



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 vast 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

El presente trabajo se concentra en el mejoramiento de CosmicWatch: Los Detectores de Muones de Escritorio, con el objetivo de evolucionar de un detector tipo contador Geiger a un espectrometro de gammas completamente funcional. Requiriendo por lo tanto buena resolución de energías y altas velocidades de sampleo, siendo estas las principales limitaciones de versiones anteriores de CosmicWatch. Usando un cristal centellador basado en Lutecio y dopado con Cerio (LYSO), se logró una resolución de $4.86\sqrt{E} \text{ [MeV]}$ al samplear datos con un osciloscopio Rohde&Schwarz RTO6.

Palabras clave: CosmicWatch, RaspberryPi Pico, Radiación gamma, Centelleo.

Abstract

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

The present work focuses on the improvement of CosmicWatch: The Desktop Muon Detectors, with the goal to evolve from a Geiger-counter type of detector to a fully functional gamma-spectrometer. Therefore requiring good energy resolution and fast sample rates, which were the main limitations on previous CosmicWatch versions. Using a Cerium doped Lutetium-based scintillation crystal (LYSO), we have achieved an energy resolution of $4.86\sqrt{E}$ [MeV] while sampling data with a Rohde&Schwarz RTO6 oscilloscope.

Keywords: CosmicWatch, RaspberryPi Pico, Gamma radiation, Scintillation.

Table of contents

Acknowledgments	II
Listado de símbolos y abreviaturas	III
Resumen	IV
Abstract	V
List of Figures	VIII
List of Tables	IX
1. Introduction	1
2. Physical aspects	2
2.1. Radioactivity	2
2.2. Cosmic Radiation	2
2.3. Particle interactions with matter	2
3. Detector description	3
3.1. History	3
3.2. Plastic vs. LYSO	4
3.3. Power Consumption	4
3.4. KiCad	4
3.5. Accessories	4
3.6. 3D printed case	4
4. Detection methods	7
4.1. Scintillation	7
4.2. Single photon detectors	7
4.3. PMT's	7

TABLE OF CONTENTS		vii
4.4.	SiPM advantages	7
5.	Electronics	8
5.1.	Amplifier	9
5.2.	Peak Detector	9
5.2.1.	Basic Peak Detector	10
5.2.2.	Preventing negative saturation	11
5.2.3.	Basic Peak Detector + Buffer	12
5.2.4.	Nuclear Phoenix	12
5.3.	Trigger	13
5.4.	Microcontroller	14
5.5.	DC to DC booster	14
5.6.	Single photons	14
6.	Geant4 Simulation	15
6.1.	What is Geant4?	15
6.2.	Geometry	15
6.3.	Muons going through the scintillator	15
6.4.	Photons collected vs. produced	15
6.5.	Optimum SiPM placement	15
6.6.	Simulated Spectra	15
7.	Measurements	16
7.1.	Rohde&Schwarz RTO6 oscilloscope	16
7.2.	CosmicWatch electronics	16
7.3.	NIM	16
8.	Ongoing work and future directions	17
8.1.	Odd features in Cesium spectra	17
8.2.	Adding LYSO radioactivity to Geant4	17
9.	Conclusion	18
A.	RaspberryPi Pico code	19
	Bibliography	20

List of Figures

3-1. 3D model of the LYSO case made on inventor, the .cad files can be found on the repository CosmicWatch-gamma-spectroscopy-PCB.	5
3-2. Tin foil tear.	6
3-3. 3D printed cases tested to reduce risk of teflon tearing.	6
5-1. Signal processing inside the detector.	8
5-2. Amplifier circuit schematic. An LT1807 op-amp is used for this and the peak detection stage.	9
5-3. Basic peak detector design.	10
5-4. Basic peak detector design, a second diode is added in order to prevent the op-amp from entering a negative saturation loop.	11
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}	12
5-6. Nuclear Phoenix peak-detector design. Taken from [1].	12
5-7. Trigger circuit.	13
5-8. DC to DC booster circuit. Careful considerations have to be made when placing the MAX5026 IC in order to reduce noise on the power line. It is advised to have a look at the datasheet in [2], section "Applications Information".	14

List of Tables

1 Introduction

CosmicWatch: The Desktop Muon Detectors [3], 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

So far, previous iterations of CosmicWatch have worked as a Geiger counter, providing information about the number of particles detected, but ignoring energy deposition due to the poor resolution of the scintillating material used, generally plastic scintillators such as BC-404. The current speed of the electronics used is also a limiting factor, creating deadtime and therefore decreasing the sample rate. By switching to a Cerium doped Lutetium-based scintillation crystal (LYSO), testing new electronics and implementing better programming paradigms, 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.

2 Physical aspects

2.1. Radioactivity

2.2. Cosmic Radiation

2.3. Particle interactions with matter

3 Detector description

3.1. History

“The desktop muon detector was initially built as a Muon Tagging Optical Modules (MTOMs) for PINGU, the proposed low energy upgrade for IceCube experiment” [4]. Since the first iteration CosmicWatch has had multiple versions, always aiming to reduce size and costs, simplify its construction and provide better documentation for new CosmicWatch users. An indepth review of the detector evolution can be found in [4] under “About the project/Project evolution”.

The previous versions of CosmicWatch used an Aduino Nano to process the signal comming from the photomultiplier¹, which has only one core. This is a disadvantage when there is a high event rate, due to the fact that one can not sample data while saving previous events.

Up until now only plastic scintillator had been used, due to how affordable and maleable it can be. Sadly, the poor resolution of this kind of scintillator makes it useless for spectroscopy. in addition to this plastics scintillators like BC-404 have a decay time of

¹see chapter 5 for an indepth description of the inner workings of the detector electronics

3.2. Plastic vs. LYSO

3.3. Power Consumption

3.4. KiCad

3.5. Accessories

3.6. 3D printed case

In order to hold the crystal in place on the SiPM PCB, it was necessary to design a 3D printed case -see Fig. 3-1 for an image of the 3D desing on inventor. 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.

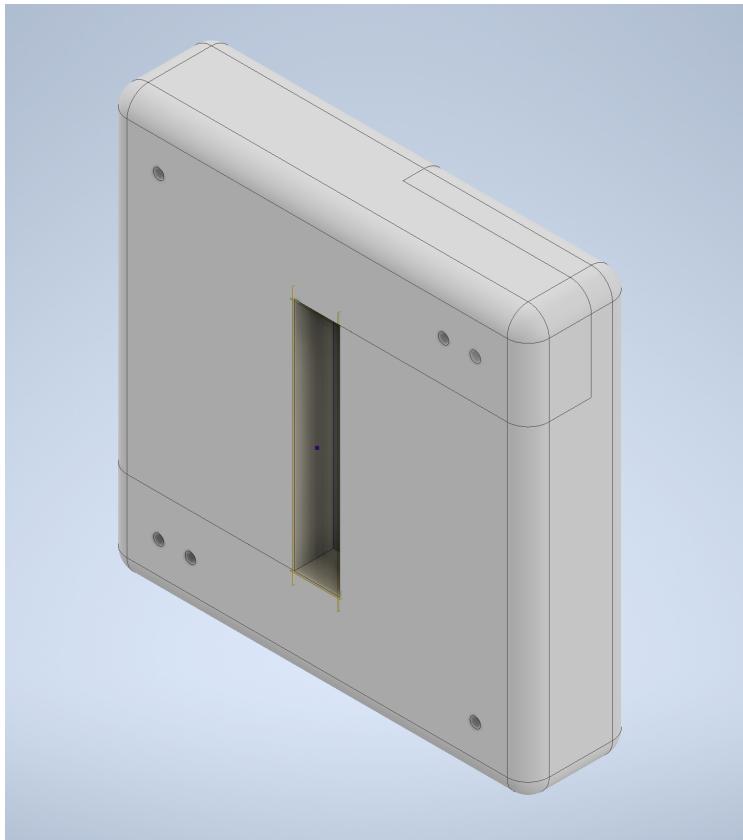


Figura 3-1: 3D model of the LYSO case made on inventor, the .cad files can be found on the repository [CosmicWatch-gamma-spectroscopy-PCB](#).

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.

Before using teflon tape, the crystal was wrapped in tin foil, which made tears common (Fig. 3-2) and greatly impacted the quality of the spectra that could be obtained with the detector.

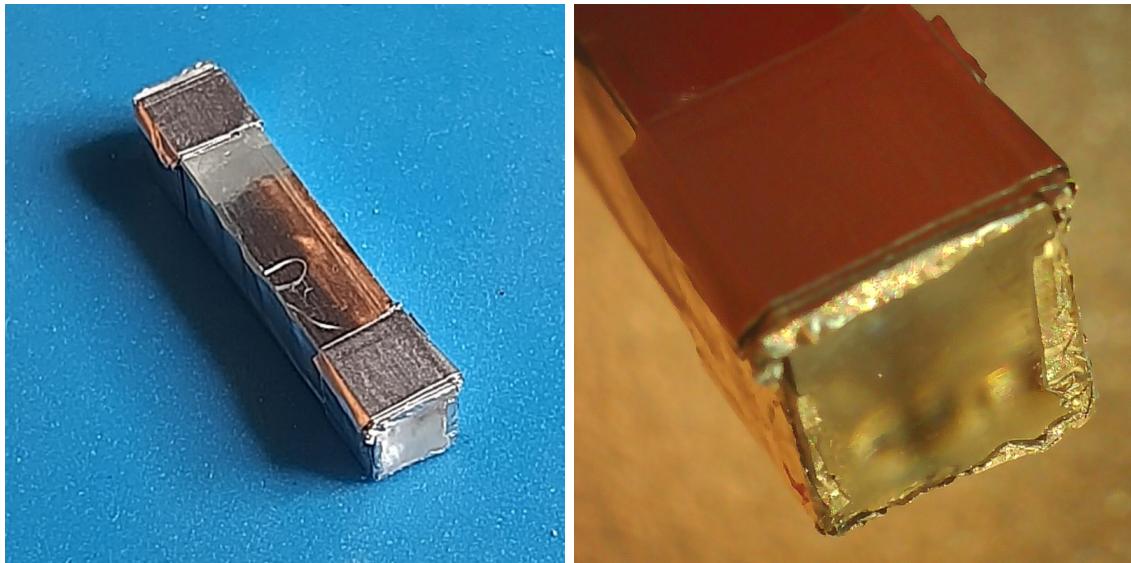


Figura 3-2: Tin foil tear.

Teflon tape seems to solve the tearing problem. However, with the intention to reduce the risk of tearing the teflon, multiple iterations of the case were designed (Fig. 3-3)

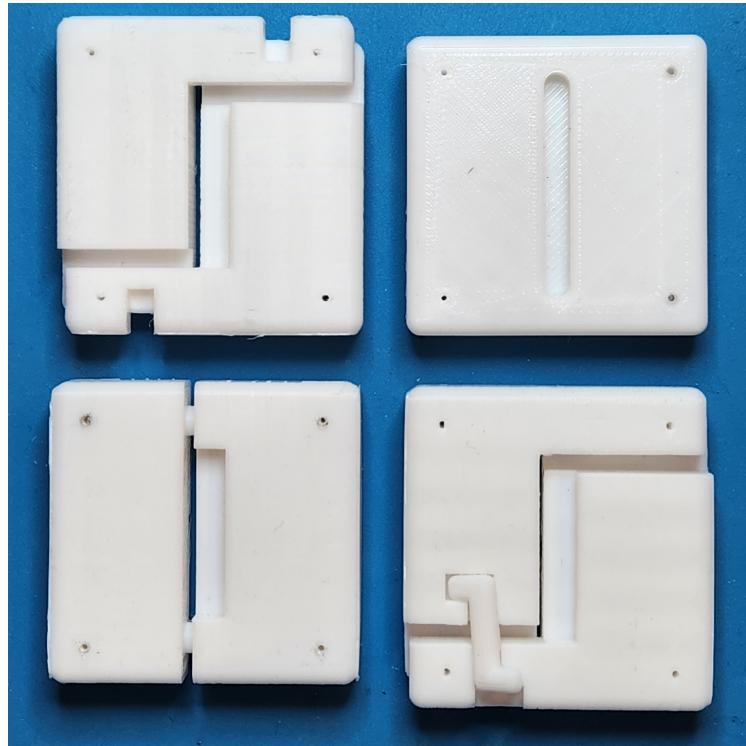


Figura 3-3: 3D printed cases tested to reduce risk of teflon tearing.

4 Detection methods

4.1. Scintillation

4.2. Single photon detectors

4.3. PMT's

4.4. SiPM advantages

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.

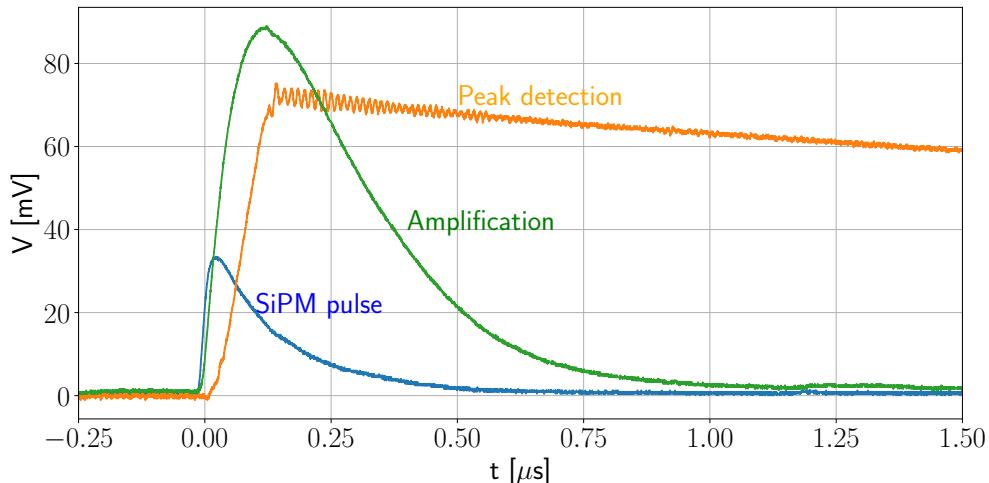


Figura 5-1: Signal processing inside the detector.

5.1. Amplifier

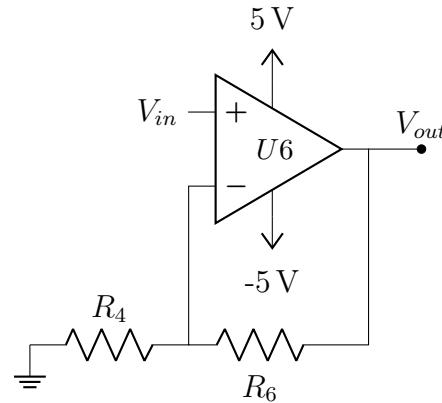


Figura 5-2: Amplifier circuit schematic. An LT1807 op-amp is used for this and the peak detection stage.

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 [5, 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 [6]) 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 $t = R_t C$.

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

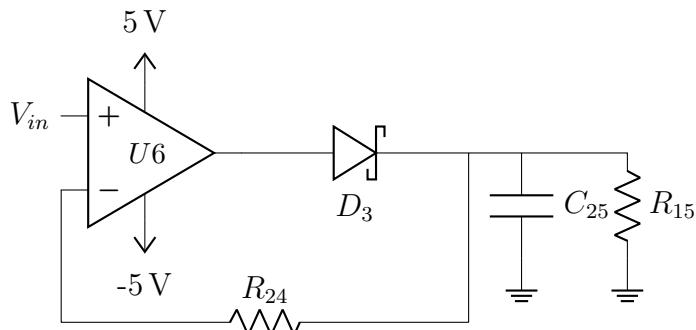


Figura 5-3: Basic peak detector design.

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} .

¹Currently 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

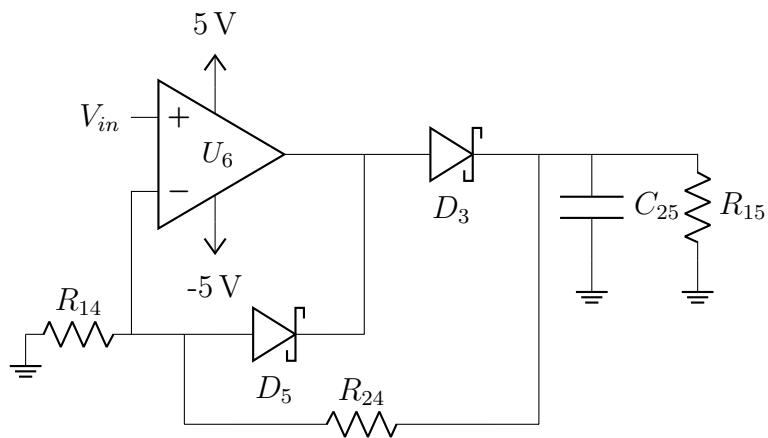


Figura 5-4: Basic peak detector design, a second diode is added in order to prevent the op-amp from entering a negative saturation loop.

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

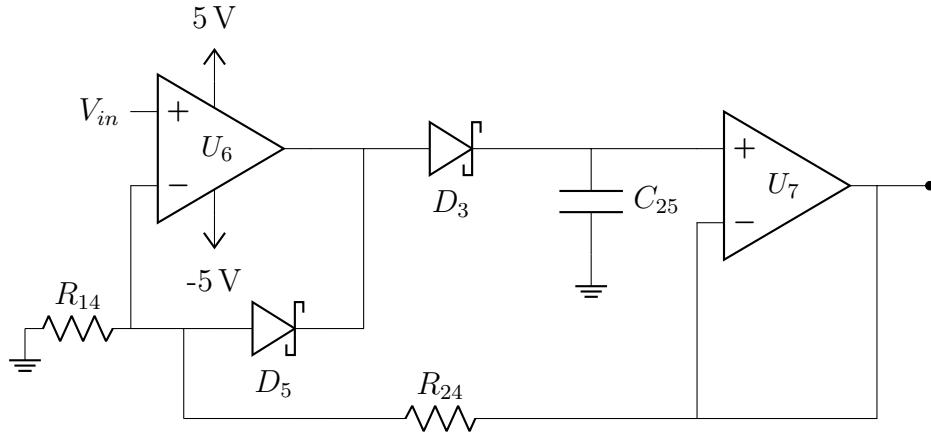


Figura 5-5: Basic peak detector design, Adding a buffer to prevent discharging of the capacitor through the resistor and instead through any load in the circuit, in this case R_{29} .

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

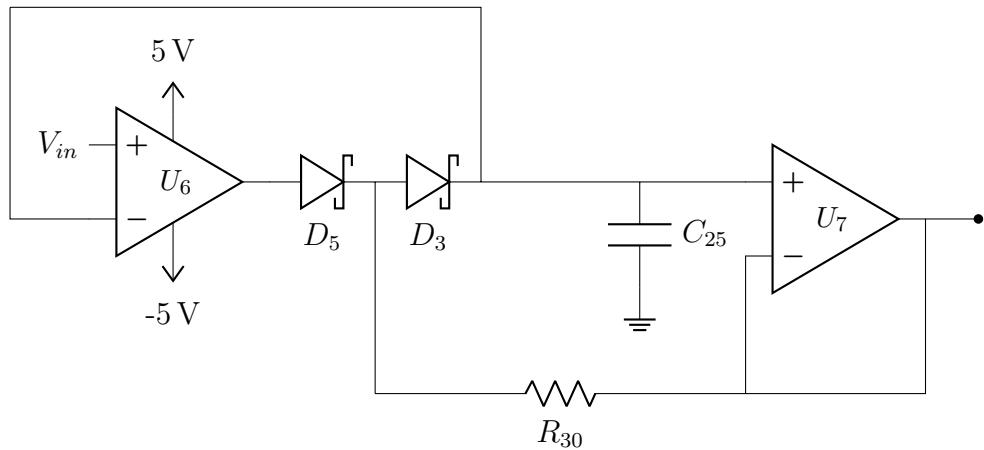


Figura 5-6: Nuclear Phoenix peak-detector design. Taken from [1].

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

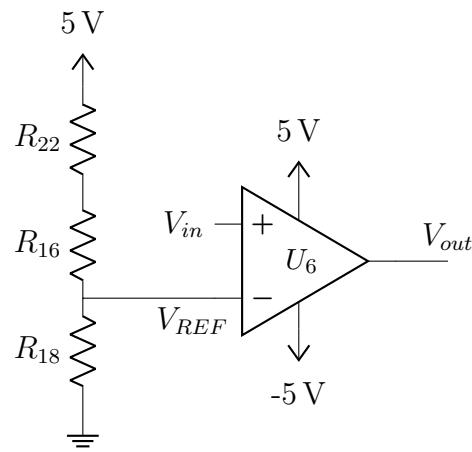


Figura 5-7: Trigger circuit.

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).

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

5.4. Microcontroller

5.5. DC to DC booster

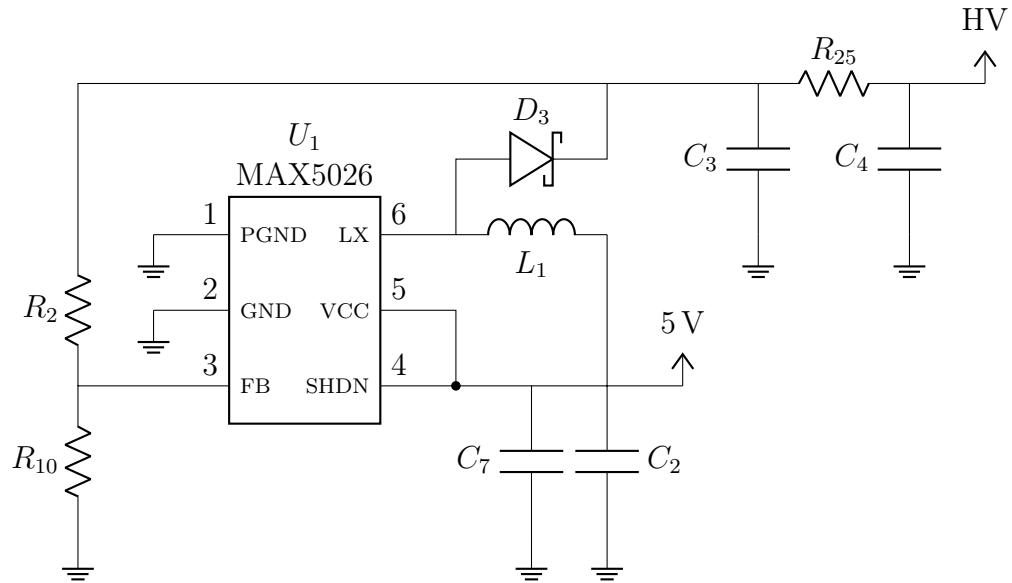


Figura 5-8: DC to DC booster circuit. Careful considerations have to be made when placing the MAX5026 IC in order to reduce noise on the power line. It is advised to have a look at the datasheet in [2], section ".Applications Information".

According to Onsemi [7], the operating voltage of a MicroFJ-300XX-TSV SiPM is 25.2-30.7 V. It is then necessary to boost V_{cc} to the operating range of the SiPM, noted as HV in Fig. 5-8. In order to achieve this, a MAX5026 PWM Step-Up DC-DC Converter is used [2], which has a user-adjustable output voltage of up to 36 V using external feedback resistors.

In the circuit shown in Fig. 5-8, R_{10} and R_2 determine the output voltage HV. According to [2], equation (5-2) allows to calculate the value of R_{10} given a desired output voltage HV and a value of R_2 between 5 and 50 k Ω .

$$R_{10} = R_2 \left(\frac{HV}{V_{REF}} - 1 \right) \quad (5-2)$$

5.6. Single photons

6 Geant4 Simulation

6.1. What is Geant4?

6.2. Geometry

6.3. Muons going through the scintillator

6.4. Photons collected vs. produced

6.5. Optimum SiPM placement

6.6. Simulated Spectra

7 Measurements

7.1. Rohde&Schwarz RTO6 oscilloscope

7.2. CosmicWatch electronics

7.3. NIM

8 Ongoing work and future directions

8.1. Odd features in Cesium spectra

8.2. Adding LYSO radioactivity to Geant4

9 Conclusion

A RaspberryPi Pico code

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