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A FPGA-based digital readout system for a multi-channel X and gamma-ray spectrometer

R. Campana[1,2], F. Fuschino[1,2,3], C. Labanti[1,2], M. Marisaldi[1,2], L. Amati[1], G. Baldazzi[2,3], M. Fiorini[4], L. P. Rignanese[2,3], and M. Uslenghi[4]

[1] INAF/IASF-Bologna, Via Gobetti 101, I-40129 Bologna, Italy
e-mail: campana@iasfbo.inaf.it
[2] INFN - Sezione di Bologna, Viale Berti Pichat 6/2, I-40127 Bologna, Italy
[3] Department of Physics, University of Bologna, Viale Berti Pichat 6/2, I-40127 Bologna, Italy
[4] INAF/IASF-Milano, Via Bassini 15, I-20133 Milano, Italy

Abstract. The XGS project aims to develop a multi-channel broadband X and γ-ray spectrometer for space applications. The experiment envisages the use of solid-state Silicon Drift Detectors coupled to inorganic scintillator bars. A prototype is under development in the framework of an INAF funded project, in which the detector signal will be digitized by a fast ADC and further digitally processed. An overview of the system architecture and the test equipment currently under development based on low-cost commercial system-on-chip FPGA boards will be given.

Key words. High energy astrophysics – X-ray detectors – γ-ray detectors – Silicon Drift Detectors

1. Introduction

The study of Gamma-Ray Bursts (GRB) is one of the most interesting and challenging for modern science. The huge luminosities, redshift distribution, and association with peculiar core-collapse supernovae and compact object mergers, make the study of these object highly interesting for several fields of astrophysics and fundamental physics, e.g. the physics of matter in extreme conditions and plasma physics, black hole physics, general relativity and generation of gravitational waves. Several open issues still affect our comprehension of these phenomena, and their exploitation.

In order to tackle these questions, we need time resolved spectroscopy (and possibly polarimetry) of the GRB prompt emission over a broad energy range from ∼1-2 keV, i.e. well below the range of past, present and near future GRB detectors, to several MeV.

We are therefore working towards a prototype for a monolithic system (*X and Gamma Spectrometer*, XGS) which would allow detection, spectroscopy and timing of GRBs and other high energy transients over an unprecedented broad energy band. The unique capabilities of such an instrument are the combination of a low energy threshold (1-2 keV) and energy resolution, up to ∼30 keV, significantly better than that of any other GRB detection system (e.g. based on scintillators or CdTe/CZT semiconductors), besides timing

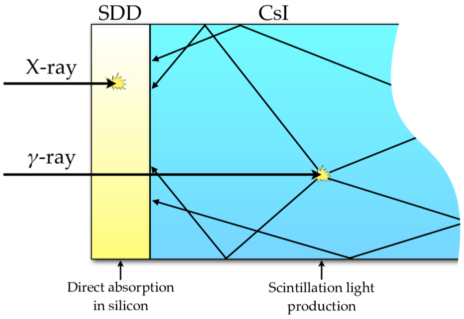

Fig. 1. The *siswich* architecture.

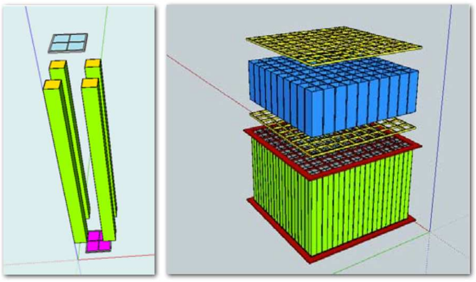

Fig. 2. The XGS concept. *Left panel:* basic unit of the module, composed by 4 CsI(Tl) bars and two 2×2 single-cell SDD arrays. *Right panel:* the complete XGS module, showing also a field of view collimator for X-rays.

capabilities down to a few micro-second resolution over the whole energy band.

In the framework of an INAF-funded project, we are developing a discrete front-end electronics prototype aiming to demonstrate such an architecture. The analog signal at the preamplifier output of the various channels will be digitized and processed offline. In this paper the overall architecture will be briefly described (Section 2), and the digital signal processing philosophy envisaged for the prototype will be summarized in Section 3. Finally, in Section 4 the FPGA-based digital back-end architecture will be introduced.

2. The XGS project

The working principle of the XGS detector is shown in Figure 1, the so-called *siswich* concept (Marisaldi et al., 2004, 2005; Labanti et al., 2008). A scintillator crystal bar, made of CsI(Tl), is coupled at both ends with a single-cell Silicon Drift Detector (SDD, Gatti & Rehak, 1984). Low-energy X-rays (from 1–2 keV to a few tens of keV) are directly absorbed by the solid-state detector, leading to a very sharp (~100–200 ns) rise-time analog signal on the detector preamplifier. Higher energy X-rays and γ-rays are instead absorbed in the CsI(Tl), thus producing a large number of optical scintillation photons. These photons are collected and detected by the SDDs, giving rise to a much slower (~few μs, dominated by the scintillator crystal characteristic light time constants) output signal.

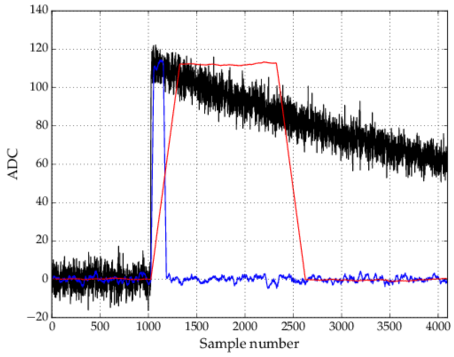

Fig. 3. Digital trapezoidal filter. An example digitized waveform from a ~10 keV X-ray photon directly absorbed in the SDD is shown, together with two possible realizations of the trapezoidal filter, with different rise and flat-top times.

The different rise times of the signals thus allow to discriminate between the two types of events, and the detector is thus collectively sensitive to a very large energy band.

For the overall XGS detector, a large number of scintillator bars are coupled to two SDDs each, resulting in a compact modular instrument. In the left panel of Figure 2, four CsI(Tl) bars are coupled to two 2×2 single-cell SDD arrays, and then the whole instrument (Figure 2, right panel) is built from a large and customizable number of these basic units. A collimator could also be added to limit the incoming directions for detectable X-rays, while the instrument has a roughly isotropic sensitivity for high energy γ-rays. For the prototype being developed, each scintillator bar has 4.5×4.5×45 mm^3 dimensions, and a complete XGS module is composed by at least 64 of these bars.

3. Digital signal processing

The preamplifier output from the SDDs is a step-like signal, with an exponential decay. In γ-ray spectroscopy, usually, an analog shaping chain is employed, consisting of several logical blocks that will filter and shape the signal in order to boost its signal-to-noise ratio. The amplitude of the shaped signal, proportional to the energy deposited in the detector, is then digitized and stored.

In digital signal processing the preamplifier signal is directly digitized by a fast ADC and further processed on- or offline by software-implemented algorithms. Digital algorithms have several advantages with respect to the traditional analog chain:

i. they closely approximate the "ideal" filter;
ii. there is no dead time associated with the peak detection and digitization, thus allowing a higher throughput;
iii. an analog system allows only a few fixed shaping choices (shaping times and shapes), while a digital system allows multiple and unlimited shapings on same data;
iv. digital filters allow much higher stability and reproducibility.

A classical digital filter for the applications considered is the *trapezoidal filter* (Jordanov & Knoll, 1994; Guzik & Krakowski, 2013), easily implementable as a cascade of finite and infinite impulse response filters. In Figure 3 a representative preamplifier waveform, digitized at 30 MS/s by a 12-bit commercial digitizer, is shown together with two possible realizations of the trapezoidal filter for this signal, having different rise and flat-top times.

4. Back-end digital architecture

4.1. Digital signal processing with RedPitaya

For the complete XGS prototype, a digital back-end architecture able to acquire the preamplifier output of several tens of channels, with a suitable trigger logic, is required. The digitized waveforms should be then digitally processed in real-time or offline. The use of a digital, FPGA-based back-end will allow to drive the design of a low-power, low-noise integrated mixed-signal electronics optimized for the future space experiment.

An attractive and low-cost solution envisages the use of a commercial ADC board, the RedPitaya[1]. 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 houses two analog input channels, with a 14-bit, 125 MS/s ADC, and can be connected to a network via a Gigabit Ethernet port. A Linux operating system, loaded via a microSD drive, runs on the ARM CPU. An interesting feature is the availability of the source code for both the operating system and the FPGA core[2], allowing for an easy customization, e.g. by adding desired features to the default configuration.

A first scalable prototype, using two boards and thus able to read out 4 analog channels, has been developed (Figure 4, left panel).

4.2. Trigger logic and board synchronization

In order to acquire simultaneously the signal from all the bars when one channel is over a given threshold, a modification of the default FPGA configuration has been implemented (Figure 4, right panel), exploiting the on-board availability of several GPIO pins. A digital signal is sent to an external pin when one or both channels in a board crosses the threshold (internal OR). This signal is mixed in

[1] `www.redpitaya.com`
[2] `https://github.com/RedPitaya/RedPitaya`

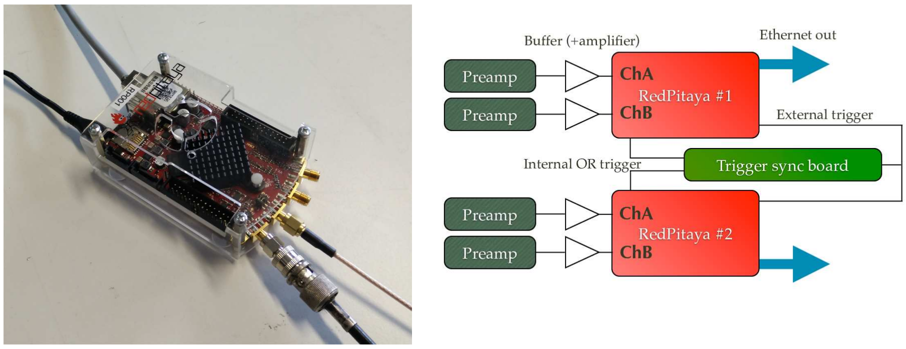

Fig. 4. *Left panel:* a RedPitaya board. *Right panel:* sketch of the multi-board setup architecture.

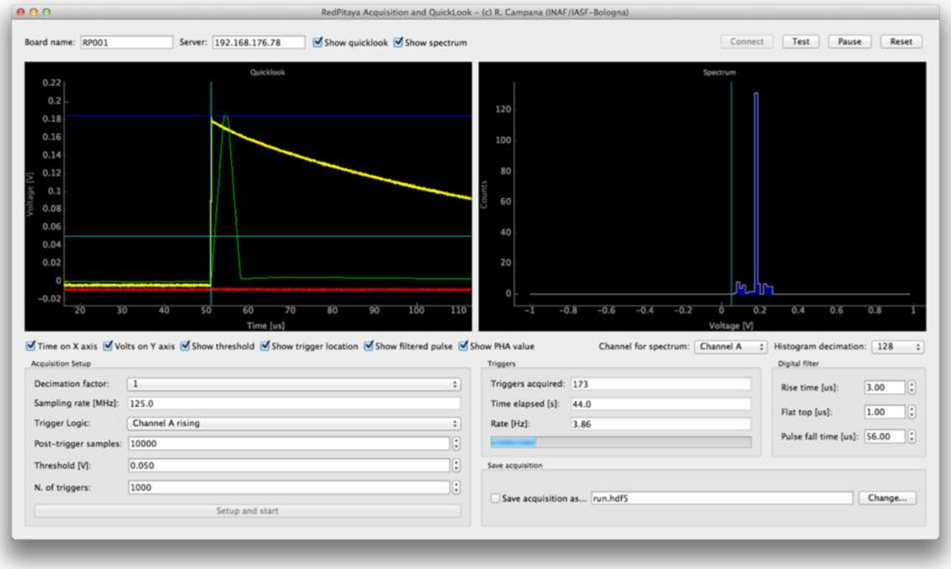

Fig. 5. Screenshot of the graphical user interface for the acquisition and quicklook of the digital back-end architecture.

a multi-port digital OR using an external trigger synchronization board, and then feed to the external trigger pin of all boards. In this way, the effective trigger logic is that of a “triple OR trigger” (internal on either channel or external), allowing for the simultaneous acquisition of the waveform across N boards and $2N$ channels. This allows to determine the amount of optical cross-talk between the bars but also to characterize Compton-scattering events (involving multiple scintillator bars) and to investigate the polarimetric performance of the system.

In Figure 5 is shown the GUI acquisition and quicklook software, developed at IASF-Bologna in Python using the Qt libraries. When launching an acquisition, a server-side program is started on the CPU of each board, configuring the acquisition parameters and the trigger logic and opening a socket for sending the waveforms as Ethernet packets. The client-side program, therefore, acquires these packets and performs digital filtering and spectrum quicklook, beside saving the digitized waveforms in a data file.

5. Conclusions

The good overall performance of the system (e.g. energy resolution, optical coupling between SDD and scintillator) has been demostrated (Campana et al., 2016). 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.

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