Towards a Pixel TPC part II: performance of a 32 chip GridPix detector

M. van Beuzekom[a], Y. Bilevych[b], K. Desch[b], S. van Doesburg[a], H. van der Graaf[a], F. Hartjes[a], J. Kaminski[b], P.M. Kluit[a], N. van der Kolk[a], C. Ligtenberg[a], G. Raven[a], J. Timmermans[a]

[a]*Nikhef, Science Park 105, 1098 XG Amsterdam, The Netherlands*
[b]*Physikalisches Institut, University of Bonn, Nussallee 12, 53115 Bonn, Germany*

Abstract

A Time Projection Chamber (TPC) module with 32 GridPix chips was constructed and the performance was measured using data taken in a test beam at DESY in 2021. The analysed data 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 for a 1 m track with 60% coverage was measured to be 3.6% for the dE/dx truncation method and 2.9% for the template fit method.

The single electron efficiency at high hit rates was studied. For hit rates up 1.4 kHz per chip a reduction of at most 0.6% in the relative efficiency was measured.

Hit bursts due to highly ionizing particles were characterized.

The resolution in the precision plane as a function of the incident track angle was measured in the B = 1 T data using circular tracks. The resolution in the precision plane is - as expected - independent of the incident angle ϕ within an uncertainty of 16 μm.

The projected particle identification performance of a GridPix Pixel TPC in ILD was presented using the B = 1 T test beam results for the measured electron resolution. The expected pion-kaon 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

*Corresponding author. Telephone: +31 20 592 2000
Email address: s01@nikhef.nl (P.M. Kluit)

(dE/dx truncation) method.

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1. Introduction

As a step towards a Pixel Time Projection Chamber for a future collider experiment [1], [2], a module consisting of 32 GridPix chips based on the Timepix3 chip was constructed. The GridPix chips have a very fine granularity of 55x55 μm^2 and a high efficiency to detect single ionisation electrons.

The 32 GridPix chip module was put in a test beam at DESY and complemented with two sets of Mimosa26 silicon detector planes. The analysed data were taken at electron beam momenta of 5 and 6 GeV/c and at magnetic fields of 0 and 1 T.

A description of the construction of the GridPix TPC module, the test beam setup and data taking conditions can be found in part I of our paper [3]. The paper explains the track reconstruction procedure and the precise TPC tracking results that were obtained.

2. Analysis topics

In the following sections the analysis results for different 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 hit bursts caused by highly ionizing particles will be presented. Fourth, the resolution in the precision plane as a function of the incident track angle will be measured. Finally, the projected particle identification performance for a Pixel TPC in the ILD experiment [4] will be presented and discussed.

2.1. Particle Identification using dE/dx or dN/dx

The distribution of the number of TPC track hits per chip 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 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.

In order to measure the track performance of dE/dx or dN/dx, the central chips - defined in ref [3] - were selected and calibrated to give the same mean number of hits per chip. By combining the hits associated to the track, a new 1 m long track is formed. The 1 m long track has a coverage of 60% because inactive regions (chip edges and e.g. guard) are included. By applying different analysis methods, the dE/dx or dN/dx resolution can be measured from data.

The first method rejects large clusters with more than 6 hits in 5 consecutive pixels. 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 full granularity of the pixel TPC.

The second method exploits the distribution of the minimum distance in the precision plane between consecutive hits. 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 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 electron. The long Landau tail in the dE/dx distribution is coming from the multi-electron clusters that will peak at low distances.

Using a large number of tracks, it is possible to measure from data the shape of the minimum distance distribution. At distances above 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. Finally, per 1 m track, a fit to distance distribution in data is performed with the following template function:

$$N(d_{xy}) = N_0 \ \mathrm{weight}(d_{xy}) \ e^{-\mathrm{slope} \ d_{xy}}. \tag{1}$$

where d_{xy} is the minimum distance in the precision plane (xy). The slope and N_0 - normalisation - are left free in the per track fit, the weights for the B = 0

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

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

and 1 T data are fixed using the whole data set.

The test beam data provides a dE/dx or dN/dx measurement for electrons. 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 30% of the hits associated to the track and applying the two methods, the response of a MIP could be measured and the linearity of the methods tested.

The relative resolution is defined as the r.m.s. of the distribution divided 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 chip 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. Note however that the diffusion contribution to the track resolution in the 1 T data is already sizeable compared to the pixel size and varies between 85-150 μm.

The results for the 1 T data are shown in Figure 1 for electrons and MIPs for the dE/dx truncation and template fit methods. The linearity - defined as the mean MIP response divided by the mean electron response divided by 0.7 - was measured to be 1.03 for method 1 and 1.07 for method 2. This value is slightly different from 1, and can be corrected for by scaling the expected values for different particles as a function of the measured momentum.

The dE/dx or dN/dx result of the 32 chip GridPix detector for electrons

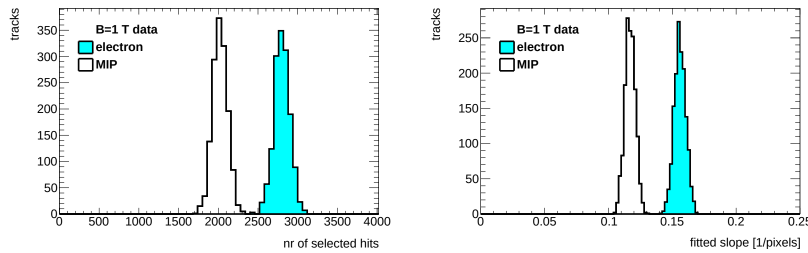

Figure 1: Distribution of the number of selected hits for the dE/dx truncation method (left) and the fitted slope for the template fit method (right) for an electron (light blue shaded) and MIP 1 m long tracks with 60% coverage for the B = 1 T data.

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 capabilities of a GridPix Pixel TPC.

2.2. Single electron efficiency at high hit rates

The efficiency of the GridPix device to detect a hit in a high (low) rate environment is measured comparing the mean time over threshold for low and high rate runs at B fields of 0 and 1 T. The mean time over threshold is sensitive to the single electron efficiency of the detector. In order to extract a precise result, hits associated to TPC tracks were used. The track selection is the same as the one that was described in the subsection on the particle identification performance. The analysed runs for the B = 0 T data set were runs 6916, 6934 and 6935 and for the B = 1 T data set run 6969 and 6983.

For each run the mean ToT values were measured for values between 0.15 and 1.4 μs. These cuts were applied to remove the noise and the upper tail of the distribution.

The results for the measured average time over threshold for different runs and hit rates are summarised in Table 2. ToT1(2) denotes the mean time over threshold for upper and lower half of the module and Hits1(2) corresponds to number of recorded raw hits. The mean Rate1(2) was calculated dividing the total number of raw hits by the total run time. For the B = 0 T data, two high rate runs 6934 and 6935 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 (denoted by -). The statistical uncertainties are - due to the high statistics - negligible.

The relative change in the mean time over threshold for the B = 0 data is -1.2% (upper) and -0.3% (lower). In this case the rate goes up to 8.5 kHz for 6 chips or 1.4 kHz per chip. The relative change in the mean time over threshold for the B = 1 T data is +1% (upper) and +1.7% (lower) The rate goes up to 5 kHz for 6 chips or 1.2 kHz per chip.

The relative change in the mean time over thresholds $\delta\text{ToT}/\text{ToT}$ can be related to the relative change in the single electron efficiency $\delta\epsilon/\epsilon$ by:

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

The derivative d is about 0.5 at the mean working point of ToT=0.65 μs and is determined from the measured efficiency-ToT curve in [2].

This means that the relative efficiency is stable at the level of +0.9% (B = 1 T) and -0.6% (B = 0 T) for hit rates up to 1.2 (1.4) kHz per chip. To conclude, running at hit rates up 1.4 kHz per chip gives a reduction of at most 0.6% in the relative efficiency.

Table 2: Mean time of threshold and rates for different runs

run	B	ToT1	ToT2	triggers	run time	Hits1	Hits2	trig rate	Rate1	Rate2
	T	μs	μs	10^3	10^3s	10^6	10^6	Hz	hits/s	hits/s
6916	0	0.628	0.653	16.8	23.2	6.25	13.1	0.72	269	565
6934	0	-	0.651	73.4	2.41	-	20.5	30.4	-	8479
6935	0	0.620	-	7.39	2.41	6.95	-	30.6	2878	-
6969	1	0.650	0.666	7.94	13.8	1.93	2.16	0.57	139	156
6983	1	0.657	0.678	6.79	2.83	11.6	14.1	24.1	4110	4986

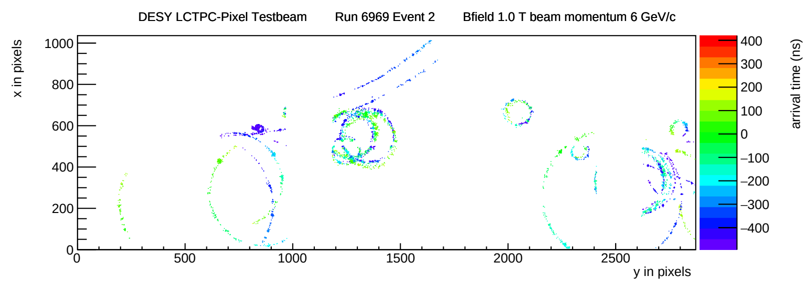

Figure 2: An event display for run 6969 event 2 in a B = 1 T field. The hits are shown in the xy plane in color the time of arrival is shown.

2.3. Characterisation of hit bursts

In event displays hit burst caused by highly ionizing particles (e.g. alpha particles or delta electrons) can be observed. An example event in run 6969 with B = 1 T field is shown in figure 2. A large variety of hit patterns can be observed: large radii (open) circles from energetic particles, smaller size radius circles, curlers and more confined bursts.

A Pixel TPC is well suited to study and characterize these typical hit bursts. A pixel TPC also allows to improve the high momentum tracking by removing these bursts.

To study the hit bursts the data of run 6969 B = 1 T was analysed. Bursts were selected with more than 100 hits in a radius of 50 pixels around the burst center 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 bursts were characterized 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 Figure 3.

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 475 ns will not be recorded, so part of the core of

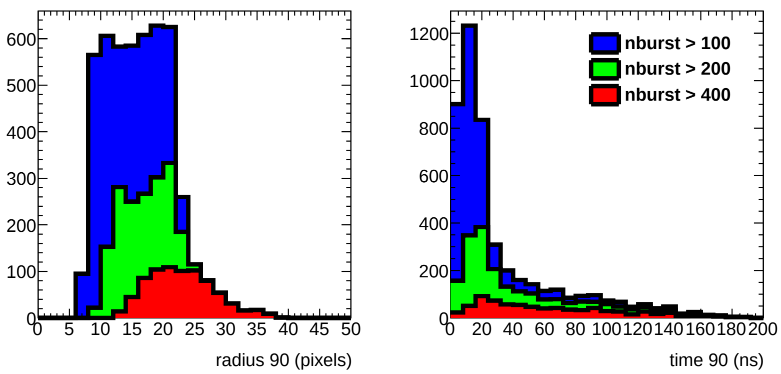

Figure 3: The stacked distributions for radius90 and time90 for burst with more than 100 (blue), 200 (green) and 400 (red) hits for run 6969 in a B = 1 T field.

the burst might stay undetected. Still the detector is able to record hit bursts of at most 7854 hits in a 50 pixel radius. The largest hit burst in 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 bursts in the B = 1 T data. One could in addition run a burst finding algorithm and down weight the hits associated to burst and the selected track. This will remove biases and improve the track parameter estimation.

2.4. Resolution study

The resolution in the precision plane as a function of the incident track angle will be measured in the B = 1 T data set. For a pad based readout system the resolution has a strong dependence on the incident angle see e.g. reference [5]. The resolution is minimal if the incident track angle is parallel to the strip direction. This is due to the geometrical strip layout.

For a GridPix pixel TPC - with squared pixels - the resolution is expected to be independent of the incident angle. In order to test experimentally this hypothesis, circular tracks were selected. Examples of circular tracks can be observed in the event display shown in Figure 2. Using these circles, the incident

ϕ angle of the individual hits (with respect to the y axis) can be probed over a large range and the resolution in xy measured.

A dedicated pattern recognition program was written to find and fit multiple circles in an event. To find circles large clusters were down weighted and hits within 15 pixels (in xy) of the chip edge were removed. In the circle fit, the resolution in xy was assumed to be 4 pixels and in z of 1 mm. Outlier hits at more than 2.5 standard deviation were iteratively rejected. For the selection of circles it was required that the fit χ^2_{xy}/dof and χ^2_z/dof was less than 5. Finally, the radius of the circle had to be larger than 50 pixels (corresponding to a momentum cut of 0.4 MeV/c), at least 20 hits should lie on the circle. The ϕ ranges from $\pi/4$ to $7\pi/4$ and total ϕ span of the selected hits on the circle should be at least 1 rad.

The selected data set has 973 circles, with a mean radius of 155 pixels and a mean number of hits of 194. Because the resolution depends on the radius and small radii span a large phi range, the data was re-weighted as a function of the radius. Finally, the resolution in xy was extracted - using a Gaussian fit in the range of $\pm 2\sigma$ around the centre. The fitted resolution in xy as a function of the ϕ incident angle of the hits on the circle is shown in Figure 4.

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 σ_0 = 0.241 mm and σ_1 = 0.016 mm and describes the modulation observed in the data.

It can therefore be concluded that the resolution in the precision plane is independent of the incident angle ϕ within an uncertainty of 16 μm.

2.5. Projected particle identification performance

The projected particle identification performance for a Pixel TPC in ILD will be presented. The TPC of ILD has an inner radius of 329 mm, an outer radius of 1770 mm and a half length of 2350 mm. The electron resolution from the test beam for momenta of 5-6 GeV/c is 2.9% for the template fit and 3.6% for the

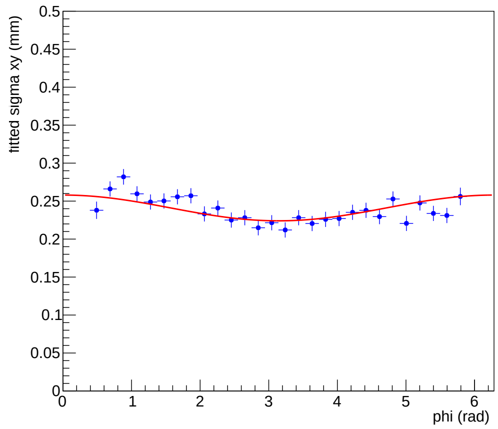

Figure 4: The fitted resolution in xy as a function of the ϕ incident angle of the hits on the circle. The fitted curved in red is given in Eq. 3.

dE/dx truncation method at B = 1 T for a 1 m long tracks with 60% coverage. In the ILD TPC this will correspond to an expected electron resolution of 2.4% (fit) and 3% (truncation) at polar a angles of $\theta = \pi/2$ ($\cos\theta = 0$) and a track length ($\mathrm{tlength}_0$) of 1441 mm. Depending on the B field value (3.5 T - foreseen at ILC - or e.g. 2 T), the transverse diffusion value in the T2K gas will be similar or worse than the test beam situation. The resolution for a GridPix TPC in ILD will therefore lie between 2.4 and 3% at $\cos\theta = 0$. The resolution for different particles can be written as:

$$\sigma = \sigma_e \sqrt{\mathrm{tlength_0\ E_e}} / \sqrt{\mathrm{tlength\ E_i}}, \tag{4}$$

where tlength 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). Clearly, the best resolution will be reached for the largest track length that corresponds in ILD to $\cos\theta = 0.85$.

The ILD parametrisations for the energy loss for different particles as a function of the momentum were used [6]. They are based on full simulations of the ILD TPC operated with a T2K gas and running at atmospheric pressure.

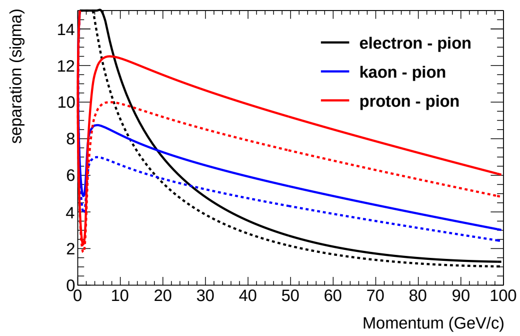

Figure 5: The projected separation for a GridPix TPC in ILD for electrons, kaons and protons w.r.t. pions at $\cos\theta = 0$. The continuous line corresponds to an electron resolution of 2.4% and the dashed to 3%.

The separation in numbers of standard deviations w.r.t. the π hypothesis for the e, K and p is defined as:

$$\text{separation} = |E_i - E_\pi|/\sigma_\pi, \quad (5)$$

In Figure 5, the separation of electrons, kaons and protons w.r.t. pions is shown as a function of the momentum of the particle for projected ILD electron resolutions of 2.4 and 3% at $\cos\theta = 0$.

The expected pion-kaon 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 very powerful particle identification.

3. Conclusion and outlook

A Time Projection Chamber (TPC) module with 32 GridPix chips was constructed and the performance was measured using data taken in a test beam at DESY in 2021. The analysed data 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 of momenta 5 and 6 GeV/c in the 1 T data for a 1 m 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. It is currently, the best resolution per meter of track length of constructed TPCs running at atmospheric pressure.

The single electron efficiency at high hit rates was studied. For hit rates up 1.4 kHz per chip a reduction of at most 0.6% in the relative efficiency was measured.

Hit bursts due to highly ionizing particles were characterized showing the pattern recognition capabilities of a GridPix Pixel TPC.

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

The projected particle identification performance of a GridPix Pixel TPC in ILD was presented using the B = 1 T test beam results for the measured electron resolution. The expected pion-kaon 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 very powerful particle identification. At the CEPC collider 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 will be installed in a heavy ion experiment at the EIC. In the DRD1 collaboration at CERN a GridPix Pixel TPC is also part of the research program.

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