



DEVELOPMENT OF A TWO-DIMENSIONAL TRACKER WITH  
PLASMA PANEL DETECTORS

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## ABSTRACT

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Plasma panel sensors are micropattern gaseous radiation detectors which are based on the technology of plasma display panels. This thesis summarizes the research that had been done on commercially available plasma display panels that were converted to plasma panel sensor prototypes and describes the construction of a two-dimensional tracker consisting of four of those prototypes, with one-dimensional readout on each, used to detect tracks of cosmic muons. A large amount of 2-point as well as 3 and 4-point tracks were detected. Qualitative analyses as well as Pearson's  $\chi^2$  tests are performed on the track angular distribution and on a histogram of the linearity measure of 3-point tracks to reject the hypothesis that these tracks result from completely random panel hits. Some RF noise effects contributing to false positives are ruled out, while it is shown that other effects can be ruled out only with a high-intensity minimum ionizing particle source.

A significant part of the tracker construction was the development of a software toolbox to acquire and analyze signals coming from plasma panel sensor devices, which enables long-term monitoring of various aspects of the experiment. The software can be used in future tracking experiments and in other scenarios of data acquisition from plasma panel sensor devices. The software architecture and pulse detection algorithm are herein described.



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# CONTENTS

---

|       |                                                                    |    |
|-------|--------------------------------------------------------------------|----|
| 1     | INTRODUCTION                                                       | 1  |
| I     | BACKGROUND                                                         | 3  |
| 2     | RELEVANT PHYSICAL BACKGROUND                                       | 5  |
| 2.1   | Radiation                                                          | 5  |
| 2.1.1 | Beta Radiation Source                                              | 5  |
| 2.1.2 | Cosmic Muons                                                       | 6  |
| 2.2   | Interaction Mechanism of Charged Particulate Radiation with Matter | 6  |
| 2.3   | Minimum Ionizing Particles                                         | 8  |
| 2.4   | Ionization in Gases, Relevant Processes and Terminology            | 8  |
| 2.4.1 | Interactions Between Electrons, Ions and Gas Particles             | 10 |
| 2.4.2 | Regions of Operation of Gaseous Particle Detectors                 | 11 |
| 2.5   | Signal Formation in Gas Detectors                                  | 16 |
| 2.6   | Relevant Detector Characteristics                                  | 17 |
| 2.6.1 | Dead Time                                                          | 17 |
| 2.6.2 | Spatial Resolution                                                 | 18 |
| 2.6.3 | Timing Resolution                                                  | 18 |
| 2.7   | Other Relevant Effects                                             | 18 |
| 2.7.1 | Scattering Effects                                                 | 18 |
| 2.7.2 | Background Radiation                                               | 19 |
| 3     | OVERVIEW OF PLASMA PANEL SENSORS                                   | 21 |
| 3.1   | Operational Principles of PDPs                                     | 21 |
| 3.2   | Converting PDP to PPS                                              | 22 |
| 3.3   | Summary of Vishay PDP Characteristics as a PPS device              | 24 |
| 3.3.1 | Selection of an Appropriate Gas Mixture                            | 24 |
| 3.3.2 | Pulse Shape                                                        | 25 |
| 3.3.3 | Quench Resistance and Dead Time                                    | 25 |
| 3.3.4 | Timing Resolution                                                  | 26 |
| 3.3.5 | Spatial Resolution                                                 | 26 |
| 3.3.6 | Constraints on the Efficiency of PDPs for Particle Detection       | 28 |
| 4     | PRELIMINARY THEORETICAL TRACKER ANALYSIS                           | 29 |
| 4.1   | PPS-Based Tracker                                                  | 29 |
| 4.2   | Expected Rate of a Tracker                                         | 29 |
| 4.2.1 | Rate of Muons through Two Vertically Aligned Planes                | 29 |

|            |                                                              |           |
|------------|--------------------------------------------------------------|-----------|
| 4.2.2      | Rate of Muons through Two or More Vertically Aligned Panels  | 31        |
| 4.2.3      | Expected Rate of a Tracker                                   | 31        |
| 4.3        | Rate of Random Coincidence                                   | 34        |
| 4.3.1      | Uncorrelated Random Coincidence Rate                         | 34        |
| 4.3.2      | Random Coincidence from Correlated Noise                     | 38        |
| 4.4        | Monte Carlo Simulation of the Tracker                        | 38        |
| 4.5        | Analysis of Tracks                                           | 41        |
| 4.5.1      | 2-Point Tracks                                               | 42        |
| 4.5.2      | 3-Point Tracks                                               | 45        |
| <b>II</b>  | <b>EXPERIMENTAL PROCEDURE</b>                                | <b>47</b> |
| 5          | PREPARATION OF THE PANELS, ELECTRONICS AND THE TRACKER SETUP | 49        |
| 5.1        | Preparation of the Panels                                    | 49        |
| 5.2        | Selection of Gas Mixture and Pressure                        | 50        |
| 5.3        | RO and HV Supply Cards                                       | 51        |
| 5.4        | Determination of Operating Voltage                           | 53        |
| 5.5        | Tracker Setup                                                | 55        |
| 5.6        | Terminology                                                  | 56        |
| 6          | DAQ USING TIME MULTIPLEXING                                  | 59        |
| 6.1        | DAQ Equipment                                                | 59        |
| 6.2        | Implementation                                               | 59        |
| 6.3        | Observation of the First Suspected Track                     | 63        |
| 7          | DAQ USING A DIGITIZER                                        | 67        |
| 7.1        | Digitizer-PC interface                                       | 67        |
| 7.2        | Digitizer-Panel Interface                                    | 67        |
| 7.3        | Trigger Setup                                                | 68        |
| 7.4        | Acquisition and Analysis Software                            | 68        |
| 7.4.1      | Architecture                                                 | 69        |
| 7.4.2      | Primary Pulse Tagging                                        | 69        |
| 7.4.3      | Analysis and Monitoring Modules                              | 73        |
| 7.4.4      | Panel Hit Monitor                                            | 73        |
| 7.4.5      | Panel Timing Monitor                                         | 73        |
| 7.4.6      | Panel Degradation Monitor                                    | 73        |
| 7.4.7      | Track Monitor                                                | 74        |
| 7.4.8      | Configuration                                                | 74        |
| <b>III</b> | <b>ANALYSIS OF RESULTS &amp; CONCLUSIONS</b>                 | <b>75</b> |
| 8          | RESULTS                                                      | 77        |
| 8.1        | Monitoring                                                   | 77        |
| 8.1.1      | Monitoring the Trigger Rate and Arrival Time Distribution    | 77        |
| 8.1.2      | Monitoring Panel Activity                                    | 78        |
| 8.1.3      | Monitoring and Analyzing Signal Waveforms                    | 81        |
| 8.2        | Analysis                                                     | 83        |
| 8.2.1      | Effects of Panels on Scintillators and Vice-Versa            | 85        |

|       |                                    |     |
|-------|------------------------------------|-----|
| 8.2.2 | Effect of Panels on Each Other     | 85  |
| 8.2.3 | 2-Point Tracks                     | 87  |
| 8.2.4 | 3-Point Tracks                     | 89  |
| 9     | CONCLUSIONS                        | 91  |
| IV    | APPENDIX                           | 93  |
| A     | DATA ACQUISITION SYSTEM            | 95  |
| A.1   | Triggering and DAQ Overview        | 95  |
| A.1.1 | Scintillator Trigger               | 95  |
| A.2   | DAQ Equipment Standards            | 96  |
| A.2.1 | NIM                                | 96  |
| A.2.2 | ECL                                | 96  |
| A.2.3 | VME                                | 97  |
| A.3   | DAQ Equipment                      | 98  |
| A.3.1 | Discriminator Units                | 98  |
| A.3.2 | Fan-In-Fan-Out Units               | 98  |
| A.3.3 | Coincidence Units                  | 98  |
| A.3.4 | Timer Units                        | 99  |
| A.3.5 | NIM to ECL Converter               | 99  |
| A.3.6 | Digital Oscilloscope               | 99  |
| A.3.7 | Digitizer                          | 99  |
| A.4   | Impedance Matching and Termination | 100 |
|       | BIBLIOGRAPHY                       | 103 |

## LIST OF FIGURES

---

|           |                                                                                  |    |
|-----------|----------------------------------------------------------------------------------|----|
| Figure 1  | Energy loss distribution for minimum ionizing particles                          | 9  |
| Figure 2  | Gaseous detector working modes                                                   | 12 |
| Figure 3  | Townsend coefficient                                                             | 13 |
| Figure 4  | Streamer formation                                                               | 15 |
| Figure 5  | Gaseous detector cell wiring schematic                                           | 16 |
| Figure 6  | PDP structure                                                                    | 21 |
| Figure 7  | Vishay panel photograph                                                          | 23 |
| Figure 8  | Vishay panel schematic                                                           | 23 |
| Figure 9  | Pulse from Vishay panel                                                          | 25 |
| Figure 10 | Vishay quench resistance plot                                                    | 26 |
| Figure 11 | Vishay pulse arrival time distribution                                           | 27 |
| Figure 12 | Vishay hit map distribution                                                      | 27 |
| Figure 13 | Two parallel planes representing the topmost and bottom-most panels in a tracker | 30 |
| Figure 14 | Pulse and acquisition window widths                                              | 36 |
| Figure 15 | Tracker rendering                                                                | 40 |
| Figure 16 | Closeup of rendered panels                                                       | 41 |
| Figure 17 | Definition of $\chi$ , $\xi$ angles                                              | 42 |
| Figure 18 | First geometric effect distorting the track angular distribution                 | 43 |
| Figure 19 | Monte Carlo generated track angular distribution                                 | 44 |
| Figure 20 | Second geometric effect distorting the track angular distribution                | 45 |
| Figure 21 | Third geometric effect distorting the track angular distribution                 | 46 |
| Figure 22 | Photograph of a panel attached to a tray                                         | 49 |
| Figure 23 | Effect of gas mixture on after pulsing                                           | 50 |
| Figure 24 | Photograph of a HV card                                                          | 51 |
| Figure 25 | Photograph of a RO card                                                          | 52 |
| Figure 26 | RO card schematic of a single line                                               | 52 |
| Figure 27 | Photograph of a flat-to-LEMO adapter                                             | 53 |
| Figure 28 | Voltage scan plot                                                                | 54 |
| Figure 29 | Photograph of the tray holder for the tracker                                    | 55 |
| Figure 30 | Photograph of the tracker setup                                                  | 56 |
| Figure 31 | Schematic of trigger and DAQ implementation for time multiplexing                | 60 |
| Figure 32 | Expected signals with time multiplexing                                          | 60 |
| Figure 33 | Screenshot of after pulsing on scope                                             | 61 |

|           |                                                                                       |    |
|-----------|---------------------------------------------------------------------------------------|----|
| Figure 34 | Photograph of panel alignment method with time multiplexing                           | 62 |
| Figure 35 | Scope screenshot of analog pulse and a resulting digital pulse with time multiplexing | 63 |
| Figure 36 | Scope screenshot of a track candidate with time multiplexing                          | 64 |
| Figure 37 | Schematic of acquisition and trigger implementation with time multiplexing            | 65 |
| Figure 38 | VME DAQ schematic description                                                         | 68 |
| Figure 39 | Normalization of waveforms                                                            | 70 |
| Figure 40 | Healthy trigger timing monitor output                                                 | 77 |
| Figure 41 | Trigger timing monitor output with a sudden rise in room temperature                  | 78 |
| Figure 42 | Healthy panel degradation monitor output                                              | 79 |
| Figure 43 | Leaking panel degradation monitor output                                              | 79 |
| Figure 44 | Timing histogram for a single healthy panel                                           | 80 |
| Figure 45 | Timing histogram of all lines on a single panel                                       | 80 |
| Figure 46 | Healthy panel hit monitor output                                                      | 81 |
| Figure 47 | Bad panel hit monitor output                                                          | 82 |
| Figure 48 | Waveform display example                                                              | 82 |
| Figure 49 | Single panel waveform and primary pulse tagging                                       | 83 |
| Figure 50 | Example of waveform with bad electric connection                                      | 84 |
| Figure 51 | Schematic of setup used to rule out PMT-panel effects                                 | 85 |
| Figure 52 | Hit rate plot used to analyze panel-panel effects                                     | 86 |
| Figure 53 | Measured track angle-distance distribution                                            | 88 |
| Figure 54 | Measured track angular distribution                                                   | 88 |
| Figure 55 | Monte Carlo track angular distribution for random hits                                | 89 |
| Figure 56 | Measured track $\chi^2$ /NDF distribution                                             | 89 |
| Figure 57 | Monte Carlo track $\chi^2$ /NDF distribution for random hits                          | 90 |
| Figure 58 | A NIM crate with NIM modules                                                          | 96 |
| Figure 59 | VME crate with digitizer and bridge                                                   | 97 |

## LIST OF TABLES

---

|         |                                                            |    |
|---------|------------------------------------------------------------|----|
| Table 1 | Some pure $\beta^-$ sources                                | 6  |
| Table 2 | Characteristics of ionization by MIPs in various materials | 10 |

|          |                                                                         |    |
|----------|-------------------------------------------------------------------------|----|
| Table 3  | Typical characteristics for various detector types                      | 17 |
| Table 4  | Vishay panel characteristics                                            | 24 |
| Table 5  | Parameters used in theoretical track rate calculation                   | 33 |
| Table 6  | Expected track rates                                                    | 33 |
| Table 7  | Parameters used in the Monte Carlo simulations                          | 39 |
| Table 8  | Cable lengths used in time multiplexing DAQ implementation              | 65 |
| Table 9  | Modules and their settings used in time multiplexing DAQ implementation | 66 |
| Table 10 | Values of thresholds for pulse analysis                                 | 74 |

## INTRODUCTION

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Plasma panel sensors (PPS) are a type of micropattern gaseous radiation detectors under development based on plasma display panels (PDP), having numerous advantages over the currently available detectors the most significant of which are the low price due to being supported by an industrial infrastructure of PDPs and the lack of necessity in external gas flow-supply systems, which are used in today's gaseous detectors.

While research and development of newer generations of PPS devices is underway (first results from the microcavity-type PPS device can be found in [1]), a lot of research has been done on the characteristics of commercially available PDP devices as PPS prototypes. As part of this research a proof-of-concept two-dimensional tracker for detection of minimum ionizing particles (MIPs) was designed and constructed from modified commercially available PDPs, with one-dimensional readout on each and is described in this thesis.

The structure of the thesis is as follows:

- Chapter 1 - this introduction.
- Chapter 2 - relevant physical background. Discusses radiation and interaction of radiation with matter in general, lists and describes radiation sources used in this work, explains the process of ionization in gases and the various gaseous detector working modes, talks about signal formation and characteristics of gaseous detectors and some additional phenomena present in detectors.
- Chapter 3 - overview of plasma panel sensors. Describes the operational principles of PDPs, the modifications needed to convert a commercially available PDP to a PPS, briefly presents the research done on the PPS prototypes and summarizes the main results and conclusions of that research.
- Chapter 4 - preliminary theoretical tracker analysis. Describes the analysis done as a preparation before constructing the tracker. Presents a detailed computation of the expected track rate in a tracker with a given geometry, discusses possible noise sources, presents calculations of false positive rates and describes analysis that will be done on resulting track measurements.
- Chapter 5 - preparation of the panels, electronics and the tracker setup. Describes the process of preparing the panels, choosing the right gas mixture and high voltage (HV), preparing the HV

and readout (RO) cards and the construction of the physical tracker.

- Chapter 6 - data acquisition using time multiplexing. Describes a failed attempt at data acquisition, using a scope and a method of time multiplexing the various tracker layers into the digital inputs of the scope. Discusses why the attempt failed and presents the observed 'first track'.
- Chapter 7 - data acquisition using a digitizer. Describes the second, successful attempt to acquire data using a VME digitizer. Presents the physical setup and gives a detailed description of the software that was developed for this purpose.
- Chapter 8 - results. Presents the acquired tracks in various forms and discusses them.
- Chapter 9 - conclusions.
- Appendix A - data acquisition (DAQ) overview and equipment. Describes the general process of data acquisition and discusses the various standards and tools used for it.

## Part I

### BACKGROUND



## RELEVANT PHYSICAL BACKGROUND

---

### 2.1 RADIATION

As this is a work on radiation detector development, it is appropriate to discuss radiation sources. Though throughout the experiments we will be using only two radiation sources - a ruthenium  $\beta$  source and energetic muons resulting from collisions of cosmic rays with atoms in the upper atmosphere, it's worthwhile to talk about radiation in general.

For most practical purposes, radiation can be categorized into 4 general types [2]:

- Fast electrons ( $\beta$  particles)
- Heavy charged particles, which are charged particles with a mass of around or greater than one atomic mass unit, such as protons and  $\alpha$  particles
- Electromagnetic radiation, comprised of photons in different energy ranges (such as X-rays, which is electromagnetic radiation with energies in the range of 100 eV - 100 keV and  $\gamma$ -rays, which is the same radiation with energies greater than 100 keV)
- Neutrons.

In this work, two sources of radiation are used.

#### 2.1.1 Beta Radiation Source

Mediated by the weak force,  $\beta$  decay of a nucleus results in a negative or positive  $\beta$  particle ( $\beta^-$ ,  $\beta^+$ ), which is an energetic electron or positron that accompanies a transformation of a neutron to a proton or vice versa, respectively, inside a nucleus. In addition to the emitted electron or positron, a neutrino is also emitted, but we almost never see a neutrino using conventional detection techniques. The  $\beta$  particle shares it's energy with said neutrino and therefore it's energy is spread in a range between it's rest mass and the  $Q$ -value of the  $\beta$  source, which is the energy of this particular beta decay transition.

Most  $\beta$  sources do not decay directly to the ground state of the product, but do so in two stages, the first one being the  $\beta$  decay and the subsequent one resulting in an emission of a  $\gamma$ -ray. Some pure  $\beta^-$  sources, that decay straight to a stable state, are given in table 1.

In the current work we used ruthenium ( $^{106}\text{Ru}$ ), a pure  $\beta^-$  emitter with a  $Q$ -value of 39.4 keV. This isotope of ruthenium has a half-life

Table 1: Some pure  $\beta^-$  sources [2]

| Nuclide           | Half-Life             | Q-value<br>(MeV) |
|-------------------|-----------------------|------------------|
| $^3\text{H}$      | 12.26 y               | 0.0186           |
| $^{14}\text{C}$   | 5730 y                | 0.156            |
| $^{32}\text{P}$   | 14.28 y               | 1.710            |
| $^{33}\text{P}$   | 24.4 d                | 0.248            |
| $^{35}\text{S}$   | 87.9 d                | 0.167            |
| $^{36}\text{Cl}$  | $3.08 \times 10^5$ y  | 0.714            |
| $^{45}\text{Ca}$  | 165 d                 | 0.252            |
| $^{63}\text{Ni}$  | 92 y                  | 0.067            |
| $^{90}\text{Sr}$  | 27.7 y                | 0.546            |
| $^{99}\text{Tc}$  | $2.212 \times 10^5$ y | 0.292            |
| $^{147}\text{Pm}$ | 2.62 y                | 0.224            |
| $^{204}\text{Tl}$ | 3.81 y                | 0.766            |

of about 1 year and decays to  $^{106}\text{Rh}$ , which is also a pure  $\beta^-$  emitter with a Q-value of 3.541 MeV and a half-life of about 30 seconds, decaying into a stable  $^{106}\text{Pd}$  [3]. We should therefore expect to have electrons with energies up to 3.541 MeV from this source.

#### 2.1.2 Cosmic Muons

Muons are created in the upper layers of the atmosphere in collisions of atmospheric particles with cosmic rays. Their life time is very short, but due to relativistic time dilation a large fraction of the atmospheric muons reaches sea level. Their average energy at sea level is about 4 GeV [3]. Since the muon's rest mass is  $\sim 0.1$  GeV, the muon is very energetic and is thus a minimum ionizing particle [3] (MIP, see section 2.3).

The incidence rate of muons at sea level is approximated by the empirical formula

$$\Phi(\theta) = \Phi_0 \cos^2(\theta), \quad (1)$$

where  $\theta$  is the polar angle from the zenith and  $\Phi_0 = 0.0083 \text{ cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$  [4].

## 2.2 INTERACTION MECHANISM OF CHARGED PARTICULATE RADIATION WITH MATTER

The operation of a particle detector is based on the interaction mechanism between the particle and the material of the detector. The de-

tectors in this work are gaseous detectors of charged particulate radiation ( $\beta$  particles and muons), so I will describe the nature of interaction between charged radiation and matter in general and of charged particulate radiation with gases in particular.

A charged particle interacts through the Coulomb force with the orbital electrons present in the material of a detector and the positively charged nuclei. Generally, for different types of charged particles at intermediate projectile velocities ( $0.1 \lesssim \beta\gamma \lesssim 1000$ ) and intermediate values of the absorber medium's atomic number, the energy loss is governed by the Bethe-Bloch formula [2] [3].

$$-\frac{dE}{dx} = \frac{4\pi e^4 z^2}{m_e v^2} N Z \left[ \ln \left( \frac{2m_e v^2}{I} \right) - \ln(1 - \beta^2) - \beta^2 \right],$$

where the minus on the left-hand side makes the expression positive and the parameters are

$ze$  - charge of the particle,

$v$  - velocity of the particle,

$\beta \equiv v/c$ ,

$N$  - density of atoms in the medium,

$Z$  - atomic number of atoms in the medium,

$m_e$  - electron rest mass,

$I$  - average excitation and ionization potential of the atoms in the medium.

From this form of the expression, we can see that the energy loss of a particle is greater for lower velocities of the charged particle, higher atomic numbers and higher atom density of the absorbing medium and a higher charge of the particle.

The loss of energy of charged particles in matter is due to either *ionization* (removal of orbital electrons from the atom) and *excitation* (transition of an electron to a higher-level shell) of atoms in the medium, collectively termed as *collisional losses* or radiative effects, such as bremsstrahlung, which is the emission of photons by energetic charged particles due to their deceleration [2]. Which one of the effects dominates for a given absorber material, depends on the energy and type of the projectile particle. For muons and electrons, we can define the *critical energy* of the projectile, at which the contributions of radiative and of collisional losses to the total energy loss are equal [3] and therefore for electrons and muons with energies significantly lower than their corresponding critical energies, energy loss would be primarily due to ionization and excitation. For muons, the critical energy ranges between hundreds of GeV for absorbers with high atomic numbers to thousands of GeV for those with low ones, while for electrons, the critical energy ranges from a few MeV for high atomic numbers to a

few tens of MeV for low ones [5] [3]. We can approximate the ratio between the energy loss due to radiation and the one due to ionization and excitation by

$$\frac{(dE/dx)_r}{(dE/dx)_c} \approx \frac{ZE}{700},$$

with E having units of MeV [2]. For our purposes, typical energies of  $\beta$  particles are below 5 MeV, typical energies of muons are 4 GeV and Z is of the order of 10, so radiative losses are negligible.

Worth mentioning is an occasional by-product of a close encounter of a charged particle with an orbital electron. When this encounter is close enough, the atom in which the orbital electron resides can be ionized and the free electron could have enough kinetic energy to create further ions. These electrons are called *delta rays* and they represent an indirect means by which the charged particle deposits its energy in the medium.

### 2.3 MINIMUM IONIZING PARTICLES

Looking at the distribution of the energy loss as a function of incident charged particle velocity in different materials (figure 1), we can see that it's very high for low velocity particles, reaches a minimum at a certain point and then slightly increases. The low end high energy loss is due to the charged particle feeling the effect of each electron in the medium for a long time and thus losing more energy in Coulomb interactions [2]. The energy loss decreases until a minimum is reached and increases after that point due to relativistic effects [3]. Note that the increase after the minimum has a weak dependence on the velocity of the particle and we can therefore say that in the velocity range around the minimum and above, the particle is a *minimum ionizing particle (MIP)*, since its energy loss in any material is close to minimal. An interesting thing to note is that the energy loss for MIPs in materials with very different atomic masses such as lead and hydrogen is of the same order of magnitude and the MIP regime incidence point is exactly the same for the entire range of materials given in figure 1 for any given particle. A MIP is therefore a 'universal' concept, not depending on the material through which it passes, so we don't need to specify this information when talking about them. We can say that on average, MIPs lose around  $1.5\text{-}2 \text{ MeVg}^{-1}\text{cm}^2$  when passing through matter [6].

### 2.4 IONIZATION IN GASES, RELEVANT PROCESSES AND TERMINOLOGY

Throughout this discussion, we assume a simple geometry of a parallel plate capacitor filled with gas and a voltage difference between

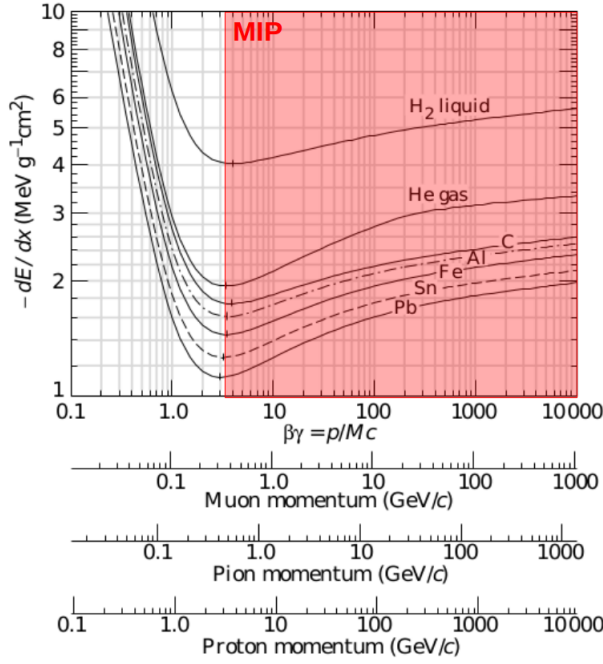


Figure 1: A plot of the energy loss as a function of particle velocity for different particles and different materials. The colored area is the velocity range where a particle is considered to be minimum ionizing [3].

the plates. The general idea of an *ionization chamber* like this is that a charged particle passing through this chamber ionizes atoms in the gas, creating pairs of positive ions and electrons, which, under the influence of the electric field between the plates, drift towards the corresponding electrodes creating a signal that can be read out by suitable electronics.

A charged particle passing through the gas excites or ionizes atoms along its way, producing  $n_p$  primary ion-electron pairs. Electron members of some pairs which have an energy in excess of 100 eV can ionize further atoms and liberate more electrons in the process. Assuming that  $W_i$  is the average energy loss per ion pair produced, the total number of ion pairs produced is

$$n_T = \frac{\Delta E}{W_i},$$

where  $\Delta E$  is the energy loss of the particle inside the gas. Values of  $W_i$ ,  $n_T$  and  $n_p$  for several gases are shown in table 2.

As some atoms become excited and not ionized, the energy fraction of the ionizing particle that went into their excitation is lost, in the sense that it does not contribute to the number of free charges in the gas and therefore to the number of charges collected at the electrodes. For that reason, a gas mixture called a *Penning mixture* is often used in gaseous radiation detectors, which is comprised of two species of gas, the secondary one having a lower ionization potential than the

Table 2: Tables of average energy loss per ion pair  $W_i$ , number of primary ion pairs  $n_p$  and total ion pairs  $n_T$  produced for MIPs, for several gases at STP [7]

| Gas                            | $W_i$ (eV) | $n_p$ (cm <sup>-1</sup> ) | $n_T$ (cm <sup>-1</sup> ) |
|--------------------------------|------------|---------------------------|---------------------------|
| H <sub>2</sub>                 | 37         | 5.2                       | 9.2                       |
| He                             | 41         | 5.9                       | 7.8                       |
| N <sub>2</sub>                 | 35         | ~10                       | 56                        |
| O <sub>2</sub>                 | 31         | 22                        | 73                        |
| Ne                             | 36         | 12                        | 39                        |
| Ar                             | 26         | 29.4                      | 94                        |
| Kr                             | 24         | ~22                       | 192                       |
| Xe                             | 22         | 44                        | 307                       |
| CO <sub>2</sub>                | 33         | ~34                       | 91                        |
| CH <sub>4</sub>                | 28         | 16                        | 53                        |
| C <sub>4</sub> H <sub>10</sub> | 23         | ~46                       | 195                       |

primary. When an excited atom of the primary gas collides with an atom of the secondary gas, the latter is ionized and the resulting free charges are collected by the electrodes. We can thus ‘see’ the energy that went into exciting the primary atom.

#### 2.4.1 Interactions Between Electrons, Ions and Gas Particles

Regardless of field strength, positive ions and electrons will move due to thermal energy. As such, they will experience collisions and will tend to diffuse from high to low concentrations. When there is no electric field or at very weak fields (region I on figure 2), all ion pairs will undergo *recombination*, which is a process where a positive ion neutralizes by recombining with a free electron or exchanging electrons with a negative ion. This process depends on the density of positive and negative particles in the gas and the equation governing it is, naturally,

$$\frac{dn^-}{dt} = \frac{dn^+}{dt} = -\alpha_r n^+ n^-,$$

where  $n^+, n^-$  are the densities of positive ions and negative particles, respectively and  $\alpha_r$  is the *recombination coefficient*. This process takes place also at higher electric fields, but in that case not all ions recombine. An ion pair created by a passing charged particle that recombines does not contribute to the charge that is collected at the electrodes and therefore to the resulting signal, so this is an unwanted effect.

Another mechanism of interaction between gas particles and electrons is *electron capture*. This is a process where molecules with several atoms accumulate low energy electrons, turning into negative ions, which behave similarly to the positive ions, but with an opposite sign. Being 'bulkier', the negative ions have a factor of 1000 lower mobility than the electrons [2], so they will affect the shape of the signal, since the free electrons in the gas will collect faster to the anode, followed by the slower negative ions. The probability for electron capture is especially high in electronegative gases such as oxygen and water vapor. A contaminating electronegative gas could significantly decrease the average time until electron capture in gases and thus adversely affect signal formation. Another reason why we should minimize electron capture is the fact that normally, the recombination coefficient between positive and negative ions is orders of magnitude larger than between positive ions and electrons [8], causing us to lose charge carriers to recombination instead of them participating in signal formation.

Another process of ions in gases is *charge transfer*, which is the transfer of an electron from a neutral to a positive ion through a collision, swapping the charges of the two. This effect is particularly significant in mixtures of gases, in which the net positive charge is transferred to the species with the lowest ionization energy.

#### 2.4.2 Regions of Operation of Gaseous Particle Detectors

The full range of possible electric fields at which the gas detector can operate can be subdivided into several regions, depending on the behavior of the charge carriers in the gas, as shown on figure 2.

When we increase the electric field above zero, the positive ions and electrons will start drifting towards the cathode and anode, respectively and will be collected there. At some point further small increases in the field will not significantly affect the collected charge at the electrodes. This region is called the *ion saturation* or *ionization chamber* region.

Above a certain value of the field (typically  $10^6$  V/m), the electrons will gain enough kinetic energy between collisions to create further ion-pairs. Thus, *Townsend avalanches* are formed, where free electrons ionize atoms, producing electrons which ionize further atoms and so on. The rise in charge carriers is exponential and can be characterized by the *first Townsend coefficient*  $\alpha$ . The change in the number of electrons with distance is governed by the equation

$$\frac{dn}{dx} = \alpha n$$

the solution of which is  $n(x) = n(0)e^{\alpha x}$ , assuming a simple case where  $\alpha$  does not depend on  $x$ . This way, the charge originating from primary ion pairs is amplified by the *gas amplification factor*  $A \equiv e^{\alpha x}$ .

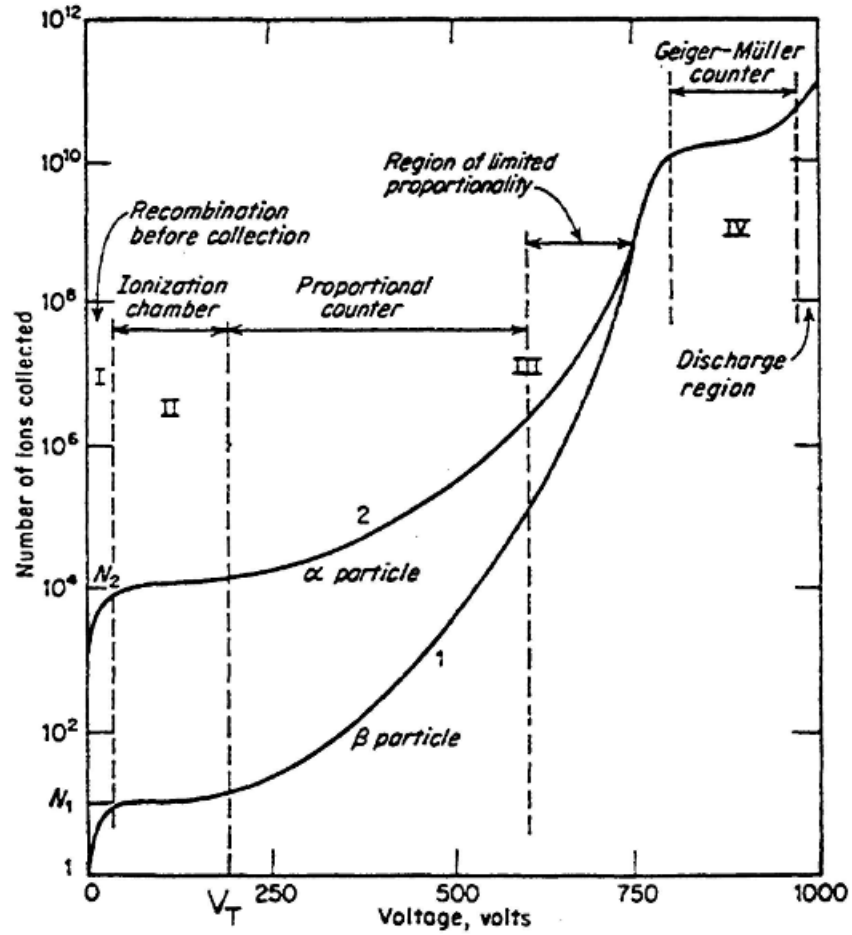


Figure 2: A plot of the number of ion pairs produced vs. the voltage applied between them for two particles types ( $\alpha$  and  $\beta$ ). Various regions of operation are marked [9].

This is called the *proportional region* and is characterized by a linear relation between the applied field and the collected charge with a proportionality factor  $A$ . In this region of operation,  $\alpha$  and therefore also  $A$  increase with voltage (figure 3). The reason for this increase are atoms that were not ionized but excited, which emit UV photons when they return to their ground states. These UV photons can cause further ionization by interacting with the gas or with the material of the cathode, producing electrons, called *photoelectrons*. If  $n_0$  electrons are formed in the primary ionization,  $An_0$  electrons will be produced and collected after the previously mentioned amplification, which will cause  $An_0\gamma$  photoelectrons to be produced in the gas, with  $\gamma \ll 1$ . These will in turn be accelerated by the field and amplified by the factor  $A$ , creating  $A^2n_0\gamma$  electrons, which are collected and which cause a further  $A^2n_0\gamma^2$  photoelectrons to be produced and  $A^3n_0\gamma^2$  electrons to be collected and so on. The gas amplification factor in-

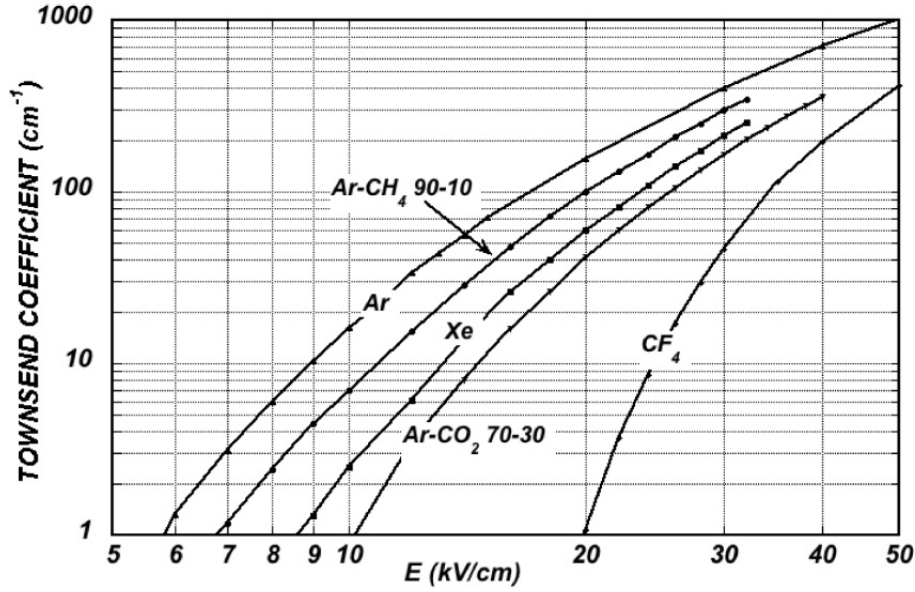


Figure 3: A plot showing the rise in the value of  $\alpha$  as a function of electric field strength for various gases [9].

cluding the contribution of photons  $A_\gamma$  is given by the sum over this iterative process of all collected electrons:

$$n_0 A_\gamma = n_0 A \sum_{n \geq 0} (A_\gamma)^n = \frac{n_0 A}{1 - A_\gamma}. \quad (2)$$

Above a certain value of the field, we enter the *region of limited proportionality*, where the relation between the applied electric field and the collected charge is very non-linear. The main reasons for this non-linearity are the factor  $A_\gamma$  in eq. (2) approaching 1, meaning that the contribution of photoelectrons to the signal is greater than the contribution of the primary electrons and the accumulation of positive ions in the gas. Since positive ions are about a 1000 times less mobile than electrons, they accumulate with each ionization while slowly (relative to electrons) drifting towards the cathode. Since the creation of avalanches depends on the magnitude of the electric field, which is diminished by the presence of the positive ions, which are created in avalanches, this will introduce higher order effects and non-linearity.

As we increase the electric field further, we enter the *Geiger-Mueller* region of operation. Here, the eventual amount of produced electrons does no longer have a distinguishable dependence on the number of ion pairs produced in the primary ionization event. In addition, the cloud of positive ions that is left over, slowly drifting towards the cathode, diminishes the field in the space between it and the anode and brings it to a low enough value to terminate the discharge. These effects cause the amplitude of the resulting pulse due to the collected electrons at the anode to be of uniform height, regardless of the number of primary ion pairs.

Still in the same region, if the detector is filled with a single gas, all positive ions that are created are of the same species and they slowly drift toward the cathode under the influence of the electric field. When the ions reach the cathode, they mostly recombine with electrons from its surface, but an energetic ion has a non-zero probability of releasing a free electron from the surface of the cathode into the gas volume. Once that happens, the electron will be accelerated towards the anode, creating avalanches and initiating a new discharge. This is an unwanted side effect of the discharge process in gaseous particle detectors causing the readout to show additional pulses after the primary pulse. This effect is known as *multiple pulsing*. To get an idea of the characteristic time intervals between a primary and a secondary pulse in a multiple pulsing scenario, we can use typical values of drift velocities of positive ions, which can in turn be calculated from typical electric field values and the mobility of positive ions in their own gas at standard temperature and pressure (STP). The drift velocity is defined by the mobility  $\mu$ , pressure of the gas  $p$  and the strength of the electric field  $\mathcal{E}$  through the relation

$$v = \mu \mathcal{E} \frac{p_0}{p},$$

where  $p_0 = 1$  atm. For example, the mobility of positive argon ions in argon at STP is  $\mu = 1.7 \text{ cm}^2 / (\text{V} \cdot \text{s})$  [8]. For a potential difference between the electrodes of 1300 V and a gas gap of 0.5 mm, which are the parameters used in our experiment, we can expect an interval of zero to around one microsecond between a primary and a secondary pulse. In order to minimize this phenomenon, we should *quench* the discharge by one (or both) of two methods. The first method is connecting a high-value resistor  $R$ , called a *quench resistor*, in series with the detector element, so that when a discharge is initiated, a current  $I$  will flow through it, causing a voltage  $IR$  to build across it, reducing the voltage drop between the electrodes and thus stopping the discharge. The resulting circuit is an RC circuit with a time constant  $\tau = RC$ . The resistance  $R$  must be large enough, so that  $\tau$  is long enough to keep the electric field between the electrodes low enough to let the positive ions recombine before reaching the cathode. Another method is mixing the primary gas in the detector with a *quenching gas*. This mixture is comprised of a primary gas and a second gas with a lower ionization potential and a more complex molecular structure. When positive ions of the primary gas are formed in an avalanche, they drift towards the cathode, while colliding with other atoms. When a collision between such an ion and an atom of the quenching gas occurs, charge is transferred from the quenching gas atom to the positive ion, neutralizing the ion. Now, instead of the original positive ion, a positive ion of the quenching gas will reach the cathode. If the concentration of the quenching gas is high enough, all ions reaching the cathode will be of the quenching gas and after

being neutralized there, the excess energy will go into disassociating the quench gas instead of releasing an electron from the cathode. A quench gas can be chosen so that the gas constituents recombine back into the original quench gas after disassociation, so that the gas is not gradually consumed. A similar mixture is also used in proportional mode, where the quenching gas has a different role of absorbing UV photons before they create photoelectrons.

As we further increase the electric field, structures called *streamers* will begin forming in the gas. This region is not seen on figure 2 and is to the right of the Geiger-Mueller region. When an avalanche is underway, the electrons, as mentioned earlier, quickly drift towards the anode leaving behind a cloud of positive ions, forming a net positive charge in the center of the avalanche (figure 4). At the same

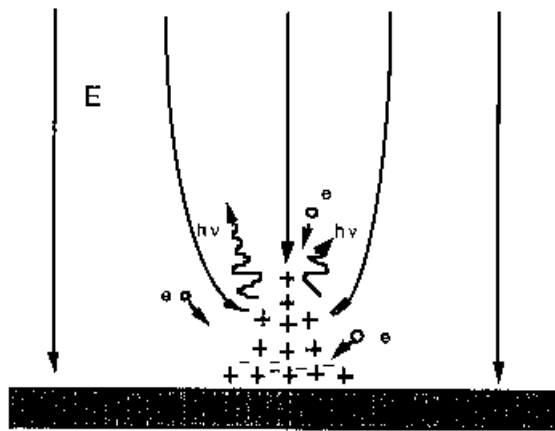


Figure 4: Schematic drawing of streamer formation [10].

time, photoelectrons are formed in the vicinity of the avalanche. If the value of the radial electric field formed between the photoelectrons and the positive ions in the center of the avalanche (this field is in a direction roughly perpendicular to the electric field between the electrodes and its field lines are pointing from the center of the avalanche outwards, thus its radial to the direction of the avalanche) is close to the value of the field between the electrodes, the photoelectrons, rather than being pulled towards the anode, will be pulled towards the avalanche center, forming a conducting filament [11]. In addition, the spatial distribution of the positively charged ions left behind after an avalanche is of conic shape, with the tip located at the tip of the avalanche. The electric field is thus very large at the tip of the avalanche, causing further avalanches to be formed in that region, extending the streamer towards the cathode. This way, a conducting filament propagates from the anode to the cathode, causing complete discharge of our parallel-plate capacitor-structured detector once the filament connects the two electrodes. A quench gas may be added to keep the number of streamers formed to a minimum. The

development time of such streamers is very fast (up to hundreds of nanoseconds [11]). The threshold for the onset of the streamer phase is the *Raether limit* [12]:

$$\text{Raether limit: } \sim 10^6 - 10^7 \text{ electrons.} \quad (3)$$

If the number of electrons produced in an avalanche is above it, the aforementioned space charge effects will be significant enough to form streamers. Note that officially, the Raether limit, as established by H. Raether in 1939 for large-gap parallel-plate detectors, is  $\sim 10^8$  electrons [13], but for small-gap micropattern-type detectors this limit is lower.

## 2.5 SIGNAL FORMATION IN GAS DETECTORS

In the proportional mode of gas detectors, the signal consists of two components - the fast electron component caused by the collection of electrons by the anode and the slower ion component, caused by the slow positive ions collected by the cathode. At very high voltage differences between the electrodes, a complete breakdown occurs, through a formation of a streamer from the anode to the cathode. Since the formation of the streamer is very fast, the signal we expect in this case is a narrow pulse resulting from the discharge of our parallel-plate capacitor-structured detector through the gas between the electrodes (see section 3.3.2 for an example). If we wire the detector as shown on figure 5, where C is the detector as a parallel-plate

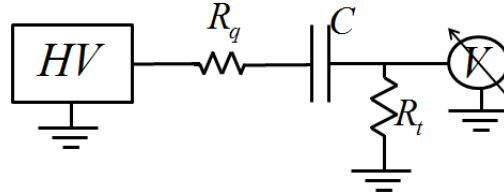


Figure 5: Schematic of the RO and HV supply to a single detector cell (C).  $R_q$  is the quench resistance and  $R_t$  is the termination resistance [9].

capacitor,  $R_q$  is a quench resistance and  $R_t$  is a termination resistance across which the signal is read, the resulting voltage pulse will behave as

$$V_{\text{pulse}}(t) = I(t)R_t = \frac{dQ(t)}{dt}R_t. \quad (4)$$

A typical value used for the termination resistance in the readout electronics is  $R_t \sim 100 \Omega$ . From experiment, the pulse rise time is typically  $\Delta t \sim 1 \text{ ns}$  and the resulting voltage pulse is of the order of magnitude of  $V_{\text{pulse}} \sim 100 \text{ V}$  [9]. Plugging these values into eq. (4), we get  $\Delta Q = 10^{-9} \text{ C}$ , or  $\sim 10^{10}$  electrons, which is indeed higher than

Table 3: Typical characteristics for various detector types [3]

| Detector Type              | Spatial Res.          | Time Res. | Dead Time       |
|----------------------------|-----------------------|-----------|-----------------|
| Bubble chamber             | 10-150 $\mu\text{m}$  | 1 ms      | 50 ms           |
| Proportional counter       | 50-300 $\mu\text{m}$  | 2 ns      | 200 ns          |
| Silicon pixel detector     | < 10 $\mu\text{m}$    | few ns    | < 50 ns         |
| Liquid argon detector      | 175-450 $\mu\text{m}$ | 200 ns    | 2 $\mu\text{s}$ |
| Scintillation tracker      | 100 $\mu\text{m}$     | < 100 ps  | 10 ns           |
| Micropattern gas detectors | 30-40 $\mu\text{m}$   | < 10 ns   | 10-100 ns       |

the Raether limit (3). Therefore, the pulse is, as expected, a result of a complete discharge of the capacitor through a streamer.

This can also be seen by a very rough approximation of the detector capacitance. The capacitance is defined as  $C = \epsilon_r \epsilon_0 A/d$ , where  $\epsilon_r \sim 1$  is the relative permittivity of the gas,  $\epsilon_0 = 8.854 \cdot 10^{-12} \text{ F} \cdot \text{m}^{-1}$  is the vacuum permittivity,  $A \sim 1 \text{ mm}^2$  is the area of the cell and  $d \sim 0.5 \text{ mm}$  is the distance between the plates. From these values we get a capacitance of  $\sim 10 \text{ fF}$ . Through the relation  $C = Q/V$  and a typical value of applied HV  $V = 1000 \text{ V}$ , we get that the stored charge on the capacitor is  $Q \sim 10^{-11} \text{ C}$ , or  $10^8$  electrons, where approximately half is released in the discharge process [14]. The amount of charge is slightly above the Raether limit (3), but note that the actual capacitance in the type of detectors we are using is higher because it is constructed as a set of intersecting read-out and high-voltage electrodes, where each intersection defines a detector cell. The capacitance of each cell is therefore higher than the above calculation for an isolated cell, giving even more stored charge.

## 2.6 RELEVANT DETECTOR CHARACTERISTICS

We will now discuss three properties characterizing detectors working in the Geiger and discharge modes. In order to establish a benchmark for the values of these properties, typical values for a variety of particle detectors are given in table 3.

### 2.6.1 Dead Time

When a particle passes through a gas in a gaseous detector, various transient changes occur in the gas that reduce the detection efficiency.

In order for the detector to return to its initial state, where the detection efficiency is at its highest, it needs to undergo a 'cleanup' process, during which, for example, positive ions recombine and excited atoms return to their ground states. The time it takes for the detector to accomplish this is called the *dead time* of the detector. A contributing factor to the dead time may also be the external readout electronics.

Within one dead time of a single detection the detection efficiency is significantly diminished and therefore the dead time defines the maximum detection rate:

$$\text{Max. detection rate} = \frac{1}{\text{Dead time}}.$$

### 2.6.2 Spatial Resolution

The minimum distance between two locations where particles are simultaneously detected in the plane of the detector (assuming it's roughly planar) of which we can say with high certainty that they belong to two distinct hits by looking at the signal coming out of the detector is called the *spatial resolution* of the detector. We can define the spatial resolution more rigorously by examining the probability density that the incident particle passed through a certain point given that a signal came from another point. The standard deviation of that distribution would be a good measure of the spatial resolution.

### 2.6.3 Timing Resolution

The arrival time of a pulse at the readout end of the detector comes a certain amount of time after a particle passes through the detector. This time has a stochastic element to it and the arrival time is roughly a Gaussian with  $\mu$  as the mean arrival time and  $\sigma$  as the *timing resolution* of the detector. It's noteworthy that timing histograms of gaseous detectors, besides having a main Gaussian body, typically have an exponential tail extending towards the higher end of the arrival time values. This effect is due to primary ion-pair creation occurring in regions of space where the electric field is relatively low, which means a longer than usual drift time of the charges towards the electrodes.

## 2.7 OTHER RELEVANT EFFECTS

### 2.7.1 Scattering Effects

There are a couple of additional effects of the material a particle detector is made of on the incident radiation the particle is meant to detect. The first one is *back scattering*, which is a deflection of an incident particle by a large enough angle so that it goes back out of

the entrance window and therefore some or all of its energy is not deposited in the detector. This effect is significant primarily in low energy  $\beta$  radiation and high atomic number media, and is negligible for heavy, energetic particles such as cosmic muons. The second effect that should be kept in mind is *multiple scattering*, in which a particle passing through the detector is scattered several times via Coulomb interactions with electrons in the material, which results in the change of direction of travel of the particle between the one it had before entering the detector and the one it has after leaving it. This can be a major issue for tracking devices that are meant to reconstruct the trajectory of a particle without distorting it. In our case, however, we will be reconstructing tracks of MIPs, which are very energetic and thus only weakly affected by multiple scattering in the material.

### 2.7.2 Background Radiation

Unwanted background radiation is a source of noise in a detector. This radiation can originate from several sources, such as natural radioactivity or radioactive impurities in the construction materials of the lab and the detector, airborne dust particles or trace amounts of radioactive gases in the air and secondary cosmic radiation (mostly muons) [2]. The effect of such radiation on a tracker the detector elements of which have low efficiencies is mostly creation of uncorrelated random noise in those elements.



## OVERVIEW OF PLASMA PANEL SENSORS

A Plasma Display Panel (PDP) is a principal component of flat panel plasma television displays. The technology of PDPs is supported by an industrial infrastructure with four decades of development. Plasma Panel Sensors (PPS) is a new particle detector technology under development and it is based on PDP technology. The performance of a PPS detector is potentially comparable to the modern standards of particle detectors with additional advantages, such as low price, low power consumption and the fact that they are, just like PDPs, hermetically sealed with a non-degrading gas, so that the cumbersome gas re-circulation systems used in today's gaseous radiation detectors in high-energy particle physics experiments are rendered unnecessary [14]. PPS detectors fall into the subfamily of gaseous ionization detectors called *micropattern gaseous detectors*, which is a growing family of pixelized detectors, in which the active volume is comprised of small cells (pixels), each behaving as a separate gaseous detector.

### 3.1 OPERATIONAL PRINCIPLES OF PDPS

The most basic PDP is comprised of two sets of parallel electrodes deposited on two glass plates, attached together so that the electrodes on one glass plate are perpendicular to the ones on the other (figure 6). In between there is a gap that is filled with a suitable gas mix-

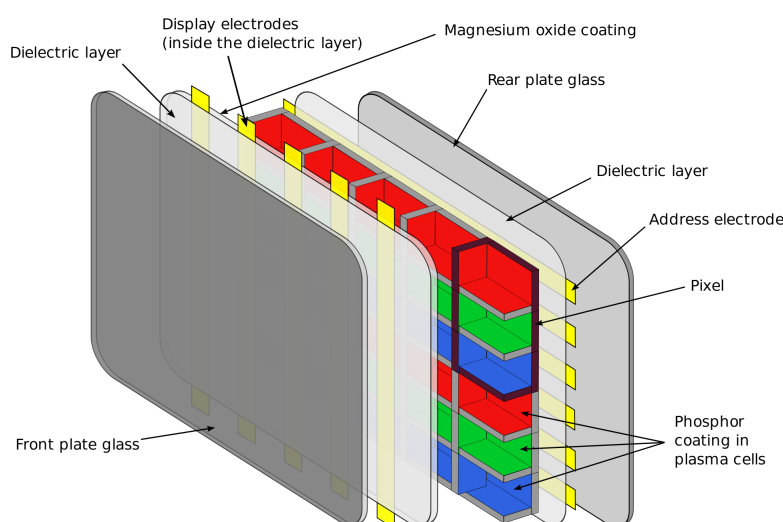


Figure 6: Inner structure of a matrix electrode configuration PDP (image taken from Wikipedia).

ture (usually a mixture of Xe and Ne [15]). This whole structure is

supported by dielectrics and incorporates a MgO layer, the purpose of which is to reduce damage to the electrodes caused by energetic ion collisions (an effect called *sputtering*) and to increase the amount of secondary electrons emitted by collisions with some of those ions, which increases the efficiency of the device (in the case of PDPs - the amount of photons emitted per unit of energy consumed). Each pixel of a color PDP is comprised of three separate cells, each surrounded by either a red, green or blue phosphor, making it possible to set the pixel's color by controlling the intensity of the discharge in the cell. This discharge is caused by applying a high voltage, above the breakdown potential of the gas, at a specific cell, so that the atoms in the gas are ionized and form a plasma, which is a gas of free electrons and free positive ions, turning the gas into a conductor. As long as the plasma is sustained by appropriate alteration of voltage between the two electrodes, excited gas atoms in the cell volume emit UV photons, which are transformed into visible photons with wavelengths in the red, green or blue regions by the phosphors.

### 3.2 CONVERTING PDP TO PPS

A very general description of how a PDP might be used as a particle detector is basically the opposite of the operation of a PDP cell. Each cell in the PDP now acts as a parallel-plate gaseous detector operating in streamer mode. A high voltage is applied across all cells in the device. When a particle passes through the gas volume in one of the cells, some gas atoms in that cell will get ionized, which will initiate a discharge and plasma formation. The gas in the cell will become conductive, which will cause a voltage drop across that cell that can be read out by suitable readout electronics.

Several things need to be done to convert a PDP to a particle detector. First, we need to remove any layers that might interfere with particle detection operation, such as unnecessary dielectrics, the phosphors and the MgO layer, which, as mentioned before, is used to increase ejection of electrons from ions colliding with it, which is an effect we want to reduce as much as possible in a gaseous particle detector (the reason why is explained in detail in section 2.4). Second, we need to implement quick discharge termination for each cell, to stop the discharge in that cell as soon as possible after a passage of an ionizing particle. Last, we want to implement a readout mechanism to read out the voltage pulses caused by a passage of a particle through any one of the cells. Luckily for us, there are very basic monochrome PDPs, without the MgO layer, dielectrics and phosphors available on the market, manufactured by Vishay, as the one shown on figure 7. The dimensions and other properties of these devices are listed in table 4 and figure 8.

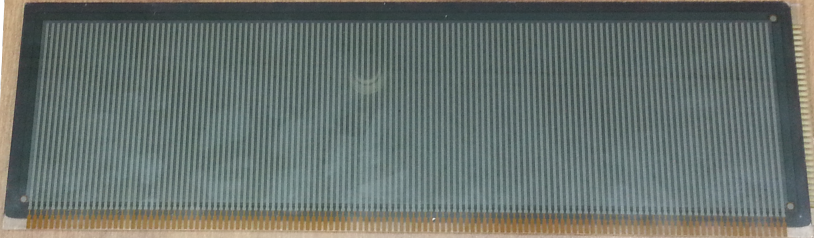


Figure 7: Commercially available Vishay PDPs which are used as proof-of-concept PPS devices.

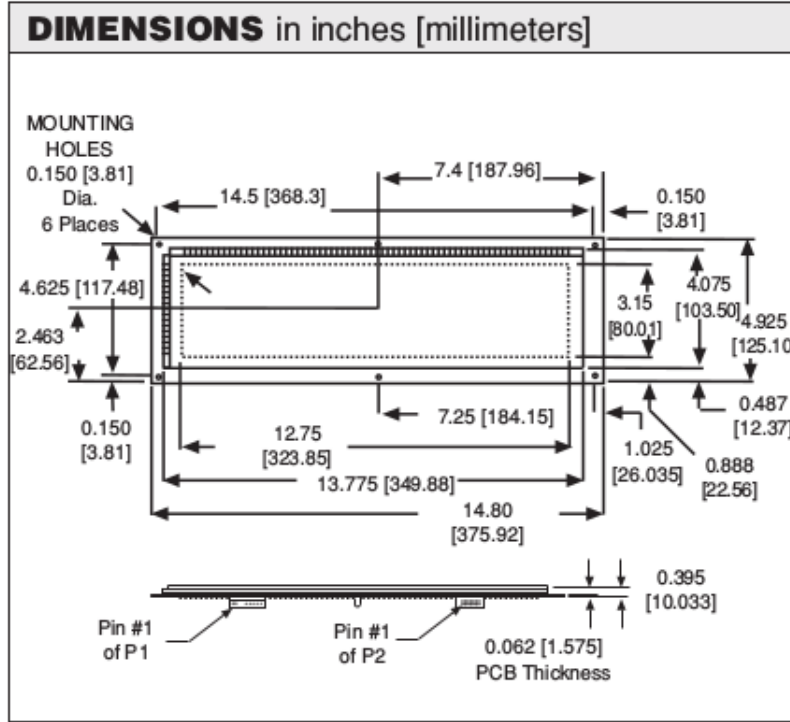


Figure 8: Dimensions of the Vishay panels used in this work [16].

In order to operate those PDPs as detectors, a lot of research needs to be done besides implementing a readout and discharge termination mechanism: a suitable gas needs to be selected, optimal high voltage ranges must be decided upon, characteristics such as efficiency, spatial resolution, timing resolution and localization of discharge must be measured, etc. This work is described in some previous papers ([17] [18] [19] [20] [21] [22] [23] [24] [14]) and some of it is still underway. However, satisfactory operation of those PDPs as particle detectors was achieved, which enables us to use them to construct a tracker.

Table 4: Some characteristics of the Vishay PDPs that will be used for tracker construction [9]

| Name                               | Value                 |
|------------------------------------|-----------------------|
| Electrode material                 | Ni                    |
| High-Voltage (HV) electrodes width | 1.397 mm              |
| Readout (RO) electrodes width      | 1.27 mm               |
| HV electrodes pitch                | 2.54 mm               |
| RO electrodes pitch                | 2.54 mm               |
| HV electrodes length               | 81.3 mm               |
| RO electrodes length               | 325.4 mm              |
| Active pixel area                  | 1.502 mm <sup>2</sup> |
| Packing fraction                   | 23.5%                 |
| Gas gap                            | 0.483 mm              |
| Glass thickness                    | 2.23 mm               |

### 3.3 SUMMARY OF VISHAY PDP CHARACTERISTICS AS A PPS DEVICE

Listed below are some important conclusions of previous research done with the Vishay PDPs.

#### 3.3.1 *Selection of an Appropriate Gas Mixture*

The gas is perhaps the most important component of the PPS device. An ideally suitable gas will maximize the efficiency, timing resolution and spatial resolution, reduce dead time to minimum while not degrading with time. Degradation under discharges is not an issue, since it is solved in PDPs. PDPs sold in the 1970's and operating continuously are still functioning today, with the same gas [14]. PPS devices, as opposed to PDPs, are meant to be placed in high-radiation environments which might cause the gas to degrade. Another problem that arises in gaseous particle detectors are due to metastable states and UV photons, created with each detection event. These must be controlled by using a Penning mixture to return excited states to their ground states mixed with a quenching agent, which is a molecular gas having non-radiative rotational and vibrational states, in order to absorb UV photons into those states and keep them tightly localized around an avalanche. Additionally, the gas must be chosen in conjunction with the materials which a PPS should be made out of due to chemical reactions between the gas and the materials which could produce corrosive agents or deposits on the electrodes and dielectrics, speeding up the aging of the device.

Proof of concept PPS devices were made of Vishay PDPs, filled with a gas which is a mixture of Ar and  $\text{CF}_4$ , that was proven to be enough to detect MIPs and  $\beta$  particles. This gas is a mixture of a primary mono-atomic gas (Ar) with a quenching agent ( $\text{CF}_4$ ), without a Penning dopant. The quenching agent in this mixture acts as an absorber of UV photons, thus mitigating the occurrence of unwanted secondary pulses immediately following primary ones.

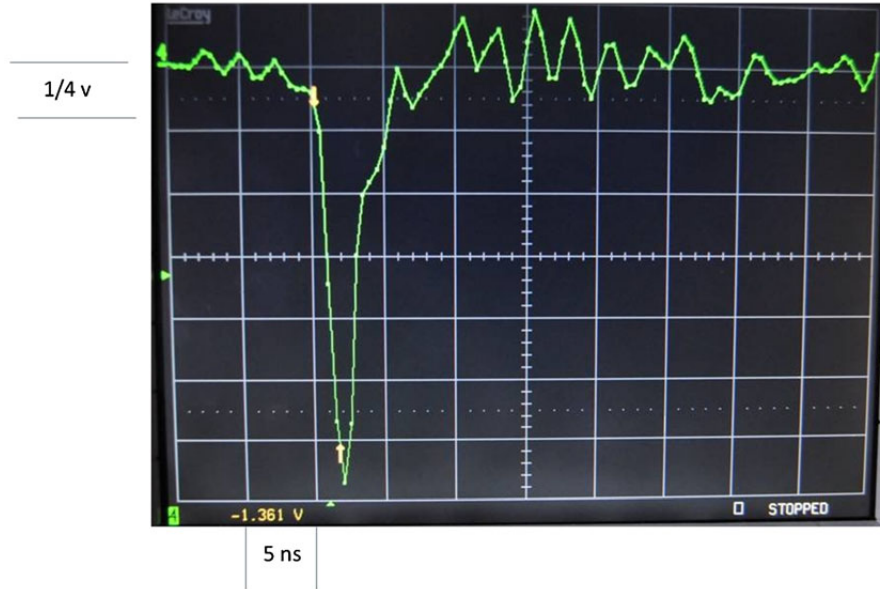


Figure 9: A pulse obtained from a single RO line of a Vishay panel. The panel was filled with 99% Ar and 1%  $\text{CO}_2$  to 600 torr and irradiated with a  $^{106}\text{Ru}$  source [18].

### 3.3.2 Pulse Shape

A pulse shape obtained from a Vishay panel is shown on figure 9. The pulse duration is roughly 2 ns and the rise time from 20% to 80% of the maximum is about 1.2 ns. Note that this pulse was obtained by instrumenting just one HV line. In order to construct a tracker, we had to instrument several HV lines and the pulses we could expect are therefore much noisier.

### 3.3.3 Quench Resistance and Dead Time

The optimal value for the quench resistance of our gas mixture was determined to be in the range 100 M $\Omega$ - 1 G $\Omega$ . These values keep the dead time low enough for a proof-of-concept detector on the one hand, while allowing for enough time to let transient effects such as metastables and positive ions to dissipate on the other. A determination of the quench resistance is done using a plot, an example of

which is shown on figure 10. Here, signal rates with a  $^{106}\text{Ru}$  source

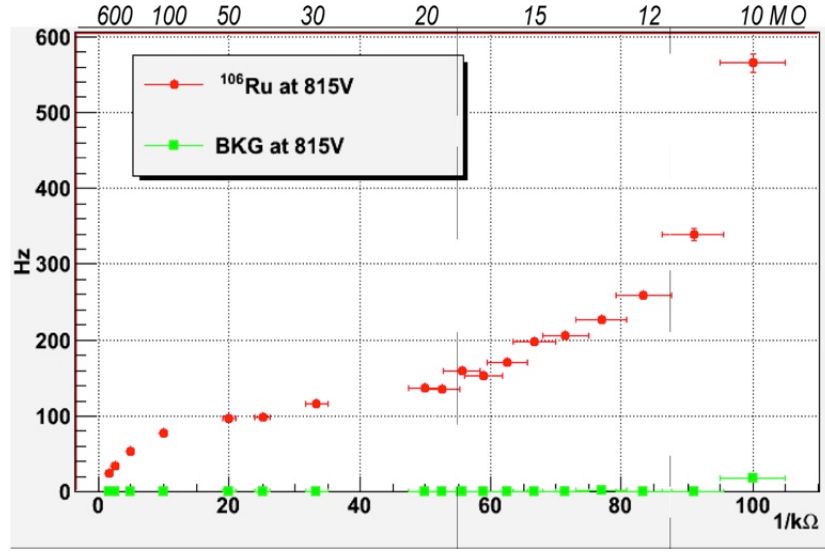


Figure 10: Plot used to determine quench resistance values [19].

and background rates (panel rate without the source) for various values of the quench resistance were measured. At low levels of the resistance (the right side of the plot) we see an abnormally high occurrence of pulses, due to secondary pulsing caused by metastables and positive ions which don't get enough time to neutralize, while at high values of the resistance we see the rates go down to zero, due to a very long dead time for each cell. The optimal range to work in is the plateau. Note that different gases behave differently and therefore may require different quench resistance values. The single-cell dead time corresponding to a 1 GΩ resistance is of the order of 10 ms.

#### 3.3.4 Timing Resolution

A histogram of the time interval between the arrival of a signal from a panel and the arrival of the trigger is plotted on figure 11. This particular plot was acquired using a panel filled with an Ar and  $\text{SF}_6$  mixture, however an Ar and  $\text{CF}_4$  mixture yields a similar result. The timing resolution is the standard deviation of the Gaussian part of this plot, which is around 5 ns. According to table 3, it's already in the lower (better) end of timing resolutions of modern detectors.

#### 3.3.5 Spatial Resolution

The spatial resolution of the PDPs we are using is of the order of the electrode pitch, which is rather large in our case, 2.54 mm. It was measured to be 0.7 mm [19]. The resolution is measured using a position scan, where a collimated radioactive source is moved across the panel, and a hit map of all readout lines is plotted and fitted to

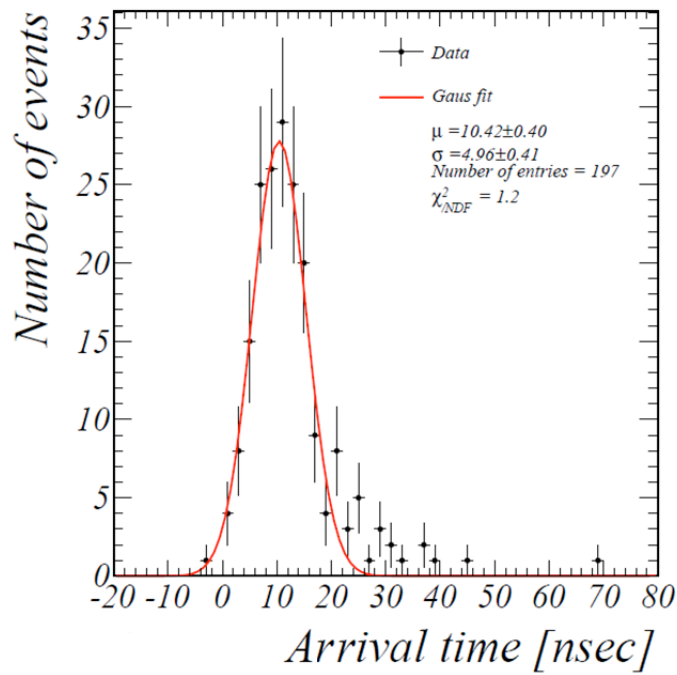


Figure 11: Plot used to determine timing resolution [22].

find its mean and standard deviation. An example is shown on figure 12.

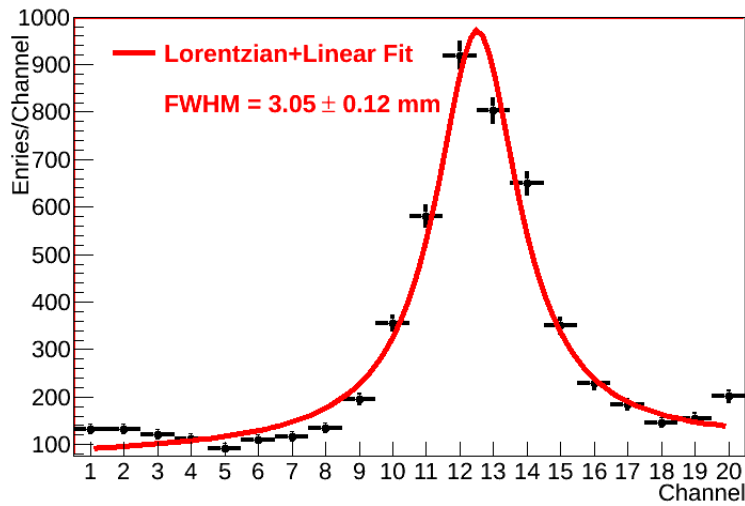


Figure 12: An example of a hit map distribution with an appropriate fit to find its standard deviation. This one was done with a different kind of PDP, having a pitch of 1 mm [9].

### 3.3.6 Constraints on the Efficiency of PDPs for Particle Detection

For this discussion, we define the theoretical efficiency of a PPS as the number of incident particles creating at least one ion pair in the device's gas volume divided by the total number of incident particles.

One problem of using the PDPs described above as detectors is the low *packing fraction* of the cells, which is defined as the area occupied by the cells divided by the total area of the panel. From table 4, this fraction is very low for this type of PDPs. Since to maximize the probability of being detected, an ionizing particle must pass through an area with a high electric field value or within the boundaries of a cell, the odds of that happening, if the entire panel is illuminated, are roughly 0.235.

Another problem, which is more general and does not apply only to the panels we are using, is the fact that ionization of gas atoms by a passing particle is a Poisson process, which means that there is a chance that no ion-pairs will be created during a passage of a particle and it will therefore go undetected. In our case, the gas that we were using is 90% Ar and 10% CF<sub>4</sub>. For a rough calculation we assume just Ar, for which ~29 ions pairs per cm are created at STP for passage of MIPs (from table 2). Detection will happen when at least one ion-pair is created, so the probability for detection is

$$P = \sum_{k=1}^{\infty} e^{-\lambda} \frac{\lambda^k}{k!} = 1 - e^{-\lambda}.$$

For a gas gap length of 0.483 mm (according to table 4), we get  $\lambda = 1.2$ , which results in  $P = 0.75$ .

For a rough estimation of the upper limit on the efficiency ( $\eta_{\max}$ ) of this kind of PDPs as particle detectors, we can say that in order for a particle to create an ion pair, it needs to pass through a cell and create at least a single ion-pair:

$$\eta_{\max} = 0.235 \times 0.75 \approx 18\%.$$

Therefore, the detection efficiencies we should expect from these panels are very low.

## PRELIMINARY THEORETICAL TRACKER ANALYSIS

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### 4.1 PPS-BASED TRACKER

A tracker based on PPS devices is constructed by vertically stacking, at fixed distances from each other, several Vishay panels and carefully aligning them, so that each cell of one panel is situated directly above or below the corresponding cell in the adjacent one. The following theoretical analysis is based on this tracker model.

### 4.2 EXPECTED RATE OF A TRACKER

In order to estimate the rate of cosmic muon track detection we expect in a vertical tracker given a certain geometry, we need to first know the flux of muons at sea level. This figure is given in the literature and is [3]

$$\Phi = 0.01 \text{ cm}^{-2}\text{s}^{-1}\text{sr}^{-1}. \quad (5)$$

In order to make our rate estimates precise, however, we cannot simply use this figure but rather take into account the geometry of the tracker setup and the angular dependence of the muon flux due to the significantly diminished solid angle subtended by the top panel, as seen by each cell of the bottom one, as opposed to the case of a single panel, which sees muons coming from an entire hemisphere. The following sections analyze the tracker geometry.

#### 4.2.1 Rate of Muons through Two Vertically Aligned Planes

The flux of muons is given by eq. (1). Assuming a setup depicted in figure 13, the number of muons passing through an area  $dA$  of the bottom plane in a time  $dt$  from a solid angle  $d\Omega'$  around the angle  $\theta$  is

$$dN = \Phi(\theta)dAdtd\Omega' = \Phi_0 \cos^2 \theta dAdtd\Omega', \quad (6)$$

using eq. (1). The differential solid angle subtended by an area element  $dA'$ , as seen by an observer in the origin is

$$d\Omega' = \frac{(\hat{r} \cdot \hat{n})}{r^2} dA' = \frac{\cos \theta}{r^2} dA',$$

where  $\hat{n}$  is the unit vector normal to  $dA'$  and  $\hat{r}$  is a unit vector from the origin to  $dA'$ . At each point  $(x, y, 0)$  on the bottom plane, the solid

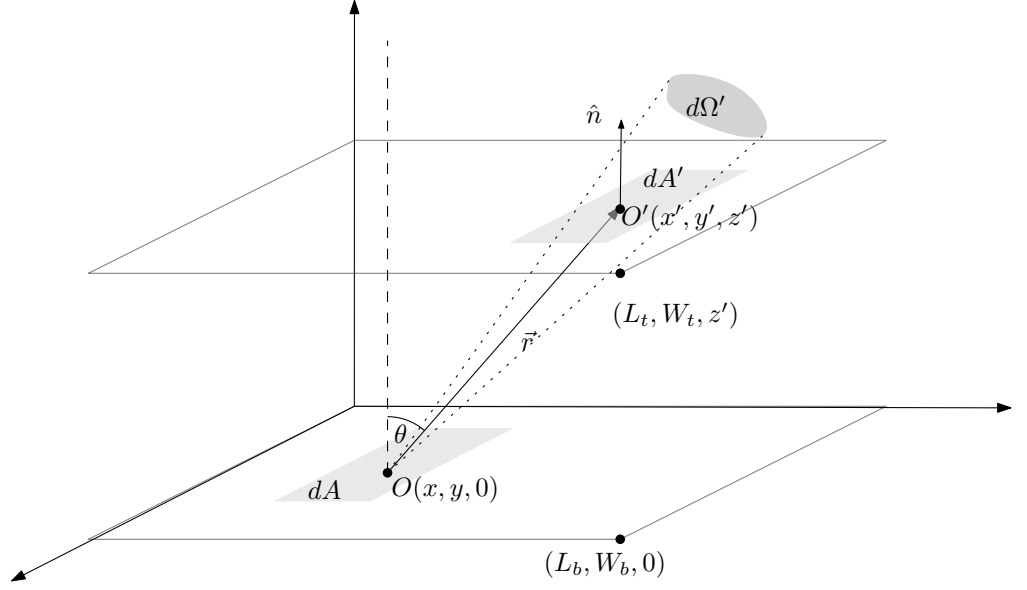


Figure 13: Two parallel planes representing the topmost and bottom-most panels in a tracker.

angle subtended by a surface area of a surface element  $dA'$  located at  $(x', y', z')$  on the top plane is therefore

$$d\Omega' = \frac{z'}{\left[(x - x')^2 + (y - y')^2 + z'^2\right]^{3/2}} dA' \quad (7)$$

The number of incident muons in a solid angle  $d\Omega'$  from that direction, passing through a surface element  $dA$  of the bottom plane in the time period  $dt$  is, from eq. (6),

$$dN_{OO'} = \Phi_0 \cos^2 \theta dA dt d\Omega' = \Phi_0 \frac{z'^2}{r^2} dA dt d\Omega'.$$

Substituting eq. (7) for  $d\Omega'$ , we get that the rate of muons incident on an area element  $dA$  of the bottom plane, located at  $(x, y, 0)$  from the direction of the area element  $dA'$  of the top plane, located at  $(x', y', z')$  is:

$$dR_{OO'} = \frac{\Phi_0 z'^3}{\left[(x - x')^2 + (y - y')^2 + z'^2\right]^{5/2}} dA dA'.$$

In order to calculate the total rate of muons that pass through both the entire bottom plane and the entire top plane, we need to perform the integration

$$R = \Phi_0 \int_0^{L_t} dx' \int_0^{W_t} dy' \int_0^{L_b} dx \int_0^{W_b} dy \frac{z'^3 dx' dy' dx dy}{\left[(x - x')^2 + (y - y')^2 + z'^2\right]^{5/2}}, \quad (8)$$

where  $L_t, W_t, L_b, W_b$  are, respectively, the length and width of the top and bottom planes and we replaced  $dA$  and  $dA'$  with  $dx dy$  and  $dx' dy'$ , respectively.

#### 4.2.2 Rate of Muons through Two or More Vertically Aligned Panels

Assume we have a vertical stack of  $N$  panels separated by distances  $\{d_i\}_{i=1}^{N-1}$ , where  $d_k$  is the vertical distance between panel  $k$  and  $k+1$ . The rate of muons through the entire stack depends on the distance between the topmost and bottom-most panels only, since any muon passing through these passes through the rest as well, so when computing the expression in (8), we set  $z' = \sum_{i=1}^{N-1} d_i$ .

To a good approximation, the panels we are using can detect radiation only inside the volume of the cells, which are distributed uniformly inside the panel, so that we can define a packing fraction, as discussed in section 3.3.6,

$$f = \frac{\text{Area occupied by cells}}{\text{Total area}}.$$

The probability that a muon track that passes through a panel hits a cell in that panel is therefore  $f$ . The rate of detected muon tracks through the stack of  $N$  panels separated by the distances  $\{d_i\}_{i=1}^{N-1}$  in which each panel has a packing fraction  $f$  and the distance between the topmost and the bottom-most panels is  $z' = \sum_{i=1}^{N-1} d_i$  is, using eq. (8)

$$R(N, z', f) = I_0 f^N z'^3 \int \frac{dx' dy' dx dy}{\left[ (x - x')^2 + (y - y')^2 + z'^2 \right]^{5/2}}.$$

Moreover, if each cell detects only a fraction  $\eta_c$  of the muons passing through it, the probability of registering a hit in some cell of a panel given a muon passed through that panel becomes  $\eta \equiv f\eta_c$ , where  $\eta$  is the efficiency of the entire panel and we can write

$$R(N, z', \eta) = I_0 \eta^N z'^3 \int \frac{dx' dy' dx dy}{\left[ (x - x')^2 + (y - y')^2 + z'^2 \right]^{5/2}}. \quad (9)$$

#### 4.2.3 Expected Rate of a Tracker

The muon detection rate for a single panel is  $2\pi\Phi A\eta$ , where  $\Phi$  is the flux given in eq. (5),  $A$  is the surface area of the panel and  $\eta$  is the efficiency of the panel for muon detection. The factor  $2\pi$  is there due to the fact that a single panel sees the whole upper hemisphere, so we should multiply the flux per steradian by  $2\pi$  steradians.

For a vertical stack of two panels separated by a distance  $d$  and assuming we are interested in detecting the same muon in both panels, the rate of detection is  $R(2, d, \eta)$ , assuming that  $\eta$  is the efficiency

of each panel (and that the efficiency is the same for both, which is true if we keep both panels at voltages resulting in roughly similar background rates). The expression can be computed by plugging the appropriate values into eq. (9). Similarly, The rate of 3-point tracks in a 3-panel tracker is  $R(3, 2d, \eta)$ .

A vertical stack of 4 panels separated by a distance  $d$  has a different computation of rate, since it's enough to register hits in at least 2 out of 4 panels to get a track. Therefore, if we number the panels from 1 to 4 and we are interested, for example, in 3 and 4-point tracks, a track will be detected if it generates a hit in the panel numbers in any member of the following set :

$$\{(1, 2, 3), (2, 3, 4), (1, 2, 4), (1, 3, 4), (1, 2, 3, 4)\}.$$

The distance  $z'$  between the topmost and bottom-most panels for each member is, respectively,  $2d, 2d, 3d, 3d, 3d$ . Thus, the rate of detection of "interesting" tracks (in which the same muon generates a signal in 3 or more panels) through this tracker is the sum of the rates through the collection of panels in each member of the set above:

$$R = R(3, 2d, \eta) + R(3, 2d, \eta) + R(3, 3d, \eta) + R(3, 3d, \eta) + R(4, 3d, \eta).$$

Our eventual goal in this analysis is to understand how many tracks per day we can expect from a given amount of readout lines and a given efficiency. We therefore further parametrize the problem by introducing as a parameter the amount of connected readout lines. We assume that the amount of connected HV lines is constant, and is the largest possible with our HV cards, 30 lines. The Mathematica code snippet shown in listing 1 is used to calculate the rate of 3 and 4-point tracks in a 4-panel tracker. The values used for the different parameters and their descriptions are given in table 5. Similar code was used to generate table 6.

It's worth to mention that the scintillators, which act as a trigger, are also a part of the stack of panels. If a muon doesn't pass through

Listing 1: Code used to generate the rate of 3 and 4-point tracks in a 4-panel tracker, based on equation (9).

---

```
xMax = (panelLength/totalNumOfHvLines) * hvLines;
yMax = (panelWidth/totalNumOfRoLines) * roLines;
R[n_, d_, eta_] :=
  I0 * (eta^n) * (d^3) * NIntegrate[((x - u)^2 +
    (y - v)^2 + d^2)^(-5/2), {x, 0, xMax}, {y,
    0, yMax}, {u, 0, xMax}, {v, 0, yMax}, Method ->
    "MonteCarlo"];
rate = 2 * R[3, 2 * dist, eff] +
  2 * R[3, 3 * dist, eff] + R[4, 3 * dist, eff];
tracksPerDay = 60 * 60 * 24 * rate
```

---

Table 5: Values of the parameters used in the Mathematica code to calculate the theoretical track rates. Those values reflect the physical dimensions of the tracker in the experiment

| Name              | Description                           | Value                                               |
|-------------------|---------------------------------------|-----------------------------------------------------|
| $I_0$             | Muon flux coefficient ( $I_0$ )       | $0.0083 \text{ cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$ |
| panelLength       | Length of panels                      | 323.85 mm                                           |
| panelWidth        | Width of panels                       | 80.01 mm                                            |
| totalNumOfHvLines | Number of HV lines                    | 128                                                 |
| totalNumOfRoLines | Number of RO lines                    | 32                                                  |
| hvLines           | Number of instrumented HV lines       | 30                                                  |
| roLines           | Number of instrumented RO lines       | 4, 8, 16                                            |
| eff               | Expected average efficiency of panels | 0.05, 0.1, 0.15                                     |
| dist              | Distance between adjacent panels (d)  | 37 mm                                               |

Table 6: Estimates of the number of expected tracks per 24 hours

| 2-Point Tracks, 4-Panel Tracker    |       |       |        |
|------------------------------------|-------|-------|--------|
| RO Lines / Efficiency              | 4     | 8     | 16     |
| 5%                                 | 14.4  | 54.0  | 187.3  |
| 10%                                | 57.3  | 221.0 | 751.2  |
| 15%                                | 131.1 | 484.6 | 1662.2 |
| 3, 4-Point Tracks, 4-Panel Tracker |       |       |        |
| RO Lines / Efficiency              | 4     | 8     | 16     |
| 5%                                 | 0.2   | 0.8   | 3.2    |
| 10%                                | 1.7   | 6.7   | 25.3   |
| 15%                                | 5.8   | 22.9  | 85.9   |
| 4-Point Tracks, 4-Panel Tracker    |       |       |        |
| RO Lines / Efficiency              | 4     | 8     | 16     |
| 5%                                 | 0.0   | 0.0   | 0.0    |
| 10%                                | 0.0   | 0.1   | 0.4    |
| 15%                                | 0.1   | 0.6   | 2.2    |

them, it's track will not be registered by the DAQ system. Therefore, we need to take them into account when computing (9). Nevertheless, the efficiencies of the scintillators are very high and the scintillators are large enough so as to not diminish the solid angle subtended by the top panel as seen by the bottom panel, even for the most oblique muons.

#### 4.3 RATE OF RANDOM COINCIDENCE

Looking for tracks is basically looking for simultaneous hits in several panels. Such hits can originate from muons, which we are interested in, or they could just be randomly coinciding signals, which pass the DAQ system's threshold for a 'hit', coming from the panels or the electronic equipment with which they are connected to the DAQ system. The origin of such signals is unrelated to muons and can be, for example, RF noise inducing signals in the cables or radioactive decays in the vicinity of the panels causing  $\beta$  particles to ionize the gas in a cell. Obviously, if this random coincidence rate is of the order of magnitude of the expected track detection rate, we will not be able to tell random coincidences apart from muon tracks. We therefore need to make sure that for the panel rates we are using, the rate of random coincidence is low enough compared to the values in table 6. There are two types of random coincidences - uncorrelated and correlated.

##### 4.3.1 *Uncorrelated Random Coincidence Rate*

We will first look at a simple setup of a double scintillator trigger placed above a single panel. The signal from the panel is acquired as soon as the double scintillator triggers the DAQ. The acquisition window is 400 ns wide and thus a random coincidence between the trigger and the panel will occur when this window contains a signal from the panel, or, in other words, if the acquisition window overlaps a signal from the panel. Therefore, in order to approximate the random coincidence probability, we can take an arbitrary time  $t \gg 400$  ns and ask what is the probability of overlap of the acquisition window and a signal from the panel within  $t$ .

Assume  $R_t, W$  are the rate and acquisition window width of the trigger and  $R, \Delta$  are the rate and signal width of the panel, respectively. Within an interval  $t \gg W, \Delta$  there could be 0 or more random signals from the trigger and the panel. The probability of coincidence is

$$P(\text{coincidence}) = \sum_{i,j=1}^{\infty} P(\text{coincidence} | S_t = i, S = j) P(S_t = i, S = j),$$

where  $S_t, S$  are the numbers of signals from the trigger and the panel, respectively. The first term is the conditional probability for coincidence given the trigger has  $i$  signals and the panel has  $j$  signals in the period  $t$  and the second term is the probability for that happening.

We assume, for simplicity, that the signals are temporally uncorrelated. Generally, this is not true, since it was observed that signals in the panels sometimes come in bursts lasting from several seconds to several minutes. However, if we look at a small enough  $t$  (that way "zooming into" such a burst), the signals can be treated as independent events. Following this logic, the number of signals in the period  $t$  is, to a good approximation, a Poisson random variable with  $\lambda_t = R_t t$  and  $\lambda = R t$ , for the trigger and the panel, respectively. Therefore,

$$P(\text{coincidence}) = \sum_{i,j} P(\text{coincidence} | S_t = i, S = j) e^{-\lambda_t} \frac{\lambda_t^i}{i!} e^{-\lambda} \frac{\lambda^j}{j!}. \quad (10)$$

The only requirement on the time period  $t$  is  $t \gg W, \Delta$  and  $t \ll t_B$ , where  $t_B$  is a characteristic duration of the aforementioned bursts. Since  $W$  is 400 ns,  $\Delta$  is of the order of nanoseconds and  $t_B$  is of the order of seconds, we can take  $t$  to be of the order of  $10^{-5}$  seconds. The rates  $R_t, R$  we will be getting will be well below 1KHz, so  $\lambda_t$  and  $\lambda$  are small (at most  $\sim 10^{-2}$ ). We can therefore ignore higher terms in eq. (10) and approximate it with just the first one

$$P(\text{coincidence}) \approx P(\text{coincidence} | S_t = 1, S = 1) e^{-(\lambda_t + \lambda)} \lambda_t \lambda$$

The probability  $P(\text{coincidence} | S_t = 1, S = 1)$  to have a coincidence given there is one signal from the trigger and one signal from the panel, can be calculated with the help of figure 14. In principle, a single pulse from the panel is much narrower than the acquisition window and a coincidence is observed when the signal is contained entirely within the window, but we also need to consider cases in which we mistakenly interpret secondary pulses extending into the window as primary pulses. Therefore, a condition for coincidence, leading to the worst case (highest) value of the random coincidence rate is  $t_1 - \Delta < t_2 < t_1 + W$  or

$$-\Delta < t_2 - t_1 < W, \quad (11)$$

with  $\Delta$  being the width of the bunch of pulses following and initiated by a single primary pulse and is usually narrower than  $W$ .

The waiting times  $t_1, t_2$  are independent waiting times for a Poisson event and are therefore distributed as

$$f_{t_1}(\tau) = f_{t_2}(\tau) = C \left( e^{\alpha(t-\tau)} - 1 \right),$$

since exactly one event must happen between  $\tau = 0$  and  $\tau = t$  and the distribution of the waiting time until a Poisson event is exponential.

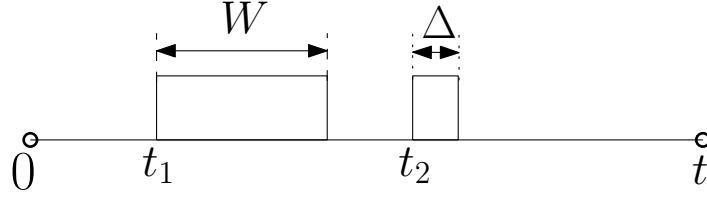


Figure 14: A signal from the trigger of width  $W$  at time  $t_1$  and from the panel of width  $\Delta$  at time  $t_2$  within a time interval  $t$ . A coincidence is registered only if  $t_1 - \Delta < t_2 < t_1 + W$ .

Here,  $\alpha$  is the rate of events, which in this case is  $1/t$  and normalization gives  $C \approx 1.4/t$ . The probability for inequality (11) occurring is

$$\begin{aligned} P(-\Delta < t_2 - t_1 < W) &= (W + \Delta) \int_0^t \left[ C \left( e^{\alpha(t-\tau)} - 1 \right) \right]^2 d\tau \\ &\approx \frac{W + \Delta}{2t} \end{aligned}$$

where we used the fact that  $W, \Delta \ll t$  and therefore the integration is along a narrow strip of width  $W + \Delta$  from  $(t_1, t_2) = (0, 0)$  to  $(t, t)$ . Thus,

$$P(\text{coincidence} | S_t = 1, S = 1) = P(-\Delta < t_2 - t_1 < W) \approx \frac{W + \Delta}{2t}.$$

This, of course, is a reasonable approximation, since, in a small time interval, we can approximate the appearance time of a signal as a uniformly distributed random variable and get the same result (just the width of both signals over the length of the interval). The probability of a signal from a panel occurring by chance inside an acquisition window is therefore

$$P(\text{coincidence}) \approx \frac{W + \Delta}{2t} e^{-(\lambda_t + \lambda)} \lambda_t \lambda = \frac{W + \Delta}{2t} e^{-(R_t + R)t} R_t t R_t.$$

For our values of parameters, the exponent is almost 1, so we can further approximate:

$$P(\text{coincidence}) \approx \frac{W + \Delta}{2} R_t R_t.$$

If we are looking at a longer period  $T \gg t$ , we can divide it into  $N = T/t$  sections of duration  $t$  each. Every period  $t$  we have the above coincidence probability  $P$ , so there will be  $NP$  coincidences within the time  $T$ . Therefore, the rate of random coincidence of a trigger and a panel, with rates  $R_t$  and  $R$  and signal widths of  $W$  and  $\Delta$  is

$$R_{r,1} = \frac{W + \Delta}{2} R_t R, \quad (12)$$

where the subscript 1 stands for '1 panel'.

This can be generalized to two and more panels. For any practical purpose, it is enough to calculate the worst case scenario of the double coincidence rate, so we can make a simplification and assume that the rates of all panels involved are equal to the highest rate and the signal widths are equal to the width of the widest signal. We'll designate these values as  $R$  and  $\Delta$ , respectively, just as before.

For  $k$  panels, assuming the signals are uncorrelated, the random coincidence probability in the interval  $t$  given there is 1 signal from the trigger and 1 from each panel, is just

$$P(\text{coincidence} | S_t = 1, \{S_i = 1\}_{i=1}^k) \approx \left( \frac{W + \Delta}{2t} \right)^k,$$

where  $S_i$  is the number of signals in interval  $t$  from panel  $i$ . The probability for 1 signal from the trigger and all  $n$  panels is (taking the most significant term, as before)

$$P(S_t = 1, \{S_i = 1\}_{i=1}^k) = e^{-\lambda_t} \lambda_t \prod_{i=1}^k (e^{-\lambda} \lambda) \approx R_t t (R t)^k.$$

Therefore,

$$\begin{aligned} P(\text{coincidence}, k \text{ panels}) &\approx \left( \frac{W + \Delta}{2t} \right)^k R_t t (R t)^k \\ &= \left( \frac{W + \Delta}{2} \right)^k R^k R_t t \end{aligned}$$

and the rate is calculated, in analogy to the previous discussion about one panel, to be

$$R_{r,k} = \left( \frac{W + \Delta}{2} \right)^k R^k R_t. \quad (13)$$

In the case of a two-panel tracker, eq. (13) (with  $k = 2$ ) is also the formula for the random track detection rate, since we need a hit location from two panels to define a track. If we add any more panels, however, the formula changes, since if just 2 out of those  $n$  panels have signals, we assume it is a track. Therefore, randomly occurring tracks can come from pulses of all possible sets of 2 and more in a stack of  $n$  panels. We can write an expression for the random track rate from a stack of  $n \geq 2$  panels as:

$$R_{\text{tracks}} = \sum_{k=2}^n \binom{n}{k} R_{r,k} = \sum_{k=2}^n \binom{n}{k} \left( \frac{W + \Delta}{2} \right)^k R^k R_t.$$

For a 4-panel tracker, in which each panel is firing at  $R = 1$  KHz,  $\Delta = W = 400$  ns and  $R_t = 3$  Hz, which are larger than the real figures, we get a worst case random track detection rate of around  $3 \cdot 10^{-6}$  Hz, or one track in 4 days. Comparing this figure to the numbers in

6 and remembering that the values of the parameters used for this calculation are exaggerated and thus the true rate will be at least one order of magnitude lower, we can say that the random coincidence rate is negligible with respect to the track rate we expect to get from a 4-panel, 8-line tracker. This should, however, be verified against the actual track detection rate we will get experimentally.

#### 4.3.2 *Random Coincidence from Correlated Noise*

We have seen that the random coincidence rate from uncorrelated noise is negligible relative to the expected track detection rate, but when noise-induced pulses are correlated, such as in the case when the noise is a RF signal coming from a pulse on a line on one of the panels and causing a signal in multiple lines on other panels, we will see a much higher contribution of this effect to the track detection rate. To mitigate this problem, we need to place the panels and the PMTs of the scintillators each in its own Faraday cage. This can be done by, for example, wrapping those components with aluminum foil and grounding it. When using high-quality cabling this effect should be minimal, however. The LEMO cables we have been using are shielded coaxial cables, forming, along with the metal casings and grounding connections of the equipment used, a well-grounded Faraday cage surrounding the signal lines. In any case, effects of this kind have not been calculated theoretically and hence we had to conduct experiments in order to measure their significance.

#### 4.4 MONTE CARLO SIMULATION OF THE TRACKER

In order to help understand and analyze the angular distribution of the resulting tracks, a toy Monte Carlo simulation was done, in which a virtual to-scale 3D model of the tracker was constructed, as shown on figures 15 and 16. The simulation was implemented entirely in C++ and the visualization was implemented with ROOT. For the simulation, random tracks with spherical angles  $\theta, \phi$  were generated, where  $\theta$  (generated by a rejection sampling algorithm [25]) is distributed as  $\cos^2 \theta$  (due to eq. (1)) and takes values in the range  $[0, \pi/2]$  and  $\phi$  is uniformly distributed in the range  $[0, 2\pi)$ . For each such track, a point of intersection with a plane slightly above the top scintillator was randomly picked from a plane much larger than the scintillators (see table 7 for numerical values used in the simulation). During the run of the simulation, a track must be intercepted by both scintillators to create a virtual 'trigger' and it has to be intercepted by at least two panels to be registered as a track. Once a track is detected, the line numbers and panels which registered the points on the track are sent to a track analysis code, which is the same code that per-

Table 7: Values of the parameters used in the Monte Carlo simulations

| Parameter                                                                | Value                     |
|--------------------------------------------------------------------------|---------------------------|
| Size of scintillators ( $x \times y$ )                                   | 270 mm $\times$ 125 mm    |
| Center of scintillator 1 ( $x, y, z$ )                                   | 0, 0, 170 mm              |
| Center of scintillator 2 ( $x, y, z$ )                                   | 0, 0, 0                   |
| Cell size in panels ( $x \times y$ )                                     | 1.397 mm $\times$ 1.27 mm |
| Cell pitch (both $x$ and $y$ directions)                                 | 2.54 mm                   |
| Number of cells ( $x$ direction)                                         | 30                        |
| Number of cells ( $y$ direction)                                         | 8                         |
| Center of panel 1 ( $x, y, z$ )                                          | 0, 0, 43 mm               |
| Center of panel 2 ( $x, y, z$ )                                          | 0, 0, 80 mm               |
| Center of panel 3 ( $x, y, z$ )                                          | 0, 0, 117 mm              |
| Center of panel 4 ( $x, y, z$ )                                          | 0, 0, 155 mm              |
| Panel gas gap thickness                                                  | 0.5 mm                    |
| Ion pairs produced per mm                                                | 2.5                       |
| $\sigma$ of Gaussian used to determine location of discharging cell      | 2.5 mm                    |
| Location of rectangular domain from which tracks originate ( $x, y, z$ ) | 0, 0, 175 mm              |
| Size of rectangular domain from which tracks originate ( $x \times y$ )  | 1 m $\times$ 1 m          |

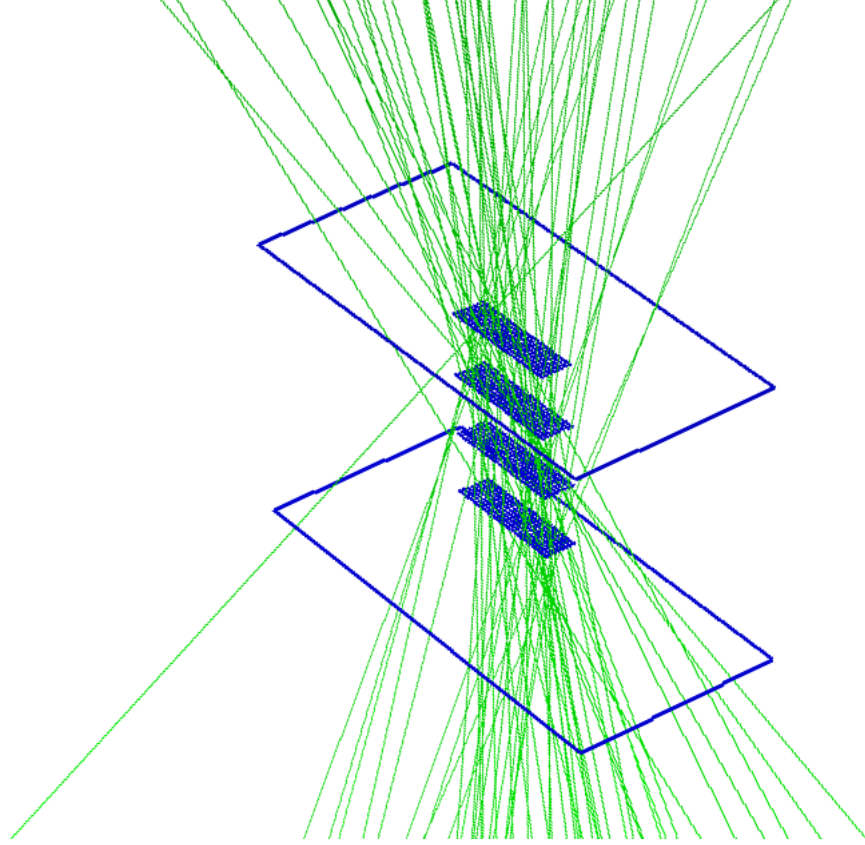


Figure 15: A rendering of the virtual tracker used for the Monte Carlo simulation. Shown here are four panels positioned between two scintillators. Each panel is a collection of cells. The green lines are a few randomly generated tracks.

forms the analysis for the data acquired from the tracker, making the same analyses and plots.

A track is marked as intercepted by a scintillator if it passes within the scintillator's boundaries with the acceptance probability depending on the efficiency defined for the scintillator. For the panels, a slightly more elaborate detection mechanism was implemented, which attempts to take into account the nature of ionization in gases. First and foremost, a track must obviously pass within the boundaries of the panels to be detected by it. The elaborate part is the following. Since the number of ionization events in a gas is a Poisson distributed variable, the distance until the first ionization is exponentially distributed. Therefore, if we define a gas gap length for the panels, we can generate a number from an exponential distribution, which will act as the distance traveled in the gas until the first ionization and see if that ionization event occurs inside the gas gap. If not, the panel 'misses' this track. After pinpointing the ionization location, we need to decide to which cell the ions drift (which cell will give the detection signal). For that, we generate a random vector in the plane of the panel with its starting point at the ionization location. The length of

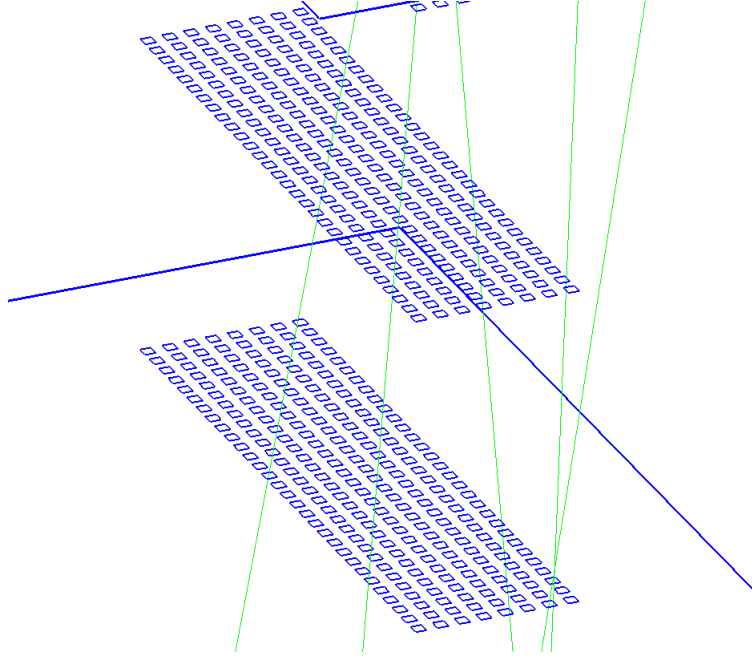


Figure 16: A close-up of the structure of the panels. Each panel is made of  $30 \times 8$  cells, corresponding to 30 HV lines and 8 RO lines.

the vector is sampled from a narrow Gaussian distribution and the direction is distributed uniformly in the range  $[0, 2\pi)$ . We then find the closest cell to the tip of that vector and that cell is the detecting cell. Note that the panel efficiency value is hidden within the parameter of the exponential distribution.

This simulation approximates the real structure of the detector, however, it does not take into account the sizes of the cells, it treats the scintillators as having a thickness of zero and a rectangular form and it ignores small effects of multiple scattering by the glass surface of the panels. Nevertheless, it qualitatively emulates the effects of the discrete geometry of the tracker on the results. We use results from the simulation to explain some geometric effects in the following section.

#### 4.5 ANALYSIS OF TRACKS

Once we detect simultaneous hits on more than one panel and rule out RF effects, we can safely assume that those hits are from cosmic muons, analyze them to reconstruct tracks and compare the result to a Monte Carlo simulation to see that we indeed get what we expect. We then plot the distribution of the number of tracks as a function of the angle of the track to analyze the measured angular distribution. Note that the tracker is two dimensional and therefore the angle calculated from a measured slope of a track is not the spherical angle  $\theta$  that appears in eq. (1), but a projection of that angle onto the observation

plane - an angle  $\chi$  of a 'square pyramid' set of coordinates which are of the form

$$\begin{aligned}\chi &\equiv \tan^{-1} (\tan \theta \cos \varphi) \\ \xi &\equiv \tan^{-1} (\tan \theta \sin \varphi).\end{aligned}\tag{14}$$

This can be easily seen by looking at figure 17.

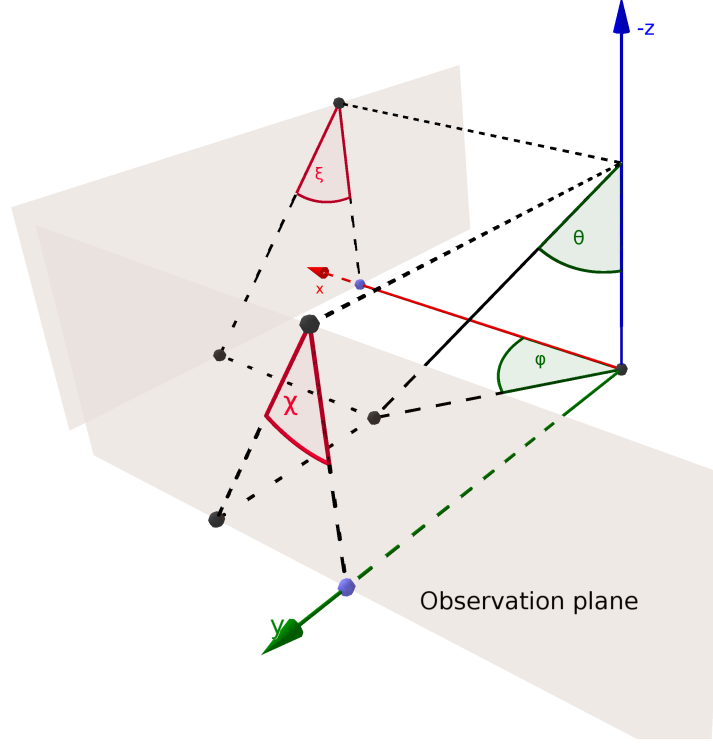


Figure 17: The spherical angles  $\theta$  and  $\varphi$  and the 'square pyramid' coordinates  $\chi$ ,  $\xi$ . The tracker sees the tracks as they appear in the observation plane.

In order to construct this angular distribution, we need to reconstruct the slope of a track from its points, which is done differently for 2-point and 3-point tracks.

#### 4.5.1 2-Point Tracks

We treat 2-point tracks because, according to table 6, we expect to have a lot more of them than 3 or 4-point tracks and eventually our data set is dominated by them. It is straightforward to calculate the slope and therefore the angle  $\chi$  of a track from 2 points along the track. The less trivial part of the analysis is understanding the artifacts of the coarse discrete geometry of the tracker and of the fact that the tracker is two-dimensional that arise in the resulting distribution of track angles.

The first geometric effect can be explained by looking at figure 18. Depicted here is a set of angles  $\{\chi_0, \chi_1, \dots\}$ , sorted by magnitude,

where the first angle is the smallest ( $\chi_0 = 0$ ). It is easy to see that, for two-point tracks, the two points making up a track with angles  $\chi_0$  or  $\chi_4$  can lie on panels (A, B), (B, C), (C, D), (A, C), (B, D) and (A, D). For  $\chi_1$  and  $\chi_3$ , only the pair (A, D) contributes while for  $\chi_2$ , the pairs (A, C), (B, D) contribute. Therefore, if we construct a histogram from the values of the angles of the tracks, we naively expect to see a picture described by:

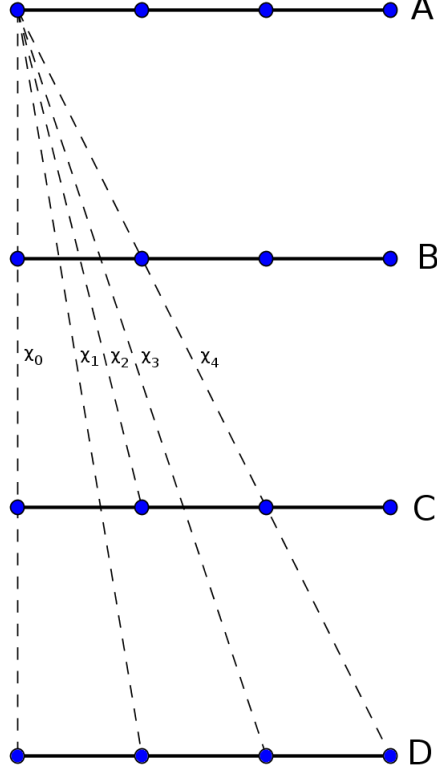


Figure 18: Panels A through D, where each point marks a cell and a set of possible 2-point tracks with their angles  $\chi_0 = 0, \chi_1, \chi_2, \chi_3$  and  $\chi_4$ .

$$N_i \propto c_i p(\chi_i),$$

where  $N_i$  is the number of entries in the bin corresponding to the angle  $\chi_i$ ,  $p(\chi_i)$  is the probability for a track with a  $\chi$  angle around  $\chi_i$  and  $c_i$  are given by

$$c_0 = c_4 = \eta_A \eta_B + \eta_B \eta_C + \eta_C \eta_D + \eta_A \eta_C + \eta_B \eta_D + \eta_A \eta_D \equiv C_1$$

$$c_1 = c_3 = \eta_A \eta_D \equiv C_2$$

$$c_2 = \eta_A \eta_C + \eta_B \eta_D \equiv C_3,$$

and so on, where  $\eta_k$  is the efficiency of panel  $k$ . The resulting histogram looks 'layered', as seen on figure 54. Each layer comes from a different value of  $c_i$ . Note that we have just three possible values for

the different  $c_i$  coefficients, since we have just 4 panels in the tracker. Those values are marked by  $C_1, C_2$  and  $C_3$  and they correspond to the three possible distances there can be between panels. Therefore, we do not plot a one dimensional angular distribution histogram, but a two dimensional one, where the first axis is the angle  $\chi$  of the track and the second axis is the distance between the two points defining the track. This distinguishes between the layers of the histograms in the direction of the distance axis, as shown on figure 19.

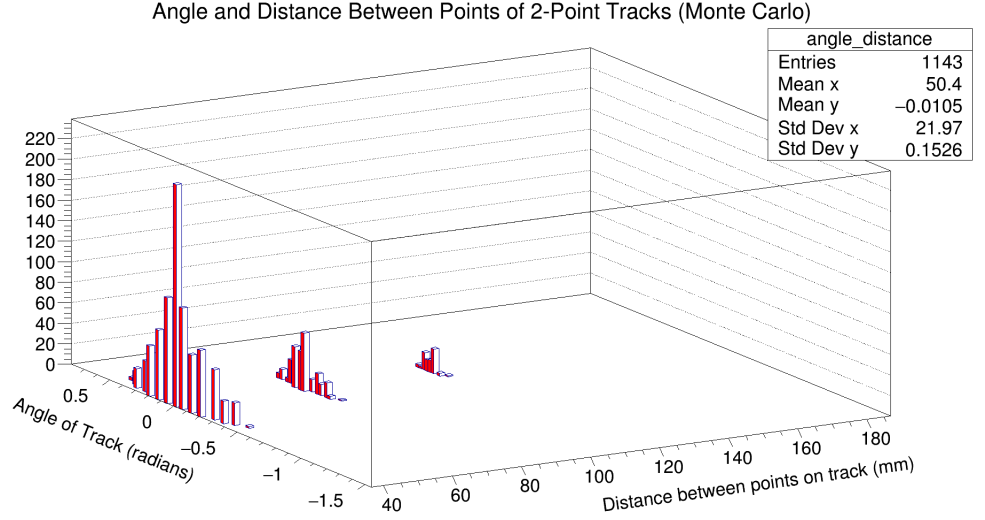


Figure 19: Separation of the layers of the track angular distribution by plotting a 2d histogram of angles and distance between points on 2-point tracks.

We may try to normalize the various layers of the histogram in an attempt to make it single-layered by taking just this one geometric effect into account, but we will see that the various layers will still be not of the same size and form and the histogram will remain layered. This is due to a second geometric effect, shown in figure 20. Here, a track with a non-zero angle will be interpreted by the tracker as coming from lines 1 and 1 of panels A and B, respectively if it's detected by panels A and B, while if it's detected by panels A and C, it will be interpreted as coming from lines 1 and 2 of panels A and C, respectively. Thus, in the former case, the track will appear to have an angle of  $\chi_0$  while in the latter case it will appear to have an angle of  $\chi_1$ . The resulting distribution of the histogram layer getting contributions from tracks coming from panels which are separated by a distance  $2d$  (i.e. tracks with the angle  $\chi_2$  as well as  $\chi_0$  and  $\chi_4$ ) will therefore have less entries in the small angle bins and for that reason will be more spread out than the layer getting contributions from panels separated by a distance  $d$  (i.e. tracks with the angles  $\chi_0$  and  $\chi_4$ ).

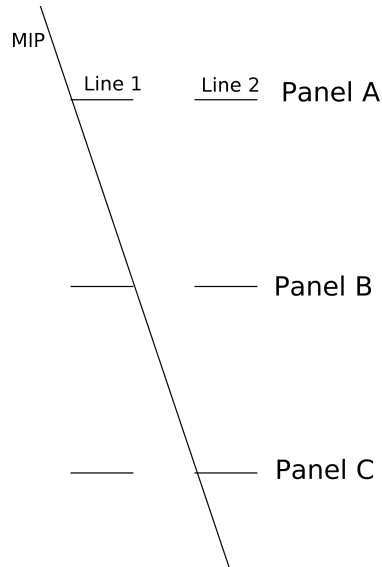


Figure 20: Another geometric effect affecting the histogram shapes.

An additional effect that significantly distorts the angular distribution of the tracks can be understood by looking at figure 21, which shows tracks coming from a single point above the tracker. All tracks in plane  $P_0$  are interpreted by the tracker as having an angle  $\chi_0$ . All tracks in plane  $P_1$  -  $\chi_1$  and so on. For any given angle  $\xi$ , the polar angle  $\theta$  which appears in the expected distribution of the angles of incoming muons given by eq. (1), is larger on plane  $P_1$  than on plane  $P_0$  and therefore the density of tracks in plane  $P_0$  is higher than in plane  $P_1$ . Therefore, in each layer of the histogram, the bins corresponding to the smaller values of the  $\chi$  angle will have more entries than the larger angles bins. In other words, the histogram will have a lot of its weight concentrated closer to the small  $\chi$  values and this further distorts the already distorted picture.

It is hard to quantify those distortions, but we can qualitatively compare the results from the measurements to a Monte Carlo simulation.

#### 4.5.2 3-Point Tracks

In order to generate an angular distribution plot for 3-point tracks, we calculate the slope of a line created by the three points making up the track. That can be done by simple linear regression. Then, the angle  $\chi$  (eq. 14) of the track can be calculated from the slope, just as in the case of 2-panel tracks. The number of 3-point tracks is expected to be significantly lower than the number of 2-point tracks and therefore it is not worthwhile to plot an angular distribution just for the 3-point tracks, due to low statistics. The interesting thing to do for 3-point tracks would be to plot a histogram of the measure of linearity of the

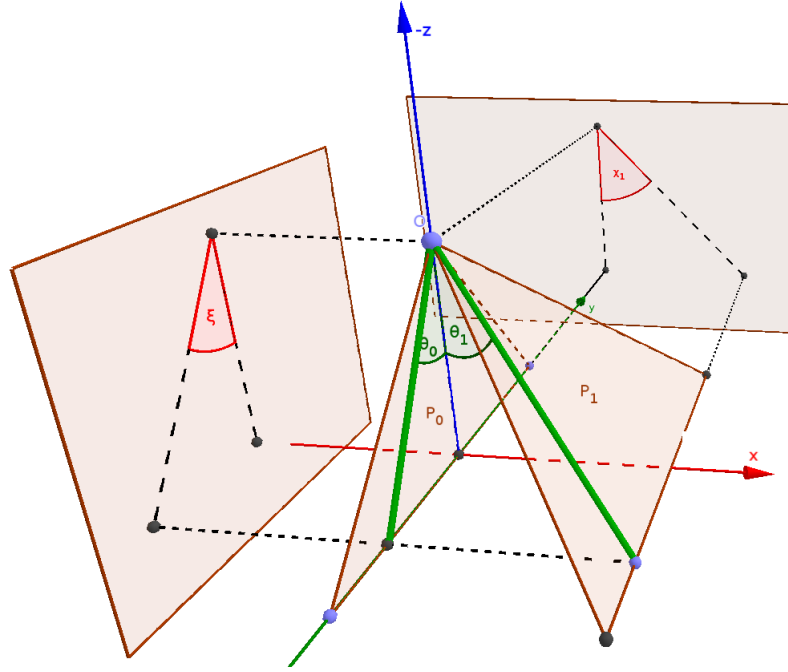


Figure 21: Two planes -  $P_0$  and  $P_1$  are shown as well as two green lines representing tracks that pass through point  $O$  - a track on  $P_0$  with it's polar angle  $\theta_0$  and a track on  $P_1$  with it's polar angle  $\theta_1$  and it's 'square pyramid' coordinates  $\chi_1$  and  $\xi$ . This is to illustrate that for a given  $\xi$ , a track on plane  $P_1$  has a larger value of the spherical  $\theta$  angle than on plane  $P_0$ .

three points comprising the track. The  $\chi^2$  per number of degrees of freedom measure given by the regression class in ROOT is suitable for this purpose. It is then interesting to plot a histogram of the values of this measure and examine the resulting distribution. If the majority of the 3-point data is coming from actual tracks, we expect to see most of the weight of the distribution concentrated near the value 0 (where all three points perfectly lie on a single line). Even though we theoretically ruled out contribution of uncorrelated random noise to track detection in section 4.3.1, this will verify the validity of the assumptions made. Another verification is obtained by using a Monte Carlo simulation to generate a similar histogram that would result if the hits on the panels were coming from completely random lines and performing a Pearson's  $\chi^2$  test to reject this hypothesis. This is done in section 8.2.4.

## Part II

### EXPERIMENTAL PROCEDURE



## PREPARATION OF THE PANELS, ELECTRONICS AND THE TRACKER SETUP

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### 5.1 PREPARATION OF THE PANELS

In order to effectively construct a tracker made out of plasma display panel elements, the panels were first connected to gas filling tubes, fixed to trays and labeled as shown on figure 22. Each panel was

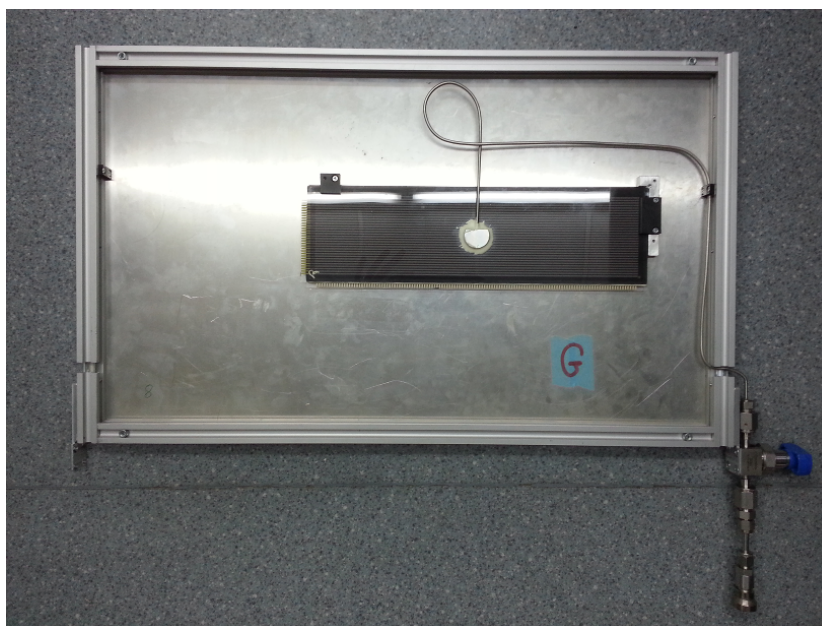


Figure 22: A Vishay panel connected to a gas filling tube, labeled and secured to a tray.

tested for leaks with an Agilent helium leak detector. The maximum acceptable leak rate was of the order of  $10^{-9}$  atm-cc/sec. Since the panels were to be filled at pressures just slightly below 1 atm, such leak rates would not significantly contribute to panel degradation at those pressure differences, which was in fact the case during the various experimental runs. The panels were later placed into a specialized oven and kept for at least 24 hours at roughly  $90^{\circ}$  C while connected to a vacuum pump in order to evacuate products of outgassing from the electrodes and dielectrics. This value of the temperature was decided upon by observing that significant leaks were formed in the vacuum sealant paste used to seal the connection between the gas supply tube to the panel at a higher temperature and the necessity to use as high a temperature as possible to maximize outgassing. Next, the panels were filled with a pre-mixed gas comprised of 10%  $\text{CF}_4$

and 90% Ar to a pressure of roughly 750 torr (following the discussion in section 5.2 below).

## 5.2 SELECTION OF GAS MIXTURE AND PRESSURE

The gas used in the panels was a gas that was successfully used before to acquire pulses from MIPs and  $\beta$  particles, as explained in section 3.3.1. It's a mixture of Ar with  $\text{CF}_4$ . Increasing the percentage of  $\text{CF}_4$  in the mixture was observed to mitigate the occurrence of secondary pulses, as can be seen on figure 23. This plot was obtained by placing

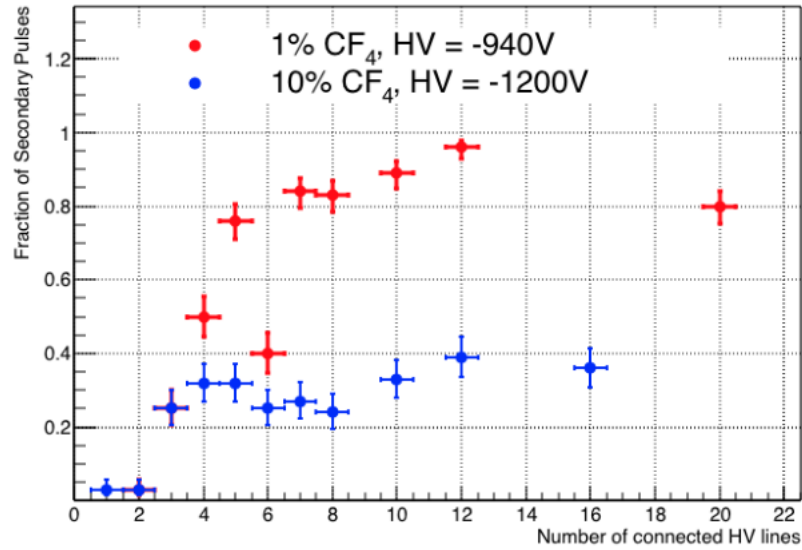


Figure 23: The fraction of events having more than one secondary pulse out of the total number of events acquired as a function of the number of connected HV lines for two gases with a different percentage of  $\text{CF}_4$ .

a  $^{106}\text{Ru}$  source on a panel, using a scope to monitor four readout lines and to visually determine if an event had secondary pulses on either one of the lines. The amount of events with multiple pulses was counted and a fraction of that number out of the total number of events acquired was plotted as a function of the number of connected HV lines. This was repeated for two gases: 99% Ar + 1%  $\text{CF}_4$  and 90% Ar + 10%  $\text{CF}_4$ . For each gas separately, a higher voltage results in a higher secondary pulsing fraction so even with the voltage being higher for the 1%  $\text{CF}_4$  mixture, the secondary pulse fraction is much lower, indicating that  $\text{CF}_4$  is a good quenching agent.

The dependence of the fraction of the secondary pulses on the number of HV lines connected requires further investigation. It may be a result of the increase in the number of active cells. As a result, we get an increase in the volume in which the electric field is high, where

photons, emitted as a result of decays of metastables and electrons, ejected from the cathode by positive ions, can form additional pulses.

The choice of gases in the lab at the time of the experiment design was rather limited. We had a cylinder of pre-mixed 90% Ar + 10% CF<sub>4</sub> and another one of a pre-mixed 99% Ar + 1% CF<sub>4</sub> gases. In addition, we had a few cylinders of pure mono-atomic gases (Ne, Ar, Xe) and a few cylinders of quenching molecular gases (SF<sub>6</sub>, CF<sub>4</sub>, CO<sub>2</sub>), but no means to mix them in a controlled and precise way. Therefore, a choice was made to use the 90% Ar + 10% CF<sub>4</sub> gas, due to its better suppression of secondary pulses.

The gas pressure inside the panels was chosen to be a little below 1 atm, for two reasons. One is that the panels are built to withstand only negative pressure, so they can not be filled with a pressure higher than 1 atm. The other is that the tracker system is meant to operate for long stretches of time and a very small pressure difference between the inside and outside of the panel will minimize leakage of contaminants into the panel in the case that small cracks are formed (which had in fact happened in some of the panels) and prolong the intervals between panel re-fills.

### 5.3 RO AND HV SUPPLY CARDS

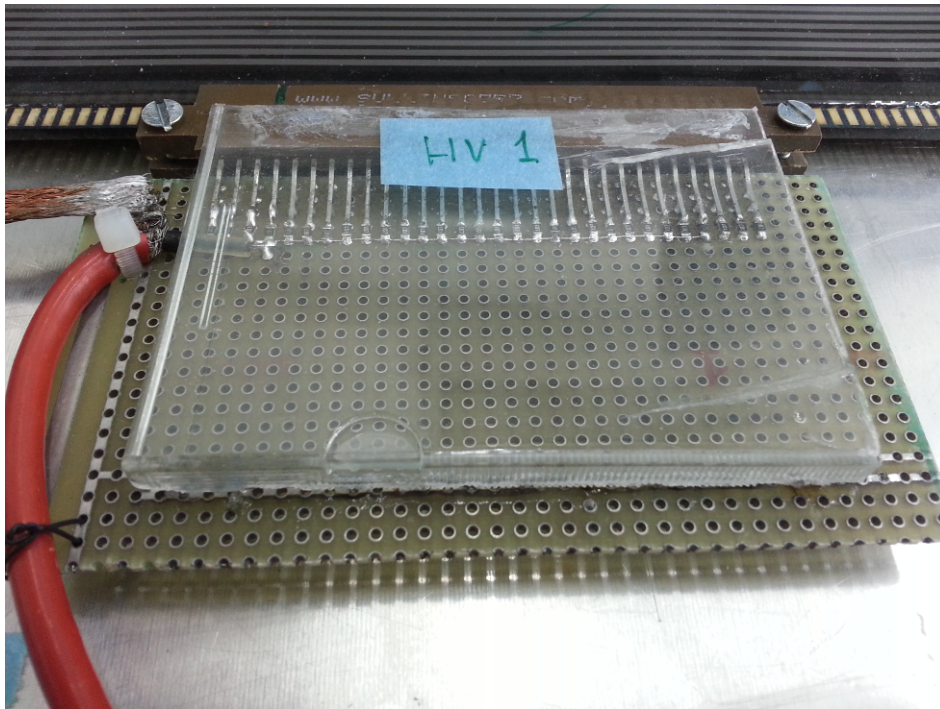


Figure 24: A HV card connected to a Vishay panel. The red wire is the HV supply wire and the schematic can be easily deduced.

Readout and HV cards previously manufactured for measurements with the PPS were unsuitable in their original form for our needs. In

this experiment, it is the first time in which a large number of HV lines is used, causing a large current flow through the RO cards, too large to be sustained by the resistors originally used there. Additionally, the original HV cards were unreliable, as they would start arcing at high voltages. Therefore, the existing RO cards were modified by replacing some of the surface-mount resistors with through-hole resistors, which have higher power ratings. A RO card can be seen on figure 25.

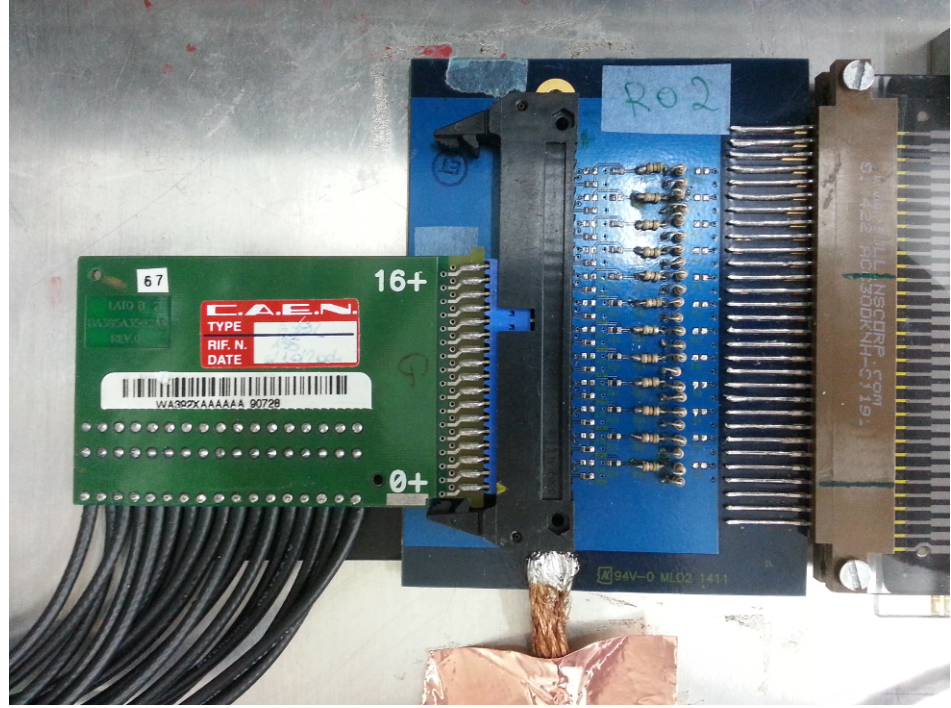


Figure 25: A modified RO card, connected to a CAEN flat-to-LEMO adapter and to a Vishay panel. A grounding copper wire is visible on the bottom.

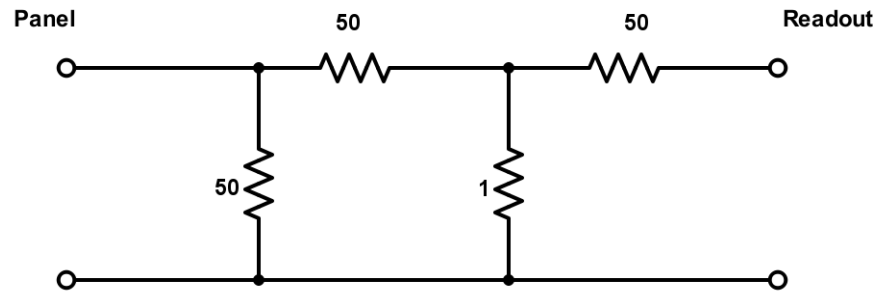


Figure 26: Schematic of a single line on the RO card.

Figure 26 shows the schematic of a single line on the RO card. The leftmost  $50\ \Omega$  resistor is used to set the impedance of the panel to  $50\ \Omega$  and the remaining 'T' structure is a T-attenuator, which attenuates

the signal by 40 db, assuming the impedance is  $50\ \Omega$  at the readout (right) side.

The HV cards were remade (figure 24). Their schematic design is demonstrated by the wiring on the card.

The RO card flat output connector was connected to the DAQ system through a flat-to-LEMO adapter. Two (self made) of the four adapters (figure 27) did not have a ground plane, as opposed to the

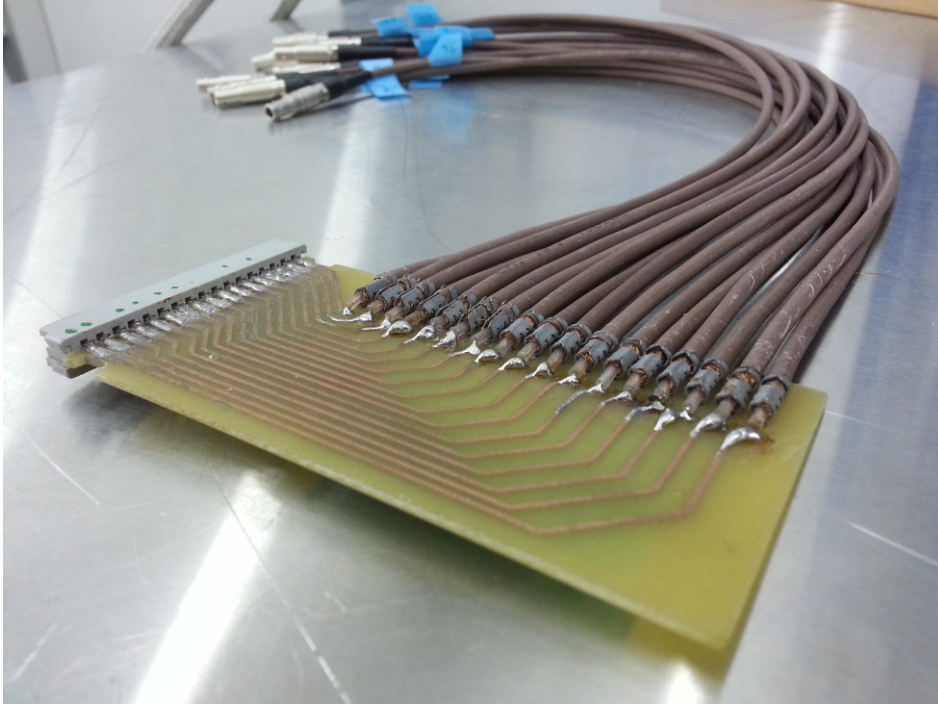


Figure 27: A self made flat-to-LEMO adapter. Note that there is no ground plane on the PCB.

CAEN adapters, so their resulting signals were slightly noisier, as can be seen in the results section on figure 48. Panels C and E are connected through the self made adapters, while B and H through the CAEN ones.

#### 5.4 DETERMINATION OF OPERATING VOLTAGE

It was observed that the rate of the panels increased with the applied HV, starting from some minimal value below which the panel did not produce pulses, as can be seen on a voltage scan on figure 28. To generate this plot, starting from some minimal value, the HV supply to the panel was increased by constant increments with an uncollimated  $\beta^-$  source placed on four monitored readout lines. The pulse rate was determined using a NIM counter module. The same procedure was done with the source removed, to determine the background rate. Both the signal and the background pulse rates increase with voltage.

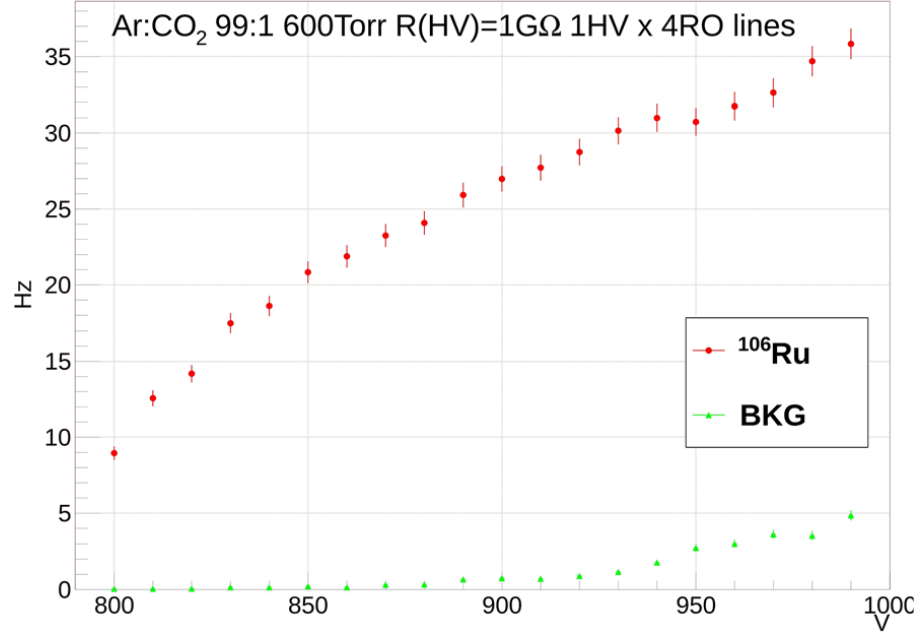


Figure 28: Example of a previously obtained hit rate versus HV of combined four pixels exposed to a  $^{106}\text{Ru}$   $\beta$  source. Background is measured in the absence of the source [18].

Naively, To increase the efficiency of the panels to MIP detection, we would operate them at the highest possible voltage. However, we should keep a few things in mind. One of them is the maximum detection rate allowed for the panel by the dead time of each cell. This rate is determined roughly by the RC constant of each cell. The capacitance of a single cell is at most 10 pF [22]. With a quench resistance of 1 G $\Omega$ , this gives a value of 0.01 seconds of dead time for an entire column of cells that share the same HV line. This corresponds to a maximum rate of 100 Hz for a HV line. Since there were about ten connected cells on each HV line (meaning their corresponding read-out lines were connected to low potential and the rest stayed dangling), we wanted to keep the individual cells at rates below about 10 Hz, to keep them away from the maximum rates and thus to improve the efficiency of the panels. At these rates of individual cells, the total pulsing rate of the entire panel is, at most, several KHz. Referring to section 4.3.1, this results in a negligible contribution of random coincidence between pulses from different panels to the amount of measured tracks.

Another upper bound to the applied HV is set by the HV supply cards, which begin intermittently arcing at voltages above 1300V as well as the amplitude of the pulse at the readout end of the panels, which must be low enough to safely deliver the signal through an attenuator to the inputs of the DAQ system. At 1300V, the pulse amplitude at the readout end of the panel measures about 80V, which, after 60 db attenuation results in a pulse of 0.1 V amplitude, which is

acceptable by the DAQ. At 1300V the rate of each cell is well below 10 Hz. We therefore settle for a HV supply value of 1300V for all panels in the tracker.

## 5.5 TRACKER SETUP

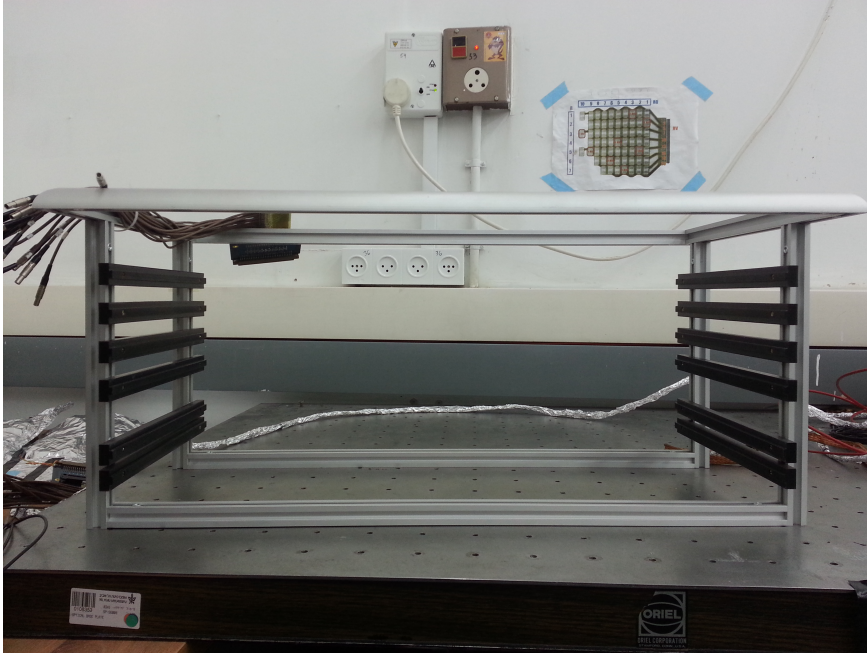


Figure 29: The tray holder built to hold the panel trays.

As a final step, the panels were connected to HV and RO cards and aligned on top of each other using two different methods. One, which was not successful, is discussed briefly in section 6.2 and shown on figure 34 and the other one, successfully used, involves a custom-made tray holder shown on figure 29. Figure 30 shows a complete setup of the tray with four panels. The black plastic tray holding strips were manually aligned to be parallel with each other using a micrometer resulting in an estimated position uncertainty of up to  $\pm 1$  mm. With the trays having a length of 65 cm and width of 39 cm, the maximum tilt (angle between the normal to the panel and the vertical) resulting from those uncertainties is  $0.3^\circ$ . The vertical distance between the holding strips was adjusted so that the vertical distance between the center points of the gas gaps of two adjacent panels is 37 mm. This was the lowest possible distance, due to the size of the blue gas valves visible on figure 30. The uncertainty in the distance is roughly estimated to be  $\pm 2$  mm (5%).

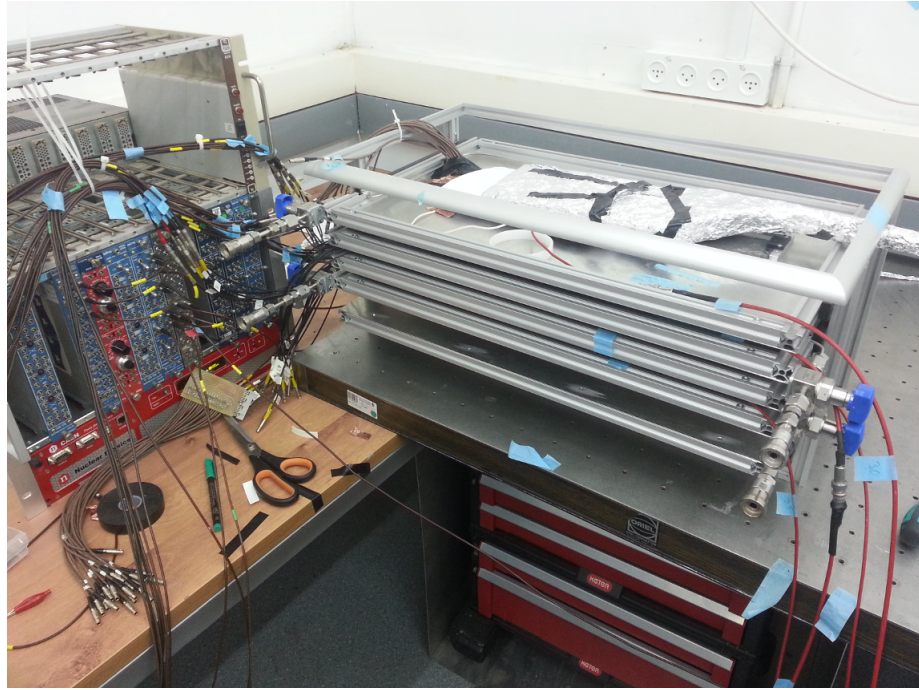


Figure 30: A complete tracker setup with four trays. The fifth, inverted tray on the bottom holds a scintillator pad and another pad can be seen on top. Compare this to figure 38.

## 5.6 TERMINOLOGY

From now on, a few terms will be used to refer to various events and configurations of the experimental setup.

- *Primary pulse* - if an ionizing particle that passes through a PPS creates ion pairs inside a small volume in or near one of the active cells of the PPS, causing a discharge in that cell, the voltage pulse coming from that cell is called the primary pulse. Any pulse coming in a window of up to a microsecond after the primary pulse from any one of the lines is considered to be a secondary pulse caused by unwanted physical phenomena in the gas. In almost all acquisition events each panel had either zero or one primary pulse.
- *Panel hit* - a primary pulse from a panel which coincides with the trigger. Whenever a trigger is generated, a snapshot is acquired of the outputs of all readout lines. If a panel has a primary pulse withing that snapshot, we report a panel hit.
- *Normal tracker setup* - the tracker setup seen on figure 30 and described schematically on the left side of figure 38, where four panels, with eight lines monitored on each are connected to a DAQ system and two scintillators, one above and one below the

stack of panels, so that the instrumented area of the panels and the scintillators overlap.



## DAQ USING TIME MULTIPLEXING

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We tried two different approaches of DAQ system implementations for the tracker. The second approach will be described in the next chapter. The first, failed approach was to use basic available equipment to make a "quick and dirty" solution, not involving any heavy software development. This chapter will briefly describe this attempt and present the first 2-point "track" observed.

### 6.1 DAQ EQUIPMENT

We have used a set of NIM discriminators, logical and linear fan-in fan-outs, NIM to ECL converters, timers and coincidence modules along with an Agilent MSO-X 4054A scope with four analog and 16 digital ECL logic inputs. In addition, we have utilized two NIM crates, LEMO cables and connectors.

### 6.2 IMPLEMENTATION

Originally, we planned to do a 5-panel tracker with 16 lines monitored on each panel. The way to connect all panels to the scope was to implement time-multiplexing of the panels, where all lines of panel  $k$  are delayed by an interval  $k\Delta t$ , where  $\Delta t$  is some constant time interval that is long enough to tell two signals apart. This way, ideally, a track would present itself as several digital pulses inside an acquisition window, separated by intervals which are multiples of  $\Delta t$ . Apart from connecting the lines of all panels to the digital scope inputs, we needed to implement a triggering mechanism, to be fed into one of the analog inputs of the scope and used as the trigger for the DAQ. This triggering mechanism must be a fairly elaborate one, since we must store the most interesting events, as the internal storage of the scope is limited to just 1000 acquisitions.

A simple implementation of DAQ and trigger for two panels and two connected lines is shown in figure 31. The lines coming out of panel B are delayed by  $\Delta t$  with respect to the lines coming from panel A. A resulting trigger and line signal is shown in figure 32. In setups of this kind, we need to make sure that we set the discriminator thresholds and widths of the resulting NIM logic signals from the various modules involved so that everything is synchronized properly before the signals reach the coincidence modules. Note that in the figure 31 setup, a trigger signal is generated when either panel A or panel B has a signal.

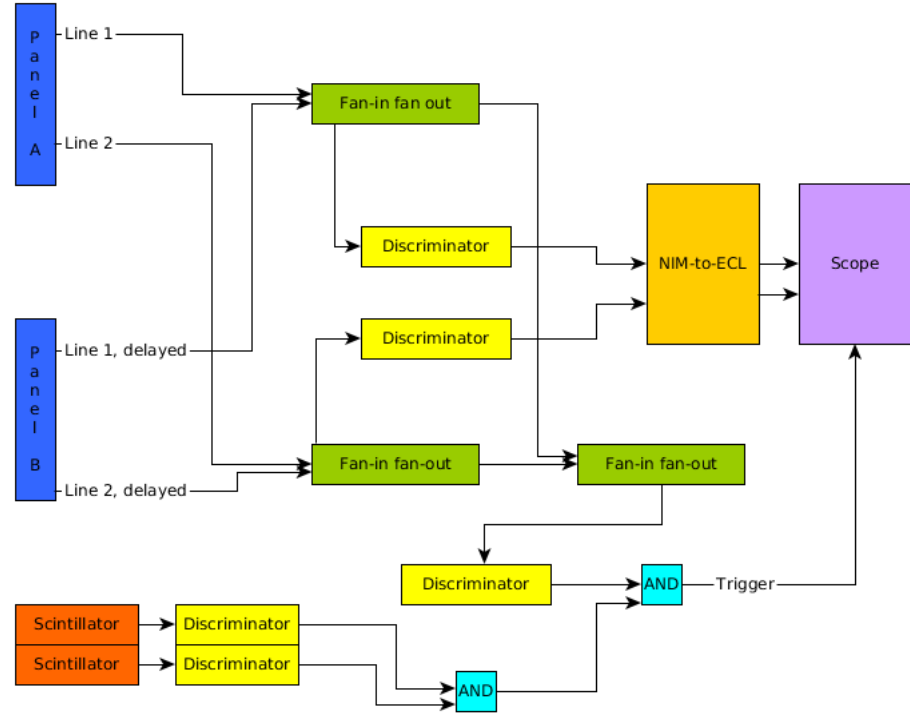


Figure 31: The initial idea of DAQ and trigger implementation using NIM modules.

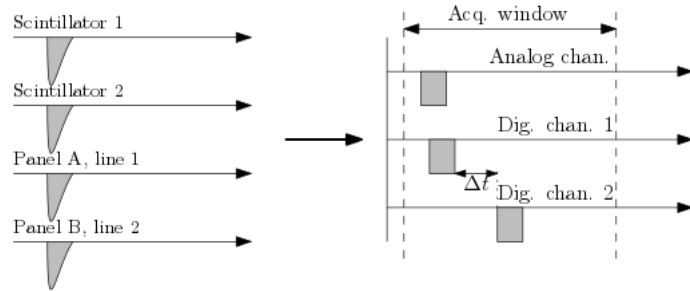


Figure 32: Shown on the left are raw signals from the two scintillators and from lines 1,2 of panels A,B, respectively. On the right are the expected inputs into the analog channel (trigger) and two digital channels of the scope, after being processed by the setup shown in figure 31. Also shown is the acquisition window of the scope, the width of which is configurable.

Ideally, this should work, but the panels we have, being first prototypes, are far from ideal and present a large amount of after-pulsing when several HV lines are connected, as shown, for example, on figure 33, as well as inducing strong electromagnetic noise in the digital inputs of the scope.

In order to solve the noise issue, a lot of shielding was successfully used to eliminate the noise. At first, we tried to shield the cables, but that did not produce any results. All cables used, besides the ones

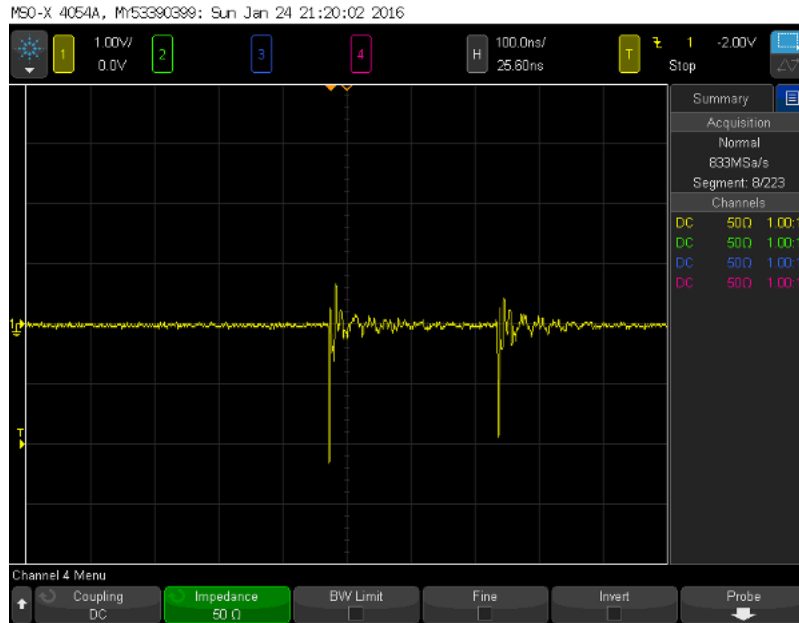


Figure 33: Example of after-pulsing on one line of a panel recently filled with 99% argon and 1%  $\text{CF}_4$  gas, connected to 930V with 3 HV lines. The first pulse is the primary, most likely caused by an electron emitted by a  $^{106}\text{Ru}$  source and the one following it is an after-pulse.

connected to the digital inputs of the scope, are coaxial cables which are already well-shielded and the shielding is well-grounded. Once that didn't work, we wrapped the trays holding the panels entirely with aluminum foil and grounded them to the metal workbench. We made sure that the workbench, all ground connections and shielding were connected to common ground and firmly connected to the metal casing of the power supply, with a thick copper braid. This eliminated the noise entirely and we could see clear digital signals on the scope.

The noise from a panel was eliminated only when the entire tray holding the panel was wrapped in aluminum foil. This prevented us from using the convenient tray holder, shown on figure 29 that was especially constructed to hold the trays so that they are almost perfectly aligned with each other. This required a new way of stacking and aligning the trays, which we did by using pieces of the rim of the tray, wrapped in aluminum foil for conductance and grounding, placed on the rims of the bottom tray, to support the upper tray, as shown on figure 34.

In order to solve the after-pulsing issue, we needed to make the implementation even more complex, introducing generation of VETO signals for the discriminators. Since each line could have after-pulses, we now needed to discriminate each line of each panel and when, for example, panel A had a primary pulse on one of it's lines, generate a VETO signal for all discriminators to which the lines of panel A are



Figure 34: Part of the outer rim of the panel tray used to suspend the top panel tray over the bottom one.

connected. This allowed just the primary pulse to reach the digital inputs and blocked any subsequent noise and after-pulses from that panel.

For testing and proof of concept, we constructed a DAQ and trigger implementation, which is described schematically on figure 37. The description of the different modules represented by block elements, their settings and their signal propagation delays are listed in table 9 and the cable lengths used for that setup are listed in table 8. The lengths of the cables were chosen carefully, so that pulses would reach their destinations at exactly the right time for the proper generation of VETO signals. The schematic shows two panels (panel C and panel B) with four lines monitored on each one. In addition, there are two scintillators, participating in the trigger generation. Each line is split using a fan-in fan-out to a trigger and veto signal generation mechanism and an acquisition mechanism. The acquisition mechanism (for a single line) is comprised of a discriminator, the output of which is fed into a logical fan-in fan-out and into the scope, through a NIM-to-ECL logic converter. The trigger and veto generation mechanism uses a separate fan-in fan-out section and a discriminator for each panel to determine if a line had a pulse. If so, a veto signal is generated by a timing module and fed into the veto port of the acquisition discriminator corresponding to that panel. A trigger is generated when both panels and both scintillators show a pulse.

An example of a digital signal resulting from a primary pulse on one of the panels is shown on figure 35. Here, all four active lines of

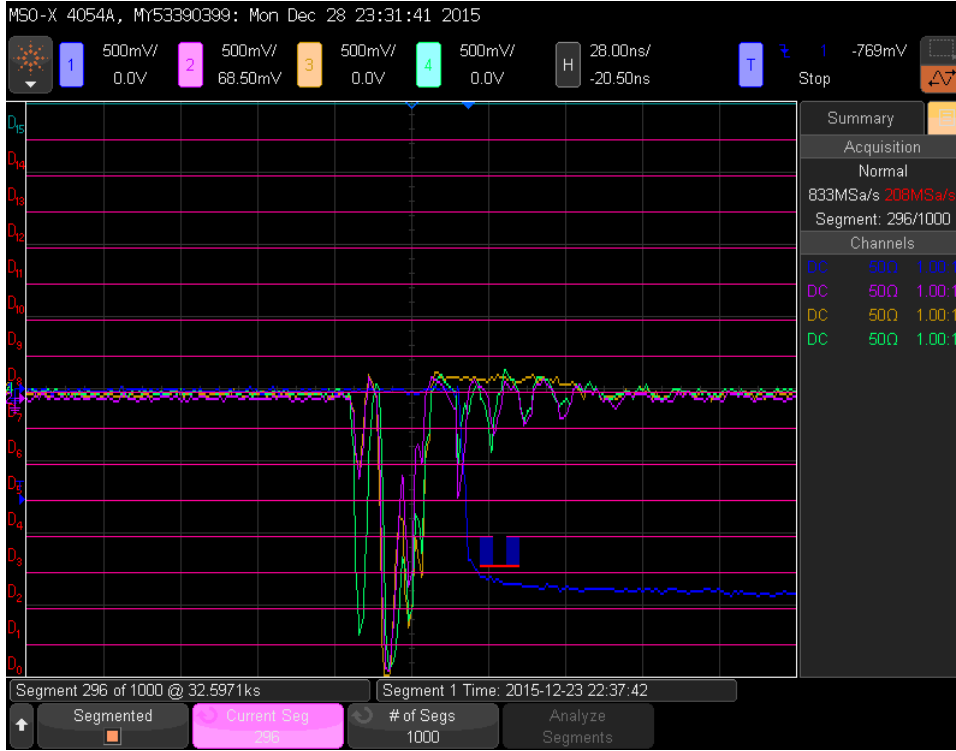


Figure 35: A digital pulse on line D<sub>4</sub> resulting from a primary pulse on line 4. The blue vertical bars in the digital signal result from decimation automatically performed by the scope, to save memory.

a single panel are connected to analog channels 1 through 4 of the scope and the corresponding digital outputs from the NIM-to-ECL converter are connected to digital inputs D<sub>1</sub> through D<sub>4</sub>. A large primary pulse can be seen as the first pulse (green, line 4) and then a set of after-pulses, which we veto out. About 45 ns later we can see a digital pulse on line D<sub>4</sub>, which corresponds to the primary pulse on analog line 4.

Obviously, when increasing the number of connected lines and adding more panels, the number of modules and the length of cable increases drastically. For four panels and eight lines, the amount of modules required becomes almost impractical.

### 6.3 OBSERVATION OF THE FIRST SUSPECTED TRACK

Though this approach was abandoned, we did manage to observe several 'tracks'. The word is in quotation marks since there aren't enough track measurements to perform any meaningful analysis on them, but the timing of the pulses is right and the odds of such a signal occurring randomly are slim.

Figure 36 shows an example of such an event. The system is wired the same way as the one that produced figure 35, where analog signals of only one panel are shown (analog lines 1-4), while the analog

signals from the other panel are not monitored. Here a primary sig-

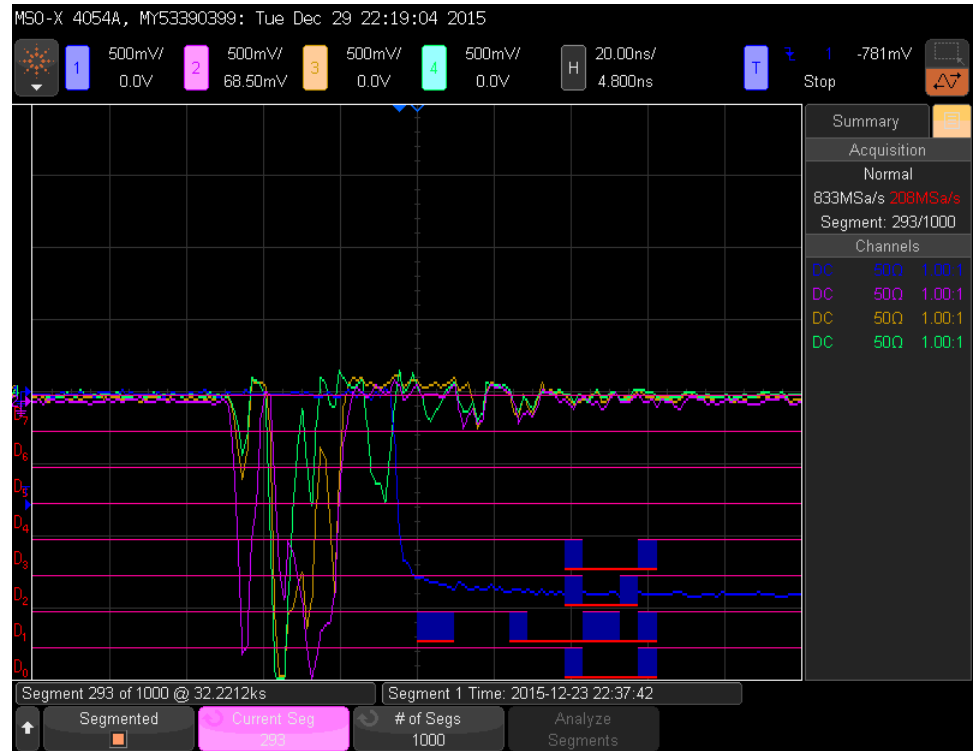


Figure 36: A good track candidate.

nal on analog line 2 (purple) causes a digital signal to be generated on line D<sub>2</sub> roughly 45 ns later. A bunch of digital signals then follow, resulting from pulses coming from the seconds panel, with a leading digital signal also on line D<sub>2</sub>. The reason for the bunching of the digital signals coming from the other panel is that we used slightly different discriminators for the two panels - 4608B and 4608C (see figure 37). The discriminator used on the panel producing the bunched signals (4608C) cannot veto all the noise that comes after the initial primary pulse as fast as 4608B can, resulting in trailing digital noise. Nevertheless, it was observed consistently that the leading digital pulse is located on a digital line corresponding to the analog line that produces the primary pulse. The interval between the start of the digital signal resulting from the first panel and the one resulting from the second one is close to 26 ns, which is the actual planned delay between the digital signals from the two panels, as can be verified by the length of the L12 cable in table 8. Figure 36 is therefore an example of a good candidate for a vertical 2-point track. I will not elaborate any further on the results from this acquisition method.

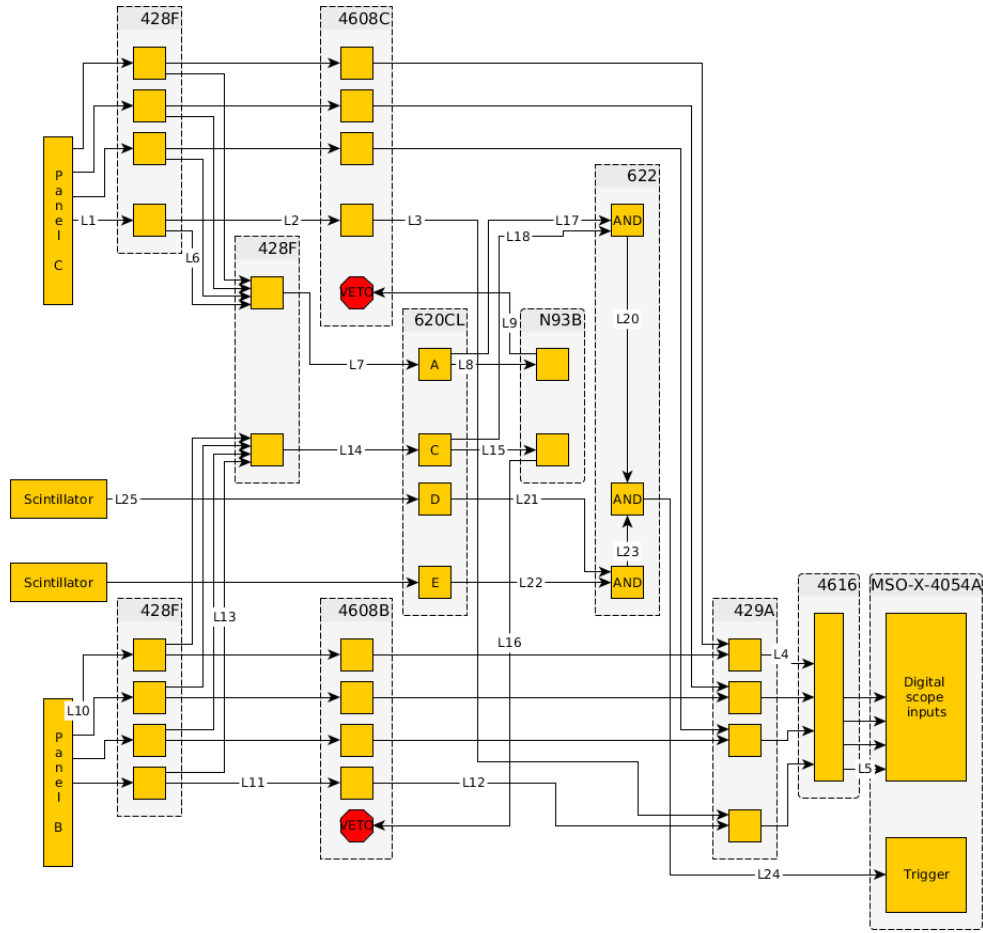


Figure 37: Schematic of acquisition and trigger implementation for 2 panels, with 4 lines connected on each.

Table 8: List of cable lengths on figure 37. The length is measured by the time it takes for a signal to propagate down the cable

| Label                                                                     | Total Length (ns) |
|---------------------------------------------------------------------------|-------------------|
| L1, L10                                                                   | 2                 |
| L2, L11                                                                   | 20                |
| L12                                                                       | 26                |
| L3, L6, L13, L7, L19, L14, L8, L20, L15, L21, L22, L23, L9, L16, L17, L18 | 1                 |
| L4, L24, L25                                                              | 10                |
| L5 (digital probe cable)                                                  | ~10               |

Table 9: List of the modules on figure 37, their descriptions, settings and the time delays they introduce to the signal

| Name          | Description                                                                            | Settings                                                                 | Max. delay                          |
|---------------|----------------------------------------------------------------------------------------|--------------------------------------------------------------------------|-------------------------------------|
| 428F          | Fan-in fan-out, linear                                                                 | Set to "Normal"                                                          | 6 ns                                |
| 4608C         | Discriminator                                                                          | Threshold: lowest (-1.08V)<br>width: narrowest                           | 18 ns                               |
| 4608B         | Discriminator                                                                          | Threshold : lowest (-9.1V) ,<br>width: narrowest                         | 18 ns                               |
| 620CL         | Discriminator                                                                          | Threshold: -5V,<br>Section A set to 20 ns, B,C,D,E set to widest (40 ns) | 8 ns                                |
| 622           | Coincidence module                                                                     | Width of all sections set to 1 $\mu$ s                                   | 9.5 ns                              |
| 429A          | Fan-in fan-out, logic                                                                  | Main switch set to 4 $\times$ 4                                          | 6.5 ns                              |
| 4616          | NIM to ECL converter                                                                   | Connected so that line 1 corresponds to D1 on scope, line 2 to D2, etc.  | 6.5 ns                              |
| MSO-X-4054A   | Digital oscilloscope                                                                   | Digital lines on, triggered on line 1, at -750 mV                        |                                     |
| Panel B       | Top panel                                                                              | At 1380V                                                                 | ~5 ns (from discharge)              |
| Panel C       | Bottom panel                                                                           | At 1380V                                                                 | ~5 ns (from discharge)              |
| Scintillators | 2 scintillators placed on top of each other over the active area of the stacked panels | At 1950V                                                                 | ~5 ns (from a muon passing through) |

## DAQ USING A DIGITIZER

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After realizing that time multiplexing is not practical, we decided to utilize a VME-based 32 channel CAEN V1742 digitizer. The digitizer specifications are listed in section A.3.7 and it is sufficient to simultaneously read out eight channels of four panels, thus making a small 4-panel tracker with just one digitizer board. The advantage of those digitizers is their scalability, allowing for expansion to a larger number of panels with increasing numbers of lines, which makes them relevant for future tracking measurements with the next generations of PPS.

Another major advantage of the digitizer is significant simplification of the trigger mechanism. The trigger in the time-multiplexing scheme was restrictive, to compensate for the limited amount of internal memory in the scope, so we wanted to record just the most interesting events. In the case of the digitizer, however, this is not required, because the amount of data we can store is now limited by the amount of PC storage, which is in the terabytes. We can therefore be much less restrictive when designing the trigger. In fact, it is enough to use a simple double coincidence of two scintillators and to record the signals on all of the lines whenever the trigger fires.

An additional advantage is the fact that the data is being fed in real-time into a PC, which enables elaborate analysis and monitoring of the whole setup in real time, enabling online monitoring of the system.

### 7.1 DIGITIZER-PC INTERFACE

The accumulation of digitized samples in the digitizer is at the rate of the triggering. Since the trigger rate in our case is of the order of a few Hz, a slow digitizer-PC interface is sufficient to read all acquired data in real time. It is therefore sufficient to connect the digitizer to the PC through the slower but easier-to-use USB port of the VME bridge and not through the optic fiber connection.

### 7.2 DIGITIZER-PANEL INTERFACE

The connection between the panels and the digitizer is schematically described on figure 38. Since the digitizer's inputs accept signals in a voltage range limited to  $\pm 0.5$  V, further attenuation is needed after the RO cards, as the pulse height in the RO card output can reach amplitudes of 5 V, depending on the HV the panel is connected to. The

attenuators we used attenuated the signal by a further 20 db, giving a total attenuation of 60 db (the RO card has on-board attenuation of 40 db).

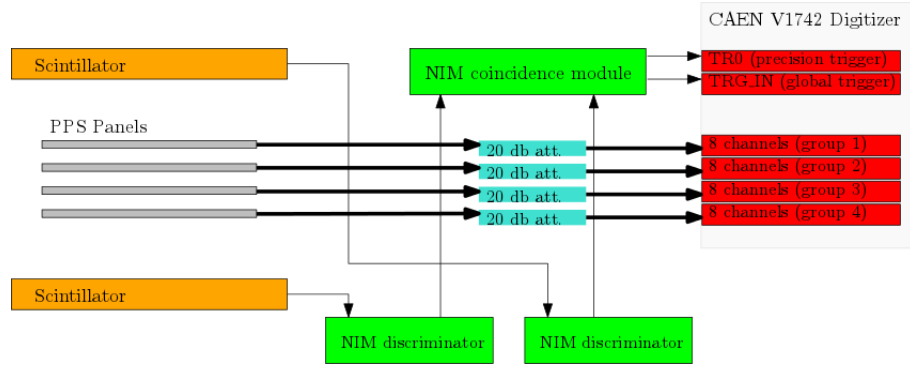


Figure 38: A diagram of the complete setup using four PPS devices, two scintillators, a coincidence and a discriminator module, 32 20db attenuators and the CAEN V1742 digitizer. The thick arrows represent eight cables and the attenuator blocks represent an attenuator on each one of the eight cables.

### 7.3 TRIGGER SETUP

The trigger is a simple double coincidence of two scintillators. The setup is shown on figure 38. The scintillators are each fed into a discriminator, then into a coincidence module set to AND and then into the TRG\_IN input of the digitizer. Since the TRG\_IN input does not acquire the trigger signal and is used just to signal the digitizer to acquire data, we split the trigger signal into the TR0 low-latency trigger input, which stores the trigger waveform along with the rest of the channels for timing analysis.

### 7.4 ACQUISITION AND ANALYSIS SOFTWARE

In order to fully utilize the power of the digitizer we need to write proprietary software to read and analyze data from it. Though there are some sample applications downloadable from CAEN's website, they need to be heavily modified to suit our needs. The software for acquisition and analysis was written in C++ integrated within the ROOT framework. The complete source code can be browsed and downloaded from

<https://github.com/davereikher/pps-daq>

#### 7.4.1 *Architecture*

The acquisition software is based on the CAENDigitizer library [26], which implements all the low-level details of communicating with the digitizer through VME and provides a convenient interface to all of its required functionality. This library is not restricted to a single digitizer model and can be used on any digitizer manufactured by CAEN.

The software was designed to be an analysis 'toolbox', with a set of three executables:

- Acquisition - for acquisition, real-time analysis, monitoring and storage of the acquired data into a ROOT file,
- Analysis - for offline analysis of the data in the ROOT file,
- Step - for looking at the acquired data event by event ("stepping" through them), to be used mainly for debugging and finding anomalies in individual events.

The acquisition and analysis tools perform the same operations on the acquired data. There are two differences between them. The first one is the delivery method of the data. In the acquisition tool the data is being delivered by the digitizer, while in the analysis tool, the data is being read from a ROOT file. The second difference is the fact that in the acquisition tool the data is processed in a separate execution thread to avoid pileup of data in the thread performing the acquisition.

The analysis and acquisition tools are comprised of a set of *analysis and monitoring modules*, where each module is responsible for analyzing and monitoring a specific aspect of the experiment. For example, there is a track monitoring module, which is responsible for analyzing any potential tracks (hits on more than one panel in a single acquisition event), a degradation monitoring module, which monitors the activity of each panel and helps see if a panel degrades with time and a few more, which are listed in the appropriate subsection below.

#### 7.4.2 *Primary Pulse Tagging*

The most important part of the software toolbox (specifically of the acquisition and analysis tools) is the ability to read a set of samples from the digitizer, analyze them and decide whether there was a pulse coming from a primary discharge on one of the panels connected to the digitizer. Very generally, each channel corresponds to a single line on a single panel. The channels are grouped together into panels in the software (this grouping is provided in an external configuration file described in section 7.4.8). At each acquisition event (once a trigger is

generated), the digitizer interfacing code reads the data from the digitizer, passing it to the analysis code, which detects whether there was a primary signal in any of the panels. The timing information and the result of this analysis are sent to the various analysis and monitoring modules which generate plots and activity logs (track characteristics, triggering rate, panel activity and so on).

A discharge signal coming from a panel is characterized by a leading large negative pulse (the primary pulse) on a single line of the panel, mixed with smaller, simultaneous induced pulses in the other lines of the panel, followed by ringing and after-pulses on multiple lines. To find a primary pulse corresponding to a discharge signal and tag it as such, we need to find the channel corresponding to a line with the first pulse on the panel and make sure that this pulse is well-separated in time from the rest of the large pulses on this panel and well separated in amplitude from the smaller simultaneous pulses that are induced on the other lines. We must also make sure that no significant voltage fluctuation precedes it. The process is realized using a set of configurable thresholds, listed in table 10 and explained in the following sections.

Before looking for the primary pulse, it is necessary to fix differences in per-channel DC offsets due to small differences in the resistances used in the attenuators connected to each channel. This is corrected in software, by bringing the zero of each waveform to 0 volts. This is done by working with several thresholds, `IDLE_LINE_DURATION`, which defines a duration of a flat line section in the waveform to calculate the DC offset from and `IDLE_FLUCTUATION_AMPLITUDE`, which defines the maximal amplitude of fluctuations below which a line is considered flat. A waveform before and after normalization is shown on figure 39. See section 7.4.2.1 for more details.

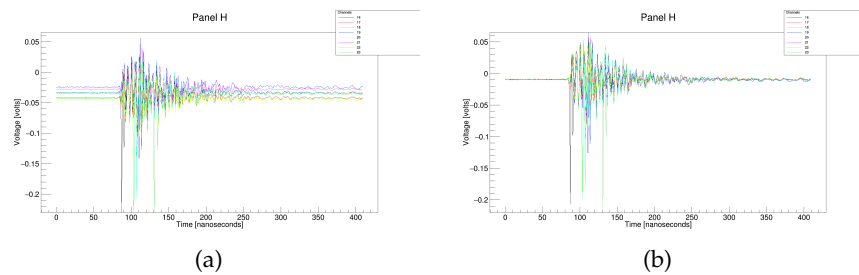


Figure 39: The same signal, showing eight lines on a single panel before bringing the waveforms from different channels to a common zero voltage (a) and after (b).

In order to tag a pulse as a primary one, the following requirements must hold for it:

- it must come before any significant fluctuation in voltage takes place (because it comes from the initial discharge),

- it must have a sufficient amplitude,
- it must appear enough time before any after-pulse.

For that, we define another three thresholds. `PULSE_THRESHOLD`, which is a voltage threshold that defines the threshold of a primary pulse (if a sample is found exceeding this threshold, the waveform potentially contains a primary pulse), `EGDE_THRESHOLD`, which is a voltage threshold that, similarly to a discriminator threshold, defines the voltage that, once exceeded, marks the start of a primary pulse (location of leading edge) and `MIN_EDGE_SEPARATION`, which is a time threshold that defines the minimum separation between the leading edge of the first pulse in a waveform and the one following it, so that the first one could be considered as a primary pulse. There are a few more auxiliary thresholds which are explained by going over the general overview of the source code in the next three sections.

#### 7.4.2.1 *Code Overview - Finding the DC Offset for Waveform Normalization*

In order to normalize the waveforms, as discussed above, we need to find the DC offset of each channel and then add to all samples in that channel the difference between the actual zero voltage and this DC offset. The steps to finding the DC offset are:

- Divide a single channel waveform into sections of length `IDLE_LINE_DURATION`.
- For each section, make sure the section is flat, by verifying that none of the samples in it exceeds `IDLE_FLUCTUATION_AMPLITUDE`.
- Once a flat section is found, calculate the average value of the samples in it and return this value.
- if a flat section is not found, this channel will not be adjusted (this almost never happens, since the sections are small and the acquisition window is wider than a typical signal, so there are always flat sections).

#### 7.4.2.2 *Code Overview - Primary Pulse Tagging*

The steps involved in tagging a primary pulse on a panel is as follows (this is done for each panel separately):

- Generate a list of pairs of the leading edge location and pulse minimum values (see section 7.4.2.3), where each pair corresponds to a single channel (a single line). The index in this list is the line number and the value is a pair (leading edge location, pulse minimum) for that line.

- Look for the line with the earliest value of the leading edge location (call it line a).
- Look for the line with the next-to-earliest value of the leading edge location (call it line b).
- If the distance between the leading edge location of line b and that of line a is greater than MIN\_EDGE\_SEPARATION, then line a has the primary pulse of this panel in this particular acquisition event and the pulse minimum is given by the pulse minimum value in the line's corresponding pair.
- If the above difference is smaller than MIN\_EDGE\_SEPARATION, generate a list of lines for which the first pulse's leading edge location is situated within a window of width MAX\_EDGE\_JITTER after the earliest leading edge.
- In the above list, find the line with the lowest minimum of the pulse. This line and all lines in this list, the minima of the first pulses of which are situated within a window of height MAX\_AMPLITUDE\_JITTER above that lowest minimum, are considered as potentially having a primary pulse (there is an ambiguity in which line had the primary pulse if there are more than one).

#### 7.4.2.3 *Code Overview - Generation of the List of the Leading Edge and Pulse Minimum Pairs*

This is an expansion of the first bullet in section 7.4.2.2, in which a list of leading edge locations and pulse minima needs to be generated. The steps for generating this list are as follows (this is done for each line):

- Look for the first fluctuation in the voltage on the line by looking for a sample that exceeds PULSE\_START\_THRESHOLD.
- If such a sample is not found, this line doesn't have a pulse and a corresponding reserved value is generated for the resulting pair to let the rest of the analysis code know that there is no pulse here.
- If such a sample is found, look for a later sample that exceeds PULSE\_THRESHOLD within a window of width EXPECTED\_PULSE\_WIDTH from the time of the initial sample.
- If such a sample is not found, this line doesn't have a pulse and a corresponding reserved value is generated for the resulting pair.

- If such a sample is found, look for the first occurrence of a sample that exceeds `EDGE_THRESHOLD` and find the lowest sample within a window of width `EXPECTED_PULSE_WIDTH` starting from that moment. Those two samples will constitute the pair corresponding to this line.

#### 7.4.3 *Analysis and Monitoring Modules*

As mentioned earlier, the results of the primary pulse detection and timing information are sent to various analysis and monitoring modules which help visualize and log important information about the experiment run. It's worth mentioning that each module can be turned on and off by the user to avoid cluttering the screen with plots. Below is the complete list of those modules.

##### 7.4.3.1 *Trigger Timing Monitor*

Monitors the timing of the trigger (double coincidence of the scintillators) and produces a plot that can be seen on figure 40. The top pad of the plot is the distribution of the time intervals between triggers and the bottom pad is the rate of the trigger.

##### 7.4.4 *Panel Hit Monitor*

For each panel, this module monitors the number of panel hits and, for each panel, generates a plot of the number of hits versus line on that panel (that way we can monitor the activity of each line) along with a second plot of the number of primary pulses detected on that panel per acquisition event as a function of time into the experiment run. An example plot is shown on figure 46.

##### 7.4.5 *Panel Timing Monitor*

Using the arrival time of the trigger signal and the arrival time of the primary pulse, this monitor generates two figures. The first one is the timing distribution histogram (jitter of primary pulse arrival time after the leading edge of the trigger pulse) and the second one is a figure with a similar histogram for each line. Those two figures help us see if the panel as a whole and the individual lines behave as expected. An example is shown on figures 44 and 45.

##### 7.4.6 *Panel Degradation Monitor*

Generates a figure for each panel, structured exactly as the one generated by the trigger timing monitor (figure 40), where each entry is now a panel hit. For an example, see figure 42.

Table 10: A list of the most important parameters and their values in the configuration file.

| Description                                                 | Value                |
|-------------------------------------------------------------|----------------------|
| EDGE_THRESHOLD                                              | -0.11 V              |
| PULSE_THRESHOLD                                             | -0.13 V              |
| PULSE_START_THRESHOLD                                       | -0.02V               |
| IDLE_FLUCTUATION_AMPLITUDE                                  | 0.05 V               |
| IDLE_LINE_DURATION                                          | 5% of acq.<br>window |
| MIN_EDGE_SEPARATION                                         | 3 ns                 |
| MAX_EDGE_JITTER                                             | 2 ns                 |
| MAX_AMPLITUDE_JITTER                                        | 0.1 V                |
| EXPECTED_PULSE_WIDTH                                        | 3 ns                 |
| Trigger pulse threshold (to detect leading edge of trigger) | -0.2V                |

#### 7.4.7 Track Monitor

After the raw signals were analyzed, a list of (panel, line) pairs are generated on which a hit was detected. This list is fed to the track monitor module which detects whether at least two panels had a hit in a single event (meaning a track was detected), calculates the slopes of the tracks, if any, and generates angular distribution histograms. An example of an angular distribution generated by this module can be seen on figure 54.

#### 7.4.8 Configuration

The entire suite is configurable through an external file written in JSON format. The configuration file contains the values of all thresholds listed above, a list of panels and the channels-to-lines association for each panel, digitizer settings (resolution, sampling rate, voltage range), various parameters for the different analysis modules and parameters for the Monte Carlo simulation. The configurable thresholds used in the analysis are listed in table 10. The values of the various thresholds were chosen by careful manual analysis of a large number of waveforms with the step tool.

### Part III

## ANALYSIS OF RESULTS & CONCLUSIONS



## RESULTS

### 8.1 MONITORING

Every time an experimental run was concluded, the quality of the data was assessed by looking at the various monitoring plots that were produced during the run. The resulting plots are shown below.

#### 8.1.1 *Monitoring the Trigger Rate and Arrival Time Distribution*

A two-pad plot with the histogram of the time intervals between subsequent triggers on the top and the rate of the trigger on the bottom, calculated every 10 minutes is plotted. An example of such a plot is shown on figure 40. The occurrence of the trigger is a Poisson process

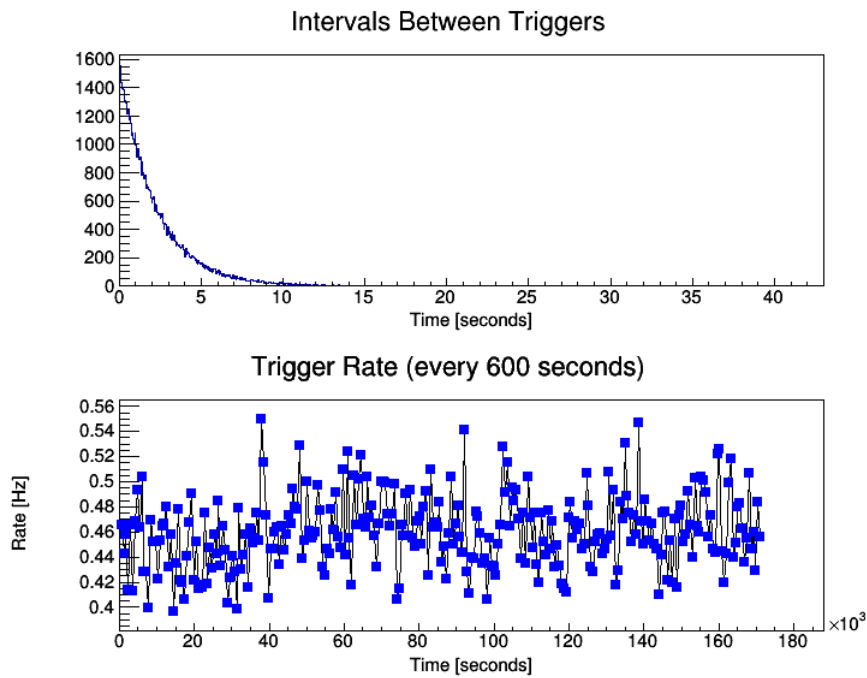


Figure 40: Trigger timing monitor. The trigger rate exhibits natural expected level of fluctuation.

so the time interval between two subsequent triggers is exponentially distributed. The rate should stay relatively constant in time. Figure 40 shows a healthy trigger, with exponentially distributed intervals and a constant rate. Figure 41 shows an example of the need to monitor the trigger rate. At some point the trigger rate falls, traced to a faulty air conditioner in the lab.

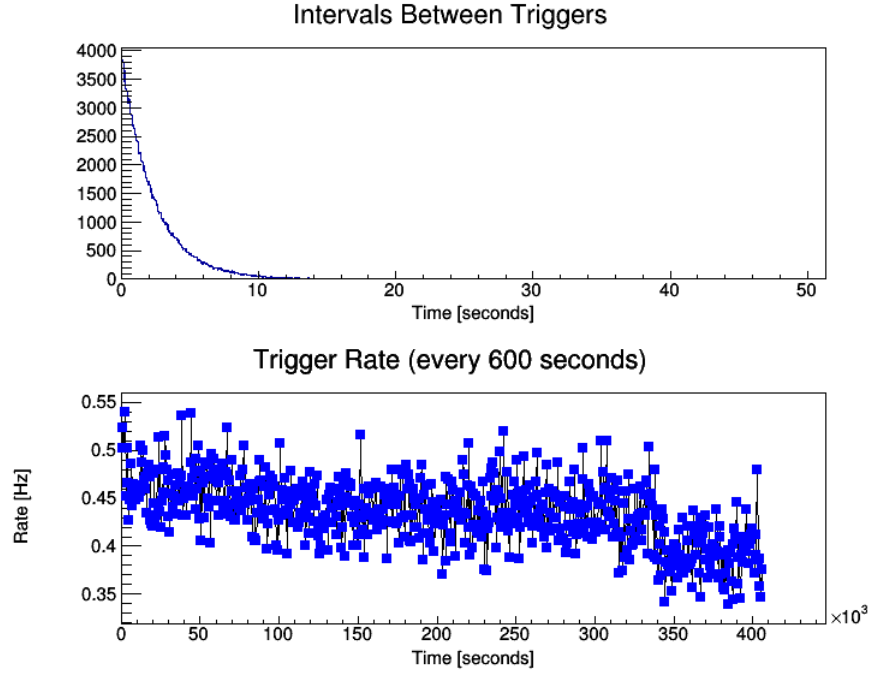


Figure 41: Trigger timing monitor. At 340000 seconds the air conditioning in the lab stopped working, which is clearly seen by the decrease in efficiency of the scintillators and reduction in the triggering rate.

#### 8.1.2 Monitoring Panel Activity

The panels are monitored for degradation (mainly due to leakage of air into the panel and degradation of the gas in the panel with time) by observing each panel's hit rate. The Poisson nature of the hits is also monitored by plotting the distribution of the time intervals between two adjacent coincidences, just as in section 8.1.1, forming a plot shown on figure 42. This figure shows a healthy panel, which does not degrade, as opposed to the example shown on figure 43, where a leaking panel was monitored.

Another way to see that a panel behaves normally is to plot a timing histogram, which is the time interval between the arrival of the leading edge of the trigger and the arrival of the primary pulse from the panel in any acquired event where this panel has a primary pulse. What we expect to get is a plot similar to figure 11 - a distribution with a main Gaussian part with a variance which characterizes the timing resolution of the panel and a power tail towards the high end of the histogram which is caused by passage of muons through areas with relatively low electric field, causing the resulting ionization electrons to drift a longer time towards the anode. Examples of healthy timing histograms are shown on figures 44 and 45.

A pulse from a panel is tagged as a primary pulse by the software after it passes certain criteria defined by thresholds set in the external

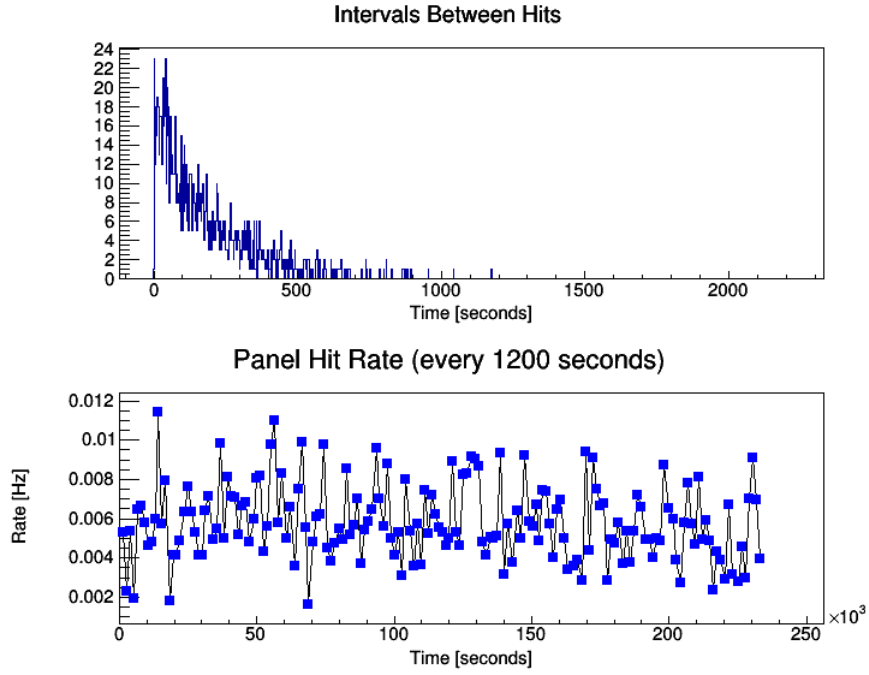


Figure 42: Example of a panel degradation monitor output for a healthy panel. The structure of the plot is identical to the one of figure 40.

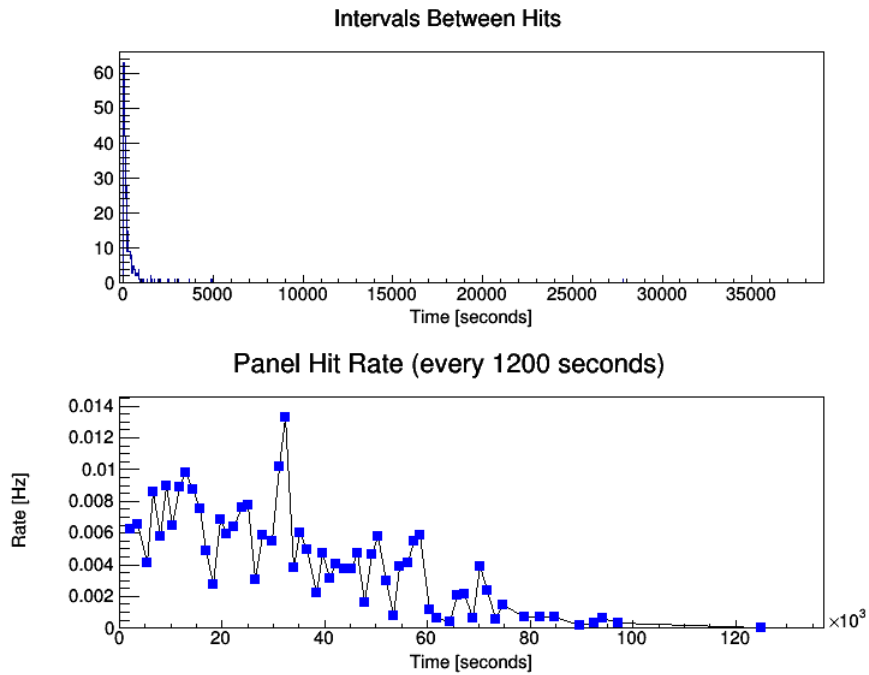


Figure 43: Example of a panel degradation monitor output for a leaking panel. Note the hit rate going down to zero.

configuration file. In order to qualitatively make sure that we have the correct values for them for a given experiment run we also monitor the number of primary pulses tagged by the software, for each panel,

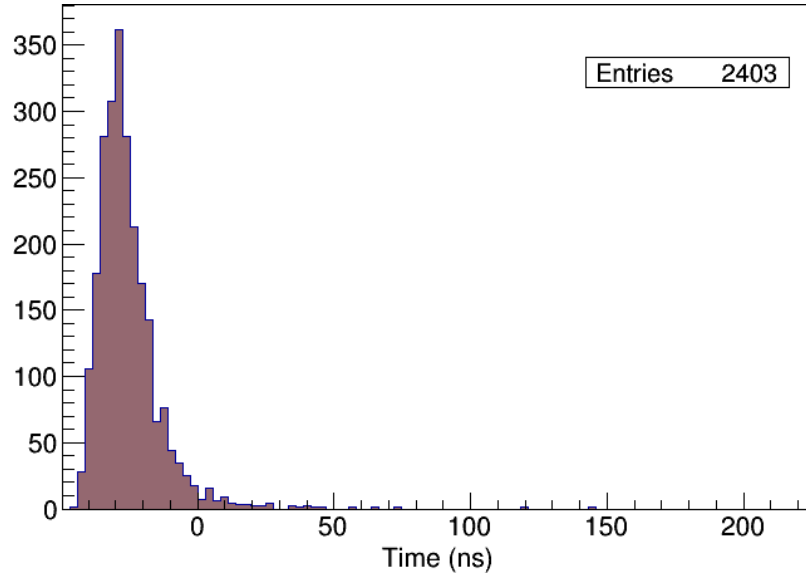


Figure 44: Timing histogram for a single healthy panel.

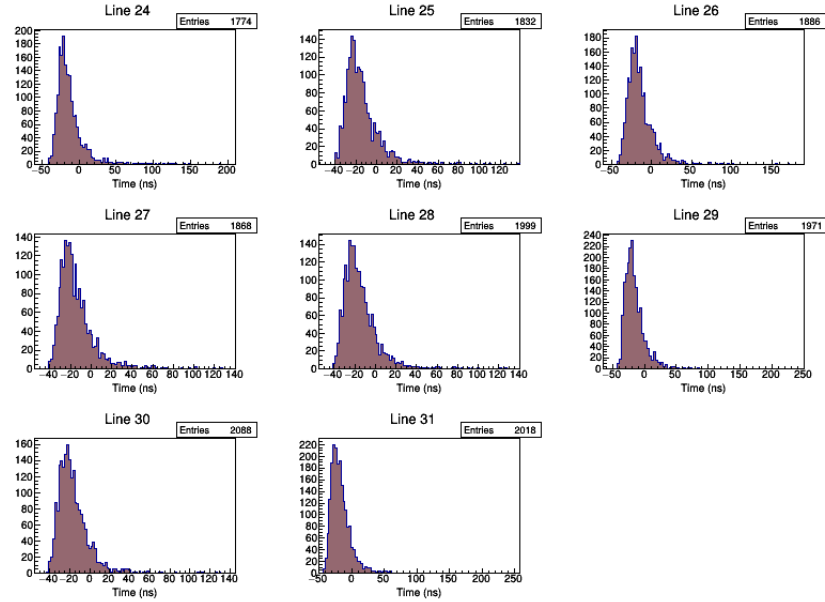


Figure 45: Timing histogram of all lines on a single panel.

at every event, as seen on the bottom pad of figure 46. Ideally, all panels should have either null or one primary pulse per event. However, occasionally two and more primary pulses per event are tagged. The lower pad on figure 46 shows a healthy distribution of the amount of primary pulses. The solid horizontal line is a dense occurrence of single primary pulses (a similar zero primary pulses line is not plotted), and the data points at higher vertical axis values represent events with a higher number of primary pulses. This distribution is 'healthy' because it results when the thresholds are carefully adjusted by looking at individual waveforms (see section 8.1.3). When an ex-

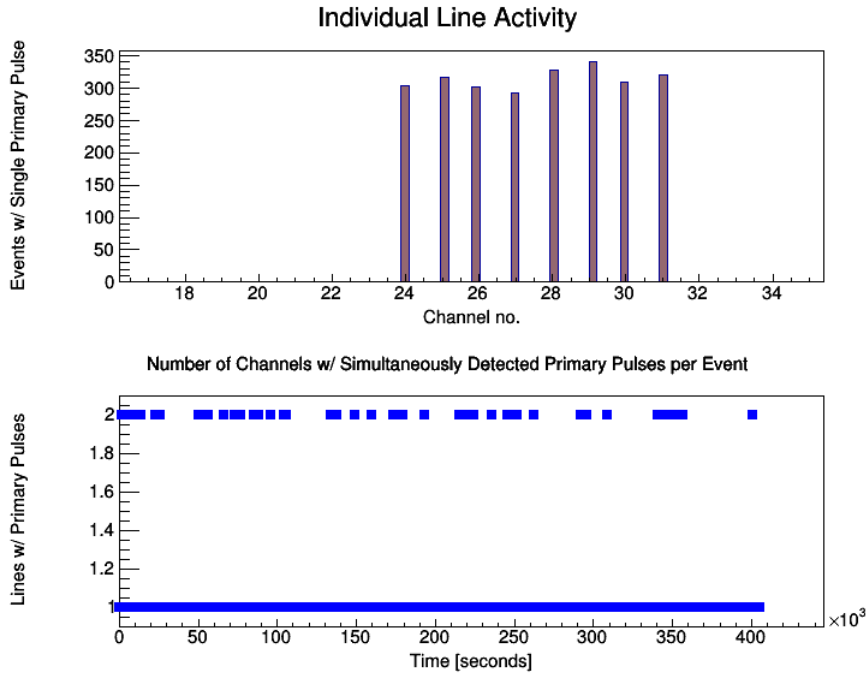


Figure 46: Line activity for eight lines connected to channels 24 to 31 (top) and primary pulse tagging monitoring plot (bottom) for a single panel. The latter shows events as a function of time, with the number of tagged primary pulses plotted.

perimental run produces a distribution which significantly deviates visually from this healthy one, such as, for example, on figure 47, we need to check the thresholds by analyzing the waveforms on all the lines associated with the problematic panel.

In addition, the monitoring checks for equal activity levels in all the lines of each panel. To do that, we look at an individual line and count the number of panel hits coming from that line. The result is shown on the upper pad of figure 46. A healthy panel with the thresholds set appropriately has all lines roughly equally active, as seen on this figure. A panel with unequally active lines is shown on figure 47. To get to the bottom of the problem we need to analyze the waveforms of the channels corresponding to the problematic lines.

### 8.1.3 Monitoring and Analyzing Signal Waveforms

In order to determine the thresholds used to tag primary pulses and to troubleshoot the system, we need to inspect individual waveforms. Figure 48 shows waveforms for all 32 channels used, grouped into four panels with eight lines on each (each line has a different color). Panel H has a primary pulse while the other panels exhibit fluctuations induced in their corresponding channels by RF noise from the primary pulse of panel H. A waveform showing a pulse coming from

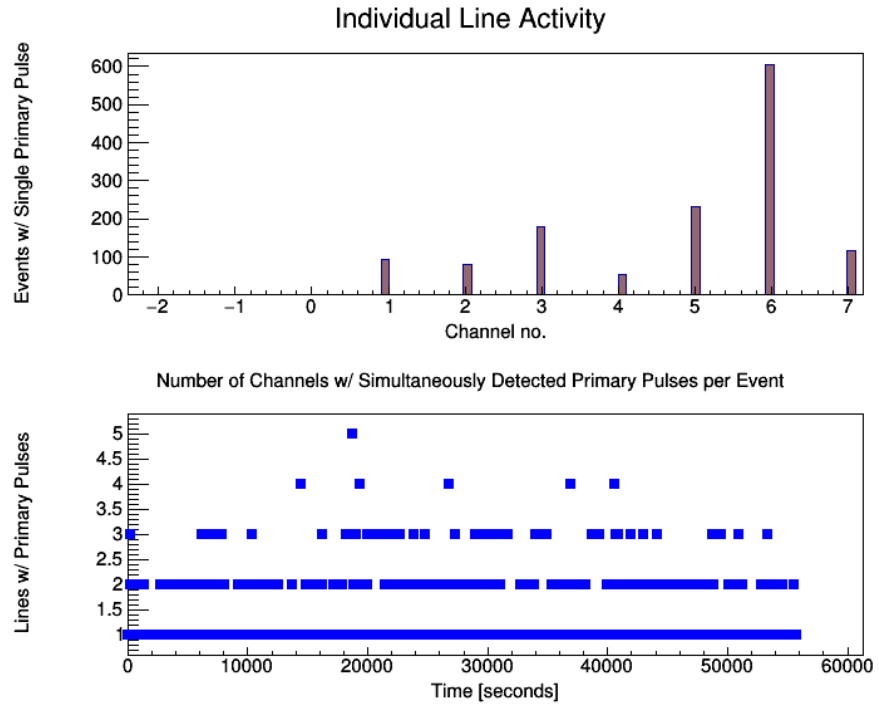


Figure 47: A plot similar to the one on figure 46, showing a non-uniform activity of the lines and bad primary pulse tagging, which can be seen by noting that there is a large number of events with three primary pulses and some events with four and five.

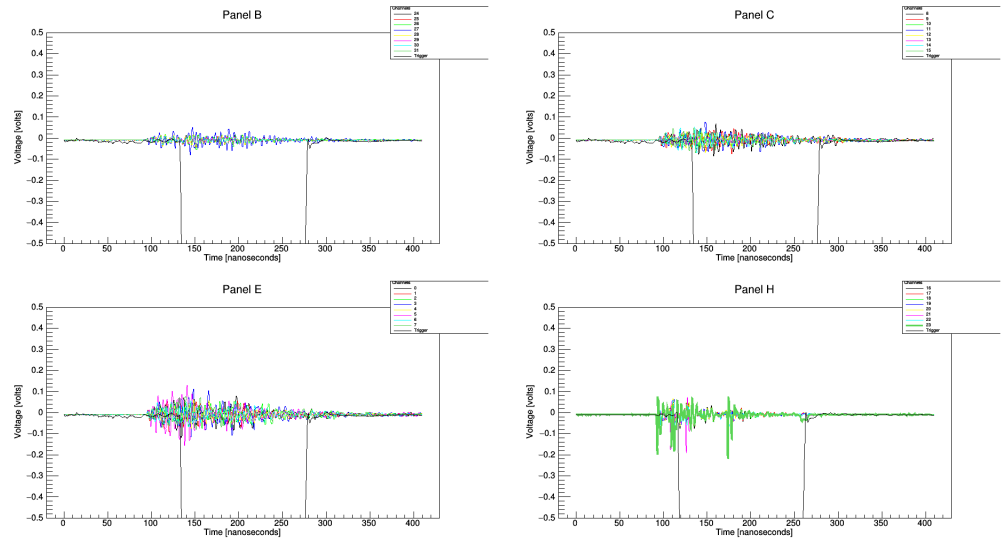


Figure 48: An example of the display of waveforms that is generated by the step tool used to examine waveforms of individual events. Each pad corresponds to a single panel, with eight lines monitored on each (marked by a different color). On the bottom right panel a pulse is visible and the line on which the pulse appears is automatically tagged and highlighted by a thicker line.

a healthy single panel with eight lines is shown on figure 49. The large square pulse is the trigger signal and the two horizontal lines mark the thresholds `EDGE_THRESHOLD` (top line) and `PULSE_THRESHOLD` (see section 7.4.2). The line that is tagged by the pulse tagging algorithm as carrying the primary pulse is plotted using a thicker line.

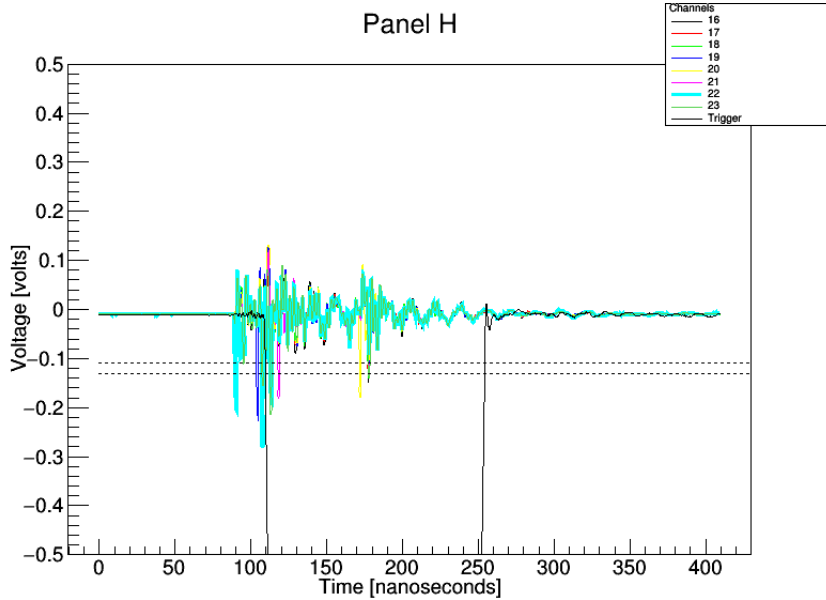


Figure 49: An example of a primary pulse waveform coming from a single panel with eight lines monitored. The channel with the primary pulse is highlighted by a thicker line.

An example of a waveform resulting from a bad connection on one of the lines is shown on figure 50. We can see that the line corresponding to channel 16 shows a repetitive pattern with a large amplitude, as opposed to the other lines.

Generally, the signals obtained from the panels are rather noisy and not optimal for a particle detector. In our experiment, however trailing noise after a primary pulse does not affect our measurements since it lasts for a very short time (hundreds of nanoseconds) compared to the trigger rate, having no noticeable effect on subsequent signals.

## 8.2 ANALYSIS

Our goal is to look for tracks, which present themselves as events with a primary pulse on several panels. In order to confidently say that such events represent actual tracks that result from MIPs passing through the tracker, we need to rule out random coincidence between pulses of separate panels and any significant effect of RF noise generated by either the PMTs of the scintillators or by any one of the panels.

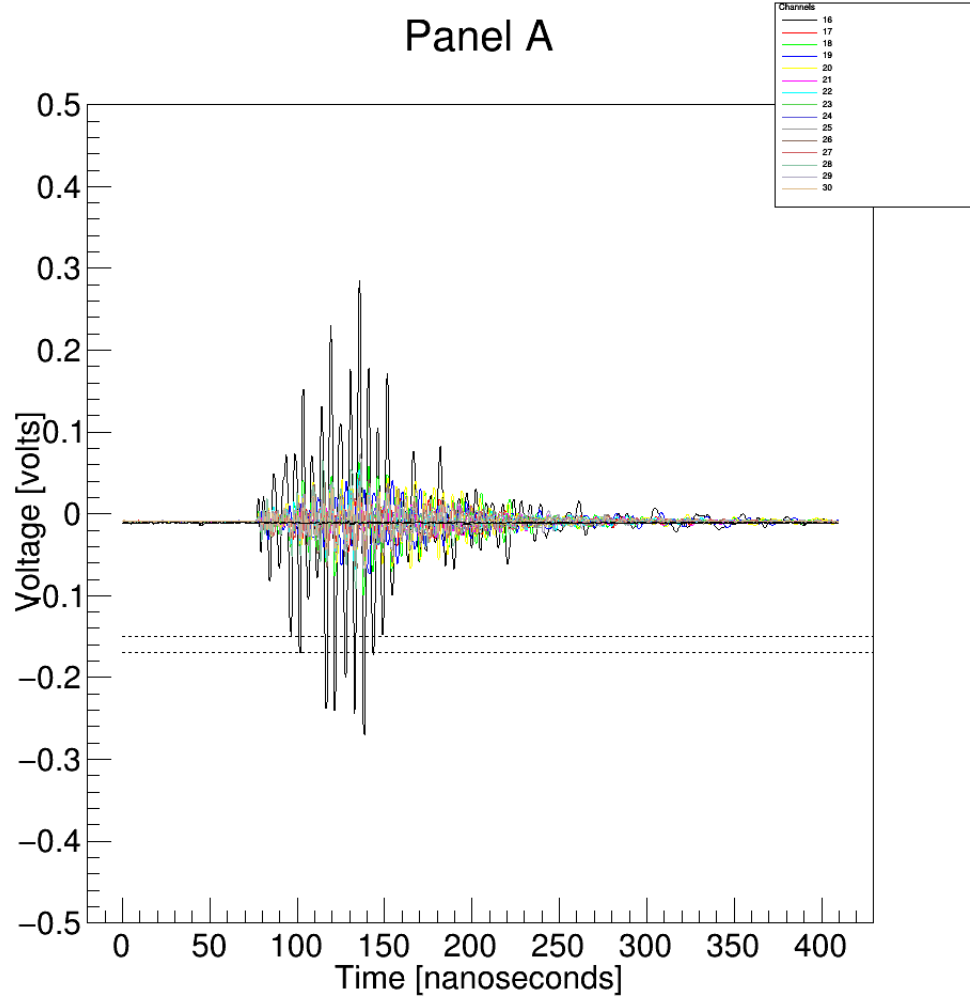


Figure 50: An example of a panel with 15 instrumented lines and a bad contact on the flat-to-LEMO adapter, on channel 16, exhibiting an abnormally large voltage fluctuation.

Such noise could create correlated pulses in some of the tracker elements (the PMTs or the panels) which could lead us to mistakenly interpret them as tracks (referred from here onward as ‘fake tracks’, as opposed to ‘true tracks’).

The total track detection rate averaged about  $10^{-4}$  Hz, which is at least one order of magnitude higher than the worst-case scenario rate of tracks resulting from random coincidences of pulses in the panels we calculated in section 4.3.1. We can therefore safely say that the contribution of random coincidence to the track rate is negligible.

RF noise poses a more serious problem. One problem with having fake tracks in our tracker setup is the low rate of total (true + false) track detection (as mentioned earlier,  $10^{-4}$  Hz), due to the low efficiency of the panels. We need to make measurements that will show, with a high confidence level, that the fake track rate is significantly lower than the total track rate. For that, we had to collect a

large data sample while limited by our low-efficiency panels and the limited rate of cosmic muons. In the following sections, whenever possible, we rule out RF effects while for more difficult cases I show that the contribution of fake tracks, if not completely negligible, is not obviously significant and propose experiments that can be done to entirely dismiss those effects.

### 8.2.1 *Effects of Panels on Scintillators and Vice-Versa*

In order to show that the contribution of the panels affecting the PMTs of the scintillators and vice-versa to the amount of true tracks is negligible we use the setup described schematically on figure 51, where

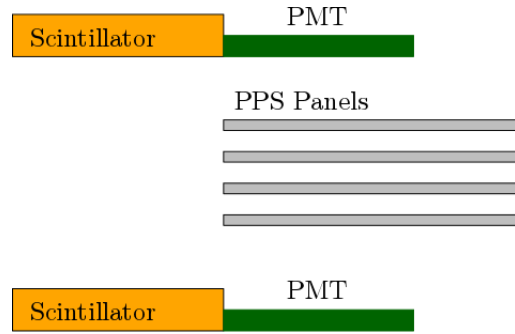


Figure 51: A schematic of the experimental setup used to test effects of PMTs on track detection rate.

the normal setup of the tracker is used, with the exception that the scintillators are moved so that the scintillator pads overlap each other, but do not overlap the stack of panels and that their PMTs are directly underneath and above the stack. This way, MIPs will not contribute to any registered 'tracks' at all and all we should see is contribution of RF noise from the PMTs on the panels and vice versa as well as random, uncorrelated pulses from the panels. The setup collected data for 250000 seconds (four days). The result was the detection of two 2-point tracks in four days.

If a significant number of tracks was originating from RF noise, we would get a track detection rate of  $10^{-4}$  Hz in this setup, but we got a rate of the order of  $10^{-6}$  Hz. We can therefore rule out any significant contribution to the fake track rate of the effect of the PMTs on the panels. In fact, this low rate is consistent with the rate we calculated at the end of section 4.3.1, resulting from random coincidence, so it might not even be a result of RF noise.

### 8.2.2 *Effect of Panels on Each Other*

Another effect that must be ruled out is the effect of panels on each other. If pulses in one panel electromagnetically induce pulses in an-

other panel, we will see fake tracks, caused by this correlation between panels. This effect should also cause an increase in pulsing rates of an active panel surrounded by active panels, versus an active panel surrounded by inactive panels. This was tested by using the normal tracker setup, running a single panel with the three surrounding panels off for a while and then applying the usual HV to the surrounding panels all at once, all the while measuring the hit rate of the single panel. The result is shown on figure 52. It can be

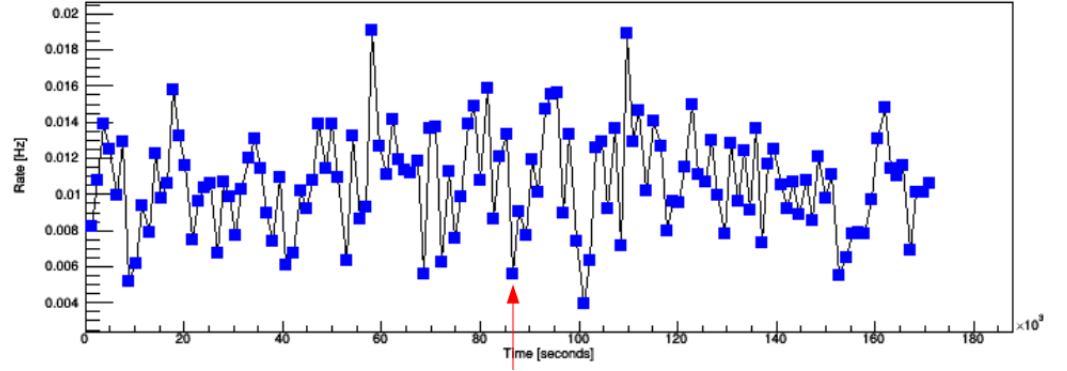


Figure 52: Hit rate (calculated every 1200 seconds) as a function of time of a single panel surrounded by three panels (two on the bottom and one on top) before and after the surrounding panels are turned on. The arrow marks the moment when they were turned on.

seen that there is no significant difference in rate before and after the activation of the surrounding panels. However, we will show that this is not enough.

To further quantify any effect of panels on each other, we can look at two-point tracks only, since they form the majority of acquired tracks. Looking at a very long interval of time  $T$ , the total number of tracks  $N$  acquired by the tracker within  $T$  can be written as the sum  $N = N_t + N_f$  of the number of true tracks ( $N_t$ ) and fake tracks ( $N_f$ ), resulting from panels affecting each other. We need to show that  $N_f \ll N$  to reject this effect. The number of true tracks can be further decomposed into a sum of contributions, each coming from a different pair of panels:

$$N_t = N_{12} + N_{13} + N_{14} + N_{23} + N_{24} + N_{34}, \quad (15)$$

where the subscript of each term are the two panels contributing in that term. If the effect of surrounding panels on a single panel (say, panel 2) is an increase of the number of hits of that panel by  $\Delta N$ , then each term involving panel 2 in eq. (15) gets a contribution of the order of  $\Delta N$  or smaller (for panels farther away, as EM effects diminish as  $1/r^2$ ). The contribution of the number of fake tracks to  $N$  is therefore of the order of  $\Delta N$ . Therefore,  $N_f \sim O(\Delta N)$  and, since we are interested in placing an upper bound on  $N_f$ , we need to find an upper bound on  $\Delta N$ .

If we mark the number of panel hits within the interval  $T$  before turning on the surrounding panels by  $N_1$  and after - by  $N_2$ , the more data we take, the smaller the uncertainties in  $N_1$  and  $N_2$  will become. We need to get enough data, so that those uncertainties are of the order of the maximal  $\Delta N$  we allow, so that we could tell that  $N_1$  and  $N_2$  do not differ from each other by more than  $\Delta N$ .  $N_f$ , and therefore also  $\Delta N$  should be at least one order of magnitude below the measured total track detection rate ( $N/T \sim 10^{-4}$  Hz). Since  $N_1/T \approx N_2/T \sim 10^{-2}$  Hz, as can be seen on figure 52, the maximum value for  $\Delta N$  is

$$\Delta N/T \approx 10^{-5} \text{ Hz} \approx 10^{-3} N_1/T \approx 10^{-3} N_2/T,$$

or

$$\Delta N \approx 10^{-3} N_1 \approx 10^{-3} N_2.$$

The uncertainty needs to be of the order of  $\Delta N$ , and since  $N_1$  and  $N_2$  are Poisson variables, their uncertainties are just their square roots, so

$$\sqrt{N_1} \approx 10^{-3} N_1$$

and similarly for  $N_2$ . This gives  $N_1 \approx N_2 \sim 10^6$ . This amount of hits at a rate of  $10^{-2}$  Hz (the hit rate of a single panel) will take about 3 years to acquire, so it's not practical and we therefore cannot completely reject inter-panel RF effects with our current setup and the natural rate of cosmic muons. In order to reject inter-panel effects, we will need to make the same measurement with a much higher luminosity MIP source, such as using a beam of muons.

### 8.2.3 2-Point Tracks

The experimentally measured distribution of the  $\chi$  angle (see section 4.5) is given on figure 53 and a histogram representing it's projection onto the observation plane is shown on figure 54. This is the form of those histograms we would expect to get for straight MIP tracks passing through the tracker, as explained in section 4.5.1. The distortion of the histograms (described in section 4.5.1), limits us from further precise angular analysis of their shape.

We use the Monte Carlo simulation to plot a similar angular distribution that would result if the hits on the panels were completely random. The result is shown on figure 55. For each iteration of the simulation, a random 0 or 1 value was generated for each panel in the stack. If the value is 1 for a panel, a hit is generated on that panel on a line the number of which is randomly selected from a uniform distribution. We note that qualitatively, figures 55 and 54 differ from each other in their structure. The histogram on figure 54 exhibits a more 'layered' structure than the one on figure 55. We also performed

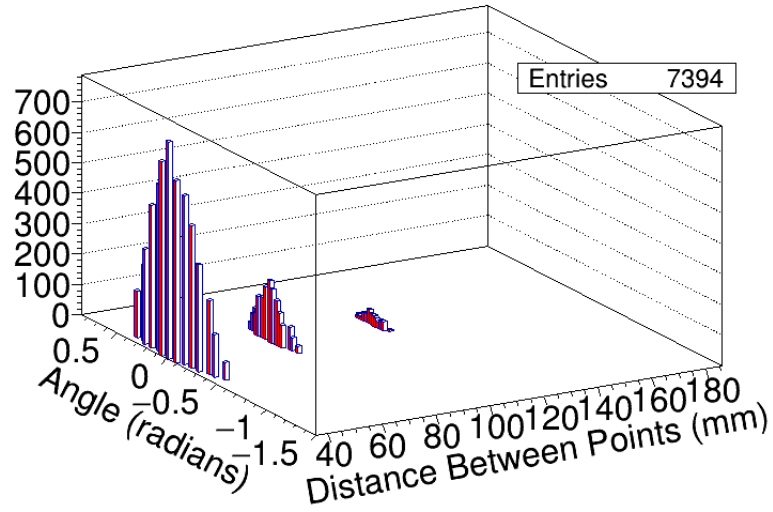


Figure 53: Two-dimensional histogram of angular distribution. The axes are the angle  $\chi$  of the track (see section 4.5.1) and the distance between points on the track.

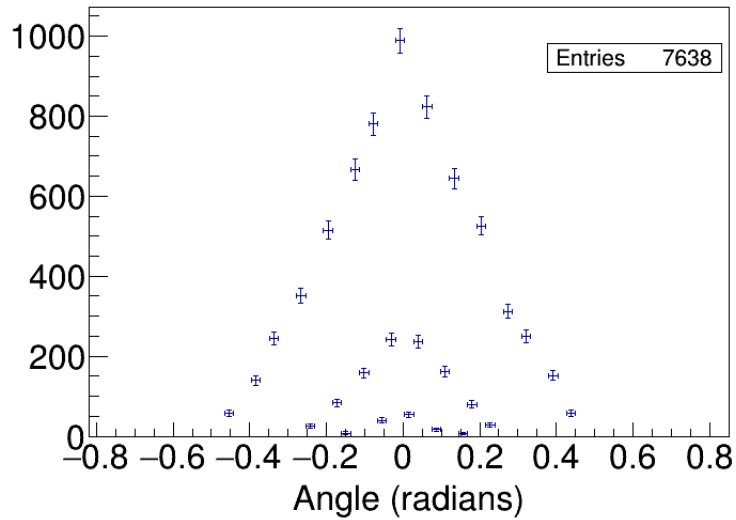


Figure 54: One-dimensional histogram representing the angular distribution of tracks as seen from the observation plane. 97% of the tracks here are 2-point tracks. Note the layered structure, explained in section 4.5.1.

a Pearson's  $\chi^2$  test to compare the two histograms, and the resulting p-value was practically zero, rejecting the hypothesis that the two histograms originate from the same distribution.

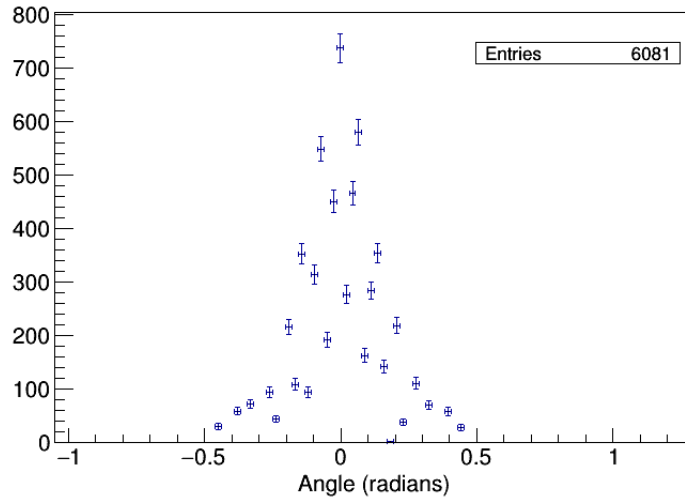


Figure 55: One-dimensional histogram representing the angular distribution of 'tracks' that would result from completely random hits on the panels.

#### 8.2.4 3-Point Tracks

Following the discussion in section 4.5.2, we plot the Distribution of the  $\chi^2$  per NDF of the resulting 3 and 4-point tracks (figure 56). Even though the histogram includes 4-point tracks, there are only a

Chi Square per NDF of 3,4 Point Tracks

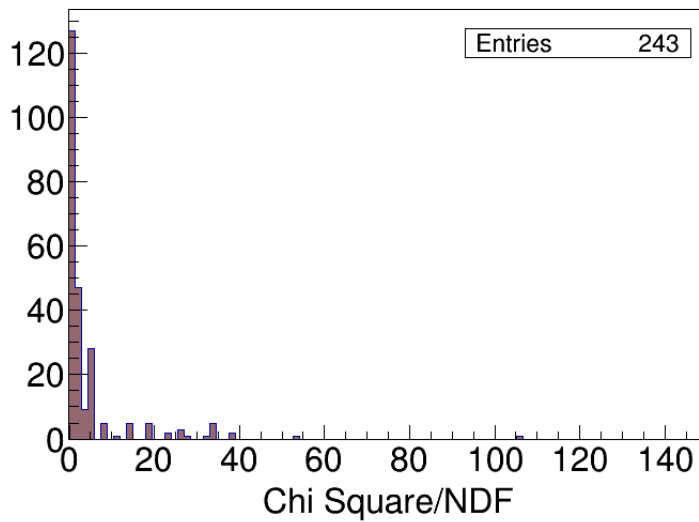


Figure 56:  $\chi^2$ /NDF histogram of the 243 3 and 4-point tracks we acquired in a period of roughly two months.

few of them, so we cannot perform any significant statistical analysis

on them. We can already see that the majority of tracks have a very low value of  $\chi^2$ , which means that the 3 points comprising them are collinear (for  $\chi^2 = 0$ , about 125 tracks) or nearly collinear. To rule out the option that this histogram could result from completely random hits on the panels, we assume a null hypothesis that the hits are completely random and run a Monte Carlo simulation, similar to the one we did for 2-point tracks, that results in the  $\chi^2/\text{NDF}$  plot shown on figure 57. Using the Chi2Test method of the TH1 class in ROOT, which

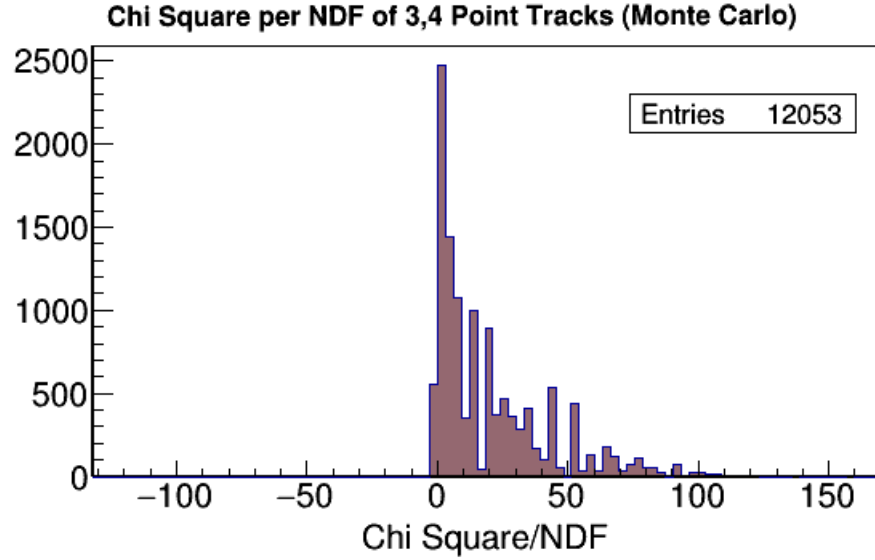


Figure 57:  $\chi^2/\text{NDF}$  histogram of 3 and 4-point tracks generated by a Monte Carlo simulation where each hit on each panel is assumed to come from a random line.

implements Pearson's  $\chi^2$  test, a comparison of the two histograms in figures 56 and 57 was performed and yielded a  $\chi^2$  value which corresponds to a p-value of practically 0 (much lower than 0.01), so we reject the null hypothesis.

## CONCLUSIONS

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Plasma panel sensors is a promising technology of particle detectors in the micropattern gaseous detector category. Previous research on prototypes of PPS devices had shown potentially high-end values of characteristics such as spatial resolution, timing resolution and dead time, characterizing detectors operating in the Geiger-Mueller region and beyond. An additional advantage of PPS devices is the low manufacturing cost, resulting from overlap of the manufacturing process with the one of commercial PDPs as well as the lack of need in cumbersome and expensive gas re-circulation systems used in today's gaseous detectors.

The work described here has shown that it is possible to use prototype PPS devices, which are no more than PDP panels filled with a different gas mixture, to perform tracking measurements of cosmic muons. In the tracker experimental setup, contribution to track measurement rate of RF noise between tracker elements was partially ruled out and we still need to perform an additional experiment with a high intensity MIP source in order to dismiss this effect completely. Nevertheless, we could not find anything that contradicts the hypothesis that the measured tracks are caused by cosmic muons.

As a part of the tracker development, a software suite for DAQ, storage and monitoring as well as real-time and offline pulse and tracking analysis and a toy tracker Monte Carlo model were implemented. These tools can be used for DAQ and analysis as well as for the construction of tracking devices with newer generations of PPS.

As a final note, the tracker constructed and described in this thesis is a two-dimensional one, consisting of 4 panels with one-dimensional readout from each panel. Development of two-dimensional readout from newer generations of similar panels is currently underway.



Part IV

APPENDIX



## DATA ACQUISITION SYSTEM

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### A.1 TRIGGERING AND DAQ OVERVIEW

The process of data acquisition is comprised of two main operations. One is the acquisition of electronic signals coming from a detector and their storage along with some basic analysis, and the other is a generation of a trigger, which, as its name implies is used to trigger the DAQ system to perform the acquisition. Trigger setups range from simple double-scintillator coincidence triggers to elaborate multi-channel triggers that analyze signals in real time and use pattern recognition techniques to detect specific signal forms. In our case, a simple double-scintillator coincidence trigger is sufficient, where data acquisition is triggered whenever pulses from two overlapping scintillators coincide, which occurs when a MIP passes through both.

#### A.1.1 *Scintillator Trigger*

The scintillator in use is a solid-state detector of ionizing radiation. It is comprised of a block of scintillating medium, which, with a high efficiency, emits photons whenever an ionizing particle (e.g. a MIP) passes through it. These photons are collected at one end of the scintillating block by a photomultiplier tube (PMT), which is comprised of an interface that emits electrons through the photoelectric effect whenever a photon interacts with its surface and a volume housing several electrodes (*dynodes*) with an increasingly large high voltage applied to each subsequent one. The electrons emitted from the interface are accelerated in the volume, multiplying their numbers with every hit of a subsequent dynode through secondary emission, until a significant current pulse is registered at the PMT's output. Due to the acceleration of charges inside, PMTs are sometimes a source of RF noise in experimental systems. We deal with that issue in section 8.2.

In theory, it is enough to use a single scintillator at the detector entrance to detect an incoming MIP and to use the resulting pulse to trigger data acquisition. In practice, a pulse from a scintillator could result from a variety of other sources, such as low-energy electrons from radioactive decays and RF noise induced in the PMTs by external sources. Therefore, to reduce false-positives, a coincidence between two scintillators is used as a trigger instead.

## A.2 DAQ EQUIPMENT STANDARDS

In order to read a signal from a detector and process it, we need suitable electronic equipment. For highly specialized experiments it's not out of the ordinary to construct proprietary equipment, but for our purposes we chose to use some ready-made modules based on the NIM, VME and ECL standards.

### A.2.1 NIM

The Nuclear Instrumentation Module (NIM) system is a mechanical and electrical standard used in experimental particle and nuclear physics. It provides electronics cards (modules), each with a distinct functionality. Some examples are discriminators (modules that convert an analog signal to a digital one using a voltage threshold), fan-in fan-out, pulse counting, coincidence between pulses and pulse timing modules. See section A.3 for further details about each module used. The modules are placed in a housing called a *NIM crate*. Figure 58 shows a photograph of a NIM crate with various NIM modules. The

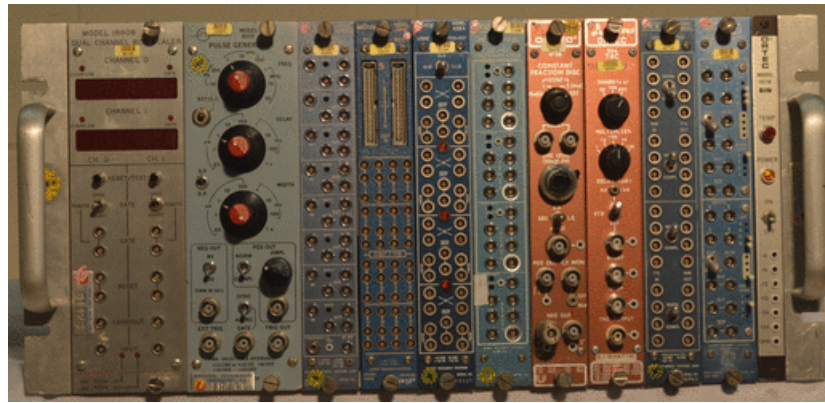


Figure 58: A NIM crate with NIM modules [27].

NIM digital signals, used, for example, in discriminator and coincidence units, use a 0 voltage as a logic 0 and a negative voltage as logic 1. This specification makes the NIM standard more susceptible to RF noise, since the logic levels are measured relative to ground, and any RF-induced noise will distort the signal (ground potential is not significantly affected by RF noise).

### A.2.2 ECL

Emitter Coupled Logic (ECL) is a newer logic standard, where the signals are transferred on two wires, one carrying the signal and the other carrying a complementary signal. The logic level is then determined by looking at the difference between the two signals. This

is more resistant to RF noise, since it affects both wires similarly. In order to convert NIM logic signals to ECL logic and vice versa a dedicated module is used. Comparison between the NIM and ECL standards can be found in [28].

### A.2.3 VME

A standard architecture commonly used by nuclear physics and particle physics experiments as well as medical and industrial studies is the computer bus “VERSAmodule Eurocard” (VME) standard [29]. This is a high-speed, high-performance bus system with power-

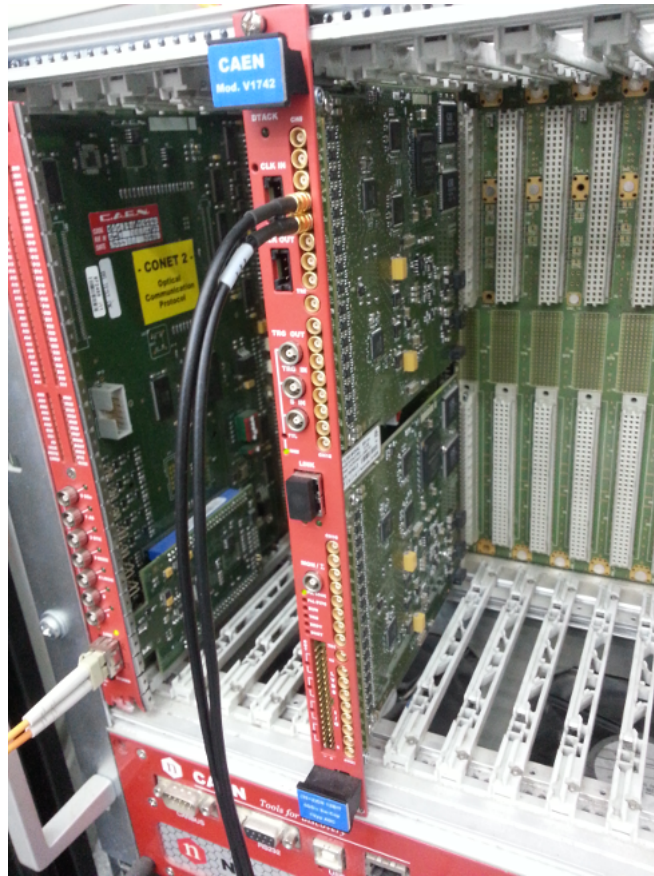


Figure 59: A VME Crate with a bridge (left) and a 32-channel digitizer module. The modules are plugged into the sockets visible on the back of the crate, which are connected to the VME bus. Gold-plated MCX-type inputs are visible on the front panel of the digitizer module as well as larger LEMO-type inputs.

ful interrupt management and multiprocessor capabilities. Similarly to a NIM system, a VME system is comprised of a VME crate and VME modules. The strength of the VME system is that VME modules are connected to a bus and can therefore communicate with each other and perform elaborate signal processing. Additionally, many modules are programmable and thus much more flexible in function-

ality than NIM modules. This enables us to build multi-channel DAQ systems with relative ease.

A VME crate with VME modules usually contains a master module called the VME bridge, through which the user can send commands and receive data to any module on the VME bus. Figure 59 shows an example of a VME crate with a bridge and a digitizer module in our lab.

### A.3 DAQ EQUIPMENT

#### A.3.1 *Discriminator Units*

An important element in detector signal analysis is the discriminator. Its purpose is to transform a signal from its analog form to a digital 'true or false' form, depending on the logic it's based on. For example, a typical NIM-logic unit has an input port and several output ports. The input port is fed with a signal and the output ports show a NIM-logic 1 signal whenever the input signal passes a threshold which can be set through turning a knob or screw on the discriminator front panel. The width of the output NIM-logic signal can also be set in a similar manner. Discriminator units are usually comprised of several sections, where each section is a separate discriminator and they all share a single VETO input. As long as a logic 1 is fed into this input, all sections are inactive and output a logic 0 signal on their outputs, regardless of the input.

#### A.3.2 *Fan-In-Fan-Out Units*

A NIM-logic fan-in fan-out unit has several input and several output channels. The purpose of the unit is to superimpose all the signals in its inputs and have the result sent to all outputs. The fan-in fan-out makes sure that all impedances are matched and therefore there is minimal signal deformation. A fan-in fan-out can be linear or logical, where the former linearly adds all the inputs and the latter behaves as a logical OR module for NIM-logic inputs.

#### A.3.3 *Coincidence Units*

A NIM-logic coincidence has two input ports and several output ports. The unit takes two logic inputs and outputs the result of their logic AND or logic OR operation. The choice is done by a switch on the front panel.

#### A.3.4 *Timer Units*

Sometimes it is necessary to generate a logic signal of a certain length, at a certain timing. This can be done with a variety of timing units. For example, a NIM-logic timing unit can have an input through which a signal can trigger generation of a signal on the output, of a length set by a knob on the front panel and delayed by a time set by another knob.

#### A.3.5 *NIM to ECL Converter*

A NIM to ECL converter is used to convert between NIM-logic and ECL-logic signals in our case, where the digital oscilloscope expects ECL-logic signals in its digital inputs while most modules at our disposal are NIM modules.

#### A.3.6 *Digital Oscilloscope*

The scope we were using is a multi-functional Agilent MSO-X 4054A scope. The features listed here are only the ones that are important for our purposes. It has 4 analog input channels and 16 digital ECL logic inputs. The sampling rate of the scope is 2.5 GHz and it can store up to 1000 snapshots of all the channels, in its internal memory, within a very wide window (hundreds of microseconds). The acquisition triggering is done by setting a threshold on one of the channels (digital or analog), that, once reached, will trigger digitization of the waveforms on all channels and will store them in the internal memory. Acquisition of signals can be done in two ways. One is single-shot acquisition, where the waveform is displayed on the screen as soon as triggering occurs and remains there until the next triggering. Such acquisition results in a high-resolution image and is good for analyzing a single event during operation of the monitored equipment. The second one is an acquisition of a pre-set number of snapshots of all the channels into internal memory. There can be up to 1000 such snapshots, but care must be taken, however, when setting the higher-end settings, since the waveform samples are decimated if we are using the most memory-demanding settings, namely acquisition of all channels, with allocation of enough space for a 1000 snapshots. Additional features are a built-in waveform generator that can be used for tests and storage of the data (after acquisition is over) on an external USB drive in various formats.

#### A.3.7 *Digitizer*

Generally, a digitizer takes analog signals as inputs and stores them, in digital form, in its internal memory for readout whenever a trigger

is generated. The digitizer at our disposal was a CAEN V1742 VME 32-channel digitizer (figure 59). This digitizer has the following set of features [30]:

- 1, 2.5, or 5 GHz sampling rate (configurable).
- 12 bit resolution digitization.
- 32 MCX analog input channels, divided into 4 8-channel groups.
- Input voltage must be in the range  $\pm 0.5\text{V}$ , adjustable by a  $\pm 0.5\text{V}$  offset.
- 1 LEMO NIM-logic trigger input acting as an overall trigger.
- MCX low-latency trigger inputs (trigger signal should be fed here in order to be saved along with the channel waveforms, for e.g. timing analysis).
- Each channel has a 128 event deep, 1024 sample long memory buffer (each sample is 12 bits). Those buffers are filled as the trigger fires and are emptied as data is read from them.
- USB and optic fiber data readout options (through a VME bridge).
- It is straightforward to connect more digitizers to accommodate more channels.

In order to communicate with the digitizer it is necessary to use a set of libraries by CAEN supporting their digitizers [26]. The digitizer can be connected to a PC trivially through USB or, by using an additional PCI card, through an optical link. The latter option enables much higher data transfer rates, however, the readout speed requirements for the application discussed in this work are low enough to use the USB interface.

#### A.4 IMPEDANCE MATCHING AND TERMINATION

When a signal propagates along a cable with a certain impedance and reaches a load which has a different impedance, the energy transfer to the load is not maximally efficient, as some of the signal energy will be reflected back, causing unwanted ringing effects, which will present themselves as a decaying sinusoidal fluctuation in voltage after each signal.

In order to maximize energy transfer and avoid those unwanted effects, we need to make sure that the inputs and outputs of all electronic modules and all cables used have the same impedance. All of the modules and cables at our disposal have the same input and output impedance - a standard  $50\Omega$ . We must also make sure that all cables that are not connected on either side are terminated there, to

prevent reflection, since an open end of a cable is equivalent to having a load at the end of it with a very high impedance.

The issue of reflection, termination and cable impedance can be better understood by looking at a coaxial cable as a long capacitor. At time  $t = 0$  a current step  $I$  starts flowing into the cable and charging it.  $I$  depends on the capacitance of the cable. Assuming the voltage is  $V$ , the impedance seen from the input, as long as the current is flowing, is  $R = V/I$ . This is the impedance of the cable. When the current step reaches the opposite end of the cable, a reflection into the cable will occur, unless there is a termination resistance equal to  $R$  at that end, between the signal wire and the shielding of the cable, effectively making the cable seem 'infinite', as seen from the input [2].



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# תקציר

גלאים מסוג פנלי פלזמה הם גלאי קרינה השייכים לקטגוריה של גלאים מודרניים המורכבים מתבניות זעירות, כאשר כל אחת מהן מהווה גלאי בפני עצמו. הטכנולוגיה של גלאים מסוג פנלי פלזמה מבוססת על זו של מסכי פלזמה. עבודה זו מסכמת את המחקר שנעשה עד כה על מסכי פלזמה מסחריים שהומרו לאבות-טיפוס של הגלאים הנ"ל ומתאר לפרטים את הבניה של מכשיר המשחזר מסלולי חלקיקים בשני ממדים (להלן "טראקר") המורכב מ-4 שכבות של הגלאים כאשר מתבצעת קריאת סיגנלים חד-ממדית מכל גלאי ושחזור באמצעותו של מסלולי מיואונים שמקורם בקרינה קוסמית.

כמות גדולה של מסלולים המורכבים מ-2 נקודות זוהו וכמו-כן נמצאו מסלולים המורכבים מ-3 ו-4 נקודות. ניתוח איכותי וכמותי (באמצעות מבחני השוואה סטטיסטיים) נעשו על ההתפלגות הזויתית של המסלולים ועל ההתפלגות של מידת הליניאריות של מסלולים המורכבים מ-3 נקודות על מנת להפריך את ההנחה שמקור הנקודות הוא בתהליך אקראי כלשהו. בנוסף, אנו מראים שחלק מהאפקטים של השראה אלקטרומגנטית התורמים לזיהוי שגוי של ארועים כמסלולים הם לא רלוונטיים בעוד שאחרים ניתן לסווג ככאלה רק ע"י ביצוע ניסויים נוספים עם מקורות קרינה בעלי עוצמה גבוהה הרבה יותר.

חלק משמעותי מבניית הטראקר היה פיתוח של כלי תכנה המאפשרים קריאה של נתונים מהגלאי וניתוחם באופן כזה שניתן יהיה לבנות מערכת לניטורם של היבטים שונים של פעולת הטראקר לטווחי זמן ארוכים. כלי תכנה אלו יכולים לשמש בעתיד לניסויים דומים בגלאים מסוג פנלי פלזמה וכן בתסריטים אחרים של איסוף נתונים מגלאים אלו. הארכיטקטורה והאלגוריתמים הנמצאים בשימוש כלי התכנה הנ"ל מתוארים בעבודה זו.

אוניברסיטת תל-אביב  
הפקולטה למדעים מדויקים  
ע"ש ריימונד וברלי סאקלר

## פיתוח גלאי מסלולי חלקיקים דו־ממדי מפנלי פלזמה

חיבור זה הוגש כחלק מהדרישות לקבלת התואר  
"מוסמך אוניברסיטה" - M.Sc. באוניברסיטת תל-אביב

ביה"ס/החוג לפיזיקת חלקיקים

על ידי  
רייכר דוד

העבודה הוכנה בהדרכתו של פרופסור ארז עציון