Towards a Pixel TPC: construction and test of a 32 chip GridPix detector

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Abstract

A Time Projection Chamber (TPC) module with 32 GridPix chips was constructed and the performance was measured using data taken in a test beam at DESY in 2021. The GridPix chips each consist of a Timepix3 chip with integrated amplification grid and have a high efficiency to detect single ionisation electrons. In the test beam setup, the module was placed in between two sets of Mimosa26 silicon detector planes that provided external high precision tracking and the whole detector setup was slided into the PCMAG magnet at DESY. The analysed data were taken at electron beam energies of 5 and 6 GeV and at magnetic fields of 0 and 1 Tesla(T).

The result for the transverse diffusion coefficient D_T is $287\,\mu m/\sqrt{cm}$ at B = 0 T and D_T is $121\,\mu m/\sqrt{cm}$ at B = 1 T. The longitudinal diffusion coefficient D_L is measured to be $268\,\mu m/\sqrt{cm}$ at B = 0 T and $252\,\mu m/\sqrt{cm}$ at B = 1 T. Results for the tracking systematical uncertainties in xy (pixel plane) were measured to be smaller than 13 µm with and without magnetic field. The tracking systematical uncertainties in z (drift direction) were smaller than 15 µm (B = 0 T) and 20 µm (B = 1 T). Finally, the result for the dE/dx resolution for a MIP particle based on a 1 meter track and a realistic GridPix coverage of 60% was measured to be 4% in a 1 T magnetic field.

Keywords: Micromegas, gaseous pixel detector, micro-pattern gaseous

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detector, Timepix, GridPix, pixel time projection chamber

1. Introduction

Earlier publications on a single chip [1] and four chip (quad) GridPix detectors [2] showed the potential of the GridPix technology and the large range of applications for these devices [3]. In particular, it was demonstrated that single ionisation electrons can be detected with high efficiency and great precision, allowing an excellent 3D track position measurements and particle identification based on the number of electrons and clusters.

As a next step towards a Pixel Time Projection Chamber for a future collider experiment [4], [5], a module consisting of 32 GridPix chips based on the Timepix3 chip was constructed.

A GridPix detector consists of a CMOS pixel Timepix3 chip [6] with integrated amplification grid added by Micro-electromechanical Systems (MEMS) postprocessing techniques. The Timepix3 chip can be operated with a low threshold of 515 e^-, and has a low equivalent noise charge of about 70 e^-. The GridPix single chip and quad detectors have a very fine granularity of 55 µm × 55 µm and a high efficiency to detect single ionisation electrons.

Based on the experience gained with these detectors a 32 GrixPix chip module - consisting of 8 quads - was built. A drift box defining the electric field and gas envelop was constructed. A readout system for up to 128 chips with 4 multiplexers readout by one speedy pixel detector readout SPIDR board [7] [8] was designed. After a series of tests using the laser setup and cosmics in the laboratory at Nikhef [9], the detector was taken to DESY for a two week test beam campaign.

At DESY the 32 chip detector was placed in between two sets of Mimosa26 silicon detector planes and mounted on a movable stage. The whole detector setup was slided into the centre of the PCMAG magnet at DESY. A beam trigger was provided by scintillator counters. The data reported here were taken at different stage positions and electron beam momenta of 5 and 6 GeV/c and at magnetic fields of 0 and 1 T. The performance of the 32 GrixPix chip module was measured using these data sets.

2. 32 GridPix chip module

A 32 GrixPix chip module was built using the quad module [2] as a basic building block. The quad module consists of four GridPix chips and is optimised for a high fraction of sensitive area of 68.9%. The external dimensions are 39.60 mm × 28.38 mm. The four chips which are mounted on a cooled base plate (COCA), are connected with wire bonds to a common central 6 mm wide PCB. A 10 mm wide guard electrode is placed over the wire bonds 1.1 mm above the aluminium grids, in order to prevent field distortions of the electric drift field. The guard is the main inactive area, and its dimensions are set by the space required for the wire bonds. On the back side of the quad module, the PCB is connected to a low voltage regulator. The aluminium grids of the GridPixes are connected by 80 µm insulated copper wires to a high voltage (HV) filtering board. The quad module consumes about 8 W of power of which 2 W is used in the LV regulator.

Eight quad modules were embedded in a box, resulting in a GridPix module with a total of 32 chips. A schematic 3-dimensional drawing of the detector is shown in Figure 1. A schematic drawing of the quads in the module is shown in Figure 2, where also the beam direction is indicated.

The internal dimensions of the box are 79 mm along the x-axis, 192 mm along the y-axis, and 53 mm along the z-axis (drift direction), and it has a maximum drift length (distance between cathode and readout anode) of 40 mm. The drift field is shaped by a series of parallel CuBe field wires of 75 µm diameter with a wire pitch of 2 mm and guard strips are located on all of the four sides of the active area. In addition, six guard wires - shown with dashed lines in Figure 2 - are suspended over the boundaries of the chips, where no guard is present, to minimise distortions of the electric drift field. The wires are located at a distance of 1.15 mm from the grid planes, and their potential is set to the drift

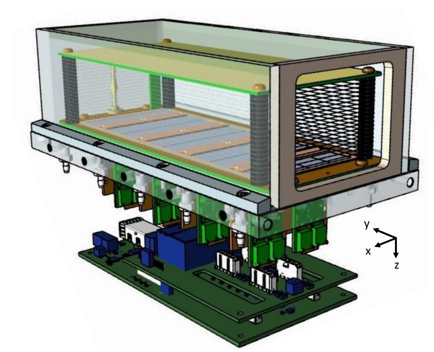

Figure 1: Schematic 3-dimensional render of the 8-quad module detector for illustration purposes.

potential at this drift distance. The box has two Kapton 50 µm windows to allow the beam to pass with minimal multiple scattering.

The data acquisition system of the quad module was adopted to allow for multiple quads to be readout. A multiplexer card was developed that handles four quads or 16 chips and combines the Timepix3 data into one data stream. For the 32 GrixPix module two multiplexers are connected to a SPIDR board that controls the chips and readout process. The readout speed per chip is 160 Mbps and for the multiplexer 2.56 Gbps this corresponds to a maximum

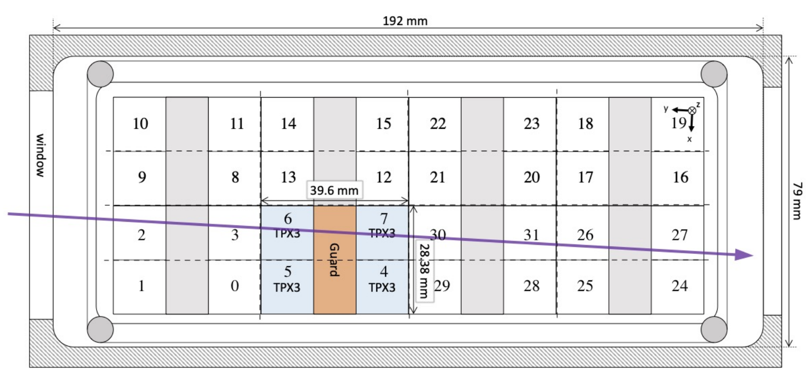

Figure 2: Schematic drawing of the 8-quad module detector with one example quad as viewed from the top of the quads. The chips are numbered and the beam direction is shown in purple.

rate of 21 MHits/s. For each pixel the precise Time of Arrival (ToA) using a 640 MHz TDC and the time over threshold (ToT) are measured.

The gas volume of 780 ml is continuously flushed at a rate of ∼50 ml/min (about 4 volumes/hour) with premixed T2K TPC gas. This gas is a mixture consisting of 95 % Ar, 3 % CF_4, and 2 % iC_4H_{10} suitable for large TPCs because of the low diffusion in a magnetic field and the high drift velocity.

3. Experimental setup

In preparation of the two weeks DESY test beam campaign, a support frame was designed to move the 32 chip GridPix module in the plane perpendicular to the beam by a remotely controlled stage such that the whole detector volume could be probed. The module was mounted upside down with respect to figure 1 thus that the electronics could be accessed from above. The support frame also held three Mimosa26 silicon detector planes [10] - with an active area of (21.2 mm x 10.6 mm) - placed in front of the detector and three Mimosa26 planes behind the detector. At DESY the (Mimosa26) silicon detector planes were provided by the test beam coordinators. The whole detector setup was slided towards the centre of the PCMAG magnet at the DESY test beam facility II [10]. A beam trigger was provided by a double scintillator counter coincidence. The data were taken at different stage positions to cover the whole sensitive TPC volume. Runs with electron beam momenta of 5 and 6 GeV/c and at magnetic fields of 0 and 1 T were analysed.

A photograph of the detector setup in the PCMAG magnet is shown in Figure 3.

The experimental and environmental parameters such as temperature, pressure, gas flow, oxyxgen content were measured and logged by a Windows operated slow control system. The experimental parameters are summarised in Table 1. The chips were cooled by circulating Glycol through the cooling channels in the module carrier plate. The cooling blocks of the multiplexers were further cooled by blowing pressurised air on them.

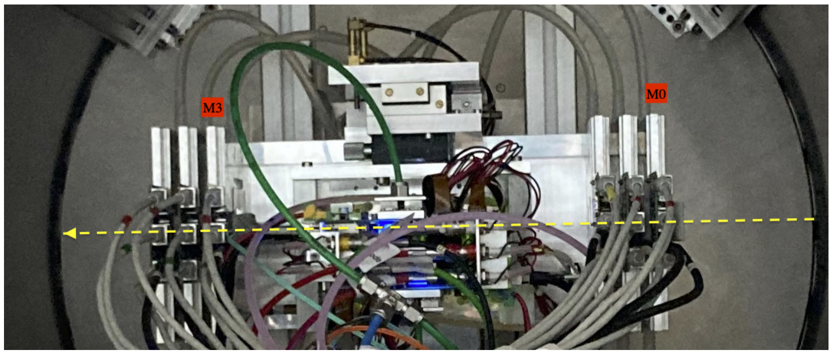

Figure 3: Photo of the detector setup at the centre of the PCMAG magnet. The Mimosa26 planes M0 and M3 are indidated in red as well as the beam direction (yellow). Centrally, the stager positions the TPC module to allow the beam to pass through.

Table 1: Overview of the experimental parameters. The ranges indicate the variation over the data taking period

Number of analysed runs at B=0 (1) T	6 (8)
Run duration	10-90 minutes
Number of triggers	3-100 k
E_{drift}	280 V/cm
V_{grid}	340 V
Threshold	550 e^-
Gas Temperature	303.3-306.6 K
Pressure	1011 – 1023 mbar
Oxygen concentration	240 - 620 ppm
Water vapour concentration	2000 - 7000 ppm

The data was produced in four main data streams: one stream produced by the Mimosa26 Telescope, two data streams by the two Timepix multiplexers and one trigger stream. The double scintillator coincidence provided a trigger signal to the Trigger Logic Unit (TLU) [11] that sends a signal to the telescope readout and the trigger SPIDR. The data acquisition system of the Telescope and trigger SPIDR injected a time stamp into their respective data streams. Hits from the Mimosa26 planes were collected with a sliding window of $-115\,\mu s$ to $230\,\mu s$ of the trigger. The data acquisition of the multiplexer and the trigger SPIDR were synchronised at the start of the run. By comparing the time stamps in these streams, Telescope tracks and TPC tracks could be matched. Unfortunately, the SPIDR trigger had - due to a cabling mistake at the output of the TLU - a common 25 nsec time jitter.

In the first week of the test beam period it was found that three HV cables had a bad connection. The cables were replaced and the module could be fully operated. Unfortunately, after a short data taking period one of the chips (nr 11) developed a short circuit and the HV on the grid of the chip was disconnected. After the test beam data taking period the module was repaired in the clean room in Bonn.

4. Analysis

4.1. Telescope Track reconstruction procedure

The data of the Telescope is decoded and analysed using the Corryvreckan software package [12]. The track model used for fitting was the General Broken Lines (GBL) software [13]. The code was extended and optmised to fit curved broken lines for the data with magnetic field. The telescope planes were iteratively aligned using the standard alignment software provided by the package. The single point Mimosa26 resolution is 4 µm in x and 6 µm in z (drift direction).

Telesope tracks were selected with at least 5 out of the 6 planes on the track and a total χ^2 of better than 25 per degree of freedom. The uncertainties on the Telescope track prediction in the middle of the GridPix module are dominated by multiple scattering. The amount of multiple scattering was estimated by comparingthe predictions from the two telescope arms for 6 GeV/c tracks at 0 T. The expected uncertainty in x and z is 26 µm on average.

4.2. TPC Track reconstruction procedure

GridPx hits are selected requiring a minimum time over threshold ToT of 0.15 µs. The drift time is defined as the measured time of arrival minus the trigger time recorded in the trigger SPIDR data stream minus a fixed t_0 (the drift time at zero drift). The drift time was corrected for time walk [2] using the measured time over threshold (ToT in units of μs) and the formula (1):

$$\delta t = \frac{18.6(ns)}{\mathrm{ToT} + 0.1577}. \tag{1}$$

Furthermore, small time shift corrections - with an odd-even and a 16×2 pixels structure - coming from the TPX3 clock distribution were extracted from the data and applied.

The z drift coordinate was calculated as the product of the drift time and the drift velocity. This implies that $z_{\mathrm{drift}} = -z$ as defined in figure 1. GridPix hits outside an acceptance window in x (± 15 mm) and z (± 7.5 mm) were not used in the track finding and reconstruction. Based on a Hough transform an estimate of the TPC track position and angles in the middle of the module (at y = 1436 pixels) was obtained. This estimate was used to collect the hits around the TPC track and fit the track parameters. For this fit a straight line (B=0 T) or a quadratic track (B=1 T) model was used. In the fit, the expected uncertainties per hit σ_x and σ_z were used. The fit was iterated three times to perform outlier removal at respectively 10, 5 and 2.5 sigma level. A TPC track was required to have a least 100 hits in each multiplexer. At least 25% of the total number of hits should be on track and the χ^2 per degree of freedom has to be less than 3 in xy and z. All track parameters were expressed at a plane the middle of the TPC.

The calibration and alignment of the detector was done using high quality tracks. The track selections are summarised in table 2.

Table 2: Table with track/event selection cuts

Track/Event Selection
$\lvert x_{\mathrm{TPC}} - x_{\mathrm{Telescope}} \rvert < 0.3\,\mathrm{mm}$
$\lvert z_{\mathrm{TPC}} - z_{\mathrm{Telescope}} \rvert < 2.0\,\mathrm{mm}$
$\lvert dx/dy_{\mathrm{TPC}} - dx/dy_{\mathrm{Telescope}} \rvert < 4\,\mathrm{mrad}$
$\lvert dz/dy_{\mathrm{TPC}} - dz/dy_{\mathrm{Telescope}} \rvert < 2\,\mathrm{mrad}$

The drift velocity was calibrated per run by fitting a linear function to the z (predicted from the Telescope track at the measured TPC hit position) versus the measured drift time in the TPC. For the B=0 field runs it varies between 61.6 and 63.0 µm/ns. For the B=1 T runs it is between 57.2 and 59.1 µm/ns. The variation comes mainly from the changes in the relative humidity of the gas volume due to small leaks.

The individual TPX3 chips were iteratively aligned fitting a shift in x (z drift) and two slopes dx(z drift)/d row(column). The alignment was done per run, because the detector was moved in x and/or z for each run. The fitted slopes also corrected for small shifts and rotations (3D) in the nominal chip position.

An example event run 6913 without B field with a TPC and a telescope track is shown in figure 4. The TPC is located between y = 0 and 2872 pixels. Three Mimosa26 planes are located at y < -1000 and three at y > 4000 pixels.

5. Hit resolutions

In order to study the single electron resolution for the data with and without magnetic field, additional selections on the Telescope and TPC tracks were applied. Due to the trigger time jitter of 25 nsec, the prediction of the telescope track in z must be used as the reference for z. Secondly, the z hits of the TPC track were fitted to correct for the common time shift and the z residuals were calculated with respect to the fitted TPC track. In the xy plane the residuals of TPC hits with respect to the telescope track were used to extract the single

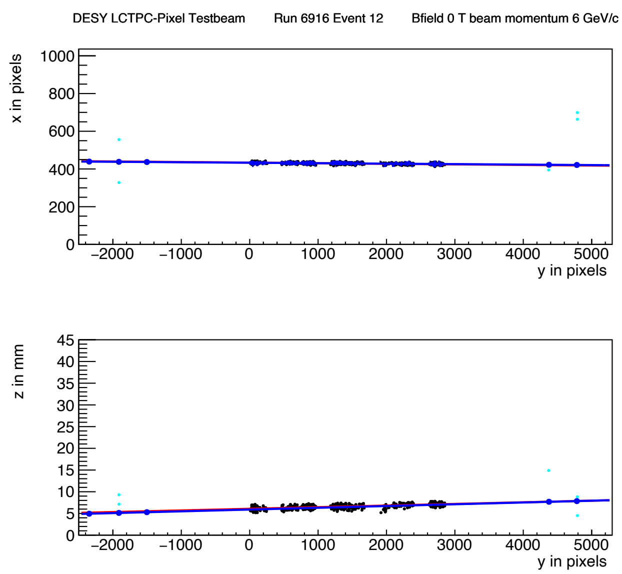

Figure 4: An event display for run 6913 without B field, with in total 1293 TPC hits (black dots) in the precision plane (xy) and driftplane (z drift y). The fitted TPC track (red line) with 1130 hits on track and the telescope track (blue line) with 5 Mimosa26 planes (blue hits) on track are shown. In green the off track Mimosa26 hits are shown.

electron resolution in xy. For the resolution studies runs at three different z stage positions of the TPC were selected where the beam gave hits in the central chips. The data of 14 central chips (9, 12, 21, 20, 17, 16, 2, 3, 6, 7, 30, 31, 26 and 27) was used. Two chips (8 and 13) were left out because of the E field deformations caused by the short circuit in chip 11.

5.1. Hit resolutions in the pixel plane

The resolution of the hits in the pixel plane (xy) was measured as a function of the predicted drift position (z_{drift}). Only hits are used crossing the fiducial region defined by the central core of the beam and staying 20 pixels away from the chip edges. The resolution for the detection of ionisation electrons σ_x is given by:

$$\sigma_x^2 = \frac{d_{\text{pixel}}^2}{12} + d_{\text{track}}^2 + D_T^2(z_{\text{drift}} - z_0), \tag{2}$$

where d_{pixel} is the pixel pitch size, d_{track} the uncertainty from the track prediction, z_0 is the position of the grid, and D_T is the transverse diffusion coefficient. The resolution at zero drift distance $d_{\text{pixel}}/\sqrt{12}$ was fixed to 15.9 µm and d_{track} to 30 µm for B=0 and 42 µm for B = 1 T data.

The expression (2) - leaving z_0 and the D_T as free parameters - is fitted to the B=0 T data shown in Figure 5. The fit gives a transverse diffusion coefficient D_T of 287 µm/$\sqrt{cm}$ with negligible statistical uncertainty. The measured value is in agreement with value of 287 µm/$\sqrt{cm}$ ± 4% predicted by the gas simulation software Magboltz [15]. The values of the diffusion coefficients depend on the humidity that was not precisely measured during the testbeam. The humidity strongly affects the drift velocity. Therefore the drift velocity prediction from Magboltz was used to determine the water content per run and predictions for the diffusion coefficients could be obtained.

A fit to the B=1 T data shown in Figure 5 gives a transverse diffusion coefficient D_T of 121 µm/$\sqrt{cm}$ with negligible statistical uncertainty. The measured value is in agreement with the value of 119 µm/$\sqrt{cm}$ ± 2% predicted by Magboltz.

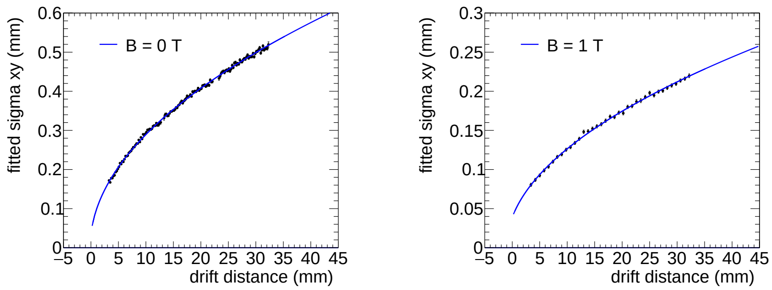

Figure 5: Measured hit resolution in the pixel plane (black points) fitted with the resolution function according to equation (2) (blue line).

5.2. Hit resolution in the drift plane

The resolution for the detection of ionisation electrons σ_z in the drift plane is given by:

$$\sigma_z^2 = \sigma_{z0}^2 + d_{\text{track}}^2 + D_L^2(z_{\text{drift}} - z_0), \tag{3}$$

where σ_{z0} is the resolution at zero drift distance, d_{track} the expected track uncertainty and D_L the longitudinal diffusion constant. Only track crossing the fiducial region were accepted and hits with a ToT value above 0.6 µs were selected. Because of the time jitter, the fitted TPC track is used for the drift residuals. For z_{drift} the Telescope prediction at the hit was used. The expected uncertainty on the Telescope track prediction is 25 µm at z = 0 mm and 75 µm at z = 30 mm.

The expression (3) - leaving σ_{z0} and the D_L as free parameters - is fitted to the B=0 T data shown in Figure 6. The value of z_0 was fixed to the result of the fit in the xy plane. The value of σ_{z0} was measured to be 138 µm. The longitudinal diffusion coefficient D_L was determined to be 265 $\pm$ 1 µm/$\sqrt{cm}$, which is higher than the expected value 236 $\pm$ 3 µm/$\sqrt{cm}$ from a Magboltz calculation [15].

A fit to the B=1 T data shown in Figure 6 gives a longitudinal diffusion coefficient D_L of 250 $\pm$ 2 µm/$\sqrt{cm}$. The measured value is in agreement with the value of 245 $\pm$ 4 µm/$\sqrt{cm}$ predicted by Magboltz. The fitted value of σ_{z0}

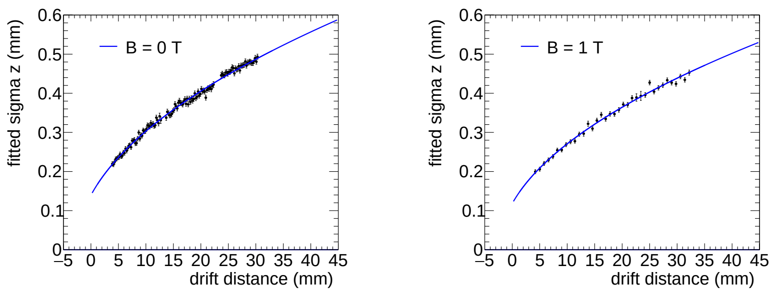

Figure 6: Resolution in the drift plane for hits with a ToT above 0.60 µs. The data are fitted with the expression of equation (3).

was 133 µm.

5.3. Deformations in the pixel and drift plane

It is important to measure possible deformations in the pixel (xy) and drift (z) plane to quantify the tracking precision. For the construction of a large Pixel TPC, deformations in the pixel plane deformation should be controlled to better than typically 20 µm because these affect the momentum resolution. The mean residuals in the pixel and drift planes are shown in figure 7 for the B=0 T data set using a large set of runs to cover the whole module. The residuals were calculated with respect to the Telescope track prediction. Because of limited statistics bins were grouped into 8×16 pixels. Bins with less than 100 hits are left out and residuals larger (smaller) than (-)100 µm are shown in red (blue).

A few critical areas can be observed in figure 7: the region around chip 11 is affected (chips 14,8 and 13), because the grid of chip 11 was disconnected. Deformations are present at the four corners of the drift box (chips 24, 10, 1 and 19) and close to the upper corner edge (chip 16) of the drift box. These come from inhomogenieties in the drift field near the supporting pilars, the field wires are too close to the chip to provide a constant electric field. It was concluded that for the deformation results the hits of these nine chips have to be removed. The track fit was redone leaving these hits out out of the fit, thus that they could not bias and affect the results.

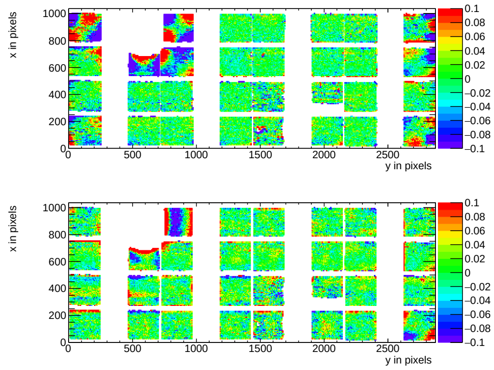

Figure 7: Mean residuals in the pixel and drift plane for B=0 T data at the expected hit position.

In order to reduce the statistical fluctuations and quantify the tracking precision, the module was regrouped horizontally in four (mcol runs from 0 till 3 along the local x axis) 256x256 pixel planes as shown in figure 8. Bins have a size of 16x16 pixels and bins with less than entries 1000 are not shown. A bias in the mean residual at the edge of the chips is expected to be present for an ideal detector because of the finite coverage and the diffusion in the drift process. Due to the presence of the dike pixels at the edge of the chip became covered and inefficient. Therefore the region near the edge of 5 pixels was removed. For the drift coordinate a region of 10 pixels was removed. The total number of measurements (bins) in xy is 895 and in z 892. One can observe that in the module plane no clear systematic deviations are present and conclude that the guard wire voltages were on average well tuned. Note that in the quad module we had no guard wires and deformation corrections had to be applied [2]. The r.m.s. of the distribution of the measured mean residual over the surface in the pixel plane is 11 µm and in the drift plane 15 µm. Similarly, regrouping the module in four vertical planes of 256x256 pixels yielded a r.m.s. in the pixel plane of 13 µm and 13 µm in the drift coordinate. The expected statistical error in xy is 4 µm and in z 5 µm.

In the B=1 T data set, the electrons will drift mainly along the magnetic

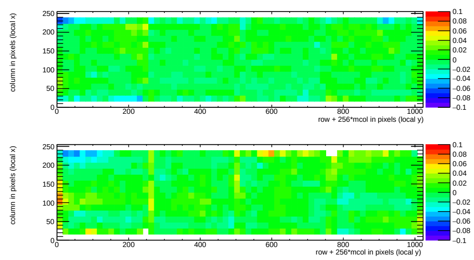

Figure 8: Mean residuals in the pixel and drift plane for B=0 T data at the regrouped expected hit position.

field lines. Deformations are in that case due to e.g. the non-alignment of the electric and magnetic field, giving ExB effects. Unfortunately, the statistics of the Telescope tracks that have a matched TPC track was insufficient and did not cover the full TPC module plane. Therefore the larger statistics of matched and unmatched TPC tracks was used. TPC tracks were required to pass angular selection cuts (dx/dy between -40 and -20 mrad and dz/dy between 0 and 14 mrad) and a momentum cut ($p > 2$ GeV and $q < 0$).

The mean residuals in the pixel and drift planes are shown in figure 9 for the B=1 T data set using a large set of runs to cover the whole module. The residuals were calculated with respect to the TPC track prediction. Because of limited statistics bins were grouped into 8×16 pixels. Bins with less than 100 hits are left out and residuals larger (smaller) than (-)100 µm are shown in red (blue).

In figure 9 the critical areas discussed above - around chip 11, the four corner chips and chip 16 in the upper corner edge - can be clearly observed. For the deformation results the hits of these nine chips have to be removed. The TPC track fit was redone leaving these hits out out of the fit, thus that they could not bias and affect the results. The TPC plane is well covered, although one can observe that due to the angle of the beam in the xy plane the chips in the upper right and lower left corners are not fully covered.

In order to reduce the statistical fluctuations and quantify the tracking precision, the module was regrouped horizontally in four (mcol runs from 0 till 3

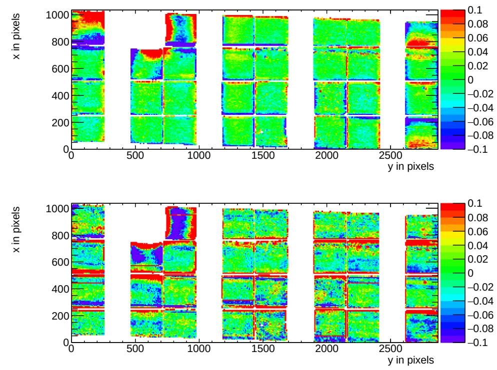

Figure 9: Mean residuals in the pixel and drift plane for B=1 T data at the expected hit position.

along the local x axis) 256x256 pixel planes as shown in figure 10. Bins have a size of 16x16 pixels and bins with less than entries 1000 are not shown. Similar to the nofield deformations studies, acceptance cuts had to be applied. The region near the edge of 16 pixels (colums) was removed. For the drift coordinate in addition a region of 10 pixels (rows) was removed. The total number of measurements (bins) in xy is 896 and in z 896. One can observe that in the module plane no clear systematic deviations are present. The r.m.s. of the distribution of the measured mean residual over the surface in the pixel plane is 13 µm and in the drift plane 19 µm. Similarly, regrouping the module in four vertical planes of 256x256 pixels yielded a r.m.s. in the pixel plane of 11 µm and 20 µm in the drift coordinate. The expected statistical error in xy is 2 µm and in z 3 µm.

5.4. Tracking resolution

A selected TPC track in the B=0 T data has on average 1000 hits. The tracking precision in the middle of the TPC was derived on a track by track and found to be on average 9 µm in the precision plane and 13 µm in z. The angular resolution in dx/dy was on average 0.19 mrad and for dz/dy 0.25 mrad. It is clear that the position resolution in the TPC in the precision and drift coordinates is impressive for a tracklength of (only) 158 mm. The values are

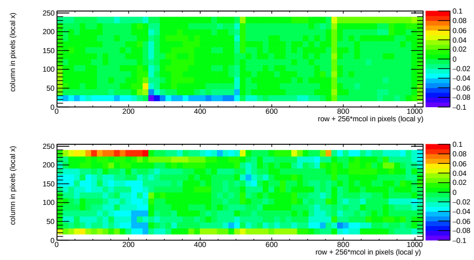

Figure 10: Mean residuals in the pixel and drift plane for B= 1T data at the regrouped expected hit position.

smaller than the uncertainty on the track prediction from the silicon telescope of 26 µm on average that is dominated by multiple scattering.

6. Particle Identification using dE/dx

The distribution of the number of TPC track hits per chip - without requiring a matched Telescope track - are shown in figure 11 for the data without magnetic field and for the B = 1 T data. The B=0 T data selects chips 2,6,7,9,16,17,26 and 27. The B=1 T data selects the same chips plus chips 12,13,20 and 21.

The mean number of hits is measured to be 124 and 89 in the B=0 and 1 T data sets. The most probable values are respectively 87 and 64. Note that the B=0 data has a much larger Landau-like tail than the 1 T data. Also the fluctuations in the core of the distribution are larger. The mean time over threshold for the B=0 T is 0.68 µs and 0.86 µs at a 1 T field. This means that the deposited charge per pixel is smaller for the 0 T data. The most probable value for the total deposited charge is similar for both data sets. The mean number of hits is in agreement with the predictions of [14] 106 electron-ion pairs for a 6 GeV/c electron at B=0 T , crossing 236 pixels or 12.98 mm and a detector running at 85% single electron efficiency.

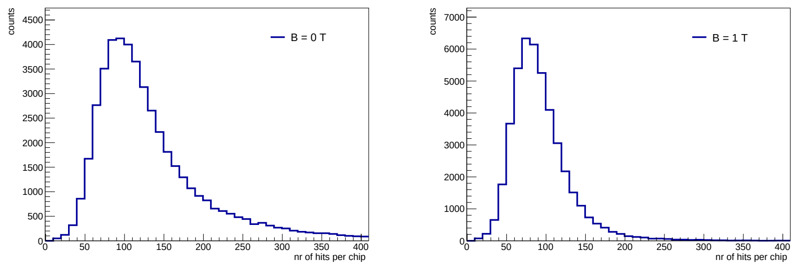

Figure 11: Distribution of the number of track hits per per chip for B=0 (left) B=1 T data.

7. Conclusion and outlook

A Time Projection Chamber module with 32 GridPix chips was constructed and the performance was measured using data taken in a test beam at DESY in 2021. The analysed data were taken at electron beam momenta of 5 and 6 GeV/c and at magnetic fields of 0 and 1 T.

The result for the transverse diffusion coefficient D_T is $287\,\mu\text{m}/\sqrt{cm}$ at B = 0 T and D_T is $121\,\mu\text{m}/\sqrt{cm}$ at B = 1 T. The longitudinal diffusion coefficient D_L is measured to be $268\,\mu\text{m}/\sqrt{cm}$ at B = 0 T and $252\,\mu\text{m}/\sqrt{cm}$ at B = 1 T. Results for the tracking systematical uncertainties in xy were measured to be smaller than 13 µm with and without magnetic field. The tracking systematical uncertainties in z were smaller than 15 µm (B = 0 T) and 20 µm (B = 1 T).

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