CosmicWatch: The Desktop Muon Detectors, exploring gamma-ray spectroscopy

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Cita 01.

Autor
Fuente

Wenn du es nicht einfach erklären kannst, hast du es nicht genug verstanden - Si no eres capaz de explicar algo claramente, es que aún no lo has entendido lo suficiente.

Albert Einstein

Declaración

Me permito afirmar que he realizado ésta tesis de manera autónoma y con la única ayuda de los medios permitidos y no diferentes a los mencionados el presente texto. Todos los pasajes que se han tomado de manera textual o figurativa de textos publicados y no publicados, los he reconocido en el presente trabajo. Ninguna parte del presente trabajo se ha empleado en ningún otro tipo de tesis.

Sede Bogotá., Fecha entrega

Andrés Felipe Vargas-Londoño

Acknowledgments

This goes to my family, my mom and my dad, who no matter how many mistakes I make, there is never a hint of judgement or disappointment. To every teacher who put his soul into letting me explore a corner of their bast knowledge. And to every friend who stood there when things did not seem to be going anywhere. But also specially to myself, for not letting me ever down.

Listado de símbolos y abreviaturas

Resumen

CosmicWatch: Los Detectores de Muones de Escritorio, explorando la espectroscopía gamma

Texto del resumen.

Palabras clave: Use palabras clave que estén en Theasaurus

Abstract

CosmicWatch: The Desktop Muon Detectors, exploring gamma-ray spectroscopy

Abstract text.

Keywords: Use keywords available in Theasaurus

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Chapter 1

Introduction

CosmicWatch: The Desktop Muon Detectors [2], are a self-contained, low-cost, and easy-to-build particle detector for students, scientists, and cosmic-ray enthusiasts. It aims to make particle detection interactive and available to anyone interested in learning about the electronics and physics involved in this area of expertise. With this in mind, the detector design prioritizes the user experience across the board, from its construction to data acquisition and processing. It uses a silicon photomultiplier (SiPM) to collect light emitted by a plastic scintillator after a charged particle, like a cosmic-ray muon, deposits some of its energy in it. This project aims to further expand the capabilities of CosmicWatch by exploiting the already existing electronics and implementing the necessary features to transform the detector into a portable gamma-ray spectrometer

Using a Cerium doped Lutetium-based scintillation crystal (LYSO), we have achieved an energy resolution of $4.86\sqrt{E\ [\mathrm{MeV}]}$ while testing in a Rohde&Schwarz RTO6 oscilloscope to sample the data.

The human body is known to have many limitations, our senses are often not the best tools to delve into the intricacies of nature. For many years scientists have taken advantage of the sensitivity of materials to further expand our capabilities to explore the world around us, bringing to our reach worlds once invisible. Scintillating crystals for example have allowed us to develop a type of detector able to distinguish the energy deposition in it, making elusive particles trackable, no longer letting them escape our curiosity. The wonders of these types of detectors are sadly not easily available to everyone, scintillating and solid-state detectors are often out of the economic capacities of most. CosmicWatch Desktop Muon Detectors are therefore an extremely powerful tool to bring particle detection closer to the public, students, and young scientists like myself. This work thus aims to further explore and expand the capabilities of CosmicWatch, hoping to one day provide a self-contained, low-cost, and easy-to-build particle detector suited for gamma-ray spectroscopy.

Chapter 2

Physical aspects

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2.2. Cosmic Radiation

2.3. Particle interactions with matter

Chapter 3

Detector description

3.1. History

3.2. Plastic vs. LYSO

3.3. Power Consumption

3.4. KiCad

3.5. Accessories

3.6. 3D printed case

In order to make the crystal easier to mount on the SiPM PCB it was necessary to design a 3D printed case. With this we made sure that the crystal would not move with respect to the SiPM, preventing scratches and providing a more stable optical coupling with the photomultiplier.

The design keeps in mind that the crystal has to be wrapped in teflon tape to increase reflectivity, which is why it comes in two pieces that come together around the crystal, lowering the risk of tears. Once the crystal is placed in the case it can be kept together by means of electrical tape.

Chapter 4

Detection methods

4.1. Scintillation

4.2. Single photon detectors

4.3. PMT's

4.4. SiPM advantages

Chapter 5

Electronics

CosmicWatches have to be mainly low-cost and easy to build. In order to achieve this, the components selected for the construction have been carefully curated to make sure these restrictions were met. This however might be greatly responsible for some of the odd features found while testing the detector, like the lack of linearity and fluctuations in amplification and peak-detected values of seemingly equal input signals. The full KiCad project can be found in the GitHub repository: CosmicWatch-gamma-spectroscopy-PCB. The component numbers shown in this chapter are the ones that would have to be placed on the PCB in order to recreate the example schematics.

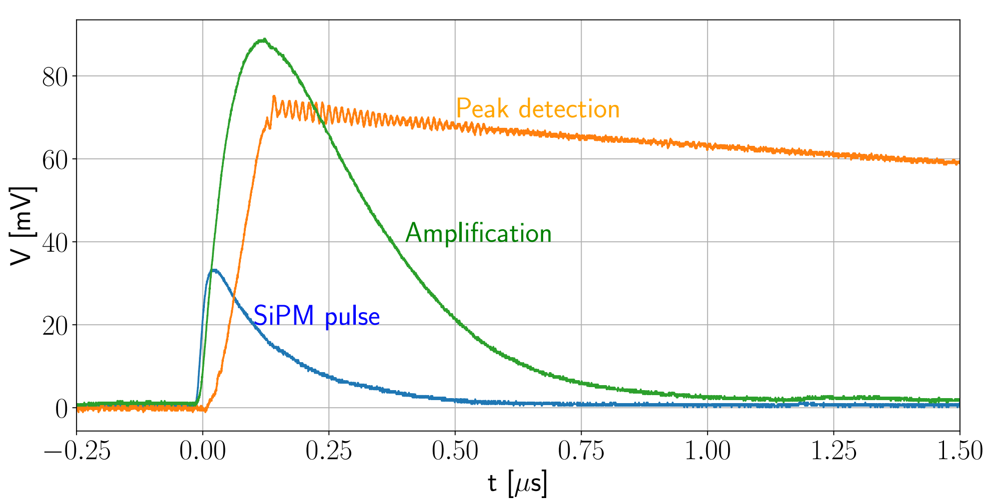


Figura **5-1**: Signal processing inside the detector.

5.1. Amplifier

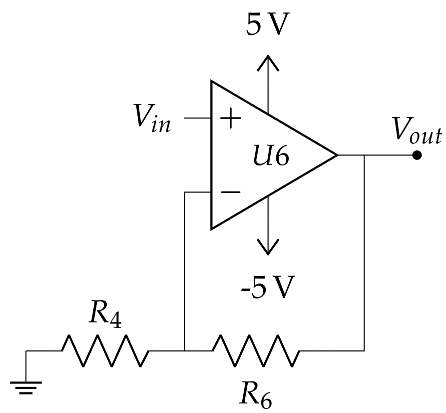


Figura **5-2**: Amplifier circuit schematic. An LT1807 op-amp is used for this and the peak detection stage.

The processing of a pulse coming out of the SiPM has to go through two main stages, amplification and peak detection, Fig. **5-1** showcases these stages. The brightest SiPM pulses seen so far do not exceed 200 mV, which covers a very small portion of the ADC range on the RP Pico (0-3.3 V [3, p. 18]). Amplification of the signal therefore allows for better resolution.

An op-amp on its own amplifies the voltage difference between the non-inverting (pin $+$) and inverting (pin $-$) inputs by its internal gain A_{int}, having then $V_{out} = A_{int}(V_+ - V_-)$. In this case, however, we are interested in controlling the gain of the circuit and therefore the amplification. In order to achieve this we introduce a feedback loop in the op-amp through $R4$ and $R6$, which controls how much of the output voltage is fed back into the op-amp. The theoretical amplification is therefore given by $V_{out} = (1 + R6/R4)V_{in}$. A simple schematic showcasing the component arrangement is shown in Fig. **5-2**.

5.2. Peak Detector

Since the LYSO crystal is so fast (36 ns of decay time [4]) the ADC sample rate and response time of the Pico both play an important role in the number of events that the detector will accurately acquire. It is therefore necessary to hold the voltage of the amplified pulse in order to increase the chances of reading the actual value of the incoming signal. This is the task of the peak detector, to widen the time window in which we can sample the ADC and get a correct reading.

The idea behind the peak detector is to store charge in a capacitor (C_{25}) through a diode (D_3), retaining the highest voltage the input signal has reached. A diode is placed before the capacitor so that once the signal's voltage goes below the peak voltage, the diode will be reverse biased, therefore preventing current from flowing while maintaining the voltage on the capacitor.

In order to measure the voltage in the capacitor, a discharging resistor has to be added (R_{15}/R_{19}). The time it takes the capacitor to discharge is given by $t = RC$. Although for example in the case of CosmicWatch-V2's peak detector, the values of R_{14} and R_{24} also play a role in the discharging time, which has proved not to be as trivial as calculating the equivalent resistance R_t of all three and simply take $t = R_tC$.

The schematic and PCB shown in the repository CosmicWatch-gamma-spectroscopy-PCB, include the connections and footprints necessary to place the components that make the designs illustrated in Subsections 5.2.1-4. Different results were found while testing these peak detector setups.

5.2.1. Basic Peak Detector

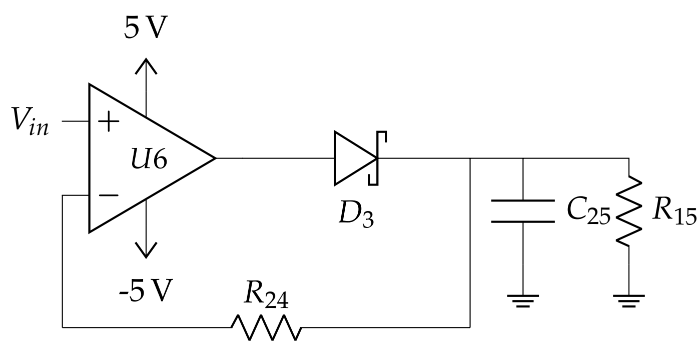


Figura **5-3**: Basic peak detector design.

Assuming ideal conditions, a diode is enough to retain the highest input voltage reached. Semiconductor diodes however don't behave ideally, they introduce a voltage drop that will keep the voltage stored in C_{25} at a lower potential than that of V_{in}. In order to prevent this, an op-amp (U_6)[1] is placed before the diode. In the configuration shown in Fig. **5-3**, the opamp will try to output the necessary current to equilibrate the inverting input voltage (pin $-$) to what it sees in the non-inverting input (pin $+$), to achieve this U_6 has to go one diode drop above V_{in}.

[1]Currently the only op-amp that has behaved reasonably well is the LT1807 by Analog Devices Inc. The LMH6658 by Texas Instruments seems to have trouble driving even small capacitors.

5.2.2. Preventing negative saturation

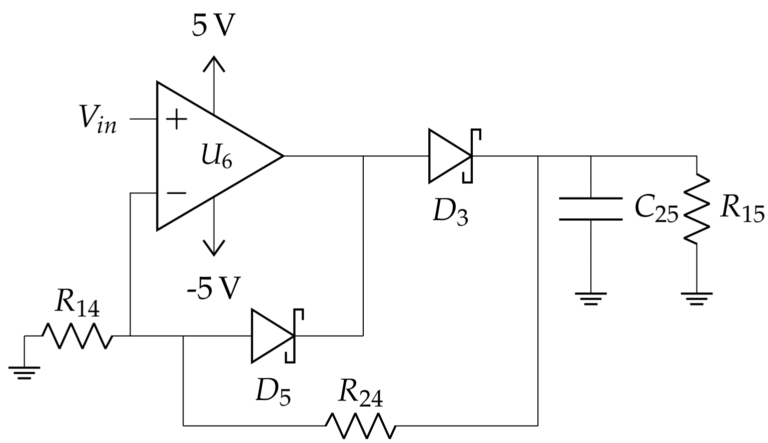


Figura **5-4**: Basic peak detector design, a second diode is added in order to prevent the op-amp from entering a negative saturation loop.

In the basic peak detector, once the signal voltage goes below the peak voltage, D_3 will be reverse biased and the inverting input of the opamp will see a higher voltage than the non-inverting input, this will force U_6 to go into negative saturation by driving the output voltage as low as it can in order to match both inputs. Once the signal gets close to the stored voltage in C_25, the op-amp will have to get out of the negative saturation, this will take some time which depends on the slew rate of the opamp and therefore limits the operating frequency range of the circuit.

In order to avoid negative saturation D_5 is added, along with an outer feedback loop through R_{24}. In this case, once the input signal goes below the stored voltage, D_5 will be forward biased, allowing for a new feedback loop that decreases the op-amp's negative saturation time.

5.2.3. Basic Peak Detector + Buffer

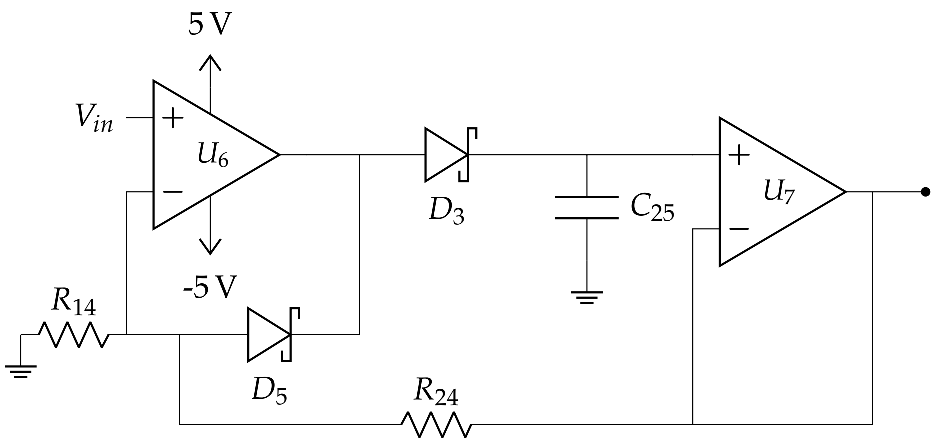


Figura **5-5**: Basic peak detector design, Adding a buffer to prevent discharging of the capacitor through the resistor and instead through any load in the circuit, in this case R_29.

This design follows the same principles as the one shown in the previous subsection. However, in this case, a buffer is added to introduce high impedance and prevent the capacitor from discharging through the resistor and instead through any load that may be applied after the circuit.

5.2.4. Nuclear Phoenix

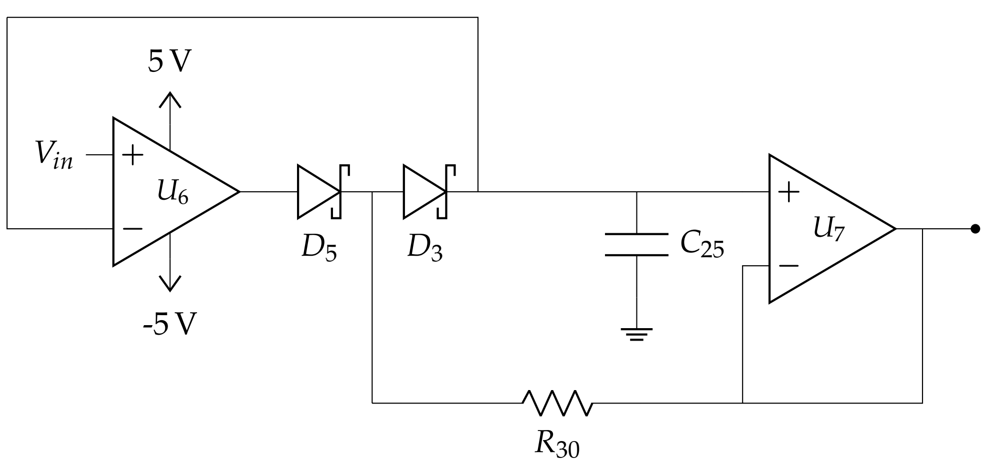


Figura **5-6**: Nuclear Phoenix peak-detector design. Taken from [1].

NuclearPhoenix is a physics student who has developed a gamma detector that also utilizes a Raspberry Pi Pico and a Silicon photomultiplier, his schematics also include a peak detection circuit which is shown in Fig. **5-6**, his project can be found in Open Gamma Detector. This design aims to prevent leakage current across D_3, this discharges the capacitor at a faster rate than intended once the peak voltage has been reached. In this case, R_30 is feeding back the peak voltage value to D_3, therefore creating a 0 V difference across the diode, preventing any leakage current from flowing out of C_{25} and into the output of the op-amp.

5.3. Trigger

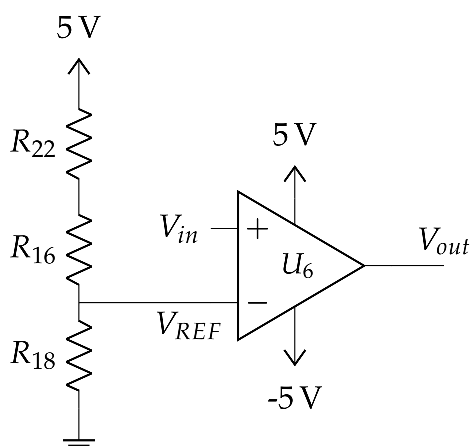


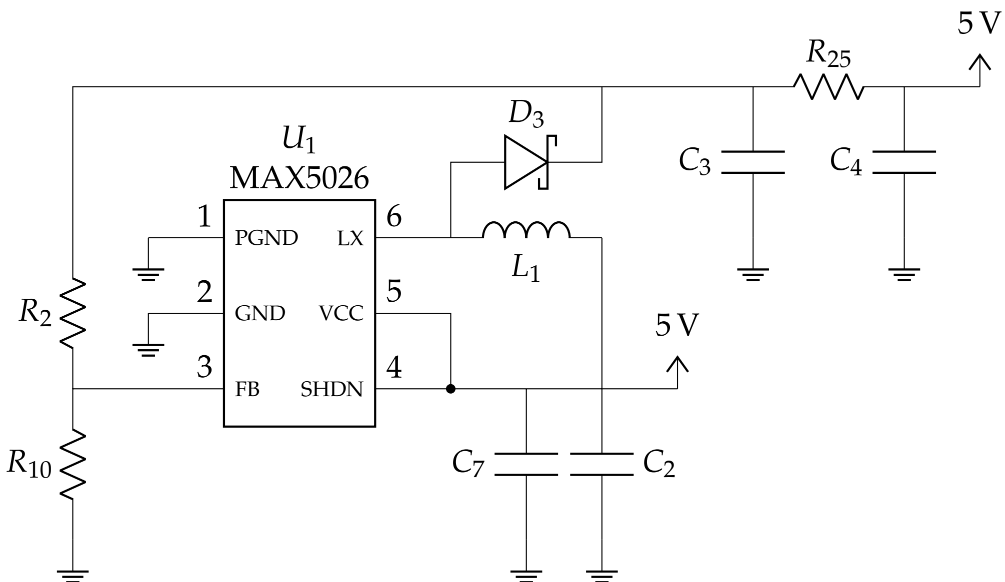
Figura **5-7**: Trigger circuit.

In this case, a voltage divider is used to force a positive saturation in the op-amp once the amplified signal reaches a threshold voltage, generating a "digital 1" that can be used to trigger the detector. The threshold, or V_{REF} as noted in Fig. **5-7**, is given by equation (5-1).

$$V_{REF} = \frac{R_{18}}{R_{22} + R_{16} + R_{18}} V_{cc} \tag{5-1}$$

5.4. Microcontroller

5.5. DC to DC booster



5.6. Single photons

Chapter 6

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8.2. Adding LYSO radioactivity to Geant4

Chapter 9

Conclusion

Appendix A

RaspberryPi Pico code

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