Design and Optimisation of Detector Cells for the PoGOLite Polarimeter

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May 28, 2015
Abstract

The field of X-ray polarimetry provides a new way to observe astrophysical objects by measuring the polarisation fraction and angle of emitted radiation flux in the X-ray regime. The PoGOLite (Polarised Gamma-ray Observer) Pathfinder experiment is a balloon-borne Compton scattering-based X-ray (15-240 keV) polarimeter whose primary target is the Crab Nebula and Pulsar. It consists of an array of 61 detector cells consisting of three types of scintillators.

The PoGOLite Pathfinder had its first successful flight in 2013, where it followed a circumpolar path for 13 days before landing in Russia. For the planned 2016 flight, a number of changes are planned to be made to the detector based on experiences from the 2013 flight. To evaluate which solutions should be used for these changes a number of tests have been performed.

One of the most noticeable issues with the current iteration of the polarimeter is unintended optical cross-talk between detector cells. Scintillation light from a scintillator in a detector cell leaks over to neighbouring cells where it induces a fake signal. These fake signals create fake polarisation events, significantly reducing the performance of the detector. By covering the detector cells with a new type of light absorbing material it was possible to eliminate this issue and significantly increase the performance of the detector.

A significant improvement could also be made to the collection of scintillation light from the "fast" scintillator. Tests to find the optimal reflective cover for the detector cell parts were performed, and it was found that it was possible to significantly improve the light collection with a change of reflective materials. By eliminating optical cross-talk and improving the light collection of the detector cells the $M_{100}$ of the polarimeter is expected to be improved by approximately 50%.

The final test performed was a comparison between two types of "fast" plastic scintillator models. It was thought that the current "fast" scintillator could be replaced by one which is superior for the polarimeters use. These two types were tested using both waveform analysis and a multichannel analyser but no significant performance improvement was found and parts of the tests were inconclusive. In the end it was decided to use the same scintillator which was used in previous iterations.

With the new design of the detector cells the polarimeter’s performance will be greatly increased. Monte Carlo-based simulations based on a six hour observation of the Crab in conditions taken from the 2013 flight show an improvement in MDP$_{90\%}$ from 25.8% to 17.4%. The increased precision will result in more statistically significant observations of the Crab Nebula and Pulsar which will allow us to understand more about the emission mechanisms for high energy radiation.
Sammanfattning


Efter en framgångsrik flygning 2013 är det planerat att göra nya detektorceller, och med det ändra en del av deras konstruktion. För att utreda vilka lösningar som är optimala så har en rad tester genomförts.

Det främsta problemet med den nuvarande designen är att scintillationsljus från en interaktion i en cells scintillator kan läcka över till en närliggande detektorcell. I denna cell detekteras då en interaktion som egentligen inte har hänt, och denna önskade effekt reducerar polarimeters precision. För att eliminera denna effekt så har flera lösningar utvärderas, och den nya detektorcellen kommer att kläss i ljusabsorberande material så att inget ljus läcker ut.


De förändringar som planeras för de nya detektorcellerna och polarimeteren kommer att nämnvärt förbättra prestandan. Detta kommer att förhoppningsleda till mer precisa observationer av ”Krabban” och låta oss förstå mer om dess struktur.
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Author’s Contribution

In preparation for the proposed 2016 flight of the PoGOLite Pathfinder experiment a number of changes have been proposed to improve the performance of the polarimeter based on experience from the 2013 flight. For my Master’s Thesis I have conducted a number of tests, a large part of them together with Håkan Wennlöf [1], to try to find solutions for the detector that are an improvement compared to what has been used before. I have participated in disassembling the polarimeter, conducted experiments, and analysed data.

In particular, I have together with Håkan Wennlöf performed tests of reflective wrapping materials for detector cells, test of light absorbing wrapping materials to prevent light leakage between detector cells, and an evaluation of the performance of PMTs used in 2013 flight.

As a final test I compared two different types of “fast” scintillators to determine if a change of scintillator would improve the performance of the polarimeter. I have analysed data from all of the performed tests, and the results from these tests will be used by the PoGOLite Collaboration to determine a new design of the polarimeter.
Chapter 1

X-ray Polarimetry

Extrasolar X-rays, first discovered by Roberto Giacconi in 1962 [2], have played a key role in the discovery of new astrophysical objects by illuminating what was not visible before. Through characterisation of energy spectra and time variations in the X-ray domain many astrophysical objects have been discovered, categorised, and analysed, but these observation techniques do not allow us to fully understand the processes which are ongoing in many of these radiative sources.

X-ray polarimetry aims to fill that gap. Many radiative processes produce polarised X-rays, and by measuring the polarisation properties it is possible to gain more knowledge about the emission processes taking place. This chapter will provide an introduction to the relatively new field of X-ray polarimetry, with a focus on areas related to the PoGOLite Pathfinder (Polarised Gamma-ray Observer) experiment.

1.1 Photon Polarisation

Photons are associated with oscillating electric and magnetic fields. The orientation of the electric field within the plane perpendicular to the momentum vector of a photon is called the polarisation of a photon. This electric field has two orthogonal components, with different phases. If the two components are oscillating in phase with each other, the photon is linearly polarised at an angle determined by the ratio between the two components. If there is a phase shift between the components, the photon will instead be elliptically polarised. If the shift is 90°, it is circularly polarised. Using current technology X-ray polarimetry is limited to measurements of linear polarisation.

1.2 Interactions

Detecting photons requires that they interact in some way with the detector material and deposit some or all of their energy. Detectors are usually made to observe one type of photon interaction, depending on its purpose, energy range, and material. The three most common interactions for photons in matter are the photoelectric effect, Compton scattering, and pair production. These have different cross sections for different energies, as can be seen in Figure 1.1. The PoGOLite Pathfinder experiment mainly utilises Compton scattering for polarisation measurements, but energy depositions through the photoelectric effect are also detected. All of the above mentioned types of photon interactions in matter have angular dependencies on the polarisation of the incoming photon. The polarisation effects will be explained in detail only for Compton scattering since this is what is used in the PoGOLite Pathfinder experiment.
1.2 Interactions

Figure 1.1: Absorption coefficients as a function of energy for different photon interactions in NaI(Tl) [3]. The photo-electric effect dominates at low energies, Compton scattering at intermediate energies, and pair production at high energies (which is outside of PoGOLite’s range).

1.2.1 Photoelectric Effect

The photoelectric effect describes the effect of matter emitting electrons when it is radiated by photons of a sufficiently high frequency. An electron in an atom absorbs the incident photon, and if the photon energy exceeds the binding energy $E_b$ of the electron it will be emitted and the atom ionised. The kinetic energy of the emitted electron is given by

$$E_k = hf - E_b,$$

(1.1)

where $h$ is Planck’s constant and $f$ is the frequency of the incident photon. For a high energy photon in the X-ray or gamma-ray regime an electron is almost certain to be emitted, and it is most likely to be emitted from the inner K-shell which has the highest binding energies for the electrons. The azimuthal emission angle of the electron depends on the polarisation of the incident photon [4].

1.2.2 Compton Scattering

Compton scattering, also called Thomson scattering in the low energy regime, occurs when a photon scatters inelastically off a free$^4$ electron. By using conservation of momentum and energy in the interaction it is possible to derive the expression for the scattered photon’s energy

$$E'_{\gamma} = \frac{E_{\gamma}}{1 + \frac{E_{\gamma}}{m_e c^2} (1 - \cos \theta)},$$

(1.2)

$^4$For photons with energies in the X-ray and gamma-ray regime the photon energy is much higher than the electron binding energy, so the electron can be considered to be free.
where $E_\gamma$ is the incident photon’s energy, $m_e$ is the electron mass, $c$ is the speed of light in vacuum, and $\theta$ is the (polar) scattering angle see Figure 1.2.

The polarisation of the incident photon also has an effect on the direction of the scattered photon. The differential cross section of the interaction in three dimensions is given by the Klein-Nishina formula [5]:

$$\frac{d\sigma}{d\Omega} = \frac{1}{2} r_0^2 \epsilon^2 \left[ \epsilon + \epsilon^{-1} - 2 \sin^2 \theta \cos^2 \phi \right].$$  (1.3)

Here $r_0$ is the classical electron radius, $\theta$ is the polar scattering angle, $\phi$ is the azimuthal scattering angle with respect to the polarisation vector of the incident photon,

$$\epsilon = \frac{E'_\gamma}{E_\gamma} = \frac{k'}{k} = \frac{1}{1 + \frac{E_\gamma}{m_e c^2} (1 - \cos \theta)},$$  (1.4)

and $k$ and $k'$ are the momenta of the incident and scattered photon, respectively. An illustration of the process can be found in Figure 1.2.

![Figure 1.2: Illustration of the Compton scattering process, adapted from [6]. An incoming photon with momentum $k$ and a polarisation vector $\vec{p}$ scatters off an electron. The photon scatters off the electron with a polar scattering angle $\theta$ and an azimuthal scattering angle $\eta$, with a final momentum of $k'$.](image)

Since the differential cross section varies with the angle $\phi$, incident polarised light will be distributed non-uniformly around the z-axis after scattering, with a maximum probability of scattering perpendicularly to the polarisation vector of the incident photon. This effect is most prominent for polar scattering angles $\theta$ where the $\sin^2 \theta$ term in Equation 1.3 is large, which has a maximum for $\theta = 90^\circ$.

### 1.2.3 Pair Production

In the pair production process, a photon with an energy of at least 1.022 MeV ($E_\gamma \geq 2m_e c^2$) is required. The photon can then create an electron and a positron, but only if there is another
particle to absorb momentum for conservation. For a photon in matter the pair production process usually occurs near a nucleus which can absorb momentum. The azimuthal distribution of the momenta of the created electron and positron, which tend to be separated by an angle 180° in the azimuthal plane, depends on the polarisation of the original photon [7].

1.3 Polarimetric Techniques

The photoelectric effect, Compton scattering, and pair production have as described an azimuthal angular dependence on the polarisation of the incoming photon involved in the process. The goal of polarimetry is to reconstruct the angular anisotropy in these processes to measure the polarisation fraction and angle of the incoming photon flux [8]. If the incoming flux is polarised, polarisation measurements would result in a so called modulation curve, see Figure 1.3.

![Modulation Curve](image)

**Figure 1.3:** Example of a modulation curve. The azimuthal angle is the polarisation dependent angle discussed in section 1.2 for three different processes; the photoelectric effect, Compton scattering or pair production. A sinusoidal modulation curve is usually a fit to histogrammed data.

From the modulation curve one can get the modulation factor [8]

\[
M = \frac{C_{\text{max}} - C_{\text{min}}}{C_{\text{min}} + C_{\text{max}}},
\]

which is a representation of the anisotropy in the process. The polarisation fraction is then given by [8]

\[
\Pi = \frac{M}{M_{100}},
\]

where \( M_{100} \) is the modulation factor resulting from a 100% polarised beam which can be acquired through measurement or simulation [8]. \( M_{100} \) is a property of a detector and depends on the detector’s geometry and the materials used. A figure of merit used in polarimetry is the Minimum Detectable Polarisation (MDP). This is the minimum source polarisation required to able to be certain that the measured signal is polarised at a certain confidence level. For a confidence level of 99%, the expression for the MDP is [6]
Chapter 1. X-ray Polarimetry

1.4 Detection Methods

1.4.1 Scintillators

Scintillators are materials which absorb ionising radiation and re-emit it as fluorescent light in the visible or ultraviolet spectrum. This scintillation of light comes from the excitation of bound electrons by free electrons which are generated by the three types of interactions mentioned above. The number of fluorescent photons emitted is proportional to the kinetic energy of the incoming particle, making scintillators suitable for energy measurements.

There are two common types of scintillators, organic and inorganic. In organic scintillators, such as plastic scintillators, the electron transitions causing florescence are made by molecular valence electrons, while in inorganic scintillators the transitions are made by electrons in the electronic band structure found in crystals [9].

1.4.2 Photomultiplier Tubes

Photomultiplier tubes (PMTs) are often used together with scintillators. They are photodetectors consisting of components sealed in a vacuum tube which convert a small light signal into an electric pulse. A schematic of the design of a PMT can be found in Figure 1.4. Incoming photons, for example from a scintillator, cause primary electrons to be emitted at a semiconductor photocathode through the photoelectric effect. These electrons are focused by a focusing electrode and accelerated by a potential difference towards the first dynode, where secondary emission from the primary electrons produces many low energy electrons. Between each dynode there is a potential difference to guide the electrons, and there are up to 19 dynodes [3]. For each dynode there is typically an amplification factor of 5-10 [10], and the total gain ranges between 10 and $10^8$ [3]. At the end of the tube the signal is extracted at the anode and can be read.

![Figure 1.4: Schematic diagram of a photomultiplier tube [3]. The stem and stem pin supply voltage levels to the dynodes.](image-url)
Even without exposure to light PMTs have a characteristic peak in their spectra, called the single photoelectron (SPE) peak. This peak is caused by spontaneous emission of photoelectrons from the photocathode which undergo multiplication. The channel position of this peak gives a good indication of the PMT’s gain, since it is proportional to the amplitude of the electric pulse signal caused by one single photoelectron. This can be used for comparison with other PMTs.

**Time Dependence**

Studies [11] show that after supplying voltage to a PMT, its noise level decreases continuously for a time before stabilising, and for precise measurements one should preferably wait at least one hour. The noise count rate was measured for a PMT of the same type as those used in the PoGOLite Pathfinder experiment, and it was found to decrease by up to a factor 3 if enough time passed. Prior to and during the measurements the PMT was in a light-tight environment to minimise exposure to ambient light and fluorescent light from the glass of the PMT.

### 1.5 Observational Targets in X-ray and Gamma-ray Polarimetry

#### 1.5.1 Emission Processes

**Inverse Compton scattering**

Inverse Compton scattering is a process which can be seen as a reversal of the Compton scattering process. Highly energetic relativistic electrons scatter with low energy photons, transferring energy to the photons. In the same way that a polarised incident flux which is Compton scattered results in a non-uniform distribution of azimuthal scattering angles, a polarised flux can be produced from an unpolarised beam. For an unpolarised beam of photons, the fraction of linear polarisation of the scattered photons depends on the polar scattering angle $\theta$ in the electrons’ rest frame [12]:

$$\Pi = \frac{\sin^2 \theta}{\epsilon + \epsilon^{-1} - \sin^2 \theta},$$  \hspace{1cm} (1.8)

where $\epsilon$ is defined in Equation 1.4.

**Cyclotron, Synchrotron, and Curvature Emission**

Cyclotron and synchrotron emission occur when charged particles, mainly electrons, are accelerated in a magnetic field. For cyclotron radiation the emission distribution has the form of a dipole with the maximum in the direction of the momentum vector of the charged particles. For synchrotron radiation the particles are highly relativistic, so the emitted photons have a higher energy and the radiation is beamed in the momentum direction of the particle. For both of these processes the polarisation vector of the emitted photons lies in the plane spanned by the acceleration vector of the particle and the directional vector of the emitted photon [12]. The observed polarisation characteristics will then be different based on the position of the observer, and the radiation will have a maximum linear polarisation for an observer viewing from a direction with a line of sight perpendicular to the magnetic field [12].

Curvature emission is also linked to magnetic fields, but occurs when charged particles move within strongly curved magnetic fields. The electrons will tend to move along the field lines and the polarisation vector of the emitted photon will be parallel to the magnetic field vector [12].
1.5.2 Pulsars

Pulsars are rotating neutron stars which are highly magnetised. They are formed when a star with a mass between approximately 8 and 20 solar masses [6] collapses, resulting in a supernova. The remnant neutron star retains the angular momentum of the star, resulting in a high rotation frequency since it is much smaller than its progenitor. If the neutron star’s magnetic field and rotational axes are not aligned the electromagnetic radiation coming from the magnetic poles of the neutron star appears to be ”pulsating” for a fixed observer.

There are currently three classes of models for the high energy radiative processes of pulsars [13]. These are the polar cap model, the caustic model and the outer gap model.

![Illustration of the location of the radiative processes for the different pulsar models.](image)

**Figure 1.5:** Illustration of the location of the radiative processes for the different pulsar models [14]. The magnetic field axis is tilted compared to the rotational axis by an angle \( \alpha \). The light cylinder region is where material which is co-rotating with the neutron star would be moving at the speed of light.

According to the polar cap model [15] electrons and positrons are accelerated along the open field lines at the polar caps of the pulsar, emitting synchrotron and curvature radiation. The caustic model [16] predicts that acceleration and emission occur at the innermost open field lines close to the closed field region, extending from the magnetic poles to the light cylinder of the pulsar. This region is called the slot gap. The outer gap model [17] assumes that electrons and positrons are accelerated in vacuum gaps between the closed and open field lines in the outer magnetosphere. The particles emit synchrotron and curvature radiation and can also cause production of new electron-positron pairs if the radiation undergoes inverse Compton scattering.

While the X-ray intensity predictions of these models are similar, their polarisation profile predictions are very different [6], see Figure 1.6. By doing polarisation measurements of pulsar X-ray radiation more can be understood about the emission processes.
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1.5 Observational Targets in X-ray and Gamma-ray Polarimetry

Figure 1.6: Plots of pulsar emission model predictions on intensity, polarisation angle, and polarisation fraction (degree) versus phase. Three different models are represented: the polar cap model (left), the outer gap model (center), and the two pole caustic model (right). The spaces between the vertical lines represent the first and second pulses, P1 and P2. Reproduced from [18] with permission, copyright (2008) Elsevier.

The Crab Pulsar

The Crab Pulsar, which is located within the Crab Nebula, is one of the most famous and prominent pulsars. It was first discovered in the 1960s, although the supernova which left the nebula as a remnant was seen in the year 1054. The Crab Pulsar has a period of 33 ms and a spin down power of $4.6 \times 10^{38}$ erg s$^{-1}$ [19]. Because of its steady and intense flux of hard X-rays the Crab Nebula is often used as a standard unit for energy flux for X-ray sources, although the flux in the 15-50 keV range decreased by 7% between 2008 and 2011 [20].

Observations from the Fermi space telescope have indicated that the emission from the Crab Pulsar cannot come from the stellar surface, disfavouring the Polar Cap model [19]. The Crab Pulsar and Nebula are the main targets of the PoGOLite Pathfinder Experiment.

1.5.3 X-ray Binary Systems

X-ray binaries are systems where an accretor, usually a white dwarf, neutron star, or black hole, accretes mass from an accompanying star, resulting in a so called accretion disk. This process produces radiation when the gravitational energy of the accreted mass is released. When the accretor is a black hole the system can become very luminous in the X-ray spectrum since it exerts a very strong gravitational force on the accreted mass.

One such system is Cygnus X-1, a secondary target of the PoGOLite Pathfinder experiment. This system consists of a galactic stellar mass black hole candidate with a measured mass between 7 and 13 solar masses [6] and its companion star. Like other X-ray binaries it has two observed spectral states, a hard X-ray spectral state and a soft X-ray spectral state. The transition between these states is believed to be caused by changes in the accretion rate, based on observations of changes in the bolometric (total) luminosity [21].

In the hard state it is thought [21] that a low accretion rate results in the accreting mass turning into two distinct components. One optically thin, geometrically thick, hot inner corona and an overlapping geometrically thin, optically thick disk. The primary hard X-ray emission would then come from thermal photons originating from the disk being upscattered through
Compton scattering by energetic electrons in the hot inner flow. This emission is not expected to be noticeably polarised since it comes from multiple Compton scatterings, but the hard X-ray spectrum also indicates that there is another component, consisting of hard X-rays from the hot inner flow that have been reflected by the colder outer disk, that will be polarised. Using polarimetry it could be possible to derive the inclination relative to the line of sight of a binary system based on the polarisation fraction of the emission in the hard X-ray state \[18\].

In the soft state \[21\], the accretion rate is higher and the accretion disk extends to the innermost stable orbit of the accretor. The hard X-ray emission in this state arises from upscattering of thermal photons in active flares above the accretion disk. The polarisation signature in the soft state is expected to be different from that of the hard state, and polarisation measurements in the soft state could provide information about the distribution of energetic electrons in these active regions \[18\].

### 1.5.4 Gamma-ray Bursts

Gamma-ray bursts (GRBs) are flashes of gamma rays which are the most luminous objects in the universe for their short duration. They are thought to come from highly relativistic jets originating from supernova events, mergers of neutron stars, or mergers of neutron stars and black holes \[22\]. A lot is still unknown about these bursts, and X-ray polarimetry could in the future give answers about the jets’ structures and emission mechanisms \[22\]. Because of the short duration of these bursts and their random position on the sky observation of them requires the detector to have a large field of view to be able to observe them within the required time frame. GRB observation is thus out of the scope of the PoGOLite Pathfinder experiment due to its small field of view.
Chapter 2

The PoGOLite Pathfinder Experiment

The PoGOLite (Polarized Gamma-ray Observer) Pathfinder experiment is a balloon-borne X-ray polarimeter designed to measure the polarisation of radiation in the 25-240 keV range [23] originating from astrophysical objects. It has a small field of view at 2.4° by 2.6° [23], with its primary intended target being the Crab Pulsar and Nebula, and Cygnus X-1 if it is in the correct state. The PoGOLite experiment was originally designed for 217 detector cells, and the current Pathfinder experiment consists of 61 detector cells. It first flew in July 2011, and a second flight took place in 2013. The experiment has to be lifted to an altitude of 40 kilometres because of the atmosphere greatly attenuating X-rays in PoGOLite’s observational range.

2.1 Current Design

The PoGOLite Pathfinder is a Compton scattering-based polarimeter designed to both detect Compton scattering and photo-absorption events in determining azimuthal Compton scattering angles [6]. It consists of 61 hexagonally shaped detector cells arranged in a segmented detector volume, see Figure 2.1.

Figure 2.1: Schematic for the detector volume of the PoGOLite Pathfinder polarimeter [8]. The 61 detector cells (purple) are arranged in a honeycomb structure surrounded by an anti-coincidence shield (green). Courtesy of the PoGOLite Collaboration.

By detecting coinciding Compton scattering and photo-absorption events in different cells it is possible to reconstruct the scattering event and find the azimuthal scattering angle. For op-
timal background rejection and signal acquisition each detector cell consists of three scintillator types. One 60 cm long hollow "slow" plastic scintillator used for collimation, one 20 cm long "fast" plastic scintillator where the events used for polarisation measurements take place, and one 4 cm long crystal BGO (bismuth germanium oxide) scintillator used for anticoincidence indication and as a light guide. These detector cells are called phoswich ("phosphor sandwich") detector cells (PDCs), and a schematic for one cell can be found in Figure 2.2. The BGO end of each PDC is connected to a PMT for signal detection, with a silicone "cookie" acting as an interface between the PMT and the BGO.

Figure 2.2: (a) Schematic representation of a PDC (not to scale), consisting of three different scintillators glued together. The slow and fast scintillator are wrapped in VM2000, a specularly reflective film, with the slow scintillator being covered on the inside as well. The BGO scintillator is covered in a diffusively reflective coating containing barium sulfate (BaSO₄). The slow scintillator is also wrapped in 50 µm thick lead and tin foils for increased collimation efficiency. The slow and fast scintillators are also covered with a blue heat shrink tube on the outside. (b) Images of the slow, fast, and BGO scintillator respectively. Courtesy of the PoGOLite Collaboration.

Since the PMT will receive signals from events taking place in either of the three PDC scintillators the signals have to be separated. This can be done through waveform discrimination of the signal. The signals from the PMTs are read by charge-sensitive amplifiers on electronic boards in the detector, which sample the signal at a rate of 37.5 MHz meaning that there is a period of ≈ 30 ns between sampling points. For each waveform recorded, 50 sample points are stored. To be able to account for baseline offsets from preceding signals the sampling starts 15 sampling points before the trigger [8].

The waveforms have very different characteristics depending on if the decay time of the scintillator material is fast (fast plastic scintillator, decay time of 1.8 ns [24]) or slow (slow plastic scintillator or BGO, decay times of ≈ 300 ns). To be able to separate the signals into
categories two properties are calculated for each waveform, the fast and the slow output. The fast or slow output is the maximum difference between sample pulse heights separated by four or fifteen samples, respectively [8]:

\[
\text{Fast output: } = \max_{1 \leq i \leq 46} \{ v[i+4] - v[i] \},
\]

\[
\text{Slow output: } = \max_{1 \leq i \leq 35} \{ v[i+15] - v[i] \}.
\]

Here \( v[i] \) is the pulse amplitude of sample point \( i \). This analysis is performed off-line. Examples of waveforms of signals originating from the fast or slow scintillators can be found in Figures 2.3 and 2.4. A constraint set on the slow output calculation is that it is measured from the starting point of the fast output.

Through off-line analysis of the waveforms the signals from events in the fast scintillator can be extracted and used for polarimetry analysis. A histogram for all events in a PDC and their slow and fast output can be found in Figure 2.5. There are two clear visible branches, with events either coming from a fast or slow scintillator.

The pulse amplitude of the waveforms is proportional to the energy deposited in the scintillator material\(^1\), and by detecting coinciding events in more than one PDC a scattering event can be reconstructed, see Figure 2.6. A candidate scattering event would have the signature of a low energy deposition in one PDC from a Compton scattering interaction, and a high energy deposition in another PDC from photoelectric absorption.

The detector volume is surrounded by 30 BGO detector cells connected to PMTs, see Figures 2.1 and 2.6. They make up a side anticoincidence shield (SAS) which is used together with the bottom BGO scintillators of the PDCs for reducing background events induced by high energy photons and charged particles coming from the side or under the detector volume. When any

\(^1\)For energy depositions lower than \(\sim 50\) keV a correction factor has to be applied since the response is non-linear [6].
event is detected in the SAS, or a slow event is detected in a PDC from the bottom BGO or slow scintillator a veto is issued resulting in events in the fast scintillator not being registered \[6\]. The waveforms from the slow scintillator and the BGO scintillator cannot be separated because their decay times are similar. This does not affect the veto since events in both these scintillators should issue veto signals.

Aside from the PDCs and the SAS there is also a neutron detector in the polarimeter which consists of a PMT and a scintillator material with a high cross section for thermal neutrons, \(\text{LiCaAlF}_6\), placed in between two BGO crystals \[26\]. This detector is used to study the flux of atmospheric neutrons and its contribution to the background of the main detector.

The whole detector is enclosed by a pressure vessel. This inner pressure vessel is held by a rotational frame, see Figure 2.7, allowing the detector to be rotated around its line of sight to minimise systematic errors and “smear” out the measured scattering angles, which would otherwise be discretely distributed since there is a finite amount of detector cells.

### 2.2 Flights

The launch window of the PoGOLite Pathfinder experiment is only a few weeks in the middle of the summer due to several constraints. The position of the Crab on the sky has to be separated from the Sun by a large enough margin, and the winds have to be able to take the balloon westward. The whole payload, including the polarimeter, is lifted by a helium balloon with a maximum volume of one million cubic metres. There have currently been two flights, in 2011 and 2013, with a third flight planned for the summer of 2016.

A first flight of the PoGOLite detector took place on July 6th 2011. During the launch the balloon was damaged, and due to the balloon leaking helium the flight was terminated and the payload cut from the balloon after four hours. Because of this no observations were possible.

A more successful flight took place in July 2013. Launched on July 12th the detector was airborne for 13 days before the flight was terminated. An image of the gondola used for the payload can be found in Figure 2.8. The payload landed near Norilsk in Russia, and had the flight not been terminated PoGOLite would have possibly drifted out over water and not been
Chapter 2. The PoGOLite Pathfinder Experiment

2.2 Flights

Figure 2.5: Histogram of all events detected in a PDC [8]. Two main "branches" are visible. The horizontal line at $\approx 2800$ comes from saturation in the electronics. Courtesy of the PoGOLite Collaboration.

Figure 2.6: A side view illustration of the PoGOLite detector array and different kinds of events (not to scale). Reproduced from [25] with permission, copyright (2007) Elsevier.

recoverable. Despite a failure in the power control system of the polarimeter, 14 hours of Crab observation were possible. The flight continued to test the attitude control systems and to observe the flight path.
Figure 2.7: Schematic of the PoGOLite detector assembly [8]. The polyethylene shields reduces background events induced by neutrons. Courtesy of the PoGOLite Collaboration.

Figure 2.8: Image of the PoGOLite Pathfinder gondola and payload. Courtesy of the PoGO-Lite Collaboration.
Chapter 3

Optimisation of PoGOLite

For the 2016 flight several changes are planned to be made for the polarimeter based on experiences from the 2013 flight. To be able to evaluate the different materials and solutions several tests have been performed with comparisons between currently used and possibly better solutions. There are currently two primary issues with the polarimeter. The signal to background ratio is very low, making it hard to extract the relevant polarisation events. The other large issue is optical cross-talk, where scintillation light is unintentionally spread between PDCs. The optical cross-talk reduces the $M_{100}$ drastically, which in turn raises the MDP, making it harder to make significant observations. Some of the issues and possible improvements that can be made to the polarimeter will be discussed in this section.

3.1 Light Collection

Several factors affect the energy resolution of detectors based on scintillators, but the most prominent one is the statistical variation in the number of photoelectrons produced in the photocathode of a photomultiplier tube by scintillation photons from an event in a scintillator. Assuming this process follows Poisson statistics, the energy resolution $R$ of the signal pulse amplitude can be found to be [9]

$$R = \frac{\text{FWHM}}{H_0} \propto \frac{\sqrt{N}}{N} = \frac{1}{\sqrt{N}},$$

(3.1)

where FWHM is the full width half maximum of the photo-absorption peak, $H_0$ is the peak position, and $N$ is the number of photoelectrons produced in the event.

The number of photoelectrons produced $N$ is proportional to the number of scintillation photons reaching the photocathode of the PMT, so to optimise the energy resolution of the detector cell the so called light collection of the PDC has to be maximised. In their current iteration the fast and slow plastic scintillators are covered in VM2000, a specularly reflective film, to allow the maximum amount of fluorescent light to stay in the PDC and reach the PMT. The BGO scintillator is covered in a diffusively reflecting barium sulfate (BaSO$_4$) instead because of its special geometry, see Figure 2.2.

A useful metric for the light collection of a complete PDC together with a PMT is the number of photoelectrons per keV deposited in an interaction event in the fast scintillator. This value can be derived by doing measurements where the PDC is irradiated with photons of a known energy, and then finding the SPE and photo-absorption peaks in the spectrum, i.e.

$$\frac{\text{Ph. e.}}{\text{keV}} = \frac{1}{E_{\text{Photons}[\text{keV}]}} \cdot \frac{\text{Ph. Abs. Peak Position}}{\text{SPE Peak Position}},$$

(3.2)
where Ph. e. stands for photoelectron and Ph. Abs. stands for photo-absorption. To improve the light collection of the PDC several different solutions were tested for the reflective cover of both the fast scintillator and the BGO scintillator, see Chapter 4.

### 3.2 Optical Cross-talk

For an optimal PDC, all fluorescent light stays in the scintillators and reaches the photocathode of the connected PMT. This is not possible to do, and light will leak through the reflective cover. Unless this light is absorbed in some way, it will reach an adjacent PDC and create a contaminating signal similar in its profile to what the polarimeter is trying to detect. Studies [6] show that for the current design this unintended effect, optical cross-talk, causes the $M_{100}$ to be reduced from 33.2% to 23.4% as a result of induced fake double hit events. An example of such an event would be when some light from a high energy photo-absorption event in a PDC leaks into a neighbouring PDC where the detector sees this light like an event where a small amount of energy has been deposited. For the detector this would look like a Compton scattering event in the second PDC and a photo-absorption event in the first PDC, and such an event would be indistinguishable from a real polarisation event. A visual image of this light leakage can be found in Figure 3.1. To try to prevent the light leakage a number of materials and solutions were tested, see Chapter 5.

![Figure 3.1: Visualisation of the light leakage of a PDC (without the slow plastic scintillator, see section 3.4). Half of the PDC is already covered in an absorbing material which was tested as a solution to the leakage. The light source used in this image does not correctly represent the wavelength distribution of the fluorescent photons emitted by the scintillator material, and the amount of fluorescent light from an event in the scintillator is a lot less than what is seen in the image. Credit: Håkan Wennlöf.](image)

### 3.3 Fast Scintillator Type

In the current detector the plastic scintillator EJ-204 [24] produced by Eljen Technology is used as the fast scintillator. After a comparison with Eljen Technology’s more standard scintillator EJ-200 [27] it was found that in theory EJ-200 could make a better fit for the detector.
The reasoning for this was that its emission spectrum has better compatibility with the chosen reflective materials and the sensitivity of the PMT’s photocathode. The spectra for the fluorescent emission of EJ-200 and EJ-204 can be found in Figure 3.2.

Figure 3.2: The emission spectra for (a) EJ-200 [27] and (b) EJ-204 [24]. The peak quantum efficiency wavelength for the PMT is marked on the spectra at 420 nm as a dashed vertical line [28].

The PMT [28] used in the polarimeter has a peak quantum efficiency at a photon wavelength of 420 nm, with its sensitivity range being 300-650 nm. Comparison with the scintillator emission spectra in Figure 3.2 shows that the PMT peak quantum efficiency wavelength is a better match for EJ-200. The chosen reflective material for the fast scintillator, ESR (see Chapter 4), is also theoretically a better match for the spectrum of EJ-200. In Figure 3.3 the reflectivity of ESR as a function of wavelength can be found. EJ-204’s emission spectrum has a significant part below 400 nm and ESR’s reflectivity decreases below 400 nm. This could affect the light collection of the PDC, and points toward EJ-200 being the better choice.

Figure 3.3: Measured data for ESR reflectivity vs. photon wavelength [29].

The characteristics of the two scintillators are very similar, with EJ-204 having rise and decay time of 0.7 and 1.8 ns respectively, while EJ-200’s values are 0.9 and 2.1 ns. Since the sampling points in the detector are separated by 30 ns this small difference should not have
any noticeable effect on the measurements. EJ-204 also has 4% better light yield at 10,400 photons per MeV compared to 10,000 for EJ-200. This together with the lower rise and decay time of EJ-204 was the reason for choosing this type for the first PDCs [30]. Tests have been performed to be able to evaluate their performances with the planned changes, see Chapter 7.

3.4 Simulation-Based Improvements

Monte Carlo-based simulations [31] in Geant4 of the detector in flight-like situations and analysis of results from the 2013 flight have shown that the slow scintillator is not as effective as anticipated, and instead the plan is to use a passive collimator made out of copper with a wall thickness of 0.5 mm (compared to 2 mm for the slow plastic scintillator). This would increase the live time of the detector since fewer slow events would take place in each PDC. The live time is the amount of time that the detector is able record an event, with the sum of the live and dead time being the total measurement duration.

Another planned change based on simulation results is the shortening of the fast scintillator to 12 cm. This is based on results which show that the reduction in background would be greater than the reduction in signal events, increasing the signal to background ratio of the detector.
Chapter 4

Light Collection Optimisation of PDC

4.1 Fast Scintillator

4.1.1 Experimental setup

To test different reflective wrapping materials for the fast scintillator an already assembled PDC without the slow scintillator was used. The BGO scintillator in this PDC was already coated in BaSO$_4$, and the wrapping of the fast scintillator could be changed between measurements.

For the measurements a PMT was used together with a pre-amplifier (Ortec Model 113 [32]), an amplifier (Canberra Model 2026 [33]) for gain control and a multi channel analyser (MCA, Amptek MCA-8000A [34]), see Figure 4.1. The MCA returns the amplitude of the signal pulse as a channel value. The channel value is proportional to the deposited energy in the detected event since the pulse amplitude is proportional to the deposited energy.

The PDC was connected to the PMT with the help of a holder to ensure that the connection was stable and consistent, see Figure 4.2. For optimal light collection a silicone cookie was used in the PMT-PDC connection like in the polarimeter. For each test the PDC was irradiated at the end (see Figure 4.2) by an $^{241}$Am source, which predominantly emits photons with an energy of 59.5 keV.

Figure 4.1: Schematic representation of the signal acquisition and the powering of the PMT.
The "optical bench" in Figure 4.2 which aligned the PDC and the sample was placed in a light-tight box to make sure that no ambient light contaminated the measurement.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure42.png}
\caption{Image of the setup used for the reflectivity tests for the fast scintillator. Credit: Håkan Wennlöf.}
\end{figure}

To ensure that the connection between the PMT and the PDC did not affect our results the connection was never broken between measurements. Instead, the PDC was rewrapped while still connected to the PMT, see Figure 4.3. The voltage supplied to the PMT’s 5 V circuit, also called bias voltage, which controls the gain of the PMT was 4.656\textsuperscript{1} V and each measurement took 120 seconds. The amplifier gain was set to 100.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure43.png}
\caption{Image of an unwrapped fast scintillator.}
\end{figure}

### 4.1.2 Results and Discussion

Each measurement made resulted in a spectrum with a clear photo-absorption peak from the 59.5 keV photons. The photo-absorption peaks of these spectra were fitted with a Gaussian function and a background function:

\[ S(x) = p_0 e^{\frac{x-p_1}{p_2}^2} + p_3 + p_4 x + p_5 e^{-\frac{x-p_6}{p_7}}. \]  

(4.1)

Here \( S(x) \) is the number of counts detected in channel \( x \), with the interesting parameter being \( p_1 \) which represents the peak position. An example of such a fit can be found in Figure 4.4. The position of the photo-absorption peak is a good indicator for the light collection of the PDC, which depends on the reflectivity of the wrapping material.

\textsuperscript{1}This voltage is increased by a DC/DC conversion factor of 250 by the PMT.
To test the reproducibility of the setup four measurements were made using VM2000 where the PDC was unwrapped and rewrapped between measurements. The resulting spectra from these measurements can be found in Figure 4.5. The fitted peak positions of these spectra were found to be within 5% of each other.

Four different kinds of materials were tested. The specularly reflective films VM2000 and ESR, both produced by 3M, and the diffusively reflective materials Tyvek, produced by DuPont, and PTFE tape (0.2 mm thick). For each material one measurement was made, and different number of layers were tested as well. The results of these measurements can be seen in Table 4.1.

<table>
<thead>
<tr>
<th>Material</th>
<th>Peak Channel</th>
<th>Improvement vs. VM2000 [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>VM2000 (Reference)</td>
<td>1512</td>
<td>N/A</td>
</tr>
<tr>
<td>Three layers of Tyvek</td>
<td>1447</td>
<td>-4</td>
</tr>
<tr>
<td>Two layers of PTFE tape</td>
<td>1582</td>
<td>+5</td>
</tr>
<tr>
<td>Three layers of PTFE tape</td>
<td>1614</td>
<td>+7</td>
</tr>
<tr>
<td>ESR</td>
<td>1744</td>
<td>+15</td>
</tr>
<tr>
<td>Two layers of ESR</td>
<td>1752</td>
<td>+16</td>
</tr>
</tbody>
</table>

Table 4.1: Table of the results of the reflective wrapping measurements for the fast scintillator. The fitting uncertainty for the peak positions are of the order of 0.1% and have a negligible effect on the results compared to the experimental systematic uncertainties.

Based on these measurements ESR results in the highest light collection. The advantage of using ESR is also that it is very thin (0.03 mm), since the space between PDCs in the instrument is limited. Based on the similar performance of one and two layers of ESR it was decided that one layer was enough.
4.2 BGO

4.2.1 Experimental Setup

The BGO light collection and reflectivity were tested similarly to the tests of the reflective wrapping of the fast scintillator, but with another PMT. A downside of testing with BGO crystals is that it is not possible to change the wrapping material without breaking the connection between the BGO and the PMT. For these tests more than one BGO was used to accommodate the different reflective solutions, and the connection between PMT and BGO was broken between each measurement. An image of a BGO scintillator connected to a PMT can be found in Figure 4.6.

For every measurement the PMT bias voltage was set to 4.557 V, and the amplifier gain was set to 200 because of the lower light yield of BGO. Between each measurement the BGO was removed and the BGO bottom, PMT, and silicone cookie was cleaned.

4.2.2 Results and Discussion

As for the fast scintillator tests, each measurement resulted in a spectrum with a photo-absorption peak. For the BGO spectra the peak has a peculiar shape, and the best fit for it has two Gaussian functions instead of one. For this reason another Gaussian was added to Equation 4.1 for the fitting of these spectra. A fit of this type can be found in Figure 4.7. The shape of photo-absorption spectra from this type of BGO scintillator has been studied earlier [35], and it was determined that it is most likely caused by the geometry of the BGO, see Figure 2.2. In this study a cylindrical BGO sample was tested and the spectrum was found to have a Gaussian photo-absorption peak.

Because of the different shape of these spectra another method was used to evaluate the light collection of the measurement. Instead of taking the peak position of a Gaussian the
position of the maximum amplitude of the total fitted function was used. This was motivated by the fact that the peak still behaves as a photo-absorption peak, with the peak positions of the two Gaussian curves both being proportional to the light collection.

![Figure 4.6: BGO connected to PMT.](image)

![Figure 4.7: A measured spectrum from an irradiated BGO, fitted with two Gaussian functions and a background function. The background increasing with channel number is most likely an effect of the fitted function not being perfect for the spectrum and the geometry of the BGO. Over a wider range the background is seen to decrease as expected.](image)

A number of different materials and reflective coating solutions were tested to find the best solution for the BGO. Because the shape of the BGO scintillator is irregular with a hexagonal part leading into a round part it is not possible to cover all of it with ESR. A solution to this was to have the ESR cover the hexagonal part of the BGO crystal while another material covered the round and intermediate conical part.

In addition to testing some materials tried for the fast scintillator and BaSO$_4$ two other solutions were evaluated as well for the BGO. These were a reflective paint from Eljen and a custom covering solution made by Scionix. A very large number of layers of Eljen paint was
used, but it was found to be very hard to apply evenly. A BGO was sent to Scionix, and they covered it with a 120 \(\mu\)m thick sheet reflector together with a 50 \(\mu\)m thick layer of aluminised mylar.

For each measurement a cap made out of ESR was placed on the end of the BGO to prevent light leaking out in that direction. Two measurements were made for each solution, and as can be seen in Table 4.2 there was a spread of up to 8% between individual measurements for the same solution. This is mostly caused by the variation in the connection quality between the PMT and BGO. The use of more than one BGO crystal should not have a large effect on the result since their performance is similar [35] and the experimental uncertainties are much greater as mentioned above.

<table>
<thead>
<tr>
<th>Reflective material</th>
<th>1st Meas.</th>
<th>2nd Meas.</th>
<th>Average</th>
<th>Improvement vs. BaSO(_4) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaSO(_4) (Reference)</td>
<td>1347</td>
<td>1296</td>
<td>1321.5</td>
<td>N/A</td>
</tr>
<tr>
<td>1 × PTFE</td>
<td>1267</td>
<td>1189</td>
<td>1228</td>
<td>-7</td>
</tr>
<tr>
<td>2 × PTFE</td>
<td>1433</td>
<td>1539</td>
<td>1486</td>
<td>+12</td>
</tr>
<tr>
<td>Eljen Paint</td>
<td>1080</td>
<td>1114</td>
<td>1097</td>
<td>-17</td>
</tr>
<tr>
<td>Scionix Solution</td>
<td>1448</td>
<td>1381</td>
<td>1414.5</td>
<td>+7</td>
</tr>
<tr>
<td>BaSO(_4) + ESR</td>
<td>1628</td>
<td>1621</td>
<td>1624.5</td>
<td>+23</td>
</tr>
<tr>
<td>2 × PTFE + ESR</td>
<td>1618</td>
<td>1645</td>
<td>1631.5</td>
<td>+23</td>
</tr>
</tbody>
</table>

Table 4.2: Results for the BGO covering solution measurements. \(N \times \text{Material}\) represents the number of layers. The two last entries are with ESR covering the hexagonal part of the BGO. As for the fast scintillator test the fitting uncertainties are much smaller than the experimental uncertainties.

As can be seen in Table 4.2 the two stand outs in these measurements, even taking into account the variation in PMT connection, are the solutions with ESR covering the hexagonal part of the BGO. In a complete PDC this would mean that the ESR cover of the fast scintillator extends and continues over the hexagonal part of the BGO.

Of these two solutions the one with two layers of PTFE tape together with ESR was chosen. This was mostly done because applying BaSO\(_4\) to the BGO is a slow and tedious process, while the application of PTFE tape to the BGO is rather straightforward. For optimal covering the ESR will be applied first with the PTFE tape overlapping the ESR. The fact that only two layers of PTFE tape was better than only BaSO\(_4\) also points toward PTFE tape being the better alternative.

The total improvement of collection of scintillation light from events in the fast scintillator can be approximated to be 40% based on the 15% improvement for the fast scintillator and 23% improvement for the BGO scintillator. The scintillation light from the fast scintillator has to pass through the BGO scintillator which acts as a light guide, so it is reasonable to assume that the results should be multiplied to get an approximated total improvement.
Chapter 5

Elimination of Optical Cross-talk

5.1 Experimental Setup

To get a quantitative figure for how much light was leaking out of a PDC two fully assembled PDCs (without slow scintillators) were used together with two PMTs and a small baseplate similar to the one in the polarimeter. This was to emulate the setup in the polarimeter itself. The PDCs were placed adjacent to each other with the PMTs being connected to them from the other side of the base plate, see Figure 5.1. A blue LED was then placed to shine pulsating light through the top of one of the PDCs. A square pulse with a duration of 200 ns was used for the diode with a pulse height of 4 V and a frequency of 20 kHz. The voltage chosen was the suggested maximum and the pulse length was increased until the diode light made a noticeable impact on the measured spectra even with some optical insulation added. The amount of light detected in the other PDC was then measured while the setup was inside a light tight box.

![Figure 5.1: Image of the setup used for cross-talk testing. The fixture at the top holds the PDCs together and fixes the diode on top of one of the PDCs. The black shrink tube in this image was what was found to be the best solution for absorbing light.](image)

Since the count rate was very important in these measurements backgrounds measurements
were taken before and after each primary measurement. This was to account for the noise count rate variation described in Chapter 1. Another thing that was done to account for this was to turn the PMT on (with supplied bias voltage) and leave it on for a few hours before measurements were taken. The signal acquisition was performed according to Figure 4.1. A bias voltage of 4.557 V was supplied to the PMT for every measurement, and the amplifier gain was set to 1000.

5.2 Results and discussion

To know how much light has leaked from the first to the second PDC the spectrum acquired when the diode was turned on was compared to the average of the two background measurements taken before and after. To see how the current PDC performs the amplifier gain had to be lowered to 500 to even see the effect of the diode because the measured pulse amplitudes were so large, see Figure 5.2.

![Figure 5.2: Spectrum for a measurement taken with the diode being on and with the current PDC wrapping. The amplifier gain was set to 500 for both measurements. The background here was not measured the same day as the diode measurement.](image)

Two difficulties were encountered during testing. Firstly it was found to be hard to cover the bottom part of the PDCs perfectly, resulting in a lot of light leaking from the BGO. Secondly it was found that some of the light escaping from the PDC reflects inside the light tight box and reaches the second PDC. To account for this the second PDC was covered by black Tedlar, one of the materials tested, on every side not touching the first PDC.

To evaluate quantitatively the performance of the light absorbing materials the number of counts normalised by live time was compared for the spectrum with the diode on with the average background taken before and after. To exclude the noisy part of the spectrum at channel values lower than 150 the count rate was integrated from 150 to 4096. The ratio of the count rates was used as a quantitative figure of merit for the light absorption. An example of a measurement can be found in Figure 5.3.
To begin with a number of types of Tedlar, a polyvinyl fluoride film produced by DuPont, was tested. To make it easier to change material the film was instead of being wrapped around the PDCs sometimes placed between them. This should not affect the result since the order of the material that the light passes through should make no difference. Later a black heat shrink tube, similar in material and thickness to the blue one used currently, was tested and found to not let any light through. It was found that it was possible to extend the black shrink tube over the BGO scintillator by modifying the plastic mounting piece used to connect the PDC to the baseplate and PMT. This eliminates any chance of light leakage from the BGO as well. The measurement results can be found in Table 5.1.

![Example spectrum from a measurement where one layer of black Tedlar for each PDC was tested.](image)

**Figure 5.3:** Example spectrum from a measurement where one layer of black Tedlar for each PDC was tested.

<table>
<thead>
<tr>
<th>Material</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1×Grey Tedlar (37.5 µm)</td>
<td>1.100</td>
</tr>
<tr>
<td>2×Grey Tedlar (75 µm)</td>
<td>1.060</td>
</tr>
<tr>
<td>1×Black Tedlar (37.5 µm)</td>
<td>1.037</td>
</tr>
<tr>
<td>1×White Tedlar (37.5 µm)</td>
<td>5.888</td>
</tr>
<tr>
<td>1×White Tedlar (50.0 µm)</td>
<td>10.024</td>
</tr>
<tr>
<td>Black Heat Shrink Tube</td>
<td>1.004</td>
</tr>
<tr>
<td>Black Heat Shrink Tube + 1×Grey Tedlar</td>
<td>0.998</td>
</tr>
</tbody>
</table>

**Table 5.1:** The result for the cross-talk measurements. The number of layers are per PDC, with the blue heat shrink tube being used unless written otherwise. Due to the above mentioned issues with covering the whole area between the PDCs there are some peculiar results, with the thinner white Tedlar having a better result than the thicker white film. The last result which is below 1 is most likely an effect of systematic errors, since it should not be possible to have a count rate lower than the background.

To be completely sure that no light is leaking from a PDC it was decided that the PDC
should be wrapped in one layer of grey Tedlar as well. Later it was also decided that the top part of the PDC should be covered in black Tedlar to prevent light from leaking out in that direction as well. Because of limited supply it was not possible to use black Tedlar for the whole PDC.
Chapter 6

Testing of Flight PMTs

6.1 Experimental Setup

To assess the quality of the PMTs that were part of the detector for the 2013 flight they were all tested using the same setup as in Chapter 4. The PMTs are connected group-wise to electronics boards in the polarimeter, and since they were still connected in groups by their cables after disassembly they were tested group-wise. For each group all of the PMTs were placed in a light tight box.

The signal from each PMT was then measured separately from the last dynode without opening the box between measurements. As in the earlier tests a pre-amplifier, an amplifier for gain control and an MCA was used for signal acquisition, with the amplifier gain set to 1000.

Additionally the current through the 5 V circuit was measured with a multimeter. The exact voltage supplied to the 5 V circuit was 4.557 V, and with this voltage the average current drawn per PMT was found to be approximately 500 µA. The same voltage was applied to all PMT groups since the measurements were done for relative comparison between the PMTs. Each measurement had a duration of 300 seconds.

6.2 Results

Every PMT except one was found to output a signal, with one PMT being dead before the last flight. All PMTs, including this one, were found to be drawing current by looking at the total current of the 5 V circuit for each group. Since there seems to be no visible damage to the dead PMT the cause of the problem is unknown. An attempt was made to measure a signal from the anode of the PMT but no signal was found, suggesting that something is broken internally.

Since the PMTs were measured in a light-tight space, the only signals visible in their spectra besides noise are their SPE peaks, whose position is proportional to the gain of the PMT. For every PMT this peak was fitted to a Gaussian function together with an added background function. This background function was the same as the one used for the spectra in Chapter 4, which results in the total function

\[
S(x) = p_0 e^{\left(\frac{x-p_1}{p_2}\right)^2} + p_3 + p_4 x + p_5 e^{-\frac{x-p_6}{x-p_7}},
\]

(6.1)

to be fitted to the spectrum. In Figure 6.1 one can see an example signal spectrum from one PMT.
Chapter 6. Testing of Flight PMTs

6.3 Analysis and Discussion

For each PMT the position of the SPE peak could be obtained from the fit, and a histogram of the SPE Peak distribution for the PMTs can be found in Figure 6.2.

To evaluate which PMTs should be replaced for the 2016 flight, the SPE peak measurements were compared to measurements made of the anode sensitivity [36]. These values were available for both the PMTs that flew and replacement PMTs available in Japan. In Figure 6.3 a comparison between the anode sensitivity and the SPE peak positions for every PMT can be

Figure 6.1: The signal spectrum from a PMT with the accompanied fit, with the same spectrum in both logarithmic and linear scale. The red whole line represents the fit, the dashed black line the Gaussian signal of the SPE peak, and the green line the background. The spectrum is zoomed in from the full channel range 0-4096.

6.3 Analysis and Discussion
Figure 6.2: Histogram distribution of the SPE Peak positions for all measured PMTs. The 91 entries are 60 PDC PMTs (one broken), 30 SAS PMTs and one neutron scintillator PMT.

It is intuitive that the two properties should be proportional to each other since the anode sensitivity is how sensitive the anode is to light incoming to the photocathode, which would depend on the gain. A difference is that for our measurements the signal is taken from the last dynode instead of the anode.

An earlier calibration measurement of the SPE peaks for the PDC PMTs [37] was made in February 2014. A comparison between the two studies can be seen in Figure 6.4. Aside from the time passed between the two measurements, a large difference between them is the equipment used. The 2014 measurement used the electronics that are used for the PoGOLite Pathfinder, while the 2015 measurement used an MCA with a pre-amplifier and an amplifier. The major difference between the two signal acquisition methods is the waveform analysis. The PoGOLite electronics outputs a whole waveform of the pulse, while the MCA only returns the pulse amplitude. The 2014 analysis [37] of the SPE peaks looked at spectra of the fast output, while the measurement performed in this study looked at the pulse amplitude (represented by channel number). If all waveforms from the SPE have the same shape the fast output should be proportional to the peak amplitude, and both the peak fast output and peak pulse amplitude would be proportional to the gain of the PMT. This would mean that the relation in Figure 6.4 would be linear. A tendency for this can be seen, but there is still a lot of spread and a linear fit is not perfect. The most probable reason for this is the difference in signal acquisition method discussed above.
Chapter 6. Testing of Flight PMTs

6.3 Analysis and Discussion

Anode Sensitivity, July 2008 [A/lm]

0
200 400 600 800 1000 1200 1400 SPE Peak Channel, March 2015

Entries 88
Mean x 586.6
Mean y 757.2
RMS x 186
RMS y 307.3

Figure 6.3: Scatter plot comparison between the anode sensitivity and SPE peak position for every tested PMT. For three PMTs the anode sensitivity was not available in the provided database.

SPE Peak Fast Output, February 2014

20 25 30 35 40 45 50 55 60 65 70 SPE Peak Channel, March 2015

Entries 60
Mean x 41.54
Mean y 920
RMS x 5.034
RMS y 292.2

Figure 6.4: Scatter plot comparing the SPE peak values for all of the PDC PMTs (excluding broken one) flown in 2013 from two different studies.
Chapter 7

Comparison of Scintillator Types

7.1 Experimental Setup

To test the two plastic scintillator models, EJ-204 [24] and EJ-200 [27], two scintillators of each model were used. They had a length of 10 cm and they were glued together with BGO crystals to create four PDCs. Another purpose of the assembly and testing of PDCs was to test a new glue, Epo-Tek 301 [38], since the previously used glue was not available anymore. They were then wrapped with reflective and light absorbing materials in line with the design of the new PDCs, with the exception that the grey and black Tedlar was omitted. This omission does not affect the tests since the tests will look at the light collection and waveforms, which are only affected by the reflective wrapping and the scintillator itself. An image of an unwrapped and a complete PDC can be seen in Figure 7.1.

![Figure 7.1](image-url): Side by side view of one bare and one complete PDC made for testing.

These PDCs underwent two different kind of tests. They were first tested with the same setup used for the light collection tests in Chapter 4 in a light-tight box. For the PoGOLite Pathfinder polarimeter light collection is not the only thing that is important, but also how well waveforms from events in different types of scintillators can be separated. Similar measurements were therefore made but using the PoGOLite electronics used for waveform analysis in the polarimeter. For the latter measurements the "optical bench" was placed in a light-tight pipe covered with a number of layers of grey Tedlar at each end.

For both types of measurement the setup on the optical bench was the same. The PDC was irradiated by the $^{241}$Am sample in the same way as the measurements made in Chapter 4, see
Chapter 7. Comparison of Scintillator Types

7.2 Results

Figure 4.2. For the MCA measurements each measurement was 120 seconds, and background measurements were taken before and after each primary measurement with the PDC being irradiated. Five primary measurements were made for each PDC, with the PDC being removed and the PMT, silicone piece, and BGO bottom being cleaned between each measurement. This was to evaluate reproducibility and to try to minimise the effect the PMT connection had on the light collection comparison of the PDCs.

With the setup using the PoGOLite electronics two primary measurements of 60 seconds for each PDC was made. This measurement duration was more than enough to get clear photo-absorption peaks. A background measurement of 300 seconds was made before each primary measurement. The same procedure of cleaning the connection interface parts between primary measurements was made for this test.

For both these tests the PMT bias voltage was set to 4.557 V. An amplifier gain of 100 was used in the MCA tests.

7.2 Results

In both tests, the background measurements were made as a precaution in the case of the background rate being high enough to affect the results of the measurements. This was seen to not be the case. The very high rate of incoming photons from the $^{241}$Am sample overshadows the background rate by a great margin in the spectra, as can be seen in Figure 7.2.

![Figure 7.2: Comparison of a signal and a background measurement with the MCA. For the background measurement the PDC was still connected to the PMT. In the signal spectrum one can also see the two photo-absorption peaks which arise from photo-absorption in either the fast scintillator or the BGO crystal. The two spectra have been normalised with respect to live time for comparison.](image)
7.2.1 MCA Tests

A directly noticeable effect of the shortened fast scintillator in the PDCs is the second peak arising in the MCA spectra, see Figure 7.2. This can be compared with Figure 4.4 where there is only one peak. The reason for this is that a large fraction of the 59.5 keV photons passes through the fast scintillator because of its shorter length, and most of them are absorbed by the very dense BGO crystal. This results in a second photo-absorption peak with a position at a lower channel (pulse amplitude) because of the lower light yield of BGO. This was confirmed by doing a measurement where only the fast scintillator was irradiated from the side close to the top end of the PDC. The spectrum from this measurement can be seen in Figure 7.3.

![Figure 7.3: Spectrum from a measurement where a PDC was irradiated from the side near the top of the fast scintillator. A photo-absorption peak at a similar position as the right photo-absorption peak in Figure 7.2 is seen, meaning that the left peak in Figure 7.2 comes from photo-absorption events in the BGO scintillator.](image)

The existence of this second photo-absorption peak provides a way to get a relative measurement of the fast scintillator’s light yield and light collection independent of the quality of the connection between the BGO and the PMT. Since the light from all photo-absorption events has to pass through the BGO-PMT interface, with a presumed equal relative light loss through this connection independent on where the event took place, the ratio between the peak positions of the fast scintillator peak and the BGO peak could act as a good relative indicator of the light collection of the fast scintillator. This is assuming that the reflective wrapping and the glue interface between the fast scintillator and the BGO of the different PDCs are entirely equal in quality. In reality is is hard to make these properties entirely equal.

The spectra for the MCA measurements were fitted with the same background function as for the measurements in Chapters 4 and 6 together with two Gaussian functions for the two photo-absorption peaks, see Figure 7.4. From the peak position values of each spectrum the light collection in photoelectrons per keV and the ratio between the peak positions can be obtained. To calculate the light collection a measurement with no PDC connected to the PMT was made with the amplifier gain set to 1000. The SPE peak position for this measured...
spectrum was calculated to be 232.3 following the method described in Chapter 6, and this value was then divided by 10 to get the presumed position of the peak at 100 gain assuming the relation between amplifier gain and SPE peak position is linear. The results for these measurements for each PDC can be found in Table 7.1. As for the measurements in Chapter 4 the fitting uncertainties for the peak positions are all of the order of 0.1%, and compared to the systematic errors from other factors in these measurements they have a negligible impact on the result.

![Figure 7.4: Measured spectrum for the MCA test with the fitted Gaussian and background functions. The black dashed lines represent the two Gaussian functions and the green line represents the background function.](image)

Because the spectrum is a mix of two photo-absorption peaks together with Compton scattering energy depositions and background, the fitted function is not perfect. In the test where entire waveforms are measured the peaks can be separated by considering the fast and slow outputs as described in Chapter 2.

### 7.2.2 Waveform Analysis Tests

For the analysis of the results from the second test using the PoGOLite electronics a ROOT script was used. This script analyses every waveform from a measurement and calculates the slow and fast outputs for every one of them as described in Chapter 2. It then analyses the distribution of the slow and fast outputs and calculates the photo-absorption peak of the slow and fast output spectra, where the events have been divided into a fast and a slow branch based on a line cutoff for simplicity, see Figure 7.5.

For the slow and fast branch spectra an initial Gaussian function is fitted to find the approximate position of the peak. Then a more sophisticated fit, with an added background function $ae^{bx}$ is made with the fitting range and starting parameters being based on the position of the initial Gaussian. This is also done similarly for the SPE peak, with the difference that it is made for the spectrum of the fast output from all detected waveforms. Examples of these three spectra and fits can be found in Figure 7.6.
### Table 7.1: Results for the MCA measurements.

The fitting uncertainties for the peak positions are all of the order 0.1% and are negligible compared to experimental and material uncertainties. Rel. Std. Error stands for relative standard error. The standard error is the standard deviation divided by the square root of the number of measurements, here 5. As expected the uncertainty in the peak ratio is smaller than for the light collection, since it is not affected by the PMT connection.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>BGO-Peak</th>
<th>Fast-Peak</th>
<th>Fast/BGO</th>
<th>Light Collection [ph.e/keV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>557</td>
<td>1049</td>
<td>1.88</td>
<td>0.75</td>
</tr>
<tr>
<td>2</td>
<td>597</td>
<td>1197</td>
<td>2.01</td>
<td>0.86</td>
</tr>
<tr>
<td>3</td>
<td>672</td>
<td>1324</td>
<td>1.97</td>
<td>0.95</td>
</tr>
<tr>
<td>4</td>
<td>626</td>
<td>1229</td>
<td>1.96</td>
<td>0.88</td>
</tr>
<tr>
<td>5</td>
<td>630</td>
<td>1264</td>
<td>2.01</td>
<td>0.91</td>
</tr>
<tr>
<td>Average</td>
<td>616.4</td>
<td>1212.6</td>
<td>1.97</td>
<td>0.87</td>
</tr>
<tr>
<td>Rel. Std. Error. [%]</td>
<td>3.1</td>
<td>3.8</td>
<td>1.1</td>
<td>3.8</td>
</tr>
</tbody>
</table>

(a) EJ-200 Sample 1: Measurement results for the first PDC made with EJ-200 in the MCA test.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>BGO-Peak</th>
<th>Fast-Peak</th>
<th>Fast/BGO</th>
<th>Light Collection [ph.e/keV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>591</td>
<td>1176</td>
<td>1.99</td>
<td>0.84</td>
</tr>
<tr>
<td>2</td>
<td>620</td>
<td>1243</td>
<td>2.00</td>
<td>0.89</td>
</tr>
<tr>
<td>3</td>
<td>596</td>
<td>1212</td>
<td>2.03</td>
<td>0.87</td>
</tr>
<tr>
<td>4</td>
<td>709</td>
<td>1452</td>
<td>2.05</td>
<td>1.04</td>
</tr>
<tr>
<td>5</td>
<td>620</td>
<td>1278</td>
<td>2.06</td>
<td>0.92</td>
</tr>
<tr>
<td>Average</td>
<td>627.2</td>
<td>1272.2</td>
<td>2.03</td>
<td>0.91</td>
</tr>
<tr>
<td>Rel. Std. Error. [%]</td>
<td>3.4</td>
<td>3.8</td>
<td>0.7</td>
<td>3.8</td>
</tr>
</tbody>
</table>

(b) EJ-204 Sample 1: Measurement results for the first PDC made with EJ-204 in the MCA test.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>BGO-Peak</th>
<th>Fast-Peak</th>
<th>Fast/BGO</th>
<th>Light Collection [ph.e/keV]</th>
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<tr>
<td>1</td>
<td>774</td>
<td>1565</td>
<td>2.02</td>
<td>1.12</td>
</tr>
<tr>
<td>2</td>
<td>740</td>
<td>1514</td>
<td>2.05</td>
<td>1.09</td>
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<tr>
<td>3</td>
<td>725</td>
<td>1473</td>
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<td>1.05</td>
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<tr>
<td>4</td>
<td>704</td>
<td>1435</td>
<td>2.04</td>
<td>1.03</td>
</tr>
<tr>
<td>5</td>
<td>662</td>
<td>1333</td>
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<td>0.96</td>
</tr>
<tr>
<td>Average</td>
<td>721</td>
<td>1464</td>
<td>2.03</td>
<td>1.05</td>
</tr>
<tr>
<td>Rel. Std. Error. [%]</td>
<td>2.6</td>
<td>2.7</td>
<td>0.2</td>
<td>3.8</td>
</tr>
</tbody>
</table>

(c) EJ-200 Sample 2: Measurement results for the second PDC made with EJ-200 in the MCA test.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>BGO-Peak</th>
<th>Fast-Peak</th>
<th>Fast/BGO</th>
<th>Light Collection [ph.e/keV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>616</td>
<td>916</td>
<td>1.49</td>
<td>0.66</td>
</tr>
<tr>
<td>2</td>
<td>657</td>
<td>968</td>
<td>1.47</td>
<td>0.69</td>
</tr>
<tr>
<td>3</td>
<td>613</td>
<td>920</td>
<td>1.50</td>
<td>0.66</td>
</tr>
<tr>
<td>4</td>
<td>633</td>
<td>941</td>
<td>1.49</td>
<td>0.68</td>
</tr>
<tr>
<td>5</td>
<td>643</td>
<td>949</td>
<td>1.48</td>
<td>0.68</td>
</tr>
<tr>
<td>Average</td>
<td>632.4</td>
<td>938.8</td>
<td>1.48</td>
<td>0.67</td>
</tr>
<tr>
<td>Rel. Std. Error. [%]</td>
<td>1.3</td>
<td>1.0</td>
<td>0.3</td>
<td>1.0</td>
</tr>
</tbody>
</table>

(d) EJ-204 Sample 2: Measurement results for the second PDC made with EJ-204 in the MCA test.
The individual scintillators are not the only thing different between each PDC. The wrapping, the glue interface between the fast scintillator and BGO, and the BGO itself can all have an effect on the result. The results for both tests show that the second PDC made with the EJ-204 scintillator is an outlier with approximately 25% worse performance based on the photo-absorption peak ratio than the other three, which are all very similar in performance. Since this result was noticeable in the MCA measurements which were performed first, the second EJ-204 PDC was rewrapped before the waveform analysis measurements. As can be seen, this did not make any noticeable difference, meaning that the wrapping of it is most likely not the cause of the anomaly. A comparison of the peak ratios in both tests for all four PDCs can be seen in Figure 7.8.

Further visual inspection, by looking through the BGO into the PDC, of all four PDCs shows no sign that the second EJ-204 PDC would be the worst performer by such a large margin. The evidence even points toward the opposite, with it seemingly looking better than the first EJ-204 PDC made which looks to have a worse glue interface with visible air pockets. This PDC also has hairline fractures on its surface, most likely caused by it being held in compression during glueing [39].

The most probable cause of the disparity is the glue interface, since the light yield of the scintillator is assumed to not vary significantly for the two EJ-204 PDCs. This together with the fact that rewrapping the PDC did not affect the result noticeably leaves only the glue or BGO left as the possible cause, and the fact that the BGO photo-absorption peak position is similar...
Chapter 7. Comparison of Scintillator Types

7.3 Analysis and Discussion

(a) The photo-absorption peak with accompanying fit for events in the fast scintillator. The spectrum is the projection of the fast output based on the cut shown in Figure 7.5.

(b) The photo-absorption peak with accompanying fit for events in the BGO crystal. The spectrum is the projection of the slow output based on the cut shown in Figure 7.5.

(c) The SPE peak with accompanying fit. The spectrum is the projection of all fast outputs without selection.

Figure 7.6: Example of photo-absorption and SPE peaks fitted to Gaussian functions with background.
Chapter 7. Comparison of Scintillator Types

7.3 Analysis and Discussion

Figure 7.7: Comparison of one fast waveform from each PDC tested. The baseline has been set to zero by subtracting a constant offset from each waveform, and the pulse height has been normalised to 1000 for each waveform. As expected there is no distinctive difference between the waveforms for the two scintillator types.

Figure 7.8: Comparison of the peak position ratios for the four tested PDCs. The second EJ-204 PDC is the clear outlier with a much worse performance than the other three, approximately 25%.

for all four PDCs indicates that the BGO is not the cause. Studies [8] of PDC performance, based on the position of the photo-absorption peak when the fast scintillator is radiated, made before the 2011 flight on PoGOLite PDCs show a spread of approximately ±15% from the mean in performance between different PDCs in a population of 80.

In the end it was decided that EJ-204 was to be used again, since it has worked in the
### 7.3 Analysis and Discussion

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Slow (BGO) Peak</th>
<th>Fast Peak</th>
<th>SPE</th>
<th>Fast/BGO</th>
<th>Light Collection [ph.e/keV]</th>
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</thead>
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<td>22.55</td>
<td>2.74</td>
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<tr>
<td>2</td>
<td>442</td>
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<td>22.52</td>
<td>2.77</td>
<td>0.91</td>
</tr>
<tr>
<td>Average</td>
<td>435</td>
<td>1199</td>
<td>22.53</td>
<td>2.76</td>
<td>0.89</td>
</tr>
</tbody>
</table>

(a) **EJ-200 Sample 1**: Measurement results for the first PDC made with EJ-200 in the waveform analysis test.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Slow (BGO) Peak</th>
<th>Fast Peak</th>
<th>SPE</th>
<th>Fast/BGO</th>
<th>Light Collection [ph.e/keV]</th>
</tr>
</thead>
<tbody>
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<td>0.98</td>
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<td>459</td>
<td>1292</td>
<td>22.64</td>
<td>2.81</td>
<td>0.96</td>
</tr>
<tr>
<td>Average</td>
<td>458</td>
<td>1298</td>
<td>22.55</td>
<td>2.83</td>
<td>0.97</td>
</tr>
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</table>

(b) **EJ-204 Sample 1**: Measurement results for the first PDC made with EJ-204 in the waveform analysis test.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Slow (BGO) Peak</th>
<th>Fast Peak</th>
<th>SPE</th>
<th>Fast/BGO</th>
<th>Light Collection [ph.e/keV]</th>
</tr>
</thead>
<tbody>
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<td>1261</td>
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<td>0.95</td>
</tr>
<tr>
<td>2</td>
<td>478</td>
<td>1345</td>
<td>22.45</td>
<td>2.81</td>
<td>1.01</td>
</tr>
<tr>
<td>Average</td>
<td>465</td>
<td>1303</td>
<td>22.43</td>
<td>2.80</td>
<td>0.97</td>
</tr>
</tbody>
</table>

(c) **EJ-200 Sample 2**: Measurement results for the second PDC made with EJ-200 in the waveform analysis test.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Slow (BGO) Peak</th>
<th>Fast Peak</th>
<th>SPE</th>
<th>Fast/BGO</th>
<th>Light Collection [ph.e/keV]</th>
</tr>
</thead>
<tbody>
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<td>1</td>
<td>432</td>
<td>946</td>
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<td>2.19</td>
<td>0.72</td>
</tr>
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<td>2</td>
<td>447</td>
<td>962</td>
<td>22.21</td>
<td>2.15</td>
<td>0.73</td>
</tr>
<tr>
<td>Average</td>
<td>440</td>
<td>954</td>
<td>22.17</td>
<td>2.17</td>
<td>0.72</td>
</tr>
</tbody>
</table>

(d) **EJ-204 Sample 2**: Measurement results for the second PDC made with EJ-204 in the waveform analysis test.

**Table 7.2**: Results for the waveform analysis measurements. As for the other results the fit uncertainty in the peak value is of the order 0.1%, which is a lot smaller than the uncertainties from the experimental and material factors.

two previous flights and the performance of EJ-200 was not noticeably better. The lower light yield of EJ-200 most likely offsets the improvement that could come from better compatibility with the rest of the PDC. The unexpected low performance of one of the PDCs also makes the measurements partly inconclusive.
Chapter 8

Conclusion and Outlook

The obtained results from the light collection and optical crosstalk tests show that a significant improvement can be made, and they have led to the redesign of the detector cells. The fast scintillator, including the top, will first be wrapped in a layer of the reflective film ESR, which will also extend over the hexagonal part of the BGO scintillator. The bottom and intermediate part, excluding the bottom surface, of the BGO will then be covered in two layers of 0.2 mm thick PTFE tape, which will overlap the ESR. A layer of grey Tedlar will then be added to the wrapping, which will cover the same area as the ESR. A cap of black Tedlar will also be placed on the top of the fast scintillator to prevent light from escaping in that direction. Finally a black heat shrink tube will be added to the PDC for light absorption, protection of the PDC, and for holding the wrapping in place. It will cover the whole PDC except the top and bottom ends. The copper collimator will not be glued to the fast scintillator, but will instead be held mechanically against the fast scintillator in the polarimeter.

The tests in Chapter 7 show that the light collection for the new PDCs can have a value of up to one photoelectron per keV. Even though the length of the tested fast scintillators have to be taken into account (10 cm compared to 12 cm planned for the new scintillators and 20 cm for the old PDCs) it is a significant improvement over the PDCs flown in 2013. These had an average light collection of 0.48 photoelectrons per keV [40] when measured before the flight. A number of these PDCs had already flown once in 2011, and the performance of them may have been decreased by them being damaged.

Proof of concept polarisation measurements in a laboratory setting [1] show an increase of 50% in \( M_{100} \) based on testing old PDCs with both old and new wrapping solutions, where the slow scintillator was removed for the measurements with the new wrapping.

Monte Carlo-based simulations [41] show that from the improvements in light collection and elimination of optical cross-talk the MDP_{99\%} would decrease from 25.8\% to 17.4\%. This simulation was based on a six hour observation of the Crab in conditions like those of the 2013 flight. This value agrees well with the 50\% improvement in \( M_{100} \) since \( \text{MDP}_{99\%} \propto \frac{1}{M_{100}} \).

The shortening of the fast scintillator, change to a passive collimator, and replacement of some of the PMTs will most likely lead to even better performance of the detector. The significant improvements in performance of the polarimeter will allow the PoGOLite Pathfinder to make more precise observations of the polarisation properties of the Crab Nebula and Pulsar.
Acknowledgements

First I would like to thank Professor Mark Pearce for giving me the opportunity to work with the PoGOLite Collaboration, and helping me along the way with my thesis. Secondly I would like to express my deepest gratitude to Mózsi Kiss. His guidance and help with laboratory measurements, data analysis, and thesis writing has been invaluable. Thanks for introducing me to ROOT and providing help with scripts making analysis so much easier.

Thank you Håkan Wennlöf for being a creative mastermind in the lab, and for keeping me good company for most of this time. I know I am not easy to deal with...

This experience would not have been the same without the rest of the PoGOLite Collaboration at KTH, Victor and Maxime, as well. Thank you for always being fun company and answering questions.

Last but not least I would like thank Rolf Helg and Kjell Hörfeldt of the AlbaNova workshop for providing immense help with material and constructions for the experimental setups and the polarimeter.

Thank you for this time and good luck in the future!
Bibliography


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[31] Private communications with Maxime Chauvin and Victor Mikhalev.


[39] Private communication with Rolf Helg.

[40] Calibration 130619. Internal PoGOLite document, available upon request.

[41] Private communication with Maxime Chauvin.