



Publication Year	2016
Acceptance in OA	2020-04-29T11:16:05Z
Title	The XGS instrument on-board THESEUS
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Publisher's version (DOI)	10.1088/1742-6596/763/1/012009
Handle	http://hdl.handle.net/20.500.12386/24303
Journal	JOURNAL OF PHYSICS. CONFERENCE SERIES
Volume	763

The XGS instrument on-board THESEUS

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Abstract. Consolidated techniques used for space-borne X-ray and gamma-ray instruments are based on the use of scintillators coupled to Silicon photo-detectors. This technology associated with modern very low noise read-out electronics allows the design of innovative architectures able to reduce drastically the system complexity and power consumption, also with a moderate-to-high number of channels. These detector architectures can be exploited in the design of space instrumentation for gamma-spectroscopy with the benefit of possible smart background rejection strategies. We describe a detector prototype with 3D imaging capabilities to be employed in future gamma-ray and particle space missions in the 0.002–100 MeV energy range. The instrument is based on a stack of scintillating bars read out by Silicon Drift Detectors (SDDs) at both ends. The spatial segmentation and the crystal double-side readout allow a 3D position reconstruction with ~ 3 mm accuracy within the full active volume, using a 2D readout along the two external faces of the detector. Furthermore, one of the side of SDDs can be used simultaneously to detect X-rays in the 2–30 keV energy range. The characteristics of this instrument make it suitable in next generation gamma-ray and particle space missions for Earth or outer space observations, and it will be briefly illustrated.

1. Introduction

Gamma-Ray Bursts (GRBs) are one of the most intriguing and challenging phenomena for modern science. Because of their luminosities up to more than 10^{52} erg/s, their redshift distribution extending up to $z > 9$ and their association with peculiar core-collapse supernovae and with neutron star/black-hole mergers, their study is of very high interest for several fields of astrophysics. Despite the huge



observational advances in the last 15 years, several open issues still affect our comprehension of these phenomena, and their exploitation for fundamental physics and cosmology.

To address these fundamental issues, time resolved spectroscopy (and possibly polarimetry) of the GRB prompt emission over a broad energy range from few keV to several MeV is needed. A low energy boundary (below a few keV) is useful to investigate possible interactions of the prompt emission with the circumburst medium, while a continuous energy coverage in gamma-rays allows to measure a broad range of burst peak energies. We are therefore working towards a prototype (X and Gamma Spectrometer, XGS) for a monolithic system, which allows spectroscopy and timing of high-energy transient events, over an unprecedented broad energy band. The proposed detector combines a low energy threshold (~ 2 keV) and energy resolution significantly better than that of any other GRB detection system based on scintillators (e.g., Fermi/GBM) up to several MeV or CZT/CdTe semiconductors (INTEGRAL/ISGRI, Swift/BAT) up to 30–50 keV. The timing capability is of few micro-seconds resolution over the whole energy band, and a possible polarimetric capabilities is linked to the true three-dimensional photon interaction reconstruction.

In this paper we report on the progress of this currently undergoing prototype activity, in preparation for the proposed XGS instrument on board the THESEUS space mission [1][2].

2. The XGS instrument architecture

Aiming at designing a compact instrument with a very large sensitivity band, the XGS instrument combines both detection capabilities of silicon detector: direct X-ray detection in the energy range from ~ 2 keV up to 30–50 keV, and detection of scintillating light from inorganic scintillators in the energy range from 20 keV up to several MeV [3][4].

When the scintillator is shaped like a bar and two Silicon devices are coupled at the ends, both interacting position and overall energy released in the bar can be derived combining the response of two photo-detectors. In this concept (Figure 1), the Silicon detectors on the “top” side of the bars play the double role of scintillator read-out and of independent X-ray detector. The inorganic scintillator bar, made of CsI(Tl), is coupled at both ends with a Silicon Drift Detector [5] developed by INFN-Trieste and Fondazione Bruno Kessler (FBK, Trento) within the framework of the ReDSOX collaboration.

Profiting of the good spectroscopic performance of SDDs, when coupled with low noise Front End Electronics (FEE) [6], the sensitivity band of the proposed architecture is therefore from ~ 2 to 50 keV (X-events) for silicon and from 20 keV to several MeVs (G-events) for CsI(Tl), allowing for some overlap of the two operating modes, as shown in Figure 1.

The X-rays and γ -rays, detected in the Silicon and in the scintillator respectively, can be distinguished by pulse shape discrimination techniques, through the different risetimes of the corresponding preamplifier signal. In the case of “X-events”, the risetime is dominated by the anode collection time (~ 100 ns), while for “G-events” the signal rises following the characteristic CsI(Tl) scintillation time constants and different light paths, amounting to a few μ s.

A CAD sketch of the instrument concept is shown in Figure 2. Four scintillator bars (each about $4.5 \times 4.5 \times 45$ mm³) are coupled with an array of 2×2 single-cell SDDs, with an active area of 25 mm² each. This constitutes the fundamental unit of the instrument module. To restrict the field of view to about 0.15 sr, increasing also the sensitivity of the instrument, a passive collimator can be placed on the top of the bar/detectors assembly.

3. Preliminary prototype

In order to demonstrate the performances of the proposed instrument, a prototype is being developed in the framework of an INAF-funded project. The overall setup is shown in Figure 3. The front-end electronics is composed of a discrete-elements charge sensitive preamplifier designed at INAF/IASF (PA-001), operated in continuous reset configuration. In order to guarantee good performances, the input stage of the charge preamplifier is arranged near the anode. The same PCB board houses four 2×2 single-cell SDD arrays, for a total of 16 channels (Figure 3). The complete detector combines four such modules for each side of the bars. An additional plug-in motherboard holds single channel preamplifiers. The preamplifier output is finally acquired through a fast digitizer and then digitally processed.

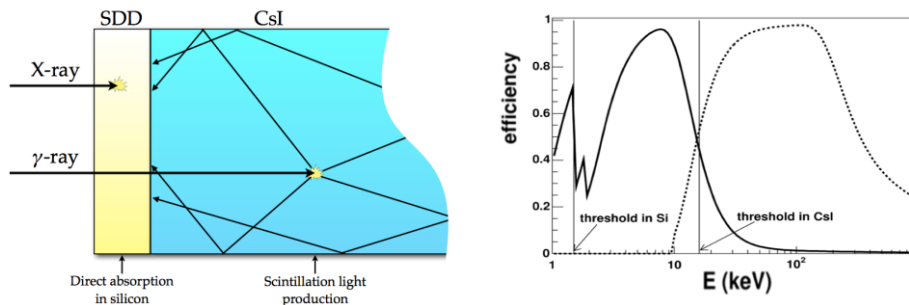


Figure 1. LEFT: The detector concept. Low energy X-rays are absorbed directly in the silicon bulk of the SDD, while high energy X-rays produce scintillation light in the CsI(Tl) crystal, that is collected by the SDDs. RIGHT: When SDD is used the detection efficiency can be extended down to few keV, reducing also the low threshold for scintillator and overlapping the two operating modes.

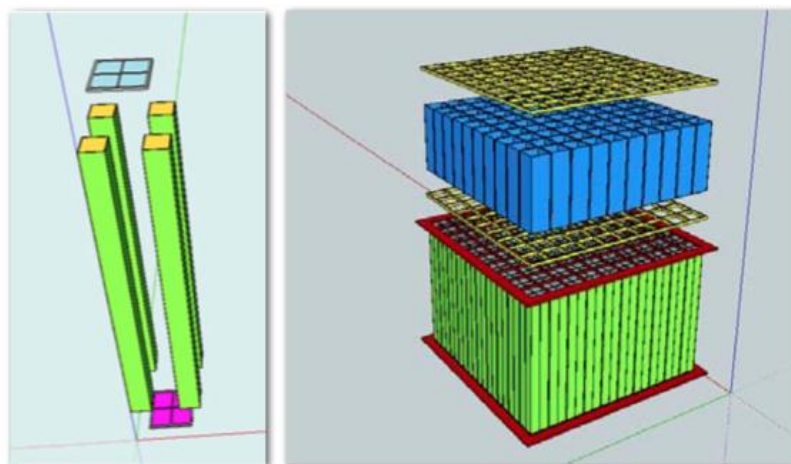


Figure 2. Left panel: the fundamental unit of XGS, composed of 4 scintillator bars coupled to two 2×2 SDD arrays. Right panel: the complete XGS module (CAD sketches).

The choice of a digital signal processing was justified by its large flexibility in this development phase, since it allows simultaneous testing of different shaping algorithms, to characterize the noise performance of the system in a rapid and extremely flexible way. Of course a custom-designed analog ASIC will be mandatory for an actual space-ready instrument, and the present prototype will allow to drive the design of this front-end electronics component.

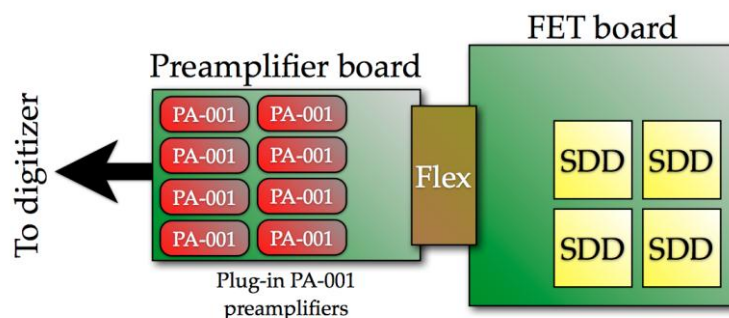


Figure 3. The overall setup of the XGS prototype

In this activity the digitized waveform was then processed with a digital trapezoidal filter [7]. When the trapezoidal filter with symmetric rise and fall times and a flat-top time is selected, it can be easily implemented as a cascade of finite and infinite impulse response filters, and is a good approximation of the “ideal” filter. The trapezoid was then sampled around the middle of the flat-top to extract the pulse height, proportional to the input energy.

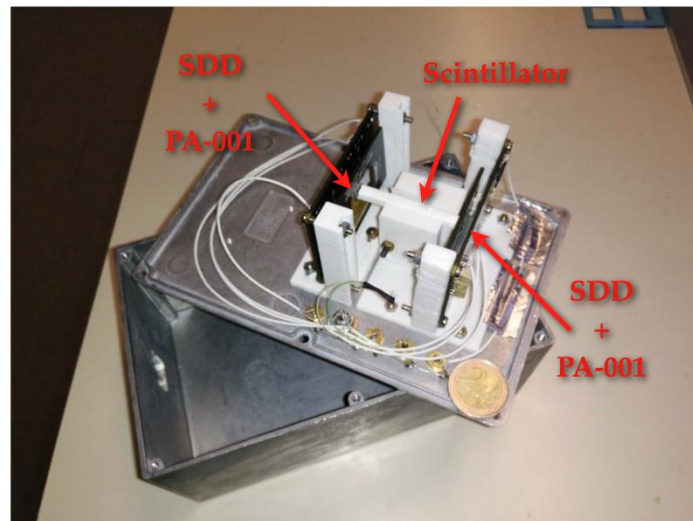


Figure 4. Preliminary XGS prototype. A single $4.5 \times 4.5 \times 45 \text{ mm}^3$ scintillator bar is coupled at both ends with $5 \times 5 \text{ cm}^2$ single-cell SDDs. Each SDD is then coupled with a discrete components charge sensitive preamplifier.

In order to investigate the optical coupling between the scintillator bar and the SDDs, and to derive realistic performance figures for the complete XGS prototype, a single-bar, 2-channel sub-unit, was realized and characterized (Figure 4). The scintillator bar shape is the same envisaged for XGS: $4.5 \times 4.5 \times 45 \text{ mm}^3$. In Figure 5 is shown a simultaneous acquisition at room temperature of two radioactive sources: ^{137}Cs and ^{241}Am . The digitizer acquired both types of events simultaneously and then by means pulse shape discrimination techniques X-events and G-events were distinguished. Two optimized digital filters were then applied separately for the two categories. In this case, an energy resolution of about 5.8% on the 662 keV line is obtained when the system is operated at room temperature. The good discrimination capabilities of the digital method were demonstrated, showing also a comparable result with respect to a more traditional analog spectroscopic chain coupled to a commercial multichannel analyzer.

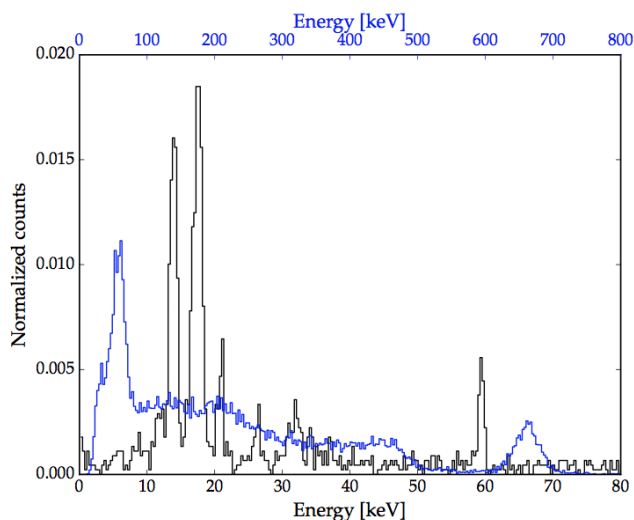


Figure 5. Simultaneous acquisition of a ^{137}Cs and ^{241}Am radioactive sources. The black curve is the spectrum of X-events, while the blue one is the spectrum of G-events. Both types of events were acquired with a digital backend electronics and digitally shaped. An energy resolution of about 5.8% on the 662 keV line is obtained when the system is operated at room temperature.

Measurements of the light attenuation, spatial and energetic resolution were performed using a collimated (~ 2 mm spot) ^{137}Cs radioactive source at various positions along the bar. The signal collected at each SDD can be represented, in a simplified model [8][9], as $U(x) = E u_0 e^{-\alpha(\frac{L}{2}-x)}$; where L is the bar length, x is the position along the bar, α is the light attenuation coefficient, E the input energy and u_0 is the signal output at the bar edge (that includes the light yield of the scintillator and the quality of the optical coupling). The energy and the interaction position can be derived from the signals U_A, U_B collected by both detectors as $E \propto \sqrt{\frac{U_A}{U_B}}$ and $x \propto \log \frac{U_A}{U_B}$.

In Figure 6, left panel, the light attenuation measured by both SDDs is shown. An attenuation coefficient of $\sim 0.021 \text{ cm}^{-1}$, consistent with [9][10], and an overall light output of $\sim 27 \text{ e}^-/\text{keV}$ were measured. In the right panel of Figure 6 the position reconstruction along the bar is shown. The average FWHM of the reconstructed position is ~ 3 mm. Considering the source spot size (~ 2 mm), the derived intrinsic resolution in position is around 2.2 mm.

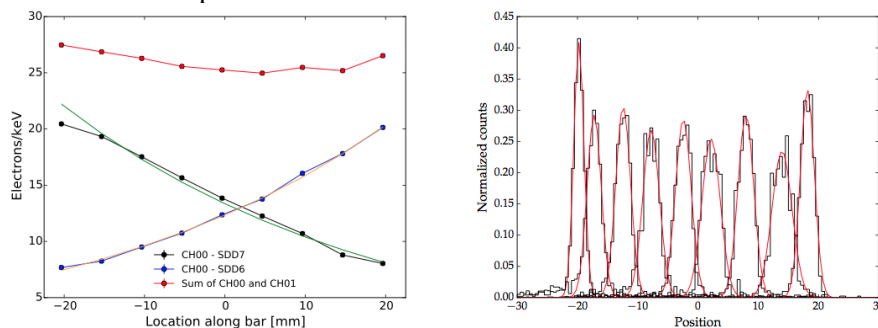


Figure 6. LEFT: Light attenuation along the bar. The signal from both detectors is shown. RIGHT: Reconstructed position for various measurements along the bar.

In Figure 7 a spectrum obtained with the collimated source at the bar center is shown. An energy resolution of 4.9% at 662 keV and a resolution of $\sim 41.8\%$ at 32 keV were measured, when the system was operated at -20°C . These results are compatible with a lower threshold of about 20 keV and confirm the expected performance of the proposed system.

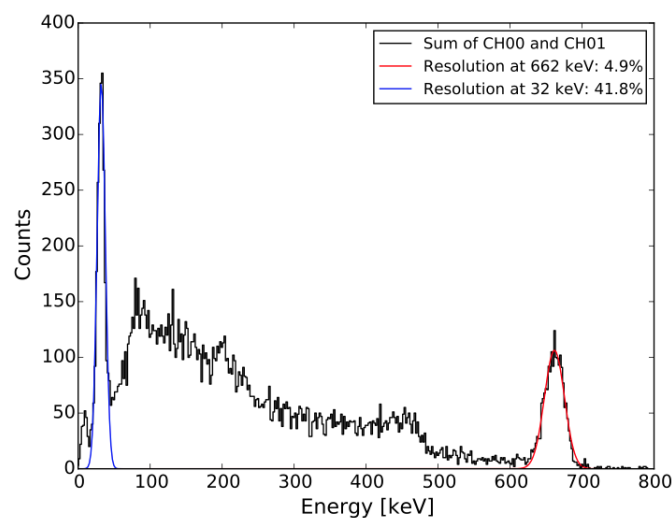


Figure 7. Spectrum of a collimated ^{137}Cs radioactive source at the center of the bar. The spectrum is reconstructed combining both SDDs signals. Gaussian fits of the 662 keV and 32 keV lines are also shown.

4. Back-end Architecture

For the complete XGS prototype, a digital back-end architecture is required. The attractive low-cost solution proposed is based on the commercial ADC board developed by RedPitaya. This board is based on a Xilinx Zynq 7010 system-on-chip, in which a FPGA is coupled to an ARM Cortex 9 CPU, allowing a great flexibility in the deployment and configuration. Each board, composed by 14-bit, 125 MS/s dual channel ADC, is equipped with an external suitable trigger logic and a custom software developed at IASF-Bologna in Python using the Qt libraries. The GUI allows to configure several RedPitaya boards, handling the acquisition and quicklook operations.

5. Conclusions

The preliminary prototypes developed (Section 3) have shown the good overall performance of the system. We are currently working towards the implementation of the complete XGS prototype, using an innovative, low-cost digital back-end (Section 4). The aim is to demonstrate the feasibility of this compact and modular architecture concept (and to drive the development of a dedicated analog front-end electronic circuit) for a space-borne, wide energy range, sensitive photon detector for the future missions for high energy astrophysics.

Acknowledgments

This project is funded by INAF through a TecnoPRIN 2014 grant. The Silicon Drift Detectors have been developed in the framework of the ReDSOX collaboration and FBK/INFN agreement.

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