Contribution ID: **257** Type: **Poster presentation + pitch**

A 144-channel Gamma-Ray Spectrometer with High Dynamic Range and Embedded Machine Learning Algorithms for Position Sensitivity in Thick Scintillators

This work presents an innovative gamma-ray spectroscopic module that is based on a cylindrical 3”×3”codoped lanthanum bromide scintillator crystal (25 [ns] decay time, 73 [ph/keV]), optically coupled to a large array of 144 NUV-HD SiPMs, produced by Fondazione Bruno Kessler (FBK, Italy) [1]. The array is made up of 9 tiles, each one counting 4×4 SiPMs. A 16-channel front-end Gain Amplitude Modulation Multichannel ASIC (GAMMA, [2]) is connected to each tile, allowing an individual, low-noise readout of the SiPMs charge up to 30 MeV incoming gamma photons.

The ASIC is specifically designed for the module; each channel provides 84 dB dynamic range, thanks to the innovative Adaptive Gain Control circuit. Moreover, thanks to the positive-feedback architecture of the input current buffer, each channel could be loaded with more than 50 nF allowing, in different applications, to connect more than 20 individual 6×6 mm² SiPM to a single channel.

In nuclear physics experiments, detected gamma rays might be subject to apparent energy shifts generated by the relativistic Doppler effect. Position sensitivity of the interaction position in the scintillation crystal with spatial resolution smaller than 2 cm on a single axis has to be met to counteract this effect [3]. Since we are dealing with a thick scintillator crystal, there is currently no suitable physical model of the system that enables position sensitivity.

To address this problem, we explored multiple machine-learning-based embeddable solutions. A training dataset was built acquiring the signals generated in 45 positions on a grid (Fig.1) from a ¹³⁷Cs collimated source (Fig.2). The acquired data were used to train and test classifiers (Decision Tree, Neural Network, Support Vector Machine), which are able to correctly identify the interaction position of new gamma photons. Comparative results of the different solutions will be presented at the conference.

Thanks to low latency and reduced area occupation on FPGA, Decision Trees are perfect candidates for an embedded solution (Fig.3). The performance of Decision Tree classifiers is described using confusion matrixes in Fig.4 and Fig.5. The rms error of this solution on the x-axis is 1.52 cm. We will also present a machine-learning-based event filter designed with the objective to discard those events whose position of interaction is more often wrongly classified; this is mainly associated with multiple scatterings or with scintillation light from events interacting far from the SiPMs. Applying the filter, the Decision Tree classifier error for x-axis position sensitivity scales down to 1.08 cm. Results for position sensitivity on the xy-plane, obtained before and after the application of the filter, are shown in Fig.5. The Decision Tree classifier was embedded in an Artix-7 FPGA-based DAQ in order to achieve real-time classification and relax constraints on data transmission for applications in nuclear physics experiments, nuclear safety, and homeland security, which otherwise often represent a bottleneck for count-rate.

The module is capable of spectroscopy measurements between 20 keV and 30 MeV, showing state-of-the-art resolution spanning from 2.6% at 662 keV down to 1.0% at 8.9 MeV, with a 35 kcps count rate. The embedded classifier in the Artix-7 presents a latency of 400 ns and an area occupation lower than 10%, allowing real-time position sensitivity and reducing data communication rate by a factor of 100.

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Session Classification: Poster session 1

Track Classification: Applications