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XGIS instrument onboard THESEUS: design and development overview

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Abstract: The X and Gamma-ray Imager and Spectrometer (XGIS) is the high-energy monitor proposed for THESEUS (Transient High-Energy Sky and Early Universe Surveyor), a candidate mission within ESA M7 program aimed at exploring the transient high-energy sky for investigating the Early Universe and advancing in Multi-Messenger Astrophysics. XGIS is designed to detect and localize transient X-ray and gamma-ray sources across a broad energy range (2 keV–10 MeV), enabling high-resolution timing and spectroscopy. The instrument consists of two identical cameras, employing coded mask techniques to image the sky in the range 2–150 keV, while acting as a half-sky monitor in the 150 keV–10 MeV energy range. Its innovative detection system is based on Silicon Drift Detectors optically coupled to CsI(Tl) scintillator bars. This configuration, combined with a low-noise distributed electronics system (ORION ASICs), enables spectroscopy over an unprecedentedly wide energy band within a single, modular and compact device. The design of XGIS emphasizes modularity and robustness, with each camera integrating 100 detector modules that require extensive development, testing and qualification. The ongoing development of XGIS includes performance testing of the

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silicon sensors and the ORION readout chain, alongside optimization of the mechanical assembly. In this review I will outline the XGIS architecture and summarize the technological advancements made in the current M7 Phase A.

KEYWORDS: Electronic detector readout concepts (solid-state); Gamma detectors (scintillators, CZT, HPGe, HgI etc); Instrument optimisation; X-ray detectors

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Contents

1 Introduction

The Transient High-Energy Sky and Early Universe Surveyor (THESEUS [1]) is a space mission developed in response to the European Space Agency (ESA) calls for medium-class (M-class) missions and currently facing the M7 Phase A study [2]. The mission scientific objectives have been defined through joint studies conducted by the ESA Study Team and the THESEUS Consortium, a collaboration coordinated by five principal contributors and involving most ESA member states. Within this framework, the coordination team members are responsible for providing the mission payload and science ground segment elements.

THESEUS is designed to exploit Gamma-Ray Bursts (GRBs) as powerful probes for exploring the Early Universe and advancing Multi-Messenger Astrophysics, by identifying the electromagnetic (IR/optical/X-ray) counterparts of gravitational wave events.

Based on the mission scientific requirements, the THESEUS payload includes three complementary scientific instruments (figure 1), whose combined operation will enable a major step forward in detecting and characterizing GRBs and other transient phenomena, exploiting a broad energy band (0.3 keV to 10 MeV) and a wide field of view (FoV):

- Soft X-ray Imager (SXI [3]): two "Lobster-eye" telescope units covering 0.3–5 keV with a total FoV of ~0.5 sr and source location accuracy $\leq 2'$;
- X- and Gamma-ray Imager and Spectrometer (XGIS [4]): two coded-mask cameras using Silicon Drift Detectors (SDDs) coupled to CsI(Tl) scintillators for X- and γ-ray detection, providing a ~2 sr imaging FoV, localization accuracy $<15'$ in 2–150 keV, and an energy coverage extending from 2 keV to 10 MeV;
- InfraRed Telescope (IRT [5]): a 0.7 m-class IR telescope offering imaging (I, Z, Y, J, H filters) and moderate spectroscopic capabilities (R≈400).

THESEUS is designed to catch high-energy transients and transmit information to the ground within few tens of seconds and full resolution data within a few hours. Most of the mission lifetime will be spent in the "Survey Mode", where the two wide field X-ray monitors (XGIS and SXI) observe portions of the sky searching for transients. Once an onboard trigger occurs due to an event localized by either XGIS or SXI (or both), the spacecraft will switch to the "Burst Mode" and will automatically slew to place the transient within the field of view of IRT, which will first acquire a sequence of images

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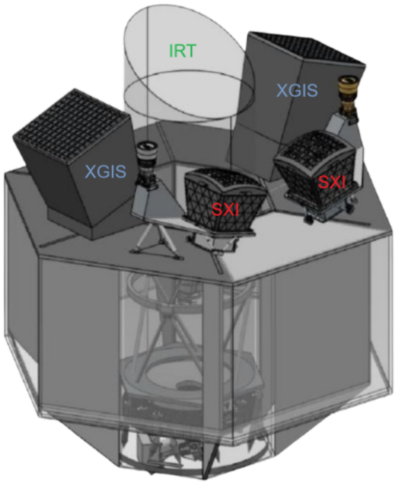

Figure 1. Schematic view of the THESEUS payload showing the allocation of the SXI, XGIS and IRT instruments on the satellite plane. Image courtesy of THESEUS collaboration.

in different filters during the “Follow-up Mode”. The latter process lasts about 12 minutes. The acquisition by IRT aims at identifying the counterpart of the high-energy source, localize it with arcsec accuracy and provide a first indication of a possible high redshift event. In order to determine onboard the redshift of the transient source, THESEUS will then enter in one of the two following modes:

- “Characterization Mode”, during which the IRT will acquire a sequence of deeper images in different filters and then the spectra;
- “Deep Imaging Mode” during which only images in different filters will be acquired, depending mainly on the IR brightness of the identified counterpart.

If the counterpart identified by the IRT is a known transient or variable source not associated with a GRB, the spacecraft will go back to the “Survey Mode”, which is anyway restored after the “Characterization Mode” or “Deep Imaging Mode” is completed [6].

This synergistic use of the instruments is key for achieving the two main scientific goals of the mission [7]:

1. exploration of the Early Universe through the detection, identification and characterization of long GRBs, with particular scientific interest on those occurring at redshifts $z > 6$. This goal demands the extension of GRB monitoring into the soft X-ray domain, with at least an order-of-magnitude increase in sensitivity compared to previous missions, improved capabilities for spectroscopy and autonomous redshift determination via on-board near-infrared (NIR) follow-up observations [6];

2. advancement of Multi-Messenger Astrophysics by enhancing the detection and localization of short GRBs, enabling wide-field, high-energy sky monitoring with a unique combination of sensitivity, positional accuracy and FoV in the soft X-ray band. The capability to extend imaging up to hard X-rays and spectroscopy up to soft γ-rays will provide crucial synergy with the next generation of gravitational wave detectors [6].

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Among the payload elements, the XGIS instrument can fulfill both mission objectives, as it provides wide-field coverage, high sensitivity and broad-band detection capabilities from soft X-rays to soft γ-rays. The following section introduces the design and configuration of XGIS, emphasizing its detection concept, architecture and role within the THESEUS payload in addressing the mission high-energy science requirements.

2 XGIS instrument concept

The X and Gamma-ray Imaging Spectrometer (figure 2) is conceived as a dual-camera system providing complementary imaging and spectroscopic capabilities across a wide high-energy range. It consists of two coded-mask X-/γ-ray cameras. The system provides imaging capabilities from 2 to 150 keV, within a field of view overlapping that of the SXI, and operates as a spectrometer over a broad energy range, from 2 keV to 10 MeV.

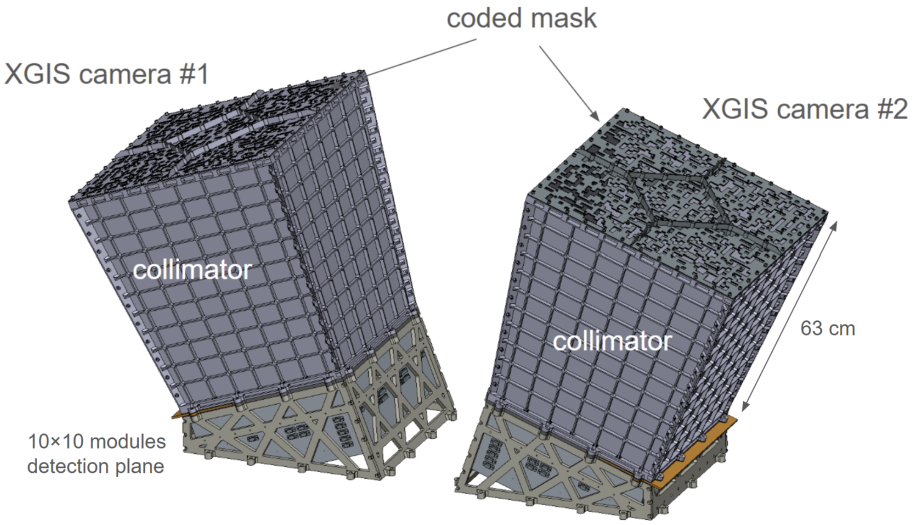

Figure 2. Schematic view of the two XGIS camera, made by the detection plane and the coded mask+collimator system.

The XGIS imaging system is based on the coded-mask technique: a tungsten mask, mounted above the collimator at a height of 63 cm from the detection plane, features a random pattern with mask elements twice the size of the detector pixels (square pixels, $5{\times}5\,mm^2$). This configuration provides an angular resolution of $\sim$1° and a source location accuracy $\leq$15' in the 2–150 keV energy band. Above 150 keV, the imaging capability is lost because tungsten becomes increasingly transparent to the incident radiation. The two cameras are misaligned by ±20° with respect to IRT axes, thus resulting in a total FoV of 117°×77°. At energies above 150 keV, the FoV of XGIS can be considered of the order of $\sim$6 sr. A summary of the main instrument characteristics is presented in table 1, focusing on the instrument capability of detecting X-rays and γ-rays.

The basic detection element of XGIS is the Pixel, composed of two Silicon Drift Detectors (SDDs) and a 3 cm long CsI(Tl) scintillator bar. Each pixel is equipped with dedicated front-end electronics that process the signals generated in both the silicon and scintillator components, operating according to the so-called SISWICH principle, which enables to combine the simultaneous data from SDDs and scintillator (figure 3).

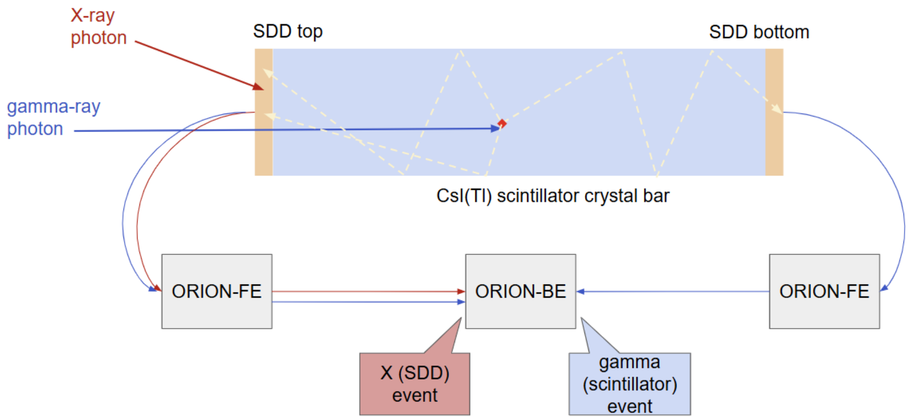

Figure 3. Schematic view of an XGIS pixel [8], composed by two SDDs and a CsI(Tl) crystal bar. The signal is processed by the Readout Electronics, ORION-FE, and a single-channel processor for the event identification, ORION-BE.

Table 1. Main structural and functional characteristics of XGIS. The values reported in the table include parameters directly set by the camera geometry (e.g. FoV and angular resolution) as well as performance requirements (e.g. energy resolution, timing and localization accuracy), which are currently defined at system level and are subject to verification during the ongoing instrument development. Reproduced with permission from [4].

	XGIS	
Energy band (keV)	2–150	150–10000
FoV	117° ×77°	~ 6 sr
Angular resolution	< 120′	—
Transient location accuracy	≤ 15′	—
Energy resolution	≤ 1200 eV FWHM at 6 keV	≤ 6% FWHM at 600 keV
Timing accuracy	7 μs	7 μs

The detector plane consists of 10×10 modules arranged side by side, while a module contains 8×8 pixels. The SDDs operate in an energy band from 2 keV to ~30 keV, while the scintillators operate between ~30 keV and ~5 MeV. XGIS geometry facilitates the detection of multiple interactions within the detection plane (Compton interactions). As a result, γ-rays with primary energy of the order of hundreds of keV are rarely absorbed in a single pixel; instead, they typically produce multiple scintillator interactions in neighboring pixels, effectively extending the detection efficiency up to 10 MeV.

The broad energy coverage (2 keV–10 MeV) allows XGIS to provide unique insight on the physics of the emission of GRBs through sensitive timing and spectroscopy. In combination with the SXI, XGIS enables the detection and localization of both short GRBs (whose hard spectra make them undetectable with SXI alone) and high-redshift GRBs, benefiting from the instrument large effective area and wide FoV.

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With its high detection efficiency, broad energy coverage and fine timing resolution (of the order of microseconds), the SDDs+scintillator system of XGIS represents a mature and scalable solution for future space-based high-energy astrophysics missions, addressing the stringent requirements of THESEUS for the detection and characterization of transient phenomena.

3 XGIS architecture overview

3.1 Detection principle and mechanical configuration

The detection architecture of XGIS relies on the integration of Silicon Drift Detectors and CsI(Tl) scintillator bars. This hybrid configuration exploits the complementary detection properties of the two media: the direct charge collection in silicon for soft X-rays and scintillation light emission in CsI(Tl) for hard X-rays and γ-rays, within a compact and modular design suitable for space applications.

SDDs were selected as the optimal photodetector technology due to their low electronic noise. Their intrinsic compactness and low capacitance make them particularly effective for the detection of low-energy X-rays, where energy resolution is limited by statistical noise. Each XGIS Pixel consists of two SDDs coupled to opposite ends of a CsI(Tl) crystal, forming a single active unit which allows to discriminate between direct X-ray interactions in silicon and scintillation events in the crystal. The silicon detectors operate efficiently up to ~30 keV, while the CsI(Tl) crystals extend the efficiency up to several MeV.

The SDDs currently in use have been developed by INFN-Trieste and Fondazione Bruno Kessler (FBK [9]). Each device features a matrix of 8×8 cells with 5 mm pitch, corresponding to an active area of 42.4×42.4 mm^2. The silicon thickness of 450 µm ensures efficient absorption of X-rays up to 30 keV, while guard structures and an optical separation grid mitigate charge loss and optical crosstalk between adjacent cells. The devices are produced at FBK, followed by extensive wafer-level characterization to ensure doping uniformity and stable depletion voltage across the active area. The current SDD design has reached a consolidated maturity, representing the baseline technology for the XGIS flight model [10].

The scintillation stage employs CsI(Tl) bars with cross-section 4.5×4.5 mm^2 and length 3 cm, optically coupled to the SDDs through thin silicone pads ensuring optimal light transmission and mechanical compliance. The lateral surfaces of the bars are wrapped with diffusive reflective material, maximizing light collection efficiency. This configuration allows efficient detection of photons in the energy range of interest.

Ongoing development and validation activities, building upon the THESEUS M5 Phase-A heritage, are focused on optimizing the detector design and improving system-level performance. A modular approach has been introduced in the Demonstration Plane Detector Module (DPDM), which is divided into a Detector Core Assembly, comprising the active elements and front-end electronics, and a Back-End Assembly responsible for data acquisition, signal processing and power (figure 4). This architecture enhances scalability, mechanical accessibility and integration efficiency.

To further increase compactness and mechanical robustness, XGIS team has initiated dedicated R&D activities aimed at replacing conventional 1.6 mm-thick printed circuit boards (PCBs) with ultra-thin flexible PCBs (<0.2 mm). This evolution in the PCB design, first proposed in late 2023, is intended to maximize the active detection area, improve electrical interconnection density and minimize passive material within the detector plane [12, 13]. Preliminary optical and X-ray absorption

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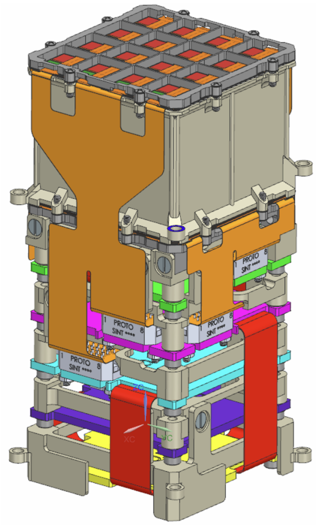

Figure 4. DPDM developed during Phase A of ESA/M7, funded by the ESA/NPMC program. The prototype has been developed following a modular approach by dividing Detector Core Assembly and Back-End Assembly. The scintillators are located inside the grey housing and the Ti grid on top allows mechanical support of the flex PCB, on which the ORION-FE ASICs are glued (Detector Core Assembly). The Back-End Assembly includes five rigid-flex PCBs for ORION-BE ASICs accommodation and I/F from the module to the external circuitry. Courtesy of OHB Italia Industries [11]. Reproduced with permission from OHB Italia Industries.

analyses indicate that adopting a thin Flex PCB architecture can significantly increase the effective area of the detector plane at low X-ray energies [10], while improving thermal and mechanical integration. Concurrent refinements in the mechanical layout, such as corner trimming of inactive SDD regions and optimization of assembly tolerances, are further contributing to enhanced robustness.

The fabrication of the first full 8×8 SDD array module is currently in progress and will be a key milestone for demonstrating the uniformity, stability and overall technological readiness of the DPDM design.

3.2 ASIC architecture

Signal discrimination in the XGIS instrument is based on the SISWICH principle, in which the two SDDs forming each pixel operate simultaneously as direct X-ray detectors and as photodiodes for collecting the scintillation light produced in the CsI(Tl) crystal. Low-energy X-rays are absorbed within the top silicon layer, generating fast charge signals with rise times of a few nanoseconds. Higher-energy photons, which pass through the silicon, deposit energy in the scintillator, producing slower pulses (microsecond rise times) collected by both SDDs. The joint processing of these signals enables accurate event identification and continuous energy reconstruction across four orders of magnitude, ensuring seamless spectral coverage from soft X-rays to MeV γ-rays.

The readout chain employs a dedicated application-specific integrated circuit system, ORION (figure 5), designed to meet the spectroscopic and timing performance requirements of XGIS. ORION follows a distributed dual-ASIC architecture comprising a Front-End (ORION-FE) and a Back-End (ORION-BE). The ORION-FE hosts low-noise charge-sensitive amplifiers and is placed in close proximity to the SDD anodes, thereby minimizing input capacitance and parasitic effects and preserving the intrinsic energy resolution of the detectors. The front-end ASIC is also compact, occupying an area

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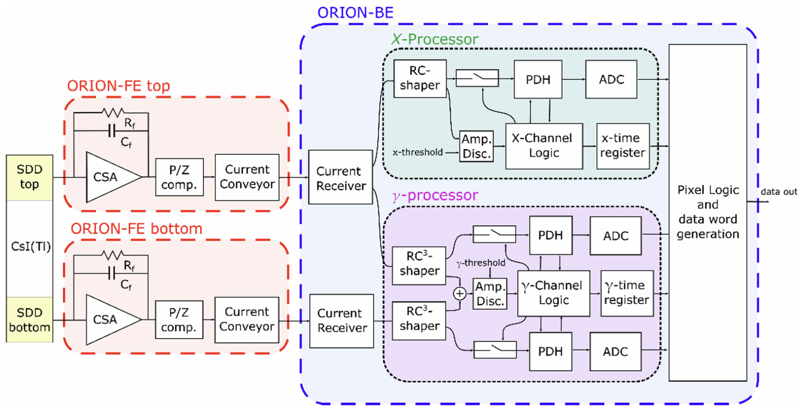

Figure 5. Block diagram of ORION electronics and logic for a single pixel, separated into ORION-FE and ORION-BE. Reproduced from [14]. CC BY 4.0.

of only about 1 mm^2. The ORION-BE, placed several centimeters away to avoid obstruction of the sensitive area, performs analog signal shaping, discrimination, digitization and digital data handling.

Each ORION-FE device provides an input channel linked to a pixel SDD anode and transmits current-mode signals to the ORION-BE. Within the ORION-BE, three parallel shaping chains are implemented per pixel: one dedicated to the X-ray branch (direct SDD absorption) and two to the γ-ray branch (scintillator readout via top and bottom SDDs). The shaping parameters are optimized for the distinct temporal characteristics of the two processes, adopting 1 µs shaping time for X-ray events and 3 µs for scintillation events, thereby maximizing energy resolution and minimizing ballistic deficit. Dedicated discriminators and peak detectors generate event triggers, assign time tags and command the sample-and-hold of the pulse amplitudes for analog-to-digital conversion. This last stage is isolated from the shapers by a Rise Time Protection (RTP) mechanism implemented in the ASIC logic, which stretches the shaped signal for ADC conversion.

For each detected event, the ASIC produces a 64-bit digital data word containing the digitized signals from the top and bottom SDDs (one ADC for X processor and two ADCs for Gamma processor), event-type flags (X or γ) and a timestamp with a timing accuracy up to 100 ns. The system supports two operating configurations:

- “Shaping Mode”, in which the analog signals are routed directly to the output buffers for diagnostic or calibration purposes;

- “Stretching Mode”, used during standard data digital acquisition, where the signal peaks are latched and digitized for event reconstruction and classification.

Both modes are currently accessible at the output stage in this preliminary ASIC version, where they provide useful flexibility for testing and calibration.

Event discrimination is performed by comparing the amplitudes of the top and bottom SDD signals. In direct X-ray interactions, only the top SDD generates a significant signal, whereas in γ events both detectors contribute, with the amplitude ratio encoding the depth of the scintillation interaction.

Experimental characterization of prototype modules integrating 2×2 SDD arrays and CsI(Tl) scintillator bars demonstrated the full functionality of the ORION readout chain. Tests with electrical

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pulses and radioactive sources confirmed the system capability to process and discriminate X and γ events, achieving [15]:

- energy resolution of 434 eV FWHM at 13.7 keV (X branch);
- electronic noise of 30–40 e^- RMS, depending on operating temperature;
- minimum detectable energies of ~0.8 keV for X-rays and ~20 keV for γ-rays;
- linear response up to ~40 keV for X processing and ~5 MeV for Gamma processing.

Prototype tests confirm that the ORION architecture satisfies stringent performance requirements of XGIS (table 1), with measured energy resolution of 3% at 14 keV, while providing high dynamic range, precise timing and efficient event classification in a compact and scalable implementation. Ongoing developments are focused on optimizing the single-channel ASIC design for integration in the next-generation Detector Plane Demonstration Module, which will consolidate the system maturity toward flight qualification.

At the system level, the integration of thousands of ORION channels requires an efficient event readout logic and data management architecture, which have been extensively modeled and validated through dedicated simulations.

3.3 Readout electronics logic: towards XGIS data stream

Building on the characterization of the ORION ASIC and its signal discrimination capabilities at the pixel level, system-level efforts have been devoted to understanding how the simultaneous activity of thousands of independent detection channels translates into a coherent and manageable data flow. Each XGIS camera hosts a focal plane comprising 6400 pixels, organized into 100 modules and 10 supermodules. This modular structure enables parallel event detection and processing, but also requires an optimized readout logic to ensure precise timing synchronization, minimal data loss and full compatibility with the on-board Data Handling Unit (DHU).

To this end, extensive simulation activities have been carried out to reproduce the expected XGIS data stream from the detector plane to the DHU [16]. Event lists derived from Geant4 simulations, including realistic background and GRB photon fluxes, were used to emulate the instrument operational environment. At module level, 64 pixels are grouped into 8 rows, with a "Look At Me" (LAM) signal raised upon event detection to trigger acquisition. Different readout schemes (figure 6) were tested to evaluate latency, event reordering and pixel conflicts due to simultaneous hits.

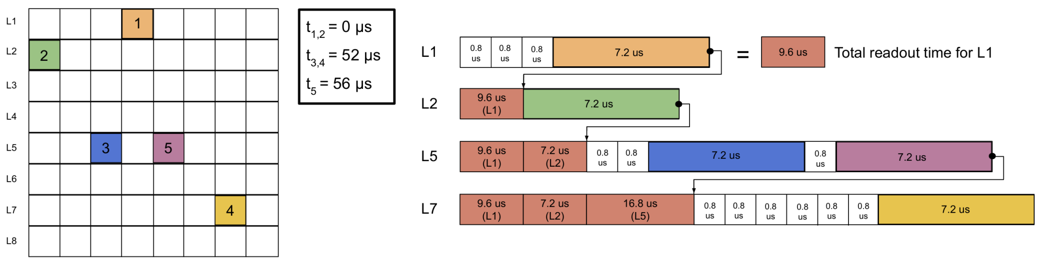

Figure 6. Five photons hit the module (represented by the grid), with different arrival times. The readout order for the five hit pixels, together with the time required to perform each process, is represented in the scheme. Reproduced from [16]. CC BY 4.0.

The optimized configuration aims to minimize temporal disorder and ensures data integrity across hierarchical readout stages, for instance from pixel to module, supermodule and camera, thus validating the scalability and robustness of the XGIS digital architecture. This simulation framework represents a critical step toward the full qualification of the readout system, providing a foundation for the subsequent hardware implementation and validation of the complete digital architecture.

4 Conclusion

The XGIS instrument, designed as a dual-camera hybrid detector system, combines wide-field imaging and broadband spectroscopy capabilities essential for the THESEUS mission scientific goals. The integration of SDDs and CsI(Tl) scintillators, coupled with the ORION ASIC readout chain, enables seamless energy coverage from a few keV to several MeV with excellent timing and energy resolution. Recent advancements in detector design, front-end electronics and readout logic demonstrate the maturity and scalability of the XGIS concept. The ongoing development of the Detector Plane Demonstration Module (DPDM) will mark a significant milestone in consolidating the system technological readiness and validating its performance under representative conditions.

Acknowledgments

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