IL NUOVO CIMENTO **44 C** (2021) 30
DOI 10.1393/ncc/i2021-21030-9

Communications: SIF Congress 2020

A SiPM-based gamma spectrometer for nuclear science

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received 15 January 2021

Summary. — The architecture of the GAMMA module and its experimental characterization are discussed in this paper. GAMMA is a novel, compact spectrometer (13 cm × 13 cm × 15 cm) that couples a 3″ × 3″ $LaBr_3$ cylindircal crystal to a large array of SiPM detectors. The custom ASIC developed features 85 dB dynamic range per channel, in order to fully exploit the high conversion efficiency of the crystal. Machine-learning algorithms embedded in the FPGA-based DAQ allow for real-time 2D spatial sensitivity of the point of interaction in the crystal. The measured energy resolution of the module is 2.7% at 662 keV, with 0.6% maximum linearity error up to 9 MeV.

1. – Introduction

The detection and processing of light pulses from scintillation crystals by means of silicon photomultiplier (SiPM) detectors is a widespread technique in nuclear instrumentation, deployed in nuclear science experiments, homeland security, environmental radioactivity monitoring, and nuclear medicine [1-5].

This work presents the GAMMA module, a novel gamma spectrometer coupling a 3″ × 3″ codoped $LaBr_3$ cylindrical crystal (85 ph/keV conversion efficiency, 25 ns decay time) to an array of individually read 144 NUV-HD SiPM [6], showing excellent energy resolution [7] and large dynamic range, spanning from few tens of keV up to 30 MeV.

The physical structure of the module is shown in fig. 1; the overall size is 13 cm × 13 cm × 15 cm. It can be divided into three main building blocks: the aluminium enclosure, the scintillation crystal coupled to the SiPM, and the readout electronics. The latter includes an ASIC-based front-end and an FPGA-based acquisition system (DAQ). The architecture of the module and its building blocks are introduced in sect. 2.

Target of the GAMMA module is the substitution of PMT-based spectroscopy modules for medium and high-energy gamma radiation. Because energies detected from the instrumentation can be modulated by relativistic Doppler effect, spatial sensitivity of the

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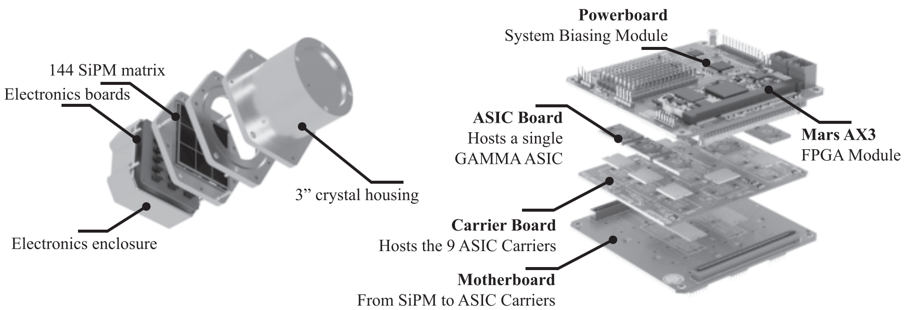

Fig. 1. – (Left) The 13 cm × 13 cm × 15 cm aluminium enclosure encompasses the scintillation crystal, the 144 SiPM detectors, front-end electronics and the DAQ. (Right) The SiPMs hosted by the motherboard generate 144 current signals, which are monolithically collected by 9 GAMMA ASICs and digitized by the FPGA-based DAQ on the powerboard.

interaction position in the scintillation crystal (which is allowed by SiPM readout matrix pixellation) can be used to mitigate this detrimental effect to energy resolution [8]. The experimental characterization of energy resolution and the dynamic range of the GAMMA module, together with the spatial sensitivity of the interaction position in the scintillation crystal, are discussed in sect. 3. In sect. 4 there are the conclusions.

2. – GAMMA module architecture

The $LaBr_3$ crystal is optically coupled to a 12×12 array of SiPM, which is composed of 9 different SiPM tiles. Each tile is a 4×4 array of 6 mm × 6 mm SiPM detectors.

When a gamma photon interacts with the scintillation crystal, photocarriers generated in the SiPMs induce current signal pulses that are processed by the electronics and converted to a digital data. Each SiPM is individually coupled to a low-impedance input node of the front-end GAMMA ASIC [9] via the motherboard (fig. 1), in order to convey signal current pulses from SiPM anodes to the analog filter stages while keeping a constant voltage across the detector.

When a current pulse is detected from one of the 144 channels, the integration starts for all channels; the readout is therefore monolithic and self-synchronized to particles or gammas interactions in the crystal.

The main feature of GAMMA ASIC is the adaptive gain control circuit, a digital part of the ASIC that optimizes the overall gain of the stage in order to minimize the electronics noise contribution. Small signals are largely amplified, while large signals are amplified less in order to obtain the desired dynamic range of 85 dB. This design constraint allows to have maximum input signal of 30 MeV while keeping good energy resolution in the low-energy part of the spectrum (which is also enabled by the codoped $LaBr_3$ crystal).

A block scheme of GAMMA module is shown in fig. 2. ASIC outputs are sampled by the FPGA-controlled ADCs.

Before the acquisition starts, the custom GUI allows to adjust the detector bias and the ASICs programming. The latter are set from the FPGA with an SPI commuication module in the ASIC.

While the acquisition runs, the detector gain is controlled in closed loop by the microcontroller on the powerboard acting on the detector voltage bias, in order to avoid spectrum drifts due to temperature fluctuations [10]. When the FPGA collects the data, a classification algorithm for spatial sensitivity runs on the same device. The output

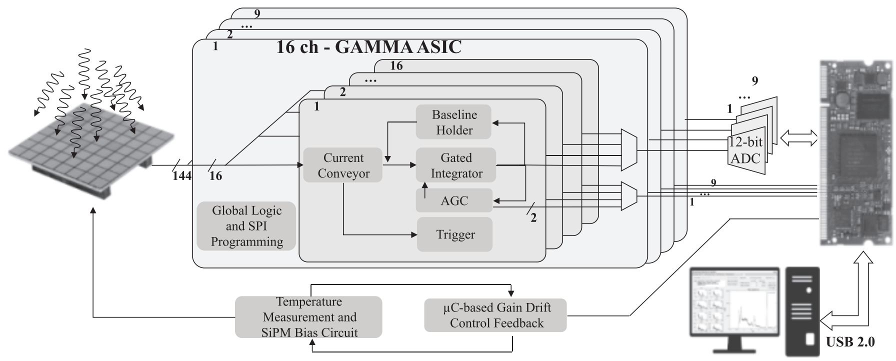

Fig. 2. – Block scheme of GAMMA module. The front-end circuit is made up of 16-channel GAMMA ASICs, allowing in the module an individual, low-noise readout of each pixel. The SiPM bias voltage is controlled in closed loop, in order to compensate for gain drifts of the system due to temperature fluctuations.

data stream, which is sent to the central unit, is an array of energies and positions that can be monitored in real time from the GUI.

The 2D position of interaction in the scintillation crystal is classified in real time by a decision tree embedded in the FPGA, leading to a sub-μs latency of the classifications. The embedded solution with decision tree classifier [11] allows relaxing data communication constraints of two orders of magnitude (data rate scales from 144 sampled outputs, therefore 288 bytes per event, down to 3 bytes per event, encoding energy and position of interaction), pointing out that the architecture adopted in the GAMMA module, where the data processing is embedded in DAQ, is an interesting paradigm for nuclear science instrumentation.

3. – Spectroscopy and position sensitivity experimental measurements

The spectroscopy capability of the system was tested using ^{133}Ba,^{137}Cs,^{60}Co and AmBe radioactive sources and using a custom laser-based setup, in order to simulate the scintillation light of $LaBr_3$ generated by the interaction with gamma photons at energies higher than the ones available.

The superposed spectra are shown in fig. 3. The experimental measurements show a 2.7% energy resolution at 662 keV that monotonically decreases at higher energies, reaching the value of 1.0% at 9.0 MeV. The energy resolution in the measured energy interval is well fit by a curve proportional to $1/\sqrt{E}$. The non-linearity error of the measurement is 0.6%, and is limited by detector non-linearity at higher energies. Maximum measured count rate is 80 kCps and the overall power consumption of the module is 6 W.

Position sensitivity was tested scanning the scintillation crystal with γ-rays emitted from a ^{137}Cs source, collimated on the orthogonal direction to the SiPM detectors plane in a 1 mm large pinhole. The scintillation crystal is irradiated from the top side on a square grid that has 1.5 cm pitch. Collected data are labelled using the scan positions, which are known, and are used as training datasets in classification algorithms.

Training a decision tree algorithm and embedding the classifier in the FPGA-based DAQ, from 80% to 90% (depending on the real beam position) of the events 2D reconstructed position are classified with an error smaller than 2 cm, computed from a validation dataset acquired using the same procedure of the training dataset (fig. 3).

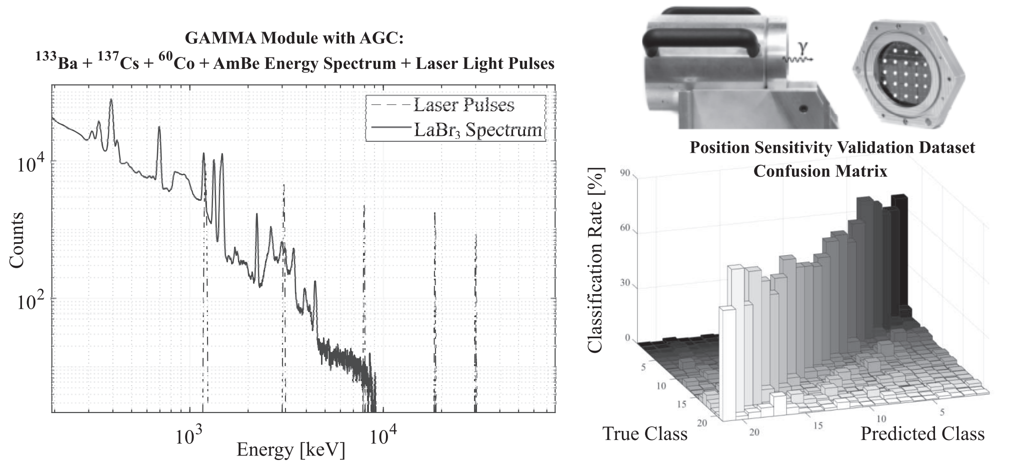

Fig. 3. – (Left) Superposition of the decay spectrum from ^{133}Ba,^{137}Cs,^{60}Co and AmBe radioactive sources and spectral lines generated by a calibrated laser-based test setup, measured with GAMMA module. (Right) Experimental position sensitivity characterization setup and 3D plot of the validation dataset confusion matrix for the decision tree algorithm embedded in the FPGA. Each true class row corresponds to a different position of the collimated ^{137}Cs source. Values on the diagonal correspond to the correct classification rates.

4. – Conclusions

The GAMMA module is a compact spectrometer designed for nuclear science experiments (13 cm $\times$ 13 cm $\times$ 15 cm, 6 W power consumption), which successfully exploits the codoped $LaBr_3$ resolution capability (2.7% at 662 keV, and 1% at 9.0 MeV) and SiPM linearity (0.6% error at 9 MeV). Pixellation of the detector matrix allows for coarse position of interaction sensitivity in the scintillation crystal.

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