Picosec Test Beam 2017

- Summer Student Work Report -

EP-DT-DD-GDD

Lukas Sohl

Supervisors: Eraldo Oliveri, Leszek Ropelewski

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1 Introduction

This report is about my work on the Picosec Project. I worked as a Summer Student at the Department of Gaseous Detector Development.
The Picosec detector based on the work principal of Micromegas detectors. With a different approach of creating the primary ionizing electron an intrinsic time jitter of gaseous detectors is substituted and time resolutions under 30 ps can be achieved.
During my internship I set up a tracker and trigger system for beam tests of different Picosec prototypes. During the beam tests in July and August I operated this system and maintained the detector prototypes as well as monitored the data taking.
With the gathered data I learned to perform a short analysis to check the data quality. Later on I will continue with a deeper analysis including the tracker informations
In this report I will first explain the work principal of the tracker system, which based on triple-GEM detectors. I explain how I determined the characteristics of the GEMs and operated the readout and slow control for the tracker.
In the second part I explain the Picosec detector and the measurements I performed in the test beam. In the end I give a first outlook of the results from these measurements.

2 Triple-GEM

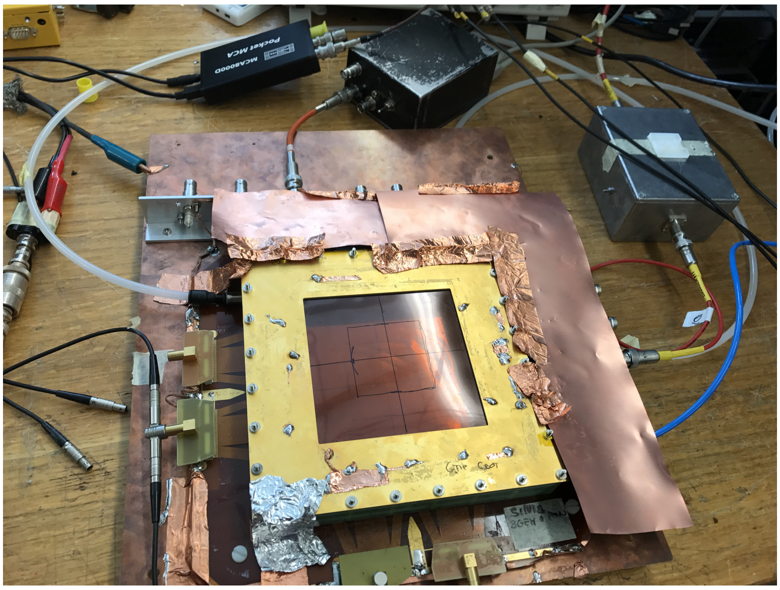

Figure 2.1: Triple-GEM detector, as used for gain measurements

The triple GEM detectors, who are used to track the beam position at the Picosec project are investigated. Therefore it is important to reach a good spatial resolution The GEM detectors consist of three layers of GEM Foil and a final anode layer. The anode has strips in a x-plane and a y-plane. Each plane has 256 strips, which can read out separately. The readout will be done by the APV25 Chip. The pitch of the stripes is $\approx 400\,\mu m$ and the achievable spatial resolution is up to $50\,\mu m$. Due to an orthogonal orientation of both layers a two dimensional reconstruction of the beam track is possible. Due to the very small scale of the holes ($30 - 50\,\mu m$) in the GEM foil, the GEM has to be assembled in a clean room. Otherwise dust particle can create sparks at hight voltage and destroy the detector.

2.1 Setup

To operate the GEM the HV current is given to each layer by a voltage divider. From layer to layer more free electrons are created. The electric field decrease between each layer. With diffusion the electrons are spread and get amplified in several holes. For

this setup values between $550\,k\Omega$ and $450\,k\Omega$ are used. A sketch of the GEM with the voltage divider can be found in figure 2.2. The voltage and electric field for each layer are exemplary calculated for a current of $600\,\mu A$.
As a HV power supply the model N470 by CAEN is used. On the last GEM the signal is amplified by a A-PIC modul, which operates as a preamplifier and a shaper. As a trigger the signal is given to a LeCroy 821 Discriminator, or to measure a pulse hight spectrum the signal is given to a MCA8000D. On the Anode the current can be read out in total by a Keithley 6847 Picoamperemeter or the induced signal is read out strip by strip with APV25 chips. The signals from the APV25 are processed with the SRS system. An explanation of this can be found in a separate chapter.

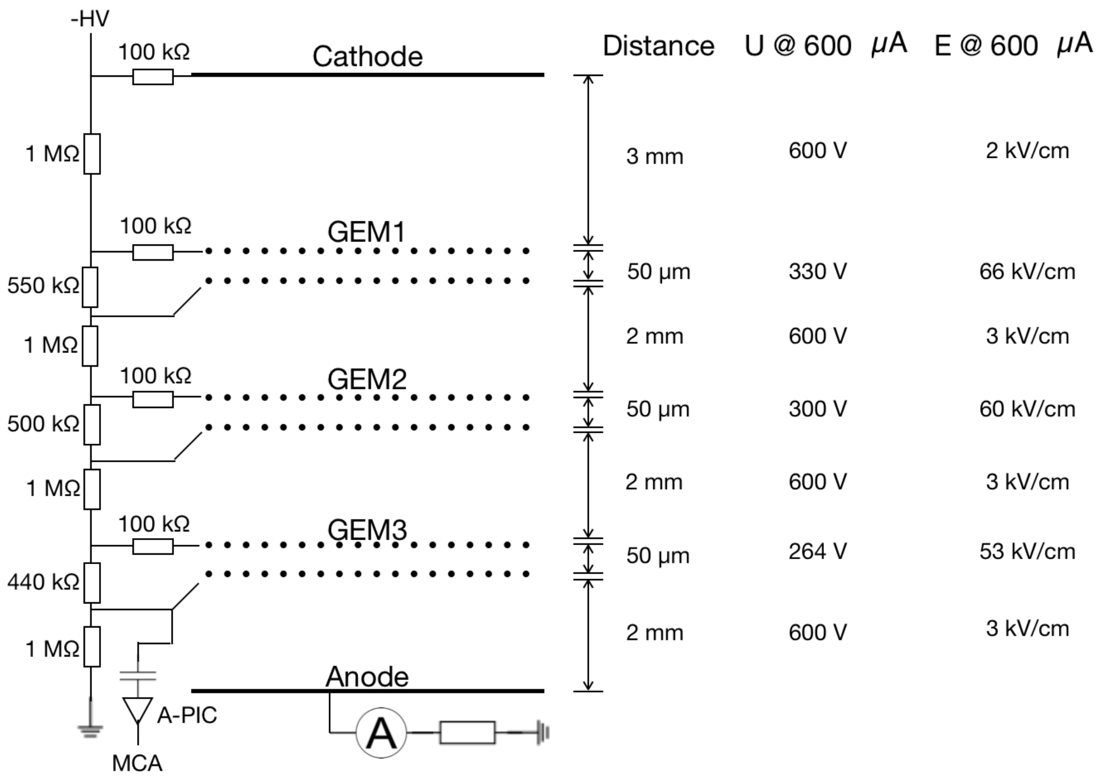

Figure 2.2: Sketch of the GEM with voltage divider and exemplary electric fields between each layer.

2.2 Gain

The gain of a GEM detector can easily measured by the ratio of the electrons collected on the anode, namely the electric current, and the electrons produced through the primary ionization of a radioactive source.

For a test measurement the x-ray source ^{55}Fe is used. The photon energy of this source is $E_\gamma = 5.9\,keV$. The GEM is operated with an argon mixture. The average ionization energy of argon is $E_{ion} = 27\,eV$. This leads to the following calculation of the gain:

$$\text{number of primary electrons: } n = \frac{E_\gamma}{E_{ion}} \approx 219 \tag{2.1}$$

$$\text{gain: } G = \frac{I}{n \cdot f \cdot e} \tag{2.2}$$

The gain of a GEM detector with a given gas mixture mainly depends on the operating current. To test one specific detector and investigate its maximal gain, a series of measurements with different voltages has been executed(table: 2.1).
The Frequency is measured by a MCA, which collects data for exactly 30 seconds. It is proceeded out of the numbers of hits during 30 seconds. The anode current is measured with an digital interface for a Keithley 6847 Picoamperemeter. The gain plotted against the HV current shows an exponential growth (figure: 2.3).

Table 2.1: Gain Measurement

HV[kV]	HV[μA]	Anode I [nA]	Δ I [nA]	Rate [Hz]	Gain $\cdot 10^3$	Δ Gain $\cdot 10^3$
4200	720	0,160	0,015	738,2	6,08	0,27
4200	720	0,151	0,014	719,0	5,92	0,26
4300	737	0,271	0,030	726,4	10,50	0,54
4300	737	0,302	0,119	735,7	11,5	2,10
4400	754	0,571	0,060	718,2	22,40	1,08
4400	754	0,595	0,498	728,6	23,00	8,90
4500	772	1,250	0,142	714,4	49,20	2,59
4600	789	2,340	0,182	714,1	92,00	3,32
4700	805	4,010	0,263	715,5	158,00	4,79
4750	814	5,060	1,010	721,0	198,00	18,30

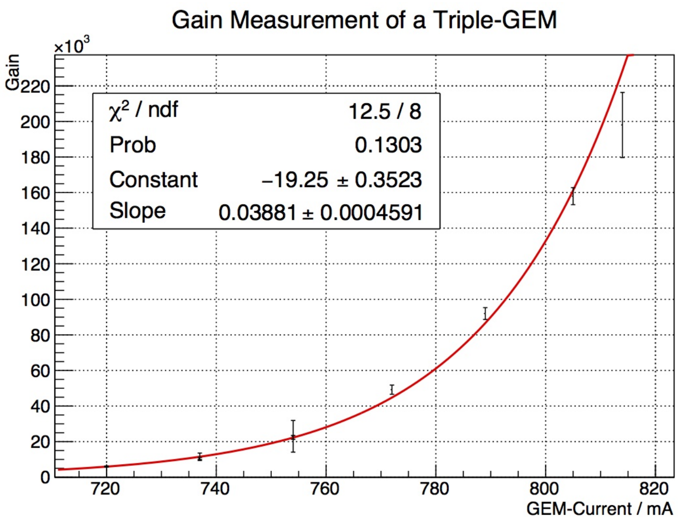

Figure 2.3: Exponential growth of the gain by rising operating current.

2.3 Spectrum

A pulsehight spectrum can be measured by reading out the induced current on the anode. It is also possible to read out the voltage on the last GEM foil with a MCA8000D. Both signals are the same with an inverted polarity. This voltage is proportional to the energy of the primary ionizing particle. A pulse high spectrum of the ^{55}Fe source is created by reading out the signal on the last GEM foil. Apart of the noise a sharp peak of the x-rays can be seen. At higher gains there is also a second peak appearing. This peak has roughly 3 keV less energy than the ^{55}Fe peak (figure: 2.4)
The peak around 3 keV is a specific escape peak of the argon gas. It occurs, when an excited argon atom transits to a lower energy state. For this transit there are two different channels. One is radiation less with a photoelectron and an auger electron. In the other one a photoelectron and a photon are emitted. The energy of the electron for both channels is around 3 keV.

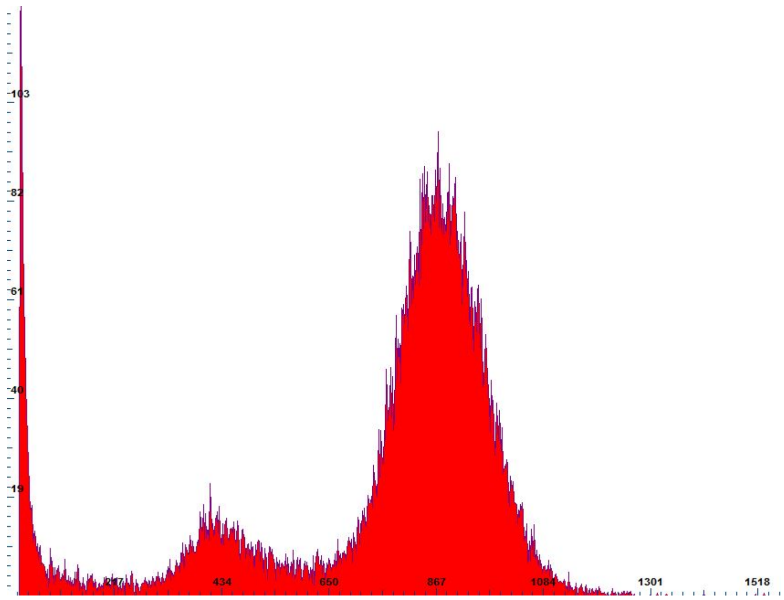

Figure 2.4: Pulsehight Spectrum of the last GEM layer. HV current I=687 mA. Gain $\approx 1.6 \cdot 10^3$. The Argon escape peak is located by the half of the ^{55}Fe peak.

2.4 SRS

The separate anode layers are read out by the Scalable Readout System (SRS). This system consist of a SlowControl to operate the trigger, determine data length and delay times. More informations about the operation of the SlowControl can be found in the corresponding manual [1].
To record and store measurements the DAQ software 'DATE' by ALICE is used. To analyse the collected data the AMORE software is used. This provides pedestal analysis, and physics analysis with different settings. With this software it is posible to create pulse hight spectra and hitmaps of cluster and single hits. More about AMORE and SRS can be found in the GEM Control manual [2].

2.4.1 Trigger Rate

For measurements in the beam or at other situations with high rates it is important to control the death time with the SlowControl. The data rate is limited by the bandwidth of the hardware interface. When there are too long packages of data arriving in too short amount of time, the DAQ can not separate the packages any more and proceed error messages.
This happens for example, when all 16 APVs with the maximum data length are read out with a death time of 386 μs. With this setting the Byterate goes to 97 MB/s.
To understand this behaviour different trigger frequencies, data length and number of APV chips are tested. With very short packages from only one APV DAQ trigger rates

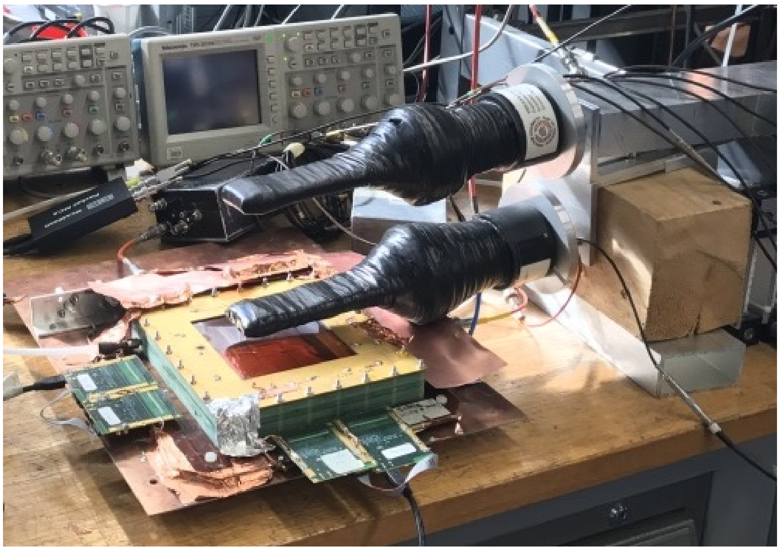

Figure 2.5: Setup of GEM with an external coincidence trigger.

up to 20 kHz are possible. It is crucial to find the right balance between data length and dead time. Therefore only those APVs should be activated, who are really used.

2.5 Trigger

The used APV25 Chips does not provide an own trigger, therefore a trigger system is needed. For this GEM detector two different trigger signals can be used. The first is an trigger signal produced inside of the GEM. Therefore the signal from the lowermost GEM layer is used and processed by a discriminator. The threshold can be as low as needed, as long it stays above the noise band. This trigger is used for measurements with sources.
The second trigger is an external trigger. This consist of two small scintillator paddles, read out by PMTs (figure: 2.5). With a coincidence module a trigger signal is generated, when a particle hits both scintillators in a straight line. With this trigger, it is possible to perform a long time measurement of cosmic rays, which ends up in an landau distribution.
With an external trigger with good time resolution the time jitter of the GEM through different positions of ionisation can be observed. This is needed to characterize the detector for position tracking and estimate its time resolution.

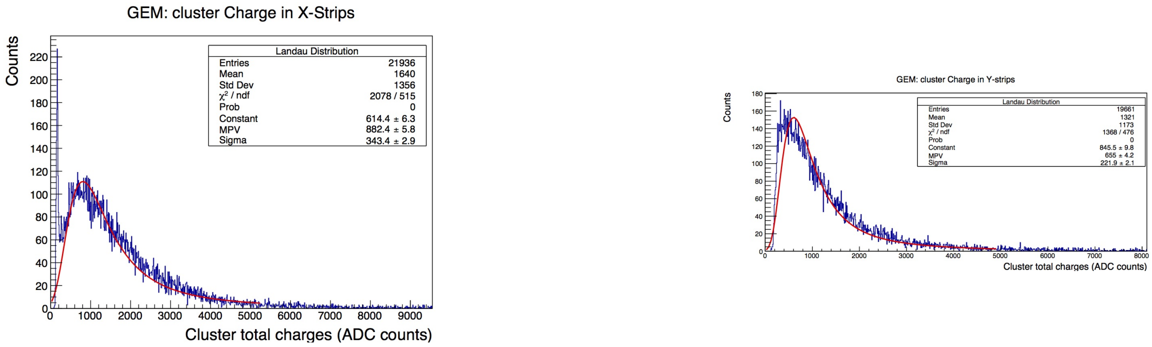

Figure 2.6: Long term measurement of cosmics shows a Landau distribution in both plane orientations. The high peak in the lower channels is contributed to noise and can be cut out by selective cuts.

2.6 Measurements with an external trigger

With the external trigger a long time measurement with 42000 hits over the weekend has been carried out. It has been performed without a source. As expected the energy spectrum shows a landau distribution (figure: 2.6). The energy spectrum can be created for both planes separately. Both spectra can be combined to a 2D heatmap of the energy (figure: 2.7). This heatmap shows a linearity between both spectra. At higher energies this linearity breaks up and the curve starts to bent. This is a clear sign, that one APV starts to saturate. The ratio of the charge distribution (figure: 2.8) clarifies this even more. It is clearly shifted from one. Therefore in the x-plane the charge rises steeper and it will reach saturation more early. As it happens at higher values in the tale of the distribution, this will be tolerated.
On the hitmap (figure: 2.9) every dot marks the position of a hit on the anode. The scintillators were mounted diagonally over the GEM. This diagonal can be seen in the hitmap. It can also be observed, that some stripes are not working. These are the blank lines in the hitmap.
With this external trigger the internal time resolution of the GEM can be measured. For this the time bin of the highest peak in each cluster is analysed (figure: 2.10). The figure shows a very narrow distribution with a derivation of under one bin. With this result a fast and precise measurement with this detector is possible. Like in the charge distribution a better result could be achieved with more precise data analysis and cuts over the noise.

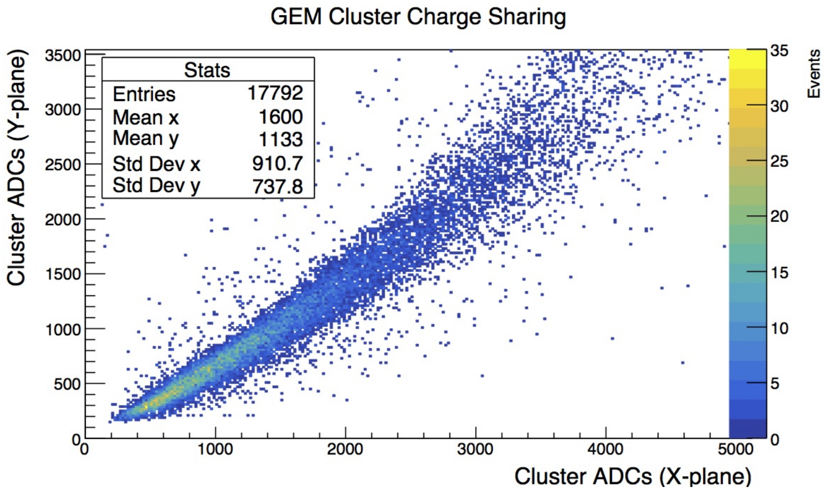

Figure 2.7: Linearity between the charge distribution of both planes at lower charge. At higher charge curve bents and one APV starts to saturate.

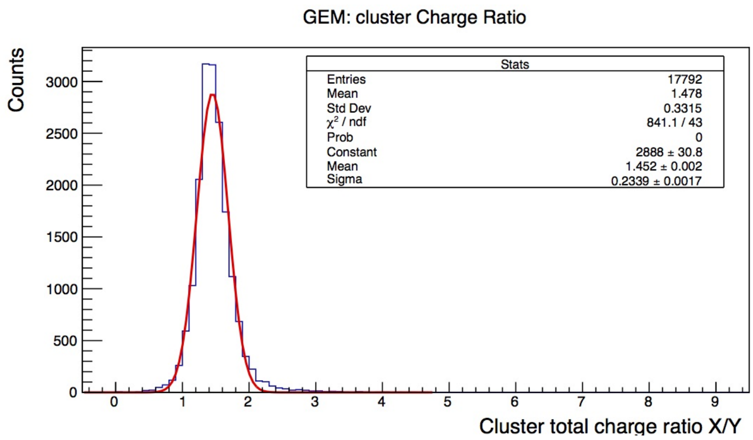

Figure 2.8: The ratio of the charge distributions is clearly shifted from one.

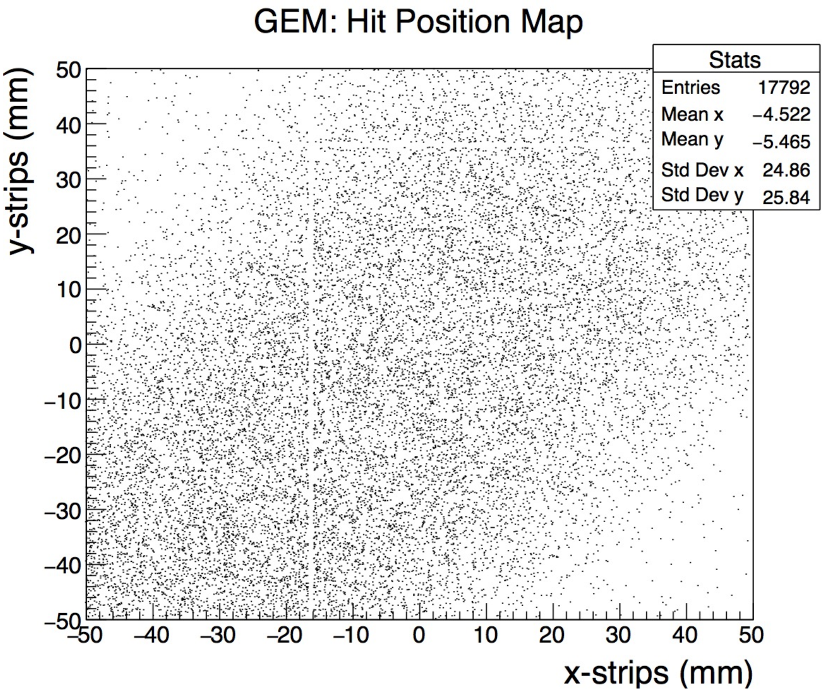

Figure 2.9: Distribution of the hit positions on the anode. The shape of the trigger scintillators can be spotted.

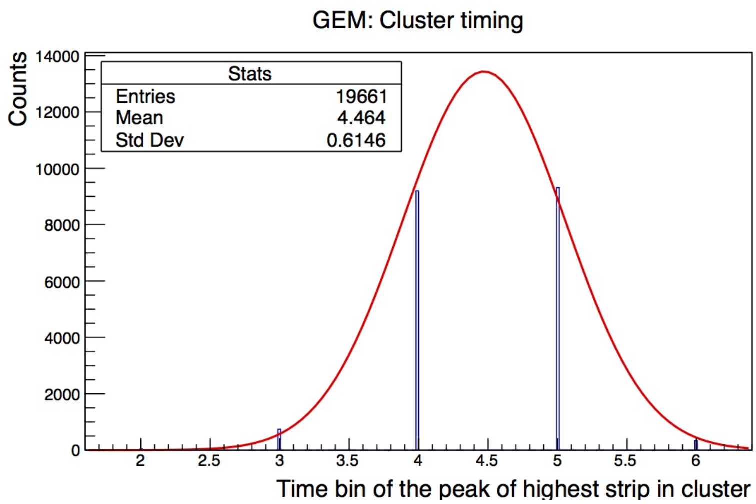

Figure 2.10: Time bins in which the highest peak in each cluster where detected. With an external trigger this represents the time jitter through different positions of ionisation.

3 Tracking with GEM

The beam at the picosec project is tracked with three triple-GEM detectors. To test this tracking setup the three detectors are mounted vertically to track cosmic muons. To produce a trigger signal for the muon detection some scintillators with PMT readout are mounted over and under the GEMs. Two 6 cm x 6 cm scintillators (S3 and S4) are mounted on top of the GEMs. Under the GEMs are two 10 cm x 4 cm bars mounted (S5 and S6) (figure: 3.1). The scintillator bars are shifted by 4 cm. Therefore particles through a larger or smaller area are tracked, when they are read out in coincidence or anticoincidence. With the scintillators over and under the GEMs it is ensured, that the signal is only read out, when a particle hits all three GEMs.

3.1 Trigger Signal

To produce a trigger signal for the SRS system the signals from the PMTs are going through several modules. With a discriminator, logical NIM signals are produced and by coincidence units those signals are connected together to generate a coincidence trigger by all scintillators. With the coincidence unit there are different coincidences between the scintillators available. For the muon tracking with the GEM there are the following possibilities:

- $S3 \wedge S4$
- $S3 \wedge S4 \wedge S5$
- $S3 \wedge S4 \wedge S5 \wedge S6$
- $S3 \wedge S4 \wedge S5 \wedge \overline{S6}$

With this it is possible to choose a smaller or wider area of the lower scintillators (S5 and S6), or disable them in total. This increase the trigger rate, but more muons pass by a steeper angel and won't hit all three GEMs.

3.2 Tracking Analysis

A possible analysis of the raw data is performed with SRS. With the tracking option at the amore configuration a mathematical alignment is performed in three iteration. A detailed explanation can be found in the manual [2].

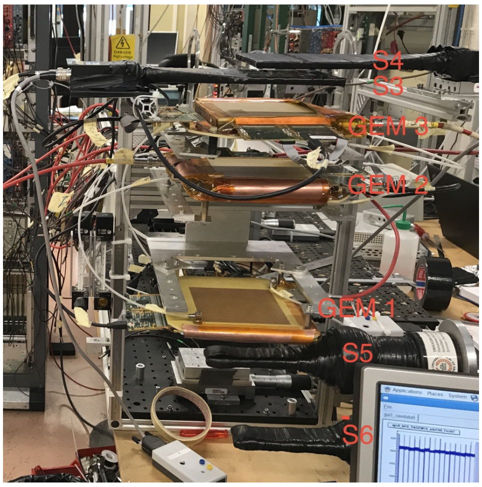

Figure 3.1: Three GEMs are stacked over each other to track muons. The trigger signal is produced by coincidence of several scintillators.

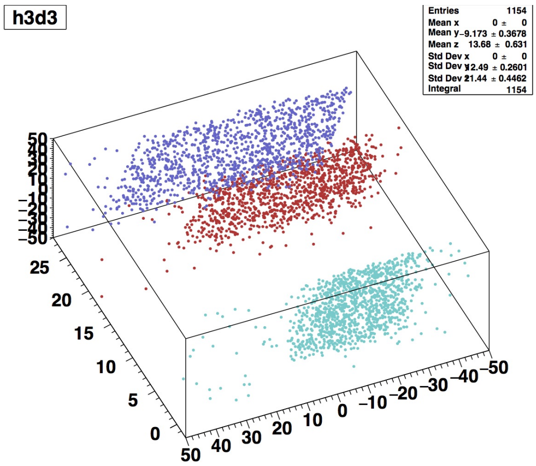

Figure 3.2: 3-D Reconstruction of the hits in each GEM.

In the end amore produces a RootTree file which contains the tracking position for every single event. A possible visualisation is a 3-dimensional hitmap of the particle. In this exemplary plot the different sizes of the scintillators can be clearly spotted (figure: 3.2). The tracks are forming a cone to the bottom where the smaller scintillator is mounted.

4 Picosec

In most gaseous detectors the position of the creation of the primary electron is not defined. It can happen anywhere in the gaseous volume. This leads to a time jitter due to different travelling distances of the primary electron inside of the detector. The sketch 4.1 visualize this problem. In the Picosec detectors a several mm thick MgF_2 window is used as a cherenkov radiator. In this radiator the minimal ionizing particles are producing a light cone. These photons are converted to the primary electrons on a photocathode. The sketch 4.2 shows the functional principal of a Picosec. As a photocathode CsI coated with Cr is used. The thickness of the photocathode is around 20 nm. For a good timing resolution the thickness and opacity of the photocathode and the Cr coating are crucial. One main part of the studies is to find the best proportion between the photocathod and the coating.[3]
The Picosec is a single stage gaseous detector. The main amplification happens in one single strong electric field. In the gaseous volume the Picosec is divided in two areas. The drift area with a length of 200 μm is between the photocathode an a mesh. This is only used for a pre amplification. Between the mesh and the read-out anode the distance is very low to archive a high electric field. There are different models of Picosecs with a distance of 128 μm and 50 μm. The electric field of both areas can be controlled separately. The ratio of the drift field and the amplification field is as well important for the timing resolution, which will be studied during the test beam.
For the mesh there are different kinds of production. The bulk ones are a woven mesh of inox steel, which are hold in place by a 128 μm thick vacrel mask. The microbulk meshs is a kapton foil (thickness 50 μm) coated on both sides with copper. The 'mesh' and the read out anode is etched out of the kapton copper structure. This method is very expensive, but it is possible to obtain thinner amplification gaps and less detector material.[4]
It is also possible to coat a resistive layer on top of the anode. This layer protects the mesh against sparks and the detector can be operated in different conditions with higher rates or with particles of a higher energy like pions. Due to the resistivity the time resolution of the signal suffers.
The functionality with different gas mixtures has been studied. Noblegases like neon or argon are used as the ionising gas. As a quenching gas there are different possibilities with CO_2, Ethan or CF_4. For the studies during my internship mainly "Compass Gas" is used. This is a well established gas mixture of 80% Ne - 10% C2H6 - 10% CF4. It is already in use for Micromegas detectors in the Compass collaboration. The quenching gas is needed to obtain fast timing resolutions. Otherwise the ionisation avalanche would last to long and the signal would be wider. At higher electric fields and without a proper amount of quenching gas the gas can be fully discharged.

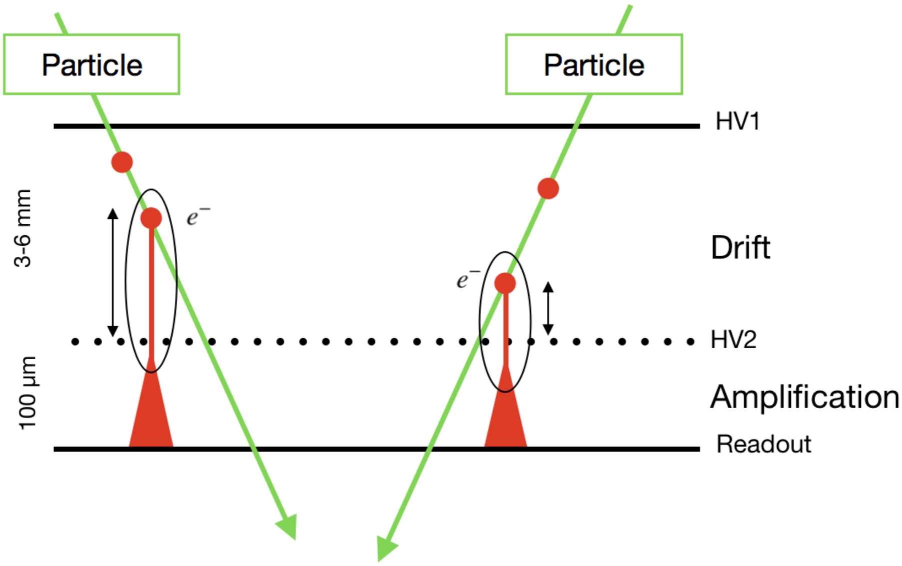

Figure 4.1: Sketch of the primary electron produced in the drift area of a Micromegas detector. A time jitter occur due to different positions of the ionisation clusters.

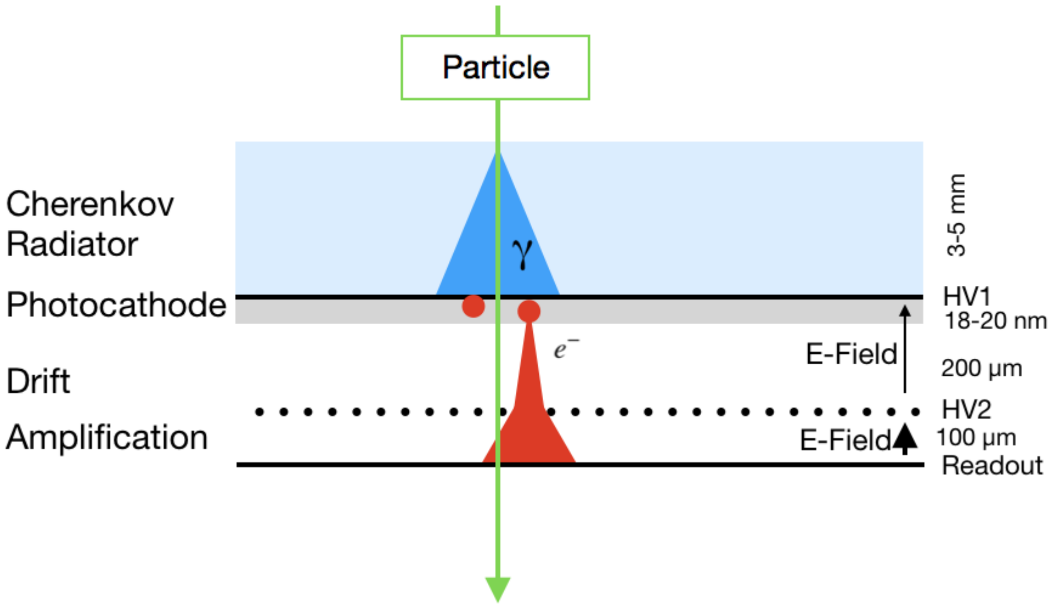

Figure 4.2: Sketch of the primary electron produced in the photocathode and multiplied in the gaseous volume. The time jitter from different ionisation positions is highly suppressed.

5 Test Beam

In the test beam campaign Picosecs with different photocathodes and resistive coatings are tested. The goal is to gain good data runs to investigate the time resolution and durability of these detectors. The used detectors have a single channel readout. Therefore a tracking of the particle only with the Picosec is not possible. To understand the timing behaviour of the Picosec a tracking of the particle is needed. The previous explained GEM Tracker is used to track the interacting particle.
To get a reference for the timing, two MCP-PMT typ R3809U-50 by Hamamatsu[5] are used. These MCP-PMTs have a time resolution of FWHM=6 ps[6]. This time resolution is way better, as we expected from the Picosec. Therefore we can use these signals as a time reference signal.
The Picosec and MCP-PMTs are read out by a digital oscilloscope. This sampels every waveform. The waveforms are analysed offline. The GEMs are triggerd by a coincidend interconnection of the previous mentioned scintillators and read out by the SRS. The tracks are not calculated by Amore. Instead a script provided by Dr. Jona Bortfeldt is used. This script uses a Kalman Filter to improve the tracks and separate hits from noise.
To match the measured Detector signals with the GEM tracks a trigger counter signal from the SRS is used. This provides the event nuber as a binary rectangular signal. This signal is monitored and stored by the same oscilloscope as the Picosec signal. In the analysis the Picosec signal can be matched to the corresponding track through the GEMs.

5.1 Alignment

To understand the time response of the detectors, a good position tracking of the events is mandantory. Therefore the exact positon of the Picosec and MCP-PMTs related to the GEMs must be measured and the active area must be aligned with the scintillator faces.
For the data taking there are two different trigger areas available. The smaller one of 5 mm diameter should fully overlap with the active area of every investigated detector. The larger area 2 cm times 3 cm should overlap with the full area of the detectors. With this configuration differences in the signals and time resolution in different regions of the detector can be studied.
As an example there are GEM hitmaps from the alignment procedure of different detectors (see: 5.1, 5.2 and 5.3). After every manual interaction with the setup a new alignment has to be accomplished. Every mechanical movemend on the setup table can

affect the alignment.

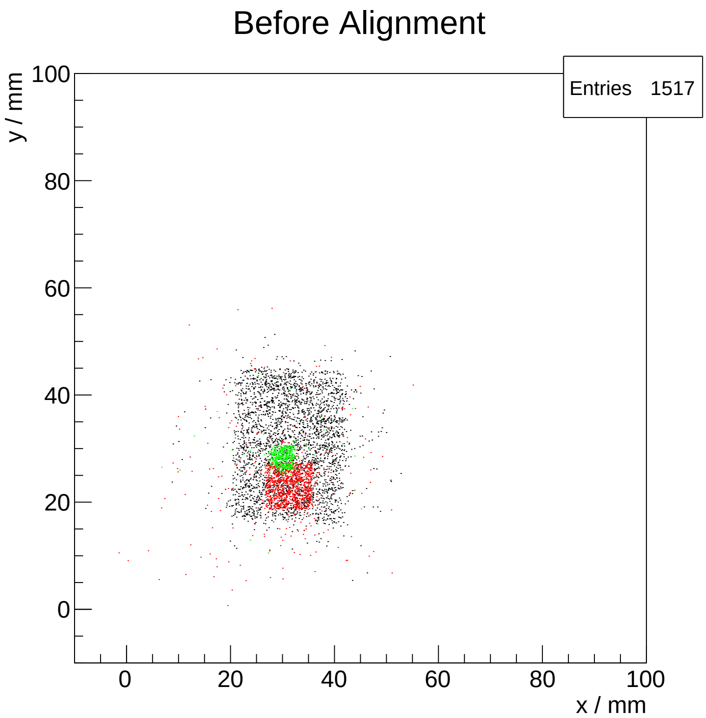

Figure 5.1: Si Detector (red) is not aligned with the small trigger area (green).

5.2 Tested Detectors

For the testbeam a 3 mm thick MgF2 window as a cherenkov radiator is used. For the photocathode different configurations are tested. First a classical 20 nm CsI photocathode coated on a 5.7 nm Cr layer. Ongoing this model is refereed as the 'CsI'-Model. With this model the ideal conditions for fast timing resolutions are worked out.
In the second model the CsI layer is replaced by a thicker Cr layer of total 20 nm Cr (ongoing 'Cr'-Model). With this model the difference of Cr and CsI as a photocathode are studies. Due to its hygroscopic characteristics CsI is difficult to handle and storage. Therefore solutions are elaborated, where the CsI layer can be substituted.
The third Detector is similar to the 'CsI'-Model with a CsI Layer of 18 nm and a Cr layer of 5.5 nm. This Detector is produced by the USTC Institute and the functionality and production quality of this one is studied.
At last two models with a resistive coating on the anode are studied ('Resistive'-Model). Due to a resistive coating a better durability in harsh conditions are expected. The main goal of this study is to use Picosec detectors for applications of higher rates or high energetic particles like pions. In former studies of pions without a resistive layer sparks damaged the mesh and the detector does not keep the voltage any more. Two

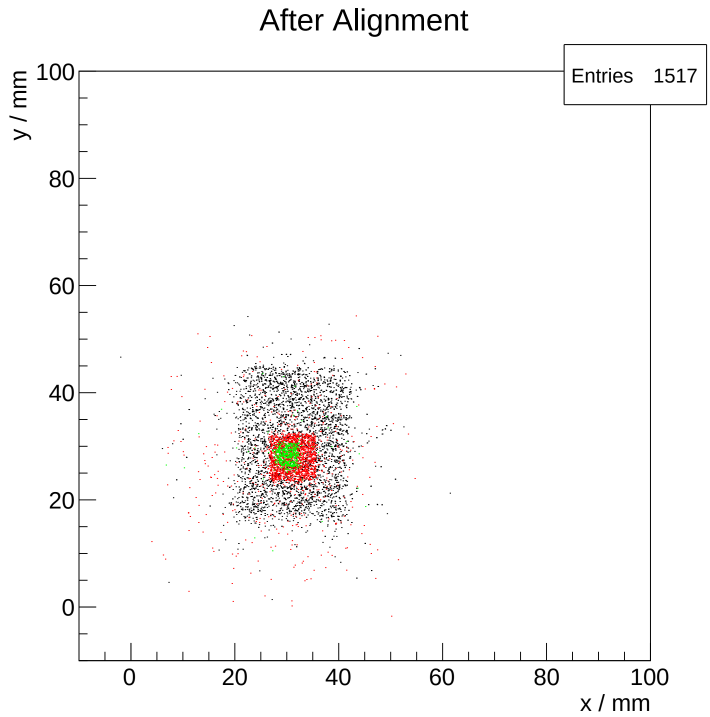

Figure 5.2: Small (green) and large (black) trigger area overlaps with the active area of the Si Detector (red).

different models are tested. One with a high resistivity of 82 $M\Omega$ and one with a much lower resistivity of 292 $k\Omega$. The photocathode has the same structure as the one from the 'USTC'-Model.
The most important test for these detectors is a field scan, where the time resolution at different electric fields in the drift and amplification gap is studied. With this tests the setting for an optimal time resolution has to be found. With these scans more information of the detectors are gathered. Especially at higher fields the detectors can become unstable and start to create sparks. It is important to know up to which conditions the detectors can be operated stable.
For the resistive detectors even runs with pion beams are performed. With these runs the ageing of the photocathode and the durability at higher energetic particle can be observed.

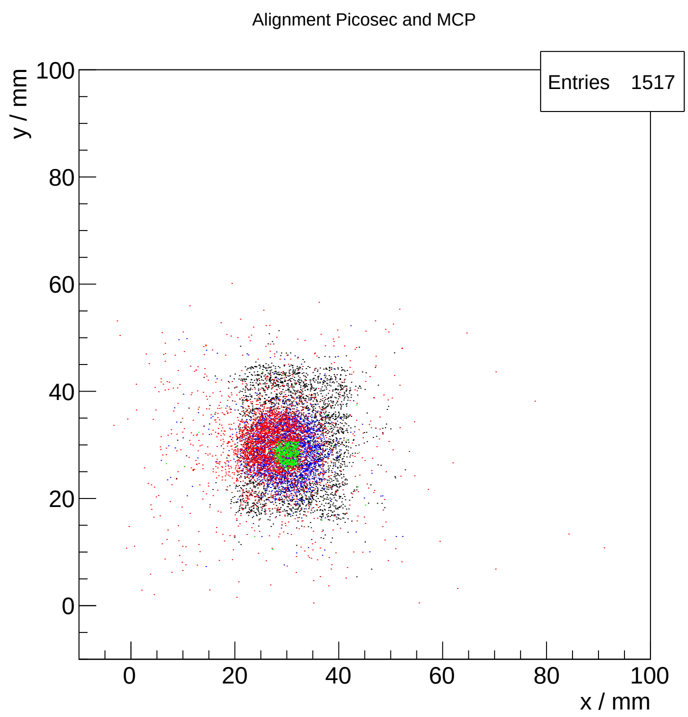

Figure 5.3: The active area of the Picosec (red), the MCP (blue) and both trigger areas (black, green) are overlapping.

6 Analysis

In a first analysis the time difference of the Picosec and the MCP-PMT are calculated. For the analysis the sampled waveforms from the scopes are available in a binary file format. With a script provided by the collaboration those files can be read and the information on the waveforms are stored as a Root TTree object.
To calculate the time difference between two signals a timepoint for each signal has to be defined. This timepoint for each signal is calculated by a CFD algorithm. With a CFD different amplitudes do not affect the timepoint of the signals.
The time difference between the Picosec and the MCP-PMT signal results in a gaussian shaped distribution. With the standard deviation of a gaus fit the time resolution can be determined. In figure 6.1 the time resolution fit for the run 596 is shown. At this run the voltage of the drift field is $U_d = 425\,V$ and of the amplification field is $U_a = 325\,V$.
A more detailed analysis of the datasets will be performed in the context of my masters thesis. During that work I will include different fit models as well as slewing correction for the time difference at different amplitudes.

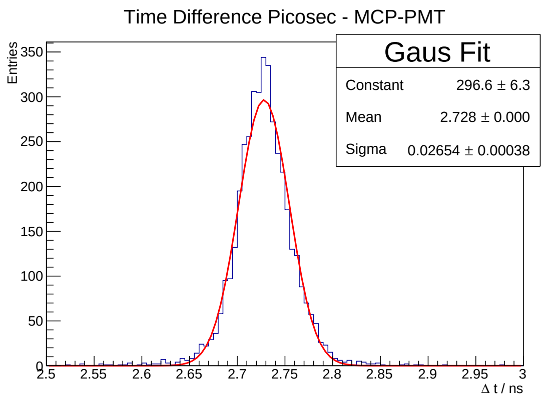

Figure 6.1: Exemplary time resolution with test beam data. $U_d = 425\,V$ and $U_a = 325\,V$.

7 Conclusion of my internship

During my work at CERN I got a deep insight of generic detector research and development. I learned to assemble and operate different kinds of gaseous particle detector. From the well established GEM to the most recent Picosec detectors.
I experienced every aspect needed to develop a new detector. I started with the basic operational principles. Learned how to assemble and operate the gaseous detectors. Taking data systematically and analyse the data.
The five week test beam campaign took a major part in my internship. At the beam I not only learned how to set up and operate an entire system. Moreover I had to take responsibility for the equipment and the beam. I had to lead and coordinate our small group of scientists during the (dis)mounting of the setup and the measurements. In this time I not only gain physical experience, but also grew in my personality.
I am thankful for the whole GDD group. All the time I was warmly welcome and I got a lot of support during my internship. In particular I want to thank Eraldo Oliveri my first supervisor, who taught my everything about the detector and the operating of the beam. Only with his confidence in me, I got the opportunity to operate the beam all by myself. I also want to thank my second supervisor Leszek Ropelewski. Only with his effort it is possible for me to continue my work in this collaboration even beyond my Summer Student internship.

Bibliography

1. *SRS Slow Control Manual* CERN, GDD.
2. Myntti, M. *GEM Control Manual* CERN, GDD, 2015.
3. Thomas Papaevangelou, e. a. *Fast Timing for High-Rate Environments with Micromegas* (CEA, CERN, Jan. 12, 2016).
4. Thomas Papaevangelou, e. a. *Development and Performance of Microbulk Micromegas Detectors* 1st International Conference on MicroPattern Gaseous Detectors, 2009.
5. *R3809U-50 SERIES* Hamamatsu. <`https://www.hamamatsu.com/resources/pdf/etd/R3809U-50_TPMH1067E.pdf`>.
6. Vignali, M. C. *I. Time Resolution of a MCP-PMT and II. Test Infrastructure in the Solid State Detector Lab* RD51 Precise Timing Workshop, 2017.