

GridPix

Development and Characterisation of a Gaseous Tracking Detector

ACADEMISCH PROEFSCHRIFT

ter verkrijging van de graad van doctor
aan de Universiteit van Amsterdam
op gezag van de Rector Magnificus
prof. dr. D.C. van den Boom
ten overstaan van een door het college voor promoties ingestelde
commissie, in het openbaar te verdedigen in de Agnietenkapel
op dinsdag 13 januari 2015, te 10:00 uur

door

Willem Jakobus Cornelis Koppert

geboren te Lelystad.

Promotor: prof. dr. F.L. Linde
Co-promotores: dr. N.P. Hessey
prof. dr. ir. H. van der Graaf

Overige Leden: prof. dr. S.J. de Jong
prof. dr. ir. E.N. Koffeman
dr. A.P. Colijn
prof. dr. ir. P.J. de Jong
prof. dr. S.C.M. Bentvelsen
dr. M. Vreeswijk
dr. N.A. van Bakel
prof. dr. K. Desch

Faculteit der Natuurwetenschappen, Wiskunde en Informatica



This work is part of the research programme of the Foundation for Fundamental Research on Matter (FOM), which is part of the Netherlands Organisation for Scientific Research (NWO). It was carried out at the National Institute for Subatomic Physics (Nikhef) in Amsterdam, The Netherlands.

ISBN: 978-94-6295-065-8

Copyright by W.J.C. Koppert © 2015

Cover design by W.J.C. Koppert © 2015

Event recorded in the SPS at CERN in 2010.

Typeset by L^AT_EX.

Printed by: Proefschriftmaken.nl || Uitgeverij BOXPress

Published by: Uitgeverij BOXPress, 's-Hertogenbosch

Aan mijn vader en moeder

Contents

1	THE NEED FOR PARTICLE DETECTORS AND GRIDPIX	13
1.1	Particle Physics and the Standard Model	13
1.1.1	Challenges in the Standard Model	15
1.1.2	Demand for High Energies and High Intensities	16
	Probing Theory at High Energies in the Far Future	16
	Probing Theory at High Energies in the Near Future	17
1.1.3	Detectors for High Energy Physics Experiments	19
	Calorimetry	19
	Muon Spectrometry	20
	Particle Identification	20
	Tracking	21
	Tracking with Gaseous Detectors	21
1.2	The ATLAS Experiment	21
1.2.1	Scientific Goals	22
1.2.2	The ATLAS Detector	22
	Inner Detector	22
	Calorimeter System	24
	Muon Spectrometer and Magnet System	24
1.3	Potential GridPix Applications in ATLAS	25
1.3.1	Gossip	25
	Requirements	25
	Advantages	27
	Disadvantages	27
	Outlook	28

1.3.2	GridPix as Level 1 Trigger	28
	Principle	28
	Requirements	28
	Additional Benefits	29
	Outlook	29
1.4	A Medical Application: GridPix in Proton Radiography	30
1.4.1	Proton Therapy	30
1.4.2	GridPix for Proton Radiography	31
1.4.3	Outlook	33
2	GASEOUS DETECTORS	35
2.1	Principle of Gaseous Drift Detectors	35
2.2	Types of Amplification	36
2.3	Read-Out	37
2.4	Performance of Gaseous Detectors	37
2.5	Detector Types	37
	GEM	38
	Micromegas	38
2.6	GridPix	39
2.6.1	GridPix Geometry	40
2.6.2	CMOS Read-Out	40
2.6.3	Protection Layer	41
2.6.4	Production	42
2.6.5	Challenges	43
	Protection Layer Quality	43
	Grid Quality	45
2.6.6	Detector Assembly	46
2.6.7	Data Acquisition	48
2.6.8	Conclusion and Outlook	49
3	PHYSICS OF GASEOUS DETECTORS	50
3.1	Energy Loss in the Gas	50
3.1.1	Charged Particle Energy Transfer Processes	50
	Theoretical Description of Energy Loss	51
3.1.2	Photon Energy Transfer Processes	53

3.1.3	Secondary Processes	54
3.2	Gas Properties	55
3.2.1	Drift Velocity	55
3.2.2	Diffusion	57
3.2.3	Amplification	59
3.2.4	Multiplication Process	59
3.2.5	Mathematical Description	59
	Moderate Electric Fields	60
	Strong Electric Fields	60
3.2.6	Ion Drift	62
3.2.7	Quenching and Dissociation	63
3.2.8	Ageing	63
3.2.9	Temperature and Pressure Variation	64
3.2.10	Justification of the Gas Mixture	64
3.2.11	Electron Detection Efficiency	65
3.2.12	Conclusion	66
4	FIELD CALCULATIONS	67
4.1	Field Calculation Methods	67
4.1.1	Finite Element Analysis	67
4.1.2	Boundary Element Method	68
4.1.3	NeBEM Validation	69
4.2	Modelling GridPix Detectors	71
4.3	Grid Transparency	74
4.4	Field Near the Last Pixel	77
4.5	Field Near the Chip Edge	78
4.6	Gain as Function of the Amplification Gap Size	79
4.7	Gain Variation in Grid Hole	79
4.8	Field Focus	82
4.9	Drift Time Variation	82
4.10	Edge Effects in the Field Cage	84
4.11	Concluding Remarks	85

5	BEAM TEST RESULTS	87
5.1	Set-up 2012	88
5.1.1	Beam Properties	88
5.1.2	Modules	88
5.1.3	Gas System	89
5.1.4	High Voltage System and Gain	90
5.1.5	DAQ and Trigger System	91
5.1.6	Data Preparation	91
	Noisy and Quiet Pixels	92
5.2	Local Track Fit Analysis	95
5.2.1	Hit	95
	t_0 Estimation	97
	Time Spectrum Shape	98
	Electric Field and Drift Velocity	99
5.2.2	Pattern Recognition	100
	Number of Track Clusters	101
	Number of Hits per Track Cluster	103
5.2.3	Local Track Fit	103
	Hit Errors	103
	Time-walk	106
	Track-fit Algorithm	108
5.2.4	Dealing with Outliers	112
	Quality Checks	112
	Positional and Angular Resolutions	117
5.2.5	Local Track Fit Summary	121
5.3	Telescope Detector Alignment	121
5.3.1	Alignment Overview	123
5.3.2	Global Frame Definition	123
	Determination of z	124
	Weak Modes	124
5.3.3	Alignment Parameters	125
5.3.4	Point Transformation	126
5.3.5	Slope Transformation	127
5.3.6	Alignment Procedure	127

5.3.7	Alignment Results	129
5.3.8	Alignment Summary	130
5.4	Telescope Resolution Check	132
5.4.1	Multiple Scattering	134
5.4.2	Telescope Error	135
5.4.3	Extracting the Resolution	135
5.4.4	Comparison of Telescope Resolutions with Local Track Fit Results	136
	Global detector resolution	136
	Resolutions of the Detectors in Run 89 (2012)	138
5.4.5	Results of Monte-Carlo and Other Runs in 2012 and 2010 . .	139
	Resolutions of the Detectors in Monte-Carlo	139
	Resolutions of the Detectors in Run 90 (2012)	139
	Resolutions of the Detectors in Run 25 (2010)	139
5.5	Particle Detection Efficiencies in Run 89	140
5.6	Particle Tracking Efficiencies in Run 89	141
5.7	Summary and Conclusion	141
6	LASER BEAM TEST	143
6.1	Experimental Set-up	143
6.1.1	Nitrogen Laser	144
6.1.2	Optics	145
6.1.3	Trigger System	147
6.1.4	Detector	148
6.1.5	Electric Field Scaling	150
6.1.6	Oxygen Content in Drift Gas	150
6.2	Amplification Properties	152
6.2.1	ToT to Charge Transformation	152
6.2.2	Average Gain	154
6.2.3	Gain Fluctuations	156
6.3	Drift Velocity and Diffusion	157
6.3.1	Measurement Methods	158
	ToA-Method	158
	ToT-Method	160

6.3.2	Drift Velocity	161
6.3.3	Transverse Diffusion	163
6.3.4	Longitudinal Diffusion	164
6.4	Conclusion	169
APPENDICES		170
A	RADIATION LENGTH OF GRIDPIXES IN THE TESTBEAM	171
REFERENCES		173
SUMMARY		179
SAMENVATTING		183
DANKWOORD		187

1

The Need for Particle Detectors and GridPix

The scope of this thesis is the development of a specific kind of gaseous detector; "GridPix", with applications in the high energy physics. To put this into a broader perspective, this chapter introduces the Standard Model and points out the importance of particle detectors for testing of the theory. It discusses several particle detection principles before briefly introducing GridPix. Subsequently the ATLAS experiment at CERN will be discussed, with specific focus on the detector. Afterwards several potential applications of GridPix in ATLAS and in the medical industry will be discussed.

The rest of the thesis will give more detailed information about gaseous detectors and GridPix.

1.1 Particle Physics and the Standard Model

Very crudely, the last 2500 years of (particle) physics has resulted in an elegant theory known as the Standard Model. The Standard Model describes particle physics and its fundamental particles and interactions. It is successfully tested to high accuracy. Currently the elementary particles in the Standard Model can be grouped by their spin. The first group, the fermions, describes 12 particles that all have half integer spin. The second group, the bosons, contains particles with integer spin. The fermions can be subdivided into 6 quarks and 6 leptons. Pairs

from each subgroup together form a generation. The first generation contains the two lightest quarks – the up (u) and the down (d) quark – and two leptons – the electron (e) and the electron-neutrino (ν_e). All stable matter around us can be described by this generation. The charm (c) and the strange (s) quark together with the muon (μ) and the muon-neutrino (ν_μ) form the second generation. The third generation contains the bottom (b) and the top (t) quark together with the tau (τ) and the tau-neutrino (ν_τ). Figure 1.1.1 shows this arrangement of the particles in the Standard Model. In addition to the described matter there is the anti-matter where some of the properties have the same magnitude but opposite sign.

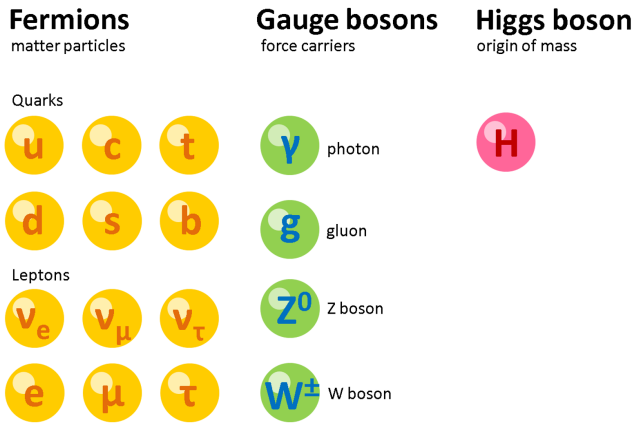


Figure 1.1.1: The particles of the Standard Model of particle physics.

All interactions between elementary particles in nature can be described by the four fundamental forces; the electromagnetic, weak, strong and gravitational force. The elementary particles in the groups interact, using the four forces as indicated, by their quantum numbers that couple to an interaction of a specific kind.

- **Electromagnetic;** both quarks and some of the leptons carry an electric charge, in the case of quarks that can be either $2/3$ or $-1/3$, in the case of the leptons that can be either -1 or 0 in case of the neutrinos. Electric charge couples to the electromagnetic force, that hold atoms and molecules together. The electromagnetic force becomes weaker at large distances but it has an infinite range. The electromagnetic force carrier is represented by the photon γ . The electromagnetic force is described with the theory of Quantum Electrodynamics (QED).
- **Weak;** flavour is the quantum number that couples to the weak force which is responsible for beta decays in nuclei. All particles can have weak interac-

tions. The force carriers of the weak force are W and Z bosons. The weak force is unified with the theory of Quantum Electro Dynamics in the electroweak theory.

- Strong; quarks carry a colour charge, represented by either red, green or blue. Colour charge couples to the strong force that is responsible for quarks staying together in nucleons, it becomes stronger at increasing distances. The force carriers of the strong force are gluons, which carry both a colour and an anti-colour simultaneously. Quarks bind together in hadrons with a net zero colour charge. The strong force is described by the theory of Quantum Chromo Dynamics.
- Gravity; the gravitational force is the weakest of the four fundamental forces. Despite its large effects on daily life and its role on the geometry of spacetime as described by general relativity, there exist no quantum theory of gravity. Since gravity is many orders of magnitude smaller than the other forces, it has no noticeable effect in present-day particle physics experiments.

Table 1.1.1 presents the force carriers and the strength and range of the forces in the Standard Model. The Standard Model contains a mechanism to cope with massive particles. This “Higgs mechanism” allows mass while maintaining self consistency [1], predicting the so-called Higgs boson (H). The recent discovery of a particle with properties similar to the Higgs boson [2, 3] (2012) verified the Standard Model, although further investigations are needed to study all properties.

Table 1.1.1: Fundamental forces and their mediators, relative strength and range [4].

Force	Mediator	Strength	Range (m)
Strong	Gluon	1	10^{-15}
Electromagnetic	Photon	10^{-2}	∞
Weak	W^+, W^-, Z^0	10^{-6}	10^{-18}
Gravitational	Graviton (predicted)	10^{-42}	∞

1.1.1 Challenges in the Standard Model

The Standard Model predicts experimental measurements with high precision and it has been verified many times, however there are several important unexplained phenomena:

- Dark matter and dark energy; cosmological observations suggest that about 74% of the universe is made of dark energy and 22% of dark matter. The leftover is baryonic matter and neutrinos, that is described by the Standard

Model. Extensive studies are currently ongoing to detect and predict the properties of dark matter and dark energy.

- Matter over anti-matter ratio; during the big-bang, matter and anti-matter should have been produced in equal amounts. Nowadays hardly any anti-matter is observed in the universe around us. This asymmetry is the subject of many speculations.
- Neutrino oscillations; it has been observed that neutrinos vary their identity periodically as they propagate. Neutrino oscillations as well as their non-zero mass are not predicted by the Standard Model.

The challenges as described above need to be studied with new accelerators and accurate new detectors.

1.1.2 Demand for High Energies and High Intensities

In addition to the challenges as described in the previous section there is the desire to test the Standard Model at high energy. Energy in high energy physics is generally expressed in units of electron volts (eV), that is defined as the energy gained by moving an electron across an electric potential difference of one volt. Energy is related to rest mass m_0 and momentum p by equation 1.1. Note that this equation is Lorentz invariant, meaning that the energy squared minus the momentum squared is the same in every reference frame

$$\sqrt{E^2 - (pc)^2} = m_0 c^2. \quad (1.1)$$

Here the momentum of a massive particle is:

$$\vec{p} = \gamma m_0 \vec{v}, \quad (1.2)$$

where $\gamma = \frac{1}{\sqrt{1-(v/c)^2}}$ is the so-called Lorentz factor and $\vec{v}$ is the velocity. In the case of a particle at rest (e.g. $\vec{p} = \vec{0}$) equation 1.1 reduces to Einstein's well known formula 1.3 [5]:

$$E = m_0 c^2. \quad (1.3)$$

Probing Theory at High Energies in the Far Future

On the long term, there is the desire to probe the Standard Model at extreme energy scales where fundamental forces might start to merge. Figure 1.1.2 shows the relative strength of the fundamental forces as function of the energy scale. At increasing energy the weak force increases and the electromagnetic force decreases, such that at about 10^2 GeV they merge into the electroweak theory. In addition it has been observed that the strong force decreases too at larger energy scales.

Therefore it is expected that at large energies (about 10^{15} GeV) the electroweak and the strong force merge into a Grand Unified Theory (GUT). At energies close to the Planck scale ($\mathcal{O}(10^{19})$ GeV [6]) it might be that also gravity unifies.

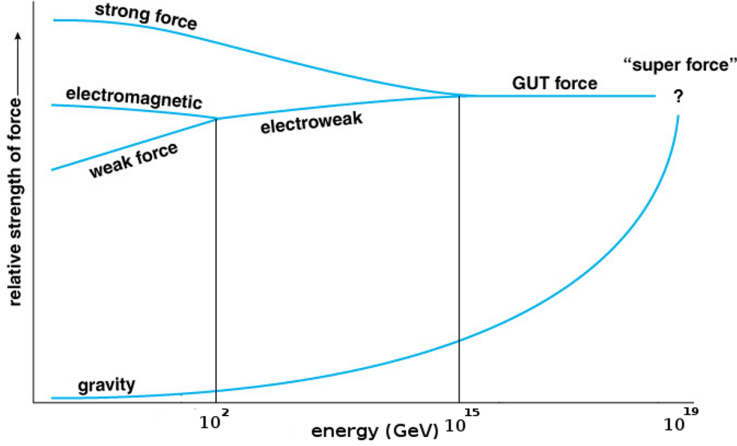


Figure 1.1.2: The relative strength of the fundamental forces as function of the centre of mass energy.

Likely the energies of future accelerators will not be increased by more than an order of magnitude. However it is known that there are sources in the universe that can accelerate particles up to 10^{11} GeV. Therefore astrophysical experiments have growing interests to study particles at those energy scales.

Probing Theory at High Energies in the Near Future

The current and near future studies are related to the desire to study heavy particles, to check whether the current theory is consistent also at higher energies. The Standard Model allows particles with masses larger than anything that has been observed in the past. Since the probability to create heavy particles is low, many measurements are required. The number of observation that can be used to study the properties of the heavy particle of interest depends on:

- Heavy particle production rate per collision;
- The number of collisions;
- The detection efficiency.

The heavy particle production rate per collision is a function of the centre of mass energy of two colliding particles. Above the rest energy cut-off, typically the heavy particle production rate grows with the energy. Therefore large accelerators like LHC (see figure 1.1.3) are required to accelerate particles up to high energies ($\mathcal{O}(10)$ TeV) meeting the statistical demands. The particle production probability is defined as the cross-section σ , in general it is expressed in terms of unit area.

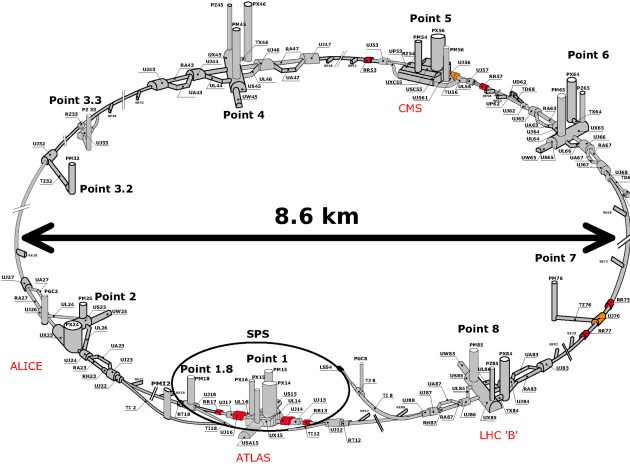


Figure 1.1.3: The layout of the current LHC, with the location of the four experiments denoted in red.

The number of collisions produced in accelerators is determined by the number of particles per bunch, the quality (emittance) of the bunch, the focussing accuracy of two colliding bunches and the bunch collision frequency. The number of collisions per unit area per second is defined as luminosity $\mathcal{L}$. The number of collisions per bunch crossing in the current LHC is about 20 for the design luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ [7]. The future High Luminosity LHC (HL-LHC, 2020) is planned to provide 140 collisions at a luminosity of $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ [7].

The heavy particle detection efficiency depends on many parameters. It is out of scope of this thesis to explain all contributions, but it must be noted that the study of heavy particles is difficult because they decay into secondary particles well before they reach the detectors. Secondary particle detection accuracies, detection efficiencies, trigger efficiencies and pile-up effects combined with many background events are limiting the collision reconstruction efficiency. Future accelerators like the International Linear Collider (figure 1.1.4) focus on reducing the background by colliding leptons at a well defined energy. Lepton collisions

are known for their clean events. In LHC the background is larger and many less interesting events are recorded.

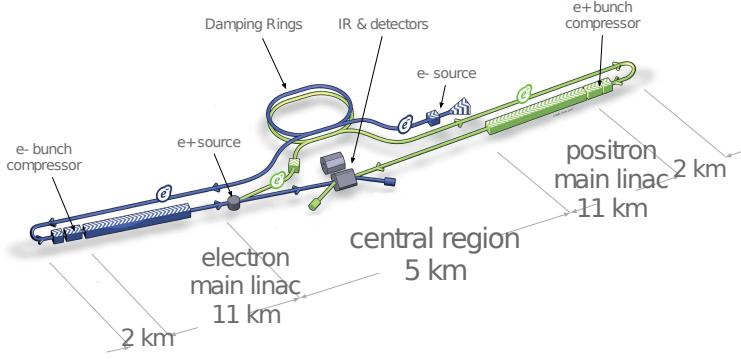


Figure 1.1.4: The layout of the proposed ILC [8].

The detection efficiency is predominantly determined by the performance of the subdetectors. The combination of high detection efficiencies and accurate measurements at high collision rates puts challenging limits on the detector specifications. In addition the detectors should be capable to operate stably in high radiation environments without being severely damaged. For detectors the radiation dose is divided in two types; ionising radiation expressed in Gray which equals the energy deposited per unit mass, non-ionising radiation which is expressed in 1 MeV neutron equivalent. The latter is dominant for most detectors.

Gaseous detectors suffer less from non-ionising radiation since the gas is hardly affected, still the read-out electronics is sensitive to this type of radiation. Ionising radiation however is a larger concern since it induces chemical processes in the gas which degrade the detector performance, this is referred to as ageing.

1.1.3 Detectors for High Energy Physics Experiments

In the LHC detectors are located at several interaction points around the ring. Each consists of several types of sub-detectors, that all have their own speciality. These types are discussed below.

Calorimetry

The kinetic energy of a particle can be measured by complete absorption. The total energy deposit is then a measure of the initial energy of the particle. Several energy loss processes are involved here depending on the initial energy, the detector material and particle type. When a particle traverses a calorimeter it produces a

shower of secondary particles that initiate showers in turn. The deposited energy is a measure of the initial particle energy. In addition to the measured energy, the shape of the shower gives an indication about the particle type.

Two types of calorimeters can be distinguished; electromagnetic and hadronic. Electromagnetic calorimeters are designed to measure the energy of particles that interact primarily via the electromagnetic interaction. In general such particles have a small penetration depth. Hadronic calorimeters measure particles that interact via the strong nuclear force.

Calorimeters can be homogeneous or sampled. In homogeneous calorimeters the entire detection volume contributes a signal and approximately all energy lost is measured. In sampled calorimeters scintillation material or gaseous or liquid ionisation chambers are sandwiched between the material that initiates a shower, in this way only a fraction of the lost energy is measured and the amount of scintillation light is proportional to the energy lost. In high energy physics sampled calorimeters are often preferred since they require less space.

Muon Spectrometry

After the calorimeters, in general only high energetic muons are left. The energy of muons can be measured by the calorimeter detectors, however it would need too much material to fully absorb their energy. Alternatively muon trackers behind the calorimeters measure the trajectories. The radius of the curvature due to the magnetic field is a measure of their energy.

Particle Identification

Particle identification is performed by the determination of the particle's mass. In general it is extracted from the particle's momentum that is measured by its deflection in the magnetic field. Given the momentum the mass can be extracted by measuring the velocity.

- Cherenkov Light; when the velocity of a charged particle moving through a dielectric medium exceeds the speed of light in that medium, a cone of Cherenkov light is produced with an angle that depends on its velocity.
- Transition Radiation; charged particles travelling from one medium into another with a different permittivity might give rise to photon emission with a probability and opening angle that depends on the particle velocity. The number of detected photons (X-rays) in a stack of traversed materials is therefore a measure of the particle velocity.
- Time of Flight; the time of flight of a particle can be measured using detectors at a known distance. From this the velocity can be extracted. However this method is not suited for velocities that approach the speed of light, since differences become too small.

- **Energy Loss;** the average energy loss per unit traversed distance in a material depends on the particle velocity. By counting the number of ionisations along a track, the velocity can be estimated.

Tracking

Close to the interaction point generally tracking detectors measure the particle trajectories with high precision such that primary and secondary vertices can be accurately reconstructed. In addition the charged particle momenta can be measured in presence of a magnetic field. It is a challenge to reduce the effect of scattering using thin, low density materials, while maintaining high resolutions, low power consumption and radiation hardness. Currently particle tracking near the interaction point is mostly done using semiconductor sensors read out with pixel chips or strips, however gaseous detectors can also be used.

Tracking with Gaseous Detectors

Gaseous detectors are frequently used in high energy physics experiments. They provide an economic way to perform relatively accurate tracking measurements over large areas. Their principle is based on a measurement of the trail of ionisations left in the gas by a traversing ionising particle. An electric field prevents recombination of the electrons and ions by drifting them towards the anode and the cathode. At the anode the electrons are multiplied and read out by an electrode.

GridPix is a gaseous detector that distinguishes itself from others in the way of electron multiplication combined with a pixel chip read-out. In addition GridPix can be compact with gas layer thicknesses down to 1 mm, while maintaining a superior position resolution. In GridPix the (2D) projection of the track on the anode is measured by the pixels, whereas the electron drift time, measured by a per pixel clock, gives the third dimension. GridPix does 3D position measurements of the emission position of drift electrons in the gas. The performance of gaseous detectors in general is predominantly determined by the gas mixture properties; the electron drift velocity and the electron diffusion. For the studies in this thesis the drift gas was CO₂:DME in a mixing ratio of about (50:50).

1.2 The ATLAS Experiment

At CERN the ATLAS experiment is one of the four high energy physics experiments in the LHC. The gaseous detector that is the subject of this thesis has been considered for several sub-detectors in ATLAS. Therefore the ATLAS detector is used to illustrate the principle of particle detection [9].

1.2.1 Scientific Goals

In the LHC protons are collided head-on at very high energies to study a wide range of particles and phenomena. ATLAS is one of the two general purpose experiments at the LHC. Since the Higgs particle is found, nowadays the study of its properties is one of main the physics goals of ATLAS. In addition it studies physics beyond the Standard Model. The ATLAS detector is used to measure particles created in ultra-relativistic proton-proton collisions. Reconstruction gives information about the physical processes that occurred during the collision.

1.2.2 The ATLAS Detector

The ATLAS detector (figure 1.2.1) has been built around the interaction point. It consists of four major components: inner tracker; calorimeter; muon spectrometer; magnet system. Each component has its own speciality to measure particle properties, as described below [10]. The dimensions and resolutions of the components are mentioned to get feeling about the sizes and accuracies.

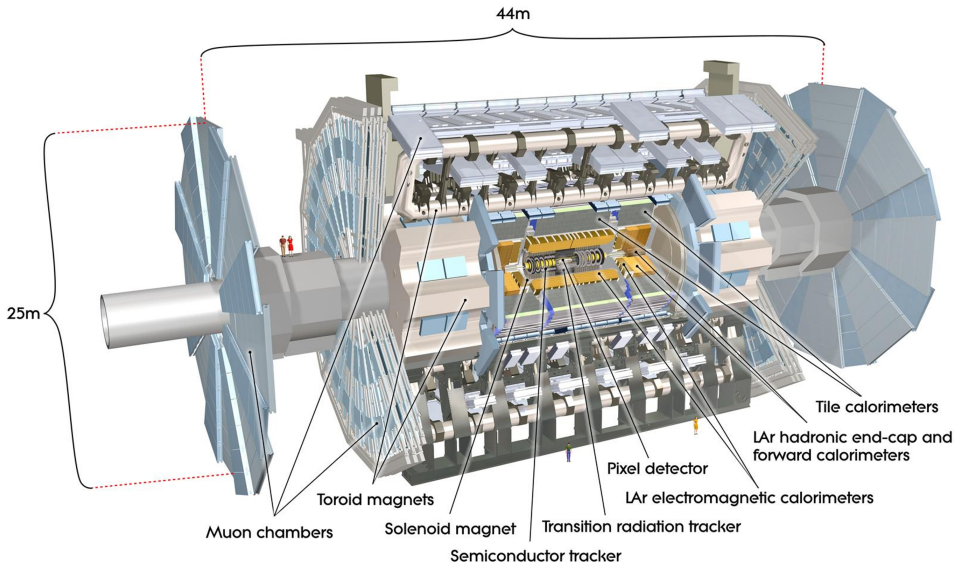


Figure 1.2.1: Sketch of the ATLAS detector at CERN.

Inner Detector

Close to the interaction point tracking detectors measure the particle trajectories with high precision such that primary and secondary vertices can be accurately

reconstructed. Figure 1.2.2 shows a quadrant of the ATLAS inner detector. From the centre outwards, the inner tracker system is composed of pixel chips, silicon strips (SCT) and Transition Radiation straw Tubes (TRT). The design of the inner tracker is particularly challenging since the detectors should have sufficient low mass not to disturb the traversing particle too much and it should be able to withstand a particle flux of $1 \text{ GHz}/\text{cm}^2$ which drops to about $1 \text{ MHz}/\text{cm}^2$ at the edge of the inner tracker [7]. Typically the inner pixels receive a challenging radiation dose of 10^{16} 1 MeV neutron equivalent per cm^2 [7].

The pixel barrel is composed of three concentric barrels. In addition there are three disks on either side referred to as pixel end-caps. Every pixel-chip is connected with a doped silicon sensor with thickness of $250 \mu\text{m}$. The nominal pixel size is $50 \times 400 \mu\text{m}^2$, leading to a total of 80 million channels for the barrel and both the end caps. The intrinsic accuracy of the pixels is approximately $10 \mu\text{m}$ in the bending plane and $115 \mu\text{m}$ along the pixel.

A silicon micro-strip detector (SCT) surrounds the pixel system. It consists of a barrel with four concentric cylindrical layers in the central region and end-caps of nine disks on either side. The 6.3 million silicon strips have a pitch of $80 \mu\text{m}$ and the sensor thickness is about $285 \mu\text{m}$. The intrinsic resolution of the strips is approximately $580 \mu\text{m}$ along and $17 \mu\text{m}$ in the plane perpendicular to the beam line.

A straw tube detector (TRT) surrounds the SCT. It contains 73 layers of tubes interleaved with fibres for the barrel and 160 planes interleaved with foils for the end-cap. The tubes have a diameter of 4 mm , the anodes are a $31 \mu\text{m}$ diameter tungsten wire plated with $0.5 \mu\text{m}$ gold. The tubes are flushed with a mixture containing 70% xenon, 27% CO_2 and 3% oxygen. The intrinsic resolution is $130 \mu\text{m}$.

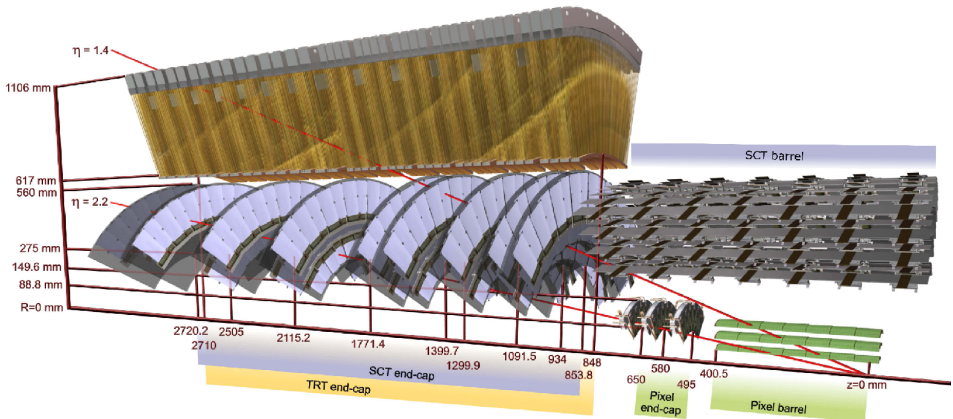


Figure 1.2.2: Quadrant of the ATLAS inner detector. The interaction point is located at $z = 0$ and is surrounded by pixels chips, silicon strips and transition radiation tubes.

Calorimeter System

The ATLAS calorimeter system (figure 1.2.3) can distinguish electromagnetic from hadronic showers and it limits punch-through into the muon system.

The ATLAS electromagnetic (EM) barrel calorimeter consists of two identical half barrels. The EM calorimeter is made of liquid argon sandwiched by accordion shaped lead plates with Kapton electrodes. Half a barrel is made of 1024 slices interleaved with read-out electrodes. The principle is based on a shower of particles causing ionisations in the liquid argon. Collection of this charge on the electrodes gives the signal. The size of the drift gap is 2.1 mm on each side of the electrode. The total EM barrel has 101.000 read-out channels. The length of a half-barrel is 3.2 m with inner and outer radii of 2.8 m and 4.0 m. Both end-caps have a thickness of 0.63 m and inner and outer radii of 0.33 m and 2.1 m.

The hadronic calorimeter surrounds the EM calorimeter and has three parts: the tile calorimeter; the end-cap hadronic calorimeter (HEC); and the liquid argon forward calorimeter (FCal). The tile calorimeter uses steel as the absorber and plastic scintillator as active medium. It consists of a central barrel and two extended barrels. The scintillators are optically connected to photomultiplier tubes by fibres. The HEC uses copper as absorber material together with liquid argon as active material. The FCal consists of three parts; one electromagnetic calorimeter that uses copper as absorber and two hadronic calorimeters using tungsten to cope with particles with larger penetration depths.

Muon Spectrometer and Magnet System

Muons with sufficient energy are not stopped by a calorimeter; hence they can be identified with detectors behind the calorimeters. In the ATLAS muon spectrometer (figure 1.2.1), the energy of muons is determined by the measurement of the radius of its curvature due to deflection in the magnetic field.

The magnet system of ATLAS consists of four magnets; the central solenoid, the barrel toroid and two end-cap toroids. The Monitored Drift Tubes (MDTs) and the cathode strip chambers (CSCs) measure the particle trajectories.

The MDTs consist of a tube with a diameter of approximately 30 mm flushed with Ar:CO₂ (93:7) gas. The electrons resulting from interactions of a traversing ionising particle are amplified near a thin tungsten-rhenium wire centred in the tube. A single muon drift tube has a resolution of 80 μm .

Cathode-Strip Chambers (CSCs) are multi-wire proportional chambers used in the forward region of the innermost tracking layer, because of their high rate capability and good time resolution. The CSCs are flushed with Ar/CO₂ (80:20) gas. The distance between the wires and the cathode is about 2.5 mm. The CSCs have a resolution of about 60 μm .

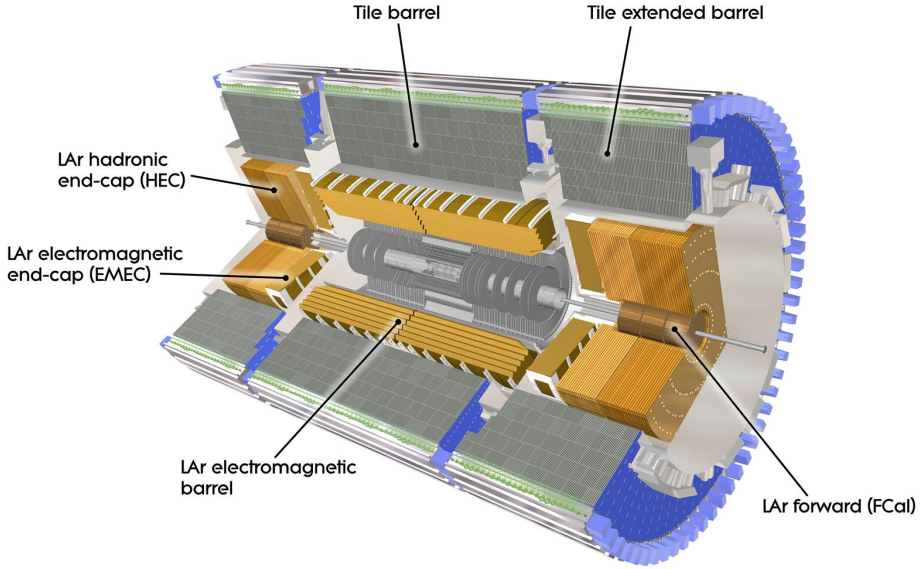


Figure 1.2.3: Drawing of the ATLAS calorimeter system.

1.3 Potential GridPix Applications in ATLAS

The upgrade from LHC to HL-LHC as planned for 2020 opens the possibility for new detector technologies to be used in ATLAS. GridPix is a new detector in R&D phase, although the technology in current stage is far from mature, a number of applications in ATLAS can be considered. This section discusses two kinds of applications; Gossip, GridPix as ATLAS inner tracker, and GasPix, a novel L1 trigger system.

1.3.1 Gossip

In 2009 a GridPix with a 1 mm drift gap (“Gossip”) was proposed as inner tracker for ATLAS [11]. Because of several complications, the technology did not evolve sufficiently fast and the project is dormant. Although there are some delays in R&D the novel application is still an interesting thought.

Requirements

In general the application of GridPix as an inner tracker demands:

1. **High rate track capability;** that is guaranteed if all charge from a track is collected in one bunch crossing (25 ns). This can be achieved in two ways; fast drift velocity and/or small drift distance. The drift velocity can be increased by increasing the electric field or by using a so-called "fast" gas. Fast gases in general also have high diffusion affecting position; a better option is to choose for a high drift field combined with a small drift distance. In CO₂:DME (50:50) at 6 kV/cm, the drift velocity is approximately 50 $\mu\text{m}/\text{ns}$. With a drift gap of 1 mm all electrons are expected to be recorded within one bunch crossing 25 ns. Using a GridPix with a planned clock frequency of 640 MHz (currently it is 100 MHz) sufficient time information is available to accurately measure the position and angle of the track. In High Luminosity LHC (HL-LHC), the charged particle rate of the innermost detectors is approximately 1 GHz/cm². Each Gossip has to record $\mathcal{O}(10)$ tracks per bunch crossing which results in $\mathcal{O}(100)$ hit pixels per chip. Due to the high granularity in the chip plane ($x - y$) and in addition the information in the drift direction (z), 10 tracks can easily be distinguished.
2. **High radiation tolerance;** The detection medium of Gossip is continuously exchanged, therefore the (non-ionising) radiation tolerance is limited by the radiation tolerance of the read-out chip, which should be studied for chips like Timepix. However many ionisations in the gas might enhance ageing of the gas leading to large polymers sticking to the electrodes, eventually this degrades the performance of the detector. The latter effect is likely to be present in molecular gases like CO₂:DME (50:50), however it is not studied in detail and therefore still an open issue.
3. **Accurate position resolution;** In chapter 5 it is explained that Gossip measures track segments. As will be shown, the track segment position resolution of a Gossip has been proven to be 10 μm in the plane of the detector, which is sufficient for a tracking detector.
4. **Low mass detectors;** The GridPixes as are used in chapter 5 have a radiation length of approximately 2%. This can be minimised by reducing the thickness of the PCB, the thickness of the read-out chip and glue. The minimised radiation length of a GridPix is expected to be about 0.7%, including mechanics and cooling [11], which assures a small effect of multiple scattering.
5. **High efficiency;** The track detection efficiency is basically determined by the probability for a traversing particle not to leave any ionisation in 1 mm gas. As discussed in chapter 5 this is >99%. However for reconstruction of a track at least three hits are required. The probability to produce three or more ionisations in the gas is about 97% as will be shown in chapter 5.

6. **Low cost.** It is difficult to give a cost estimation of GridPix since it depends on production yield, which is currently not stable. The costs of the wafer post-processing is expensive but depends on the quantities that are ordered.

Advantages

As has been shown GridPix meets some of requirements for application as inner tracker, while others should be studied/improved. In addition GridPix does not suffer too much from dead pixels since the resolution goes with $\sqrt{n}$ and the mean number of hit pixels is about 6. Furthermore GridPix measures track segments that contain direction information. As is shown in chapter 5 the angular resolution is approximately a few degrees. With a reduction of the effect of time-walk in a recently released successor this resolution is expected to be improved. The angular information is not only useful for trigger purposes, it also makes track finding algorithms more efficient. In addition the third (z) component acts as an additional tool to disentangle crossing tracks, something that cannot be achieved in a stand-alone detector that measures projections in 2D.

GridPix measures individual electrons, therefore the number of ionisations of a traversing particle can be determined. The number of ionisations is a measurement of the energy loss that can be used for particle identification.

Disadvantages

The major concern of GridPix is breakdown due to discharges in the high electric field amplification region. Since discharges in general cannot be avoided, several mechanisms are considered to prevent any lethal damage to the chip. The high resistivity protection layer has been proven to be reliable and robust in the past. However recent efforts to produce such layers on wafer scale were only partly successful. Other ideas are related to a double protection layer, in which the grid is also covered with Silicon rich Silicon Nitride, or an additional electrode surrounding the pixels acting as a charge drain, such that high currents do not enter the sensitive pixel circuitry. Clearly this issue must be solved to continue the project.

Another concern is the effect of ageing. The large molecules that are used as drift gas in Gossip tend to dissociate. In high electric fields the resulting radical molecules tend to stick to impurities that will eventually result in a thin layer of insulating materials on the boundaries of the amplification gap. The charging up of this layer reduces the amplification field thereby affecting the electron detection efficiency and the spatial resolutions. Currently it is unknown how large the effect of ageing in GridPix will be. Since many parameters are involved this effect should be studied empirically.

Outlook

The application of GridPix as an inner tracker detector is challenging. The difficulties in making a proper discharge protection are a major concern. Reliability is one of the main reasons of the lack of interest in GridPix. Future concerns are related to ageing and mass production. However when these problems somehow can be solved GridPix will be very interesting to use in experiments.

1.3.2 GridPix as Level 1 Trigger

Experiments like ATLAS are particular interested in high momentum electrons to measure Higgs events. A high momentum electron L1 trigger can be used to select such events from background. Specifically in the future HL-LHC, where the track density is large, the data acquisition system would benefit from such a trigger.

Principle

High energy particles are hardly affected by the magnetic field; they tend to give straight tracks that are pointed to the primary vertex. This property can be used to trigger on, requiring accurate angle measurements to determine the momentum. A subsequent detector can distinguish high energy electrons from high energy pions.

The GasPix project [12] proposes a plane of GridPix detectors to be placed at the outer radii of the Inner Tracker, at about 1 meter distance from the beam pipe. The GridPix detectors have a drift gap of approximately 1 cm. The position and angle of high momentum particles created in the primary vertex are measured by a GridPix. The positional resolution is approximately 10 μm . The line through the measured position and the primary vertex determines the track direction in case of infinite momentum. The incident angle of 20 GeV particles measured by GridPix will deviate from this line by approximately the angular resolution of a GridPix, about 10 mrad. The principle is illustrated by 1.3.1. In this way a single GridPix can select >20 GeV particles.

An additional measurement of particle identification (PID) is required to determine whether the particle is an electron. The positional and angular information from the GridPix can be used to determine the position of the calorimeter the particle traversed, such that the particle can be identified. Hence the combined momentum-PID information can be used to trigger on the event.

Requirements

For HL-LHC a fast data rate is required to avoid pile-up. The expected electron collection time of a GasPix detector is below 200 ns. To save valuable time it is es-

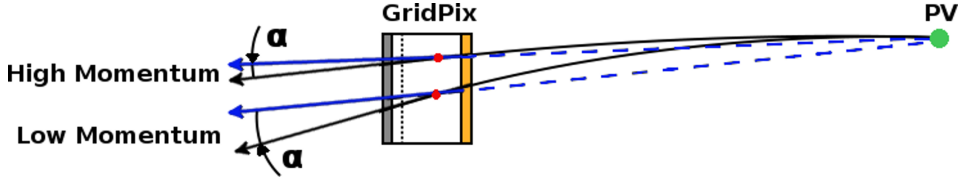


Figure 1.3.1: An illustration of the triggering principle for a low and a high momentum track. The primary vertex is indicated in green, the measured positions of GridPix in red. The particle trajectories are indicated in black, the “primary vertex” line in blue. The arrows are the reconstructed tracks given by GridPix. It shows that when α is small the traversing particle was a high momentum track.

essential that the GridPix determines the track angles and positions on-chip, which requires an intelligent front-end to do a basic track fit. It seems that the calculation of this information takes only a small fraction of the electron collection time. Clearly the current TimePixes are not suited for this application, therefore the feasibility of the novel idea to implement fitting intelligence on a read-out chip should be studied.

Additional Benefits

The positional but specifically the angular information as obtained by GridPix can be used to avoid mismatching of a detector in a track fit, which makes the track reconstruction algorithm more efficient. In addition the novel idea of a layer of transition radiator in front of GridPix combined with a high-Z drift-gas like xenon is considered to do simultaneous tracking and X-ray measurements to distinguish electrons [12].

Outlook

The application of GridPix as a Level 1 trigger is a promising way to significantly reduce the background events in ATLAS. The proof-of-principle has been established. Since this application implies many efforts, its benefits for ATLAS should be studied with priority. In addition the GridPix reliability should be improved to take away concerns from the community.

1.4 A Medical Application: GridPix in Proton Radiography

The properties of GridPix detectors allows application in other fields than high energy physics. Currently Nikhef together with KVI Groningen is investigating the feasibility of GridPix in proton radiography.

1.4.1 Proton Therapy

A common method to treat cancer is radiation therapy. By irradiation of the tumour tissue the aim is to damage or destroy the DNA of cancer cells leading to reduction of differentiation or cellular death. Exposure to radiation causes ionisation in the irradiated tissue, which can lead to direct DNA damage or indirect damage where free radicals are created which damage the DNA.

A conventional way of radiotherapy is tumour irradiation by X-rays, that are capable to easily penetrate through the body to reach the tumour. However there are several limitations to radiation with X-rays:

- The energy loss is described by the photon curve in figure 1.4.1. It suggests a significant part of the X-rays is absorbed before and after the tumour, leading to undesired damage to healthy tissue. The effect of X-ray radiation on healthy tissue is reduced by spreading the treatment over time (so-called fractionation), such that healthy tissue can recover and tumour cells that were in radio-resistant phase to cycle into a sensitive phase. This results in long total treatment times, which is undesired for patients and hospitals.
- The (indirect) damage due to X-rays is caused by creation of free radicals predominantly by ionisation of oxygen in the tissue. However hypoxic tumours outgrow their blood supply, leading to a lack of oxygen which makes them less sensitive to X-ray radiation. Fractionation may reoxygenate the hypoxic cells improving the efficiency to kill tumour cells.
- At moderate energies X-rays undergo Compton scattering; a photon knocks out electrons from one of the atomic shells, part of the initial energy is transferred to shell electrons, the remaining energy is released by photon emission. The secondary photons result in additional radiation dose that is deposited elsewhere.

A novel way of radiation therapy is hadron therapy where proton therapy [13] is currently most feasible. The fundamental difference with X-rays is that protons undergo many interactions while traversing the body. The majority of their energy is lost in the so-called Bragg peak which has a width of a few millimetres.

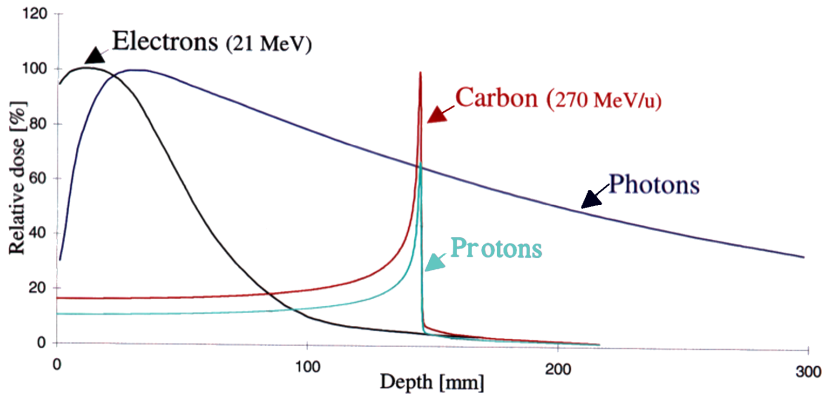


Figure 1.4.1: Normalised dose deposition in tissue as function of the penetration depth for several types of radiation. The Bragg peaks of proton and carbon ions is visible at about 150 mm.

The advantage with respect to X-rays is that the dose deposition is very well localised and healthy tissue is less affected, therefore the long total treatment time due to fractionation can be reduced. The scattering of protons is larger than for X-rays, but is still small enough to direct them precisely to the tumour. The energy transferred from the ionising particle to the tissue per traversed unit distance is referred to as Linear Energy Transfer (LET). Hadrons in general have a larger LET than photons, leading to more efficient direct damage to tumour cells which makes hadron therapy more interesting for treatment of hypoxic tumours.

1.4.2 GridPix for Proton Radiography

A challenge of proton therapy is to position the Bragg peak inside the tumour. This position depends on the stopping power in the traversed medium. This must be measured before treatment, to tune the beam such that the Bragg peak is positioned inside the tumour tissue.

In conventional radiation therapy the radio density of the tissue tumour and the tissue around is imaged before treatment. This is done with Computed Tomography (CT) scans, but it can also include magnetic resonance imaging (MRI), positron emission tomography (PET), and ultrasound scans. In this way the absolute position of the tumour is extracted with respect to the scan apparatus. Since often patients are moved to another room to perform radiation therapy, the alignment is lost and only relative position of the tumour is known. In addition tumours might be displaced because of a different posture. These problems might

be solved by performing the scans just before or during the radiation therapy and by conserving the patients posture.

Conventional types of imaging can be used to estimate the stopping power to tune the proton energy such that the Bragg peak is located inside the tumour. However the conversion of the radio density from X-rays scans to stopping power, introduces an inherent uncertainty of up to 3% [14]. To reduce this uncertainty, an alternative approach is imaging with protons themselves.

This method requires higher proton energies, such that the Bragg peak is located outside the patient. When the position and angle are measured proton-by-proton before and after traversing the patient a most likely path can be calculated. The measurement of the proton energy gives information about the energy lost along its path. It has been reported that the path of a proton inside the patient can be predicted with sub-mm precision [15]. Figure 1.4.2ab shows a picture of a ballpoint taken with protons using two dose-depth calibration-curves (e.g. different proton energies). Comparison with the X-ray picture in 1.4.2c illustrates a superior positional resolution of the X-ray picture, however the proton pictures show parts of the ballpoint are invisible with X-rays.

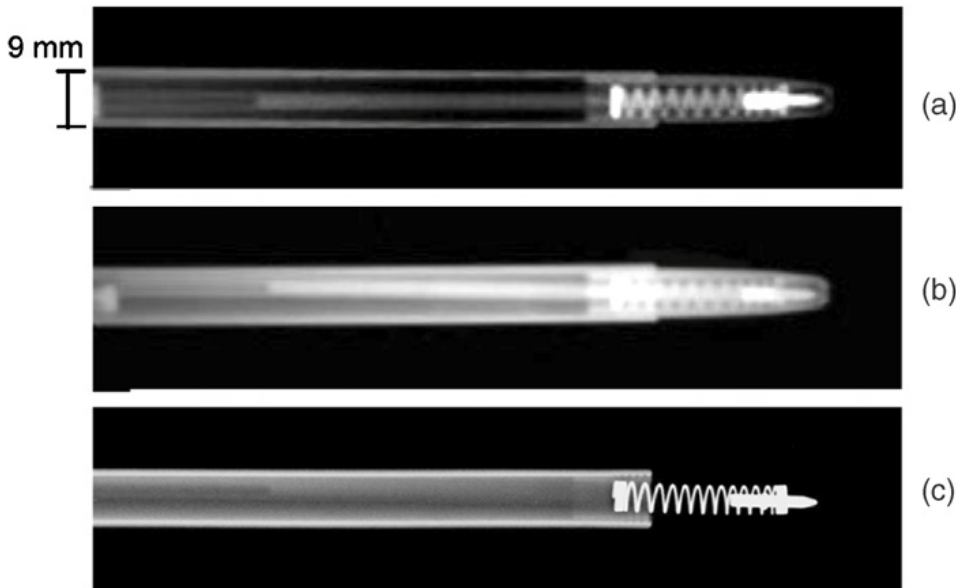


Figure 1.4.2: An image of a ballpoint taken with protons with two different dose-depth calibration curves in a) and b). For comparison c) shows an X-ray image [16].

GridPix detectors are proposed to be used in proton therapy [17]. The performance of GridPix detectors located before and after the patient combined with a

calorimeter are currently studied [18] [19]. Figure 1.4.3 shows the experimental set-up of a feasibility test done in 2011. The light weight detectors with superior positional and angular resolutions are novel devices, that promise to be of great value for proton CT.

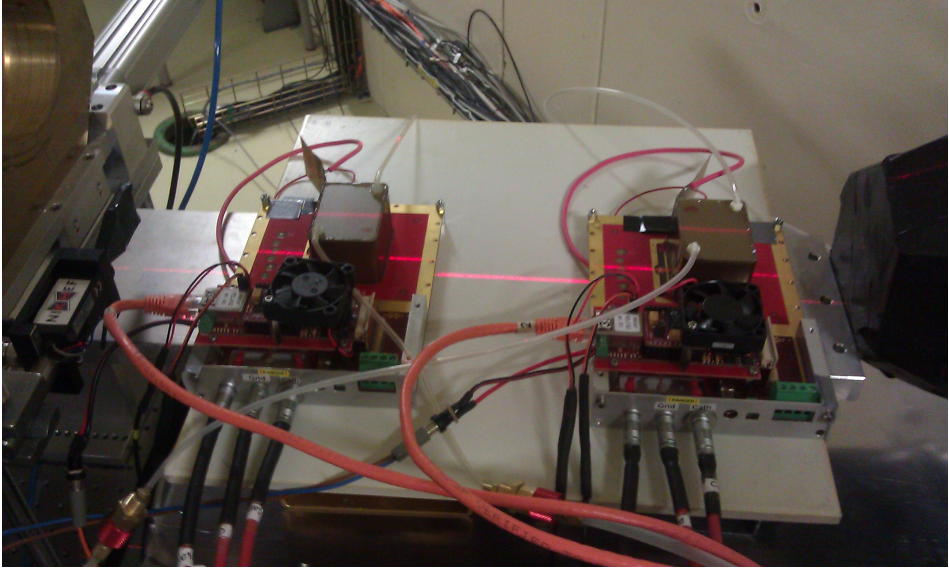


Figure 1.4.3: The experimental set-up of two GridPixes in a proton beam at KVI Groningen. The beam pipe is visible at the top-left, the calorimeter in black at centre-right. Two GridPixes are mounted in series. The laser beam indicates the direction of the beam [20].

1.4.3 Outlook

Besides the established challenges of GridPix that should be solved for clinical use as described in the previous chapter, in the medical field an additional requirement is imaging time. For proton imaging it is found that $\mathcal{O}(100)$ proton per mm^3 are required for a good quality image [15], i.e. $\mathcal{O}(10^8)$ for a complete head. To limit imaging time to approximately 6 minutes the detector should be able to cope with a 2 MHz proton rate. Not only the data rate should be increased to 100 kHz assuming about 20 tracks per frame. Also pile-up should be avoided by requiring electrons to be recorded within approximately $10 \mu\text{s}$, which requires high fields or fast gases. Furthermore the large data rate demands a powerful algorithm to efficiently analyse the data that should be achieved while the uncomfortably secured patient is waiting for his treatment. All challenges described here can be over-

come, however much effort is needed to bring this to a practical method. Current studies are related to the proof-of-principle.

2

Gaseous Detectors

Many different gaseous detectors were invented in the last century; the first one was the well known Geiger counter in 1908 [21], that was able to count the number of traversing ionising particles. A more evolved version was invented by Charpak in 1968 [22]. His multi-wire proportional chamber could additionally measure the one dimensional position of traversing ionising particles. Since the signal is proportional to the number of initial ionisations, it can be used to determine the particle velocity and hence type. A major breakthrough came with the proposal of the Time Projection Chamber (TPC) by Nygren [23] in 1974. In a TPC the magnetic field and the electric field are parallel and diffusion is reduced significantly. In this way the spatial resolutions of drift chamber are less affected by diffusion and the amount of electronics could be reduced, which led to significant cost reduction.

2.1 Principle of Gaseous Drift Detectors

An ionising particle interacts with the gaseous medium by ionising gas molecules along its trajectory, leaving a trail of ion-electron pairs. The released electron-ion pairs are pulled apart by a moderate electric field drifting the ions to the cathode and the electrons to the anode, see figure 2.1.1. The geometry of the electrodes in a drift chamber is made such that the field near the anode increases. Subsequently, when the primary electrons approach the anode they gain enough kinetic energy to ionise gas molecules along their paths. This multiplication process eventually results in charges that are large enough to be recorded by read-out electrodes.

Since electrons follow the field lines and the geometry of the field is precisely known, the position of the hit electrode and the measurement of the drift time can be used to reconstruct the three-dimensional position of where the primary ionisation occurred. When this process is done simultaneously for several primary ionisations corresponding to the same ionising particle, the particle trajectory can be reconstructed.

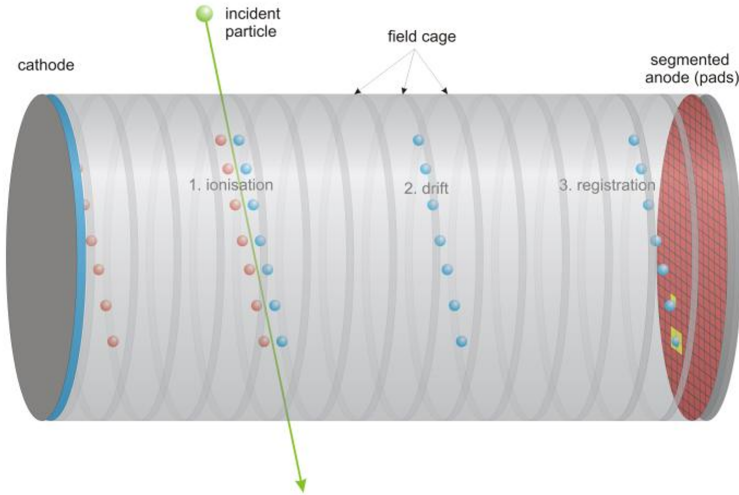


Figure 2.1.1: The principle of a classical drift chamber. In an electric field electrons as emitted from the gas molecules by an incident particle drift towards the read-out anode where the projected position is measured. The drift time is proportional to the drift length.

2.2 Types of Amplification

A large variety of electrode geometries can be used to create the multiplication process. In the traditional approach the radial field around anode wires provides an easy way to increase the electric field to start a multiplication process. Wires have been commonly used in the past in drift chambers. A basic wire chamber only measures (2D) particle trajectories in a plane parallel to the wires, since the position along the wire cannot be extracted. The principle of a wire chamber can be extended to three dimensions by using a plane of sensing electrodes parallel to the wires, such that the induced charge of the amplification on the sensing electrodes can be used to determine the position of the multiplication along the wire. The sensing electrodes can be wires or a plane of pads or strips.

In modern high energy physics experiments high spatial resolutions and high rate capability is often required. Therefore the geometry of the detector has been the subject of many studies. Initially wires in many different geometries combined or not with read-out pads, were used as amplification electrodes. As technology evolved better resolutions came in reach. Since wires had their limits, new detector geometries and read-out were developed by replacing the wires with meshes of different kinds; so-called Micro Pattern Gaseous Detectors.

2.3 Read-Out

The multiplication process induces a charge pulse on the read-out electrode that can be either the electrode at which the avalanche develops to or an electrode that measures the induced signal from a distance. In drift chambers the Time-of-Arrival (ToA) of the electrons in the avalanche region is recorded in a Time to Digital Converter (TDC). An Analogue to Digital Converter can also be used to measure the charge. This can be used to improve the spatial resolution.

2.4 Performance of Gaseous Detectors

The performance of gaseous detectors is a trade-off of a large variety of desires:

- Positional and angular resolutions should be as good as reasonably possible;
- The track detection efficiency should be high, preferably close to 100%;
- The specific energy loss of traversing particles in the detectors can be determined in terms of the number of ionisations. Coupled with the momentum of the particle this can be used to determine the particle identity;
- Minimal radiation length, the particle should hardly be disturbed while traversing the detectors in order not to compromise the measurements performed beyond the tracker;
- High radiation hardness, at the extreme conditions in which tracking detectors are operated a long lifetime is desired;
- Low cost.

2.5 Detector Types

The modern kind of drift chambers are called Micro Pattern Gaseous Detectors (MPGDs). Currently the Gas Electron Multiplier (GEM) and the Micromegas (MICROMesh GAS) are the most promising detectors.

GEM

GEMs were proposed by Sauli in 1996 [24]. A thin polymer sheet sandwiched between two copper layers makes a GEM foil (figure 2.5.1a). A matrix of holes is made in the foil by photo-lithography and acid etching processes. The thickness of a typical GEM foil is about $(60\text{--}70)\text{ }\mu\text{m}$, with hole diameters of about $(30\text{--}50)\text{ }\mu\text{m}$. The primary electrons are multiplied in the holes by a field due to the potential difference between the two copper layers (figure 2.5.1b). Since the resulting number of electrons after multiplication is not sufficient with this technology, a stack of two or three foils are often used as additional amplification stages.

GEMs are commonly read out with a segmented read-out plane like pads or strips with a width of a few millimetres. Multiple strips or pads measure the induced current and track positions are measured accurately using a centre of gravity method.

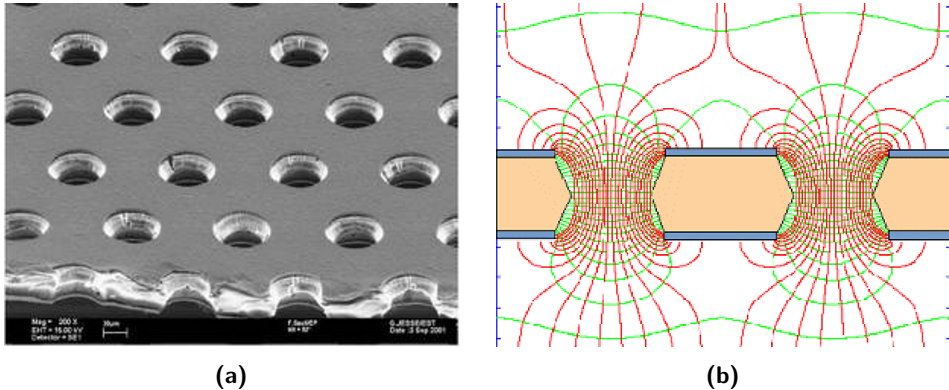


Figure 2.5.1: a) A picture of a GEM foil with Kapton foil sandwiched by copper layers. b) The electric field in a GEM detector, amplification takes place in the high electric fields in the holes.

Micromegas

Micromegas is invented by Giomataris in 1996 [25]. A thin metal mesh is located at a distance of about $(40\text{--}100)\text{ }\mu\text{m}$ from the anode supported by insulating spacers, see figure 2.5.2a. The anode and the mesh define the amplification region of the detector. At high fields (figure 2.5.2b) of about $(40\text{--}100)\text{ kV/cm}$ sufficient charge is produced to be read out by either strips, pads or pixel chips. The pitch of the holes $(20\text{--}50)\text{ }\mu\text{m}$ is smaller than the size of the read-out pad. For the small amplification gaps as used in Micromegas variations in the mesh might result in large variations of the gain eventually resulting in discharges. However with the right

choice of gas and amplification distance the detector is approximately insensitive for variations [25].

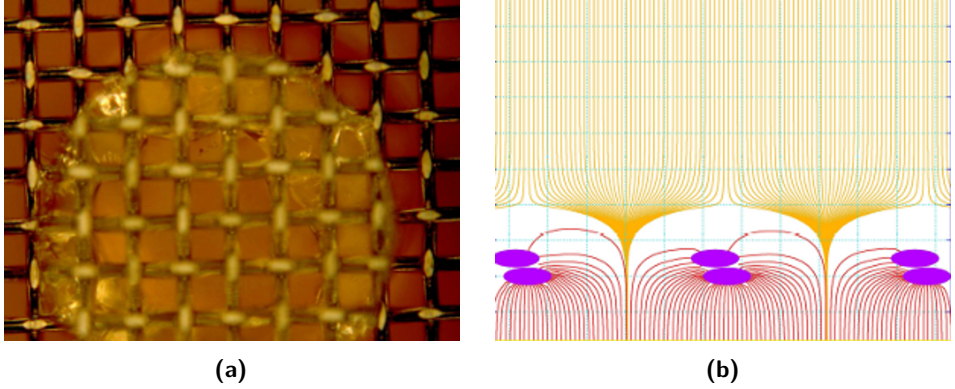


Figure 2.5.2: a) A picture of a Micromegas mesh, with an insulating pillar in the centre. b) The electric field in a Micromegas detector [26], the amplification takes place below the mesh. This picture is purely illustrative, the strength of the field cannot be extracted.

The GridPix detector is the subject of this thesis. GridPix is an improved type of Micromegas. It will be discussed in detail in the next section.

2.6 GridPix

A GridPix is a Micromegas type of detector. Similar to Micromegas it has a conductive grid and insulating supporting pillars. The detector is read out with a fine granularity pixel chip. A fundamental difference with Micromegas is that every hole of the grid is aligned to one pixel input pad, requiring pillars with a diameter smaller than the pixel pitch. To solve the issue of misalignment the grid is integrated on top of the chip by wafer post-processing techniques, assuring alignment, a well defined amplification gap size and a high quality grid. Since the avalanche charge of a single primary electron is sufficient to be measured by the pixel, the single electron detection efficiency approaches 100%. The drift time of primary electrons is measured by a per-pixel oscillator. The chip electronics is extremely sensitive, allowing low-noise running at thresholds of approximately 500 electrons input charge. Unfortunately large charges, like discharges, can be lethal for the pixel electronics. Therefore a high-resistive, silicon-rich silicon-nitride protection layer covers the full chip surface to quench discharges in an early stage.

Note that GridPix is the general name of this detector. Specific kinds of GridPixes as are used in this thesis are called Gossip, which is a GridPix with a small

drift gap (about 1 mm), and GasPix, which has a large drift gap (several mm up to several cm). More detailed information about the kinds of GridPixes can be found in the related sections.

2.6.1 GridPix Geometry

In the R&D phase GridPixes with many geometries were produced. Figure 2.6.1a shows a Scanning Electron Microscope (SEM) picture of a GridPix with a part of the grid removed. The dimensions of the separate parts in the GridPix are indicated with the arrows. A dyke structure is added at the four edges of the GridPix as a mechanical termination of the grid. Figure 2.6.1b shows the corner of the chip where the outer 10 pixels are covered by the SU-8 dyke, and are therefore inactive. The grid ends about $110\text{ }\mu\text{m}$ before the edge of the dyke to reduce edge leakage currents. In addition the picture shows a gap between two perpendicular dykes. Each edge of the dyke has another two spaces at $1/3$ and $2/3$ of the side. These gaps were intended to improve the drainage of solutions during the production process, but are no longer needed for this [27].

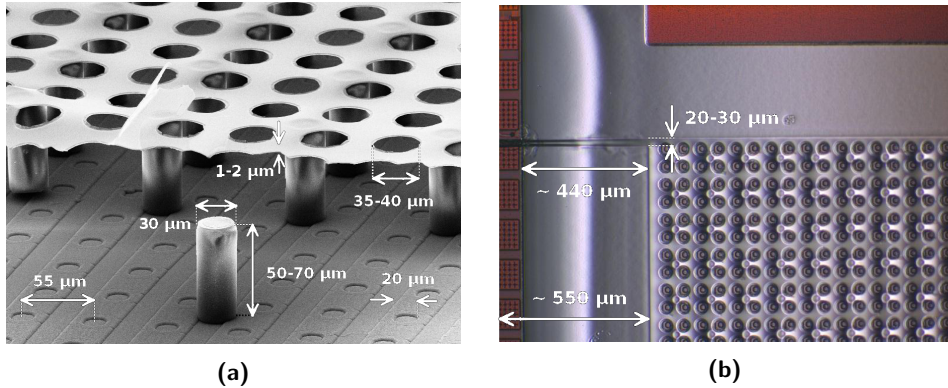


Figure 2.6.1: a) A SEM picture of a GridPix with a ripped-off grid. The dimensions of the separate parts are indicated by the arrows. b) A SEM picture of the corner of the chip, the SU-8 dykes are located below the grid at the edges of the chip.

2.6.2 CMOS Read-Out

A GridPix detector is read-out with a charge sensitive CMOS pixel-chip. Currently it is read out by a TimePix-1 chip [28], previously also Gossipo-2 [29], MediPix-2 [30] and PSI-46 [31] were used, however the latter two are not suited to measure drift time. Timepix-1 has 256×256 pixels with a pitch of $55\text{ }\mu\text{m}$. The chip

is developed by the Medipix collaboration and is based on the Medipix-2 design. Timepix-1 has a noise floor of about 108 electrons; a minimum threshold of about 500 electrons is required for proper operation.

Figure 2.6.2 shows a simplified diagram of the analogue front-end of a pixel in Timepix-1. The output of the discriminator is directed towards the digital part which contains a 100 MHz oscillator that can be used to:

- Measure the amount of charge in terms of Time over Threshold (ToT-mode); or
- Measure the time at which a signal on a pixel goes over threshold (ToA-mode); or
- Count the amount of times that a signal on a pixel exceeds the threshold (MediPix-mode).

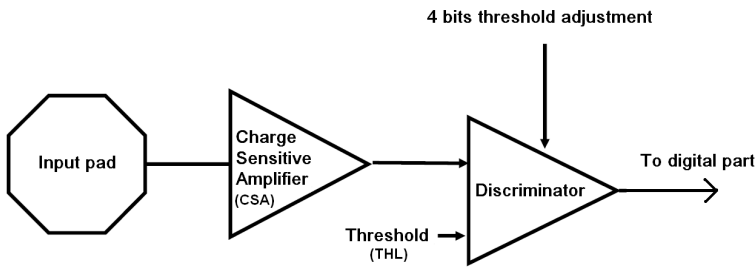


Figure 2.6.2: The (simplified) analogue part of a pixel in Timepix-1 [32].

2.6.3 Protection Layer

Currently GridPix detectors based on TimePix-1 chips have to be run at high gain to minimise the effect of time-walk, which dominates the z resolution (chapter 5). The high field needed can give rise to sparks, especially in the presence of heavily ionising particles such as low energy alphas. These sparks can damage the sensitive read-out electronics and/or damage the aluminium grid. This damage can be prevented by coating the chip surface with a resistive layer, which charges up at the start of a discharge, quenching the discharge and spreading it over several pixels.

During operation the avalanche charge deposited on the protection layer slowly drains away via the pixel pads. The relaxation time of the protection layer is a function of the resistance of the layer, that can be tuned to the expected ionisation rate in GridPix. When the resistance is too high the layer does not discharge fast

enough at high rates and the gas gain drops. The current protection layer is made of Silicon Rich silicon Nitride (SiRN) for reasons of robustness and resistivity that can be tuned easily. It is believed that a resistance of about $10^{13} \Omega \text{ cm}$ is sufficient for current purposes, more extreme conditions with particle rates of 1 GHz/cm^2 require $10^9 \Omega \text{ cm}$ [32]. The current thickness is $8 \mu\text{m}$, but thinner protection layers are considered [17].

2.6.4 Production

From 2008 to 2010 GridPixes were made on a 3×3 chip array. To meet the demands in 2010 the first attempts to full 8" wafers were made. The production technology is similar and it is described below [27, 33]:

1. The bare 8" TimePix wafer (blue) contains 107 chips. The aluminium pixels are indicated in grey, the silicon nitride passivation layer in green. Prior to processing the wafer is probed to track chips with an electronic failure, and cleaned to improve adhesion and quality of the deposited layers. In addition the wafer is inspected on defects and remaining dust.



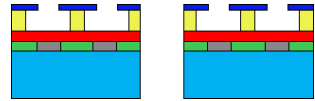
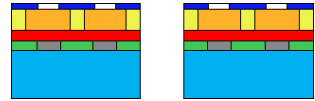
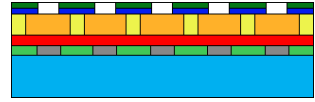
2. A high resistive SiRN protection layer (red) is deposited on the whole wafer surface in four layers of about $2 \mu\text{m}$. A final thickness of about $8 \mu\text{m}$ is believed to be sufficient to quench discharges. It is important to avoid SiRN deposition on the wire bond pads to guarantee electrical connection. Therefore the bonding pads are covered with polyimide first. After SiRN deposition, the SiRN on top of the wirebond pads is removed by dissolving the polyimide (lift-off technique).



3. The wafer surface is covered with SU-8 photo-resist (orange) by spin coating. The general thickness of the layer is about $50\text{--}70 \mu\text{m}$.



4. Exposure to UV light initiates cross linking of the SU-8, in this way the pillar structure is made (yellow).
5. A layer of about 1 μm thick aluminium is sputtered on top of the SU-8 structure (blue).
6. A photo-resist (dark green) is applied on top of the aluminium. Exposure to UV light through a mask defines the position of the grid holes (white). Subsequently the holes are made by wet chemical etching and the photo-resist is removed.
7. The wafer is diced into single chips with a saw. Since the SU-8 is not yet developed the structure is still sufficiently robust to survive the dicing.
8. Finally, the SU-8 is dissolved through the holes leaving just the pillars. The GridPix chips are visually inspected and probed selecting the good ones for assembly into detectors.



2.6.5 Challenges

From 2008 to 2010 GridPixes have been produced on a 3×3 array at MESA+. As will be discussed in chapter 5 the last series made in 2010 seemed to successfully quench discharges. Moving to full wafer processing, MESA+ could not process full wafers for all steps. Hence the production was moved to IZM Berlin in 2010. MESA+ continued to deposit the protection layer for IZM. In GridPix production challenges are related to produce reliable protection layers and high quality grids.

Protection Layer Quality

Problems with the quality of the protection layer were experienced in full wafer processing at IZM. After a failure in 2010, in 2011 and 2012 two trial runs of GridPix production on full 8" wafers were finished at IZM; IZM-2 (2011), IZM-3 (2012).

The IZM-2 batch exhibited poor spark tolerance. Detailed analysis of the chips revealed an apparent process error during the SiRN deposition leading to a relatively rough SiRN upper surface and vertical cracks in the film as seen in figure 2.6.3a. In IZM-3 a specific effort was made to check the quality of the protection layer. Figure 2.6.3b shows the cross-section of the protection layer above a pixel. Comparing that with IZM-2 it can be seen that cracks in the layer have vanished. However, experience from testbeam in 2012 showed there are still problems with the discharge protection, with only three of the six GridPixes surviving the run.

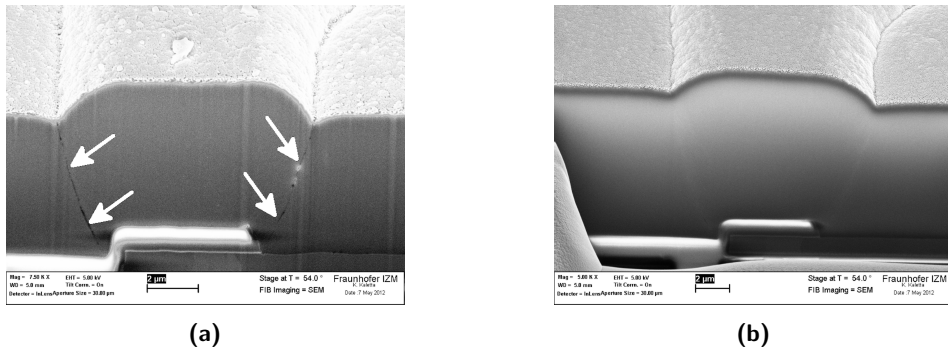


Figure 2.6.3: A cross-section of the protection layer on the edge of a pixel. The cross-sections were made with a Focussed Ion Beam (FIB). The pictures show the protection layer of a) an IZM-2 chip and b) an IZM-3 chip. Inhomogeneities can be observed in the picture on the left.

More extensive analysis by IFAE (Barcelona) on the broken GridPixes revealed holes in the protection layer, likely caused by discharges [34]. Figure 2.6.4a shows 9 pixels of a GridPix chip that broke down in the 2012 testbeam. The grid was removed before taking the picture. The picture shows a clear hole in the protection layer in which pixel electronics can be distinguished. The hole is probably caused by one or more discharges. Observation of other pixels revealed vertical cracks in the protection layer. In case of a streamer the protection layer around the crack charges up. Eventually it might happen that an ionising path is created through the crack resulting in a sudden discharge of the protection layer through the pixel below the crack and resulting in lethal damage to the pixel or a whole chip. Figure 2.6.4b shows the cross-section of a pixel taken in a similar way as figure 2.6.3a, here a crack is clearly visible. These cracks might be related to initial dust or damage to the wafer before processing. The charging up of those dust particles while depositing the protection layer might induce crack propagating through the layer. Currently studies to produce better quality protection layers are ongoing, to try to extend the successful protection on 3×3 chip array to full-wafer production.

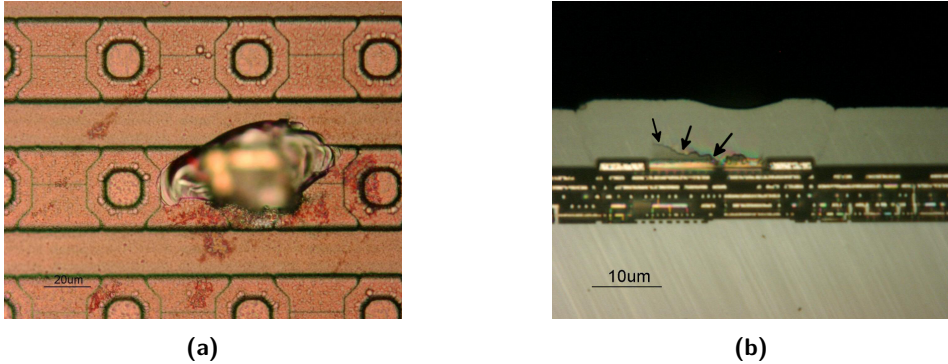


Figure 2.6.4: a) A close-up picture of the result of one or more discharges, the pixel input pad has vanished and the underlying electronics can be observed in the hole. b) A cross-section of a GridPix read-out chip above a pixel input pad, from top to bottom; the protection layer, the chip pixel electronics, and the bulk material. The protection layer shows a clear irregularity, larger versions of those cracks might be lethal to the chip.

Grid Quality

Uniform grids at a constant distance from the chip are required to obtain a uniform response over the chip surface and among the individual chips on the wafer. The area with the smallest grid-chip distance limits the maximum amplification field, therefore the homogeneity of the grid directly affects the efficiency. The MESA+–2009 batch (Figure 2.6.5a) has a poor quality grid, however chips were operational without problems. The MESA+–2010 batch (figure 2.6.5b) has a perfect quality grid, showing that the technology can work.

IZM-1 (figure 2.6.6a) had poor quality grids due to thermal stress, releasing the dykes. IZM-2 (figure 2.6.6b) had good quality grids, but poor spark protection. IZM-3 (figure 2.6.6c) had a slightly worse grid quality due to problems with the aluminium deposit machine, but chips could be operated and some had good spark resistance.

The height of the grid above the chip is only measured for a dummy wafer produced at similar conditions as the IZM-3 batch, which is the same batch where the chips used in this thesis are taken from. The average height and the variation of the SU-8 on the dummy wafer gives a good indication about the amplification gap size for the chips used in IZM-3. Figure 2.6.7 shows the dummy wafer height-profile of the SU-8 after spinning but before soft-baking. The cause of the variations is not understood. The mean height is approximately 61 μm with a spread of about 3 μm .

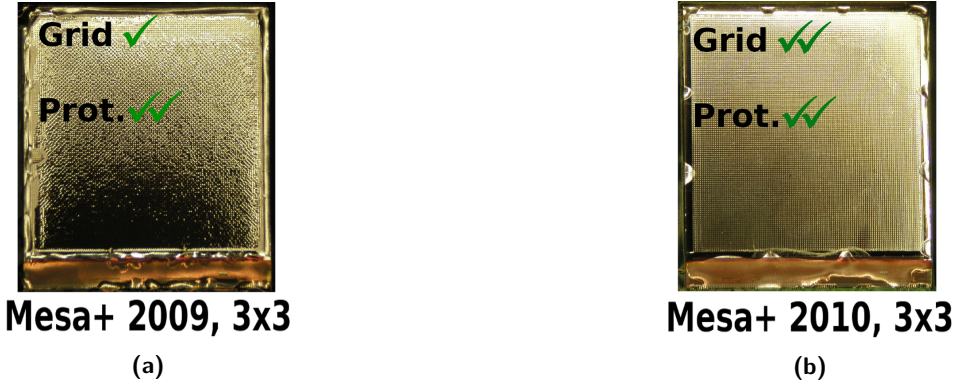


Figure 2.6.5: a) A GridPix produced on a 3×3 matrix in 2009, the quality of the grid is poor, but chips were operational and spark proof. b) A MESA+ GridPix produced in 2010, the chip has a perfect grid and is spark proof. The check-marks indicate the quality of the grid and the protection layer. Note that both chips have glue applied at the edges to reduce leakage currents. Pictures from [35].

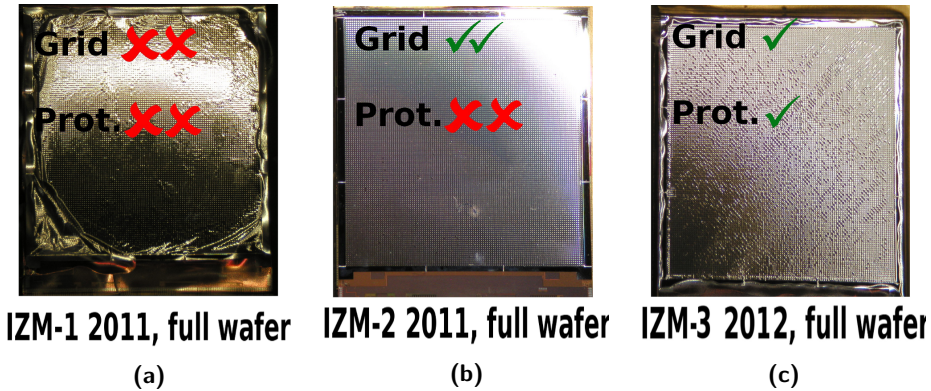


Figure 2.6.6: Pictures of a GridPix originating from the a) IZM-1 (2011) b) IZM-2 (2011) and c) IZM-3 (2012) series. The check-marks and crosses indicate the quality of the grid and the protection layer. Note that chips have glue applied at the edges to reduce leakage currents. Pictures from [35].

2.6.6 Detector Assembly

In addition to the GridPix chip a detector requires many more parts before it can be operated. Detector assembly is described next. Note that the assembly as described is specifically for single chip GridPix prototypes. Future designs will be focussed on tiling multiple chips for application in High Energy Physics experi-

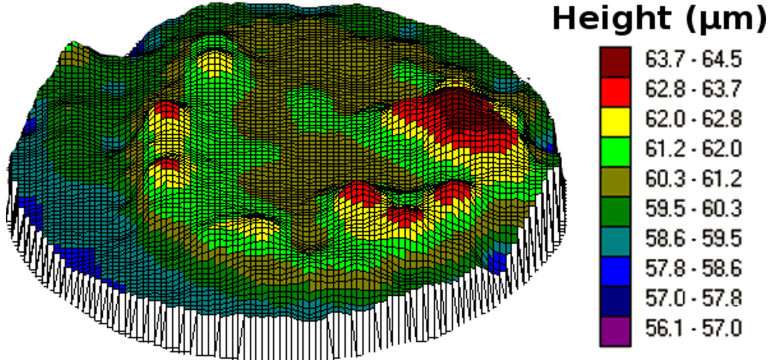


Figure 2.6.7: The SU-8 height profile of the dummy wafer with respect to the protection layer. Since the dummy wafer is produced at similar conditions as IZM-3, the mean height and variation are expected to be the same.

ments, requiring a large reduction of the material, and more advanced off-detector electronics and cooling, as well as accurate mounting and field shaping.

A GridPix chip is glued on a carrier board (known as ReNext) with two component silver glue to improve thermal conductivity, see figure 2.6.8. The chip is electrically connected to the carrier board by wire bonds. The HV voltage connection is made by wire-bonds on the grid to a HV pad on the board. After a successful electronic test, the edges of the chip are covered with UV cured GlobTop. This is done to prevent discharge propagation between the grid and the edge of the chip or the wire bonds. The disadvantage of using GlobTop is that it might charge up while operating the detector, resulting in field distortions near the edges. In addition Glob-Top gives rise to an undesired leakage current. For large scale GridPix detectors the usage of GlobTop should be avoided. The GridPix low and high voltage lines on the board go to connectors for cables from the power supplies.

Depending on the application, a field cage is either glued or screwed on the carrier board. In the case of GridPix detectors with a small drift gap (approximately 1 mm) no field shaping electrodes (figure 2.6.9) were used. A copper Printed Circuit Board (PCB) with a PCB spacer was glued on the carrier board over the chip, making the field chamber. The copper part is connected to the cathode HV pad on the board. The spacer has gas inlet and outlet ports which are connected using small plastic gas tubes to connectors on an aluminium frame. The board also carries a Relaxd read-out board and a cooling fan.

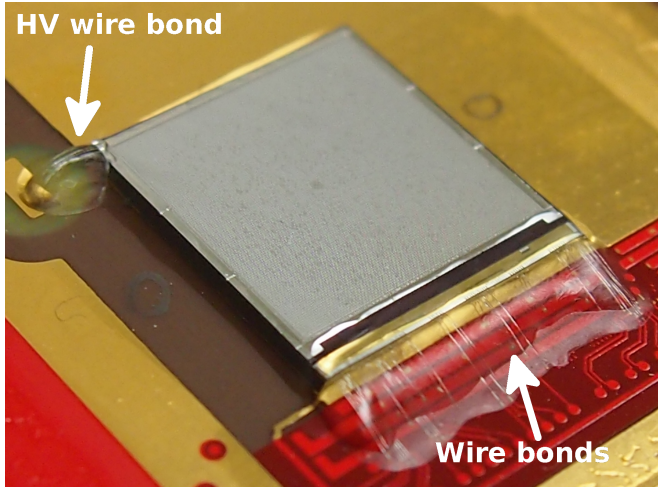


Figure 2.6.8: A GridPix chip glued on a ReNext carrier board. The chip is bonded to the carrier board with wire bonds at the right of the picture. The HV grid connection is made by wire-bonds on the left. The edges of the chip as well as all the wire-bonds are covered by UV cured GlobTop to reduce leakage currents.

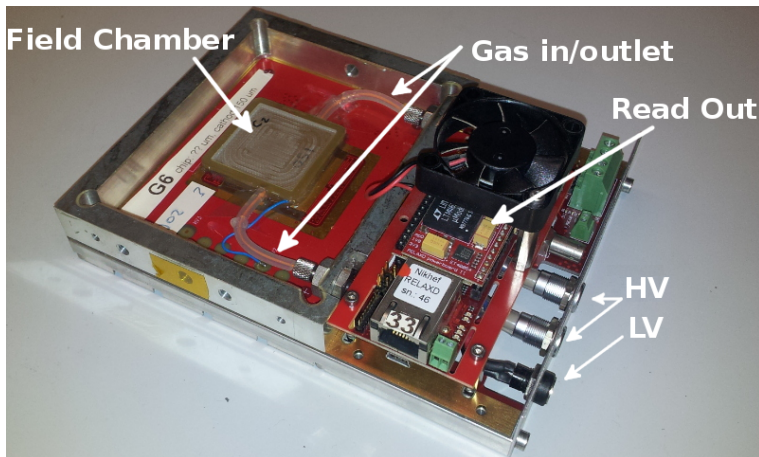


Figure 2.6.9: A GridPix chip covered by 1.2 mm thick field cage on a ReNext board. A cooling fan is placed on top of the Relaxd read-out system. At the right low and high voltage connectors are visible.

2.6.7 Data Acquisition

For Timepix-1 several data acquisition systems have been developed; an USB interface [36], FitPix [37], Muros [38] and Relaxd [39]. In addition a few data ac-

quisition software packages are available; Pixelman [40] and RelaxdDAQ [41]. In the early experiments done in this thesis a Muros read-out system was used combined with Pixelman, this combination had a frame read-out frequency of only 4 Hz. Later measurements used Relaxd combined with either Pixelman or Relaxd-DAQ. The latter combination resulted in a maximum frame rate of 120 Hz.

2.6.8 Conclusion and Outlook

The principle of production and operation of GridPix has been proven to be successful. However the step from GridPix production on a 3×3 matrix to full wafer processing revealed irregularities in the protection layer, that seem to be related to initial dust on the unprocessed wafer. This results in cracks in the protection layer and the incapability to quench discharges. Currently, specific effort is made in cleaning of the wafer and mapping of the irregularities. It is expected this effort will eventually result in reliable protection layers. As an additional assurance currently the possibilities are studied to cover the grid with a protection layer, in order to have a double protection. However to achieve this several technological challenges should be overcome.

3

Physics of Gaseous Detectors

3.1 Energy Loss in the Gas

Ionising particles traversing a gas interact with the gas molecules along their trajectory. In this way a fraction of the energy is transferred to the gas molecules. This section discusses several interaction processes.

3.1.1 Charged Particle Energy Transfer Processes

A traversing charged particle with a mass $M \gg m_e$, the mass of an electron, might lose energy due to one of the following processes:

Scattering off nuclei

High energetic charged particles traversing a gas scatter off nuclei, referred to as Coulomb scattering. This is elastic process, which slightly changes the direction of the particle. It should be taken into account for detector resolution studies as will be explained in chapter 5.

Vibration of a molecule

In contrast to single atoms (hydrocarbon) molecules have many mechanical modes of vibration. A traversing ionising particle can lose energy by leaving a molecule in a vibrating mode. Since the energy of the mode is much smaller than the lowest ionisation energy, this process does not free up electrons and is not detected in ionisation chambers.

Excitation or ionisation of an atom

By kicking out an electron a traversing particle leaves a molecule in an excited or ionised state. In case of an ionisation the electron may have such a high energy that it ionises in turn, referred to as a “delta ray”. When the molecule is excited it might decay by emission of one or more photons with a characteristic energy. Large molecules tend to break into fragments referred to as dissociation. An ionised molecule will eventually catch an electron, then it dissociates or it decays to the ground state by emission of one or more photons.

For a complete picture it should be noted that under specific conditions it is possible to generate Cherenkov light and Bremsstrahlung.

Theoretical Description of Energy Loss

For a relativistic particle with mass $M \gg m_e$ of moderate energy, the mean energy-loss rate is theoretically described by the Bethe formula [42] in equation 3.1. It only describes the energy loss due to excitations and ionisations:

$$\left\langle \frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \left(\frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} \right) - \beta^2 \right], \quad (3.1)$$

with

$$K = 4\pi N_A r_e^2 m_e c^2$$

and the maximum energy transfer in a single collision is

$$T_{\max} = \frac{2m_e c^2 \beta^2 \gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2}.$$

The path length x is measured in units of mass/area of material traversed. The parameter z is the charge in terms of electrons, Z is the atomic number of the atoms in the medium, A is the atomic mass of the gas, β is the ratio of particle velocity to the speed of light, γ is the Lorentz factor, m_e is the electron mass, c is the speed of light, M is the incident particle mass, N_A is Avogadro’s number, r_e is the classical electron radius and I is the mean excitation energy of a gas molecule. The mean excitation potential is essential for calculating the energy loss. Since I is difficult to calculate, it is empirically determined for many elements by fitting measured energy losses.

Figure 3.1.1 shows the energy loss per unit path length for muons as function of the muon energy for several gases. The mean excitation energy of DME is unknown, therefore it was approximated using [43]. The energies for the other gases are obtained from [42]. At the left of figure 3.1.1 for growing energies the drop in energy loss is proportional to $1/\beta^2$ since the particle is approaching the speed of light and it has less time to transfer momentum. At about 250 MeV the energy

drop saturates and a minimum appears. At higher energies the electric field increases due to Lorentz contraction, therefore the energy loss increases. In the case of denser material and higher energies the Bethe function has a few correction terms. In the scope of this thesis those can be neglected.

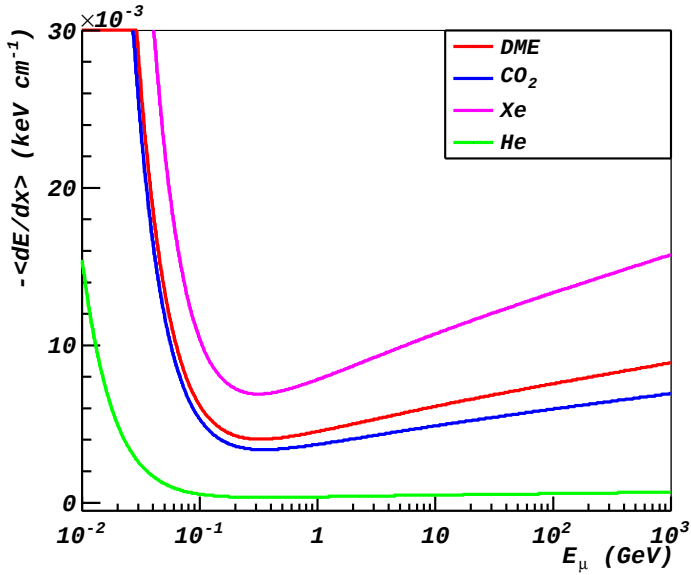


Figure 3.1.1: The energy loss per unit path length for muons against their kinetic energy for several gases at room conditions.

For tracking with gaseous detectors the number of ionisations per unit path length is an important number. Every ionisation can be related to a primary interaction. In the gaseous detector community a primary interaction is referred to as a cluster. The number of clusters along the particle trajectory is Poisson distributed. Note that the term cluster will be used later on in a different context. Every cluster may contain multiple secondary ionisations that might be measured by a detector. Figure 3.1.2 shows the most probable number of ionisations per unit path length for pions, muons and electrons against their energy in CO $_2$:DME gas in a 50:50 mixing ratio, as extracted from a Landau fit.

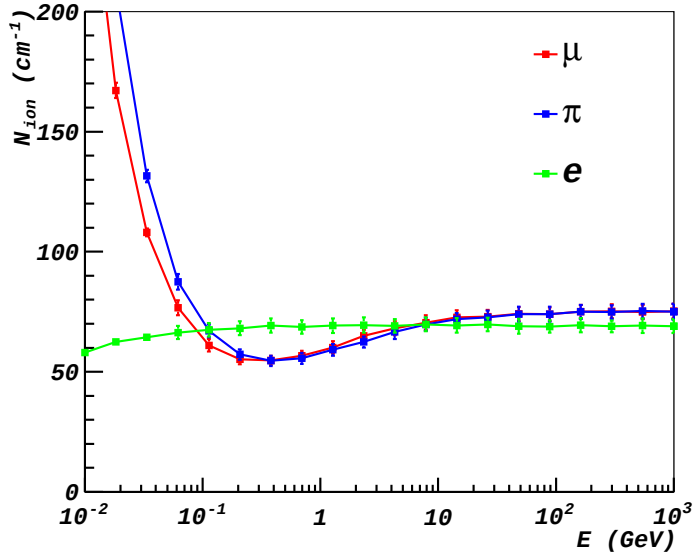


Figure 3.1.2: The most likely number of ionisations per cm for several particles against their kinetic energy in CO₂:DME (50:50), the calculation is performed with Garfield.

3.1.2 Photon Energy Transfer Processes

A photon travelling through matter has a certain possibility to interact. The interaction probability is a function of the density of the medium. In a solid this probability is larger than in gas. A photon travelling through matter can undergo the following interactions:

Rayleigh Scattering

A photon scatters off a molecule, an elastic process. After scattering the state of the molecule is unchanged.

Compton Scattering

A photon of sufficient energy knocks out an electron from one of the atomic shells. The photon continues in a different direction at lower energy.

Photo Electric Effect

A photon knocks out an electron from one of the shells of the atom and is absorbed. When the energy of the photon is larger than the electron binding energy, the electron is released from the atom, with a kinetic energy such that energy is conserved. In turn the remaining ion might undergo the

Auger effect; the vacancy of the knocked out electron is filled by an electron from one of the outer shells. The energy that is released by this process might be emitted in terms of a photon or once the energy is high enough a second electron.

Pair Production

In the field of a nucleus a photon with sufficient energy might convert to an electron-positron pair.

Figure 3.1.3 shows the mean free path of photons inside CO₂ DME (50:50) gas against their energy. For energies that are typical for a radioactive source like ⁵⁵Fe at 5.9 keV it shows that the photo electric effect is dominant.

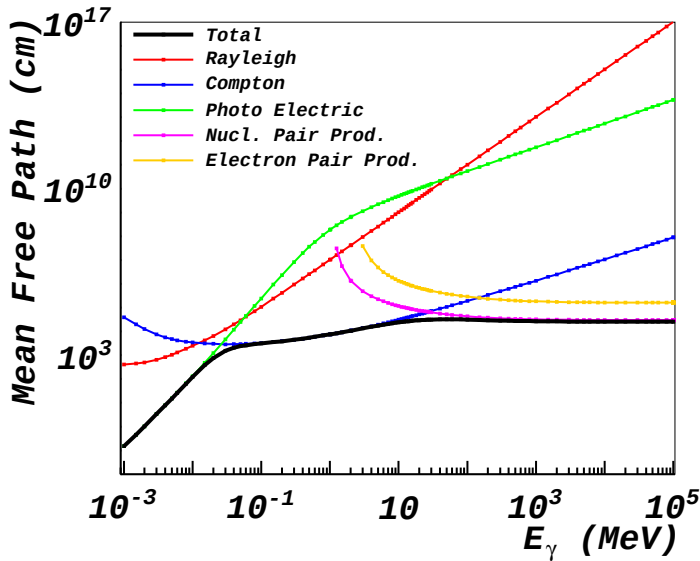


Figure 3.1.3: The mean free path for several processes for photons against their energy in CO₂:DME (50:50) [44].

3.1.3 Secondary Processes

The primary interaction processes as described in the previous subsection result in one of the following situations:

Excited Molecule

An excited molecule is metastable. After a while it either dissociates or it

decays to ground state by emitting one or more photons. In specific gas mixtures when the energy of an excited state of molecule A^* is higher than the ionisation potential of another molecule B , then in a collision of A^* with B , the energy can be transferred resulting in an ionised molecule B^+ and e^- . This is known as the Penning effect [45].

Electrons with Small Kinetic Energy

Electrons with an energy lower than the ionisation potential of the gas can excite vibrational modes of the molecules. In this way they lose energy until thermalised.

Electrons with High Kinetic Energy

An ionisation electron with a kinetic energy higher than the ionisation potential of the molecules in turn might ionise further gas molecules. Such electrons are referred to as delta-rays.

Figures 3.1.4 and 3.1.5 show the cross section for low energy electrons scattering off CO_2 and DME against their energy. The ionisation energies start from about 10 eV on. Note that a “thermal” electron has a mean free path of a few micrometers at room conditions. At drift fields of a few kV/cm “thermal” electrons have an energy of < 0.1 eV, therefore they interact with the gas without excitation or ionisations. These cross-sections are used in Magboltz/Garfield.

3.2 Gas Properties

The multiplication and the charge transport through the gas depend on the gas type and mixture ratio. The result of the charge transport directly affects the detector resolution. In this section important gas properties are explained. Afterwards the choice of the gas mixture is justified by studying the effect of the charge transport on the detector performance.

3.2.1 Drift Velocity

Free electrons inside the gas have a thermal energy. In addition electrons gain kinetic energy from the electric field E . The electrons frequently collide with gas molecules. Since the mass of electrons is much smaller than the mass of gas molecules, the electrons scatter isotropically such that the direction of motion is randomised. The electric field accelerates the electrons between collisions in one direction, giving a net speed called drift velocity. The drift velocity is much smaller than the typical electron velocity. Reference [47] derives the following

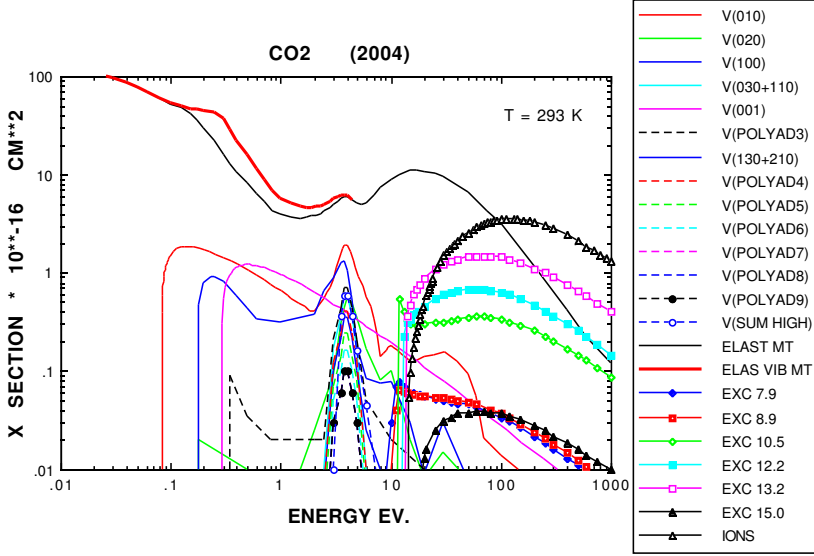


Figure 3.1.4: The cross sections for electrons in CO_2 against their kinetic energy. The vibrational modes are denoted by V, the excitational modes by EXC, the elastical modes with ELAS and the ionisations with IONS. Picture taken from [46]

formula:

$$v_d = \frac{eE}{mN\sigma} \sqrt{\frac{\lambda}{2}}, \quad (3.2)$$

where e is the charge of the electron, E is the magnitude of the electric field, m is the electron mass, σ is the cross section, N the gas density and λ is the average fractional energy loss per collision. Both σ and λ are a function of the electron energy. Equation 3.2 shows that the drift velocity vanishes when the transferred energy gets very small. The drift velocity also reduces with increasing cross-section.

In noble gases the atoms do not have vibrational modes and electrons scatter inelastically, therefore in this case λ is small. Molecular gases have many vibrational modes in which energy can be absorbed therefore λ is large. Adding a small fraction of molecular gas to the noble gas can dramatically increase the drift velocity.

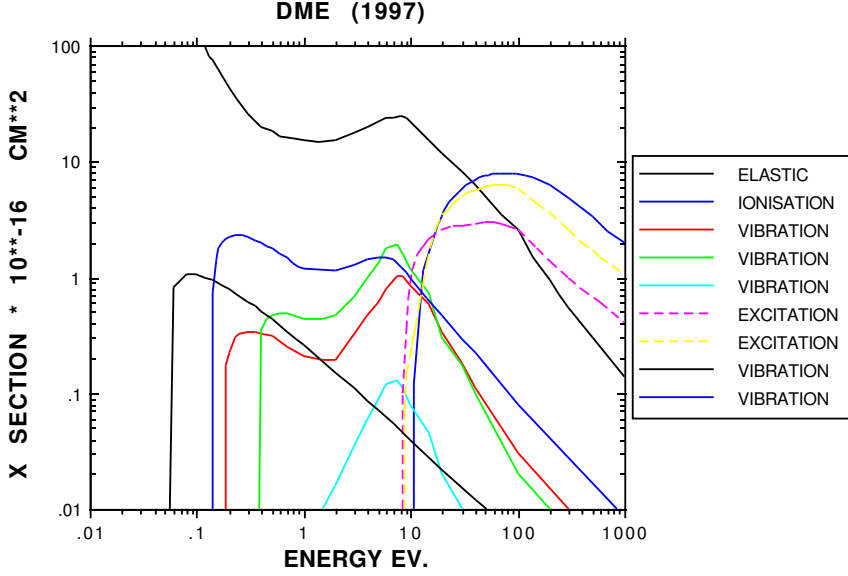


Figure 3.1.5: The cross sections for electrons in DME against their kinetic energy. Picture taken from [46]

3.2.2 Diffusion

As described in the previous section electrons drifting in the gas continuously scatter off gas molecules resulting in a deviation from their path long the field lines. Their motion can be described by a collective term due to the average drift velocity v_d and a random motion term which is due to diffusion:

$$\vec{J} = n\vec{v}_d - D^e \vec{\nabla} n, \quad (3.3)$$

where D^e is the diffusion constant and n is the electron density. Assuming the electron current $\vec{J}$ is conserved it satisfies the continuity equation:

$$\frac{\partial n}{\partial t} + \vec{\nabla} \cdot \vec{J} = 0. \quad (3.4)$$

The solution for a point-like cloud produced at the origin at time 0 is a Gaussian density distribution:

$$n = \left(\frac{1}{\sigma \sqrt{2\pi}} \right)^3 e^{-r^2/(2\sigma^2)}. \quad (3.5)$$

Here $r = \sqrt{x^2 + y^2 + (z - v_d t)^2}$ and the diffusion $\sigma = \sqrt{2D^c t}$, where t is the drift time. For a large number of scatterings assuming a mean free path with an exponential probability distribution and isotropic scattering it can be shown that [47]:

$$\sigma^2 = \frac{4\varepsilon L}{3eE}, \quad (3.6)$$

where L is the drift distance and ε is the electron energy. This shows that gases with low electron energies at high E fields, i.e. cool gases, are required for minimisation of diffusion. Cool gases in general have many vibrational modes available at small energies, hence a large fraction of the electron kinetic energy can be absorbed. The minimum diffusion is obtained at the thermal electron energy (ε_T); approximately 0.04 eV at room conditions. Gases like argon have $\varepsilon \gg \varepsilon_T$ even at very low fields and are called hot gases.

The latter calculation assumes isotropic scattering, therefore there is no difference between the diffusion along the several axes. However experiments [48] show a significant difference between diffusion perpendicular and parallel to the drift direction. Since electrons that travel in the direction of the field have larger energies, their mean free path is reduced. When observing a drifting electron cloud this effect results in a reduced drift velocity in the leading edge of the cloud. This explanation leads to an adjustment of equation 3.5 that results in the anisotropic case:

$$n = \frac{1}{\sigma_1 \sqrt{2\pi}} \left(\frac{1}{\sigma_t \sqrt{2\pi}} \right)^2 e^{-\frac{x^2 + y^2}{(2\sigma_t)^2} - \frac{(z - v_d t)^2}{(2\sigma_1)^2}}, \quad (3.7)$$

where σ_t and σ_1 are the widths corresponding to D_1^c and D_t^c to the diffusions in the transversal and longitudinal directions [49]. The diffusions as used in the rest of this thesis are extracted from Garfield for a specific electric field E and drift velocity v_d in terms of:

$$D_t = \sqrt{\frac{2D_t^c}{v_d}} \quad (3.8)$$

$$D_1 = \sqrt{\frac{2D_1^c}{v_d}} \quad (3.9)$$

such that

$$\sigma_t = D_t \sqrt{L} \quad (3.10)$$

$$\sigma_1 = D_1 \sqrt{L}. \quad (3.11)$$

3.2.3 Amplification

Without multiplication single drift electrons measured by a pixel will not exceed the noise rate of typically 105 e^- [28] in Timepix-1. Therefore the single electrons are multiplied by a strong field between the grid and the chip. The amplification process is stochastic with a large spread, requiring large amplification factors (many times the noise) to give good electron detection efficiency. In addition, as will be explained in the next section, large amplification factors are required for high accuracy time measurements. For simplicity the fields are assumed to be uniform in this section.

3.2.4 Multiplication Process

When the electron energy gathered from the electric field in between two collisions exceeds the lowest ionisation energy, the electron might liberate a secondary electron from a gas molecule. Figures 3.1.4 and 3.1.5 show the cross-sections for electrons against their energy. Energies of order 10 eV are just enough to ionise gas molecules, but electrons might reach higher energies.

In turn after gaining sufficient energy from the field the secondary electron might also release an electron from a gas molecule. Eventually this results in an exponential increase of electrons in the gas. This avalanche process is of crucial importance for the operation of gaseous detectors. In general more charge leads to higher primary electron detection efficiency and better time measurements. The terminology used for the total number of electrons participating in an avalanche induced by an individual primary electron is the gain n . The value of the average gain $\bar{n}$ is often used to compare the performance among detectors. In a uniform field the average gain is described as:

$$\bar{n} = e^{\alpha d}, \quad (3.12)$$

where d is size of the amplification gap and α is the first Townsend coefficient. In inhomogeneous fields α depends on the local field and it should be integrated over the drift path. Relating $\bar{n}$ to the detection efficiency requires knowledge of the fluctuations on n . The following sections discuss fluctuations for several cases.

3.2.5 Mathematical Description

The mathematical description of the gain spectrum and its physical interpretation has been the subject of many publications [50–55]. In fields where electrons can be accelerated to an energy that exceeds the lowest ionisation potential of the gas molecules, the average distance between two ionising collisions is $1/\alpha$, where α is the first Townsend coefficient. The minimum distance an electron starting at rest needs to travel to gain enough energy is $x_0 = U_i/E$, where U_i is the ionisation

energy and E is the electric field. Legler [51] proposed to express these parameters with the relaxation parameter χ :

$$\chi = x_0 \alpha. \quad (3.13)$$

Using χ two cases can be isolated. In moderate electric fields $\alpha \ll x_0$ therefore $\chi \approx 0$. In this case the electrons undergo many inelastic scatterings before an ionisation, therefore there is no correlation between two succeeding ionisations. In contrast, in strong electric fields $1/\alpha \approx x_0$ i.e. $\chi \approx 1$ and the electron state at one ionisation depends on the result of the previous ionisation leading to correlations. The correlation directly affects the ionisation distance distribution, which is crucial to describe the gain spectrum.

Moderate Electric Fields

It was reported by [56] that the gain spectrum in uniform moderate electric field could be described with an exponential function:

$$P(n) = \frac{1}{\bar{n}} e^{-n/\bar{n}}, \quad (3.14)$$

with a standard deviation that is equal to the mean $\sigma = \bar{n}$. The behaviour is explained with the Yule-Furry model [51, 57, 58] for large $\bar{n}$, where the distance between two succeeding ionisations is exponentially distributed. This model is independent of the electron energy, but depends on the path length since the last ionisation. Since the distribution is peaked at zero, the probability to have a number of electrons smaller than the noise level is a significant fraction of the total, suggesting large electron detection inefficiencies for moderate fields.

Strong Electric Fields

For strong electric field there might be a correlation between two succeeding ionisations. Two models that try to describe the gain spectrum are presented here:

Legler's Model

The Yule-Furry model does not match with the gain spectra for strong fields. Specifically low gains seem to be less probable in the measured spectra. Legler [51] suggested that the probability to ionise is zero when the electron does not have enough energy e.g. when the distance it travelled from the last ionisation $x < x_0$. Therefore an ionisation probability distribution was introduced as a step function:

$$p(x) = \begin{cases} 0, & \text{for } x < x_0 \\ \frac{\alpha}{2e^{-\chi} - 1}, & \text{for } x \geq x_0, \end{cases} \quad (3.15)$$

here the electron has zero possibility to ionise until it gained enough energy at x_0 . The ionisation distance distribution falls off exponentially after x_0 . To avoid negative probabilities $0 < \chi < \log 2$.

This model is basically a shifted Yule-Furry model. The shape of the gain spectrum can only be evaluated numerically. However for large $\bar{n}$ the variance was found to be [53]:

$$\sigma^2 = \bar{n}^2 \frac{(2e^{-\chi} - 1)^2}{4e^{-\chi} - 2e^{-2\chi} - 1}. \quad (3.16)$$

Legler's model appears to have reasonable agreement with measured spectra [51], however it was criticised on the physical interpretation [59].

Byrne's Model

Initially Byrne [54] proposed a model which was based on reduction of the field-dependent Townsend coefficient by a factor that depends on the instantaneous number of electrons in the avalanche n :

$$\alpha(x) \rightarrow \alpha(x) \left(1 + \frac{\theta}{n}\right) \quad (3.17)$$

where θ is a parameter to be determined empirically. This is motivated by the simple idea that electrons need to re-gain energy from the field before being able to ionise again. Therefore once a large fluctuation $n(x)$ occurs at x the number of electrons at $x + \delta x$ is reduced. For large n this assumption results in the Polya distribution:

$$P(n) = \frac{1}{\bar{n}} \frac{(\theta + 1)^{\theta+1}}{\Gamma(\theta + 1)} \left(\frac{n}{\bar{n}}\right)^{\theta} e^{-(\theta+1)n/\bar{n}} \quad (3.18)$$

with the variance:

$$\sigma^2 = \frac{\bar{n}^2}{\theta + 1}. \quad (3.19)$$

Although the Polya distribution shows good agreement with measured spectra, the physical interpretation is dubious [52, 59]. A more plausible interpretation of the shape might be found in the presence of space charge [60]. However, despite the strong criticism, the Polya distribution is very useful as a phenomenological function, therefore it will be used to describe several gain spectra in this thesis. Figure 3.2.1 shows the Polya distribution for an average gain of 5000 with different values of θ . Note that at $\theta = 0$ the Yule Furry model is recovered; the distribution is exponential.

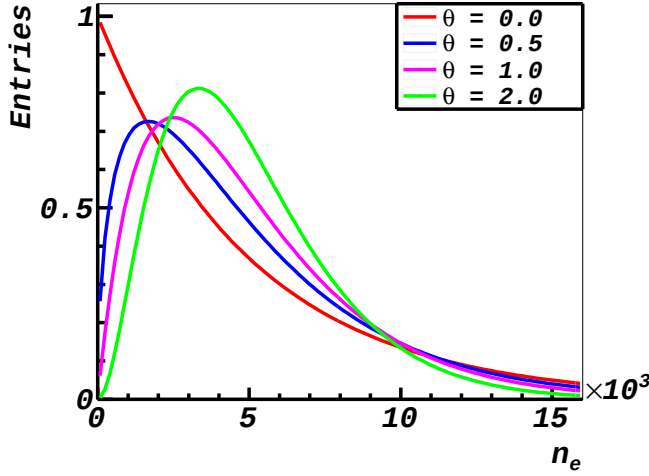


Figure 3.2.1: The Polya function for an average gain of 5000, for several values of θ . It approximates the probability distribution of the number of electrons produced in an avalanche from a single electron.

3.2.6 Ion Drift

The drifting of ions is not studied in this thesis, but for a complete picture it should be mentioned. Every primary ionisation leaves an ion drifts towards the cathode. The ions approximately the field lines and are hardly deflected due to their large mass. In gaseous detectors like the one in this thesis, primary ions are not used for particle detection, since they are too heavy to be multiplied.

Secondary ions are originating from the electron multiplication process. As will be shown in chapter 4, the majority of the field lines end up at the grid, therefore most ions traverse towards the grid. Ions are slow ($0.56 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$ for DME^+ and $1.09 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$ for CO_2^+ [61]). For a 100 kV field and a amplification region of about $50 \text{ } \mu\text{m}$ the majority of the ions is recombined within about 50 ns, which allows high event rates.

A major concern is the effect of ions flowing back into the drift region. Even when only a tiny fraction of the ions flows back at high data rates space charge might degrade the detector performance. A detailed study is performed by M. Chefdeville [62].

3.2.7 Quenching and Dissociation

Along with the ionisations in the gas as described in the previous section, there are many excitations. Excited noble gases might decay by photon emission. If such a photon has a large mean free path it might ionise gas molecules or emit photoelectrons from the grid elsewhere, leading to secondary avalanches. This might result to a chain reaction that will eventually lead to detector instability or breakdown.

Such chain reactions are avoided by adding quenching gases. A well chosen quenching gas has many absorption bands in the energy range of the photons emitted by the corresponding noble gas. Absorption of photons leads to gas molecules in an excited state. In turn they either decay by photon emission in one or two steps to ground state or by dissociation. A UV photon might be reabsorbed many times before it is absorbed by the quencher, the grid, or the chip surface. In case it is absorbed by the grid and it has an energy larger than the aluminium work function (4 eV), it might create additional electrons by the photoelectric effect. For some gas mixtures the Penning effect might increase the gas gain.

For CO₂ and DME gases there are many vibrational and rotational modes, absorbing most of the energy in an avalanche. In addition to the ionisation cross section; figures 3.1.4 and 3.1.5 show many excitations in the range of 10-20 eV. Once excited the molecule often dissociates into fragments [63]. Therefore, unlike drift gases with noble gases, the number of electrons emitted due to UV photons is assumed to be small.

3.2.8 Ageing

The ageing of gaseous detectors results in degradation of their performance due to radiation exposure. It depends on the gas mixture, pollutants and out-gassing materials inside the detector. Since there are many parameters involved the analytical description of ageing is complex, therefore most approaches are based on experience. Three mechanisms of ageing can be distinguished:

Polymer Formation

The presence of many molecular fragments and radicals produced leads to polymer formation inside the avalanche plasma. This process might be enhanced by the presence of pollutants in the gas or from out-gassing materials.

Direct Deposition of Pollutants

Pollutants in the gas might attach to surfaces by electrostatic forces. The source of the impurities might be out-gassing materials, or new polymers produced in the amplification process. Another issue is that the gas itself

might affect certain detector materials, for instance DME and rubber is a bad combination.

Eroding Surfaces

Some initially neutral gases become very reactive when interacting with species made in the amplification process. These aggressive gases are capable of removing surface layers and therefore damage the detector.

Ageing might result in polymer growth on the detector electrodes. These insulating layers charge up and therefore reduce the gain. The effect of ageing can be reduced by a clever selection of the assembly materials and the drift gas mixture.

3.2.9 Temperature and Pressure Variation

The gas properties are measured as function of the electric field $\vec{E}$. However in the context of measurements of gas properties, instead of $\vec{E}$ it is common to use the “reduced” electric field expressed in the ratio $\vec{E}/N$, where N is the number density of the gas. Equation 3.20 expresses the number density in terms of pressure p and temperature T :

$$N = \frac{p}{p_0} \frac{T_0}{T} L. \quad (3.20)$$

The parameter $L = 2.687 \times 10^{19}$ molecules/cm³ is a constant known as Loschmidt’s number. In general the electric field is expressed with respect to room conditions ($T_0 = 293.15$ K and $p_0 = 1$ bar). The range of electric field inside gaseous detectors in general is 100-100,000 V/cm. Since E/N is expressed in V cm² it has a very small value, therefore it is usually expressed in the Townsend unit (Td) [64] which equals 10^{-17} V cm². The value of 1 Td at room conditions corresponds to about 250 V/cm at room conditions. In this thesis some important parameters are both expressed in Td and in V/cm at room conditions.

3.2.10 Justification of the Gas Mixture

Two of the most important parameters for the detector performance are spatial resolution and efficiency. The resolution is directly influenced by the diffusion and the number of ionisations in the gas, whereas the efficiency only depends on the number of ionisations. One contribution to the resolution is the diffusion $D(z)$ that goes with $\sqrt{z}$. Subsequently, a good resolution requires low diffusion. Many ionisations further improves the resolution.

An additional requirement is the drift velocity, that is specifically important in high rate experiments; pile-up can be reduced by increasing the drift velocity.

Diffusion

From equation 3.10 it is evident that cool gases, in which drift electrons have

low energy, are required to obtain small diffusions. This is specifically the case in molecular gases like CO_2 and DME. It turns out that the diffusion for CO_2 :DME (50:50) is very small, about $30\text{ }\mu\text{m}$ for 1 mm drift at $E = 2\text{ kV/cm}$.

Number of Ionisations

In general the energy loss due to ionisation and excitations is larger in the case of heavy molecules/atoms or in denser media, see figure 3.1.1. However a drawback is that the diffusion for heavy molecules/atoms is approximately an order of magnitude larger. Figure 3.1.2 shows that the most likely number of ionisations in a 1 mm path length in CO_2 :DME (50:50) is at least 6. The number of clusters is Poisson distributed. Given a mean of 6 it can be estimated that the probability to produce at least one electron in 1 mm gas is larger than 99%, leading to very high detection efficiency.

Drift Velocity

Equation 3.2 shows the drift velocity as function of the average fraction of energy lost λ per collision. It shows that for increasing λ the drift velocity grows. The fraction of energy loss is large for gas molecules with many elastic cross sections. Specifically large molecules like DME and CO_2 have many vibrational states where the electron energy can be absorbed.

3.2.11 Electron Detection Efficiency

The electron detection efficiency is defined as the fraction of primary drift electrons of the total that are measured by the chip. The inefficiency is related to four different effects:

Electron Attachment

While drifting, electrons might attach to electronegative molecules and form negatively charged ions that slowly drift towards the amplification region. Because of their mass ions do not participate in the amplification process and therefore they will not be detected.

Grid Transparency

Drift electrons approaching the grid can be lost on the grid. This tends to happen to electrons created along field lines that end on the grid rather than pass through the holes. In addition it can happen that electrons drifting towards the amplification region hit the grid because of diffusion. The grid transparency is the ratio of the number of electrons that pass the grid to the total number of electrons reaching the grid plane.

Gain Fluctuations

Drift electrons that enter the amplification region produce different numbers of electrons in the avalanche. Sometimes the number produced is below threshold for detection by a pixel.

Pile-up

The signals of multiple electrons entering the same hole are superimposed. Current designs of pixel electronics can only register up to one hit per read-out sequence, so second and subsequent electrons are not seen. The effect is the strongest for tracks perpendicular to the GridPix. But even for large incident angles several electrons from one cluster will enter the same hole if the diffusion is low.

3.2.12 Conclusion

CO₂:DME (50:50) has a very low diffusion of 30 μm per mm drift at 2 kV/cm. The most likely number of electrons per mm emitted by a minimum ionising particle is about 6. This allows track positional resolutions of around 10 μm , limited by the 55 μm pixel pitch, in 1 mm gap GridPixes.

In this case, assuming that the number of measured electrons is approximately the number of clusters, the inefficiency probability of zero ionisations out of a Poisson distribution with an average of about 6 is 0.7%. The probability to have three or more hits, allowing a track fit is about 90%. The determination of resolutions and efficiencies is one of the main subjects of this thesis.

4

Field Calculations

Diffusion, drift velocity and amplification depend on the electric field. Therefore GridPix Monte-Carlo simulation [65] studies need detailed knowledge of electric fields. Complicated geometries of electric fields in GridPix detectors require sophisticated field calculation methods. In this section the performance of a recently developed Boundary Element Method is evaluated. Then this method is used to calculate fields in GridPix detectors. Later on the fields are used in a Monte-Carlo simulation to check the measurements presented in chapter 6. The calculations are performed at a pressure of 1.0000 bar and a temperature of 293.15 K, in CO₂:DME (50:50) at a grid potential of -600 V. All fields are calculated in 3D and visualised in 2D.

4.1 Field Calculation Methods

This section gives a brief description of the popular Finite Element Method (FEM) and the Boundary Element Method (BEM).

4.1.1 Finite Element Analysis

FEA is widely used for calculations in mechanical engineering, thermal physics, fluid dynamics and electric field calculations. Several commercial packages are available and the advantages and drawbacks are well understood. In the electro-

static case using conductors the FEA solves the Laplace equation:

$$\nabla^2 \varphi = 0, \quad (4.1)$$

which results from Maxwell's equations in a region with no charges, where φ is the electric potential. As the name suggests 3D FEA methods in general mesh a predetermined volume "the world" with a finite number of small polyhedral elements with a predetermined number of vertices (i.e. nodal points). Satisfying the boundary conditions, matrix inversion leads to the unique solution on the nodal points and the potential at an arbitrary point can be calculated by interpolation. Calculation time and accuracy can be optimised by varying the number of elements and/or the number of nodal points on a single element.

For electric field simulations the calculated potentials on the nodal points are stored in a matrix; the potentials at arbitrary point can be calculated with n^{th} order interpolation. The electric field is obtained by taking the derivative resulting in an $(n - 1)^{\text{th}}$ order field approximation.

4.1.2 Boundary Element Method

Different from FEMs, BEMs mesh only the boundaries of conductors present in the geometry, and calculate the electric field directly. The charge on conductors is located at the surface, making BEMs a more natural approach to the problem. The 2D elements on the surfaces represent their charge as a point charge in the centre of the element. Since the field of a point charge has an analytical expression, the field at any position can be calculated in an exact way. BEMs approximate the charge distribution along the surfaces, therefore the boundary conditions are not strictly satisfied. The electric field at a point is calculated by summing the contributions of all elements in the geometry, which can result in large calculation times if a large number of points is requested.

In general the number of elements in the boundary element method is much smaller than in the FEM case, speeding up BEMs. Specifically in the case of GridPix detectors where the drift space is large compared to the electrode this is an advantage. However a major drawback in the case of basic BEMs are the strong singularities near the boundaries. In the case of point charges this can give unnaturally large electric fields near the boundaries.

The Near exact Boundary Element Method (NeBEM) [66][67] is a recently developed method for calculating electric fields for arbitrary geometries. The developers of NeBEM found an analytic expression of the field of a uniformly charged triangular element, thus avoiding the effects of the point-charge singularity in traditional BEM. This expression is successfully implemented in the NeBEM field solver. The authors of NeBEM propose to use the program for field calculation in micro pattern gaseous detectors [68] like GridPix. Therefore recently NeBEM became accessible in the Garfield framework [46] in order to combine electron drift

calculations with accurate field calculations. After considerable effort collaborating with both the developers of NeBEM and Garfield several bugs and shortcomings were fixed resulting in a stable program. Table 4.1.1 compares NeBEM and FEM

Table 4.1.1: NeBEM vs FEMs

Feature	NeBEM	FEM
Number of Elements	$\propto$ surface area	$\propto$ volume
Solution in terms of	surface charge	potentials
Electric field	exact	interpolated
Range Solution	infinite	predetermined volume
Boundary Conditions	not strictly	strictly
Symmetries	not available	available
Auto meshing	not available	available

4.1.3 NeBEM Validation

To check NeBEM a geometry is studied that can be solved analytically using the method of images [69]. The geometry chosen is a point charge in a grounded infinite parallel plate capacitor. The NeBEM field solver is unable to use infinite sized plates therefore plates of sufficient size are used, however edge effects might be visible. In addition the fineness of the mesh on both plates is a dominant factor for calculating the electric field. Clearly the calculations can be performed more accurately using finer or more efficient meshes. This performance study is limited by a predetermined calculation time chosen to be four minutes. Because of a lack of an automated meshing tool the surface facing the point charge of each plate is meshed with equal-sized elements. For the sake of symmetry the mesh fineness on both plates is chosen to be the same. The unit point charge is approximated with a cube with a size of about $1\text{ }\mu\text{m}$, each face is meshed into two triangles. The field gradients are studied while varying the mesh fineness. The fixed size of the planes is $160\times 160\text{ }\mu\text{m}$, their distance is $50\text{ }\mu\text{m}$. In order to study the edge effects near the surface the point charge is shifted by $1\text{ }\mu\text{m}$ parallel to the plates off centre. Figure 4.1.1a shows the geometry fed into NeBEM.

Figure 4.1.1b compares the analytical field with NeBEM results with each plate divided in respectively $10\times 10\times 2$; $20\times 20\times 2$; $30\times 30\times 2$; and $40\times 40\times 2$ triangular elements. Figure 4.1.1a shows a mesh of 10×10 squares that contain two triangles each. The field near the charge is accurately calculated since the elements on the cube's surface are very small, but the precision worsens as the plates are approached. The size of the elements determines the size of the error near the

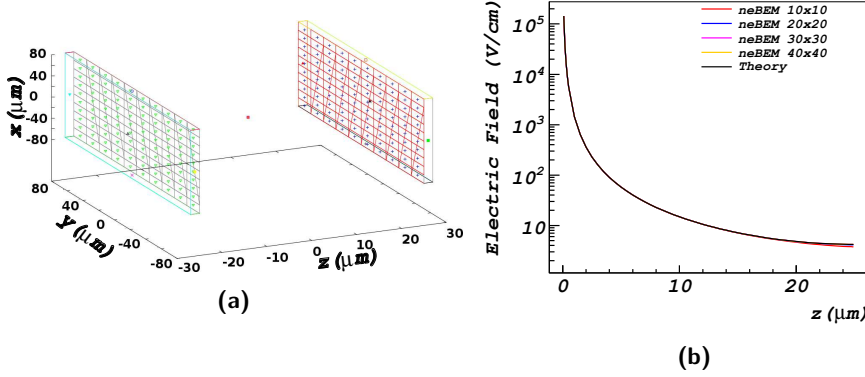


Figure 4.1.1: a) Geometry of the parallel plate capacitor with a point like charge used in NeBEM. b) Field along a line through the point charge perpendicular to the plates. The point charge is located in the middle between the plates. Even for large meshes the agreement with theory is good, with differences only visible near the plates.

plates. Figure 4.1.2a shows the fractional errors. When an accuracy of about 10^{-3} is desired the distance between the point where the electric field is calculated and the boundary should be at least as big as the cathetus length of an element.

As a check the effect of the finite size of the elements is measured by performing a $1 \mu\text{m}$ shift of the charge out of the centre. The dashed lines in figure 4.1.2a show the influence on the field. Figure 4.1.2b shows the relative calculation time for solving the problem as function of the fineness of the mesh, showing that as the element size reduces, there is less gain in accuracy for much longer calculation times.

From this performance study it can be concluded that the NeBEM principle gives promising results. A more detailed study of the accuracy of NeBEM in vicinity of the boundaries is studied in detail in [67]. For advanced future calculations, (semi-)automised meshing and faster matrix inversion are required. In addition the advantage of calculating the electric field by superimposing the field of all elements at the desired position in the NeBEM case over the interpolation of the field within one element in the FEM case is questionable. Since the solution of NeBEM is given in surface charge, the electric field is calculated by looping over all elements, this takes time. In FEMs the electric field is calculated by interpolation between a few nodal points within an element. This is less time consuming than in the BEM case. In calculations in which electric fields at many points are requested, FEM calculations might be more efficient.

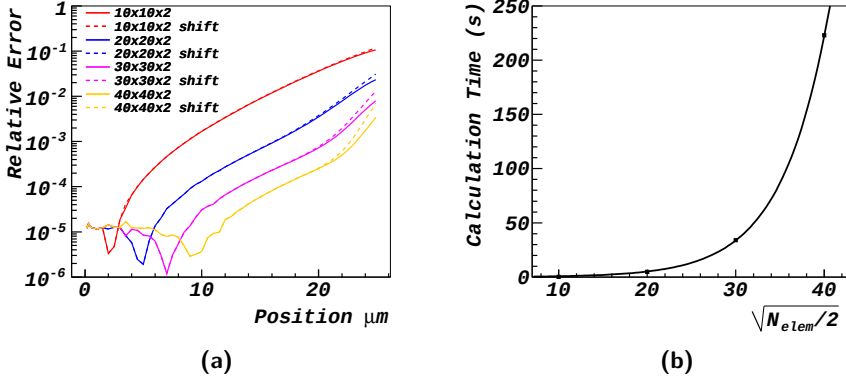


Figure 4.1.2: a) Fractional error (NeBEM/Theory) of the field along a line through the point charge perpendicular to the plates, b) Relative calculation time as function of the fineness of the mesh. The points are fitted with an exponential.

4.2 Modelling GridPix Detectors

A GridPix detector has a complicated geometry and the size of the pixel is very small compared with the drift height above it. Therefore the modelling of a full GridPix detector leads to unacceptable calculation times and a few geometric simplifications are made:

- The protection layer is connected to the pixels. At long time scales it is considered grounded. Subsequently the pixel input pads and the chip electronics below the protection layer do not affect the electrostatic field, therefore they are not modelled.
- The SU-8 pillars supporting the grid are located in the middle of four pixels. Since they are located far away from the pixel input pad, their effect on the electric field is assumed to be negligible. Therefore the pillars are not modelled.
- The shape of a grid hole in reality is circular. In the NeBEM the hole is approximated as a regular sided polygon with 12 panels. Finer holes would increase the calculation time, hardly gaining any additional accuracy.

The GridPix is modelled by repetition of one pixel cell. One cell has a surface of one pixel ($55 \times 55 \mu\text{m}$) and a height of the sum of the thickness of the protection layer, the amplification gap, the grid, the drift region and the cathode. Figure 4.2.1 shows a picture of one cell.

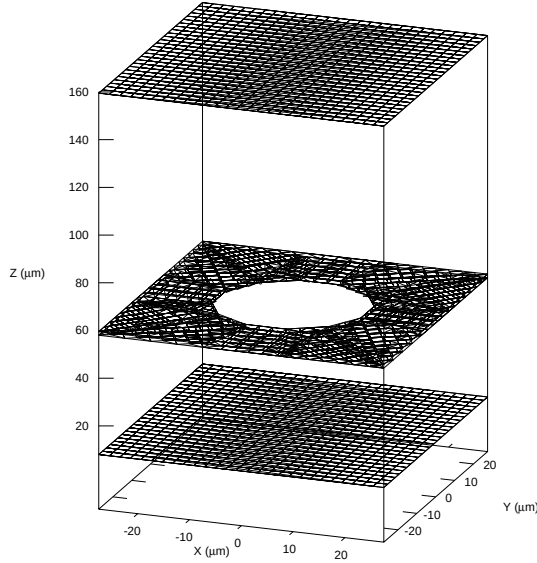


Figure 4.2.1: A representation of one meshed pixel cell with the protection layer below the grid, the hole in the centre, and the cathode at the top. In this example the cathode height has been much reduced to save computation time.

In one pixel cell the height to width ratio is large, this results in large edge effects that can be reduced by repetition of a single pixel cell. The influence of the edge effects on the field is a function of the aspect ratio of a geometry, that is defined as the height over half the width of a pixel cell, times the number of repetitions. For a GridPix with a drift-gap of 1 mm the aspect ratio of one cell is about 36. As a rule of thumb the aspect ratio of the total geometry should be about 5 for a negligible edge effect in the centre pixel cell. This means that the a single pixel cell should be repeated about 200×200 times in the $x - y$ plane for a proper result. This would lead to unacceptable calculation times, therefore more clever ways of reducing the calculation time are used:

- For many studies in this chapter, only the field near the grid is of interest. Therefore the drift gap size is reduced by a factor 10 to 100 μm , resulting in a reduction of a factor 10 in the number of repetitions.
- The single pixel cell is repeated in a 3×3 matrix. In the rest of the cells the grid is approximated by a plane without holes. All surfaces have a coarse mesh such that the distance of the coarse mesh to the part of the field that is studied is a few times the cathetus length of an element. This assures a negligible effect of the fineness of the mesh in the region of interest.
- The centre pixel of the 3×3 matrix is given an even finer mesh (see figure 4.2.2).

Figure 4.2.2 shows the resulting 3×3 matrix of cells. These improvements reduce the calculation time to about 40 minutes. This is the time to perform the meshing and calculate the solution in terms of surface charge. Graphical representations in terms of equipotential lines of the field require significantly more time.

Table 4.2.1 shows the dimensions of the parts of the GridPix detector as modelled in this chapter. In some studies the dimensions are varied to study a specific effect.

Table 4.2.1: Dimensions used in the GridPix model (height or thickness h or radius r).

	Size (μm)
Cathode	$h = 3$
Drift gap	$h = 100 - 500$
Grid	$h = 3$
Grid hole	$r = 10 - 20$
Amplification gap	$h = 20 - 120$
Protection layer	$h = 8$

The quality of the calculation is checked in several ways:

- The accuracy of the model depends on the fineness of the mesh. The decision on that is a trade-off between accuracy and calculation time. The minimum mesh fineness can be estimated by studying the distance between electron drift path and a surface. Typically the accuracy drops when the electron approaches the surface at a distance of the order of the cathetus length of an element. A more empirical approach is to vary the mesh size to study the effect on the results.

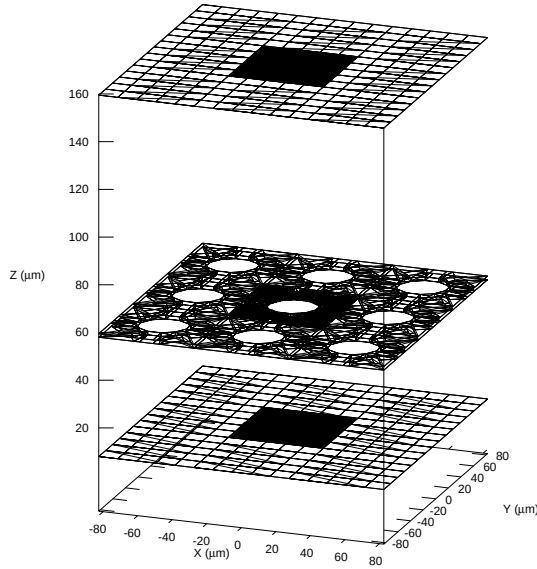


Figure 4.2.2: A representation of 3×3 meshed pixel cells with the protection layer below the grid and the hole in the centre and the cathode at the top.

- By calculating the equipotential lines with Runge Kutta Fehlberg integration, the smoothness of the lines near a surface is studied. Smooth lines indicate sufficiently small elements.
- The equipotential lines far away from the surfaces reflect the effect of edge effects. Since the modelled geometry is symmetric the field in the centre pixel cell should be similar to the adjacent pixel cells. In case large variations are visible an increase of the number of repetitions should be considered.

4.3 Grid Transparency

In the limit of no diffusion, drift electrons will precisely follow the field lines, in which case the transparency can be estimated by calculating the fraction of field

lines that pass through the holes. The grid transparency is a function of the ratio of the field below and above the grid, therefore in this section the drift field is varied while the amplification field is kept constant. Several hole radii are studied.

Figure 4.3.1a shows the equipotential lines in the cross section of a grid hole for a high ratio between the drift and amplification field. The slightly curved equipotential lines at the top of the plot result from edge effects. They have negligible effect on the electron drift. The blue vectors indicate the electron drift direction at the selected positions. Since the drift direction near the centre of the grid points towards the grid, drift electrons are likely to be lost on the grid. Figure 4.3.1b shows the same geometry but with a larger field ratio, where the field ratio is defined as the electric field in the amplification gap divided by the electric field in the drift gap. In this case the electron drift direction points away from the grid, resulting in electrons initially being pushed back towards the cathode.

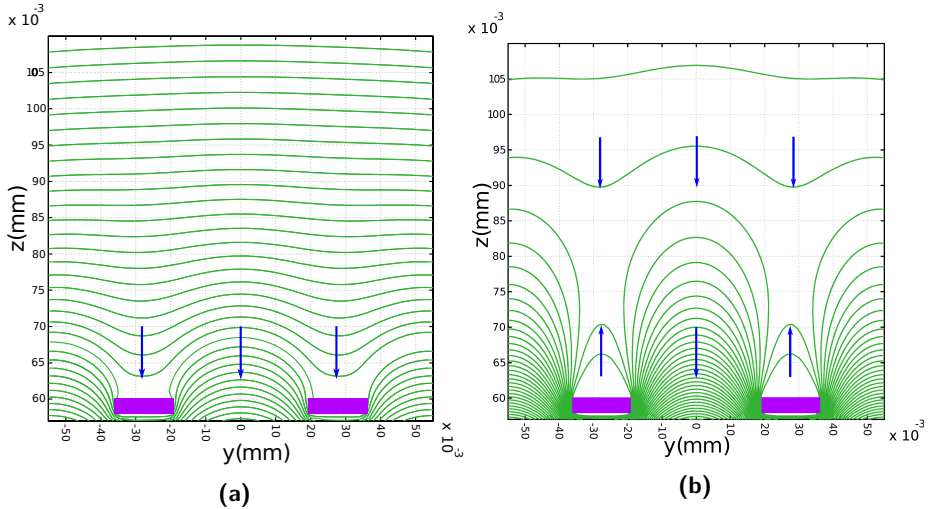


Figure 4.3.1: a) Equipotential lines plotted in the cross section of a pixel cell. The drift field to amplification field ratio is 6:1. The grid is indicated in purple, it has a potential of -600 V. b) similar as a) but with a field ratio of 51:1. The blue vectors indicate the electron drift direction at the selected positions.

The transparency as function of the field ratio is calculated by releasing electrons randomly in a $55 \mu\text{m}$ square in the centre pixel cell, $100 \mu\text{m}$ above the grid. Electron drift lines are calculated using Runge Kutta Fehlberg integration in Garfield [46]. Figure 4.3.2 shows growing transparency at large field ratios. For

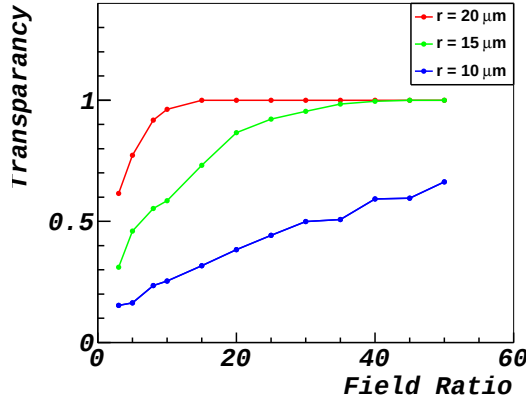


Figure 4.3.2: Transparency as function of the amplification field to drift field ratio for several hole radii. The grid potential is -600 V. Electrons are randomly released at a height of 100 μm in the centre pixel cell. This simulation is performed in the limit of no diffusion.

large hole radii it saturates faster than for small radii. With the current GridPix hole radius of 20 μm , high transparency requires a field ratio of 20 or more.

However at small electric fields the thermal velocities of the electrons dominate the drift velocities gathered from the field. Since the field in the centre between the grid holes is very small, diffusion probably plays a role. For the Micromegas case reference [70] reports that the transparency in the zero diffusion approximation is overestimated by about 20%. Therefore in future more accurate simulations on transparency should be performed without approximations on diffusion.

4.4 Field Near the Last Pixel

The edges of the chip are covered by SU-8 dykes. These start roughly half-way through the outermost pixels and extend inwards covering 10 row/columns of pixels (figure 2.6.1). The aluminium grid ends roughly $110\text{ }\mu\text{m}$ from the outer edge of the dykes, and does not have holes above the dyke. Figure 4.4.1a shows a picture of the corner of a GridPix.

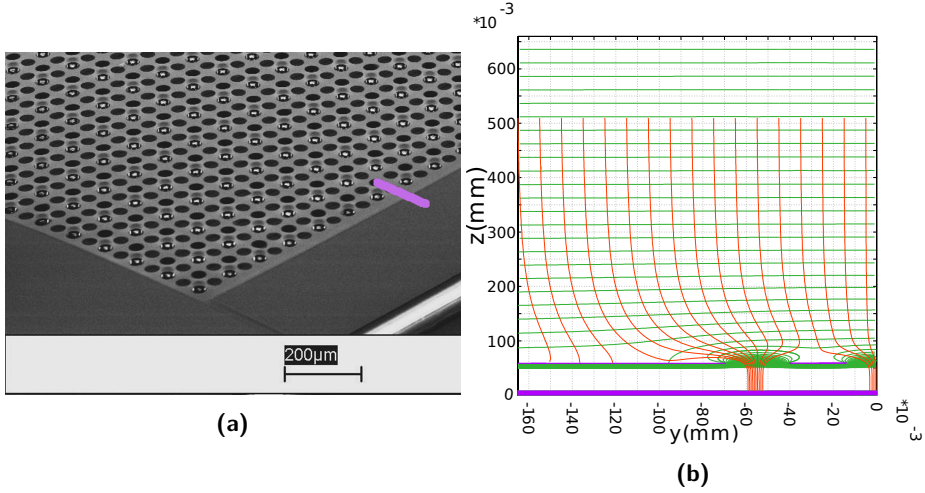


Figure 4.4.1: a) A close-up Scanning Electron Microscope (SEM) picture of the corner of a GridPix chip. The grid and the pillars can be observed. The dark grey part at the left and at the bottom are the SU-8 dykes. b) The field near the edge of the chip. For simplicity the dyke is not taken into account in the calculation. The grid potential is -600 V , the drift field is 800 V/cm .

Since the regular pattern of holes ends at the edge, the field changes in the other pixels which can have effects on the performance. The edge is modelled with a 3×3 matrix of pixel cells with a fine mesh, surrounded by an 18-cell wide region with continuous aluminium grid along the purple line as indicated in figure 4.4.1a. This row of 18 cells has a mesh size increasing from the inner to outer edges. For simplicity the dyke and pillars have not been modelled; they have little effect on the field above the grid. Figure 4.4.1b shows the results. Clearly the field is not symmetric, with edge-pixels collecting charge from a wider region than non-edge pixels. Furthermore this volume is not centred above the edge pixels. This has the benefit of reducing the width of the dead region around the pixel chip, but needs correction to electron position measurements to avoid systematic distortion of the tracks near the edges. The effect is small (approximately $25\text{ }\mu\text{m}$)

and it would require a high precision telescope with large data samples to study it.

4.5 Field Near the Chip Edge

Sharp edges at the sides of the chip induce strong electric fields which can lead to leakage currents and sparks. The field has been studied both in the region of the dykes, and in the gaps in the dykes (figure 4.5.1).

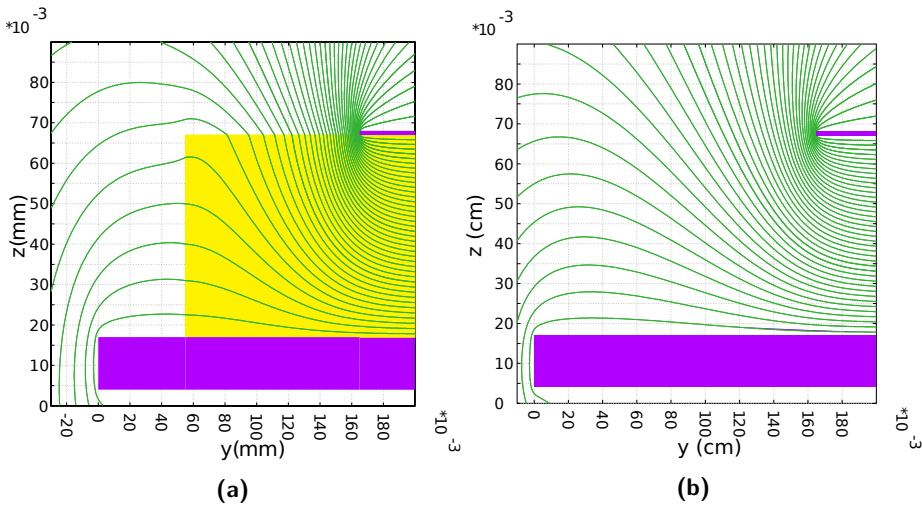


Figure 4.5.1: a) The equipotential lines near the dyke before operating the detector. The grid and the protection layer are indicated in purple, the SU-8 dyke in yellow. The dielectric distorts the equipotential lines at its edge. b) The field in the drainage gaps (see figure 2.6.1b) is strong enough to enhance discharges, therefore this part of the chip is indicated as spark “hotspot”.

The grid terminates before the edge of the dykes. Any leakage current on the surface of the dyke then has to pass through a low-field area (bottom left of the dyke), so should not be a problem. Note however that the electric field is more or less parallel to the dyke surface, this tends to enhance leakage currents.

The gaps between the dykes however have a short direct path to the chip surface through high electric field regions. Corona discharges at the grid edge could lead to discharges. These gaps are critical spots and damage has been observed near them. The purpose of the gaps used to be drainage of the solutions in the production process; nowadays these are obsolete. Therefore designs without gaps

should be made. Currently the best solution is to fill the gaps with for example UV-cured Glob-Top.

4.6 Gain as Function of the Amplification Gap Size

The average number of electrons inside an avalanche is a function of the amplification field and the amplification gap size. In the case of a grid with hole diameter zero, i.e. a parallel plate capacitor (PPC), the amplification field is homogeneous and exactly known. Once an electron is released high near the grid, the gain is obtained by calculation of the exponentiated integral of the Townsend coefficient over the drift path.

As gain is a function of the amplification gap size, local variations in grid height give gain variations. The gain increases with the amplification field at small gap sizes. For a GridPix with a fixed grid potential the field reduces when the gap increases. This leads to a certain gap size in which the gain variation is minimised with respect to height changes.

As has been shown by reference [25] the optimum is calculated to be located somewhere in between 60 and 100 μm for Argon:DME (95:5) or for He:Isobutane (94:6) (unfortunately from reference [25] it is unclear what gas is used). Using Magboltz [71], the gain was calculated for a PPC filled with CO_2 :DME (50:50) with -650 V on the grid. It turns out that the optimum is located at about 20 μm .

Figure 4.6.1 shows the gain as function of the amplification gap size for a PPC and for GridPixes with several holes sizes. The GridPix is modelled with a 100 μm drift gap and a drift field of 500 V/cm. The Grid potential is -600 V. The gain reduces as the hole radius increases, the location of the optimum is hardly affected. At small amplification gaps the gap size reaches the size of the elements, therefore no simulations are performed for amplification gaps smaller than 5 μm .

Local variation in amplification gap size is less of an issue with modern technology, while high gains are currently more important given the dominant behaviour of time-walk. Therefore there is no need for aiming at 20 μm . For future detectors a decrease of the amplification gap might be interesting for reducing the signal propagation time. Alternatively one might decide to increase the amplification gap, to a size where only small variations in gain occur (60-100 μm), and adjust the grid voltage for sufficient gain.

4.7 Gain Variation in Grid Hole

In this section the variation of the gain across the hole is studied. The 3D field inside a pixel cell is calculated and used in Garfield which simulated electron trajectories with diffusion turned off. The gain is obtained by integrating the expo-

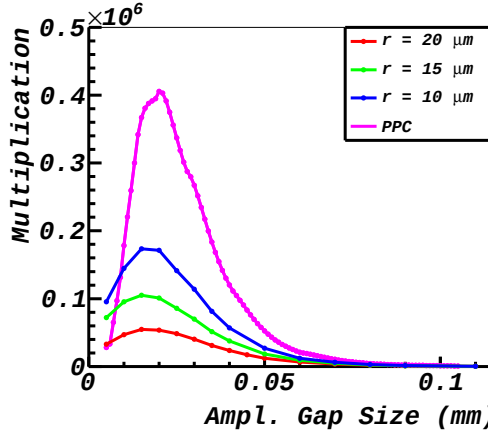


Figure 4.6.1: The gain as calculated using Magboltz in a GridPix as function of the amplification gap size for several hole radii: 0 (PPC); 10; 15; and 20 μm . The calculation is performed for $\text{CO}_2\text{:DME}$ (50:50), with -600 V on the grid.

nentiated Townsend coefficient over the electron path. Note that it is a challenge to simulate the absolute gain matching with reality since there are many external parameters involved. However the relative multiplication as obtained from this study is expected to be reasonably determined.

Gain variations inside the hole are affected by:

- the hole size;
- the field ratio.

The starting point of an avalanche has a big effect on the gain. For low field ratios (<10) the avalanche starts above the grid giving high gain. At typical field ratios (>50) the amplification field below the hole “leaks” away into the drift region, reducing the field, so avalanches start in or below the hole and the gain is reduced. In addition smaller hole size leads to less “leakage” and thus a stronger field at the entrance of the grid hole.

For this study electrons are released at systematic distances from left to right in three different regions: left of the hole, at a small distance above the grid; above the center of the hole, high in the drift gap; and right of the hole, at a small distance above the grid. The electron paths are illustrated with the red lines in figure 4.8.1b in the next section. Per electron the exponentiated Townsend coefficient is integrated over the electron path to get the gain, in addition the position where they cross the hole plane is measured.

Figure 4.7.1a shows the gain as function of the field-ratio for electrons released vertically above the centre of the hole. It is calculated that operation of a detector

at a field ratio of 10 has a 30% higher gain than a detector that is operated with a field ratio of 50.

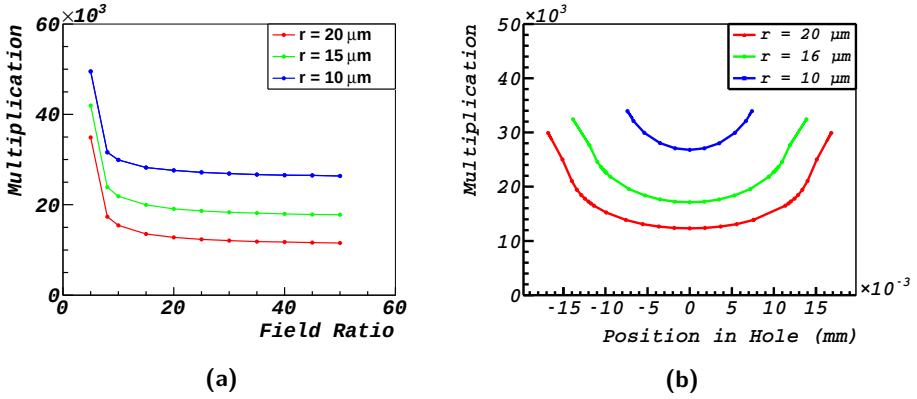


Figure 4.7.1: a) The gain as calculated using Magboltz in a GridPix as function of the amplification gap size for several hole radii typically GridPixes are operated at a field ratio of >50 . b) The gain as function of the position where the electron crosses the hole for several hole radii. For both figures the grid potential was fixed at -600 V . The current GridPix design has a hole radius of about $20 \mu\text{m}$.

As can be seen from figure 4.3.1b the field across the drift gap varies dramatically. Because of the sharp edges of the grid the field is compressed, resulting in a larger multiplication near the hole edges. Figure 4.7.1b shows the variation in multiplication as function of the position in the hole. Small holes have less variation which follows the fact that in the limit of $0 \mu\text{m}$ diameter hole size (e.g. a parallel plate capacitor) no variation is present. At large hole sizes however differences of up to a factor 2 are shown.

As has been explained in section 4.1.3 the accuracy of the field depends on the proximity distance to the boundaries and the element sizes; in case of a flat square boundary surface a reasonable relative accuracy of better than about 0.1% is achieved when the distance from the boundaries is larger than the cathetus length of an element. In that case the field is calculated with dominant contribution for multiple elements such that variations due to singularities are minimised. In this study the cathetus sizes of the elements near the hole are about $2 \mu\text{m}$, which suggests that the drift paths of electrons that approach the boundaries at a distance smaller than about $2 \mu\text{m}$ are affected. The small effect of this can be seen at the outer points of specifically the red and the green curves in figure 4.7.1b; they tend to deviate from the rest of the curve with a slightly lower gain.

4.8 Field Focus

Figure 4.8.1b shows the equipotential lines together with electron drift lines in the limit of no diffusion. Clearly in this case, electrons coming from high in the drift gap will never approach the grid edges. This is because of the focussing of the field inside the gap. The leakage of the amplification into the drift gap results in a bulb that acts like a lens. Basically the more spherical the shape of the bulb is, the stronger the focus. The shape of the bulb is a function of the field ratio. Figure 4.8.1a shows the radius of the focal point on the chip as function of the field ratio for several hole diameters. Currently this information only has a small effect on the signal development, however future devices with smaller pitches might be affected by this.

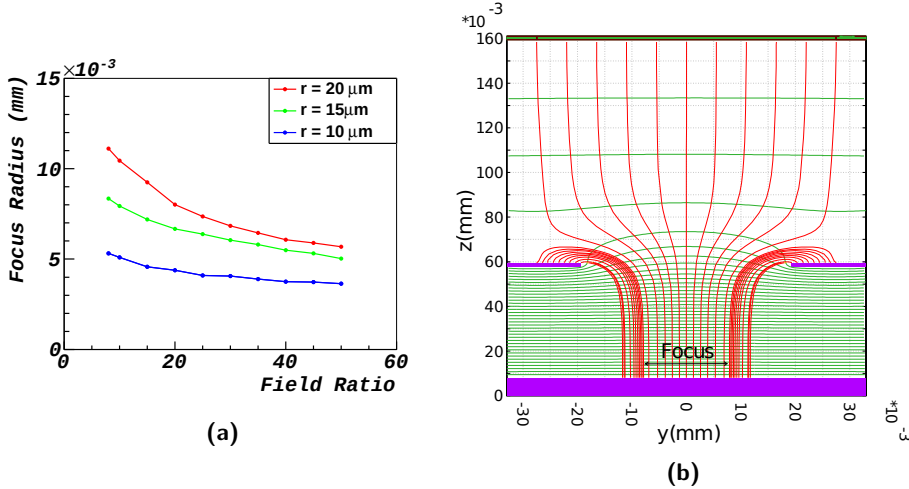


Figure 4.8.1: a) The diameter of the focus point as function of the field ratio for several hole sizes. In both figures the grid potential is -600 V. b) The equipotential lines of the field near the grid hole are plotted together with the drift lines of electrons released near the cathode and near the grid. The figure shows a cross-section of the 3D field, with a field ratio of 15:1.

4.9 Drift Time Variation

The path length of drift electrons at a fixed height is a function of the distance to the central axis of the hole. Electrons emitted far from the central axis in between four grid holes have larger drift paths (up to $30 \mu\text{m}$). They also experience smaller fields. Both effects affect the drift time. Figure 4.9.1 shows the drift times of elec-

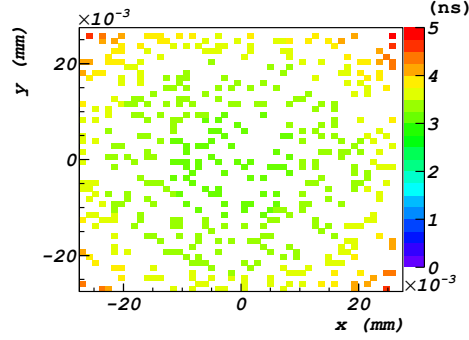


Figure 4.9.1: The (x, y) position of electrons released in a plane parallel to the grid 100 μm distance above it. The color indicates the drift time (ns). The figure shows a time drift difference of up to 3 ns depending on the distance to the hole centre.

trons released 100 μm above the grid. The differences are up to 3 ns. In TimePix-1 time-walk is much bigger, but TimePix-3 has 1.6 ns time bins and much less time-walk, and this can give a significant contribution to the resolution.

Eventually when time resolutions, time-walk and diffusion are significantly lower than this effect, it might be possible to use this effect to improve the determination of the position of the ionisation projected on the $x - y$ plane. Further study including diffusion is required.

The field near the hole affects the drift velocity, and hence the electron arrival time. For large drift distances this effect can be treated as a small offset in time. However for small drift distances the variation becomes important. This effect is studied in a 1.2 mm drift gap. Without diffusion, it is chosen to release electrons at consecutive heights 50 μm apart from each other. Figure 4.9.2a shows the drift length versus the time of arrival for $\text{CO}_2:\text{DME}$ (50:50) at $E = 1100 \text{ V/cm}$. For larger drift lengths a linear relation is observed. The drift velocity as extracted from the fit ($4.88 \mu\text{m/ns}$) is slightly higher than $4.86 \mu\text{m/ns}$, the drift velocity in a homogeneous field. Figure 4.9.2b shows the pull of this fit in the height direction. The curvature suggests a deviation from the linear behaviour due to stronger fields near the hole. It can be concluded that the strong field near the grid affects the time of arrival, therefore for proper analysis of small drift distances a correction should be applied.

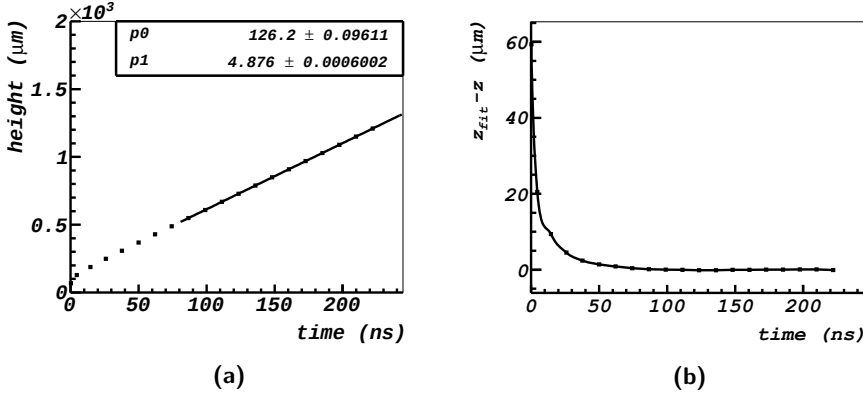


Figure 4.9.2: a) The initial z -position of the electrons against the time of arrival at $E = 1100 \text{ V/cm}$. The small relative time of arrival near the grid is a result of the stronger field. b) The pull of the fit performed in a. The systematic effect is due to field variations near the grid.

4.10 Edge Effects in the Field Cage

The production design of GridPix detectors with larger drift distances was studied for the GasPix project [12]. Because of the vector tracking feature GasPix is proposed to be used as a level 1 trigger in the ATLAS Inner Tracker (see section 1.3.2). Figure 4.10.1a shows a picture of a GasPix. Currently, the field cages are made of a thin glass fibre epoxy foil with field shaping electrodes. The electrodes have a width of 0.5 mm with a pitch of 1 mm. The foil is folded to a cuboid that is closed with a cathode and a guard electrode to reduce edge effects around the GridPix. The field electrodes are connected by means of a resistor chain to the cathode. In this section the edge effects are studied for a simplified field chamber with a 2.5 mm drift.

Figure 4.10.1b shows that inhomogeneities near the electrodes in the field chamber do not reach the active gas volume. It can be seen that the regions near the guard ring edge are slightly affected. In order to reduce the calculation time the element density below the guard electrode is reduced, therefore this part is not realistic. It is known however that reducing the distance in between the chip and the guard ring will reduce edge effects in this region.

For the current field chamber a homogeneous field is studied. For future large scale detectors a geometry resulting in a focussed field might be interesting to reduce the dead space between tiled chips.

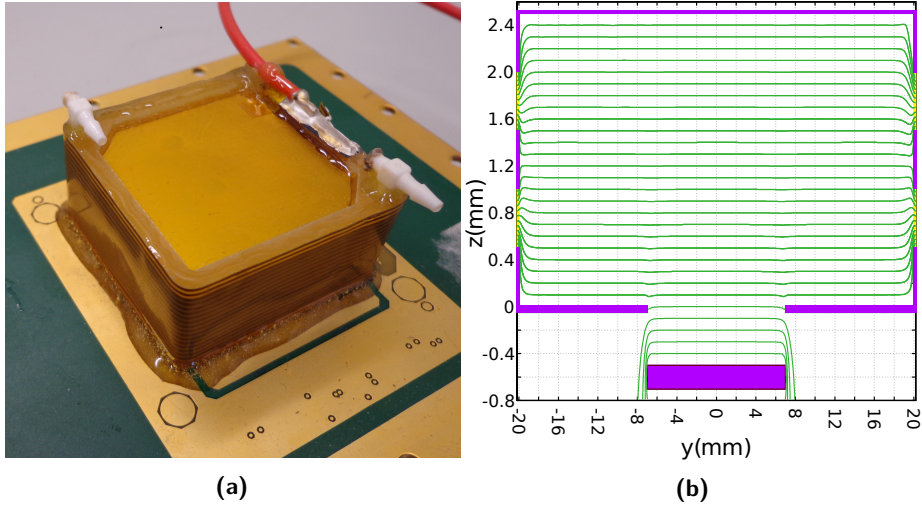


Figure 4.10.1: a) A picture of an actual GridPix with approximately 20 mm drift height, showing the field shaping cage. b) The field inside a GridPix field chamber with the cathode at 2.5 mm distance from the guard electrode and the chip about 0.5 mm below the guard electrode. Edge effects hardly affect the homogeneity. Note that the field at $z < 0$ is unrealistic since the chip is approximated as a conductor and the ground plane of the carrier board is not modelled.

4.11 Concluding Remarks

The comparison of the results of NeBEM with the exact solution of a point charge in a PPC confirms NeBEM can give correct results. Table 4.1.1 gives the pros and cons of NeBEM and FEM. NeBEM has been used for field calculations to study several field dependent parameters.

From calculations in the limit of no diffusion it appears that the transparency reaches 100% at a field ratio of about 20. The drift field near the dyke is affected by edge effects; calculations show that the edge pixels have a larger collection gas volume. The next-to-last row of pixels also has a slight enlargement. The amplification field is hardly affected by the edge effects.

In the drainage gaps in the dykes (see section 2.6.1) the electric fields are large, therefore they are spark hotspots. Research and development should be focussed on avoiding them.

The hole diameter affects the gain, drift time and transparency. These issues become more important in future GridPix detectors with a smaller pitch and better time resolution.

The field of a GridPix with a large drifter is calculated using NeBEM: measurements using the GasPix field cage are expected not to be affected by edge effects in the drift field. However, straightening the field near the guard electrode requires specific effort. In addition it is a challenge to assemble the field cage with a sufficient accuracy to make the cathode parallel to the chip.

5

Beam Test Results

In two separate beam test experiments a three-GridPix telescope was irradiated with muons. The goals of these experiments are to study basic detector properties like positional, angular and time resolutions and track detection efficiencies. The telescope was flushed with a mixture of CO_2 and DME gas in a ratio of 57:43. As part of the analysis, a framework was developed for which track separation and track fitting were studied in detail. In 2010 the GridPixes were studied while tilted away from perpendicular to the beam by 45° about the vertical (y) axis. In 2012 an improved follow-up experiment was performed with an additional tilt of 10° about the resulting horizontal (z) axis. In this chapter the analysis is illustrated using run 89 (2012). The total number of event is about 150×10^3 , however due to discharges in the centre detector only 70×10^3 events could be used.

This chapter presents the results in detail from the 2012 dataset. Resolutions as obtained from both standalone detectors and the telescope are compared. Finally, results of the 2010 dataset and a Monte-Carlo simulation [65] are shown and compared with the 2012 dataset results.

One of the main goals of the analysis is to measure the track resolution of a GridPix detector with a 1.2 mm drift gap. Per track this is done by performing a straight line fit on a set of 3D points as measured by the detector. After a careful estimation of the resolutions on the 3D points, the fitted (local) track is described in terms of a (b_x, b_y) position and two slopes (m_x, m_y) . The track resolution is quantified by the error matrix corresponding to the fit containing $(\sigma_{b_x}, \sigma_{m_x})$, $(\sigma_{b_y}, \sigma_{m_y})$ and their covariances.

The analysis proceeds with a check on the latter results using all three GridPix detectors (G_0 , G_1 and G_2) as a telescope. This requires a software alignment of the three GridPixes to transform their local tracks to a common reference frame. Global track fits are made to carry out this alignment. Then the residuals of these fits are analysed to confirm the track resolutions derived in the local track fits.

5.1 Set-up 2012

Four GridPix detectors are arranged into a telescope, as shown in figure 5.1.1. They are equally spaced 165 mm apart from each other. Three are Gossips and one is a GasPix. The Gossips have a drift gap of approximately 1.2 ± 0.1 mm. The GasPix has a much larger drift gap of approximately 1 cm and it is not used in this analysis. Every GridPix is attached to a rotary carrier on an optical bench. The detectors are tilted away from perpendicular to the beam by 45° about the vertical (y) axis. Because the effect of diffusion is smaller than the pixel pitch an additional 10° tilt about the resulting horizontal (z) axis avoids events with all hits in a single pixel row or column. The trigger scintillators have a size of about 13×13 mm, they can be observed at the left and the right of the telescope in figure 5.1.1.

5.1.1 Beam Properties

The second test beam period lasted eight days. Measurements were performed at several angles, voltages, and thresholds. The main analysis as described here covers one run, run 89. Here for 4 hours the telescope was exposed to 180 GeV muons in the T2-H4 branch at the Super Proton Synchrotron (SPS) at CERN. In periods of 48 seconds the beam was present during spills of 8 seconds with an intensity of about 30×10^3 particles. The cross section of the beam profile was approximately Gaussian with a spread of about 3 cm.

The telescope was positioned such that the scintillators were located in the centre of the beam, which has approximately a zero divergence. The beam was not affected by any other experiment or object located upstream, therefore the effect of showers can be neglected. Hardly any background radiation was detected during the acquisitions.

5.1.2 Modules

Figure 5.1.2a shows the cross section of a GridPix detector. The cathodes are made of copper Printed Circuit Boards (PCBs). By milling, the thickness of the centre part of the PCB is minimised to about 200 μm reducing the effect of multiple scattering. The cathode is glued on a 2 mm PCB spacer that is attached to the chip carrier board using UV cured Glob-top. The thickness of the glue layers is

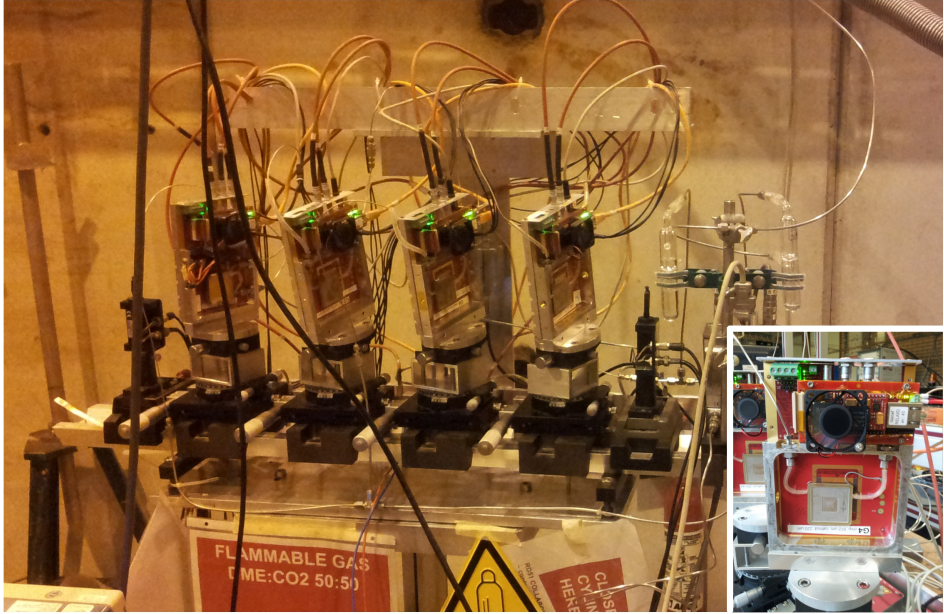


Figure 5.1.1: The 2012 GridPix telescope with from left to right a GasPix detector and three Gossips G_0 , G_1 and G_2 . There is a trigger scintillator at each end (one partly obscured by a cable). Each GridPix sits on two rotation stages, fixed on an optical bench. The insert shows a single Gossip from the front.

not well known, giving an uncertainty to the drift gap size that is estimated to be $100\text{ }\mu\text{m}$. In the beam direction the total radiation length of one GridPix is 2.77% , see appendix A.

5.1.3 Gas System

Figure 5.1.2b shows the gas tube connections in the telescope, giving a larger gas flow than connecting all in series. The connections to the telescope and between the detectors are made by $1/16$ inch stainless steel tubes mounted to a reducer in the mechanical support of the individual detectors. From the detector mechanics plastic tubes with a diameter of $1/32$ inch connect the reducer to the field cage. One detector has a gas volume of about 2.8 ml .

The gas was mixed by the Nikhef gas filling system. The target ratio in the bottle was 50:50. However a faulty valve led to excess CO_2 . From the final pressure we estimate the mixture was CO_2 :DME in a ratio of 57:43. The pre-mix bottle is located below the telescope. From the control room LabView monitors and

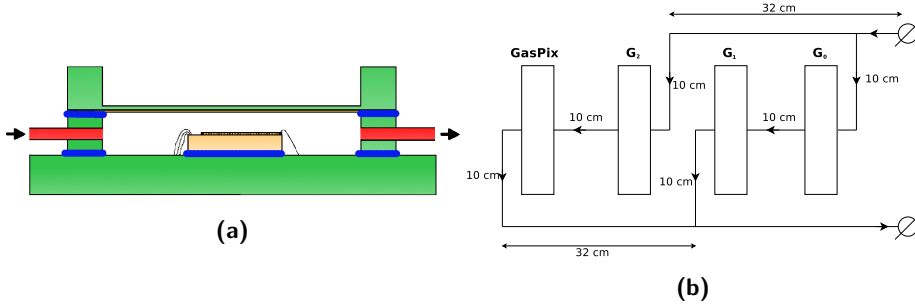


Figure 5.1.2: a) A cross section of a single GridPix in the telescope (not to scale). The chip and the cathode are indicated in yellow, the glass-fibre epoxy mechanical support is indicated in green, the layers of glue are indicated in blue, the plastic gas tubes in red. b) A gas flow diagram of the telescope. G_0 and G_1 are coupled in series, G_2 and GasPix are coupled in series. The two groups are coupled in parallel.

controls the inlet and the outlet of the total gas flow by two mass flow controllers. This allows to monitor gas leaks. The gas flow through the individual detectors is not monitored. The measurement was performed at atmospheric pressure of about 0.975 bar and an air temperature of about $19.7 \pm 0.1^\circ\text{C}$.

5.1.4 High Voltage System and Gain

Three mini-HVs [72] supply high voltage to the grids of the detectors. The GridPixes are operated preferably with large amplification fields to improve the efficiency and the time resolution. However, the amplification field is limited by the discharge rate. Discharges result in large leakage currents and dead-times, but the major concern is that they damage the protection layer and finally damage the read-out chip. The latter resulted in three chips with an operational failure before starting the run.

The amplification field was increased carefully in steps of 10 V while observing the discharge rate. At a constant -640 V on the grid, corresponding to an amplification field $E_a = 100 \text{ kV/cm}$, the GridPixes operated stably with hardly any discharges while exposed to the beam. The leakage current from the grid was measured to be less than 10 nA without beam exposure.

The mean height of the amplification gaps of the Gossips can be estimated from figure 2.6.7. Given the mean height and the grid voltages, the average multiplication of electrons in an avalanche can be simulated. For several amplification gaps and grid voltages this is done in chapter 6; from figure 6.2.5 it can be concluded that the gain of the detectors used in this chapter is approximately 12×10^3 at $E_a = 100 \text{ kV/cm}$.

The cathodes of the three detectors were connected to one mini-HV. The currents and voltages were monitored and controlled remotely from the control room.

The error on the position measurement of electrons in the drift direction is dominated by the error on the time measurement Δt . The effect of the error on the time measurement on the z position Δz is lowered by decreasing the drift velocity v_d . Therefore it was decided to set the cathode voltages at -736 V, aiming for a drift field of 800 V/cm, corresponding to a time-spectrum with a range of about 30 bins at a clock frequency of 100 MHz.

5.1.5 DAQ and Trigger System

At the start of the run all chips in the telescope are configured using Pixelman [40]. The pixel thresholds were equalised using “the noise edge threshold equalisation tool”. Then the THL DAC was set to give a threshold of about 500 e^- which is about 5 times the TimePix-1 noise of 105 e^- [28]. With this threshold the probability to have a noise hit in the area of a passing track (20×20 pixels) was less than 0.27 %. In addition background hits are reduced offline, by cutting on the drift time.

The clock frequency was set at the maximum of 100 MHz for the best time resolution. The measurement is performed in Time of Arrival (ToA) mode.

Figure 5.1.3 shows a block schematic of the trigger system. The centre timer opens the shutter once the status of the read-out goes from busy to not-busy. A coincidence of the two scintillators PMT₁ and PMT₂ starts a 5 μ s timer. The end of this closes the shutter, safely after the maximum drift time of approximately 3 μ s in the GasPix detector. The timer in the top of the picture resets the system every ten seconds when needed. Figure 5.1.4 shows the time diagram corresponding to figure 5.1.3.

Each hit pixel records the number of clock cycles from the hit to the end of the shutter, referred to as common stop mode. Note that when a pixel is hit multiple times, only the first hit counts. The estimated average time between two particles through the detectors $t_{\text{part}} = \mathcal{O}(10^{-3} \text{ s}) \gg t_{\text{shut}}$, therefore hardly any multiple track events are expected except for showers. The maximum data rate of the read-out system is 100 Hz, corresponding to a read-out time $t_{\text{dead}} = 10 \text{ ms}$. Since this is much greater than t_{part} , events were recorded at this read-out limit.

5.1.6 Data Preparation

Figure 5.1.5 explains the data flow through the framework. The raw data is transformed to a binary ROOT [73] tree together with the run header. Bad pixels are found and logged as described below. The data flows into the Analysis block and

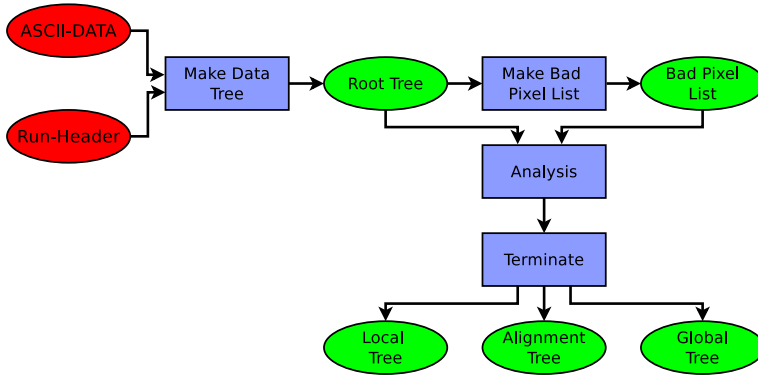


Figure 5.1.5: Simplified structure of the analysis framework. Red balloons indicate the raw data input of the framework. Purple boxes indicate functions that shape the data, including the Analysis. Green balloons indicate the output; either containing histograms related to the local frames of the detector, the global frames of the detector, the alignment of the telescope or the Data Tree and the Bad Pixel List.

of the chip. At the wire-bond side of the chip (bottom of the pictures) the dyke is located at the peripheral of the chip, therefore no trace of a dyke is visible.

G_1 shows a large inactive spot. This is caused by thin SU-8 residuals covering the grid holes, the result of a fabrication error. It can be seen that the inactive area has a large variety in how often the pixels are hit. Likely, the residuals in the grid holes are charged up, resulting in a field focus to adjacent open grid holes.

Figures 5.1.6b, 5.1.6d and 5.1.6f show the spectrum of the number of times a pixel has been hit. There are no noisy pixels, since they have been deactivated during the threshold equalisation. Dead pixels as well as pixels in the regions defined by the contours of the scintillators result in the peak on the left in the figures. All pixels that are hit less than 8 times are defined as quiet and therefore excluded from the analysis. Pixels above 8 hits are considered to be active. The right part of the distribution is fitted with a Gaussian, with a width mainly determined by the statistical spread with a small contribution from the beam profile. The error on the threshold equalisation of about 50 e^- hardly affects this width.

Table 5.1.1 shows the fraction of the size of the illuminated area for each GridPix together with the fraction of quiet pixels in the illuminated area. The extraordinary number of quiet pixels in G_1 is the result of the large inactive spots due to the SU-8 residuals. The number of dead pixels is estimated by selection of a window of 150×170 pixels inside the illuminated area, but far away from the edges. Due to statistics some good pixels are defined as quiet because they count less than eight. This is corrected for by performing a Gaussian fit to the hit spectrum of all pixels in the fiducial area. Table 5.1.1 shows the results. For G_0 and G_2 the fraction of

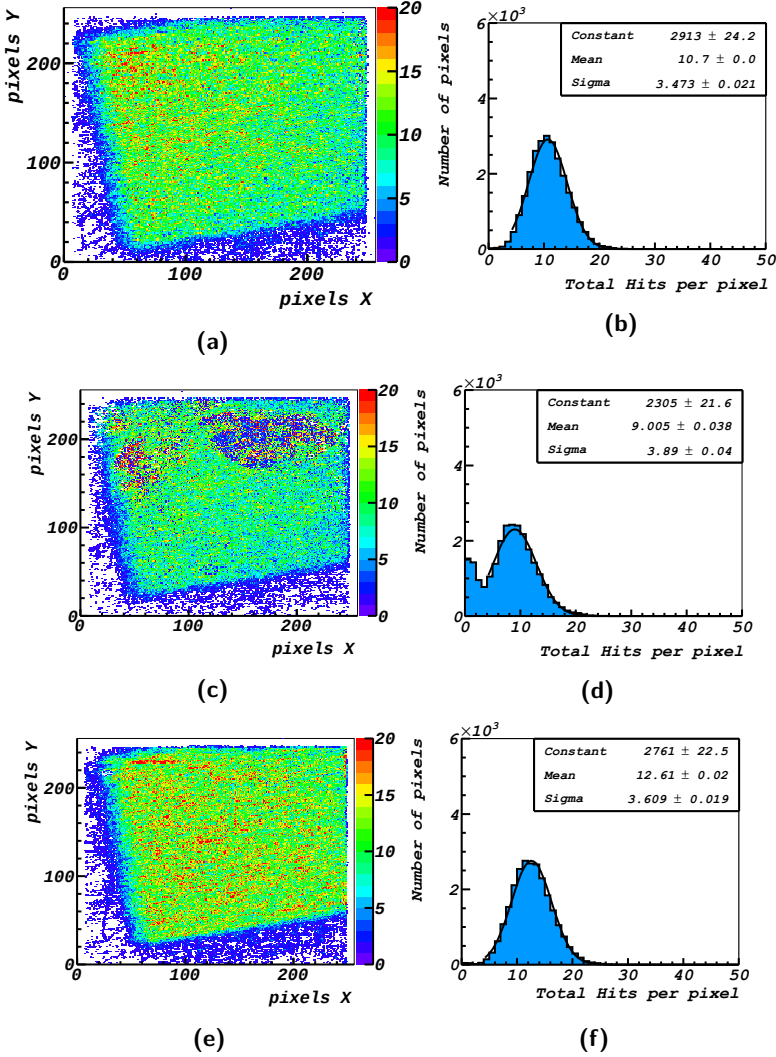


Figure 5.1.6: The occupancies and the number of hits per pixel distribution inside the illuminated area over the events in run 89; from top to bottom, G_0 , G_1 and G_2 . At the left: the occupancy plots show the scintillator contours of the detectors that are tilted by 10 degrees. At the right: Number of pixels with a given total number of hits within a 150×170 window inside the illuminated area. Peaks near 0 are related to pixels in the inactive spots of the chips. The peaks at the right are fitted with a Gaussian, showing $\sigma = \sqrt{N}$ as expected.

good pixels in the fiducial area is better than 99.6%. For G_1 the fraction of quiet pixels is large, because of the inactive spot.

Table 5.1.1: Fraction of the size of the illuminated area of the chip, together with the fraction of quiet pixels in the total illuminated area and the estimated fraction of dead pixels in the fiducial area.

GridPix	illuminated area	quiet pixels(%)	estimated dead pixels(%)
0	0.70	4	0.088
1	0.67	21	14
2	0.67	3	0.34

5.2 Local Track Fit Analysis

The analysis of the data measured by the individual local detectors in run 89 is done in two main stages:

- Calibrating the data and determine single hit resolution;
- Making local track fits to obtain the track resolution.

Table 5.2.1 shows the definitions used to perform the latter stages. In general lower case letters denote local tracks as measured in the individual detectors. Local tracks are parametrised by position and slope (b_x, m_x) and (b_y, m_y) with corresponding angles $\omega = \arctan m_x$ and $\nu = \arctan m_y$ respectively. Capitals denote tracks as measured by the telescope. Primes denote parameters measured in the global frame. Note that for historical reasons the detector rotations β , α and γ are about the x -, y - and z -axis respectively (note the inconvenient swap of α and β). Figure 5.2.1 illustrates the track parameter using a real event. It shows the measured points together with their error bars. The blue and green lines show the fitted projections on the $x-z$ and $y-z$ plane. Figure 5.2.2 illustrates the definitions of the parameters related to the telescope tracks.

5.2.1 Hit

Each hit pixel contains a raw position coordinate (n_x, n_y, n_t) , where n_x is the pixel number in the x -direction, n_y is the pixel number in the y -direction and n_t is the number of clock cycles after the signal in a pixel is over threshold until the end of the shutter.

Table 5.2.1: Definitions of the parameters used in the analysis. Primes denote quantities measured in the global frame, otherwise quantities are measured in the local frame of an individual detector.

x_h	y_h	z_h	Position of hit pixel with the corresponding height in the local frame
b_x	b_y	$\bar{z}_{xz,yz}$	Intercept of the local track with $\bar{z}_{xz,yz}$, the weighted centre of gravity
m_x	m_y		The slope of the local track projected on the $x - z$ and $y - z$ plane
ω	ν		Arctangent of the slope of the local track projected on the $x - z$ and $y - z$ plane
b'_x	b'_y	$\bar{z}'_{xz,yz}$	Intercept of the global track with $\bar{z}'_{xz,yz}$, the weighted centre of gravity
m'_x	m'_y		The slope of the global track projected on the $x' - z'$ and $y' - z'$ plane
ω'	ν'		Arctangent of the slope of the global track projected on the $x' - z'$ and $y' - z'$ plane
b'_X	b'_Y		Intercept of the global telescope track in the global frame
m'_X	m'_Y		The slope of the global telescope track projected on the $x' - z'$ and $y' - z'$ plane
β	α	γ	local to global rotations of a detector about the x -, the new y - and new z -axis (rad)
x_G	y_G	z_G	local to global translations of a detector along the x -, y - and z -axis

The raw position coordinates are translated to calibrated hits using equations 5.1, 5.2 and 5.3:

$$x_h = d_p(n_x - x_o) \quad (5.1)$$

$$y_h = d_p(n_y - y_o) \quad (5.2)$$

$$z_h = v_d t_b(t_o - n_t) \quad (5.3)$$

where:

- (x_h, y_h, z_h) is the local position of the hit in mm
- $(x_o, y_o) = (127.5, 127.5)$ sets the pixel coordinate origin to the centre of the chip
- d_p is the pixel pitch, measured to be $55 \mu\text{m}$ [28]

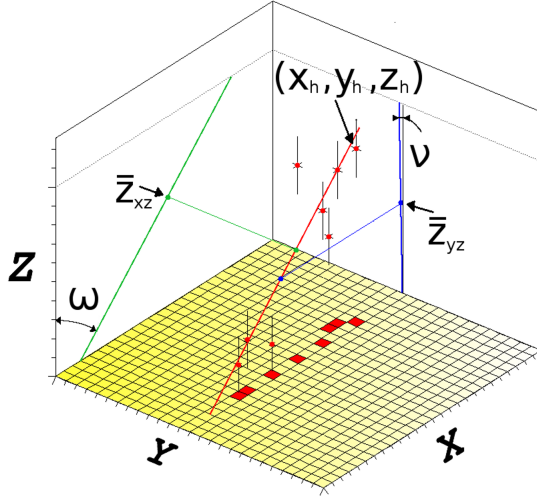


Figure 5.2.1: Visualisation of the parameters using an event from real data. A 26×26 pixel region of the chip is indicated in yellow located in the $z = 0$ plane. The hit pixels are indicated by the red squares. The red points indicate the hit position (x_h, y_h, z_h) with their 3D error bars. The blue and green lines are the projections of the fits on the $x = 0$ and $y = 0$ planes, the red line is their combination. The blue and the green dots show the weighted means of the z -coordinates (weights given in section 5.2.3).

- t_b is the period of the TDC clock, measured with an oscilloscope to be 10.0 ns
- v_d is the drift velocity of the electrons
- t_0 is the TDC value for an ionisation produced at the grid ($z = 0$); the value is estimated below

t_0 Estimation

The detectors are operated in common stop mode. An ionisation produced at the grid ($z = 0$) gives the maximum TDC count that is defined by the length of the shutter. These t_0 values are estimated from the raw time spectra shown in figure 5.2.3 and are about 516 clock cycles for all GridPixes. In the 2010 data however

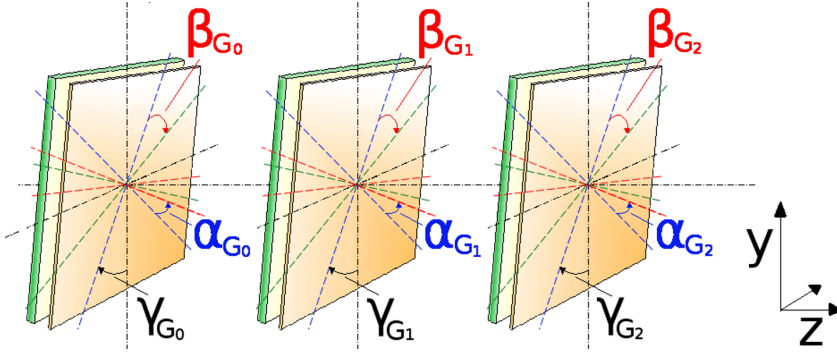


Figure 5.2.2: Sketch of the telescope with G_0 , G_1 and G_2 illustrating the alignment angles. The rotations are performed using the Euler 321 sequence; γ defines the rotation about the (black) z -axis; α the rotation around the new (blue) y -axis; β the rotation around the new (red) x -axis. The green frame indicates the final global frame.

the trigger was opened after a coincidence of the PMTs. Therefore hits from very near the grid were missed, this was accounted for by a correction to t_0 .

Time Spectrum Shape

The start positions of drift electrons in the drift gap are homogeneously distributed. Naively one would expect a uniform block function in the n_t distribution for all chips. However when two electrons enter the same hole the pixel only measures the first one. This happens more to electrons released near the grid because of the small drift distances and low diffusion, resulting in less entries at the right side of the time spectrum. Time-walk affects the rising and falling parts and gives a large tail at low n_t . The high-end slope of the timespectrum of G_2 (figure 5.2.3c) is less steep; it is likely that this is due to a smaller amplification gap as is evident from figure 2.6.7, resulting in lower gain. G_0 and G_1 have another feature; there are hits missing at the low n_t end of the track. Most likely this is caused by attachment of electrons to electronegative impurities like oxygen. The attachment probability increases with drift time, so electrons are more likely to be absorbed when originating from high in the drift gap. The difference in the attachment rates of the chips can be explained by the gas flow scheme (figure 5.1.2b). If impurities are caused by gas leaks, diffusion or out-gassing the effect will be the least near the inlets, supplying “fresh” gas, as is the case for G_0 and G_2 . However because G_1 is using recycled gas from G_0 , the fraction of impurities in the gas is larger causing more attachments.

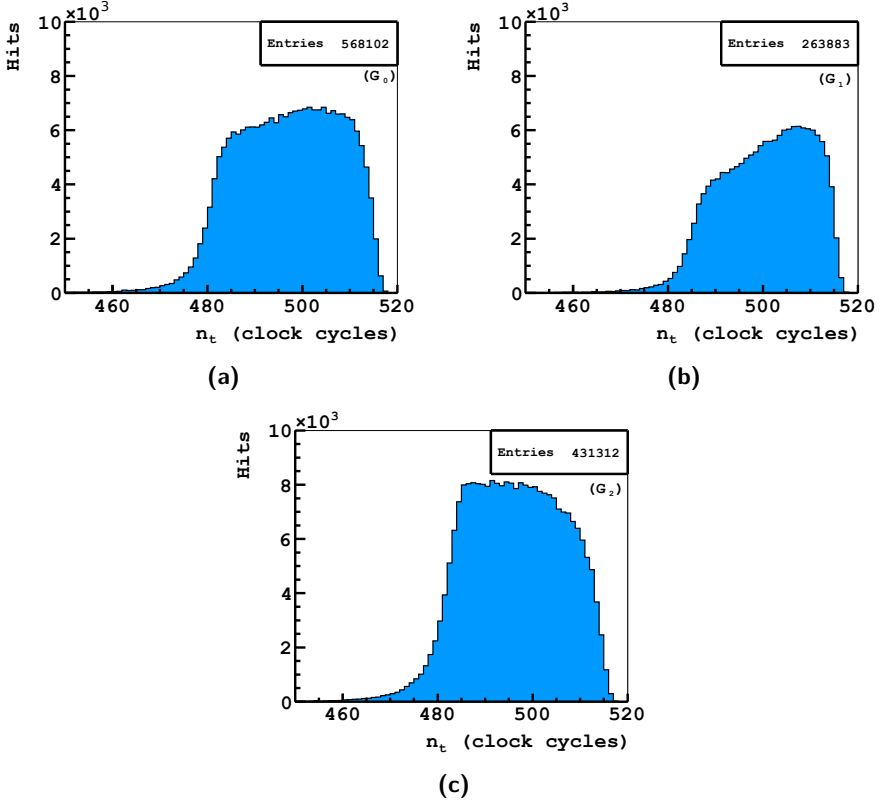


Figure 5.2.3: The raw time spectra of a) G_0 , b) G_1 and c) G_2 . The rising edge shows t_0 to be 516 clock cycles for all three detectors. The long tails are dominated by time-walk.

Electric Field and Drift Velocity

As explained in section 5.1.4 it was decided to use a lower drift field to reduce the effect of the time error. The target was 800 V/cm, corresponding to a drift velocity of $3.74 \mu\text{m/ns}$. Figure 5.2.4 shows the drift velocity as function of the electric field for $\text{CO}_2\text{:DME}$ (57:43), as extracted from MagBoltz [71]. With this field and a 1.2 mm drift gap the widths of the raw time spectra are expected to be about 32 counts, which is in agreement with figure 5.2.3.

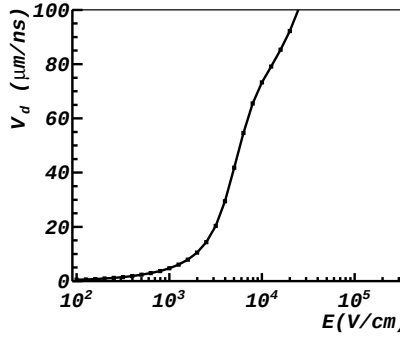


Figure 5.2.4: Drift velocity of electrons in CO₂:DME (57:43) at room conditions as function of the electric field extracted from MagBoltz [71].

5.2.2 Pattern Recognition

In the 2010 testbeam primary beam particles passed through matter upstream of the detectors. Which caused production of secondary particles resulting in multiple tracks per event. In the data these events appear as several clusters of hits. Because of a lack of statistics in 2010 an algorithm has been developed to disentangle the hits into separate clusters corresponding to single particles, to recover bad events. Note that in the 2012 dataset this algorithm is of less importance, since there was less scattering and more statistics.

The algorithm starts off with a list of calibrated hits in an event. It projects the hits on the y -axis. Then it searches through the bins looking for a hit; this starts a group. Hits are included in this group until a number of bins t_y are encountered with no hits; this ends the group. In this way several groups might be found.

Each of the groups is projected on the x -axis. In a similar process the groups are split in clusters separated by gaps with at least t_x bins wide.

The tolerance t_x and t_y are tuned by verifying the numbers of clusters found while observing the event display. It turns out that for the detectors in this experiment tolerances of $t_x = 20$ pixels and $t_y = 8$ pixels are sufficient to disentangle all tracks. The difference in the tolerances is related to the direction of the tracks, that tend to make a 10° angle with the x -axis and 45° with the y -axis.

Figure 5.2.5a illustrates the principle using a multiple track event in a Gossip. To test the limit figure 5.2.5b illustrates the principle with a worst case scenario; a shower with crossing clusters in a detector with a large drift volume. The arrow indicates that a few hits near the crossing point are assigned to the wrong cluster. In the unlikely case of crossing tracks the algorithm is less successful.

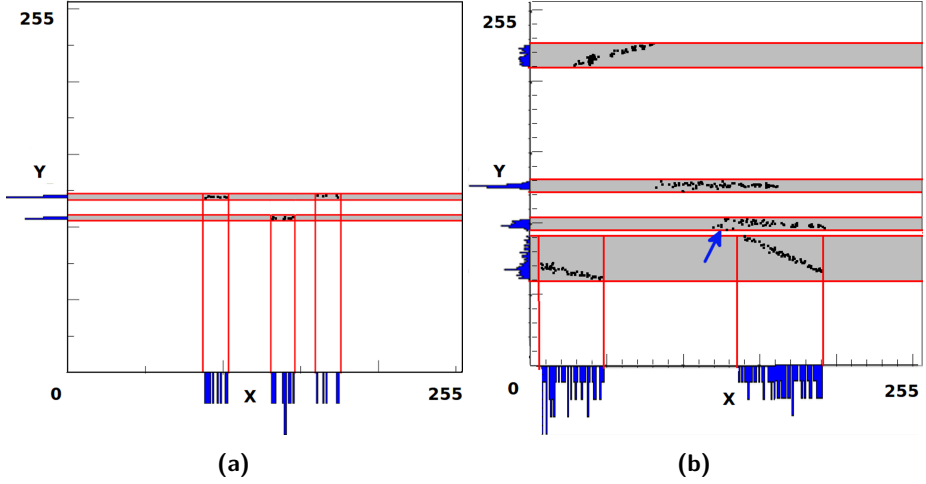


Figure 5.2.5: a) Illustration of the cluster finding algorithm. After scanning the projection of the hits on y -axis the algorithm found the two grey areas with groups of hits. Next, all hits inside the grey area are projected on the x -axis in order to find clusters. This cluster algorithm works well even on events containing multiple tracks in Gossips. b) For illustration: a shower of particles as measured by a detector with a 1.9 cm drift gap, an overlapping diagonal track gives problems, the hits indicated by the arrow are assigned to the wrong track.

In addition the cluster widths in the x - and y -direction also give an indication about the quality of the algorithm. Figure 5.2.6a shows the cluster width in the x -direction. The 45° tilt about the y -axis produces clusters up to the size of the drift gap. This maximum length is slightly reduced by the 10° tilt about the resulting z -axis. Figure 5.2.6b shows the cluster width in the y -direction. The 10° results in a small width of about 4 pixels. The widths in both the figures meet the expectations suggesting a successful cluster finding algorithm.

Number of Track Clusters

Figure 5.2.7a shows the number of track clusters per event in the 2012 data. Very few multiple cluster events are observed. About a quarter of the events are empty, mostly due to tracks passing through the scintillators but not through the active parts of the detector. Most of the rest have one cluster. In about 1.5 % of the events the cluster finding algorithm finds multiple clusters. After an investigation by eye it turns out that most of those events contain delta electrons that confuse the algorithm. The numbers of events that have multiple clusters due to multiple tracks or noise hits is approximately zero. In the 2010 data after performing the

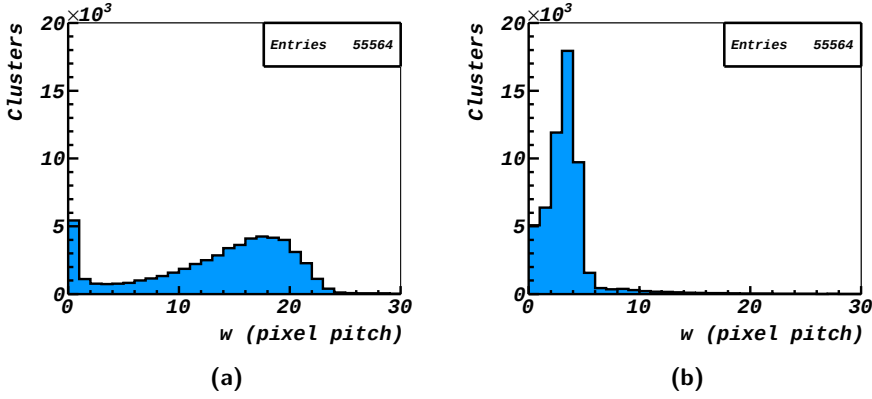


Figure 5.2.6: a) The cluster width in terms of pixels in the x -direction from G_0 . b) The cluster width in pixels in the y -direction. The first bin shows the number of clusters where hits are exactly aligned in one pixel column or row. The maximum widths correspond to what is expected from the projection of the track length on the GridPix plane.

experiment it turned out that an experiment located upstream had large cooling fins. In the worst case the particles travelled 10 cm through copper increasing the number of showers. This resulted in 6 % events with multiple clusters.

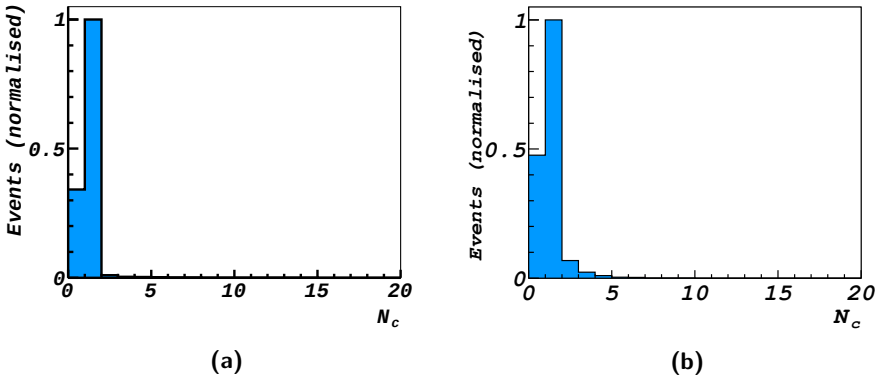


Figure 5.2.7: a) The normalised number of track clusters per event in G_0 in 2012. b) The normalised number of clusters per event in 2010. In 2010 cooling ribs in an upstream experiment increased the number of multiple cluster events to 6 %.

Number of Hits per Track Cluster

The number of primary ionisation interactions along a track is Poisson distributed:

$$P(n) = \frac{\mu^n e^{-\mu}}{n!}. \quad (5.4)$$

Each interaction can produce one or more electrons very close together. However given the low diffusion and the short drift length, most of the time all electrons belonging to the same primary ionisation pass through the same grid hole, producing only one pixel hit. Hence the number of hit pixels is expected to be Poisson distributed too, with a mean that is slightly higher than the number of interactions. Figure 5.2.8 shows these distributions, with mean of 7.8, 6.6 and 9.3 hits per event. The low value of G_1 is due to the dead areas of the chip. The slightly lower value of G_0 relative to G_2 is probably due to electrons attaching to oxygen impurities possibly combined with a smaller drift gap. The gain variations from detector to detector due to amplification gap differences also contribute to the distributions.

5.2.3 Local Track Fit

Clusters are fitted with straight lines using Williamson and York's weighted total least square method in the $x - z$ and $y - z$ planes separately. Usually it is better to do a single fit of a track in 3D. However, particularly in the 2010 data hits frequently line up in one row of pixels in y , confusing such an approach. Furthermore the fitting of straight lines to points with errors in two coordinates is complicated enough. A 3D equivalent to Williamson and York's method has not been found in the literature and given the hits-lining-up problem, we have not derived it ourselves. The fitting procedure is explained below, beginning with the origin of the errors.

Hit Errors

Here the main sources of errors on the measurements of the position (x_h, y_h, z_h) of an interaction producing a pixel hit are discussed. Whilst the electron creation positions have approximately a flat distribution in x and y , they are always attributed to the centre of a pixel, introducing a spread of $d_p/\sqrt{12}$, where the $\sqrt{12}$ comes from the calculation of the standard deviation of a uniform distribution from 0 to 1, representing the binning error of a bin with width 1. In addition, due to transverse diffusion, electrons that arrive at the grid are displaced randomly in x and y with an RMS of $D_t/\sqrt{d_d}$, where d_d is the drift distance and D_t is the transversal diffusion coefficient. Hence the errors in x and y are:

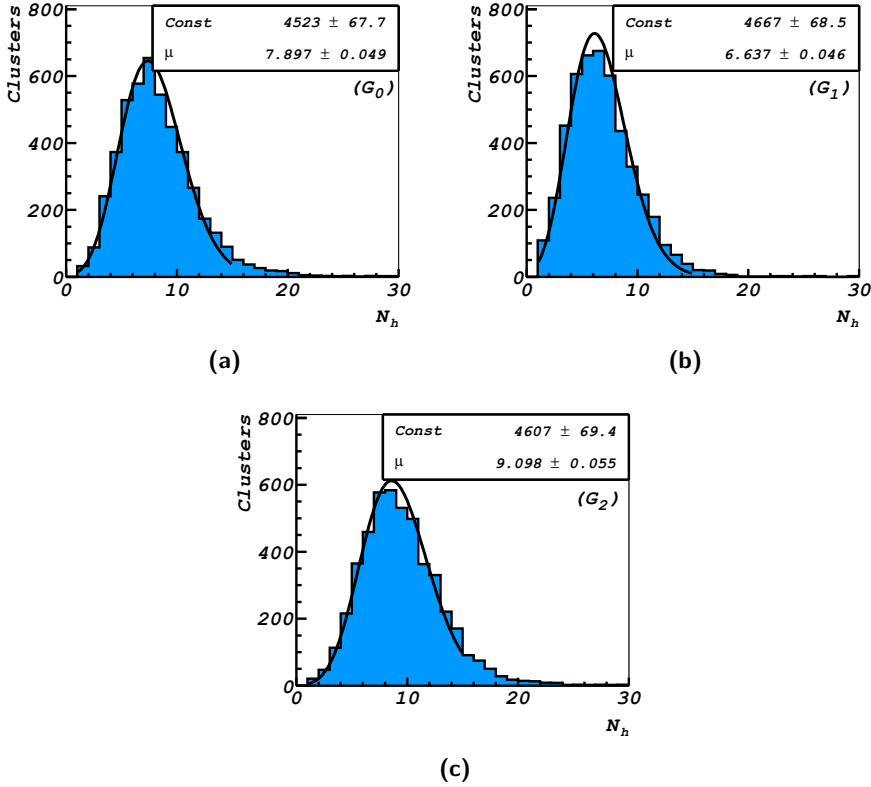


Figure 5.2.8: The number of hits per track cluster in a) G_0 , b) G_1 and c) G_2 . The variations on the average are related to the effect of inactive areas, electron attachment and gain variations.

$$\sigma_{x_h}^2 = \frac{d_p^2}{12} + D_t^2 z \quad (5.5)$$

$$\sigma_{y_h}^2 = \frac{d_p^2}{12} + D_t^2 z. \quad (5.6)$$

Electrons are created with a flat distribution in z , but in the digitisation process they get attributed to a single time bin with a width t_b equal to the clock period. This time can be converted to a distance by multiplying it with the drift velocity v_d contributing an error of $v_d t_b / \sqrt{12}$. Longitudinal diffusion smears the electron arrival time out further with $D_1 / \sqrt{d_d}$, where D_1 is the longitudinal diffusion coeffi-

cient. Gas gain fluctuations and electronic noise make further contributions to the time error, dominated by a process called time-walk which is further discussed later on in this subsection. Hence the error in z is:

$$\sigma_{z_h}^2 = \frac{(t_b v_d)^2}{12} + D_l^2 z_h + (\Delta t_w v_d)^2. \quad (5.7)$$

Here Δt_w is the effect of time-walk. Table 5.2.2 shows the errors on the positions for electrons emitted at grid height and 1 mm height.

Table 5.2.2: The errors on the (x_h, y_h, z_h) for hits at $z = 0$ mm and $z = 1$ mm assuming a field of $E = -800$ V/cm:

direction	hit error (μm) at $z = 0$ mm	hit error (μm) at $z = 1$ mm
σ_{x_h}	15.9	31.5
σ_{y_h}	15.9	31.5
σ_{z_h}	92.7	96.7

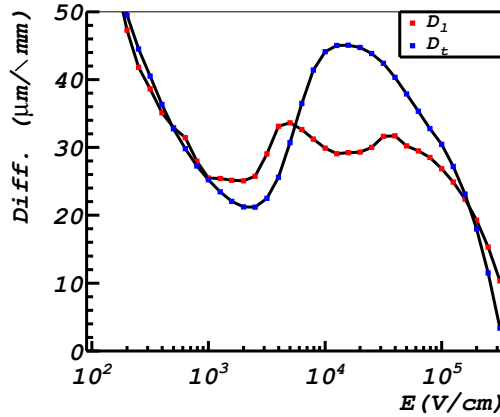


Figure 5.2.9: The transverse diffusion (blue) and longitudinal diffusion (red) of electrons in $\text{CO}_2:\text{DME}$ (57:43) at conditions similar to the experiment ($T = 292.6$ K and $P = 0.960$ bar). The data is extracted from MagBoltz [71].

The hit position depends on v_d , hence precise knowledge of v_d is important. Relying on MagBoltz, the value v_d is extracted using the gas composition, conditions (temperature and pressure) and the electric field:

- Gas composition

After a careful investigation the gas composition is determined to be 57 % CO₂ and 43% DME (section 5.1.3), this ratio is obtained after correcting for a faulty valve. The estimated error on the ratio is 1% in either way.

- Conditions

The temperature and pressure during the experiment were accurately measured during the experiment. They are not expected to be the origin of large uncertainties.

- Electric Field

This gives the largest uncertainty. The voltage on the cathode with respect to the grid is set to be (96 ± 1) V. The distance between the two electrodes is not precisely known because of 3 layers of glue in the mechanical support (figure 5.1.2a). Measurement of the spacer height and chip height before assembling the anode to the detector lead to an estimate of the drift gap of 1.2 mm. The uncertainty because of the glue layers is estimated to be about 0.1 mm.

The above input using the MagBoltz program gives a drift velocity of $v_d = (3.7 \pm 0.4)$ $\mu\text{m}/\text{ns}$. The large error leads to a large systematic error on the reconstructed track angle of about 3° . Therefore other ways to extract the drift velocities are studied.

The telescope was aligned to the beam in a lengthy process, based on maximising count rates. In the vertical plane this alignment was very precise through the use of a spirit level and screw feet on the telescope. In the horizontal direction, there was no fine adjuster. The final optimised horizontal positions of the trigger scintillators indicate the telescope was misaligned 0.2° to the muon beam.

Each Gossip was rotated 10° about z -axis and 45° about the resulting y -axis. This gives an angle of 45.8° between the final z -axis onto the $x - y$ plane. Adding the estimated initial misalignment of 0.2° means the expected beam angle ω (figure 5.2.1) is 46° , with an estimated uncertainty of 1° from build up of stage and detector alignment errors. This is much smaller than the 3° from the drift gap uncertainty. Therefore the drift velocity in each detector was tuned to put the mean track angle at 46° in each detector. The resulting values were used to find the electric field and the corresponding diffusion coefficients from MagBoltz. Table 5.2.3 gives the results. The systematic errors on the field and diffusion were obtained by propagation of the 1° track angle error.

Time-walk

The counter of a pixel in GridPix starts once a signal on the pixel input pad goes over threshold and stops at the end of the shutter. It takes some time from the start

Table 5.2.3: The tuned drift velocities with the corresponding electric fields, transverse diffusions, longitudinal diffusions at the experiment conditions and the implied drift gap for each detector. The diffusion coefficients are given for 1 mm drift.

GridPix	v_d ($\mu\text{m}/\text{ns}$)	E (V/cm)	D_t (μm)	D_l (μm)	Implied gap (mm)
0	3.78 ± 0.13	790^{+26}_{-27}	$27.2^{+0.36}_{-0.31}$	$26.8^{+0.32}_{-0.35}$	1.215
1	4.27 ± 0.13	891^{+25}_{-26}	$26.1^{+0.29}_{-0.25}$	$25.9^{+0.08}_{-0.06}$	1.077
2	4.17 ± 0.13	870^{+26}_{-26}	$26.3^{+0.29}_{-0.25}$	$25.9^{+0.22}_{-0.07}$	1.103

of a signal to when the signal reaches threshold (figure 5.2.10), referred to as Time to Threshold (TtoT). TtoT depends on the rise time of the front-end amplifier and the charge in the signal. The variations in TtoT with charge is called time-walk. The front-end is characterised in terms of a time-walk parameter defined as the difference between the time measured from an input charge that is 1 ke^- over threshold and an infinite input charge [28].

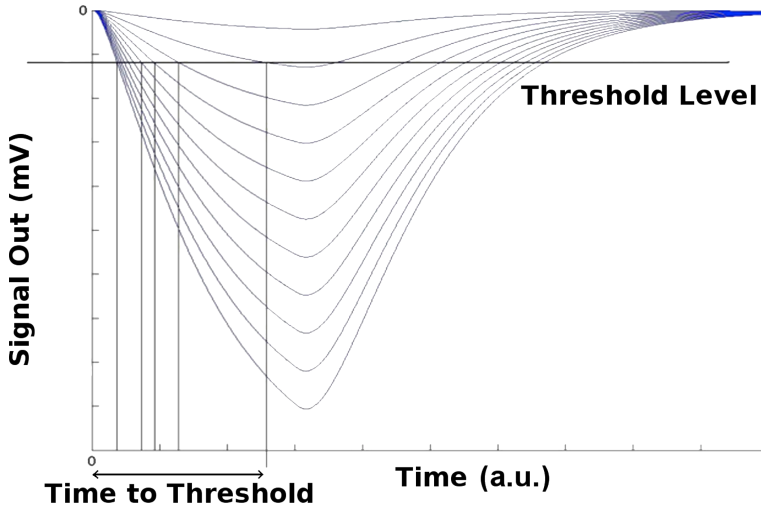


Figure 5.2.10: For illustration: the convolution of the induced signal on a pixel and the system response for several amplitudes without noise.

The Timepix chip has a slow rise time of 100 ns [74]. The charge produced by single electrons also varies widely due to statistical fluctuations in the avalanche process, see Chapter 3. The combination of slow rise-time and large gas gain fluctuations leads to a large time-walk effect, dominating the error on hit position and with major impact on the analysis and track resolution.

The long tails in figure 5.2.3 are the result of time-walk, which is the dominant error on the time measurement. A cut on electrons that appear to come from outside the drift gap reduces the effect of time-walk for electrons released near the cathode. Time-walk has a tail to long times that tends to systemically pull up hits in z . When two simultaneously created electrons enter the same grid hole the clock starts counting when the sum of the two signals goes over threshold, reducing the TtoT. Note that the time-walk distribution is asymmetric, however to simplify the analysis it is treated as a Gaussian.

As explained in section 5.2.1, the raw hit Time of Arrival (ToA) spectra are affected by several factors including pile-up of electrons in the same pixel, attachment, diffusion and time-walk. We deconvolute the timespectrum with a toy Monte-Carlo simulation. It simulates 50×10^3 tracks with angles similar to the data. The number of hits per track is taken from a Poisson distribution with a mean chosen to match with the data (figures 5.2.8). In addition diffusion in both directions, double hits and attachment are taken into account. Since time-walk is independent of z while attachment increases with z they can be tuned individually such that the simulated spectrum matches the measured spectrum.

Figure 5.2.11abc show the simulated spectra together with the measured spectra. The contribution of time-walk is also shown. It turns out that the attachment rate for electrons released in the top of the drift gap of G_0 is about 35%, for G_1 it is about 65% and G_2 has a negligible attachment rate. The simulated spectra show excellent agreement with the measured spectra.

Track-fit Algorithm

A straight line fit through the set of hits (x_i, y_i, z_i) with errors in all directions reconstructs the particle trajectory. The fit procedure is simplified by considering the projections of the hits on the $x - z$ and $y - z$ planes. Because the tracks tend to be almost parallel with the z -axis, infinite slopes were avoided by fitting x or y against z .

Specific effort is put in finding a fast and proper fitting algorithm. From the beginning of the last century [75] several papers have been published on straight line fitting algorithms in 2D with errors on both variables. One of the last papers has been published in 2004 [76]. As mentioned, the error in z is significantly larger than the error in x and y due to the effect of time-walk. Most of the algorithms are capable of dealing with small errors in z , however dealing with large errors in z is challenging. Furthermore, some fitting methods [77] are not invariant under exchange of x or y and z , a physically unwanted feature.

Cantrell [78] compares several methods using a Monte-Carlo simulation and a standard data set known as Pearson's data with York's weights, proposed by York [79]. Specifically Williamson and York's weighted least square method [79–81] turns out to give the best results. Williamson and York's method basically projects

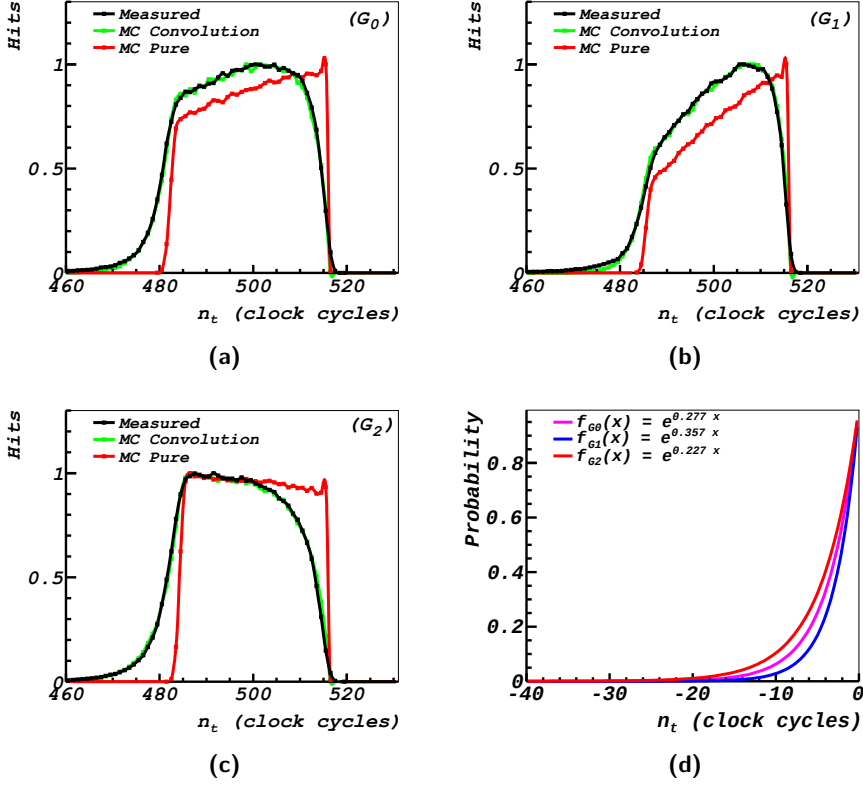


Figure 5.2.11: The simulated timespectra with and without the contribution of time-walk – “MC Convolution” and “MC Pure” respectively– shown together with the measured spectrum of a) G_0 , b) G_1 and c) G_2 . The spectra show good agreement with the measured spectra indicating a good understanding of the data. d) The estimated time-walk contributions for each detector used to match the measured spectra.

the error in z on the slope which requires knowledge of the slope. Therefore this is a non-linear problem and it is solved iteratively.

A track is fitted in the $x - z$ plane to a set of hits (x_i, z_i) in the form of:

$$x = mz + b. \quad (5.8)$$

As is the case for all least square methods this method is based on minimisation of the χ^2 :

$$\chi^2 = \sum_i W_i [x_i - (mz_i + b)]^2. \quad (5.9)$$

Here W_i is the result of the usual projection of the z error on the x -axis, note that it depends on the slope m :

$$\begin{aligned} W_i &= \frac{w_{x_i} w_{z_i}}{w_{z_i} + m^2 w_{x_i}} \\ &= \frac{1}{\sigma_{x_i}^2 + m^2 \sigma_{z_i}^2}, \end{aligned} \quad (5.10)$$

where $w_{x_i} = 1/\sigma_{x_i}^2$ and $w_{z_i} = 1/\sigma_{z_i}^2$. The minimisation of χ^2 is not straight forward since W_i is a function of m . Williamson and York's method gives the following solution (its rather complicated derivation is given in [79]):

$$b = \bar{x} - m\bar{z} \quad (5.11)$$

$$m_{j+1} = \frac{\sum_i W_i(m_j) \beta_i(m_j) V_i(m_j)}{\sum_i W_i(m_j) \beta_i(m_j) U_i(m_j)} \quad (5.12)$$

with

$$\begin{aligned} U_i &= z_i - \bar{z} \\ V_i &= x_i - \bar{x} \\ \beta_i &= W_i \left(\frac{U_i}{w_{x_i}} + \frac{m V_i}{w_{z_i}} \right) \end{aligned} \quad (5.13)$$

and

$$\begin{aligned} \bar{x} &= \frac{\sum_i W_i x_i}{\sum_i W_i} \\ \bar{z} &= \frac{\sum_i W_i z_i}{\sum_i W_i}. \end{aligned} \quad (5.14)$$

The subscript on m labels successive iterations. The iterations are continued until

$\Delta \left(\frac{\chi^2}{ndf} \right) < 0.001$. The errors in the intercept b and the slope m are calculated with:

$$\begin{aligned} \sigma_b^2 &= \frac{1}{\sum_i W_i} + \left(\bar{z} + \frac{\sum_i W_i \beta_i}{\sum_i W_i} \right)^2 \sigma_m^2 \\ \sigma_m^2 &= \frac{1}{\sum_i W_i (\beta_i - \sum_i W_i \beta_i / \sum_i W_i)^2}. \end{aligned} \quad (5.15)$$

The covariance of the slope and the intercept is the same as in the traditional least square method and is given by:

$$\text{Cov}(m, b) = -\bar{z} \sigma_m^2. \quad (5.16)$$

To avoid correlations the fit is performed with all z coordinates shifted to the weighted centre of gravity. In this frame in which $\bar{z} = 0$ the errors on m and b are independent and the covariance is 0; furthermore the errors on m and b are minimised.

A similar set of equations is used for fits of a set y_i to z_i . Note that $\bar{z}$ depends on the slope m which is different in the $x-z$ and $y-z$ planes. Having two values leads to some difficulties later when rotating the local tracks to a global frame. Figure 5.2.12 shows that the difference is small, $\bar{z}$ from the $x-z$ fits is always used in further analysis.

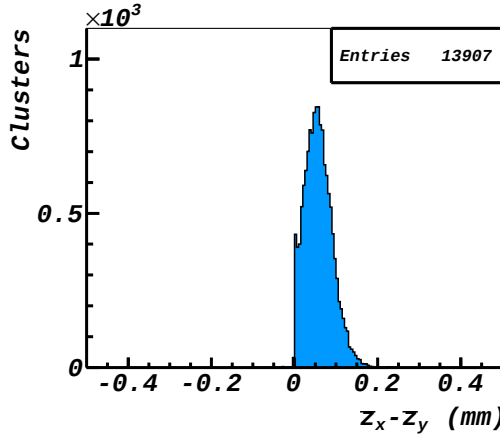


Figure 5.2.12: Difference between $\bar{z}$ for the x and y fits in G_0 . $\bar{z}_x$ tends to be larger than $\bar{z}_y$ because of the contribution of the slope. The difference is small.

5.2.4 Dealing with Outliers

Noise hits, δ -rays and time-walk effects can give “outlier” hits –far from the track–distorting the fits. After fit convergence, for tracks with four or more hits, a search is made for outliers. If the hit furthest from the track in z is more than $3\sigma_{z_h}$ away from the track it is dropped and the fit is repeated.

Quality Checks

The “fit probability” gives the probability that a track with the actual fitted parameters would, through statistical fluctuations, give a χ^2 equal or larger than the observed χ^2 . For a good model with correct errors the probability distribution should be flat between 0 and 1. The time-walk contribution to the error in the fit is unknown a-priori. It is estimated by varying it to make the fit probability distributions flat. The distributions between 0.1 and 0.95 are fitted with a constant for various time-walks in the $x - z$ plane. The χ^2 of each fit reflects how flat it is. Figure 5.2.13 shows the χ^2 of the fits in G_0 versus several values of time-walk. The second column in table 5.2.4 shows the time-walk parameter that minimises the χ^2 .

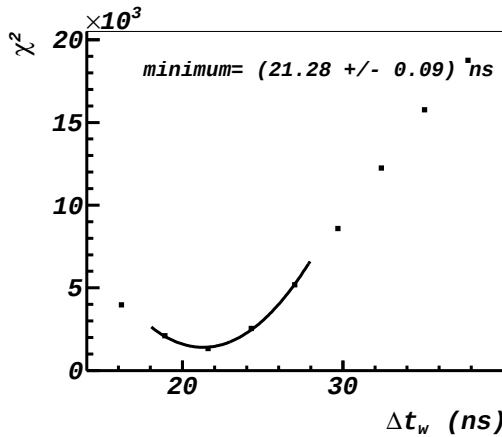


Figure 5.2.13: χ^2 from flat line fits on the confidence level distributions in the $x - z$ plane corresponding to G_0 , as function of Δt_w . It turns out that $\Delta t_w = 21.28$ ns is the best estimate.

A comparison with the time-walk functions in figure 5.2.11d is not trivial; for the mean time-walk values, as extracted from the confidence level distributions, a significant fraction of bad data is cut away and time-walk is assumed to be Gaussian, whereas the functions in figure 5.2.11d have been estimated using all data

Table 5.2.4: Optimal Δt_w as found by minimizing the χ^2 of a flat line fit through the fit probabilities (second column). Mean Δt_w as found by disentangling time-walk from the time spectrum (third column).

GridPix No.	Δt_w (ns) from conf. lev.	Δt_w (ns) from timewalk func.
0	21.3	25.9
1	18.9	24.8
2	23.0	26.6

and they are clearly not Gaussian. It is assumed that cutting on the confidence levels of the track fits effectively results in cutting away tracks with time-walk dominated hits e.g. approximately $\gtrsim 3\sigma \approx 60$ ns. The third column in table 5.2.4 shows the means of the functions in figure 5.2.11d calculated within a 3σ window. The table shows a reasonable consistency between the two methods despite the simplifications made.

Figure 5.2.14 shows the probability distributions of the fits after optimising time-walk. Note that from now on the same order is used for many of the upcoming histograms.

For $x - z$ it is flat between 0.1 and 0.99. Due to time-walk, delta electrons, etc. tracks that would have been in the central region of the spectrum are now pulled towards the left. This results in an excess below 0.1 and a slight dip in the central region. For both projections a peak shows up at 1.0. This is related to tracks giving hits that are all in the same row of pixels, referred to as “one line tracks”, which have a χ^2 of 0. One line tracks are most likely to occur for low diffusion and tracks near the centre of a row of pixels. These events therefore come from the high probability end of the spectrum. This accounts for the slight dip above 0.8. All three confidence level distribution for $x - z$ are approximately flat in most of the central part (0.1 – 0.8).

However the distribution $y - z$ tend to decrease with the probability. This effect has been studied using a toy Monte-Carlo simulation. It turns out that the decrease is the result of double hits. Since two electrons released near the same position are only measured as two electrons when one has a diffusion larger than approximately the size of a pixel, the error on the track is slightly worse than expected. This effect is not visible in the $x - z$ plane since time-walk washes it out.

The effect of delta electrons should be the same for fits in both $x - z$ and $y - z$. The difference in width of the peak at 0 suggests that time-walk effects dominate badly reconstructed tracks.

Figure 5.2.15 shows the pull distributions for the fits in $x - z$ and $y - z$. The distributions are centred around zero. In addition there is very little z depen-

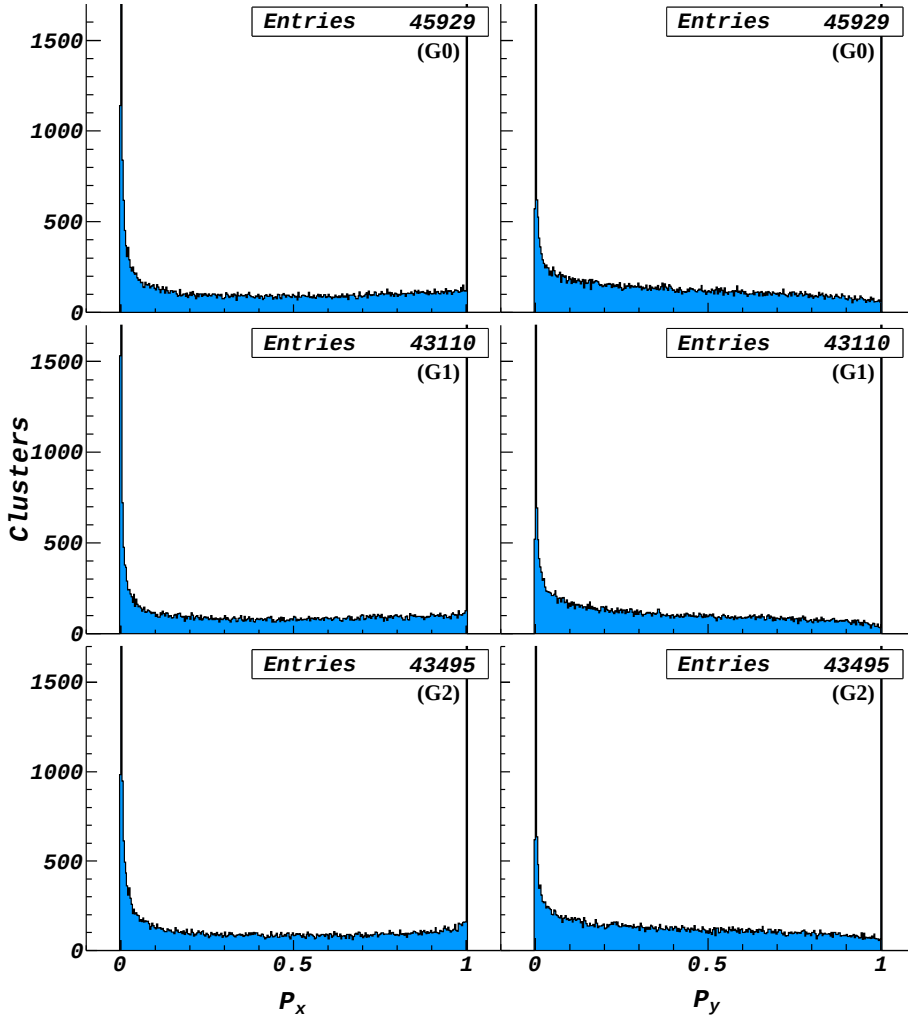


Figure 5.2.14: The confidence level distributions of track fits done in the $x-z$ (left column) and $y-z$ (right column) planes for G_0 (first row), G_1 (second row) and G_2 (third row). Tracks with all hits in one line show up at a confidence level of one.

dence, suggesting a reasonable understanding of the errors as function of z . The asymmetric trend is a result of time-walk.

Figure 5.2.16 shows the projected distributions of figure 5.2.15. The distributions are centred at zero with width 0.8. This is reduced from 1.0 because two

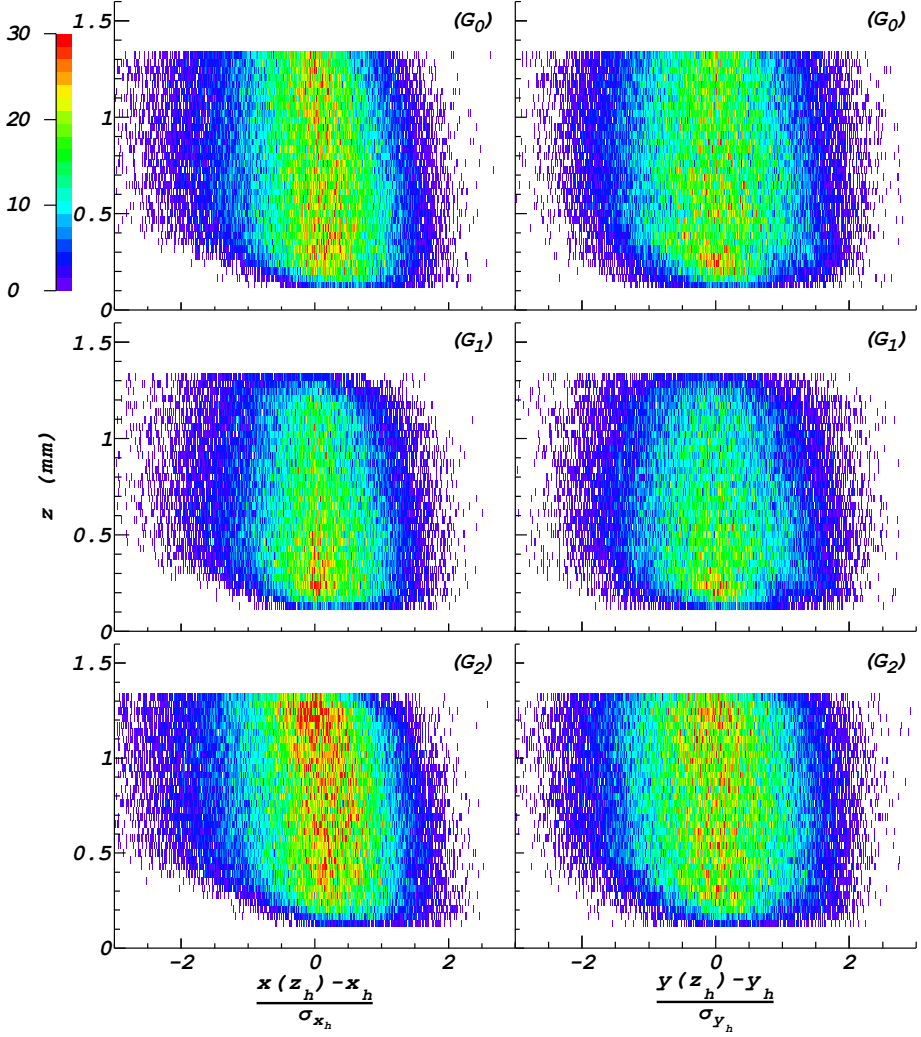


Figure 5.2.15: The pull distributions as function of the height of the hits for the fits done in both planes (same definitions as in figure 5.2.14). Hits with a 3σ distance from the fitted track in the z -direction as well as tracks with a confidence level $<10\%$ and $<5\%$ for fits done in the $x-z$ and $y-z$ plane respectively are excluded.

measure points are sacrificed to estimate the fitting parameters. The correction factor is $\sqrt{\mu/\text{ndf}}$, where μ is the mean number of hits per track as can be extracted

from figures 5.2.8. For a 2D line fit the number of degrees of freedom $\text{ndf} = \mu - 2$. Table 5.2.5 shows the corrected widths of the distributions in figure 5.2.15.

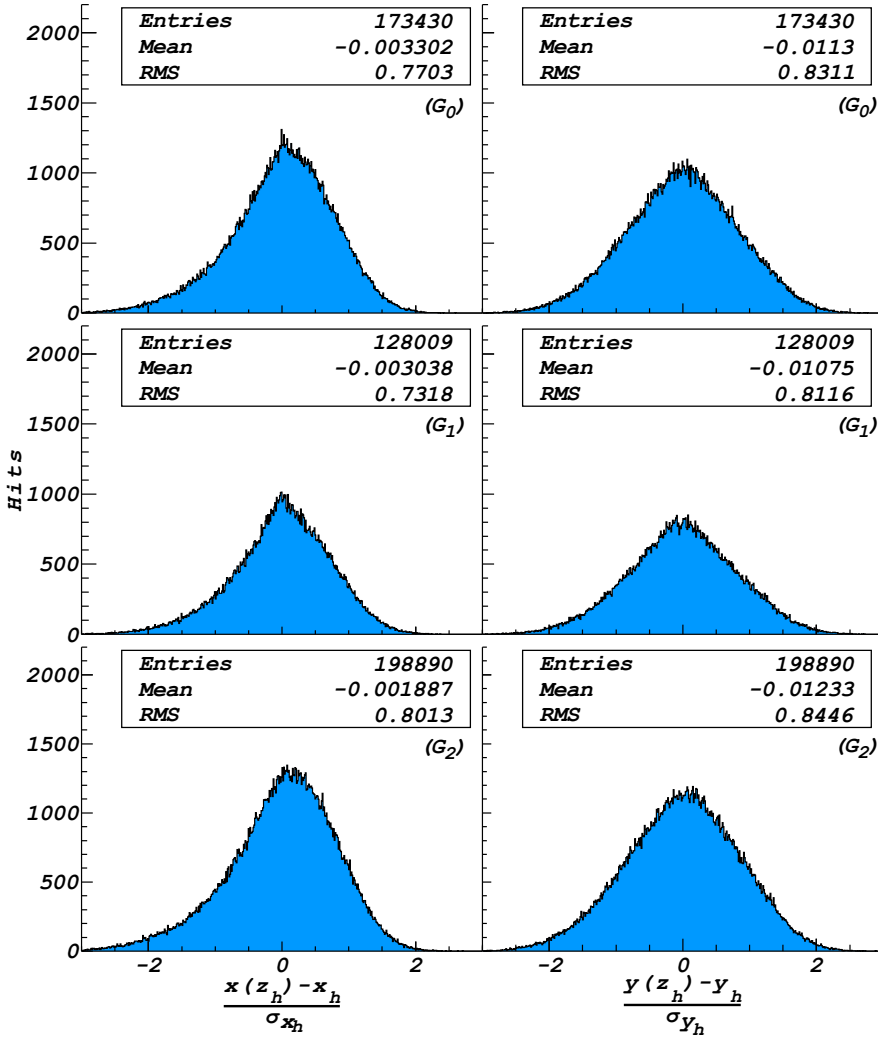


Figure 5.2.16: The pull distributions corresponding to figure 5.2.15. The distributions are centred at zero suggesting successful fits. The initial widths of about 1 reduce to about 0.8 as a result of the cuts on the quality of the hits and the fits.

Table 5.2.5: Corrected widths from figure 5.2.16

GridPix	width in $x - z$	width in $y - z$
0	0.89	0.96
1	0.88	0.97
2	0.91	0.96

The widths deviate from 1.0 due to the dropping of outliers and selecting only tracks with confidence level $>10\%$ and $>5\%$ for the $x - z$ and $y - z$ planes. These cuts reduce the effects of time-walk to the fits, but they also affect the width of the distributions. It is checked that without cuts the width of the distributions is about 1.0. In addition a Monte-Carlo simulation shows similar results.

Positional and Angular Resolutions

Figures 5.2.14 to 5.2.16 suggest a reasonable understanding of the hit errors. Therefore the errors on the fitted positional parameters give an indication of the track resolution of the detectors. Figure 5.2.17 shows the distributions of the positional errors for all tracks passing the cuts, obtained from the covariance matrix for each track fit given by Williamson and York's method. The resolution varies depending mainly on the number of hits and where they are in z . The mean resolutions are about $40 \mu\text{m}$ and $13 \mu\text{m}$ in x - and y -directions. In a similar way the error on the track angles can be extracted from the covariance matrices. Figure 5.2.18 shows the errors on the angular parameters. The average angular resolution of the detectors is about 70 mrad in ω and 45 mrad in ν respectively.

The fit parameter b_x and b_y and the centre of gravity $\bar{z}$ make a point $(b_x, b_y, \bar{z})$ which lies on the fitted track. In the local coordinate frame in which the fit is carried out only the errors on b_x and b_y matter. However when transforming to another coordinate system, as will be done later for telescope track analysis, the error in $\bar{z}$ also becomes important. In fact the detector has a more fundamental set of resolution parameters $(\sigma_x, \sigma_y, \sigma_{\bar{z}})$ from which the errors $(\sigma_{b_x}, \sigma_{b_y}, 0)$ can be derived. The error in $\bar{z}$ projects onto the track (analogous to fitting with errors in both coordinates) according to the slope of the track:

$$\begin{aligned}\sigma_{b_x}^2 &= m_x^2 \sigma_{\bar{z}}^2 + \sigma_x^2 \\ \sigma_{b_y}^2 &= m_y^2 \sigma_{\bar{z}}^2 + \sigma_y^2.\end{aligned}\tag{5.17}$$

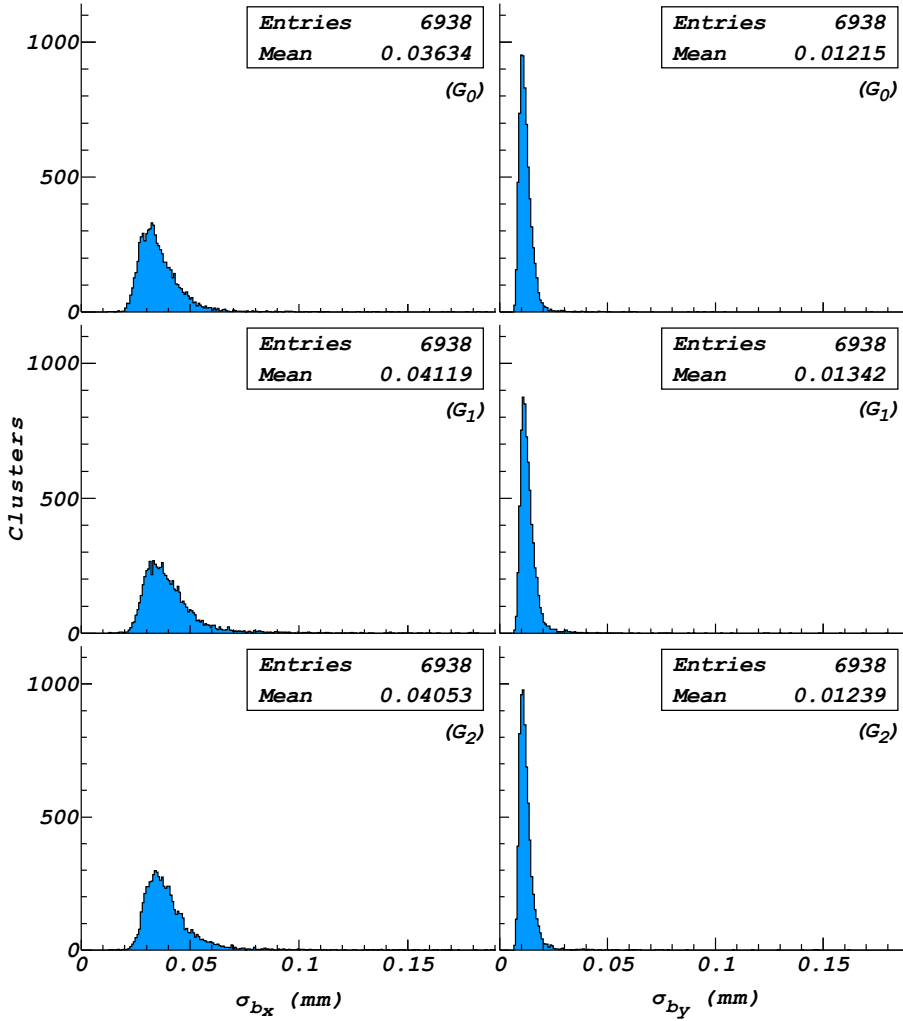


Figure 5.2.17: In the familiar order, the positional error distribution from the covariance matrices measured by the standalone detectors. The average error gives an indication of the resolution and is about 40 μm in the x - and 13 μm in the y -direction for all detectors.

From the symmetry of the detector, $\sigma_x = \sigma_y$ so σ_z can be expressed as:

$$\sigma_z^2 = \frac{\sigma_{bx}^2 - \sigma_{by}^2}{m_x^2 - m_y^2}. \quad (5.18)$$

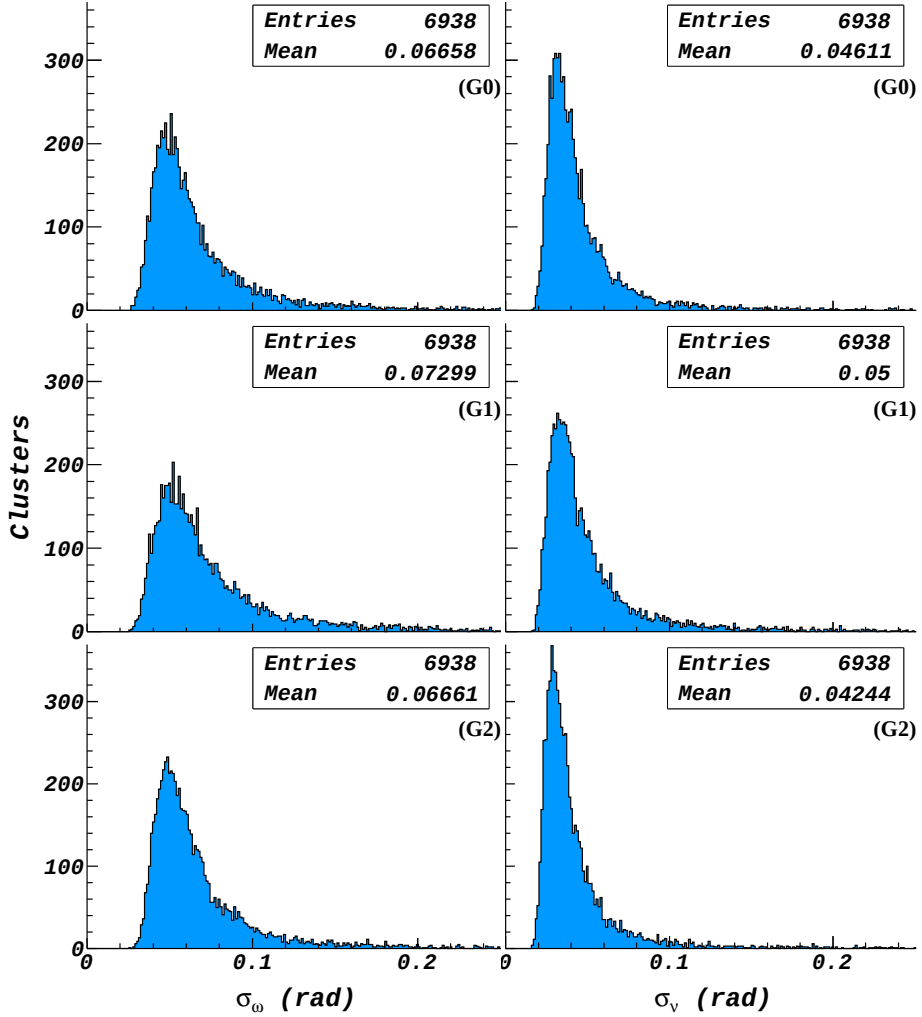


Figure 5.2.18: In the familiar order, the angular error distribution from the covariance matrices measured by the standalone detectors. The average error gives an indication of the resolution and is about 70 mrad in the $x - z$ plane and 45 mrad in the $y - z$ plane.

Since the slopes m_x and m_y are known, σ_z can be extracted. By filling in σ_z in equation 5.17 also $\sigma_{x,y}$ is extracted.

Doing this for each fitted track results in figure 5.2.19. It can be seen that because the errors in z are taken out, the means of the histograms in figure 5.2.17

reduce to the means of figure 5.2.19 (left column). Tracks with more hits have better resolution, but the position resolutions overlap giving one smooth peak.

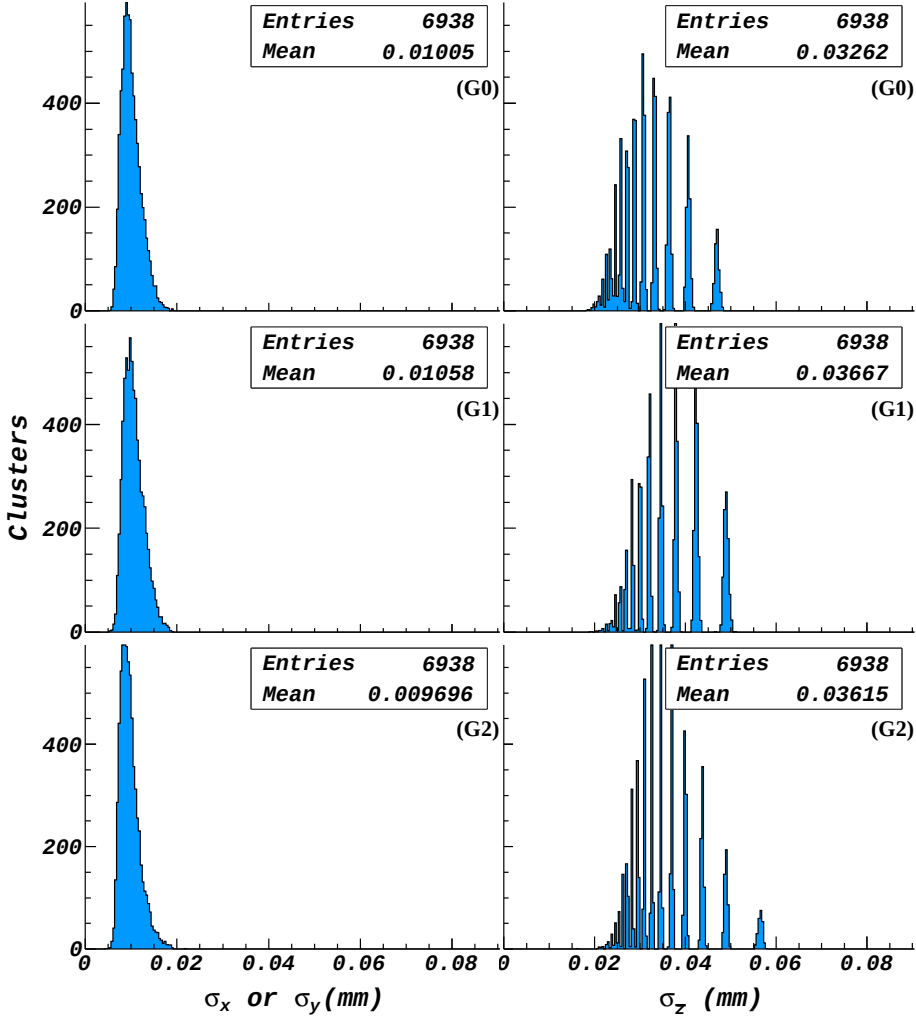


Figure 5.2.19: In the familiar order, the positional error distribution in the x - and z -directions as measured by the standalone detectors. The error in y equals the error in x . The spikes on the right are due to the different number of hits in the track; see the text.

The right column of figure 5.2.19 shows the errors in z for every fit in each detector. The peaks are related to the number of hits (N) participating in the fit. The peaks at the far right correspond to fits with three hits. Clearly the value of the error in z is approximately proportional to $\sqrt{N}$. The average errors in the x -direction are about $10\ \mu\text{m}$, the average errors in the z -direction depend heavily on the number of hits, averaging about $35\ \mu\text{m}$. G_0 has the best performance due to its high gain and having no SU-8 residuals blocking pixels, which makes G_1 have the worst performance.

The angular spread of the particles in the beam is small compared with the angular resolution. Therefore, as a consistency check, the mean errors in 5.2.18 can be compared with the widths of the angular distribution of the tracks. Figure 5.2.20 shows the angular distributions from the fitted tracks in the standalone detectors. The widths lie between the mode and the mean values in figure 5.2.18, giving further confidence in the analysis.

5.2.5 Local Track Fit Summary

The 2012 data has been analysed treating each Gossip on its own. Several important steps went into the analysis. Bad events and pixels have been filtered out; the raw data has been calibrated to distances; multiple tracks per event are successfully disentangled; the drift velocity is estimated accurately through knowledge of the track angle; the electric field has been determined with Magboltz followed by the diffusions.

The time-walk error has been estimated by requiring a flat confidence level. The tracks were fitted with Williamson and York's method. The flatness of the confidence levels, the dependencies of the pull distributions and the widths confirm the quality of the analysis.

The covariance matrices from the track fits give the positional and angular track errors, from which the detector resolution can be characterised. For a good Gossip detector (G_0), the track position resolution is $(\sigma_x, \sigma_y, \sigma_z) = (10.1, 10.1, 32.6)\ \mu\text{m}$. σ_z is dominated by time-walk which can be almost eradicated in future chips such as TimePix-3.

In the next section the detectors are combined into a telescope, as a further check of the track resolutions derived here.

5.3 Telescope Detector Alignment

The previous section gives the spatial and angular resolutions derived from the stand-alone track fits. The arrangement of three similar GridPix detectors as a telescope along the beam allows further stringent tests. Tracks fitted through two detectors can be compared to the local fit through the third detector. The large

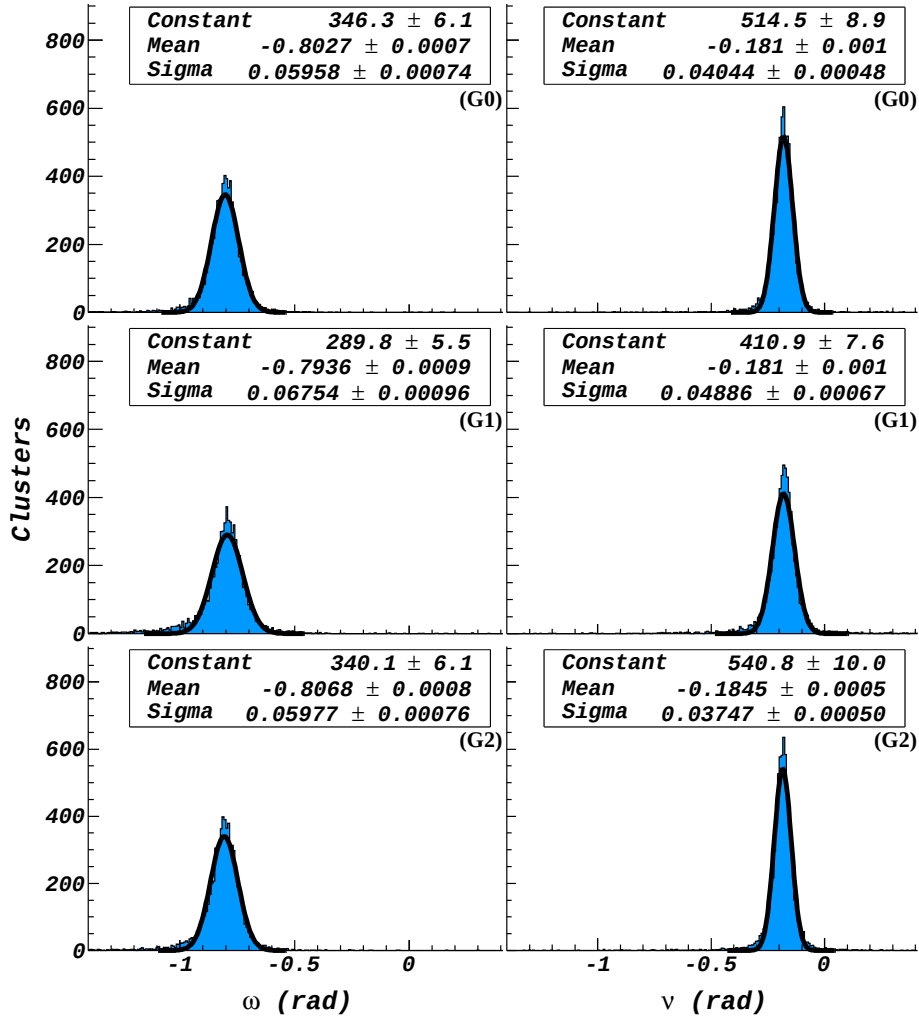


Figure 5.2.20: In the familiar order, the fitted angular distribution from the fitted tracks in the standalone detectors. The widths give the average angular resolution and lie between the means and the modes in figure 5.2.18 (NB. the means are not precisely at $46.0^\circ = 0.803$ rad due to minor analysis changes made after deriving the drift velocities).

spacing along the beam gives very high precision on the track angle, even in presence of systematic errors in the local fits.

The telescope tracks are determined by transforming the local track fits to a global reference frame. The telescope track is then chosen to pass through the (b_x, b_y) intercept of two detectors; here the angles are not used. This requires transformations from the local to global frame. These transformations are derived in a “software alignment procedure” described in this section.

5.3.1 Alignment Overview

The most important alignment parameters are measured using global tracks by studying residuals. The procedure is iterative: an initial guess of the parameters gives residuals not centred around zero. The offset gives a measure of how far out the current system is. With this the guess is updated and the procedure is repeated.

It is on purpose that no χ^2 minimisation procedure is used for the alignment. Such a procedure tends to find the mean of the distributions. Because of the presence of distributions with tails to one side at large angles, selection of the most probable value is desired. Therefore the alignment is performed by iteratively fitting Gaussians to the distributions, reducing the effect of the tails.

For the fitting of tracks for alignment two approaches are considered:

- Transformation of all individual hits in local tracks of all 3 detectors to the global frame before fitting a track through all hits.
- Transformation of the fitted crossing points of the local fits in all detectors to the global frame and fitting them with a straight line.

The ratio between the separation of individual hits in a detector and the distance between detectors is about $1/165$, consequently a cluster of hits in a detector is approximately seen as one point weighted by all hits inside the detector. Therefore the difference between the first and the second approach is expected to be negligible. For practical reasons it was decided to use the second approach.

In the alignment procedure the angles of the tracks are not taken into account. There are two reasons for this: due to time-walk the precision of the angles from a fit in individual detectors is poor compared to the angles of the telescope track; in addition the accuracy on the drift velocity that propagates to the angles is insufficient. Hence only the telescope track angle is used in the alignment.

Before using the alignment procedure it was successfully tested using a toy Monte-Carlo simulation.

5.3.2 Global Frame Definition

Every detector has 6 parameters: three translations $(x_{G_i}, y_{G_i}, z_{G_i})$ and three rotations $(\alpha_{G_i}, \beta_{G_i}, \gamma_{G_i})$ as defined in table 5.2.1 and sketched in figure 5.2.2, giving a total of 18.

Six of these are fixed by choosing a particular global reference frame, without any loss of precision. The z -axis is chosen to pass through the centres of G_0 and G_2 with $z = 0$ centred in G_1 . The y -axis is pointed approximately vertically up, by fixing the γ angle of G_0 to 10° , which was its nominal roll angle:

For G_0 :

$$\begin{pmatrix} x_{G_0} \\ y_{G_0} \\ \gamma_{G_0} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ -0.1745 \end{pmatrix}; \quad (5.19)$$

G_1 :

$$(z_{G_1} = 0); \quad (5.20)$$

and G_2 :

$$\begin{pmatrix} x_{G_2} \\ y_{G_2} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}. \quad (5.21)$$

The definition of the global frame leaves 12 degrees of freedom. From these x_{G_1} , y_{G_1} , γ_{G_1} and γ_{G_2} have dominant contributions to the resolutions.

Determination of z

The parameters z_{G_0} and z_{G_2} are manually measured with about 1 mm accuracy. Since $1 \text{ mm} \ll 165 \text{ mm}$, the distance between two detectors, the result on the resolution due to misalignment in the z -direction can be neglected. A study on the effect on the width of the residuals by variation of the nominal values of z did not show differences, since the residuals were too broad to observe significant changes. Therefore the contribution of the misalignment of parameters z_0 and z_2 can be neglected. Below the values are presented:

$$\begin{pmatrix} z_{G_0} \\ z_{G_2} \end{pmatrix} = \begin{pmatrix} -165 \\ 165 \end{pmatrix}. \quad (5.22)$$

Weak Modes

A weak mode is a geometric distortion which leaves the fit quality of tracks unchanged. In the remaining set of alignment parameters every angle α , β and γ has two weak modes. The first occurs when all three detectors are rotated by the same angle about their x - or y -axis. Setting α_{G_0} and β_{G_0} at their nominal angles fixes these. Figure 5.3.1 illustrates the second weak mode. The fit quality does not change when α_{G_1} , β_{G_1} or γ_{G_1} has an angle of half α_{G_2} , β_{G_2} or γ_{G_2} . Setting α_{G_2} , β_{G_2} , γ_{G_2} at their nominal values fixes these. That is to achieve convergence in the iterations. We set:

$$\begin{pmatrix} \alpha_{G_0} \\ \beta_{G_0} \end{pmatrix} = \begin{pmatrix} 0 \\ 0.8001 \end{pmatrix} \quad (5.23)$$

and

$$\begin{pmatrix} \alpha_{G_2} \\ \beta_{G_2} \\ \gamma_{G_2} \end{pmatrix} = \begin{pmatrix} 0 \\ 0.8001 \\ -0.1745 \end{pmatrix}. \quad (5.24)$$

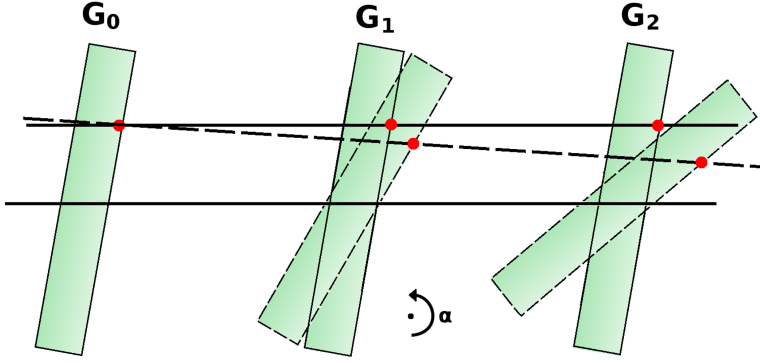


Figure 5.3.1: An illustration of the weak mode of angle α ; the result is a continuum rather than an unique solution. This problem is cancelled by fixing α_{G_2} to its nominal value.

The definition of the global frame, the measurement of detector positions along z and the method to cancel the effect of weak modes reduces the number of parameters from the initial 18 to 12 to 10 to 5 respectively; and with the choices made all 5 are alignments of G_1 . The parameters $x_{G_1}, y_{G_1}, \alpha_{G_1}, \beta_{G_1}$ and γ_{G_1} are found in the software alignment.

5.3.3 Alignment Parameters

Table 5.3.1 shows the nominal transformation parameters. In here the parameters are divided in four groups, using superscripts:

- (1) parameters used to define the global frame;
- (2) parameters insensitive and therefore not used in the iteration;
- (3) parameters that fix weak modes;
- (4) parameters varied for alignment.

It is convenient to split the alignment parameters in two parts: a nominal value, plus a deviation from nominal referred to as a differential value. The nominal values are used as the start point and then each iteration gives a new set of differential corrections to be added to the nominal.

Table 5.3.1: Nominal alignment correction; distances in millimetres, angles in radians. Only parameters with superscript (4) are varied.

GridPix	x_G	y_G	z_G	α_D	β_D	γ_D
0	$0^{(1)}$	$0^{(1)}$	$-165^{(2)}$	$0.8001^{(3)}$	$0^{(3)}$	$-0.1745^{(1)}$
1	$0^{(4)}$	$0^{(4)}$	$0^{(1)}$	$0.8001^{(4)}$	$0^{(4)}$	$-0.1745^{(4)}$
2	$0^{(1)}$	$0^{(1)}$	$165^{(2)}$	$0.8001^{(3)}$	$0^{(3)}$	$-0.1745^{(3)}$

5.3.4 Point Transformation

Equation 5.25 shows the transformation of a local point (x, y, z) to a global point (x', y', z') . It is a function of nominal and differential translations $(x_G^{\text{nom}}, y_G^{\text{nom}}, z_G^{\text{nom}})$ and $(x_G^{\text{diff}}, y_G^{\text{diff}}, z_G^{\text{diff}})$ and rotations $(\alpha_G^{\text{nom}}, \beta_G^{\text{nom}}, \gamma_G^{\text{nom}})$ and $(\alpha_G^{\text{diff}}, \beta_G^{\text{diff}}, \gamma_G^{\text{diff}})$ respectively. In general rotations are performed first followed by translations. Rotations are performed around the z –, the new y – and the new x –axis in that order, referred to as the Euler 321 sequence:

$$\begin{aligned}
 \begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} &= \mathbf{R}_G^{\text{diff+nom}} \cdot \begin{pmatrix} x \\ y \\ z \end{pmatrix} - \mathbf{T}_G^{\text{diff+nom}} \\
 &= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(\beta_G^{\text{diff}} + \beta_G^{\text{nom}}) & -\sin(\beta_G^{\text{diff}} + \beta_G^{\text{nom}}) \\ 0 & \sin(\beta_G^{\text{diff}} + \beta_G^{\text{nom}}) & \cos(\beta_G^{\text{diff}} + \beta_G^{\text{nom}}) \end{pmatrix} \cdot \\
 &\quad \begin{pmatrix} \cos(\alpha_G^{\text{diff}} + \alpha_G^{\text{nom}}) & 0 & \sin(\alpha_G^{\text{diff}} + \alpha_G^{\text{nom}}) \\ 0 & 1 & 0 \\ -\sin(\alpha_G^{\text{diff}} + \alpha_G^{\text{nom}}) & 0 & \cos(\alpha_G^{\text{diff}} + \alpha_G^{\text{nom}}) \end{pmatrix} \cdot \quad (5.25) \\
 &\quad \begin{pmatrix} \cos(\gamma_G^{\text{diff}} + \gamma_G^{\text{nom}}) & -\sin(\gamma_G^{\text{diff}} + \gamma_G^{\text{nom}}) & 0 \\ \sin(\gamma_G^{\text{diff}} + \gamma_G^{\text{nom}}) & \cos(\gamma_G^{\text{diff}} + \gamma_G^{\text{nom}}) & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} x \\ y \\ z \end{pmatrix} \\
 &\quad - \begin{pmatrix} x_G^{\text{diff}} \\ y_G^{\text{diff}} \\ z_G^{\text{diff}} \end{pmatrix} - \begin{pmatrix} x_G^{\text{nom}} \\ y_G^{\text{nom}} \\ z_G^{\text{nom}} \end{pmatrix}.
 \end{aligned}$$

For each fit the variance-covariance matrix $\mathbf{c}$ is composed of the local positional resolutions $\sigma_x, \sigma_y, \sigma_z$ as histogrammed in figure 5.2.19 as:

$$\mathbf{c} = \begin{pmatrix} \sigma_x^2 & 0 & 0 \\ 0 & \sigma_y^2 & 0 \\ 0 & 0 & \sigma_z^2 \end{pmatrix}. \quad (5.26)$$

It is assumed that there is negligible correlation between the track parameters $(b_x, b_y, \bar{z})$ i.e. the off-diagonal elements in the covariance matrix are zero. Note that $\sigma_x^2 = \sigma_y^2$. In general the transformation of a covariance matrix from one frame to another frame is performed as [82]:

$$\mathbf{c}' = \mathbf{D} \cdot \mathbf{c} \cdot \mathbf{D}^T, \quad (5.27)$$

where D is the derivative matrix:

$$\mathbf{D} = \begin{pmatrix} \frac{\delta x'}{\delta x} & \frac{\delta x'}{\delta y} & \frac{\delta x'}{\delta z} \\ \frac{\delta y'}{\delta x} & \frac{\delta y'}{\delta y} & \frac{\delta y'}{\delta z} \\ \frac{\delta z'}{\delta x} & \frac{\delta z'}{\delta y} & \frac{\delta z'}{\delta z} \end{pmatrix}. \quad (5.28)$$

Hence the covariance matrix $\mathbf{c}$ of each fit in a specific detector G transforms to the global frame as:

$$\mathbf{c}'_G = \mathbf{R}_G^{\text{diff+nom}} \cdot \mathbf{c}_G \cdot (\mathbf{R}_G^{\text{diff+nom}})^T. \quad (5.29)$$

5.3.5 Slope Transformation

The result of a track fit in the local frame is expressed by start point $\mathbf{p} = (b_x, b_y, \bar{z})$ and slopes m_x, m_y . Equation 5.25 transforms $\mathbf{p}$ to the global frame. Similarly a point $\mathbf{q} = (b_x + m_x \delta z, b_y + m_y \delta z, \bar{z} + \delta z)$ on the track at distance δz along in z is transformed to the global frame.

Then the slopes in the global frame are:

$$m'_x = \frac{q'_x - p'_x}{q'_z - p'_z} \quad (5.30)$$

$$m'_y = \frac{q'_y - p'_y}{q'_z - p'_z}. \quad (5.31)$$

5.3.6 Alignment Procedure

The alignment is carried out in two stages. First the dominant alignment parameters x_{G_1} , y_{G_1} and γ_{G_1} are found in four iterations. Then the remaining parameters α_{G_1} and β_{G_1} are found. The stages are repeated until a convergence is reached. Both stages use hit residuals; the distance from a measured position of a hit to the global track.

To ensure sufficiently precise local tracks and to remove noise hits, only tracks with 3 or more hits in every detector are selected for the alignment. In addition events in which one or more of the local fits have a confidence level of $< 10\%$ or $< 5\%$ in the fit done in $x - z$ and $y - z$ respectively, are rejected. About 10 % of the total number of events pass these requirements.

Equation 5.32 shows the global track composed of global points in $(b_{x_0}, b_{y_0}, \bar{z}_0)$ and $G_2(b_{x_2}, b_{y_2}, \bar{z}_2)$. The composition of global tracks in the other detectors is done in a similar way:

$$\begin{aligned} X'(z') &= m'_X z' + b'_X \\ Y'(z') &= m'_Y z' + b'_Y. \end{aligned} \quad (5.32)$$

Here the slopes and the intercepts of the global track in the global $x - z$ and $y - z$ planes are:

$$\begin{aligned} m'_X &= \frac{b_{x'_2} - b_{x'_0}}{\bar{z}'_2 - \bar{z}'_0} \\ m'_Y &= \frac{b_{y'_2} - b_{y'_0}}{\bar{z}'_2 - \bar{z}'_0} \\ b'_X &= \frac{b_{x'_0} \bar{z}'_2 - b_{x'_2} \bar{z}'_0}{\bar{z}'_2 - \bar{z}'_0} \\ b'_Y &= \frac{b_{y'_0} \bar{z}'_2 - b_{y'_2} \bar{z}'_0}{\bar{z}'_2 - \bar{z}'_0}. \end{aligned} \quad (5.33)$$

The list below explains how the alignment parameter correction per iteration step is obtained:

- x_{G_i} The residual $X'(\bar{z}'_1) - b'_{x_i}$ is plotted and fitted with a Gaussian. The fitted mean is used to perform a shift;
- y_{G_i} The residual $Y'(\bar{z}'_1) - b'_{y_i}$ is plotted and fitted with a Gaussian. The fitted mean is used to perform a shift;
- γ_{G_i} The residual $\text{atan2}[Y'(\bar{z}'_1), X'(\bar{z}'_1)] - \text{atan2}[y'_1, x'_1]$ is plotted and fitted with a Gaussian. The fitted mean is used to perform a tilt.
- α_{G_i} a scatter plot of the residual $X'(\bar{z}'_1) - b'_{x_i}$ is plotted versus $\bar{z}'_1$ and fitted with a straight line. The arctangent of the slope defines the rotation;
- β_{G_i} a scatter plot of the residual $Y'(\bar{z}'_1) - b'_{y_i}$ is plotted versus $\bar{z}'_1$ and fitted with a straight line. The arctangent of the slope defines the rotation.

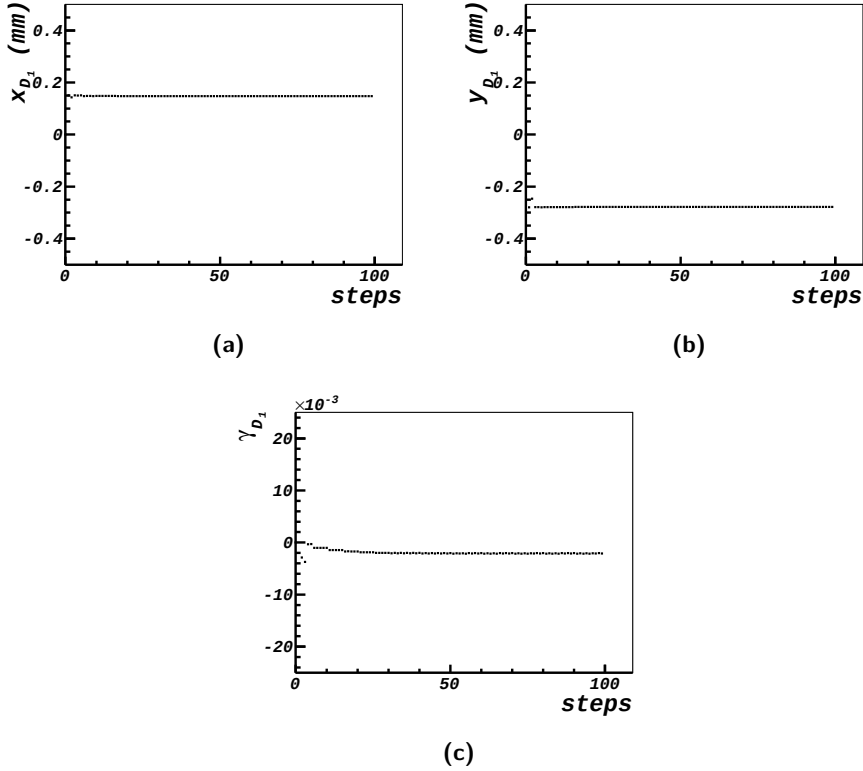


Figure 5.3.2: The convergence monitor of a) x_{G_1} , b) y_{G_1} and c) γ_{G_1} as function of the iteration steps. Every 5 steps α_{G_1} and β_{G_1} are re-evaluated.

5.3.7 Alignment Results

The above alignment procedure has been used to align the detectors in the beam telescope in run 89. Figure 5.3.2 shows the convergence of the alignment parameters x_{G_1} , y_{G_1} and γ_{G_1} . Figure 5.3.3 shows the convergence of α_{G_1} and β_{G_1} .

Figures 5.3.4 show the final positional residuals of all detectors from top to bottom: the telescope track composed of G_1 and G_2 with respect to G_0 ; the telescope track composed of G_0 and G_2 with respect to G_1 ; and the telescope track composed of G_0 and G_1 with respect to G_2 . The residuals are unbiased meaning that the specific detector is not used for the telescope track. Consequently the widths of the residuals of the centre detector G_1 are about half the width of G_0 and G_2 ,

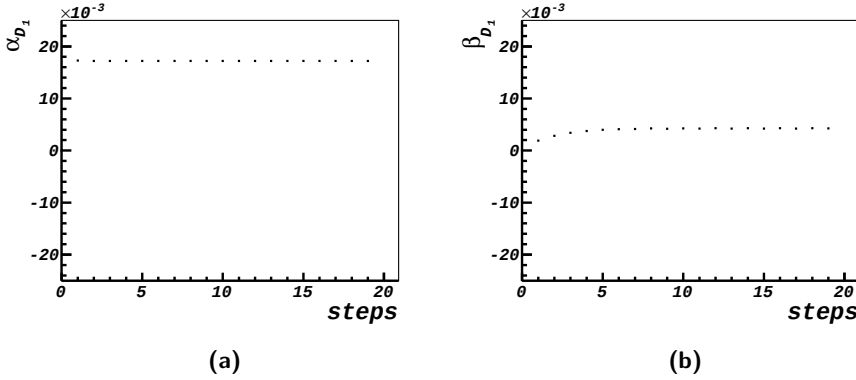


Figure 5.3.3: The convergence of a) α_{D_1} and b) β_{D_1} as function of the iteration steps.

because of extrapolation. The distributions are peaked around zero suggesting a successful alignment.

Figure 5.3.5 shows the final angular residuals. As has been mentioned, the fitted angles are affected by time-walk, particularly α , and they are not used for alignment. Figure 5.3.6 shows a small offset because of this effect for all detectors. The offset for α are of order 20 times their precision; those of β are about 10 times their precision.

The resulting differential shifts in positions and angles after iteration are shown in table 5.3.2. The values are consistent with expectations for misalignments.

Table 5.3.2: Differential alignment corrections for aligned data from run 89; distances in μm , angles in mrad.

GridPix No.	x	y	z	α	β	γ
0	0	0	0	0	0	0
1	148	-278	0	-16.6	3.03	-1.48
2	0	0	0	0	0	0

5.3.8 Alignment Summary

The global telescope frame has been defined in order to compare the tracks in a common frame. The transformation of the tracks to the global frame has been

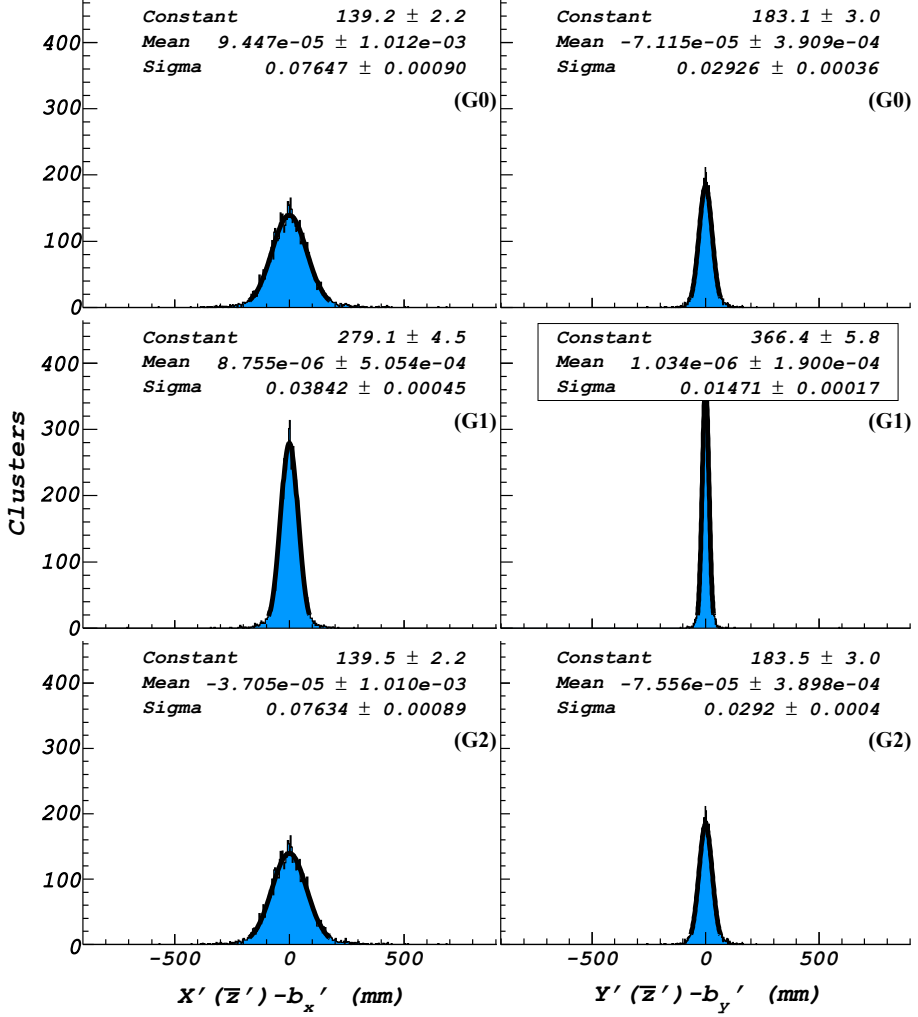


Figure 5.3.4: In the familiar order, the positional residuals in the global (telescope) frame. The distributions are centred around zero suggesting a successful alignment. The widths in the centre detector are about half the width of the residuals of the detectors on the outside because of extrapolation of the telescope track. The usual fit quality cuts are used.

done. Since time-walk affects the slopes, they are not taken into account in the iterative procedure. Instead the positions were used to obtain the angles. The correction on the parameters converges as is expected for a successful alignment.

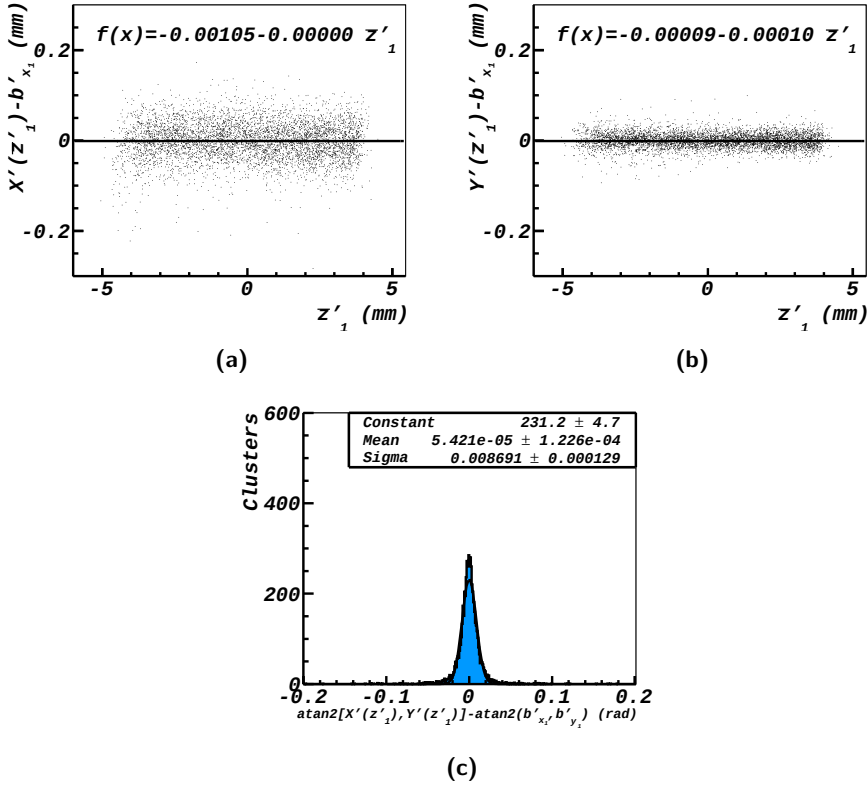


Figure 5.3.5: The final residuals of a) α_{G_1} , b) β_{G_1} and c) γ_{G_1} . All distributions are centred at zero suggesting a successful alignment.

The resulting residuals are centred as expected, except for small offsets in the angles which results from time-walk.

5.4 Telescope Resolution Check

Armed with the local-to-global transformation alignment parameters, and telescope tracks from the above alignment procedure, the track resolutions of the Gossips can be derived using the telescope. The results can be compared with the track resolutions derived from local track fits in section 5.2.4. This gives a stringent cross-check of the methods used.

Most of the work has been done in section 5.3. We again take tracks defined by G_0 and G_2 (equation 5.32). The track prediction at G_1 is compared with the local

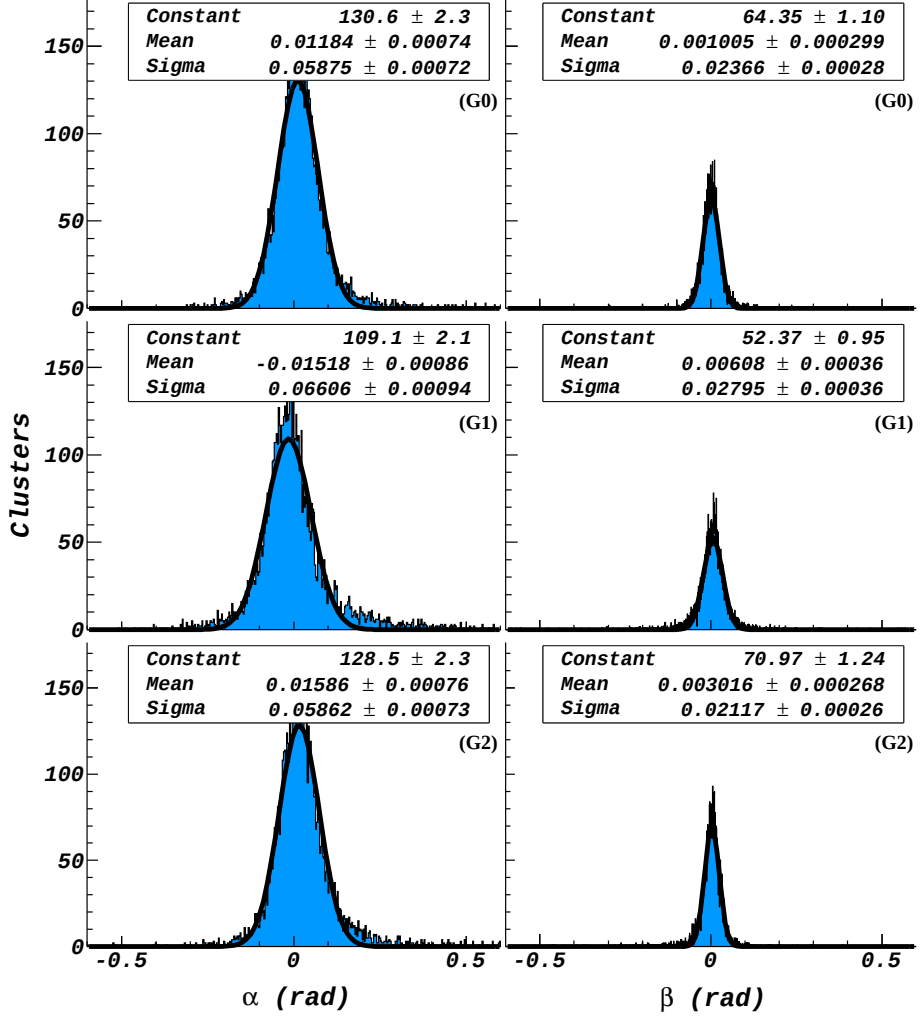


Figure 5.3.6: Residuals of the local track with respect to the telescope track, measured in the global frame. The effect of time-walk results in a systematic offset in the angles, this effect is larger in α than in β because of the larger slope. In addition this results in larger tails on one side.

measurement by G_1 transformed to the global frame; these residual distributions are shown in the centre row of figure 5.3.4. Their widths σ'_R are the results of

several contributions: the detector resolution σ'_{G_1} , the telescope resolution σ'_T and multiple scattering σ'_{MS} :

$$\sigma_R'^2 = \sigma_T'^2 + \sigma_{G_1}'^2 + \sigma_{MS}'^2. \quad (5.34)$$

Our task is to extract σ'_{G_1} from this. σ'_R is measured from figure 5.3.4; the next section calculates σ'_{MS} which is more or less negligible; and section 5.4.2 derives σ'_T in terms of σ'_{G_0} and σ'_{G_2} . We then assume all detectors have the same performance allowing equation 5.34 to be solved for σ'_{G_1} . Note that if we omit a contribution to σ'_R in equation 5.34 we overestimate σ'_{G_1} .

5.4.1 Multiple Scattering

The muon direction changes during passage through the material due to multiple Coulomb scattering. Each Gossip has the same amount of material $x/X_0 = 2.77\%$ for normal incidence, see section 5.1.2. This increases with $1/\cos \varphi$, for an angle of incidence φ . For $\varphi = 45^\circ$, this results in an $1/\cos \varphi = \sqrt{2}$ increase.

The RMS scattering angle projection on a plane from Moliere's Theorem [83] is:

$$\begin{aligned} \theta_0 &= \frac{13.6}{\beta c p} z \sqrt{\frac{x}{X_0}} [1 + 0.0038 \ln(\frac{x}{X_0})] \\ &= \frac{13.6}{p(\text{MeV})} z \sqrt{\frac{x}{X_0} \frac{1}{\cos \varphi}} \\ &= 14.8 \mu\text{rad}. \end{aligned} \quad (5.35)$$

The RMS deviation in both the x - and y -directions in the next Gossip, situated 165 mm downstream is $\theta_0 \ell = 2.4 \mu\text{m}$. This affects the track fit which tends to reduce the effect of multiple scattering on residuals. For extrapolating a track through G_0 and G_1 , the scattering in G_0 is fully absorbed in the fit. The residual contribution in G_2 is then only this $2.4 \mu\text{m}$, due to scattering in G_1 . By symmetry, the same is true for residuals in G_0 .

We are interested in the residuals in G_1 . From figure 5.4.1 the fitted track goes through the hit position in G_0 and G_2 . The track position in G_1 is $1/2(\theta_{G_1} \ell + 2\theta_{G_0} \ell)$, while the hit position in G_1 is $\theta_{G_0} \ell$; the difference is the residual $r = \theta_{G_0} \ell / 2$, so in G_1 the contribution of multiple scattering is $1.2 \mu\text{m}$.

This is rather negligible compared to the other contributions, but is included for completeness.

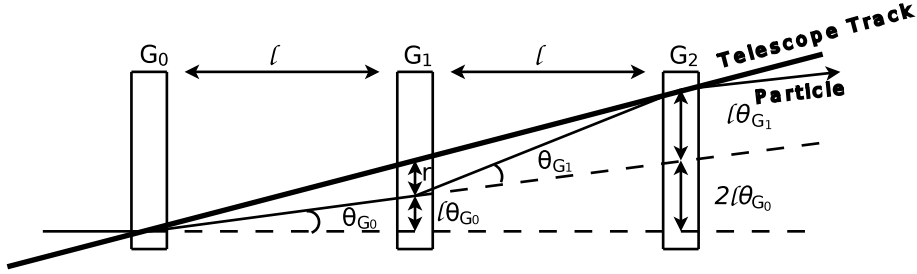


Figure 5.4.1: Residuals in G_1 due to multiple scattering. Because the fitted track absorbs much of the effect of multiple scattering, the residual is reduced.

5.4.2 Telescope Error

Equation 5.32 gives the expression for the telescope track. With the simplification, for error calculation purposes, that $\bar{z}'_1 \approx 0$ and $\bar{z}'_1 - \bar{z}'_0 \approx \bar{z}'_2 - \bar{z}'_1$ it reduces to:

$$\begin{aligned} X'(\bar{z}'_1 = 0) &= \frac{1}{2}(x'_0 + x'_2) \\ Y'(\bar{z}'_1 = 0) &= \frac{1}{2}(y'_0 + y'_2). \end{aligned} \quad (5.36)$$

Hence by propagating the errors this results in:

$$\begin{aligned} \sigma'^2_{T_x} &= \sigma^2_{X'} = \frac{1}{4}(\sigma^2_{x'_0} + \sigma^2_{x'_2}) \\ \sigma'^2_{T_y} &= \sigma^2_{Y'} = \frac{1}{4}(\sigma^2_{y'_0} + \sigma^2_{y'_2}) \end{aligned} \quad (5.37)$$

5.4.3 Extracting the Resolution

Substituting for σ'_T in equation 5.37 and using 5.34 gives:

$$\sigma'^2_R = \frac{1}{4}(\sigma'^2_{G_0} + \sigma'^2_{G_2}) + \sigma'^2_{G_1} + \sigma'^2_{MS}. \quad (5.38)$$

With the assumption that all Gossips have the same resolution $\sigma'_{G_0} = \sigma'_{G_1} = \sigma'_{G_2} = \sigma'_D$ ⁽¹⁾. Even in our case where there are clearly differences between the detectors, this is reasonable given the resolution in figure 5.2.19. Then the resolution in both

¹Note: One might hope to avoid this assumption by also looking at residuals in G_0 and G_2 . This gives three equations with three unknowns, but in fact the equations are linearly dependent.

x and y is given by:

$$\sigma_D'^2 = \frac{2}{3} (\sigma_R'^2 - \sigma_{MS}'^2), \quad (5.39)$$

with σ_R' as the width of a Gaussian fit in figure 5.3.4. Table 5.4.1 gives the results:

Table 5.4.1: The mean positional resolutions of all detectors in the global frame.

$\sigma_{D_x}' (\mu\text{m})$	$\sigma_{D_y}' (\mu\text{m})$
31.4	12.0

5.4.4 Comparison of Telescope Resolutions with Local Track Fit Results

The previous section gives the Gossip-track position-resolution in the global frame, derived from telescope residuals. This section compares these with position resolutions derived from local track fits (see section 5.2.4). The comparison should be made in the same reference frame, so either the telescope values have to be transformed to the local frame or vice versa. The telescope gives only two elements of the 3×3 covariance matrix of position errors: σ_z and the off-diagonal terms are not known. The local track fits have all three diagonal elements, and by working in the centre-of-gravity frame the off-diagonal elements are zero. Hence we transform the results of the local track fits to the global frame.

Strictly speaking σ_{D_x} and σ_{D_y} in table 5.4.1 have some σ_{D_z} folded in. But the telescope was very well aligned to the beam so the effect is negligible.

Global detector resolution

Using equation 5.29 the diagonal local-track error-matrix $(\sigma_x, \sigma_y, \sigma_z)$ from section 5.2 is transformed to the global frame. Figure 5.4.2 shows the resulting distribution of global errors (square root of leading diagonal) in each detector. Table 5.4.2 gives the means of these distributions, which are to be compared with the results in table 5.4.1. The values in the tables differ approximately 15%, which is close but still more than what can be expected from the statistical errors.

Table 5.4.2: The mean positional resolutions as extracted from the standalone detectors transformed to the global frame (extracted from the mean in figure 5.4.2).

$\sigma_{D_x} (\mu\text{m})$	$\sigma_{D_y} (\mu\text{m})$
26.3	10.1

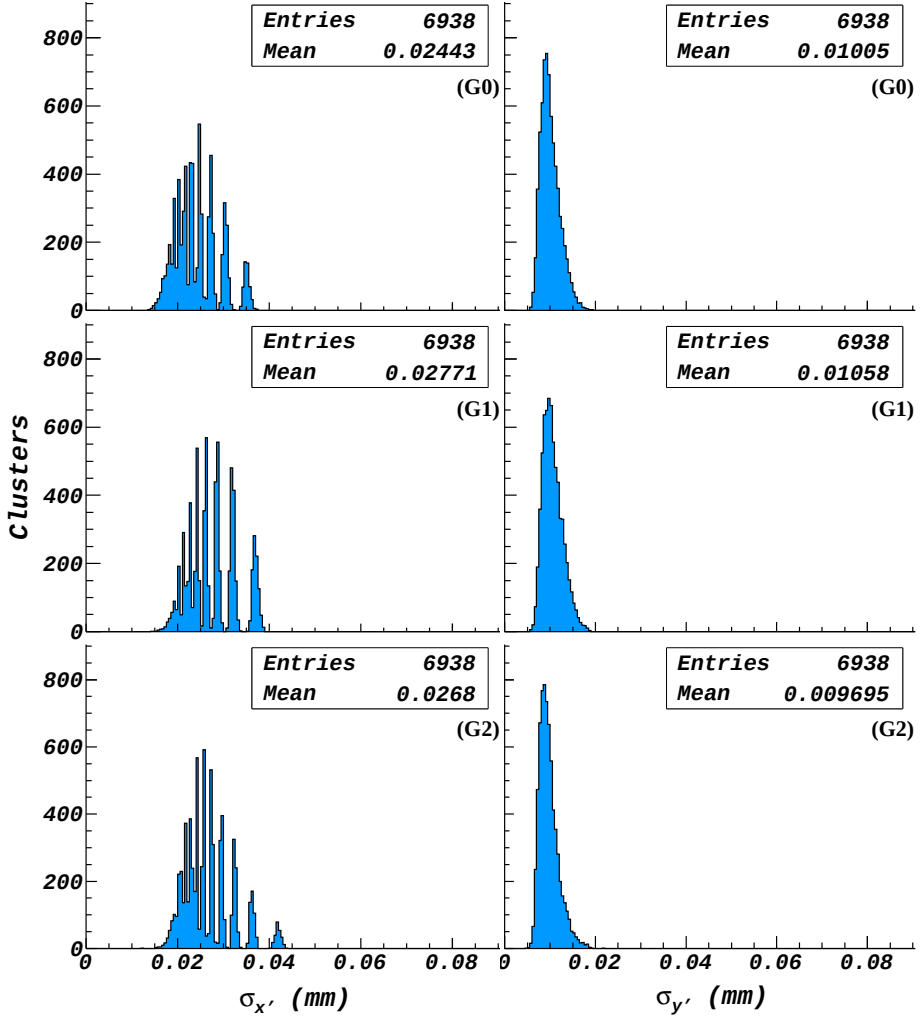


Figure 5.4.2: In the familiar order, the positional error distribution from the covariance matrices transformed to the global frame measured by the standalone detectors. Due to the rotation of about 46° the error in z rotates in, therefore the errors in the x' -direction carry a large z -component. This is true to less extent for the errors in the y' -direction because of the rotation of only 10° .

One can think of several issues that can cause the observed difference; inconsistent analysis, vibrations in the telescope due to the cooling fans and time-walk

related issues. The consistency of the analysis was checked using a toy Monte-Carlo, which was aimed to be similar to the data in run 89. In the MC case the values are the same within the statistical errors suggesting a consistent analysis.

Another dataset was analysed; run 90, with similar settings as run 89 except for $\alpha = 20^\circ$. The results of this run show variations within the statistical errors, ruling out effects of vibration in the telescope due to cooling fans. The variations as observed in the results of run 89 should therefore be caused by time-walk related issues, that is also suggested by the fact that the absolute difference in the x resolution is larger than the y resolution, probably caused by the 46° angle.

During the analysis of run 89 it has been discovered that a fraction of the dataset suffered significantly more from time-walk than the rest of the data. After a more thorough investigation it was concluded that this was caused by the temporary reduction of the strength of the amplification field, during periods of continuous discharge. Reduced gain increases time-walk and affects the alignment. Periods of continuous discharge were identified from the logbook (G_1 was turned off for a while to reduce the discharge rate) and from periods where the alignment drifted far from the average. This fraction of data has been excluded from the analysis. However presumably some discharges still occurred in the remaining data affecting the alignment and so broadening the telescope residuals.

Resolutions of the Detectors in Run 89 (2012)

It has been shown that the resolutions as extracted from the telescope measurement (table 5.4.1) are approximately the same as the resolutions in table 5.4.2. This suggests a consistent analysis and reasonable understanding of the errors on the position measurements of the detectors in run 89. Therefore the mean resolutions as extracted from the local track fits are believed to be a proper measurement of the detector resolutions. The resolutions of the standalone detectors in run 89, with the detectors oriented at $\alpha = 46^\circ$ and $\beta = 10^\circ$ are presented in table 5.4.3. The resolutions in x and y are $10\ \mu\text{m}$ which is exceptionally precise for gaseous detectors.

Table 5.4.3: The standalone mean positional and angular resolutions from run 89 in the local frame, with the detectors oriented at $\alpha = 46^\circ$ and $\beta = 10^\circ$.

$\sigma_x\ (\mu\text{m})$	$\sigma_y\ (\mu\text{m})$	$\sigma_z\ (\mu\text{m})$	$\sigma_\alpha\ (\text{mrad})$	$\sigma_\beta\ (\text{mrad})$
10.1	10.1	34.9	68.7	46.2

5.4.5 Results of Monte-Carlo and Other Runs in 2012 and 2010

To check the consistency of the analysis framework a Monte-Carlo study was made. In addition several runs from 2012 at different angles are analysed; this section summarises the results as well as one run from 2010 data.

Resolutions of the Detectors in Monte-Carlo

To test the consistency of the framework a toy Monte-Carlo is performed. 50000 events were generated in three GridPixes. The tracks were generated randomly across the chip without a spread on the direction such that the average angles were similar to the average angles in run 89. The number of hit pixels is distributed according Poisson distributions similar to the fitted distributions in run 89. In addition time-walk, attachment and double hits are taken into account as has been shown by figures 5.2.11a, 5.2.11b and 5.2.11c. Inactive pixels from run 89 are turned off in the Monte-Carlo. Note that delta electrons and multiple scattering are not taken into account. Table 5.4.4 shows the mean resolutions from the standalone detectors in the Monte-Carlo simulation.

Resolutions of the Detectors in Run 90 (2012)

The detectors as used in run 89 are also used in run 90, with similar electric fields and gas flow. However the detector is tilted approximately 20° instead of 45° . The number of events in this run is low but sufficient to extract the resolutions. Note that the resolutions are slightly worse compared to run 89 because of the length of the track. The difference is approximately a factor $\sqrt{\frac{\cos \pi/9}{\cos \pi/4}} \approx 1.15$. Table 5.4.4 shows the mean resolutions from the standalone detectors in this run.

Resolutions of the Detectors in Run 25 (2010)

The three detectors as used to record run 25 in 2010 have drift gaps of about 0.95 mm. The gain is lower and therefore time-walk is more dominant. The gas flow is higher consequently hardly any attachment is observed. The detectors are tilted approximately 45° and 0° about the x - and y -axis respectively. Because of the inefficient MUROS data acquisition system the number of events in the run is low; the resolutions are extracted from about 800 events. The drift field is about 2000 V/cm resulting in a lower diffusion of about $21 \mu\text{m}$ and $23 \mu\text{m}$ in the transversal and longitudinal direction instead of $26 \mu\text{m}$ and $27 \mu\text{m}$ respectively. This results in an improvement of the $x - y$ resolution with respect to the detectors in run 89 of a factor 0.8, that is almost cancelled out by a factor $\sqrt{1.2[\text{mm}]/0.95[\text{mm}]}$ because of the smaller drift gap that results in less hit pixels. Note that the drift velocity is approximately a factor 3 larger resulting in larger

binning in the drift direction. Table 5.4.4 shows the mean resolutions from the standalone detectors in this run.

Table 5.4.4: The standalone mean positional and angular resolutions from the several runs and MC in the local frame together with the results of run 89. Positions in μm , angles in rad.

run	α	β	σ_x	σ_y	σ_z	σ_α	σ_β
MC ₈₉ (2013)	45	10	9.92	9.92	37.1	67.0×10^{-3}	42.6×10^{-3}
89 (2012)	45	10	10.1	10.1	34.9	68.8×10^{-3}	46.2×10^{-3}
90 (2012)	20	10	11.3	11.3	44.3	67.0×10^{-3}	47.0×10^{-3}
25 (2010)	45	0	9.44	9.44	69.4	170×10^{-3}	62.5×10^{-3}

5.5 Particle Detection Efficiencies in Run 89

A practical way of calculating the efficiency requires a good quality track in two reference detectors and count the number of detections in a third one. Since the detectors are not aligned very well with respect to the scintillator, a frame of $6 \times 6 \text{ mm}^2$ is selected, this is covered by all three detectors. We require good local tracks in two detectors and extend this to the third. If there is at least one hit within 5σ of the track, where σ includes the residual width and the track error, the detector registered the track. Otherwise it contributes to the inefficiency Table 5.5.1 shows the efficiencies of each detector.

Table 5.5.1: Efficiencies of the three GridPixes in a 5σ window to see at least one hit.

GridPix	Efficiency
0	0.993 ± 0.001
1	0.998 ± 0.002
2	0.996 ± 0.001

These numbers are checked by using the fitted Poisson functions from figure 5.2.8. The efficiency from these plots is calculated by integration from 1 to infinite hits for every detector. The results are shown below:

The values as obtained from the spectrum of the number of hits (table 5.5.2) are consistent with the values as obtained by telescope counting (table 5.5.1). Gossips are very efficient to see at least one hit.

Table 5.5.2: Efficiencies of the three GridPixes as extracted from integration of the number of hits spectrum.

GridPix	Efficiency
0	0.998 ± 0.001
1	0.996 ± 0.001
2	0.999 ± 0.001

5.6 Particle Tracking Efficiencies in Run 89

A proper track fit requires three or more hits. From the fitted Poisson functions in figure 5.2.8 the probability that a track leaves three or more hit pixels can be extracted. This is an estimation of the particle tracking efficiency. Table 5.6.1 shows the particle tracking efficiencies for each detector:

Table 5.6.1: Particle tracking efficiencies of the three GridPixes as extracted from integration of the number of hits spectrum.

GridPix	Efficiency
0	0.972 ± 0.001
1	0.933 ± 0.001
2	0.988 ± 0.001

Note that due to the inactive area the particle tracking efficiency in G_1 is significantly lower. In the case of good quality chips the particle tracking efficiency is about 97%.

5.7 Summary and Conclusion

A detailed analysis has been performed of the data recorded with a telescope consisting of three GridPix detectors with approximately a 1.2 mm drift gap tilted by 46° with respect to the beam and rotated 10° around the beam. The GridPixes were flushed with a mixture of CO_2 and DME in a mixing ratio of approximately 57:43. In run 89 about 150×10^3 events were recorded. About 30% of the events were empty because of misaligned scintillators. About 50×10^3 events were discarded because one detector started discharging. The rest were used to estimate and check the errors on the data-points.

The tracks were fitted separately in the $x - z$ and $y - z$ plane. The detector resolution from the local standalone detectors were extracted in terms of σ_x , σ_y and σ_z . The resolution in the x - and y -direction is approximately 10 μm and in

the z -direction approximately $35\text{ }\mu\text{m}$ for all detectors. The angular resolutions are about 3.9° in the 46° angle and about 2.6° in the 10° angle.

As a check, the global resolutions as measured by the standalone detectors is compared with the resolutions as extracted from the telescope residuals. Since at least three hits with good quality track fits were required in all detectors only 10% of the total number of events could be used. The resulting resolutions in both the x - and y -direction are approximately 15% worse. This difference can be explained partly by the fact that the detectors do not have entirely the same resolution. In addition a small gradient in time-walk is observed among the events in the runs, making the telescope residuals broader. Likely this effect can be attributed to temporarily reduced fields due to charge up after discharges.

Since it is difficult to analyse Timepix-1 data with dominant time-walk, future experiments should avoid using a telescope composed of GridPix detectors. Preferably a silicon telescope should be used. In addition detailed knowledge about the gas mixing ratio, the drift gap size and the detector orientation is required to avoid difficulties and approximations during the analysis.

The new Timepix-3 chip [84] will have a much faster front-end and will simultaneously record Time over Threshold (ToT) and Time of Arrival (ToA). This will reduce time-walk, and allow its effect to be more or less eliminated by using ToT to correct for it [17]. This will give a σ_z comparable to the current σ_x and σ_y and improved angular resolutions.

The resolutions as presented here are the results of measurements with GridPixes suffering from several issues (inactive pixels, time-walk and discharges). With improved wafer post-processing techniques, the quality of the GridPixes is expected to be improved. GridPixes will reach resolutions below $10\text{ }\mu\text{m}$.

6

Laser Beam Test

Understanding the behaviour of charged particles in gases is crucial for understanding the performance of GridPix detectors. Gas properties can be measured by probing the detector with radiation or an ionising laser beam. Such a laser beam has the advantage of generating a confined charge at a fixed position at a well-defined time inside the drift volume. Comparing this knowledge with the position and time of the arrival of the charge as measured by a GridPix gives an indication about the physics inside the gas. In this chapter the gain, gain fluctuations, drift velocity, transversal diffusion and longitudinal diffusion of CO_2 :DME in a mixture ratio of about 47:53 are studied. It must be noted that during the filling procedure of the gas bottles, due to a faulty valve, similar problems were encountered as in the previous chapter. Initially the gas mixture was estimated to be CO_2 :DME in a ratio of approximately 50:50, however by comparing results of the drift velocity measurements with simulations, the ratio seems to be 47:53.

6.1 Experimental Set-up

A nitrogen laser generates photons that create an ionisations in the gas. The laser is mounted on an optical rail and is focussed inside a GridPix detector. Three remotely controlled stages position the focal point anywhere in the drift volume. The beam is attenuated until individual pixels below the focal point collect at most one primary electron. After drifting the GridPix measures either the Time over

Threshold (ToT) or Time of Arrival (ToA), as well as the coordinates on the pixel matrix.

6.1.1 Nitrogen Laser

For the DELPHI and L3 experiments at LEP (CERN) a UV laser with low divergence was developed for calibration of gaseous drift chambers. In addition a short pulse length (about 1 ns) and sufficient energy to produce a trail of ionisations were required. For this purpose a nitrogen laser operating according to the Master Oscillator Power Amplifier principle [85] was used. Such a laser was developed by Nikhef [86].

In the laser two stages can be distinguished. The first stage referred to as the “oscillator”, consists of a cavity in between two metal plates (P1 and P2) flushed with nitrogen gas, (figure 6.1.1). Plate P1 is connected to a spark gap. Initially both plates are at the same potential. Once the spark gap fires the voltage on P1 drops rapidly. This results in a large electric field across the cavity inducing a flow of electrons from the cathode to the anode. The collisions of the electrons with the gas leaves the nitrogen molecules in one of the following states:

- ground state;
- lower excited state;
- higher excited state.

Population inversion occurs when the system is in a state with more molecules in an excited state than in lower energy states. The average life time of the higher excited state is 40 ns but statistically a few photons are emitted almost immediately. While travelling, these photons induce other excited molecules to emit a photon as well. The newly emitted photons have the same direction and phase as the initial photons (stimulated emission). In principle this process occurs in all directions, but only photons that are emitted in the longitudinal direction of the cavity experience a substantial amplification. The resulting beam has a divergence that is given by the length and the width of the gas discharge in the cavity. The divergence is improved by adding a mirror M1 at one end of the cavity. This results in a single reflection that is allowed to achieve the desired 1 ns duration of the laser pulse. Usually a laser has two mirrors and the laser light reflects back and forth to increase the intensity of the beam, however this results in an undesired long duration of the pulse.

The beam is directed to the three-mirror-assembly M2 and through a telescope pair of lenses L1 and L2 expanding the diameter by a factor 29. Consequently the divergence of the beam reduces by the same factor at the cost of greatly reduced intensity.

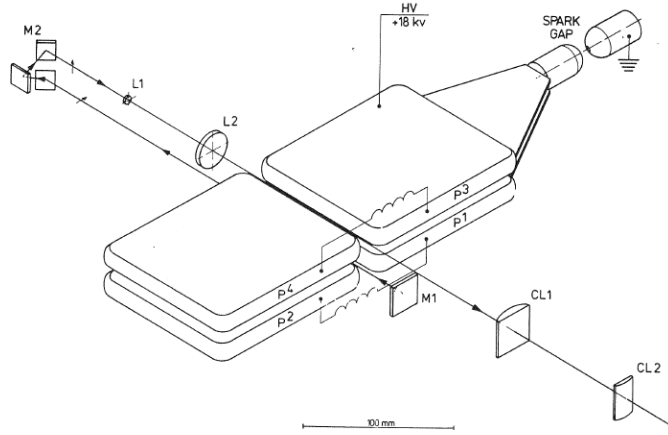


Figure 6.1.1: Artist view of the Nikhef nitrogen laser. The picture is extracted from [86].

Subsequently, the weak but parallel beam is guided to the second stage of the laser; the “amplifier”. This stage has the same layout as the previous stage but the width in between the plates is adjusted such that the resulting discharge time difference just compensates for the path length of the laser light between the two stages. In a similar way, as in the previous stage, this results in a strongly amplified and almost diffraction limited beam that is suited to be used for detector response studies.

Due to various rotational and vibrational transitions, the laser light has a wavelength in a range of 336.5-337.1 nm. There is no effect of the difference in wavelength on the measurements. The pulse energy is about 80 μJ with a duration of less than 1 ns and a maximum repetition frequency of 5 Hz.

6.1.2 Optics

The cross-section of the parallel laser beam has an elliptic shape 3 mm wide and 0.35 mm high. The beam is made circular by cylindrical lenses CL1 and CL2 (figure 6.1.2). A small fraction of the circular beam splits off in M3 and is directed to a photo detector to be used as a trigger. The diameter of the remaining beam is expanded by a factor 20 and directed to two two-mirror-assemblies M4 and M5 and a strong focus lens FL1. Two remotely controlled stages can move the focal point in an accurate way: M4 moves in x and M5 moves in z . One remotely controlled stage moves the focal point in the y -direction by shifting lens FL1. Figure 6.1.3 shows a photo of the set-up.

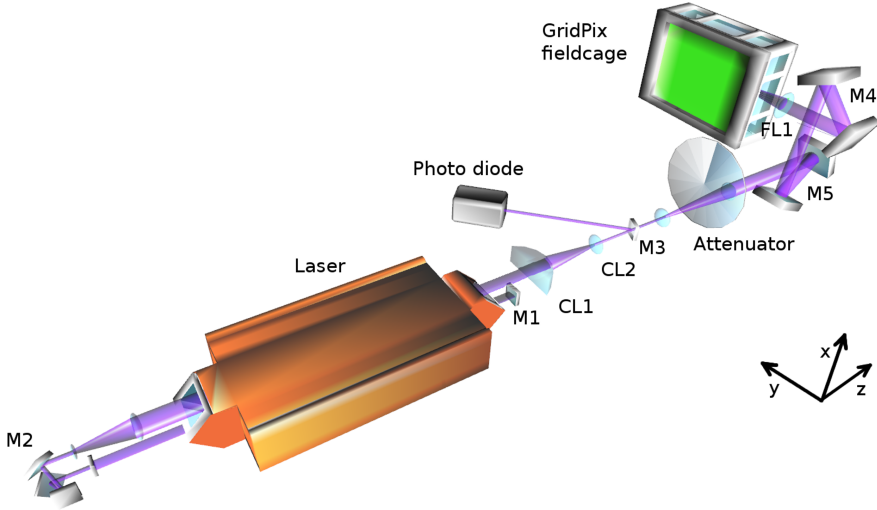


Figure 6.1.2: A cartoon of the optics as used in the laser test set-up. The laser is indicated in orange, the laser beam in magenta. The beam enters via a window on the side of the GridPix field cage. The GridPix chip is located parallel to the $x - y$ plane and the drift direction is along z .

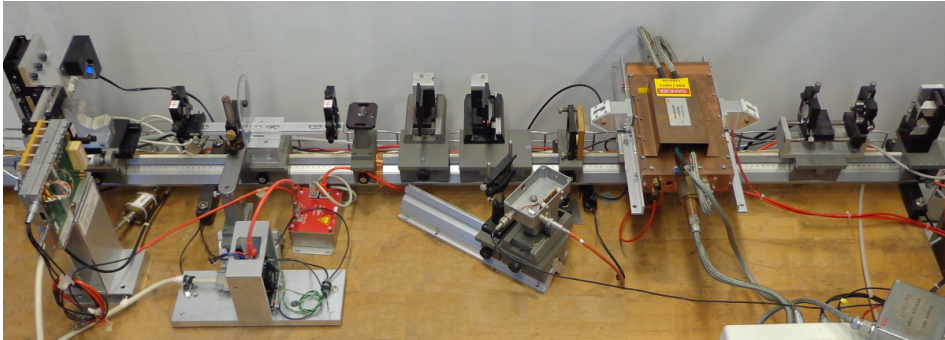


Figure 6.1.3: A picture of the laser set-up with the laser in the copper box and the GridPix detector on the far left.

The laser is pointed inside the drift gap parallel to the y -direction. Electrons are emitted along the laser beam position, see figure 6.1.4. The strongly focussed laser has a focal point with a width of about $13\text{ }\mu\text{m}$ perpendicular to the beam and a length of about $500\text{ }\mu\text{m}$. Due to the quadratic relation between the light intensity and the number of ionisations, the majority of the electrons are emitted in the focal point as shown in figure 6.1.5. Transversal diffusion measurements

need a small focal point. Since transversal diffusion is symmetric in the $x - y$ plane and the focal width in the y -direction is large, only the projection in $x - z$ plane is considered. Electrons that are emitted in any place but the focal point broaden the distributions, hence a cut of 50 pixels to either side is placed in the y -direction.

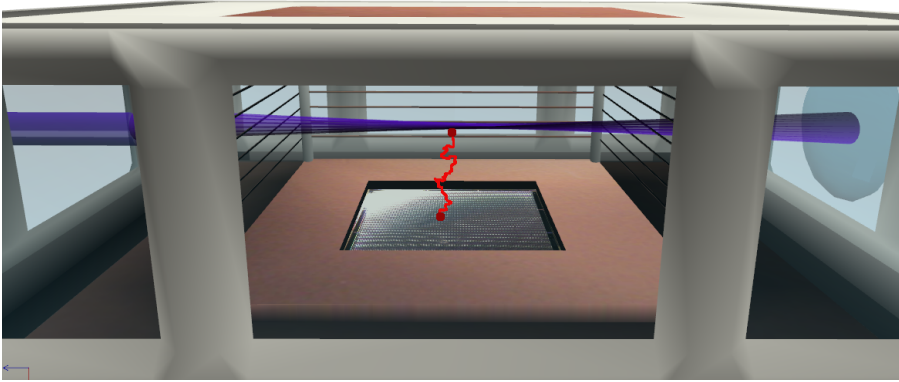


Figure 6.1.4: Drawing of the laser (purple) focussing in the field cage. An electron (red) is emitted and drifts toward the GridPix (bottom). The lens is visible at the right, the guard electrode is surrounding the GridPix. The field shaping wires define the edge of the field chamber.

6.1.3 Trigger System

The laser is triggered by a pulse generator with a maximum frequency of 5 Hz, it is limited by the charging time of the plates of the laser stages. The delay between the trigger and the firing of the laser is about $(1 \pm 0.3) \mu\text{s}$. The shutter that is used for the GridPix is opened simultaneously with the laser trigger, i.e. before the actual firing of the laser. Once the laser fires, the signal of the photo detector triggers a gate generator with a fixed width defining the time from the firing of the laser until the end of the GridPix shutter with an accuracy of a few ns. The trigger system is connected to the monitor and control system that automatically blocks the trigger when the remotely controlled stages are moving. Figure 6.1.6 shows a simplified scheme of the trigger circuit. Figure 6.1.7 shows a time diagram of the system.

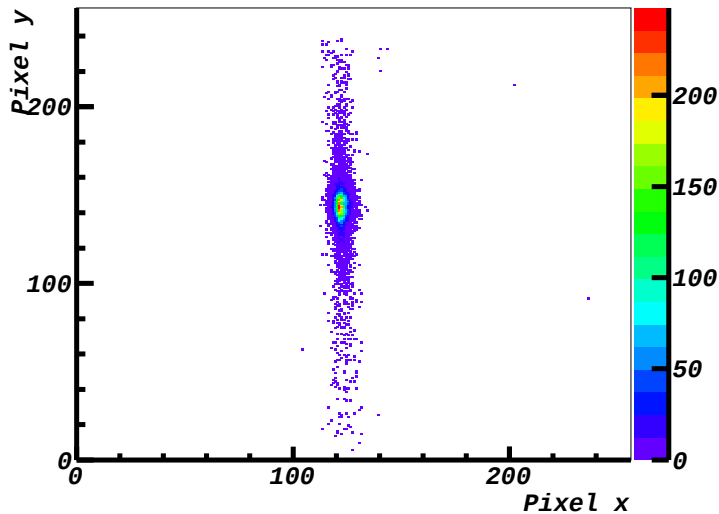


Figure 6.1.5: Occupancy plot of the laser focussed in the drift gap, the focal point is clearly visible in red. The pixel pitch is 55 μm .

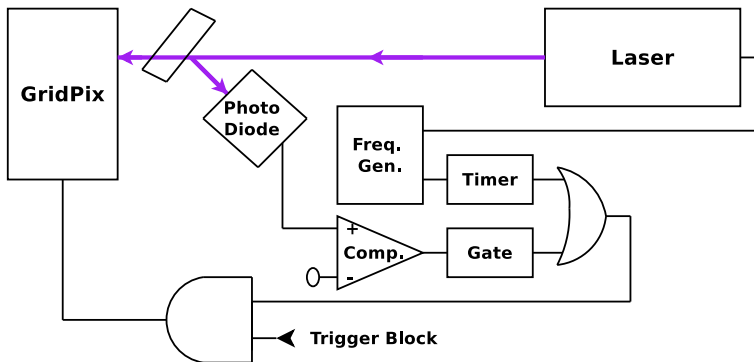


Figure 6.1.6: A scheme of the trigger circuit in the experiment.

6.1.4 Detector

The gas chamber of the detector has a field cage, shown in figure 6.1.8. Ceramic pillars support a double ring of field shaping wires. A resistor chain provides equal potential steps between the wires resulting in a homogeneous drift field. The cathode and a guard electrode sandwich the field shaping wires; the guard is

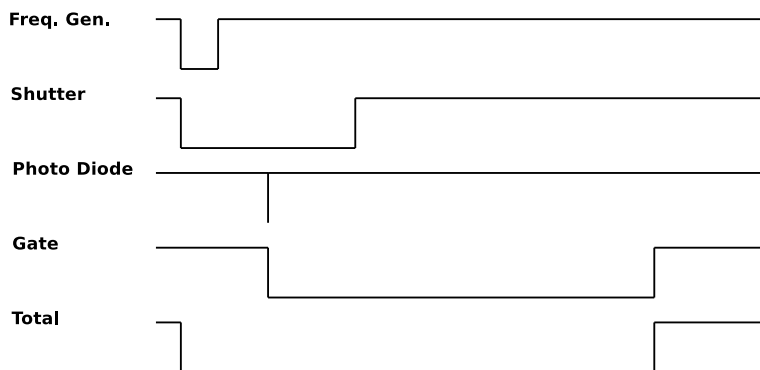


Figure 6.1.7: A time diagram of the trigger system.

positioned at about 0.5 mm above the grid and the cathode is positioned 21 mm above the guard. The structure is placed in a housing with a quartz entrance window at one of the sides of the field cage. The housing is made gas tight by silicone glue. It is observed that daylight enhances noise due to photoelectric effect on the grid or cathode, therefore the experiments are performed with reduced background light.

For probing the GridPix detector, one should have sufficient energy to ionise gas molecules. The photons from the nitrogen laser used in this experiment have a wavelength of about 337 nm corresponding to an energy of 3.7 eV. The lowest ionisation energies of CO₂ and DME are 13.8 eV and 10.0 eV, respectively. Clearly the energy of a single or a double photon process is not sufficient to make ionisations in the gas. Since the laser is creating ionisations in the gas it is assumed that there exists impurities in the gas, which have an ionisation energy of less than 7.4 eV. Although this ionisation energy is rather low for gases it does not seem to be impossible, given the existence of chemicals with energies sufficiently low to create an ionisation by a two (3.7 eV) photon process that have been used for gaseous detector calibration [87]. Although the study of this process is out of scope for this thesis, it might be interesting to investigate this effect in future.

Ideally one electron per shot is desired, but the number of electrons is Poisson distributed. Therefore the laser beam is attenuated such that the average number of electrons is 0.5 per shot in the gas volume. Note that the process of double photon absorption automatically implies a quadratic relation between the light intensity and ionisation. Therefore the ionisation occurs mainly at the focal point where the intensity is the highest.

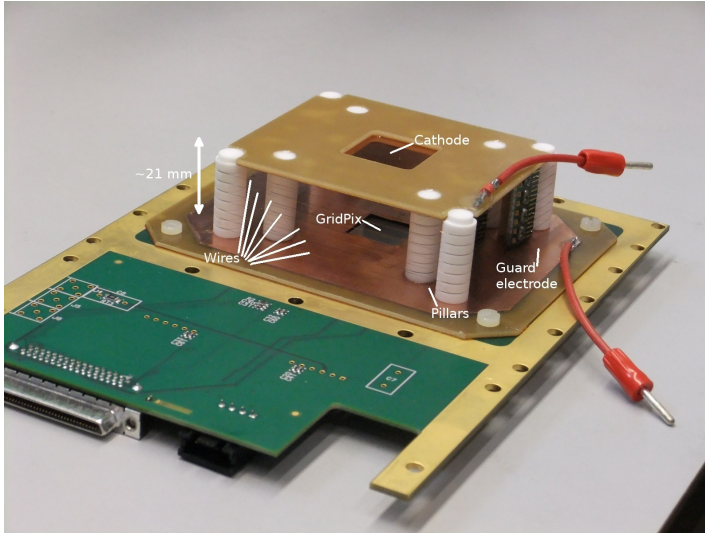


Figure 6.1.8: A picture of the chip carrier board with the chip below the guard electrode. On top of the guard electrode a double ring of field shaping wires is supported by the white pillars. On top of that a PCB supports the cathode foil. A hole is milled out to reduce the effect of multiple scattering in case of the use of a radioactive source.

6.1.5 Electric Field Scaling

As explained in chapter 3, the gas properties are expressed as function of the reduced electric field. In the next sections the temperature and pressure are measured at the beginning and at the end of each measurement. The average results are used to scale the electric field to room conditions (293.15 K, 1 bar). However since some measurements take about six hours and the temperature and pressure in the laboratory cannot be tuned, the small effect of gradients might be visible in the measurements.

6.1.6 Oxygen Content in Drift Gas

Attachment of electrons in the gas is caused by electronegative molecules in the gas. Likely this is due to the presence of oxygen. In addition oxygen together with CO_2 can create metastable electronegative carbon molecules. The attachment rate is a function of the number of collisions along the drift path. Reduction of the drift velocity results in an increased attachment rate. Oxygen affects the electron detection efficiency but the influence on diffusion and drift velocity can be neglected. The cause of oxygen in the gas can be related to three sources:

- the initial gas contains oxygen;

- the system contains out-gassing materials or has trapped oxygen in poorly accessible places;
- oxygen diffuses in.

The oxygen contents of the initial premix bottle is measured to be 40 ppm at a flow of 40 ml/min, with a Mettler Toledo M400 device [88]. This might be caused during the filling or evacuation of the premix bottle. Likely the system contains materials that emit other electronegative molecules, however the effects of this are not expected to be dominant. The most probable scenario is oxygen that diffuses into the detector chamber from outside. A large effort is made to guarantee a gas-tight system; all known leaks are covered with silicone glue. A well known effect of silicone is that oxygen can diffuse through, specifically for thin layers of glue.

If not too large the effect of attachment can be reduced by either reducing the drift time or by increasing the gas flow. The goal of the oxygen content measurements is to study whether it is feasible to reduce the oxygen content by increasing the flow. The oxygen content is measured at the outlet of the detector for different flow rates. Figure 6.1.9a shows the fraction of oxygen at the outlet as function of the flow together with the oxygen content in the gas bottle (in red).

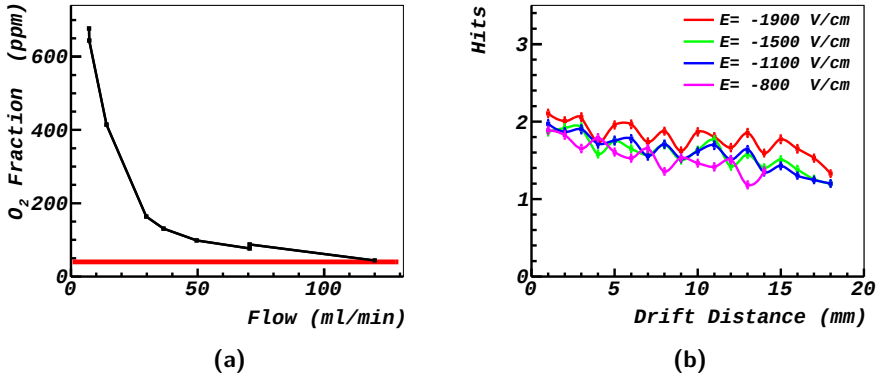


Figure 6.1.9: a) The oxygen content in parts per million (ppm) as function of the flow. The initial oxygen content as measured at the outlet of the premix bottle is indicated by the red line. b) The average number of hit pixels per laser shot from a Poisson fit as function of the drift distance for different drift fields.

In principle the ideal flow would be as high as possible, however since the premix gas bottle has a limited content, it was decided to limit the flow at about 40 ml/min. The number of hit pixels per laser shot was measured as function of the drift distance.

Figure 6.1.9b shows the average number of detected electrons as function of the drift distance for a fixed attenuation of the laser beam and a fixed gas flow of 42 ml/min for several electric fields. As expected the number of detected electrons drops linearly with the drift distance as result of attachment. The figure shows that the attachment probability for an electron emitted near the cathode is approximately 20%.

Another cause of inefficiency is related to multiple electrons hitting the same pixel, which specifically occurs at small drift distances. However since the laser focal point has the shape of an ellipse with a transverse diameter of about 8 pixels, this effect is expected to be smaller than the effect of attachment. It can be safely concluded from figure 6.1.9b that the inefficiency because of attachment is not larger than 20%, which is sufficient for the measurements.

6.2 Amplification Properties

The induced signal on a pixel is a function of the amount of charge participating in the avalanche and the velocity of the charges. Figure 6.2.1 shows a schematic representation of the induced current. The peak at the left is the result of the electrons and contains about 15% of the total charge [11]. The long tail to the right is the result of the drifting ions, that slowly drift away. The ion tail is typically $\mathcal{O}(30)$ times longer than the electron peak. The shaping time of the amplifier in Timepix-1 is long compared to the duration of the induced current. Therefore the pre-amplifier output is expected to be proportional to the total charge participating in the avalanche and does not depend on the drift velocities of electrons and ions in the amplification gap. Timepix-1 measures the total induced charge in terms of ToT. Figure 6.2.2 shows the calibrated ToT against the input charge for one pixel from the measurements with a test pulse directly on the pixel. Note that the collected charge by a pixel is lower than the charge that is generated in the avalanche, because of the presence of a protection layer, diffusion [32] and cross talk.

6.2.1 ToT to Charge Transformation

Figure 6.2.2 cannot be used to convert ToT to avalanche charge because (1) we used different settings in the TimePix and (2) it does not take into account the signal losses. Instead we use a conversion measured in [32], for which the GridPix geometry and settings were similar to ours. A description of these measurements is given below.

In [32], the average gas gain of a GridPix detector was measured by irradiating it with a ^{55}Fe source near the cathode. The GridPix had a 10 cm drift gap flushed

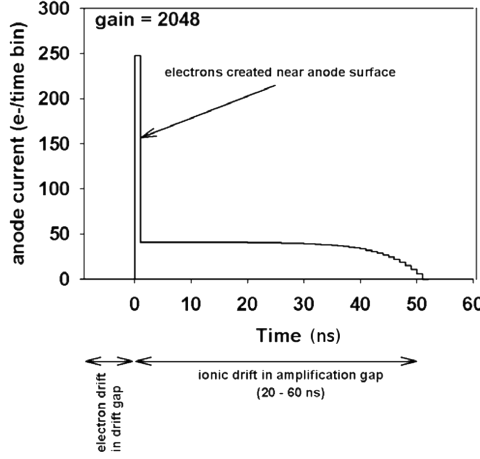


Figure 6.2.1: Time structure of anode current after avalanche in GridPix, from [11].

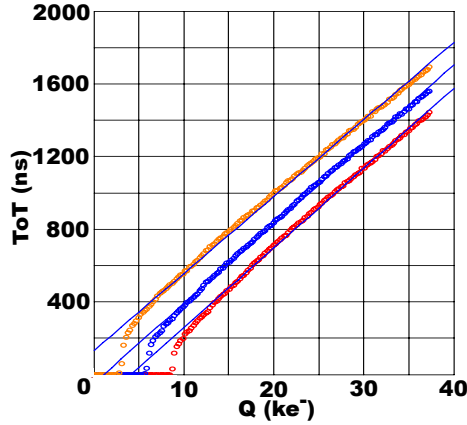


Figure 6.2.2: Time over Threshold versus the input charge for thresholds of 3.5 ke^- (orange), 6 ke^- (blue), and 8.5 ke^- (red). Above a certain value the behaviour is linear. The measurements are performed with a single pixel, but they might vary slightly from pixel to pixel. The figure is taken from [28].

with $\text{Ar}:\text{iC}_4\text{H}_{10}$ (80:20). The detector was irradiated high in the drift gap such that, due to diffusion, the probability for drift electrons to hit the same pixel was minimised. The 5.9 keV quanta in $\text{Ar}:\text{iC}_4\text{H}_{10}$ (80:20) create on average about 226 drift electrons.

The total amplified charge from all electrons was measured by connecting the grid capacitively to a charge sensitive amplifier. The chip was read out in ToT

mode⁽¹⁾. The sum of all ToT values in an event were summed over the number of events and divided by 226 times the number of events to get the mean ToT. Similarly, the measured charge per event was summed over all events and divided by 226 times the number of events to get the mean charge.

Figure 6.2.3 shows the mean ToT against the mean charge per pixel. The shape is similar to figure 6.2.2, but quantitatively very different for the reasons mentioned. It is believed that the ToT for a given charge in figure 6.2.2 is much smaller because a higher Krumenacher current is used. Following [89] the points have been fitted with the empirical function 6.1:

$$\bar{n} = a + b \cdot \overline{ToT} - \frac{c}{\overline{ToT} - d} \quad (6.1)$$

in which:

$$a = -90.5 [\text{ke}^-];$$

$$b = 0.015 [\text{ke}^-/\text{ns}];$$

$$c = 5.5 \cdot 10^5 [\text{ke}^- \cdot \text{ns}];$$

$$d = 6.037 [\text{ns}].$$

Low gain corresponds to the entries at the far left in figure 6.2.3. In this non-linear part the assumption that the average grid signal corresponds with ToT is less true; low charge entries might result in overestimation of the charge. In the section below the ToT-to-Charge transformation function is used to convert the gain $\bar{n}$ in terms of ToT to electron charge.

6.2.2 Average Gain

By attenuation of the laser beam it is possible to measure the response of single electrons in terms of ToT. With the ToT-to-Charge function 6.1 the ToT for each drift electron can be converted into charge. Figure 6.2.4a shows the ToT spectrum as measured with -650 V on the grid. Figure 6.2.4b shows the corresponding charge spectrum, which is fitted with a Polya function (equation 3.18) to obtain the average gain.

The average gain as obtained from the ToT measurements is compared with the results of a Garfield calculation using a detailed NeBEM field map. The GridPix is modelled as in chapter 4.

¹Note: The measurements are made separately because the chip read-out disturbs the grid charge measurement.

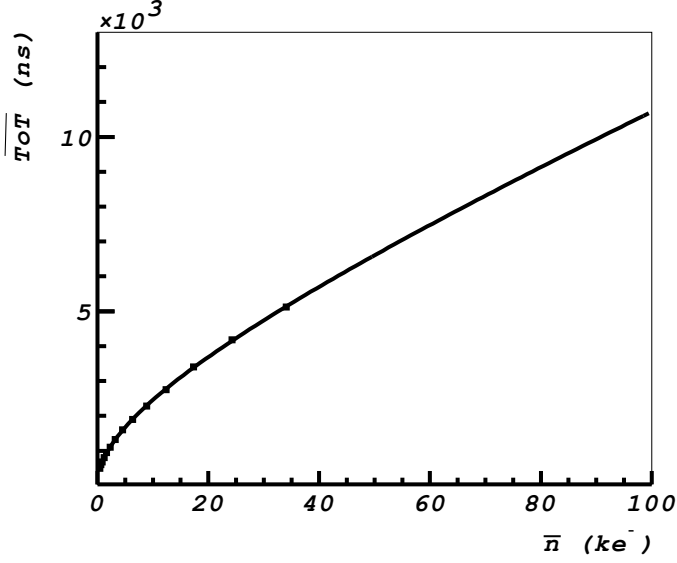


Figure 6.2.3: The average ToT versus the average gain as extracted from [32]. The data points are for different grid voltages and fitted with the (inverted) ToT-to-Charge function (equation 6.1).

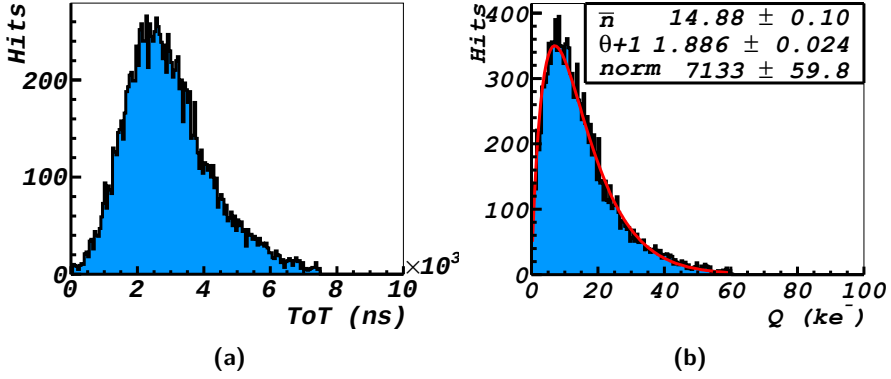


Figure 6.2.4: a) The ToT spectrum for single electrons measured with -650 V on the grid. b) The charge spectrum as obtained from ToT to charge conversion using figure 6.2.3. The distribution is fitted with a Polya function.

The Townsend coefficient is integrated over the electron path. Figure 6.2.5 shows the measured gain as function of the grid voltage together with the gains as extracted from the simulations for several amplification gaps.

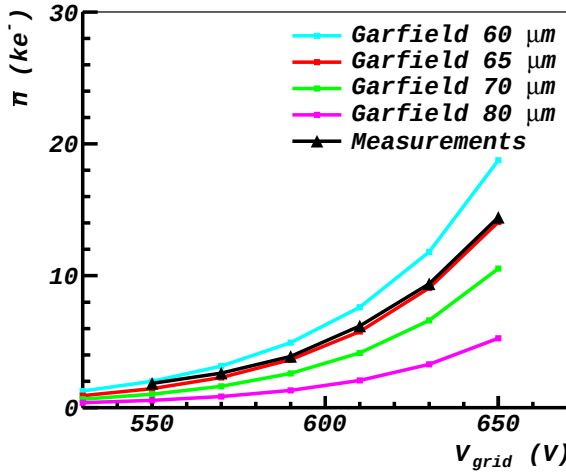


Figure 6.2.5: The gains as extracted from the measurements against the grid potential plotted together with simulated results from Garfield.

The amplification gap height of the GridPix as used during the measurements is unknown. However it can be estimated by comparing the calculated gains with the measured gains. Figure 6.2.5 suggests that the gain measurements (in black) approximately agree with the calculated gains of a GridPix with an amplification gap that is slightly smaller than 65 μm (in red).

This height is consistent with the SU-8 height profile of a dummy wafer after spin coating as has been shown by figure 2.6.7. Note that the grid heights in figure 6.2.5 are measured from the top of the 2 μm thick grid to the protection layer surface. The mean amplification gap height of 61 ± 2 μm as measured on the dummy wafer and the suggested height from figure 6.2.5 are consistent, implying a Townsend coefficient from MagBoltz that agrees with the measurements.

6.2.3 Gain Fluctuations

In addition to the average gain, the gain fluctuations are of specific interest to estimate the electron detection efficiency or the effect of time-walk. Figure 6.2.6 shows the fluctuations in terms of $\sigma/\bar{n}$, where σ is calculated by equation 3.19 using Polya fit results from the measurements.

Using Legler's model, for a given homogeneous field E , an average ionisation energy U_{ion} in $\text{CO}_2:\text{DME}$ (50:50) of 11.8 eV and the Townsend coefficient $\alpha(E)$ extracted from MagBoltz, the relaxation parameter $\chi = E/(\alpha(E)U_{\text{ion}})$ is calculated. With this, in a homogeneous field, the variance can be calculated by equation 3.16. Figure 6.2.6 shows the results plotted versus the average gains corresponding to the gains in figure 6.2.5. Despite the fact that two different models are compared, apparently the results are fairly consistent.

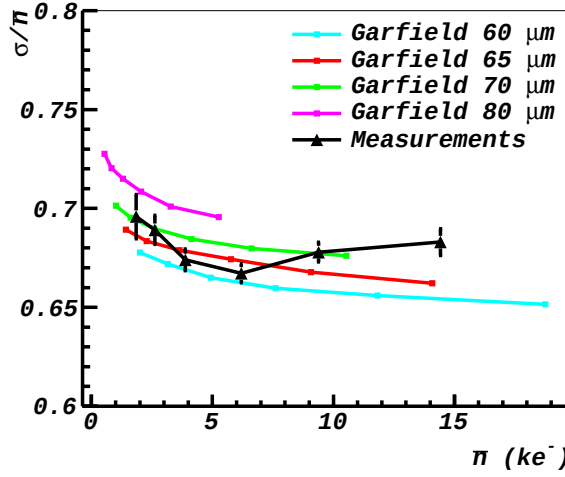


Figure 6.2.6: The spread in gain σ over the mean gain $\bar{n}$ as function of $\bar{n}$ corresponding to the gains in figure 6.2.6, for several amplification gap sizes, together with $\sigma/\bar{n}$ as extracted from the Polya fits from the measurements. The measurements and the calculations are comparable.

Figure 6.2.6 shows that smaller amplification gaps tend to have a better σ to $\bar{n}$ ratio. This suggests that smaller gaps are desired to reduce the effect of fluctuations.

6.3 Drift Velocity and Diffusion

The results on drift velocity, transversal diffusion and longitudinal diffusion are presented in this section. For all measurements a new method is used to extract the drift time; the so-called Time over Threshold method. This method considerably improves the time resolution compared to the classical Time of Arrival

method. Specifically the longitudinal diffusion measurements benefit from this novel method.

6.3.1 Measurement Methods

The measurement of drift velocity, transversal diffusion and particularly longitudinal diffusion require accurate time measurements. The next section describes two types of time measurements with a TimePix-1 chip: the classical Time of Arrival (ToA) method; and a novel method using Time over Threshold (ToT) referred to as ToT-method as developed by the author. Note that the latter method might be somewhat counter intuitive, since ToT is used to measure ToA.

The name ToA is defined as the time from when a signal goes over threshold until the end of the shutter. This is misleading since the time of an electron to arrive at the pixel is in fact the ToA subtracted from the shutter time, however we stick to the conventions. Figure 6.3.1 illustrates the definitions.

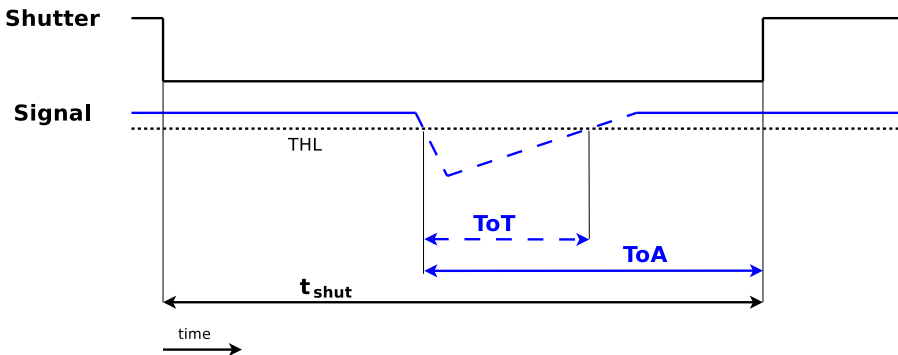


Figure 6.3.1: An illustration of the Time of Arrival (ToA) method, the "real" ToA is measured by subtracting it from the shutter time.

ToA-Method

A GridPix detector is capable of measuring the ToA in 10 ns time bins by counting the number from clock cycles of when a pixel is hit until the end of the shutter. This "classical" straight forward method is generally used by the GridPix community to measure the drift time of electrons in a drift gas. However the method has a disadvantage; time-walk smears out the time measurements as has been explained in section 5.2.3.

Figure 6.3.2a shows the ToA spectrum of electrons emitted at a fixed value z . The RMS of the spectrum is a convolution of diffusion, the error due to the clock frequency, time-walk and the width of the focus point:

$$\sigma_z = \sqrt{D_1^2 z + \frac{(t_b v_d)^2}{12} + (\Delta t_w v_d)^2 + d_f^2} \quad (6.2)$$

Here D_1 is the longitudinal diffusion coefficient, z is the drift length, t_b is the width of a time-bin, v_d is the drift velocity, Δt_w is the effect of time-walk and d_f is the width of the focal point. Similar to time-spectra (figure 5.2.3) measured in chapter 5, figure 6.3.2a shows that the spectrum is asymmetric, due to time-walk.

All terms in equation 6.2 are approximately Gaussian except for time-walk. The tail at the left in figure 6.3.2a corresponds to hits with small charge. Figure 6.3.3 shows the TimePix-1 time-walk variation with charge for different thresholds [28]. The stochastic variations in avalanche charges causes a spread in ToA due to this time-walk, and since the variation is not known, it is difficult to estimate Δt_w . As is shown later on, even with a high average gain still about 40% of the hits have a time-walk of more than one clockcycle.

Since the time-walk contribution is larger than the diffusion term in equation 6.2, this is not a good way to measure longitudinal diffusion and a better way had to be found.

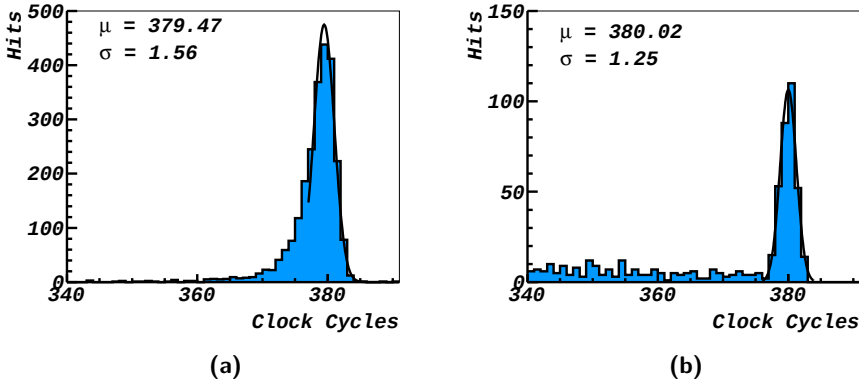


Figure 6.3.2: a) The raw time spectrum of electrons released at a fixed z as measured in ToA mode. b) The raw time spectrum of electron released at a fixed z as measured in ToT mode. The entries left of the peak are due to signals with an amplitude too small to last until the end of the shutter. The peak is fitted with a Gaussian with a 3σ cut on both sides to get rid of the background. The spectra in both pictures are produced with $E = 1.87$ kV/cm $= 7.52$ Td at room conditions.

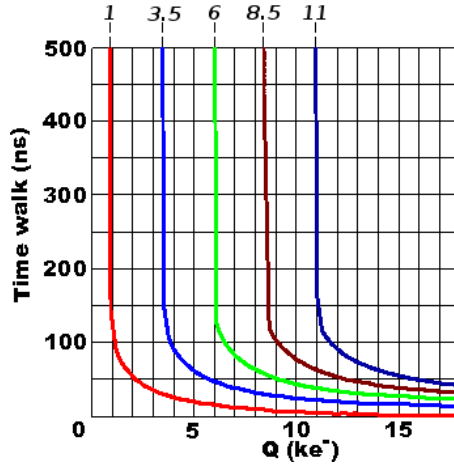


Figure 6.3.3: TimePix-1 time-walk versus input charge for several thresholds in ke^- . The threshold used in the experiment (800 e^-) corresponds approximately to the red curve [28].

ToT-Method

In ToT mode the TimePix counter measures the charge of the signals, by measuring how long the signal is over threshold. Coupled with a solid state sensor this can be used for measuring the energy and identity of the incident particle or/and to improve position resolution. In GridPix ToT is a measure of the number of electrons in an avalanche. ToT cannot be used simultaneously with ToA, however in specific cases ToT can be used to measure ToA.

For small input charge the signal goes below threshold and it goes above threshold again well before the end of the shutter (see figure 6.3.1). However sufficiently large input charges remain under threshold until the end of the shutter. For these the ToT interval recorded is the same as the ToA interval that would have been recorded in ToA mode, figure 6.3.4. In this way the ToA is measured for large signals. Time-walk is minimum for large gain, therefore selecting large ToT signals minimises the contribution of time-walk.

Electrons released near the grid arrive significantly earlier than electrons released near the cathode. The fraction of electrons released near the cathode with signals that exceed the maximum ToT is therefore significantly lower than the fraction of electrons with signals that exceeds the maximum ToT released near the grid. The current discharge rate of the pre-amplifier is controlled by the Krumenacher current. Since similar settings are desired for all measurements, the length of the signals is increased by reducing the Krumenacher current to 1 (Pixelman settings) and the shutter length is set at $16 \mu\text{s}$. In this way it is guaranteed that

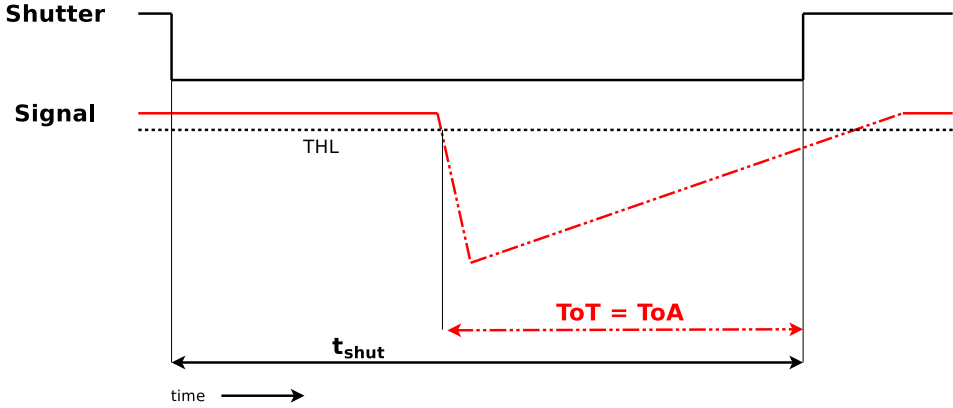


Figure 6.3.4: An illustration of the time over Threshold (ToT) method; Sufficiently large signals exceed the shutter window, hence the ToA interval equals the ToT interval.

for measurements performed with electric fields in the range of $0.2 - 2.5 \text{ kV/cm}$ electrons arrive in time and a significant fraction of the electrons released at all heights exceed the maximum ToT, such that they can be used for the measurements. In the case of electrons released near the cathode in low drift fields the strongest 80% of the signals ($\gtrsim 10 \text{ ke}^-$) are selected. For electrons released near the grid in high drift fields this fraction drops to 25%.

Figure 6.3.2b shows a measurement similar to figure 6.3.2a but performed in ToT mode. In both plots it is observed that the distributions peak at approximately the same value, but the ToT width is smaller because the contribution of time-walk is significantly reduced. Ignoring the tail, the distribution is fitted with a Gaussian. The contribution due to longitudinal diffusion can be extracted by studying the widths for several drift distances. Note that this method requires knowledge about the drift time beforehand to set an appropriate shutter time and Krumenacher current. In the rest of this chapter measurements are performed using the ToT-method.

6.3.2 Drift Velocity

To determine the drift velocity the laser is focussed at several drift distances. For each drift distance a time spectrum, similar to figure 6.3.2b, is obtained. The time spectra are fitted with a Gaussian and the mean is plotted versus the drift distance for several electric fields in figure 6.3.5. The data points are fitted with a straight line and the slope of the line is the drift velocity. The crossing point of the curves gives the absolute position of the grid. The drift distance and times have been adjusted such that this crossing point is the origin in the figure. In the ideal case all curves cross exactly at the origin, however possibly due to temperature and

pressure variations during the measurements the spread is about $200\text{ }\mu\text{m}$. The ToT method is inefficient especially at small electric fields, so long measurement times are required. This means variations in temperature and pressure can be significant.

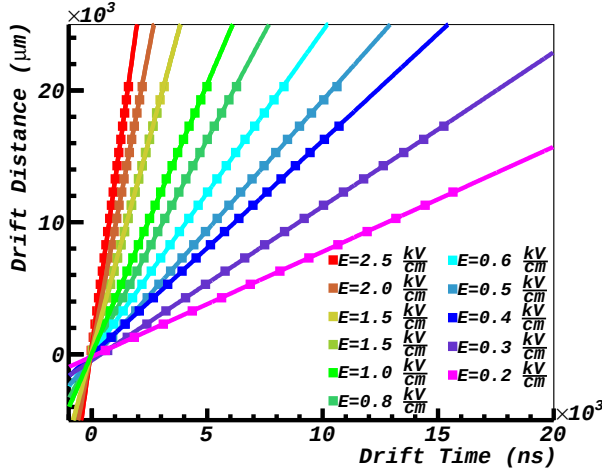


Figure 6.3.5: The fitted drift times as function of the drift distance for several electric fields. The slopes indicate the drift velocities, the crossing point represents the absolute grid position. The data points are not corrected for temperature and pressure changes.

The prototype detector has been assembled by hand. Despite the effort to mount the parts very precisely it is still possible that crucial parts like the cathode, the guard and the wires are tilted by tens of microns, resulting in distortions in the drift field. This effect is expected to be smaller than 1% and can therefore be neglected.

Figure 6.3.6 shows the z -distance of the measured points with respect to the fitted straight line for every fit. The similar systematic that can be observed for each fit is believed to be a geometric effect as result of small distortions in the electric field due to displaced or tilted electrodes. The size of the observed variations gives systematic errors of order 1% on the drift velocity, therefore they can be neglected.

The measured drift velocity as function of the electric field is compared with the results from MagBoltz for various ratios of the CO_2 :DME mixture in figure 6.3.7. The measured curve is slightly below the 50:50 line but has a similar shape.

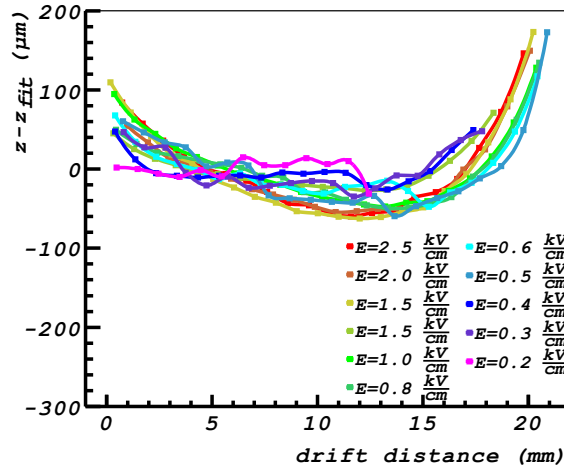


Figure 6.3.6: The pulls of the fits in figure 6.3.5. The systematic offsets suggests distortions in the drift field. Statistical errors are drawn but smaller than the points.

From this measurement it can be concluded that the gas mixing ratio of CO_2 :DME in this experiment was approximately 47:53.

6.3.3 Transverse Diffusion

The transverse diffusion of electrons in the gas is a function of the number of collisions in the gas, therefore it depends on the electric field. The coefficient can be measured using the laser to release single drift electrons inside the drift gap. It is extracted from the distribution of hit pixels in the x -direction (transverse to the beam).

Figure 6.3.8 shows all fitted distributions of hit pixels for electrons released at several heights for $E = 1.0 \text{ kV/cm}$. The most narrow (pink) curve is the response for electrons released at approximately 0.5 mm from the grid, which hardly suffer from diffusion. The broadest (red) curve has the laser focussed close to the cathode, with the largest diffusion component. The shift in the peak centres of about half a pixel is the result of misalignment of the detector and laser stages.

Figure 6.3.9 shows the corresponding fitted widths versus the drift distance. The data points are fitted with equation 6.3 to extract the transverse diffusion coefficient D_t . Here the offset c contains the errors due to the pixel pitch and the

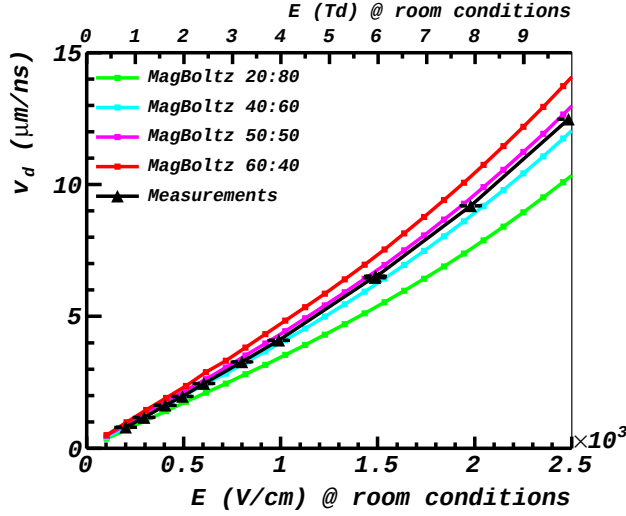


Figure 6.3.7: The drift velocities as obtained from the ToT measurements compared with the drift velocities as extracted from MagBoltz as function of the electric field for different gas mixing ratios of the CO_2 :DME mixture.

width of the focal point. Given the pixel pitch, the laser focal width can be extracted from the parameter c ; the width of the focal point turns out to be $12.6 \mu\text{m}$.

$$\sigma_t(z) = \sqrt{D_t^2 z + c^2} \quad (6.3)$$

Figure 6.3.10 shows curves similar to figure 6.3.9 for several electric fields. For convenience the curves are corrected for the offset c such that they go through the origin.

Figure 6.3.11 shows the transverse diffusion coefficients from the measurements plotted against the drift field together with the coefficients as extracted from MagBoltz. Note that the data points are corrected for temperature and pressure. Again there is a good agreement with MagBoltz, with a measured diffusion slightly better than prediction.

6.3.4 Longitudinal Diffusion

The longitudinal diffusion of electrons in the CO_2 :DME mixture is approximately the same as the transverse diffusion. The measurement is challenging since the longitudinal diffusion is pointed in the same direction as time-walk which is a-

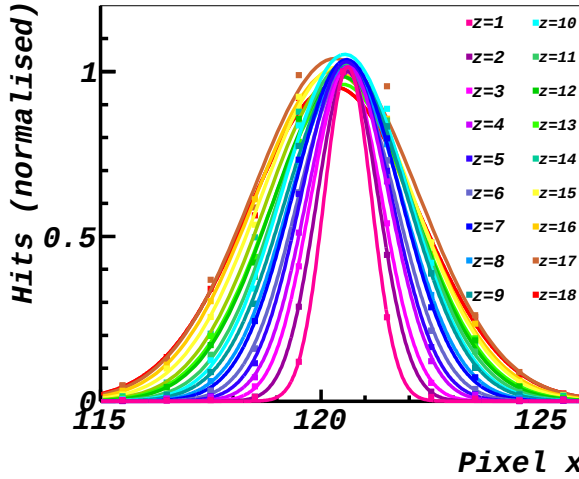


Figure 6.3.8: All fitted distributions of hit pixels for electrons released at several consecutive heights for $E = 1.0$ kV/cm. The most narrow (pink) curve is the response to electrons released close to the grid. For every consecutive curve the drift distance is 1 mm larger.

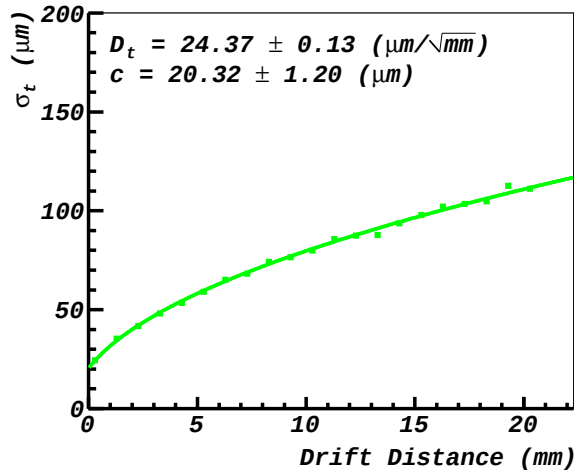


Figure 6.3.9: The fitted widths from figure 6.3.8 versus average drift distance. The data points are fitted with equation 6.3 to extract the transversal diffusion coefficient.

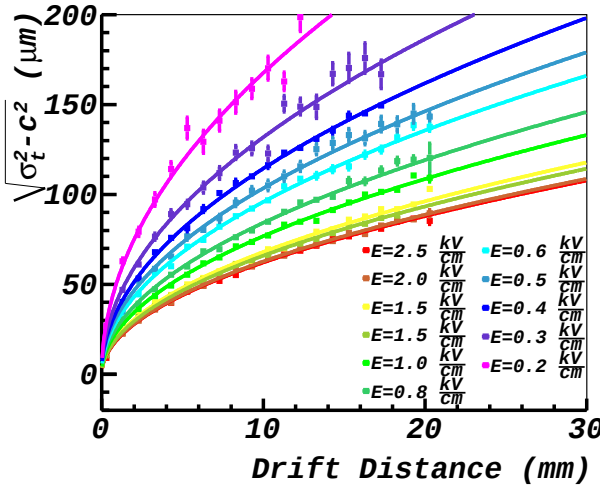


Figure 6.3.10: $\sqrt{\sigma_t^2 - c^2}$ from the hits spectra versus the drift distance. The data points are fitted with a function with a square root dependency of the drift distance, giving the diffusion parameter D_t .

symmetric and has a comparable magnitude. Here the advantage of the ToT-method enables accurate measurements of longitudinal diffusion.

The laser is focussed at several heights. For each height a spectrum similar to figure 6.3.2b is measured. The width is extracted by fitting the spectrum with a Gaussian. Figure 6.3.12 shows the widths versus the drift distance for several electric fields. For each value of E the data points are fitted with equation 6.2, grouping the last 3 terms in a parameter c . The diffusion coefficients are extracted from the fits. Figure 6.3.13 shows these together with MagBoltz values for several gas compositions. Again the measurements are in good agreement with MagBoltz.

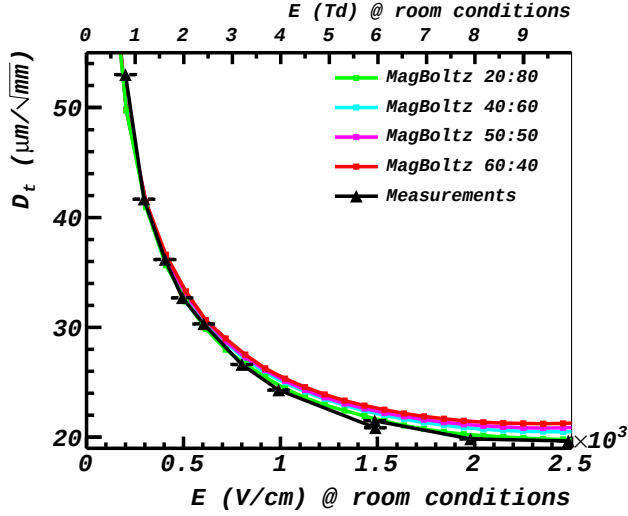


Figure 6.3.11: The measured transverse diffusions as function of the electric field compared with MagBoltz results for different gas mixing ratios. The data points are corrected for temperature and pressure.

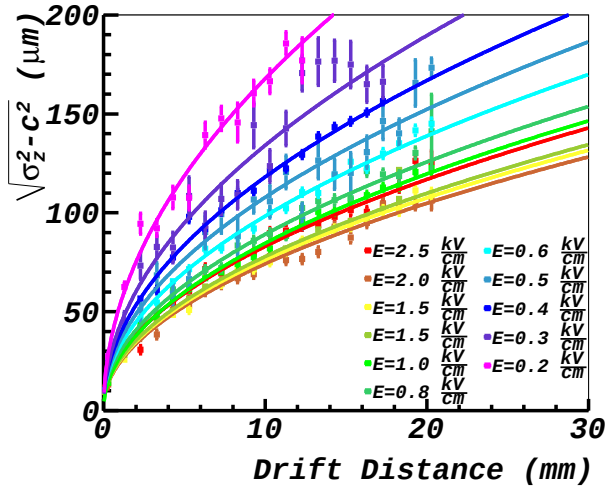


Figure 6.3.12: $\sqrt{\sigma_z^2 - c^2}$ plotted against the drift distance. The data points are fitted in order to extract the longitudinal diffusion.

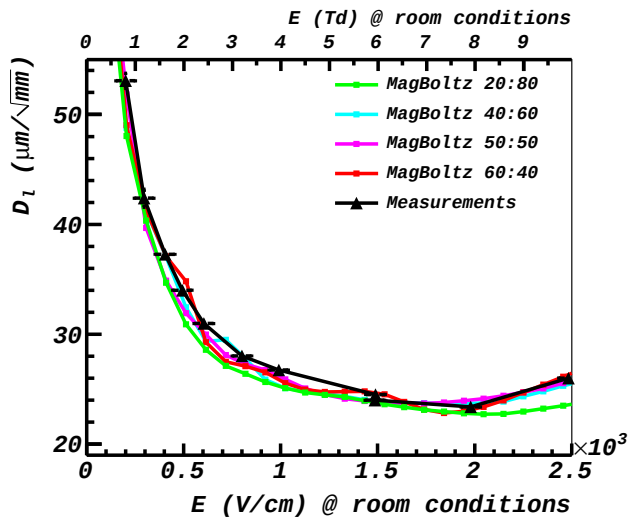


Figure 6.3.13: The longitudinal diffusion coefficients as function of the electric field as extracted from measurements done in ToT mode. These are compared with MagBoltz results for different gas mixtures.

6.4 Conclusion

The nitrogen laser as is used for the measurements has proven to be an ideal tool to study gas properties in GridPix. However, because of the low firing frequency, low drift fields require long measurement times. In this time the environmental conditions may change, which can affect the results. A larger firing frequency to reduce the measure sequence time or online monitoring of temperature and pressure might improve the systematic uncertainties.

The leaks in detector mechanics have been repaired with silicone glue, which is known for its oxygen diffusion. The presence of oxygen in the gas reduces the detection efficiency. Electrons released high in the drift gap tend to have an attachment rate of about 20% at a flow of 120 ml/min. This does not affect properties like diffusion and drift velocity and amplification. The systematic deviation on the gas mixture ratio is reproducible. No effects in the results are observed by replacing bottles. The gas mixture was not measured independently but a ratio of CO₂:DME of 47:53 was extracted from the drift velocity measurements by comparing them with MagBoltz. Therefore the results rely on simulations and they are not independent. Nevertheless, it has been shown that the laser measurements using the ToT method give accurate results. Sufficient knowledge about the gas mixture is required for future experiments.

Measuring the longitudinal diffusion with the ToT method gives significantly better results than the traditional ToA method. The results perfectly match simulations and might even be used to improve MagBoltz performance. Although the drift velocity and the diffusion measurements are corrected for the long term temperature and pressure change, short term variations slightly affect the results. Despite this the results show good agreement with MagBoltz. The advantage of releasing single electrons makes the measurements of the fundamental parameters for charge transport in gas more direct.

The uncertainty on temperature, pressure, the amplification gap size, gas mixture ratio and the calibration of charge give rise to systematic errors. Apparently they are small since the measurements show good agreement with simulations performed in Garfield with a NeBEM field map.

Appendices



Radiation Length of GridPixes in the Testbeam

Figure A.0.1 shows an illustration of a GridPix detector. In the picture the components together with their thicknesses are presented; the PCB material is indicated in green, the copper ground planes and the copper cathode in orange, the silver epoxy glue in blue, the silicon chip bulk material in yellow, the silicon rich silicon nitride protection layer in red. Table A.0.1 shows the materials and their corresponding thickness and radiation length. From this the total radiation length of a single Gossip is 2.77 %.

Table A.0.1: Properties of material layers used a single GridPix detector. The values are obtained from reference [90] and [42].

Material	Thickness (mm)	X_0 (mm)
Copper on PCB board (2×)	0.03	14.4
PCB (Glass fibre epoxy) board	1.6	159.3
Epoxy silver glue	0.1	39
Silicon	0.7	93.7
Silicon Rich Silicon Nitride	0.01	110
Copper Cathode (2×)	0.03	14.4
PCB (Glass fibre epoxy) Cathode	0.2	159.3

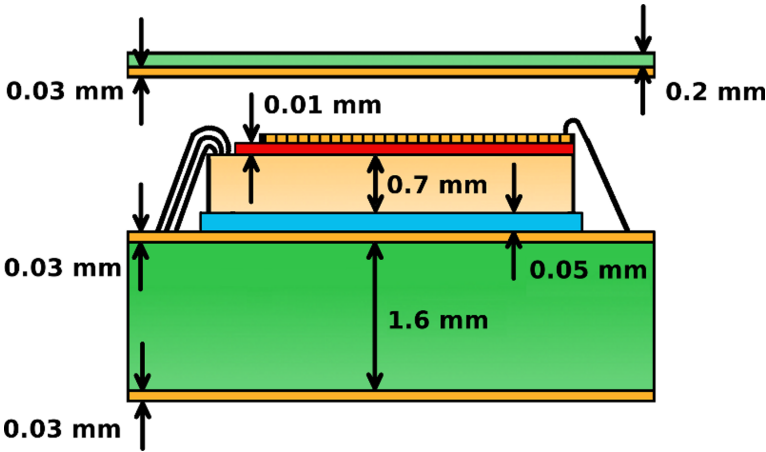


Figure A.0.1: Illustration of a single Gossip detector (not to scale), the color indicates the material type (see text).

References

- [1] P. W. Higgs. Broken symmetries and the masses of gauge bosons. *Physical Review Letters*, 13:508–509, 1964.
- [2] The ATLAS Collaboration. Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC. *Physics Letters B*, 716:1–29, 2012.
- [3] The CMS Collaboration. Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC. *Physics Letters B*, 716:30–61, 2012.
- [4] F. Halzen and A.D. Martin. *Quarks & Leptons: An introductory Course in Modern Particle Physics*. Wiley, 1984. ISBN 0471887412.
- [5] A. Einstein. Zur elektrodynamik bewegter körper. *Annalen der Physik*, 322 (10):891–921, 1905.
- [6] A Guth. Inflationary universe: A possible solution to the horizon and flatness problem. *Physical Review D*, 23:347–356, 1981.
- [7] The ATLAS Collaboration. Letter of Intent for the Phase-II Upgrade of the ATLAS Experiment. Technical Report CERN 2012-022, LHCC-I-023, CERN, December 2012. URL <https://cds.cern.ch/record/1502664/files/LHCC-I-023.pdf>.
- [8] The ILC collaboration. The International Linear Collider Technical Design Report. <http://www.linearcollider.org/ILC/Publications/Technical-Design-Report>, 2013.
- [9] The ATLAS Collaboration. The ATLAS Experiment at the CERN Large Hadron Collider. *Journal of Instruments*, 3, S08003, 2008.
- [10] E. Lyndon et al. The CERN Large Hadron Collider: Accelerator and Experiments, volume Volume 1: LHC Machine. *Journal of Instruments*, 3, S08001, 2008.
- [11] H. Band et al. Performance and prospects of GridPix and Gossip detectors. *ATLAS Note No: ATL-P-MN-0016*, 2009.

- [12] F. Hartjes et al. Test beam studies of the GasPixel transition radiation detector prototype. *Nuclear Instruments and Methods A*, 706:59–64, 2013. ISSN 0168-9002.
- [13] R. Wilson et al. Radiological use of fast protons. *Radiology*, 47(5):487–491, 1946.
- [14] S.N. Penfold et al. A more accurate reconstruction system matrix for quantitative proton computed tomography. *Medical Physics*, 36:4511–4518, 2009.
- [15] H. Sadrozinski et al. Development of a head scanner for proton CT. *Nuclear Instruments and Methods A*, 699:205–210, 2013.
- [16] H. Ryu et al. Density and spatial resolutions of proton radiography using a range modulation technique. *Physics in Medicine and Biology*, 53(19):5461–5468, 2008.
- [17] W.J.C. Koppert et al. Charge protection characterisation and drift time resolution improvement for GridPix. *IEEE NSS-MIC*, pages 1799–1802, 2011.
- [18] P.C. Tsopelas. Applying GridPix as a 3D particle tracker for proton radiography. Master’s thesis, University of Amsterdam, 2011.
- [19] B. Huisman. Proton Imaging with Gridpix Detectors. Master’s thesis, University of Amsterdam, 2012.
- [20] J. Visser. Private communication, 2014.
- [21] E. Rutherford. An electrical method of counting the number of α -particles from radio-active substances. *Proceedings of the Royal Society of London A*, 81 (546):141–161, 1908.
- [22] G. Charpak et al. The use of multiwire proportional counters to select and localize charged particles. *Nuclear Instruments and Methods*, 62(3):262–268, 1968.
- [23] D.R. Nygren. Proposal to investigate the feasibility of a novel concept in particle detection. Technical report, LBL internal report, 1974.
- [24] F. Sauli. GEM: A new concept for electron amplification in gas detectors. *Nuclear Instruments and Methods A*, 386:531–534, 1997.
- [25] Y. Giomataris et al. Development and prospects of the new gaseous detector ‘Micromegas’. *Nuclear Instruments and Methods A*, 419:239–250, 1998.
- [26] L. Ounalli. *Micromegas Time Projection Chamber Development for Rare Event Detection*. Université de Neuchâtel, 2006.

- [27] Y. Bilevych. Private communication, 2012.
- [28] X. Llopart et al. Timepix, a 65k programmable pixel readout chip for arrival time, energy and/or photon counting measurements. *Nuclear Instruments and Methods A.*, 581:485–494, 2007. ISSN 0168-9002.
- [29] R. Kluit et al. Development of a small-scale prototype of the GOSSIPO-2 chip in 0.13 μm cmos technology. In *Proceedings of the Topical Workshop on Electronics for Particle Physics, September 3–7, Prague, Czech Republic, 2007*.
- [30] X. Llopart et al. Medipix2: a 64-k pixel readout chip with 55- μm square elements working in single photon counting mode. *IEEE Transactions on Nuclear Science.*, 49(5):2279–2283, 2002.
- [31] M. Barbero et al. Design and test of the CMS pixel readout chip. *Nuclear Instruments and Methods A.*, 517:349–359, 2004.
- [32] Martin Fransen. *Gridpix: TPC development on the right track*. PhD thesis, University of Amsterdam, 2012.
- [33] Víctor Manuel Blanco Carballo. *Radiation imaging detectors made by wafer post-processing of CMOS chips*. PhD thesis, University of Twente, 2009.
- [34] T. Lux. Private communication: IFAE Broken GridPix Analysis Summary Report, 2013. URL https://wiki.nikhef.nl/detector/pub/Main/GridPix/report_brokenGridPix.pdf.
- [35] W.J.C. Koppert et al. GridPix detectors: Production and beam test results. *Nuclear Instruments and Methods A.*, 732:245–249, 2013.
- [36] Z. Vykydal et al. USB interface for Medipix2 pixel device enabling energy and position-sensitive detection of heavy charged particles. *Nuclear Instruments and Methods A.*, 563:112–115, 2006.
- [37] V. Kraus et al. FITPix 2014: fast interface for Timepix pixel detectors. *Journal of Instrumentation*, 6, C01079, 2011.
- [38] G. Bardelloni et al. A new read-out system for an imaging pixel detector. *IEEE NSS*, 2:12–57, 2000.
- [39] Z. Vykydal et al. The RELAXd project: Development of four-side tilable photon-counting imagers. *Nuclear Instruments and Methods A.*, 591:241–244, 2008.
- [40] D. Turecek et al. Pixelman: a multi-platform data acquisition and processing software package for Medipix2, Timepix and Medipix3 detectors. *Journal of Instrumentation*, 6, C01046, 2011.

- [41] V. Van Beveren and Others. Relaxd module: User instructions & software manual, 2011. URL <https://lbtwiki.cern.ch/pub/VELO/VeloTestbeam2012/Relaxd-manual.pdf>.
- [42] K. Nakamura et al. The Review of Particle Physics. *Journal of Physics G.*, 37: 075021, July 2012. URL <http://pdg.lbl.gov/>.
- [43] C. Leroy and P.G. Rancoita. *Principles of Radiation Interaction in Matter and Detection*. World Scientific, 2004. ISBN 9789812389091.
- [44] M.J. Berger et al. Xcom: Photon cross sections database. URL <http://www.nist.gov/pml/data/xcom/>.
- [45] F.M. Penning. Über ionisation durch metastabile atome. *Naturwissenschaften*, 15(40):818–818, 1927.
- [46] R.J.D. Veenhof. Garfield 9; simulation of gaseous detectors, 2010.
- [47] W. Blum et al. *Particle Detection with Drift Chambers*. Springer, 2008. ISBN 9783540766834.
- [48] E.B. Wagner et al. Time-of-Flight Investigations of Electron Transport in Some Atomic and Molecular Gases. *Journal of Chemical Physics*, 47:3138–3147, 1967.
- [49] J.H. Parker and J. Lowke. Theory of electron diffusion parallel to electric fields. *Physical Review*, 181:290–301, 1969.
- [50] W. Legler. Zur statistik der elektronenlawinen. *Zeitschrift für Physik*, 140(2): 221–240, 1955.
- [51] W. Legler. Die statistik der elektronenlawinen in elektronegativen gasen, bei hohen feldstärken und bei großer gasverstärkung. *Zeitschrift Naturforschung Teil A*, 16:253–261, 1961.
- [52] W. Legler. The influence of the relaxation of the electron energy distribution on the statistics of electron avalanches. *British Journal of Applied Physics*, 18 (9):1275–1280, 1967.
- [53] G.D. Alkhazov. Statistics of electron avalanches and ultimate resolution of proportional counters . *Nuclear Instruments and Methods.*, 89:155–165, 1970.
- [54] J. Byrne. Statistics of the Electron-Multiplication Process in Proportional Counters. *Proceedings of the Royal Society of Edinburgh A.*, 66:33–41, 1962. ISSN 1473-7124.

- [55] H. Neu. Eine erweiterung det Townsendschen Naherungsformel fur die Ionisierung im Homogenen Elecktrischen Feld. *Zeitschrift für Physik*, 152:294–305, 1958.
- [56] L. Frommhold. Zur Statistik der Elektronenlawinen im ebenen Feld. *Zeitschrift für Physik*, 150:172–181, 1958.
- [57] U.G. Yule. A Mathematical Theory of Evolution, Based on the Conclusions of Dr. J. C. Willis, F.R.S. *Philosophical Transactions of the Royal Society of London B.*, 213:21–87, 1925.
- [58] W.H. Furry. On Fluctuation Phenomena in the Passage of High Energy Electrons through Lead. *Physical Review*, 52:569–581, 1937.
- [59] A.H. Cookson and T.J. Lewis. Variations in the Townsend first ionization coefficient for gases. *British Journal of Applied Physics*, 17:1473–1483, 1966.
- [60] W. Riegler and C. Lippmann. The physics of resistive plate chambers. *Nuclear Instruments and Methods A.*, 518:86–90, 2004.
- [61] A. Sharma. Properties of some gas mixtures used in tracking chambers. 1998. URL <http://www.slac.stanford.edu/pubs/icfa/summer98/paper3/paper3.pdf>.
- [62] M. Chefdeville. *Development of Micromegas-like gaseous detectors using a pixel readout chip as collecting anode*. PhD thesis, University of Amsterdam, 2009. URL http://www.nikhef.nl/pub/services/biblio/theses_pdf/thesis_MA_Chefdeville.pdf.
- [63] Y. Itikawa. Cross sections for electron collisions with carbon dioxide. *Journal of Physical and Chemical Reference Data*, 31:749–767, 2002.
- [64] L.G.H. Huxley et al. Use of the parameter E/N. *British Journal of Applied Physics*, 17(9):1237–1238, 1966.
- [65] N. Metropolis and U. Stanislaw. The monte carlo method. *Journal of the American Statistical Association*, 44:335–341, 1949.
- [66] P. Bhattacharya. Realistic three dimensional simulation on the performance of micromegas. *Nuclear Instruments and Methods A*, 628:465–469, 2011.
- [67] S. Mukhopadhyay and N. Majumdar. A study of three-dimensional edge and corner problems using the NeBEM solver. *Engineering Analysis with Boundary Elements*, 33:105–119, 2009.
- [68] N. Majumdar and S. Mukhopadhyay. Simulation of 3D electrostatic configuration in gaseous detectors. *Journal of Instrumentation*, 2, P09006, 2007.

- [69] J.D. Jackson. *Classical Electrodynamics*. Wiley, 3 edition, 2004. ISBN 9780471427643.
- [70] K. Nikolopoulos. Electron transparency of a Micromegas mesh. *Journal of Instrumentation*, 6, P06011, 2011.
- [71] S.F. Biagi. A description of the Magboltz program, with results compared to experiment. *Nuclear Instruments and Methods A.*, 421:234–240, 1999.
- [72] H.L. Groenstege and J.J. Kuijt. MiniHV V2: A modular, remote controlled high voltage system, 2011. URL <http://www.nikhef.nl/pub/services/biblio/technicalreports/ETR2011-02.pdf>.
- [73] R. Brun and F. Rademakers. ROOT - An Object Oriented Data Analysis Framework. *Nuclear Instruments and Methods A.*, pages 81–86, 1997.
- [74] K. Akiba et al. Charged particle tracking with the Timepix ASIC. *Nuclear Instruments and Methods A.*, 661:31–49, 2012.
- [75] K. Pearson. On lines and planes of closest fit to systems of points in space. *Phil. Mag.*, 6, 2:559–572, 1901.
- [76] D. York et al. Unified equations for the slope, intercept, and standard errors of the best straight line. *American Journal of Physics*, 72:367–375, 2004.
- [77] S. Krane and L. Schecter. Regression line analysis. *American Journal of Physics*, 50:82–84, 1982.
- [78] C.A. Cantrell. Technical Note: Review of methods for linear least-squares fitting of data and application to atmospheric chemistry problems. *Atmospheric Chemistry and Physics*, 8:5477–5487, 2008.
- [79] D. York. Least squares fitting of a straight line. *Canadian Journal of Physics*, 44:1079–1086, 1966.
- [80] J.H. Williamson. Least-squares fitting of a straight line. *Canadian Journal of Physics*, 46:1845–1847, 1968.
- [81] D. York. Least squares fitting of a straight line with correlated errors. *Earth and Planetary Science Letters*, 5:320–324, 1968.
- [82] R.J. Barlow. *Statistics: a guide to the use of statistical methods in the physical sciences*. Wiley, 1989. ISBN 9780471922957.
- [83] H.A. Bethe. Molière’s theory of multiple scattering. *Physical Review*, 89:1256–1266, 1953.

- [84] T. Poikela et al. Timepix3: a 65k channel hybrid pixel readout chip with simultaneous ToA/ToT and sparse readout. *Journal of Instruments*, 9, C05013, 2014.
- [85] E.E. Bergmann. Coherent UV from a TEA N₂ laser system. *Applied Physics Letters*, 31:661–663, 1977.
- [86] F. Hartjes. *A diffraction limited nitrogen laser for detector calibration in high energy physics*. PhD thesis, University of Amsterdam, 1990.
- [87] S. Beingessner et al. First Running experience With the Laser Calibration System of the UA1 Central Detector. *CERM-EP/89-62*, 1989. URL <http://cds.cern.ch/record/197455/files/cer-000109092.pdf>.
- [88] Mettler toledo m400, 2012. URL <http://www.mt.com>.
- [89] J. Jakubek et al. Pixel detectors for imaging with heavy charged particles. *Nuclear Instruments and Methods A*, 591:155–158, 2008.
- [90] C. Adler. Radiation length of the ALICE TRD., 2006. URL <http://www-physics.lbl.gov/~gilg/PixelUpgradeMechanicsCooling/Material/Radiationlength.pdf>.

Summary

Particle Detection in High Energy Physics

The collision position in accelerators like LHC is surrounded by several layers of radiation detectors, which use a broad spectrum of technologies to extract information for collision reconstruction. For detectors close to the interaction point it is important to accurately measure traversing particles without disturbing their trajectory, in favour of measurements performed in subsequent detectors. Gaseous tracking detectors are perfectly suited for this.

Gaseous Tracking Detectors

Gaseous radiation detectors are used for reconstruction of charged particle trajectories. Interaction of the charged particles with the gas molecules results in a trail of ion-electron pairs in the gas. An electric field separates ions and electrons; ions drift to the cathode and electrons to the anode. Electrons approximately follow the field lines to an amplification area. By measuring the electron position on the anode, the particle track projection is measured. In addition the drift distance is known from the electron time of arrival on the anode and the electron drift velocity. With this the particle trajectory can be reconstructed in three dimensions.

GridPix

The combination of photo-lithographic technology and high granularity pixel chips allow gaseous detectors to be made more efficient and more accurate than previous technologies. GridPix is a gaseous detector in R&D phase. The detectors can be distinguished by the high resolution pixel chip (256×256 pixels, with a $55 \mu\text{m}$ pitch) with a grid that is attached to the chip by insulating pillars, by photo-lithographic processes. Between the grid and the chip the field of about 100 kV/cm is sufficient to create amplification (figure 6.0.2). With such a high

field there is a significant probability to create discharges between the grid and the chip, which can be lethal for the sensitive pixel electronics. Therefore the chip is covered by a slightly conductive layer to quench discharges before damage occurs.

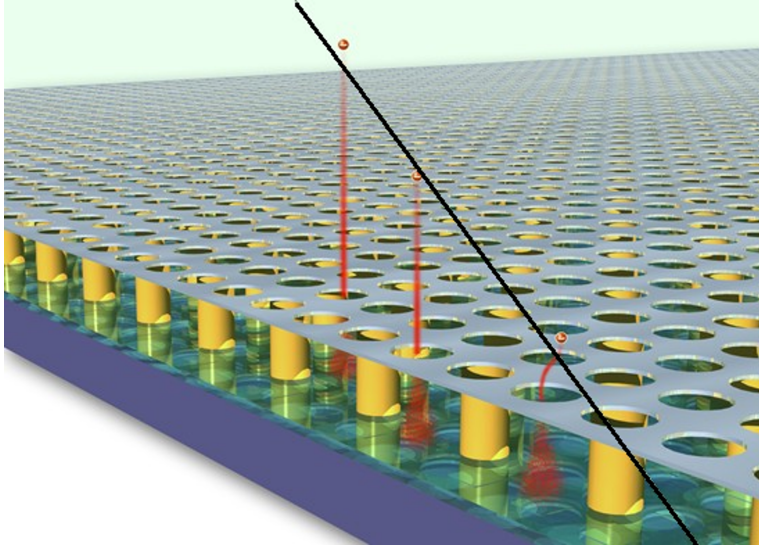


Figure 6.0.2: Illustration of the GridPix principle. The path of the traversing particle is indicated in black, the electrons and their drift path in red. Electrons drift towards the grid, after passing through the holes an amplification occurs, that is detected by the pixel.

The resolution in a plane parallel to the chip is limited by the pixel size and electron diffusion. The resolution in the drift direction is limited by the error in the time measurements. Current pixel chips have a large time-walk, dominating the drift direction resolution, but this will be fixed in future.

Results

In this thesis GridPix is characterised extensively. The contributions to the resolutions are studied in detail. A beam test with 180 GeV muons was performed in 2012 using GridPixes with a 1.2 mm drift gap with Timepix-1 read out chips. The field cage was flushed with $\text{CO}_2:\text{DME}$ (57:43). The detectors were oriented at about 45° to the beam. The in-plane track resolution was $10.1 \mu\text{m}$; the resolution in the drift direction was $35 \mu\text{m}$, dominated by high time-walk. The angular resolution was about 2.6° in one direction and 3.9° in the other direction, again limited by time-walk. The particle detection efficiency of GridPix for 180 GeV muons was

> 99%. The probability on three or more ionisations from a traversing muon was about 97%, in this case the path can be accurately determined.

A track fitting procedure has been developed which gives not only the track parameters and resolutions, but also their error matrix. The procedure has been verified by studying residuals with a telescope of GridPix detectors.

An ultra-violet laser has been used to produce single ionisations in GridPix, to measure gas properties and detector response. The distribution of the number of electrons participating in the amplification has been measured. The mean and fluctuations of this agrees with the results of electric field calculations combined with Monte-Carlo simulations. In addition measurements on drift velocities and diffusions in CO₂:DME (57:43) show good agreement with simulations.

Furthermore the effect of the drift field on the detector performance has been studied. These studies are performed using a recently developed electric field calculation method. In collaboration with the the developers the method is tested and optimised within the framework for gaseous detector simulations. Calculations on GridPix resulted in proposals for small changes in the GridPix geometry, to avoid discharges. Furthermore it is concluded that future GridPix detectors with improved time resolution should correct for time variations as results of field distortions. In addition a correction on the measurements from the edge pixels is required, due to small field distortions at the chip edge. The field-cage geometry of GridPix detectors with a 2 cm drifter is based on the results of electric field calculations.

Outlook

Future GridPix applications can be found in high energy physics and the medical industry. However the success of the applications depends on whether current challenges can be overcome; the discharge protection of current GridPixes is questionable. In the past it has been shown that GridPixes produced on small scale can be made reliable, however large scale production revealed several issues. Furthermore there are doubts about the long term influence of CO₂:DME (57:43) on the detectors; detailed studies on ageing are required. When these two challenges can be solved, GridPix might become of large value for science.

Samenvatting

Deeltjes Detectie in Hoge Energie Fysica

De positie waar de botsing heeft plaatsgevonden in een versneller zoals de LHC is omgeven door vele lagen stralingsdetectoren die gebruikmaken van een breed scala aan technologieën om de benodigde informatie voor reconstructie te vergaren. Voor detectoren dichtbij de botsing is belangrijk dat ze het passerende deeltje zo nauwkeurig mogelijk en met zo min mogelijk verstoring waarnemen, zodat metingen in opeenvolgende detectoren niet beïnvloed worden. Gas gevulde detectoren zijn daar zeer geschikt voor.

Gas Gevulde Volg Detectoren

Gas gevulde detectoren worden gebruikt voor het reconstrueren van positie en richting van passerende geladen deeltjes. Interactie van een geladen deeltje met gas leidt tot een spoor van ion-elektron paren in het gas. De ionen en elektronen worden van elkaar gescheiden door middel van een elektrisch veld; de ionen drijven richting de kathode en de elektronen richting de anode. Doordat de richting van het veld bekend is en elektronen bij benadering het elektrisch veld volgen kan, na versterking, de projectie van het pad van het deeltje op de (gesegmenteerde) anode gereconstrueerd worden. Doordat de drijf snelheid bekend is en de aankomst tijd gemeten wordt, kan bepaald worden welke afstand het elektron heeft afgelegd. Uiteindelijk kan het pad van het deeltje op deze manier in 3 dimensies gereconstrueerd worden.

De versterking van elektronen gebeurt in een gebied waarin het elektrisch veld groot genoeg is om ze genoeg snelheid te geven om zelf te ioniseren. De gas versterking die daarop ontstaat resulteert in genoeg lading om te worden gedetecteerd door gevoelige elektronica.

GridPix

Het concept van gas detectoren is al oud, maar de combinatie moderne fotolithografische technieken met gevoelige pixel chips kunnen gas detectoren efficiënter en accurater gemaakt worden dan ooit tevoren. GridPix is een detector met een gasvormige sensor in ontwikkelingsfase. De detector onderscheidt zich van anderen doordat gebruik is gemaakt van een hoge resolutie pixel chip (256×256 pixels met een afstand van $55 \mu\text{m}$), waarop met fotolithografische processen een plaatvormige elektrode is aangebracht die via kleine pilaartjes op de chip bevestigd is. In de elektrode zijn zeer kleine gaatjes gemaakt die precies uitgelijnd zijn met de pixels. Tussen de elektrode en de chip staat een elektrisch veld met een sterkte van orde 100 kV/cm , dat groot genoeg is om versterking te laten plaatsvinden, zie figuur 6.0.3. Met zulke grote velden is de kans op ontladingen tussen de elektrode en de chip significant. Voor de gevoelige elektronica kan een ontlading desastreuze gevolgen hebben. Een licht geleidende protectielaag is daarom op de chip aangebracht zodat tijdens een ontlading het elektrisch veld lokaal reduceert en de ontlading gestopt wordt voordat schade ontstaat.

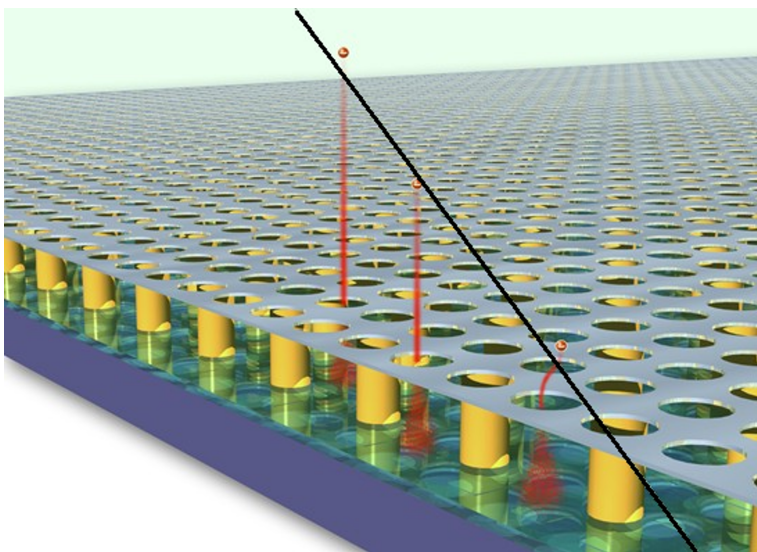


Figure 6.0.3: Een illustratie van het principe van een GridPix detector. Het pad van het passerende deeltje is aangegeven met de zwarte lijn, de elektronen en hun drijf pad in rood. De elektronen drijven naar beneden door de gaten waar vervolgens een amplificatie plaatsvindt, hierin ontstaat genoeg lading om door de pixel te worden waargenomen.

De resolutie in een vlak parallel aan de chip word gedomineerd door het effect van elektronen die tijdens het drijven continu van hun baan afgestoten worden door botsingen met gasmoleculen; diffusie. De resolutie in de drijf richting word gedomineerd door een onzekerheid in de tijdsmeting van de pixel; de pixel heeft de neiging elektronen later te meten dan dat ze daadwerkelijk binnengekomen zijn.

Resultaten

In dit proefschrift wordt de GridPix aan een breed scala aan testen onderworpen, om zo de detector te karakteriseren. Alle bijdragen aan de resolutie zijn nauwkeurig bestudeerd. Uit resultaten van een testbeam met 180 GeV muonen in 2012 is gebleken dat een GridPix met een maximale drijf afstand van 1.2 mm met een oriëntatie van 45 graden ten opzichte van de inkomende muonen een gemiddelde positie resolutie heeft van $10.1 \mu\text{m}$ in een vlak parallel aan de chip. Hierbij is het drijf gas $\text{CO}_2:\text{DME}$ (57:43) gebruikt. De resolutie in de drijf richting is $35 \mu\text{m}$. De hoek resolutie is ongeveer 2.6° in een richting en 3.9° in de andere richting door de onzekerheid in de tijdsmeting. De recent ontwikkelde TimePix-3 chip kan de aankomsttijd veel preciezer meten, waardoor toekomstige GridPix detectoren hoek resoluties zullen hebben van $< 2.6^\circ$. De efficiëntie voor het detecteren van een 180 GeV muon is $> 99\%$. De kans op drie of meer ionisaties door een passerend muon is ongeveer 97%. In deze gevallen is een goede reconstructie te maken van het pad van het deeltje.

Met behulp van een ultraviolet laserlicht zijn individuele ionisaties gemaakt in een GridPix detector. Hiermee zijn verschillende gas en detector eigenschappen gemeten. De verdeling van het aantal elektronen dat deelneemt aan de gasversterking is gemeten met de GridPix. Het gemiddelde komt overeen met de resultaten uit elektrische velden berekeningen in combinatie met Monte-Carlo simulaties. Ook de fluctuatie op het gemiddelde aantal elektronen is bestudeerd. In andere metingen zijn zowel de drijf snelheid en de diffusie coëfficiënten van elektronen in the transversale en longitudinale richting gemeten voor verschillende elektrische velden in $\text{CO}_2:\text{DME}$ (47:53). Ook deze resultaten tonen goede overeenkomsten met gesimuleerde data.

In dit proefschrift is verder onderzoek gedaan naar het effect van elektrische velden op de prestaties van de detector. Daarvoor is een recent ontwikkelde methode gebruikt om elektrische velden te berekenen. In samenwerking met de ontwikkelaars is deze methode getest en geoptimaliseerd binnen het raamwerk voor simulaties aan gas detectoren. De resultaten hebben geleid tot voorstellen tot kleine veranderingen in de GridPix geometrie ter voorkoming van ontladingen in het GridPix ontwerp. Tevens zijn de invloeden van de velden op de prestaties van de detector onderzocht; toekomstige GridPix detectoren met betere tijdsresolutie zouden de tijdsinformatie van elektronen met een kleine drijf afstand moeten

corrigeren voor veld effecten. Verder is een correctie nodig op de metingen van de laatste pixel, door kleine veld verstoringen aan de randen van de chip. Het ontwerp van GridPixen met een maximale drijf afstand van 2 cm is gebaseerd op resultaten die verkregen zijn met deze methode.

Toekomst

Toekomstige toepassingen van GridPix zullen gerelateerd zijn aan de hoge energie fysica of de medische industrie. Echter, er zullen een aantal probleem overwonen moeten worden; de betrouwbaarheid van huidige GridPix detectoren laat te wensen over. Hoewel in het verleden op kleine schaal geproduceerde betrouwbare GridPixen geproduceerd zijn is dat op grote schaal nog niet bewerkstelligd. Verder zijn er binnen het vakgebied twijfels over de lange termijn invloed van CO₂:DME (57:43) op de detectoren, hiervoor zijn studies nodig om de effecten te onderzoeken. Als deze onzekerheden niet meer in de weg staan, kan GridPix een goede bijdrage leveren aan de wetenschap.

Dankwoord

My studies on GridPix detectors were overloaded with challenges and opportunities (as Niels would say). As a result Murphy's Law was verified more often than any other law. However I think this is inherent in research.

I would like to thank my first co-promotor Harry; without you, GridPix would not exist. I am grateful for talking me into this research in your well known enthusiastic way. From you I learned that nothing is impossible and that there is a solution for every problem.

Nigel thanks for willing to become my second co-promotor in the third year and for sharing your knowledge about data analysis in a systematic way and particle physics in general. I will never forget how you locked the door after I left your office around 19:00; next day you claimed it was to prevent others to walking in;).

Frank, thanks for being my promotor and stimulating me in taking the last steps to finish.

Fred, your experience is of large value for the group. You taught me many lab skills related to the gas systems, electronics, mechanics, test beams and the laser. Besides that, your structured way of working set my standards.

Rob Veenhof, you learned me about modelling gaseous detectors and electric field calculation, since this knowledge was not present at Nikhef. Your interesting lectures, your unnatural working hours and your unlimited knowledge about the menu of Restaurant 2 I will never forget.

Martin Fransen, we discussed many issues and solutions of GridPix that helped me during my research, the rabbits left the day you left, but a woodpecker replaced them. I wish you the best in being a father.

Rolf and Francesco many thanks for helping me with "my" testbeam and for supporting me at the endless day and night shifts, while slowly losing the majority of the detectors. Francesco, the first time I made you a coffee, I completely messed up and I lost my permit; from that point on you made me a coffee more then 1000 times, if you were a girl I would hug you for this. Rolf, thanks for the discussions about GridPix production for your help with Latex and cheering me up. Even now, when pressure increases for you, you are still the most happy person in the office, impressive!

Thanks to all colleagues in the R&D group; Niels, Els, Jan, Jan, Martin, Enrico, Marten, Matteo, Panagiotis, Deepak and later Stergios, Michele and Afroditi. Actually it wasn't an actual group when I started, Niels I think you did a great job! Joop, thanks for bonding the large number of GridPixes that I needed for my research, even though you were fed up with it. Bas and Vincent thanks for fixing the bugs in the data acquisition programs in your spare time, such that things worked out in the testbeams. Oscar and Ad thanks for making the beautiful pieces of mechanics required for the set-ups.

Femke, ik denk dat jij het meest te lijden hebt gehad onder dit project. Alleen al in het laatste jaar heb ik 30% van de werkdagen een mailtje gestuurd naar de bewaking omdat ik langer bleef. Die dagen heb jij er (bijna) altijd voor gezorgd dat het eten klaarstond ondanks het feit dat je zelf ook veels te lange dagen maakte. Ook heb je ervoor gezorgd dat alle 112 dagen waarop ik niet thuis sliep het huishouden gewoon doorging. En dan hebben we natuurlijk nog die 9 maanden durende verbouwing die we na ons werk en in het weekend deden en die laatste vakantie waarin ik overdag op het strand sliep en 's nachts commentaar verwerkte. Hoe hebben we dat in hemelsnaam doorstaan? Wat mij betreft kan dat alleen met onvoorwaardelijke liefde!

Pap en Mam, ik heb jullie veel te weinig gezien en dat betreur ik. Ondanks dat weet ik dat jullie mij steunden, zoals jullie dat altijd gedaan hebben en altijd zullen doen. Pap ik ben erg dankbaar dat je de voltooiing van mijn proefschrift kan meemaken en ik kan niet uitdrukken hoe gelukkig ik met jou en mamma ben. Ciska, Floris, Margreet en Bas jullie leven is erg veranderd, ondanks mijn eeuwige drukte zal ik proberen jullie en mijn neefjes vaker te bezoeken. Rien en Ted, jullie hebben mij en Fem heel wat werk uit handen genomen, daarbij heb ik mijn rust vaak bij jullie teruggevonden, bedankt!