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Development and Evaluation of a backend Trigger-Algorithm for POLAR-2

Evaluation of existing Concepts for FPGA feasibility using
simulations and ESRF-Data

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This work is dedicated to all the people who supported me on my journey to write this thesis. In particular, my mom, my high school physics teachers, and all the professors who did their best to introduce me to physics. Special thanks go to Professor Santangelo, and Jörg Bayer as well as the complete POLAR-2 collaboration who supported me with much effort and made this thesis possible.

Eigenständigkeitserklärung

Hiermit erkläre ich, Aaron Feder, dass ich die vorliegende Arbeit mit dem Titel „Development and Evaluation of a Backend Trigger Algorithm for POLAR-2“ selbstständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe. Alle sinngemäß oder wörtlich aus fremden Quellen übernommenen Textstellen wurden als solche kenntlich gemacht.

Im Rahmen der Erstellung dieser Arbeit wurden KI-basierte Werkzeuge zur Unterstützung bei der Fehlersuche und beim Debugging von Programmen sowie zum sprachlichen Korrekturlesen der Arbeit eingesetzt. Sämtliche dabei erzeugten Vorschläge und Korrekturen wurden eigenständig geprüft und gegebenenfalls überarbeitet. Die Verantwortung für die wissenschaftlichen Inhalte, die verwendeten Methoden, die Auswertung der Ergebnisse und die endgültigen Formulierungen liegt vollständig bei mir.

Ich versichere, dass die Arbeit weder vollständig noch in wesentlichen Teilen bereits veröffentlicht wurde.

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Abstract

POLAR-2 is a next generation Compton polarimeter, designed to measure the polarization of gamma-ray bursts. In this work a global back-end trigger is investigated, which complements the local trigger decisions of the detector modules. Different trigger concepts were evaluated and a neighborhood-based coincidence trigger was selected. Simulations showed, that this trigger is involved in approximately 15% of the accepted events. Measurements performed at the European Synchrotron Radiation Facility were used to study the spatial distribution of coincident hits. The measured distance spectrum peaks at 75 mm. The results demonstrate the feasibility of the proposed trigger concept and provide constraints for its further optimization and implementation in POLAR-2.

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Chapter 1

Theoretical Background

It is essential for understanding the trigger mechanisms, detector response, and experimental data analysis discussed in the subsequent chapters, that a solid theoretical foundation is built. This chapter establishes this foundation by introducing gamma-ray bursts (GRBs) and the concepts relevant to the detection and polarization measurement of their prompt emission.

1.1 Scientific motivation

1.1.1 The importance of GRBs in modern astrophysics

Gamma-ray bursts (GRBs) are among the most luminous transient events observed in the Universe. They release a large amount of energy on timescales ranging from fractions of a second to several minutes and can be detected over cosmological distances [80, 20]. This makes them valuable objects in modern astrophysics. They can be used to study very energetic explosions, relativistic outflows, compact central engines, and the evolution of massive stars.

Because GRBs can be observed at high redshift, they can also provide information about the distant and therefore early Universe. In this sense they can act as very bright probes of star formation and galaxy evolution. GRBs are not standard candles in the same simple way as Type Ia supernovae, because their intrinsic luminosities span a broad range and depend on jet geometry, viewing angle, radiation physics, and the surrounding medium. Nevertheless, with afterglow observations and host-galaxy redshifts they are still valuable tools for studying the high-redshift Universe [80].

A further field in which GRBs are important is relativistic astrophysics. Their emission is connected to ultra-relativistic jets, compact central engines, strong gravity, high magnetic fields, and non-thermal radiation. Therefore, GRBs are useful probes for physical conditions which cannot be reproduced in terrestrial experiments.

1.1.2 The importance of polarization measurements in GRB astrophysics

Most of the classical information about GRBs comes from light curves, spectra, localization, and afterglow observations. These observables tell us much about the temporal and energetic structure of a burst, but they do not uniquely determine the geometry and magnetic-field structure of the emitting region. For this reason, polarization became an important additional observable in GRB astrophysics.

Knowing the polarization of the incoming photons allows conclusions to be drawn about the magnetic-field structure, the radiation mechanism, and the jet geometry. Linear polarization is sensitive to the ordering of magnetic fields, the anisotropy of the radiation field, and the viewing geometry of the observer [9, 44]. Therefore, the polarization degree Π and the polarization angle ψ provide information which cannot be obtained from the light curve or spectrum alone.

For prompt GRB emission, different physical models can lead to different polarization signatures. Synchrotron emission in an ordered magnetic field, synchrotron emission in a turbulent field, photospheric emission, and Compton-drag scenarios can all produce different polarization degrees and different time evolution of the polarization angle [32, 28, 9]. At the same time, one must be careful not to over-interpret a single polarization value. Limited photon statistics, detector systematics, and a changing polarization angle during the burst can smear out the measured signal [82, 45]. Thus, polarization measurements are powerful, but they need careful analysis.

1.1.3 Relevance to POLAR-2

At this point it is useful to introduce POLAR-2. POLAR-2 is the successor mission of POLAR and is dedicated to the study of GRB polarization in the prompt-emission phase. The instrument will be described in detail in chapter 2. POLAR was a Compton polarimeter on board the Chinese Tiangong-2 space laboratory. During its science operation it observed GRBs and demonstrated both the potential and the difficulty of prompt-emission polarization measurements [44, 82, 45].

The motivation for POLAR-2 follows directly from the limitations of previous measurements. A good GRB polarization measurement requires many detected photons, a large effective area, careful calibration, and a good understanding of the detector response. POLAR-2 aims to improve on POLAR by increasing the effective area and by using plastic scintillators coupled to silicon photomultipliers for Compton polarimetry [35, 61]. In the context of this thesis, POLAR-2 is especially relevant because the trigger mechanism and detector response determine which bursts can be detected, localized, and later used for polarization analysis.

1.2 Description of GRBs

Having established the scientific motivation, this section introduces the discovery, observational properties, and classification of GRBs. GRBs are transient phenomena observed primarily at hard X-ray and gamma-ray energies. They are characterized

by an intense prompt-emission phase of relatively short duration, followed in many cases by a longer-lasting afterglow at lower photon energies. [80].

1.2.1 Discovery of GRBs

GRBs were first discovered with the Vela satellites. These satellites were launched by the United States to monitor compliance with the nuclear test ban treaty. The first events were detected in 1967, but the discovery was published later by Klebesadel et al. [40]. In this publication, short bursts of gamma-ray photons were reported which could not be explained by terrestrial sources.

The Vela satellites consisted of several spacecraft. This made it possible to constrain the direction of the bursts by comparing the arrival times at different satellites. These observations showed that the bursts were not obviously coming from Earth or from the plane of the Solar System. At this point it was still not clear whether GRBs were Galactic or extragalactic.

A major step forward was provided by the Burst and Transient Source Experiment (BATSE) on board the Compton Gamma Ray Observatory. BATSE detected a large number of GRBs and showed that their distribution in the sky is approximately isotropic [20, 58]. This isotropy, together with the observed number–flux distribution, strongly supported a cosmological origin instead of a population concentrated in the Galactic disk.

In Figure 1.1 this distribution is shown using data from the BATSE catalogue. As can be seen, there is no strong clustering toward the Galactic plane. This all-sky distribution is one of the classical observational arguments for the extragalactic nature of most GRBs.

1.2.2 Basic observables

Following the discussion of the nature and discovery of GRBs, this section introduces their principal observational properties. One of the most fundamental is the burst’s position on the sky. Determining this position is challenging at high photon energies because gamma rays cannot generally be focused using conventional optical techniques. Consequently, several alternative methods have been developed to localize GRBs. These include coded masks, triangulation between different spacecraft, Compton-event reconstruction, and localization from the count-rate pattern in different detector modules. For instruments such as POLAR and POLAR-2, simulations of the detector response are needed in order to relate the measured count distribution to the incoming burst direction [44, 61].

It has been shown, that the GRBs are distributed uniformly across the sky. This is shown in figure 1.1. From this observation a cosmic origin was established due to the lack of a concentration in the galactic plane.

The next observable is the duration of the burst. This quantity is later used to distinguish between different GRB classes and is therefore important for the following subsection. The duration is commonly described by T_{90} . This is the time interval in which the cumulative detected counts increase from 5% to 95% of the total burst counts. Therefore, the first and last 5% of the counts are not included.

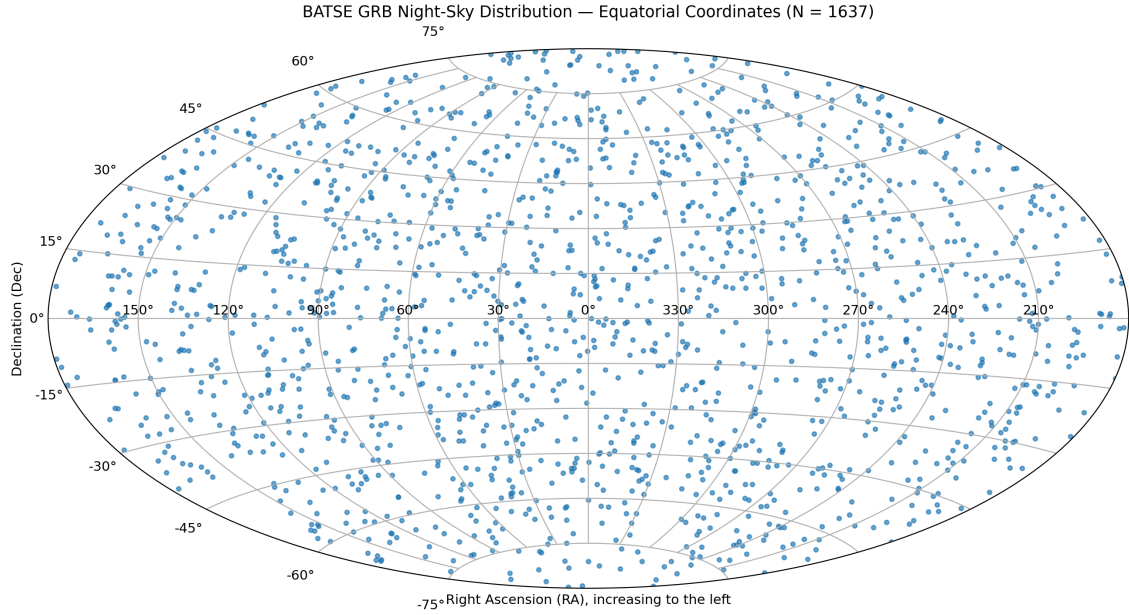


Figure 1.1: All-sky distribution of GRBs from the BATSE 4B catalogue excerpt in equatorial coordinates. Each point marks the reconstructed sky position of one detected burst, shown by right ascension and declination. The map uses an Aitoff projection and illustrates the approximately isotropic sky distribution of the BATSE GRB sample. Data taken from [55].

It should be noted that T_{90} is an observed quantity and depends on the detector, the energy range, and the background treatment [49, 58].

Furthermore, the energy spectrum can be derived. GRB prompt spectra are non-thermal and are often described by empirical functions. One commonly used model is the cutoff power law [33, 11],

$$N(E) = A \left(\frac{E}{100 \text{ keV}} \right)^\alpha \exp \left(-\frac{E}{E_c} \right),$$

where $N(E)$ is the photon spectrum, A is a normalization factor, α is the photon index, and E_c is the cutoff energy. In the $E^2 N(E)$ representation the peak energy is then given by

$$E_{\text{peak}} = (2 + \alpha)E_c,$$

provided that $\alpha > -2$.

To describe a wider energy range, the spectrum is often modeled with the Band function [7],

$$N(E) = \begin{cases} A \left(\frac{E}{100 \text{ keV}} \right)^\alpha \exp \left(-\frac{E}{E_0} \right), & E \leq (\alpha - \beta)E_0, \\ A \left(\frac{(\alpha - \beta)E_0}{100 \text{ keV}} \right)^{\alpha - \beta} \exp(\beta - \alpha) \left(\frac{E}{100 \text{ keV}} \right)^\beta, & E > (\alpha - \beta)E_0. \end{cases}$$

Here again A is the normalization, α and β are the low- and high-energy photon indices, and E_0 is the characteristic break energy. The peak of the $E^2 N(E)$ spectrum

is then given by

$$E_{\text{peak}} = (2 + \alpha)E_0.$$

The Band function is not a physical radiation model by itself, but it is a useful empirical description of many observed GRB prompt spectra [7, 2].

In Figure 1.2 such a spectrum is shown for GRB 080916C.

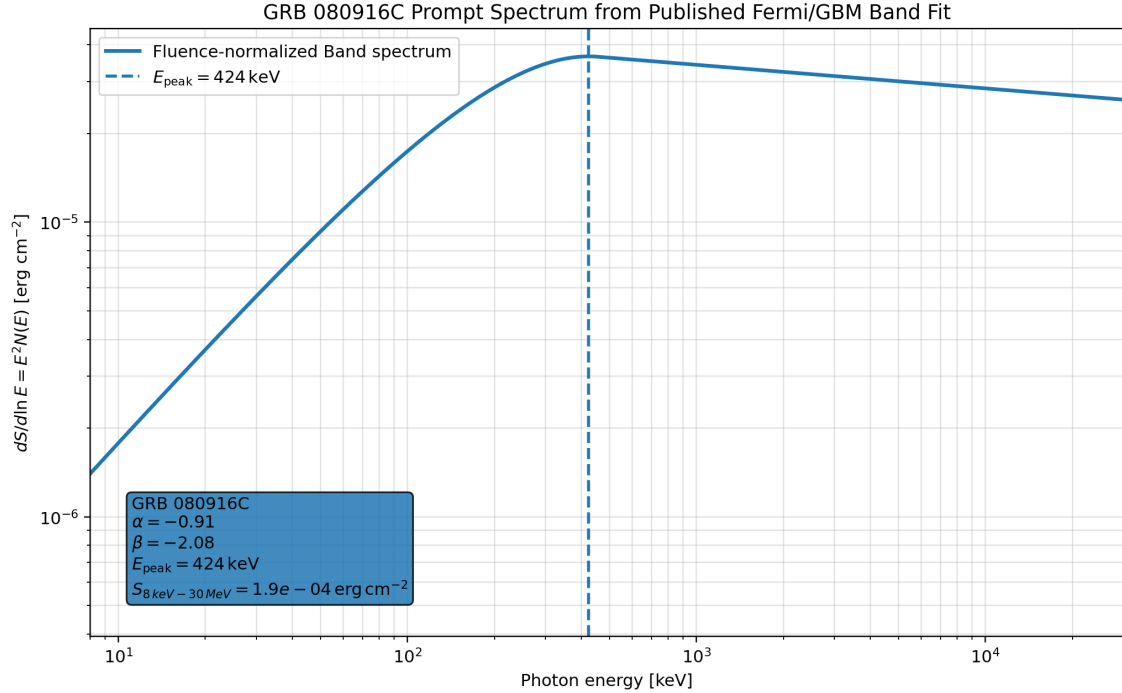


Figure 1.2: Time-integrated prompt-emission spectrum of GRB 080916C based on a Band-function fit. The plotted quantity is the energy fluence spectrum per logarithmic energy interval, $dS/d\ln E = E^2 N(E)$, where $N(E)$ is the photon spectrum. The Band-function parameters used for the calculation are $\alpha = -0.91$, $\beta = -2.08$, and $E_{\text{peak}} = 424 \text{ keV}$. The spectrum was normalized to a fluence of $S_{8 \text{ keV} - 30 \text{ MeV}} = 1.9 \times 10^{-4} \text{ erg cm}^{-2}$. The dashed vertical line marks E_{peak} , the maximum of the $E^2 N(E)$ representation.

The last observable discussed here is the afterglow. In contrast to the previous quantities, the afterglow is not one single number, but a longer-lasting emission component after the prompt emission. It can be observed from X-rays through optical and infrared wavelengths down to radio frequencies. The afterglow is generally interpreted as synchrotron emission produced when the relativistic ejecta interact with the surrounding medium [15, 83, 80]. Afterglow observations are very important because they allow a much more accurate localization of the burst. They also make it possible to identify the host galaxy and to measure the redshift. With this information, the distance and the energetics of the GRB can be constrained.

1.2.3 Classification of GRBs

Now these observables can be used to classify GRBs. The most classical classification is based on the duration. With the statistical sample provided by BATSE,

Kouveliotou et al. [49] showed that the duration distribution is bimodal. This led to the empirical distinction between short and long GRBs.

Figure 1.3 shows the distribution of GRB durations using the parameter T_{90} . The commonly used boundary between the two classes is

$$T_{90} \simeq 2 \text{ s}.$$

Bursts with $T_{90} < 2 \text{ s}$ are usually called short GRBs, while bursts with $T_{90} > 2 \text{ s}$ are called long GRBs.

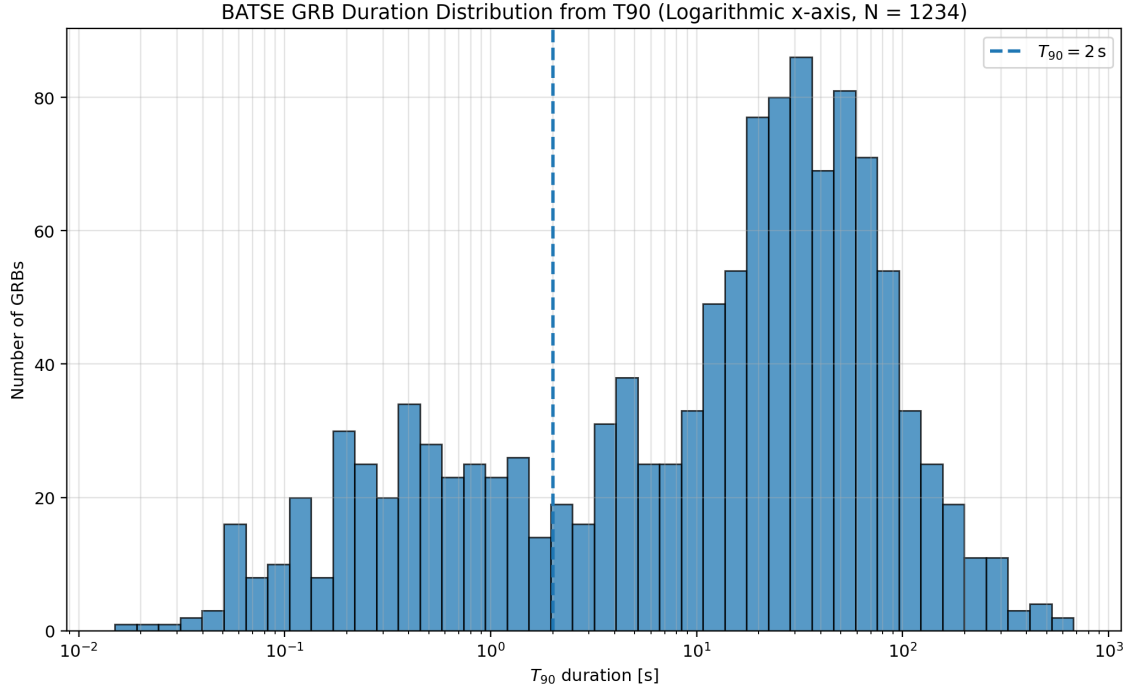


Figure 1.3: Histogram of BATSE gamma-ray burst durations based on the T_{90} parameter. The horizontal axis is shown on a logarithmic scale. The dashed vertical line at $T_{90} = 2 \text{ s}$ indicates the commonly used empirical boundary between short and long gamma-ray bursts. The data are taken from the Batse4B-Catalogue [55]

The two duration classes nevertheless point toward different dominant progenitor channels. This is why the formation of long and short GRBs will be discussed separately in the following section.

1.2.4 Prompt emission and afterglow

The prompt emission is the initial high-energy emission phase. It is observed mainly in hard X-rays and gamma rays and usually contains a large fraction of the observed radiated energy in this energy band. The prompt light curves show a large variety. Some bursts have one sharp peak, while others show several peaks or a broad and complex structure [20, 80].

This variability contains important information about the central engine and the relativistic outflow. However, one has to be careful with a direct geometrical interpretation. A broader peak does not automatically mean a wider emitting region.

The observed structure can also depend on central-engine activity, internal dissipation, magnetic reconnection, radiative cooling, relativistic curvature effects, and the viewing angle. Therefore, prompt light curves are important constraints, but they do not by themselves uniquely determine the geometry or the radiation mechanism.

The afterglow follows the prompt emission and is observed over much longer timescales. It is often detected in X-rays, optical and infrared wavelengths, and sometimes in radio. Compared to the prompt emission, the afterglow usually evolves more smoothly. It is commonly interpreted as emission from an external shock, where the relativistic ejecta are decelerated by the surrounding medium [80]. Through afterglow observations, the position of the burst can be determined much more accurately than with gamma-ray data alone. In addition, absorption or emission lines in the host-galaxy spectrum can be used to measure the redshift and therefore the distance of the GRB.

1.3 Formation of Gamma-Ray Bursts

Now that the observable parameters of GRBs have been described, the relevant question is how these massive explosions are produced. This section explains the main progenitor channels while also pointing toward open questions in GRB science. A natural outline for this discussion follows the empirical classification into long and short GRBs.

1.3.1 Progenitors of long GRBs

The standard interpretation of long GRBs is the core collapse of massive stars. Several nearby long GRBs are associated with energetic broad-lined Type Ic supernovae [22, 34, 68]. Type Ic supernovae lack strong hydrogen and helium lines. This points toward a stripped massive star progenitor rather than a normal hydrogen-rich star. This connection between long GRBs and Type Ic supernovae is one of the central reasons why long GRBs are connected to the collapse of massive stars.

To describe this model more deeply, one usually starts from a compact massive star which has lost its outer envelope, often described as a Wolf-Rayet-like progenitor. In the collapsar model, the core of a massive rotating star collapses and forms a black hole or compact central object with an accretion disk [76, 52]. A relativistic jet can then be launched along the rotation axis. For an observable GRB to occur, this jet has to penetrate the stellar material and break out of the star before the central engine stops. The outcome depends on several parameters, such as the angular momentum of the progenitor, the accretion rate, the stellar structure, the jet luminosity, and the viewing angle [52, 80].

Another independent constraint on long-GRB progenitors comes from their host galaxies. Fruchter et al. [21] found that long GRBs are more concentrated toward the brightest regions of their host galaxies than ordinary core-collapse supernovae. This is interpreted as evidence that long GRBs are connected to very massive stars and active star-forming regions. Metallicity also plays an important role, because stellar winds can remove angular momentum from the progenitor. In the single-star models of Yoon et al. [79], GRB production is favored at low metallicity, approximately

$Z \leq 0.004$ in their model grid. This value should however be understood as model-dependent and not as a universal threshold.

Binary evolution could also contribute to the formation of long-GRB progenitors. In a binary system, mass transfer, tidal interaction, or a merger can remove the envelope and help the core to retain enough angular momentum. Therefore, both single-star and binary channels remain relevant.

Even if the collapsar model is well established, there are events which cannot be classified reliably by duration alone. GRB 060614 is an important example. It had a duration of about 102 seconds, but no accompanying supernova was detected to deep observational limits [27, 17]. This shows that one must be careful when drawing conclusions only from T_{90} . Progenitor identification should also use afterglow observations, host-galaxy information, and possible supernova or kilonova signatures.

1.3.2 Progenitors of short GRBs

The standard interpretation of short GRBs is the merger of compact objects. The most important progenitor systems are binary neutron-star mergers and possibly neutron-star–black-hole mergers. This interpretation was first motivated by theory and later strengthened by afterglow localizations, host-galaxy studies, and the absence of ordinary supernovae in nearby well-observed short GRBs [56, 8].

This compact-merger picture differs from the collapsar model in several ways. First, the time between the formation of the progenitor system and the GRB can be very long. Therefore, short GRBs do not have to occur in the brightest star-forming regions of their host galaxies. They can also occur in older stellar populations or at larger offsets from their host galaxy. Second, the central engine is formed after the merger of compact objects. This can produce a black hole with a short-lived accretion disk or a massive neutron-star remnant. Third, neutron-rich material can be ejected during the merger. This material can power a kilonova through radioactive decay of heavy elements produced by rapid neutron capture.

The strongest evidence for this progenitor model came from the joint detection of GW170817 and GRB 170817A. The gravitational-wave signal was produced by a binary neutron-star merger, and a weak short gamma-ray burst was detected shortly afterwards by Fermi/GBM and INTEGRAL [1, 30, 67]. This event directly showed that binary neutron-star mergers can produce short GRBs and opened the field of GRB multi-messenger astronomy.

However, one should not assume that every short GRB is identical to GRB 170817A. Short GRBs show a range of luminosities, durations, spectral hardnesses, host environments, and afterglow properties. The observed prompt emission also depends strongly on the viewing angle and jet structure. Therefore, compact-object mergers are the dominant model for short GRBs, but individual events still require multi-wavelength and, if possible, gravitational-wave information for a robust interpretation.

1.3.3 Relativistic jet formation

As already shown, GRBs show very high luminosities and short variability timescales. If this emission were produced isotropically and without relativistic motion, the source would be extremely compact and optically thick to pair production. Therefore, the observed gamma-ray emission requires an ultra-relativistic outflow. In the standard picture, the central engine launches a relativistic jet with a large bulk Lorentz factor, often of order $\Gamma \geq 100$ [60, 50, 80].

The formation of such a jet is one of the central questions in GRB physics. The central engine must release a large amount of energy in a small region and must channel part of this energy into a narrow outflow. In long GRBs, this engine is usually connected to the collapse of a massive star. In short GRBs, it is connected to the merger remnant of compact objects. In both cases, the engine is expected to consist of a compact object, an accretion flow, and strong magnetic fields.

There are two broad ways to think about the energy source of the jet. In one case, energy is extracted from the accretion flow around the compact object. In another case, rotational energy of a spinning black hole can be extracted through magnetic fields, often described by the Blandford–Znajek mechanism [10]. Which of these channels dominates is still an open question and can depend on the magnetic-field strength, accretion rate, black-hole spin, and the structure of the surrounding material.

For long GRBs, the jet must first propagate through the stellar envelope. During this phase, the jet interacts with the stellar material and forms a hot cocoon around it. If the central engine is active for long enough, the jet can break out of the star. Only after breakout can the ultra-relativistic outflow produce the observed prompt gamma-ray emission efficiently. If the engine stops too early or the jet loses too much energy inside the star, the result may be a weak or failed GRB [52, 80].

After the jet has been launched and accelerated, part of its energy has to be dissipated into radiation. This dissipation can happen through internal shocks, magnetic reconnection, or photospheric emission. The exact mechanism is still debated and is directly connected to the interpretation of prompt-emission spectra and polarization measurements. This is why GRB polarimetry is valuable: the observed polarization can give information about whether the jet is dominated by ordered magnetic fields, turbulent fields, or more thermal/photospheric emission components [9, 28].

Finally, when the jet interacts with the surrounding medium, it decelerates and produces the afterglow. In this phase, the observed emission depends on the jet energy, opening angle, circumburst density, microphysical shock parameters, and viewing angle. Therefore, jet formation, prompt emission, and afterglow emission should not be treated as separate topics only, but as connected phases in the evolution of the same relativistic outflow.

1.3.4 Prompt Emission Models

The prompt emission is the most direct radiation from the relativistic outflow, while at the same time remaining the least completely understood phase of a GRB. A successful model has to explain several observables at once: short time scales, high luminosity, strong variability, the non-thermal spectrum, and possible polarization.

In modern discussions the open questions are often separated into three connected problems: the composition of the jet, the mechanism by which energy is dissipated, and the radiation process that converts this energy into the observed photons [60, 50, 59]. Three important families of models are discussed here: internal shocks, photospheric emission, and magnetic reconnection.

In the internal-shock model, the central engine ejects several relativistic shells with different Lorentz factors. Faster shells catch up with slower shells and collide at large radii. In these collisions, part of the bulk kinetic energy is converted into internal energy, electrons are accelerated, and synchrotron radiation can be emitted in the magnetic field of the shocked plasma [63, 43, 16]. This model naturally connects rapid central-engine variability to rapid variability in the prompt light curve. It also gives a non-thermal radiation component if the accelerated particles follow a non-thermal energy distribution. However, the model has important difficulties. One of them is the efficiency problem: depending on the contrast of Lorentz factors and on the shell energies, only a limited fraction of the kinetic energy is converted into radiation. A second difficulty concerns the observed spectral shapes. Some observed low-energy spectral slopes are harder than expected for the simplest optically thin synchrotron scenarios [60, 50, 59].

The photospheric-emission model starts from the fact that a relativistic fireball is initially optically thick. Radiation is trapped and advected outward with the flow. At the photospheric radius, where the optical depth becomes of order unity, photons can escape. In the simplest case this would lead to a quasi-thermal spectrum. If additional dissipation occurs below or close to the photosphere, for example by shocks, magnetic dissipation, or collisional processes, the spectrum can be broadened and can become closer to observed prompt spectra [64, 59]. These models are attractive because the radiation field is already present in the outflow and the radiative efficiency can be high. Their main challenge is that a purely thermal spectrum is usually too narrow, so additional broadening mechanisms such as Comptonization, angular effects, or subphotospheric dissipation are required.

A third class of models assumes that a large fraction of the jet energy is carried by magnetic fields. In such a Poynting-flux-dominated outflow, magnetic reconnection can dissipate magnetic energy and accelerate particles. One example is the internal-collision-induced magnetic reconnection and turbulence model, in which collisions between magnetized shells distort the magnetic field, trigger reconnection, and produce turbulent regions in which particles radiate efficiently [81]. The main advantage of magnetic-reconnection models is their natural connection to ordered magnetic fields and potentially high radiative efficiency. The main difficulty is that the detailed particle acceleration, reconnection rate, and resulting spectra depend on complex plasma physics and on the magnetic-field geometry.

In practice, the observed prompt emission may contain more than one component. A thermal or quasi-thermal photospheric contribution can coexist with non-thermal synchrotron radiation from shocks or reconnection regions [59, 50]. Polarization is therefore an important diagnostic. Synchrotron radiation from a large-scale ordered magnetic field can produce a high polarization degree, while turbulent magnetic fields reduce the net polarization through cancellation. Photospheric emission is often expected to give lower time-integrated polarization for a symmetric outflow, but geometrical effects and viewing angle can change this.

Magnetic-reconnection models can produce either high or moderate polarization depending on whether large-scale ordered field structures survive the dissipation process [32, 28, 81]. Therefore, POLAR-2 can provide valuable constraints on the physical origin of the GRB prompt emission.

1.4 Polarization in GRBs

After having described GRBs in detail, it has been shown that the light curve and the spectrum are important measurements in describing GRBs. But alone from those quantities the constraints are too wide to distinguish between models. Polarization could add further constraints, as described above. This section will provide a description of polarization in general and give a brief overview on polarization measurement possibilities.

1.4.1 Definition of linear polarization

To define linear polarization, the electromagnetic wave description is needed. Starting from Maxwell's equations, one may describe an electric field propagating in the z -direction by two transverse components [66, 9]:

$$\vec{E}(z, t) = E_x \cos(kz - \omega t) \hat{x} + E_y \cos(kz - \omega t + \delta) \hat{y}.$$

where $\vec{E}$ is the moving electric field vector, k is the wave number and ω is the angular frequency. The most important quantity for polarization is δ , which describes the phase shift between the two components E_x and E_y . Depending on the parameters δ , E_x and E_y , the polarization changes. Linear polarization occurs, when the resulting electric field vector oscillates on one fixed line. This is the case, when either one of the components E_x or E_y is 0, or when

$$\delta = 0 \quad \text{or} \quad \delta = \pi.$$

Circular polarization should also be mentioned briefly here. This occurs when

$$E_x = E_y, \quad \delta = \pm \frac{\pi}{2}.$$

The general case is the elliptical polarization, where linear and circular polarization are special cases of.

The most interesting parameter, when looking at polarization coming from GRBs would be the degree of polarization Π . It lies between zero and one:

$$0 \leq \Pi \leq 1,$$

When $\Pi = 0$, we have completely unpolarized light, when $\Pi = 1$ we have completely linear polarized light.

The second important parameter is the polarization angle ψ . This angle describes the orientation of the linear polarization direction in the sky, relative to a chosen axis in the sky. It is important to notice, that

$$\psi \equiv \psi + 180^\circ.$$

This is due to the fact, that the electric field vector is oscillating along one direction and has no arrow direction.

1.4.2 The Stokes Parameters

It is useful to introduce the Stokes parameters, named after the Irish mathematician and physicist George Gabriel Stokes, to describe polarization. The Stokes parameters provide a convenient description of polarization because they are additive for incoherent radiation. In scattering polarimeters, they can therefore be estimated for individual events and summed across time intervals, energy ranges, and detector regions. This makes them particularly well suited to high-energy polarimetry [38, 9].

For a wave propagating along the z-axis the stokes parameters are defined in the following way:

$$\begin{aligned} I &= \langle E_x^2 + E_y^2 \rangle, \\ Q &= \langle E_x^2 - E_y^2 \rangle, \\ U &= \langle 2E_x E_y \cos \delta \rangle, \\ V &= \langle 2E_x E_y \sin \delta \rangle. \end{aligned}$$

Here $\langle \circ \rangle$ notes the time average. I is the total intensity, Q describes the linear polarization along the chosen x/y axes, U describes the linear polarization along axes rotated along 45° . V describes the circular polarization.

For a polarization detector in gamma-ray astronomy it is more intuitive to describe the stokes parameters Q and U through the intensities measured along different polarization directions:

$$\begin{aligned} Q &= I_{0^\circ} - I_{90^\circ}, \\ U &= I_{45^\circ} - I_{135^\circ}. \end{aligned}$$

So if $Q > 0$ we have the polarization more aligned with 0° than 90° . Similar for all other polarization axis. Using normalized stokes parameters:

$$q = \frac{Q}{I}, \quad u = \frac{U}{I},$$

and therefore:

$$q = \frac{I_{0^\circ} - I_{90^\circ}}{I_{ges}}, \quad u = \frac{I_{45^\circ} - I_{135^\circ}}{I_{ges}},$$

the degree of polarization could be calculated via:

$$\Pi = \sqrt{q^2 + u^2}.$$

The polarization angle can be calculated from the stokes parameters from

$$\psi = \frac{1}{2} \text{atan2}(U, Q).$$

Now we have a set of equations relating the measured intensity along different axis with the polarization degree and the polarization angle. because those equations are bijective, we could calculate the Stokes parameters from Π and ψ :

$$q = \Pi \cos(2\psi), \quad u = \Pi \sin(2\psi).$$

Q as well as U are defined along a specific reference axis. If another reference axis is chosen, rotated by an angle χ the stokes parameters also transform:

$$\begin{aligned} Q' &= Q \cos(2\chi) + U \sin(2\chi), \\ U' &= -Q \sin(2\chi) + U \cos(2\chi). \end{aligned}$$

1.4.3 Polarization from synchrotron emission

Synchrotron radiation is emitted by relativistic electrons moving in a magnetic field. Since the electron acceleration is perpendicular to the magnetic field, the emitted radiation is intrinsically linearly polarized [66, 32, 28]. An electron with Lorentz factor γ radiates predominantly around the characteristic frequency

$$\nu_{\text{syn}} \simeq \frac{3}{4\pi} \gamma^2 \frac{eB \sin \alpha_p}{m_e c},$$

where e is the elementary charge, α_p is the pitch angle between the electron velocity and the magnetic field, m_e is the electron mass, and c is the speed of light.

For an optically thin population of electrons following a power-law energy distribution,

$$N(\gamma) d\gamma = K \gamma^{-p} d\gamma,$$

the resulting synchrotron spectrum is also a power law,

$$F_\nu \propto \nu^{-\alpha_\nu}, \quad \alpha_\nu = \frac{p-1}{2}.$$

To determine the polarization degree, the emission is separated into components perpendicular and parallel to the magnetic field projected onto the plane of the sky. Choosing the Stokes reference axis such that positive Q corresponds to the perpendicular component gives

$$I = j_\perp + j_\parallel, \quad Q = j_\perp - j_\parallel.$$

For a uniform magnetic field, symmetry allows the coordinate system to be chosen such that $U = 0$, and the linear polarization degree is therefore

$$\Pi_L = \frac{Q}{I} = \frac{j_\perp - j_\parallel}{j_\perp + j_\parallel}.$$

For a single electron, the two polarization components can be expressed in terms of the synchrotron functions

$$F(x) = x \int_x^\infty K_{5/3}(\xi) d\xi, \quad G(x) = x K_{2/3}(x),$$

where K_ν is a modified Bessel function and

$$x = \frac{\nu}{\nu_{\text{syn}}}.$$

Apart from common proportionality factors, the components are

$$P_\perp \propto F(x) + G(x), \quad P_\parallel \propto F(x) - G(x).$$

Consequently, integration over the electron distribution gives

$$j_I(\nu) \propto \int \gamma^{-p} F(x) d\gamma, \quad j_Q(\nu) \propto \int \gamma^{-p} G(x) d\gamma.$$

Using

$$x = \frac{\nu}{CB_{\perp}\gamma^2}, \quad C = \frac{3e}{4\pi m_e c}, \quad B_{\perp} = B \sin \alpha_p,$$

and changing the integration variable from γ to x , both emissivities acquire the same frequency and magnetic-field dependence,

$$j_I, j_Q \propto KB_{\perp}^{(p+1)/2} \nu^{-(p-1)/2}.$$

Their ratio is therefore independent of frequency:

$$\Pi_L = \frac{\int_0^{\infty} x^{(p-3)/2} G(x) dx}{\int_0^{\infty} x^{(p-3)/2} F(x) dx}.$$

Evaluation of these integrals yields the maximum polarization degree for an optically thin power-law electron population in a uniform magnetic field,

$$\Pi_{\max} = \frac{p+1}{p+\frac{7}{3}} = \frac{3p+3}{3p+7}.$$

Using $\alpha_{\nu} = (p-1)/2$, this can equivalently be written as

$$\Pi_{\max} = \frac{\alpha_{\nu} + 1}{\alpha_{\nu} + \frac{5}{3}}.$$

For typical spectral indices $\alpha_{\nu} = 0.5$ – 1 , this corresponds to

$$\Pi_{\max} \simeq 0.69$$
– 0.75 .

Thus, synchrotron radiation can reach a linear polarization degree of approximately 75% under idealized conditions [66, 28].

This value represents a theoretical upper limit. In realistic sources, variations in the magnetic-field direction and polarization angle lead to partial cancellation when integrating over the unresolved emitting region and over time. If the source consists of N independent patches with comparable intensities and randomly oriented polarization angles, the expected net polarization approximately scales as

$$\Pi_{\text{net}} \sim \frac{\Pi_{\max}}{\sqrt{N}}.$$

Consequently, turbulent magnetic fields or strong spatial and temporal variations generally produce substantially lower observed polarization degrees [28].

1.4.4 Geometrical effects

As seen at the end of the last subsection, polarization is not only determined by the radiation mechanism but also by how the emitting region is seen by the observer [32, 28]. If we divide the emitting regions in several patches, the stokes parameters sum from each patch:

$$I_{\text{tot}} = \sum_i I_i,$$

$$Q_{\text{tot}} = \sum_i Q_i = \sum_i I_i \Pi_i \cos(2\psi_i),$$

$$U_{\text{tot}} = \sum_i U_i = \sum_i I_i \Pi_i \sin(2\psi_i).$$

The observed polarization is then

$$\Pi_{\text{tot}} = \frac{\sqrt{Q_{\text{tot}}^2 + U_{\text{tot}}^2}}{I_{\text{tot}}}.$$

Because the matter in the jets of a GRB move relativistically, the radiation is beamed into a cone with a relatively small angular size. If this beam is aligned with the line of sight of the observer, a strong cancellation is possible. If the jet moves slightly out of the line of sight, the cancellation decreases and the observed polarization increases.

1.4.5 Time-Resolved Polarization

For the timing the same is true as for spatial parameters. If we observe the polarization in several time bins, we also need to add the Stokes parameters to gain the polarization of the burst:

$$Q_{\text{int}} = \sum_i Q_i, \quad U_{\text{int}} = \sum_i U_i, \quad I_{\text{int}} = \sum_i I_i.$$

Then the time-integrated polarization degree is

$$\Pi_{\text{int}} = \frac{\sqrt{(\sum_i I_i \Pi_i \cos(2\psi_i))^2 + (\sum_i I_i \Pi_i \sin(2\psi_i))^2}}{\sum_i I_i}.$$

Therefore, low time-integrated measurements do not necessarily imply intrinsically low polarization [82, 45, 28]. Due to the high variability a good timing resolution in the polarization detection is needed. The polarization angle may change over time because of changes in the magnetic field direction, or the visible region changes due to relativistic curvature effects, or that the emission mechanism changes. To avoid all those problems, a good timing resolution is needed. The next section describes how these challenges have been addressed and reviews selected historical polarization measurements and their findings.

1.5 Historic GRB Polarization Measurements

GRB prompt-emission polarimetry has a long history of promising, but difficult, measurements. Early analyses often suggested high polarization, but the statistical and systematic uncertainties were large. Later dedicated and semi-dedicated instruments improved the situation, but the interpretation still remained limited by photon statistics, instrumental response, background modeling, and possible fast evolution of the polarization angle. In this section, a brief overview of different instruments and measurements is given [9, 44, 28].

1.5.1 Early attempts

Early polarization measurements were often performed with instruments that were not originally built as GRB polarimeters. Existing gamma-ray detectors were used as Compton polarimeters because the azimuthal distribution of Compton scattering carries information about the polarization angle. Such measurements require a detailed understanding of detector geometry, spacecraft mass distribution, source position, background, and detector response [51, 9].

One early approach used BATSE data in an indirect way. The prompt gamma-ray flux was interpreted after Compton scattering in the Earth’s atmosphere. This system was called the BATSE Albedo Polarimetry System (BAPS). Evidence for polarization was reported for GRB 930131 with $\Pi > 35\%$ and for GRB 960924 with $\Pi > 50\%$ [74]. However, the method was not able to strongly constrain the polarization degree beyond systematics-based estimates. Therefore, the result is best understood as evidence for possible polarization, not as a precise measurement of the polarization fraction.

1.5.2 Measurements by dedicated or semi-dedicated instruments

The question of GRB polarization remained important, and several instruments were used to investigate it further. The first important example is RHESSI. RHESSI was primarily built for solar observations in the X-ray and gamma-ray range, but its segmented germanium detectors allowed Compton-scattering analyses. For GRB 021206, an initial analysis reported a very high polarization of $\Pi = 80\% \pm 20\%$ [14]. Later reanalyses challenged this result. One analysis found no reliable polarization signal [65], while another obtained $\Pi = 41^{+57}_{-44}\%$ and concluded that the data quality was insufficient to constrain the polarization degree [73]. This case is one of the classical examples showing how sensitive prompt GRB polarimetry is to event selection and systematics.

INTEGRAL provided another important step. For the bright burst GRB 041219A, analyses with SPI and IBIS reported high or variable polarization values. With SPI, a polarization fraction of about $\Pi = 99\% \pm 33\%$ was obtained in the 100–350 keV band, but the authors stated that this was not a statistically secure polarization detection and that instrumental systematics could not be ruled out [37]. With IBIS, GRB 041219A showed variable polarization, including a value of $\Pi = 43\% \pm 25\%$ for the second peak and a much lower time-integrated value in another interval [31]. This demonstrated that time dependence of the polarization degree and angle can be essential.

The next major step toward dedicated GRB polarimetry was the Gamma-Ray Burst Polarimeter (GAP) on board IKAROS. GAP was designed specifically for prompt GRB polarimetry. It reported a polarization degree of $\Pi = 27\% \pm 11\%$ for GRB 100826A, together with a significant change of polarization angle during the burst [77]. Later GAP measurements of GRB 110301A and GRB 110721A also reported high polarization degrees [78]. These results strengthened the idea that prompt emission can be highly polarized, but the small sample size was still not sufficient to establish a general picture.

The Cadmium Zinc Telluride Imager (CZTI) on board AstroSat can be used as a Compton polarimeter above about 100 keV because multiple-pixel events carry azimuthal scattering information. A five-year CZTI catalog presented time-integrated polarization measurements for 20 GRBs in the energy range 100–600 keV. The majority of the sample was consistent with low or null polarization, while five bursts showed high-polarization candidates [13]. The authors discuss whether low time-integrated polarization is intrinsic or caused by changing polarization angle during the burst.

The most relevant predecessor for POLAR-2 is POLAR. POLAR was a dedicated GRB polarimeter on board Tiangong-2 and operated in the approximate energy range 50–500 keV. It detected 55 GRBs, of which 14 were bright enough for polarization analysis. The time-integrated polarization results were mostly compatible with low or zero polarization. However, when time-resolved analysis was possible, moderate polarization together with rapidly changing polarization angle was observed [82, 45]. This does not necessarily mean that the prompt emission is intrinsically unpolarized; instead, it can indicate that polarization angles change rapidly and cancel in time-integrated analyses.

All this is summarized in Table 1.1. The development from early indirect measurements to dedicated GRB polarimeters is shown.

These observations show four key lessons that are essential for POLAR-2. First, a dedicated detector design is necessary. A useful polarimeter needs a detector geometry with a well-understood azimuthal response, a sufficient modulation factor, and enough effective area to collect many photons during the short prompt-emission phase. Second, detailed simulations are required because the observed modulation depends not only on source polarization, but also on energy response, event selection, spacecraft scattering, and detector geometry. These simulations need to be validated by calibration measurements with polarized and unpolarized beams.

Third, systematics can imitate polarization. If the detector is not sufficiently uniform or if the detector response is not correctly modeled, an artificial azimuthal modulation can appear. Fourth, time-resolved analysis is essential. Because the Stokes parameters from different time intervals can partially cancel if the polarization angle evolves during the burst, a larger effective area is needed to collect enough statistics in shorter time bins [82, 45, 35, 61].

1.6 Compton Scattering and Compton Polarimetry

After having seen that most historical GRB polarimeters used Compton scattering, this section lays the basis for understanding such instruments and therefore also understanding POLAR-2, which makes it possible to constrain the trigger algorithm used in POLAR-2. It starts with the physical scattering process and then builds up to modulation curves, modulation factors, and the minimum detectable polarization [51, 9].

Table 1.1: Selected historical GRB prompt-emission polarization measurements.

Instrument	Example GRB(s)	Reported result	Main limitation or lesson
BATSE/BAPS	GRB 930131, GRB 960924	Evidence for high polarization	Indirect albedo method with strong systematic uncertainties [74]
RHESSI	GRB 021206	Initially reported high polarization, later not confirmed	Low statistics and strong sensitivity to systematic effects [14, 65, 73]
INTEGRAL/SPI	GRB 041219A	$\Pi \simeq 99\% \pm 33\%$	Large uncertainty; not usually treated as a firm detection claim [37]
INTEGRAL/IBIS	GRB 041219A	Evidence for variable polarization	Shows that time dependence of the polarization signal is important [31]
GAP	GRB 100826A, GRB 110301A, GRB 110721A	Moderate to high polarization reported	Small sample size and limited event statistics [77, 78]
AstroSat CZTI	20 GRB catalog	Mostly low or null polarization, with some high-polarization candidates	Careful analysis of systematics is essential [13]
POLAR	14 bright GRBs	Mostly low or null time-integrated polarization	Evolution of the polarization angle can wash out the time-integrated signal [82, 45]

1.6.1 Physical principle

Compton scattering is photon–electron scattering,

$$\gamma + e^- \rightarrow \gamma' + e^{-'}.$$

The incoming photon has energy $E = h\nu$, whereas the scattered photon has energy $E' = h\nu'$. Usually $E' < E$, because part of the photon energy is transferred to the recoil electron. For gamma-ray polarimetry it is important that not only the photon energy loss, but also the scattering direction, is connected to the polarization direction. Therefore, the detector has to reconstruct at least two interactions: the first Compton scatter and a second interaction, often photoabsorption or another scattering. If the source location is known, the azimuthal scattering angle can be reconstructed. This azimuthal scattering direction is the key observable for linear polarization measurements [51, 38].

1.6.2 Compton kinematics

The scattered photon energy is related to the polar scattering angle by the Compton formula [41, 51],

$$E' = \frac{E}{1 + \frac{E}{m_e c^2} (1 - \cos \theta)}.$$

Here E is the incoming photon energy, m_e is the electron mass, c is the speed of light, and θ is the Compton scattering angle. By introducing

$$\epsilon = \frac{E}{m_e c^2},$$

this can be written as

$$E' = \frac{E}{1 + \epsilon(1 - \cos \theta)}.$$

This equation shows that for $\theta = 0^\circ$ the photon does not change direction and no energy is transferred. The photon energy loss becomes maximal for backscattering, $\theta = 180^\circ$, where

$$E' = \frac{E}{1 + 2\epsilon}.$$

In literature, the same relation is often written as the wavelength shift

$$\lambda' - \lambda = \frac{h}{m_e c} (1 - \cos \theta).$$

If the incoming photon energy is known and the scattered photon energy is reconstructed, the scattering angle can be written as

$$\cos \theta = 1 - m_e c^2 \left(\frac{1}{E'} - \frac{1}{E} \right).$$

In an ideal event with only two interactions, the photon deposits E_1 in the first Compton scatter and E_2 in the second interaction. Then one can write

$$E = E_1 + E_2, \quad E' = E_2,$$

and therefore

$$\cos \theta = 1 - m_e c^2 \left(\frac{1}{E_2} - \frac{1}{E_1 + E_2} \right).$$

1.6.3 Klein–Nishina cross section

The probability for a photon to Compton scatter into a given direction is described by the Klein–Nishina cross section [41]. For linearly polarized incoming photons it can be written as

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

Here r_0 is the classical electron radius, E and E' are the incoming and scattered photon energies, θ is the polar scattering angle, and η is the azimuthal scattering angle measured relative to the electric-field vector. The polarization dependence is introduced by the term

$$-2 \sin^2 \theta \cos^2 \eta.$$

This shows that the cross section is smallest when $\eta = 0^\circ$ or $\eta = 180^\circ$, which corresponds to scattering parallel to the electric-field vector. It is largest when

$$\eta = 90^\circ,$$

which corresponds to scattering perpendicular to the electric-field vector. Thus, linearly polarized photons preferentially Compton scatter perpendicular to their electric-field vector. This is the physical reason why Compton scattering can be used for polarimetry [51, 9].

For completeness, in the unpolarized case the azimuthal dependence averages out:

$$\left(\frac{d\sigma}{d\Omega} \right)_{\text{unpol}} = \frac{r_0^2}{2} \left(\frac{E'}{E} \right)^2 \left[\frac{E}{E'} + \frac{E'}{E} - \sin^2 \theta \right].$$

Therefore, unpolarized radiation does not produce a physical azimuthal modulation.

1.6.4 Azimuthal scattering distribution

As shown in the previous subsection, the Klein–Nishina cross section yields a scattering probability that depends on η . Because of the geometrical relation

$$\cos^2 \eta = \frac{1 + \cos(2\eta)}{2},$$

the azimuthal dependence has a 180° periodicity. This matches the 180° periodicity of linear polarization.

If the energy and polar scattering angle θ are kept fixed, the azimuthal dependence can schematically be written as

$$\frac{d\sigma}{d\eta} \propto 1 - A(\theta, E) \cos(2\eta),$$

where $A(\theta, E)$ describes the strength of the polarization asymmetry. The sign convention depends on the direction from which η is measured. In this convention, η is measured from the electric-field vector.

It is important to note that at higher energies forward scattering becomes more probable. This creates a compromise in detector design: scattering near 90° is more sensitive to polarization, but it is not always the most probable interaction. Therefore, detector optimization requires an interplay between cross section, scattering angle, effective area, event selection, and modulation sensitivity [51].

1.6.5 Modulation curve

In a Compton polarimeter, many events are measured and many azimuthal scattering angles are reconstructed. These angles are filled into a histogram. For a polarized source, this histogram is modulated. The idealized modulation curve is

$$N(\eta) = A [1 + \mu_{\text{obs}} \cos(2(\eta - \eta_0))].$$

Here $N(\eta)$ is the number of events at azimuthal scattering angle η , A is the average number of counts, μ_{obs} is the observed modulation amplitude, and η_0 is the phase of the modulation. For practical fitting, this curve can also be written as

$$N(\eta) = A + B \cos(2(\eta - \eta_0)).$$

The observed modulation is then

$$\mu_{\text{obs}} = \frac{B}{A}.$$

Another common definition of μ_{obs} is derived from the maximum and minimum of the azimuthal distribution:

$$\mu_{\text{obs}} = \frac{N_{\text{max}} - N_{\text{min}}}{N_{\text{max}} + N_{\text{min}}}.$$

1.6.6 Modulation factor

The observation of a fully polarized beam does not usually produce a modulation amplitude of one, because the measured modulation depends on detector response. Therefore, the modulation factor for a fully polarized beam is defined as

$$\mu_{100} = \frac{N_{\text{max}}^{100} - N_{\text{min}}^{100}}{N_{\text{max}}^{100} + N_{\text{min}}^{100}}.$$

Here, N_{max}^{100} and N_{min}^{100} are the maximum and minimum of the modulation curve for a 100% polarized source. This value has to be determined in simulations and validated in calibration setups [51, 44].

For a partially polarized source one obtains

$$\mu_{\text{obs}} = \Pi \mu_{100}.$$

Therefore, the polarization degree can be calculated as

$$\Pi = \frac{\mu_{\text{obs}}}{\mu_{100}}.$$

This is the key relation for the classical modulation-curve approach in Compton polarimetry.

The value μ_{100} is one of the most important quantities of a Compton polarimeter. A detector with larger μ_{100} is more sensitive to polarization, if all other parameters are comparable. However, μ_{100} is not a universal constant. It depends on photon energy, incident direction, detector geometry, event-selection cuts, interaction-position resolution, energy thresholds, and reconstruction methods. This is why simulation and calibration are essential.

1.6.7 Minimum detectable polarization

The minimum detectable polarization (MDP) describes the smallest polarization degree that an instrument can detect at a specified confidence level. It should not be confused with the uncertainty of a measured polarization. Rather, it is a sensitivity measure. For a confidence level of 99%, a commonly used expression is [71, 38]

$$\text{MDP}_{99} = \frac{4.29}{\mu_{100} R_S} \sqrt{\frac{R_S + R_B}{T}}.$$

Here μ_{100} is the modulation factor for a fully polarized source, R_S is the source count rate, R_B is the background count rate, and T is the observation time. This expression illustrates several useful dependencies. A larger modulation factor improves sensitivity,

$$\text{MDP}_{99} \propto \frac{1}{\mu_{100}},$$

a larger source rate improves sensitivity,

$$\text{MDP}_{99} \propto \frac{1}{R_S},$$

a larger background worsens sensitivity,

$$\text{MDP}_{99} \propto \sqrt{R_S + R_B},$$

and a longer observation improves sensitivity,

$$\text{MDP}_{99} \propto \frac{1}{\sqrt{T}}.$$

This causes a major limitation for GRB polarization measurements because T is fixed by the burst duration and cannot be increased arbitrarily.

With this description, the theoretical part is complete. The fundamental observables of GRBs have been described, together with their connection to prompt-emission models. Furthermore, the physical foundation of polarization and Compton scattering has been laid. Based on historical missions, the difficulties of GRB polarization measurements have been shown, and the main instrumental parameters relevant for improved sensitivity have been highlighted.

Chapter 2

The POLAR-2 Mission

2.1 Mission Overview

POLAR-2 is the successor mission to POLAR and is being developed to study the prompt emission of gamma-ray bursts (GRBs). Its central objective is to measure linear polarization with substantially higher sensitivity and photon statistics than POLAR. Polarization complements timing and spectral measurements by probing the magnetic-field structure, radiation mechanism, and geometry of the relativistic outflow [9, 28, 44, 35, 61, 47].

POLAR-2 is planned for installation on the China Space Station. The internal project planning used in this thesis currently targets the beginning of 2028 for the launch [57]. The international collaboration includes institutes in China, Switzerland, Poland, Germany, and further partner institutions [69, 47].

2.1.1 Instrument Suite and Scope of This Thesis

The current POLAR-2 mission concept comprises three complementary instruments distributed over two payloads. The High-energy Polarimetry Detector (HPD) forms one payload, while the Spectroscopy and Polarimetry Detector (SPD) contains the Broad-band Spectrometer Detector (BSD) and the Low-energy Polarization Detector (LPD). Together, they provide polarization, spectral, timing, and localization information over a broad energy range [47, 29].

The relationship between the two payloads and the measurement tasks of the three instruments is summarized in Figure 2.1. The overview illustrates that the instruments are complementary rather than interchangeable: the HPD and LPD measure polarization in different energy bands, while the BSD supplies the spectral and directional information needed to interpret these measurements.

The HPD is the European detector contribution relevant to this thesis. It is a segmented plastic-scintillator Compton polarimeter optimized for approximately 40–1000 keV. The BSD uses GAGG scintillators and a coded mask to measure GRB spectra and arrival directions, while the gas-based LPD extends polarization measurements into the soft X-ray band. Spectral and localization information from the BSD are also important for the HPD analysis because its polarization response depends on photon energy and incident direction. Unless stated otherwise, the detector and electronics discussed in the remainder of this chapter therefore refer

HPD 40–1000 keV Plastic scintillators Compton polarimetry	BSD 10–1000 keV GAGG scintillators and coded mask Spectroscopy and localization	LPD 2–10 keV Gas-pixel detectors Photoelectric polarimetry
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Figure 2.1: Schematic overview of the three POLAR-2 instruments and their principal measurement tasks. The HPD forms one payload; the BSD and LPD together form the SPD payload. The energy ranges indicate the current design goals [47, 29].

specifically to the HPD. Detailed descriptions of all three instruments are given by Kole et al. [47], while the expected HPD science performance is discussed by Gill et al. [29].

2.1.2 Scientific Goals

POLAR-2 is designed to determine how GRB jets convert their energy into prompt radiation. The prompt phase probes the internal dissipation region more directly than the later afterglow, while polarization provides information that cannot be obtained from light curves and spectra alone [80, 28, 29].

The scientific questions addressed by POLAR-2 can be summarized as follows:

- What is the dominant radiation mechanism of GRB prompt emission?
- Are the magnetic fields in the emitting region ordered or turbulent?
- Is the outflow matter-dominated or Poynting-flux dominated?
- Does the polarization angle evolve during the burst?
- Can time- and energy-resolved polarization distinguish between synchrotron, photospheric, and magnetic-dissipation scenarios?

These questions cannot generally be answered from one polarization value alone. The observed polarization also depends on source brightness, viewing angle, jet geometry, and the time and energy interval used in the analysis. POLAR-2 is therefore intended to provide both detailed measurements of individual bright GRBs and population-level information from a substantially larger sample [32, 28, 82, 45, 29].

A first central goal is to create a large catalog of prompt-emission polarization measurements. Current performance estimates predict the detection of several hundred GRBs per year and polarization constraints for several tens of events, although the exact number depends on the adopted sensitivity and event-selection criteria [69, 35, 47]. Such a catalog enables studies of

- the distribution of polarization degrees,

- possible differences between long and short GRBs,
- correlations with flux, fluence, and spectral hardness,
- correlations with the spectral peak energy E_{peak} ,
- differences between time-integrated and time-resolved polarization, and
- the relation between polarization-angle evolution and light-curve structure.

Population studies are important because different physical models can produce overlapping polarization ranges for individual viewing geometries. A large sample allows these model predictions to be compared statistically rather than through a few exceptionally bright bursts alone.

A second major goal is time- and energy-resolved polarization. The POLAR observations indicated that the polarization angle may evolve during a burst. If emission intervals with different polarization angles are combined, their Stokes parameters partially cancel and the time-integrated polarization can be small even when the individual intervals are significantly polarized. For intervals indexed by i , this can be written as

$$\Pi_{\text{int}} = \frac{\sqrt{(\sum_i I_i \Pi_i \cos 2\psi_i)^2 + (\sum_i I_i \Pi_i \sin 2\psi_i)^2}}{\sum_i I_i}, \quad (2.1)$$

where I_i , Π_i , and ψ_i are the intensity, polarization degree, and polarization angle of interval i , respectively. The larger photon statistics of the HPD make it possible to divide bright bursts into shorter intervals and test whether the polarization follows individual pulses or the spectral evolution [82, 45, 29].

Energy-resolved polarization provides a complementary observable. Changes with energy can indicate that several radiation components contribute to the prompt emission. The HPD can perform such studies within its own energy range, while joint HPD and LPD measurements extend the comparison from soft X-rays to gamma rays [28, 47, 29].

These measurements are ultimately intended to test prompt-emission models. Spectra and light curves alone often cannot uniquely distinguish between synchrotron radiation, photospheric emission, internal shocks, and magnetic dissipation. Polarization adds information about the geometry of the radiation field and the magnetic-field configuration. A high polarization degree can indicate synchrotron emission in an ordered magnetic field or a strongly asymmetric radiation field. A low degree can instead result from turbulent fields, geometrical averaging, a weakly polarized photospheric component, or rapid polarization-angle evolution. The polarization degree and angle must therefore be interpreted together with the spectrum, light-curve structure, and incident direction [32, 28, 9, 29].

Finally, POLAR-2 also contributes to the multi-messenger context. The joint detection of GW170817 and GRB 170817A demonstrated that gravitational-wave and gamma-ray measurements provide complementary information about compact-object mergers and their relativistic outflows [1, 30, 67]. POLAR-2 can contribute by detecting faint gamma-ray transients, distributing triggers, and measuring or constraining polarization when sufficient statistics are available. Polarization can

add information about the magnetic-field geometry, jet structure, viewing angle, and radiation mechanism. Such coincident events are expected to be rare and often faint; therefore, meaningful upper limits are also scientifically useful. The BSD supports this role by providing rapid localization and spectral information for follow-up observations [69, 47, 29].

2.1.3 Mission Heritage

POLAR was a dedicated GRB Compton polarimeter operated on board the Chinese Tiangong-2 space laboratory. It observed in the approximate 50–500 keV energy range and collected about six months of science data during 2016–2017. During this period, it detected 55 GRBs, of which 14 were bright enough for detailed catalog-level polarization analysis [44, 82, 45].

The POLAR results are important for two reasons. First, they demonstrated that space-based Compton polarimetry of GRB prompt emission is feasible with a dedicated segmented scintillator instrument. Second, they showed the limitations of time-integrated polarization measurements when photon statistics are limited. The time-integrated polarization results for the analyzed POLAR GRB sample were generally compatible with low or zero polarization, but time-resolved analyses showed indications of polarization-angle evolution during individual bursts. This means that a low time-integrated polarization degree does not necessarily imply intrinsically unpolarized emission [82, 45, 44].

POLAR-2 can therefore be understood as a direct continuation of POLAR. It retains the Compton-polarimetry principle but scales the detector concept to a larger effective area, a larger event sample, and improved readout technology. The purpose is not only to obtain individual high-quality polarization measurements, but also to build a statistically useful GRB polarization sample that can be compared with prompt-emission model predictions [35, 61, 47, 29].

2.1.4 Improvements Compared to POLAR

The first major improvement is the larger sensitive area and the resulting increase in polarization sensitivity. The HPD has four times as many detector channels as POLAR and a substantially larger effective area. The exact sensitivity gain depends on photon energy, incident direction, background, and event selection [35, 61, 29, 47].

The sensitivity of a polarimeter is commonly expressed through the minimum detectable polarization (MDP). For a confidence level of 99%, a frequently used form is

$$\text{MDP}_{99} = \frac{4.29}{\mu_{100} R_S} \sqrt{\frac{R_S + R_B}{T}}, \quad (2.2)$$

where μ_{100} is the modulation factor for a fully polarized beam, R_S is the source count rate, R_B is the background count rate, and T is the observation time [71, 9]. Increasing the effective area generally increases the detected source rate and therefore improves the MDP, although the exact scaling depends on background, threshold, event selection, and detector response.

The second improvement is the replacement of the multi-anode photomultiplier tubes used in POLAR by silicon photomultipliers (SiPMs). SiPMs are compact

and mechanically robust, operate at much lower bias voltages than photomultiplier tubes, and provide a high photon-detection efficiency. Their noise and gain depend on temperature and operating voltage and must therefore be monitored carefully [39, 48, 53].

The third improvement is the redesigned readout electronics. The larger number of channels requires a low-power and modular system that reads the SiPM signals and provides local trigger information. The 64-channel front-end design developed for the HPD can also be adapted to the GAGG scintillators of the BSD [48, 47]. This electronics chain is central to this thesis because it determines how channel-level signals become front-end and back-end trigger decisions.

2.2 Detector Concept

This section describes the HPD, which is the POLAR-2 instrument studied in this thesis. The HPD is a segmented plastic-scintillator Compton polarimeter. Segmentation is essential because the azimuthal direction of a scattered photon can only be inferred if at least two spatially separated energy deposits are measured. Their relative positions provide an estimate of the projected scattering angle [41, 51, 9, 46].

The signal chain can be summarized schematically as

$$\begin{aligned}
 \gamma &\rightarrow \text{Compton scatter in scintillator} \rightarrow \text{scintillation light} \\
 &\rightarrow \text{SiPM pulse} \rightarrow \text{FEE amplification and trigger} \\
 &\rightarrow \text{ADC values} \rightarrow \text{BEE event building} \\
 &\rightarrow \text{polarization analysis.}
 \end{aligned} \tag{2.3}$$

Here FEE denotes the front-end electronics and BEE denotes the back-end electronics. The later trigger analysis is concerned with the transition from local FEE-level activity to BEE-level event acceptance.

2.2.1 Segmented Scintillator Design

In the simplest Compton-polarimetry event, the incoming photon scatters in one scintillator bar and subsequently deposits energy in another bar. The relative bar positions define a projected scattering direction. For a linearly polarized beam, the distribution of these directions is modulated because the Klein–Nishina cross section depends on the angle between the scattering plane and the electric-field vector [41, 51, 9]. The reconstruction and interpretation of this modulation are described in Section 2.3.

If the detector granularity is too coarse, the reconstructed azimuthal angles become strongly quantized and the modulation curve loses information. A monolithic detector could measure deposited energy, but without position segmentation it would not provide the interaction positions required for Compton polarimetry. Segmentation solves this problem, but it introduces additional detector effects: optical crosstalk, channel-to-channel gain variations, non-uniform thresholds, dead or noisy channels, and event-ordering ambiguity. These effects must be measured, simulated, or corrected in the response model [51, 46, 9].

In the HPD, optical crosstalk is reduced by optically separating scintillator bars and by optimizing the scintillator–SiPM coupling. Remaining crosstalk and non-uniformity are detector-response effects and must be included in calibration and simulation. Recent prototype work explicitly compares measured polarized-beam data with simulations, which is essential for validating the response model used in polarization reconstruction [46].

2.2.2 Detector Modules

The HPD flight model contains 100 identical polarimeter modules. Each module comprises an 8×8 array of plastic scintillator bars, resulting in 64 readout channels per module and 6400 channels in total [36, 57]. A module acts as a small segmented Compton detector, while the complete array provides the effective area required for GRB observations.

The selected scintillator, EJ-248M, is based on polyvinyltoluene (PVT), a low- Z material that favors Compton scattering relative to photoelectric absorption in the relevant energy range and therefore supports the Compton-polarimetry principle. The suffix “M” denotes a crosslinked base polymer. According to the manufacturer, this crosslinking is useful when the scintillator is exposed for extended periods to temperatures above its softening point because it improves the stability of the material. EJ-248M also combines a high light output with a fast decay time and an emission maximum near 425 nm, within the blue wavelength range detected by the SiPM readout. Its optical performance has been studied for the POLAR-2 detector geometry, and separate proton-irradiation measurements tested the material at doses relevant to and exceeding the expected mission exposure [18, 54, 47].

The manufacturer quotes a scintillation efficiency of approximately 9200 photons per MeV of electron energy deposition, a rise time of 0.9 ns, and a decay time of 2.1 ns [18]. These properties are included in the detector simulation described later. The measured emission spectrum is shown in Figure 2.2. Its maximum near 425 nm is relevant because the number of detected photons depends on the overlap between this spectrum and the wavelength-dependent SiPM sensitivity.

When a gamma ray Compton scatters in a bar, the recoil electron loses energy by exciting and ionizing the scintillator material. A fraction of this energy is re-emitted as optical scintillation light and guided towards the SiPM. The light pulse is fast, but the measured channel time also depends on light transport, the SiPM response, the front-end shaping, and the discriminator threshold. These contributions must be considered when defining trigger-coincidence windows.

Each SiPM contains many small avalanche-photodiode cells operated in Geiger mode. A detected optical photon can trigger one cell, and the summed signal from all fired cells provides a measure of the deposited energy. Thermally generated avalanches produce dark counts, while secondary avalanches in neighboring cells or in the same cell are referred to as optical crosstalk and afterpulsing, respectively. These effects, together with the temperature dependence of the gain, influence the trigger threshold and noise rate. They are therefore characterized during calibration and included in the detector operating strategy [39, 23, 53].

The charge released when one microcell fires is approximately determined by its capacitance and by the overvoltage. The overvoltage $V_{\text{ov}} = V_{\text{bias}} - V_{\text{bd}}$ is the

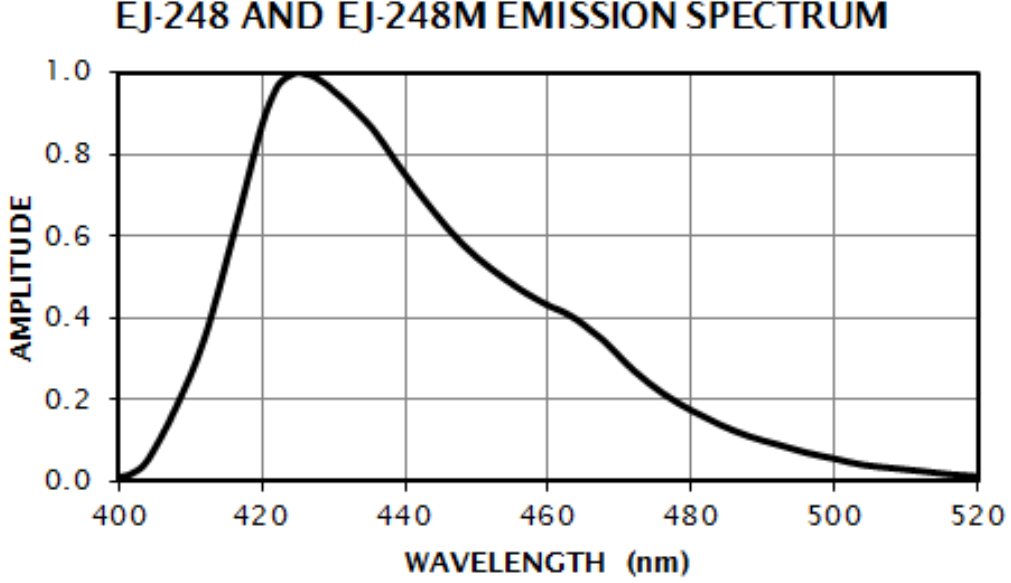


Figure 2.2: Relative emission spectrum of EJ-248/EJ-248M. The maximum near 425 nm lies in the blue spectral region and is used when matching the scintillator light output to the wavelength-dependent SiPM sensitivity and when modelling optical-photon transport in the detector simulation. Adapted from Eljen Technology [18].

amount by which the applied bias voltage exceeds the breakdown voltage. Dividing the released charge by the elementary charge e gives the approximate SiPM gain,

$$G = \frac{C_{\text{cell}} V_{\text{ov}}}{e}, \quad (2.4)$$

where C_{cell} is the capacitance of one microcell. The gain therefore changes if either the bias voltage or the temperature-dependent breakdown voltage changes. This is why the operating voltage and detector temperature must be known during calibration and data taking [39].

Not every optical photon incident on a SiPM produces a recorded avalanche. The photon-detection efficiency (PDE) can be expressed schematically as

$$\text{PDE}(\lambda, V_{\text{ov}}) = QE(\lambda) P_{\text{Geiger}}(\lambda, V_{\text{ov}}) F_{\text{fill}}, \quad (2.5)$$

where QE is the probability that an absorbed photon generates a charge carrier, P_{Geiger} is the probability that this carrier initiates an avalanche, and F_{fill} is the fraction of the sensor surface occupied by active microcell area. The wavelength dependence of the PDE connects the emission spectrum in Figure 2.2 to the number of detected photons. Radiation damage can increase the dark current and dark-count rate and is therefore relevant for operation in space [39, 23, 53].

2.2.3 Front-End Electronics

The front-end electronics (FEE) convert the SiPM pulses into amplitude measurements and digital trigger signals. The back-end trigger therefore does not receive ide-

alized energy deposits; it receives signals that have already been amplified, shaped, compared with a threshold, and processed by the local module logic.

Each 64-channel module uses two CITIROC 1A application-specific integrated circuits (ASICs), with one ASIC channel assigned to each SiPM channel. A CITIROC provides separate high- and low-gain paths for measuring small and large signals, together with a fast path that indicates whether a programmable trigger threshold has been exceeded [70, 48]. These parallel processing paths are shown in Figure 2.3.

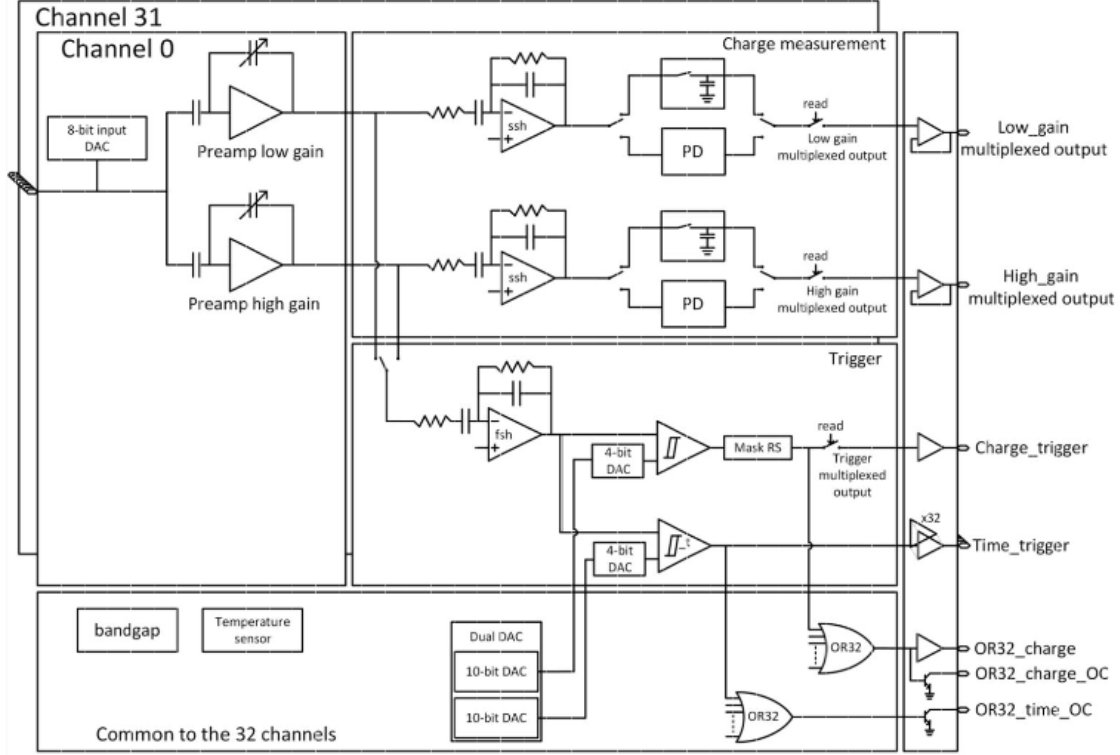


Figure 2.3: Signal processing in the CITIROC 1A front-end ASIC. Each SiPM input is amplified in parallel high- and low-gain branches to cover a broad signal range. The shaped charge signals are stored for amplitude readout, whereas the faster discriminator branch compares the signal with a programmable threshold and supplies channel-level trigger information. The multiplexers combine the analog outputs from the individual channels for digitization. Adapted from WEEROC [70].

Figure 2.3 illustrates the separation between amplitude measurement and trigger generation. The high- and low-gain branches preserve charge information for later energy reconstruction, whereas the fast discriminator branch determines whether and when a channel contributes to the trigger. In the electronics design used in this thesis, the module FPGA receives these threshold decisions, ignores masked noisy or defective channels, and forms the local trigger signals sent to the back-end electronics [57].

The subsequent combination of the channel-level decisions inside the module is shown in Figure 2.4. This second diagram therefore starts at a later stage of the signal chain than Figure 2.3: it describes the logical decision that follows the analog

processing inside the CITIROC.

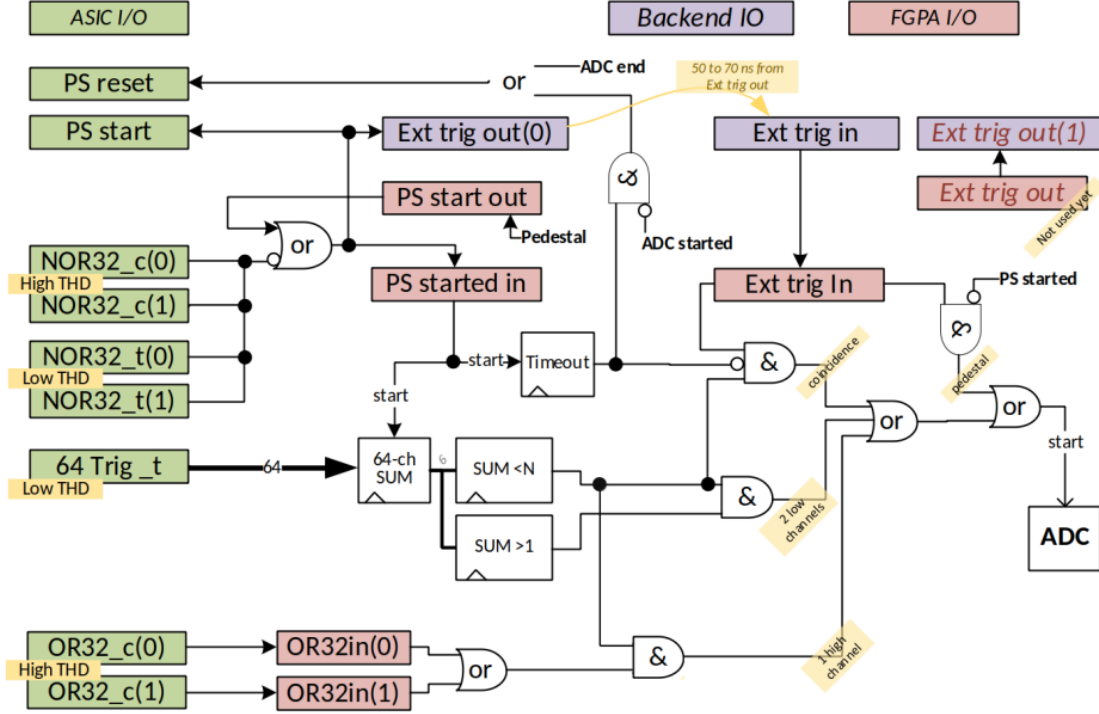


Figure 2.4: Front-end trigger logic of one HPD module. Local charge and timing triggers are combined with an external trigger from the BEE. Multiplicity conditions count how many channels exceed their threshold within the relevant time window, while masks suppress channels that should not participate in the decision. An accepted condition starts the analog-to-digital conversion (ADC) and module readout. Adapted from POLAR-2 Collaboration [57].

As shown in Figure 2.4, the internal electronics scheme considered in this thesis allows analog-to-digital conversion (ADC) to be started by local charge or timing activity, or by an accepted external trigger from the BEE. A multiplicity condition specifies how many channels must cross a threshold within a given time window. Local triggering is required because a Compton event can be fully contained within one module and should not depend on activity in another module [57].

2.2.4 Back-End Electronics

The back-end electronics connect the module-level FEEs to the global HPD readout and trigger system. Each FEE sends trigger and event data to the BEE and receives clock, command, and control information in return. The BEE is responsible for higher-level trigger decisions, event building, data handling, housekeeping, and communication with the platform.

In the internal architecture used in this thesis, the BEE is divided into three main functional blocks. The trigger FPGA evaluates trigger information from the modules and forms global event decisions. A communication unit distributes commands to the FEEs, for example to adjust thresholds or mask defective channels. The central

computer coordinates these functions, packages the recorded data, and provides the interface to the China Space Station. Their functions and interconnections are summarized in Figure 2.5 [57].

Figure 2.5 also shows the separation of data and power connections. For the trigger studies in this thesis, the important path is the data connection from the FEEs to the trigger unit: the BEE receives local trigger information from many modules and must decide whether an event should be accepted, rejected, or combined with additional readout information. The communication and central-computer branches do not form the trigger itself, but configure the FEEs and transfer the resulting event data.

2.3 Polarimetry with the HPD

The HPD uses the same measurement principle as other Compton polarimeters. A linearly polarized photon preferentially scatters perpendicular to its electric-field vector. A population of such photons therefore produces a sinusoidal modulation in the measured azimuthal scattering-angle distribution, as described in Chapter 1.

2.3.1 Event Types

In a segmented Compton polarimeter, events can be grouped into single-hit, double-hit, and multi-hit classes. Single-hit events contain only one channel above threshold. They can contribute to count-rate and spectral information, but they do not provide a projected Compton-scattering direction and therefore cannot by themselves be used as Compton-polarimetry candidates. Double-hit events are the simplest polarimetry candidates because two spatially separated interactions define a projected scattering direction. Multi-hit events contain three or more triggered channels and can contain additional polarimetric information, but their reconstruction is more ambiguous because the interaction sequence is not directly known [51, 9, 46].

Table 2.1: Basic event classes in a segmented Compton polarimeter.

Event type	Description	Use in analysis
Single-hit	One channel above threshold	Count rate, trigger studies, and spectroscopy, but no direct Compton azimuth
Double-hit	Two channels above threshold	Basic Compton-polarimetry candidate with a simple projected scattering-angle estimate
Multi-hit	Three or more channels above threshold	Additional polarimetry candidates requiring statistical or likelihood-based reconstruction

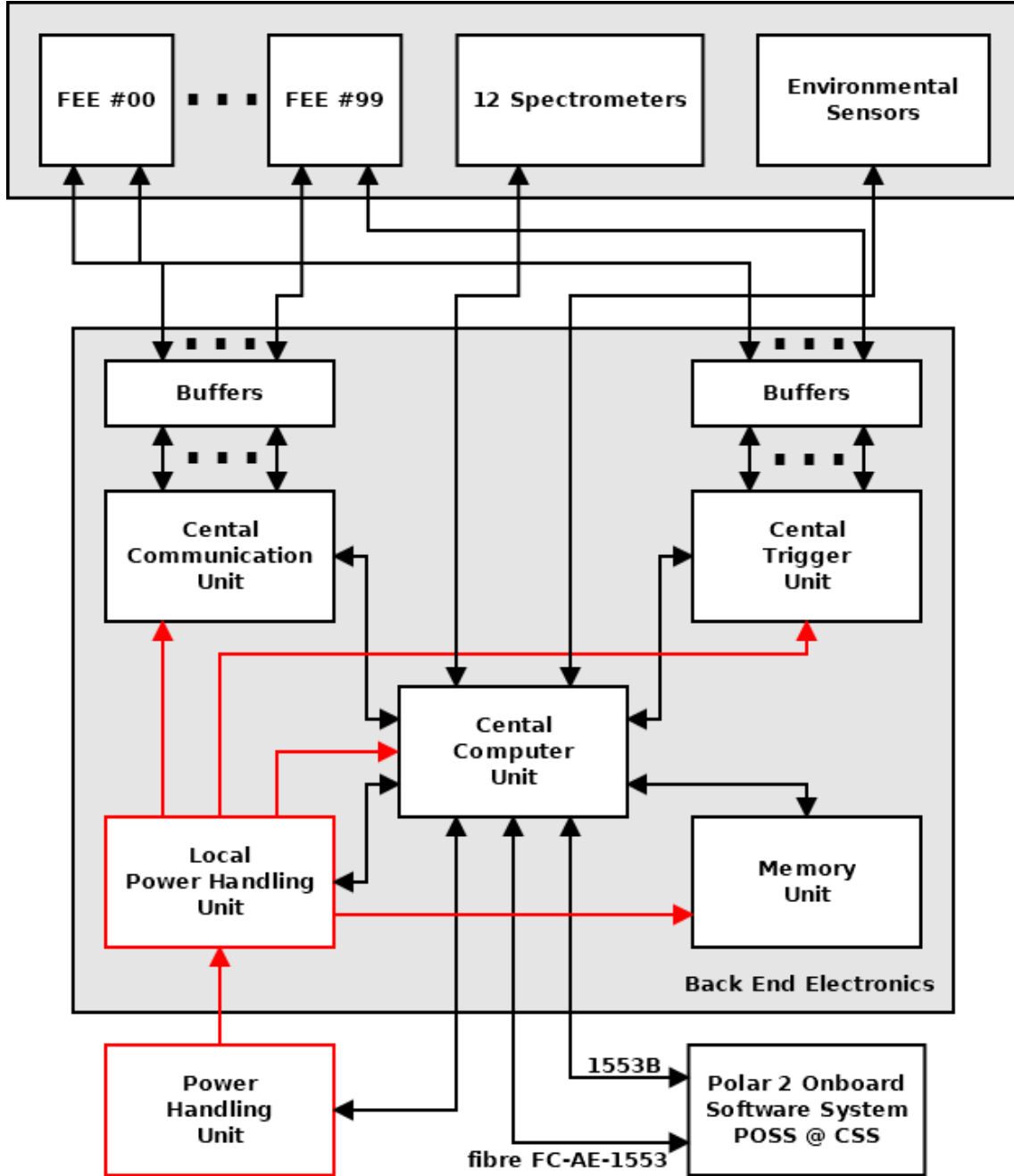


Figure 2.5: Structure of the HPD back-end electronics. The trigger unit receives local trigger information from the FEEs and issues global decisions. The communication unit distributes configuration and control commands, while the central computer coordinates data handling and communication with the station. Black lines denote data and control connections; red lines denote power connections. Adapted from POLAR-2 Collaboration [57].

2.3.2 Reconstruction of Compton Candidates

For a two-hit candidate in the detector plane, the projected azimuthal scattering angle can be estimated as

$$\eta = \text{atan2}(\Delta y, \Delta x), \quad (2.6)$$

with

$$\Delta x = x_2 - x_1, \quad \Delta y = y_2 - y_1. \quad (2.7)$$

Reversing the order of the two interactions changes η by 180° and therefore does not change the polarization modulation. The finite bar size nevertheless limits the angular precision. For independent coordinate uncertainties that are small compared with the hit separation, standard error propagation gives

$$\sigma_\eta^2 = \frac{(\Delta y)^2 \sigma_{\Delta x}^2 + (\Delta x)^2 \sigma_{\Delta y}^2}{[(\Delta x)^2 + (\Delta y)^2]^2}. \quad (2.8)$$

Here $\sigma_{\Delta x}$ and $\sigma_{\Delta y}$ describe the uncertainties of the separation between the two hits. If both coordinates have the same uncertainty,

$$\sigma_{\Delta x} = \sigma_{\Delta y} = \sigma_\Delta, \quad (2.9)$$

the expression reduces to $\sigma_\eta \simeq \sigma_\Delta / r$, where r is the projected hit separation.

For the HPD, an interaction is localized to one scintillator bar. If its transverse position is assumed to be uniformly distributed within a bar of pitch $p = 6$ mm, the one-dimensional position uncertainty and the uncertainty of the separation of two independent hits are [46, 57]

$$\sigma_x = \frac{p}{\sqrt{12}} \approx 1.73 \text{ mm}, \quad \sigma_\Delta = \sqrt{2} \sigma_x \approx 2.45 \text{ mm}. \quad (2.10)$$

For a projected hit separation $r = \sqrt{(\Delta x)^2 + (\Delta y)^2}$, the corresponding angular uncertainty is approximately

$$\sigma_\eta \simeq \frac{\sigma_\Delta}{r}, \quad \sigma_\eta [\text{deg}] \approx \frac{140.4}{r [\text{mm}]}. \quad (2.11)$$

Thus, hits in neighboring bars provide less precise azimuthal information than well-separated hits. This inverse dependence on r is visualized in Figure 2.6; the steep decrease at small separations explains why the hit distance can be relevant for event selection and response modelling.

A finite angular resolution reduces the measured modulation because events are redistributed around their true azimuthal angles. If this uncertainty is approximated by a Gaussian with standard deviation σ_η in radians, convolution with a $\cos(2\eta)$ modulation gives

$$N_{\text{meas}}(\eta) = A \left[1 + \mu_{100} \Pi \exp(-2\sigma_\eta^2) \cos(2(\eta - \eta_0)) \right]. \quad (2.12)$$

The exponential factor shows how angular smearing reduces the amplitude. It can be absorbed into an effective modulation factor,

$$\mu_{\text{eff}} = \mu_{100} \exp(-2\sigma_\eta^2). \quad (2.13)$$

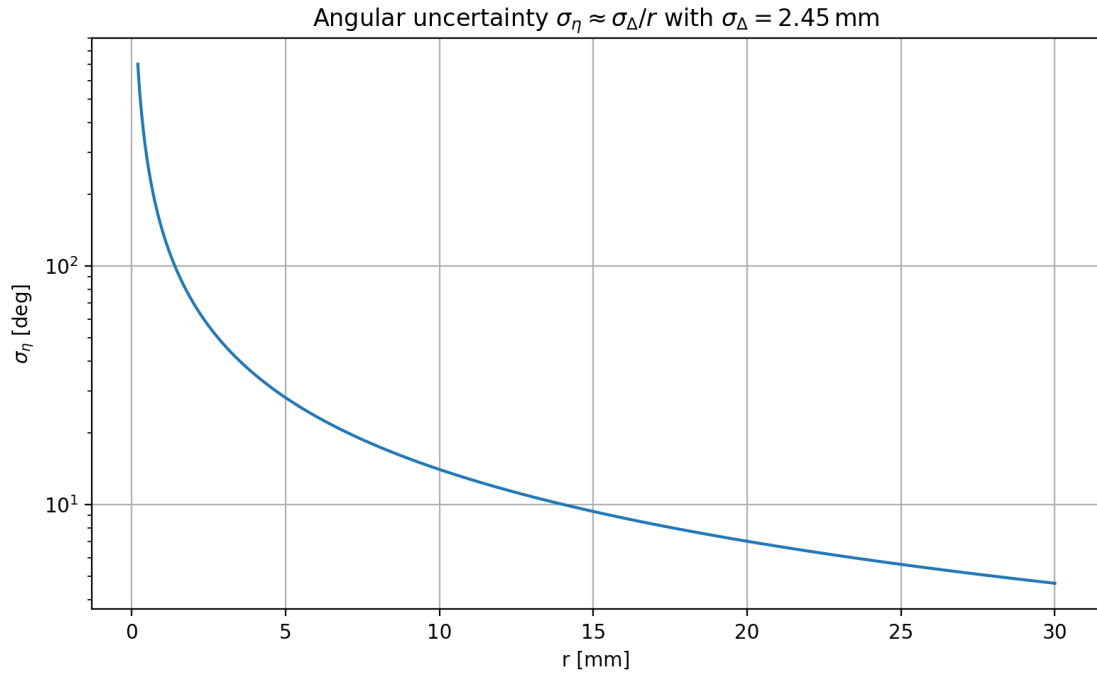


Figure 2.6: Estimated uncertainty of the reconstructed azimuthal scattering angle as a function of the projected hit separation r . The curve assumes a 6 mm bar pitch and uniformly distributed interaction positions within each bar. The decreasing uncertainty illustrates why well-separated double-hit events constrain the scattering direction more precisely.

This analytic expression illustrates the influence of detector granularity, but the actual HPD response is more complex and is obtained from calibration and detector simulations. Sampling positions within a bar can avoid artificial binning patterns in simulated distributions, but it does not improve the physical event-by-event position resolution [51, 9, 46].

2.3.3 Creation of the Modulation Curve

For each selected Compton candidate, an azimuthal angle η_i is reconstructed and entered into a histogram. Schematically, this distribution can be written as

$$N(\eta) = \sum_i w_i \delta(\eta - \eta_i), \quad (2.14)$$

where δ denotes the Dirac delta distribution and w_i is an optional event weight. In the actual analysis, the delta distributions are replaced by finite histogram bins or by an unbinned likelihood. Event weights can account for selection efficiency, angular uncertainty, or detector quality.

After treating the background and accounting for the detector response, the modulation curve can be described by

$$N(\eta) = A [1 + \mu_{\text{obs}} \cos(2(\eta - \eta_0))], \quad (2.15)$$

where A is the mean event level, μ_{obs} is the measured modulation amplitude, and η_0 determines the polarization angle according to the adopted angular convention. The polarization degree is obtained by comparing μ_{obs} with the modulation factor μ_{100} expected for a fully polarized source,

$$\Pi = \frac{\mu_{\text{obs}}}{\mu_{100}}. \quad (2.16)$$

The value of μ_{100} is not a universal detector constant. It must be determined from calibration and simulation for the relevant source spectrum, incident direction, detector configuration, and event selection [51, 9, 46].

If the angular-resolution loss is separated from the remaining detector response through the effective modulation factor defined in Equation 2.13, the same relation becomes

$$\Pi = \frac{\mu_{\text{obs}}}{\mu_{\text{eff}}}. \quad (2.17)$$

In practice, the preferred procedure is to determine the complete response for the same energy range, incident direction, and event selection as used for the measured data.

Background subtraction can be represented as

$$N_{\text{src}}(\eta) = N_{\text{on}}(\eta) - \alpha_{\text{bkg}} N_{\text{off}}(\eta), \quad (2.18)$$

where N_{on} and N_{off} are the distributions measured during the burst and background intervals, respectively, and α_{bkg} accounts for their different exposures.

The detector response maps the physical scattering-angle distribution to the reconstructed distribution. In a simplified integral notation, this mapping can be written as

$$N_{\text{obs}}(\eta_{\text{rec}}) = \int R(\eta_{\text{rec}} \mid \eta; E, \theta_{\text{inc}}, \phi_{\text{inc}}) N_{\text{phys}}(\eta) d\eta, \quad (2.19)$$

where R gives the probability of reconstructing η_{rec} for a physical angle η , photon energy E , and incident direction $(\theta_{\text{inc}}, \phi_{\text{inc}})$. In addition, the response depends on thresholds, inactive or noisy channels, optical crosstalk, energy resolution, hit reconstruction, and event selection. Accurate calibration and simulation are therefore central to POLAR-2 data analysis.

Chapter 3

The Back-End Trigger

Having introduced the operating principle of POLAR-2 and its principal design challenges, this chapter focuses on the global trigger implemented in the back-end electronics. The objective is to determine whether a suitable global trigger concept can be selected and implemented on the designated FPGA within the available timing and resource constraints. The trigger must retain inter-module Compton-event candidates while limiting accidental coincidences and the associated readout volume.

The detector interfaces, prescribed signal definitions, and hardware resources form the boundary conditions of this study. The contributions presented in this chapter are the analytical estimate of the accidental-hit scaling, the comparison and selection of an existing trigger concept, its implementation and synthesis for the target FPGA, and the development of lossless encoding concepts for the trigger packet. The selected trigger is subsequently evaluated using simulations and ESRF measurement data in the following chapters. Thus, this chapter establishes both the technical basis and the implementation whose physical performance is assessed later in the thesis.

3.1 Introduction to the Back-End Trigger

The back-end electronics coordinate data handling from all 100 FEEs, which directly read out the SiPMs. The overall architecture is shown in Figure 2.5.

The BEE architecture contains three FPGAs, one of which is dedicated to the global trigger decision. The remaining BEE functions include command communication, acquisition of the FEE data, and communication with the China Space Station.

Each FEE communicates with the BEE through three signal lines. The trigger-request line is asserted when at least two scintillator bars exceed the trigger threshold. The **TooMany** line flags an unusually high local multiplicity and is used to identify cosmic-ray-like events. The precise FEE condition that produces this signal is not specified in this thesis. Because the signal is primarily used for cosmic-ray rejection, it is also referred to as the cosmic signal and is denoted by C in the following. In response to a valid request, the BEE asserts the trigger-accept line and initiates data readout in the participating FEE.

Although an FEE can identify events involving multiple bars within its own

module, it cannot detect coincidences spanning different modules. Such events occur particularly near module boundaries and are valuable because a greater separation between two Compton interactions reduces the angular uncertainty, as discussed in Chapter 2. The BEE trigger is therefore required to identify these events and initiate their readout. The corresponding requirements are presented in the following section.

3.2 Requirements

The requirements of the BEE trigger form the design basis for the developments presented in this chapter. They can be divided into three groups: the essential trigger functions, periodic pedestal acquisition, and communication with the other BEE units.

3.2.1 Essential functions

At the detector interface, the trigger FPGA receives the 100 trigger-request signals T_{00} to T_{99} and the 100 **TooMany** signals C_{00} to C_{99} . Cosmic-ray-like events are normally rejected, but a configurable prescaler retains one out of every n such events for detector monitoring. The corresponding prescaled cosmic signal is denoted by PC_i , with $PC_i = 1$ indicating that the event is retained. The valid request of module i can therefore be written as

$$T_i^{\text{valid}} = T_i \wedge (\neg C_i \vee PC_i). \quad (3.1)$$

The trigger FPGA evaluates these valid requests and produces the 100 trigger-accept signals A_{00} to A_{99} . A global decision must be returned within less than 100 ns. This response-time requirement is distinct from the 100 ns coincidence window used to group simultaneous module requests, although the two values constrain one another.

In addition to the event decision, the trigger FPGA must provide the following timing, monitoring, and control functions:

- operate from an internal 120 MHz clock that can be started, stopped, counted, and reset by the central computing unit;
- derive and distribute a 40 MHz synchronization clock to the FEEs so that detector signals can be associated in time;
- generate a trigger packet for each decision and send it to the central computing unit for event association and diagnostics;
- maintain counters for trigger requests T , **TooMany** signals C , and trigger accepts A ;
- receive configuration parameters and support reprogramming through the BEE; and
- issue the periodic pedestal request described in the following subsection.

3.2.2 Pedestal

Each SiPM and ASIC channel has a baseline ADC distribution whose mean and width can differ between channels and evolve during operation. This baseline must be measured so that the pedestal can be subtracted from recorded amplitudes during ground-based data processing. Periodic pedestal data also allow changes in the channel baselines and noise widths to be monitored.

The pedestal distribution is closely related to the discriminator-threshold setting. A lower threshold improves sensitivity to small energy deposits but also increases the rate of threshold crossings caused by dark counts and electronic noise. In practice, the threshold is therefore selected relative to the measured pedestal mean and width of each channel. The exact operating point represents a compromise between the low-energy threshold and the accidental trigger rate.

During operation, the trigger FPGA uses a dedicated counter to issue a pedestal-readout request to all FEEs at a frequency of 1 Hz. The resulting values are stored with the detector data and processed on the ground; the trigger FPGA does not perform the pedestal correction itself.

3.2.3 Communication with the BEE

The final communication protocol between the trigger FPGA and the other FPGAs on the BEE board has not yet been specified. Nevertheless, the functional requirements of this connection can be stated. It must provide a throughput of several gigabits per second and transfer trigger packets, trigger statistics, configuration parameters, and control information between the trigger FPGA and the central computing unit. The uncompressed trigger packet has a length of 364 bit, as derived in Section 3.7.

The connection must additionally provide sufficiently low latency, error detection, and data integrity. Its detailed physical and protocol-level implementation is independent of the trigger algorithms compared in this chapter and is therefore not discussed further.

3.3 Hardware

The available logic, memory, I/O, and timing resources constrain which trigger algorithms can be implemented. The trigger is implemented on an AMD/Xilinx Kintex UltraScale XCKU040 FPGA in the FFVA1156 package. Its principal hardware resources are summarized in Table 3.1.

For the trigger design, the most relevant constraints are the number of user I/O pins, the amount of LUT and memory capacity available for parallel logic and buffering, and the achievable combinatorial delay. High-speed transceivers are also available for communication interfaces. The effect of these constraints on the implemented trigger logic is evaluated in Section 3.6.2; the individual device specifications are not repeated here because they are already listed in Table 3.1.

Table 3.1: Technical overview of the AMD/Xilinx Kintex UltraScale XCKU040 in the FFVA1156 package.

Parameter	XCKU040-FFVA1156
FPGA family	Kintex UltraScale
Technology node	20 nm
System logic cells	530,250
CLB LUTs	242,400
CLB flip-flops	484,800
Distributed RAM	7.0 Mb
Block RAM	21.1 Mb
Block RAM blocks	600×36 Kb
Equivalent 18 Kb BRAM blocks	1200×18 Kb
DSP slices	1,920
Clock management tiles	10
MMCMs	10
PLLs	20
I/O DLLs	40
System Monitor	1
HR I/O pins	104
HP I/O pins	416
Total user I/O pins	520
GTH transceivers	20
Maximum GTH line rate	up to 16.375 Gb/s
PCIe hard blocks	3× PCIe Gen3 x8 capable
Available speed grades	$-3, -2, -1, -1L$

3.4 Trigger Algorithm

The BEE trigger must identify coincident requests from different FEEs and return accept signals within the required response time so that the participating modules are read out. If the accepted neighborhood is too restrictive, valid multi-module Compton events are lost. If it is too broad, unrelated threshold crossings increase the accidental-coincidence rate and the amount of data to be read out. The trigger concepts considered in this section therefore balance event acceptance against accidental triggers and data volume. The scaling of accidental channel-level threshold crossings is estimated first.

3.4.1 Noise Scaling

To quantify one of the principal trade-offs in the trigger selection, an analytical estimate of the accidental-hit scaling is developed in this thesis. In this section, a noise hit denotes an accidental channel-level threshold crossing that is unrelated to the Compton event under consideration. Its rate combines contributions from SiPM dark counts, electronic noise, and physical background interactions. For this estimate, these threshold crossings are treated as independent Poisson processes. Let r_i be the combined noise-hit rate of channel i and let Δt be the event-building coincidence window. The probability of at least one accidental threshold crossing in that channel during the window is

$$p_i = 1 - e^{-r_i \Delta t}. \quad (3.2)$$

For $r_i \Delta t \ll 1$, this becomes

$$p_i \approx r_i \Delta t. \quad (3.3)$$

Each FEE contains $N_{\text{ch}} = 64$ channels. The expected number of accidental threshold crossings in one FEE during the coincidence window is therefore

$$\lambda_{\text{noise}, \text{FEE}} = \sum_{i=1}^{N_{\text{ch}}} r_i \Delta t. \quad (3.4)$$

If a common rate r is assumed for all channels, this simplifies to

$$\lambda_{\text{noise}, \text{FEE}} = N_{\text{ch}} r \Delta t. \quad (3.5)$$

For a trigger region containing n_{FEE} modules, the expected number becomes

$$\lambda_{\text{noise}} \approx n_{\text{FEE}} N_{\text{ch}} r \Delta t. \quad (3.6)$$

Thus, within this approximation, the accidental-hit expectation increases linearly with the number of FEEs included in the trigger region.

The probability of at least one accidental threshold crossing in the region is

$$P_{\geq 1} = 1 - e^{-\lambda_{\text{noise}}}. \quad (3.7)$$

The probability of observing exactly k independent accidental crossings is

$$P(k) = \frac{\lambda_{\text{noise}}^k}{k!} e^{-\lambda_{\text{noise}}}. \quad (3.8)$$

For $\lambda_{\text{noise}} \ll 1$, the probability of exactly α accidental hits scales as

$$P(\alpha) \approx \frac{\lambda_{\text{noise}}^\alpha}{\alpha!}. \quad (3.9)$$

Consequently, accidental coincidences involving several independent channels become progressively less likely.

Let the initially requesting FEE have the matrix indices (i_0, j_0) . For the square neighborhoods considered here, a module (i, j) belongs to a trigger region with an integer radius R_{readout} if

$$\max(|i - i_0|, |j - j_0|) \leq R_{\text{readout}}. \quad (3.10)$$

The number of included FEEs can then be written generally as

$$n_{\text{FEE}}(R_{\text{readout}}) = \sum_{i,j} \Theta(R_{\text{readout}} - \max(|i - i_0|, |j - j_0|)). \quad (3.11)$$

For an interior module, this gives

$$n_{\text{FEE}}(R_{\text{readout}}) = (2R_{\text{readout}} + 1)^2. \quad (3.12)$$

At detector edges and corners, the number is smaller because part of the nominal neighborhood lies outside the detector. Equation 3.6 therefore shows that enlarging the trigger radius increases the accidental-hit expectation through the corresponding increase in n_{FEE} . This result provides the analytical basis for comparing the spatial extent of the candidate trigger regions.

3.4.2 Full Lookup-Table Trigger

One possible implementation is a full lookup table evaluated after the 100 ns coincidence window. The raw trigger-request and `TooMany` inputs are first combined with the prescale decision according to Equation 3.1. The resulting 100-bit vector of valid trigger requests is then used as the address of a table whose stored 100-bit accept vector directly defines the output signals.

This concept would provide a short and deterministic decision path because the trigger result is obtained from one table lookup. It would also be reconfigurable by replacing the stored accept patterns. Its decisive limitation is the required memory. A 100-bit address has

$$N_{\text{addr}} = 2^{100} \approx 1.27 \times 10^{30} \quad (3.13)$$

possible values. Storing one 100-bit accept vector for every address would require

$$N_{\text{storage}} = 2^{100} \cdot 100 \text{ bit} \approx 1.27 \times 10^{32} \text{ bit} \approx 1.58 \times 10^7 \text{ YB}. \quad (3.14)$$

This exceeds the available FPGA memory by many orders of magnitude. A complete truth-table implementation is therefore not feasible and is not considered further.

3.4.3 Radius-Dependent Coincidence Trigger

A more compact implementation uses the spatial relationship between the FEEs instead of storing the response to every possible global request pattern. A module is accepted if it has a valid trigger request and at least one other module within the selected neighborhood also has a valid request. Only the participating modules receive an accept signal. The neighborhood radius must be chosen carefully: a small radius rejects valid events with widely separated interactions, whereas a large radius increases accidental coincidences and the readout volume.

For one ring of adjacent modules in the 10×10 FEE matrix, the trigger condition can be written as

$$A_{ij} = PED \vee \left[T_{ij}^{\text{valid}} \wedge \left(\bigvee_{\Delta i=-1}^1 \bigvee_{\Delta j=-1}^1 T_{i+\Delta i, j+\Delta j}^{\text{valid}} \right) \right], \quad (\Delta i, \Delta j) \neq (0, 0). \quad (3.15)$$

Here PED is the periodic pedestal-readout request, which accepts all modules independently of event activity. The indices (i, j) identify one FEE in the 10×10 matrix. The central index combination $(\Delta i, \Delta j) = (0, 0)$ is excluded from the logical OR so that a module cannot satisfy its own coincidence condition. Indices outside the detector boundaries are ignored. The use of T^{valid} includes both the `TooMany` rejection and the retained prescale events defined in Equation 3.1.

Figure 3.1 shows the measured distance between the first and second interactions of selected events in POLAR. This distribution provides qualitative guidance for choosing the spatial range of the BEE coincidence search.

The measured event rate decreases with increasing interaction separation, although events with larger separations remain present. A neighborhood-based trigger can therefore retain many spatially compact coincidences while limiting the number of unrelated FEEs included in the decision. The suitability of a one-ring neighborhood is evaluated with simulation and ESRF data in the later analysis chapters.

3.4.4 Alternative Trigger Algorithms

Several simpler alternatives to the trigger algorithms described above are considered here to enable a more comprehensive comparison.

One option is an energy-threshold trigger applied across several modules or the entire detector. A trigger is generated when the total deposited energy exceeds a specified threshold. This approach is commonly used in instruments designed primarily to measure high-energy radiation flux. However, an energy threshold alone cannot identify the event topologies required for Compton polarimetry. POLAR-2 already applies channel-level energy thresholds in its front-end electronics.

Another option is a multiplicity trigger, where the multiplicity is the number of scintillator bars registering a signal within a defined coincidence window. If the minimum multiplicity is set too high, valuable Compton events may be rejected. If it is set too low without considering the distances between interactions, the resulting data rate may exceed the available telemetry. A two-sided multiplicity trigger, which accepts only events within a specified multiplicity range, can additionally reject high-multiplicity events produced by cosmic rays.

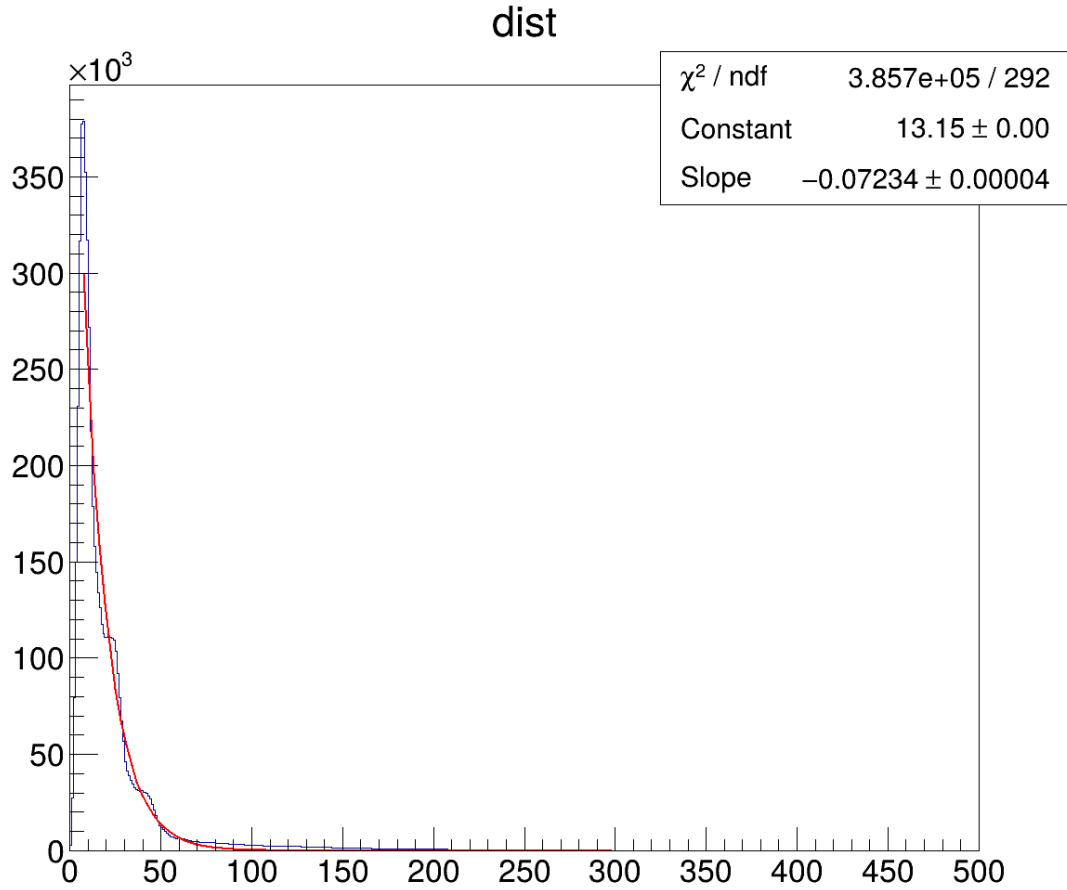


Figure 3.1: Distance between the first and second interactions of selected events measured by POLAR. The horizontal axis gives the interaction separation in millimetres and the vertical axis gives the number of events. The blue curve shows the measured distribution, while the red curve is an exponential fit that captures its overall decrease without reproducing every feature. Adapted from [57].

3.5 Trigger Selection

The comparison performed in this thesis identifies the radius-dependent coincidence trigger as the most suitable compromise between implementation complexity, retention of multi-module Compton events, and suppression of unrelated module activity. The complete lookup table is not feasible because of its prohibitive memory requirement, whereas a purely global energy or multiplicity condition does not use the spatial information available from the segmented detector.

The one-ring neighborhood trigger is therefore selected for further investigation. The concept itself was one of the existing options under consideration and was not developed as part of this thesis. The contribution of the present work is its comparison with the alternative concepts, its FPGA implementation, and its subsequent evaluation. The selection is not an official POLAR-2 baseline decision. Its performance is evaluated using simulations and data from a test campaign at the European Synchrotron Radiation Facility (ESRF), as described in Chapter 5.

3.6 Hardware Implementation

As part of this thesis, the selected one-ring trigger logic was implemented to determine whether the available FPGA inputs, outputs, logic resources, and combinatorial delay are sufficient for the trigger. In particular, the implementation must process the required module signals and return its result within the 100 ns response-time limit. The design was synthesized using Vivado, the FPGA development environment provided by Advanced Micro Devices, Inc. (AMD). The evaluation reported here is restricted to synthesis and does not constitute a hardware test or a complete qualification of the flight firmware.

3.6.1 Vivado

Vivado converts a register-transfer-level hardware description into logic resources of the selected FPGA and reports the resulting resource utilization and signal delays. This makes it possible to assess whether a parallel trigger circuit is compatible with the target device before a complete firmware design is available. The trigger logic can process the module-level request and cosmic signals concurrently, which is required for a deterministic decision within the specified response time.

The work presented here covers the synthesis stage of this design flow. Consequently, the reported utilization and delay characterize the synthesized trigger core; they do not demonstrate operation on the physical BEE hardware. Placement, routing, integration of the remaining interfaces, and hardware validation are outside the scope of the present implementation.

3.6.2 Implementation and Resource Utilization

The FPGA implementation developed in this thesis uses 200 inputs, comprising the 100 trigger-request and 100 `TooMany` signals, and produces 100 trigger-accept

outputs. It implements the trigger equation described above, including the generation of trigger packets. FPGA resource utilization and the worst-case combinatorial delay were evaluated after synthesis. The synthesis results are

- 59% of the available I/O resources,
- 1% of the available LUTs, and
- a worst-case combinatorial delay of 7 ns.

These results demonstrate the synthesis-level feasibility of the core trigger logic. The estimated worst-case combinatorial delay satisfies the 100 ns response-time requirement, while the low LUT utilization leaves logic resources for additional functions. The high fraction of allocated I/O resources is instead a relevant integration constraint. These results describe a preliminary implementation rather than the complete flight firmware: synchronization, final communication interfaces, configuration logic, and further monitoring functions must still be included in the complete resource and timing assessment.

3.7 Trigger Packet

Each trigger decision generates a trigger packet that is transmitted to the central computing unit. There it is used for event association and diagnostic information. The raw packet contains the following fields:

$$P_{\text{raw}} = [t \mid T(99:0) \mid C(99:0) \mid A(99:0)]. \quad (3.16)$$

Here t is a 64-bit timestamp. In the packet concept considered in this thesis, it is assumed to represent nanoseconds relative to the Unix epoch; the final time representation must be confirmed as part of the interface specification. The remaining fields contain the 100 trigger requests T , the 100 **TooMany** signals C , and the 100 trigger accepts A . The prescaled cosmic signal PC is used internally and is not transmitted as a separate field because its effect can be inferred from the stored request, cosmic, and accept fields. The uncompressed packet therefore has a total length of

$$N_{\text{raw}} = 64 \text{ bit} + 3 \times 100 \text{ bit} = 364 \text{ bit}. \quad (3.17)$$

Because the three 100-bit fields are expected to be sparsely populated for many events, several lossless packet encodings were developed conceptually as part of this thesis. Their purpose is to reduce the packet size while retaining an encoding structure that can be implemented and decoded with limited additional complexity.

3.7.1 Sparse Index-List Encoding

Instead of transmitting all 100 bits of a field, the sparse index-list representation transmits only the indices of the bits that are set. The fields T , C , and A are encoded separately. One index requires

$$N_{\text{index}} = \lceil \log_2(100) \rceil = 7 \text{ bit}. \quad (3.18)$$

Since the encoded field has a variable length, an additional 7-bit counter is required to indicate to the decompressor how many indices follow for that field. If k bits are set to one, the sparse representation therefore requires

$$N_{\text{sparse,field}} = 7 + 7k \quad (3.19)$$

bits in total. Sparse encoding is shorter than the raw 100-bit field when $7 + 7k < 100$, corresponding to at most 13 set bits. A different representation is preferable at higher occupancy.

3.7.2 Hybrid Raw/Sparse Encoding

The hybrid encoding selects the shorter representation independently for each of the three 100-bit fields. The number of set bits is counted first. A field with at most 13 set bits is represented by its sparse index list, whereas a field with more than 13 set bits is transmitted in raw form. A three-bit header records the selected mode for T , C , and A . The encoded packet can be written schematically as

$$P_{\text{hybrid}} = [t \mid H \mid \mathcal{E}(T) \mid \mathcal{E}(C) \mid \mathcal{E}(A)], \quad (3.20)$$

where H is the three-bit mode header and $\mathcal{E}(X)$ denotes either the raw or sparse representation of field X . Its length is

$$N_{\text{packet}} = 64 + 3 + \sum_{X \in \{T, C, A\}} \min(100, 7 + 7k_X). \quad (3.21)$$

The reduction therefore depends on the occupancy of the individual fields and is greatest for events with few active modules.

3.7.3 Timing Compression Modes

The timing information can be compressed using relative timestamps, reducing the per-packet timing field to 16 bits or fewer. Shorter relative timestamps require full timestamps to be transmitted more frequently. To prevent synchronization errors from accumulating, each relative timestamp should refer directly to the most recent full timestamp rather than to the preceding relative timestamp. Full timestamps should therefore be transmitted at regular intervals.

Several trigger packets can be combined in one frame. The frame contains one complete base timestamp, the timestamp difference for each subsequent packet, and the encoded trigger fields:

$$F = [H_{\text{frame}} \mid t_0 \mid \Delta t_1, \Delta t_2, \dots, \Delta t_{n-1} \mid \mathcal{E}_0, \mathcal{E}_1, \dots, \mathcal{E}_{n-1}], \quad (3.22)$$

where $\mathcal{E}_m$ contains the encoded T , C , and A fields of packet m . Assuming 16-bit time differences and uncompressed 300-bit trigger fields, an upper estimate of the required working buffer is

$$N_{\text{buffer}}(n) = 64 + 16(n - 1) + 300n. \quad (3.23)$$

This estimate excludes the frame header and any additional bookkeeping. Combining more packets reduces the relative timestamp overhead but increases the required buffer size and the time for which packets must be retained before transmission.

3.7.4 Entropy Coding

Entropy-coding methods such as Huffman coding, arithmetic coding, or LZ-type compression were considered qualitatively but were not implemented or benchmarked. Their variable-length output would require additional metadata, buffering, and control logic. For the short trigger fields considered here, the expected reduction was not judged sufficient to justify this additional FPGA complexity. This conclusion should therefore be understood as a design argument rather than as a quantitative comparison of implemented compression methods.

3.7.5 Assessment of the Encoding Concepts

The synthesis results indicate that FPGA resources remain available for packet encoding. Among the lossless concepts considered here, hybrid raw/sparse encoding provides a simple field-by-field reduction while retaining a fixed and easily decoded structure. If sufficient buffer resources are available, grouping several packets into a frame can additionally reduce the timestamp overhead. The final choice should be confirmed using representative field-occupancy statistics and a complete firmware implementation.

3.8 Chapter Summary and Intermediate Results

This chapter has established the design basis and presented the development work for the global BEE trigger. An analytical model derived in this thesis shows that the expected number of accidental channel-level threshold crossings increases linearly with the number of FEEs included in the trigger region. This relation identifies the central trade-off between retaining spatially separated Compton interactions and limiting accidental readout. The comparison of the candidate concepts excludes a complete lookup-table trigger because of its prohibitive memory requirement and selects the existing one-ring neighborhood concept for further investigation.

The selected trigger equation was implemented and synthesized for the XCKU040 FPGA. The resulting core uses 1% of the available LUTs and has an estimated worst-case combinatorial delay of 7 ns, demonstrating feasibility with respect to the available logic and the 100 ns response-time requirement at the synthesis level. The allocation of 59% of the available I/O resources remains an important constraint for integration. In addition, sparse, hybrid raw/sparse, and frame-based packet encodings were developed. Their final efficiency cannot yet be quantified because they have not been benchmarked with representative occupancy distributions or integrated into complete firmware. The results of this chapter therefore establish a feasible trigger core and a set of packet-format options; the physical event-selection performance of the chosen trigger is evaluated in the subsequent simulation and measurement chapters.

Chapter 4

Geant4 Simulation and Digitization Workflow

4.1 Purpose of the Simulation

The primary objective of the simulation study is to determine the spatial separation of energy deposits in multi-module events and thereby evaluate whether the one-ring BEE trigger selected in Chapter 3 retains the relevant Compton-event topologies. Firmware synthesis, as discussed in the preceding chapter, establishes whether the trigger logic can be realized on the FPGA. The Geant4 simulation addresses the complementary physical question of whether the selected spatial neighborhood is appropriate for the event patterns produced in the detector [3, 4, 5, 35, 61].

For a segmented Compton polarimeter, the trigger-relevant event signature is determined not only by the deposited energy, but also by the spatial and temporal relation between individual detector hits. A Compton-candidate event may involve two or more separated energy deposits, potentially in different FEEs. The simulation must therefore preserve the position, deposited energy, and time of each interaction in the sensitive volumes of the polarimeter [41, 51, 9].

In this work, Geant4 forms the first stage of a processing chain that transforms direct Monte Carlo interaction records into detector-like quantities. Here, direct Monte Carlo information denotes quantities generated by the particle-transport simulation before detector and electronics effects are applied, including the simulated interaction position, deposited energy, time, and particle identity. The digitized output is subsequently used to study the spatial hit distribution, local FEE activity, and BEE involvement. Conceptually, the workflow can be summarized as

$$\begin{aligned} &\text{source definition} \rightarrow \text{Geant4 detector simulation} \rightarrow \text{hit collection} \\ &\rightarrow \text{digitization} \rightarrow \text{trigger analysis.} \end{aligned} \tag{4.1}$$

This sequence separates the physical simulation of particle interactions from the modeling of the detector readout and trigger decisions. The separation is required because the trigger logic receives thresholded and time-discretized channel signals rather than the direct Geant4 interaction records. A secondary objective is to quantify the fraction of accepted simulated events in which the BEE trigger is involved and to test whether the summary observables considered here change when an explicit source polarization is introduced.

4.2 Geant4 Simulation Framework

Geant4 is a Monte Carlo toolkit for simulating the passage of particles through matter [3, 4, 5]. A Geant4 application is typically defined by the detector geometry, the material definitions, the primary particle generator, the selected physics list, and the user actions or sensitive detector classes that record simulation output [25, 26].

The simulation framework used in this work is **Geant4/POLAR2sim**. It describes the propagation of primary and secondary particles through the POLAR-2 detector model and records energy deposits in the sensitive volumes of the polarimeter. The output of this stage consists of ROOT files with names of the form [12]

```
sim_out_*.root
```

ROOT provides both a file format and an analysis framework developed at the Conseil Européen pour la Recherche Nucléaire (CERN) for storing and processing large data sets. The ROOT files from the simulation contain the Geant4-level hit information required for subsequent digitization. In particular, the relevant hit collection is

```
HitsCol_Polarimeter
```

which stores simulated interactions in the polarimeter. The collection includes timing information through the quantity **PreGlobalTime**. This information is essential for constructing detector-like hit times and for later studying coincidence-based trigger conditions.

The Geant4 output is not yet equivalent to the electronic detector output. It is an intermediate data product containing simulated energy deposits, positions, and times before channel mapping and electronics response. These quantities must be converted into channel-based detector observables before they can be used for trigger studies.

4.3 Detector Geometry and Sensitive Volumes

The detector geometry defines the spatial and material configuration through which particles are transported. In a complete POLAR-2 simulation, this includes the scintillator bars, module structure, optical or mechanical interfaces, support materials, inactive regions, and the surrounding simulation environment.

For a segmented Compton polarimeter, the geometry of the scintillator array is a central part of the simulation. The reconstructed or selected event topology depends directly on the relative positions of individual detector elements. The pitch of the scintillator bars, module spacing, inactive material, and channel mapping can all affect the simulated hit multiplicity, the distribution of inter-hit distances, and the probability that an event satisfies a given trigger condition. Consequently, an accurate detector model is required not only for energy-deposition studies, but also for evaluating trigger-relevant topologies [51, 35, 61].

Energy deposits are recorded in sensitive detector volumes. A sensitive detector class collects information whenever a particle deposits energy in an active detector

element. In Geant4 terminology, a hit can store information associated with a simulation step, such as position, time, deposited energy, track momentum, track energy, and geometrical information [26].

For a detector element i , the total deposited energy can be written as a sum over all Geant4 steps k assigned to that element:

$$E_i^{\text{dep}} = \sum_{k \in i} \Delta E_k, \quad (4.2)$$

where ΔE_k denotes the energy deposited in step k . This expression emphasizes that a detector-level hit may be constructed from several individual Geant4 steps. The later digitization stage must therefore combine the relevant energy-loss contributions before forming channel-level detector signals.

4.4 Primary Particle Generation

The Geant4 simulation is configured through a General Particle Source (GPS) macro. The GPS specifies the particle type, spatial and angular source distributions, energy spectrum, and, when required, the polarization vector [24]. The configuration used for the simulations discussed in this chapter generates gamma rays from a circular plane source centered above the detector. Its parameters are summarized in Table 4.1.

Table 4.1: GPS configuration used for the detector-wide simulation.

Parameter	Value
Particle type	Gamma ray
Source type and shape	Plane, circle
Source center	(0, 0, 50 cm)
Source radius	20 cm
Polar-angle range	$0^\circ \leq \theta \leq 10^\circ$
Azimuthal-angle range	$0^\circ \leq \phi \leq 360^\circ$
Energy distribution	Power law, $N(E) \propto E^{-1.8}$
Energy range	50–500 keV

In the Geant4 GPS convention, $\theta = 0^\circ$ corresponds to incidence along the negative z -direction. The source therefore illuminates the detector approximately perpendicular to its plane, with an angular spread of up to 10° . The power-law energy distribution covers the energy range relevant to the present trigger study.

The reference source macro does not specify a polarization vector. For the polarized comparison, all source parameters were retained and the command

```
/gps/polarization 1 0 0
```

was added. This command defines a global polarization vector along the positive x -direction. The comparison is used only to test the sensitivity of the spatial and trigger-summary observables considered in this chapter. It is not intended as a precision reconstruction of the polarization modulation.

An external ROOT-based time profile can optionally be supplied through

-t <time_profile.root>

to assign the primary events a predefined temporal distribution. Such a profile is relevant when accidental coincidences, event overlap, or rate-dependent trigger behavior are studied. It is not required for observables based exclusively on the positions and energies within an individual simulated event.

4.5 Physics Processes

The physics list determines which interaction models are used during particle transport. In the simulated energy range of 50–500 keV, the primary photon processes relevant to the present analysis are Compton scattering and photoelectric absorption, together with the transport and energy loss of the resulting secondary electrons. These processes determine the scattering-angle distribution, hit multiplicity, and spatial distribution of deposited energy [25].

The complete physics list registered by the POLAR-2 simulation framework contains electromagnetic, hadronic, ion, and stopping-physics components. Not every component contributes to the gamma-ray simulations considered here. The relevant component is the Livermore polarized electromagnetic physics, because it provides the photon-interaction models, including polarization-dependent Compton scattering, used in the present energy range. The remaining components are retained as part of the general simulation framework and support other particle species or higher-energy interactions.

The principal simulation parameters are:

- Geant4 version: 4.10.7.2
- Physics list registered by the framework:
 - ion physics;
 - stopping physics;
 - hadron elastic physics;
 - gamma-nuclear physics;
 - neutron tracking cut;
 - ion QMD physics;
 - ion elastic physics;
 - hadron physics; and
 - Livermore polarized electromagnetic physics.
- Production or range cuts: no additional cuts were specified in the simulation configuration.
- Output thresholds: hit threshold 0.1 eV and bar threshold 100 eV.
- Number of simulated events per production: $\geq 10^5$.

The two threshold values are not the simulated photon-energy range. They determine which deposited-energy records are retained at the hit and bar levels. The source-energy range is specified independently in Table 4.1.

4.6 Hit-Level Simulation Output

For each simulated event, Geant4 transports the primary photon and all relevant secondary particles through the detector geometry. Whenever energy is deposited in a sensitive volume of the polarimeter, the corresponding information is written to the hit collection `HitsCol_Polarimeter`. This hit collection forms the interface between the particle-transport simulation and the digitization stage. In Geant4, such hit collections are produced by sensitive detector classes and are attached to the corresponding event [26].

A generic simulated hit can be represented as

$$h_i = \left(E_i^{\text{dep}}, \mathbf{r}_i, t_i, m_i, c_i \right), \quad (4.3)$$

where E_i^{dep} is the deposited energy, $\mathbf{r}_i$ is the interaction position or detector-element position, t_i is the hit time, m_i denotes the module or FEE assignment, and c_i denotes the corresponding channel or bar identifier. This notation is schematic; the actual ROOT output stores these quantities in a different form across several branches.

The hit time is derived from the Geant4 timing information. In the available hit collection, the relevant quantity is `PreGlobalTime`, which provides the global time associated with the beginning of a simulated interaction step. During digitization, this information is used to construct detector-level timing quantities and coincidence conditions. The present analysis uses the resulting digitized timing fields and does not infer additional timing conventions that are not explicitly stored in the output.

The hit-level output is still an idealized representation. It does not yet include all effects associated with the detector readout chain, such as threshold behavior, finite resolution, electronic noise, channel calibration, dead time, or ADC conversion. These effects are introduced, if implemented, during digitization.

4.7 Digitization Workflow

The digitization step converts the direct Geant4 hit records into quantities that resemble the POLAR-2 detector readout. This transformation is necessary because the trigger system operates on channel-based electronic signals rather than on simulated interaction steps.

The digitization maps the simulated energy deposits to detector channels. Conceptually, this can be written as

$$i \rightarrow j, \quad (4.4)$$

where i labels a simulated hit or detector element and j labels the corresponding readout channel. For POLAR-2, this mapping must preserve the hierarchy of bars, modules, FEEs, and the BEE-level detector organization [35, 61].

For a detector channel j , the digitized signal can be expressed generically as

$$S_j = \sum_{i \in j} f_i \left(E_i^{\text{dep}}, t_i \right), \quad (4.5)$$

where S_j is the signal assigned to channel j , and f_i denotes the detector and electronics response implemented by the digitizer for a given deposited energy and hit time. This response maps the simulated energy deposits to the channel-level quantities used by the trigger analysis.

A simplified threshold condition can be written as

$$T_j = \begin{cases} 1, & S_j > S_{\text{thr}}, \\ 0, & S_j \leq S_{\text{thr}}, \end{cases} \quad (4.6)$$

where S_{thr} is the threshold applied to the digitized channel signal and T_j indicates whether the channel passes the threshold. This expression is intended as a conceptual description. The actual implementation may apply thresholds to ADC values, calibrated amplitudes, shaped electronic signals, or other internal quantities.

The digitization can therefore be summarized as the transformation

$$\left\{ E_i^{\text{dep}}, \mathbf{r}_i, t_i \right\}_{\text{Geant4}} \rightarrow \{ S_j, T_j, m_j, c_j, \text{trigger flags} \}_{\text{digitized}}. \quad (4.7)$$

This transformation reduces detailed Monte Carlo step information to detector-level observables that can be used for trigger and readout studies.

4.8 Digitized ROOT Output

After digitization, the output is stored in ROOT structures such as [12]

```
PolInfo
PolModules
PolTrigger
```

These structures represent different levels of the digitized event description. Only the quantities used in the present analysis are discussed here.

PolInfo contains event-level information and metadata associated with the digitized event.

PolModules represents module-level or detector-unit-level information. It can be used to preserve the connection between physical detector regions and electronic readout units. For a detector organized into bars, modules, and FEEs, this layer is necessary for studying local activity and the spatial structure of simulated events.

PolTrigger contains trigger-related quantities. This structure is central for BEE-trigger studies because it contains variables such as

```
final_startADC
bee_trigger_accept
```

The variable **final_startADC** identifies events for which the local ADC-start condition is fulfilled. The variable **bee_trigger_accept** identifies events accepted by the BEE trigger logic. These quantities make it possible to separate local FEE-level activity from globally accepted events.

The digitized ROOT output is therefore not simply a reformatted version of the Geant4 hit collection. It represents a higher-level detector data product, in which the simulated physical interactions have been mapped onto the readout and trigger structure of POLAR-2.

4.9 Use in Trigger Studies

The digitized simulation output is used to evaluate how physical event patterns are treated by the trigger logic. Two complementary descriptions are required. First, the spatial separation of energy deposits determines whether an event is contained within one FEE, spans the one-ring neighborhood, or extends beyond the selected BEE trigger radius. Second, the trigger flags stored in `PolTrigger` indicate whether the BEE participated in the acceptance of a digitized event.

The relevant selections can be written without placing long code expressions in the running text as

$$\text{final_startADC} = 1 \quad \wedge \quad \text{bee_trigger_accept} = 0 \quad (4.8)$$

and

$$\text{final_startADC} = 1 \quad \wedge \quad \text{bee_trigger_accept} = 1. \quad (4.9)$$

The first condition describes a final trigger packet without BEE acceptance, whereas the second identifies a final packet for which the BEE acceptance flag is set. Because one physical event can produce more than one trigger packet, the final classification is performed using unique event identifiers. An event is classified as BEE-involved if at least one of its final trigger packets has `bee_trigger_accept = 1`; otherwise it is classified as FEE-only.

If N_{BEE} and N_{FEE} denote the numbers of unique BEE-involved and FEE-only events, respectively, the BEE-involved fraction is

$$R_{\text{BEE}} = \frac{N_{\text{BEE}}}{N_{\text{FEE}} + N_{\text{BEE}}}. \quad (4.10)$$

This fraction measures how often the BEE trigger participates in the accepted simulated sample. It is neither the fraction of events initiated exclusively by the BEE nor the absolute physical detection efficiency of POLAR-2.

The principal spatial observable is the separation between two detector hits. For detector positions $\mathbf{r}_i$ and $\mathbf{r}_j$, it is

$$d_{ij} = |\mathbf{r}_i - \mathbf{r}_j|. \quad (4.11)$$

For a regular detector grid with pitch p , this can be written as

$$d_{ij} = p\sqrt{(\Delta x)^2 + (\Delta y)^2}. \quad (4.12)$$

Here, Δx and Δy are the differences in bar-grid indices. At the module level, the same event can be classified by the differences in FEE indices or by the corresponding neighborhood ring. This event-level distance distribution, evaluated as a function of photon energy, is the direct observable required to assess the one-ring trigger. A detector-wide hit map instead combines all events and is useful for visualizing the ensemble response, but it cannot by itself determine the separation probability of the deposits within an individual event. In Compton polarimetry, this distinction is important because a spatial trigger selection can modify the accepted scattering-angle distribution and therefore the measured modulation curve [51, 9].

4.10 Simulation Results

Having described the simulation setup, this section presents the results. The current analysis focuses on two aspects: the detector-wide distribution of hit counts and the proportion of accepted events in which the BEE trigger is involved. The hit-count distribution provides an ensemble-level view of the spatial response and reveals structures at the module boundaries. The event-level separation of energy deposits remains the direct quantity required for a quantitative assessment of the one-ring trigger.

4.10.1 Spatial Distribution of Detector Hits

To characterize the spatial distribution of detector activity and the decrease in hit rate at the source boundaries, the circular source described in Table 4.1 was centered above the detector. Its radius was 20 cm and its center was located 50 cm above the detector plane. The incident photons followed a power-law spectrum between 50 and 500 keV and arrived within 10° of the negative z -direction. The simulated output was digitized and used to produce the hit-count map shown in Figure 4.1. Each map bin corresponds to one scintillator bar and contains the number of recorded hits in that bar.

The approximately circular illuminated region and its decreasing hit count toward the detector edges are visible in Figure 4.1. The central region is not perfectly uniform. Narrow enhancements coincide with several FEE boundaries and produce local maxima in the central profiles. The map alone does not establish whether these structures arise from the simulated detector geometry, the mapping and aggregation of bars into modules, or another boundary-dependent response. Their origin therefore requires an event-level comparison of hits in module interiors and at module boundaries.

Central horizontal and vertical strips were extracted from the map. Figure 4.2 shows their normalized hit-count profiles. The red curves are empirical flat-top fits used to quantify the plateau width and the transition at both source boundaries. They reproduce the overall envelope of the distribution but not the narrow enhancements at individual module boundaries.

The fit results are summarized in Table 4.2. The close agreement between the horizontal and vertical values indicates that the large-scale response is approximately symmetric in the detector plane.

Table 4.2: Plateau and transition widths obtained from the horizontal and vertical hit-count profiles of the reference simulation.

Fit quantity	Horizontal	Vertical
Plateau width	331.46 mm	331.93 mm
Low-coordinate 10–90% width	72.88 ± 1.49 mm	71.93 ± 1.41 mm
High-coordinate 90–10% width	70.09 ± 1.36 mm	72.47 ± 1.45 mm

The transition widths cannot be attributed exclusively to Compton scattering.

POLAR-2 hit-count map

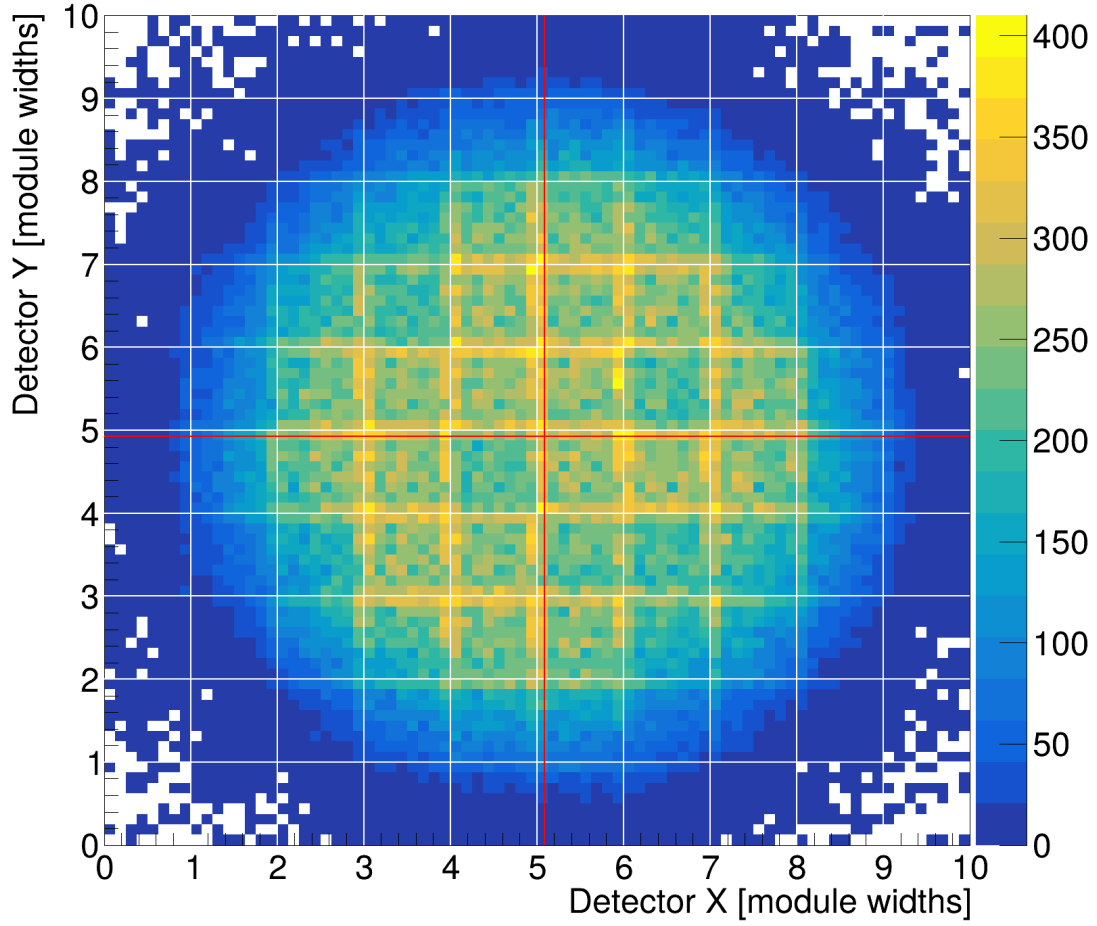


Figure 4.1: Simulated POLAR-2 hit-count map for the circular source described in Table 4.1. The color scale gives the number of hits recorded in each scintillator bar. Both detector axes are expressed in FEE-module widths. White grid lines mark the boundaries of the 10×10 FEE matrix, while the red lines delimit the central horizontal and vertical strips used to obtain the profiles in Figure 4.2.

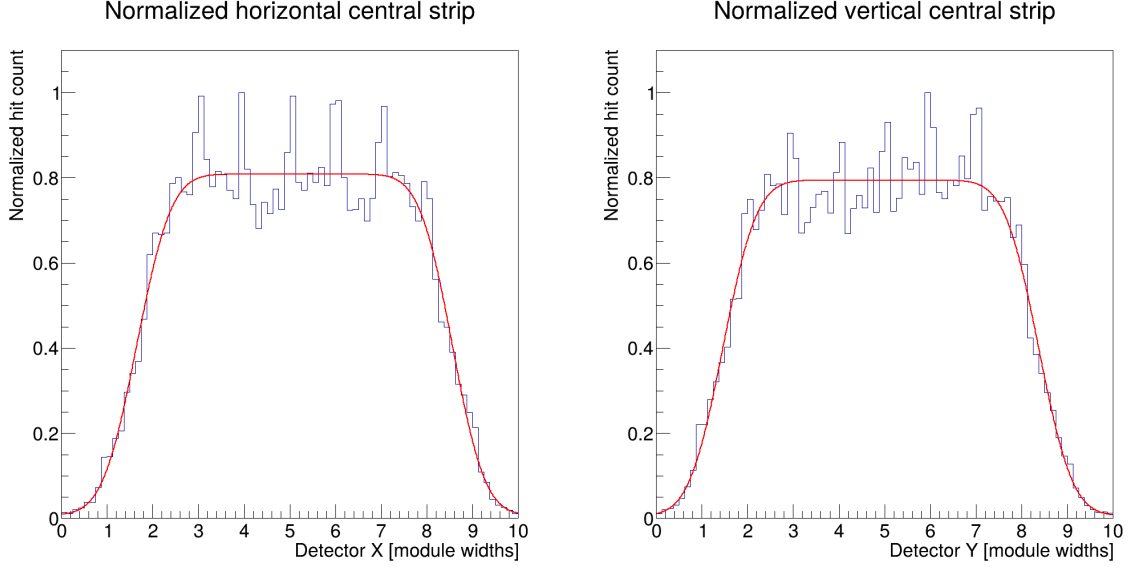


Figure 4.2: Normalized hit-count profiles of the central horizontal strip (left) and vertical strip (right) marked in Figure 4.1. The blue step curves show the simulated profiles, normalized to their respective maxima. The red curves show empirical flat-top fits used to determine the plateau widths and the 10–90% transition widths. Positions are expressed in FEE-module widths.

The angular source extent alone permits a maximum lateral displacement of

$$\Delta r_{\max} = 50 \text{ cm} \tan(10^\circ) \approx 88 \text{ mm.} \quad (4.13)$$

between the source plane and the detector. The measured 10–90% widths of approximately 70–73 mm are therefore compatible in scale with broadening from the source geometry itself. Consequently, these profiles characterize the combined source and detector response, but they do not determine the probability that two deposits from the same event are separated by more than one FEE neighborhood. The earlier inference that fewer than 10% of scattered events extend beyond the adjacent module is therefore not made from this plot.

4.10.2 Comparison of Polarized and Reference Simulations

The detector-wide simulation was repeated with identical source parameters after adding the polarization vector along the positive x -direction. The digitized polarized sample contained 659,724 entries in `PolModules`, of which 41,028 fulfilled the hit-map selection. The hit-weighted centroid of the accepted sample was located at (5.090, 4.921) in module-width coordinates, close to the geometrical centre of the 10×10 detector plane.

Figure 4.3 shows the hit-count map obtained from the polarized simulation. Its approximately circular footprint, the reduction in hit count toward the source boundary, and the local enhancements near several module boundaries reproduce the principal features of the reference map in Figure 4.1. The maximum of an

individual map bin was 35 hits. Owing to the lower number of accepted hits, the bin-to-bin statistical fluctuations are more pronounced than in the reference sample.

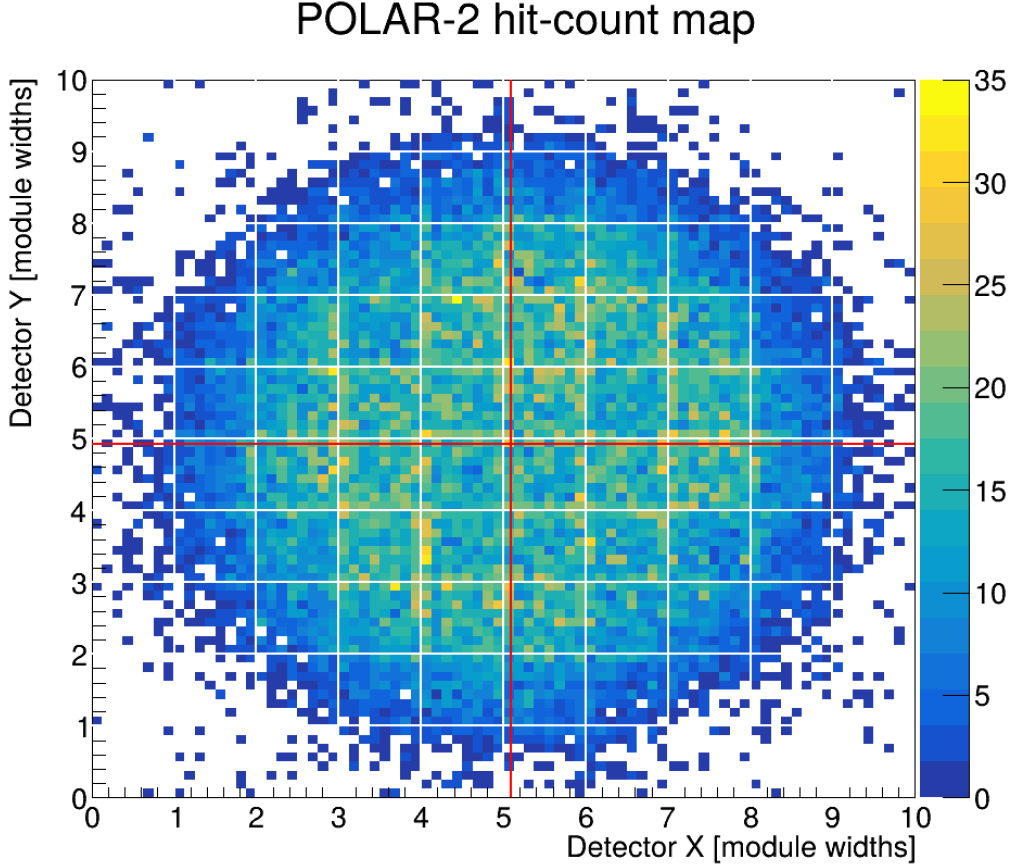


Figure 4.3: Simulated POLAR-2 hit-count map for the source polarized along the positive x -direction. The source geometry and energy spectrum are otherwise identical to those of the reference simulation. The color scale gives the number of selected hits per scintillator bar. White lines mark FEE boundaries, while the red lines pass through the hit-weighted centroid and define the horizontal and vertical strips used for Figure 4.4.

The normalized central profiles of the polarized sample are shown in Figure 4.4. The fit parameters are summarized in Table 4.3. The fitted plateau extends over approximately 6.9 module widths in both directions. The transition widths range from 1.20 to 1.43 module widths.

No distinct polarization-dependent anisotropy is visible in these detector-wide maps or one-dimensional profiles. This is expected because they aggregate the positions of individual hits over all events and thereby discard the relative azimuthal direction between the deposits belonging to one event. The comparison therefore does not imply that the detector response is independent of polarization. Linear polarization changes the azimuthal distribution of Compton scattering, which is the basis of the POLAR-2 measurement principle [41, 51]. The corresponding polarization signature must be studied with an event-level, azimuthally resolved observable such as the modulation curve presented for the ESRF data in Section 5.9.

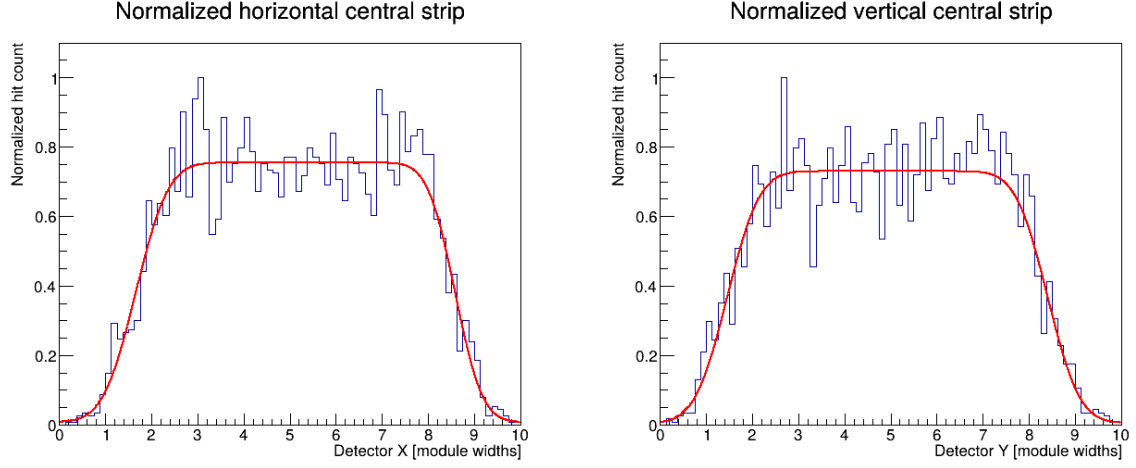


Figure 4.4: Normalized horizontal (left) and vertical (right) central hit-count profiles of the polarized simulation. The blue step curves show the selected hit counts normalized to the maximum of the respective profile. The red curves are empirical flat-top fits used to characterize the plateau and the transitions at the source boundaries.

Table 4.3: Fit results for the central profiles of the polarized simulation. Widths are given in FEE-module widths.

Fit quantity	Horizontal	Vertical
Plateau width	327.71 mm	315.72 mm
Low-coordinate 10–90% width	$91.45 \pm 6.72\text{mm}$	$90.31 \pm 6.65\text{mm}$
High-coordinate 90–10% width	$76.61 \pm 6.14\text{mm}$	$89.61 \pm 7.25\text{mm}$

4.10.3 BEE-Trigger Involvement

The digitized simulation was also used to determine how frequently the BEE trigger participates in accepted events. The classification follows the event-level definition introduced in Section 4.9: a unique event is BEE-involved if at least one final `PolTrigger` packet has `bee_trigger_accept` = 1. All other accepted unique events are classified as FEE-only.

The resulting counts are summarized in Table 4.4. The quoted uncertainties are binomial statistical uncertainties expressed in percentage points.

Table 4.4: Event-level FEE/BEE classification of the digitized simulation.

Category	Number of events	Fraction
FEE-only	1,164,776	$(84.918 \pm 0.031) \%$
BEE-involved	206,867	$(15.082 \pm 0.031) \%$
Total	1,371,643	100 %

Equation 4.10 therefore gives

$$R_{\text{BEE}} = 0.15082 = 15.082 \%. \quad (4.14)$$

The corresponding ratio of FEE-only to BEE-involved events is

$$N_{\text{FEE}} : N_{\text{BEE}} = 5.631 : 1. \quad (4.15)$$

Thus, the BEE participates in approximately 15% of the accepted simulated events, while approximately 85% are classified as FEE-only. This result quantifies the operational relevance of the BEE trigger but does not by itself establish the completeness of the one-ring neighborhood. That assessment requires the event-level distribution of interaction separations, including its dependence on photon energy and the fraction of events contained within zero, one, or more FEE-neighborhood rings.

4.11 Chapter Summary

The simulation and digitization chain developed and applied in this work connects Geant4 interaction records to the channel- and module-level quantities used by the BEE trigger analysis. A detector-wide source with a power-law spectrum between 50 and 500 keV was used to characterize the spatial hit-count distribution. The resulting profiles show an approximately symmetric large-scale response with 10–90% transition widths of about 70–73 mm, together with narrow enhancements at several module boundaries. Because the source divergence can itself produce a lateral displacement of up to approximately 88 mm, the edge profiles cannot be interpreted directly as event-level Compton-interaction separations.

The event classification shows that the BEE trigger is involved in $(15.082 \pm 0.031) \%$ of accepted unique events. The polarized simulation produces the same qualitative detector-wide footprint as the reference simulation, and no distinct polarization-dependent anisotropy is visible in the spatially aggregated hit map or central profiles. This is not a test of the polarimetric response, because these observables do

not retain the event-level azimuthal direction. The principal remaining quantity for a complete evaluation of the selected trigger radius is the event-level separation distribution as a function of photon energy and FEE-neighborhood ring. This distribution, rather than the detector-wide hit-map envelope, provides the direct test of whether the one-ring trigger retains the relevant multi-module Compton events.

Chapter 5

ESRF Data Analysis for POLAR-2 Trigger Studies

5.1 General Description of the ESRF

The European Synchrotron Radiation Facility (ESRF) is an international synchrotron facility in Grenoble, France. It provides intense and well-controlled X-ray beams for a broad range of scientific applications, including detector development and characterization. In the context of this thesis, the ESRF provides controlled irradiation conditions for studying the timing and spatial response of the POLAR-2 detector modules [19, 62].

Synchrotron radiation is emitted when relativistic charged particles are accelerated transversely, for example by bending magnets, wigglers, or undulators. Depending on the accelerator mode and beamline configuration, the resulting photon beam can be intense, collimated, tunable in energy, and strongly polarized [75, 72]. These properties allow detector responses to be studied under conditions that cannot be obtained from astrophysical sources and are difficult to reproduce with conventional radioactive calibration sources.

The data analysed in this chapter were recorded by the POLAR-2 collaboration at the ID19 beamline from 2 to 9 February 2026. The irradiated detector consisted of nine FEEs arranged in a 3×3 configuration. Photon energies between 30 and 190 keV were used during the campaign. The results presented below combine the measurements from all available beam energies unless stated otherwise.

5.2 Objectives of the Data Analysis

In this chapter, the term *ESRF data analysis* refers to the processing chain developed to synchronize the recorded master and slave data, construct timing clusters, account for the finite spatial granularity of the detector, calculate hit-distance spectra, and reconstruct a raw azimuthal modulation curve. The synchronization, clustering, sub-bar smearing, distance, and azimuthal-analysis software used for the presented results was implemented and executed as part of this thesis. Methodological choices were additionally refined through discussions within the POLAR-2 collaboration.

The primary objective is to measure the temporal and spatial structure of de-

tector activity relevant to the POLAR-2 BEE trigger. In particular, the analysis determines whether temporally correlated two-hit clusters are confined to neighbouring bars or extend across larger parts of the detector. This measured distance distribution provides experimental input for assessing trigger concepts that combine information from several FEEs. In addition, the folded azimuthal distribution of the selected pairs is used to demonstrate the polarization-dependent detector response present in the ESRF data.

The ESRF measurements complement the Geant4 study presented in Chapter 4. Geant4 produces simulated interaction positions, deposited energies, and times before detector and electronics effects are applied. The ESRF data instead contain the response of the detector and acquisition system, including measured timing behaviour, channel occupancy, readout effects, and synchronization uncertainties. The two data sets therefore describe different stages of the detector response and cannot be compared quantitatively unless the source configuration, event selection, and reconstructed observables are matched.

5.3 Detector and Data-Acquisition Configuration

The detector configuration used during the ESRF campaign consisted of nine FEEs arranged as a 3×3 system. Each FEE reads an 8×8 grid of scintillator bars. The complete detector plane used in the analysis can therefore be represented as a 24×24 global bar grid. This coordinate system is required to calculate distances between hits located in different FEEs. The configuration refers specifically to the ESRF measurement setup and must be distinguished from the full POLAR-2 flight-instrument layout described in Chapter 2.

The scintillator-bar pitch is $p = 6$ mm. Before sub-bar smearing is applied, a hit position is represented by discrete global bar indices. The metric position follows from the global index and the bar pitch.

The flight BEE implementation was not yet available for the ESRF campaign. The detector was therefore read out using two Zynq-based acquisition systems, officially designated as the master and the slave systems. A single system could not process the expected input rate from all nine FEEs. Five FEEs were consequently connected to the master system and four FEEs to the slave system, approximately dividing the input rate between the two acquisition paths.

The FEE IDs assigned to the master system were 201, 209, 207, 204, and 206. The FEE IDs assigned to the slave system were 203, 241, 213, and 212. Their physical arrangement in the detector plane is shown in Figure 5.1. This mapping is required for transforming module-local bar coordinates into the global detector coordinates. An incorrect FEE placement would directly distort the reconstructed distance spectrum.

5.4 Input Data and Synchronization Files

The analysis starts from master–slave pair files recorded during the ESRF campaign and stored in ROOT format [12]. After synchronization, the files are stored in paths of the form

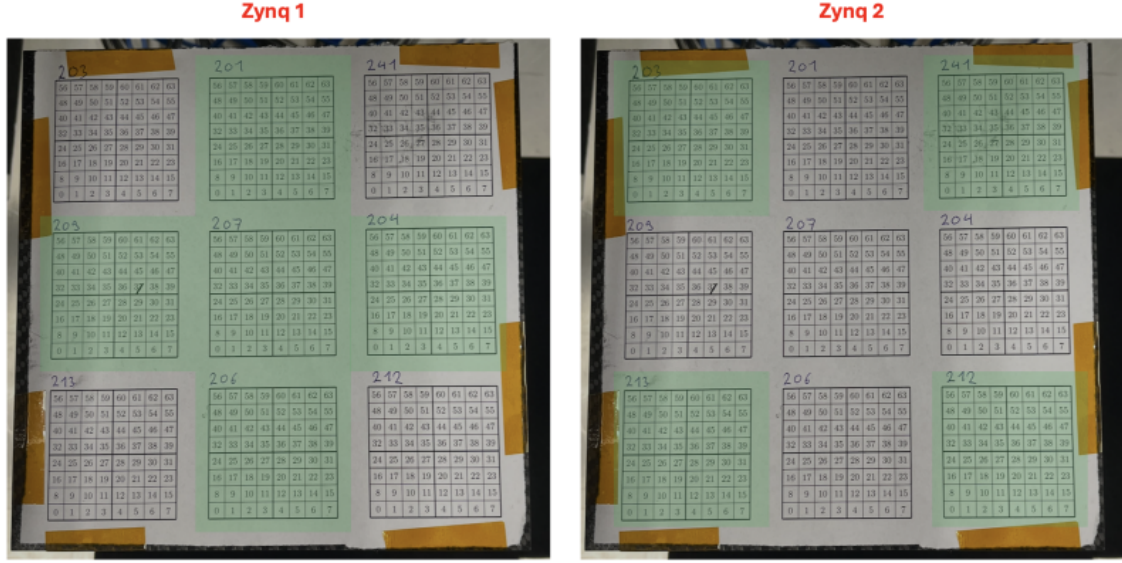


Figure 5.1: Arrangement of the nine FEE modules in the ESRF detector configuration and their assignment to the two Zynq-based acquisition systems. Zynq 1 is the officially designated master system and reads five FEEs, while Zynq 2 is the slave system and reads four FEEs. The numbers denote the FEE IDs used for mapping local bar positions to the global 24×24 bar grid.

`pair_*/synced_pair.root`

Each synchronized pair file contains an event tree named `event_sync`

which stores the matched timing information for one master–slave data set. Position-corrected files may additionally be stored in paths of the form

`pair_*/pos/*_cor_pos.root`

with a tree named

`pos`

The fields required for the present analysis include `utime`, `srot`, `sz`, `yrot`, `mod_id`, `bar_id`, `energy`

Their roles are as follows:

- `utime` stores the Unix time associated with the recorded data;
- `srot`, `sz`, and `yrot` store the detector-position settings used during irradiation;
- `mod_id` and `bar_id` identify the FEE module and scintillator bar in which a hit was recorded; and
- `energy` stores the photon-beam energy assigned to the measurement.

Not every recorded master–slave pair data set contributes to the final analysis. A data set is excluded if its count rate is insufficient or if the relative timing relation cannot be determined with the required quality. The selection criteria are described in the following section.

5.5 Timing Synchronization

Timing synchronization is required before hits recorded by different acquisition systems can be combined into one cluster. Each FEE records local detector activity, but the reconstruction of multi-FEE topologies requires the master and slave timestamps to be expressed in a common timing convention. Without synchronization, a difference between two timestamps could be caused by a relative clock offset or drift rather than by the detector event.

The pair-wise synchronization procedure developed for this analysis determines the relative timing relation between the master and slave data streams. The time-dependent offset is evaluated for each master–slave pair data set, and data sets with sufficient statistics and a stable timing relation are retained. The resulting synchronized files form the basis for the subsequent timing-cluster reconstruction.

Figure 5.2 shows the relative timing offset for one representative master–slave pair. A changing offset indicates a relative clock drift between the two acquisition systems.

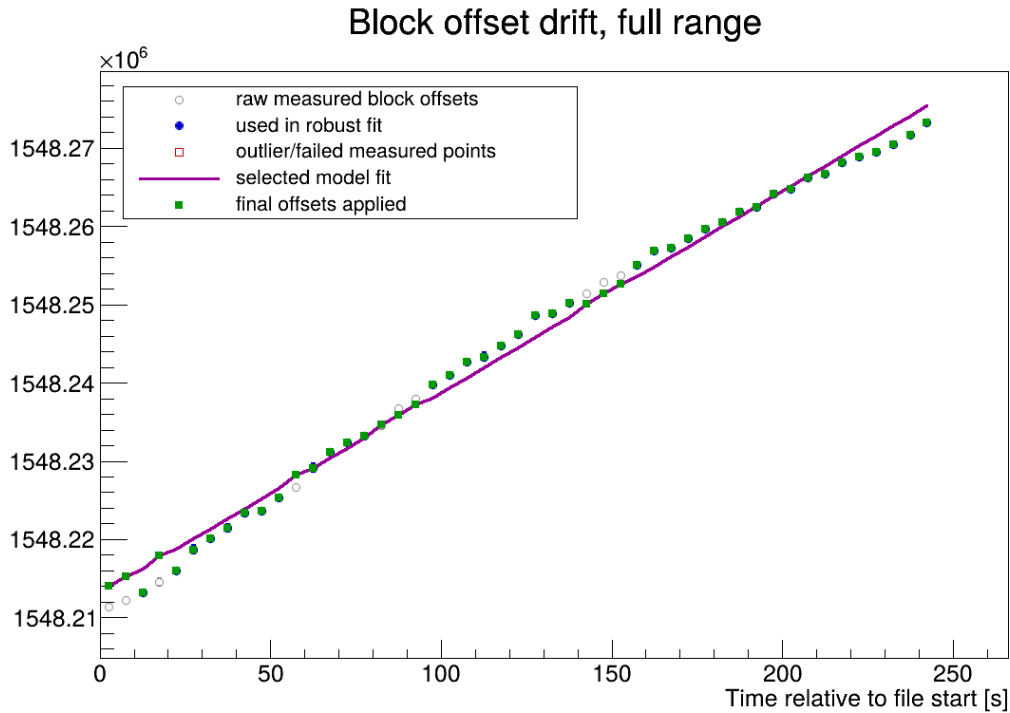


Figure 5.2: Relative timing offset between the master and slave acquisition systems for one representative pair data set. The horizontal axis gives the elapsed time since the start of the measurement, and the vertical axis gives the relative master–slave timing offset in milliseconds. The slope of the offset determines the relative clock drift.

In total, 148 master–slave pair data sets were identified. Of these, 89 fulfilled the synchronization-quality criteria. An accepted data set was required to have an absolute relative drift below 2 ppm and a median absolute deviation (MAD) of the timing residuals below 50000 ns. For the accepted data sets, the mean relative drift was 0.318 ppm, with values ranging from 0.104 to 0.589 ppm.

The synchronization quality directly affects all subsequent timing-cluster and distance analyses. A residual synchronization error broadens the reconstructed time difference between correlated hits. It can therefore cause physically related hits to be separated into different clusters or unrelated hits to be combined within the selected coincidence window.

5.6 Timing-Only Clustering

After synchronization, detector hits are grouped using timing information only. Spatial coordinates are deliberately excluded from the cluster definition because the spatial-distance distribution is one of the target observables. Using hit positions during clustering would bias this distribution by construction.

The nominal clustering window is 50 ns, following the timing requirements of the BEE trigger described in Chapter 3. The analysis uses an earliest-seed clustering mode. The earliest unassigned hit defines the start of a cluster, and subsequent hits are assigned to that cluster if their timestamps lie within 50 ns of the seed time. The cluster multiplicity M_C is the number of hits assigned to cluster C .

Only clusters with exactly two hits are used for the distance spectrum presented below. Such a cluster provides one unambiguous pair distance. Higher-multiplicity clusters contain several possible hit pairs and would require an additional pairing or ordering rule. Moreover, timing alone does not determine which of the two recorded hits represents the first physical interaction of the photon. The two entries are therefore referred to simply as the two hits of the cluster rather than as the first and second Compton interactions.

5.7 Spatial Distance Reconstruction

Once the timing clusters have been constructed, the distance between the two hits in each exact-two-hit cluster is calculated as described in Chapter 4. For detector-plane positions $\mathbf{r}_1 = (x_1, y_1)$ and $\mathbf{r}_2 = (x_2, y_2)$, the reconstructed separation is

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}. \quad (5.1)$$

The spatial granularity is limited by the 6 mm pitch of the scintillator bars. Assigning every hit to the centre of its bar would therefore discretize the reconstructed distances, although the actual interactions can occur anywhere within the bar.

To account for this uncertainty, each hit position is assigned a random offset sampled uniformly across one bar pitch in both detector-plane coordinates. This sub-bar smearing approximates the unknown interaction positions and allows the effect of the detector's finite spatial resolution on the reconstructed distances to be included. The smeared position is

$$\mathbf{r}'_i = \mathbf{r}_i + \delta \mathbf{r}_i, \quad \delta x_i, \delta y_i \sim \mathcal{U}\left(-\frac{p}{2}, \frac{p}{2}\right), \quad (5.2)$$

where $\mathbf{r}_i$ is the nominal bar-centre position and $p = 6$ mm. The distance is recalculated from the two independently smeared hit positions. The resulting spectrum, combined over beam energies from 30 to 190 keV, is shown in Figure 5.3.

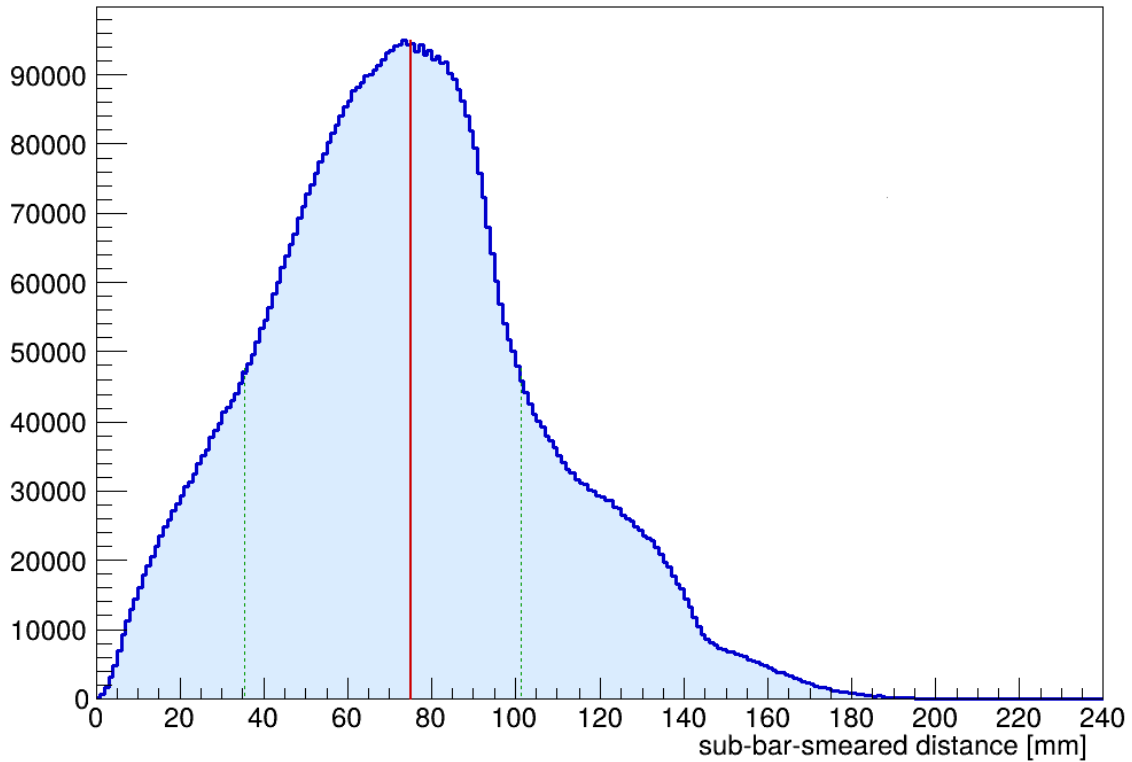


Figure 5.3: Reconstructed distance between the two hits in each exact-two-hit timing cluster, combined over ESRF beam energies from 30 to 190 keV. The horizontal axis gives the smeared detector-plane distance between the two hits in millimetres. The vertical axis gives the number of exact-two-hit clusters. The red vertical line marks the maximum of the distribution at 75.00 mm. The measured features are discussed in Section 5.8.

The distance spectrum provides an event-level description of the spatial structure of temporally correlated detector activity. Distances below 12 mm correspond to hits in the same bar or nearby bars. The width of one FEE is approximately eight bar pitches, or 48 mm, so larger separations frequently involve activity distributed over substantial parts of a module or across module boundaries. This makes the spectrum directly relevant to trigger algorithms that combine information from several FEEs.

5.8 Observed Distance-Spectrum Features

For exact-two-hit clusters constructed with the nominal 50 ns timing window, the measured distance spectrum has its maximum at 75.00 mm and a mean of approximately 73.76 mm. Of the selected clusters, 8.7 % have distances below 30 mm, 46.1 % lie between 60 and 100 mm, and 19.3 % have distances above 100 mm.

The concentration between 60 and 100 mm shows that a substantial fraction of temporally correlated two-hit activity is separated by more than the width of one FEE. The result therefore supports the need for a trigger stage that can combine trigger requests from different FEEs. It does not, by itself, establish that every selected pair is a correctly ordered Compton event, because the timing-only selection does not reconstruct the physical interaction sequence or impose Compton-kinematic consistency.

No simulation reproducing the complete ESRF source and acquisition configuration was available for a direct comparison. The detector-wide simulation in Chapter 4 also shows a decrease in spatial activity away from the dominant region, but its hit map and the ESRF pair-distance spectrum are different observables obtained with different source configurations. A quantitative agreement between the simulation and the ESRF measurement is therefore not claimed.

The stability of the distance distribution was evaluated by repeating the clustering with timing windows of 25, 50, and 75 ns. Figure 5.4 shows the normalized spectra. The main features remain stable over the tested range, indicating that the measured shape is not produced by the specific choice of the nominal 50 ns window.

5.9 Raw Modulation Curve

The ID19 beam used for the measurements was 100 % linearly polarized, with the polarization direction perpendicular to the beam plane. Linear polarization changes the azimuthal distribution of Compton scattering and can therefore be studied using the orientation of the two-hit separation vector [51, 9]. For the sub-bar-smeared positions introduced in Equation 5.2, the azimuthal angle is calculated as

$$\eta = \text{atan2}(y'_2 - y'_1, x'_2 - x'_1) \bmod \pi. \quad (5.3)$$

Folding the angle into the interval $0^\circ \leq \eta < 180^\circ$ removes the ambiguity caused by exchanging the two hits, because reversing the separation vector changes its azimuth by 180° . The same exact-two-hit clusters as in the distance analysis are used; no interaction order is assigned.

The polarization-sensitive component of a modulation curve has a period of 180° and can be written schematically as

Timing-window stability of exact-two-hit distance

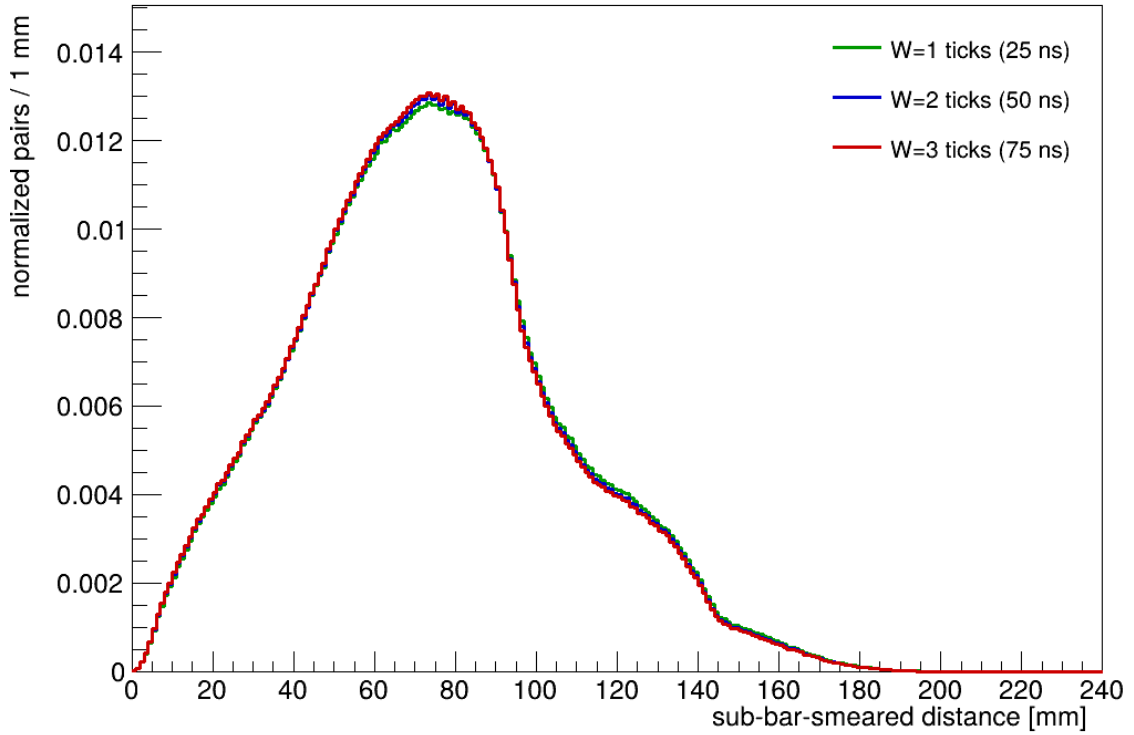


Figure 5.4: Comparison of normalized exact-two-hit distance spectra obtained with clustering windows of 25, 50, and 75 ns. The horizontal axis gives the reconstructed distance between the two hits in millimetres, and the vertical axis gives the normalized fraction of selected hit pairs. The main features of the distribution remain stable over the tested timing-window range.

$$N(\eta) = A [1 + \mu_{\text{raw}} \cos(2(\eta - \eta_{\text{max}}))] + N_{\text{geom}}(\eta), \quad (5.4)$$

where A sets the normalization, μ_{raw} is the relative amplitude of the polarization-sensitive second harmonic, and η_{max} is the azimuth of its maximum. The term $N_{\text{geom}}(\eta)$ represents additional structure caused by the finite detector geometry and non-uniform acceptance. These contributions are retained in the empirical fit shown below because the distribution has not been corrected with an unpolarized reference response.

Figure 5.5 shows the folded distribution in 5° bins. The fit gives

$$\mu_{\text{raw}} = 0.28338 \pm 0.00056 = (28.34 \pm 0.06) \%, \quad (5.5)$$

and a maximum at

$$\eta_{\text{max}} = (90.49 \pm 0.05)^\circ. \quad (5.6)$$

The quoted uncertainties are statistical fit uncertainties only.

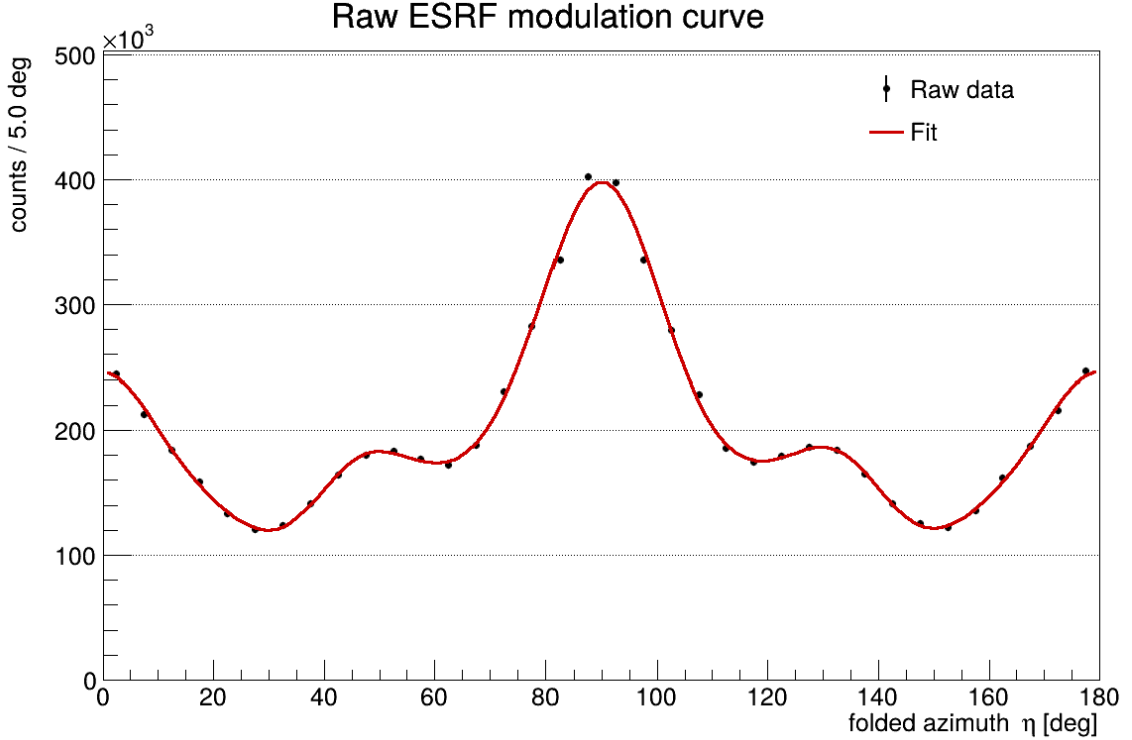


Figure 5.5: Raw folded azimuthal modulation curve obtained from the sub-bar-smearred exact-two-hit ESRF clusters. Black points show the measured counts in 5° bins and the red curve shows the empirical fit. The distribution combines the accepted measurements over beam energies from 30 to 190 keV. The fitted second-harmonic modulation is $\mu_{\text{raw}} = (28.34 \pm 0.06) \%$, with its maximum at $\eta_{\text{max}} = (90.49 \pm 0.05)^\circ$.

The pronounced maximum near 90° demonstrates a preferred two-hit orientation in the detector plane. The additional structure visible across the curve shows that the raw distribution is influenced by the 3×3 detector geometry, the combined

source positions and energies, and the acceptance of the timing-only event selection. Consequently, μ_{raw} characterizes the response of this measurement and selection, but it is not by itself a reconstructed polarization fraction or the final modulation factor of the flight instrument. Such an interpretation would require an acceptance correction based on an unpolarized reference or a source-matched simulation, together with a complete Compton-event selection.

5.10 Relevance for Trigger Studies

The ESRF analysis provides experimentally measured timing and spatial distributions of detector activity. These results are relevant to the BEE trigger because the accepted hit topology can affect the azimuthal scattering distribution used for polarization reconstruction [51, 9, 44].

The synchronization procedure demonstrates that data recorded by the two acquisition systems can be combined with a residual timing spread compatible with the selected coincidence window. The timing-cluster analysis then provides a detector-level sample of temporally correlated hit pairs without imposing a spatial selection. The measured distance spectrum quantifies the spatial extent of these pairs and shows that many are not confined to neighbouring bars or a single FEE. The raw modulation curve further demonstrates that the selected pairs retain a pronounced azimuthal response. It also illustrates why a trigger-dependent spatial selection must be evaluated carefully: changing which inter-FEE pairs are accepted can modify the observed modulation.

These results provide experimental support for retaining inter-FEE coincidences in the BEE trigger. They do not constitute a direct measurement of the trigger efficiency because the ESRF setup did not use the final flight BEE and the exact-two-hit sample was not subjected to a complete Compton-event reconstruction. A complete Compton selection would additionally require energy-dependent kinematic consistency and, where possible, reconstruction of the interaction order [51, 46].

The ESRF measurements and the Geant4 simulation therefore serve complementary purposes. The ESRF analysis establishes the measured timing and spatial behaviour of the detector and acquisition chain, while a source-matched simulation would be required to associate the selected clusters with their underlying gamma-ray interaction histories and to quantify the efficiency of a particular trigger radius.

5.11 Limitations

Several limitations must be considered when interpreting the results. First, the distance spectrum combines measurements over the complete beam-energy range from 30 to 190 keV. It therefore does not show how the characteristic separation changes with photon energy. An energy-resolved analysis would be required to provide this dependence.

Second, the usable data set is determined by the synchronization-quality selection. Pair data sets with insufficient statistics or ambiguous timing relations are excluded, which can introduce a spatial selection if particular FEE combinations are removed more frequently than others.

Third, timing-only clustering avoids an explicit spatial bias, but it does not prove that the two hits originate from the same photon. The stability observed for windows between 25 and 75 ns shows that the principal distance features are robust against the tested window choice, but no independently constructed off-time sample was used to quantify accidental coincidences.

Fourth, the sub-bar smearing assumes a uniform interaction probability across one bar pitch. It approximates the unknown intra-bar positions but does not model possible non-uniformities in the scintillator response or the exact interaction-position distribution.

Finally, the modulation curve is a raw distribution combined over all accepted beam energies and synchronized pair data sets. It has not been divided by an unpolarized detector response or corrected with a source-matched simulation. In addition, the exact-two-hit timing selection does not impose Compton-kinematic consistency and no off-time subtraction was applied. The reported value of μ_{raw} must therefore be interpreted as the modulation of this selected ESRF data set rather than as a reconstructed polarization fraction or a calibrated flight-instrument response. Its quoted uncertainty includes the statistical fit uncertainty but not systematic contributions from synchronization, acceptance, sub-bar smearing, or the event selection.

5.12 File-Flow Summary

The data-analysis chain developed and applied in this thesis can be summarized as follows:

```

ESRF detector data from the master and slave systems
|
v
pair-wise timing synchronization and quality selection
|
v
sync_all_pairs_robust/pair_*/synced_pair.root
|
v
global FEE and bar-position mapping
|
v
timing-only clustering
|
v
selection of exact-two-hit clusters
|
v
uniform sub-bar position smearing
|
v
distance spectra and timing-window comparison

```

```

|
v
folded azimuthal distribution and raw modulation fit
|
v
trigger-relevant topology interpretation

```

This workflow connects the measured ESRF detector data to the timing, spatial, and azimuthal observables required for POLAR-2 BEE-trigger studies. The analysis shows that the synchronized data contain a substantial population of temporally correlated hit pairs with separations extending beyond one FEE width. The same sample produces a pronounced raw modulation with $\mu_{\text{raw}} = (28.34 \pm 0.06) \%$ and a maximum at $(90.49 \pm 0.05)^\circ$. The results therefore provide experimental motivation for an inter-FEE trigger and demonstrate the polarization-sensitive response of the selected detector data. A source-matched simulation, an unpolarized acceptance correction, and a complete Compton-event selection remain necessary for quantitative trigger-efficiency and polarization measurements.

Chapter 6

Conclusions and Outlook

In this last chapter, a conclusion shall be drawn as well as an outlook shall be given on the future work, which still has to be done on the trigger algorithm.

6.1 Conclusions

The feasibility and the expected relevance of the global back-end trigger has been investigated in this thesis. The purpose of this trigger is to complement the local front-end trigger decisions by adding spatially distributed detector events that are not fully contained within a single front-end module. Those events are particularly interesting for Compton polarimetry because larger hit separations can provide improved azimuthal angle resolution. Inappropriate trigger selections there can reduce the useful event sample or bias the accepted event topology.

Several different trigger concepts were considered. A lookup table containing all possible inputs has been found infeasible because the number of possible input patterns will lead to an unrealistically large memory requirement. A neighborhood-based coincidence trigger can exploit the regular detector geometry and can be implemented with a comparatively simple combinatorial logic. The resulting baseline accepts coincidence activity in a requesting module and its neighboring modules while retaining additional provisions for pedestal acquisition and cosmic-event handling.

A preliminary FPGA implementation indicates that this trigger concept is compatible with the chosen FPGA. It has been shown, that approximately 59% of the available I/O resources and about 1% of the lookup tables were used. The longest reported logic delay was approximately 7 ns. These results only demonstrate the feasibility of the chosen logic but do not yet constitute a complete verification of the flight firmware, because final interfaces, clock-domain crossings, board-level pin allocations and post-route timing behavior still must be included.

Digitized GEANT4 simulations have been used to investigate the detector response and the contribution of the BEE to the accepted event sample. $84.92\% \pm 0.031\%$ have been classified as FEE-only events whilst $15.08\% \pm 0.031\%$ were triggered with a BEE involved. This made the ratio of expected FEE-triggers to BEE-triggers equal to 5.631 : 1.

Measurements obtained at the ESRF provided an experimental complement to the simulations. Due to a different experimental setup synchronization in the data

has been needed to be established where it was shown, that the mean clock drift magnitude was 0.318 ppm. After having synchronized the data, timing-only clustering was performed using a 50 ns window. The sub-bar smeared distance spectrum of exact two hit clusters showed a maximum at 75 mm and a mean distance of 73.76 mm. The normalized spectral shape was found to be stable for tested clustering windows of 25, 50 and 75 ns.

The measured distance distribution demonstrates the need of the detector wide trigger capable of combining information from different FEEs. However the obtained spectrum is conditional on the synchronization quality selection. This therefore provides an experimental constraint on the trigger design rather than a direct measurement of the flight trigger efficiency.

Overall the work demonstrates that a neighborhood-based coincidence trigger in the BEE is technically feasible and that this trigger contributes meaningfully to the instrument. The simulations and measurements at ESRF provide quantitative constraints on the relevant spatial and temporal scales.

6.2 Outlook

The next development step is to finalize some specifications. Those include mainly the inter-FPGA communication protocol of the BEE as well as the allowed data throughput of the BEE to decide for a compression algorithm.

The FPGA implementation should then be expanded into a flight-ready firmware design. The design should be verified using test benches that cover all relevant trigger patterns, cosmic-ray vetoes, and pedestal requests. Post-place-and-route timing analysis should then be performed for the relevant voltage and temperature corners.

The GEANT4 simulations could be enhanced by adding electronic noise as well as the expected background in space. This would help to verify the assumed background scaling model used in this work.

Also on the data from ESRF some more studies could be done. The electronic noise could be measured, as well as the background in the lab. The modulation curve of the setup could be improved with background subtraction and acceptance corrections to demonstrate the overall capabilities of the detector in more detail.

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