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Single photoelectron time resolution studies of the PICOSEC-Micromegas detector

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PICOSEC-Miromegas collaboration

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Abstract: Detectors with a time resolution of a few tens of picoseconds and long-term durability in high particle fluxes are necessary for an accurate vertex separation in future particle physics experiments.

The PICOSEC-Micromegas detector concept is a Micro-Pattern Gaseous Detector (MPGD) based solution addressing this particular challenge. It is based on a Micromegas detector coupled to a Cherenkov radiator and a photocathode. Primary electrons from the incident particles are generated in the photocathode and the time fluctuations due to different primary ionisation positions in the gaseous volume is reduced. The feasibility to reach a good time resolution using this concept was demonstrated in test beam studies, and time resolution values down to 24 ps were measured with muon beams at the CERN SPS accelerator complex.

The effects of different detector parameters on the time resolution were simulated and confirmed by measurements. For these measurements, a femtosecond laser system is used. For a single photoelectron, a time resolution of better than 50 ps is achieved mostly by minimising the drift gap distance. Furthermore, gain and risetime measurements with different gas mixtures are compared.

Keywords: Micropattern gaseous detectors, Timing detectors, Photon detectors for UV, visible and IR photons, Electron multipliers

Contents

1 Introduction

Future particle collision experiments will face increasing pileup conditions due to a higher instantaneous luminosity. For the HL-LHC upgrade, a pileup of up to 140 events is foreseen during normal operations. One solution to mitigate this effect and to improve the separation of the collision vertices are tracking detectors with good time resolution located near the interaction point [1]. A time resolution of the order of 20-30 ps is needed to achieve a z-vertex resolution of a few millimeters and thus reduce the effect of pileup by a factor of 4-5, while the luminosity is expected to increase to $\sim(5-10)\cdot 10^{34} cm^{-2}s^{-1}$ [2]. These fast detectors will need to withstand high particle fluxes and ensure reliable operation over the whole experiment lifetime. Different detector concepts are being developed and studied with the goal of achieving the required characteristics of robust and stable operating conditions with a time resolution of 20-30 ps. For this task one possibility is to use well-known radiation-hard MicroPattern Gaseous Detectors (MPGDs) like Micromegas [3]. PICOSEC-Micromegas is the first MPGD that reaches a sub-nanosecond time resolution for muons [4]. A time resolution of ~24 ps was measured in a muon beam with a photocathode providing 11 photoelectrons [5]. This work will present further studies of the PICOSEC-Micromegas detector with a focus on the electric field (see section 4) and gas mixture (see section 5) optimisation. A femtosecond UV laser with a precise single photoelectron configuration has been used for the measurements (see section 3).

2 The PICOSEC-Micromegas detector

The main idea of the PICOSEC-Micromegas concept is to reduce the inevitable time jitter due to the spatial uncertainty of the localisation of the first ionisation in a classical Micromegas. In a classical Micromegas, the free moving electrons are generated by direct ionisation of the gas atoms in the drift stage of the detector. The drift gap of a classical Micromegas is several millimetres long and the drift time from different ionisation cluster positions is generating an inevitable time jitter of a few nanoseconds. The PICOSEC-Micromegas detector does not only consist of a gaseous volume where the detection of a particle as well as the amplification of the signal takes place; but a crystal that radiates light by traversed particles and a photocathode are placed in front of the gaseous volume where the primary electrons are instead emitted. The gaseous volume of the PICOSEC-Micromegas detector is only used for the amplification of previously generated free-moving photoelectrons. Figure 1 illustrates the PICOSEC-Micromegas detector concept. Charged particles generate Cherenkov light in the radiator and the light is emitted by the crystal in a conical shape in the direction of the passing particle. The Cherenkov light is absorbed by the photocathode and electrons will thus be emitted. All electrons are emitted on the surface of the photocathode into the gaseous volume and they all experience the same electric field with the same distance to the mesh. The detector is also sensitive to UV photons directly emitting electrons from the photocathode. This method is illustrated in the right panel of Figure 1 and is the one used in this work. A laser beam is shone directly onto the radiator crystal and photoelectrons are generated in the photocathode and any effect of the Cherenkov light propagating inside the crystal window can be neglected. Each detector component, like the gap distances or the gas mixture, can be studied and optimised individually.

The gaseous volume of the PICOSEC-Micromegas is only needed to amplify the electrons and to induce a large readable signal on the anode. The detector has a grounded mesh that separates two regions of parallel but different electric fields. The drift gap distance is reduced to the same order as the amplification gap of a classical Micromegas. The particles do not need to ionise the gas atoms as the electrons are already emitted by the photocathode. The first pre-amplification of the photoelectrons happens already in the drift gap region that is subject to an electric field similar to that of the amplification gap. The impact of the early pre-amplification on the time resolution is studied.

3 Laser setup

A PICOSEC-Micromegas detector prototype has been tested at the LYDIL laser laboratory at CEA-LIST (Saclay, Paris). The FLUME laser setup has been used. The system is tuned to a wavelength of 265 nm. A repetition rate between 4.76 MHz and 25 kHz can be selected, which leads to an energy per pulse between 40 pJ/pulse and 18 pJ/pulse. The light beam is split at the laser output and one part is sent to a photodiode. The signal from the diode is used to trigger the data acquisition system and its output is used as the t_0 timing reference for measuring the time resolution of the PICOSEC-Micromegas prototype. An accurate determination of the photodiode time resolution is not given and only the combined time resolution of the t_0 reference and the PICOSEC-Micromegas detector is measured.

The laser beam provides a large quantity of light to a small area on the photocathode. This light would generate many photoelectrons in the photocathode without an attenuation. The unattenuated laser beam can harm the detector when operated with a high electric field and a high repetition rate of the laser. Many electrons will be formed and the electric field may become unstable and the detector may start to spark. The sparks may damage the photocathode material as well as the

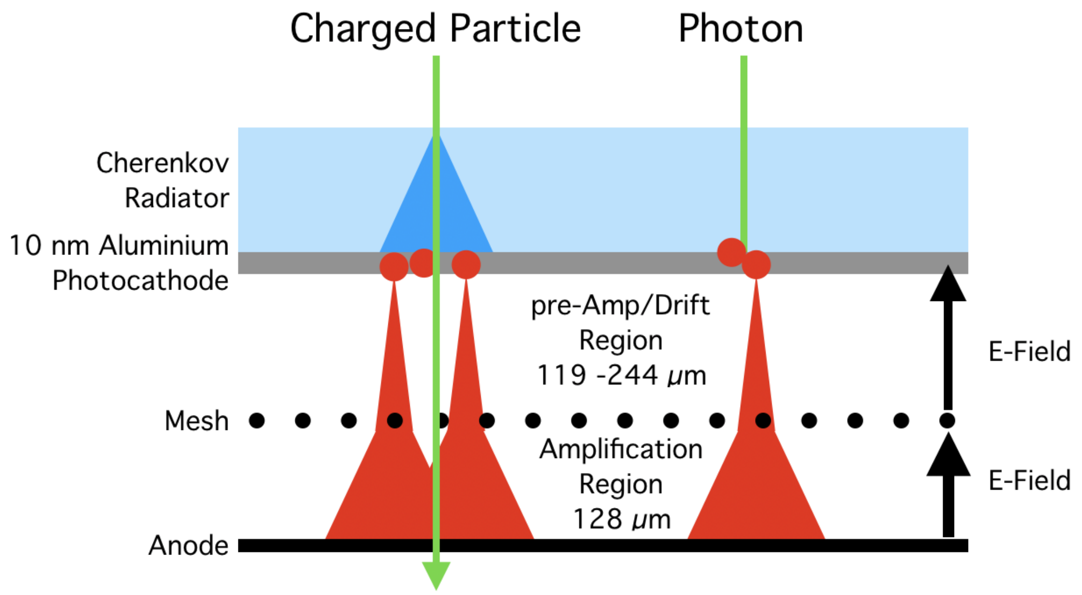

Figure 1. Charged particles passing through the Cherenkov radiator producing UV photons, which are absorbed at the photocathode and partially converted into electrons. Photons from the laser are directly converted to electrons on the photocathode. The electrons are subsequently pre-amplified and then amplified in the two high electric field stages. Finally, a signal is induce between the anode and the mesh.

detector mesh itself. The robustness of photocathode materials under sparks and high ion back-flow as well as the use of resistive PICOSEC-Micromegas have been previously studied [6]. Attenuation of the light is therefore important to control the exact amount of photoelectrons generated in the detector. Similar operation conditions as in a muon beam can be simulated with the laser where the Cherenkov light generates several photoelectrons on the photocathode. By attenuating the laser light output it is possible to measure the single photoelectron response. This measurement offers a clean and comparable environment to evaluate the impact of the individual components of the detector on the timing performance.

The amount of light at the laser output is controlled by semi-transparent meshes of different opacity. The exact number of photoelectrons is set by placing a combination of several attenuators in the beamline directly in front of the detector. Figure 2 shows a picture of the PICOSEC-Micromegas prototype placed in the laser setup. The path of the laser beam is highlighted by a dashed light blue line. The round metallic disc in front of the detector is a fine mesh used as a light attenuator.

During one set of measurements, the number of photoelectrons should be kept constant. For this purpose, a calibration of the setup has to be established. The first step is to find and verify a combination of attenuators to reach a single photoelectron condition in the detector. Attenuators are added to the beamline to dim the light intensity until the mean amplitude is not further reduced. Two measurements with different sets of attenuators have to be performed to verify the single photoelectron condition. When the signal charge for both measurements shows the same distribution, the single photoelectron condition has been reached. Further diminishing of the light will only decrease the detection efficiency of the detector.

After finding one set of attenuators that provides the right amount of light for emitting a single photoelectron, the attenuators can then be removed to provide configurations with several photoelectrons for detector characterisation. More light reaches the photocathode by removing the attenuators and more photoelectrons are formed. The mean signal charge for each distribution is estimated by using a Polya fit. The fraction of the mean signal charge between the single photoelectron and the other attenuator settings defines the number of photoelectrons for each setting.

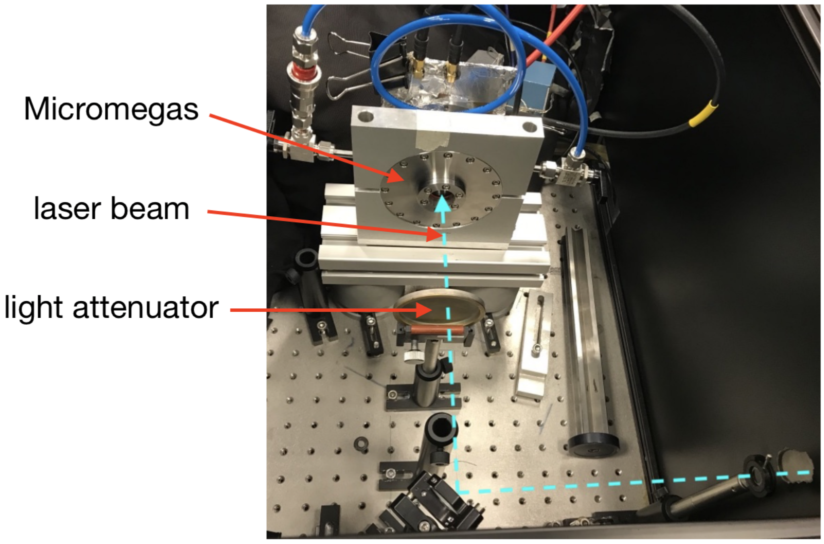

Figure 2. Photograph of the PICOSEC-Micromegas detector in the laser setup. The path of the laser beam is indicated with a dashed blue line. The disk in front of the detector holds a variable light attenuator to adjust the intensity of the laser beam.

4 Time resolution of different drift gaps

The time resolution for several electric field settings and drift gap distances is measured. The distance of the amplification gap is kept constant at 128 μm. The drift gap has been varied between 119 μm and 244 μm. The gap is formed by 25 μm-thick Kapton rings. Three different voltage settings have been applied to the fixed amplification gap. These settings are: 1) 400 V, a setting with the highest possible gain, 2) 350 V, a balanced setting that allows a stable operation, and 3) 275 V, the lowest voltage setting. A higher drift field is possible with a lower voltage applied to the amplification gap [5]. The best time resolutions were obtained with 275 V in the amplification stage in previous measurements. Here, all laser measurements are performed with a gas mixture consisting of Neon (80 %) + Ethane (10 %) + CF_4 (10 %). It is the same mixture as used in the previously published PICOSEC-Micromegas measurements [5].

A scan of the time resolution over different drift fields is performed for each fixed drift gap and amplification field setting. The electric field applied to the drift gap is chosen individually for each gap distance and amplification field setting. The highest possible drift field before reaching instability is chosen for each setting. The field is then reduced in steps of 100-200 V/mm. Figure 3 shows the time resolution as a function of the drift fields for different photoelectron settings and one fixed drift gap distance. Measurements are performed for single- or multi-photoelectron laser settings. The Aluminium photocathode had to be changed several times during the measurements due to technical issues. Not every photocathode had the same efficiency and not all photoelectron settings could be measured for the different drift gap settings.

The measurements for all settings show an improved time resolution with increased drift fields. The same behaviour had been previously reported [5] and can be explained with the higher gain and better signal-to-noise ratio of the detector [7]. The number of initial photoelectrons is also affecting the time resolution. The time resolution (σ) is depending on the number of photoelectrons ($N_{\text{p.e.}}$) by

$$\sigma \approx \frac{1}{\sqrt{N_{\text{p.e.}}}}$$

With many photoelectrons, the time resolution improves even at lower detector gain. The best time resolution in this measurement is σ=17.5±0.3 ps, reached with 35 photoelectrons and a drift gap of 244 μm. At approximately 20 ps, the time resolution starts to saturate at higher fields or number of photoelectrons.

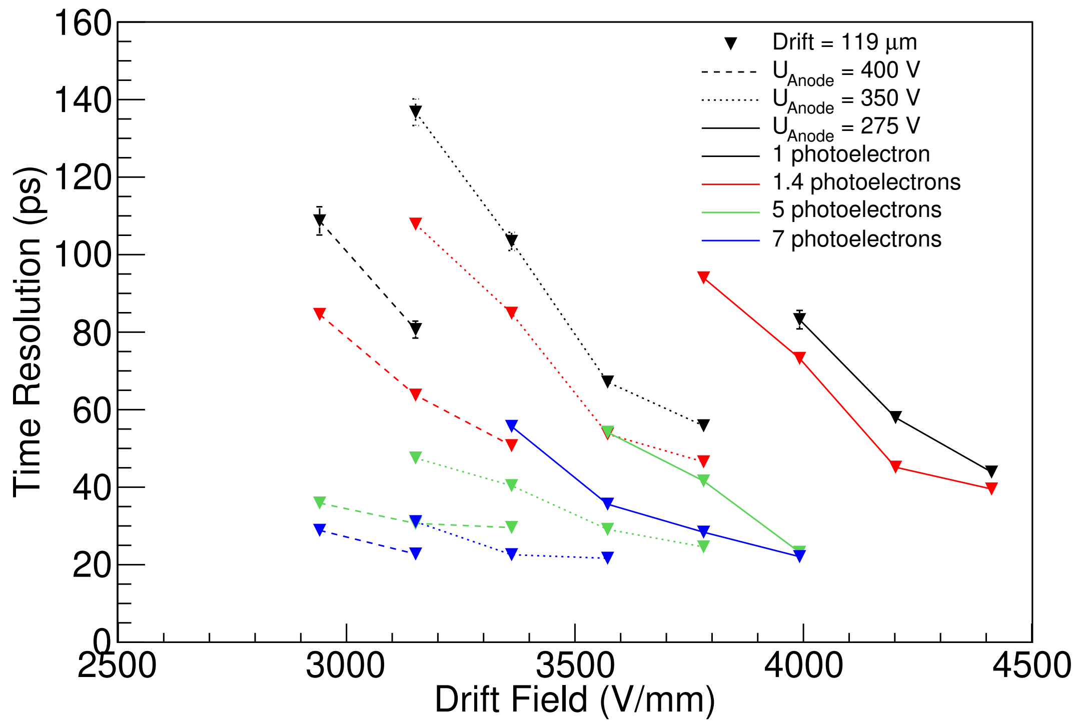

Figure 3. Time resolution as a function of the drift field for different number of photoelectrons and a fixed drift gap of 119 μm.

4.1 Time resolution of the drift gaps with single photoelectrons

The impact of the drift gap distance and thus the drift field on the time resolution is studied more in detail by only considering the measurements under single photoelectron conditions. These are suitable to study the effect of the drift gap distance as no other effect from multiple photoelectrons are altering the measurement. The time resolution for different drift fields and drift gap distances is shown in Figure 4. The best time resolution of 44±1 ps with a single photoelectron is measured for the smallest drift gap of 119 μm and the highest stable field setting. With these settings, the electric field of the pre-amplification in the drift gap is higher than in the amplification gap.

A smaller drift gap has the advantage that a higher field can be applied without initiating discharges due to a high electron multiplication. The drift gap distance can not be too short; otherwise, it would not provide enough gain before reaching the electrical breakdown [8]. In general, a detector with a higher electric field has a higher gain and provides a better time resolution. The PICOSEC-Micromegas is a two-stage detector and the amplification field needs to be lowered for a higher drift field to operate in stable conditions. Figure 5 shows the same measurements as in Figure 4, with the time resolution shown as a function of the overall gain of the detector. The gain is calculated by the signal charge divided by the amplifier gain and the single electron charge. Field settings with a smaller drift region are reaching a better time resolution than settings with larger drift regions and comparable gain.

A large electric field has to be applied to the first stage (drift field) of the detector in order to improve the time resolution, even if it leads to a smaller field in the second stage (amplification) to maintain a stable operation. The drift of the primary electron before starting an avalanche is shorter at a higher field. Simulations have shown that the propagation velocity of the avalanche is faster than the drift velocity of an individual electron [7]. This leads to a better time resolution at higher drift fields, even when the overall gain remains constant. A smaller drift gap can help to apply higher electric fields, and the drift distance of the electrons before amplification can thus be reduced. The measurements in Figure 5 show that time resolutions smaller than 50 ps are possible with the PICOSEC-Micromegas for a single photoelectron.

5 Outlook on gas mixture studies

In the previous section it was shown that an optimisation of the time resolution can be achieved by increasing the electric field in the first stage (drift field). Another component that can be optimised is the gas mixture. Previously, a gas mixture based on Neon (80 %) with an addition of Ethane (10 %) and CF_4 (10 %) was used. In the following, a study of the characteristic waveforms for different gas mixtures is presented.

The previous studies have shown that the initial drift distance of the electron can be further reduced by a strong electric field. In this operating mode, the gain becomes more important for the time resolution than the longitudinal diffusion. The idea is to try different gas mixtures with a lower percentage of quenching gas (such as Ethane) to increase the gain. Preliminary studies of Neon gas mixtures with different percentages of Ethane were performed.

A UV-lamp is used for these measurements. Light is diffusely radiated from the lamp and single photoelectrons are emitted from the photocathode. With this method, the gain and waveform

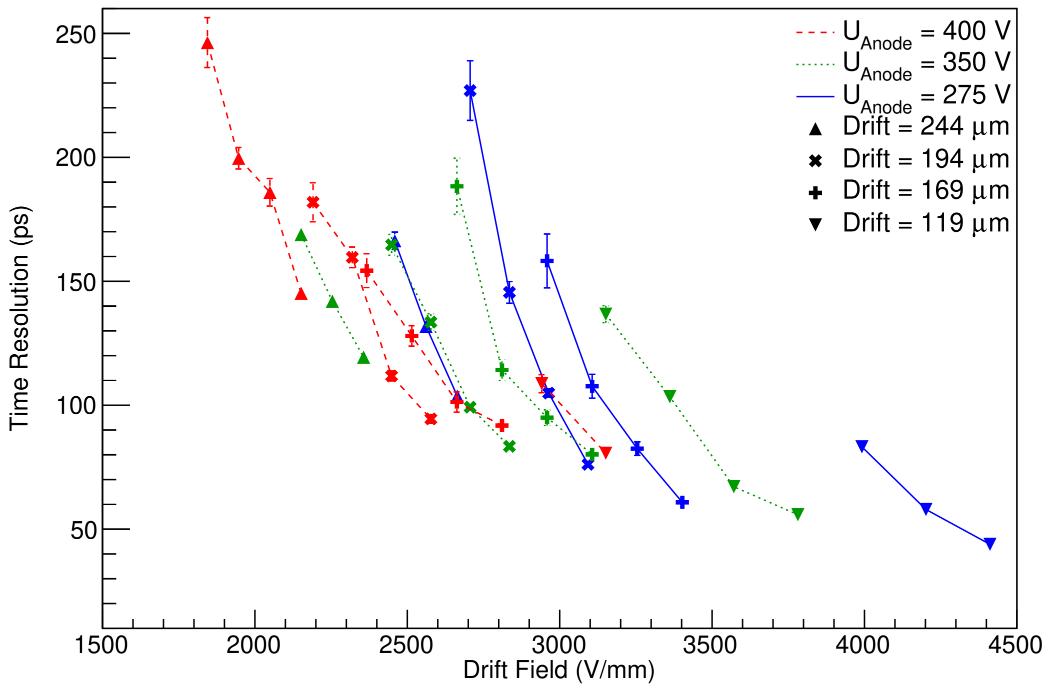

Figure 4. Time resolution as a function of the drift field for different drift gaps under single photoelectron condition.

characteristics of the PICOSEC-Micromegas with different gas mixtures and field settings can be studied, but no timing information can be obtained due to the continuously and diffuse emission of the light. The time resolution for single- and multi-photoelectron settings will be measured with different gas mixtures in a future laser test. It is expected that a mixture with added CF_4 will provide shorter and larger signals and thus a better timing performance than mixtures with only Ethane and a higher percentage of Neon.

Figure 6 shows the results of the study. The waveform characteristics are compared for different Neon-Ethane ratios, and the previously used mixture with Neon (80 %) + Ethane (10 %) + CF_4 (10 %). The gain is estimated from the signal charge defined by the integral of the signal waveform (also known as "electron peak" in Ref. [5]) divided by the electron charge and the gain of the amplifier in the readout circuit. The amplitude-to-signal-charge ratio (A/Q) describes the width of the waveform. A higher A/Q ratio means a narrower but higher signal which leads to a shorter rising edge and thus a better time resolution. Each mixture is measured with different electric fields and different field ratios between the drift and the amplification region. The measurement shows the different points for each gas mixture on the same line. This leads to the assumption that the A/Q ratio is a characteristic of the gas mixture and independent of the field ratios.

The gas mixture with added CF_4 shows a characteristic A/Q ratio with steeper waveforms even though the gas mixtures with a higher Neon composition can provide a higher overall gain at lower electric fields. Additional gas mixtures with higher Neon percentage and added CF_4, such as Neon

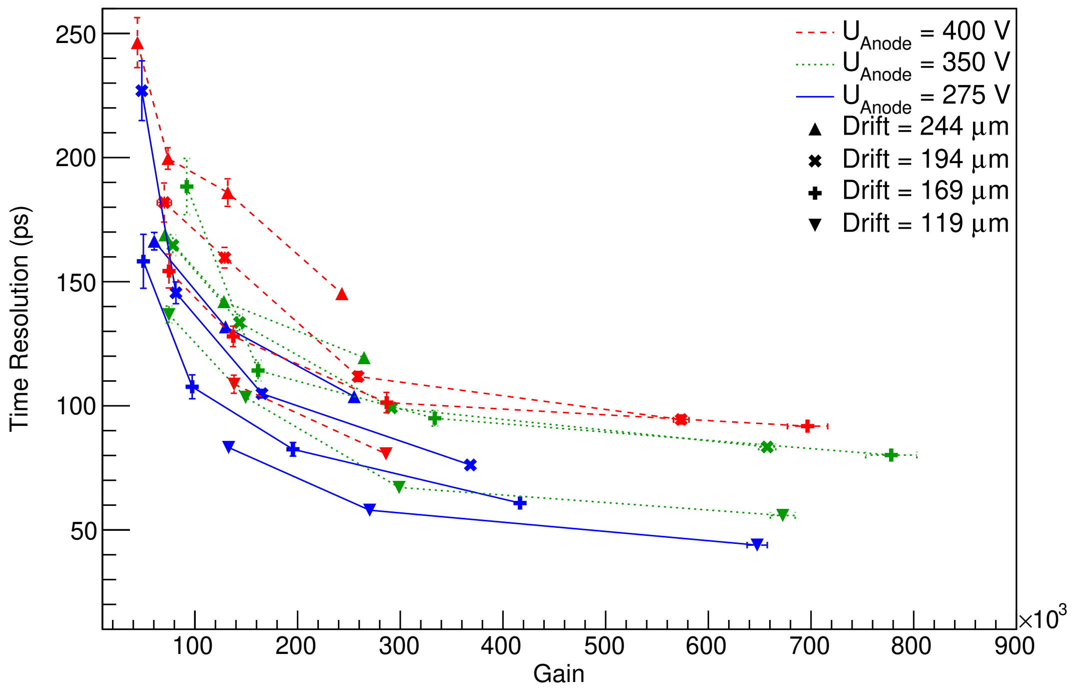

Figure 5. Time resolution as a function of the gain for different gap region thicknesses and anode bias voltages under single photoelectron conditions.

(89 %) + CF_4 (9 %) + Ethane (2 %) will be tested. Such gas mixtures are expected to achieve a better time resolution as a signal with a higher overall gain and a shorter rising slope due to the presence of Neon and CF_4 can be obtained.

6 Summary

The results presented summarize the progress in the understanding of the PICOSEC-Micromegas detection concept and outline the potentialities for future applications. Measurements with different electric fields have been performed in a clean and controlled environment using a laser beam. The laser setup allows to estimate the precise number of photoelectrons used in the test such that single photoelectron measurements can be easily reproduced. Higher drift fields are reached with shorter drift gap distances. The time resolution improves with a higher drift field and a single photoelectron time resolution of 44±1 ps is measured in the most optimal settings. These results indicate that it is possible to retain or even improve the time resolution by properly optimizing the detector settings, and pave the way for the development of robust photocathodes where ~(3 – 4) photoelectrons/MIP can be produced, as only a few photoelectrons are needed to provide a time resolution of the order of 20-30 ps.

An additional study shows that the drift field plays an important role in improving the time resolution. A higher drift field reduces the initial drift distance of the primary electrons before an

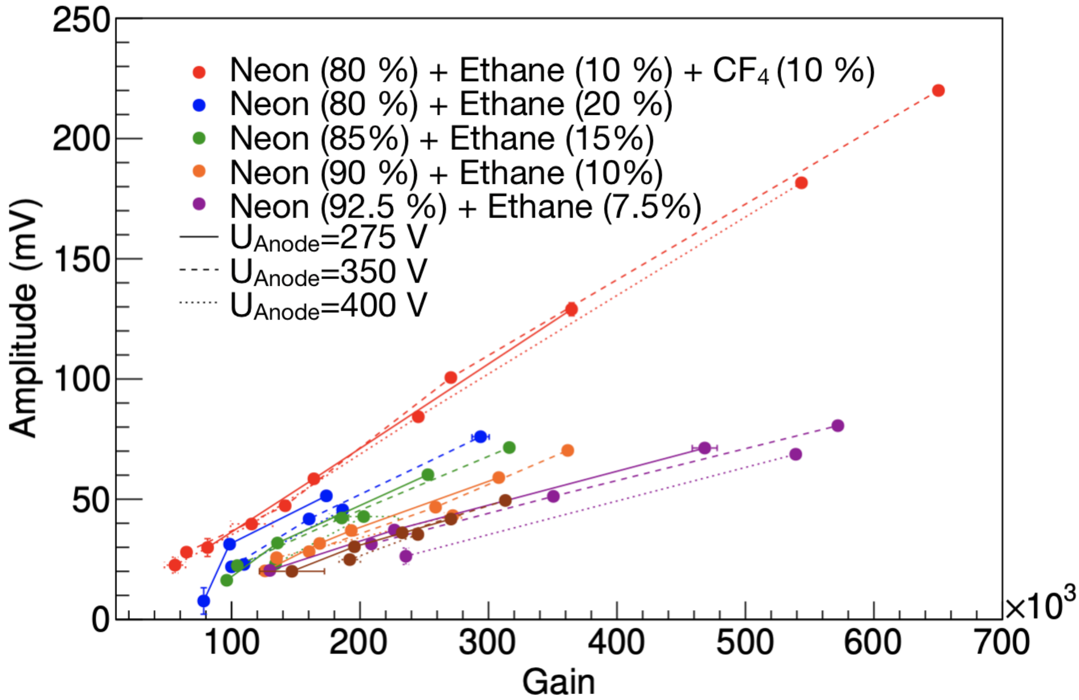

Figure 6. Electron peak amplitude as a function of the gain for different gas mixtures and anode voltages.

avalanche amplification sets in. The reduction of the electron drift distance is crucial for improving the time resolution as the propagation of an electron avalanche is faster than the mean drift velocity of the single photoelectrons.

Furthermore, preliminary studies of different gas mixtures were performed and the characteristic waveforms for different mixtures of Neon, Ethane, and CF_4 were investigated. A higher percentage of Neon shows that a higher gain with lower electric fields can be achieved; the addition of CF_4 reduces the longitudinal diffusion of the electrons which leads to shorter and steeper signals.

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References

[1] White, S., *Experimental challenges of the european strategy for particle physics*, *Proc. Int. Conf. on Calorimetry for the High Energy Frontier* (CHEF 2013)

[2] Va'vra, J., *PID techniques: Alternatives to RICH methodsNucl. Instrum. Meth.* **A876** (2017) 185-193.

[3] Giomataris, Y. et al., *MICROMEGAS: a high-granularity position-sensitive gaseous detector for high particle-flux environments*, *Nucl. Instrum. Meth.* **A376** (1996) 29 - 35.

[4] Papaevangelou, T. et al., *Fast Timing for High-Rate Environments with Micromegas*, *EPJ Web Conf.* **174** (2018) 02002.

[5] Bortfeldt, J. et al., *PICOSEC: Charged particle timing at sub-25 picosecond precision with a Micromegas based detector*, *Nucl. Instrum. Meth.* **A903** (2018) 317-325.

[6] Sohl, L. et al., *PICOSEC-Micromegas: Robustness measurements and study of different photocathode materials*, *J. Phys. Conf. Ser.* **1312** (2019) 012012.

[7] Kordas, K. et al., *Progress on the PICOSEC-Micromegas Detector Development: towards a precise timing, radiation hard, large-scale particle detector with segmented readout*, *Nucl. Instrum. Meth.* **InPress** (2019).

[8] Giomataris, Y., *Development and prospects of the new gaseous detector "Micromegas"*, *Nucl. Instrum. Meth.* **A419** (1998) 239-250.