noted that this functional relationship makes no prediction about offset temperature, and cannot be expected to be extrapolated upon. Nevertheless temperatures contained within the range if this dataset (∼290 K to ∼306 K) can be reliably predicted. The residual analysis in figure 31 does not show any clear sign of a systematic
6.2.3 Conclusion

With the inclusion of a temperature offset, the PDPC follows the typical SiPM relationship between TCBR and temperature. This offset is due to the positioning of the internal temperature sensor with respect to the light sensitive panel within the PDPC device itself. As it is, the two sections which ought to be in thermal contact are separated by a PCB board. Whether the recommended operating temperatures were determined with this sensor or an external sensor is of utmost importance. Thus it is highly recommended that further testing with calibrated sensor in better thermal contact with light sensitive panel.

Furthermore the functional relationship established in this chapter will allow for reliable predictions to be made for the total noise (cross talk and thermal) between $\sim 290^\circ K$ and $\sim 306^\circ K$.

6.3 Dynamic Range

A basic characteristic of SiPMs is their dynamic range. The bigger the dynamic range of a device the more useful it will be in general, but knowing the saturation point of a device is essential in determining its limitations. Thus finding the dynamic range of an SiPM is essential before its implementation. However, as motivated in section 4 the light source used to determine the dynamic range of the PDPC has too large incremental steps in its output power. Thus the light will first have to be attenuated with the use of neutral density
(ND) filters. This will begin with selection and testing of ND filters with a trusted device which is not itself under test. **Aim:** To determine the uncertainty of an independent low level light sensor, then use it to determine the transmittance of ND filters. Once done, these ND filters will be used to attenuate the magnitude of the LED output so that an accurate dynamic range can be determined. Once an appropriate level of light attenuation is selected, it will be used to determine the dynamic range of the PDPC and Excelitas sample devices in terms of the LED input current.

### 6.3.1 Apparatus

Two ND filters (filter A and filter B) were used from an unknown manufacturer with an unquoted transmittance spectrum. These filters were to be placed in the chamber between the LED and the PDPC. Filter A was expected to have a transmittance of \(\sim 0.05\%\), and filter B a transmittance of \(\sim 5.1\%\), both with a flat spectrum. Each filter was tested with the Illumia Lite AQ-80010-005, a handheld spectrometer using charge-coupled devices (CCDs) was used to measure spectral flux in the range of 380 nm to 820 nm.\(^3\)

---

\(^3\)Only data between 400 nm and 800 nm was considered as this was the full emission range of the LED.
6.3.2 Procedure

To determine the systematic uncertainty on the Illumia Lite AQ-80010-005 the transmittance curve of a calibrated ND filter (Thorlabs OD 1.0) was compared to the known transmittance curve. This calibrated ND filter was not used for LED attenuation due to its small surface area (radius ~1 cm). Once the uncertainty of the spectrometer was understood, the device was used to determine the transmittance per wavelength bin of each filter (filter A and filter B). This was done by measuring the irradiance\(^4\) of a light source, then measuring it again with the filter in place. Dividing the filtered irradiance by the other gave the transmittance. Percentage uncertainty was determined by adding the two uncertainties in quadrature.

Once the ND filters transmittance had been verified they were installed in the apparatus between the LED and the PDPC. Then the LED was cycled between 0 A to 500 mA in 1 mA increments. The PDPC data recorded in the same fashion as section 5b. However instead of collecting each data point for ~30 minutes, the collection time was reduced to ~3 seconds. This not only reduced the collection time of the measurement, but also the time taken to analyse the data. Three dynamic range measurements were taken; one with filter A in place, one with filter B in place, and one with both filters in place.

To capture the Excelitas dynamic range the sample mounted on the DC coupled PCB was used. From there the same procedure as the PDPC was used.

\(^4\)Irradiance is defined as the rate at which energy falls on a surface area. It is measured in units of W/cm\(^2\).
### Table 3: Reference Spectral Flux Uncertainty measurements from Illumia [23].

<table>
<thead>
<tr>
<th>Wavelength [nm]</th>
<th>380.0</th>
<th>450.0</th>
<th>555.0</th>
<th>654.5</th>
<th>820.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral Flux Uncert.</td>
<td>6.49%</td>
<td>4.80%</td>
<td>3.96%</td>
<td>3.60%</td>
<td>3.18%</td>
</tr>
</tbody>
</table>

**Uncertainty Analysis:** The uncertainty in the figure illustrating the detected and expected transmittances of the calibrated Thorlabs filter (figure 32) comes from the manufacturers of the spectrometer itself. The spectrometer came with quoted wavelength dependent systematic uncertainties for its irradiance measurements [23].

Interpolating these values gave a systematic uncertainty for each wavelength bin. Given that the transmittance (T) is a ratio of the filtered and unfiltered irradiance (equation 9), the data given in figures 33 and 34 comes from this calculation.

\[
T = \frac{I_{\text{filtered}}}{I_{\text{unfiltered}}} \tag{15}
\]

Resultantly, the uncertainty was propagated according to Gaussian Uncertainty Propagation:

\[
\frac{\Delta T}{T} = \sqrt{(\frac{\Delta I_{\text{filtered}}}{I_{\text{filtered}}})^2 + (\frac{\Delta I_{\text{unfiltered}}}{I_{\text{unfiltered}}})^2} \tag{16}
\]

The value taken for the data points in figures 35 and 36 is the mean count rate per die. The uncertainty was taken as the standard deviation between the rates of the 16 dies.

#### 6.3.3 Discussion

The figure illustrating the detected and expected transmittances of the calibrated Thorlabs filter (figure 32) clearly shows that these two curves are not in agreement. Should the shape be consistent a calibration of the spectrometer would be in order. However, there is no more reason to trust this than there is the systematic uncertainty quoted by Illumia. Thus all we would be doing is exchanging one assumption for another without any particularly good empirical or theoretical justification.

The approach considered more appropriate was to enlarge the systematic uncertainty of the measured transmittance to include the expected curve. Arriving at the new uncertainty of the irradiance from this point is a simple matter of following equation 10, with the understanding that \(\frac{\Delta I_{\text{filtered}}}{I_{\text{filtered}}} = \frac{\Delta I_{\text{unfiltered}}}{I_{\text{unfiltered}}}\).

The figures displaying the filter transmittances (figures 33 and 34) both show relatively flat transmittance spectrums between 400 nm and 800 nm. It is notable that below 500 nm additional systematic influences appear to be affecting the spectrums. The irregular shape here cannot be attributed to the statistics of small numbers as the data represents an average of \(\sim 20\) independent measurements. This effect is discussed in more detail in section 6.4 where it may be
Figure 32: Thorlabs calibrated filter transmittance, detected values and reference values. Dashed black lines indicate systematic uncertainty.

an issue. But for the purposes of attenuating the LED this is not a concern, as it will only alter the spectrum of the transmitted photons in a predictable way. Figure 35 shows the attenuated light once filter B has been installed. The spectrum clearly requires greater attenuation, as it peaks somewhere between 0 and 1 mA. Figure 36 shows the peaks when the light source is attenuated by filter A alone, and both filters A and B. The filter B spectrum peaks at 10 mA, which is improved upon by the combined filters which peaks at 73 mA. This makes the combined filter attenuation the logical choice of the 3 as it provides the best spread for the dynamic range. Nevertheless, this can be improved upon by installing additional filters. An ideal position to take most advantage of the dynamic range would be to have the spectrum peak around ~500 mA.

Both plots in figures 35 and 36 also do not follow the typical spectrum for SiPMs as they are never allowed to reach saturation. This is because the readout system is the limiting factor for the PDPC. Instead of seeing the cells saturate, we see the buffer which temporarily stores data from the PDPC before it is written to disk be over written with new data packets before the old data can be saved. This explains why we see both curves drop below the DCR set for the run at 0 mA.

It is worthy of note that these spectrums include both thermal and crosstalk noise events. Furthermore without a longer runtime temperature control was not possible. However, even with temperature control precautions taken, there
will still be temperature variations between data points. Given this, for the dynamic range seen we can expect variation depending on ambient temperature conditions. Finding the relationship between the maximum input current and the saturation point will only be possible with better information about ambient temperature.

Another drawback of this apparatus for this analysis is the lack of information about LED input current and incident photon flux. To resolve this, a calibrated photo-detector will have to be installed to analyse the LED output.

Figure 37 shows the dynamic range for the Excelitas sample between 0 mA and 500 mA for the LED input current. It includes four curves, one for each ND filter combination. The raw SiPM output voltage was divided by the maximum output voltage (i.e. the voltage output for the no filter case with the LED at 500 mA).

An unusual feature of this plot is the changing saturation point between the curves. Although we expect the shape of the curve to change as it does, the saturation point is expected to remain the same within certain a certain temperature dependence fluctuation. Independent analysis on the output voltage fluctuation dependence on temperature saw no more than a ±1 mV variation within a normal operating temperature range. The overwhelming dependence on the saturation point seems to be on the actual ND filter being used; as transmittance increases the saturation point also seems to increase. There is no
known reason for this to occur and remains an open question of the setup. Despite this inability to precisely determine the saturation point, the results do clearly show a vastly improved dynamic range with respect to the PDPC. For the same level of light attenuation (combined filter condition) the PDPC dynamic range reaches a maximum at 73 mV, whereas the Excelitas sample does not reach saturation. This places a lower limit on the saturation point at 500 mV, which represents a $\times\sim 6.6$ improvement to the dynamic range before accounting for compression effects arising from LED input current to photon flux conversion.

### 6.3.4 Conclusion

From figure 32 we see that the systematic uncertainty on the ND filters is higher than referenced. New uncertainty measurements need to be used which account for the discrepancy between the detected and referenced transmittance curves. Nevertheless with both ND filters installed, source light is attenuated enough to ensure a workable dynamic range is reached. Additionally, the dynamic range spectrum is not typical of an SiPM. Instead we see the normally expected spectrum cut off by the limitations of the PDPC readout system. The Excelitas sample dynamic range on the other hand is quite typical for
an SiPM (see figure 37). It displays a sharp rise, followed by a plateau as it approaches saturation. Attenuating the light only stretches out the sharp rise region and extends the dynamic range of the device. Although none of the attenuated curves seem to reach saturation, the combination of both filters still seems to be a workable option for this apparatus.

It is recommended for further analysis that an ambient temperature sensor be installed so a relationship between the ambient temperature and maximum LED input current can be examined. Also a calibrated photo-detector should be installed to examine the relationship between the LED input current and the incident photon flux.

6.4 Wavelength vs. Photon Detection Efficiency

Lacking a light source with a tuneable wavelength output it was not possible to verify the PDE varies wavelength directly for the PDPC. However the quoted PDE could be tested with the use of several colour filters. Ideally this procedure would have also been replicated on the Excelitas sample, however without a calibrated photo-detector in the chamber there was no certain way to convert the devices voltage output into an irradiance. This paired with a suspected non linear relationship between voltage output and detected photon flux in the Excelitas sample would lead to compressions that change the value of any cal-
Figure 36: PDPC Dynamic Range with ND filter A and combined filters in place. Dashed lines represent systematic uncertainty.

Aim: Test the quoted PDPC PDE curve by comparing total irradiance measurements with colour filters in place and removed.

6.4.1 Procedure

Using 3 Kodak gelatine filters (blue, yellow and red) three independent light settings were used. For each case the expected number of photons was calculated ($E_B$, $E_Y$ and $E_R$) along with the expected number of photons in the absence of a filter ($E_W$). Each value was calculated by first determining the emittance of the LED (LED), the transmittance of the ND (ND) and colour filters (CF) and then combining these with the expected PDPC PDE (PDE) for the resultant wavelength band:

$$E_n = LED \times ND \times PDE(\times CF_n)$$

(17)

In this calculation only one colour filter was used at a time. From this the expected transmittance of each filter ($T_E$) was calculated:

$$T_{EB} = \frac{\int E_B d\lambda}{\int E_W d\lambda}, \quad T_{EY} = \frac{\int E_Y d\lambda}{\int E_W d\lambda}, \quad T_{ER} = \frac{\int E_R d\lambda}{\int E_W d\lambda}$$

(18)
These three ratios were then compared to their corresponding measured transmittances \((T_M)\) taken from the PDPC:

\[
T_{MB} = \frac{M_B}{M_W}, \quad T_{MY} = \frac{M_Y}{M_W}, \quad T_{MR} = \frac{M_R}{M_W}
\]  \hspace{1cm} (19)

These measured values \((M_n)\) were found by collecting 11 sets of temperature controlled data for each filter condition, and looking for coincidences between the filtered and unfiltered cases. These measured values then had the expected crosstalk and thermal noise subtracted from the measurements. Crosstalk is quoted at 25\%±1\% [16], and thermal noise as a function of temperature was found in section 6.2.

When calculating the PDE, three models were used. The first was the model quoted by Philips (PDPC 6400). However this had a shape uncharacteristic of an SiPM so the second model used was for its sister device (PDPC 3200) which had a more typical SiPM response curve, but had an unusual cut off. The final model used was a combination of the two, one which retained the fundamental shape of the PDPC 6400 model, but also included the tail and overall amplitude of the PDPC 3200 model (PDPC 6400 Adjusted).

**Uncertainty Analysis:** The emittance and transmittance values used in the expectation calculation were done with the Illumia Lite AQ-80010-005 [23]. This device is a handheld spectrometer using CCDs to measure the spectral flux in the range of 380 nm to 820 nm. The systematic uncertainty on the device \((\Delta\text{ CCD})\) was found by taking the transmittance curve of a calibrated ND filter (Thorlabs OD 1.0), then comparing it to the known transmittance curve. Thus
the uncertainty was given by:

$$\Delta CCD[\%] = 1 - \frac{\text{Known Transmittance}}{\text{Detected Transmittance}}$$ \hspace{1cm} (20)

Where detected transmittance is given by:

$$\text{Detected Transmittance} = \frac{\text{Mean Irradiance}_{\text{FILTERED}}}{\text{Mean Irradiance}_{\text{UNFILTER}}$$ \hspace{1cm} (21)

Because the LED emittance was found by directly measuring of the light source, this meant that the uncertainty on this measurement was simply $\Delta CCD$. Two neutral density filters were used (A and B), with each ones transmittance ($T_A$ and $T_B$) being a ratio of two independent irradiance measurements. The uncertainty on each measurement was found by adding the two uncertainties in quadrature:

$$\Delta T_n[\%] = \sqrt{\Delta CCD[\%]^2 + \Delta CCD[\%]^2}$$ \hspace{1cm} (22)

This same method was used for the uncertainties of the colour filter transmittances ($T_B$, $T_Y$ and $T_R$). Combining all these uncertainties to get the uncertainty for each $E_n$ was also done by adding in quadrature. Finally each $T_E$ ratio had its uncertainty determined by adding the two in quadrature again.
6.4.2 Discussion

Figure 39: PDE spectrum quoted in manual the relative systematic uncertainty on this plot is ±4.3%.

The standout result in this section is the comparison between the measured and expected transmittances in figure 42. Comparing the measured value to the adjusted PDPC shows that the blue filter is short by between 2.3σ to 3.0σ, over the expected yellow transmittance by between 1.6σ to 2.6σ and within −σ and σ of the expected red transmittance depending on which model it is being compared. Due to the low statistical uncertainty in figure 42, the variation from the mean must be due to systematic effects. However if this variation were purely systematic we might expect a trend in how the observed data varies from the expected data. As it is for lower wavelengths (blue) the transmittance is less, in the middle (yellow) it is higher, and for longer wavelengths (red) it is equal. However, as stated by Schulze [16], the uncharacteristic oscillation seen in the PDPC PDE model 39, is due to diffractive effects on the SiPM array grid. Thus a slight variation to the angle of the PDPC to the incident light flux could lead to a different diffraction grating and give a different PDE response curve. This could lead to an increased amplitude to the oscillations providing a systematic uncertainty which looks distinctly statistical. Although soundly based as a hypothesis this is no conclusion, and is best left as an open question for the next phase of setup development where a tuneable light source will be installed. This new setup will also be able to answer the open question surrounding the steep cut off which appears at 730 nm for the 6400 model in
Figure 40: Combined ND Filter Transmittance. Dashed lines represent systematic uncertainty. Mean Transmittance = \( \sim 0.007\% \).

Figure 39, which seems to be caused by a limitation in the device used by Philips to produce this curve.

This small statistical uncertainty (\( \sim 10\% \) of the systematic uncertainty) is a result of the high collection rate of the PDPC and the long collection time. Even though only events which were taken in thermal coincidence could be considered, the rates of these coincidences was large, with each set of irradiance data varying from \( \sim 2.5 \times 10^5 \) to \( \sim 2.5 \times 10^6 \). It is clear from the disagreement between measurement and expectation that there is an undescribed systematic influence within the experimental design. A possible source is the spectrometer used to generate the LED, ND and CF curves. However given this had an uncertainty defined by a calibrated ND filter, it is just as likely that the systematic influence comes from the PDPC curve not being appropriately defined.

When comparing figure 38 and the quoted LED emittance curve from Bridgelux [24] a discrepancy appears in the shape of the measured curve and the quoted curve. What stands out in particular is the shoulder at \( \sim 550 \text{ nm} \). This particular discrepancy stands as a reminder to experimentalists to always independently verify ones own data and not rely on manufactural specifications alone.

The combined ND filter transmittance shown in figure 40 has an interesting shape between \( \sim 400 \text{ nm} \) and \( \sim 500 \text{ nm} \). This fluctuation seems to be the result of an undescribed systematic uncertainty. However, it should be noted this systematic effect seems to be no larger than \( \sim 10^3 \), which will be outweighed by the systematic uncertainty which has been accounted for. Considering the
Figure 41: Kodak filter transmittance curves with systematic uncertainty represented by the dashed lines.

scale of this plot compared to CF (figure 41) and the LED (figure 40), this is effectively a flat spectrum (all transmittances are of order $10^{-4}\%$ to $10^{-5}\%$ as opposed to $10^{0}\%$ to $10^{1}\%$ for the Kodak and ND filters).

6.4.3 Conclusion

The results of this analysis do not invalidate the PDE curve supplied by Philips (figure 42). However, a question still remains about the nature of the discrepancy between the quoted 6400 curve and the 3200 curve, which are only magnified by the fact that the best fit for our data was a curve which was formed as a modification of the two curves combined. It is recommended in the next iteration of this setup with a tuneable light source the PDPC PDE is directly measured to get to the bottom of this.

6.5 Multi Photo-Equivalent Peak Spectrum

As motivated in section 3 a fundamental description of any SiPM includes the characteristic peak of the device to a single photon. This was not possible to find for the PDPC; as the internal logic of the kit’s readout electronics was not accessible. However it was possible to examine for the Excelitas sample. Thus for this setup to be capable of future SiPM characterisations it is essential that
Figure 42: Expected and measured filter transmittances, with three expected models represented.

is found.

**Aim**: Find the single PE peak maximum for the Excelitas SiPM.

### 6.5.1 Apparatus

The setup here is similar to previous setup arrangements; however the PDPC was replaced with the Excelitas sample mounted on the AC coupled PCB. No signal light was used; instead the signal from individual photons was mimicked by thermal breakdowns. Temperature was not controllable given the lack of back-plate to mount the SiPM on the Peltier element, and lack of thermal sensor to ensure stability. The SiPM was fed through an amplifier before its signal reached the oscilloscope.

The Oscilloscope used was a LeCroy HDO4000 [25]. It has a bandwidth of 200 MHz to 1 GHz, 2.5 GS/s sample rate, a minimum detectable pulse width of 2 ns, and a Maximum Input Frequency of 250 MHz.

The SiPM amplifier was a Digikey LMH6629 high speed, low noise device with \( \times 10 \) gain [28].

52
Figure 43: Multi PE peak spectrum with PE peaks given a Gaussian fit and with means labelled.

6.5.2 Procedure

Data was collected from the Excelitas sample by feeding its signal through a digital oscilloscope. From this data a random sample of signals was collected whilst the oscilloscope was set to a random trigger. These signals were collected as waveforms, each waveform lasted for 100 ns with a digitisation of 400 ps. In total 100,000 waveforms were collected for analysis. This raw data was analysed by a pre-existing tool which is fully described in chapter 7.1 of [26]. The result of this analysis was the multi PE peak spectrum seen in figure 43. From there a Gaussian curve was fitted to each peak, from which the mean was taken. These four means were combined to give a calculation of the 1 PE pulse height, and give a statistical uncertainty.

6.5.3 Discussion

Figure 43 shows the multi PE peak spectrum for the Excelitas sample on the AC coupled PCB. The sharp peak at 2 mV comes about from a minimum cut within the analysis tool. It would seem unlikely that the 1 PE peak occurs below this
value as a clear 1 PE peak appears at ~6.2 mV, with regular peaks appearing at multiples near this value up to 4 PE. Even though there is no light source for the SiPM to detect, thermal excitations will generate the same signal in the SiPM. This will create a 1 PE peak identical to a flashing light source, and with crosstalk 2 PE, 3 PE and 4 PE peaks will also become pronounced. The shoulders of each peak are not symmetric due to after pulses not always being detected. The 1 PE peak is easily the most pronounced of the four peaks, with each resulting peak becoming less defined. The main reason for this is because the Excelitas sample is made up of an array of 14,400 cells, each with individual differences due to manufacturing inconsistencies. Each PE peak is a multiple of the 1 PE peak in theory. Thus each one gives an independent measurement of the 1 PE peak. This is given in table 4 along with the combined result. From this table the measured 1 PE level is within 1.3 $\sigma$, the 2 PE within 0.2 $\sigma$, the 3 PE within 3.1 $\sigma$ and 4 PE within 1.7 $\sigma$. This is within good agreement and provides confidence in the result. Crosstalk probability can also be calculated from this spectrum by dividing the number of events above 1 PE by the number of all events. In figure 1 the 1 PE peak ends around 10 mV, which gives a crosstalk probability of 23%±1%.

6.5.4 Conclusion

In conclusion the 1 PE peak for the Excelitas sample occurs at 5.93 mV for the given setup. This means the setup is capable of determining the 1 PE peak of SiPMs, albeit with an external amplifier if need be. This result also shows a crosstalk probability of 23%±1%.

Upon the next iteration of the apparatus triggering can be improved by a flasher, and a calibrated light source to map LED input current to incident photon flux.
7 Conclusion

7.1 Silicon Photomultiplier Comparison

Looking at the Excelitas sample and PDPC side-by-side allows for a determination to be made about which would be better suited for use in CHEC. The DCR for each device at 25°C are essentially equal with the Excelitas sample DCR at $1.5 \times 10^7 \pm 3.0 \times 10^6 \text{ Hz/cm}^2$ [27] and the PDPC at $1.7 \times 10^7 \pm 3.0 \times 10^4 \text{ Hz/cm}^2$ [Chapter 6.2]. The crosstalk probability is also comparable with the PDPC crosstalk probability being $25\% \pm 1\%$ [16], and the Excelitas being $23\% \pm 1\%$ [Chapter 6.5].

![Wavelength vs. PDE](image)

Figure 44: PDE of PDPC and Excelitas side-by-side. PDPC PDE from [16], Excelitas from [27]. The uncertainty for the PDPC is represented by dashed lines, and comes about from the uncertainty in the described model explained in section 6.2.

The one characteristic in which the Excelitas sample clearly outperforms the PDPC is in its dynamic range. In figures 36 and 37 we clearly see the PDPC dynamic range peaks at an LED input current of 73 mA. This corresponds to cell breakdown rate of 44 MHz/cm², less than the 100 MHz/cm² expected background cell breakdown rate from the current HESS data [15]. This short coming of the PDPC represents the biggest issue surrounding the PDPC, the readout electronics and firmware around its SiPMs. Not only does it limit the dynamic range of the device, but the slow activation time (~10 seconds) will prevent fast triggering making the kit useless to CHEC. Should Philips provide access to the raw SiPMs, they may indeed be competitive with
the Excelitas samples. However in the absence of this the logical choice between these two devices is the Excelitas sample.

7.2 Setup Development and Recommendations

As the setup currently stands it is light tight ($\alpha=0.01$) and temperature controlled (within $2.22 \times 10^{-4} K \pm 1.11 \times 10^{-4} K$). This makes it well placed to determine SiPM dynamic range, dark count rate, photon detection efficiency, 1 PE level and crosstalk probability. Based on the analysis conducted in this thesis several recommendations stand out for future setup development.

- Installation of a calibrated photo-detector. This will allow for a mapping of LED input current to emitted photon flux, which will remove any possible horizontal compression in the Excelitas dynamic range measurements. This will also allow for a PDE measurement similar to that conducted on the PDPC in section 6.4 to be conducted.

- Installation of a tuneable light source, capable of emitting light in narrow wavelength bins. This will allow for direct measurement of SiPM PDE.

- Installation of a temperature sensor for the SiPM. This will allow a DCR analysis similar to section 6.2 to be completed.

- Establish precise control over ambient temperature. This will improve temperature control over the sensor and reduce collection time in most analyses.
References


8 Acknowledgements

This research was supported by CTA, API and NIKHEF. I thank my colleagues from these institutions who provided insight and expertise that greatly assisted the research. In particular I would like to thank my supervisor David Berge and daily supervisors Arnim Balzar and Maurice Stephan for assistance and support during my research. Also for their comments which greatly improved the final draft of this thesis.

I would also like to show my gratitude to Niels van Bakel and the NIKHEF R&D group for sharing their research and experience with me over the course of this project. I am also immensely grateful to Oskar van Petten, Guido Visser and Taco Walstra for providing hardware support, helping me make my apparatus a reality.