

School of Science
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**X/Gamma-ray Imaging Spectrometer
Instrument onboard the THESEUS ESA M7
candidate mission: experimental tests and
Monte Carlo simulations**

Master Thesis

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Summary

Understanding the formation of the first generations of stars and galaxies, the evolution of the early Universe, and the nature of the most energetic transient phenomena remains one of the major challenges of modern astrophysics. Observations of high-redshift Gamma-Ray Bursts (GRBs) provide a unique opportunity to investigate these questions, as their extreme luminosities allow them to be detected across cosmological distances and to probe epochs that are otherwise difficult to access. At the same time, the growing field of multi-messenger astronomy requires instruments capable of rapidly detecting and characterizing transient sources over a broad energy range.

The *Transient High-Energy Sky and Early Universe Surveyor* (THESEUS) mission has been proposed to address these scientific objectives. By combining wide-field monitoring, rapid source localization, and multi-wavelength follow-up capabilities, THESEUS aims to investigate the early Universe, discover large populations of high-redshift GRBs, and contribute to the study of transient phenomena associated with gravitational-wave and neutrino events.

Within the THESEUS payloads, the *X/Gamma-ray Imaging Spectrometer* (XGIS) is responsible for the detection and characterization of high-energy transient sources from the X-ray to the gamma-ray domain. The instrument combines Silicon Drift Detectors (SDDs), CsI(Tl) scintillator bars, coded-mask imaging, and dedicated front-end electronics in order to provide broad-band spectroscopy, source localization, and trigger capabilities over a wide field of view. The detector concept is based on the *siswich* principle, which enables the simultaneous detection of low-energy X-rays directly in the silicon detectors and higher-energy gamma rays through scintillation processes in the crystal bars.

This thesis presents an experimental and simulation study of an XGIS detector prototype developed in the framework of the THESEUS mission. The primary objective is to characterize the detector response, evaluate the performance of the ORION readout electronics, and develop simulation tools capable of reproducing and extending the experimental results.

The first part of the thesis introduces the scientific and instrumental context of the work. Chapter 1 discusses the role of Gamma-Ray Bursts as probes of the distant Universe and reviews their observational properties, progenitor models, and importance for transient astrophysics. Chapter 2 presents the THESEUS mission and the XGIS instrument, describing the scientific motivations, detector architecture, detection principles, and readout system.

The second part focuses on the activities carried out during this project. Chapter 3 describes the experimental characterization of a four-pixel XGIS prototype equipped with the ORION front-end and back-end electronics. The detector setup and acquisition system are presented, followed by the validation of the top–bottom channel coupling logic required for scintillation measurements. The chapter then addresses the calibration of the X and gamma branches, the determination of the effective test capacitance, the characterization of the electronic noise, the evaluation of the scintillation light output, and the study of the uniformity of the response along the bars.

Chapter 4 complements the laboratory measurements through Monte Carlo simulations developed using the Geant4 toolkit. A reduced detector geometry is first implemented to reproduce the experimental configuration and investigate the detector response under controlled conditions. The simulations are subsequently extended to include detector-noise effects, depth-of-interaction information, and an updated implementation of the XGIS coded-mask geometry. Particular attention is devoted to the potential use of depth-of-interaction observables for future studies of detector background and event classification.

By combining experimental detector characterization with numerical simulations, this work contributes to the validation and development of the XGIS detection concept. The results provide useful inputs for future optimization of the instrument and support its scientific role within the THESEUS mission and future high-energy transient astrophysics investigations.

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1

Gamma-Ray Bursts as High-Energy Transient Phenomena

This chapter introduces Gamma-Ray Bursts (GRBs) as high-energy transient phenomena and summarizes the main observational and physical concepts needed for the following chapters. After a brief overview of their discovery and basic properties, the prompt and afterglow emission phases are discussed, together with the main progenitor scenarios for long and short GRBs.

1.1 Gamma-Ray Bursts in the High-Energy Sky

Gamma-Ray Bursts (GRBs) are transient events characterized by intense flashes of radiation in the X-ray and gamma-ray energy range, from a few keV up to the MeV–GeV domain. Their emission can last from milliseconds to several hundreds of seconds and is associated with highly variable temporal and spectral behaviour. Assuming isotropic emission, the released energy can reach values up to $\sim 10^{54}$ erg, making GRBs among the most energetic phenomena observed in the Universe (Vedrenne & Atteia, 2009b).

GRBs were first detected in the late 1960s by the *Vela* satellites, originally developed to monitor possible nuclear tests during the Cold War. The detected gamma-ray flashes were inconsistent with terrestrial or solar phenomena, and their discovery was publicly reported several years later by Klebesadel et al. (1973). Since then, the observational study of GRBs has progressed through major advances in space instrumentation, allowing the detection of transient events over increasingly broad energy ranges and with improved temporal and spectral resolution.

The development of dedicated space missions has progressively revealed the main observational properties of GRBs, including their isotropic sky distribution, bimodal duration distribution, non-thermal spectra, and long-lasting multi-wavelength emission. These observations established GRBs as cosmological phenomena associated with relativistic outflows and compact astrophysical sources. At the same time, they highlighted the importance of wide-field high-energy instruments capable of detecting and localizing transient events over large portions of the sky.

1.1.1 Discovery and observational properties

The first systematic observations of GRBs became possible with space missions dedicated to high-energy astrophysics. Among them, the Burst and Transient Source Experiment (BATSE, Fishman et al. 1989), onboard the *Compton Gamma Ray Observatory*, played a fundamental role in establishing the main observational properties of GRBs. BATSE detected several thousand bursts and showed that their sky distribution is nearly

isotropic, with no significant concentration toward the Galactic plane, as shown in Figure 1.1. This result strongly suggested that GRBs originate at cosmological distances rather than from Galactic sources.

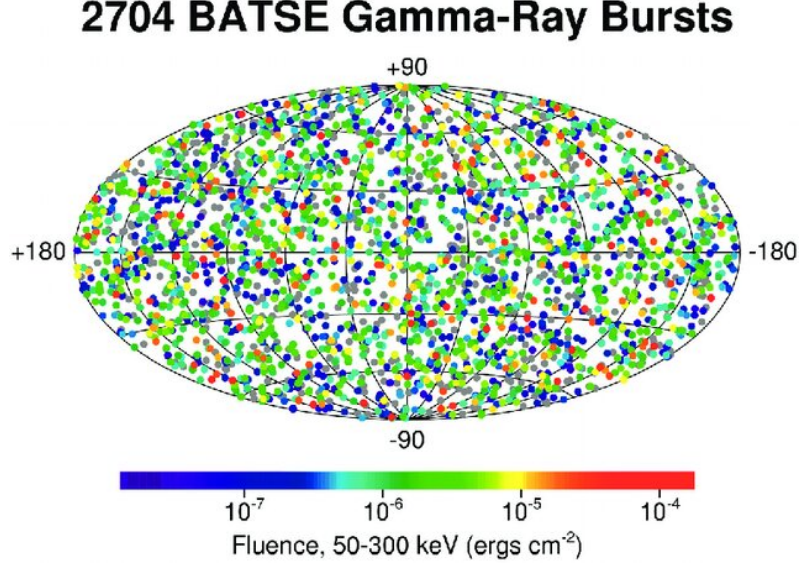


Figure 1.1. Sky distribution of GRBs detected by BATSE in Galactic coordinates, showing the nearly isotropic distribution of the sources (Fishman, 2013).

The temporal duration of a burst is commonly characterized through the parameter T_{90} , defined as

$$T_{90} = t_{95} - t_5, \quad (1.1)$$

where t_5 and t_{95} correspond to the times at which 5% and 95% of the total cumulative counts are detected above the background level, respectively.

Observations performed with BATSE revealed a bimodal duration distribution, indicating the existence of two main GRB populations separated approximately at $T_{90} \sim 2$ s (Kouveliotou et al., 1993) as shown in Figure 1.2. Bursts with durations shorter than ~ 2 s are classified as short GRBs, while longer events are classified as long GRBs.

Examples of GRB prompt-emission light curves are shown in Figure 1.3, illustrating the rapid variability and diversity of burst morphologies observed by BATSE.

In addition to their different durations, the two populations also exhibit different spectral properties. Short GRBs are generally characterized by harder spectra, meaning a relatively larger fraction of high-energy photons compared to long GRBs. This behaviour is commonly quantified through the *hardness ratio*, defined as the ratio between the detected photon flux in different energy bands (Kouveliotou et al., 1993). The differences in duration and spectral hardness suggest that the two classes may originate from different physical mechanisms.

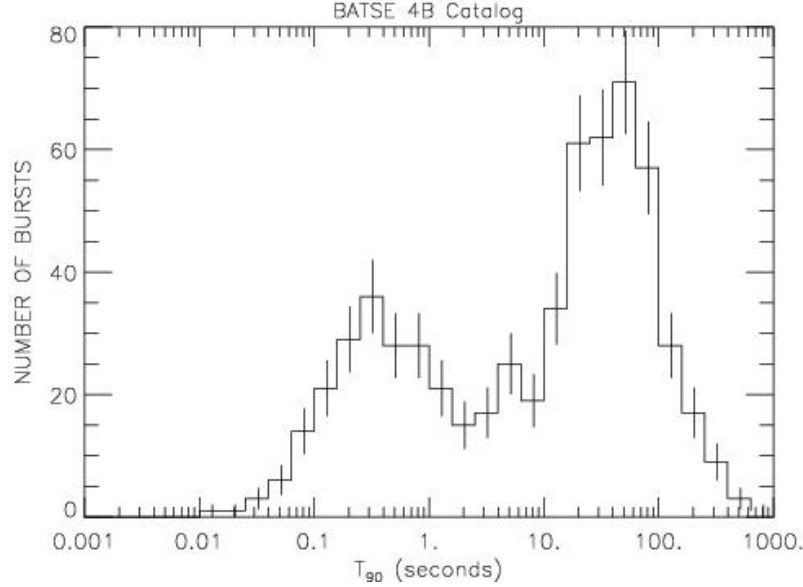


Figure 1.2. Distribution of T_{90} durations for GRBs detected by BATSE, showing the bimodal structure associated with short and long GRB populations ([Kouveliotou et al., 1993](#)).

1.2 Prompt Emission

The prompt emission is the initial high-energy phase, through which GRBs are first detected. It consists of a sudden release of radiation mainly observed in the hard X-ray and gamma-ray energy range, typically from a few keV up to the MeV domain, although higher-energy components extending to the GeV range have also been observed in some events ([Band et al., 1993](#); [Gehrels et al., 2009](#)). The prompt phase is characterized by strong temporal and spectral variability, reflecting the complex physical processes occurring within the relativistic outflow launched by the central engine.

1.2.1 Temporal properties

One of the main observational characteristics of prompt emission is the large diversity of the observed light curves, where the term light curve refers to the detected photon count rate as a function of time. Some GRBs exhibit smooth single-pulse structures, while others show multiple peaks, irregular variability, quiescent intervals, and rapid fluctuations down to millisecond timescales ([Fishman & Meegan, 1995](#)). This variability indicates that the emitting region must be compact and that the emission process is associated with relativistic motion.

The duration of the prompt phase is commonly quantified through the parameter T_{90} , introduced in Section 1.1.1, and spans from milliseconds to several hundreds of seconds depending on the burst population. Although the short-long classification is observationally useful, the measured duration can also be affected by detector sensitivity,

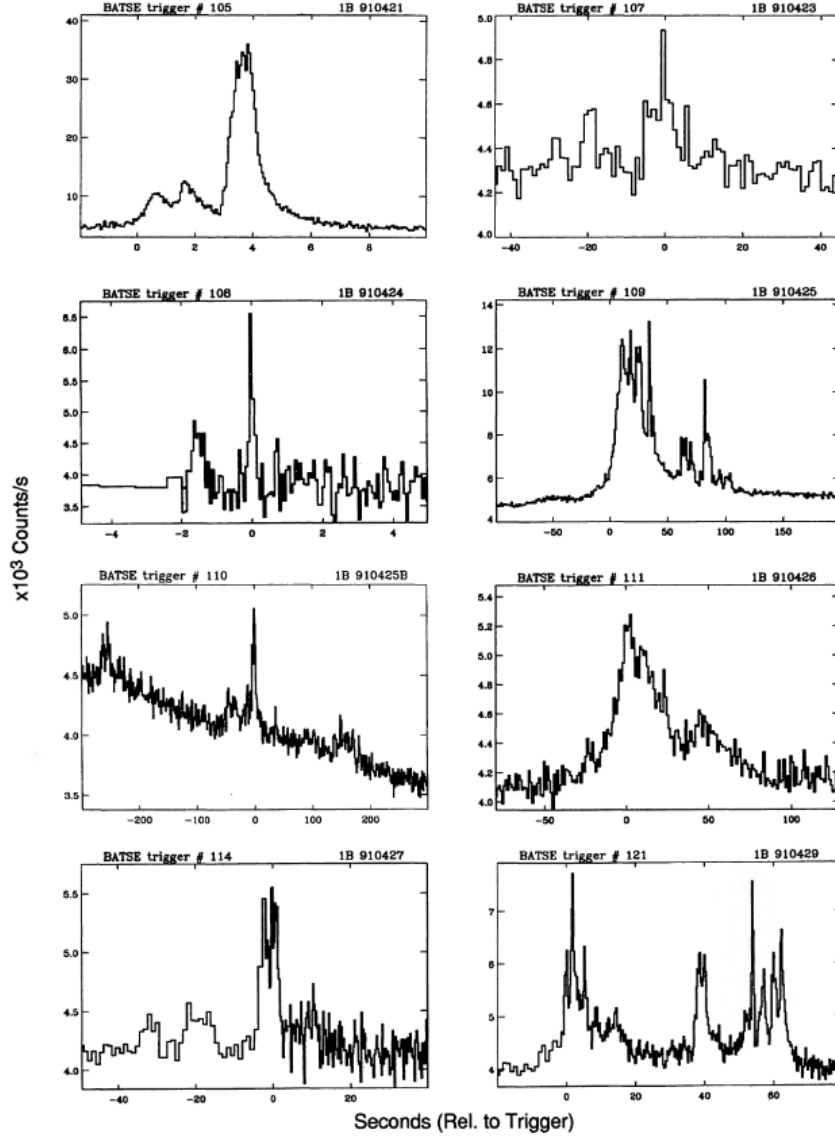


Figure 1.3. Examples of BATSE GRB prompt-emission light curves, showing the diversity of temporal profiles, intensities, and durations observed in the first BATSE catalog. Adapted from [Fishman et al. \(1994\)](#).

instrumental energy range, and redshift effects (Zhang et al., 2009).

The temporal structure of GRB light curves is often interpreted as the result of intermittent activity of the central engine powering the burst. In the internal-shock scenario, variability arises from collisions between relativistic shells ejected with different velocities within the outflow (Rees & Mészáros, 1994). Part of the kinetic energy of the flow is converted into non-thermal radiation through shock dissipation processes. Alternative models instead attribute the prompt variability to magnetic reconnection or to dissipation processes occurring close to the photospheric region of the outflow (Pe’er, 2015; Kumar & Zhang, 2015).

1.2.2 Spectral properties and the Band function

The prompt-emission spectra of GRBs are predominantly non-thermal and typically exhibit a broken power-law shape. A phenomenological description widely used to model GRB spectra is the Band function, introduced by Band et al. (1993). The photon spectrum can be written as

$$N(E) = \begin{cases} A \left(\frac{E}{100 \text{ keV}} \right)^\alpha \exp \left(-\frac{E}{E_0} \right), & E < (\alpha - \beta)E_0 \\ A \left[\frac{(\alpha - \beta)E_0}{100 \text{ keV}} \right]^{\alpha - \beta} \exp(\beta - \alpha) \left(\frac{E}{100 \text{ keV}} \right)^\beta, & E \geq (\alpha - \beta)E_0 \end{cases} \quad (1.2)$$

where A is a normalization factor, α and β are the low- and high-energy photon indices, respectively, and E_0 is the characteristic break energy.

The spectral energy distribution is commonly represented through the quantity νF_ν , whose maximum corresponds to the spectral peak energy E_{peak} . For the Band function, the peak energy is given by

$$E_{\text{peak}} = (2 + \alpha)E_0, \quad (1.3)$$

for $\beta < -2$ and $\alpha > -2$ (Preece et al., 2000). Observed GRB spectra typically show $\alpha \sim -1$, $\beta \sim -2.3$, and E_{peak} values around a few hundred keV, although broad distributions are observed depending on the burst properties and the detector energy band (Gehrels et al., 2009; Vedrenne & Atteia, 2009b).

The role of E_{peak} in shaping the prompt spectrum is illustrated in Figure 1.4, together with other spectral models commonly adopted in GRB studies.

The non-thermal shape of prompt spectra suggests that the observed radiation is produced by particles accelerated within relativistic outflows. Synchrotron emission has long been considered one of the main physical mechanisms responsible for the prompt emission, since relativistic shocks and magnetic dissipation processes can accelerate electrons to very high energies in the presence of strong magnetic fields (Mészáros, 2006; Kumar & Zhang, 2015).

However, the physical origin of the prompt-emission spectrum is still not fully understood. In particular, the observed low-energy spectral slope is not always easily reproduced by the simplest synchrotron models. This has motivated the development of alternative or hybrid scenarios involving photospheric emission, inverse-Compton scattering, and magnetic reconnection processes (Pe’er, 2015; Kumar & Zhang, 2015).

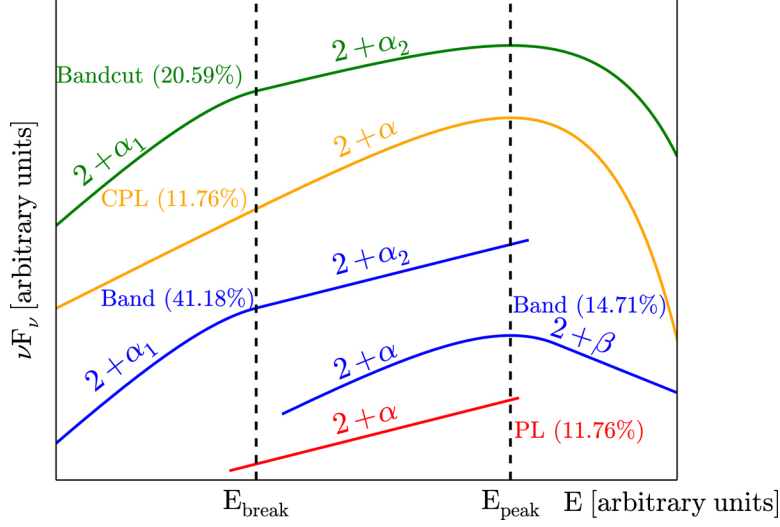


Figure 1.4. Spectral models commonly used to describe GRB prompt-emission spectra in the νF_ν representation. The figure compares a Band function with a high-energy exponential cutoff, a cutoff power-law model, a Band function, and a single power-law model. Reproduced from [Oganesyan et al. \(2018\)](#).

1.2.3 Spectral-energy correlations and the Amati relation

For GRBs with measured redshift, the observed prompt-emission properties can be transformed into the cosmological rest frame. In particular, the intrinsic spectral peak energy and the isotropic-equivalent radiated energy can be estimated and compared across different bursts.

The intrinsic peak energy is related to the observed value through

$$E_{\text{peak},i} = E_{\text{peak,obs}}(1+z), \quad (1.4)$$

where z is the cosmological redshift of the source.

One of the most important empirical correlations observed in long GRBs is the Amati relation, which connects the intrinsic peak energy $E_{\text{peak},i}$ with the isotropic-equivalent emitted energy E_{iso} ([Amati et al., 2002](#)). In general, bursts with larger emitted energies tend to exhibit higher peak energies.

The isotropic-equivalent radiated energy is defined as

$$E_{\text{iso}} = \frac{4\pi d_L^2}{1+z} S_{\text{bolo}}, \quad (1.5)$$

where d_L is the luminosity distance and S_{bolo} is the bolometric fluence measured over the burst duration.

The Amati relation is shown in Figure 1.5. Although the physical origin of the correlation is still debated, it provides important constraints on GRB emission models and on the energetics of relativistic jets.

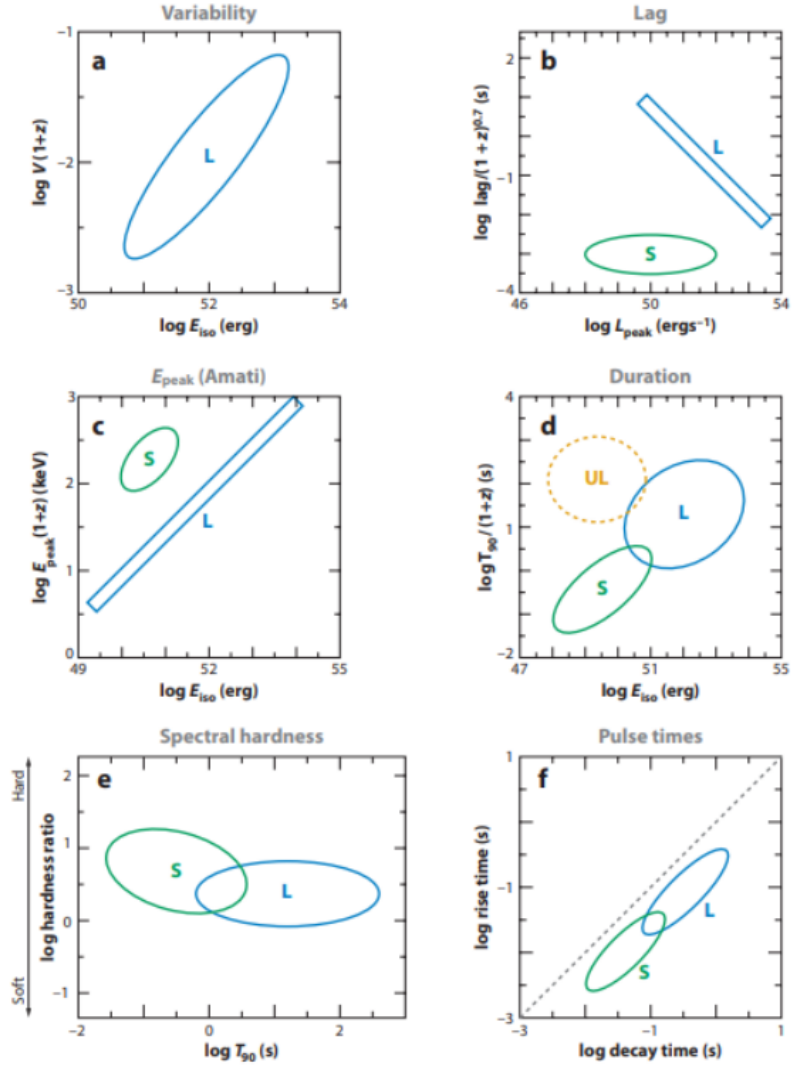


Figure 1.5. Correlation between the intrinsic spectral peak energy and the isotropic-equivalent emitted energy for long GRBs. Adapted from [Gehrels et al. \(2009\)](#).

1.3 Afterglow Emission and Host Galaxies

1.3.1 Multi-wavelength afterglows

The discovery of long-lasting emission following the prompt phase represented one of the major breakthroughs in GRB studies. While the prompt emission is mainly detected in hard X-rays and gamma rays, many GRBs exhibit delayed and progressively fading emission observable at lower energies, including X-ray, optical, infrared, and radio wavelengths. This emission component is commonly referred to as the *afterglow*.

The first X-ray afterglow was detected in 1997 by the *BeppoSAX* satellite following GRB 970228 (Costa et al., 1997). The rapid localization provided by BeppoSAX enabled follow-up observations at multiple wavelengths, leading to the discovery of optical and radio counterparts and, later, to the identification of host galaxies. These observations established the cosmological origin of GRBs and transformed them from poorly localized transient events into astrophysical sources that could be studied in detail.

Afterglow emission is generally interpreted within the external-shock scenario, in which the relativistic ejecta interact with the surrounding medium (Sari et al., 1998). As the outflow propagates outward, shocks accelerate electrons to relativistic energies and amplify magnetic fields, producing broadband synchrotron radiation over a wide range of frequencies.

The observed afterglow flux typically follows a power-law evolution in both time and frequency,

$$F_\nu(t) \propto t^{-\alpha} \nu^{-\beta}, \quad (1.6)$$

where α and β are the temporal and spectral indices, respectively. Their values depend on several physical parameters, including the external density profile, the geometry of the relativistic jet, the magnetic-field strength, and the energy distribution of accelerated electrons.

The synchrotron afterglow spectrum is commonly described through a sequence of spectral segments separated by characteristic break frequencies associated with synchrotron cooling, self-absorption, and minimum electron energies. As the blast wave decelerates, these characteristic frequencies evolve with time, producing different temporal behaviours in different wavelength bands.

In addition to the forward shock propagating into the external medium, a reverse shock traveling backward into the ejecta may also contribute to the early afterglow emission, particularly at optical and radio wavelengths. Reverse shocks are often associated with rapidly decaying optical flashes observed shortly after the burst onset.

Figure 1.6 summarizes the typical evolution of GRB afterglow emission across different wavelength bands within the synchrotron external-shock framework.

Many observed afterglows exhibit more complex behaviours than predicted by the simplest external-shock models. X-ray plateaus, flares, chromatic breaks, and rebrightening episodes suggest that additional physical processes may contribute to the observed emission. Proposed explanations include prolonged central-engine activity,

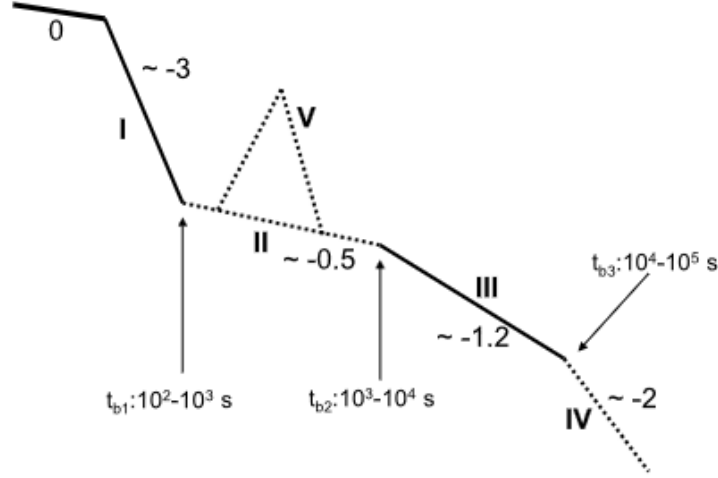


Figure 1.6. Schematic representation of the temporal evolution of GRB afterglow emission at different wavelengths within the synchrotron external-shock framework. Adapted from Zhang et al. (2006).

structured jets, energy injection, and variations in the circumburst environment (Zhang et al., 2006).

A particularly important observational feature is the jet break, corresponding to a steepening of the afterglow light curve when the relativistic beaming angle becomes comparable to the jet opening angle. The observation of jet breaks provides evidence that GRB outflows are collimated rather than isotropic, reducing the true emitted energy relative to the isotropic-equivalent estimate.

1.3.2 Redshift determination and host-galaxy identification

The accurate localization provided by afterglow observations enabled spectroscopic studies of GRB counterparts and host galaxies, allowing redshift measurements for a large number of bursts. Absorption and emission lines detected in optical spectra made it possible to determine cosmological distances and to study the environments surrounding GRB progenitors.

The observed redshift distribution extends from nearby bursts up to events at $z > 8$, demonstrating that GRBs can be detected over a large fraction of cosmic history. Their extreme luminosity allows them to remain observable even at distances where ordinary galaxies become difficult to detect. As a consequence, GRBs represent powerful probes of star formation, galaxy evolution, and the interstellar medium in the early Universe. This potential is illustrated in Figure 1.7, which compares the current redshift distribution of long GRBs with the expected high-redshift sample detectable by THESEUS that will be discussed in more detail in Chapter 2.

Host-galaxy observations revealed significant differences between long and short GRBs. Long GRBs are preferentially associated with actively star-forming galaxies and

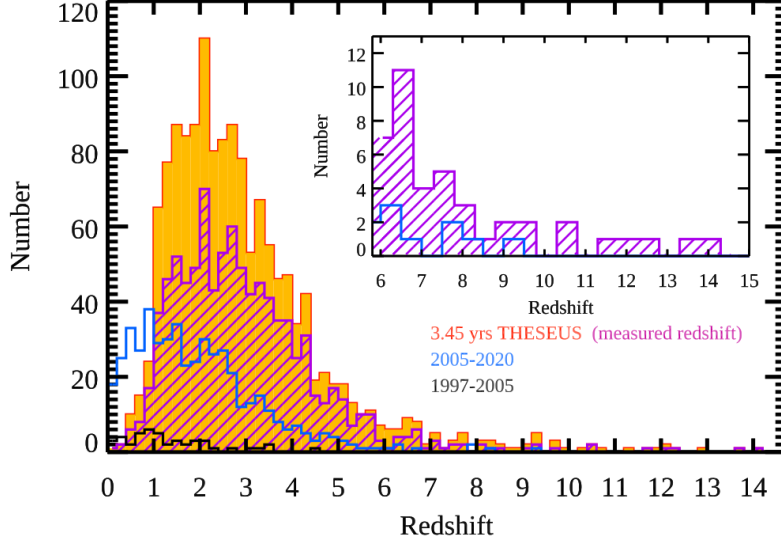


Figure 1.7. Expected redshift distribution of long GRBs detectable by THESEUS during 3.45 yr of scientific operations, compared with the redshift distribution of the currently known GRB sample. The figure illustrates the expected increase in the number of detected high-redshift GRBs, especially at $z > 6$, where current samples are still limited by small-number statistics. Adapted from [Tanvir et al. \(2021\)](#).

regions characterized by young massive stellar populations ([Woosley & Heger, 2006](#)). In several cases, long GRBs have also been directly associated with Type Ic supernovae, supporting the connection between long GRBs and the collapse of massive stars.

Short GRBs, instead, are observed in a broader variety of galactic environments, including elliptical galaxies with low star-formation activity ([Berger, 2014](#)). This suggests progenitor systems with longer evolutionary timescales, consistent with compact-object mergers involving neutron stars and/or black holes.

A major confirmation of the compact-merger scenario was obtained through the joint detection of the gravitational-wave event GW170817 and the short GRB 170817A ([Abbott et al., 2017](#)). This event established the first direct connection between short GRBs and binary neutron-star mergers, marking the beginning of multi-messenger GRB astrophysics.

The electromagnetic counterpart associated with GW170817 was detected across multiple wavelength bands, from gamma rays to radio frequencies, providing unprecedented information on relativistic jets, ejecta dynamics, and heavy-element nucleosynthesis.

The study of GRB afterglows and host galaxies has therefore transformed GRBs from transient high-energy events into fundamental tools for investigating relativistic astrophysics, compact objects, stellar evolution, and the distant Universe.

1.4 Physical Interpretation and Progenitor Models

1.4.1 Relativistic fireball framework

The large luminosities, rapid temporal variability, and non-thermal spectra observed in GRBs require extremely compact and energetic sources. Variability on millisecond timescales implies that the emitting region must be very small, while the enormous observed luminosities correspond to extremely high photon densities. Under these conditions, high-energy photons should efficiently interact through photon–photon pair production,

$$\gamma + \gamma \rightarrow e^+ + e^-, \quad (1.7)$$

making the source opaque to gamma rays. This apparent contradiction is commonly known as the compactness problem.

The standard solution involves ultra-relativistic expansion of the emitting plasma. The relativistic motion of the outflow reduces the photon density in the comoving frame and allows high-energy photons to escape without being strongly attenuated by pair production processes (Piran, 2004; Mészáros, 2006).

The bulk Lorentz factor of the relativistic outflow is defined as

$$\Gamma = \frac{1}{\sqrt{1 - \beta^2}}, \quad (1.8)$$

where $\beta = v/c$ is the outflow velocity normalized to the speed of light. For GRBs, typical inferred values range from $\Gamma \sim 10^2$ up to $\Gamma \sim 10^3$, indicating velocities extremely close to the speed of light.

Relativistic motion also produces strong beaming effects, causing the emitted radiation to be concentrated within a narrow angular region around the direction of propagation. As a consequence, the observed emission is strongly anisotropic and the measured variability timescales become shorter than those in the comoving frame of the outflow.

Within the fireball framework, a large amount of energy is released in a compact region surrounding the central engine, producing an optically thick plasma composed of photons, electrons, positrons, and baryons. Radiation pressure accelerates the plasma outward, progressively converting internal energy into kinetic energy of the relativistic ejecta.

Dissipation processes occurring within the relativistic outflow are commonly associated with the prompt gamma-ray emission. In the internal-shock scenario, shells moving with different Lorentz factors collide at large distances from the central engine, generating shocks capable of accelerating charged particles and amplifying magnetic fields (Rees & Mészáros, 1994). The resulting non-thermal particle distributions produce high-energy radiation, commonly interpreted as synchrotron and inverse-Compton emission.

At larger radii, the interaction between the relativistic ejecta and the surrounding medium generates external shocks responsible for the afterglow emission observed at X-ray, optical, and radio wavelengths. The temporal evolution of the afterglow depends

on the jet geometry, the external density profile, and the microphysical properties governing particle acceleration and magnetic-field amplification.

Although the fireball framework successfully explains many of the main observational properties of GRBs, several aspects remain uncertain. In particular, the dominant dissipation mechanism responsible for the prompt emission, the role of magnetic fields, and the composition of the relativistic jet are still actively debated topics (Kumar & Zhang, 2015).

1.4.2 Long GRBs and the collapsar scenario

Long GRBs are widely associated with the collapse of massive rapidly rotating stars at the end of their evolution. In the collapsar scenario, the core of a massive star undergoes gravitational collapse, forming a black hole or, in some cases, a highly magnetized neutron star surrounded by an accretion disk (Woosley, 1993; MacFadyen & Woosley, 1999).

Matter accreting onto the compact object releases enormous amounts of gravitational energy, part of which powers relativistic bipolar jets propagating through the stellar envelope. If the jets successfully break out from the progenitor star, highly relativistic outflows become observable as gamma-ray bursts.

The collapsar framework is strongly supported by observational evidence linking long GRBs to broad-line Type Ic supernovae. These supernovae are associated with stripped-envelope massive stars that have lost most of their hydrogen and helium layers prior to collapse. Several nearby long GRBs, including GRB 980425 and GRB 030329, were directly associated with supernova explosions, establishing a connection between long GRBs and the final evolutionary stages of massive stars (Hjorth et al., 2003; Stanek et al., 2003).

Long GRBs are preferentially observed in actively star-forming galaxies characterized by young stellar populations and relatively low metallicities. These environments favour the formation of massive rapidly rotating progenitors capable of sustaining relativistic jet production during core collapse.

Figure 1.8 illustrates the main physical components commonly associated with GRB progenitor scenarios, including both collapsar-driven long GRBs and compact-object mergers.

Although the collapsar scenario successfully explains many observational properties of long GRBs, several aspects remain uncertain, including the nature of the central engine, the jet-launching mechanism, the role of magnetic fields, and the efficiency of energy conversion within the relativistic outflow.

1.4.3 Short GRBs and compact binary mergers

Short GRBs are generally associated with mergers involving compact objects, particularly binary neutron-star systems and neutron-star–black-hole binaries (Berger, 2014). These systems gradually lose orbital energy through gravitational-wave emission until the two compact objects merge, producing a transient remnant surrounded by extremely energetic ejecta.

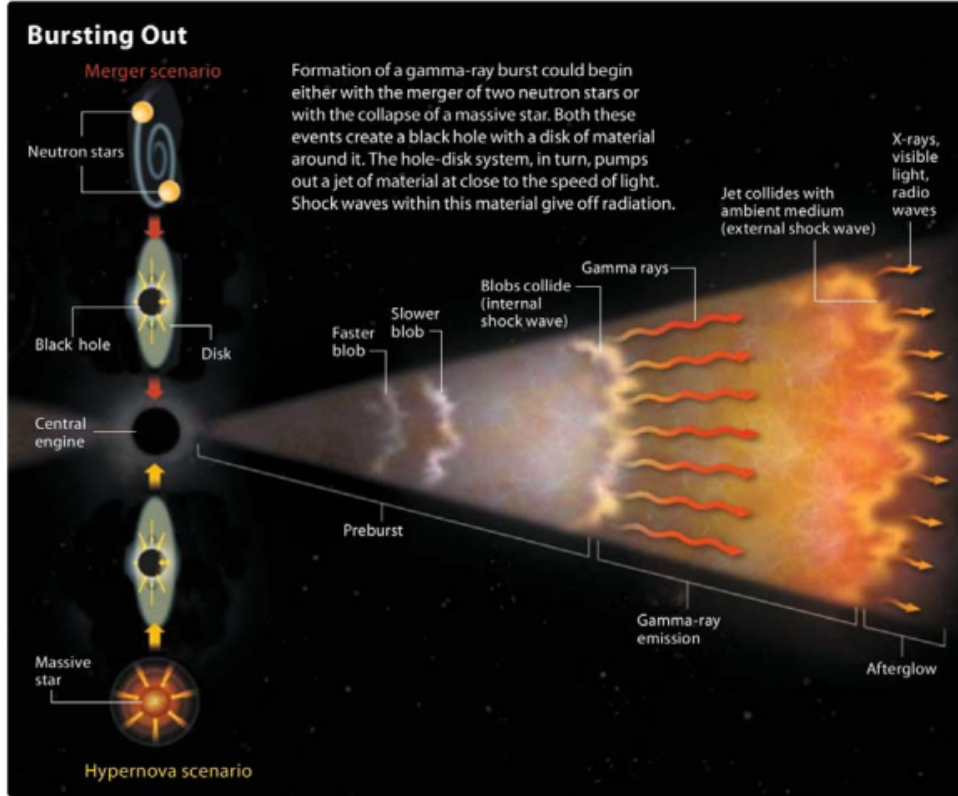


Figure 1.8. Schematic representation of the main physical processes involved in GRB progenitor scenarios. Long GRBs are associated with the collapse of massive stars, while short GRBs are connected to compact-object mergers. The relativistic jet produces prompt gamma-ray emission through internal dissipation processes, followed by multi-wavelength afterglow emission generated by the interaction with the external medium (Vedrenne & Atteia, 2009a).

Binary neutron-star (NS–NS) systems consist of two neutron stars orbiting each other, while neutron-star–black-hole (NS–BH) systems are composed of a neutron star and a stellar-mass black hole. In both cases, the compact binary gradually loses orbital energy through gravitational-wave emission, causing the orbital separation to decrease until the two objects merge.

During the merger process, large amounts of gravitational energy are released within a very short timescale. Numerical simulations indicate that the merger can produce a compact remnant surrounded by an accretion disk and relativistic ejecta capable of launching bipolar jets (Berger, 2014). If one of these jets is aligned with the observer line of sight, the event may be detected as a short GRB.

The relativistic jets produced during the merger process are believed to generate the observed short-duration gamma-ray emission. Compared to long GRBs, short bursts are typically characterized by harder spectra, lower isotropic energies, and shorter prompt-emission durations. They are also observed in a broader range of galactic environments, including elliptical galaxies with little ongoing star-formation activity, indicating older progenitor populations.

As we have mentioned, the joint detection of the gravitational-wave event GW170817 and the short GRB 170817A in 2017 (Abbott et al., 2017) marked the first direct observation of a binary neutron-star merger. The temporal association between the gravitational-wave signal and the gamma-ray emission is shown in Figure 1.9.

The electromagnetic counterpart associated with GW170817 was detected across multiple wavelength bands, from gamma rays to radio frequencies. Optical and infrared observations revealed the presence of a *kilonova*, powered by the radioactive decay of heavy elements synthesized in the neutron-rich merger ejecta. The emission is commonly interpreted as the combination of different ejecta components, including a blue kilonova associated with faster and less opaque material and a red kilonova associated with slower, lanthanide-rich ejecta (Abbott et al., 2017; Metzger et al., 2018). A schematic representation of these components is shown in Figure 1.10.

The joint detection of gravitational waves and electromagnetic emission from GW170817 demonstrated the importance of multi-messenger observations for studying compact-object mergers. Such events provide direct constraints on relativistic jet formation, ejecta dynamics, neutron-star matter, and heavy-element nucleosynthesis.

Although the traditional GRB classification is based on burst duration, several studies have shown that duration alone is not always sufficient to identify the physical origin of a burst. A complementary classification distinguishes between Type I GRBs, generally associated with compact-object mergers, and Type II GRBs, associated with the collapse of massive stars (Zhang et al., 2009). In some cases, long-duration bursts may exhibit observational properties more consistent with merger scenarios, while some short bursts may originate from collapsar systems. This indicates that the physical classification of GRBs cannot rely exclusively on the observed T_{90} duration. Figure 1.11 shows an example of how the minimum variability timescale can provide additional information beyond the duration alone.

The study of both long and short GRB progenitors remains one of the main scientific motivations for modern transient missions. Wide-field instruments with rapid localization

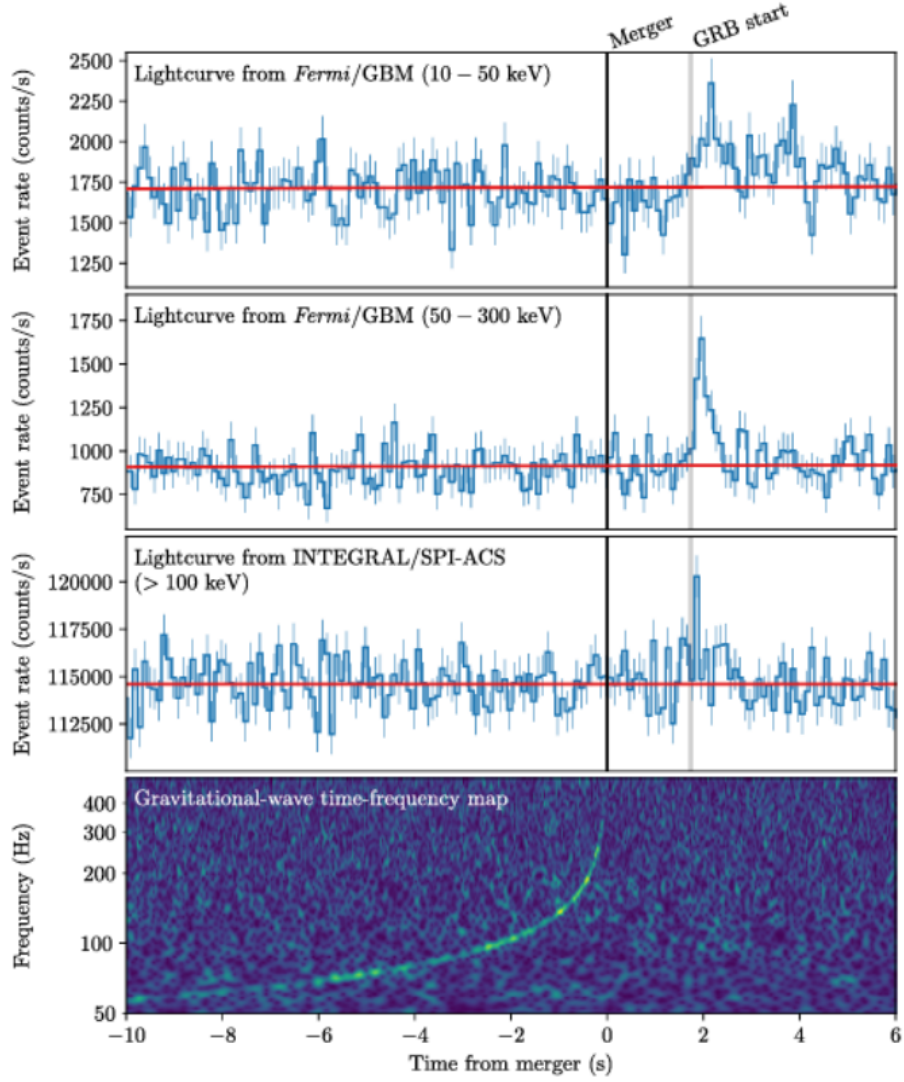


Figure 1.9. Joint multi-messenger detection of GW170817 and GRB 170817A. The figure shows the gravitational-wave chirp signal together with the gamma-ray light curves measured by different instruments, illustrating the temporal coincidence between the neutron-star merger and the short GRB detection. Adapted from [Abbott et al. \(2017\)](#).

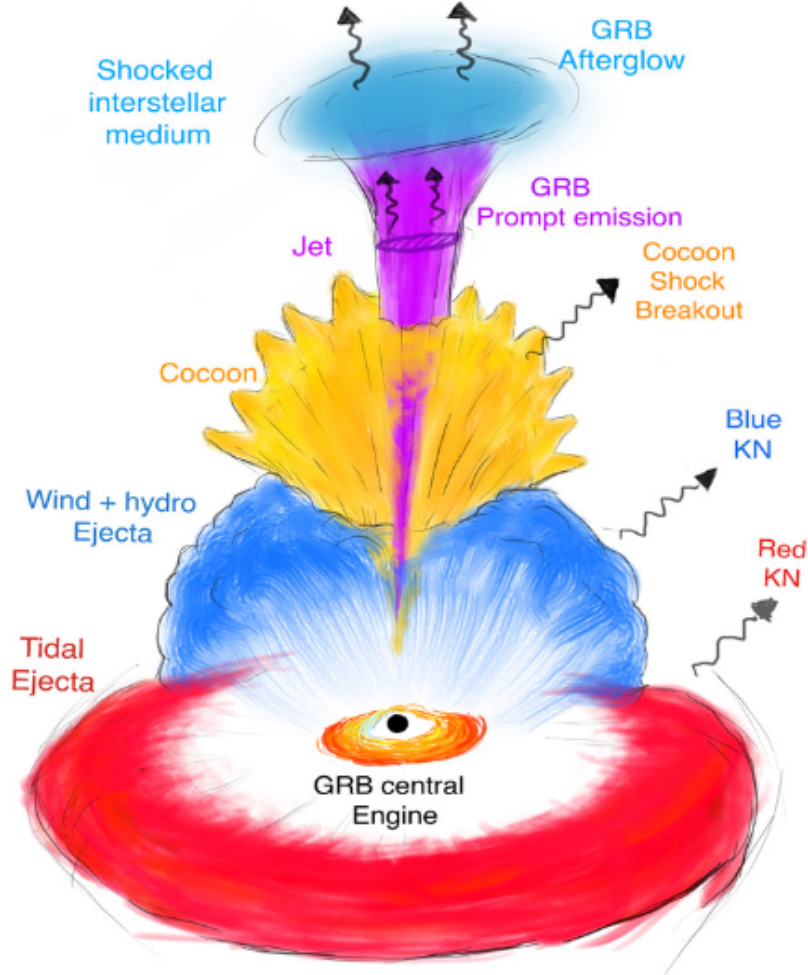


Figure 1.10. Schematic representation of the current interpretation of the binary neutron-star merger associated with GW170817/GRB 170817A. The figure illustrates the relativistic jet responsible for the prompt GRB emission, the cocoon generated by the jet interaction with the merger ejecta, the blue and red kilonova components, and the external-shock region producing the long-lasting afterglow emission. Adapted from [Ascenzi et al. \(2021\)](#).

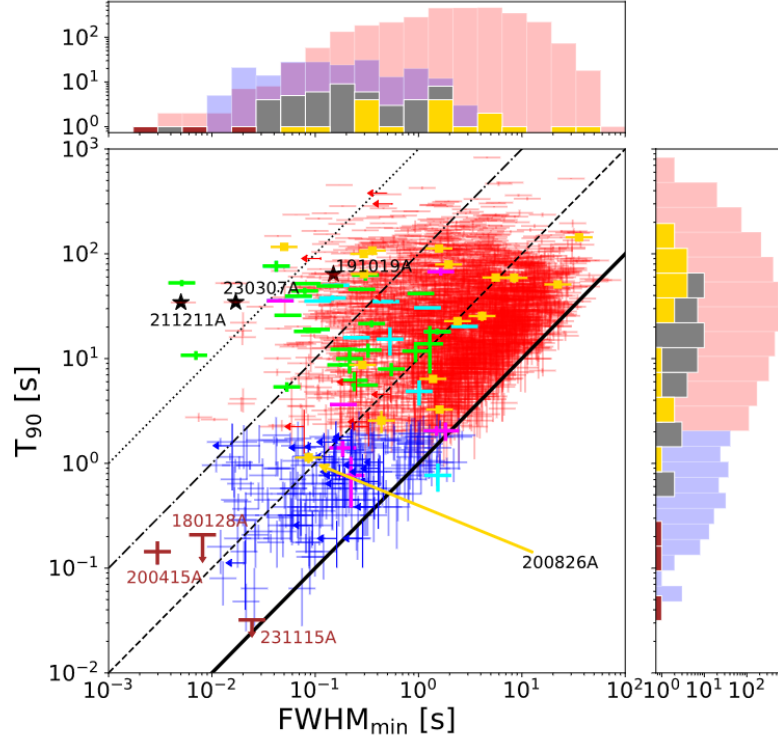


Figure 1.11. Minimum variability timescale as a function of T_{90} for different GRB populations. The figure highlights long-duration type-I GRB candidates whose short variability timescales are more consistent with compact-object merger scenarios than with ordinary collapsar-driven long GRBs. Adapted from [Maccary et al. \(2025\)](#).

capability and broad spectral coverage are essential for detecting GRBs and enabling coordinated multi-wavelength and multi-messenger follow-up observations.

The ESA M7 candidate mission THESEUS and the XGIS detector system

The *Transient High-Energy Sky and Early Universe Surveyor* (THESEUS) is a mission concept proposed to the European Space Agency (ESA) within the framework of the *Cosmic Vision* programme ([Amati et al., 2021](#); [THESEUS Consortium, 2021](#)). Cosmic Vision is ESA’s long-term scientific programme defining the main questions and mission opportunities for space science, including the selection of large-, medium-, and small-class missions. THESEUS is designed for time-domain and multi-messenger astrophysics, with particular focus on Gamma-Ray Bursts, electromagnetic counterparts of gravitational-wave events, and high-redshift transient phenomena.

THESEUS was proposed as a medium-class (M-class) mission candidate, corresponding to ESA missions with a cost at completion of approximately 600 million euros and foreseen launch opportunities in the 2030s. The mission underwent two *Phase A* studies within the ESA selection programme in 2018–21 and 2023–26. In ESA mission development, a Phase A study corresponds to a preliminary assessment phase aimed at evaluating the scientific objectives, mission architecture, instrumental configuration, technical feasibility, and estimated mission costs before the following development stages ([THESEUS Consortium, 2021](#)).

This chapter presents the scientific objectives and instrumental architecture of the THESEUS mission, with particular focus on the X/Gamma-ray Imaging Spectrometer (XGIS), its detector system, and the associated ORION readout electronics for XGIS.

2.1 Scientific objectives of THESEUS

THESEUS combines wide-field monitors in the X-ray and gamma-ray bands with an onboard near-infrared telescope. This payload concept is designed to detect GRBs and other high-energy transients, localize them autonomously, and start a rapid follow-up sequence without waiting for ground-based facilities. In this way, the mission links the prompt high-energy emission with the early afterglow phase, which is fundamental for source identification and redshift determination.

2.1.1 High-redshift GRBs and the early Universe

A central objective of THESEUS is the detection of GRBs at high redshift. Since long GRBs are associated with the collapse of massive stars, their occurrence traces star formation across cosmic time. Their very high luminosity makes them observable at distances where ordinary galaxies are difficult to study spectroscopically, so their

afterglows can be used as background sources to probe the interstellar and intergalactic medium.

For events at high redshift, the prompt spectrum and the afterglow emission are shifted toward lower observed energies. This is why sensitivity in the soft X-ray band and rapid near-infrared follow-up are both important. The wide-field high-energy instruments are used to discover the transient, while the infrared telescope is used after the spacecraft slew repointing towards the estimated sky location of the source to identify the afterglow and estimate the redshift. In this context, THESEUS aims to increase the sample of GRBs detected during the so-called Cosmic Dawn¹, when the first generations of stars and galaxies formed.

The expected improvement in the detection of high-redshift GRBs is illustrated in Figure 2.1.

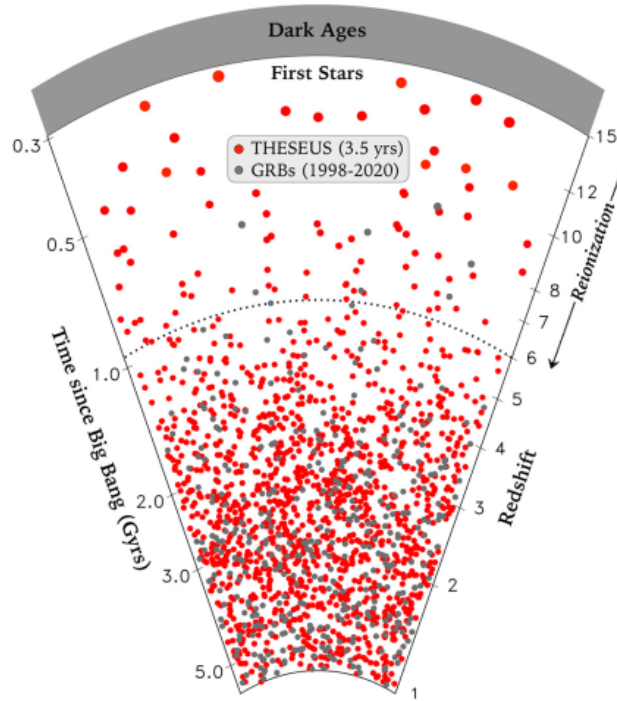


Figure 2.1. Expected capability of THESEUS to detect and autonomously identify high-redshift GRBs compared with previous observations accumulated over the last decades. Adapted from [THESEUS Consortium \(2021\)](#).

2.1.2 Multi-messenger astronomy

The joint detection of GW170817 and GRB 170817A demonstrated that compact-object mergers can be studied by combining gravitational waves and electromagnetic radiation.

¹The Cosmic Dawn refers to the epoch when the first stars and galaxies formed, roughly 100–500 Myr after the Big Bang, corresponding approximately to redshifts $z \sim 30$ –10. It precedes and partly overlaps the Epoch of Reionization.

For this type of event, the high-energy signal is short and the localization region from gravitational-wave detectors can be large, so wide-field X-ray and gamma-ray monitors are needed to identify the electromagnetic counterpart and reduce the search area for follow-up observations (Abbott et al., 2017; Goldstein, 2017).

2.1.3 Time-domain astronomy and transient science

The THESEUS science case also includes the broader transient sky. GRBs, X-ray flashes, magnetar bursts, tidal disruption events, supernova shock breakouts, and other fast transients evolve on timescales from milliseconds to days. Their study requires continuous monitoring, a reliable trigger logic, and fast communication of the event position to the ground.

These scientific goals determine the main instrumental requirements: a large field of view, broad spectral coverage from soft X-rays to MeV energies, arcminute-class localization in the triggering instruments, and autonomous follow-up in the near-infrared. The next sections describe how these requirements are translated into the payload layout and, in particular, into the architecture of the XGIS detector studied in this thesis.

2.2 Mission requirements and observing strategy

The scientific objectives described above require a payload that can discover transients without any prior knowledge of their position, classify them rapidly, and provide fast localization for follow-up observations. The mission therefore combines two wide-field high-energy instruments, SXI (*Soft X-ray Imager*) and XGIS (*X and Gamma Imaging Spectrometer*), with a narrower-field near-infrared telescope, IRT (*InfraRed Telescope*). The wide-field instruments perform the discovery and localization, while the IRT is used after the spacecraft slew for counterpart identification and redshift measurement.

The first mission requirement is the sky coverage. GRBs and merger counterparts occur randomly on the sky, so the detection probability increases with the field of view and with the duty cycle of the monitors. The two XGIS cameras provide the widest high-energy coverage of the payload, while SXI covers a smaller but more sensitive soft X-ray field.

The two XGIS cameras are oriented with an offset of $\pm 20^\circ$ with respect to the IRT pointing direction, producing a wide combined field of view that includes the SXI one and allows transient events to be observed in complementary energy bands (THESEUS Consortium, 2021).

A second requirement is broad spectral coverage. Long and short GRBs have prompt spectra extending from a few keV to the MeV range, and high-redshift events are shifted toward softer observed energies. SXI covers the soft X-ray band, XGIS extends the response to hard X-rays and gamma rays, and IRT observes the near-infrared afterglow. This combination allows THESEUS to connect the prompt emission, the early afterglow, and the redshift estimate within the same mission concept.

The third requirement is autonomous operation. During the nominal Survey Mode, SXI and XGIS continuously monitor the accessible sky while their Data Handling Units

(DHUs) search for transient candidates in the X-ray and gamma-ray bands. This mode maximizes the probability of detecting unpredictable events such as GRBs, whose time and position cannot be known in advance. When a trigger is detected and validated onboard, THESEUS can switch to Burst Mode and autonomously slew toward the reconstructed source position, placing the transient within the IRT field of view. The IRT then performs the near-infrared follow-up sequence for counterpart identification, refined localization, and redshift estimation. Therefore, the IRT does not need to continuously overlap with the full field of view of the wide-field monitors during Survey Mode, since transient events detected by SXI or XGIS can subsequently be observed through rapid spacecraft repointing toward the source.

The relative fields of view are shown in Figure 2.2. The two XGIS partially coded fields are represented by the red and green squares, SXI by the yellow rectangle, and the IRT pointing direction by the blue square. This geometry illustrates the operational hierarchy of the payload: wide-field discovery with XGIS and SXI, followed by near-infrared characterization with IRT after repointing.

The payload is therefore not a set of independent instruments placed side by side, but a coordinated transient-detection system.

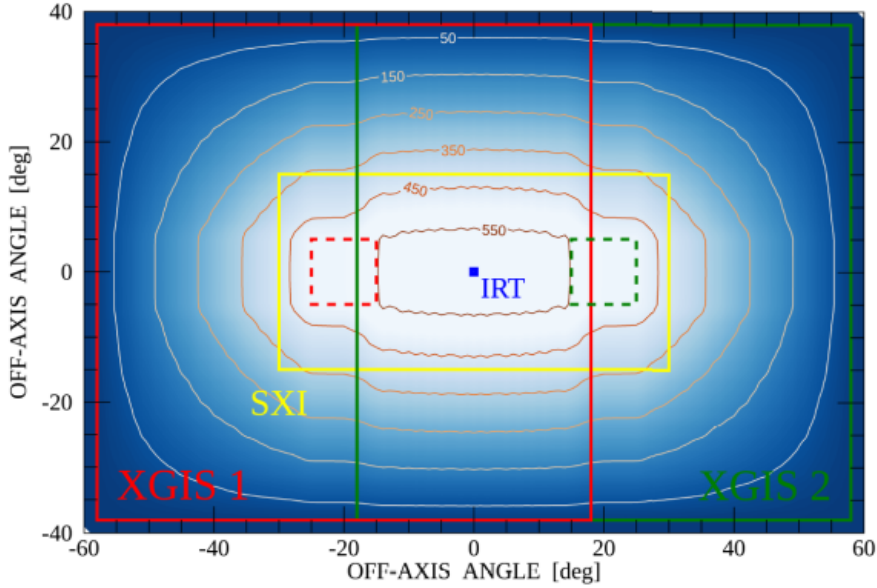


Figure 2.2. Fields of view of the THESEUS instruments. The red and green squares show the partially coded fields of view of the two XGIS units, while the yellow rectangle indicates the global SXI field of view. The blue square marks the pointing direction of the IRT. Contour lines represent the effective area at 10 keV from the combined XGIS units. Adapted from [Mereghetti et al. \(2021\)](#).

2.2.1 Orbit and background environment

The choice of orbit is an important element of the THESEUS mission design, since the sensitivity of the high-energy monitors depends not only on their intrinsic performance, but also on the stability of the in-orbit background. THESEUS is designed to operate in a near-equatorial Low Earth Orbit (LEO), with an altitude of approximately 550–640 km and an inclination of about 5.4° (THESEUS Consortium, 2021). This configuration is particularly advantageous for XGIS, for which a low and stable background is required to identify weak and short-duration transient signals.

The in-orbit background of an X-ray and gamma-ray detector originates from several contributions, including diffuse cosmic emission, Earth albedo radiation, cosmic rays, secondary particles, and charged particles trapped in the terrestrial magnetosphere. Among these, trapped particles are particularly relevant during passages through the South Atlantic Anomaly (SAA), the region where the inner Van Allen radiation belt approaches closest to the Earth’s surface because of the offset and inclination of the geomagnetic dipole (Figure 2.3a). As a consequence, satellites crossing this region are exposed to an enhanced flux of energetic charged particles (Campana, 2022).

Figure 2.3b shows the expected integral flux of trapped protons above 100 keV at an altitude of 600 km. The lines corresponding to latitudes of $\pm 5^\circ$ and $\pm 30^\circ$ illustrate the strong dependence of the SAA exposure on orbital inclination. A low-inclination orbit, such as that adopted for THESEUS, only grazes the external region of the anomaly, resulting in shorter passages and substantially lower trapped-particle fluxes than would be encountered in a higher-inclination orbit (Campana, 2022). This orbital choice therefore contributes to preserving the low-background conditions required for sensitive transient detection by XGIS. The detailed treatment of the background components and their impact on detector performance is beyond the scope of this chapter.

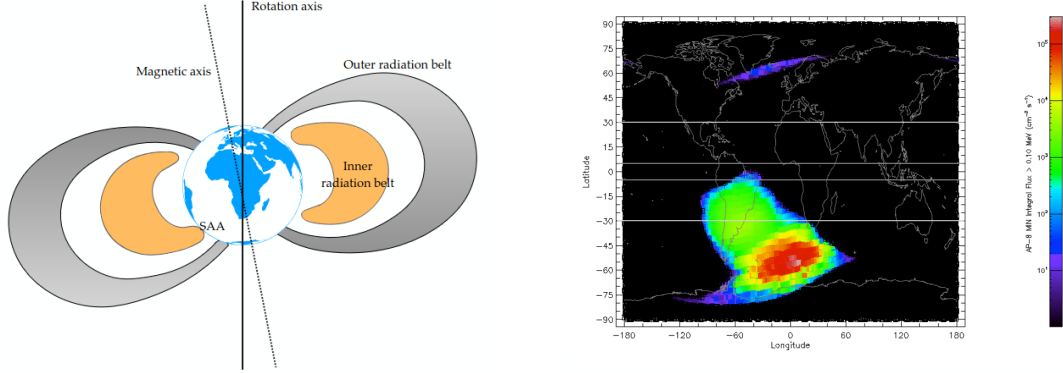
2.3 The THESEUS payloads

As we have seen, the THESEUS payload consists of three instruments: the Soft X-ray Imager (SXI), the X/Gamma-ray Imaging Spectrometer (XGIS), and the InfraRed Telescope (IRT). A schematic view of the payload is shown in Figure 2.4.

2.3.1 Soft X-ray Imager (SXI)

The Soft X-ray Imager (Figure 2.5) is dedicated to wide-field imaging in the soft X-ray band. It operates in the 0.3–5 keV energy range and is designed to localize transients with an accuracy better than a few arcminutes (THESEUS Consortium, 2021). This energy band is important for high-redshift GRBs, X-ray flashes, and soft counterparts of multi-messenger events.

SXI uses *lobster-eye* optics. In this configuration, the optics are made of square micro-pore optics (MPOs), whose internal walls reflect incoming X-rays at grazing incidence. Depending on the number of reflections inside the pores, photons are focused into a central spot and cross-shaped arms on the focal plane. This geometry gives a



(a) Schematic representation of the Van Allen radiation belts. The SAA corresponds to the region where the inner radiation belt reaches the lowest altitudes.

(b) Empirical model trapped-proton integral flux above 100 keV at an altitude of 600 km under solar minimum conditions. The horizontal lines mark geographic latitudes of $\pm 5^\circ$ and $\pm 30^\circ$.

Figure 2.3. Radiation-belt environment relevant for the THESEUS orbit. Left: qualitative representation of the Van Allen belts and of the South Atlantic Anomaly. Right: trapped-proton flux map showing that an orbit with inclination close to 5° only grazes the external region of the SAA, whereas a higher-inclination orbit would cross regions of considerably larger particle flux. Adapted from [Campana \(2022\)](#); the right panel was produced using SPENVIS (www.spenvis.oma.be).

much larger field of view than conventional focusing X-ray telescopes while preserving imaging capability. The main SXI characteristics are reported in Table 2.1.

Table 2.1. Main structural and functional characteristics of SXI. Adapted from [THESEUS Consortium \(2021\)](#).

SXI parameter	Value
Energy band	0.3–5 keV
MPO size	$40 \times 40 \text{ mm}^2$
Module optics configuration	8×8 MPOs
Module FoV	$\sim 0.25 \text{ sr}$
Total SXI FoV	$\sim 0.5 \text{ sr}$
SXI mass	82 kg
Transient location accuracy	$< 2'$

2.3.2 X/Gamma-ray Imaging Spectrometer (XGIS)

The X/Gamma-ray Imaging Spectrometer is the hard X-ray and gamma-ray monitor of THESEUS. It consists of two coded-mask cameras and covers the 2 keV–10 MeV energy range. In the lower part of this band, up to about 150 keV, XGIS provides imaging and source localization through the coded-mask technique; at higher energies, where the

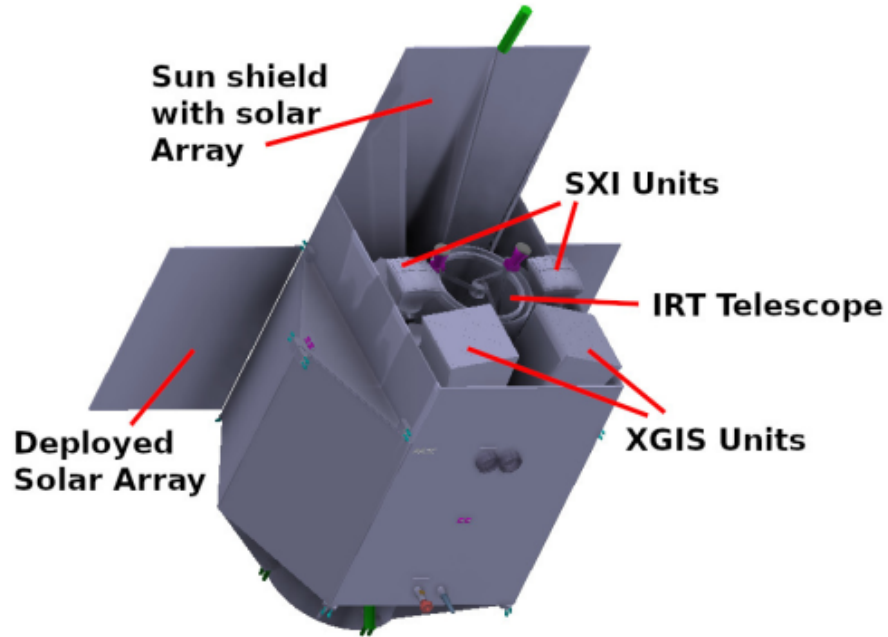


Figure 2.4. Schematic overview of the THESEUS payload. Adapted from [THESEUS Consortium \(2021\)](#).

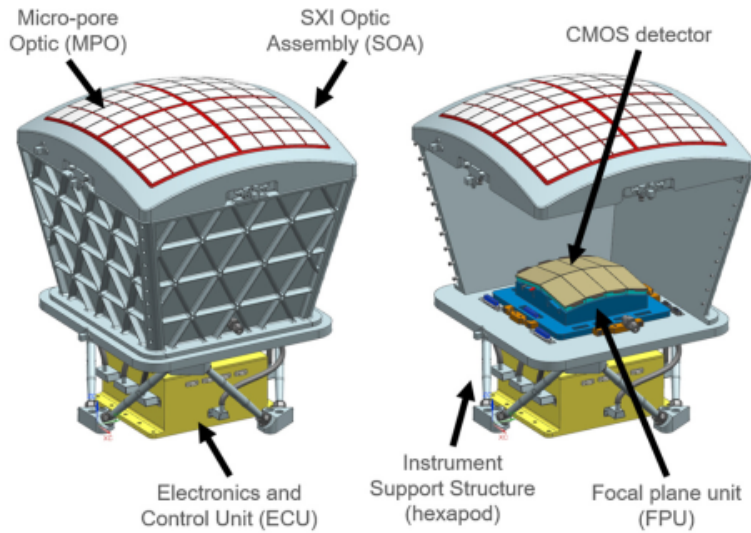


Figure 2.5. Conceptual scheme of the lobster-eye optical system adopted by SXI. Incoming X-rays are reflected inside square micro-pore optics and focused onto the focal plane, allowing wide-field soft X-ray imaging. Adapted from [THESEUS Consortium \(2021\)](#).

mask becomes increasingly transparent, it operates mainly as a wide-field spectrometer (THESEUS Consortium, 2021; Labanti et al., 2021).

XGIS is based on a hybrid detector concept, combining Silicon Drift Detectors with CsI(Tl) scintillator bars in order to detect both direct X-ray events and scintillation events produced by hard X-rays and gamma rays. The detailed system hierarchy, detector modularity, top–bottom geometry, and readout logic are discussed more in detail below, in Section 2.4. The main XGIS characteristics are summarized in Table 2.2.

Table 2.2. Main structural and functional characteristics of XGIS. Adapted from THESEUS Consortium (2021).

XGIS parameter	2–150 keV	150 keV–1 MeV
FoV	$117^\circ \times 77^\circ$	~ 6 sr
Effective area	~ 500 cm ²	~ 1000 cm ²
Angular resolution	$\sim 1^\circ$	–
Transient location accuracy	$\leq 15'$	–
Energy resolution	≤ 1200 eV FWHM at 6 keV	$\leq 6\%$ FWHM at 600 keV
XGIS mass	190 kg	

2.3.3 InfraRed Telescope (IRT)

The InfraRed Telescope (Figure 2.6) performs the follow-up of transients discovered by SXI and XGIS. Its role is to identify the near-infrared counterpart, refine the source position, and estimate the redshift onboard. This is essential for high-redshift GRBs, whose optical emission can be strongly absorbed by the intergalactic medium and shifted into the near-infrared band.

The IRT is a 0.7 m class telescope operating between 0.7 and 1.8 μm . Its optical design is based on a three-mirror configuration, which provides compact near-infrared imaging and spectroscopy in space. The instrument includes imaging filters and a spectroscopic mode based on a dispersive element, allowing photometric and spectroscopic characterization of GRB afterglows (THESEUS Consortium, 2021). The main IRT parameters are reported in Table 2.3.

Table 2.3. Main structural and functional characteristics of IRT. Adapted from THESEUS Consortium (2021).

IRT parameter	Value
Photometric wavelength range	0.7–1.8 μm
Photometric FoV	$15' \times 15'$
Photometric redshift accuracy	$< 10\%$
Spectroscopic wavelength range	0.8–1.6 μm
Spectroscopic FoV	$2' \times 2'$
Resolving power	~ 400
IRT mass	220 kg

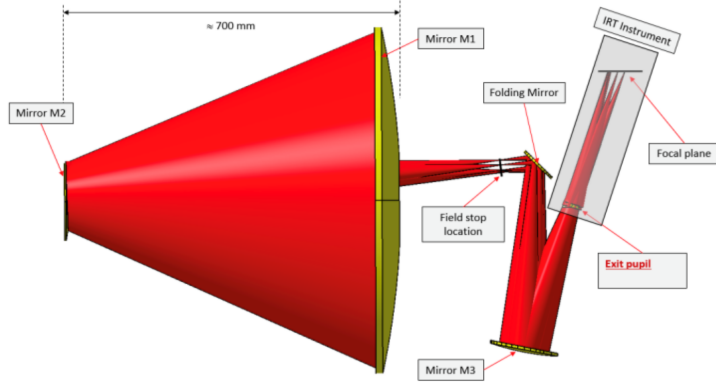


Figure 2.6. Optical scheme of the IRT onboard THESEUS. The design follows a three-mirror configuration for near-infrared imaging and spectroscopy. Adapted from [THESEUS Consortium \(2021\)](#).

2.4 XGIS architecture and operating principle

In Section 2.3.2 we provided a payload-level overview; here we will focus on the XGIS instrument architecture and on the physical principle used by its detector plane. XGIS is the instrument most directly connected to the work presented in this thesis: it combines the coded-mask imaging principle and an hybrid detector based on Silicon Drift Detectors (SDDs), scintillator bars, and on the ORION readout electronics to detect, localize, and characterize high-energy transients over the 2 keV–10 MeV range.

The term *hybrid detector* is used here in a precise sense: each XGIS detection element uses the SDDs both as a direct detector for low-energy X-rays and as a photodetector for the scintillation light produced in the thallium-doped cesium iodide, CsI(Tl), crystal by hard X-rays and gamma rays. The same pixel therefore integrates two detection channels, one through direct charge collection in silicon and another via indirect scintillation readout through the crystal.

2.4.1 XGIS architecture

The XGIS system is organized hierarchically, from the complete instrument down to individual detector pixels. At system level, XGIS includes two camera units, two XGIS Supply Units (XSUs), a Data Handling Unit (DHU), and the harness connecting the subsystems. The DHU provides the interface with the spacecraft for commands and data handling, and it also hosts the onboard trigger and instrument-control functions. Each camera is a self-contained coded-mask unit, including the mask, collimator, detector plane, detector mechanical frame, thermal interface, and camera back-end electronics. This system architecture is shown in Figure 2.7.

The detector plane is modular. Each camera is composed of *super-modules*, each super-module groups several detector *modules*, and each module contains an 8×8 matrix of *pixels*. In this hierarchy, the module is the basic unit of the detector plane, while

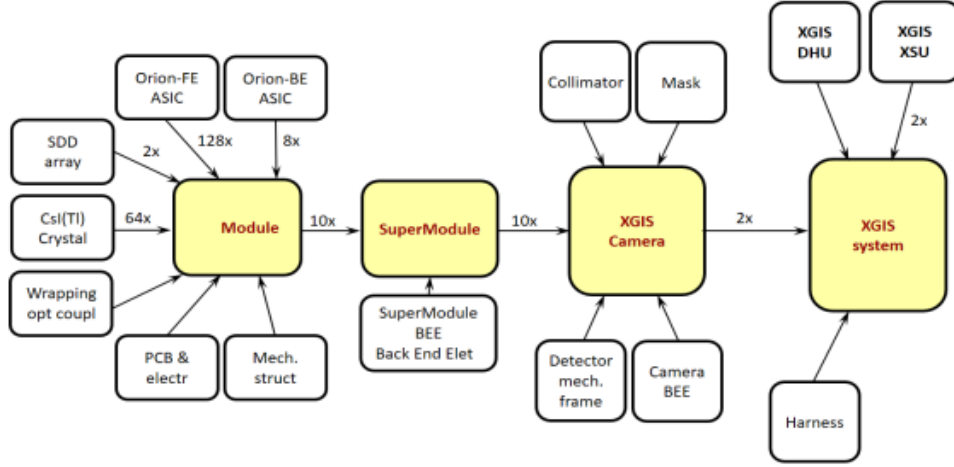


Figure 2.7. Functional block diagram of the XGIS system, showing the hierarchy from the complete instrument to the cameras, super-modules, modules, and detector pixels. Adapted from [THESEUS Consortium \(2021\)](#); [Labanti et al. \(2021\)](#).

the pixel is the basic detection element. A pixel is formed by a CsI(Tl) scintillator bar coupled to two corresponding SDD cells, one on the entrance side and one on the opposite side of the crystal bar.

The internal structure of a detector module is shown in Figure 2.8. Each module contains two SDD matrices, one on the top side and one on the bottom side, optically coupled to an array of CsI(Tl) scintillator bars. The ORION-FE ASICs are placed close to the SDD anodes, while the ORION-BE ASICs and the control and power electronics are hosted in the lower part of the module. This layout illustrates how the detector, optical coupling, mechanics, and readout electronics are integrated within a compact self-contained unit.

This modularity is important both for the flight design and for the laboratory work presented in Chapter 3. In the full instrument, it makes the detector scalable and allows assembly and testing to be performed module by module. In the laboratory prototype, only a reduced number of bars and SDD channels is used, but the same top–bottom coupling, scintillation-light collection, and ORION-based readout logic are preserved. For this reason, the prototype can test the same basic detection principle adopted in the complete XGIS detector module. Each module can be tested independently before integration into a super-module, and damaged or defective modules can be replaced during detector-plane assembly ([Labanti et al., 2020](#)).

In the following, the expression *top* refers to the SDD plane placed on the entrance side, exposed to the incoming radiation from the sky, while *bottom* refers to the SDD plane coupled to the opposite side of the scintillator bars. The top and bottom signals are fundamental for distinguishing direct silicon events from scintillation events and for estimating the interaction position along the crystal, as discussed in Section 2.4.5.

Each XGIS unit is a coded-mask camera composed of a mask, a collimator, and a

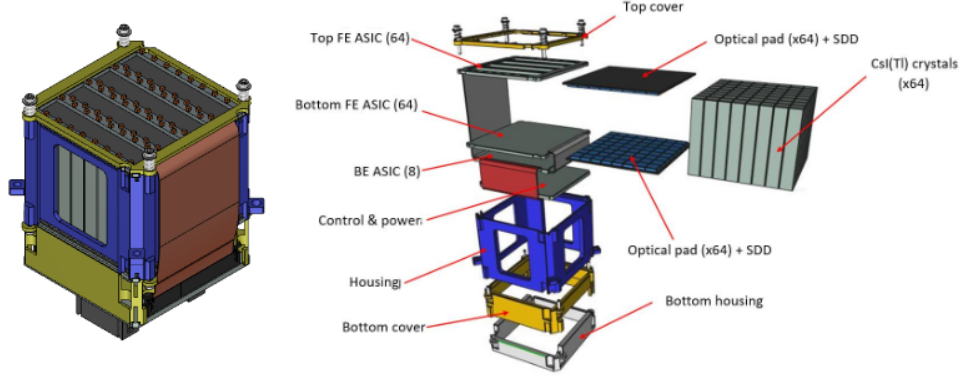


Figure 2.8. Detector module design for XGIS. The exploded view shows the integration of the top and bottom SDD matrices, CsI(Tl) scintillator crystals, optical coupling pads, ORION-FE ASICs, ORION-BE ASICs, control and power electronics, and mechanical housing designed for M5 studies. Adapted from [Labanti et al. \(2020\)](#).

detector plane. The two cameras are pointed with a relative offset to increase the sky coverage and to keep the SXI field inside the effective XGIS field of view during survey observations. A schematic view of the two XGIS cameras is shown in Figure 2.9.

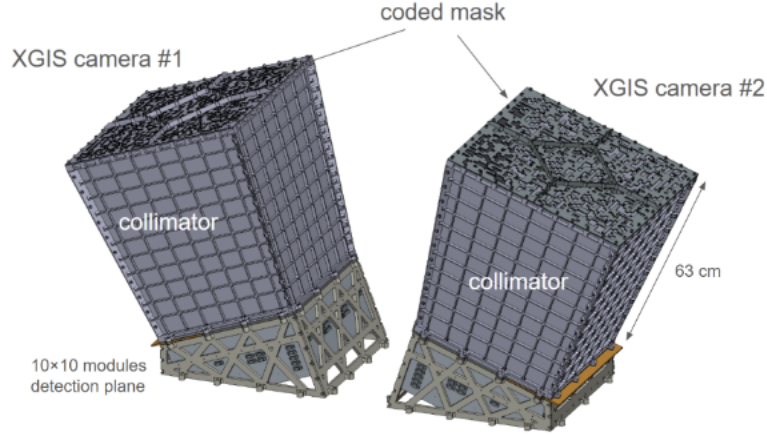


Figure 2.9. Schematic view of the two XGIS cameras, including the coded mask, collimator system, and detector plane. Adapted from [Mattioli et al. \(2026a\)](#).

2.4.2 Coded-mask imaging

XGIS uses coded-mask imaging in the 2–150 keV range ([THESEUS Consortium, 2021](#); [Labanti et al., 2020](#)). This technique is adopted since conventional focusing optics are not practical over the hard X-ray band covered by XGIS. In a coded-mask system, a mask made of opaque and transparent elements arranged in a known pseudo-random pattern projects a shadow pattern, or *shadowgram*, onto a position-sensitive detector plane.

The source direction is reconstructed by comparing the recorded shadowgram with the known mask pattern, following the general principle of coded-aperture imaging (Caroli et al., 1987). Figure 2.10 shows the imaging principle of the coded mask technique.

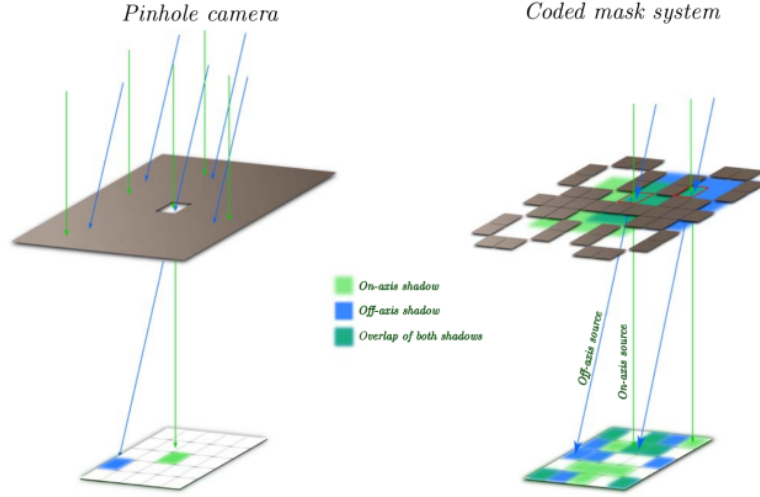


Figure 2.10. Schematic representation of the coded-mask imaging principle. The shadow pattern projected onto the detector plane depends on the direction of the incoming radiation and can be reconstructed to determine the source position. Adapted from Labanti et al. (2021).

For XGIS, the coded mask is located 63 cm above the detector plane and is made of tungsten. The mask element size is chosen in relation to the detector pixel size, so the angular resolution is set mainly by the mask pitch and the mask–detector distance. Below 150 keV, the mask and collimator define the imaging field of view and allow source localization. Above 150 keV, tungsten becomes increasingly transparent, the shadow contrast is lost, and the instrument works as a wide-field spectrometer rather than as an imager.

The geometrical and material properties of the coded mask also contribute to the *effective area* of the instrument. The effective area is defined as the area of an ideal detector that would record the same number of source photons as the real system for a given incident flux. In simplified form, it can be written as

$$A_{\text{eff}}(E, \theta, \phi) = A_{\text{geom}} \epsilon(E, \theta, \phi), \quad (2.1)$$

where A_{geom} is the geometrical area of the detector plane and $\epsilon(E, \theta, \phi)$ is the energy- and direction-dependent efficiency of the complete detection system. For a coded-mask instrument such as XGIS, this term includes both the absorption efficiency of the detector plane and the transmission properties of the mask–collimator system. Consequently, changes in the mask material, thickness, or geometrical pattern can modify the effective area of the instrument (Labanti et al., 2021).

The coded-mask system is therefore connected directly to the modular detector plane: the detector pixels do not form an image by focusing, but record the spatial modulation produced by the mask. For this reason, the pixel pitch, mask pattern, and detector-plane geometry are part of the same imaging design.

2.4.3 Photon interactions and scintillation detection

The response of XGIS depends on where the incoming photon deposits its energy. At low energies, photons are efficiently absorbed in silicon and are thus detected directly by the top SDD. At higher energies, the interaction probability in silicon decreases and photons reach the CsI(Tl) scintillator, where the dominant interaction mechanism depends on energy and absorber atomic number. Photoelectric absorption is most important at lower energies, Compton scattering dominates over a broad intermediate range, and pair production becomes possible above 1.022 MeV.

The probability that an incident photon interacts while crossing a material thickness x can be expressed in terms of the linear attenuation coefficient $\mu(E)$ as

$$P_{\text{int}}(E, x) = 1 - \exp[-\mu(E)x]. \quad (2.2)$$

For photons in the X-ray and gamma-ray range relevant to XGIS, the total attenuation coefficient can be described as the sum of the main interaction contributions,

$$\mu(E) = \mu_{\text{pe}}(E) + \mu_{\text{C}}(E) + \mu_{\text{pp}}(E), \quad (2.3)$$

where the subscripts indicate photoelectric absorption, Compton scattering and pair production, respectively. Their relative importance depends both on photon energy and on the atomic number of the absorbing material, as illustrated in Figure 2.12.

The physical processes responsible for the energy deposition in the scintillator can be summarized as follows:

- **Photoelectric absorption.** The incident photon is completely absorbed by an atomic electron, which is ejected from its shell. Neglecting the recoil of the atom, the kinetic energy of the emitted photoelectron is

$$K_e = E_\gamma - E_B, \quad (2.4)$$

where E_γ is the incident photon energy and E_B is the binding energy of the electron. Since almost all the photon energy is deposited locally, this process contributes to the formation of the full-energy peak. It is favoured at low photon energies and in materials with high atomic number, such as CsI(Tl).

- **Compton scattering.** The incident photon transfers only part of its energy to an electron and is scattered through an angle θ . Treating the electron as initially free and at rest, the energy of the scattered photon is

$$E'_\gamma = \frac{E_\gamma}{1 + \frac{E_\gamma}{m_e c^2} (1 - \cos \theta)}, \quad (2.5)$$

or, equivalently,

$$\frac{1}{E'_\gamma} - \frac{1}{E_\gamma} = \frac{1 - \cos \theta}{m_e c^2}. \quad (2.6)$$

The energy deposited by the recoil electron is

$$K_e = E_\gamma - E'_\gamma. \quad (2.7)$$

Since the scattering angle can vary continuously, Compton interactions generate a continuum of deposited energies. The maximum transferred energy corresponds to back-scattering, $\theta = \pi$, and defines the Compton edge.

- **Pair production.** When the incident photon energy exceeds twice the electron rest-mass energy,

$$E_\gamma \geq 2m_e c^2 = 1.022 \text{ MeV}, \quad (2.8)$$

the photon can be converted, in the electric field of the absorber, into an electron–positron pair. Neglecting the small nuclear recoil, the kinetic energy shared by the two particles is

$$K_{e^-} + K_{e^+} \simeq E_\gamma - 2m_e c^2. \quad (2.9)$$

After losing its kinetic energy, the positron annihilates with an electron, producing two photons of energy 511 keV. Depending on whether these photons are absorbed or escape from the scintillator, full-energy, single-escape or double-escape features may appear in the measured spectrum.

The spectral signatures associated with these interaction processes are summarized in Figure 2.12. In the energy range relevant to the measurements and simulations presented in this thesis, photoelectric absorption and Compton scattering are particularly important for interpreting the energy-deposition spectra obtained with the CsI(Tl) detector.

The dominant interaction mechanism of gamma rays in matter depends on both the photon energy and the atomic number of the absorber. As shown in Figure 2.11, photoelectric absorption dominates at low energies, Compton scattering is the main process at intermediate energies, and pair production becomes relevant at high energies.

A scintillator converts part of the deposited energy into optical photons. The incident photon first transfers energy to charged particles produced in the interaction. These particles excite states in the crystal lattice; the subsequent de-excitation produces scintillation light. The charge is proportional, to first order, to the energy deposited in the crystal, which allows spectroscopic measurements.

The scintillator material adopted for XGIS is CsI(Tl). The high atomic numbers of cesium and iodine provide strong stopping power for hard X-rays and gamma rays, while the thallium activator increases the scintillation efficiency. The XGIS bars have a square section matched to the SDD pixel pitch and a length of 3 cm. Their lateral surfaces are wrapped with reflective material to guide scintillation light toward the two SDDs, and the optical coupling to the SDDs is provided by thin silicone pads, 0.5 mm thick.

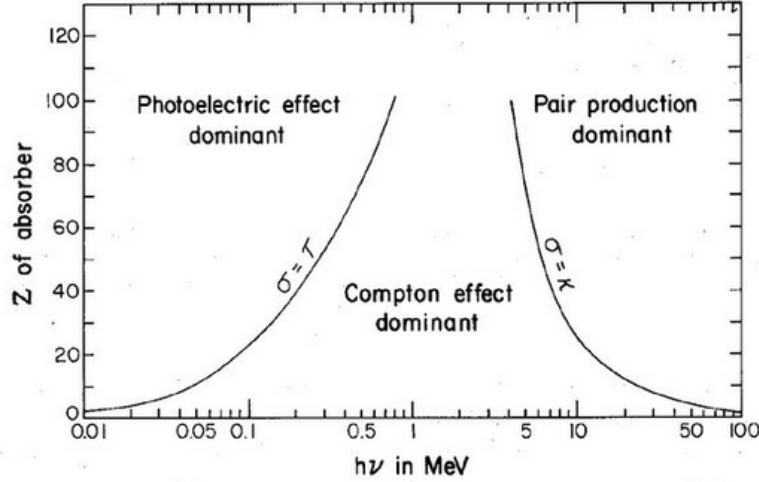


Figure 2.11. Relative importance of the three principal gamma-ray interaction mechanisms in matter as a function of photon energy and absorber atomic number. The figure shows the regions where photoelectric absorption, Compton scattering, and pair production dominate. Adapted from [Evans \(1955\)](#).

Examples of CsI(Tl) scintillator bars used in the laboratory are shown in Figure 2.13. Their different dimensions reflect the prototype-oriented approach used to test the scintillation response and light-collection properties before integration in the complete detector geometry.

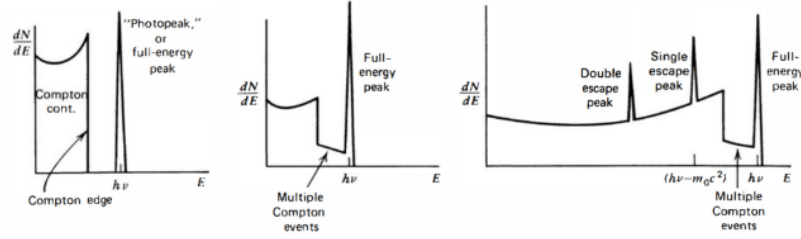
2.4.4 Silicon Drift Detectors

Silicon Drift Detectors provide both low-energy X-ray detection and optical readout of the scintillator light. An SDD is a reverse-biased silicon detector in which a set of biased drift electrodes creates an electric field that transports the electrons produced by ionizing radiation toward a small collecting anode. Because the anode capacitance is low, the electronic noise remains low even for a relatively large detector area ([Hartmann et al., 1997](#)).

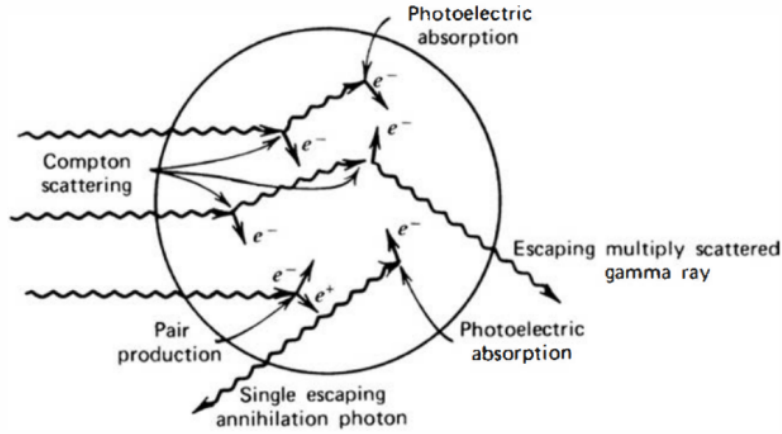
When an X-ray photon is absorbed in silicon, most of the energy is converted into electron-hole pairs. In silicon, the average energy required to create one electron-hole pair is 3.6 eV. The electrons drift toward the anode and the collected charge is proportional to the deposited energy. This makes the SDD a spectroscopic detector for the X-ray band. Working principle of a Silicon Drift Detector is shown in Figure 2.14.

The electrostatic potential inside the SDD has a funnel-like shape that guides the charge toward the anode, as shown in Figure 2.15. This field geometry is what allows the detector to combine a large sensitive area with low readout capacitance.

The SDDs adopted for XGIS are matrix devices developed for the detector modules. Each SDD matrix is made of 8×8 cells with a pitch of 5 mm, corresponding to the pixel geometry of the scintillator bars. The silicon thickness is 450 μm , sufficient for direct



- (a) The processes of photoelectric absorption and single Compton scattering give rise to the low-energy spectrum.
- (b) In addition to the continuum from single Compton scattering and the full-energy peak, the spectrum at medium energies shows the influence of multiple Compton events.
- (c) The single escape peak corresponds to initial pair production interactions in which only one annihilation photon leaves the detector without further interaction. A double escape peak will also be present due to those pair production events in which both annihilation photons escape.



(d) Representation of the possible interactions between γ -ray photons and scintillator material.

Figure 2.12. Representation of the principal interaction processes between gamma rays and scintillator materials together with their corresponding spectral features. The figure illustrates the contributions of photoelectric absorption, Compton scattering, and pair production processes at different energies. Adapted from [Knoll \(2010\)](#).



Figure 2.13. CsI(Tl) scintillator bars of different sizes.

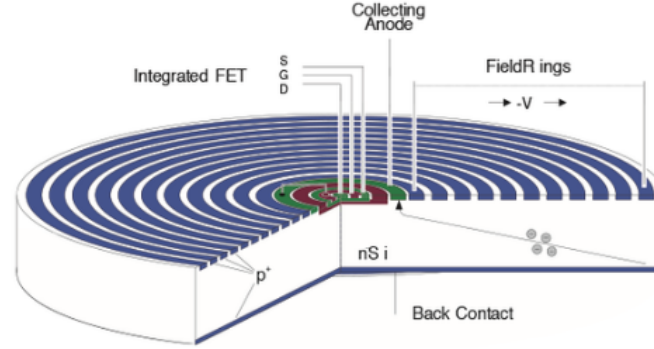


Figure 2.14. Working principle of a Silicon Drift Detector (SDD). The drift field generated by the biased rings guides the electrons produced by ionizing radiation toward the collecting anode characterized by very low capacitance. Adapted from [Hartmann et al. \(1997\)](#).

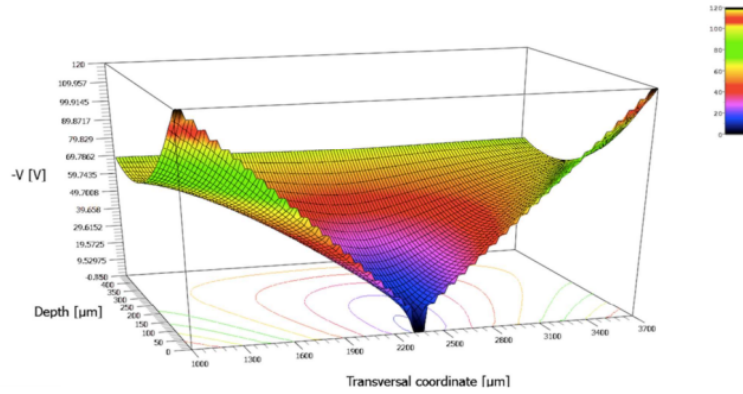


Figure 2.15. Numerical simulation of the electrostatic potential distribution inside a Silicon Drift Detector. The funnel-shaped potential profile guides the electrons toward the collecting anode located at the center of the detector. Adapted from [Vacchi et al. \(1991\)](#).

detection of photons in the XGIS low-energy range. A picture of the SDD front-end assembly used in the prototype work is shown in Figure 2.16.



Figure 2.16. SDD front-end assembly used in the XGIS prototype activity. The SDD matrix is coupled to the front-end readout chain in order to minimize the input capacitance and preserve low-noise performance.

The two sides of a full XGIS SDD matrix are shown in Figure 2.17. This figure is useful to distinguish the side exposed to the incoming X-ray radiation from the side optically coupled to the scintillator light. In the XGIS design, the n-side contains the anodes and drift electrodes and is used as the entrance side for direct X-ray detection, while the p-side acts as the optical entrance window for the scintillation light generated in the CsI(Tl) bars (Labanti et al., 2020).

2.4.5 The *siswich* detection principle

As mentioned above, the hybrid XGIS pixel detection system follows the *siswich* principle, from “silicon sandwich”. A scintillator bar is coupled to two SDD cells, one on the top side and one on the bottom side. This geometry allows the same pixel to work in two modes: direct conversion in silicon for X-rays and indirect conversion in the scintillator for hard X-rays and gamma rays (Labanti et al., 2020; Mele et al., 2021). The *siswich* detection principle is Shown if Figure 2.18.

For an X-event, a photon in the 2–30 keV range is absorbed in the top SDD. The event is localized in one SDD cell, and the energy is measured from the charge collected by that cell. Since the signal is fast and only the top SDD is involved, the event is processed by a dedicated branch of the front-end electronics (Section 2.5), the so-called

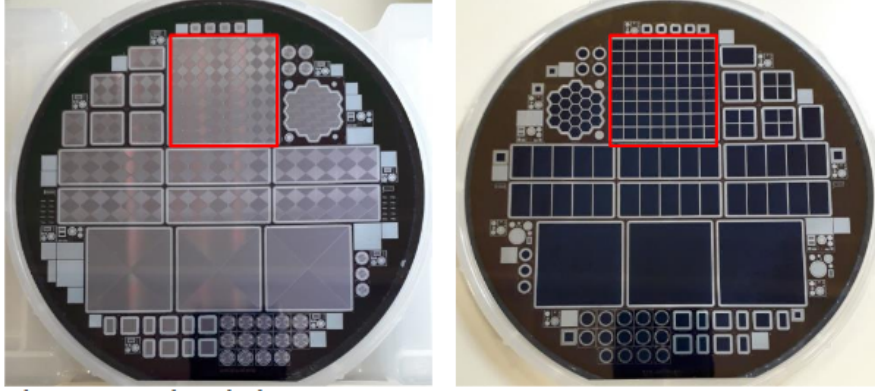


Figure 2.17. Photos of the two sides of a wafer from the FBK ReDSOX 2019 production batch, with the monolithic SDD matrix designed for the XGIS instrument highlighted, among other sensor types. Left: anode and drift-electrode side, corresponding to the n-side and used as the entrance side for X-ray radiation. Right: entrance-window side, corresponding to the p-side and used for the scintillation light produced in the CsI(Tl) crystal. Adapted from [Labanti et al. \(2020\)](#).

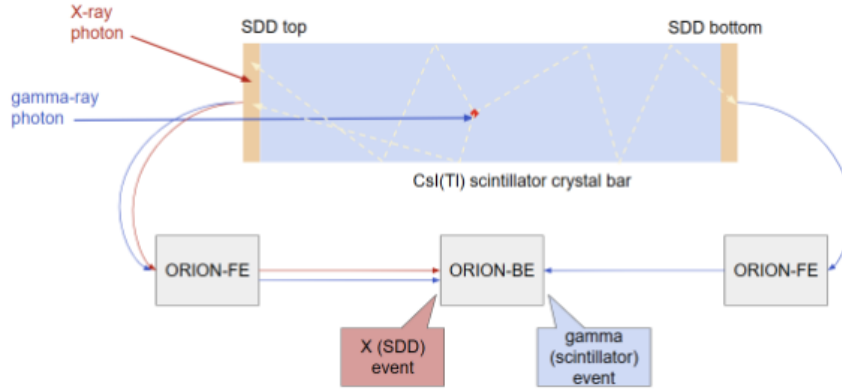


Figure 2.18. Schematic representation of an XGIS pixel based on the *siswich* detection principle. Direct X-ray events are detected by the top SDD, while gamma-ray interactions in the CsI(Tl) scintillator produce light collected by both the top and bottom SDDs. The top-bottom signal logic is processed by the ORION front-end and back-end electronics. Adapted from [Mattioli et al. \(2026a\)](#); [Mele et al. \(2021\)](#).

X-branch.

For a gamma-event, the photon reaches the CsI(Tl) bar and deposits energy in the scintillator. The generated scintillation light propagates toward both ends of the bar and is collected by the top and the bottom SDDs. The deposited energy is reconstructed from the two measured signals, through two other dedicated branches of the front-end electronics (Gamma Top and Gamma Bottom branches), while their ratio gives information on the interaction position along the bar because of optical attenuation. This top–bottom logic is therefore not only an event-discrimination tool, but allows also for a full 3-D position-sensitive response of the detector.

The distinction between silicon-based events and scintillator-originated events is necessary because the two media produce charge signals with different amplitudes and time profiles. The ORION front-end electronics use the topology of the signal, the coincidence between top and bottom SDDs, and three different shaping branches to assign each event to the correct physical channel, as discussed below.

2.5 The ORION readout electronics

Given that the same detector element must process two different signal classes, the hybrid XGIS pixel requires dedicated electronics. Summarizing the discussion in the previous Section, the direct X-ray absorption in the top SDD produces a fast charge signal from a single cell, while a gamma-ray interaction in the CsI(Tl) bar produces slower scintillation light collected by both the top and bottom SDDs. The ORION chipset is the custom-made *Application Specific Integrated Circuit* (ASIC) readout developed to perform this task with low noise, low power consumption, and compact geometry (Mele et al., 2021; Grassi et al., 2022).

The ORION architecture is divided into a front-end ASIC, ORION-FE, and a back-end ASIC, ORION-BE. This separation is imposed by the detector geometry. The first amplification stage must be placed very close to the SDD anode to reduce parasitic capacitance and electronic noise, but the more complex analog and digital processing can be placed a few centimeters away from the sensitive detector area. The result is a distributed readout chain compatible with the modular XGIS detector plane. The ORION processing logic for a single XGIS pixel is shown in Figure 2.19.

ORION-FE: first amplification close to the detector

The ORION-FE is the first stage of the readout chain. Its main function is to convert the transient current pulse collected by the SDD anode into a voltage step-like signal. This is done by a Charge Sensitive Amplifier (CSA), followed by signal-conditioning stages that prepare the signal for transmission to the back-end electronics.

The front-end stage is kept small so that it can be placed close to the SDD without shadowing the entrance side of the detector. This is particularly important for X-events, because low-energy photons must reach the top SDD with minimal obstruction from passive material. After pre-amplification, the signal is transmitted from ORION-FE to ORION-BE.

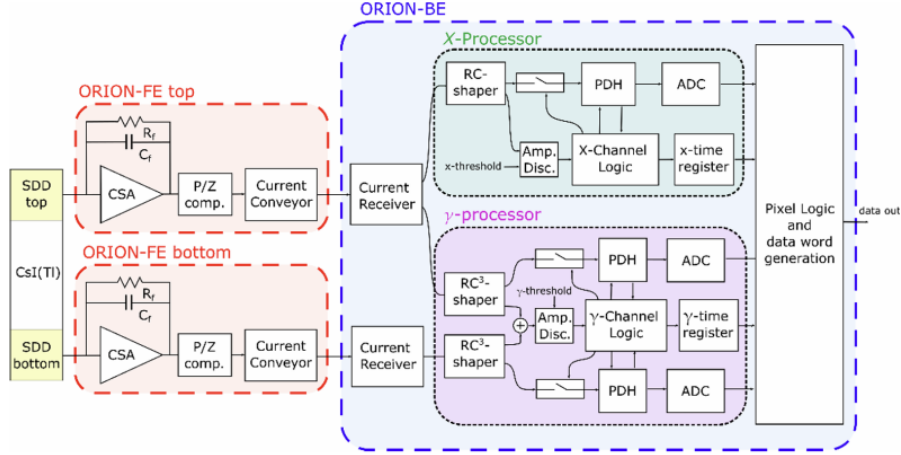


Figure 2.19. Block diagram of the ORION electronics and processing logic for a single XGIS pixel, divided into ORION-FE and ORION-BE stages. The front-end electronics are directly connected to the top and bottom SDDs coupled to the CsI(Tl) scintillator bar, while the back-end stage performs shaping, trigger generation, digitization, and event discrimination. Adapted from [Mele et al. \(2021\)](#); [Grassi et al. \(2022\)](#).

ORION-BE: shaping, trigger, digitization, and event logic

The ORION-BE receives the two pre-shaped signals from the top and bottom ORION-FE chips associated with one pixel. Its processing chain contains dedicated branches for the X and gamma channels. The X branch processes the fast signal from the top SDD, while the gamma branches use the top and bottom signals associated with scintillation light from the CsI(Tl) bar.

Besides the different energy range, which is about 2–30 keV for X-ray branch, and about 30 keV to the MeV range for gamma branch ([THESEUS Consortium, 2021](#)), the other difference between the branches is the *shaping time*. The X signal is fast, so the X branch uses a shorter shaping time to optimize the signal-to-noise ratio for direct silicon events. The scintillation signal is slower, so the gamma branch uses a longer shaping time to avoid *ballistic deficit*. This effect occurs when the electronics' shaping time is too short compared with the duration of the input signal. In that case, the shaped pulse does not reach the amplitude corresponding to the total collected charge, resulting in an underestimation of the deposited energy. The logic is summarized in Table 2.4. This is also the natural stage of the chain where shaping, peak detection, stretching, and digitization are performed ([Marisaldi et al., 2005](#)).

In addition to the different shaping branches, ORION-BE can be configured in different operating modes. In shaping mode, the shaped analog outputs of the X and γ branches are routed to the output buffer, while the discriminator, peak detector, and trigger logic are not used for autonomous event acquisition. In stretching mode, the discriminator, peak detector, trigger logic, and peak-stretching circuit are enabled; the

signal peak is held long enough to be digitized and associated with the corresponding event information. This configurable operation is important for laboratory tests, where the ASIC response can be studied either by observing the shaped analog signals directly or by using the complete trigger–stretching–digitization chain (Mattioli, 2024; Mele et al., 2021).

Table 2.4. Main ORION processing branches for one XGIS pixel.

Branch	Physical event	Input signal	Shaping time
X branch	Direct X-ray event	Top SDD	1 μ s
γ -top branch	Scintillation event	Top SDD	3 μ s
γ -bottom branch	Scintillation event	Bottom SDD	3 μ s

After shaping, the signals are compared with programmable discriminator thresholds. When a valid trigger is generated, the peak detector identifies the pulse maximum and the stretching circuit holds the peak level for the analog-to-digital conversion. Here ADC denotes an Analog-to-Digital Converter, namely the circuit that converts the analog pulse amplitude into a digital value proportional to the deposited energy. In the XGIS design, the ORION-BE processing includes three shaping branches followed by 12-bit ADCs, while the event time is assigned at ASIC level with a time resolution of the order of 1 μ s (Labanti et al., 2020).

For an X-event, a trigger in the X branch indicates that the photon was absorbed in the top SDD. The event is stored as an X event, and the digitized amplitude gives the deposited energy in silicon. For a gamma event, the top and bottom gamma branches are active in coincidence. The two shaped signals are used by the gamma discriminator, digitized by the ADCs, and combined to reconstruct the deposited energy in the scintillator.

This event logic is the electronic implementation of the *siswich* principle. A top-only fast signal corresponds to direct silicon absorption, while a time-coincident top–bottom signal corresponds to scintillation light produced in the CsI(Tl) bar. The same logic also preserves the position information along the bar, because the relative amplitudes of the top and bottom signals depend on where the photon interacted inside the crystal.

For each accepted trigger, the ORION-BE assembles a 64-bit data word containing the timing information, the digitized amplitudes of the three processing branches, and the event-classification flags. In the updated format, the data word includes 24 bits for the timestamp, three 12-bit ADC fields corresponding to the X, γ -top, and γ -bottom branches, three flag bits identifying the X trigger, the gamma trigger, the X/ γ event classification, and one spare bit (Mattioli et al., 2026b). The corresponding 64-bit event data word produced by the ORION-BE for each triggered pixel is summarized in Table 2.5.

It is important to note that the ADC fields are always present in the output word.

The ORION output for each event includes timing information, event type, and digitized amplitudes for the relevant SDD channels. These quantities are the starting point for the laboratory analysis presented in Chapter 3, where the X branch, gamma-top branch, gamma-bottom branch, and top–bottom summed configurations are calibrated

Table 2.5. ORION-BE event data word for one triggered pixel. Adapted from [Mattioli et al. \(2026b\)](#).

Field	Number of bits
Time	24
X and γ event flag	3
X ADC	12
γ Bottom ADC	12
γ Top ADC	12
spare bit	1
Total	64

using radioactive sources and the electronic noise is calculated using pulser signals.

Experimental characterization of the XGIS prototype

This chapter presents the experimental activity performed on the four-pixel XGIS prototype equipped with the ORION readout electronics. First, the detector assembly, the readout configuration, and data-acquisition setup are described. The calibration procedure for the X and gamma branches is then presented, together with the determination of the effective value of the test capacitance and of the electronic noise. Finally, the scintillation light output and the response uniformity of the CsI(Tl) bars are investigated using radioactive-source measurements.

3.1 Experimental Setup

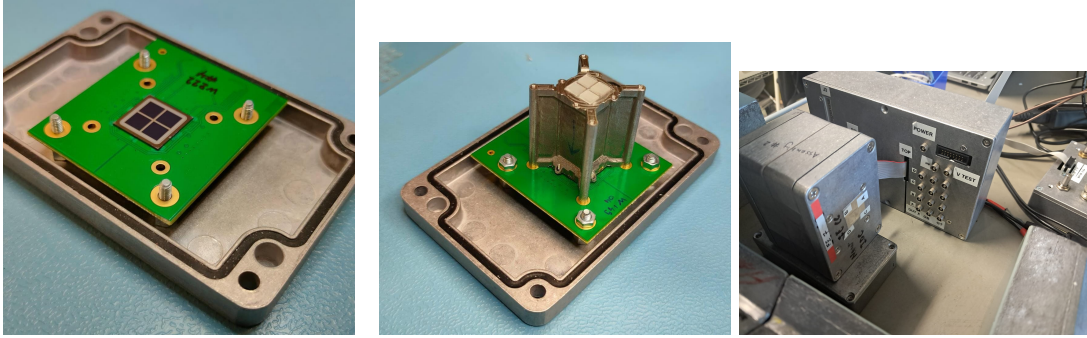
The experimental activity presented in this work was carried out using a 4-pixels prototype of the XGIS detection system, based on Silicon Drift Detectors (SDDs), produced by Fondazione Bruno Kessler (Trento, Italy), optically coupled to CsI(Tl) scintillator bars and read out. The front-end analog part was developed by Politecnico di Milano, the mixed-signal and digital part by University of Pavia ([Mele et al., 2021](#); [Grassi et al., 2022](#)), and produced by the Austria Microsystems (AMS) foundry in a multi-project wafer 0.35 μm technology run. The system operates according to the siswich detection principle described in Chapter 2, enabling the detection of both X-ray photons directly absorbed in the SDDs and higher-energy photons interacting within the crystal, whose scintillation light is collected at both ends of the crystal. A picture of the setup is shown in Figure 3.1.

The detector assembly made by OHB Milano consists of scintillator bars coupled to SDDs and read out by the ORION ASIC system. The ORION readout architecture and the functions of the ORION-FE and ORION-BE stages have been described in Section 2.5. In this chapter, the focus is therefore on the laboratory configuration adopted for the measurements and on the experimental characterization results.

The measurements were performed using different configurations, testing at first the front-end boards. In particular, attention was devoted to the relation between electronic channels and detector elements, as well as to the validation of the readout configuration before the calibration and position-dependent measurements.

3.1.1 Data Acquisition

The data acquisition system was based on an Amptek ([Amptek Inc., 2026b](#)) Digital Pulse Processor (model DP5) which integrates a Multi-Channel Analyzer (MCA), which records the detected events as spectra in instrumental units. Throughout this Chapter, the word (*ADU*) is used for Analog-to-Digital Units (ADU) bins, while *bar* refers to the



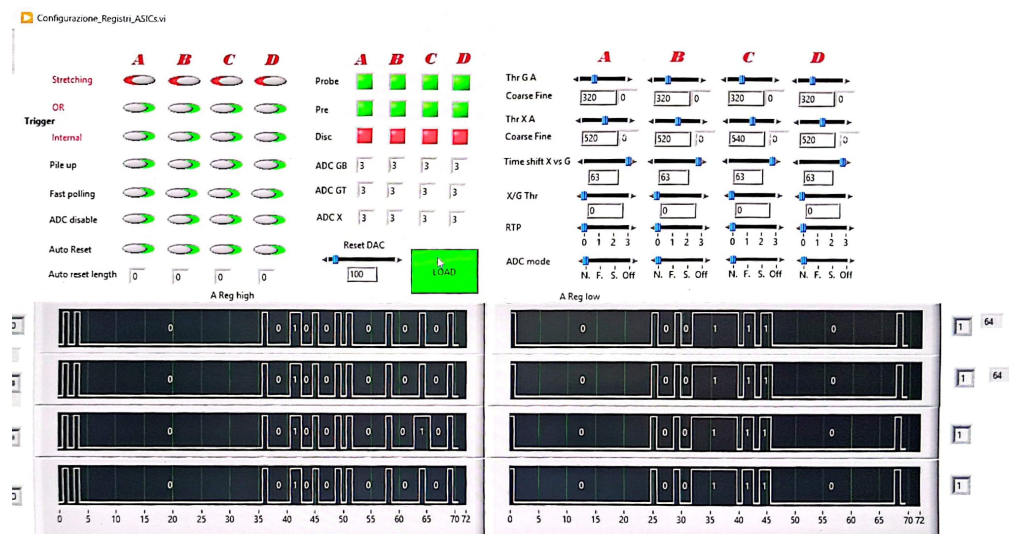
(a) Top front-end assembly before mounting the scintillator housing. The four SDD pixels are visible at the centre of the PCB, together with the mechanical supports used for the assembly.

(b) Bottom front-end assembly with the CsI(Tl) crystal housing mounted above the two front-end assemblies connected to the back-end electronics through the top and bottom bus cables. In this configuration, the power supply, test-voltage lines, and output connections are not yet connected.

(c) External view of the experimental setup, including the integrated front-end detector box connected to the back-end electronics through the top and bottom bus cables. In this configuration, the power supply, test-voltage lines, and output connections are not yet connected.

Figure 3.1. Prototype of the XGIS detector system used for the experimental activity. Figures 3.1a and 3.1b show the two front-end assemblies before final closure, while Figure 3.1c shows the integrated front-end detector box connected to the back-end electronics. The top and bottom front-end boards are identical in design; their role is defined only by their position in the assembled detector configuration.

The acquisition and ASIC-control parameters were configured through a LabVIEW-based interface developed within the ORION test activity at INAF/OAS Bologna, following the same test-bench logic described in a previous ORION characterization work (Borcianni, 2023). Before each acquisition, the ORION configuration registers were loaded to define the ASIC operating conditions, including the selected output mode, the discriminator thresholds, the internal trigger configuration, the ADC activity, and the reset sequence required to pass from configuration mode to acquisition mode. These settings determine which branch is read out and how the analog pulses are selected, held, and digitized. During the measurements, the discriminator level was adjusted to suppress low-amplitude electronic noise while preserving the X-ray and scintillation-induced spectral features. An example of the LabVIEW register-configuration panel is shown in Figure 3.2, while the general acquisition workflow is shown in Figure 3.3.



A set of radioactive sources was used to characterize the detector response over the energy range relevant to the measurements. In particular, ^{55}Fe and ^{241}Am were

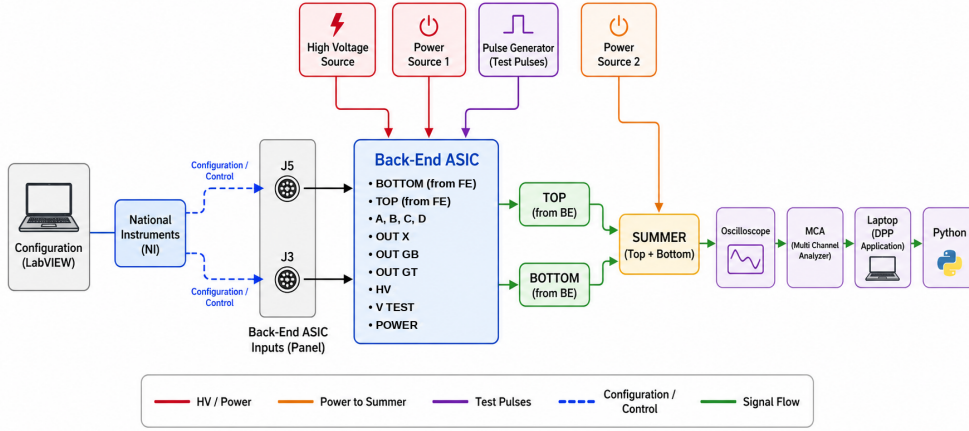


Figure 3.3. Experimental setup workflow

employed for the calibration of the X branch, while ^{241}Am and ^{137}Cs were used for the characterization of the gamma branch and of the scintillation response. The main photon emissions relevant to the present analysis are summarized in Table 3.1.

Table 3.1. Main photon emissions of the radioactive sources relevant to the experimental measurements. Energies and emission probabilities are taken from the IAEA recommended decay-data standards for detector calibration ([International Atomic Energy Agency, 2007](#)). For the ^{241}Am source, the Np $L_{\beta\eta}$ entry is reported as an unresolved low-energy X-ray group, with the IAEA weighted mean at 17.81 keV.

Source	Emission	Energy (keV)	Probability/decay
^{55}Fe	Mn $K_{\alpha 2}$ X-ray	5.8877	0.0845
	Mn $K_{\alpha 1}$ X-ray	5.8988	0.1656
	Mn K_{β} X-ray group	6.49–6.54	0.0340
^{241}Am	Np L_l X ray	11.89	0.0085
	Np L_{α} X-ray group	13.90	0.1303
	Np $L_{\beta\eta}$ X-ray group	16–18, mean 17.81	0.1886
	Np L_{γ} X-ray group	20.82	0.0481
	γ ray	26.3446	0.0240
^{137}Cs	γ ray	59.5409	0.3578
	γ ray from $^{137\text{m}}\text{Ba}$ de-excitation	661.657	0.8499

In addition, a Tektronix AFG1022 arbitrary function generator ([Tek, 2015](#)) was used to inject test signals of known amplitude into the readout chain. The generator was operated in ramp mode, with a frequency of 50 Hz and a $50\ \Omega$ load. The high level was set to 0 mV, while the low level was set to the selected negative amplitude.

For the X branch, the injected amplitudes were typically 50 and 80 mV. For the gamma branch, the injected amplitudes were 100, 200, 300, and 400 mV. Each acquisition

typically lasted 30 min to accumulate sufficient counts for spectral fitting.

For the X-branch calibration and the evaluation of the electronic noise, the radioactive source was positioned directly above the SDD side under investigation, either top or bottom. In this configuration, the measurements are primarily based on photons directly absorbed in the silicon detector, since the corresponding spectral peaks provide the reference response of the SDD and its readout electronics. The short source–detector distance also increases the number of directly detected events, allowing spectra with suitable statistical quality to be acquired within a reasonable measurement time. Any scintillation-induced contribution present in the spectrum was excluded from the X-branch calibration analysis later on.

In the case of combined measurements on the gamma branch, where the signals from the top and bottom SDDs were summed, the source was instead positioned at the center of the scintillator bars, at a distance of approximately 10 cm from the detector.

For the position-dependent measurements, a collimated ^{137}Cs source was used together with a motorized translation system controlled through the PIMikroMove software¹, shown in Figure 3.4. The radioactive source was housed behind a lead collimator provided with a 2 mm narrow slit, with a distance of 10 cm from the detector. The data acquisition was done at 6 different positions along each bar with the same distance of 6 mm from each other, so that only a localized region of the scintillator bars was irradiated. The detector assembly was displaced relative to the fixed, collimated beam along the longitudinal direction of the bars, allowing the scintillation response to be measured at different interaction positions. This configuration was used to investigate the uniformity of the light collection along each crystal bar.

During these measurements, the scintillator bars were oriented perpendicularly to the collimator slit, and the motorized stage displaced the detector with respect to the fixed collimated beam. A preliminary position calibration was performed to associate the coordinates of the translation stage with physical positions along each bar. Spectra were subsequently acquired at several positions along the active crystal length using the 661.657 keV emission line of ^{137}Cs .

The acquired spectra were processed using a Python-based analysis pipeline developed for this work (Appendix B). The pipeline reads the MCA output ASCII files, converts the spectra into numerical arrays, identifies the regions of interest corresponding to the relevant peaks, and extracts the quantities needed for the detector characterization. In particular, it was used to determine the calibration parameters, evaluate the response to the different radioactive sources, and extract the location in ADU and net counts associated with the ^{137}Cs photopeak in the position-dependent measurements.

A preliminary optimization of the acquisition parameters was required before performing the calibration measurements. In particular, the MCA Lower Level Discriminator (LLD) was adjusted to suppress low-channel events dominated by electronic and environmental noise. The LLD acts as a discriminator that removes signals below a selected threshold. An initial configuration with a threshold set too high resulted in the partial suppression of the scintillation signal. The discriminator level was therefore optimized to reject noise while preserving both the X-ray signals and the scintillation-induced events.

¹<https://www.physikinstrumente.com/en/products/software-suite/motion-control-software>

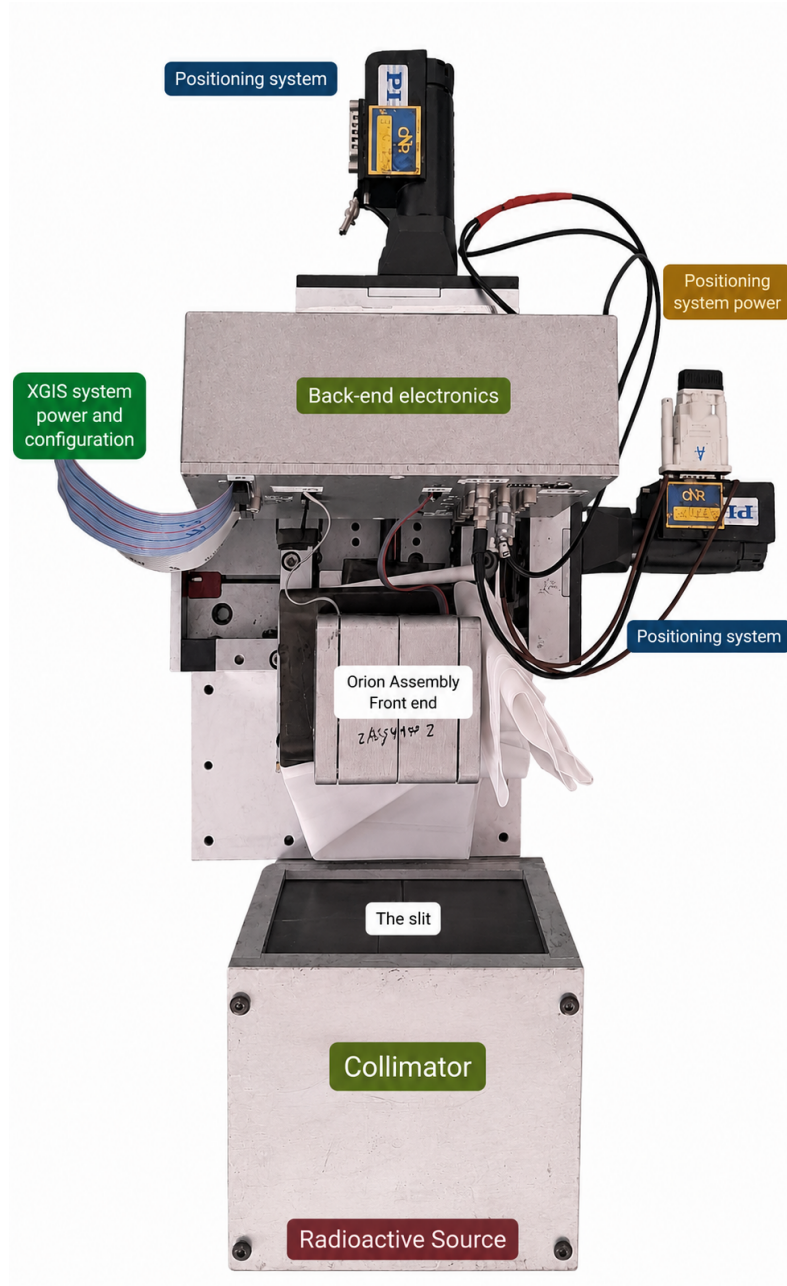


Figure 3.4. Experimental setup adopted for the Uniformity of the Light Output measurements with the collimated ^{137}Cs source. The radioactive source is placed behind the lead collimator with a 2 mm narrow slit for 30 minutes. The slit defines a localized irradiation region on the scintillator bars. The ORION detector assembly is moved with respect to the fixed beam by the motorized positioning system controlled through PIMikroMove.

This test setup allowed a comprehensive characterization of the detector prototype, including calibration, light-output evaluation, and position-dependent measurements, which are presented in the following sections.

3.1.2 Top–Bottom Channel Coupling Logic

Each CsI(Tl) scintillator bar is optically coupled to two Silicon Drift Detectors (SDDs), positioned at the opposite ends of the crystal. Consequently, scintillation events generated inside the bar produce signals simultaneously on both detector sides.

In the prototype assembly, the detector is read out by two identical Front-End boards, mounted on the two opposite sides of the scintillator-bar array and therefore referred to as the top and bottom boards, as already shown in Figure 2.16. Although the two boards have the same design and the same local channel labels, their physical orientation inside the assembly and the routing toward the Back-End electronics introduce a non-trivial correspondence between electronic channels and scintillator bars.

In an ideal configuration, each scintillator bar would correspond to matching top and bottom channel labels, for example $A_{\text{top}}-A_{\text{bottom}}$. In the present prototype, however, the electronic channel ordering does not directly follow the geometrical arrangement of the detector elements. As a consequence, the effective top–bottom channel associations used for the gamma summation are:

- $A_{\text{top}} \leftrightarrow D_{\text{bottom}}$
- $B_{\text{top}} \leftrightarrow C_{\text{bottom}}$
- $C_{\text{top}} \leftrightarrow B_{\text{bottom}}$
- $D_{\text{top}} \leftrightarrow A_{\text{bottom}}$

This non-trivial mapping, and therefore the correct assembling of the system, was experimentally verified through oscilloscope measurements and collimated ^{241}Am acquisitions performed on individual scintillator bars before the calibration and light-output analyses. In order to reconstruct the total scintillation signal, the outputs of the corresponding top and bottom gamma channels were processed by a dedicated analog summing module developed at INAF/OAS Bologna that is shown in Figure 3.6. The ORION-BE analog outputs exhibit a DC baseline offset of approximately 0.7–1 V, which prevents their direct acquisition with the standard dynamic range of the available Amptek Multi-Channel Analyzer (MCA, see next Section and Appendix A). The summing module, therefore, first subtracts the baseline offset from each input signal, providing two independent offset-corrected outputs suitable for MCA acquisition. The corrected top and bottom signals are then combined through an operational-amplifier summing stage, yielding an output proportional to the total scintillation light collected at the two ends of the crystal. The components of the circuit were selected in order to preserve the shape of the ORION-BE output pulses during offset subtraction and summation.

Figure 3.5 shows the validated top–bottom coupling configuration adopted during the laboratory measurements.

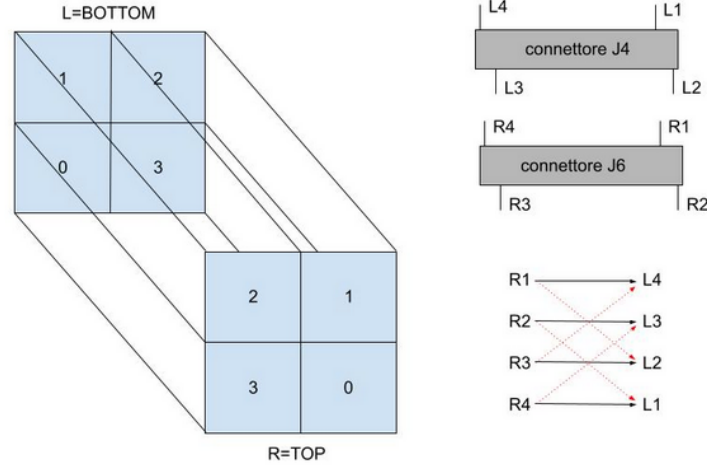


Figure 3.5. Schematic top-bottom coupling configuration between the Front-End channels used for the gamma signal summation. Corresponding channels from the two detector sides are combined through the summing electronics to reconstruct scintillation events in the CsI(Tl) bars. R represents the top panel, and L represents the bottom panel, and J4 and J6 are the connectors to the Back-end electronics.

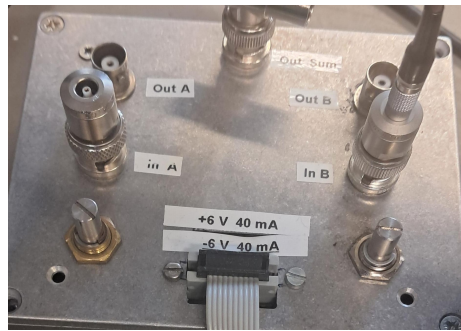


Figure 3.6. Analog summing module used during the gamma measurements to combine the signals from the top and bottom SDD channels.

3.2 Calibration and Noise Analysis

The calibration of the detector was performed in order to establish the relation between the MCA analog to digital channel (ADU) and the deposited energy, as well as to characterize the electronic noise of the system. The procedure was carried out using radioactive sources and pulser signals, allowing a consistent calibration over a wide dynamic range.

3.2.1 Energy Calibration

The calibration procedure was performed separately for the X and gamma branches, since the two branches correspond to different physical signals and dynamic ranges (see Section 2.5).

The first step consisted in the identification of the spectral features associated with the radioactive sources and with the pulser signals. The peak positions were extracted using a dedicated Python-based analysis pipeline (see Appendix B) and verified using the DPP software (see Appendix A). The pulser signals, injected at known amplitudes, were mainly used to characterize the electronic response of the system, extend the calibration range, and estimate the electronic noise.

For both branches, the calibration curve was obtained by associating the channel positions of the selected peaks with their corresponding reference energies. A linear relation between deposited energy and MCA channel was assumed:

$$E = m \cdot \text{ADU} + q, \quad (3.1)$$

where E is the deposited energy expressed in keV, ADU is the MCA channel, m is the calibration gain expressed in keV/channel, and q is the energy offset expressed in keV. The parameters were obtained through a linear fit, and the goodness of the fit was evaluated using the coefficient of determination R^2 and the residuals.

X-Branch Calibration

The identification of the relevant spectral features required particular care because of the presence of overlapping contributions in different channel regions. For the semiconductor response calibration, the low-energy X-ray lines of ^{241}Am , namely 13.95, 17.75, 20.78, and 26.34 keV, together with the ^{55}Fe line at about 5.9 keV, were used as primary calibration references. In addition, injected pulser signals with amplitudes of 50 and 80 mV were included as electronic reference peaks. Some test pulses in 90 and 110 mV range were also injected, but they have been excluded from the calibration calculation since they are outside of the linearity range of the front-end electronics.

In the intermediate channel region, additional spectral features attributed to fluorescence processes due to the physics of the crystal scintillator itself from Cesium and Iodine were observed. Since these contributions do not correspond to our energy source, they were excluded from the calibration procedure (see Figure 3.7). At higher channel values, the pulser signals were clearly identified and used to constrain the electronic

response of the system, ensuring a reliable extension of the calibration beyond the energy range covered by the radioactive sources. Their main use is to determine the electronic noise. The acquired spectrum of one of the channels for ^{55}Fe is shown in Figure 3.8.

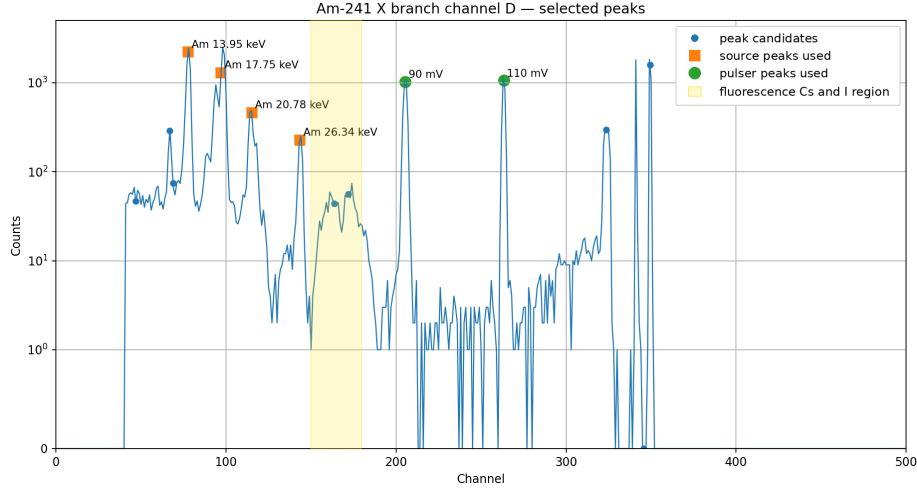


Figure 3.7. Example of peak identification for an X-branch channel. The selected ^{241}Am X-ray lines (59.54 keV is excluded), pulser peaks, and the excluded fluorescence region are indicated. The additional peaks in the intermediate-energy between Am 26.34 keV and the 90 mV pulse (shown in the yellow shadowed region) are associated with fluorescence X-rays from the CsI(Tl) scintillator, mainly iodine K_α and K_β lines, and cesium K_α and K_β . ([National Institute of Standards and Technology, 2005](#))

Table 3.2. Energy calibration parameters for the X-branch channels. The calibration is described by $E = m \cdot \text{ADU} + q$.

Channel	m (keV/ADU)	q (keV)	R^2
A	0.166 ± 0.006	1.07 ± 0.09	0.990
B	0.175 ± 0.005	1.43 ± 0.09	0.992
C	0.161 ± 0.005	0.91 ± 0.08	0.993
D	0.171 ± 0.005	0.95 ± 0.07	0.994

The X-branch calibration shows a linear response for all four channels shown in Table 3.2, with coefficients of determination in the range $R^2 = 0.990$ – 0.994 . The fitted calibration gains vary between 0.161 and 0.175 keV/ADU, while the offsets remain close to zero, between 0.91 and 1.43 keV. The small channel-to-channel variations in gain and offset are attributed to differences in the individual electronic chains and detector coupling. An example of the Calibration is shown in The plot 3.9

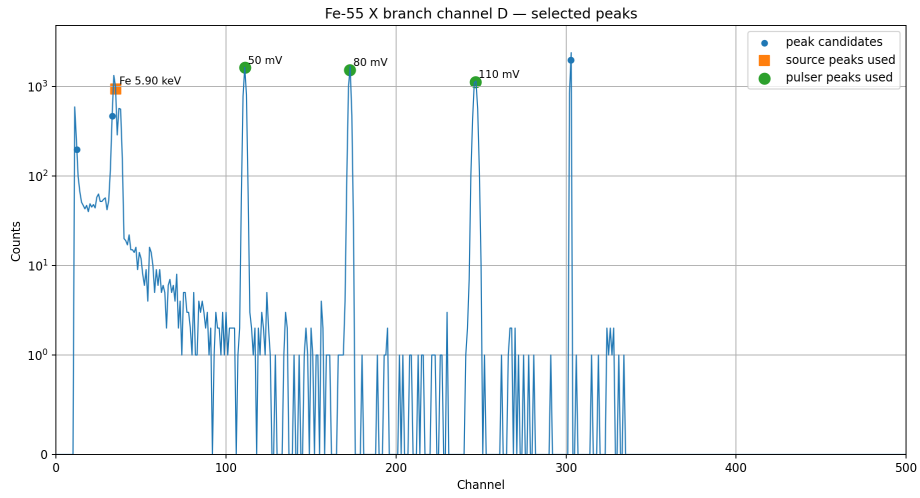


Figure 3.8. Example of peak identification for an X-branch channel, showing the selected ^{55}Fe X-ray lines, the 5.9 keV contribution and pulser peaks. from the pulser peaks only 50 and 80 mV were used for the calibration.

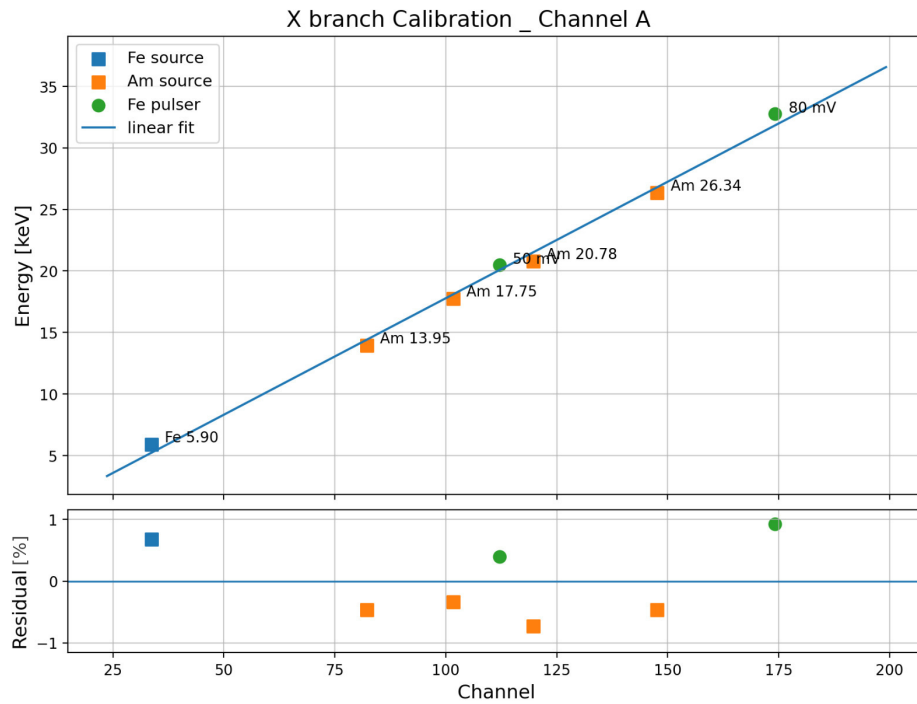


Figure 3.9. Example of X-branch calibration curve for channel A obtained from combined ^{241}Am , ^{55}Fe , and pulser peaks. The residuals of the linear fit are also shown.

Gamma-Branch Calibration

For the calibration of the gamma branch, the selected peaks were those produced by X rays and gamma rays directly absorbed in the SDD, even though the corresponding signals were processed by the gamma-branch electronics. In this case, the deposited energy is known directly and can therefore be used for the energy calibration of the electronic chain.

Particular care was required for the 59.5 keV line of ^{241}Am , which can produce two distinct features in the gamma-branch spectrum. The peak at the higher channel, around channel 305 in the representative spectrum, corresponds to direct absorption of the 59.5 keV photon in the SDD and was included in the calibration together with the other selected ^{241}Am lines. The first peak, around channel 27, corresponds instead to scintillation light produced by absorption in the CsI(Tl) crystal and read out by the SDD. This latter peak was not used for the electronic energy calibration, because its channel position depends on the scintillation light output and collection efficiency. It was instead used later for the light-output analysis in Section 3.3.

An example of the ^{241}Am spectrum acquired with the gamma branch is shown in Figure 3.10. The corresponding calibration curve for this channel is reported in Figure 3.11. Finally, the calibration parameters obtained for all gamma-branch channels are listed in Table 3.3.

Table 3.3. Linear calibration parameters obtained from the relation $E = m \cdot \text{ADU} + q$, expressed in energy units for gamma branch.

Branch	Channel configuration	m (keV/ADU)	q (keV)
Top	A	0.205 ± 0.001	1.63 ± 0.09
Top	B	0.215 ± 0.001	1.20 ± 0.08
Top	C	0.1882 ± 0.0002	0.13 ± 0.08
Top	D	0.1990 ± 0.0004	0.64 ± 0.04
Bottom	A	0.1947 ± 0.0006	-2.53 ± 0.02
Bottom	B	0.2005 ± 0.0004	0.79 ± 0.05
Bottom	C	0.1940 ± 0.0002	0.25 ± 0.07
Bottom	D	0.1887 ± 0.0002	0.38 ± 0.01

Later, after the acquisitions performed in the single-channel configuration, the full-bar response was measured using the analog summer device shown in Figure 3.6. The summed gamma-channel acquisitions were carried out in two different configurations: first with the ^{241}Am source placed on the top SDDs, and then with the source placed on the bottom SDDs. The corresponding calibration parameters are reported in Table 3.4. In the table, the “Irradiation” column indicates the side of the bar where the ^{241}Am source was positioned during the acquisition.

Overall, the gamma-branch calibration shows a stable and approximately linear response for all investigated channel combinations. The average summed-channel gain is (0.198 ± 0.009) keV/ADU. This corresponds to a relative spread of $(4.5 \pm 1.2)\%$, confirming that the calibration parameters are consistent among the gamma channels

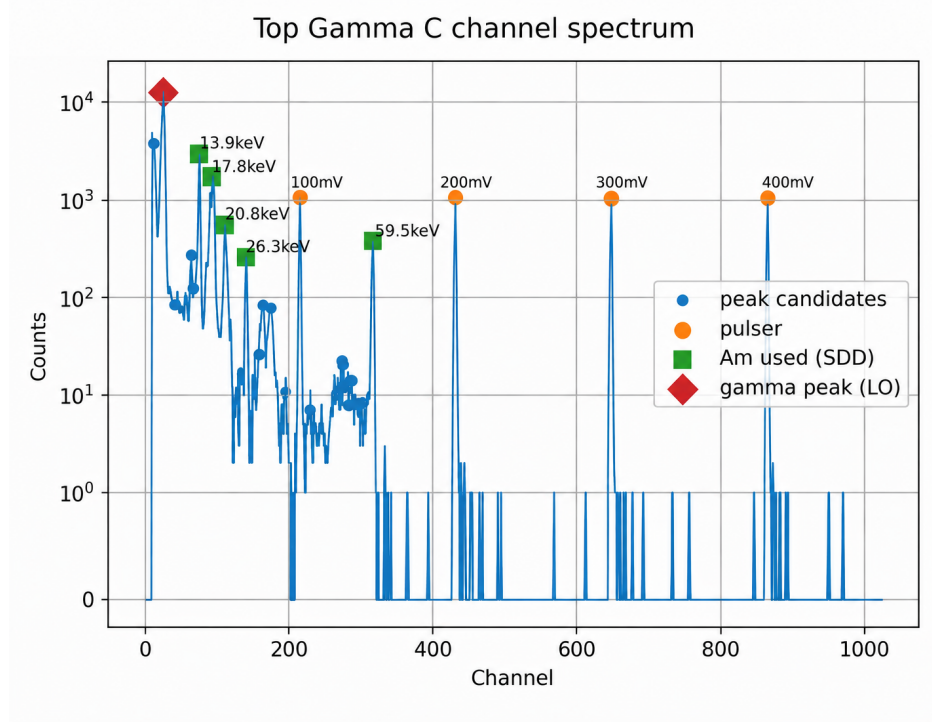


Figure 3.10. Representative ^{241}Am spectrum used for peak identification in the top-C gamma branch. The spectrum shows the low-energy ^{241}Am X-ray lines, the 13.9, 17.8, 20.8, 26.3, and 59.5 keV photon lines, and the injected pulser peaks. Blue points indicate the peak candidates identified by the peak-search algorithm. Green squares mark the ^{241}Am peaks selected for the calibration, corresponding to energy depositions directly detected in the SDD but processed by the gamma-branch electronics. Orange circles indicate the pulser peaks. The red diamond marks the scintillation feature produced in the CsI(Tl) crystal, which is not used for the energy calibration and is instead considered later in the light-output analysis.

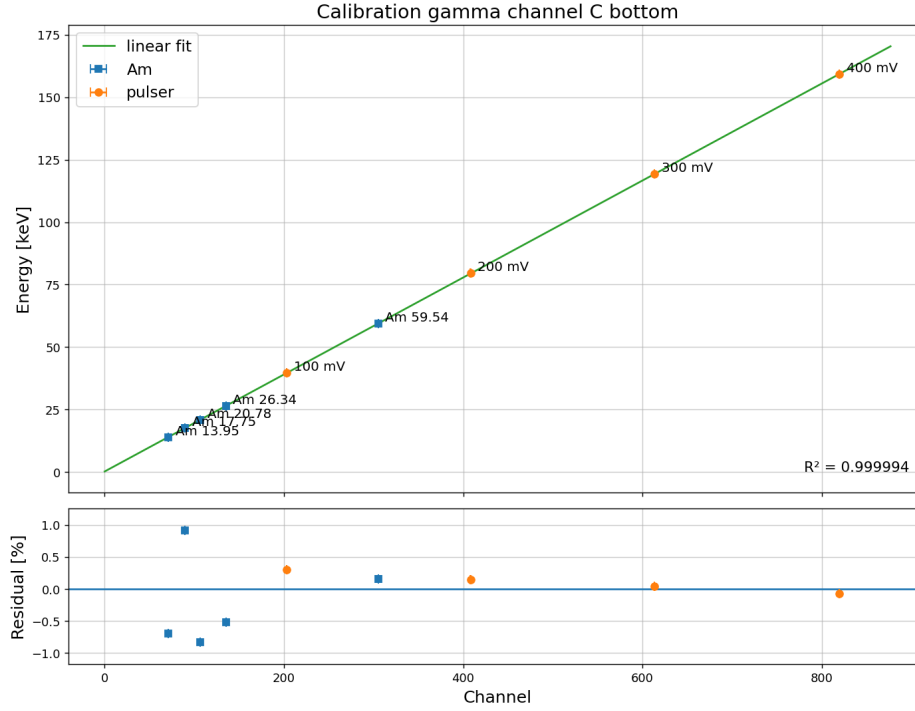


Figure 3.11. Energy calibration of the top SDD pixel C for gamma detection. The calibration is obtained by combining the X-ray lines of ^{241}Am (blue squares) with pulser signals of known amplitude (orange circles), covering an extended dynamic range. The solid line represents the linear fit used to convert channel values into deposited energy. The lower panel shows the residuals of the fit, demonstrating deviations below 1% over the full range. Error bars are derived from the statistical uncertainty on the peak centroid, estimated from the peak width (FWHM) and the number of counts. The high linearity of the response ($R^2 \approx 0.999 \pm 0.001$) confirms the stability and reliability of the electronic readout.

within the expected differences between the electronic chains. Due to non-identical wrapping and photo-coupling and the electronics.

Table 3.4. Linear calibration parameters for the summed gamma channels.

Irradiation	Channel configuration	m [keV/ADU]	q [keV]
Bottom	$A_{\text{top}} - D_{\text{bottom}}$	0.1904 ± 0.0002	0.33 ± 0.02
Bottom	$B_{\text{top}} - C_{\text{bottom}}$	0.1958 ± 0.0002	0.27 ± 0.02
Bottom	$C_{\text{top}} - B_{\text{bottom}}$	0.2037 ± 0.0004	0.37 ± 0.03
Bottom	$D_{\text{top}} - A_{\text{bottom}}$	0.1993 ± 0.0005	0.66 ± 0.05
Top	$A_{\text{top}} - D_{\text{bottom}}$	0.2104 ± 0.0003	0.014 ± 0.02
Top	$B_{\text{top}} - C_{\text{bottom}}$	0.2219 ± 0.0004	0.44 ± 0.03
Top	$C_{\text{top}} - B_{\text{bottom}}$	0.1893 ± 0.0004	0.22 ± 0.04
Top	$D_{\text{top}} - A_{\text{bottom}}$	0.2017 ± 0.0006	-0.15 ± 0.05

3.2.2 Characterization of the Test Capacitance

The pulser signals were used to characterize the electronic response of each channel by injecting a known charge into the readout chain. The nominal value of the test capacitance, C_{test} , is defined by the circuit design at 18 fF (F. Mele, PoliMI, private communication); however, its effective value can differ from the nominal one due to fabrication tolerances, parasitic contributions, and possible variations in the ASIC and board implementation. For this reason, the effective capacitance was experimentally verified.

For a pulser voltage amplitude V_{pulser} , the injected charge is

$$Q_{\text{inj}} = C_{\text{test}} V_{\text{pulser}}. \quad (3.2)$$

The corresponding number of injected electrons is

$$N_e = \frac{Q_{\text{inj}}}{e} = \frac{C_{\text{test}} V_{\text{pulser}}}{e}, \quad (3.3)$$

where e is the elementary charge ($1.602 \cdot 10^{-19}$ C). Therefore, for each assumed value of C_{test} , the pulser peaks can be converted into an equivalent number of injected electrons.

The calibration relation is then also expressed in electron units as

$$N_e = G \cdot \text{ADU} + N_0, \quad (3.4)$$

where G is the electronic gain in e^-/ADU and N_0 is the offset expressed in electrons. This electron calibration will also be used later to convert the centroid of the scintillation-induced gamma peak into collected charge, from which the light output is derived (Section 3.3).

A dedicated Python analysis script was developed for this work. The script was written independently and adapted to the specific format of the laboratory data, while

following the general analysis logic adopted in the MESCAL calibration pipeline (Dilillo et al., 2024). A more detailed description of the Python analysis workflow is reported in Appendix B.

For each assumed capacitance value, the calibration was repeated and the corresponding R^2 was computed. The effective test capacitance was identified as the value that maximizes the linearity of the calibration curve. This procedure provides an experimental verification of the capacitance value implemented in the readout chain (Knoll, 2010).

The results of the test capacitance values obtained for the gamma top and bottom channels can be seen in Table 3.5. one example of the R^2 plot to find the best value for the capacitance is shown in Figure 3.12.

Table 3.5. Test capacitance values obtained for the gamma top and bottom channels. The uncertainties are derived from the capacitance scan used to maximize the calibration linearity.

Channel	Top (fF)	Bottom (fF)
A	18.23 ± 0.05	17.71 ± 0.05
B	18.16 ± 0.04	18.40 ± 0.04
C	18.07 ± 0.04	17.71 ± 0.04
D	17.81 ± 0.04	17.83 ± 0.04

3.2.3 Electronic Noise Evaluation

The electronic noise was evaluated from the FWHM of the identified peaks in the calibrated spectra. The total variance of the signal can be expressed as:

$$\sigma_{\text{tot}}^2 = \sigma_{\text{el}}^2 + \sigma_{\text{Fano}}^2 \quad (3.5)$$

where the statistical contribution is given by:

$$\sigma_{\text{Fano}}^2 = F \cdot N_e, \quad N_e = \frac{E}{\varepsilon} \quad (3.6)$$

where F is the Fano factor, N_e is the average number of electron–hole pairs produced by an energy deposition E , and ε is the mean energy required to create one electron–hole pair in silicon. In this analysis, $\varepsilon = 3.6$ eV and a representative value $F = 0.1$ were adopted, consistently with the approximation commonly used for the experimental evaluation of electronic noise in SDD systems (Perotti & Fiorini, 1999). Assuming a Gaussian peak profile, the total standard deviation was derived from the measure full width at half maximum as:

$$\text{FWHM} = 2.355 \cdot \sigma_{\text{tot}} \quad (3.7)$$

The analysis was performed for different channels and configurations, allowing a comparison of the noise performance across the system.

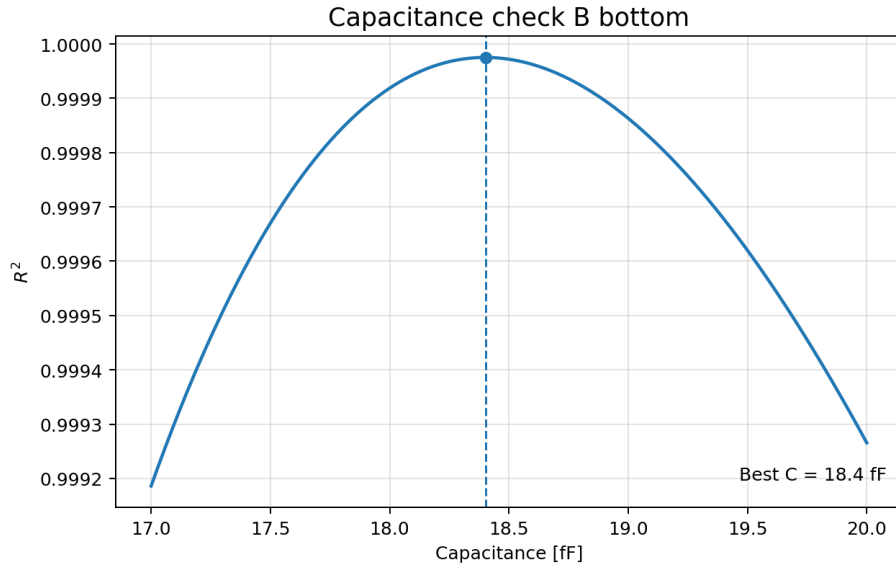


Figure 3.12. Determination of the effective test capacitance for the bottom SDD channel B. The coefficient of determination (R^2) of the linear calibration fit is shown as a function of the assumed capacitance used to convert pulser amplitudes into injected charge. The optimal value is identified at $C \simeq 18.4 \pm 0.04$ fF, corresponding to the maximum linearity of the calibration. The smooth parabolic trend reflects the sensitivity of the charge-to-energy conversion to the assumed capacitance. The selected value is used in the subsequent analysis to ensure a consistent conversion from voltage to charge and to derive physically meaningful gain and light output parameters.

The resulting electronic noise of the X branch is reported in Table 3.6, while those for the gamma branch in Table 3.7.

Table 3.6. Electronic gain, total noise, and electronic noise for the X-branch channels. The uncertainties were obtained from the Gaussian fitting of the selected Fe peak.

Channel	Gain (e^-/ADU)	σ_{tot} (e^- RMS)	σ_{el} (e^- RMS)
A	46.260 ± 0.007	78 ± 2	67 ± 3
B	48.550 ± 0.006	61 ± 2	46 ± 3
C	44.840 ± 0.004	76 ± 1	64 ± 1
D	47.560 ± 0.004	60 ± 1	45 ± 1

Table 3.7. Measured noise contributions for top and bottom gamma-branch channels using 13.95 keV line.

Channel	Gain (e^-/ADU)	FWHM (ch)	σ_{tot} (e^- RMS)	σ_{el} (e^- RMS)
AGtop	57.4 ± 0.5	4.49 ± 0.02	109 ± 1	107 ± 1
BGtop	59.9 ± 0.6	3.21 ± 0.03	82 ± 1	79 ± 1
CGtop	52.6 ± 0.5	3.40 ± 0.03	76 ± 1	73 ± 1
DGtop	55.3 ± 0.1	2.79 ± 0.03	65 ± 1	63 ± 1
AGbot	55.9 ± 0.9	6.85 ± 0.04	162 ± 3	161 ± 3
BGbot	57.4 ± 0.8	6.27 ± 0.03	152 ± 2	151 ± 2
CGbot	55.7 ± 0.8	5.18 ± 0.03	122 ± 2	121 ± 2
DGbot	54.2 ± 0.8	3.46 ± 0.02	79 ± 1	77 ± 1

The observed channel-to-channel differences are compatible with the present prototype assembly conditions. In particular, the scintillator wrapping and optical coupling were performed as carefully as possible, but in a standard laboratory environment. Therefore, although the same procedure was applied to all channels, the optical contact and wrapping conditions cannot be perfectly identical from one bar to another. These non-identical coupling conditions can contribute to the larger dispersion observed in the gamma branch, especially for the bottom channels. Overall, the measured noise levels are sufficiently low and stable for the energy reconstruction performed in this work.

3.3 Light Output and Response Uniformity

The light output is a key physical parameter of the scintillator–photosensor system, as it directly quantifies the efficiency of conversion from deposited energy into a measurable electrical signal. A higher light output corresponds to a larger number of charge carriers generated for a given energy deposition, resulting in improved signal-to-noise ratio and enhanced energy resolution.

Furthermore, the light output affects the stability and linearity of the response over a wide energy range. A well-characterized and uniform light output across the

scintillator bar is essential to ensure consistent performance and reliable calibration, especially in systems based on multiple readout elements, such as scintillator bars with dual-ended readout (Knoll, 2010).

In the context of space-borne high-energy detectors, such as those based on the XGIS concept, the light output also impacts the capability to detect and reconstruct gamma-ray events over a broad energy range, where scintillation signals must be accurately measured and distinguished from background contributions.

The response of the scintillator bars was investigated using both a ^{137}Cs source and a ^{241}Am source, positioned at a distance of 10 cm from the detector in order to avoid saturation effects. The measurements were designed to evaluate two complementary aspects: the absolute light output of the system and the uniformity of the detected response along the bar. Central irradiations with both sources were also performed to extract the light output and to validate the calibration.

3.3.1 Definition of Light Output

The effective light output (LO) is defined as the number of electrons collected by the readout system per unit energy deposited in the scintillator crystal. It is expressed in units of e^-/keV .

The centroid position of the scintillation peak, measured in ADC channels, was converted into an equivalent number of collected electrons using the charge-calibration relation introduced in equation 3.4.

The light output is then defined as:

$$LO = \frac{N_e}{E}, \quad (3.8)$$

where E is the energy deposited in the scintillator crystal. In this work, the light output was evaluated using both the ^{241}Am and ^{137}Cs gamma lines, corresponding to energies of 59.5 keV and 661.7 keV, respectively.

For each case, the centroid of the scintillation peak is converted into an equivalent number of electrons through the calibration parameters, and the light output is obtained by dividing by the corresponding photon energy.

It is important to note that the light output is derived from the centroid position of the scintillation peak, while the peak full width half maximum (FWHM) is used to evaluate the statistical quality of the measurement and to compare the relative response along the bar.

This procedure is applied to the experimental data to extract the light output for each channel combination.

3.3.2 Light Output Results

The light output was evaluated for all channel combinations using the centroid of the scintillation peaks measured in central irradiation conditions. The resulting values, obtained for both ^{241}Am and ^{137}Cs sources, are summarized in Table 3.8.

Pixel	LO (Am center) [e^-/keV]	LO (Cs center) [e^-/keV]
AG _{top} –DG _{bot}	27 ± 2	28.3 ± 0.4
BG _{top} –CG _{bot}	27 ± 2	26.5 ± 0.5
CG _{top} –BG _{bot}	31 ± 2	28.6 ± 0.5
DG _{top} –AG _{bot}	34 ± 3	27.2 ± 0.5

Table 3.8. Light output values obtained from central irradiation measurements using both ^{241}Am and ^{137}Cs sources.

The light-output values obtained with ^{241}Am and ^{137}Cs are not expected to be identical, because the scintillation response of CsI(Tl) is not perfectly proportional to the deposited energy. The light yield per unit energy depends on the energy released in the crystal, a known effect in scintillation detectors (Knoll, 2010). In particular, non-proportionality measurements of scintillators show that the relative light yield of CsI(Tl) is higher at energies of a few tens of keV than at several hundred keV, with a difference of the order of 10% between the region around the 59.5 keV ^{241}Am line and the ^{137}Cs energy range. This explains why the light output estimated from the ^{241}Am scintillation peak can be systematically higher than the value obtained from the 661.7 keV ^{137}Cs photopeak.

Representative spectra for central irradiation are shown in Figure 3.13. These illustrate the scintillation peaks used for the extraction of the centroid positions, as well as the pulser peaks employed in the calibration procedure.

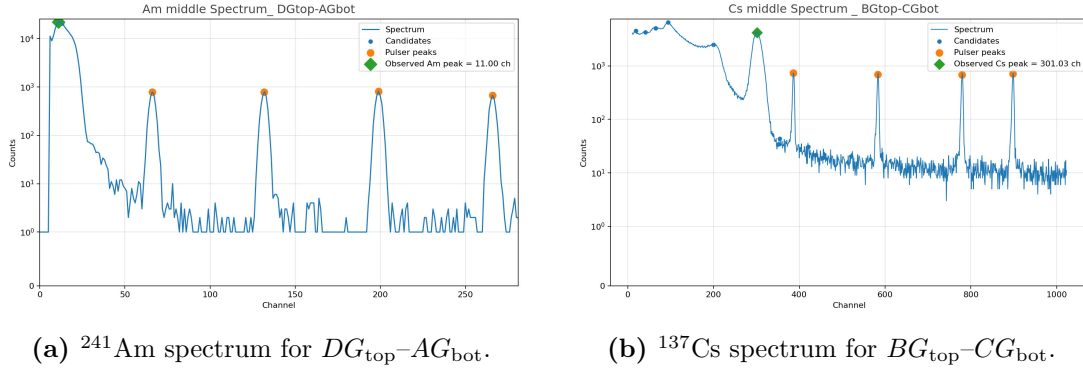


Figure 3.13. Example spectra used for calibration and light output extraction (central irradiation).

3.3.3 Uniformity of the Light Output along the Bars

The position-dependent response of the detector was studied using a 2 mm collimated ^{137}Cs source in combination with a motorized positioning system (PiMikroMove), allowing controlled displacement of the source along the longitudinal axis of the scintillator bars. The collimator is made of lid with a 2 mm slit made in INAF/OAS. The configuration is shown in Figure 3.14. A preliminary position calibration was performed

in order to establish the correspondence between the mechanical coordinates of the positioning system and the physical positions along each bar. This step ensured that each acquisition point could be associated with a well-defined location along the crystal.

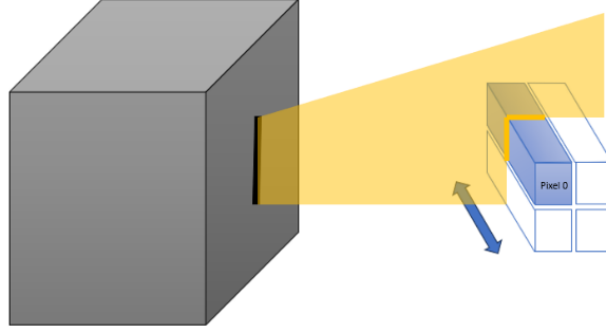


Figure 3.14. Schematic representation of the collimated irradiation configuration used for the study of the position-dependent response. The arrow indicates the displacement of the scintillator bars with respect to the fixed beam emerging from the lead slit collimator. Reproduced from [Mattioli \(2024\)](#).

Following the calibration, measurements were carried out at several discrete positions along each bar in 6 points, covering the full active length. Spectra were acquired with typical acquisition times of 30 minutes.

An example of the spectra acquired from one of the six irradiation positions along one scintillator bar is shown in Figure 3.15. A couple of data points are missing because the corresponding acquisition files were not recoverable during the final data analysis.

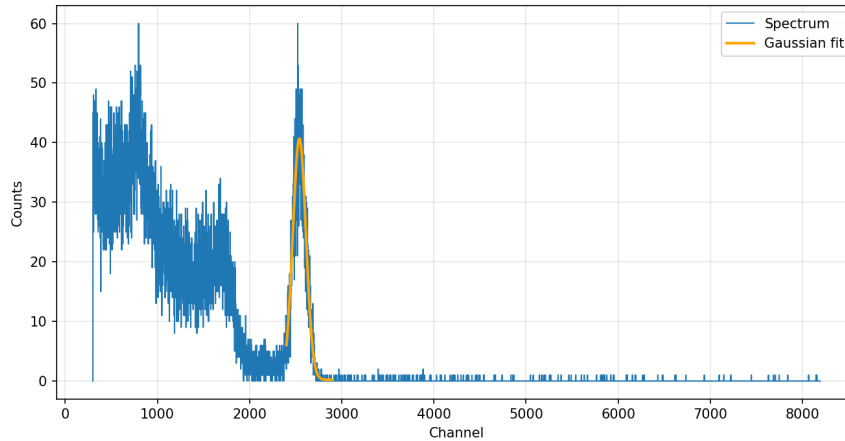


Figure 3.15. Spectra acquired with the collimated ^{137}Cs source at one of the six irradiation positions along the scintillator bar read out through the summed $D_{\gamma,\text{top}} - A_{\gamma,\text{bottom}}$ channel combination. The 661.657 keV photopeak was used to evaluate the detector response as a function of irradiation position.

The Light output (LO) have been calculated from the ^{137}Cs acquisitions for each measurement and normalized to the acquisition time, allowing a direct comparison of the Light output as a function of irradiation position.

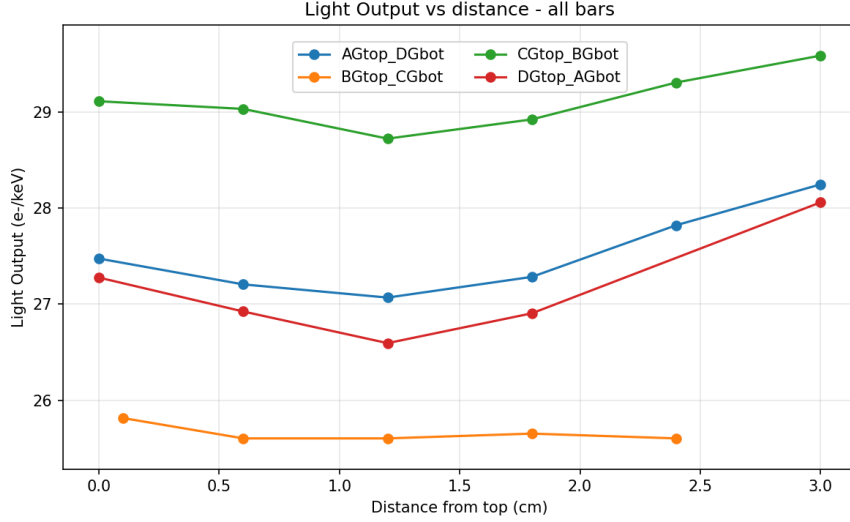


Figure 3.16. Light output obtained from the ^{137}Cs acquisition as a function of the irradiation position along the scintillator bars for each pixel.

The normalized Light outputs are shown in Figure 3.16 as a function of the position along the bar. The response is generally stable along the central region of the bars, indicating that no strong position-dependent effects are present within the explored range. The $B\gamma_{\text{top}}-C\gamma_{\text{bot}}$ pixel shows a systematically lower response compared to the others. Since this behaviour is observed at all positions, it cannot be attributed to the source location and is instead consistent with a global reduction in light-collection efficiency for that specific pixel. This effect may be related to the optical coupling between the SDDs and the scintillator, or to the scintillator wrapping.

3.3.4 Consistency Check of the Summed-Channel Calibration

After deriving the calibration parameters for the summed gamma-channel combinations, an additional check was performed using the pulser peaks acquired together with the central irradiation measurements. This step was not used to define a new calibration, but only to verify that the calibration procedure remained coherent when applied to the summed top-bottom readout configuration used for the light-output analysis.

As shown in Figure 3.17, the measured pulser positions are well reproduced by the predicted values. Although only one representative pixel is shown in the plot, the same check was performed for all summed channel combinations. In all cases, the residuals remain below 1%, confirming the mutual consistency of the gain, offset, and capacitance conversion used for the summed-channel calibration.

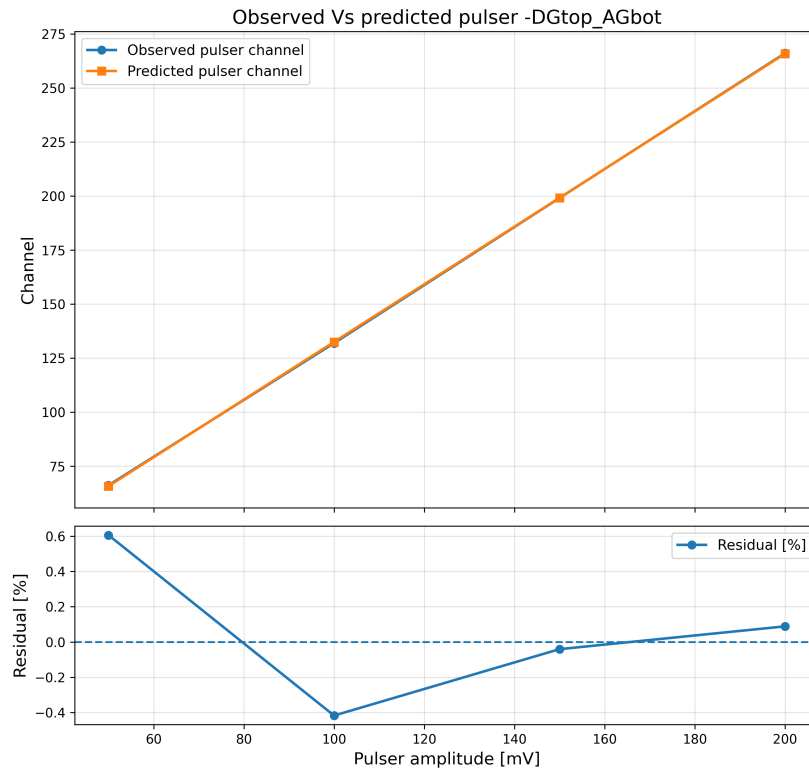


Figure 3.17. Comparison between the observed pulser peak positions and the positions predicted from the calibration parameters for one representative summed gamma-channel combination. The residuals remain below one channel, showing that the pulser peaks are consistent with the adopted calibration.

4

Monte Carlo Simulations of the XGIS Detector

This chapter presents the Monte Carlo simulation activity carried out for the XGIS detector using the GEANT4 (*GEometry ANd Tracking*) toolkit. After a general introduction to Monte Carlo methods and to the structure of a Geant4 simulation, the XGIS module simulation model is described as the starting point of the work. A reduced 2×2 -pixel detector configuration is then introduced as a controlled validation geometry, directly related to the prototype investigated experimentally. This reduced configuration is used to study the monoenergetic ^{241}Am 59.5 keV irradiation, to validate the depth-of-interaction output, and to apply the detector-noise post-processing based on the measured laboratory parameters. The final part of the chapter returns to the full XGIS camera model, discussing the usefulness of depth-of-interaction information for background studies and the implementation of an updated self-supporting coded-mask geometry.

4.1 Monte Carlo Simulations and Geant4

Monte Carlo methods are widely used in high-energy astrophysics and radiation-detector studies because the interaction of photons and particles with matter is intrinsically stochastic. When a high-energy photon propagates through a material, the location of its interaction, the amount of energy transferred, and the production of possible secondary particles are governed by probability distributions derived from the relevant physical cross sections, as discussed for photon interactions in Section 2.4.3. Rather than describing only the average behavior of a radiation field, a Monte Carlo simulation follows a large number of individual particle histories and reconstructs the statistical response of the system.

In a detector simulation, each event begins with the generation of one or more primary particles with assigned properties, such as particle type, energy, position, and direction of propagation. The particles are then transported through a geometrical model composed of different materials and volumes. At each step, the possible interactions are sampled according to their probabilities. For photons in the X-ray and gamma-ray energy range, the most relevant electromagnetic processes include photoelectric absorption, Compton scattering, and pair production, depending on the photon energy and on the material crossed. The energy deposited in the detector volumes, together with the trajectories and secondary particles produced during the event, can then be recorded and analysed.

The simulations performed in this thesis are based on GEANT4 (*GEometry ANd Tracking*, [Agostinelli et al. 2003](#)), a general-purpose Monte Carlo toolkit developed for the simulation of the passage of particles through matter. Geant4 was originally developed within an international collaboration led by CERN and is now extensively

used in particle physics, nuclear physics, medical applications and space-instrumentation studies. The toolkit is written in C++ and provides a modular framework in which the user can define the experimental geometry, the materials, the primary-particle generation, the physical interaction processes and the quantities to be recorded during the simulation (Agostinelli et al., 2003; Allison et al., 2016).

A Geant4 simulation is organized according to a hierarchical structure based on *runs*, *events*, *tracks* and *steps*. Once the detector geometry, the physical processes and the primary-particle generation have been defined, the simulation sequence is controlled by the `G4RunManager` class. A *run* consists of a collection of events generated with an unchanged detector and physics configuration. Each *event* contains the primary particle and all secondary particles produced during its interaction history. The trajectory of every particle is described by a *track*, which is subdivided into successive *steps*. At the step level, the particle is transported through the geometry and any interaction or energy deposition occurring in a detector volume can be recorded. This organization is summarized schematically in Figure 4.1.

The interaction processes to be considered are specified through a *physics list*. This associates each particle with the physical models required to describe its transport and interactions over the relevant energy range. Geant4 includes models for electromagnetic, hadronic decay and optical processes, among others. For simulations involving X-rays and gamma-rays, the electromagnetic description is particularly important, since it determines the probabilities and outcomes of the interactions responsible for energy deposition in the detecting medium.

The geometry of the simulated apparatus is constructed by defining *solids*, *logical volumes* and *physical volumes*. A solid describes the shape and dimensions of an object, a logical volume assigns a material and possible detector properties to that shape, and a physical volume places it within the overall geometry. This approach makes it possible to reproduce detectors with complex structures, including active elements, passive layers, shielding components and support structures. Volumes in which deposited energy or other interaction information should be recorded can be declared as sensitive detectors.

The output of a Monte Carlo simulation is obtained by analyzing the information collected over a sufficiently large number of events. Depending on the purpose of the simulation, this may include deposited-energy spectra, interaction positions, detection efficiencies, particle transmission or the contribution of secondary particles. Since the results are statistical, their accuracy depends on the number of simulated events. At the same time, the physical reliability of the results depends on the accuracy of the implemented geometry, material composition, and selected physics models.

Geant4 therefore provides a suitable framework for modeling radiation detectors and studying their response under controlled irradiation conditions. Its modular structure allows different geometrical configurations or analysis quantities to be introduced within the same simulation environment, enabling a direct comparison of the resulting detector responses.

In the simulations presented in this work, this general structure was applied to the modelling of the XGIS detector. The geometry includes active detection volumes, passive structural components and the coded-mask system, while the sensitive detector

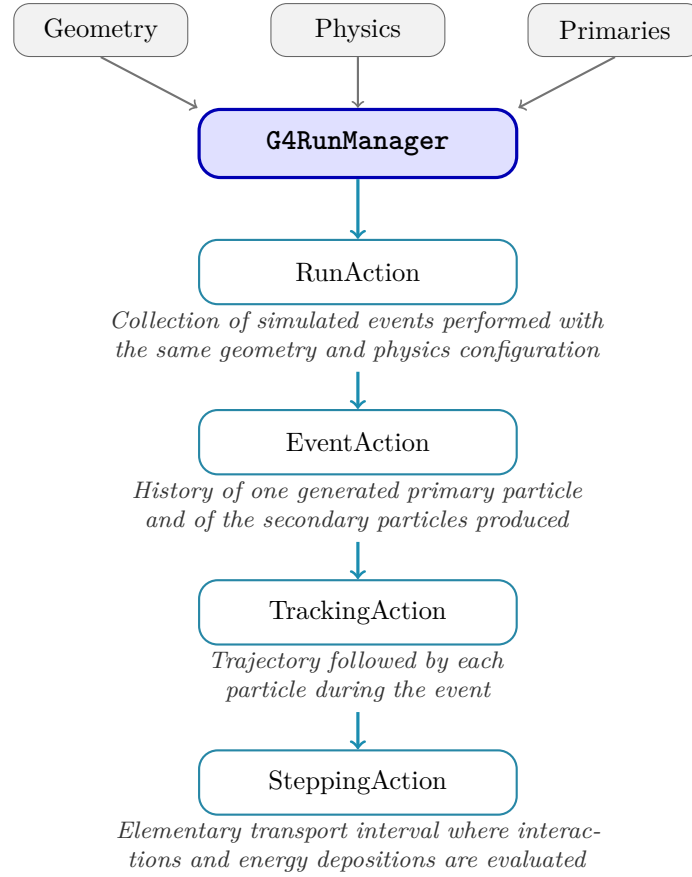


Figure 4.1. Schematic representation of the hierarchical organization of a Geant4 simulation. Once the geometry, physics configuration and primary-particle generation have been defined, the **G4RunManager** class controls the simulation sequence. A run contains a collection of events, each event contains one or more particle tracks, and each track is propagated through successive steps at which interactions and energy depositions can be recorded. Adapted from [Campana \(2019\)](#).

output provides the quantities needed for the subsequent analysis of deposited energy and interaction position. The following sections describe the baseline simulation model and the modifications introduced for the studies carried out in this thesis. The physical operating principle of XGIS has already been presented in Chapter 2.

4.2 The XGIS Module Simulation Model

The starting point of the simulation activity presented in this thesis is the XGIS mass model developed along the M7 Phase A study. That model, described in detail by [Pisapia \(2025\)](#), was built using the GEANT4 toolkit and represented an XGIS camera with geometrical detail to evaluate quantities such as the in-orbit background count rate. The present work adopts this model as the baseline and modifies it for the specific studies described in the following sections.

4.2.1 Geometry and materials

The XGIS camera is represented as a set of nested native GEANT4 volumes, each with a material assigned and, where relevant, declared as a sensitive detector. The main components of the model are the coded mask, the tungsten–aluminium collimator system, and the detection plane. The detection plane consists of an array of CsI(Tl) scintillator bars, each coupled at both ends to a Silicon Drift Detector layer. The scintillator bars have a square cross-section of $4.5 \times 4.5 \text{ mm}^2$ and a length of 30 mm, while each SDD layer is modelled as a 450 μm -thick silicon slab. An optical coupling layer of 1 mm-thick silicone is placed between each scintillator face and the corresponding SDD.

The collimator consists of an aluminium layer 1000 μm thick and a tungsten layer 250 μm thick. The coded mask is a 500 μm -thick tungsten plate placed 63 cm above the top surface of the detection plane. The mask and collimator together define the imaging field of view and the energy range over which XGIS operates as an imager, as discussed in Chapter 2. The support structure connecting the mask to the detector frame is modeled as a simplified aluminum box with an effective density chosen to reproduce the nominal mass budget. A schematic view of the simulated geometry as rendered in the GEANT4 interactive mode is shown in Figure 4.2.

All material compositions and physical dimensions are read at runtime from an external parameter file, `detectorParam.inp`, so that different configurations can be tested without recompiling the executable. The mask pattern is read from a separate external file, allowing its replacement without modifying the detector-construction code. This design choice was useful both for reducing the geometry to the 2×2 validation configuration and for replacing the previous mask with the updated self-supporting pattern that will be discussed in Section 4.4.2.

4.2.2 Event classification and data output

Within the simulation, each photon interaction is classified according to the volume in which it deposits energy. Interactions occurring in a Silicon Drift Detector layer

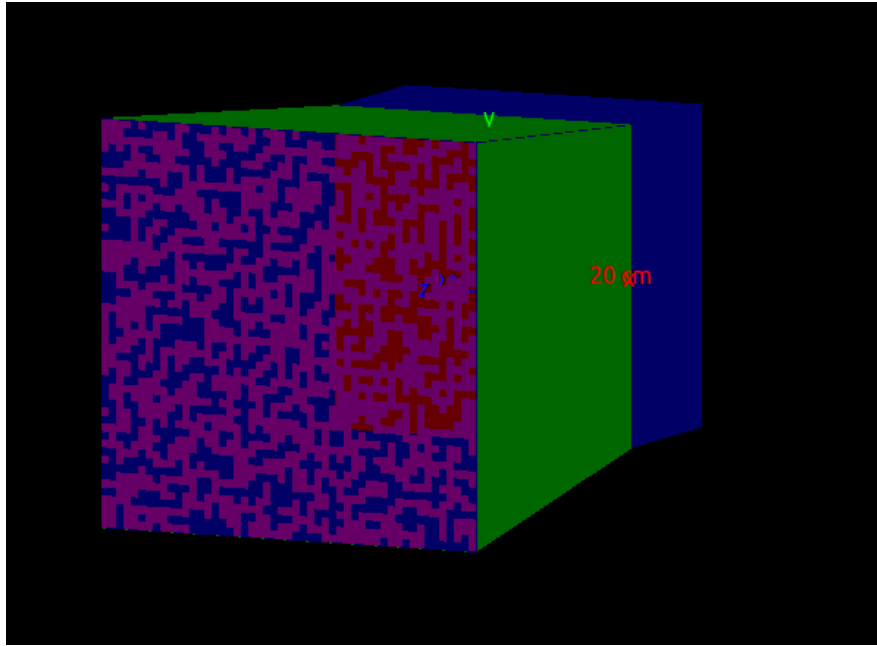


Figure 4.2. Geant4 interactive-mode rendering of the XGIS full-camera mass model. The tungsten collimator is shown in green, the aluminium support structure in blue, and the coded-mask pattern in pink. The detection plane, containing the CsI(Tl) scintillator bars and the SDD layers, is visible at the bottom of the assembly.

are recorded as X-mode events, while interactions occurring in a CsI(Tl) scintillator bar are recorded as S-mode events. This classification mirrors the siswich detection principle implemented in the XGIS hardware, where a fast signal from a single SDD cell identifies a direct X-ray event and a coincident signal from the two SDD sides identifies a scintillation event, as discussed in Chapter 2.

Since a single primary photon may produce multiple secondary particles that deposit energy in different volumes, the event identifier is preserved in the simulation output. This makes it possible to group energy depositions associated with the same primary particle before producing spectra or applying post-processing. This step is especially important at higher energies, where Compton scattering and secondary-particle production can distribute the deposited energy over several steps or detector volumes.

The output of the GEANT4 application is a ROOT¹ file containing one entry per recorded interaction, with columns for the event identifier, the deposited energy, the interaction position, and the detector-volume information. This ROOT file is then converted into FITS format using a Python pipeline adapted for this work, extending the conversion procedure originally used in the previous XGIS simulations (Pisapia, 2025). The FITS output retains the quantities needed for the subsequent spectral analysis, depth-of-interaction study, and detector-noise post-processing.

4.2.3 Simulation code structure

The application is built around the mandatory GEANT4 user classes. The `DetectorConstruction` class reads the external parameter files and constructs the geometry at the start of each run. The physics configuration specifies the interaction models used for particle transport and energy deposition. Atomic de-excitation processes were activated through the user interface in order to describe low-energy photon interactions in the high- Z materials of the detector and passive structures. The primary-particle source is defined through the `G4GeneralParticleSource` class, which allows the irradiation configuration to be changed through macro files.

The simulation can be launched either in interactive mode, allowing visual inspection of the geometry and particle tracks as shown in Figure 4.3, or in batch mode, in which macro files are passed directly to the executable. In this work, interactive runs were used mainly to check the geometry and event topology, while batch runs were used to produce the ROOT files analyzed in the following sections.

4.3 Reduced 2×2 Pixel Simulation

A reduced detector configuration was implemented to study a simpler case before applying the same analysis strategy to the more complex full-camera geometry. The purpose of this simulation is not to reproduce the response of the complete XGIS camera, but to isolate the behavior of a small group of scintillator bars under controlled irradiation conditions. An important point is that this intermediate configuration

¹<https://root.cern>

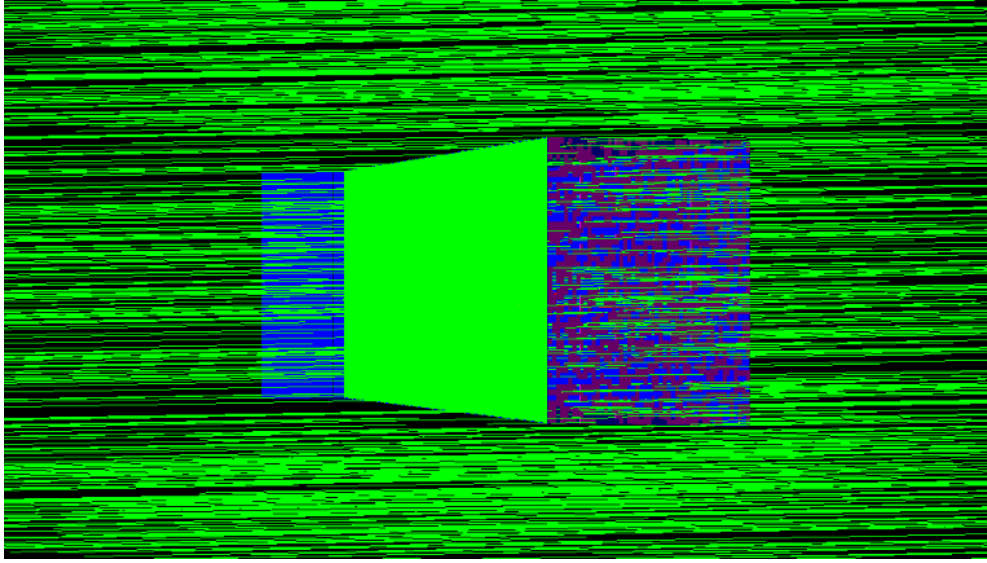


Figure 4.3. Interactive-mode visualization of a Geant4 simulation of the XGIS camera. The display is used to inspect the geometry, particle tracks, and interaction positions during the simulation.

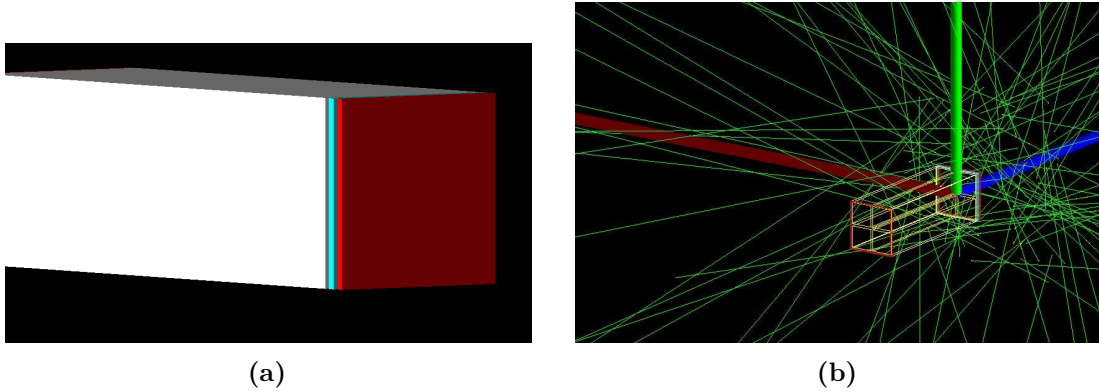


Figure 4.4. Geant4 visualization of the reduced 2×2 scintillator-bar geometry. (a) Geometry view of the simplified detector configuration. The white volumes represent the CsI(Tl) scintillator bars, the red volumes correspond to the SDD layers, and the thin blue layer represents the optical coupling between the scintillator and the readout detector. (b) Event-display view during a simulation run for ^{241}Am . In this visualization the scintillator volumes are hidden in order to make the particle tracks and interactions inside the 2×2 geometry visible. The scintillators are hidden only graphically and remain active sensitive volumes in the simulation.

provides a useful bridge between the complete Monte Carlo model and the experimental measurements discussed in Chapter 3.

The geometry was simplified by keeping only a 2×2 array of scintillator bars, corresponding to a total of four CsI(Tl) bars. The other passive components of the camera, including the coded mask and collimator elements, were assigned *vacuum* as a material. In this way, attenuation and scattering from the passive structures were removed, and the simulated spectra could be interpreted mainly in terms of the response of the active detector elements. This configuration is therefore useful for checking the detector geometry, the event output, the pixel indexing, and the analysis pipeline before applying the same procedures to more complex simulations.

The main parameters adopted for the reduced simulation are summarized in Table 4.1.

Table 4.1. Main parameters of the reduced 2×2 simulation configuration.

Parameter	Value or configuration
Total number of scintillator bars	4
Scintillator material	CsI(Tl) $\rightarrow$ G4_CESIUM_IODIDE
Scintillator cross-section	$4.5 \times 4.5 \text{ mm}^2$
Scintillator length	30 mm
Simulated source	^{241}Am , 59.5 keV gamma line

A visualization of the reduced geometry is shown in Figure 4.4. The small number of detector elements makes it possible to inspect the simulated hits and verify that the output quantities are assigned to the expected detector volumes.

4.3.1 Simulation of the ^{241}Am Irradiation Configuration

The first irradiation test was performed using a mono-energetic gamma source at 59.5 keV, corresponding to the γ -ray emission of ^{241}Am . This source was selected since ^{241}Am was also used in the experimental characterization presented in Chapter 3, where its X-ray and γ -ray lines were employed for calibration and detector-response studies. In the simulation, the source was defined through a Geant4 macro using the General Particle Source. In the run considered here, only the 59.5 keV gamma line was generated; therefore, the result should be interpreted as a mono-energetic validation run rather than as a complete simulation of the full ^{241}Am decay spectrum.

The corresponding Geant4 macro used for this monoenergetic irradiation run is reported in Listing 4.1.

Listing 4.1. Representative Geant4 macro file used for the reduced 2×2 simulation of the 59.5 keV gamma line of ^{241}Am . The source is defined as a square planar surface of side 4 cm, centred at (0,0,1) cm, emitting monoenergetic gamma rays with an isotropic angular distribution. A total of 5×10^6 primary photons was simulated.

```

/gps/particle gamma
/gps/pos/type Plane
/gps/pos/shape Square

```

```

/gps/pos/halfx 2 cm
/gps/pos/halfy 2 cm
/gps/pos/centre 0 0 1 cm
/gps/ang/type iso
/gps/energy 59.5 keV
/process/em/fluo true
/process/em/auger true
/run/beamOn 5000000

```

The output of the simulation was processed using the same event-based logic described in Section 4.2.2. For each event, the deposited energy was recorded together with the information identifying the detector element in which the interaction occurred. Energy deposits in the SDDs and in the scintillator bars are treated separately according to the X-mode and S-mode classification introduced previously.

The raw deposited-energy spectrum obtained from the reduced 2×2 simulation in X mode is shown in Figure 4.5. Since this spectrum corresponds to the ideal Geant4 energy deposition, no detector-noise broadening has yet been applied. The main peak at 59.54 keV corresponds to the full-energy absorption of the primary ^{241}Am photons. In addition, characteristic fluorescence structures are visible in the intermediate-energy region. These features are produced by the CsI(Tl) scintillator material and correspond mainly to the iodine $K\alpha$ lines at 28.32 keV and 28.61 keV, and to the cesium $K\alpha$ lines at 30.63 keV and 30.97 keV (Deslattes et al., 2003). In the raw Geant4 spectrum, these transitions can appear as separated narrow lines, whereas in the laboratory spectra the finite detector resolution and electronic broadening merge the close components into broader structures around 28.5–31 keV. Similar fluorescence-related features were also observed in the laboratory ^{241}Am spectra used for the X-branch calibration, shown in Figure 3.7.

The raw Geant4 spectrum represents an ideal detector response and cannot be directly compared with the experimental spectra discussed in Chapter 3. The application of the experimentally derived detector-noise broadening to this same reduced simulation is described in Subsection 4.3.3.

4.3.2 Depth of Interaction in the Reduced Geometry

A first validation of the depth-of-interaction implementation was performed using the reduced 2×2 simulation. The aim of this test is therefore to implement in the simulation not only the hit pixel and deposited energy, but also the position of the interaction along the scintillator bar.

In the updated simulation, the 3 cm CsI(Tl) bars was subdivided into several slices along its longitudinal direction. For each energy deposition in the scintillator, the local interaction coordinate was used to assign the hit to the corresponding slice. This discretization of the depth coordinate, indicated as z_{DOI} , was then propagated to the output together with the event identifier, deposited energy, and detector-pixel information. For direct SDD events the scintillator depth coordinate is not physically defined in the same sense and these events were treated separately in the analysis. In

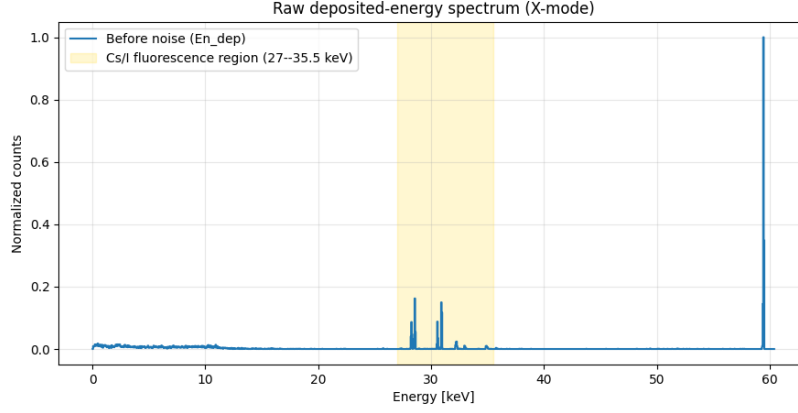


Figure 4.5. The X mode deposited-energy spectrum obtained with the 2×2 geometry for a monoenergetic 59.5 keV photon source. The spectrum corresponds to the ideal Geant4 deposited energy before the application of the detector-noise model. The main peak close to 59.5 keV corresponds to full-energy absorption of the incident photons, while the intermediate-energy structures are associated with fluorescence X-rays from the CsI(Tl) scintillator, mainly iodine and cesium K lines.

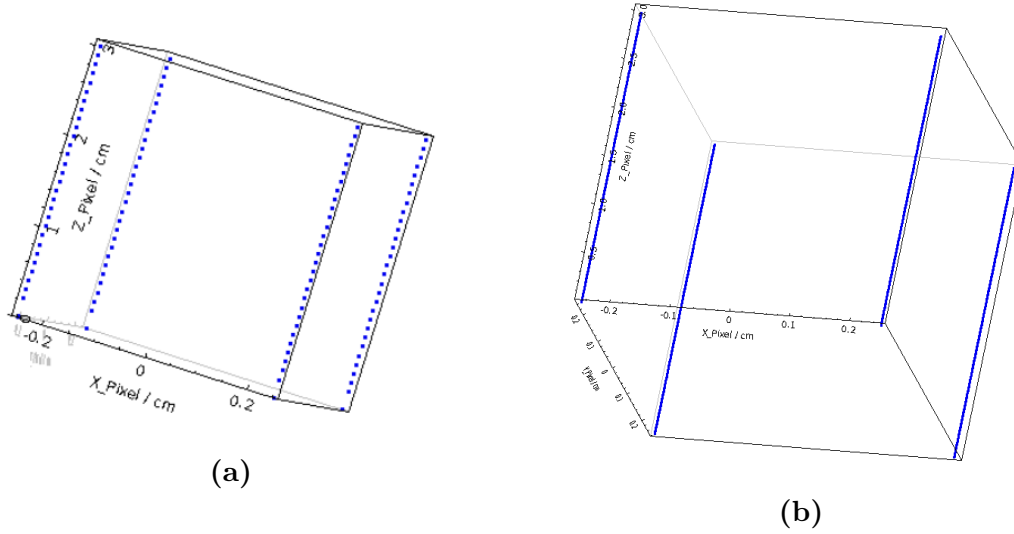


Figure 4.6. Visualization of the reduced 2×2 scintillator-bar geometry used to verify the depth-of-interaction implementation. the 3 cm CsI(Tl) bar is subdivided along its longitudinal direction and the recorded interaction position is assigned to the corresponding depth interval. Panel (a) shows the configuration with $N_{\text{slices}} = 30$, corresponding to a slice thickness of $\Delta z = 1$ mm. Panel (b) shows the finer configuration with $N_{\text{slices}} = 300$, corresponding to $\Delta z = 0.1$ mm.

order to store the depth of interaction inside each CsI(Tl) bar, the bar length was discretized along the local z direction. Two different discretization schemes were tested. The first one used a coarse segmentation with $N_z^{\text{coarse}} = 30$ slices, corresponding to a slice thickness of 1 mm. This choice gives one DOI bin per millimetre along the 3 cm scintillator bar. A second, finer segmentation with $N_z^{\text{fine}} = 300$ slices was then implemented, corresponding to a slice thickness of 0.1 mm. The fine segmentation was introduced to check that the DOI coordinate was correctly reconstructed and to avoid losing information because of an excessively coarse binning.

In general, the slice thickness can be written as

$$\Delta z = \frac{L_{\text{bar}}}{N_z}, \quad (4.1)$$

where $L_{\text{bar}} = 3$ cm is the scintillator-bar length and N_z is the number of slices used in the chosen discretization. Therefore, for the two cases considered here:

$$\Delta z_{\text{coarse}} = \frac{3 \text{ cm}}{30} = 1 \text{ mm}, \quad (4.2)$$

and

$$\Delta z_{\text{fine}} = \frac{3 \text{ cm}}{300} = 0.1 \text{ mm}. \quad (4.3)$$

For an interaction occurring at local coordinate z along the bar, with the origin placed at the centre of the scintillator, the corresponding slice index is computed as

$$i_z = \left\lfloor \frac{z + L_{\text{bar}}/2}{\Delta z} \right\rfloor. \quad (4.4)$$

The term $z + L_{\text{bar}}/2$ shifts the coordinate range from $[-L_{\text{bar}}/2, +L_{\text{bar}}/2]$ to $[0, L_{\text{bar}}]$, so that the first slice corresponds to the lower end of the bar and the last slice to the upper end. The index is then constrained to the interval

$$0 \leq i_z < N_z. \quad (4.5)$$

In the final implementation used for the DOI study, the fine discretization with $N_z^{\text{fine}} = 300$ was adopted, while the coarse case with $N_z^{\text{coarse}} = 30$ was used as an initial test and for comparison.

The implementation required changes in the sensitive-detector and output simulation code. In the sensitive detector, the interaction position inside the scintillator was used to assign the hit to a depth slice. The run-output routine was then updated so that the depth coordinate was written in the ROOT n-tuple together with the other event quantities. The Python conversion script was also updated to propagate the new position information from ROOT to the FITS files used for the following analysis.

A qualitative visualization of the segmented reduced geometry is shown in Figure 4.6.

The resulting depth distribution is shown in Figure 4.7. The vertical axis is represented in logarithmic scale in order to display both the large number of interactions close to the entrance region and the lower-count tail extending along the scintillator bar. For a monoenergetic photon beam crossing a material, the intensity can be approximated by

$$I(z) = I_0 e^{-\mu z}, \quad (4.6)$$

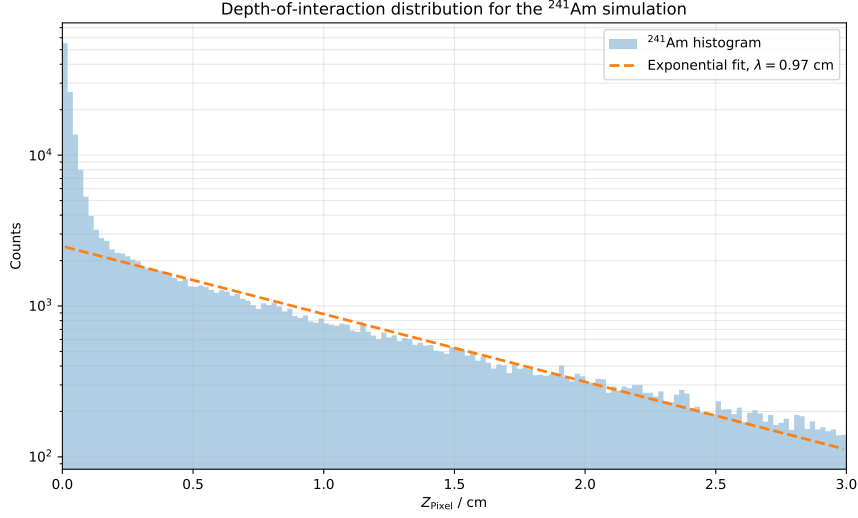


Figure 4.7. Depth-of-interaction distribution obtained from the reduced 2×2 pixel ^{241}Am simulation. The histogram shows the recorded Z_{Pixel} coordinate for interactions in the CsI(Tl) scintillator bars. The dashed line shows an exponential fit of the form $N(z) = N_0 e^{-z/\lambda}$ applied to the selected depth range. The fitted value $\lambda = 0.97 \pm 0.05$ cm represents an effective attenuation length for this simulated configuration.

where μ is the linear attenuation coefficient found to be $\lambda = 0.97 \pm 0.05$ cm. Equivalently, the depth distribution can be described using an effective attenuation length $\lambda = 1/\mu$,

$$N(z) = N_0 e^{-z/\lambda}. \quad (4.7)$$

An exponential fit was therefore applied to the depth distribution as an empirical description of the attenuation trend. The fitted value should be interpreted as an effective depth scale for this simulated configuration, rather than as a direct measurement of the tabulated attenuation length of CsI(Tl), since the distribution also depends on the source geometry, event selection, secondary interactions, and detector geometry.

The depth coordinate is also useful because a single primary photon can produce more than one energy deposition before the event is completed. For example, a gamma ray may undergo Compton scattering inside the scintillator and subsequently interact again in the same bar or in a neighboring detector element. For this reason, the event identifier is preserved in the output, so that multiple energy depositions associated with the same primary particle can be recognized and, when needed, summed or analyzed together.

4.3.3 Detector Noise Post-Processing

The Geant4 simulation records the energy deposited in the detector by each event. This quantity represents the ideal deposited energy before the effect of the detector readout is included. In order to obtain a more realistic reconstructed-energy distribution, the

simulated deposited energies were post-processed by applying the detector-noise model based on the calibration and noise parameters measured in Chapter 3, to which we refer for a discussion on the statistical origin of the energy broadening.

The original deposited energy was kept in the FITS column `En_dep`, while the post-processed reconstructed energy was stored in a new column called `En_dep_Noise`. This makes it possible to compare directly the ideal Geant4 output with the spectrum obtained after including the measured detector broadening. When multiple energy depositions were associated with the same primary particle, they were first grouped using the event identifier before applying the noise post-processing.

Figure 4.8 shows the effect of this procedure for the reduced 2×2 simulation of ^{241}Am . The raw Geant4 spectrum, obtained from `En_dep`, contains narrow structures corresponding to the ideal deposited energy. After the post-processing, the spectrum obtained from `En_dep_Noise` shows the expected broadening of the same features. This comparison illustrates how the simulated output can be kept both in its ideal Monte Carlo form and in a reconstructed form including the experimentally derived detector noise.

Table 4.2. Comparison between the noise values obtained from the noise post-processing of the simulated ^{241}Am events and those measured in the laboratory. All values are expressed as RMS equivalent noise charge in electrons.

Quantity	X branch (e^-)	Gamma branch (e^-)
Simulation total noise	58 ± 1	135 ± 5
Laboratory double-channel total noise	–	154 ± 1
Laboratory total noise	68 ± 1	106 ± 2
Laboratory electronic noise	55 ± 2	104 ± 2

Table 4.2 compares the noise values obtained from the simulation post-processing with the corresponding laboratory measurements. In the gamma branch, the simulated total noise corresponds to the combined contribution of the two readout channels coupled to the scintillator bar. For this reason, the laboratory reference value was obtained from Table 3.7 by combining each top–bottom channel pair in quadrature,

$$\sigma_{\text{el,combined}} = \sqrt{\sigma_{\text{el,top}}^2 + \sigma_{\text{el,bottom}}^2}.$$

The average of these combined values was used as the laboratory double-channel noise. This provides a consistent comparison with the simulated gamma-branch noise. In contrast, the X-mode signal involves only one readout channel, so the simulated X-branch noise can be compared directly with the laboratory X-branch noise.

It should be noted that the post-processing model includes only the statistical broadening of the deposited energy through a Gaussian noise term derived from the experimental detector parameters. It does not reproduce the full laboratory spectral environment. In the measured spectra, additional contributions can be present, such as residual environmental background, electronic baseline fluctuations, low-channel electronic events, and possible non-Gaussian distortions of the peak shape. These effects

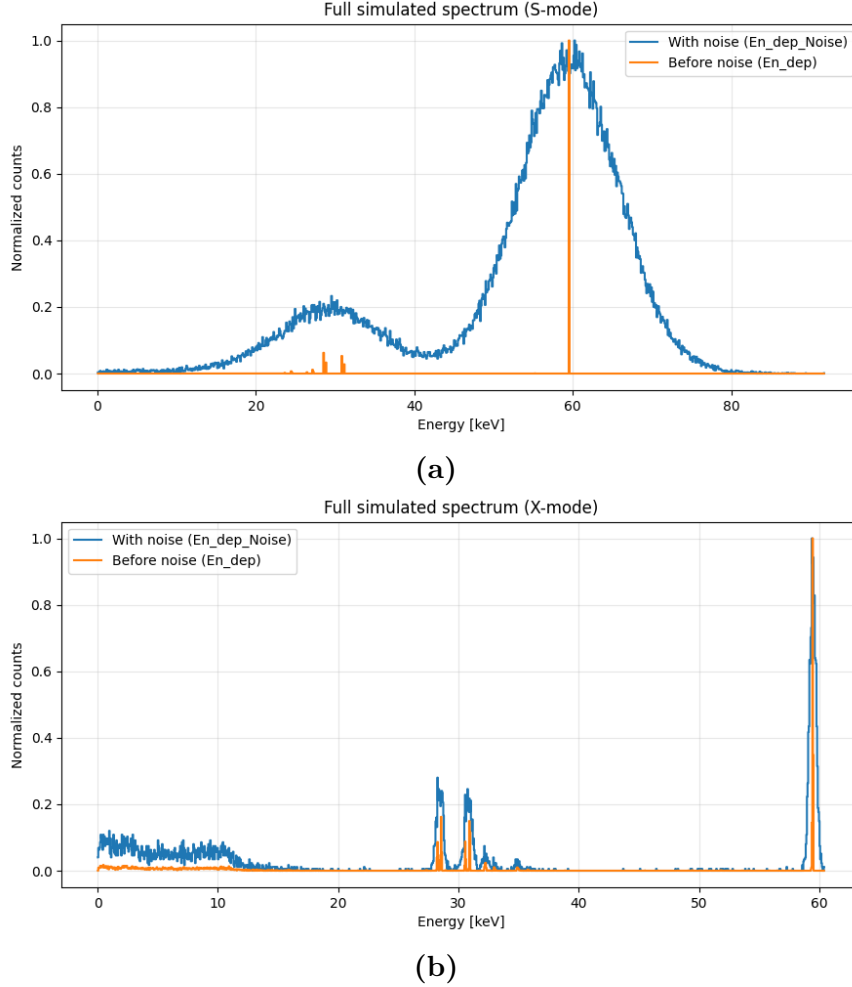


Figure 4.8. Comparison between the ideal deposited-energy spectrum and the spectrum after detector-noise post-processing for a monoenergetic 59.5 keV ^{241}Am photon source simulated with the reduced 2×2 geometry. Panel (a) shows the S-mode events, corresponding to interactions in the CsI(Tl) scintillator, while panel (b) shows the X-mode events, corresponding to direct interactions in the SDD. In each panel, the orange curve represents the raw Geant4 deposited energy stored in `En_dep`, while the blue curve represents the reconstructed noisy energy stored in `En_dep_Noise`. The spectra are independently normalized to their maximum value in order to compare their shapes rather than their absolute count levels. The effect of the noise model is to redistribute the events around the original deposited energies, broadening the narrow structures of the ideal spectrum. This effect is more pronounced in S-mode because the scintillator energy resolution is dominated by the larger electronic-noise contribution converted through the measured light output.

can contribute to a broader measured peak, especially in the X branch, but are not explicitly included in the simplified Monte Carlo post-processing.

For this reason, the comparison between the simulated and measured noise should be interpreted as a validation of the noise scale rather than as an exact peak-width reproduction. The agreement obtained for both the X and gamma branches indicates that the adopted model captures the dominant detector-noise contribution, while the remaining difference is compatible with laboratory effects not included in the simulation.

The reconstructed 59.5 keV peak was fitted with a Gaussian function to quantify the broadening introduced by the detector-noise post-processing. The fit was performed separately for the S-mode and X-mode spectra, as shown in Figure 4.9. The numerical fit results are reported in Table 4.2. This provides a useful consistency check with the laboratory tests discussed in Chapter 3, where the same ^{241}Am line was used to characterize the detector response.

As expected, the X-mode peak is significantly narrower, in relative terms, than the S-mode peak. In X-mode, the photon energy is deposited directly in the silicon detector. In S-mode, the energy is instead deposited in the CsI(Tl) scintillator and converted into scintillation light, which is collected by the two SDDs. The reconstructed energy therefore, includes the additional contributions from scintillation-light statistics and dual-ended readout noise, resulting in a broader peak.

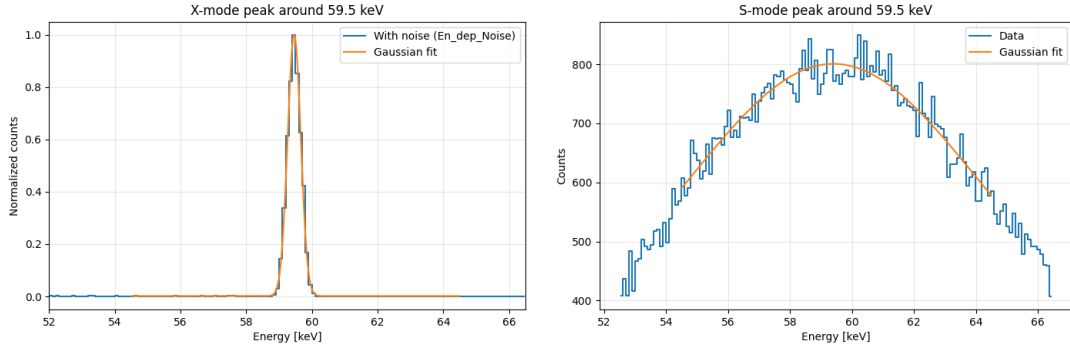


Figure 4.9. Gaussian fit of the reconstructed 59.5 keV peak after detector-noise post-processing in the reduced 2×2 simulation. Right: S-mode spectrum, corresponding to interactions in the CsI(Tl) scintillator. Left: X-mode spectrum, corresponding to direct interactions in the SDD. The comparison shows the larger peak broadening of the S-mode peak due to scintillation-light statistics and dual-ended readout noise. The Fit calculation was done to cover the full Gaussian, but only for visualization; the range of the X-axis (energy) and the orange Gaussian fit were kept the same in both S and X modes.

4.4 Updated XGIS Camera

The simulation activity described in this section extends the previous detector-level studies to the full XGIS camera model. The main objective is to use the updated

Geant4 output to study the depth of interaction (DOI) inside the CsI(Tl) scintillator bars. This information is a new feature introduced in the latest version of the simulation chain developed in this work. The workflow is therefore the following: first, the DOI observable is recalled and its role in the full-camera output is defined; then, the updated self-supporting coded mask is described as part of the current camera mass model; after that, the background input sources used in the Geant4 macro files are summarized; finally, the simulated background interactions are analysed as a function of depth in order to investigate whether this information can help distinguish astrophysical photons entering the instrument from background photons and particles.

4.4.1 Depth of Interaction in the Updated Camera

The goal of introducing the depth-of-interaction information in the full XGIS camera model is to obtain an additional spatial observable for events occurring inside the CsI(Tl) scintillator bars. In the original output, the simulation identified the detector element in which energy was deposited and allowed the separation between X-mode interactions in the SDDs and S-mode interactions in the scintillator. The updated output adds information on where along the scintillator bar the interaction occurred. This is useful not only for studying the detector response to controlled sources, as shown in Section 4.3.2, but also for improving the event reconstruction and for investigating the spatial distribution of background-induced events.

In the full-camera simulations, the DOI coordinate is especially relevant because different event classes are not expected to populate the scintillator volume in the same way. Photons from an astrophysical source are selected by the coded-mask aperture and reach the detector from the instrument field of view, while several background components can enter from different directions or be produced by interactions in the surrounding materials. Therefore, the DOI information does not replace the energy spectrum or the coded-mask reconstruction, but it provides an additional diagnostic that can be used to study the topology of the recorded events.

4.4.2 Self-Supporting Coded Mask

The coded-mask imaging principle adopted by XGIS has already been introduced in Section 2.4 and illustrated in Figure 2.10. Therefore, this section only describes the update introduced in the Geant4 mass model and the corresponding imaging performance reported in the recent INAF XGIS imaging-simulation technical note (Arrigoni & Mereghetti, 2026).

A modification implemented in the simulation code concerns the coded-mask pattern. In the previous version of the mass model, the mask was based on a pseudo-random configuration with an open fraction close to 50%. This configuration was useful for simulation studies, but it did not fully represent the current mechanical design of the instrument. In the latest XGIS design, the coded mask must also satisfy structural constraints; for this reason, the adopted pattern is *self-supporting*, meaning that the closed tungsten elements form a mechanically connected structure.

The mask consists of a 51×51 array of 11 mm-wide elements, corresponding to a useful pattern size of about $56.1 \times 56.1 \text{ cm}^2$. The material is a $500 \text{ }\mu\text{m}$ tungsten layer placed at a distance of 63 cm from the detector plane. The main geometrical difference is therefore the replacement of the previous random pattern by the self-supporting one, whose open fraction is about $\sim 42\%$ (Arrigoni & Mereghetti, 2026).

In the Geant4 implementation, the update was performed by replacing the external mask-pattern file and adapting the corresponding geometrical parameters used to build the mask elements. The closed elements of the pattern are converted into tungsten volumes, while the open elements are left empty. The imaging simulations based on this updated Geant4 code provide a useful quantitative reference for the expected performance of the updated mask. For the current self-supporting configuration, the reported intrinsic angular resolution is $\vartheta_{\text{Res}} = 66'$ and the relation between the source-location accuracy and the image signal-to-noise ratio is fitted with an additional constant term,

$$R_{90} = k_0 \frac{\vartheta_{\text{Res}}}{\text{SNR}_{\text{img}}} + k_1, \quad (4.8)$$

with $k_0 = 1.02 \pm 0.03$ and $k_1 = 1.71 \pm 0.08$ (Arrigoni & Mereghetti, 2026). The same study reports that this corresponds to a source-localisation accuracy about $1.5'$ worse than the optimized random 55×55 mask pattern, mainly because of the reduced open fraction and the lower angular resolution of the self-supporting mask. Nevertheless, the updated design still satisfies the XGIS localisation requirements: for sources detected with $\text{SNR}_{\text{img}} > 6$, the probability of obtaining $R_{90} > 7'$ is reported as 0.29, while the probability of obtaining $R_{90} > 15'$ is below 10^{-3} (Arrigoni & Mereghetti, 2026). The comparison between the previous and updated mask patterns is shown in Figure 4.10. The updated imaging simulation results plot is shown in the Figure 4.11.

This update is relevant for the background simulations discussed in the following, since the mask is part of the full camera geometry crossed by photons before they reach the detector plane. The main focus of the analysis remains the DOI information recorded in the scintillator, but the use of the current mask pattern makes the simulated camera configuration closer to the present XGIS design.

4.4.3 Background Input Sources

The DOI study was performed using background simulations of the full XGIS camera. The background samples were generated using dedicated Geant4 macro files, one for each background component. These macros define realistic particle or photon spectra and an extended source geometry surrounding the full camera model. For example, in the the Cosmic X-ray Background (CXB) simulation, the General Particle Source is defined on the surface of a sphere centered on the detector, with a radius of 5 m. The emitted particles are gamma-ray photons, and their energies are sampled from an arbitrary tabulated spectrum. The adopted CXB spectrum is based on the model of Gruber et al. (1999), as implemented for Low-Earth-orbit background simulations following the approach described in Campana et al. (2013). In this way, each simulated primary particle is not generated at a fixed energy, but is statistically extracted from



(a) Previous pseudo-random mask pattern. (b) Updated self-supporting mask pattern.

Figure 4.10. Comparison between the coded-mask pattern used in the previous simulation configuration and the updated self-supporting pattern implemented in the Geant4 mass model. The new mask follows the current XGIS design and consists of a 51×51 array of 11 mm elements with an open fraction of about 41–42%.

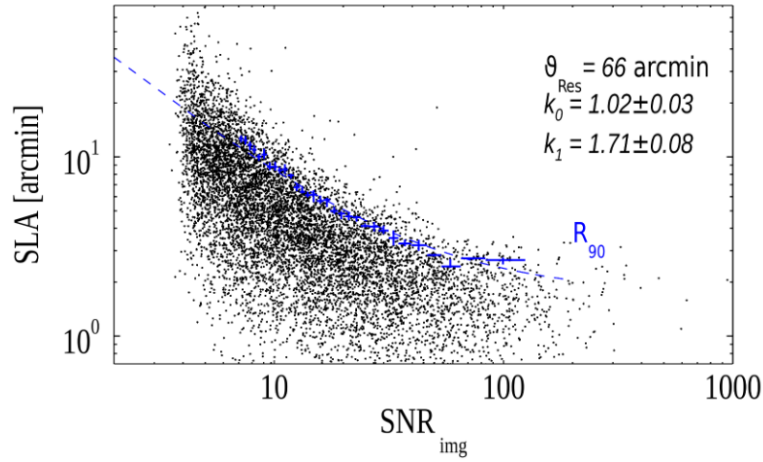


Figure 4.11. Imaging-simulation result for the updated self-supporting mask, showing the source-location accuracy as a function of image signal-to-noise ratio and the fitted R_{90} trend. Adapted from Arrigoni & Mereghetti (2026).

the corresponding input background spectrum.

For the CXB macro, the angular distribution is defined with a cosine law and restricted to the angular region required to illuminate the detector volume. The same general strategy is used for the other background components, changing the particle type and the input spectral distribution. The number of generated primary particles was chosen according to the available simulation statistics and computational cost. In particular, 10^6 primaries were used for the CXB, neutron albedo, photon albedo, secondary electrons, secondary positrons, and secondary protons, while 10^5 primaries were used for the primary alpha, electron, positron, and proton components. The resulting scorefiles contain the detector interactions produced by realistic background populations rather than by mono-energetic pencil beams.

The input background spectra used by these macro files are shown in Figure 4.12. The corresponding Geant4 macro files used for the background simulations were developed for the XGIS background-simulation activity (Campana et al., 2020).

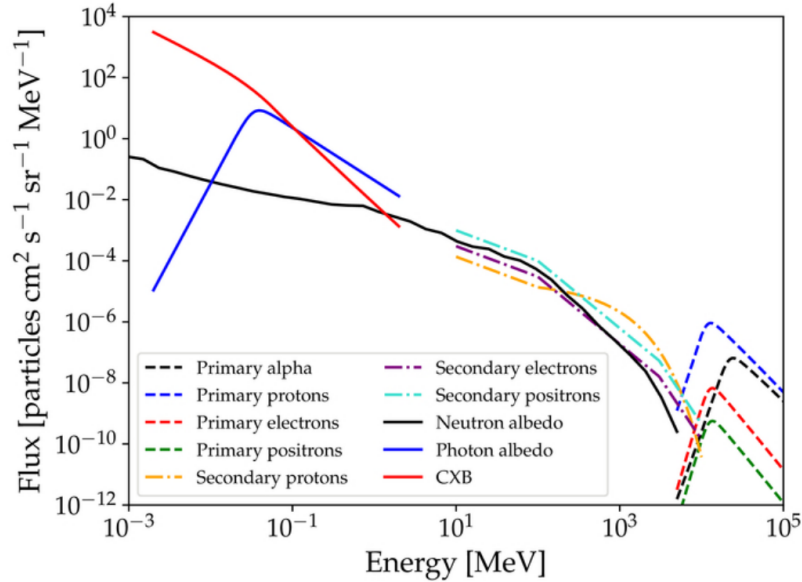


Figure 4.12. Differential spectra of the Low-Earth-orbit background sources used as input for the XGIS background simulations. Adapted from Campana et al. (2020).

Before studying the depth-of-interaction information derived from the background scorefiles, it is useful to summarize the spectral composition of the XGIS background obtained in the previous M7 simulation activity.

The simulations were run generically for each background component, without forcing the events to belong in advance to the X-mode or S-mode branch. The classification is performed afterwards from the output scorefile, according to the detector volume where the energy deposit is recorded. In the simulation output, an energy deposit in the SDD is identified by a valid `Pixel_ID`, while `Scint_ID = -1000` is used as a flag; these events are classified as X-mode events. Conversely, an energy deposit in a CsI(Tl)

scintillator bar is identified by a valid `Scint_ID`, while `Pixel_ID = -1000` is used as a flag; these events are classified as S-mode events. Therefore, the distinction between X-mode and S-mode is not imposed at the generation level, but follows from the physical interaction of the incident photons or particles with either the SDDs or the scintillator bars.

For the X-mode energy range, the dominant contribution is the CXB, while the other simulated components are negligible. In the S-mode energy range, photon background components dominate up to several hundred keV, whereas particle-induced background becomes more important at higher energies. The S-mode spectrum also shows fluorescence features associated with tungsten in the mask and collimator. These previous results provide the spectral context for the present DOI study: the aim here is not to repeat the full background-rate calculation, but to use the newly stored depth coordinate to investigate where the simulated background interactions occur inside the detector volume. The contribution of the different Low-Earth-orbit background components to the two modes is shown in Figure 4.13.

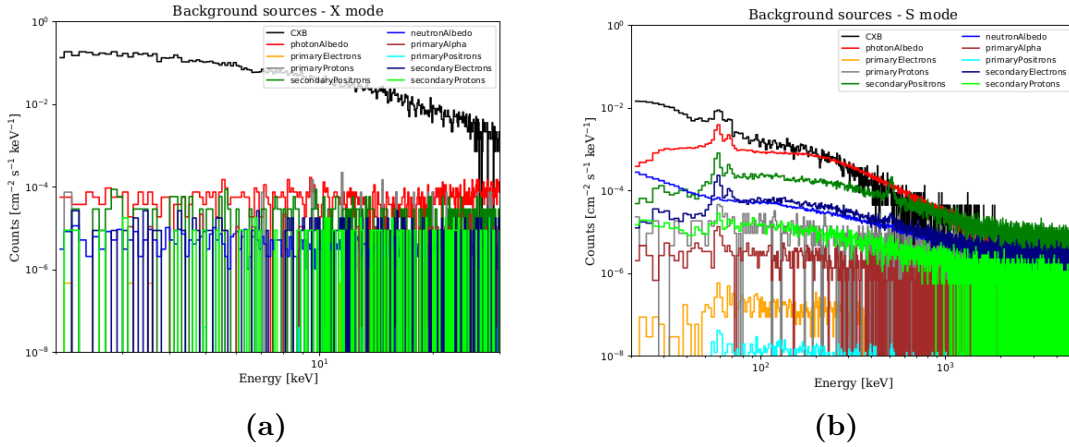


Figure 4.13. Simulated background contributions obtained in the previous M7 XGIS simulation activity. (a) X-mode background spectrum, corresponding to direct interactions in the SDD energy range. (b) S-mode background spectrum, corresponding to interactions in the CsI(Tl) scintillator energy range. The X-mode background is dominated by the cosmic X-ray background, while in S-mode photon background dominates up to several hundred keV and particle-induced components become more relevant at higher energies. Adapted from [Pisapia \(2025\)](#).

This behaviour can be understood from the combination of the incident background spectra and the different detection volumes involved in the two acquisition modes. As discussed in Sect. 2.2.1, the CXB is the dominant diffuse photon component in the soft X-ray range, while the atmospheric photon albedo and the particle populations originate mainly from cosmic-ray interactions with the Earth atmosphere and with the spacecraft/instrument materials ([Gruber et al., 1999](#); [Campana, 2022](#)). Since X-mode events correspond to direct energy deposits in the thin SDD layers, they mainly sample

the low-energy photon background, where the CXB contribution is largest. In contrast, S-mode events are produced in the thicker CsI(Tl) scintillator bars, which remain sensitive over a much broader hard-X/soft-gamma energy range. Therefore, diffuse photon components dominate the S-mode spectrum up to several hundred keV, whereas at higher energies the decreasing photon flux and the increasing penetration of energetic particles make particle-induced events progressively more relevant.

4.4.4 Depth-of-Interaction Results for Background Simulations

After defining the camera geometry and the input background populations, the simulated scorefiles were analysed by selecting the events that deposit energy in the CsI(Tl) scintillator. This is the relevant event class for the DOI study, because the depth coordinate is defined along the scintillator bar. The analysis is motivated by the fact that different background components do not necessarily enter the instrument from the same direction as astrophysical photons passing through the coded mask. Particle-induced backgrounds, atmospheric albedo components, and photon backgrounds can therefore populate different regions of the detector volume. The depth coordinate can consequently provide information that is not available from the deposited-energy spectrum alone.

Table 4.3. Simulation statistics for the background samples used in the depth-of-interaction study. The table reports the number of generated primaries and the fraction of interacting primaries that produced at least one hit inside the CsI(Tl) scintillator, identified in the FITS output by `Pixel_ID = -1000`. The percentages were computed using unique EventID values.

Background component	Generated primaries	Scintillator / interactions [%]
CXB	1.0×10^6	73.02
Neutron albedo	1.0×10^6	98.43
Photon albedo	1.0×10^6	99.32
Primary alpha particles	1.0×10^5	91.89
Primary electrons	1.0×10^5	96.66
Primary positrons	1.0×10^5	96.77
Primary protons	1.0×10^5	97.18
Secondary electrons	1.0×10^6	96.80
Secondary positrons	1.0×10^6	97.05
Secondary protons	1.0×10^6	96.36

The statistics reported in Table 4.3 were computed using unique EventID values. This choice avoids counting the same generated primary particle more than once when it produces multiple hit entries in the detector. The last column reports the fraction of interacting primaries that produced at least one hit inside the scintillator. This value is high for most background components, indicating that, once a particle produces a recorded detector interaction, the scintillator is frequently involved. The CXB component shows a lower scintillator fraction because part of the low-energy photon population can be absorbed in the silicon detectors or in other sensitive regions before reaching the

scintillator. These statistics confirm that the DOI analysis is based on the subset of simulated events that actually deposit energy in the scintillator volume.

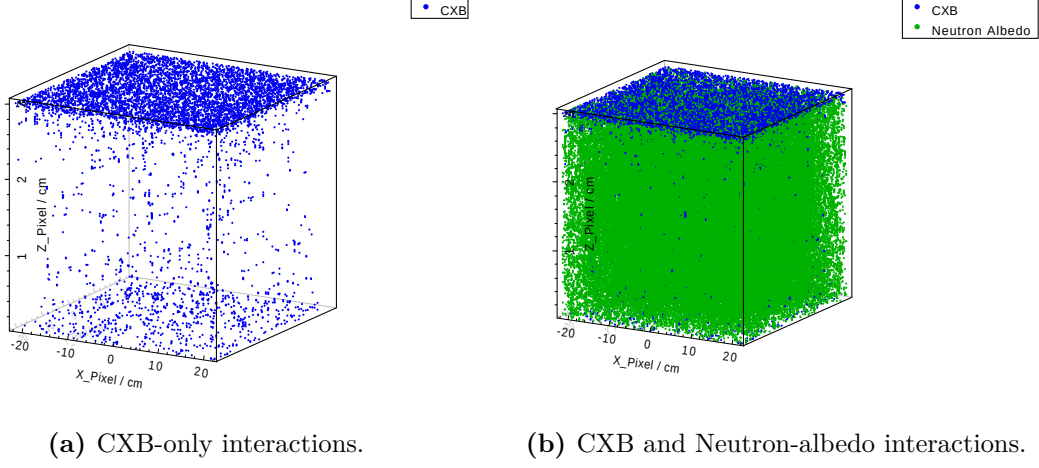


Figure 4.14. Visualization of simulated interaction positions recorded in the full XGIS camera model for different background components. The panels illustrate how the depth-of-interaction information can be used to inspect the spatial topology of background-induced events.

A qualitative visualization of the recorded interaction positions for two background components is shown in Figure 4.14. These displays were used as a first check that the position information is correctly propagated in the full-camera simulations and that different background samples can be inspected in three dimensions.

Figure 4.15 shows the distribution of simulated background interactions for the components described in Figure 4.13 as a function of depth. This plot illustrates the practical use of the DOI observable for background studies. In particular, it makes it possible to check whether some components are concentrated preferentially in specific regions of the scintillator depth.

The CXB and photon-albedo components show the clearest dependence on depth. Their counts are enhanced close to the two detector surfaces, corresponding to the first few millimetres near the top and bottom of the scintillator, while the central part of the bar is comparatively flatter. This behaviour suggests that a significant fraction of these photon-induced background events interacts soon after entering the detector volume, or after reaching it from the opposite side.

In contrast, most charged-particle components and the neutron-albedo contribution show a much smoother dependence on depth. Apart from small variations, their distributions are approximately uniform along the scintillator thickness. This indicates that these particles are able to penetrate the detector more deeply and deposit energy throughout the full volume of the bars.

Overall, the depth-of-interaction information provides a useful diagnostic for studying background components with different interaction topologies. This is particularly evident for the CXB component. Considering the selected scintillator interactions in the physical

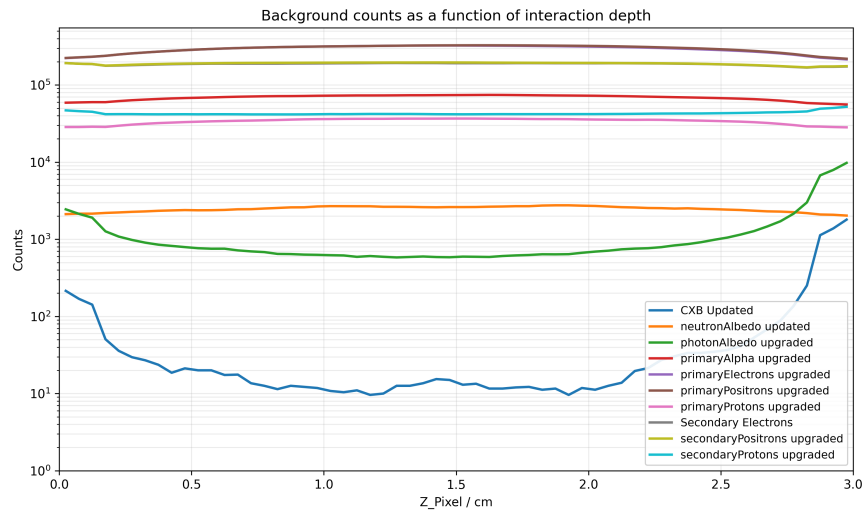


Figure 4.15. Distribution of simulated background interactions as a function of the depth coordinate in the detector, obtained from the available background scorefiles associated with the previous M7 XGIS simulation activity. The different components include cosmic X-ray background, albedo photons, albedo neutrons, and primary and secondary charged particles. This comparison illustrates the possible use of depth-of-interaction information for studying the spatial distribution of background-induced events.

range $0 < Z_{\text{pixel}} < 3$ cm, a total of 7362 interactions were recorded. By defining an enhanced region as one in which the depth distribution is at least 20% above the average, two surface-dominated regions are identified.

The strongest enhancement is located close to the source-facing side of the scintillator (Top) and contains 5532 interactions, corresponding to 75.1% of the selected CXB scintillator interactions. This region shows the surface-dominated nature of the CXB interactions, but it cannot be used as a rejection criterion, because photons from an astrophysical source would enter the detector from the same side and would therefore be topologically indistinguishable using DOI alone. The opposite surface-enhanced region contains 590 interactions, corresponding to 8.0% of the selected CXB scintillator interactions. This latter region is the only one relevant for a possible geometrical rejection, since true source photons are not expected to enter from that side.

Therefore, the DOI coordinate should not be interpreted as a standalone method to identify astrophysical events. Instead, it can provide complementary information together with the deposited energy, the event multiplicity, and the coded-mask imaging reconstruction. In this sense, the updated simulation output provides a first indication that the interaction depth may help future event-selection strategies, especially for identifying surface-enhanced background components.

Conclusions and Future Work

5.1 Conclusions

This thesis presented an experimental and simulation study of the X/Gamma-ray Imaging Spectrometer (XGIS), one of the instruments proposed for the THESEUS mission. The work focused on the characterization of a four-pixel XGIS prototype equipped with the ORION ASIC readout electronics and on the development of Monte Carlo simulations studying the detector response and the use of depth-of-interaction information.

The experimental activity provided a comprehensive characterization of the detector performance. A dedicated validation of the top–bottom channel coupling logic was first performed, allowing the correct association of the scintillation signals collected at the two ends of each CsI(Tl) bar. This step was essential for the reconstruction of gamma-ray events and for all subsequent scintillation measurements.

The energy calibration of both the X and gamma branches demonstrated a stable and highly linear detector response. For the X branch, coefficients of determination above $R^2 > 0.99$ and residuals below 1% were obtained for all channels, confirming the reliability of the calibration procedure and the compliance of the ORION ASIC with the scientific requirements for spectroscopy. Consistent results were obtained for the gamma branch, where the reconstructed scintillation signals showed a stable response across all channel combinations. The average calibration gain was (0.167 ± 0.005) keV/ADU for the X branch and (0.198 ± 0.009) keV/ADU for the gamma branch, where the quoted uncertainties represent the channel-to-channel standard deviation. These values show that the calibration parameters remain consistent among the channels, with relative spreads of about 3% for the X branch and 5% for the gamma branch.

The effective test capacitance values are consistent across the top and bottom gamma channels, with an average value of $\bar{C} = (17.99 \pm 0.09)$ fF and a channel-to-channel standard deviation of $\sigma_C = (0.26 \pm 0.07)$ fF, corresponding to a relative spread of 1.5%. This value is in excellent agreement with the nominal design value of $C_{\text{nom}} = 18.0$ fF.

The electronic-noise characterization confirmed a stable response of the prototype readout chain. The average electronic noise is $\bar{\sigma}_{\text{el},X} = (56 \pm 6)$ e[−] RMS for the X branch and $\bar{\sigma}_{\text{el},\gamma} = (104 \pm 9)$ e[−] RMS for the gamma branch, with relative channel-to-channel spreads of 21% and 36%.

A central result of this work is the determination of the scintillation light output of the CsI(Tl)–SDD system. From the central irradiation measurements, the light-output values range from (26.5 ± 0.5) e[−]/keV to (34 ± 3) e[−]/keV. The average value obtained with ^{241}Am is $\bar{LO}_{\text{Am}} = (30 \pm 1)$ e[−]/keV, with a relative channel-to-channel spread of 11%, while the average value obtained with ^{137}Cs is $\bar{LO}_{\text{Cs}} = (27.7 \pm 0.5)$ e[−]/keV, with a relative channel-to-channel spread of 3%.

The light-output values obtained with ^{241}Am and ^{137}Cs are not expected to be identical, because the scintillation response of CsI(Tl) is not perfectly proportional

to the deposited energy. The light yield per unit deposited energy depends on the energy released in the crystal, a known effect in scintillation detectors (Knoll, 2010). In particular, non-proportionality measurements of scintillators show that the relative light yield of CsI(Tl) is higher at energies of a few tens of keV than at several hundred keV, with a difference of the order of 10% between the region around the 59.5 keV ^{241}Am line and the 661.7 keV ^{137}Cs photopeak. This explains why the light output estimated from the ^{241}Am scintillation peak can be systematically higher than the value obtained from the ^{137}Cs photopeak. The difference between the two averages is about 8%, which is therefore compatible with the expected non-proportionality effect within the experimental uncertainties.

The experimental measurements were complemented by Monte Carlo simulations developed using Geant4. A reduced 2×2 detector geometry was implemented in order to reproduce the laboratory configuration and validate the detector response under controlled conditions. The simulations successfully reproduced the deposited-energy spectra of the ^{241}Am monochromatic peak at 59.5 keV and provided a framework for studying interaction processes inside the scintillator bars.

Particular attention was devoted to the implementation and validation of depth-of-interaction information. The simulation framework allowed the interaction depth of individual events to be recorded and analyzed, demonstrating the capability of the model to reproduce the expected attenuation behaviour inside the scintillator volume. The resulting depth distribution was found to be consistent with an exponential attenuation law, yielding an effective attenuation length of approximately 0.97 ± 0.05 cm.

Finally, the detector-noise post-processing model provided a direct connection between the laboratory characterization and the Monte Carlo simulations. For the reconstructed 59.5 keV peak of ^{241}Am , the simulated total noise was found to be (58 ± 1) e $^-$ for the X branch and (135 ± 5) e $^-$ for the gamma branch, expressed as RMS equivalent noise charge. The X-branch value is in good agreement with the laboratory total noise, (68 ± 1) e $^-$, which can be attributed to additional broadening contributions present in the measured spectra. For the gamma branch, the simulated value corresponds to the combined top-bottom readout contribution and is therefore compared with the laboratory double-channel noise of (154 ± 1) e $^-$. The agreement is reasonable, considering the simplifications of the post-processing model and the experimental uncertainties. Overall, this comparison shows that the adopted noise model reproduces the correct scale of the measured detector noise and supports the use of experimentally determined detector parameters in the Monte Carlo reconstruction framework. The difference can be ascribed to experimental effects not included in the simplified post-processing model, such as residual gain and offset variations, calibration uncertainties, background radiation in the laboratory, and possible deviations of the measured peak shape from an ideal Gaussian.

The simulation activity also included the implementation of the updated self-supporting coded-mask geometry in the full XGIS camera model. This represents an important step toward a more realistic description of the instrument and provides the basis for future studies of effective area, imaging performance, source localization, and background characterization.

Overall, the results obtained in this work demonstrate the validity of the XGIS detection concept in the current M7 configuration. The agreement between experimental measurements and simulation activities confirms the capability of the detector system to provide stable calibration, low-noise operation, and efficient scintillation-light collection. At the same time, the developed simulation framework provides the tools required for future optimization of detector performance and background-rejection strategies. Beyond the specific implementation considered in this thesis, the methods and results presented here are relevant for the development of future space-borne X-ray and gamma-ray detectors based on scintillator–SDD readout concepts, including THESEUS and other possible high-energy astrophysics missions.

5.2 Future Work

The work presented in this thesis opens several interesting directions for the continued development and characterization of the XGIS detector system and of similar detector concepts for future space missions.

An additional development would be the acquisition and analysis of the top and bottom gamma channels independently, rather than considering only the summed scintillation signal. This is directly supported by the updated ORION readout, where the output data word includes separate ADC fields for the X, γ -top, and γ -bottom processing chains (Mattioli et al., 2026b). Since the amount of scintillation light collected at each end of the crystal depends on the interaction position, the relative contribution of the two gamma signals contains information on the location of the energy deposition along the scintillator bar. Similar approaches have been extensively investigated for position-sensitive CsI(Tl) detectors, where the interaction coordinate is reconstructed from the ratio of the signals measured at the two ends of the crystal (Labanti et al., 1991). This capability could therefore provide a natural experimental extension of the depth-of-interaction studies introduced in the simulation part of this work.

A dedicated calibration campaign based on individual top and bottom spectra acquired at multiple irradiation positions could therefore be used to establish a quantitative relationship between signal asymmetry and interaction position. Such a study would represent an important step toward the experimental reconstruction of the depth of interaction in the detector and would provide a direct comparison with the depth-of-interaction information currently available from the Geant4 simulations. In the longer term, combining experimentally reconstructed interaction-depth information with energy and event-topology observables may contribute to the development of advanced event-classification and background-rejection techniques.

The observed light-output values and their overall uniformity indicate that the optical coupling between the CsI(Tl) crystals and the Silicon Drift Detectors is already effective in the current prototype configuration. Future investigations may further explore the relationship between optical coupling conditions, detector assembly procedures, and scintillation performance, contributing to the optimization of future detector modules. The detector characterization carried out in this work also provides a valuable reference for additional studies of the ORION readout electronics. Measurements performed

under different operating conditions, including temperature-controlled environments, could offer further insight into the long-term stability of the detector response and support future qualification activities.

From the simulation perspective, the Geant4 framework developed during this thesis offers a versatile platform for extending the comparison between experimental measurements and Monte Carlo models. Additional source configurations and detector geometries can be incorporated to further refine the description of the detector response and strengthen the connection between simulations and laboratory data. The preliminary analyses performed in this work suggest that DOI distributions contain information beyond that available from deposited-energy spectra alone. Building on these results, future studies may investigate the behavior of different background components after proper normalization to their physical fluxes and observational conditions.

A further improvement of the simulation model concerns the description of the ^{241}Am source. In the present work, the reduced-geometry simulations were performed using a monoenergetic photon beam at 59.5 keV. A natural next step, already under development, is to replace this simplified source description with a more realistic multi-line ^{241}Am spectrum, including the main X-ray and gamma-ray emissions with their relative intensities. This would allow a more direct comparison between simulated and experimental spectra, especially in the low-energy region where fluorescence and source-emission lines contribute to the observed spectral shape.

A natural continuation of this activity is the exploration of whether depth-of-interaction information can be combined with energy deposition, event multiplicity, and interaction topology to identify characteristic signatures of background-induced events. Such studies would help assess the feasibility of developing event-selection techniques capable of distinguishing background interactions from photons originating from astrophysical sources, with potential benefits for the overall sensitivity of the instrument.

Finally, the implementation of the updated self-supporting coded-mask geometry provides the basis for more advanced end-to-end simulations of the XGIS instrument and of similar wide-field high-energy detector systems. These studies may include investigations of imaging performance, source-localization capabilities, detector sensitivity, and background response using increasingly realistic instrument configurations.

The combination of experimentally validated detector parameters and detailed Monte Carlo simulations will continue to support the optimization of XGIS and its scientific exploitation within the THESEUS mission, while also providing a useful framework for the development of other future space missions dedicated to high-energy transient astrophysics and multi-messenger astronomy.



The Amptek MCA-8000D Digital Multichannel Analyzer

The spectral acquisitions performed during the experimental activity were carried out using an Amptek MCA-8000D Digital Multichannel Analyzer (MCA). An MCA measures the amplitude of incoming analog pulses and sorts the recorded events into discrete channels according to their pulse height. In a radiation-detection system, provided that the signal amplitude is proportional to the deposited energy, the resulting pulse-height histogram represents the measured energy spectrum.

The MCA-8000D is designed to operate downstream of an analog pulse-shaping stage: it does not perform signal shaping internally, but digitizes shaped input pulses and determines their peak amplitude. The instrument is equipped with a high-speed 100 MHz, 16-bit analog-to-digital converter and can acquire spectra using up to 8192 channels. The input dynamic range can be selected by software between 0–1 V and 0–10 V, while the input signal must be a positive unipolar or bipolar shaped pulse with a peaking time of at least 500 ns. In addition, the manufacturer specifies that the DC level of the input signal must be zero ([Amptek Inc., 2026a](#)).

This last requirement is relevant for the measurements reported in this thesis. The analog outputs delivered by the ORION-BE electronics exhibit a DC offset, and therefore they cannot be directly connected to the MCA input without an offset-removal stage. For this reason, the signals were processed through the analog summing module described in Chapter 3, which subtracts the DC baseline from the individual gamma-branch outputs before either sending them separately to the MCA or combining them to reconstruct the summed scintillation signal.

During the measurements, the selectable input range of the MCA was adapted to the signal amplitude. The 0–1 V range was adopted for the gamma-branch acquisitions, where the signals were smaller, while the 0–10 V range was used for the X-branch acquisitions in order to avoid saturation. The acquired spectra were recorded using the Amptek DPPMCA acquisition software, which allows the user to configure the number of channels, input range and discrimination threshold, as well as to visualize and save the measured spectra.

Table A.1. Main characteristics of the Amptek MCA-8000D used for the spectral acquisitions ([Amptek Inc., 2026a](#)).

Parameter	Value / configuration
Digitizer	100 MHz, 16-bit ADC
Maximum number of channels	8192
Selectable input ranges	0–1 V or 0–10 V
Minimum pulse peaking time	≥ 500 ns
Differential non-linearity	$< \pm 0.6\%$
Integral non-linearity	$< \pm 0.02\%$
Input DC level requirement	0 V
Acquisition software	Amptek DPPMCA
Communication interfaces	USB, RS-232, Ethernet

B

Python-based analysis pipeline

The experimental data discussed in Chapter 3 were processed with a dedicated Python-based analysis pipeline developed during this thesis work. The pipeline was designed to provide a reproducible treatment of the MCA spectra acquired during the calibration, noise, light-output, and position-dependent response measurements.

The analysis scripts were written in Python and organized around a common workflow: reading the MCA files, extracting the relevant metadata, identifying spectral peaks, associating them with radioactive-source lines or pulser signals, performing the calibration, and producing diagnostic plots and summary tables. The numerical analysis was mainly based on NumPy for array operations, pandas for tabular outputs, Matplotlib for visualization, and SciPy for peak search and fitting routines. In particular, the function `scipy.signal.find_peaks` was used in the peak-identification step, together with additional selection criteria based on channel range, peak height, prominence, separation between peaks, and experimental constraints specific to each acquisition.

The input files were ASCII spectra exported from the Amptek MCA software. The pipeline first searched for the data block inside each file and converted the counts into a numerical array as a function of MCA channel. When needed, information such as the pulser amplitudes, channel name, acquisition branch, source type, and irradiation position was extracted automatically from the file name using regular expressions. This reduced the need for manual input and ensured that all spectra belonging to the same measurement set were processed consistently.

For the X-branch analysis, the pipeline combined the spectra acquired with the ^{241}Am and ^{55}Fe sources. The peak-selection logic was adapted to the experimental configuration: source peaks and pulser peaks were selected in separate channel regions, while fluorescence features from the CsI(Tl) crystal were identified and excluded from the calibration. The selected centroids were then used to build the channel-to-energy calibration and to generate calibration plots with residuals.

The characterization of the effective test capacitance was treated as a step of the pipeline. This part of the analysis used the pulser peaks to determine the capacitance value that provided the most linear relation between injected pulser amplitude and measured channel position. A scan over possible capacitance values was performed for each relevant top and bottom channel, and the value corresponding to the maximum linearity was selected. The output of this step was saved separately and then used as an input parameter in the following calibration and light-output analyses.

For the gamma-branch analysis, separate scripts were used for the individual top and bottom channels and for the summed top–bottom configurations. The individual gamma-channel calibration used the selected ^{241}Am X-ray lines and the pulser peaks, after applying the capacitance values obtained from the independent capacitance-characterization step. For the summed-channel analysis, the top and bottom capacitance values were combined consistently with the corresponding channel pair. The predicted pulser positions in the summed spectra were then compared with the observed ones as

a consistency check, while the calibration itself relied on the selected physical peaks.

The pipeline also included routines for the extraction of the light-output quantities. After the calibration of the electronic response, the scintillation-related peak observed in the gamma branch was treated separately from the direct X-ray absorption peaks. This distinction was important because the direct X-ray lines were used to calibrate the electronic chain, while the scintillation peak was used later to estimate the light output of the CsI(Tl) bars.

A dedicated part of the analysis was developed for the collimated ^{137}Cs measurements used to study the response uniformity along the scintillator bars. In this case, the code fitted the 661.657 keV photopeak in a selected region of interest and extracted the centroid, width, net peak area, and associated uncertainty. The results were then grouped by channel combination and irradiation position, allowing the response of each bar to be compared as a function of the source position.

The pipeline automatically produced intermediate and final outputs for quality control. These included annotated spectra showing the selected and excluded peaks, calibration curves, residual plots, capacitance-scan plots, fitted ^{137}Cs spectra, and CSV summary files containing the extracted numerical results. These diagnostic outputs were essential for checking the stability of the peak selection and for identifying problematic acquisitions, such as spectra affected by peak overlap, excessive low-channel noise, or incorrect acquisition settings.

Overall, the Python pipeline provided a consistent and reproducible framework for the experimental characterization of the XGIS prototype. It allowed the same analysis logic to be applied to different branches, channels, sources, and irradiation configurations, while still keeping enough flexibility to account for the specific conditions of each measurement.

Pipeline file organization

The analysis files were organized according to the detector branch, radioactive source, and channel configuration. A schematic view of the adopted structure is shown below. The tree is intended to describe the logical organization of the pipeline rather than the complete list of all raw acquisition folders.

```
python_analysis_pipeline/  
|  
|-- x_branch/  
|   |  
|   |-- data/  
|   |   |-- Am241/  
|   |       |-- channel_A/  
|   |       |-- channel_B/  
|   |       |-- channel_C/  
|   |       |-- channel_D/  
|   |   |  
|   |   |-- Fe55/
```

```

|   |   |-- channel_A/
|   |   |-- channel_B/
|   |   |-- channel_C/
|   |   |-- channel_D/
|   |
|   |-- scripts/
|   |   |-- x_branch_combined_Fe_Am_calibration.py
|   |
|   |-- results/
|   |   |-- channel_A/
|   |   |   |-- spectrum.png
|   |   |   |-- calibration_plot.png
|   |   |   |-- peaks_info.csv
|   |   |   |-- summary.csv
|   |   |
|   |   |-- channel_B/
|   |   |-- channel_C/
|   |   |-- channel_D/
|   |
|-- gamma_branch/
|   |
|   |-- data/
|   |   |-- Am241_on_top/
|   |   |   |-- channel_A/
|   |   |   |-- channel_B/
|   |   |   |-- channel_C/
|   |   |   |-- channel_D/
|   |   |
|   |   |-- Am241_on_bottom/
|   |   |   |-- channel_A/
|   |   |   |-- channel_B/
|   |   |   |-- channel_C/
|   |   |   |-- channel_D/
|   |   |
|   |   |-- Am241_middle/
|   |   |   |-- channel_A/
|   |   |   |-- channel_B/
|   |   |   |-- channel_C/
|   |   |   |-- channel_D/
|   |   |
|   |-- scripts/
|   |   |-- gamma_single_channel_calibration.py
|   |   |-- gamma_summed_channel_calibration.py
|   |   |-- Am_middle_analysis.py

```

```

|   |
|   |-- results/
|       |-- single_channels/
|           |   |-- top/
|               |   |-- channel_A/
|               |   |-- channel_B/
|               |   |-- channel_C/
|               |   |-- channel_D/
|               |
|               |-- bottom/
|                   |-- channel_A/
|                   |-- channel_B/
|                   |-- channel_C/
|                   |-- channel_D/
|
|       |-- summed_channels/
|           |-- AGtop_DGbot/
|           |-- BGtop_CGbot/
|           |-- CGtop_BGbot/
|           |-- DGtop_AGbot/
|
|       |-- calibration_plot.png
|       |-- spectrum.png
|       |-- data_results.csv
|       |-- peaks_info.csv
|
|-- test_capacitance/
|   |
|   |-- data/
|       |-- pulser_measurements/
|       |
|       |-- scripts/
|           |-- capacitance_scan.py
|           |
|       |-- results/
|           |-- capacitance_scan_plots/
|           |-- final_channel_C_L0.csv
|
|-- light_output/
|   |
|   |-- data/
|       |-- Am241_middle/
|       |-- Cs137_middle/
|       |

```

```

|   |-- scripts/
|   |   |-- light_output_analysis.py
|   |
|   |-- results/
|       |-- LO_summary.csv
|       |-- calibration_validation_plots/
|       |-- spectra/
|
|-- cs137_position_response/
|   |
|   |-- data/
|       |-- AGtop_DGbot/
|       |-- BGtop_CGbot/
|       |-- CGtop_BGbot/
|       |-- DGtop_AGbot/
|       |
|   |-- scripts/
|       |-- cs_collimated_analysis.py
|       |
|   |-- results/
|       |-- fitted_spectra/
|       |-- response_vs_position.png
|       |-- cs_collimated_summary.csv
|
|-- common_outputs/
    |-- calibration_tables/
    |-- noise_tables/
    |-- light_output_tables/
    |-- diagnostic_plots/

```

In this structure, the X-branch and gamma-branch analyses are separated from the test-capacitance characterization. The capacitance scan produces intermediate calibration constants, which are stored independently and then used as input parameters in the gamma calibration and light-output analysis. The final outputs of the pipeline consist of diagnostic spectra, calibration plots, peak-identification tables, and summary CSV files used to build the tables and figures reported in the thesis.

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Declaration on the use of generative artificial intelligence tools

During the preparation of this thesis, generative artificial intelligence tools were used as support for language revision, grammatical correction, text polishing, and the preparation or refinement of some illustrative figures. These tools were not used to replace the scientific work, experimental activity, simulations, data analysis, interpretation of results, or critical evaluation presented in this thesis.

All scientific content, calculations, data analysis, figures, and conclusions were checked and validated by the author, who remains fully responsible for the final content of the thesis.