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Towards a Pixel TPC part II: particle identification with a 32-chip GridPix detector

--Manuscript Draft--

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Abstract:	A Time Projection Chamber (TPC) module with 32 GridPixes was constructed and the performance was measured using data taken in a test beam at DESY in 2021. The data analysed were taken at electron beam momenta of 5 and 6 GeV/c and at magnetic fields of 0 and 1 Tesla(T). Part I of the paper has described the construction, setup and tracking results. The dE/dx or dN/dx resolution for electrons in the 1 T data per meter of track length with 60% coverage was measured to be 3.6% for the dE/dx truncation method and 2.9% for the template fit method using the successive distances between the hits. The single-electron efficiency at high hit rates was studied. For hit rates up to 5.7 kHz per GridPix a reduction of at most 0.6% in the relative efficiency was measured. Large localised hit bursts from low energetic curling electrons were characterised. The single-electron resolution in the xy precision plane as a function of the local track angle φ was measured in the B = 1 T data using reconstructed circular tracks. The resolution is - as expected - independent of the local track angle within an uncertainty of 16 µm. The projected particle identification (PID) performance for a GridPix Pixel TPC in the proposed ILD experiment at a future ILC e+e- collider is presented using the B = 1 T test beam results for the measured electron PID resolution. The expected pion-kaon PID separation for momenta in the range of 2.5-45 GeV/c at cosθ =0 is more than 5.5(4.5)σ for the template fit (dE/dx truncation) method.
Opposed Reviewers:	

Dear Reviewers

Thank you for the very careful reading of the manuscript and the kind words, comments and questions.

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

See you Peter Kluit

Reviewer #1: This paper deals with the construction and the performance evaluation of a Time Projection Chamber (TPC) module featuring 32 GridPix detectors. Tested at DESY using electron beams of 5 and 6 GeV/c with magnetic fields 1 Tesla and without magnetic field, the TPC achieved impressive particle identification (PID) resolutions with two different analysis methods: (1) the dE/dx Truncation Method and (2) the Template Fit Method achieving respectively 3.6% of 2.9% of resolutions for the same conditions (1 T data for electrons).

Both methods demonstrate the GridPix detector's effective capabilities in particle identification.

The single-electron efficiency remained largely stable even at high hit rates, highlighting the GridPix's capabilities for effective tracking and PID, particularly in distinguishing pions from kaons at various momenta in proposed future experiments.

This paper is written is written in a well understandable English.

A minor revision has to be done and comments have to be taken into account before publication.

Suggested revisions:

* In Abstract:

- l. 30: Add a space: "... using the B = 1 T test beam..."

-> Done

* In § 1. Introduction

- l. 39: "... was constructed. A GridPix has a very fine ..."

-> Done

- l. 48: Precise the 'small amount of oxygen and water vapour'. (i.e. < 400 ppm).

-> Changed text “amount of oxygen ($<$ 620 ppm) and water vapour ($<$ 7000 ppm). “

- l. 56: "The time-over-threshold (ToT) is related ..."

-> Done

* In § 2.

- l. 66: Add a comma in "In a GridPix detector, one can measure both ..."

-> There is now a more elaborated text (see answer to Reviewer #2)

- l. 80: Need to say how is made the calibration (add a reference...).

-> Answer: per chip a constant weight is applied.

- Changed text: leave out "calibrated" that suggests a (more) complicated procedure.

- l. 99: Add a comma in "At distances above approximately 10 pixels, the

distribution ..."

-> Done

* In § 3.

- l. 167: remove one "runs"

-> Done

- l. 168: "Runs with high rate and low rate were taken for beam momentum of 6 GeV.

* In the Table 2. the column 'E_e' should be added for more clarity (instead of run numbers).

- l. 179: "... two high rate runs (121.7 and 122.5 Hz) taken at beam momentum of 5 GeV/c ..."

-> Answer

1) Added a column to Table 2 with the electron beam momentum (P).

2) replaced the sentence with "The analysed runs with a trigger rate above 90 Hz were taken at a beam momentum of 5 GeV/c. The runs that were taken at a beam momentum of 6 GeV/c have a trigger rate below 3 Hz."

- l. 187: add the comma after "... (lower half). The rate ..."

-> Added a dot "."

* In § 5.

- l. 228: "... has been measured in the run of B = 1 T data ..."

-> Done

- l. 246: "... and in z = 1 mm".

-> Replaced by "z equal to 1 mm"

- l. 254: "... radius of 155 pixels (8.5 mm) ...

-> Done

- l. 259: Remove the Em dash "-" in the sentence.

-> Done

- l. 277: For better readability, it could be better to replace track length

'tlength_0' of 1441 mm by explicit term like 'track_{\rm length}^{0}' and track

length 'tlength' by 'track_{\rm length}^{0}'.

-> Indeed, we replaced "tlength" by $t_{\rm length}$" etc.

Comments:

- Avoid wordiness "In order to ...", please replace it in l. 74, l. 165 and l.234 by "To .."

-> Done

- The runs numbers are not relevant. Everything can be replaced by electron beam momentum (E_e) at 5 and 6 Gev/c.

-> The run numbers are relevant in case one wants to reproduce the results. We just mention them for this purpose and list them in the Table. The beam momentum is added.

Reviewer #2: The manuscript describes measurements with a GridPix-based gaseous

detector. A measurement campaign at an accelerator site has been conducted and the results

from the analysis are presented.

The topic of the paper is very important for the future of particle detectors.

The concept has the potential to significantly improve key parameters of TPCs, e.g. the energy resolution and therefore the particle identification capabilities.

On the one hand the manuscript is well written, I also had the impression that the measurements were carefully conducted and analysed.

On the other hand, I found important aspects of the paper not well explained if at all.

For example the concept of dN/dx is not well explained, which is one of the core topics of the paper.

I assume that the authors could improve the paper by adding a few sentences of explanation for the mentioned paragraphs.

Therefore, I ask the authors to provide a revision of the paper.

Major comments:

line 64ff:

The difference between dE/dx and dN/dx is one of the main topics of the paper.

In my opinion, the dE/dx is a concept that is widely used in the community.

The dN/dx concept is a rather new approach and one of the highlights of this

paper.

Therefore I suggest to give a brief introduction to dN/dx and to point out why

it is better (compared to dE/dx) and why GridPix are capable of measuring it.

->We added to the text:

" In a classical TPC with pad read out, the charge is measured and used to estimate dE/dx using a truncation method that reduces the Landau tail. In a Pixel TPC based on a GridPix detector, the number of ionisation electrons is measured with high granularity as a function of the distance along the track.

The number of ionisation electrons is proportional to the energy loss of the particle in the gas and has a Landau-like distribution. However, if the charge is used to estimate the energy loss - as in the pad read out scheme - the large Polya fluctuations from the gas-amplication process will contribute to the measurement. Due to the digital read out of the GridPix, these fluctuations do not contribute. Due to the fine granularity, a GridPix is sensitive to the primary clusters that are described by a Poissonian distribution. The best PID performance is expected to be reached by counting the clusters and measuring dN/dx.

A Pixel TPC is sensitive to dE/dx by counting the number of electrons and to dN/dx by exploiting the distance along the track."

Line 76f:

Why do you combine tracks to get a new 1 m long track?

This seems to be an important choice but it is not motivated at all.

-> Changed text to:

"The chosen length of 1 m is typical for a TPC and allows for extrapolations to different detector size."

One could also use a shorter or longer track length The disadvantage of a shorter distance e.g. 30 cm is that one gets slightly more sensitive to the Landau tail. Extrapolation to other track length values can be done with Eq (4) in the paper.

Line 115ff

It is not clear to me how you can "define" the response of a MIP by dropping 30%of the hits. Can you explain this to me? And how did you decide which hits to drop?

Was the percentage of dropped hits varied, e.g. between 20% and 40% or was it fix?

-> Answer

The procedure is as follows: We draw for each hit a flat random number[0-1] and if this is below 0.3, the hit gets dropped. So we use a fixed/constant number of 0.3.

In the text we use the word "define" because a real MIP does not have on average exactly 70% of the Eloss of an electron of 5/6 GeV. One could also say 70% is a convention for a MIP.

-> Changed text to:

"By dropping - randomly chosen - 30\% of the hits associated… ."

It is not clear to me Line 127ff:Why could one argue that the results from the template fit method will move more towards the results of the dE/dx truncation method when more diffusion occurs?

-> Answer

The dE/dx truncation method is insensitive to the diffusion (the fine granularity of the distance distribution is not really exploited). The slope method is expected to be sensitive to the transverse diffusion because the multi-electron peak at low distance -diffusion will spread more to higher distance values and will reduce (a bit) the sensitivity of the fitted slope. So the spread on the slope will increase.

This effect was studied and confirmed on a small toy MC, where additional smearing in the transverse plane was added to the hits.

->Changed text to add reason:

"One might argue that with more diffusion the results from the template fit method will move more towards the results of the dE/dx truncation method,

because the statistical error on the slope will increase."

Line 151:

Single-electron efficiency is not well defined. I would suggest calling it the "Single-electron detection efficiency".

Furthermore, I would clarify that you are referring to ionization electrons and not electrons from your beam.

-> Done

We changed the text to "Single-electron detection efficiency"

We start now the section by: “The detection efficiency of single ionisation electrons in…”

Line 172ff:

Why do you separate the results into upper and lower half? Was there a difference in the chips, e.g. in the resistive layer?

-> Answer

One would not expect a difference between the two halfs of the module, so one expects the same numbers and behaviour for the two regions. The chips are the same but they will vary (a bit) e.g. in mean <ToT>.

Line 189ff:

What is your explanation that the single electron efficiency rises by 1% if the magnetic field is set to 1T? Could it be that the measurement uncertainty on the value is greater and not negligible (as stated in line 182)?

-> Answer

Indeed, the 1% change is within the expected uncertainty (the temperature and pressure for the 0 and 1 T runs were also different)

Line 226:

To me, it is not clear what a "single-electron resolution" is.

-> Added to text: “The resolution is measured using the single-electron residuals to the track”.

More details about the single electron resolution can be found in our part I paper (ref [3], doi:10.1016/j.nima.2025.170397).

Line 273ff:

Here, you argue that the template fit yields a significantly better energy resolution compared to the truncation method. Earlier (in lines 127ff), you argued that with increasing diffusion, you would expect that these two methods yield the same result.

In the ILD, the maximum drift length is 2350 mm, therefore diffusion dominates. Why do the two methods still differ?

-> Answer

Indeed, we argued that increasing the diffusion would bring the performance of the slope method closer to the truncation method.

The diffusion in xy is always dominant (both in the module and ILD). Note that ILD will run at 3.5 T and that will bring down significantly the transverse diffusion to 25 microns/sqrt(cm). What matters is the product of Dxy sqrt(L). And in that respect the ILD and test beam conditions are not that different.

One can say for sure is that the performance will lie in between the two methods. Where exactly, one can only answer by using a model based on these key performance numbers. E.g. for angles with a shorter drift length the performance will be closer to the slope method results.

Why do the two methods still differ?

-> Answer

Because we extrapolate the test beam results (so the two resolutions) that represent the best and the worst case scenarios. The real situation will be somewhere between.

Not mentioned:

The quality of your gas was rather poor (according to your previous paper, you had up to 620 ppm oxygen and up to 7000 ppm water in your detector gas). How does this influence your results especially with respect to the energy resolution? I would assume that especially due to the high oxygen content, you suffer from electron attachment? Has this somehow been taken into account?

-> Answer

That is a very correct observation. For a large TPC gas tightness is very important. The drift distance in the module was rather short (max 35 mm) so the impact of electron attachment is rather small. No corrections were made for this effect.

The results on the PID performance include all possible single-electron detection efficiency losses (due to limited acceptance, different chips operating points, electron attachment etc.).

Minor:

Line 76f:

How do you define a hit?

-> Answer

A signal in a pixel over threshold

What is an event?

-> Answer

Hits in the detector in a time slice (around the trigger time)

Line 147ff:

You state that these measurements show the best dE/dx and dN/dx resolution of

TPCs at atmospheric pressures. Could you confirm this by citing the corresponding values for some TPCs, e.g. ALICE or sPHENIX?

-> Answer

We added to the text a reference to the performance of the ALICE experiment:

"E.g. the ALICE experiment published a dE/dx resolution of 5\% for a track length of 1.65 m \cite{YU201355}." https://doi.org/10.1016/j.nima.2012.05.022}

Line 228:

Phi is not defined.

-> Added to the text:

" defined as the azimuthal angle in the xy plane,"

Line 290ff:

How do these numbers compare to other TPCs?

-> Answer

1) We added in section 7 more context: a reference for ILD dEdx performance to line:

"It is clear from the above that a GridPix Pixel TPC in ILD will provide powerful particle identification".

Added:

"Studies have shown that for a pad readout in ILD, the PID resolution is expected to be 5\% \cite{einhaus2019}." (https://arxiv.org/abs/1902.05519)

2) For other TPCs we now quote the ALICE dEdx performance in section 2.

Table 2:

Include beam momentum in the table.

-> Done

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 II: particle identification with a 32-chip GridPix detector

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Abstract

A Time Projection Chamber (TPC) module with 32 GridPixes was constructed and the performance was measured using data taken in a test beam at DESY in 2021. The data analysed were taken at electron beam momenta of 5 and 6 GeV/c and at magnetic fields of 0 and 1 Tesla(T). Part I of the paper has described the construction, setup and tracking results.

The dE/dx or dN/dx resolution for electrons in the 1 T data per meter of track length with 60% coverage was measured to be 3.6% for the dE/dx truncation method and 2.9% for the template fit method using the successive distances between the hits.

The single-electron efficiency at high hit rates was studied. For hit rates up to 5.7 kHz per GridPix a reduction of at most 0.6% in the relative efficiency was measured.

Large localised hit bursts from low energetic curling electrons were characterised.

The single-electron resolution in the xy precision plane as a function of the local track angle ϕ was measured in the $B = 1$ T data using reconstructed

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circular tracks. The resolution is - as expected - independent of the local track angle within an uncertainty of 16 μm.

The projected particle identification (PID) performance for a GridPix Pixel TPC in the proposed ILD experiment at a future ILC e^+e^- collider is presented using the $B = 1$ T test beam results for the measured electron PID resolution. The expected pion-kaon PID separation for momenta in the range of 2.5-45 GeV/c at $\cos\theta = 0$ is more than $5.5(4.5)\sigma$ for the template fit (dE/dx truncation) method.

Keywords: Micromegas, gaseous pixel detector, micro-pattern gaseous detector, Timepix, GridPix, pixel Time Projection Chamber

1. Introduction

As a step towards a Pixel Time Projection Chamber for a future collider experiment [1], [2], a module consisting of 32 GridPixes based on the Timepix3 ASIC was constructed. A GridPix has a very fine granularity of 256×256 pixels of 55×55 μm^2 and a high efficiency of about 85% to detect single ionisation electrons. Besides the Time-of-Arrival (ToA) of the signals on a pixel, the Timepix3 also measures the Time-over-Threshold (ToT). The ToT is related to the deposited charge of the signal.

The 32-GridPix chip detector was put in a test beam at DESY and complemented with two sets of silicon detector planes. The data analysed were taken at electron beam momenta of 5 and 6 GeV/c and at magnetic fields of 0 and 1 T. The TPC was operated using a so-called T2K gas mixture of 95/3/2% of $Ar/CF_4/iC_4H_{10}$ (by volume) with some amount of oxygen ($<$ 620 ppm) and water vapour ($<$ 7000 ppm).

The construction of the GridPix TPC module, the test beam setup and data taking conditions have been described in part I of our paper [3], that also presents the track reconstruction procedure and the precise TPC tracking results.

In the following sections, the test beam analysis results for several topics will be presented. Firstly, the particle identification performance using dE/dx or dN/dx will be measured. Secondly, the single-electron efficiency at high hit rates will be determined. Thirdly, the characterisation of large localised hit bursts caused by low energetic curling electrons will be presented. Fourth, the single-electron resolution in the xy precision plane as a function of the local track angle will be measured. Finally, the projected particle identification performance for a Pixel TPC in the proposed ILD experiment at ILC [4] will be presented and discussed.

2. Particle Identification (PID) using dE/dx or dN/dx

Particles can be identified by their characteristic energy loss per unit of track length, dE/dx and/or the number of primary clusters, dN/dx produced along the track. In a classical TPC with pad read out, the charge is measured and used to estimate dE/dx using a truncation method that reduces the Landau tail. In a Pixel TPC based on a GridPix detector, the number of ionisation electrons is measured with high granularity as a function of the distance along the track. The number of ionisation electrons is proportional to the energy loss of the particle in the gas and has a Landau-like distribution. However, if the charge is used to estimate the energy loss - as in the pad read out scheme - the large Polya fluctuations from the gas-amplication process will contribute to the measurement. Due to the digital read out of the GridPix, these fluctuations do not contribute. Due to the fine granularity, a GridPix is sensitive to the primary clusters that are described by a Poissonian distribution. The best PID performance is expected to be reached by counting the clusters and measuring dN/dx. A Pixel TPC is sensitive to dE/dx by counting the number of electrons and to dN/dx by exploiting the distance along the track.

The distribution of the number of TPC track hits per GridPix for the $B = 0$ T and for the $B = 1$ T data sets are a starting point for a measurement of the dE/dx or dN/dx performance. As was discussed in part I of the paper [3], the mean number of hits per GridPix were 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.

To measure the track performance of dE/dx or dN/dx, a track selection was applied selecting tracks crossing the central chips - defined in [3]. By combining the hits associated to the track from several events, a new 1 m long track was formed. The chosen length of 1 m is typical for a TPC and allows for extrapolations to different detector size. The 1 m long track has a coverage of 60% because inactive regions (chip edges and e.g. guard plate) were included. The number of hits of different GridPixes were weighted to give the same mean number of hits per GridPix.

By applying two different analysis methods, the dE/dx or dN/dx resolution is measured from data. Both methods project the hits along the track on the y axis - along the beam direction - of the xy pixel readout plane. This gives a distribution of hits as a function of the distance along the track in pixel units. The first method rejects large multi-electron clusters with more than in total 6 hits in 5 consecutive pixel bins. Finally, a dE/dx truncation at 90% is performed using samples of 20 pixels; so the 10% largest dE/dx values are removed and dE/dx re-estimated. This method does not fully exploit the granularity of the Pixel TPC.

The second method exploits the distribution of the minimum distance between consecutive hits in the pixel readout plane. If only single-electron clusters were produced in a gas, one would expect an exponentially falling distance distribution. Multi-electron clusters will give rise to a peak at low distances in the dN/dx distribution that is smeared out by the transverse diffusion process. The slope of the exponential distribution is proportional to the dN/dx i.e. the clusters produced by the traversing beam electron.

Using a large number of tracks, it is possible to determine from data the shape of the minimum distance distribution. At distances above approximately 10 pixels, the distribution follows an exponential distribution. At lower distance, weights for the $B = 0$ T and 1 T data are determined and applied to ensure an exponential distribution over the whole range. The values of the weights at low distances depend on the transverse diffusion coefficient and the drift length. The distribution of hits as a function of the distance d_y is shown with black points in Fig. 1 for the $B = 1$ T data. The weighted distribution is shown in blue and the exponential fit result - in the range of above 10 pixels - with a red line.

Finally, per event with 1 m of track length, a maximum likelihood fit to the distance distribution in data is performed with the following template function:

$$N(d_y) = N_0 \text{ weight}(d_y)\ e^{-\alpha \cdot d_y}, \tag{1}$$

where d_y is the minimum distance of the hits in the y direction of the precision

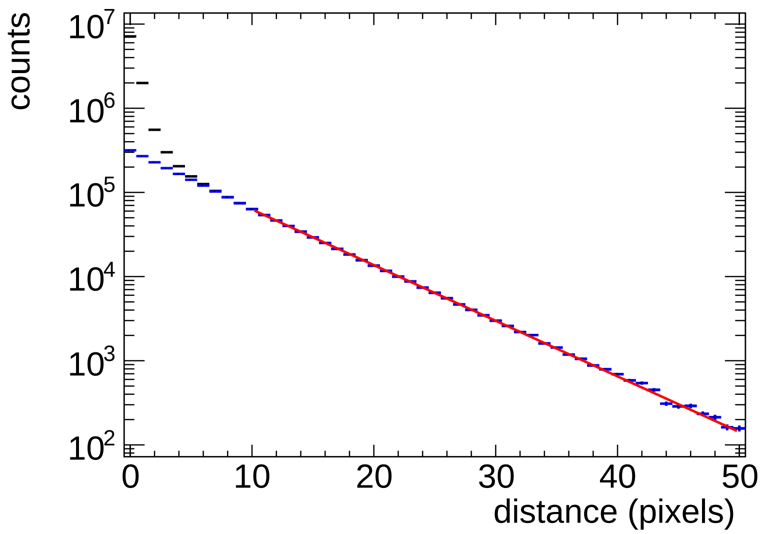

Figure 1: Distribution of the number of selected hits as a function of the distance d_y in pixel units for the $B = 1$ T data is shown in black. The weighted distribution is shown with blue points and the exponential fit result with a red line.

plane in pixel units. The slope α and N_0 - normalisation - are left free in the per track fit. The weights for the $B = 0$ and 1 T data are fixed using the whole data set. The fit per event is performed in the full d_y range.

The test beam data provide a dE/dx or dN/dx measurement for electrons with a beam momentum of 5 or 6 GeV/c. The data were also used to perform a measurement of the response of a minimum ionising particle (MIP) - here defined as a particle that produced 70% of the electron dE/dx. By dropping - randomly chosen - 30% of the hits associated to the track, the response of a MIP in terms of the number of hits (truncation method) and the fitted slope (template) was measured.

The relative resolution is defined as the r.m.s. of the distribution, di-

Table 1: dE/dx or dN/dx relative resolution for different methods and data sets

Method	$B = 0$ T	$B = 1$ T
dE/dx truncation	6.0%	3.6%
template fit	5.4%	2.9%

vided by the mean and the results are shown in Table 1. The resolution of the $B = 1$ T data is about 40% better than the $B = 0$ T data. This is consistent with the smaller fluctuations that are present in the distributions of the number of hits per GridPix in the $B = 1$ T data [3]. The template fit method has in the $B = 1$ T data a 20% better performance than the dE/dx truncation method. One might argue that with more diffusion the results from the template fit method will move more towards the results of the dE/dx truncation method, because the statistical error on the slope will increase. Note, however, that the diffusion contribution to the track resolution in the $B = 1$ T data is already sizeable compared to the pixel size and varies between 85-150 μm.

The results for the $B = 1$ T data are shown in Fig. 2, for electrons and MIPs and for the dE/dx truncation and template fit methods. The relative error on the measured resolutions are smaller than 2.6% and therefore neglected. The unit of the fitted slope is inverse pixel, as is clear from the formula in Eq. 1.

To estimate the performance for different particles it is important to quantify the linearity of the methods. The linearity is defined as the mean MIP response, divided by 0.7 times the mean electron response. Clearly, one wants to use an algorithm for which the linearity is close to 1. E.g. a value of 1.2

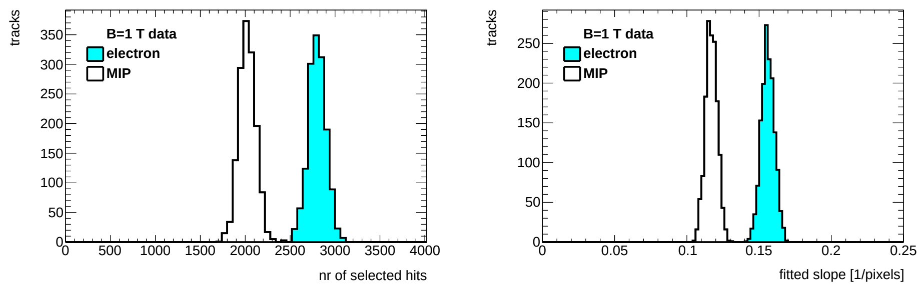

Figure 2: Distribution of the number of selected hits per track for the dE/dx truncation method (left) and the fitted slope for the template fit method (right) for an electron (light blue shaded) and for a MIP, using 1 m long tracks with 60% coverage, for the $B = 1$ T data.

would imply that the MIP-electron separation is 20% smaller. In our case the linearity was measured to be 1.03 for the truncation method and 1.07 for the template fit method. The statistical error on this measurement is less than 0.1% and therefore neglected. This value is slightly different from one. The projected PID performance for different particles can be corrected for by scaling the expectation values as a function of the measured momentum.

The dE/dx or dN/dx result of the 32-chip GridPix detector for electrons is impressive. It has currently, the best resolution per meter of track length of constructed TPCs running at atmospheric pressure - and demonstrates the particle identification (PID) capabilities of a GridPix Pixel TPC, e.g. the ALICE experiment published a dE/dx resolution of 5% for a track length of 1.65 m [5].

3. Single-electron detection efficiency at high hit rates

The detection efficiency of single ionisation electrons in the GridPix detector can be reduced in a high background environment due to the charge up of the resistive layers and the effective reduction of the amplification field. It is therefore important to measure the single-electron efficiency in different background conditions. The Time-over-Threshold (ToT) is related to the deposited charge on the pixel and the single-electron detection efficiency of the detector. The relative change in the single-electron detection efficiency $\delta\epsilon/\epsilon$ can be related to the relative change in the mean ToT by

$$\delta\epsilon/\epsilon = f \ \delta\text{ToT}/\text{ToT}. \tag{2}$$

The proportionality factor f of about 0.5 is determined from the slope of the measured efficiency-ToT curve in Fig. 4.7 of [2] at the mean working point of ToT=0.65 μs. By measuring the mean ToT in high (low) rate environment at B fields of 0 and 1 T, the relative change in single-electron detection efficiency is extracted.

To obtain a precise result for the mean ToT, hits associated to TPC tracks were used. The track selection is the same as in section 2. The analysed runs with a trigger rate above 90 Hz were taken at a beam momentum (P) of 5 GeV/c. The runs that were taken at a beam momentum of 6 GeV/c have a trigger rate below 3 Hz. For each run the mean ToT values were measured in the interval between 0.15 μs and 1.4 μs. These cuts were applied to remove the noise and the upper tail of the distribution.

The results for the measured mean ToT for different runs and hit rates are summarised in Table 2. ToT1(2) denotes the mean ToT for upper and lower

Table 2: Measured mean ToT and rates for different runs

run	P	B	ToT1	ToT2	triggers	run time	Hits1	Hits2	trig rate	Rate1	Rate2
	GeV/c	[T]	[μs]	[μs]	10^3	[10^3s]	10^6	10^6	[Hz]	[10^3hits/s]	[10^3hits/s]
6916	6	0	0.628	0.653	16.8	5.81	6.25	13.1	2.9	1.08	2.26
6934	5	0	-	0.651	73.4	0.60	-	20.5	121.7	-	33.92
6935	5	0	0.620	-	73.9	0.60	6.95	-	122.5	11.51	-
6969	6	1	0.650	0.666	7.94	3.45	1.93	2.16	2.3	0.56	0.62
6983	5	1	0.657	0.678	67.9	0.70	11.6	14.1	96.2	16.44	19.94

half (in x) of the module and Hits1(2) corresponds to number of recorded raw hits. The number of triggers and trigger rate are not corrected for the trigger efficiency of about 31%. The mean Rate1(2) was calculated dividing the total number of raw hits by the total run time. The instantaneous rate can be up to about a factor 3 higher (due to the duty cycle of the machine).

For the $B = 0$ T data, two high rate runs 6934 and 6935 taken at a beam momentum of 5 GeV/c had to be analysed because the beam crossed either the upper or the lower part of the module and therefore no measurement could be performed in one of the parts (denoted by -). The statistical uncertainties are negligible.

The relative change in the mean ToT for the $B = 0$ data is -1.3% (upper half) and -0.3% (lower half). In this case the rate goes up to 34 kHz for 6 chips or 5.7 kHz per GridPix. The relative change in the mean ToT for the $B = 1$ T data is +1.1% (upper half) and +1.8% (lower half). The rate goes up to 20 kHz for 6 chips or 3.3 kHz per GridPix.

Using Eq. 2, this means that the relative change in the single-electron detection efficiency $\delta\epsilon/\epsilon$ is stable at the level of +0.9% ($B = 1$ T) and -0.6%

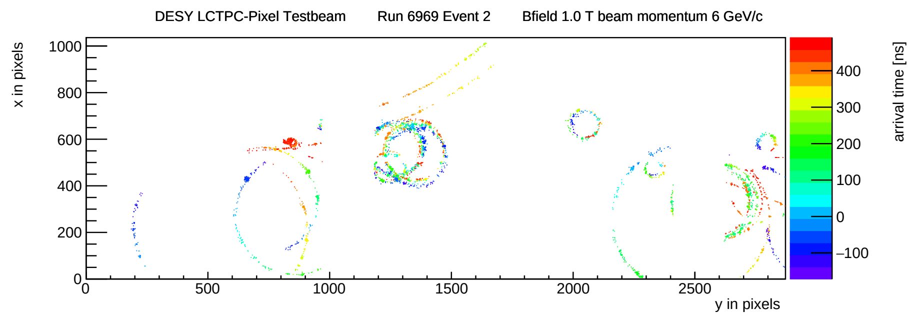

Figure 3: An event display for run 6969 event 2 taken at a 6 GeV/c beam momentum in a $B = 1$ T field. The hits are shown in the xy plane, in colour the time of arrival is shown.

($B = 0$ T) for hit rates up to 3.3 (5.7) kHz per GridPix. To conclude, running at hit rates up to 5.7 kHz per GridPix gives a reduction of at most 0.6% in the relative efficiency.

4. Characterisation of large localised hit bursts

In event displays large localised hit bursts from low energetic curling electrons can be observed. An example event is shown in Fig. 3. A large variety of hit patterns can be observed: large radii (open) circular tracks, smaller size radius circular tracks from low momentum particles, curlers and more confined bursts. At $B = 1$ T a track with a momentum of 1 MeV/c will have a typical radius of 60 pixels. A Pixel TPC is well suited to study and characterise these typical hit bursts. After a reconstruction and characterisation of the burst it is possible to reject the hits associated to the bursts. This will improve the measurement of the track parameters in the final track fit.

To study the large localised hit bursts, the data of run 6969 - taken at a 6 GeV/c beam momentum in a $B = 1$ T field - were analysed. Bursts were

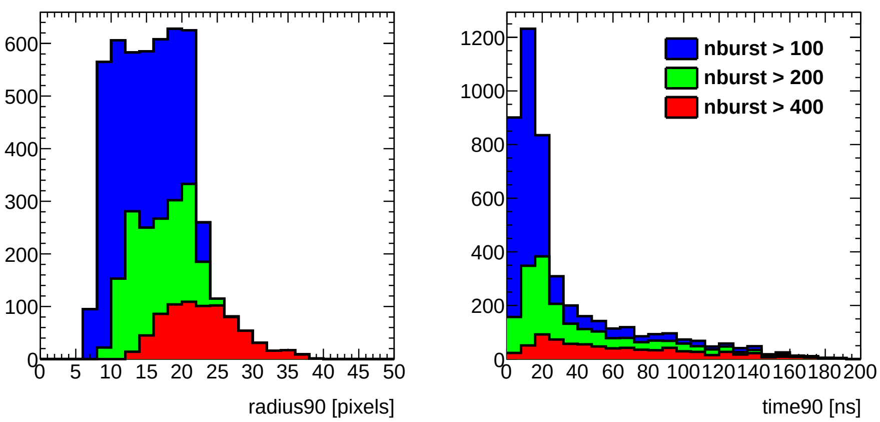

Figure 4: The stacked distributions for radius90 and time90, for large localised hit bursts with more than 100 (blue), 200 (green) and 400 (red) hits, in run 6969.

selected with more than 100 hits in a radius of 50 pixels around the burst centre within a time window of 200 ns around the mean time. The mean position in xy and the mean time of the burst were iteratively estimated. The large localised hit bursts were characterised by the number of associated hits, the radius in which 90% of the hits are found (radius90) and the time in which 90% of the hits are detected (time90). The stacked distributions for the radius90 and time90 variables for different burst sizes are shown in Fig. 4.

It is clear that the radius90 and time90 distributions broaden as a function of the number of hits. In particular the time90 distribution develops a long tail for high number of hits. Note that hits that end up on the same pixel within the Timepix3 pixel dead time of minimally 475 ns [6] will not be recorded, so part of the core of the burst may remain undetected. The largest hit burst in the analysed run 6969 had 3180 hits.

For high momentum tracking it is important to cut tightly on the track residuals in xy and z. In particular the cut in z reduces the impact of hit bursts in the $B = 1$ T data. Therefore in future pattern recognition software one could run a hit burst finding algorithm and down weight in the track fit the hits associated to bursts. This will remove biases and improve the track parameter estimation.

5. Single-electron resolution as function of the local track angle

The single-electron resolution in the xy precision plane as a function of the local track angle ϕ, defined as the azimuthal angle in the xy plane, has been measured in the run 6969 of the $B = 1$ T data set taken at a beam momentum of 6 GeV/c. The resolution is measured using the single-electron residuals to the track. For a pad based readout system the resolution has a strong dependence on the local track angle see e.g. [7]. The resolution is the smallest if the local track angle is parallel to the strip direction.

For a GridPix Pixel TPC - with squared pixels - the resolution is expected to be independent of the local track angle. To test experimentally this hypothesis, reconstructed circular tracks were selected. Examples of circular tracks can be observed in the event display shown in Fig. 3. For circular tracks, the local track angle ϕ depends on the position of the individual hits on the circle in the xy plane. The range of ϕ angles depends on the radius. For radii smaller than 500 pixels a large ϕ range can be probed. Using the track residuals in the xy plane, it is possible to measure the single-electron resolution of the hits as a function of the local track angle.

A dedicated pattern recognition program was written to find and fit multiple circular tracks in an event. To find candidate circular tracks, a Hough transform was used to find the centre of the circle in the xy plane. In the circle fit, the coarse uncertainty in xy was estimated to be about 4 pixels and in z equal to 1 mm. Outlier hits at more than 2.5 standard deviations were iteratively rejected. For the selection of circular tracks it was required that the fit $\chi^2_{xy}/d.o.f.$ and $\chi^2_z/d.o.f.$ were less than 5. Finally, the radius of the circle had to be larger than 50 pixels (corresponding to a momentum cut of 0.8 MeV/c) and at least 20 hits should lie on the circle. The total ϕ span of the selected hits on the circle should be at least 1 rad. The hits with local ϕ values below $\pi/8$ and above $15\pi/8$ were removed due to low statistics.

The selected data set has 973 circular tracks, with a mean radius of 155 pixels (8.5 mm) and a mean number of hits of 194. Because the resolution depends on the radius (due to the multiple scattering that increases at low momentum) and small radii span a large ϕ range, the data were re-weighted as a function of the circle radius. The weights made the momentum distribution flat as a function of the local track angle ϕ. Finally, the resolution in xy was extracted using a Gaussian fit to the track residuals in the range of $\pm 2\sigma$ around the centre. The fitted resolution in xy as a function of the local track angle ϕ for the hits on the circle is shown in Fig. 5.

A curve was fitted to the data using the following expression:

$$\sigma_{xy} = \sigma_0 + \sigma_1 \cos\phi, \tag{3}$$

where σ_0 and σ_1 where left free. The fit result yielded $\sigma_0 = 0.241$ mm and $\sigma_1 = 0.016$ mm and describes the modulation observed in the data.

It can therefore be concluded that the single-electron resolution in the xy precision plane is independent of the local track angle ϕ within an uncertainty

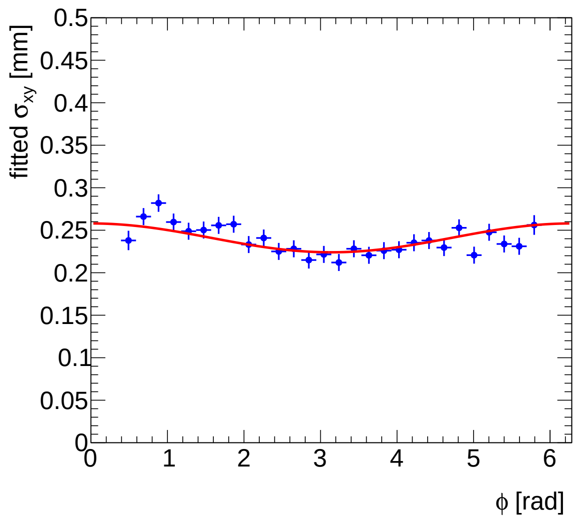

Figure 5: The fitted single-electron resolution in xy as a function of the local track angle ϕ for the hits on the circle. The fitted curve in red is given in Eq. 3.

of 16 μm.

6. Projected particle identification performance for a Pixel TPC in the proposed experiment ILD at a future ILC

The particle identification (PID) performance of electrons in the test beam for momenta of 5-6 GeV/c was measured to be 2.9% for the template fit and 3.6% for the dE/dx truncation method at $B = 1$ T for 1 m long tracks with 60% coverage. The TPC of the proposed ILD detector [4] has an inner radius of 329 mm, an outer radius of 1770 mm and a half length of 2350 mm. The electron PID resolution in the ILD TPC is expected to be 2.4% (template fit) and 3% (truncation method) at polar angles of $\theta = \pi/2$ ($\cos\theta = 0$) and a track length (t^0_{length}) of 1441 mm. The PID resolution for different particles can be written as:

$$\sigma_i = \sigma_e \sqrt{t^0_{\text{length}} \ \cdot \ E_e} / \sqrt{t_{\text{length}} \ \cdot \ E_i}, \tag{4}$$

where t_{length} is the track length and E_i is the expected energy loss for particle i (electron = e, muon = μ , pion = π, kaon = K, proton = p). [1]

The ILD parametrisations of dE/dx for different particles as a function of the momentum were used as given in [8]. They are based on full simulations of the ILD TPC operated with a T2K gas and running at atmospheric pressure. The PID separation in numbers of standard deviations w.r.t. the π hypothesis for e, K and p are defined as:

$$\text{PID separation}_i = |E_i - E_\pi| / \sigma_\pi. \tag{5}$$

In Fig. 6, the separation of electrons, kaons and protons w.r.t. pions are shown as a function of the momentum of the particle, for the projected ILD electron PID resolutions of 2.4% and 3% at $\cos\theta = 0$. The expected pion-kaon PID separation for momenta in the range of 2.5-45 GeV/c at $\cos\theta = 0$ is more than $5.5(4.5)\sigma$ for the two resolution scenarios. At a momentum of 100 GeV/c the separation is still $3.0(2.0)\sigma$. Protons can be separated from pions for momenta in the range of 2.5-100 GeV/c with more than $6.0(4.8)\sigma$.

It is clear from the above that a GridPix Pixel TPC in ILD will provide powerful particle identification. Studies have shown that for a pad readout in ILD, the PID resolution is expected to be 5% [9].

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[1] Clearly, the best PID resolution will be reached for the largest track length, which corresponds to $|\cos\theta| = 0.85$ in ILD.

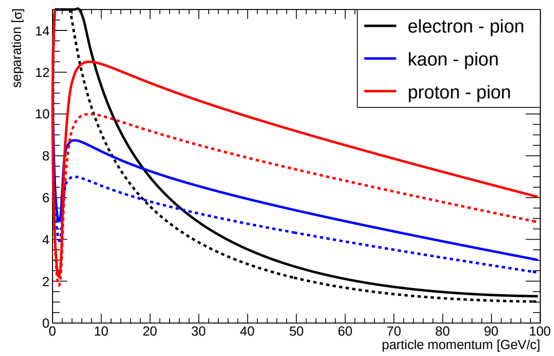

Figure 6: The projected PID separation for a GridPix TPC in ILD for electrons, kaons and protons w.r.t. pions at $\cos\theta = 0$. The continuous lines correspond to an electron PID resolution of 2.4% and the dashed to 3%.

7. Conclusions and outlook

A Time Projection Chamber (TPC) module with 32 GridPixes was constructed and the performance was measured using data taken in a test beam at DESY in 2021. The data analysed were taken at electron beam momenta of 5 and 6 GeV/c and at magnetic fields of 0 and 1 T. The precise tracking results for the module were presented in part I of the paper [3].

The dE/dx or dN/dx resolution for electrons with a momentum of 6 GeV/c in the 1 T data for a 1 m long track with 60% coverage was measured to be 3.6% for the dE/dx truncation method and 2.9% for the template fit method. This result is impressive and is currently the best PID resolution per meter of track length of constructed TPCs running at atmospheric pressure.

The single-electron detection efficiency at high hit rates was studied. For hit rates up 5.7 kHz per GridPix a reduction of at most 0.6% in the relative efficiency was measured.

Large localised hit bursts from low energetic curling electrons were characterised showing the pattern recognition capabilities of a GridPix Pixel TPC.

The single-electron resolution in the xy precision plane as a function of the local track angle was measured in the $B = 1$ T data using reconstructed circular tracks. It was demonstrated that the resolution in the precision plane is - as expected - independent of the local track angle ϕ within an uncertainty of 16 μm.

The projected particle identification performance for a GridPix Pixel TPC in ILD was presented using the $B = 1$ T test beam results for the measured electron PID resolution. The expected pion-kaon PID separation for momenta in the range of 2.5-45 GeV/c at $\cos\theta = 0$ is more than 5.5 (4.5) σ for the template fit (dE/dx truncation) method.

It is clear that a GridPix Pixel TPC in ILD will provide powerful particle identification. At the CEPC a Pixel TPC is proposed, because of the precise tracking and particle identification capabilities. The GridPix detector will be further tested and developed for a TPC that could be installed in a heavy ion experiment at the Electron Ion Collider. In the DRD1 collaboration at CERN a GridPix Pixel TPC is also part of the research program.

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Association (HGF).

References

[1] M. Lupberger, Y. Bilevych, H. Blank, D. Danilov, K. Desch, A. Hamann, J. Kaminski, W. Ockenfels, J. Tomtschak, S. Zigann-Wack, Toward the Pixel-TPC: Construction and Operation of a Large Area GridPix Detector, IEEE Trans. Nucl. Sci. 64 (5) (2017) 1159–1167. doi:10.1109/TNS.2017.2689244.

[2] C. Ligtenberg, A GridPix TPC readout for the ILD experiment at the future International Linear Collider, Ph.D. thesis, Free University of Amsterdam (2021). URL www.nikhef.nl/pub/services/biblio/theses_pdf/thesis_C_Ligtenberg.pdf

[3] M. van Beuzekom et al., Towards a Pixel TPC part I: construction and test of a 32-chip GridPix detector, Nucl. Instrum. Meth. A 1075 (2025) 17039. doi:10.1016/j.nima.2025.170397.

[4] T. Behnke, J. E. Brau et al., eds. The International Linear Collider. Technical Design Report. Vol. 4: Detectors. Linear Collider Collaboration, 2013. arXiv: 1306.6329. doi:10.48550/arXiv.1306.6329. URL https://www.linearcollider.org/

[5] Weilin Yu, Particle identification of the ALICE TPC via dE/dx, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 706, (2013), 55–58. doi.org/10.1016/j.nima.2012.05.022.

[6] T. Poikela, J. Plosila, T. Westerlund, M. Campbell, M. De Gaspari, X. Llopart, V. Gromov, R. Kluit, M. van Beuzekom, F. Zappon, V. Zivkovic, C. Brezina, K. Desch, Y. Fu, A. Kruth, Timepix3: a 65K channel hybrid pixel read out chip with simultaneous ToA/ToT and sparse read out, JINST 9 (05) (2014) C05013.
URL http://stacks.iop.org/1748-0221/9/i=05/a=C05013

[7] LCTPC Collaboration, David Attié et al., A Time Projection Chamber with GEM-Based Readout, Nuclear Instruments and Methods in Physics Research. Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 856, 1 (2017), 109–118. arXiv:1604.00935v1, doi:10.1016/j.nima.2016.11.002.

[8] iLCSoft, Linear Collider Software,
URL https://github.com/iLCSoft/MarlinReco/blob/master/Analysis/PIDTools/, based on version v02-02-01.

[9] U. Einhaus, U. Krämer and P. Malek, Studies on Particle Identification with dE/dx for the ILD TPC, arXiv:1902.05519.