Performance of a Gridpix detector based on the Timepix3 chip

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Abstract

A Gridpix readout for a TPC based on the Timepix3 chip is developed for future applications at a linear collider. The Gridpix detector consists of a gaseous drift volume read-out by a single Timepix3 chip with an integrated amplification grid. Its performance is studied in a test beam with 2.5 GeV electrons. The Gridpix detector detects single ionization electrons with high efficiency. The Timepix3 chip allowed for high sample rates and time walk corrections. Diffusion is found to be the dominating error in the pixel plane and in the drift direction, and systematic distortions in the pixel plane are below 10 µm. Using a truncated sum, an energy loss dE/dx resolution of 4.1% is found.

Keywords: Micromegas, gaseous pixel detector, Micro-pattern gaseous detector, Timepix, Gridpix

1. Introduction

In the context of a Time Projection Chamber for a future linear collider a gaseous pixel detector is developed based on the Timepix3 chip. The Gridpix single chip detector discussed here, allows for a detection of single electrons with a granularity of 256×256 pixels of size $55\,\mu m \times 55\,\mu m$. By counting the number of single electrons, the number of clusters can be estimated allowing for a precise measurement of the energy loss dE/dx.

Since the invention of the device [1, 2], a series of developments have taken place that culminated in Gridpix detectors using the Timepix1 chip [3]. In this paper the results using a Timepix3 chip will be described. In the design of the detector special attention has been given to minimize the distortions in the pixel and drift plane in order to meet the tracking precision needed for a TPC at a linear collider. The device can also be applied for medical imaging, proton radiotherapy or used in other particle physics experiments [4]. Here testbeam results taken at the ELSA facility in Bonn will be presented. Some results using this device in a laser setup were presented at TIPP17 [5].

2. Description of the Gridpix device

A Gridpix is a CMOS pixel readout chip for a gaseous detector with an amplification grid added by photo-lithographic post-processing techniques [3]. It consists of a Timepix3 chip [6] with a 8 µm thick Silicon-Rich Nitride protective layer, and 50 µm high SU8 pillars that support the 1 µm thick Al grid that has 35 µm diameter circular holes aligned to the pixels. The growing of the protection layer of Timepix chips has been further optimized at the Fraunhofer Institute for Reliability and Microintegration (IZM) in Berlin, making the device more spark proof. An ionizing particle will liberate electrons in the TPC drift volume that will drift towards the grid and enter the avalanche region. The avalanche yields an electronic signal on the pixel. The Timepix3 chip has low noise ($\approx$70 e^-) and allows per pixel for a precise measurement of the arrival time and the time over threshold using a TDC (clock frequency 640 MHz). For the read-out the SPIDR software is used [7].

In Figure 1 a cross-section of the Gridpix detector (14.1 mm × 14.1 mm) located in a small drift volume is shown. The box has length of 69 mm, a width (not shown) of 42 mm and a height of 28 mm with a maximum drift length of about 20 mm. The beam enters the drift volume through the window from the right side. The electric drift field is defined by a series of parallel strips in the cage and is about 280 V/cm. On the guard plane - located 1 mm above the grid - a voltage is applied that matches the local drift voltage.

3. Testbeam measurement

In July 2017 measurements were performed at the ELSA facility in Bonn. ELSA delivered a beam of 2.5 GeV electrons at a maximum rate of 10 KHz. To acquire a precise reference track, a silicon tracking telescope was introduced in the setup as shown in Figure 2. Electrons from the beam first passed through a scintillator that was used to provide a trigger signal. This was followed by the tracking Mimosa telescope, consisting of 6 silicon detection planes

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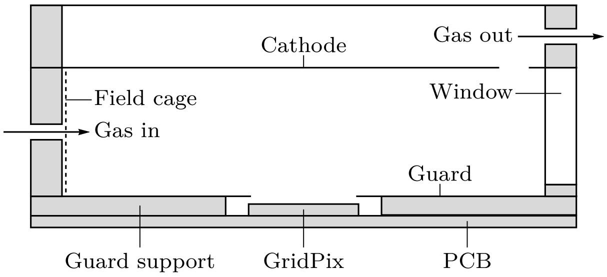

Figure 1: Schematic drawing of the Gridpix detector.

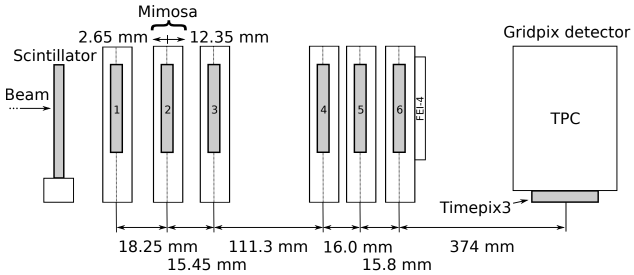

Figure 2: Setup with telescope and Gridpix detector.

mounted on a slider stage with each 1152×576 pixels sized $18.4\,\mu m \times 18.4\,\mu m$. Finally, the beam crosses the gas volume of the Gridpix detector. The whole Gridpix detector was mounted on a remote-controllable rotation stage. On the last telescope plane a inactive FEI4 chip [8] was present that caused multiple scattering of the beam corresponding to a r.m.s. of 0.25 mm at the Gridpix detector.

Both the Mimosa telescope and the Timepix3 chip were operated in data-driven mode. For synchronization, triggers were numbered by a Trigger Logic Unit (TLU) [9] and saved in the two data-streams. The Mimosa chips were continuously read-out with a rolling shutter taking $115.2\,\mu s$, meaning that a single frame can contain multiple triggers. The Timepix3 hits are attributed to a single trigger by considering all hits within 400 ns of a trigger.

During data-taking the gas volume of the Gridpix detector was flushed with a premixed gas consisting of 95 % Ar, 3 % CF_4, and 2 % iC_4H_{10}. This gas - called *T2K TPC gas* - is suitable for a large TPC because of the low diffusion in a magnetic field. The cathode and guard voltage of the Gridpix were set such that the electric field was 280 V/cm, near the value at which the drift velocity is maximal for this gas. With Magboltz the drift velocity is predicted to be $75\,\mu m/ns$ [10]. To achieve a high efficiency, the grid voltage was set at 350 V. The threshold per pixel was put at 800 e^- to reduce the number of noise hits to a minimum. The temperature and pressure at time of data taking were stable at 301.6 K and 1034.20 mbar. The Oxygen concentration in the gas was 211 ppm. In Table 1 the parameters of the analyzed run are summarized.

From the measured time of arrival of the Timepix hits, the z-position is calculated using the predicted drift velocity of $75\,\mu m/ns$. This value is found to be consistent, but

Table 1: Parameters of the analyzed run.

Length	60 minutes
Triggers	4 733 381
V_{grid}	350 V
E_{drift}	280 V/cm
Rotation (z-axis)	17 degree
Rotation (y-axis)	0 degree
Threshold	800 e^-
Temperature	(301.63 ± 0.08) K
Pressure	(1034.20 ± 0.05) mbar
Oxygen concentration	211 ppm

because of systematic uncertainties there was no attempt at a precise determination.

4. Track reconstruction and event selection

4.1. Track fitting

To reconstruct a track, a straight line is fitted to the hits. The x-axis is chosen parallel to the beam, and the y, z-axes are perpendicular to the beam. The drift direction is parallel to the z-axis. Tracks are fitted using a linear regression fit in $y(x)$ and $z(x)$. Hits are assigned errors in the 2 directions perpendicular to the beam σ_y, σ_z. This will be discussed in detail in section 5.3 and 5.4.

To achieve an accurate reconstruction of the tracks, the telescope and the Gridpix detector have to be aligned. In a first step, the positions of the 6 telescope planes are independently aligned. The planes are placed perpendicular to the beam, and their position along the beam is measured. The 5 rotations and 4×2 shifts are iteratively determined from data. In the second step, the Gridpix detector is aligned to the beam by rotating it along 3 axes and measuring the shifts in the directions perpendicular to the beam.

Since the telescope track is affected by multiple scattering, the most precise track fit is obtained by fitting the hits from the Gridpix detector with the combined hits in the telescope. The hits in the telescope planes are merged in one super-point with a $10\,\mu m$ error. An example of Gridpix hits with a fitted track is shown in Figure 3.

4.2. Selections

The performance of the detector is measured using events with one clean track in the Gridpix detector and the telescope. Given the large amount of data-collected, priority in the selection has been given to clean tracks over efficiency.

In the telescope we require the track to have hits in at least 4 out of the 6 planes. Moreover the extrapolated telescope track should go through the TPC. For the Gridpix detector we select hits that have at least a magnitude corresponding with a time over threshold of $0.15\,\mu s$ to reject the hits with the worst time walk error, see section

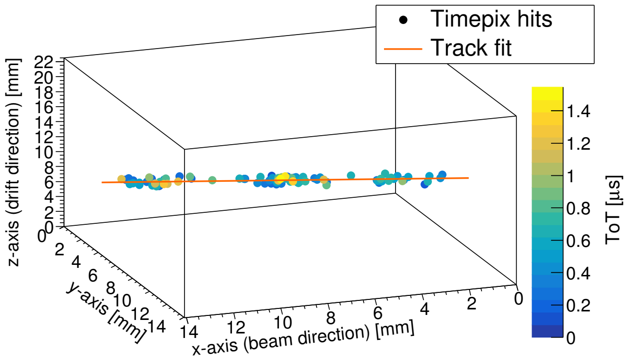

Figure 3: An example event with 108 Gridpix detector hits including the time-walk correction and the extrapolated telescope track.

Table 2: Table with selection cuts.

Telescope
At least 4 planes hit
Reject outliers (> 700 µm)
Telescope track goes through TPC
Gridpix detector
Hit ToT > 0.15 µs
At least 30 hits
Reject outliers ($> 3\sigma_{drift}$, $> 2\sigma_{plane}$)
At least 75% of total number of Gridpix hits in fit
Track projection crosses first and last pixel row
Matching of telescope and Gridpix detector
Tracks closer than 1 mm at center of TPC
A unique track-pair match

5.2. A track is rejected if it has less than 30 Gridpix hits. The Gridpix track should pass the whole TPC, that is the projection crosses the first and last pixel row. After a first fit, the refit accepts only hits that are within $3\sigma_{\mathrm{drift}}$ and $2\sigma_{\mathrm{plane}}$. Backgrounds and tracks with delta electrons are suppressed by requiring that at least 75% of all Gridpix hits are used in the track fit and only one track is found. A telescope-Gridpix track-pair is defined as matched if the extrapolated telescope track is less than 1 mm away from the center of the Gridpix track. Events with an unmatched track-pair or multiple matches (due to the rolling shutter) are rejected.

About 69 % of the events passes all selection cuts. An overview of the selections is given in Table 2.

5. Testbeam results

5.1. Number of hits on track

In Figure 4 the number of Gridpix hits associated to the track in the fiducial volume (216 pixels) is shown for a grid voltage of 350 V. The most probable number of hits is 91 and the mean is 114 for an effective track length of 12 mm. This is in agreement with the expected 100 electron-ion pairs/cm [11]. The shape of the distribution is Landau-like with a long tail due to delta electrons.

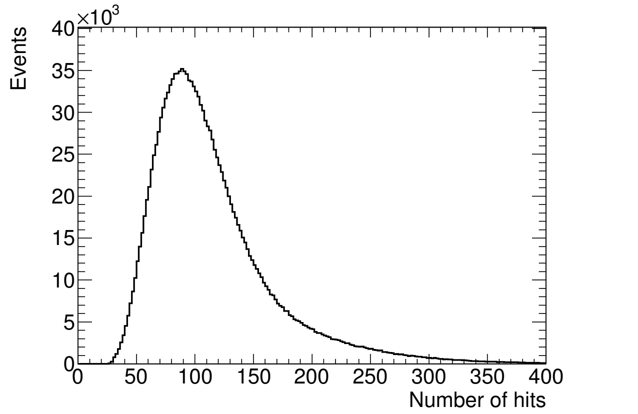

Figure 4: Distribution of number of hits on the track at a grid voltage of 350 V.

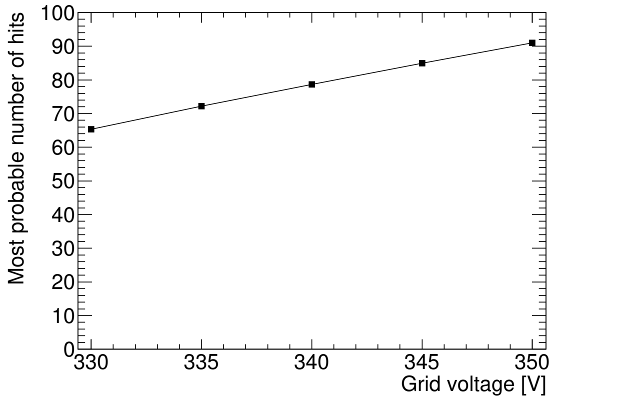

Figure 5: Most probable number of hits on the track as a function of grid voltage.

In Figure 5 the most probable number of hits is shown as a function of the grid voltage. One expects that the efficiency of the Gridpix detector increases with grid voltage until it reaches a plateau at an efficiency of almost 100 %. Increasing further the grid voltage will induce cross-talk and far above 400 V sparks would be produced. The analyzed run was taken at a voltage of 350 V, close to the plateau and at a high efficiency. A search for double hits did not yield any indication for cross-talk.

5.2. Time walk correction

A pixel is hit when the collected charge is above the threshold. Because it takes longer to reach the threshold for a small signal than it does for a large signal, the measured Time of Arrival (ToA) depends on the magnitude of the signal. This is called the time walk. The capability to record simultaneously both ToA and Time over Threshold (ToT) per pixel is one of the main improvements of the Timepix3 chip over its predecessor the Timepix1. The

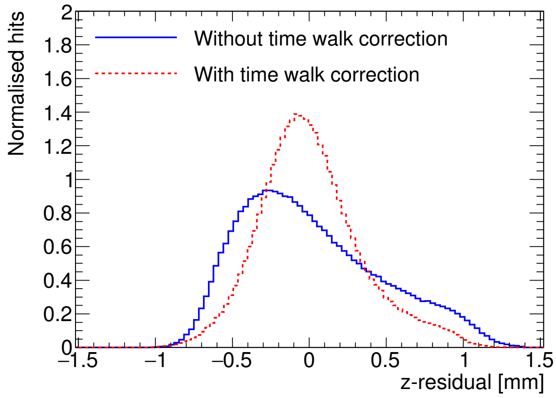

Figure 6: Distribution of z-residuals before and after time walk correction

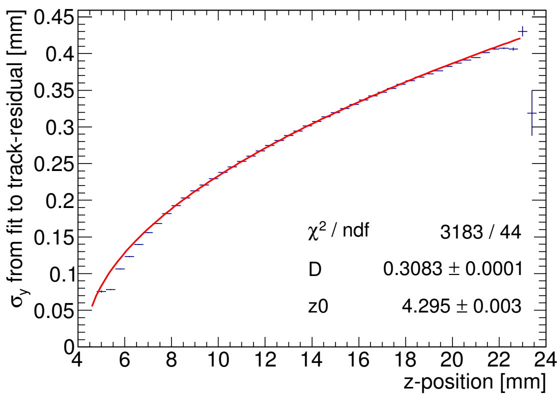

Figure 7: Hit resolution in pixel plane fitted with equation (2).

Timepix3 allows to correct for the time walk by using the ToT as a measure of the signal magnitude.

First, the ToT was found to vary as a function of the column and therefore per column a correction factor for the ToT was introduced. The time walk z_{tw} can then be parametrised as a function of the corrected ToT t_{ToT} using the following formula:

$$\delta z_{\text{tw}} = \frac{c_1}{t_{\text{ToT}} + t_0}, \tag{1}$$

where c_1 and t_0 are constants determined from a fit. The distribution of z-residuals - defined as the difference of the track fit prediction and the z-position of the hit - before and after applying the time walk correction, is shown in Figure 6. Functions with more parameters were also tried, but did not improve the results.

5.3. Hit resolution in the pixel plane

The momentum resolution of a TPC depends on the hit resolution in the pixel plane. There are two important factors for the hit resolution in the pixel plane: a constant contribution caused by the pixel size d_{pixel} and a transverse drift component that scales with drift distance and the diffusion coefficient D_T. The resolution σ_y is given by:

$$\sigma_y^2 = \frac{d_{\text{pixel}}^2}{12} + D_T^2(z - z_0), \tag{2}$$

where z_0 is the position of the grid. The hit resolution as a function of z-position is shown in Figure 7. The diffusion gives the largest contribution to the error in most of the detector volume. The measured diffusion coefficient $D_T = 308\,\mu\text{m}/\sqrt{\text{cm}}$ is close to the expected $D_T = 310\,\mu\text{m}/\sqrt{\text{cm}}$. The χ^2 is too high for the degrees of freedom, because no systematic uncertainties were taken into account.

5.4. Hit resolution in the drift plane

The hit resolution in the drift plane is related to the ToA distribution. There are three contributions. A constant contribution from the time resolution $\tau = 1.56$ ns, other noise sources such as jitter and time walk, and a contribution from longitudinal diffusion with coefficient D_L. The resolution σ_z is given by

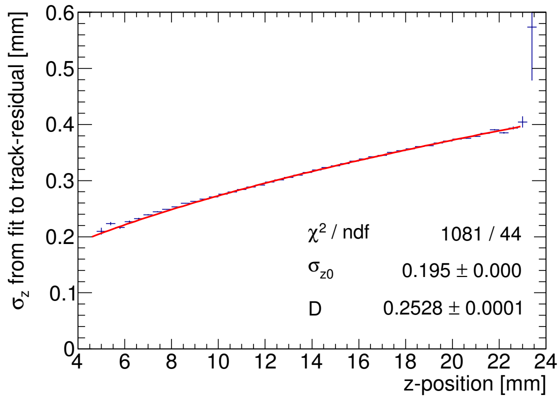

Figure 8: Hit resolution in drift direction fitted with equation (3).

$$\sigma_z^2 = \frac{\tau^2 v_{\text{drift}}^2}{12} + \sigma_{z0}^2 + D_L^2(z - z_0) \tag{3}$$

The hit resolution in the drift plane is shown in Figure 8. The grid position was fixed to $z_0 = 4.295$ mm found in the fit to Figure 7. The diffusion is found to be $D_L = 253\,\mu\text{m}/\sqrt{\text{cm}}$, which is slightly higher than the expected value of $D_L = 230\,\mu\text{m}/\sqrt{\text{cm}}$.

5.5. Deformations

For a large TPC with pixel read-out it is important that systematic deviations are small and stay well below typically 20 µm. Here we study deformations in the pixel and drift planes. The chip is divided in 64×64 bins of 4×4 pixels each for which the mean deformation is calculated. For every hit, the expected originating position on the track is traced and the residual is filled at that bin. In Figure 9 and Figure 10 the mean residual in the xy-plane and the mean z-residual are shown respectively. In the

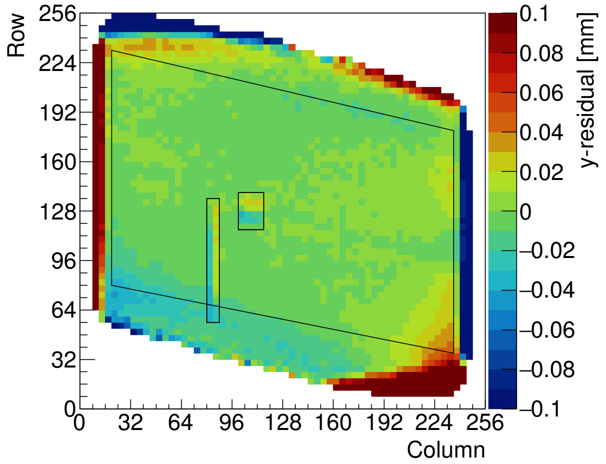

Figure 9: Mean residuals in the pixel plane at the expected hit position.

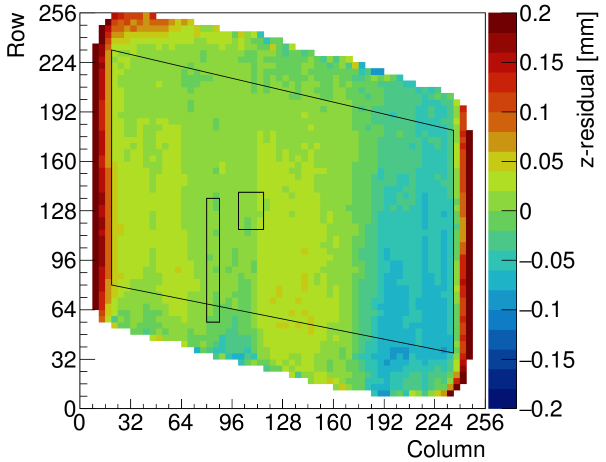

Figure 10: Mean residuals in the drift direction at the expected hit position.

diagram only bins with more than 1000 entries are shown. Only bins in the selected fiducial area were used to make the distribution of the mean residuals shown in Figure 11. The r.m.s. of the deviations is 8 µm in the pixel plane and 31 µm (0.4 ns) in the drift direction. This means that the systematics on the position measurement in the pixel plane - the bending plane of the TPC - are less than 10 µm.

5.6. *Energy loss measurement*

A TPC can identify particles using their characteristic energy loss. The Gridpix detector measures the energy loss dE/dx by counting the number of detected electrons. Because of the large fluctuation in energy loss, the mean is dominated by a few high-energy deposits. To retrieve a better estimate, the truncated sum of electrons is calculated.

Along the track, the number of electrons is counted for 20 pixel intervals. A fixed fraction of intervals with the

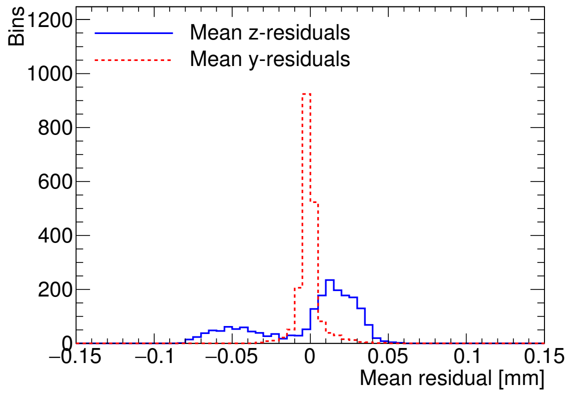

Figure 11: Distribution of the mean residuals from 4×4 bins within the selected region.

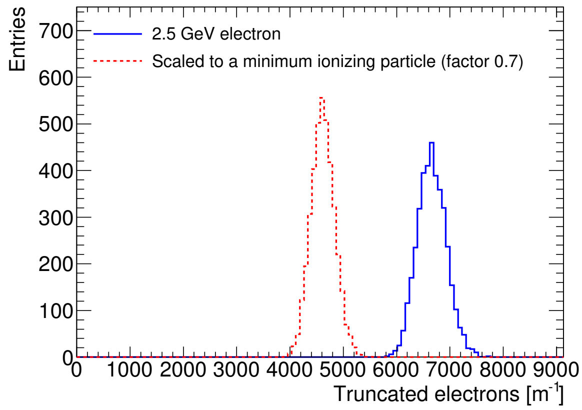

Figure 12: Distribution of truncated electrons per meter for the 2.5 GeV electron and the expected distribution for a minimum ionizing particle.

highest number of electrons is rejected. Optimally, the top 10% of intervals with the highest number of electrons are rejected and from the other 90% of the intervals a truncated sum is obtained. In Figure 12 the truncated sum is shown for an effective track length of 1 m or 83 events. The resolution, expressed as the standard deviation divided by the mean, is 4.1%.

In order to estimate the separation power, the energy loss distribution for a Minimum Ionizing Particle (MIP) is estimated, see also Figure 12. The hit positions of the electron data are scaled track by track by a factor 0.7 to acquire the estimated ionization for a MIP, i.e. 0.7 m of electron data is scaled to 1 m of expected MIP data. The expected resolution for a MIP is 4.8% and the separation between a MIP and an electron is 5.9σ.

The truncated sum using slices of 20 pixels, does not make use of the fine granularity of the Gridpix detector. We expect that particle identification can be improved by employing the full resolution to resolve primary ionization clusters.

6. Conclusions and Outlook

A Gridpix detector based on the Timepix3 chip was operated reliably in a testbeam setup. The resolution of the detector in the pixel planes and in the drift direction is limited by diffusion. The additional systematic uncertainties are smaller than 10 µm in the pixel plane. Furthermore, by counting the ionization electrons, the energy loss dE/dx can be measured with a precision of 4.1% for an effective track length of 1 m.

The next step towards a TPC for future applications, is the construction of larger size prototype detectors. R&D has started to build a 4-chip module based on the Timepix3 that can be used to cover larger areas. With these developments, a pixelised readout is on its way to become a mature technology option for a large TPC at a future linear collider.

Acknowledgements

This research was funded by the Netherlands Organisation for Scientific Research NWO. The authors want to thank the accelerator group at the ELSA facility in Bonn.

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