Development of Micromegas-like gaseous detectors using a pixel readout chip as collecting anode

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One of the main applications foreseen for GridPix is to read out a Time Projection Chamber. It should hence be demonstrated that its tracking and particle identification performance is similar or superior to that achieved with standard pad readout. This task is beyond the scope of this thesis, nevertheless a first step in this direction was made by measuring the performance of a small GridPix TPC with cosmic particles.

The TPC has a sensitive volume of 1 cm$^3$ and its readout plane consists of a TimePix chip covered with an amorphous silicon layer and equipped with an InGrid. In a He/iC$_4$H$_{10}$ 77/23 gas mixture, a few thousand tracks of cosmic particles were recorded. Using the arrival time information from the TimePix chip, the three dimensional trajectories were reconstructed. I will report on a first estimate of the point resolution in the pixel plane and a measurement of the number of electron clusters per unit length. Also, some implications for an ILC TPC will be shortly discussed.

9.1 Introduction

The ionization from relativistic particles consists of clusters of electron/ion pairs distributed along the trajectories (cf. chapter 3). TPCs read out with pads of several mm$^2$ area are used to measure the charge produced along segments of tracks. In a pixel-readout TPC, almost all primary electrons are individually detected and if the diffusion is not too large, the cluster structure may be preserved during the drift and studied.
This study was conducted by means of a small TPC read out by a SiPro-
tected and InGrid-equipped TimePix chip. In order to have a good separation
between clusters, a mixture of He/iC$_4$H$_{10}$ 77/23 was used for low primary ion-
ization density and a small drift gap of 1 cm was adopted for small transverse
diffusion.

The measurement of the drift lengths of the primary electrons requires the time
at which the particles cross the detector. For this purpose, a coincidence set-up
provides the detector with a trigger signal. Another task of the coincidence set-up
is to ensure that the primary ionization density is the lowest and similar for all
recorded tracks.

9.2 Experimental set-up

9.2.1 The chamber

The chamber consists of a 12 × 16 cm$^2$ printed circuit board (or PCB) and a 12
× 10 × 1 cm$^3$ cover. A TimePix chip is glued and wire-bonded to the PCB and
the cover is formed by a metal square frame and a kapton foil with a thin metal
layer on one side which is used as the cathode. A 6 × 8 cm$^2$ thin metal layer is
printed on the PCB and etched in its middle to a 2 × 2 cm$^2$ square area where the
chip is glued. This layer acts as a guard electrode and is set at the same voltage
as the grid to improve the electric field uniformity.

Two holes were drilled into the metal frame for the gas circulation. The grid,
guard and cathode are connected to high voltage supplies through the PCB. For
the measurements, the chamber is placed vertically to record tracks oriented pre-
dominantly parallel to the pixel plane.

9.2.2 The TimePix chip

The TimePix chip (E09-W0014) is equipped with a 20 μm layer of amorphous
silicon and an InGrid of about 50 μm gap. The dimensions of the grid are similar
to those of D08 chip InGrid and can be found in section 8.4.1. The spread of the
pixel thresholds was minimized by the equalization procedure. After equalization,
the detection efficiency is uniform across the chip area except in the top left corner,
on the edges, along one dead column and on a localized spot were the grid was
damaged. The sensitive area is visible in Figure 4.13 (b). The chip is operated
in the TIME mode in order to record the relative arrival time of the primary
electrons. The clock frequency is set to 100 MHz and the active time of the
detector (given by the duration of the shutter signal) to 13 μs.
9.2 Experimental set-up

9.2.3 Cosmic MIP trigger

Cosmic rays

The cosmic ray spectrum above the earth atmosphere includes all stable charged particles and nuclei with life-times of order $10^6$ years or longer [216]. When entering the atmosphere, cosmic particles interact with the nuclei of nitrogen and oxygen molecules and produce charged and neutral nuclear particles. The latter rapidly decay into secondary particles (muons, neutrinos, electrons, positrons and photons) producing cascades of particles called air showers.

The secondary particles lose some energy in the atmosphere and at sea level, muons are the most numerous charged particles with an integral intensity of roughly $1 \text{ cm}^{-2}\text{min}^{-1}$ in an horizontal plane. They have a mean energy of about 4 GeV and an energy spectrum almost flat below 1 GeV which steepens gradually between 10 and 100 GeV to reflect the primary spectrum in $E^{-2.7}$. At energies much larger than 1 TeV, the spectrum becomes one power steeper [217].

Muons have an overall angular distribution proportional to $\cos^2 \theta$ where $\theta$ is the angle between the trajectory and the vertical. The muon spectrum is a rapidly decreasing function of energy with a tail in $E^{-2.7}$ for energies larger than $100 \text{ GeV/}\cos \theta$ and $\theta < 70^\circ$ [216].

Trigger signal

The trigger signal results from the time coincidence of signals from three scintillators. Two $4 \times 12 \text{ cm}^2$ scintillators are placed horizontally above the chamber, with an overlap area of about $4 \times 4 \text{ cm}^2$. Lead plates of $30 \times 30 \text{ cm}^2$ area for a total thickness of 10 cm are placed below the chamber and the third scintillator (1 m$^2$ area) is installed below the plates. The total lead thickness corresponds to 113.5 g/cm$^2$ which is equal to the mean range of 250–300 MeV/c muons in this material [194]. As a result, the third scintillator is traversed mainly by muons on the minimum of ionization or with larger energies, the lower energy part of the muon spectrum being vetoed. The coincidence setup is shown in Figure 9.1.

The scintillators are read out by photo-multiplier tubes (so-called PMTs). The PMT signals are fed to discriminators and to a coincidence unit. Upon coincidence, a trigger signal is sent from the coincidence unit to the chip through the MUROS (so-called shutter signal). The time between the passage of a particle through the three scintillators and the arrival of the shutter signal at the chip was measured to be about 100 ns. This delay is the result of the scintillator and PMT response times, the cable lengths and the processing times of the discriminators, the coincidence unit and the MUROS.

The trigger geometrical acceptance is slightly too large and some tracks may trigger the detector without traversing the sensitive volume. In the first measurement period, however, the software version would not permit to disregard empty frames and their content would be written to file. To decrease the probability to write empty files, the acquisition consisted in integrating the recorded frames
over a period of 12 min. In this case, some frames contained more than one track and the analysis of those data requires a track finding algorithm. Later on, empty frames could be filtered out and single acquisitions were used: the recorded frames likely contain only one track and the need for such algorithm is less justified.

![Figure 9.1: Photograph (a) and sketch (b) of the coincidence set-up. The lead plates and the third scintillator are not visible in the photograph.](image)

9.3 Measurements

9.3.1 Operating conditions

A series of measurements was performed at six values of grid voltage between -380 and -450 V in a gas mixture of He/iC$_4$H$_{10}$ 77/23. The trend of the gas gain $G$ with the grid voltage $V_g$ was measured and obeys the following relation:

$$ G = 0.0231 \cdot \exp(0.030V_g) $$

The drift field was kept at 670 V/cm. The expected drift velocity and diffusion coefficients calculated by MAGBOLTZ are listed in Table 9.1.
9.3 Measurements

\[
\begin{array}{ccc}
 v_d \, (\text{cm/\mu s}) & D_t \, (\mu \text{m}/\sqrt{\text{cm}}) & D_1 \, (\mu \text{m}/\sqrt{\text{cm}}) \\
 2.4 & 195 & 144
\end{array}
\]

Table 9.1: Electron drift parameters calculated by MAGBOLTZ at 670 V/cm in He/iC\(_4\)H\(_{10}\) 77/23. The chamber drift gap is 1 cm.

### 9.3.2 Event example

An event is shown in Figure 9.2 together with the drift time distribution. Due to the time-walk input signals smaller than a few thousand electrons are detected later than larger ones (cf. chapter 8). This effect explains the right tail of the drift time distribution in Figure 9.2 (b).

![Event example](image)

**Figure 9.2:** A cosmic track recorded in He/iC\(_4\)H\(_{10}\) 77/23 at a grid voltage of -450 V (a) and the corresponding drift time distribution (b).

The drift time of each detected electron is derived from the number of counted clock cycles \(C_{\text{hit}}\). The latter is proportional to the time between the hit and the end of the shutter signal. Hence, the time \(\Delta t\) between the arrival of the shutter signal at the chip and the hit is:

\[
\Delta t = (C_{\text{max}} - C_{\text{hit}}) \cdot \delta t
\]

(9.2)

where \(\delta t = 10\) ns is the duration of a clock cycle and \(C_{\text{max}}\) is the maximum number of clock cycles that can be recorded by a pixel during the shutter time. \(C_{\text{max}}\) is determined from the clock cycle distribution of all hits. Eventually, the drift time is obtained by adding to \(\Delta t\) the 100 ns delay due to the coincidence set-up.
9.3.3 Drift time distribution of all hits

At the various grid voltages, the drift time distributions of all hits have a similar shape: a tail on the right side and a peak on the left side. The sums of all distributions, corrected and not corrected for the effect of time-walk, are plotted in Figure 9.3. For a given track, the drift times corrected for time-walk are obtained by projecting all the hits onto the reconstructed track; this procedure is detailed in section 9.4.5.

The tail can be explained by the electron longitudinal diffusion and the time-walk while the peak is due to the primary electrons that arrive at the chip before the shutter signal. A pulse that crosses the threshold during the 100 ns delay may still be above threshold when the shutter signal arrives. In this case, the pixel counts during the full shutter time and the measured drift time is 100 ns.

![Figure 9.3: Raw and time-walk corrected time distributions of all hits.](image)

The time distribution corrected for time-walk extends up to 400 ns which yields a drift velocity of 2.5 cm/μs. This agrees well with the prediction from MAGBOLTZ of 2.4 cm/μs.
9.4 Data analysis

Our goal is to measure the point resolution and the mean number of electron clusters per unit length (so-called cluster density). The analysis should hence reconstruct the initial positions of the detected electrons, group them into clusters. The cluster density is then determined from the distribution of the distances between clusters as will be explained in section 9.6. In the following, the various steps of the track reconstruction are detailed.

9.4.1 Definition of the axes

The track reconstruction is realized using a cartesian coordinate system with the $x$ and $y$ axes parallel to the chip rows and columns and with the origin at the bottom left corner of the pixel matrix. The projection of a track in the $xy$-plane defines the $s$-axis whose origin is at the intersection of the projected track with the $y$-axis. The four axes are drawn in Figure 9.4.

![Coordinate system used for the track reconstruction](image)

**Figure 9.4:** Coordinate system used for the track reconstruction.

9.4.2 Hit selection

The hit selection is intended for suppressing eventual noise hits. The time distribution of a typical event has a width of about 500 ns and a main peak when most of the hits are recorded. Hence, hits recorded 500 ns before or after this peak are
likely noise hits and are removed from the distribution. Although the probability that the distribution still contains noise hits is very small, a second cut is applied to the time distribution. The r.m.s. of the distribution is used to suppress hits outside a window centered at the distribution maximum and with a half width of three times the r.m.s.

If a noise hit is still identified as a signal hit, it has a large probability to be located far from the track and likely will be rejected during the track fit.

9.4.3 Track finding

Some frames contain more than one track and a dedicated algorithm is used to separate them. The algorithm is based on the Hough transform and identifies straight lines in a given pattern of points [218].

The idea of the Hough transform in two dimensions is the following. A line passing through a hit is defined by two parameters, for instance the distance of closest approach to the origin $\rho$ and an angle $\theta$. When the line is rotated around the hit, these parameters change and eventually all the lines passing through this hit correspond to a curve in the $\rho \theta$-plane (so-called Hough plane). Hence, all hits distributed along a line $(\rho_0, \theta_0)$ in the $xy$-plane yield curves in the Hough plane which cross at the point $(\rho_0, \theta_0)$. In practice, the Hough plane is a two-dimensional histogram and estimates of the projected track parameters are obtained by searching for the position of the maximum in this histogram.

This technique is illustrated in Figure 9.5 where a pattern of hits from two tracks is shown, together with a top view of the two-dimensional histogram in the Hough space. Two main intersections corresponding to two peaks in the histogram are seen in the Hough space. The selected track is the one that corresponds to the highest peak.

The selection of the hits belonging to the track is done by first calculating the shortest distances between the hit positions (taken at the center of the pixels) and the Hough line: these distances are called the residuals. The mean and r.m.s. of the residuals to the Hough line are then used to reject hits with residuals three times the r.m.s. larger than the mean.

The Hough track is a good approximation of the true projected track. As it will be shown in section 9.5.1, the distribution of the hits w.r.t. to the projected track is governed primarily by the transverse diffusion. Hence, 99 % of the hits should be at a distance smaller than $3 \sigma$ from the track (and from the Hough track) and mainly noise hits or $\delta$-rays are removed when such cut is made on the residuals.

9.4.4 Track fit in the $xy$-plane

The parameters of the projected track in the $xy$-plane are precisely determined by fitting a straight line to the hit pattern [43]. The line parameters are determined by a linear regression method which consists in minimizing the quantity:
9.4 Data analysis

![Data analysis graph]

Figure 9.5: Hit pattern showing the Hough line (a) and a top view of the corresponding histogram in the Hough space (b).

\[ S = \sum_{i=1}^{N} (y_i - ax_i - b)^2 \]  \hspace{1cm} (9.3)

where \((a, b)\) are the parameters of the line and \(N\) the number of hits. If \(S\) is to be minimum, these parameters should be equal to:

\[ a = \frac{1/N \cdot \sum (x_i - \bar{x}) \cdot (y_i - \bar{y})}{1/N \cdot \sum (x_i - \bar{x})^2} \]  \hspace{1cm} (9.4)

and

\[ b = \bar{y} - a \cdot \bar{x} \]  \hspace{1cm} (9.5)

with \(\bar{x}\) and \(\bar{y}\) the means of the hit coordinates along the pixel rows and columns respectively. The goodness of the fit is estimated by means of the correlation coefficient:

\[ R = \frac{1/N \cdot \sum (x_i - \bar{x}) \cdot (y_i - \bar{y})}{\sigma_x \sigma_y} \]  \hspace{1cm} (9.6)

which is equal to 1 if all points are aligned \((\sigma_x\) and \(\sigma_y\) are the hit coordinates r.m.s. along the pixel rows and columns respectively).

This procedure is illustrated in Figure 9.6 (a) where a pattern of hits and the fitted line are shown. Using the fit parameters, one calculates the residuals of the hits coordinates w.r.t the line and the coordinates along the s-axis.
Figure 9.6: Track fit in the xy-plane (a) and the sz-plane (b).
9.4.5 Track fit in the $sz$-plane

The coordinates of the hits along the $z$-axis are determined from:

$$z_i = ((C_{\text{max}} - C_i) \cdot \delta t + t_{\text{delay}}) \cdot v_d$$  \hspace{1cm} (9.7)

where $v_d = 2.5 \text{ cm/\mu s}$ is the measured drift velocity.

The fit of the track in the $sz$-plane is done with the method described in the previous section. Due to the time-walk, a significant fraction of hits has a number of clock cycles lower than expected which leads to over-estimated drift lengths. As a result, the hits in the $sz$-plane exhibit a large spread (Figure 9.6 (b)) and the track parameters in this plane are not accurately determined.

In order to improve the precision on the track parameters, the fit is done twice. First, all the hits are included and their residuals to the fitted line are calculated. This time, the residuals are calculated as the distances from the hits to the fitted line at constant $s$. In the second fit, only hits with residuals within one sigma from the mean are used. The two fitted lines are drawn in Figure 9.6 (b). Finally, the reconstructed initial positions of the primary electrons are the positions of the hits projected onto the fitted line.

9.5 Spatial resolution study

A TPC is intended for measuring the momentum of particles and what matters eventually is the resolution on the helix parameters that are fitted to the curved tracks. This resolution depends on the point resolutions $\sigma_{xy}$ and $\sigma_z$ and on the number of measured points along the tracks (Equations 4.9 and 4.11).

The spread of the hits w.r.t. to the reconstructed tracks in the $xy$ and $sz$-plane is an indication of the point resolution of the detector. Ideally, the resolution should be derived from the spread of the hits w.r.t. the track measured by precise external detectors (e.g. silicon pixel detectors). Our experimental setup does not provide such information and the fitted track is used instead.

9.5.1 Hit residuals in the $xy$-plane and drift length

Introduction

In the $xy$-plane, the residuals $r_{xy}$ of the hit coordinates w.r.t. to the fitted projected track are governed by the following effects:

- the electron transverse diffusion in the gas. At a given distance from the anode, the coordinates of an electron in a plane perpendicular to the drift field are distributed according to a two-dimensional gaussian;

- the segmentation of the readout plane. The position of a detected electron is uniformly distributed over the pixel area;
• the range of the primary electrons.

Delta-rays with sufficient energy generate some hits far from the projected track and hence increase the variance of the residual distribution. In pure helium, the probability that an ejected electron covers an effective distance (or practical range) larger than 100 $\mu$m is about 2% ([53] and Equation 3.17). Assuming a cosmic path length of 14 mm and 25.6 primary interactions per centimeter, the probability per track is 60% [119]. We thus expect the $\delta$-rays to impact on the shape of the residual distribution.

- The signal induction on neighbouring pixels (enhanced by SiProt) which produces indirect hits next to direct hits.

Let’s assume that the gain distribution, the pixel thresholds and the SiProt thickness and composition are uniform across the chip area and consider a pixel above which no electron multiplication takes place.

In this case, the probability that this pixel records an indirect hit is proportional to the number of avalanches that develop above the neighbouring pixels. Because of the transverse diffusion, this number decreases with the distance from the projected track. Accordingly, the number of indirect hits per direct hit also decreases with this distance and the residual distribution of all hits should be slightly more peaked than that of the direct hits.

We think that this effect has little impact on the residuals and will check this statement by comparing the shape of the residual distributions of hits of short and large drift lengths;

- the error on the fit parameters biases the measured residuals.

The effect on the residual distribution should be very little because the track projected on the pixel plane is accurately measured. Nevertheless, to ensure a precise estimation of the projected track parameters, only tracks with a minimum length of 0.4 cm are used in the analysis.

In what follows, only the effects of diffusion and segmentation are considered.

**Variance of the residuals**

At the pixel plane, the coordinates $(x, y)$ of an electron produced at a distance $z$ from the anode plane is distributed according to the following two-dimensional gaussian (cf. section 2.3.3):

$$
G(x, y, z) = \frac{1}{2\pi D_t^2 z} \exp\left(-\frac{1}{2} \frac{x^2 + y^2}{D_t^2 z}\right)
$$

which implies that the projected distributions against the $x$ and $y$ axes are a one-dimensional gaussian of same width as $G(x, y, z)$. Because the orientation of the $x$ and $y$ axes is arbitrary, the residuals $r_{xy}$ are also gaussian distributed:
9.5 Spatial resolution study

\[ G(r_{xy}, z) = \frac{1}{D_t \sqrt{2\pi z}} \exp \left( -\frac{1}{2} \frac{r_{xy}^2}{D_t^2 z} \right) \]  

(9.9)

by definition, the variance of the residual is then:

\[ \sigma_{xy}^2 = D_t^2 \cdot z \]  

(9.10)

The coordinates \((x,y)\) of a detected electron are uniformly distributed over the pixel area and are determined with a precision of:

\[ \sigma_{xy,0} = p/\sqrt{12} \]  

(9.11)

which is valid if the grid holes and pixels are arranged in a square pattern and have the same pitch \(p\). With a pitch of 55 \(\mu\)m, a point resolution at zero drift length of 16 \(\mu\)m is expected. The two contributions to the variance are not correlated and add up quadratically:

\[ \sigma_{xy}^2(z) = p^2/12 + D_t^2 \cdot z \]  

(9.12)

If the other effects previously listed can be neglected, it should be possible to measure \(D_t\) and \(\sigma_{xy,0}\) by fitting a linear function to \((\sigma_{xy}^2, z)\) points.

Measurements

The two-dimensional histogram of the measured hit residuals \(r_{xy}\) with the reconstructed drift length \(z\) is shown in Figure 9.7 (a).

![Figure 9.7](image-url)

Figure 9.7: Two-dimensional histogram of the hit coordinate residuals in the xy-plane and the drift length (a). Variance of the residuals and drift length (b).
The variance of the residuals at a given \( z \) is determined by dividing the two-dimensional histogram in slices along the \( z \)-axis. The entries in each slice (or in one-dimensional histogram) have similar drift lengths. Afterwards, a gaussian function is fitted to each one-dimensional histogram and the function parameters are stored. This slicing-fitting routine is available within the ROOT data analysis program [219].

The trend of the variance of the residuals with drift length is illustrated in Figure 9.7 (b). Due to the 100 ns delay and the 2.5 cm/\( \mu \text{s} \) drift velocity, the variance is not measured at drift lengths below 0.25 cm. Also, the points between 0.25 and 0.5 cm correspond to the peak of the drift time distribution and might be wrongly measured. Still, this effect seems small as the observed trend is fairly linear up to \( z \sim 0.9 \text{ cm} \). At larger distances, the statistics are too low and the points are not shown.

A straight line is then fitted to the points. From the line slope, the measured transverse diffusion coefficient is 189 \( \pm 18 \mu \text{m/} \sqrt{\text{cm}} \), in good agreement with the MAGBOLTZ prediction of 195 \( \mu \text{m/} \sqrt{\text{cm}} \). The extrapolation to zero drift length yields an unphysical negative value which could be attributed to a systematic error on the drift time (error on the 100 ns delay or drift velocity).

**Effect of the SiProt**

As previously mentioned, the residual distribution at short drift length should be slightly more peaked than at larger distances. This is illustrated in Figure 9.8 where a gaussian function was fitted to the distributions at \( z = 0.3-0.4 \text{ cm} \) and \( z = 0.7-0.8 \text{ cm} \).

![Figure 9.8: Residual distributions in the xy-plane at z = 0.3–0.4 cm (a) and z = 0.7–0.8 cm (b).](image-url)
In the latter case, the distribution is gaussian while at $z = 0.3-0.4$ cm the relative number of hits with small residuals increases. In both cases, a tail on the two sides of the distributions are observed and can be attributed to the $\delta$-rays.

### 9.5.2 Hit residuals in the $sz$-plane

The distribution of the residuals in the $sz$-plane is also governed by the effects listed in section 9.5.1. In this case, however, the point resolution at zero drift length should be limited by the clock frequency. At 100 MHz and for a drift velocity of 2.5 cm/$\mu$s, 70 $\mu$m are expected.

Projections of the residual distribution at $z = 0.3-0.4$ cm (a) and $z = 0.7-0.8$ cm are shown in Figure 9.9. Long tails that correspond to late detection times are observed due to the effect of the time-walk. Furthermore, the distributions are not centered at zero which shows that the residuals were not accurately measured. Accordingly, the point resolution $\sigma_z$ is very poor.

![Residual distributions in the $sz$-plane at $z = 0.3-0.4$ cm (a) and $z = 0.7-0.8$ cm (b).](image)

### 9.5.3 Discussion

The measured point resolution in the pixel plane is compatible with the diffusion limit. In a GridPix TPC, this should improve the tracking performance for particles traversing the endplates, in particular those emitted at a small angle w.r.t. to the beam pipe (forward direction). In standard TPCs, the tracking performance degrades in the forward region because of a limited granularity close to the beam axis. With pixels, the performance could in principle be maintained down to very small angles because most primary electrons would be collected on
individual pixels. In this case, the point resolution along the drift direction would be very important. Our measurements show that it is rather poor due to the effect of the time-walk. Nevertheless, it could be improved with a thinner SiProt (or without SiProt, e.g. with multi-stage grids) or by a design of the electronics that would minimize the time-walk or allow to correct for it (e.g. if both the time and charge information are available at the pixel).

9.6 Study of the number of clusters

A motivation for a GridPix TPC is the possibility to measure the cluster density along the tracks and use this information for particle identification. In order to identify a cluster, the electron diffusion should be as small as possible. In this respect our experimental conditions (small gap, large distance between clusters) are well suited. The study is realized with data recorded at a grid voltage of -450 V in order to have the highest detection efficiency for single electrons (~ 95%).

The hits are grouped into clusters by comparing the distances between two consecutive hits along the reconstructed track to a certain step. If the distance between two hits is larger than the step, the hits belong to different clusters, otherwise to the same. Afterwards, the position of each cluster is calculated as the centre-of-gravity of the hits belonging to this cluster. The distribution of the distances $l$ between two adjacent clusters, determined with a step size of 275 $\mu$m (i.e. 5 pixels), is shown in Figure 9.10 (a). The number of clusters per unit length is then derived by fitting a decreasing exponential function to the distribution:

$$f(l) = p_0 \exp(-p_1 l)$$ (9.13)

where $p_0$ and $p_1$ are the function parameters and $p_1$ is an estimate of the number of clusters per unit length $n_c$ (Equation 3.19). Because the shape of the distribution departs from that of an exponential for distances close to the distribution maximum, the fit is performed from a given distance $d^*$ to 5000 $\mu$m. For 1000 $\mu$m $\leq d^* \leq 2000$ $\mu$m, the absolute variation of $p_1$ is smaller than 0.5 and the value of $n_c$ is taken as the mean value of $p_1$ over that range.

The advantage of this counting technique w.r.t. to the one used in [220] is that the tail of the distribution (and hence $p_1$ and $n_c$) is relatively insensitive to the step size because it corresponds to hits separated by large distances (w.r.t. the mean distance between clusters).

The obtained number of clusters per unit length $n_c$ depends on the step size as illustrated in Figure 9.10 (b). In the same plot, the prediction from the HEED program of 25.6 clusters/cm for 300 MeV muons is indicated by a dashed line. Also, the counting algorithm was applied to HEED generated tracks and the resulting trend is also shown (the number of tracks in both cases is similar). Detection inefficiency, charge sharing between pixels and the effect of time-walk were neglected. The tracks are oriented parallel to the pixel plane with a uniform
distribution along the drift direction and an angle w.r.t. to the $x$-axis uniformly distributed between $-\pi/4$ and $\pi/4$.

For step sizes of 20–200 $\mu$m, the values of $n_c$ derived from the simulated distributions is about 26 clusters/cm, close to the input value of 25.6 clusters/cm. This supports the validity of our counting technique. In the same range of step sizes, the measured value of $n_c$ is close to 25.5 clusters/cm which is in good agreement with the HEED prediction. For larger step sizes, the probability to count different clusters as a single cluster increases such that the distribution tail is not exponential anymore. The counting technique yields inaccurate results, in particular $n_c$ drops.

9.7 Conclusion

A small TPC read out by a SiProtected and InGrid-equipped TimePix chip was built and used to record tracks of cosmic particles. During one month, the TPC was continuously operated in a mixture of He/iC$_4$H$_{10}$ 77/23 until it was stopped and a few thousand tracks were recorded.

The data analysis consisted in reconstructing the tracks in three dimensions and studying the distribution of hits along the tracks. Doing so, the drift velocity and transverse diffusion coefficient could be measured and showed a good agreement with MAGBOLTZ calculations.
The estimated point resolution in the pixel plane $\sigma_{xy}$ is close to the diffusion limit. Accordingly, with a diffusion coefficient of $20 \mu m/\sqrt{cm}$ (at 40 V/cm and 4 T in an Ar/CH$_4$ 95/5 gas mixture), a point resolution of 200 $\mu m$ could in principle be achieved for radial tracks (averaged over a drift length of 2 m). The ILC performance goal for a pad readout TPC is $\sigma_{xy} \sim 100 \mu m$. With a pixel TPC the number of points measured along the track would be much larger (e.g. 40 times larger in argon-based mixtures for radial tracks) and the final precision on the track parameters in the readout plane should be equivalent or better, matching the ILC requirement.

The point resolution along the drift direction $\sigma_z$ is severely affected by the time-walk and exceeds by far the expectation from the longitudinal diffusion limit (by a factor seven). It might be improved with a thinner SiProt thickness or a different design of the electronics.

The numbers just quoted give a first impression on the detector performance and more tests with external tracking information will be necessary to draw a final statement.

An electron cluster density along the tracks of 25.5 clusters/cm was measured, compatible with simulation results. This agreement tends to prove the cluster counting capability of a GridPix chamber of 1 cm drift gap in He/iC$_{4}$H$_{10}$ 77/23. The extrapolation to other gas mixtures, larger drift gaps and different particle types and energies remains to be done. In this perspective, data have recently been collected at the CERN test beam facilities and their analysis is ongoing.

In view of a possible application at ILC, if a diffusion-limited point resolution can be achieved, a pixel TPC might show a better performance than standard readout TPCs in some respects. In particular, the tracking performance of GridPix in the forward regions should be superior because of the larger statistics and a few very accurately measured points close to the endplates. The dE/dx resolution should be comparable if the energy loss is measured by electron counting and may be improved by cluster counting.

These conclusions assume a full coverage of the TPC endplates with GridPix detectors. Several practical aspects e.g. detector assembly, powering and cooling are not considered and would impact on the final design and performance of a pixel TPC.