Development of the SPHiNX Gamma-Ray Burst Polarimeter

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Abstract

Satellite Polarimeter for High energy X-rays, or SPHiNX, is an X-ray Compton polarimeter designed to measure polarization features from gamma-ray bursts (GRBs) in the energy range 50-600 keV. The emission mechanism of GRBs is still not known, and measuring polarization from these sources can help differentiate between the emission models proposed.

SPHiNX detector system consists of plastic and Germanium Aluminium Gadolinium Garnet (GAGG) scintillators coupled to photomultiplier tubes (PMTs) and multi-pixel photon counters (MPPCs) respectively. The signals from the photosensors are sent to an ASIC for data acquisition. An Application Specific Integrated Circuit (ASIC) is a miniaturized system providing pre-amplification, shaping and track-and-hold functions.

This thesis aims to study the performance of a newly acquired ASIC, Citiroc, providing 32 individually programmable channels with both high and low gain amplifiers. Initial tests with Citiroc are performed using the GAGG scintillator coupled to a single MPPC. The thesis also discusses the feasibility of coupling a single MPPC with the plastic scintillator. This is first investigated through a theoretical comparison of response of an MPPC and a PMT with different plastic scintillators. Later tests are done in the lab to compare the performance of the photosensors. As the area of SPHiNX plastic scintillator is bigger than the photosensitive area of the MPPC, a MPPC array is also tested to check its suitability. To understand the behavior of the MPPC array, it is first tested with the GAGG scintillator. Lastly, a plastic scintillator with area matching that of the single MPPC is tested to see if the desired energy ranges can be achieved.

Using Citiroc the GAGG scintillator provides an energy range of 7-110 keV in the high gain amplifier and 35-700 keV in the low gain amplifier, which fulfills the requirement of SPHiNX. However, the plastic scintillator coupled to a single MPPC does not give the required energy range for SPHiNX, mainly because of the area mismatch. The obtained energy range is 15-203 keV. After testing the MPPC array with the GAGG scintillator, it was concluded that it is not suitable to be used with the plastic scintillator (for low energy photon detection).

The plastic scintillator with similar area as that of a single MPPC yielded an energy range of 10-130 keV in the high-gain amplifier of the Citiroc. This is better than the SPHiNX plastic, at low energies. The thesis ends with further suggestions to improve the performance of a plastic scintillator coupled to a single MPPC. It is concluded from this thesis that a single MPPC can be used to read out a plastic scintillator.
Sammanfattning

Satellite Polarimeter for High eNergy X-rays, eller SPHiX, är en röntgenpolarimeter som använder sig av Comptonspridning för att mäta polarisationen av röntgenstrålar från gammastrålkastare (GRBs), i energiintervallet 50-600 keV. Då strålningsmekanismen för GRBs fortfarande är okänd kan polarisationsmätningar av röntgenstrålning från dessa källor hjälpa till att skilja mellan de föreslagna strålningsmodellerna.

SPHiX detektorsystem består av plastscintillatorer kopplade till fotomultiplikatorror (PMTs) och Germanium Aluminium Gadolinium Garnet (GAGG)-scintillatorer kopplade till multi-pixel photon counters (MPPCs). Signaler från dessa fotosensorer skickas till en Application Specific Integrated Circuit (ASIC) för datainsamling. En ASIC är ett miniatyriserat system som tillhandahåller signalförstärkning, signalformning samt track-and-hold funktionaliteter.


Author’s contribution

This Master’s thesis is done as part of the SPHiNX project. The laboratory tests done by the author are prerequisites towards the development of a proof-of-principle polarimeter. All tests have been carried out in the laboratory at AlbaNova, KTH. Results presented in this thesis are produced by the author, unless otherwise stated. Results have been presented and discussed at SPHiNX project meetings.
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<tr>
<td>ADC</td>
<td>Analog-to-Digital Converter</td>
</tr>
<tr>
<td>APD</td>
<td>Avalanche PhotoDiode</td>
</tr>
<tr>
<td>ASIC</td>
<td>Application Specific Integrated Circuit</td>
</tr>
<tr>
<td>Citiroc</td>
<td>Cherenkov Imaging Telescope Integrated Read Out Chip</td>
</tr>
<tr>
<td>DAC</td>
<td>Digital-to-Analog Converter</td>
</tr>
<tr>
<td>FSH</td>
<td>Fast SHaper</td>
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<tr>
<td>FWHM</td>
<td>Full Width Half Maximum</td>
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<tr>
<td>GAGG</td>
<td>Germanium Aluminium Gadolinium Garnet</td>
</tr>
<tr>
<td>GRB</td>
<td>Gamma-Ray Burst</td>
</tr>
<tr>
<td>HG</td>
<td>High Gain</td>
</tr>
<tr>
<td>LG</td>
<td>Low Gain</td>
</tr>
<tr>
<td>MAPMT</td>
<td>Multi-Anode Photomultiplier</td>
</tr>
<tr>
<td>MCA</td>
<td>MultiChannel Analyzer</td>
</tr>
<tr>
<td>MDP</td>
<td>Minimum Detectable Polarization</td>
</tr>
<tr>
<td>MPPC</td>
<td>Multi-Pixel Photon Counter</td>
</tr>
<tr>
<td>PDE</td>
<td>Photon Detection Efficiency</td>
</tr>
<tr>
<td>p.e.</td>
<td>PhotoElectron</td>
</tr>
<tr>
<td>PMT</td>
<td>PhotoMultiplier Tube</td>
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<tr>
<td>SiPM</td>
<td>Silicon PhotoMultiplier</td>
</tr>
<tr>
<td>SPHiNX</td>
<td>Satellite Polarimeter for High eNergy X-rays</td>
</tr>
<tr>
<td>SSH</td>
<td>Slow SHaper</td>
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<tr>
<td>Quantum Efficiency</td>
<td>QE</td>
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Chapter 1

X-ray Polarimetry

The ability to view beyond the optical spectrum has made a huge impact on how we see the Universe. New astrophysical objects and phenomena have been discovered using, for example, X-ray telescopes and observational techniques [1]. But, as more than often is the case, the picture is not completely understood. X-ray polarimetry along with spectroscopy, imaging and timing studies can help solve these remaining problems. Determining the polarization of astronomical sources will shine a light on their geometrical properties and give information of the radiative processes taking place within which will broaden our understanding of the Universe. One of these astrophysical phenomena where the theory is currently incomplete is explosions known as Gamma-Ray Bursts (GRBs). Polarization measurement of the gamma-rays emitted by GRBs can tell us more about the processes behind the emission.

This chapter will describe the basic concepts of X-ray polarization, X-ray interaction with matter, and GRBs as celestial X-ray sources. Furthermore it will also describe scintillators and two different types of photosensors. This chapter will be the foundation around which this thesis is built.

1.1 Photon Physics

1.1.1 X-ray Polarization

All photons are electromagnetic waves that have both an electric and a magnetic field oscillating in a direction orthogonal to the direction of motion, see Figure 1.1. Traditionally the polarization of an electromagnetic wave is said to be the direction of the electric field.

The superposition of two linearly polarized waves will give a new wave which can be described by Equation 1.1 [2].

\[ E(z = 0, t) = E_x(0, t)\cos(\omega t - \phi_1) + E_y(0, t)\cos(\omega t - \phi_2) \] (1.1)

where the z-coordinate has been set to zero, \( \omega \) is the angular frequency, \( t \) is the time, and \( \phi_i \) is an arbitrary phase connected to the two waves respectively. Depending on the values these parameters can take, different types of polarization acquired by waves are summarized below.

- Elliptically polarized when \( \phi_1 - \phi_2 = \text{constant} \)
- Circularly polarized when \( \phi_1 - \phi_2 = \pm \pi/2 \)
- Linearly polarized when \( \phi_1 - \phi_2 = 0 \)

From this it is clear that all polarized waves are elliptically polarized light, but the linearly and circularly polarized waves are special cases of this. Light is said to be unpolarized when the polarization is non-measurable due to random oscillations between different polarization states. However, the detection method to be discussed in this thesis is limited to linear polarization.
The wave propagates in the direction of the arrow, electric and magnetic field vectors oscillate perpendicular to the direction of propagation and each other. $E$-field drawn in red and $B$-field in blue.

To be able to measure polarization, one has to be able to detect photons. Detecting photons is simply put as looking at interactions between photons and a medium. Therefore how photons interact with matter is of high importance when measuring the polarization of light.

### Photon Interactions With Matter

High Energy photons mainly interact with matter in three different ways, the photoelectric effect, Compton scattering and pair production. How it will interact depends on the energy of the incoming photon, and the material with which it interacts, see Figure 1.2. When the photon interacts, it deposits energy which can be measured using different techniques. In the SPHiNX detector, Compton scattering and photoelectric effect are used to measure polarization.

#### 1.1.2 The Photoelectric Effect

The photoelectric effect is the dominating interaction for low energy X-rays, few tens of keV. If the incident photon has an energy higher than the binding energy of an electron in an atom, the photon may be completely absorbed whilst one electron is ejected from the atom. When the electron is ejected a vacancy in the inner shell is created, this is quickly filled and in the process another photon, typically in the X-ray spectra, is released. Sometimes a so-called Auger electron is created instead of the X-ray photon. The process is illustrated in Figure 1.3. The photoelectric effect is used to measure the full energy of the the incoming photon, the electron freed in the process will have an energy equal to the incoming photon energy minus the binding energy of the electron [4]. For the energies considered here, the binding energy is usually negligible. In a spectrum, the photoelectric effect will give a clear defined peak, a so called photopeak.
1.1.3 Compton Scattering

The interaction where an incoming photon scatters off a stationary electron in an absorbing material is called Compton scattering. Compton scattering is the dominant photon interaction with matter at intermediate energy ranges, tens of keV to tens of MeV. The photon will scatter at an angle, \( \theta \), and a part of its energy will be transferred to the electron which then recoils at an angle \( \alpha \). The photon energy will decrease in the interaction, from \( h\nu \) to \( h\nu' \) where \( \nu \) and \( \nu' \) is the photon frequency before and after the interaction respectively. The interaction can be seen in Figure 1.4.

The energy of the scattered photon can be expressed as [4]:

\[
h\nu' = \frac{h\nu}{1 + \frac{h\nu}{m_e c^2}(1 - \cos \theta)}
\]  

(1.2)
In Equation 1.2, $m_e c^2$ is the rest mass energy of the electron. The photon scattering angle $\theta$ can vary between 0 and $\pi$. If $\theta = 0$ there is no energy difference from the incoming and scattered photon. This is the lower limit on the energy transferred to the electron. The upper limit on the electron energy is obtained when $\theta = \pi$, the photon has scattered back in the same direction it came from, giving the maximum energy to the electron in the interaction. For a 662 keV photon, the Compton edge will be at 478 keV. Since the photon cannot transfer more energy than this, it will theoretically be seen as a sharp edge in the energy spectrum, and this is called the Compton edge.

Another interesting feature connected to Compton scattering is called backscattering. Photons will be emitted isotropically from a source, i.e. going in every direction. Some of these photons will Compton scatter at $\theta = \pi$ in the material surrounding the source and enter the detector to be photoabsorbed. For example, for a 662 keV photon, the backscatter peak with energy 184 keV will be seen in the spectrum.

**Figure 1.4:** Compton scattering in two dimensions.

**Figure 1.5:** A spectrum of $^{137}$Cs obtained in the laboratory at KTH, using an inorganic scintillator. $^{137}$Cs decays to $^{137}$Ba which also is radioactive and decays, therefore two photopeaks are seen. The right most peak belonging to the highly energetic $^{137}$Cs.
1.1.4 Pair Production

For high energy photons, above one MeV, the dominant interaction with matter is pair production. If the photon energy exceeds or equals twice the rest energy of an electron ($2 \times 0.511 \text{ MeV} = 1.022 \text{ MeV}$), the photon can decay into a electron-positron pair. This reaction may however only occur in the vicinity of an atomic nucleus because of the conservation of momentum [4]. The process is illustrated in Figure 1.6.

\[ \text{Figure 1.6: Pair production can only happen in the vicinity of an atomic nucleus to conserve momentum.} \]
1.2 Scintillators and Photosensors

The detector in SPHiNX will be scintillators connected to photosensors. These different parts are described below.

1.2.1 Scintillators

A scintillator is a material which emits photons when energetic radiation deposits energy in it. The radiation, e.g. X-rays from stellar sources, passes through a scintillating material and excites the atoms. When they de-excite to their ground state, scintillation photons (scintillations) are emitted, mostly in the region of visible or ultraviolet light [5]. Some properties that a scintillator needs are [4]: i) the ability to convert kinetic energy of charged particles to detectable light, this conversion should be linear in energy dependence. ii) The scintillator should be transparent to the wavelength of the scintillations emitted. iii) The material should have a short decay time to allow for fast signal pulses.

There are two types of scintillators, organic and inorganic. Organic scintillators have a lower density, low Z value, which makes the probability for Compton scattering higher. Organic scintillators have fast decay times, but they yield less light than inorganic scintillators. Inorganic scintillators are often denser than organic ones, high Z value, this makes the probability for photoabsorption higher. In SPHiNX both of these kinds will be used, a less dense plastic scintillator (organic) which will scatter the incoming photons and a denser GAGG scintillator (inorganic) which will absorb the scattered photon. The scintillators also differ in light output. Light output of two scintillators can be compared by knowing the number of scintillations (photons) produced when 1 MeV electron interacts with a given scintillator. To detect these scintillations, scintillators are coupled to a photosensor. The following sections will describe two commonly used photosensors.

1.2.2 Multi-Pixel Photon Counter

The silicon photomultiplier (SiPM) also goes by the name Multi-Pixel Photon Counter (MPPC) and is a solid state detector with the capability of detecting individual photons [6]. The MPPC is an array of avalanche photodiodes (APD), each operating in Geiger-mode. An APD is a highly sensitive photodiode that multiplies photocurrent, if a reverse voltage is applied over it [7]. Each APD is connected to a quenching resistor ($R_q$), these make up one pixel of the array. The APD pixels are variations of p-n junction photodiodes, see Figure 1.7, and are connected in parallel.
In the middle of Figure 1.7 a p-n junction is displayed where the p-side is the anode and the n-side the cathode, and between them is an intrinsic electric field. This intrinsic field together with the externally applied inverse bias creates the electric field over the APD, displayed in the top of Figure 1.7, keeping the electrons and holes to the n-side and p-side respectively. An incident photon can, if its energy is greater than the band gap energy $E_G$, start an avalanche in the APD. The photon is absorbed creating an electron-hole pair, these are accelerated and can collide with bound electrons producing more electron-hole pairs. This avalanche effect can produce $10^5 - 10^6$ charge carriers, depending on the applied voltage over the MPPC.

For the MPPC to work one has to supply sufficient voltage. The minimum voltage at which the MPPC operates is called the breakdown voltage, $V_{BR}$. Voltage over the breakdown defines the gain of the MPPC. It is called over voltage, $\Delta V$, and is expressed as the difference between the operating voltage, $V_{OP}$, and the breakdown voltage.

$$\Delta V = V_{OP} - V_{BR}$$  \hspace{1cm} (1.3)

An MPPC can read out multiple photons simultaneously, but one pixel can only handle one photon at a time. When a photon causes an avalanche in one of the APD pixels the voltage goes down to the breakdown voltage, and it takes a short period of time for the voltage to rise to the operating voltage again. This time is called the recovery time, the pixel is saturated while it recovers. Since all the pixels are connected in parallel, which means that they work independently, the output will be the sum of the current from all of the pixels. The amplitude of the signal is proportional to the number of pixels triggered.

The amount of light an MPPC can detect is expressed in terms of photon detection efficiency (PDE). It is defined as the percentage of incident photons on the photosensitive area of the MPPC that are detected. This quantity is also used to compare two different types of MPPCs. The PDE plot for two types of MPPCs is shown in Figure 1.8.
Figure 1.8: Photon detection efficiency of two types of MPPCs as a function of wavelength [8]. The difference between the two types, PE and CS, is the geometrical area (smaller for PE) and window material.

Like all photosensors, MPPCs experience noise of different kinds. The dark noise of an MPPC can be caused by a number of different sources. One is the thermal development of charge carriers in the depletion region of the APD, these then enter the multiplication area and start an avalanche. Other noise factors are afterpulsing and cross-talk.

Due to the recovery time, the incoming photons will affect the measurements. If there are too many, the MPPC will quickly saturate and the outgoing current no longer remain linear to the energy of incoming photon. So, when using the MPPC connected to, for example, a scintillator it is important that the average count rate per cell is much lower than the inverse recovery time [9].

1.2.3 Photomultiplier Tubes

A photomultiplier tube (PMT) is another type of photosensor which just like an MPPC converts light to electric charge. The PMT consists of a photocathode, dynodes and anodes. Incoming photons hit the photocathode and is absorbed through the photoelectric effect, the electrons created in this process are focused towards the first dynode in the system. Here the electrons are multiplied by a process called secondary emission. Due to potential differences between the dynodes, all electrons are accelerated towards the next dynode in the chain, this repeats a number of times until the electrons reach the anode where the signal is measured. The gain of a PMT depends on the applied voltage and the number of dynodes [4, 10], and is mathematically expressed as:

\[ G \propto V^aN \]  

where \( G \) is the gain at supply voltage \( V \). The coefficient \( a \) (0.7-0.8) is set by the dynode material and its geometry, and \( N \) is the number of dynodes [4].

1.2.4 Energy Range and Resolution

All detectors are different, and they can be compared by a few different quantities. Two important ones are dynamic energy range and energy resolution. The energy range is simply the range from
the minimum detectable energy to the maximum. The energy resolution is the detector’s ability to distinguish between two closely spaced energy peaks. The energy resolution at a specific energy can be calculated as

$$\text{%Resolution} = \frac{\Delta E}{E} = \frac{\text{FWHM} \cdot 100}{E} = \frac{2.35\sigma}{E} \cdot 100,$$

where $E$ is the energy of the incoming photon and the Full Width Half Maximum (FWHM) is defined as $2\sigma\sqrt{2\ln 2} \approx 2.35\sigma$ where $\sigma$ is the standard deviation of the fitted Gaussian function. The photopeak in the energy spectrum is fitted with a Gaussian due to the fluctuations of the measured signal, which result from the interaction, the amplification and the electronic noise.

### 1.3 Polarimetry Parameters

The SPHiNX satellite will use Compton polarimetry to measure the polarization of incoming X-rays. This technique uses a segmented detector, i.e. multiple detector cells (see Chapter 2). One detector cell is defined as one scintillator connected to a photosensor. If a photon Compton scatters in one detector cell and then gets absorbed in another, a two-hit event has occurred. After many of these events are recorded the polarization parameters described below can be calculated.

![Figure 1.9: Compton Scattering in 3D. An incident photon, traveling in the z-direction, with polarization in the x-direction is scattered at the origin by an angle $\theta$.](image)

Expanding the discussion of Compton scattering in section 1.1.3, one can see the interaction in a three dimensional view in Figure 1.9. Compton scattering is defined by the Klein-Nishina formula, which gives the probability to scatter into an infinitesimal solid angle $d\Omega$. Integration over a finite solid angle gives the scattering probability for a photon to scatter at a specific polar angle $\theta$ relative to the direction of incidence and the azimuthal angle, $\phi$, relative to the vector of polarization[11].

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

(1.6)

where the probability for photon scattering is given by the differential cross-section $\frac{d\sigma}{d\Omega}$ and is a function of the classical electron radius, $r_0$, the ratio between the energy of the incident and scattered photon $\frac{E'}{E}$ and the two angles $\theta$ and $\phi$.

Equation 1.6 gives a higher probability for scattering when $\phi \to 90^\circ$ and maximum probability for scattering occurs when scattering is orthogonal to the polarization direction of the incident
photon. The aim for Compton polarimetry is to reconstruct the distribution for the azimuthal scattering angle, and if the incoming radiation is polarized, the angle will be modulated [12]. A histogram of reconstructed angles is known as a modulation curve, Figure 1.10 shows an example of such a curve. The phase of the modulation curve provides the angle of polarization, while the amplitude provides the fraction of polarization.

![Figure 1.10: The number of counts, arbitrary here, as a function of the azimuthal angle \( \phi \), the dashed lines correspond to the maximum and minimum number of counts.](image)

The modulation factor \( M \) can be obtained from Figure 1.10. \( M \) is a representation of the anisotropy in the Compton scattering process, and is mathematically defined as follows [13]:

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

(1.7)

Where \( C_{\text{max}} \) is the maximum count rate in the distribution, and \( C_{\text{min}} \) is the minimum. The fraction of polarization is given by:

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

(1.8)

where \( M_{100} \) is the modulation factor for a 100% polarized beam of photons, this is obtained through simulations and lab tests. The \( M_{100} \) is dependent on the detector geometry and material etc. [13].

Another interesting parameter is the MDP or Minimum Detectable Polarization, which defines the polarimetric sensitivity of the detector. It is a figure of merit which is used to compare polarimeters. The MDP is defined as the lowest fraction of polarization that can be measured by a detector with 99% confidence level.

\[
MDP = \frac{4.29}{M_{100} R_s} \sqrt{\frac{R_s + R_b}{T}}
\]

(1.9)

In Equation 1.9, \( T \) is the observation time, \( R_s \) and \( R_b \) are the signal and background counting rates for polarized events [14].
1.4 Gamma-Ray Bursts

SPHiNX is designed to observe Gamma-Ray Bursts. The following sections will describe how GRBs were discovered, one possible theory about their origin and mention a few earlier missions in the same area of research.

1.4.1 Background

Gamma-ray bursts (GRBs) were first observed in 1967 by the Vela satellites sent to space by the US military to look for Russian nuclear testing [15]. GRBs are the largest electromagnetic explosion in the Universe that we have observed [16]. Their very high luminosity gives us the opportunity to observe objects at very large distances and therefore look back into the early Universe. Emission from a GRB is divided into two parts, the gamma-ray part that comes with the prompt burst, and then the afterglow in lower energy ranges from X-rays to infrared [16]. Depending on the timescale of the prompt burst, it is either considered short or long, the division is at 2s, emission light curves for four GRBs are shown in Figure 1.11. It is believed that the different lengths of GRBs originate in different events, for example short bursts are believed to arise from the merging of neutron stars [17].

![Figure 1.11](image)

**Figure 1.11:** The variety of different GRBs is displayed with these four different graphs from the second BATSE catalog. The t-axis is in seconds. [18].

One plausible model that explains the GRBs is the fireball model, which can be seen in Figure 1.12.
Some event results in a sudden massive energy release of gravitational energy. This energy converts to neutrinos and gravitational waves, but a small fraction becomes a fireball [16] with very high temperatures. This fireball, consisting of $e^\pm$, gamma-rays and baryons, is transparent to the gravitational waves and to some extent the neutrinos as well. This will lead to the prompt emission. As the fireball interacts with the surrounding material it leads to a shock in the outflow direction, the emission from this shock will last for a longer time and would correspond to the afterglow of a GRB.

Since the military data was not made public right away it took a few years for scientists to provide theories for the GRBs, and in 1975 a review paper for the Texas Symposium on Relativistic Astrophysics listed 100 different possible models [16]. Since then progress has been made and a few different models have survived until now, for example the aforementioned fireball model.

Although it is known that GRBs result from the collapse of a black hole or the merging of neutron stars, the emission mechanism is not known. Existing models for the emission mechanism are for the i) synchrotron emission in ordered and random magnetic fields. ii) photospheric jet emission. iii) Compton drag [20]. The models proposed are hard to constrain through the usual observational techniques such as spectral and temporal measurements. Polarimetry could solve some of the ambiguities around the emission mechanism of these bursts [21]. There have been a few earlier missions with the goal to measure polarization of astronomical sources and some will be briefly discussed below.

### 1.4.2 GRB Polarimeter Missions

Even though the discovery of GRBs was made in the 1960s [16] polarization measurements would have to wait until the new century, and they were done by an instrument dedicated to imaging solar flares called RHESSI (Reuven Ramaty High Energy Solar Spectroscopic Imager). RHESSI was a segmented detector and this allowed polarization measurements of the GRB021206, a polarization degree of $(80 \pm 20)\%$ was measured [22]. But, another analysis of the data was made to confirm the result and this yielded a polarization degree of $(41^{+57}_{-44})\%$ [23]. The uncertainties in the measurements and the quality of the data concluded that dedicated GRB polarimeters were needed.

One example of such a polarimeter is the Gamma-Ray Burst Polarimeter (GAP) which was mounted on board IKAROS [24]. GAP is a segmented detector consisting of a large area plastic scintillator surrounded by 12 CsI scintillators, which allows scattering in the plastic and absorption in the CsI. Three GRBs were observed during the years 2010-2012, one significantly brighter than the other two [25]. The polarization fractions of the two less bright GRBs where $\Pi = (70 \pm 22)\%$ and $\Pi = (84^{+16}_{-28})\%$. The brighter GRB named GRB100826A had a polarization fraction of $\Pi = (27 \pm 11)\%$, and even though it differ from the other two, all favor the Synchrotron emission model.

The latest GRB polarimetry mission is POLAR, a segmented detector installed on the Chinese space station Tiangong-2 in 2016 [26]. Its grid of plastic scintillators is designed to study polar-
ization of X-rays emitted from GRBs in the energy range 50-500 keV. The detector consists of 25 modules where each is made of an array of 64 plastic scintillators, the signal from each module is read out from a multi-anode photomultiplier (MAPMT). During the first half year of operation POLAR detected 55 GRBs, 10 of these were bright enough for polarization measurements [27]. In April 2017 POLAR suffered from technical failure, the high voltage power supply died.

The CZTI instrument on board AstroSat is a coded aperture spectrometer, but has been able to measure polarization of GRBs [28]. As it is not a dedicated polarimeter the measurements have large uncertainties. SPHiNX is a proposed GRB polarimeter which will be able to differentiate between the different models proposed for the emission mechanisms.
Chapter 2

SPHiNX

SPHiNX is developed for the Swedish InnoSat small satellite project [29], this puts strict requirements on the mass and geometrical properties of the payload. The InnoSat project was initiated by the Swedish National Space Agency to provide standardized platforms for scientific payloads for Swedish research groups, the platform is developed by OHB Sweden and AAC Microtec, see Figure 2.1. SPHiNX is a Compton polarimeter with two kinds of scintillators in a honeycomb-like structure. A less dense plastic scintillator for scattering and a more dense GAGG scintillator for absorption. This chapter will describe the design of the SPHiNX instrument in more detail.

Figure 2.1: The SPHiNX polarimeter on the InnoSat platform [20]. The platform has dimension $58 \times 53 \times 34$ cm$^3$, the solar panel is 83 cm tall. The payload mass is 25 kg.

2.1 SPHiNX Detection Principle

For Compton polarimetry to work well both Compton scattering and photoabsorption must be recorded. SPHiNX will look for two-hit events, when two of the scintillators have interactions simultaneously. Plastic has a low Z-value and photons will therefore interact via Compton scat-
tering while GAGG has a high Z-value and provides high photoabsorption cross section. If a hit is registered in a GAGG scintillator, one can check to see if any of the plastic scintillators has had a simultaneous trigger. If yes, the hit is recorded and if no, it is discarded. The aim for SPHiNX is to be able to measure polarization for photons in the energy range 50-600 keV. If a 50 keV photon scatters at 90° angle, it deposits around 5 keV, see Equation 1.2. This sets a low-energy detection limit for the plastic scintillators. It plays an important role in choosing a suitable photosensor and readout system. The detection principle is shown in Figure 2.2.

![Detection Principle](image)

**Figure 2.2:** One plastic and four GAGG scintillators are sufficient to show the detection principle of SPHiNX. The black dots represent hits and the red circles the most probable scattering angles. The figure is not to scale.

The incoming photon is most likely to scatter in the plastic scintillator perpendicular to its electric field vector, see Equation 1.6. In the scenario shown in Figure 2.2 a hit would be registered in the GAGG (second to the left) and after checking for coincidence hits, the hit in the plastic would be found.

### 2.2 Payload Design

SPHiNXs detector array is shown in Figure 2.3 and consists of 42 plastic scintillators and 120 GAGG scintillators packed in a honeycomb-like structure.
Each scintillating piece, plastic (blue) and GAGG (yellow), has its own photosensor, so that an incoming photon scattered inside the detector will give a signal in two pieces. The output signal from the different scintillators differ both in the number of scintillation photons as well as the wavelength of these. The GAGG, being an inorganic scintillator has a higher light yield than the organic plastic scintillator. Table 2.1 shows more qualities of the two scintillators. The scintillators are designed to be read out by PMTs, for plastic, and by MPPCs, for GAGG. The functionality of an MPPC and PMT is explained in section 1.2.2 and 1.2.3 respectively. The details of the specific type of PMT and MPPC can be seen in Table 2.2. The signals from the photosensors will be registered using an ASIC (Application Specific Integrated Circuit). An ASIC has inbuilt components providing pre-amplification, shaping and track-and-hold functions. The resulting pulses are digitized using an analog-to-digital converter (ADC). An ASIC is a miniaturized system which operates at low power. Thus, it is suitable for satellite-borne detectors.

In this thesis an ASIC called Citiroc (Cherenkov Imaging Telescope Integrated Read Out Chip) produced by Weeroc has been tested [31]. Citiroc is designed for MPPC readout and has 32 individually controllable channels. Each channel has a low and a high gain amplifier. More about the Citiroc in section 3.1. To handle signals from all photosensors a number of ASICs are required.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Plastic scintillator</th>
<th>GAGG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supplier/type</td>
<td>Eljen Technology EJ-204</td>
<td>C&amp;A</td>
</tr>
<tr>
<td>Light yield ($\gamma$/MeVee)</td>
<td>$1 \times 10^4$</td>
<td>$5.6 \times 10^4$</td>
</tr>
<tr>
<td>Decay-time [ns]</td>
<td>1.8</td>
<td>88</td>
</tr>
<tr>
<td>Density (g/cm$^3$)</td>
<td>1.02</td>
<td>6.63</td>
</tr>
<tr>
<td>Peak wavelength [nm]</td>
<td>408</td>
<td>520</td>
</tr>
<tr>
<td>Refractive index</td>
<td>1.58</td>
<td>1.9</td>
</tr>
</tbody>
</table>

**Table 2.1:** Properties of the scintillators [20].
Table 2.2: Some characteristics of the MPPC and the PMT [8] [32].

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>MPPC S13360-6050CS</th>
<th>PMT R7600U-200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photosensitive area [mm(^2)]</td>
<td>6.0 (\times) 6.0</td>
<td>18 (\times) 18</td>
</tr>
<tr>
<td>Gain</td>
<td>(1.7 \times 10^9)</td>
<td>(2.4 \times 10^9)</td>
</tr>
<tr>
<td>Recommended operating voltage (V_{OP}) [V]</td>
<td>(V_{BR} + 3), where (V_{BR} = 53 \pm 5)</td>
<td>-900</td>
</tr>
<tr>
<td>Collection efficiency</td>
<td>(\approx 50%)</td>
<td>80%</td>
</tr>
<tr>
<td>Peak wavelength [nm]</td>
<td>450</td>
<td>400</td>
</tr>
</tbody>
</table>

Figure 2.4: 6 plastic scintillators forming a hexagon with red lines added to show the edges. The diameter of the hexagon is approximately 15 cm [33].

Figure 2.5: Two 6 \(\times\) 3 cm\(^2\) GAGG scintillators [33].

Figure 2.4 and 2.5 depicts the different scintillators in SPHiNX. One plastic hexagon is cut into six individual pieces in order to increase the spatial resolution. Higher spatial resolution yields higher angular resolution. This results in more number of bins on the x-axis of the modulation curve, making the measurement more accurate. The same is true for the GAGG scintillators, more pieces gives better resolution which is desirable.

The work discussed in this thesis aims at characterization of different components of the SPHiNX detector system. The SPHiNX project is yet to be funded and is therefore not planned for a space mission in the near future. The current detector was designed under strict mass and size requirements due to the satellite platform intended. But with no platform in mind, SPHiNX instrument could also be re-designed and re-sized to obtain better and more reliable polarization measurements.

With this in mind, this thesis will also test to see if plastic can be read out with MPPCs instead of PMTs. The MPPC and the PMT have roughly the same quantum efficiency, but the MPPCs are favorable to PMTs in a few aspects. i) The MPPC is more robust and compact than the PMT. ii) The supply voltage needed is much lower for the MPPC. iii) The MPPC is immune to high magnetic fields [20].
Chapter 3

Citiroc Characterization

This chapter describes the functionality of Citiroc and describes a linearity test performed. It also presents the results from tests performed with an MPPC photosensor read out by Citiroc, both the dark signal from a bare MPPC and an MPPC coupled to a GAGG scintillator described in Chapter 2. The goal of this chapter is to characterize the setup and see if it is suitable for the required energy range (50-600 keV) of SPHiNX.

3.1 Citiroc

The previously considered ASIC for the SPHiNX mission was SIPHRA by IDEAS [34]. SIPHRA has 16 channels for reading out signals and is designed for reading negatively biased signals, suiting both PMTs and MPPCs. However, tests carried out previously showed that the energy range was not sufficient as desired by SPHiNX application. Also, the gain on each channel was not individually programmable [33]. This led us to explore another ASIC, Citiroc.

Citiroc is an ASIC with 32 channels, numbered 0-31, designed for MPPC read out with a positive polarity. Each of the 32 channels have two separate chains for high- and low gain (HG and LG) amplification, and is individually programmable. This leads to an overlap in energy spectra obtained from HG and LG amplifiers which in turn results in a wide energy range in each channel. See Figure 3.1 for the block schematics of the ASIC. All ASICs should implement a trigger of some sort to discard data coming from background sources. The trigger in Citiroc is implemented in a separate chain and does not have a sharp cut. The current setup uses a 12-bit ADC, giving each channel an ADC range from 0-4095. In this thesis an evaluation board built by Weeroc, see Figure B.7, is used containing all electronics needed to connect to a laptop for data acquisition.
3.2 Linearity

One of the objectives of this thesis is assessing capability of detection of lower energies, which is carried out using the HG amplifier of Citiroc. The linearity of the HG amplifier is tested using a pulser, RIGOL DG1062Z, while that of the LG amplifier has not been covered in this thesis. This test is done to calibrate the ASIC and the photosensors. The input from the pulser is sent to channel 0 of Citiroc via a 100 pF capacitor and a 50 Ω resistor. The charge input at channel 0 is calculated with the following equation:

\[ q = C \cdot V_{in} = 100 \, \text{pF} \cdot V_{in} \]  \hspace{1cm} (3.1)

where \( q \) is the charge, \( C \) the capacitance and \( V_{in} \) the input voltage signal from the pulser. To cover the full ADC range of Citiroc, data acquisition is done at different input voltages. Even though the input is a fixed voltage pulse, a spread of approximately 10 channels was observed and therefore each spectrum is fitted with a Gaussian function and the peak ADC channel is noted. The variation of ADC channel with input charge is shown in Figure 3.2, the plot is fitted with a linear equation. The fit shows that channel 0 of Citiroc is linear in most of the ADC range. The interception point between the fit and the y-axis corresponds to the channel number of baseline noise of channel 0, which is at ADC channel 964. The same test can be done for the rest of the 31 channels of Citiroc, this has not been performed in this thesis.
3.3 MPPC

The MPPC model that has been proposed for the SPhiNX project is of type S13360-6050PE but the one available for testing in this thesis is S13360-6050CS, both developed by Hamamatsu. The difference between the two types is the geometrical area and window material. Table 2.2 summarizes some of its characteristics.

![MPPC Types](image)

**Figure 3.3:** Different types of MPPCs [8], type S13360-6050CS used in this thesis is circled.

To characterize the MPPC, it is powered and connected to the ASIC without any scintilla-
tor, i.e. a bare MPPC. The MPPC consists of many pixels, see section 1.2.2, that can trigger simultaneously. If one pixel triggers, one electron-hole pair is produced and amplified over the depletion region. This will correspond to what is called one photoelectron peak (p.e. peak) [6]. If two pixels trigger at the same time a peak corresponding to the 2 p.e. will be shown in the obtained spectrum. This presents an opportunity to characterize the MPPC, using the channel number of a specific p.e. peak to calculate the gain. These p.e. peaks can be both because of photons detected by the MPPC and thermal noise. Once the behavior of the MPPC is known, a scintillator is optically coupled to it. The scintillator is irradiated with radioactive sources in order to estimate the light yield of the scintillator. This is further described in the following sections.

The MPPC has been tested both using the Citiroc board and with a Multichannel Analyzer (MCA) of type Amptek 8000 A. The block scheme for the two different setups is seen in Figure 3.4.

![Block diagram for the two different setups](image)

**Figure 3.4:** Block diagram for the two different setups. The MCA setup follows chain A, and Citiroc setup chain B

### 3.4 Bare MPPC with Citiroc

The bare MPPC is connected to the Citiroc board. For the MPPC to function, an operating voltage, $V_{OP}$, bigger than the break down voltage, $V_{BR}$, must be applied. The spectrum of the bare MPPC is acquired for different $V_{OP}$ and the result is shown in Figure 3.5.
As explained the first p.e. peak correspond to one pixel of the MPPC being triggered. This peak, and the second, third, fourth and so on, will shift with $V_{OP}$. This because the gain of an MPPC increases as the bias over it increases. In Figure 3.5 it is clear which peaks shift, the first p.e. peak is marked in the figure. The pedestal peak, or zeroth p.e., is the peak farthest to the left and does not shift. It corresponds to the baseline noise occurring due to various components of the detection setup. From the p.e. peaks, one can calculate the gain of the MPPC from the following steps:

- The first p.e. peak falls on channel 988
- From the linearity of Citiroc, see Figure 3.2, one gets the ADC channel number as a function of the input charge, $Q$.

$$\text{ADC channel} = 265 \cdot Q + 964 \quad \text{(3.2)}$$

Channel 988 corresponds to a charge of 90.7 fC.

- So 90.7 fC corresponds to the first photoelectron peak, which simply is the triggering of one pixel in the MPPC. Meaning that one electron charge has been multiplied to 90.7 fC. The gain of the MPPC can be calculated accordingly:

$$\varepsilon \cdot \text{Gain}_{\text{MPPC}} = Q \quad \text{(3.3)}$$

This gives the gain for this specific MPPC to be $\text{Gain}_{\text{MPPC}} = 5.7 \cdot 10^5$. The gain stated by Hamamatsu is $1.7 \cdot 10^6$ [8] when the MPPC is operated at a voltage of $V_{OP} = V_{BR} + 3$. The reason for the lower gain achieved could be that the MPPC is not operated at its recommended voltage. To calculate the correct $V_{BR}$ and hence the $V_{OP}$ for each MPPC, I-V and C-V characteristics need to be done.

### 3.5 GAGG Scintillator with Citiroc

The MPPC is now optically coupled to a GAGG scintillator, see Figure 3.6. The scintillator is wrapped with two layers of ESR and one layer of Tedlar, since earlier studies have shown this to
be the most lightproof and reflective wrapping [33]. The scintillator is irradiated by radioactive sources to be able to calculate the energy range and energy resolution of the scintillation detector. The energy resolution is calculated using Equation 1.5 and the energy range is calculated using the following steps:

- Figure 3.2 shows that Citiroc is linear in the ADC channel range of 1000-3700, for given settings. The lower ADC value (1000) is set by the threshold and the higher (3700) is due to saturation. The lower value may however change if a higher trigger is needed for reasons such as higher background noise. By using the linearity of Citiroc, one can calculate the energies at these specific channel numbers to get the range.

- From the linearity the baseline noise is seen at channel number 964. This gives the following linear relationship:

\[ y = kx + 964 \]

where \( y \) is the channel number, \( x \) is the energy and \( k \) is a constant obtained by the fit.

- The photopeak from the decay of \(^{241}\)Am gives a specific energy of 59.5 keV. Using the channel number of this energy one can calculate \( k \) from the equation above.

- Setting \( y_{\text{min}} \) and \( y_{\text{max}} \) gives the energy range \([x_{\text{min}}, x_{\text{max}}]\).

\[ \text{Figure 3.6: The MPPC connected to a piece of GAGG scintillator, the GAGG is wrapped with two layers of ESR and one layer of Tedlar.} \]

The spectrum with GAGG coupled to an MPPC is acquired with both MCA and Citiroc, see Figure 3.4. The MCA has been used primarily for comparison and to understand Citiroc fully. GAGG is irradiated with \(^{241}\)Am and \(^{55}\)Fe simultaneously and the spectra are shown in Figure 3.7 and 3.8. In Figure 3.7, 6 keV photopeak of \(^{55}\)Fe is seen but it is not seen in Citiroc spectrum in Figure 3.8.
Figure 3.7: *Spectrum from the MCA of both $^{241}$Am and $^{55}$Fe, the peak at the far left is the 6 keV of $^{55}$Fe.*

The Citiroc spectrum is expanded and fitted with a Gaussian function, as shown in Figure 3.9. The energy resolution from the fit is 40% at 59.5 keV. Following the steps mentioned above, the energy range is estimated to be 7-110 keV. This also provides the reason for why the $^{55}$Fe peak at 6 keV is not seen in Figure 3.8. If the overall noise of the system is reduced, a lower trigger can be set resulting in detection of lower energies.

Figure 3.8: *Spectrum from the Citiroc of the $^{241}$Am, $^{55}$Fe has not been seen.*

Figure 3.9: *The photopeak of the $^{241}$Am fitted with a Gaussian function.*

To get the energy range and resolution in the LG amplifier, another radioactive source is needed. LG amplifier is used for high energies because it less amplification is needed for their detection. $^{137}$Cs is therefore used to characterize the LG amplifier with its photoabsorption peak at 662 keV. Figures 3.10 and 3.11 show the spectrum using the MCA and the Citiroc.
Figure 3.10: Spectrum from the MCA of $^{137}\text{Cs}$. 

Figure 3.11: Spectrum from the Citiroc of $^{137}\text{Cs}$. 

Assuming that the LG amplifier is linear in the given ADC range, the energy range can be calculated to be 35-702 keV, see Figure 3.11. And at the peak of $^{137}\text{Cs}$ the Citiroc gives an energy resolution of 11%.
Chapter 4

MPPC Measurements with Plastic

Now that the MPPC has been tested with GAGG, it will instead be coupled to a plastic scintillator. As previously mentioned the SPHiNX plastic scintillators are proposed to be read out by PMTs, but from reasons stated in Chapter 2, an MPPC module might be preferable. This chapter consists of two sections, the first being a solely theoretical study performed to compare the behavior of the MPPC and PMT coupled to different plastic scintillators. The second section describes laboratory tests that compare the performance of the plastic scintillator coupled to an MPPC and a PMT.

4.1 Scintillator Study

The plastic scintillators in SPHiNX have been picked and designed to match the area and wavelength range of a PMT. This section will compare the efficiency of the scintillator coupled to a PMT and an MPPC.

The efficiency of a scintillator detector is dependent on how many photons the photosensor absorbs. To maximize this number, the wavelength of the output photons from the scintillating material must match the sensitive wavelength range of the photosensor. The plastic scintillators, EJ-204 from Eljen Technology, proposed for the SPHiNX project [30] has been chosen with respect to a PMT as the read out module. But, if the plastic scintillators were to be read out with an MPPC, the choice of a different plastic might be preferable. This chapter aims to compare different scintillators from Eljen Technology in a purely theoretical study.

Four plastic scintillators were considered keeping their scintillation efficiency and peak emission wavelength in mind. Scintillation efficiency is defined as how large fraction of the incident radiation energy is converted to fluorescent light [4]. It is expressed as the number of optical photons created in the scintillator when an electron with the energy of 1 MeV interacts in the material, see Table 4.1.

Important to note is that this study only takes two factors into account, the emission spectrum of the plastic scintillator and the PDE of the PMT and the MPPC. Other factors, such as geometric area and wrapping material of the scintillators will also be of importance for the efficiency of the detector.

<table>
<thead>
<tr>
<th>Scintillator type</th>
<th>Scintillation efficiency [Photons/1 MeV electron]</th>
<th>Peak wavelength of scintillator [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>EJ-200</td>
<td>10000</td>
<td>425</td>
</tr>
<tr>
<td>EJ-204</td>
<td>10400</td>
<td>408</td>
</tr>
<tr>
<td>EJ-208</td>
<td>9200</td>
<td>435</td>
</tr>
<tr>
<td>EJ-212</td>
<td>10000</td>
<td>423</td>
</tr>
</tbody>
</table>

Table 4.1: Properties of different plastic scintillators [35].
<table>
<thead>
<tr>
<th>Photosensor type</th>
<th>Model name</th>
<th>Peak wavelength [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMT</td>
<td>R7600U-200</td>
<td>400</td>
</tr>
<tr>
<td>MPPC</td>
<td>S13360-6050PE</td>
<td>450</td>
</tr>
</tbody>
</table>

Table 4.2: Properties of different photosensors [32][8].

All scintillators have their own characteristic output, they scintillate in different wavelength ranges and have different intensities for these wavelengths. An example of such a curve is shown in figure 4.1. The photosensors have different PDEs for different wavelengths, and the PDE curves for two different MPPCs can be seen in Figures 4.2. For PMTs one usually talks about quantum efficiency (QE) instead of PDE which differs slightly. The QE of a PMT is the ratio of output electrons to incident photons while the PDE of an MPPC is the statistical probability that an incident photon interacts with a cell of the MPPC to create an avalanche. A few QE curves are seen in Figure 4.3. The following steps were made in order to obtain the number of absorbed photons for the different combinations scintillator and photosensor.

- The discrete values in emission spectra for the plastic scintillators and the PDE/QE curves for the photosensors were obtained using a plot digitizer.

- The emission spectra were re-scaled using the scintillation efficiency using the following equation:

  \[
  \text{Scintillator Efficiency} = \text{Area under the curve} \cdot \text{Normalization constant} \quad (4.1)
  \]

- Multiplying the PDE/QE distributions and the emission distribution, one can obtain the absorption spectrum for the different combinations of plastic scintillator and photosensor as a function of wavelength.

- The area under these curves will be the number of absorbed photons, the results are shown in Table 4.3.

- Figures for these steps can be seen in Appendix B.

![EJ-204 Emission Spectrum](image)

Figure 4.1: Emission spectrum from EJ-204 [35].
Figure 4.2: PDE curve for two types of MPPCs, the black line correspond to the type proposed for SPHiNX [8].

Figure 4.3: The QE curve for several PMTs, the red line is for the type proposed for SPHiNX [32].

<table>
<thead>
<tr>
<th>Scintillator</th>
<th>With PMT</th>
<th>With MPPC</th>
<th>Normalized value, PMT</th>
<th>Normalized value, MPPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>EJ-200</td>
<td>3528</td>
<td><strong>3887</strong></td>
<td>0.877</td>
<td>1</td>
</tr>
<tr>
<td>EJ-204</td>
<td><strong>4023</strong></td>
<td>3861</td>
<td>1</td>
<td>0.933</td>
</tr>
<tr>
<td>EJ-208</td>
<td>3087</td>
<td>3585</td>
<td>0.767</td>
<td>0.922</td>
</tr>
<tr>
<td>EJ-212</td>
<td>3471</td>
<td>3877</td>
<td>0.863</td>
<td>0.997</td>
</tr>
</tbody>
</table>

Table 4.3: The number of absorbed photons for the different combinations of plastic and photosensor.

The conclusion drawn by this study is that the different plastic scintillators will not affect the light yield of the detector significantly. If the other factors such as area, wrapping and optical coupling between sensor and scintillator are comparable for the two different sensors, an MPPC would function almost as well as the PMT. This study gave the confidence to test a plastic scintillator with an MPPC.

4.2 Single MPPC with Plastic

This section will test a single MPPC module with a SPHiNX plastic scintillator. The plastic scintillator is designed for PMT readout, and is therefore a bad match for an MPPC when it comes to area. The area of the plastic surface is $30 \times 30 \text{ mm}^2$ and the area of the light sensitive surface of the MPPC is $6 \times 6 \text{ mm}^2$, this means that many of the scintillation photons will miss the sensor. Figures 4.4 and 4.5 show the spectrum of $^{241}\text{Am}$ on a plastic scintillator using a PMT and an MPPC respectively.
Both spectra from Figure 4.4 and 4.5 have been obtained using the MCA setup. Both the PMT and the MPPC are operated at their recommended voltages, PMT at -900V and MPPC at 53.5V, the signal then passes through an amplifier with a gain of 50. As can be seen from the figures, there is a large channel difference between the spectrum obtained from PMT and that from MPPC. The reasons for the lower light yield are:

- Mismatch in area between MPPC and plastic scintillator, as seen in Figure 4.6. Photons produced by an X-ray will not get collected efficiently since many will miss the MPPC. This will give a lower ADC channel for the photopeak. The PMT matches the scintillator and more scintillation photons get collected, yielding a higher ADC channel number for the photopeak.

- The gain of the PMT is said to be $2.4 \cdot 10^6$ [32] and the gain of the MPPC $1.7 \cdot 10^6$ [8]. However, as previously mentioned the MPPC used in the lab has provided a gain of $5.7 \cdot 10^5$. The lower gain of the MPPC makes the photopeak fall on a lower ADC channel.

Figure 4.4: SPHiNX plastic read out by PMT.

Figure 4.5: SPHiNX plastic read out by MPPC.

Figure 4.6: Area of the MPPC compared to SPHiNX plastic scintillator.
In Figure 4.7, the scintillator has been irradiated with an $^{241}$Am source with higher activity than the source used in Figure 4.5. The spectrum clearly shows a number of p.e. peaks as well as the 59.5 keV peak of americium. The estimated energy range is 15-230 keV.

Table 4.4 shows the estimated energy ranges for the different scintillators when coupled to a single MPPC module. From this it is understood that, as proposed, the GAGG works well with the MPPC. But for the plastic scintillator, the lowest detectable energy is 15 keV. Considering 15 keV to be the deposited energy via Compton scattering at a 90° angle, the energy of the incident photon becomes $\sim$ 95 keV. This does not meet the SPHiNX requirements.

Table 4.4: Energy ranges for the GAGG and Plastic scintillator with a single MPPC photosensor.
Chapter 5

MPPC Array Measurements

The SPHiNX proposal states that the plastic scintillators will be read out using PMTs. However, as earlier discussed, it could be beneficial with an instrument only using MPPC devices as read out modules. As concluded in the previous chapter, a single MPPC module could lead to lower light yield of the SPHiNX plastic scintillator. Another idea is to replace the PMT with an MPPC array, the motivation being a larger area. In this chapter, the MPPC array is discussed and explained. Tests done together with the Citiroc ASIC are presented, for a bare MPPC array and also when it is coupled to scintillators.

5.1 MPPC Array

The MPPC array tested in this thesis consists of 16 cells, each functioning as a single MPPC. Figure 5.1 shows the physical array and Figure 5.2 shows the schematics of it. The main reason why the array was considered is the better area match with the plastic scintillator. This section describes the functionality of the array.

![Figure 5.1: MPPC array on the adapter board.](image-url)
Some characteristics about the array are listed in Table 5.1. All cells of the array have different $V_{OP}$, these can be fine tuned using specific setting in the Citiroc that powers the array.

![Figure 5.2: Sketch of the array [36]. On the citiroc board cell A-1 is read out by channel 0, A-2 by channel 1 and so on.](image)

**Table 5.1:** *Some characteristics of the MPPC Array [36].*

<table>
<thead>
<tr>
<th>MPPC array</th>
<th>S13360-6050AE-04</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photosensitive area of each cell [mm]</td>
<td>6.0 × 6.0</td>
</tr>
<tr>
<td>Number of cells</td>
<td>16</td>
</tr>
<tr>
<td>Gain</td>
<td>1.7 x 10^6</td>
</tr>
<tr>
<td>Breakdown voltage $V_{BR}$ [V]</td>
<td>53 ± 5</td>
</tr>
<tr>
<td>Recommended operating voltage $V_{OP}$ [V]</td>
<td>$V_{BR} + 3$</td>
</tr>
</tbody>
</table>

The tests performed with the MPPC array follow the schematics of Figure 5.3. The array gives 16 signals simultaneously, one for each channel. It therefore uses 16 channels of the Citiroc. It is placed so that cell A-1 is read by channel 0. Because of this the MCA setup can not be used for comparison, and this section will only include spectra taken by Citiroc.
5.2 Bare MPPC Array with Citiroc

The array is connected to the Citiroc board and a spectrum is acquired without a scintillator or a radioactive source. One spectrum for each cell of the array will be obtained, Figure 5.4 shows the spectrum for cell A-1. All 16 spectra show p.e. peaks like the single MPPC unit.

![Figure 5.3: Block diagram of the MPPC array test setup.](image)

Figure 5.3: Block diagram of the MPPC array test setup.

In Figure 5.4 a formation below the baseline can be seen, circled in red in the figure. These are not registered as hits by Citiroc, but data is still collected. This could be because of reflection in cables, or features in the data acquisition software and is still to be worked upon. It is not affecting the measurements done with the MPPC array.

As for the single MPPC, the gain can be calculated by fitting a Gaussian to see which channel number the first p.e. falls on. For cell A-1, read out by channel 0, the gain is calculated to be approximately $6 \cdot 10^5$ using the same steps as in Section 3.4. This is, as for the single MPPC, about one third of the gain mentioned in the data-sheet [36]. This can be done for all 16 cells of the array, but for this linearity tests for 16 channels of the Citiroc must be acquired.

![Figure 5.4: Bare array spectrum for cell A-1, read out with channel 0 on the Citiroc.](image)

Figure 5.4: Bare array spectrum for cell A-1, read out with channel 0 on the Citiroc.
5.3 MPPC Array with GAGG

To get a better understanding of how the array functions when coupled to a scintillator, tests are primarily done with the GAGG scintillator. The goal is for the array to be used with the plastic scintillators, but since GAGG has a higher light yield, it is tested before the plastic scintillator.

5.3.1 Source Position Test

When the first tests were performed the placement of the radioactive source was noticed to affect the acquired spectra. Therefore three tests were done with the source placed in three different positions, see Figure 5.5.

**Figure 5.5:** The GAGG scintillator optically coupled to all cells of the array. The numbering corresponds to which channel it will be read by the Citiroc. The source in its casing is placed on three different positions labeled A, B and C.

**Figure 5.6:** $^{241}\text{Am}$ channel 0.

**Figure 5.7:** $^{241}\text{Am}$ channel 10.
When the source was placed in position A the center channels, 5-6 and 9-10, showed a spectrum as in Figure 5.7 and the other as in Figure 5.6. This behavior was not seen when the source was moved and is therefore understood to be an interaction between the emitted photons from $^{241}$Am and the array itself. To further test this the array was irradiated without any scintillator and it showed similar behavior in the center channels that were irradiated more, see Figure 5.8. The figures above show different noise in the beginning of the ADC range. This is because the different cells of the MPPC array, and the different channels of Citiroc introduce different amounts of disturbances.

![Figure 5.8](image)

**Figure 5.8:** The following spectrum was obtained in the four center channels of the array when an $^{241}$Am source was placed directly on top of it without any scintillator.

Position B and C show similar spectra for all cells of the array, but the cells closest to the source show the peak at a slightly higher ADC channel number due to more scintillation light being detected in these. See Figure 5.9 and 5.10. The peak in Figure 5.9 does not show a full Gaussian because it is cut by the trigger of Citiroc, this makes it appear narrower than the peak in Figure 5.10.

![Figure 5.9](image)

**Figure 5.9:** $^{241}$Am channel 0.

![Figure 5.10](image)

**Figure 5.10:** $^{241}$Am channel 15.

This study with the radioactive source at different position guided us to avoid irradiating the MPPC array directly. Hence for studies done in following section a suitable source position is chosen.

### 5.3.2 Division of Scintillation Light

The usage of an MPPC array differs in one major aspect compared to using a single MPPC or a PMT. When using the MPPC or PMT, all the scintillation photons will be detected by the same
device. However, the array can be seen as 16 individual MPPCs closely packed, and therefore the scintillation photons will be distributed quite randomly among these. Summing the signal from each cell can be done either in software, after acquisition, or in hardware, before acquisition. To understand the division of signal among different cells of the array, tests were carried out with optical coupling to one, two, three and four cells for comparison. Figure 5.11 shows four different ways in which different cells are coupled to the GAGG scintillator. The numbering corresponds to the reading out channel of Citiroc. Note that the GAGG is now standing on top of the array with its smallest side coupled and the source is not irradiating the array directly.

![Diagram](image)

(a) The GAGG scintillator optically coupled to one cell of the array.  
(b) The GAGG scintillator optically coupled to two cells of the array.  
(c) The GAGG scintillator optically coupled to three cells of the array.  
(d) The GAGG scintillator optically coupled to four cells of the array.

**Figure 5.11:** Each cell of the array will be read by one channel between 0 and 15 by Citiroc.

Figure 5.12 - 5.15 show the spectra for the 16 cells of the array when irradiated by $^{137}$Cs, for the positions in Figure 5.11. Red represents the LG amplifier and blue the HG amplifier of Citiroc. The optical grease used for coupling could have spilled to nearby cells causing light leakage. This is seen as a few counts in nearby channels. The scintillation photons captured by each cell reduce when more cells are added. This is clearly depicted in Figure 5.16.
Figure 5.12: Spectra from all 16 channels, GAGG scintillator coupled to cell 15.

Figure 5.13: Spectra from all 16 channels, GAGG scintillator coupled to cell 15 and 14.
Figure 5.14: Spectra from all 16 channels, GAGG scintillator coupled to cell 15, 14 and 13.

Figure 5.15: Spectra from all 16 channels, GAGG scintillator coupled to cell 15, 14, 13 and 12.
The behavior shown in Figure 5.16 is expected and can be explained in the following way. When one cell of the MPPC array is coupled, all scintillations will be detected by this. When two cells are coupled to the GAGG, the scintillations can go into any of these cells, it should be quite equally distributed between the two. So compared to the first case, less light is measured by the individual cells in this case. When more cells are added, the scintillations get more and more divided. This gives smaller signal on individual cells. Figure 5.17 shows the channel number as a function of number of cells coupled.

![Figure 5.16: $^{137}$Cs spectra from channel 15 for the different steps in Figure 5.11.](image)

In Figure 5.17 it can be seen that the points tend to flatten as more number of cells are used. This made us test the MPPC array coupled to the SPHiNX plastic scintillator. However, the photopeak of $^{241}$Am at 60 keV was not observed. This could be because the plastic scintillator has a low light yield and the scintillations produced got distributed among the 16 cells of the MPPC array making the signal too low to be detected. The MPPC array can therefore not be used with the plastic scintillator in the current setup.

![Figure 5.17: The channel number of the photopeak for channel 15 as a function of the number of cells optically coupled to the GAGG scintillator.](image)
It is possible to sum the signal from the different channels in software but that also sums the noise from each channel reducing the signal to noise ratio by at least 4 times ($\sqrt{16}$). Some attempts at software summing has been done, but no results are reported in this thesis. Another possible way is to sum the signals electronically, this has not been tested yet.

5.4 Modified Plastic Scintillator

A possible way to go forward is to use a single MPPC with a change in design of the plastic scintillator, i.e. use a plastic scintillator with a cross section area matching that of the sensitive area of the MPPC. Such a plastic scintillator was cut in the workshop at KTH, see Figure 5.18. Figure 5.19 shows an $^{241}$Am spectrum using this setup to be able to compare to the results from the SPHiNX plastic scintillator.

![The plastic scintillator cut by the workshop at KTH.](image)

**Figure 5.18:** The plastic scintillator cut by the workshop at KTH.
Figure 5.19: $^{241}$Am spectrum obtained using the workshop plastic scintillator.

The energy range of this plastic scintillator is 10-130 keV in the HG amplifier. This is a better performance compared to that of the SPHiNX plastic scintillator, but the lower limit is still too high. If a design using only MPPC modules is wanted, the best way would be to alter the size of the scintillators in order to obtain the wanted range. Other factors that can improve the energy range are i) better surface treatment of the plastic scintillator, ii) a slight increase in the MPPC voltage, iii) performing tests in lower temperature.
Chapter 6

Conclusion and Outlook

In Chapter 3 the ASIC Citiroc was tested and found to be linear in the ADC range of 1000-3700 for the current set of measurements. In this chapter the MPPC module was tested with the Citiroc board, both bare and together with a GAGG scintillator. From altering the supply voltage one could see the photo electron (p.e.) peaks of the photosensor shifting. From the ADC channel number of the first p.e. peak the gain of the MPPC module tested was calculated to be $5.7 \cdot 10^5$, less than a third of the gain suggested by the manufacturer.

When the MPPC was optically coupled to the GAGG scintillator test were done to calculate the energy range and resolution of the detector. The energy ranges for the high and low gain amplifier of the Citiroc were calculated to be 7-110 keV and 35-700 keV respectively. The energy resolution was 40% at 59.5 keV.

In Chapter 4 the MPPC is compared to PMT in a theoretical study. This study shows that if area and other factors were similar between the two, the number of photons detected after interaction of one MeV electron in the plastic scintillator would be 4023 for the PMT and 3887 for the MPPC. This study also shows that if MPPCs were to be used instead, a different plastic scintillator called EJ-200 would be preferable to the one used now, EJ-204. Furthermore, lab tests were done when the single MPPC was coupled to a plastic scintillator to compare it to a PMT. The plastic scintillators are planned to be used with PMTs and it is seen that the results of the PMT exceeds the MPPC. The energy range of the MPPC and plastic scintillator detector is 15-230 keV. This does not meet the requirements for SPHiNX.

Since the single MPPC did not give the expected results with the SPHiNX plastic scintillator, an MPPC array is tested in Chapter 5. The idea originated from the bigger photosensitive area of the MPPC array which matches the plastic scintillator. However, tests were initially performed with the GAGG scintillator due to its higher light yield.

The array was tested in similar way to the single MPPC. The gain of one of the 16 cells was calculated to be $6 \cdot 10^5$, also around a third of the gain expected. After seeing that different cells gave different spectra when a radioactive source was used, it was understood that the source photons interacted with the array itself in some way. Tests were also done to see how the light was divided among the cells when the same scintillator was optically coupled to the MPPC array. This was done by letting the scintillator connected to 1, 2, 3 or 4 cells of the MPPC array and observing the photopeak of $^{137}$Cs. The photopeak channel of $^{137}$Cs fell on a lower channel number for each cell added.

When MPPC array was coupled to the SPHiNX plastic scintillator, the 60 keV photopeak of $^{241}$Am was not seen.

Lastly, a plastic scintillator with smaller area cut by the workshop was examined coupled to an MPPC. The energy range obtained was 10-130 keV. This is a better result than for the SPHiNX plastic, but the lower limit is still too high and does not meet the requirements for SPHiNX.

To conclude, the ASIC Citiroc works well in a majority of its ADC range and can therefore be used in the SPHiNX project. The GAGG scintillator coupled with an MPPC module of type S13306-6050CS fulfills the requirements for SPHiNX. However, neither the single MPPC or
the MPPC array coupled to the current design of the SPHiNX plastic scintillator, of type EJ-204, fulfills the requirements of SPHiNX. When the plastic scintillator was coupled to the PMT, measurements were done with the MCA setup, no measurement with Citiroc has been done. This is due to the polarity of PMT. Previously measurements have been performed with SiPHRA and an energy range of 10-500 keV has been achieved. From measurements of the workshop plastic scintillator it is seen that the response of the plastic scintillator detectors can be improved. The tests done in this thesis were a first step towards a polarimeter in the energy range 50-600 keV only using MPPCs. It is concluded that the MPPC can read out the plastic scintillators, if the design is altered.

### Proof-of-Principle Polarimeter

The studies done in this thesis pave the way towards a proof-of-principle polarimeter. The best way to build a proof of principle polarimeter would be to put together one full cell of the instrument, i.e. 6 plastic scintillators surrounded by 24 pieces of GAGG. But with the scintillator pieces available this would not be doable. With the material available in the lab, two different design are possible, one using both a PMT and three MPPCs and one only using MPPCs.

The design for the first proof-of-principle polarimeter is one piece of plastic surrounded by three pieces of GAGG, see figure 6.1. The plastic scintillator is read out by a PMT while the GAGGs are coupled to MPPCs. The polarimeter will be placed under a source that will be, unpolarized and then also polarized. It will be rotated with small steps a full 360 degrees and after that the modulation curve can be plotted.

![Proof-of-principle polarimeter using the SPHiNX plastic and three GAGG scintillators.](image)

Figure 6.1: Proof-of-principle polarimeter using the SPHiNX plastic and three GAGG scintillators.

The second proof-of-principle polarimeter could be done using the plastic scintillator cut by the workshop. This would use only MPPCs and could look like in Figure 6.2.
Figure 6.2: Proof-of-principle polarimeter using only MPPCs as readout modules.

If one wants to design SPHiNX completely with MPPCs the best solution is to re-size the plastic scintillators so that the area matches the photosensitive area of the MPPC better. If this is to be done, one might also consider to get an MPPC that detects more photons since the efficiency was shown to be less than that of a PMT. A theoretical comparison between two MPPC types has been done and can be found in Appendix A.
Chapter 7

Acknowledgements

I would like to thank my supervisors Prof. Mark Pearce and Dr. Rakhee Kushwah for giving me the opportunity to work with the SPHiNX project and broaden my view of how to do science. Rakhee, you will find a short text below.

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Appendix A

This part is comparing two different MPPC types for GAGG readout after contact with the developer, Hamamatsu, about the project specifics.

MPPC Models

The GAGG scintillators in SPHiNX will be read out by MPPCs. The proposed model is S13360-6050PE, and the newer competitor is S14160-6050HS. Following the same steps as in section 4.1 one can obtain the number of detected photons by the two MPPC types when optically coupled to a GAGG scintillator. However, this only takes the emissions spectrum from GAGG and the PDE curves of the MPPCs into consideration. To better understand which MPPC type that would be preferable laboratory tests should be done.

The GAGG scintillator creates around 56000 photons when one 1 MeV electron interaction in the material [37], the emission spectrum can be seen in Figure A.1. The PDE curves of the two different MPPC types are shown in Figures 4.2 and A.3.

![Emission spectra for the GAGG scintillator](image)

Figure A.1: Emission spectra for the GAGG scintillator [37].
Figure A.2: Emission spectra for the GAGG scintillator obtained using a plot digitizer.

Figure A.3: Photon detection efficiency of the MPPC type S14160-6050HS [38].

From Figure A.2 and A.3 one gets the number of absorbed photons as a function of wavelength for the GAGG scintillator.
Figure A.4: The number of absorbed photons as a function of wavelength for the GAGG scintillator with the two different MPPC models.

<table>
<thead>
<tr>
<th>Scintillator</th>
<th>S14160-6050HS</th>
<th>S13360-6050PE</th>
</tr>
</thead>
<tbody>
<tr>
<td>GAGG</td>
<td>19922</td>
<td>17349</td>
</tr>
</tbody>
</table>

Table 7.1: The number of absorbed photons for the different scintillators.

From Table 7.1 it is clear that the S14160-6050HS gives a higher number of absorbed photons when coupled to the GAGG scintillator. Therefore it might be worth testing this in the lab before building the complete instrument.
Appendix B

Scintillator study

Step by step figures from the study done in Section 4.1

Figure B.1: The emission spectrum for all four scintillators[35]. The spectra have been obtained using a "plot digitizer" and are therefore a bit rough.

Figure B.2: Number of emitted photons as a function of wavelength for the four different plastic scintillators.

Figure B.3: The PDE of the MPPC and PMT as a function of wavelength.

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**Figure B.9:** The light proof box (Mörkburk in Swedish) the laboratory tests were done in.
Bibliography


[38] Internal Communication with Hamamatsu 2018.