Prepared for submission to JINST

Innovative Particle and Radiation Detectors 2019 - IPRD19
14th - 17th October 2019
Siena

Time performance studies of the PICOSEC-Micromegas detector concept with < 50 ps time resolution for a single photoelectron

PICOSEC Micromegas

PICOSEC-Miromegas collaboration

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Abstract: Detectors with a time resolution of several 10 ps and robustness in high particles flux are necessary for an accurate vertex separation in future particle physics experiments like the HL-LHC.

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. By this way, all primary electrons are located in the photocathode and the time jitter due to different primary ionisation positions in the gaseous volume is substituted. The feasibility to a high time resolution with this concept has been demonstrated and time resolution values of down to 24 ps have been measured with muons from the CERN SPS particle beam.

The effects of different detector parameters (like electric field strength, drift distance and light yield of the photocathode) on the time resolution have been simulated as well as measured. For these measurements, a femtosecond laser system has been used. This system can be tuned to generate precisely a certain number of photoelectrons in the detector and provides a cleaner study of different detector parameters compared to a particle beam. Under single photoelectron conditions, a time resolution of better than 50 ps has been archived by minimising the drift gap distance.

Furthermore, the gain and rise time of gas mixtures with different Neon Ethan ratios have been measured. The signal rise time improves with a higher fraction of Ethan and additional CF4, even thou a higher neon percentage provides better gain.

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 pile up due to a higher nominal luminosity. For the HL-LHC upgrade, a collision pileup of up to the level of 140 events is foreseen, while one frame record of a collision in the ATLAS or CMS experiment includes up to 30-40 proton-proton collisions. One solution to mitigate these pile-up and to separate the collision vertices are tracking detectors with improved spatial resolution located near the interaction point [1]. A time resolution in the order of 20-30 ps is prospected for an accurate vertex separation with the demanded tracking detectors, while the luminosity is expected to increase towards $\sim 5 - 10 \cdot 10^{34} cm^2 s^1$ [2].

The demanded fast-tracking detectors need to withstand high particle flux and ensure reliable operation over the whole experiment lifetime. Different detector concepts are developed and studied to archive the demanded characteristics of robust and stable operating tracking detectors with a time resolution of 20-30 ps. One concept is to use well-known radiation-hard MPGDs like Micromegas for this task [3].

PICOSEC-Micromegas is the first MPGD that reaches a time resolution sub-nanosecond for muons [4]. A time resolution of $\sim$ 24 ps in a muon beam with a photocathode providing 11 photoelectrons has been reported [5]. This work will present further time performance studies of the PICOSEC-Micromegas 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 PICOSEC-Micromegas

The PICOSEC-Micromegas detector concept is based on the Micromegas amplification principle. The main idea of the PICOSEC-Micromegas concept is to suppress the inevitable time jitter occurring due to the spatial uncertainty of the 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 Micromegas is several millimetres long and the drift time from different ionisation cluster position is generating an inevitable time jitter of some 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. A crystal and a photocathode are placed in front of the gaseous volume and the primary electrons are emitted from the photocathode. The gaseous volume of the PICOSEC-Micromegas detector is only used for the amplification of previously generated free-moving electrons. Figure 1 illustrates the PICOSEC-Micromegas detector concept.

Charged particles are generating Cherenkov light in the radiator. The light will be emitted by the crystal in a conical shape in the direction of the passing particle. The Cherenkov light will be absorbed by the photocathode and electrons will be emitted. All electrons are emitted on the surface of the photocathode into the gaseous volume and all electrons experience the same electric field with the same distance to the mesh. The detector is also sensitiv to UV photons directly emitting electrons from the photocathode. This method is illustrated in the right part of figure 1. This method of generating electrons is used in the presented work. A Laser beam is directly generating photoelectrons in the photocathode and any effects of the Cherenkov light propagation inside of the window can be neglected. Each detector component, like the drift distance or the gas mixture, can be studied and optimised individually with this measurement method.

The gaseous volume of the PICOSEC-Micromegas is only needed to amplify the electrons and to induce a readable signal on the anode. The detector has a grounded mesh between two electric fields with parallel field lines. The drift gap distance is reduced to the same order as the amplification gap compared to a classical Micromegas. The particles do not need to ionise the gas atoms anymore as the electrons are already emitted by the photocathode. The drift gap is operated with an electric field similar to the amplification gap and a first preamplification of the electrons is happening. The impact of the early preamplification on the time resolution is studied with the presented measurements.

3 Laser set-up

A PICOSEC-Micromegas prototype has been tested at the LYDIL Laser laboratory belonging to CEA-LIST. 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 of 40 pJ/pulse to 18 pJ/pulse.

The light beam is split after the Laser and one part is given to a photodiode. The signal from this diode is used to trigger the data acquisition system and its signal is additionally used as the t_0 timing reference for measuring the time resolution of the PICOSEC-Micromegas prototype. An accurate determination of the photodiodes time resolution is not given and only the combined time resolution of the t_0 reference and the PICOSEC-Micromegas is measured.

The Laser beam provides a lot 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

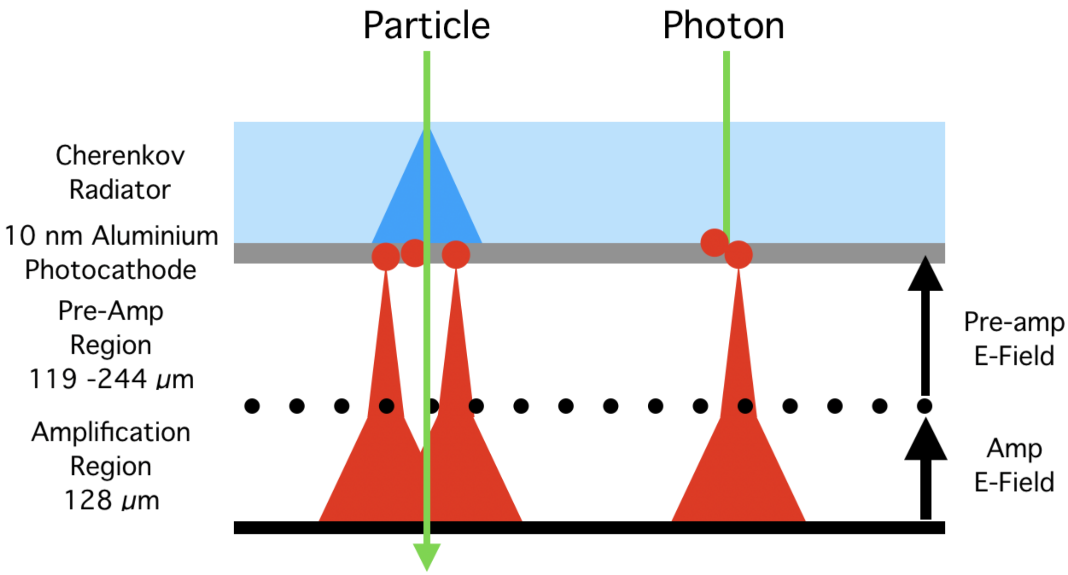

Figure 1. Charged particles passing through the Cherenkov radiator produceing UV photons, which are absorbed at the photocathode and partially converted into electrons. Photons from the Laser are directly converted to electrons on the photocathode. The electrons are subsequently preamplified and then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

Laser. Many electrons will be formed and the electric field can become unstable and the detector starts to spark. The spark can damage the photocathode material as well as the detector mesh itself. The impact of the ion back-flow on the photocathode as well as the use of resistive PICOSEC-Micromegas have been previously studied [6]. Attenuation of the light is moreover important to control the exact amount of photoelectrons generated in the detector. Similiar operation conditions as in a muon beam can be simulated where the Cherenkov light generates several photoelectrons depending on the photocathode material. Another important setup is the measurement in single photoelectron conditions. It gives a very clean and comparable measurement environment to evaluate the impact of the individual components of the detector on the timing performance.

The amount of light is controlled by mechanical 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 is showing a picture of the PICOSEC-Micromegas prototype placed in the Laser setup. The path of the Laser beam is highlighted by a 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 constant. For this purpose, a calibration of the setup has to be done. The first step is to find and verify a combination of attenuators to reach a single photoelectron condition in the detector. More and more attenuators will be added to the beamline to diminish the light. The mean amplitude will not be further reduced after adding a certain number of attenuators. Two measurements with different sets of attenuators have to be done 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 when the single photoelectron condition is reached.

After finding one set of attenuators providing the right amount of light for single photoelectrons, one attenuator after the other can be removed to provide more configurations with several photoelectrons for the detector characterisation. More light reaches the photocathode by removing the attenuators and more photoelectrons are formed. The mean signal charge for each distribution is calculated by 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.

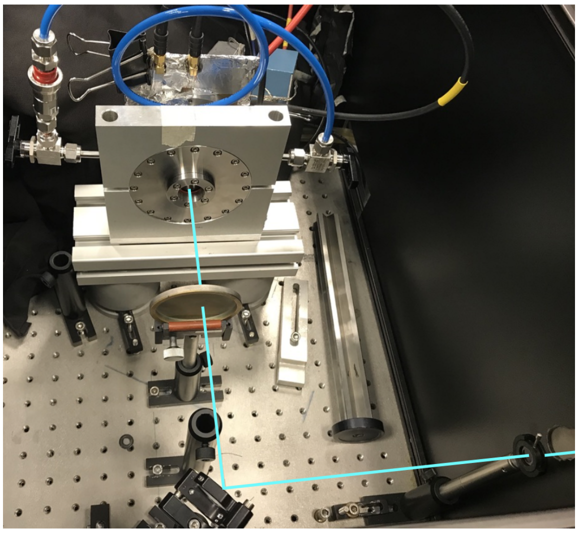

Figure 2. Photograph of the PICOSEC-Micromegas detector in the Laser Setup. The path of the laser beam is indicated with a blue line. A light attenuator is placed in front of the detector.

4 Time resolution of different drift gaps

The time resolution for several electric field settings and drift gaps has been measured. The distance of the amplification gap is kept constant at 128 μm. The drift gap has been variated between 119 μm and 244 μm. The gap is formed by distance rings of 25 μm thick Kapton. Three different voltage settings have been applied to the fixed amplification gap. These settings are 400 V, a setting with the highest possible gain, 350 V, a balanced setting that allows very stable operation, and 275 V. A higher drift field is possible with a lower voltage applied to the amplification gap. The best time resolutions have been reached with 275 V in the amplification stage in previous measurements [5]. All shown measurements with the Laser are performed with a gas mixture consisting of 80 % Neon, 10 % Ethan and 10 % CF_4. It is the same mixture as used in all previously published measurements. A first outlook in the study of other gas mixtures is given in section: 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 afterwards reduced in steps of 100-200 V/mm. Figure 3 shows the scanned time resolution against the drift fields for all photoelectron settings and one fixed drift gap. Measurements have been done with single photoelectron and with many photoelectrons settings of the Laser. The Aluminium photocathode had to be changed several times during the measurement due to technical issues. Not every photocathode had the same efficiency and not all photoelectrons settings could be measured with all drift gap settings.

The measurement shows for all settings an improving time resolution with rising drift fields. The same behaviour has been previously seen [5] and can be explained with the higher gain and better signal to noise ratio of the detector due to stronger amplification [7]. The number of initial photoelectrons is also affecting the time resolution. The time resolution (σ) is depending on the number of photoelectrons ($N_{p.e.}$) by

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

With many photoelectrons, a good time resolution can be reached even if the detector setup is not on its limit. The best time resolution in this measurement is 17.5±0.3 ps. It has been reached with 35 photoelectrons and a drift gap of 244 μm. Around 20 ps the time resolution starts to saturate even at higher fields or number of photoelectrons. One possible explanation is the limitation by the measurement set-up.

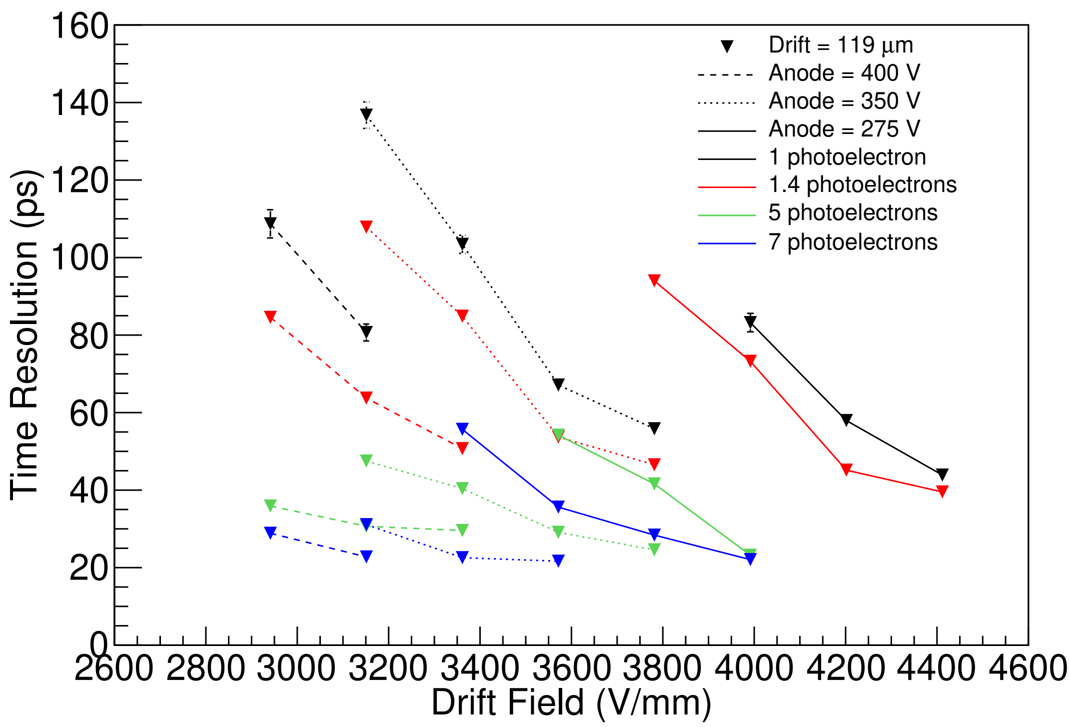

Figure 3. Time resolution against drift field for photoelectrons and a fixed drift gap of 119 μm.

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 has been studied more in detail by only considering the measurements under single photoelectron conditions. These are suitable to study the effect of the drift gap as no other effects from multiple photoelectrons are effecting the detector time resolution. The time resolution for different drift fields of all tested drift gap distances is shown in figure 4. The best time resolution with a single photoelectron is reached with the smallest drift gap of 119 μm and the highest stable field setting. A combined time resolution of 44±1 ps is reached. In this setting, 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 provoking discharges due to a high electron multiplication. While a field gap too short would not provide enought gain before reaching the electrical breakdown [8]. In general, a detector with a higher electric field has a higher gain and provides 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 figure 4 with the time resolution plotted against the overall gain of the detector. The gain is not higher for the measurements at the highest possible drift field compared to other settings with an inferior time resolution.

This measurement shows the importance of applying an electric field as large as possible to the first stage of the detector, even if it leads to a smaller field in the second amplification stage to maintain a stable operation of the detector. The drift of the primary electron before starting an avalanche amplification is shorter at a higher field in the first gap. 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 be reduced. The measurements have shown that time resolutions smaller than 50 ps are possible with the PICOSEC-Mircomegas and a single photoelectron.

5 Outlook on gasmixture studies

The presented study has shown a possible optimisation of the time resolution by increasing the electric field in the first stage. The next component that is characterized and optimised is the gas mixture. Previously a gas mixture based on Neon with an addition of 10 % Ethan and 10 % CF_4 is used. In the following, a pre-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. At this operation mode, the gain of the gas 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 to increase the gain and consequentially reduce the percentage of quenching gas. First pre-studies of Neon gas mixtures with different percentages of Ethan have been done.

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

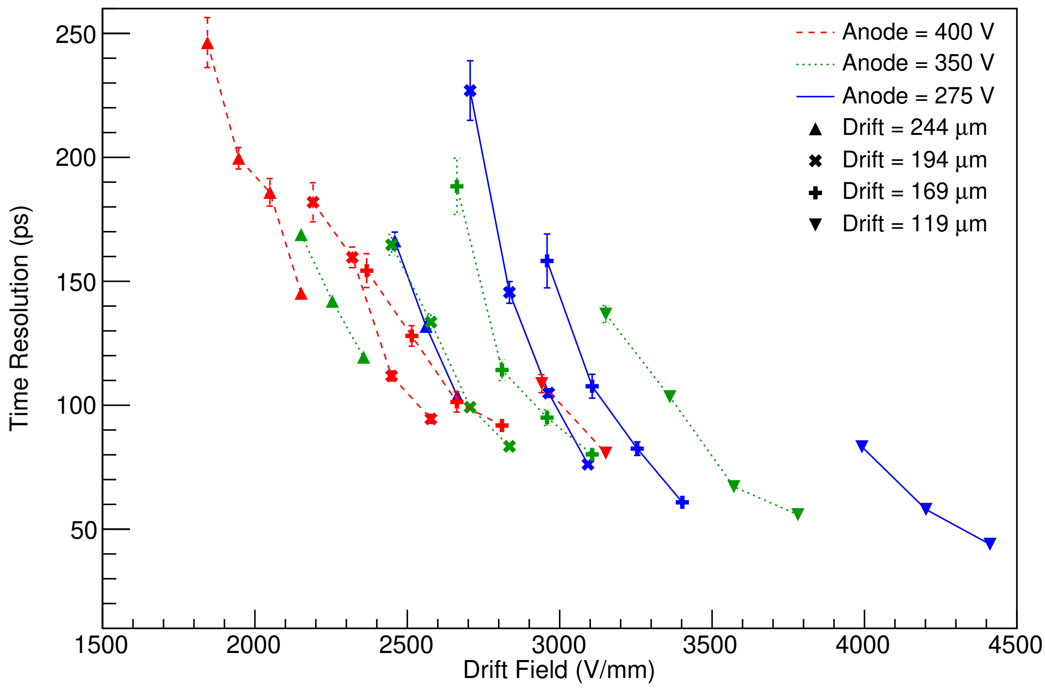

Figure 4. Time resolution against drift field for different drift gaps and one single photoelectron.

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 outcome of this pre-study will be verified by a future Laser test. The time resolution for a single and for many photoelectrons will be measured with different gas mixtures. It is expected that a mixture with added CF_4 will provide shorter and higher signals and thus a better timing performance than mixtures with only Ethan and a higher percentage of Neon.

Figure 6 shows the results of the pre-study. The waveform characteristics are compared for different Neon Ethan ratios and the previously used Neon with 10 % Ethan and 10 % CF_4 mixture. The gain is calculated with the signal charge defined by the integral of the electron peak divided by the electron charge and the gain of the electric amplifier. The shown ratio of the amplitude to signal charge describes the characteristic width of the waveform. A higher amplitude to charge 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 amplitude to signal charge ratio is a characteristic of the gas mixture and independent of the field ratios.

The gas mixture with added CF_4 shows a characteristic amplitude to signal charge ratio in favour for steeper waveforms even though the gas mixtures with a higher Neon percentage can provide a higher overall gain at lower electric fields. The findings of this pre-study will be verified in a future Laser measurement campaign. Additional gas mixtures with higher Neon percentage

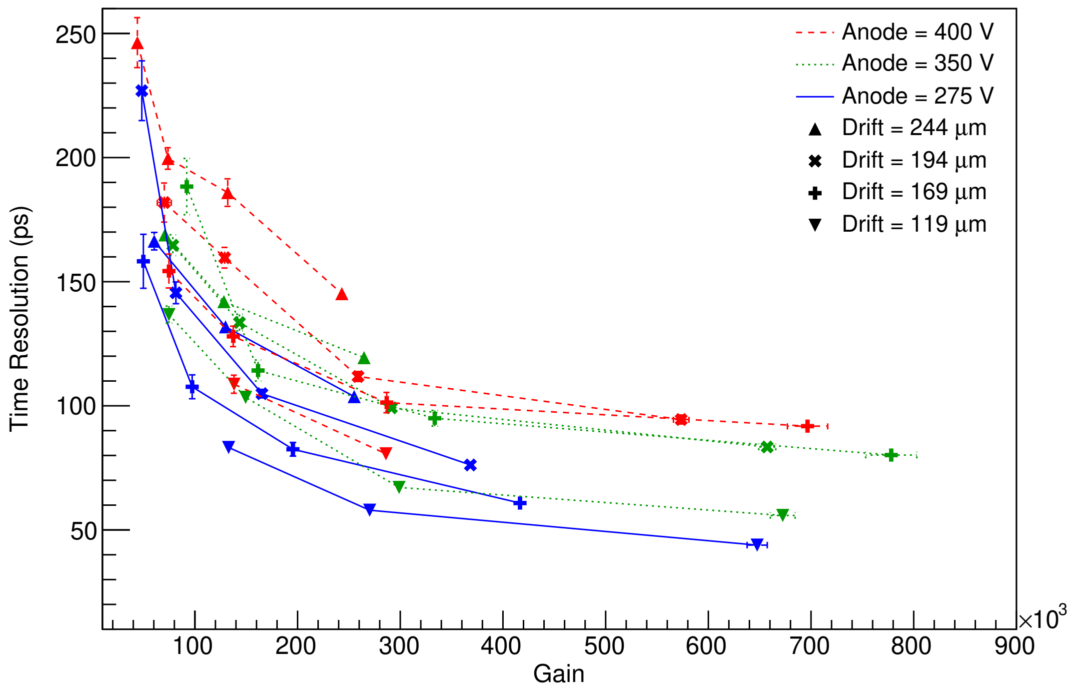

Figure 5. Time resolution against gain for different drift gaps and one single photoelectron.

with added CF_4 like 80 % Neon, 9 % CF_4 and 2 % Ethan will be tested. It is expected to archive better time resolutions as a higher overall gain with short rising edges due to the Neon and CF_4 can be archived.

6 Summary

The presented work shows the progress and possibilities of the PICOSEC-Micromemgas detection concept. Measurements with different electric fields have been performed in a clean measurement environment of a Laser beam. The Laser setup allows to select a precise number of photoelectrons and 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 reached in the most optimal setting. This result provides more possibilities for the development of robust photocathodes, as only few photoelectrons are needed to provide a time resolution in the order of 20-30 ps.

The further study shows that improvement of the time resolution is not only caused by the higher detector gain at higher electric fields. The drift field plays a superior role in improving the time resolution. A higher drift field reduces the initial drift distance of the primary electrons before an avalanche amplification sets in. The reduction of the electron drift distance is crucial for the time resolution as the propagation of an electron avalanche is faster than the mean drift velocity of single electrons.

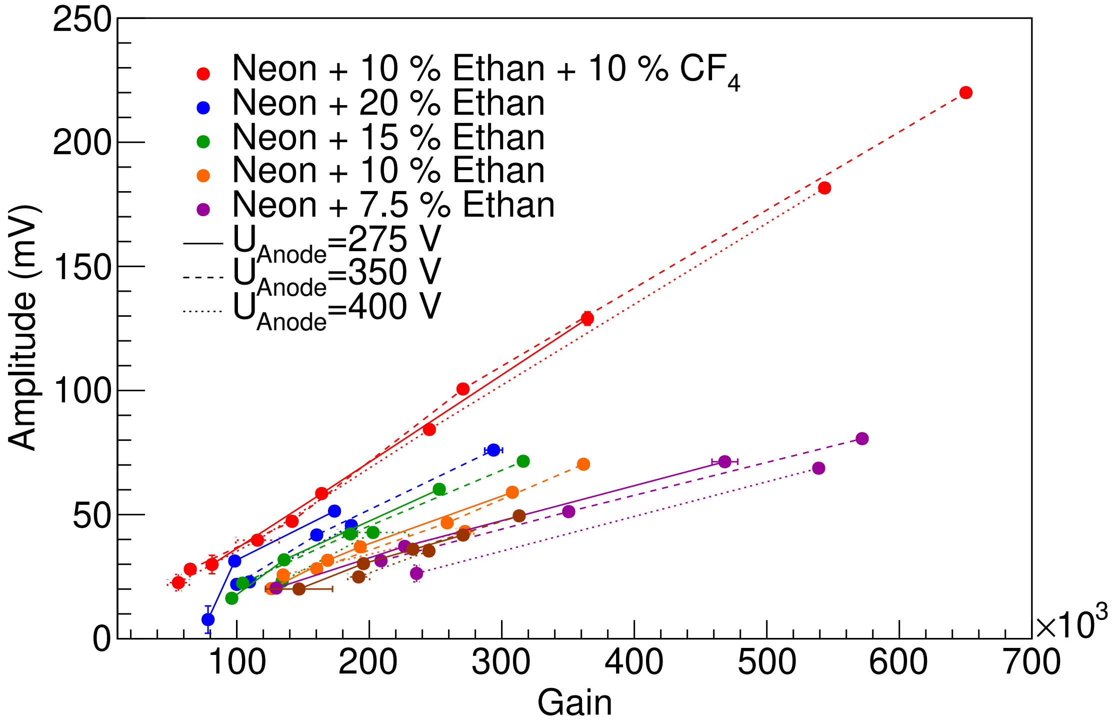

Figure 6. Electron peak amplitude against integrated charge for different gas mixtures describes the width of the peak.

Furthermore, first pre-studies of different gas mixtures are done and the characteristic waveforms for different mixtures of Neon, Ethan and CF_4 are investigated. A higher percentage of Neon shows an improved gain at lower electric fields and the addition of CF_4 reduces the longitudinal diffusion of the electrons which leads to shorter and steeper signals. The effect of the different gas mixtures on the time resolution will be investigated in further Laser measurements.

Acknowledgments

We acknowledge the financial support of the Cross-Disciplinary Program on Instrumentation and Detection of CEA, the French Alternative Energies and Atomic Energy Commission; the RD51 collaboration; and the Fundamental Research Funds for the Central Universities of China. L. Sohl acknowledges the support of the PHENIICS Doctoral School Program of Université Paris-Saclay. J. Bortfeldt acknowledges the support from the COFUND-FP-CERN-2014 program (grant number 665779). M. Gallinaro acknowledges the support from the Fundação para a Ciência e a Tecnologia (FCT), Portugal (grants IF/00410/2012 and CERN/FIS-PAR/0006/2017). F.J. Iguaz acknowledges the support from the Enhanced Eurotalents program (PCOFUND-GA-2013-600382). S. White acknowledges partial support through the US CMS program under DOE contract No. DE-AC02-07CH11359.

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