Nuclear Inst. and Methods in Physics Research, A

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

--Manuscript Draft--

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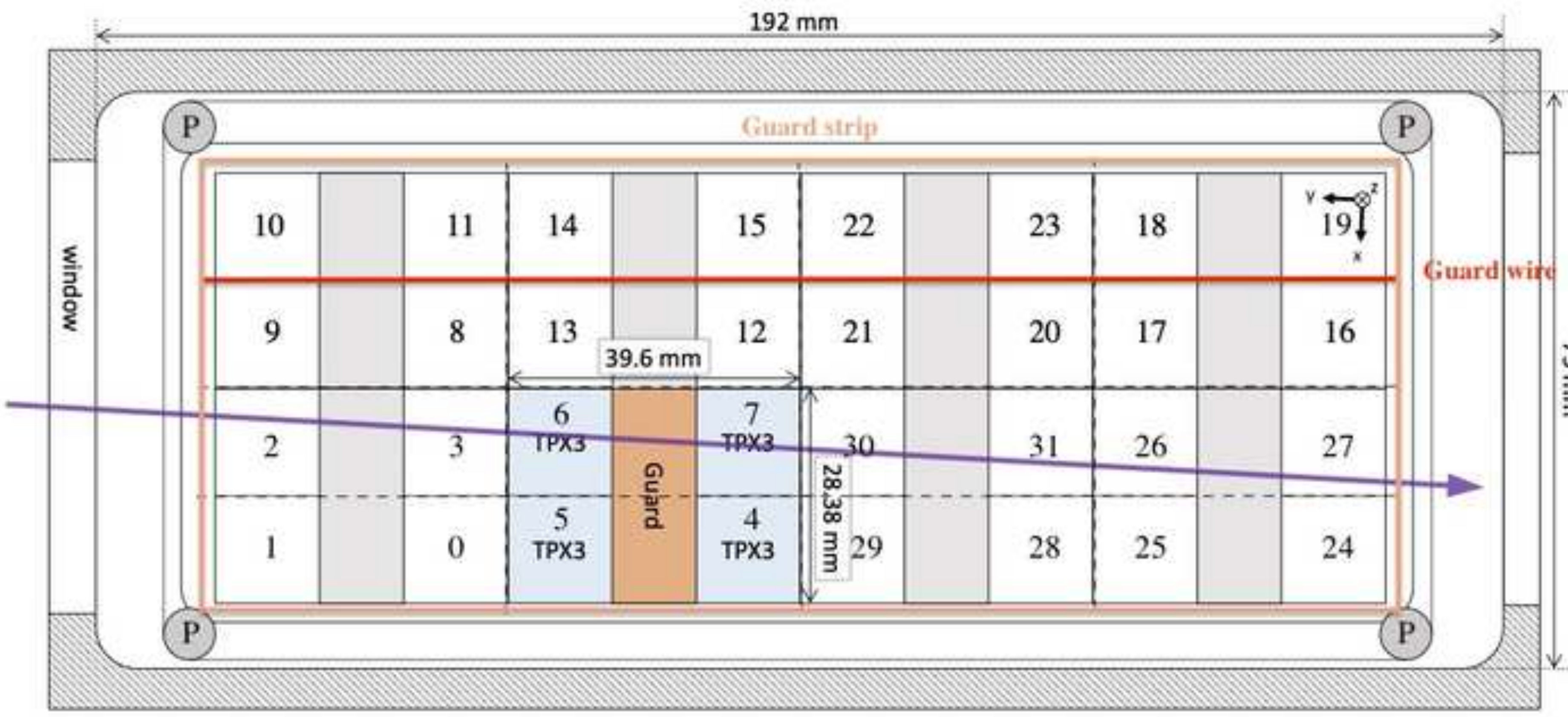
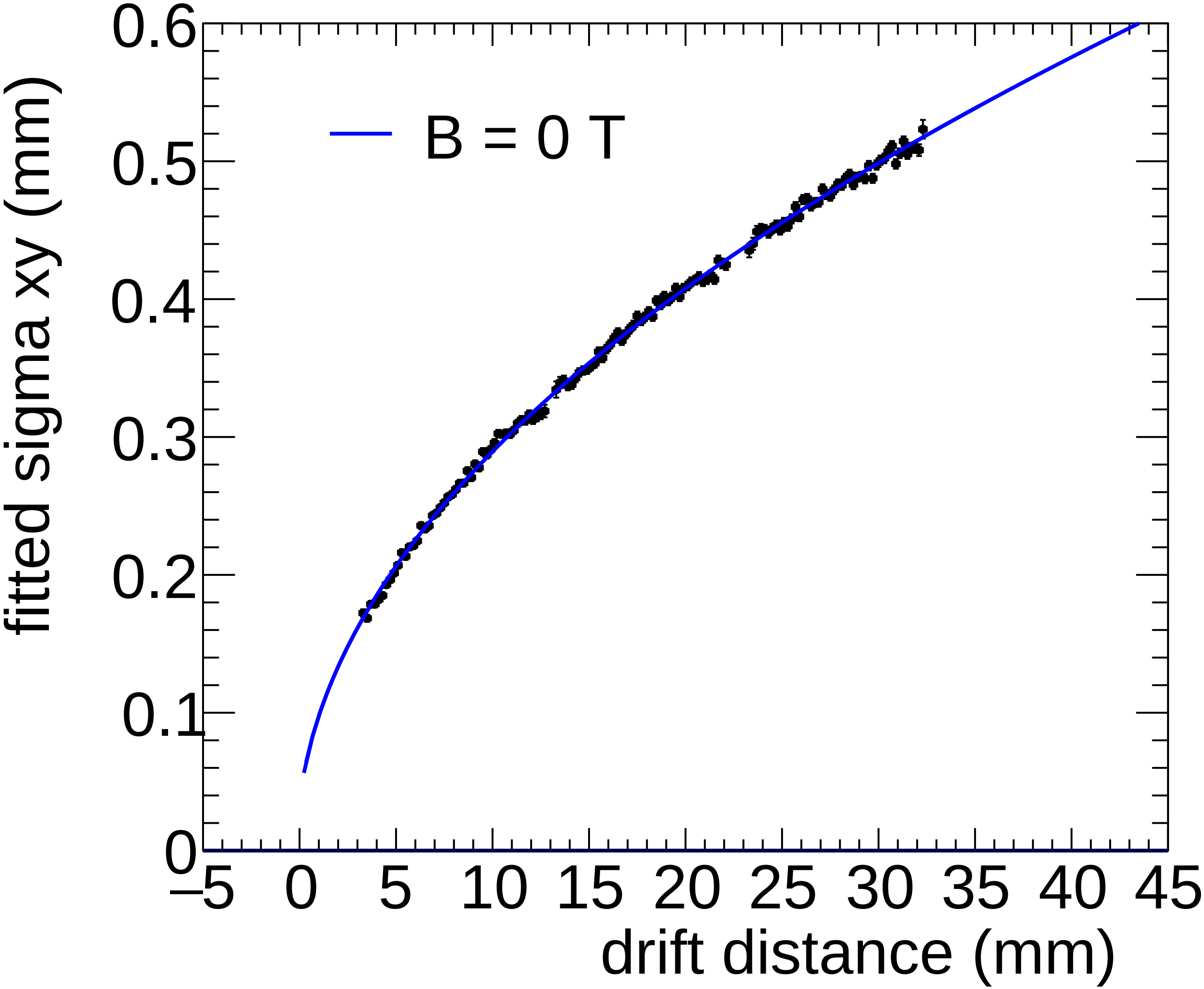
	Jochen Kaminsky, Dr other authors not listed here
Abstract:	A Time Projection Chamber (TPC) module with 32 GridPix chips was constructed and the performance was measured using data taken in a testbeam at DESY in 2021. The GridPix chips each consist of a Timepix3 ASIC (TPX3) with an integrated amplification grid and have a high efficiency of about 85% to detect single ionisation electrons. In the testbeam 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 slid into the PCMAG magnet at DESY. The TPC could be operated reliably and used a 93.6/5.0/1.4 gas mixture (by volume) of Ar/iC4H10/CO2 with a small amount of oxygen and water vapour. The analysed data were taken at electron beam momenta of 5 and 6 GeV/c and at magnetic fields of 0 and 1 Tesla(T). The result for the transverse diffusion coefficient DT is (287.2 ±0.5) μm/[[EQUATION]]at B = 0 T and DT is (120.3 ±0.5) μm/[[EQUATION]] B = 1 T. The longitudinal diffusion coefficient DL is measured to be (251 ±14) μm/[[EQUATION]]at B = 0 T and (224 ±14) μm/ [[EQUATION]] 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).
Opposed Reviewers:	

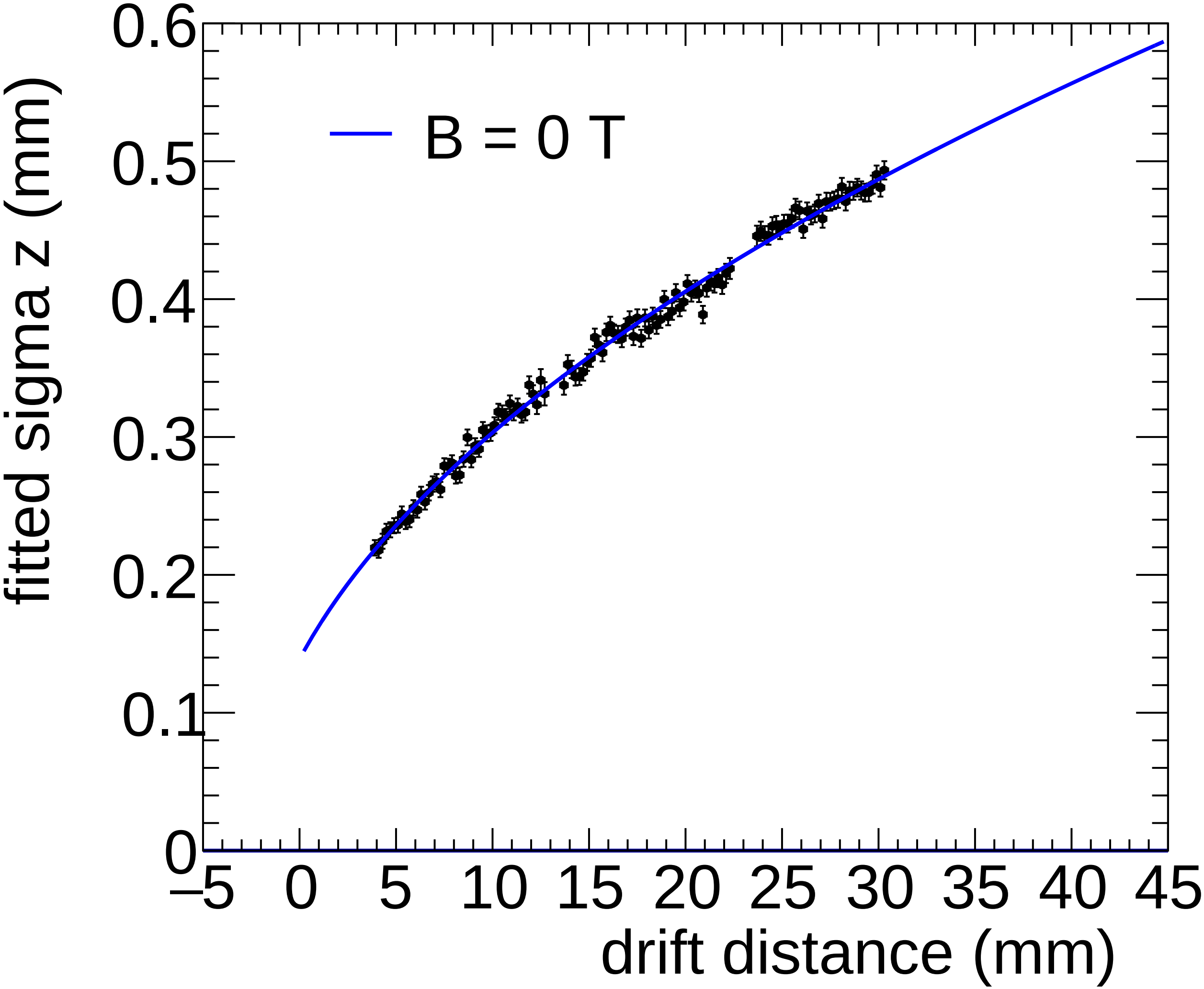
Figure

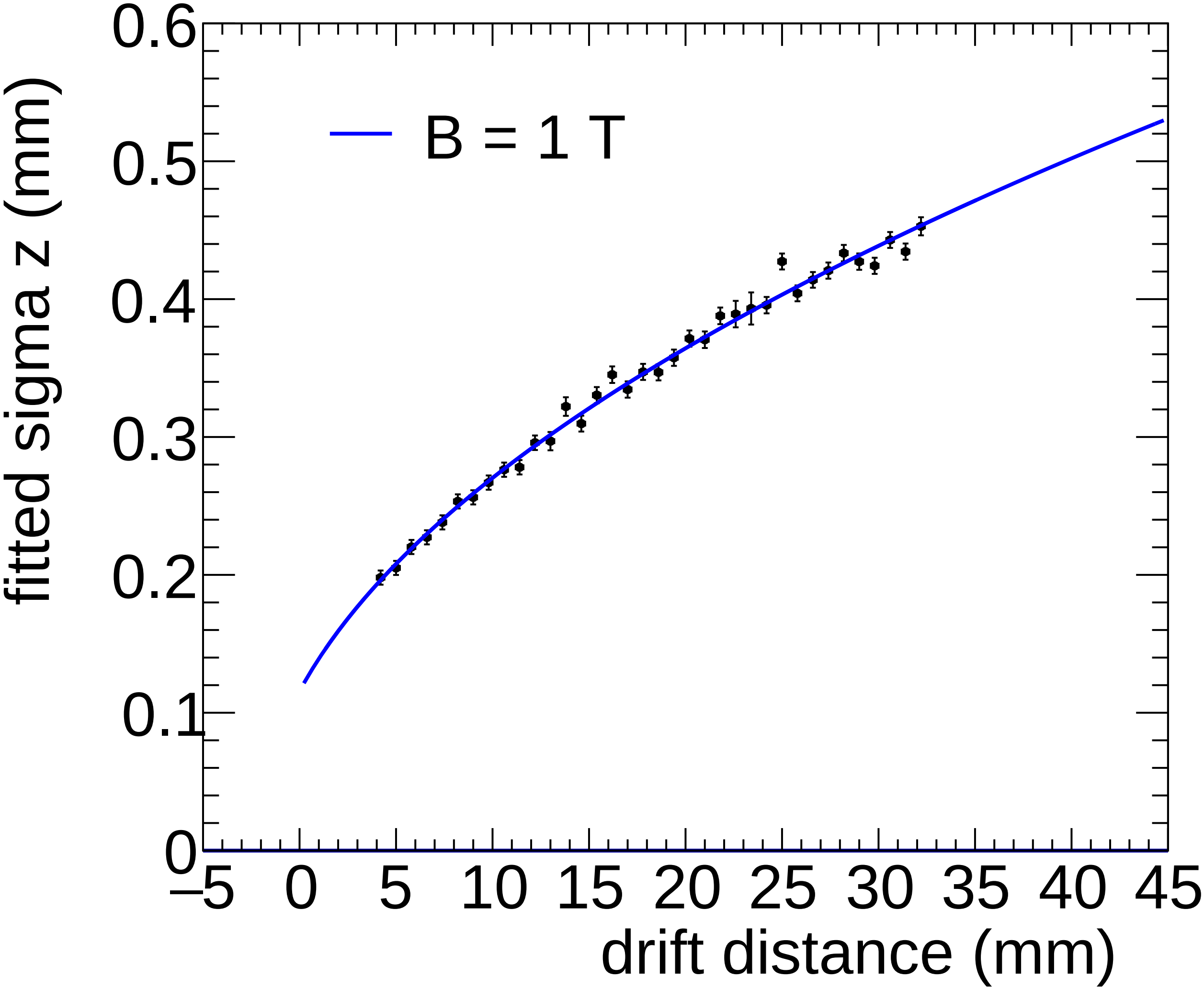
Click here to access/download;Figure;quadBoxOneQuadDrawing_v5.jpg



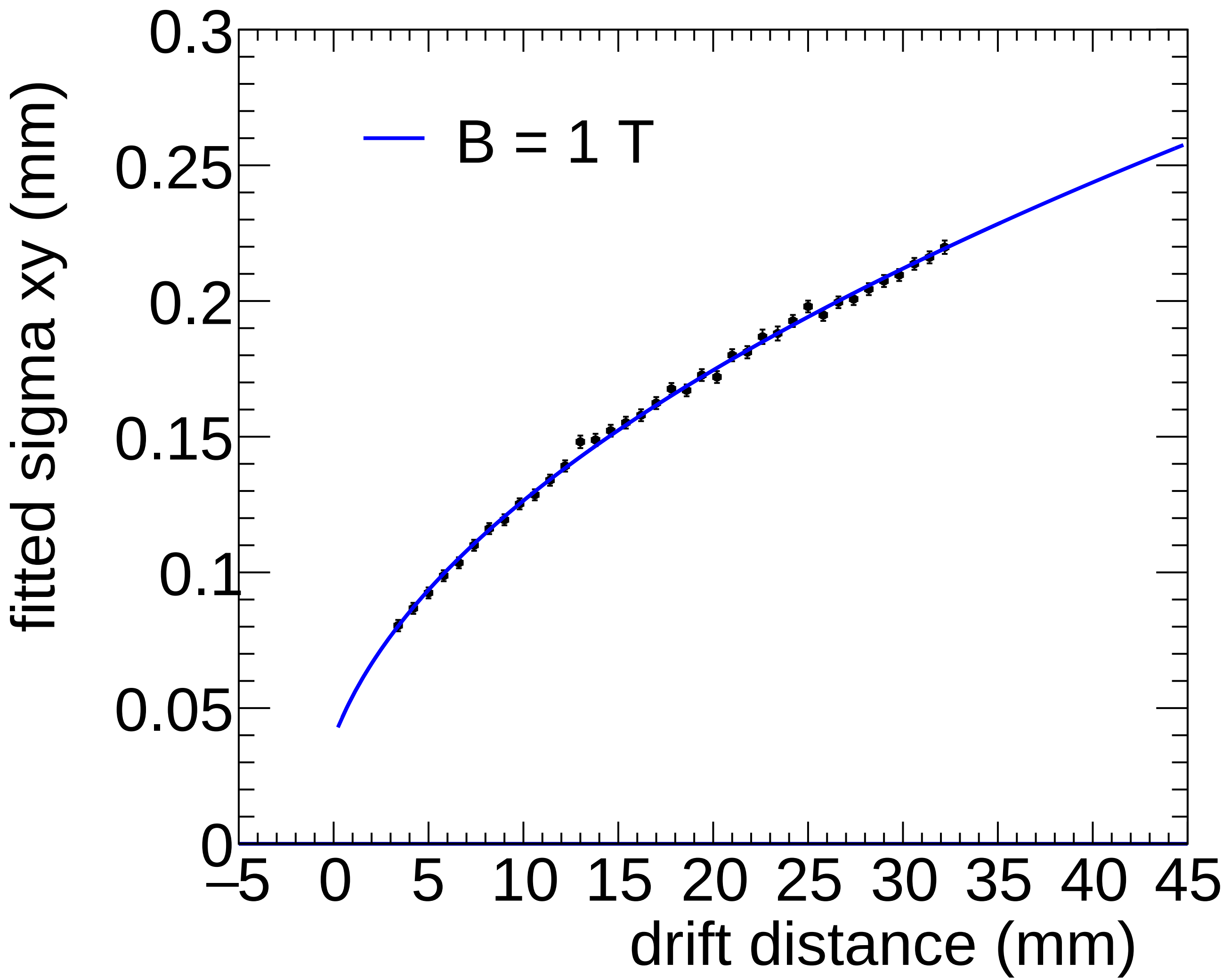


B = 0 T
fitted sigma xy (mm)
0
0.1
0.2
0.3
0.4
0.5
0.6
−5
0
5
10
15
20
25
30
35
40
45
drift distance (mm)


fitted sigma z (mm)
0.6
0.5
0.4
0.3
0.2
0.1
0
B = 0 T
–5
0
5
10
15
20
25
30
35
40
45
drift distance (mm)



fitted sigma z (mm)
0
0.1
0.2
0.3
0.4
0.5
0.6
B = 1 T
−5
0
5
10
15
20
25
30
35
40
45
drift distance (mm)



B = 1 T
fitted sigma xy (mm)
drift distance (mm)
0
0.05
0.1
0.15
0.2
0.25
0.3
−5
0
5
10
15
20
25
30
35
40
45

Dear Reviewers

Thank you for the very careful reading of the manuscript. Your comments and questions have improved the quality of the manuscript significantly.

Here below the replies/answers to questions and remarks and actions in blue that were taken.

See you Peter Kluit

Reviewer #1: Please find minor line-by-line comments below:

50: readout -> read out

Done

50: SPIDR -> "SPIDR"

Done: replaced by (SPIDR)

61: In this paper,

Done

Table 1: was water content measured or determined from drift velocity measurements are described below?

Answer: We did not have a (e.g. sensor) measurement of the water content - only an estimate from the drift velocity measurements. NB: This point is mentioned in line 235.

232, 241: Please give values for the errors even if they are small.

Done: Dt 287.2 +- 0.5 (B=0) Dt 120.3 +- 0.5 (B=1)

279: Specify which hits were excluded - radius around pillars?

Answer: Only chips were excluded (detailed in lines 274-277).

The hits near the pillars were not rejected.

Hits near the edge in zone of 5 (10) pixels were removed.

As mentioned in lines 290-291.

289: Due to the presence of the dike,

Done

290: Therefore,

Done

312: Because of limited statistics,

Done

340: bias -> basis

Done

349: Telescope -> telescope

Done in many other places it was changed

363: place reference at end behind number to improve readability

Done: rephrased like: " for the T2K gas by \cite{Garfield},"

367: Time Projection Chamber -> TPC - already defined above

Done

Reviewer #2:

The manuscript entitled "Towards a Pixel TPC part I: construction and test of a 32 chip GridPix detector" reports on the construction and first test beam results of a Time Projection Chamber (TPC) read out by 4 x 8 GridPix chips, 256 x 256 pixels each, and a maximum drift length of 40mm. Building upon previous detectors employing a single or four GridPix chips, the results presented in the manuscript are significantly new and important, a priori justifiying publication in Nucl. Instr. Meth. Before doing so, however, a number of issues, related to the presentation and the analysis should be addressed.

Major comment a):

a) The manuscript is a bit sloppy about the use of the terms "resolution and residual". I insist that this is corrected. The resolution is related to the intrinsic performance of the detector. It does not include external uncertainties like the uncertainty of the reference track. The residual is the difference (measured - expected) hit positions for a single track/plane. The residual distribution is the distribution of residuals over many tracks. Being a distribution, it has a mean and a width. In this sense, e.g. Eq. (2) gives an expression for the width of the residual distribution, not the resolution. Figure 5 shows the measured width of the residual distribution (could be called residual width, if defined like that). Figure 7 shows the mean of the residual distribution (could be called residual mean, if defined). Similar examples can be found all along the manuscript. In addition, it is not explained in unambiguous terms, how exactly the residuals in xy and z are calculated. For every hit, one normally calculates the 3D-vector of the closest distance to the track. This vector projected onto the xy plane gives the residual in xy, its projection onto the z axis gives the residual in z. What value is used for the z coordinate (hit z position or track z position at DCA)? Please explain in the text. In Section 5.4, the authors talk about "tracking precision in the middle of the TPC". Please clearly define the term and explain how the numbers were obtained. Uncertainties (or rms values of the corresponding distributions) should be given for the numbers quoted.

Answer to Major Comment a)

Indeed, possible confusion about the residuals and the detector resolution should be avoided.

The definition of residual in xy and z is added. We use the standard definition: the distance of closest approach of the track in the xy plane is used and at that point the xy and z residuals are defined.

The text was corrected - in the following places - as proposed by the reviewer to avoid confusion.

Added at the beginning of section 5:

“The single electron hit resolutions in xy and z will be extracted from the residuals with respect to the fitted track. The track residual in xy is the closest point of the track in the xy plane to the hit at the center of the pixel. The residual in z is calculated at this point of closest approach. “

Rephrased subsection Hit resolutions in the pixel plane

"The residual of the hits in the pixel plane (xy) was measured as a function of the predicted drift position ($z_{\rm drift}$).

The spread on the residual in xy for an ionisation electron is given by:

\begin{equation}

\sigma_{xy}^2= \sigma_\text{track}^2 + \frac{d_\text{pixel}^2}{12} + D_T^2(z_{\rm drift} -z_0),

\label{eq:sigmax}

\end{equation}

where σ_track is the uncertainty from the track prediction, d_pixel is the pixel pitch size, z_0 is the position of the grid, and D_T is the transverse diffusion coefficient. The last two terms correspond to the single electron detector resolution (squared).”

Caption of Figure 5 is also rephrased:

\caption{Measured spread on the residuals in the pixel plane (black points) fitted with equation \eqref{eq:sigmax} (blue line).}

Rephrased subsection Hit resolutions in the drift plane:

The spread on the residuals in z of the ionisation electrons σ_z is given by:

\begin{equation}

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

\label{eq:sigmaz}

\end{equation}

where σ_track is the expected track uncertainty, σ_{z0} the detector resolution at zero drift distance and D_L the longitudinal diffusion constant. The last two terms in the equation correspond to the single electron detector resolution (squared).”

Recall the definition of "the middle of the TPC"

The exact location of the "the middle of the TPC" was defined in line 177 as (at y = 1436 pixels). We added the location to the text in section 5.4 to remind the reader.

Major Comment b)

b) It is somewhat surprising that the statistical uncertainties on the measured diffusion coefficients are so small. What is the reduced chi2 of the fits in Figs. 5 and 6? The authors say a few lines later that "the values of the diffusion coefficients depend on the humidity that was not precisely measured". In Line 192f, they write about "changes in the relative humidity of the gas volume due to leaks". Why does this not affect the extraction of D_T and D_L from the data? In addition, the statements in Line 234ff are hard to understand. Do the authors want to say that they obtained an estimate for the humidity from a comparison of the measured drift velocity with Magboltz, and that these humidity values were then used to obtain the \pm 4% quoted for the Magboltz "prediction" in Line 233? In any case, uncertainties (statistical or systematic or both) have to be attached to the measured values of the diffusion constants.

Answer to Comment b):

We agree that uncertainties for the transverse diffusion should be quoted in the paper (the uncertainties on the longitudinal diffusion were quoted).

The uncertainties are now quoted in the paper.
Dt 287.2 +- 0.5 (B=0)   Dt 120.3 +- 0.5 (B=1)

The uncertainties are small because of the high statistics.

Q; What is the reduced chi2 of the fits in Figs. 5 and 6?

Answer: The fit chi2 for Figures 5 and 6 are:
Fig 5 left: 120.485 NDF 137   right: chi2 18.9573 NDF 35
Fig 6 left: 120.775 NDFz 121 right: chi2 47.5922 NDFz 34

Q: Why does this not affect the extraction of D_T and D_L from the data?

Answer The humidity will affect the MagBoltz predictions. The procedure to determine the humidity that was not measured is well described by the reviewer. The prediction from MagBoltz gets an uncertainty that is quoted.

Concerning systematic uncertainties. it was found out that there is a systematic uncertainty that affects the extraction of the longitudinal coefficient. The paper was corrected for this and a systematic error of 14 mu m /sqrt(cm) is quoted.   Uncertainties (statistical or systematic or both) are attached to the measured values of the diffusion constants in the new version of the paper. Text is added to the paper to explain this.

Major Comment c)

c) It is somewhat difficult to reconcile the results for the resolution, the deformations and the efficiency, because it seems that they are based on different data sets or at least on different cuts applied to the data. For example, the track selection seems to be much stricter for the resolution studies in terms of fiducial cuts and amplitude (ToT) than for the efficiency. I understand that there may be reasons of statistics, etc. to do so, but I still want to express my concern that in the end, for physics measurements, it is the combined performance for a given set of cuts that counts, not the best possible value for each single parameter, obtained under different conditions.

Answer to Comment c):

There are good reasons to apply selection and acceptance cuts. In particular for the studies that focus on the systematics in the TPC one has to apply strict cuts on matching cuts of the Telescope to the TPC to reject backgrounds.

We share the concern of the reviewer and the question "how does this extrapolate to a real experiment?" For TPC tracking in a real experiment the tracking efficiency is very close to one for the module because of the high single electron efficiency and the high number of electrons per crossed chip (See Fig 11: 124 B=0 and 89 B=1) and the high number of hits on the track that crosses the module of 8 chips (8*124 and 8*89). Note that the number of electrons per crossed chip is after the hit selection (including a ToT cut).

Major Comment d)

d) The procedure leading to Figs. 8 and 10 is not understandable, at least not to this referee. The text in Lines 263 - 301 and in Lines 323 - 336 has to be completely rephrased in my opinion.

Answer to Comment d): the text is rephrased (see details below).

Q: "the module was regrouped in four 256x256 pixel planes put side by side on the horizontal axis",

Answer: To explain this better it was rephrased and a sentence was added

“the module was regrouped in (4$\times$256)$\times$256 pixel planes put side by side on the horizontal axis, as shown in figure \ref{fig:deformationsGroupedB0}. E.g. the selected chips from the upper left and bottom left quad detectors are combined into the 0-256 (x) and 0-256 (y) plane”

and

"Similarly, regrouping the module in 256x(4x256) pixels put them side by side on the vertical axis,"

Q: "A bias in the mean residual..." => shouldn't this statement also be true for Figs. 7 and 9? If yes, it should be moved there.

Answer: Indeed we move the sentence up.

Q: "due to the presence of the dike pixels..." => dike pixels have not been defined

Answer: a comma was missing. "due to the presence of the dike, pixels"

Q; "the region near the edge of 5 pixels was removed"

Answer: "the region near the edge of the chip of 5 pixels"

Q: "a region of 10 pixels was removed"

Answer: "a region of 10 pixels near the edge of the chip was removed

Q: what is the "expected statistical error"?

Answer: It is the expected uncertainty on the r.m.s. in the pixel (drift) plane for the regrouping and the available statistics. This is obtained by propagating the uncertainties. This is now added to the text.

Major Comment e)

e) Generally, the presentation towards the end of the manuscript (End of Section 5 and Section 6) seems to decline in quality with respect to the other Sections. I suggest that the authors have a closer look at these sections.

Answer: we followed up on the suggestions.

Q: In Section 5.4, no details are given on how the numbers are defined or extracted (see also comment a) above).

Answer: the uncertainties on the track parameters (position and angle) are propagated and the mean of these are given in this section. This explanation is added to the text.

Q: In Section 6, the difference between the number of hits (corresponding to number of ionization electrons) and the time over threshold (corresponding to charge after amplification in the Micromegas grid) should be made clear. In addition to the distributions of the number of hits, also the distributions of the ToT could be shown.

Answer: A sentence is added to explain that the ToT is related to the deposited charge. We will refer Fig 5.5 of the thesis of C Ligtenberg for a ToT distribution.

Q: The authors mention that the measured mean number of hits is in agreement with the prediction from ref. [13]. But given the Landau fluctuations of the number of ionization electrons and the large tail, wouldn't the most probable value be a better number for this comparison? Alternatively, one could show the predicted distribution along with the measured one.

Answer: From the MagBoltz calculations we have only the mean number for the T2K gas. We did not perform a full MC event-by-event simulation with Garfield/MagBoltz of the detector that would allow to extract the most probable value.

Additional comments:

Abstract:

- Line 19f: quoting the result for transverse and longitudinal diffusion coefficients without specifying the gas does not make sense.

Answer The uncertainties are quoted. Also a line is added to specify the gas.

- Line 20: remove "D_T is"

Done

- Line 22: the phrase "the diffusion measurements have negligible errors" is not valid. Every measurement must be accompanied by an estimate of the uncertainty!

Answer The line is removed and the results are quoted with uncertainties.

Introduction:

- Line 36: what clusters are meant here? Ionization clusters?

Answer: The primary clusters that each several ionization electrons.

- Line 43f: with an ENC of 70 e-, why is the threshold set to more than 7 sigma?

Answer To suppress the noise. The distribution has a non-gaussian tail. We don't want to flood our byte stream with noise hits. See also our previous publications.

- Line 45: be quantitative instead of claiming "high efficiency" I did not find the information on the number of pixels per TPX3 chip in the paper.

Answer: Indeed it is better to be quantitative. In the single chip paper an efficiency of about 80% is stated. In this paper we show a 85\% single electron efficiency. We added in the introduction the 256x256 pixels.

We rephrased as "and a high efficiency of about 85\% - demonstrated in this paper - to detect single ionisation electrons."

In the abstract we put: "high efficiency of about 85\% ..."

- Line 50: "readout" => "read out"

Done (in many places)

Section 2:

- Line 72 and 89: "guard" => "guard electrode"

Done in more places we changed guard to guard electrode/strip etc.

- Line 86: "diameter"

Done

- Line 86: check use of "and"; what are the "guard strips"? Can they be indicated in Fig. 2?

Done "and" is removed. Guard strips are on the 4 sides of the module (in the quad plane).

Done: Fig 2 was updated: the different guard wires etc. are indicated

- Line 92: "two 50 um thick Kapton windows"

Done

Figure 1: should be enlarged

Done

- labels and a scale should be added

Not needed: Scales are in the text and in Figure 2

- "rendering"?

Done

- stick to either "32-GridPix module" instead of "8-quad module" throughout the text

Done

Figure 2: add labels, e.g. for guard wires, guard strips, guard electrodes, pillars for field wires, etc.

Done: We added color coding and explanation in the caption

Section 3:

- Line 114: "At DESY, the Mimosa26 silicon..." (add comma and remove parentheses)

Done

- Line 124: "parameters"

Done everywhere parametres->parameters

- Line 125: add "and" before "oxygen"

Done

- Line 134: "systems"

Done

- Line 137: "of" => "with respect to"

Done (rephrased)

Figure 3: is this a top or side view?

Answer Side view:
Captions reads as "Photo of the detector setup - side view - at the centre of the PCMAG magnet (the circular contour) . The Mimosa26 planes M0 and M3 are indicated in red as well as the beam direction (yellow)."

The main text now has "The stage positions the TPC module with respect to the beam and the Mimosa26 planes can be adjusted."

Table 1:

- is the number of runs important?

Answer: Not crucial, but this is important if somebody wants to redo the analysis (Open Data Acces)

- are the beam momenta relevant? (see also corresponding comment below)

Answer: Yes, the multiple scattering is a bit different and the electron/trigger rates are different.

Section 4:

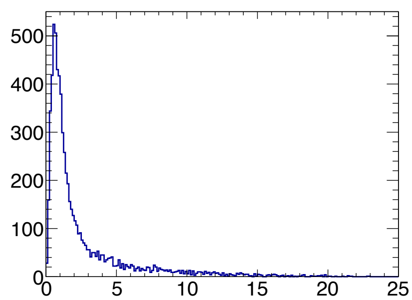
- Line 155: check language in "Telescope tracks were selected with at least 5 out of 6 planes on the track" => "Telescope tracks were required to have hits in at least 5 out of the 6 planes"

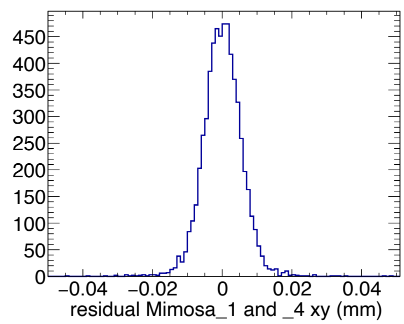
Done

- Line 156: why is the track chi2 cut so large? What is the distribution of the reduced chi2?

Answer: The value was chosen to keep a high tracking and silicon plane "on track" efficiency.

Plots for the chi2/ndof and the residuals in the M1 plane





- Line 176: with respect to what has the acceptance window for GridPix hits been defined?

Answer: it reflects the size of the quartz window

- Line 177: "was" => "were"

Done

- Line 179: check language in "quadratic track B=1 T model"

Done

- Line 180: give values for the "expected uncertainties". How were they obtained?

Answer: A sentence was added to clarify this "The expected uncertainties were derived using the parametrisations discussed in section \ref{sec:hitResolution}."

- Line 181f: the phrase "outlier removal at respectively 10, 5 and 2.5 sigma level" is hard to understand, please rephrase. What sigma do you refer to here?

Answer: Here sigma means the expected uncertainty on the hit. Text change to "The fit was iterated three times to reject outlier hits at respectively 10, 5 and 2.5 sigma."

- Line 183: why do only 25% of all hits lie on the track? Figure 4 looks much cleaner. Please explain.

Answer: the text says "More than 25%". In most (clean) cases all the hits end up on the track.

- Line 185: what orientation does the "plane in the middle of the TPC" have?

Answer: y = constant. So x and z any value: so orthogonal to the main beam direction.

- Line 199: add "from" before "run"

Done

Figure 4: - red and blue lines are hard to distinguish- green points are hardly visible

Answer: not easy to make this better without spoiling the overall picture. In the electronic version one can zoom and see it.

- "driftplane => "drift plane"

Done

Section 5:

- Line 208: "Secondly" would require a "firstly" before

Done Added Firstly,

- Line 220: "staying 20 pixels away from the chips edges" => are all 4 chips edges meant here?

Answer: Only the chip edges in local x (orthogonal to the beam).Text is now "staying 20 pixels away in local x from the chip edges'

- Line 221: see above comment on "resolution"

Answer already discussed under Major Comment a)

- Eq. (2): give a reference, e.g. [Yonamine et al., JINST 9 (2014) C03002]

Answer: We think it is not needed to cite a reference: one can also find the expression in our previous papers.

- Line 228f: "sensors", "windows"

Done

- Line 244f: "resolution ... in the drift plane" => should be "residual width in z direction"? The expression "drift plane" has not been defined.

Answer: this has been rephrased. The z direction is the drift direction.

- Lline 249: why is the ToT cut chosen for the z residuals so much higher than the one applied for the xy residuals (0.6us vs 0.15us)? How does this affect the efficiency?

Answer: The time slewing - that depends on the ToT - has an important impact on the resolutiom of the detector. This has been discussed in our single chip paper ref 1. There we used a ToT cut at 0.6us. The efficiency of the cut is about 50%. NB For TPC tracking we use of course all hits with ToT > 0.15 mus.

- Line 257: what do the authors conclude from the discrepancy between the measured value of D_L and Magboltz? Is Magboltz data wrong, or are there systematic effects that were not taken into account?

Answer we followed up on the longitudinal Diffusion this point and found a systematic uncertainty that was over looked - as discussed above. The results are in better agreement now.

- Line 274f: it would greatly facilitate reading if the chip numbers quoted in the text were visible in Figs. 7 and 9, without having to go back a few pages to Fig. 2.

Answer: The reader can find the information and the text also explains where the chips are ("corner chips").

- Line 302: "electrons will drift mainly along the magnetic field lines" seems not entirely correct. What is the value of \omega\tau? I suggest to remove the sentence, as it is not needed.

Answer: Omega tau is about 4.5 and. So the electrons drift mainly according to the B field lines.

- Line 312: mention that these are now biased residuals, in contrast to the ones for B=0T, where the external track was used as reference

Done

Figures 7, 9:- add labels and units for z axis

Answer: We changed the caption "Mean residuals (color coded in mm) ...

- is the binning really 8 x 16 pixels? Zooming in, it seems that there is an equal number of bins in x and y for each chip, which would imply an 8 x 8 binning.

Answer: Thanks for spotting this. The bin size is indeed 16x16 in xy and z. This is now corrected in the paper.

Figures 8,10:- add labels and units for z axis

Answer: see above: we changed the caption "Mean residuals (color coded in mm) ...

- what is the "regrouped expected hit position"?

Answer: "the expected hit position" (in the plane). Text changed.

Section 6:

- Line 350f: check language in "the B=0T analysis selects the ...." => "For the analysis of the data with B=0T, the chips ... were selected" or similar?

Done

- Line 352: why were chips 12, 13, 20, and 21 excluded for the B=0T analysis? For a proper comparison of B=0 and 1T data, wouldn't it be advisable to use the same data set?

Answer For B=1 chips 12, 13, 20, and 21 could be included because of the different Beam angle in the B=1 data set that allowed a larger acceptance. One could remove these chips (12,13,20,21) for “consistency” but that would decrease the statistics.

- Line 362: typo in "possibility"

Done

Figure 11:

- typo in "per per" - check language in caption

Done

Section 7:

- the authors emphasize here again that data were taken at two different beam momenta, but throughout the analysis in the previous sections, no mention is made, which beam momentum the data correspond to. Have both momenta been used, e.g. also for Section 6? Probably the authors should state for each Section, which beam momenta were used

Answer: The data correspond to beam momenta of 5 and 6 GeV in all sections. In section 6 too (this has been corrected).

- Line 380f: this statement does not make much sense, unless an explicit public link to the data is given

Answer: One can contact LCTPC/DESY or the author for the links (note that Grid links do change).

Language and format:

- put symbols for physical quantities in italics: B, x, y, etc.

- do not put units in italics, e.g. GeV, cm

- use mathematical symbols where applicable, e.g. "\times" instead of "x"

- use SI units where applicable, e.g. there is no need to define T as Tesla when talking about magnetic field strength

- check use of hyphens (missing very often, especially in compound modifiers like "32-chip module", "high-precision tracking",...)

- references: should be in square brackets, not in parentheses; use [1,2] instead of (1), (2).

- format tables 1 and 2 for better readibility

- slided => slid

- avoid use of jargon, e.g. "quads", "guard", etc.

- avoid unphysical statements like "great precision", "high efficiency", ...

- check use of commas

All Done

Click here to access/download
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DESYsetup_v1.jpg

Declaration of interests

☒The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Towards a Pixel TPC part I: 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 testbeam at DESY in 2021. The GridPix chips each consist of a Timepix3 ASIC (TPX3) with an integrated amplification grid and have a high efficiency of about 85% to detect single ionisation electrons. In the testbeam 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 slid into the PCMAG magnet at DESY. The TPC could be operated reliably and used a 93.6/5.0/1.4 gas mixture (by volume) of $Ar/iC_4H_{10}/CO_2$ with a small amount of oxygen and water vapour. 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 (287.2 ± 0.5) $\mu m/\sqrt{cm}$ at B = 0 T and D_T (120.3 ± 0.5) $\mu m/\sqrt{cm}$ at B = 1 T. The longitudinal diffusion coefficient D_L is measured to be (251 ± 14) $\mu m/\sqrt{cm}$

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at $B = 0$ T and (224 ± 14) μm/$\sqrt{\text{cm}}$ 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).

Keywords:
Micromegas, gaseous pixel detector, micro-pattern gaseous 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 accuracy, allowing 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 TPX3 chip was constructed.

A GridPix detector consists of a CMOS pixel TPX3 chip [6] with integrated amplification grid added by photo-lithographic - Micro-electromechanical Systems (MEMS) - post-processing techniques. The TPX3 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 55×55 μm^2 with 256×256 pixels per chip. The device has a high efficiency of about 85% - discussed in this paper - to detect single ionisation electrons.

Based on the experience gained with these detectors a 32 GridPix detector module - consisting of 8 quad detectors - was built. A drift box defining the electric field and gas envelop was constructed. A read out system for up to 128 chips with 4 multiplexers read out by one Speedy Pixel Detector Readout (SPIDR) board [7] [8] was designed. After a series of tests using the laser setup [9] and cosmics in the laboratory at Nikhef, the detector was taken to DESY for a two week testbeam 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 slid 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 GridPix detector module was measured using these data sets.

In this paper, part I of the results will be presented with the main focus on the detector spatial resolution and tracking performance. A second follow up paper will discuss the dE/dx (or dN/dx) and other results.

2. The 32-GridPix detector module

A 32 GridPix detector module was built using the quad detector 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 electrode 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 GridPix detectors 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 detector 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 quad detectors 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 read out 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. Guard strips are located on all of the four sides of the active area. In addition, six guard wires - shown with dashed lines (one colored red) in Figure 2 - are suspended over the boundaries of the chips, 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 potential at this drift distance. The box has two 50 μm thick

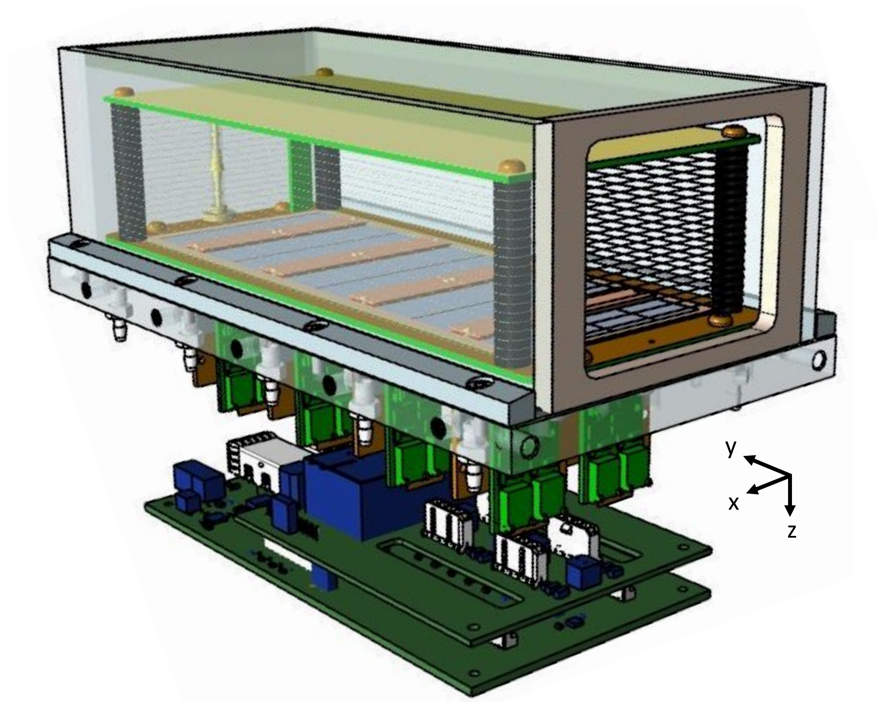


Figure 1: Schematic 3-dimensional rendering of the 32-GridPix module detector for illustration purposes.

Kapton windows to allow the beam to pass with minimal multiple scattering.

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 transverse diffusion in a magnetic field and the high drift velocity.

The data acquisition system of the quad module was adopted to allow for reading out multiple quad detectors. A multiplexer card was developed that handles four quad detectors or 16 chips and combines the TPX3 data into one data stream. For the 32 GridPix module two multiplexers are connected to a SPIDR board that controls the chips and read out process. The read out speed per chip is 160 Mbps and for the multiplexer 2.56 Gbps this corresponds to a maximum 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.

3. Experimental setup

In preparation of the two weeks DESY testbeam campaign, a support frame was designed to move the 32-chip GridPix detector 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 to allow access to the electronics from above.

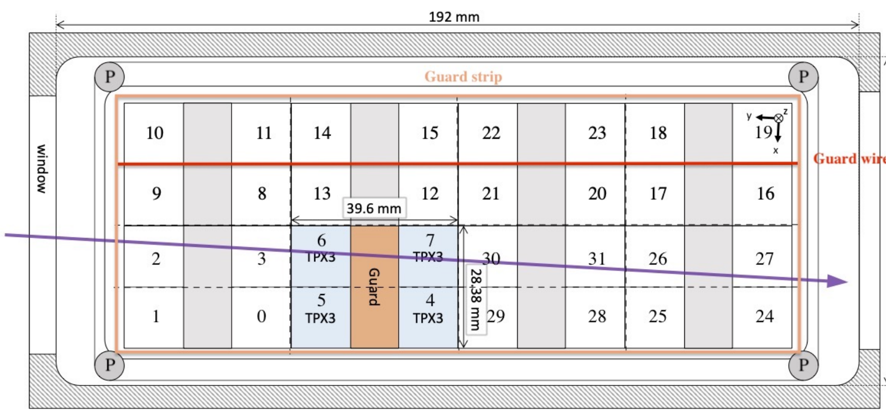


Figure 2: Schematic drawing of the 32-GridPix module detector with one example quad as viewed from the top of the quad detectors. The chips are numbered and the beam direction is shown in purple. A guard electrode of a quad detector is shown in orange. The four surrounding guard strips are shown -not to scale- in orange. Six guard wires - are shown with dashed lines (one colored red) and the pillars of the drift box are shown a circles with a P in the centre.

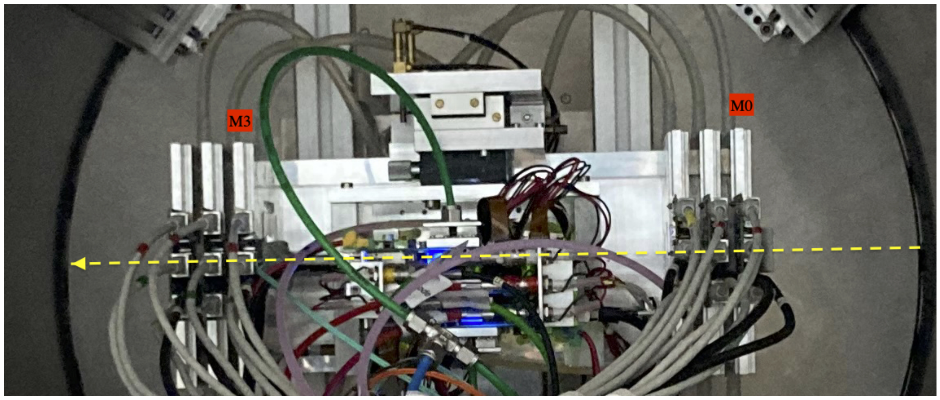


Figure 3: Photo of the detector setup - side view - at the centre of the PCMAG magnet (the circular contour). The Mimosa26 planes M0 and M3 are indicated in red as well as the beam direction (yellow).

The support frame also held three Mimosa26 silicon detector planes [10] - with an active area of (21.2 mm × 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 testbeam coordinators. The whole detector setup was slid towards the centre of the PCMAG magnet at the DESY II testbeam facility [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 stage positions of the TPC module with respect to the beam and the Mimosa26 planes can be adjusted.

The experimental and environmental parameters such as temperature, pressure, gas flow and oxygen 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.

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 per run	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 read out and the trigger SPIDR. The data acquisition systems 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 μs to 230 μs around the trigger time. 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 ns flat time jitter.

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 testbeam 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 [14]. The code was extended and optimised 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) [10].

Telescope tracks were selected were required to have hits in at least 5 out of the 6 planes 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 detector module are dominated by multiple scattering. The amount of multiple scattering was estimated by comparing the predictions from the two telescope arms for 6 GeV/c tracks at $B = 0$ 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):

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

Furthermore, small time shift corrections - with an odd-even and a 16$\times$ 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 $z_{\text{drift}} = -z$ as defined in Figure 1. GridPix hits outside an acceptance window of 30 mm wide in x and 15 mm wide in z 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) were obtained. This estimate was used to collect the hits around the TPC track and fit the track parameters. For this fit a linear (for $B = 0$ T data) or a quadratic track (for $B = 1$ T data) model was used. In the fit, the expected uncertainties per hit σ_{xy} and σ_z were used. The expected uncertainties were derived using the parametrisations discussed in section 5. The fit was iterated three times to reject outlier hits

Table 2: Table with track/event selection cuts

Track/Event Selection
$\|x_{\text{TPC}} - x_{\text{telescope}}\| < 0.3\,\text{mm}$
$\|z_{\text{TPC}} - z_{\text{telescope}}\| < 2\,\text{mm}$
$\|dx/dy_{\text{TPC}} - dx/dy_{\text{telescope}}\| < 4\,\text{mrad}$
$\|dz/dy_{\text{TPC}} - dz/dy_{\text{telescope}}\| < 2\,\text{mrad}$

at respectively 10, 5 and 2.5 sigma. 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 had to be less than 3 in xy and zy. All track parameters were expressed at a plane in the middle of the TPC module.

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

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 $B = 0$ T 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 $dx(z\ drift)/drow(column)$. The alignment was done per run, because the detector was moved in x and/or z for each run. The fitted slopes were also corrected for small shifts and rotations (3D) in the nominal chip position.

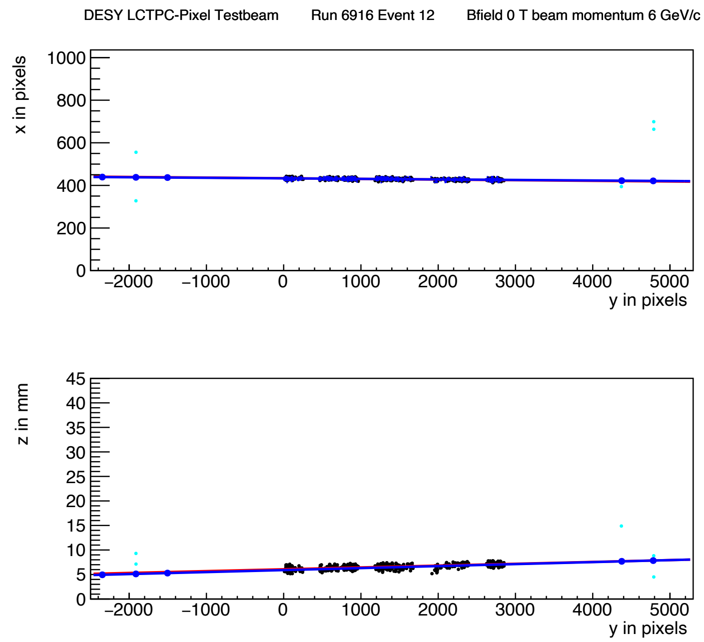


Figure 4: An event display for run 6916 without B field, with in total 1293 TPC hits (black dots) in the precision plane (x, y) and drift plane $(z\ drift, y)$. The fitted TPC track (red line) with 1130 hits on track and the telescope track (blue line) with 5 Mimosa26 planes (blue hits) on track are shown. In green the off track Mimosa26 hits are shown.

An example event from run 6916 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

The track residual in xy is the closest point of the the hit at the center of the pixel to track in the xy plane. The residual in z is calculated at this point of closest approach. The single electron hit resolutions in xy and z will be extracted from the track residuals. 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. Firstly, due to the trigger time jitter of 25 ns (corresponding to 1.5 mm drift), 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 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) were 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 residual of the hits in the pixel plane (xy) was measured as a function of the predicted drift position (z_{drift}). Tracks were selected that crossed the fiducial region defined by the central core of the beam. Hits were removed in a region of 20 pixels near the chip edges in x. The spread on the residual in xy for an ionisation electron is given by:

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

where σ_{track} is the uncertainty from the track prediction, d_{pixel} is the pixel pitch size, z_0 is the position of the grid, and D_T is the transverse diffusion coefficient. The last two terms correspond to the single electron detector resolution (squared). The resolution at zero drift distance $d_{\text{pixel}}/\sqrt{12}$ was fixed to 15.9 μm and σ_{track} to 30 μm for $B = 0$ T and 42 μm for $B = 1$ T data. The uncertainty on the track prediction was measured and is larger than the Mimosa plane resolution because of multiple scattering in the sensors and in the entrance and exit windows.

The expression (2) - leaving z_0 and 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 (287.2$\pm$ 0.5) μm/$\sqrt{\text{cm}}$. The measured value is in agreement with the value of 287 μm/$\sqrt{\text{cm}}$ $\pm$ 4% predicted by the gas simulation software Magboltz 11.9 [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, also shown in Figure 5, gives a transverse diffusion coefficient D_T of (120.3 $\pm$ 0.5) μm/$\sqrt{\text{cm}}$. The measured value is in agreement with the value of 119 μm/$\sqrt{\text{cm}}$ $\pm$ 2% predicted by Magboltz.

5.2. Hit resolution in the drift plane

The spread on the residuals in z of the ionisation electrons σ_z is given by:

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

where σ_{track} is the expected track uncertainty, σ_{z0} the detector resolution at zero drift distance and D_L the longitudinal diffusion constant. The last two terms in the equation correspond to the single electron detector resolution (squared). Only tracks crossing the fiducial region - defined by the central

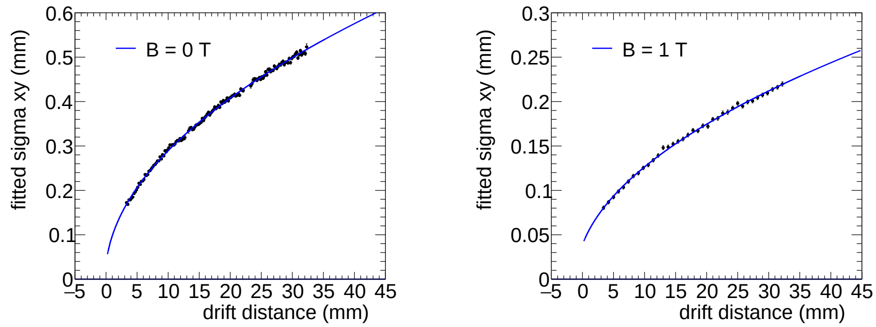


Figure 5: Measured spread on the residuals in the pixel plane (black points) fitted with equation (2) (blue line).

core of the beam - 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 TPC track prediction is propagated and amounts to 50 μm at $z = z_0$. The systematic uncertainty on $sigma_{\text{track}}$ is estimated to be 25 μm.

The expression (3) - leaving σ_{z0} and 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 129 μm. The longitudinal diffusion coefficient D_L was determined to be (251 $\pm$ 1 (stat) $\pm$ 14 (sys)) $\mu\text{m}/\sqrt{\text{cm}}$, which is higher than the expected value 236 ± 3 $\mu\text{m}/\sqrt{\text{cm}}$ from a Magboltz calculation [15]. The quoted systematic uncertainty on D_L is rather large and obtained from a fit using $\sigma_{\text{track}} = 25$ μm.

A fit to the $B = 1$ T data shown in Figure 6 gives a longitudinal diffusion coefficient D_L of $(224 \pm 2$ (stat) ± 14 (sys)) $\mu\text{m}/\sqrt{\text{cm}}$. The measured value

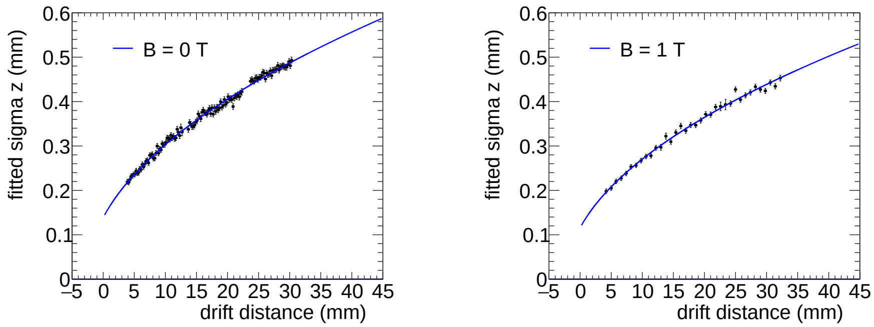


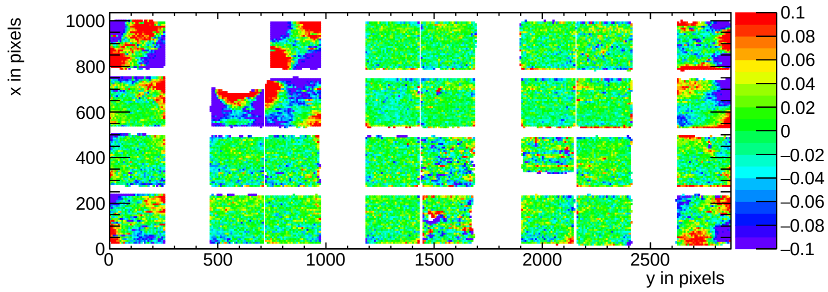
Figure 6: Measured spread on the residuals in the drift plane for hits with a ToT above 0.60 μs. The data are fitted with the expression of equation (3).

is lower than the value of (245 ± 4) $\mu\text{m}/\sqrt{\text{cm}}$ predicted by Magboltz. The fitted value of σ_{z0} was 114 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.



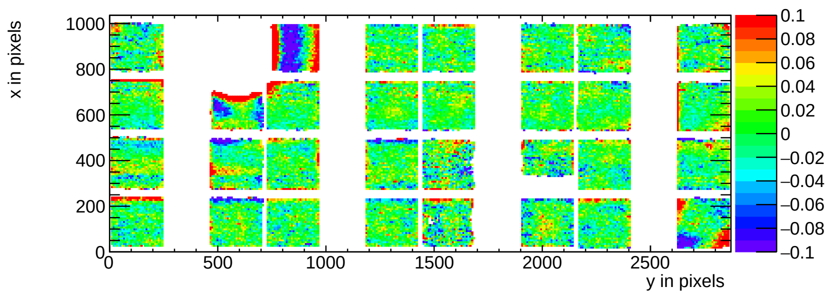


Figure 7: Mean residuals (color coded in mm) in the pixel (top) and drift (bottom) plane for $B = 0$ T data at the expected hit position.

Deformations are present at the four corners of the drift box (chips 1, 10, 19 and 24) and close to the upper corner edge (chip 16) of the drift box. These come from inhomogenieties in the drift field near the supporting pillars, the field wires are too close to the chip to provide a constant electric field. It was concluded that for the deformation studies the hits of these nine chips have to be removed. The track fit was redone leaving these hits out of the fit, such that they could not bias and affect the results. Note that 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.

In order to reduce the statistical fluctuations and quantify the tracking precision, the module was regrouped in $(4{\times}256){\times}256$ pixel planes put side by side on the horizontal axis, as shown in Figure 8. E.g. the selected chips from the upper left and bottom left quad detectors are superimposed into the 0-256 (x) and 0-256 (y) plane. Bins have a size of $16{\times}16$ pixels and bins with less than 1000 entries are not shown. Due to the presence of the dike, pixels at the edge of the chip became covered and inefficient. Therefore, the region of 5 pixels in y near the edge of the chip was removed. For the drift coordinate studies, a region of 10 pixels near the edge of the chip in x and y 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 detector 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

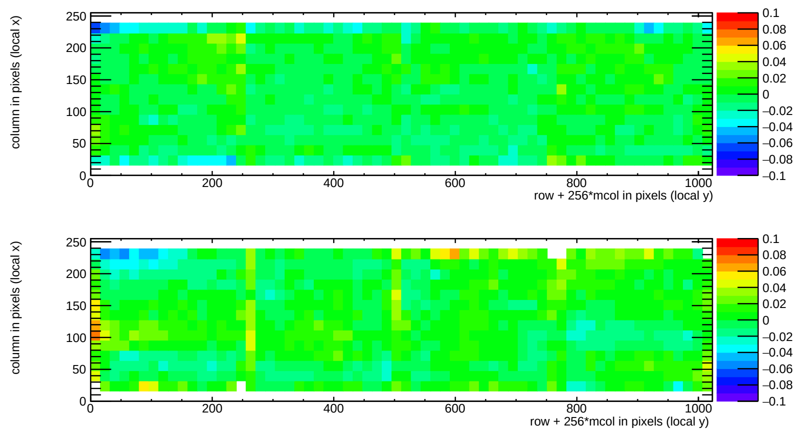


Figure 8: Mean residuals (color coded in mm) in the pixel (top) and drift plane (bottom) for $B = 0$ T data at the expected hit position.

256×(4×256) pixels put them side by side on the vertical axis, yielded a r.m.s. in the pixel plane of 13 μm and 13 μm in the drift coordinate. The expected statistical error - obtained by propagating the uncertainties on the residuals - 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 field lines. Deformations are in that case due to e.g. the non-alignment of the electric and magnetic field, giving $E \times B$ 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/c 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

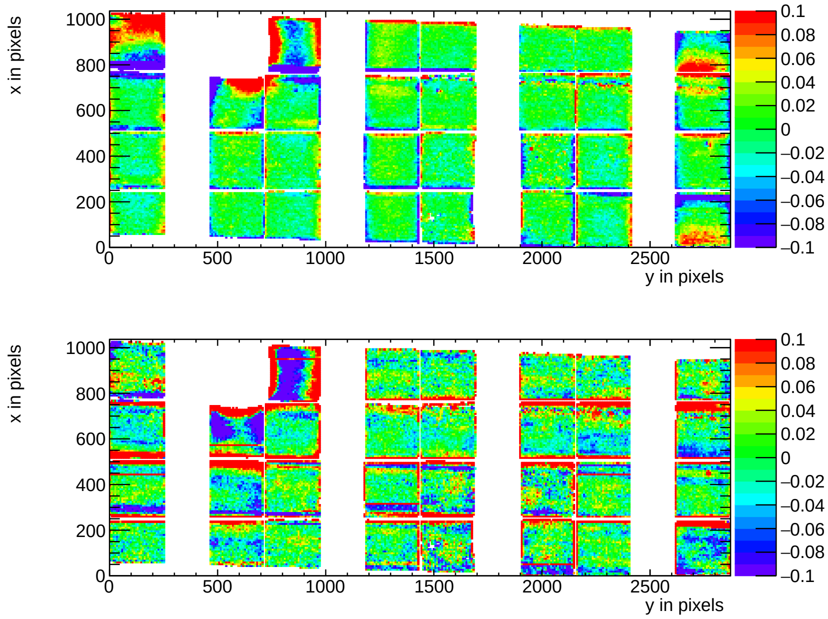


Figure 9: Mean residuals (color coded in mm) in the pixel and drift plane for $B = 1$ T data at the expected hit position.

(biased) residuals were calculated with respect to the TPC track prediction. Because of limited statistics, bins were grouped into 16×16 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 studies, the hits of these nine chips were removed. The TPC track fit was redone leaving these hits 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.

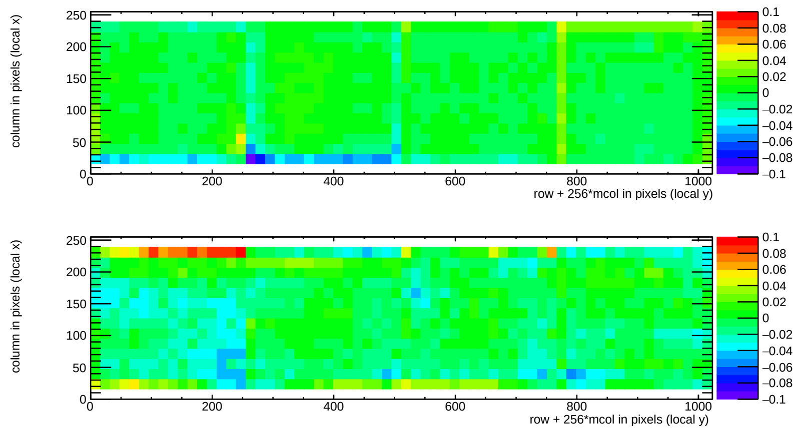


Figure 10: Mean residuals (color coded in mm) in the pixel and drift plane for $B = 1\mathrm{T}$ data at the expected hit position.

In order to reduce the statistical fluctuations and quantify the tracking precision, the module was again regrouped in $(4{\times}256){\times}256$ pixels as described above, as shown in Figure 10. Bins have a size of $16{\times}16$ pixels and bins with less than 1000 entries are not shown. Similar to the no-field deformations studies, acceptance cuts had to be applied. The region of 16 pixels in y near the edge of the chips was removed. For the drift coordinate studies, in addition a region of 10 pixels in x near the edge of the chip 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 $256{\times}(4{\times}256)$, 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.

In summary, the deformations studies for the $B = 0$ and 1 T data demonstrate that the systematical uncertainties in xy are smaller than 13 μm with and without magnetic field. The systematical uncertainties in z were smaller than 15 μm ($B = 0$ T) and 20 μm ($B = 1$ T).

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 (at $y = 1436$ pixels) was derived on a track-by-track basis, by propagating the pixel TPC hit uncertainties. It was 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 track length of (only) 158 mm. The values are smaller than the uncertainty on the track prediction from the silicon telescope of 26 μm in x and z on average that is dominated by multiple scattering.

6. Single electron efficiency

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. For the $B = 0$ T data, the central chips 2,6,7,9,16,17,26 and 27 were selected. For the $B = 1$ T data, the same chips plus chips 12,13,20 and 21 were selected.

The mean number of hits is measured to be 124 and 89 in the $B = 0$ T and 1 T data sets respectively. The most probable values are respectively 87 and 64. Note that the $B = 0$ T data have a much larger Landau-like

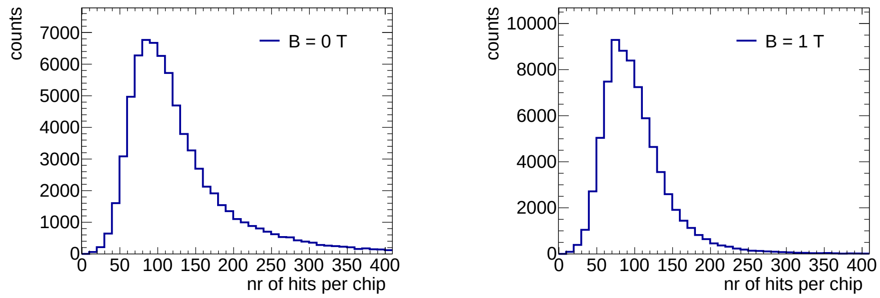


Figure 11: Distribution of the number of TPC track hits per chip for $B = 0$ T (left) $B = 1$ T data.

tail than the 1 T data. Also the fluctuations in the core of the distribution are larger. The mean time over threshold (ToT) is 0.68 μs for the $B = 0$ T and 0.86 μs at a $B = 1$ T data. A typical ToT distribution can be found in Figure 5.5 of ref.[4]. The time over threshold is related to the deposited charge. 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. A possible explanation for this behavior is that because of the reduced transverse diffusion in the $B = 1$ T data, the possibility of two primary electrons ending up in a single grid hole is higher. The mean number of hits is in agreement with the prediction of 106 electron-ion pairs for a 5 and 6 GeV/c electron at $B = 0$ T for the T2K gas by [13], crossing 236 pixels or 12.98 mm and a detector running at 85% single electron efficiency. The measured single electron efficiency at this working point is in agreement with the efficiency vs mean time over threshold curve that was measured using a Fe source [4].

7. Conclusion and outlook

A TPC module with 32 GridPix chips was constructed and the performance was measured using data taken in a testbeam at DESY in 2021. The TPC could be operated reliably and used a 93.6/5.0/1.4 gas mixture (by volume) of $Ar/iC_4H_{10}/CO_2$ with a small amount of oxygen and water vapour. 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 (287.2 $\pm$ 0.5) μm/$\sqrt{\text{cm}}$ at B = 0 T and D_T is (120.3 $\pm$ 0.5) μm/$\sqrt{\text{cm}}$ at B = 1 T. The longitudinal diffusion coefficient D_L is measured to be (251 $\pm$ 14) μm/$\sqrt{\text{cm}}$ at B = 0 T and (224 $\pm$ 14) μm/$\sqrt{\text{cm}}$ 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).

The mean number of hits is in agreement with the predictions of [13] and a detector running at 85% single electron efficiency.

Not all data were analysed and users are welcome to study them using the data sets on available on the Grid.

The GridPix detector will be further tested and developed in view of a TPC that will be installed in a heavy ion experiment at the EIC or other future colliders. A follow up paper is in preparation on the measured dE/dx or dN/dx resolution and other performance topics.

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