8th International Conference on Higher Education Advances (HEAd'22)
Universitat Politècnica de València, València, 2022
DOI: http://dx.doi.org/10.4995/HEAd22.2022.14258

Development of a Muon detector for educational purposes.

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Abstract

In the effort to communicate modern physics to a vast audience, the flux of cosmic ray muons is commonly mentioned as the most abundant, naturally available particle/radioactivity source. The detection of atmospheric muons can therefore make up a powerful workbench for educational purposes, allowing many laboratory experiences in different topics of modern physics like special relativity, cosmic rays, statistics and particle detection. Unfortunately, a particle detector being suitable for cosmic-ray muon identification is typically expensive, cumbersome and requires high voltage, thus preventing its widespread application in laboratory sessions based on cosmic ray muons, ex. gr. for undergraduate courses. Here we describe the project for a low-cost muon detector based on a plastic scintillator coupled with silicon photomultipliers, whose signals are acquired and preprocessed via a common FPGA evaluation board. Besides the detector, which was developed by supervised master students, we describe some possible physics measurements.

Keywords: *Muon Detector; Scintillator; Data Acquisition; FPGA.*

Editorial Universitat Politècnica de València

1. Introduction

Modern society, economy, health and politics are strongly influenced by scientific developments. For this reason, effective science communication is important to enabling informed decision-making and participation of citizens in society and political discourse. However, modern physics communication, ranging from public talks to participatory projects, often reaches only limited parts of society. This could be sometimes attributed to the very faint effects involved by quantum mechanics or special relativity; the absence of macroscopic quantum/relativistic phenomena in the everyday life limits modern physics communication to a theoretical/phenomenological description and often, for the vast audience, most of the modern physics concepts are misspelt or distorted by science-fiction. In the effort to communicate modern physics to a vast audience, as an example, the flux of cosmic ray muons is commonly mentioned as being the most abundant particle/radioactivity source naturally available in our environment. The detection of atmospheric muons could be a powerful tool for educational purposes, allowing many laboratory experiences in different topics of modern physics like special relativity, cosmic rays, statistics and particle detection. Unfortunately, a particle detector, suitable for relativistic muon identification, is typically expensive, cumbersome and requires high voltage, this prevents widespread laboratory demonstration sessions or public talks based on the detection of cosmic rays. As an example, the Extreme Energy Events (EEE) project (Abbrescia et al. 2018) is a joint educational and scientific initiative and operated 50 muon telescopes distributed in Italian high schools. Each EEE telescope is built at CERN by high school teams under the supervision of researchers and technicians, and is a high-performance particle detector with an area of 0.82×1.58 m^2 and requires continuous gas fluxing and the use of 10kV voltage bias. Beyond the costly production and operation, a similar gas detector cannot be simply moved or transported, for this reason, more recent educational projects for muon detection are based on plastic scintillators coupled to a silicon photomultiplier (SiPM) that allows avoiding risks related to high voltage in the didactic tool. Aramo et al. (2017) installed an educational muon telescope based on a plastic scintillator and SiPMs in the Toledo Metro station of Naples; this is a portable detector, but it is still expensive and complex being able to track the muon direction thanks to 200 SiPM readouts, the detector was developed at the Gran Sasso National Laboratory (LNGS-INFN). Both these projects are characterized by high cost and high complexity and the detector construction and track reconstruction cannot be pursued simply by the students but requires advanced expertise developed at CERN or LNGS. On the other hand, cheap and simple projects for portable muon detectors exist, they use microcontrollers like Arduino (Bocci et al. 2015) or Raspberry Pi (He et al. 2019) for data acquisition (DAQ) of a single (or few) SiPM readout connected to a plastic scintillator, similar projects can be fully developed by supervised students. The main drawback of the microcontroller-based DAQ is the necessity for the development of a custom interface board for the SiPM readout and the relatively low achieved sampling frequency. In our project, we choose to develop a muon telescope DAQ using a commercial Field Programmable Gate Array (FPGA) development board (Xilinx Spartan-3A/3AN) this avoids the necessity of additional custom boards and allows much faster sampling frequency, maintaining the overall cost as low as the microcontroller-based detectors. Moreover, this FPGA development board allows the simultaneous acquisition of two readout channels permitting the coincidence of two scintillators in a telescopic configuration, this is a major educational virtue concerning the single SiPM Arduino based DAQ. The detector design, software, test and prototype development are performed by supervised students during a laboratory stage session within the course “Laboratory of Advanced Electronics” held at the University of Trento. We use these muon telescopes for cosmic ray laboratory measurements in another course: “Experimental Techniques in Nuclear and Subnuclear Physics” at the same University, moreover thanks to the portability and usage simplicity, such a muon telescope is suitable for the measurement of zenith angle muon distribution performed by high school students during the yearly outreach event “International Cosmic Day” worldwide organized by DESY (Hutten et al. 2017).

2. The Plastic Scintillator and the Silicon Photomultiplier (SiPM)

Particle detection is one of the pillars of modern experimental physics. The particle detector used for the muon telescope described here is a plastic scintillator EJ-200 from Eljen Technology, consisting of the polymer base Polyvinyltoluene. The working principle of the scintillator is summarized as follows: when a charged particle crosses the detector material, it releases energy in the form of ionization, a small part of which produces several visible photons proportional to the deposited energy; for EJ-200 material we expect an average number of 10 photons/keV released within few ns from the particle ionization. For the prototype of the portable muon detector described here, a plastic scintillator bar with dimensions 18x4x1 cm^3 was used, while the detector was coupled to two Silicon Photomultipliers (SiPM) placed at the centre of each side of the bar. The raw side of the scintillator bar was smoothed using (thin) sandpaper and polished using a common plastic headlight restoration kit. An example of a raw and polished scintillator along with two SiPMs is shown on the left side of Figure 1. In this prototype the 4x4mm^2 NUV-4S-P SiPM produced by AdvanSiD was used; we suggest using SiPM mounted on small PCB boards.

Figure 1. Left) Example of raw and polished EJ-200 plastic scintillator bars and two commercial SiPM boards. Right) The scintillator is equipped with SiPMs and wrapped with black tape to avoid external stray photons.

To improve the optical coupling and avoid the presence of small air gaps, the gel couplant EJ-550 was applied to the SiPM surface. The SiPM is an electronic device that can convert light photons into electrical pulses whose amplitude can be acquired by suitable DAQ electronics. From the electrical point of view, the SiPM is made of many cells containing avalanche photodiodes connected in parallel (see Fig. 2 left). Each SiPM is reverse biased to a negative voltage of about 30 V. When a bunch of photons hits the SiPM cells, a current pulse, proportional to the number of hit cells, is generated. In this application, to match the 245 kHz FPGA sampling rate (see below), a sufficiently long recovery time of the SiPM signal is desired. For this reason, a 100kOhm load resistor was used to match the parasitic capacitance of the SiPM. An example of different SiPM pulses, due to muons and acquired by an oscilloscope, is shown in Fig. 2 right.

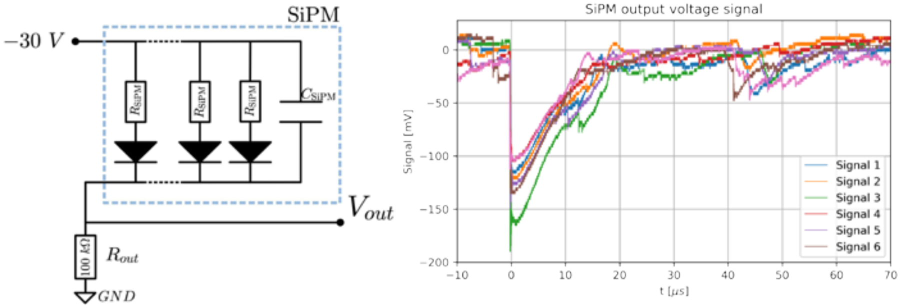

Figure 2. Left) Simplified electrical model of the SiPM in reverse bias polarization. Right) Some examples of voltage response of the SiPM after the arrival of a muon acquired by an oscilloscope.

Finally, the plastic scintillator was wrapped with both white teflon tape to improve the photon collection along the bar and with black tape to obtain a light-tight envelope that minimizes the occurrence of environmental stray photons (Fig. 1 right). In the case of a still significant residual environmental light, the related noise could be rejected by requiring the coincidence of signals in both SiPM. However, the use of an additional light-tight external box, possibly 3D printed, is suggested.

3. Data acquisition through an FPGA development board

As anticipated above, for the data acquisition of this portable muon detector a *Xilinx Spartan-3A/3AN FPGA* development board was used. It has however to be stressed that other cheaper and faster FPGA development boards are presently available, sometimes providing even more analogue inputs. An FPGA is a device containing a large number of basic logic cells, gates and flip-flops, whose interconnections can be programmed by using a hardware description language. As a result, by relying on an FPGA, it is possible to implement many kinds of digital electronic circuits and even processors. We have chosen this kind of tool to acquire and process signals, and send the results to a computer. Our development board provides two analogue input channels, each one equipped with a pre-amplifier whose gain can be programmed from 1 to 100. Each amplified signal is then inverted and digitally acquired by a 14 bit Analog to Digital Converter (ADC) working in the range 0.4-2.9V. The resulting digital number is processed by the FPGA. Figure 3 summarizes the DAQ chain.

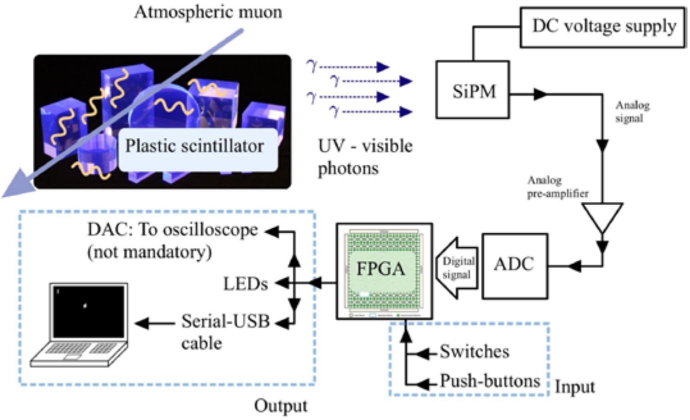

Figure 3. Block diagram of the proposed muon detector showing the roles played by the scintillator, the SiPM, the FPGA, and all the I/O devices integrated on the FPGA development board

The FPGA software was developed by using Verilog HDL codes. The first task is to determine the signal baseline, namely a relatively small DC voltage component due to the currents flowing within a biased SiPM when no photon is impinging on the detector. For each channel, the signal baseline is determined by evaluating the moving average of 1024 samples of the signal digitized at a 245 kHz sampling rate. Thereupon, when a sample of one of the two channels crosses a threshold preset by the user above the baseline, the maximum value of the resulting signal is stored and replaced (peak detector). When the signal returns below the threshold, the recorded value is sent to the DAQ management system and the peak detector goes back to its *idle state*. The coincidence detection among the two channels is implemented within the DAQ system whenever the signals stemming from both channels are simultaneously above the thresholds. At this point, a suitable chronometer records the time of the events, and the resulting information is sent to the serial interface together with the two signal amplitudes described above. To collect, visualize, and analyze data, the FPGA board is connected to a PC via a serial USB cable by using the UART protocol. The PC serial ports of the PC can be read by using common software like *GTKTerm* on *Linux*, or *Instrument Control Toolbox* on *MATLAB*, as well as via *Python* routines that use the *PySerial* package. Finally, the LCD display placed on the FPGA development board can be used to count the muons. Suitable switches and pushbuttons allow resetting the counts.

4. Example of measurements performed with a portable muon detector

In this section, some didactic activities offered to the students of the course “Experimental Techniques in Nuclear and Subnuclear Physics” are summarised; the cooperative learning approach was adopted in the laboratory by organising students in small groups. The first measurement that can be performed with the portable muon detector is the integrated muon flux at the ground, which is obtained by dividing the detector count rate by the detector surface (in this case 72 cm^2). Performing this measurement in Trento (200 m above sea level) led us to obtain a muon flux $\phi_0 = (113 \pm 1)$ m^{-2} s^{-1}. This value is in reasonable agreement with the expected muon flux reported by Particle Data Book (Zyla et al. 2020) for horizontal detectors at sea level. We note that small variations in the muon flux might be due to different latitude, altitude and atmospheric pressure or temperature, as well as to the different building structures/thicknesses whenever the flux measurements are not performed outdoors. From a modern physics point of view, the measurement of muon flux at different elevations is a powerful test of special relativity and Lorentz transformations. As an example, with the portable muon detector it is possible to repeat the flux measurement in the nearby small village of Vason (1650 m above sea level, 40 min by car or 1.5 h by bus from Trento) obtaining $\phi_h = (141 \pm 1)$ m^{-2} s^{-1} that is just a bit higher value despite the relatively large elevation difference. Knowing that the muon lifetime is □ = 2.2□s we argue that the time it takes for the muons to descend from Vason elevation to Trento elevation (T = 4.8□s in our lab. frame) must be shrunk in the muon rest frame by a factor □ = (T/□)/ln(ϕ_h/ϕ_0) ~ 10. This demonstrates that muons are arriving at the ground with a relativistic velocity of ~99% of the speed of light. Another interesting measurement relies on the ability of this muon detector to measure the energy deposited by the muon crossing the scintillator slab. The left panel of Figure 4 shows the correlation of event amplitudes measured by the left side SiPM Ch1 and right side SiPM Ch2. The energy deposited by a charged particle crossing a small material thickness is described by the Landau distribution: for relativistic muons crossing 1cm of plastic we expect an energy deposited of 1.75 MeV (Zyla et al. 2020), which allows an energy calibration of the measured ADC counts. In the right panel of figure 4, the distribution of the average of the two ADC channels is shown. The red curve is a fit performed by using the Landau distribution with an additional exponential contribution. For signal amplitudes below the Landau peak, the electronic noise is the dominant contribution, whereas the long right tail is due to different factors like the Landau distribution, the existence of some inclined muons in the cosmic ray flux and the limited energy resolution due to a low surface of SiPM readout.

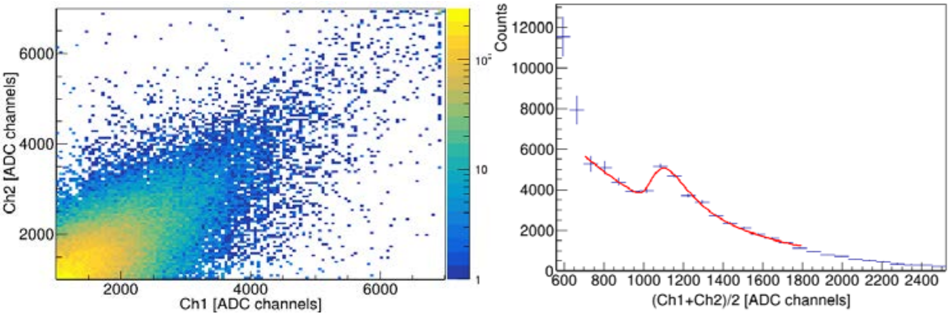

Figure 4. Left) Correlation of signal amplitudes. Right) Measured average amplitude distribution.

Another interesting measurement regards the statistics. The distribution of time differences for consecutive events can be plotted and compared with the exponential distribution that is expected considering a memoryless Poisson process (fig. 5 left panel). The fit of the experimental time difference distribution using an exponential function provides the rate of R = (0.817 ± 0.004) Hz.

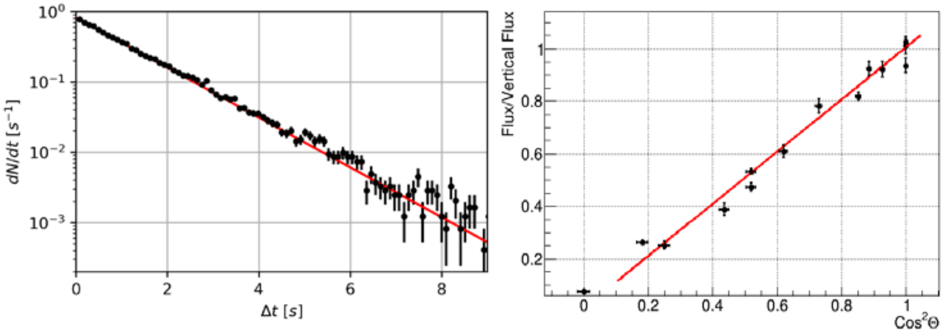

Figure 5. Left) Distribution of time difference for consecutive events. Right) Measured muon angular distribution.

Finally, it is possible to use two different scintillators in a telescopic configuration and perform many flux measurements changing the telescope zenith angle Θ. In the right panel of figure 5, the angular distribution of the muon flux is shown. The expected $\cos^2\Theta$ behaviour is measured indeed, which demonstrates that atmospheric muons travel mostly vertically due to their being produced as secondary particles by primary cosmic rays that hit the top of the atmosphere.

7. Conclusions

In this report, we summarize how a low-cost portable muon detector can be built by exploiting the digital electronics incorporated within an FPGA development board. This is a powerful educational tool and we suggest building it with the students in a course of “Laboratory of Advanced Electronics” and to use it for many measurements in high-level courses or also to communicate modern physics to a vast audience during public events like the yearly “International Cosmic Day”. Some examples of possible measurements involving muon detection are shown, in particular, simply counting the number of muons detected in a time interval, i.e. the muon rate, it is possible to test the time dilation effect of special relativity and to measure the muon angular distribution proving that muons come from the sky.

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