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 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 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 5.7 kHz per chip a reduction of at most 0.6% in the relative efficiency was measured.

Hit bursts due to highly ionising particles were characterised.

The resolution in the precision plane as a function of the local track angle was measured in the $B = 1$ T data using reconstructed circle tracks. The

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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 (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 GridPix chips based on the Timepix3 chip was constructed. The GridPix chips have 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.

The 32-GridPix chip detector 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], which explains the track reconstruction procedure and the precise TPC tracking results that were obtained.

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 ionising particles will be presented. Fourth, the resolution in the 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 loss and/or the number of primary clusters, dN/dx produced along the track. In a GridPix detector one can measure both the number of hits produced along the track and their relative distance.

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 per chip 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.

In order 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]. The individual chips were calibrated to give the same mean number of hits per chip. By combining the hits associated to the track from several events, a new 1 m long track was formed. The 1 m long track has a coverage of 60%

because inactive regions (chip edges and e.g. guard plate) were included.

By applying different analysis methods, the dE/dx or dN/dx resolution can be measured from data.

Both methods project the hits along the track in the xy 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 full granularity of the pixel TPC.

The second method exploits the distribution of the minimum distance between consecutive hits in the xy precision 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 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. 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 approximately 10 pixels the distribution follows an exponential distribution - see Fig 5.19 in [2]. 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 of track length, a fit to the distance distribution in data is performed with the following template function:

$$N(d_{xy}) = N_0 \text{ weight}(d_{xy}) \ e^{-\alpha \ \cdot \ d_{xy}}, \quad (1)$$

where d_{xy} is the minimum distance of the hits in the precision plane (xy). 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 test beam data provide 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 was 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 Fig. 1, for electrons and MIPs and for the dE/dx truncation and template fit methods. The unit of the

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 %

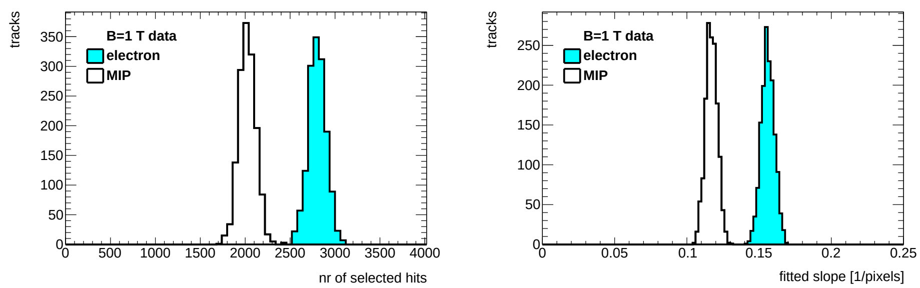

Figure 1: Distribution of the number of selected hits per track for the dE/dx truncation method (left) and the fitted slope for the template fit method (right) for an electron (light blue shaded) and for a MIP, using 1 m long tracks with 60% coverage, for the $B = 1$ T data.

fitted slope is inverse pixel, as is clear from the formula in Eq. 1. 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 the template fit method. This value is slightly different from 1, and can be corrected 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 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.

3. 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 (ToT) for low and high rate runs at B fields of 0 and 1 T. The mean ToT 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 in section 2. The analysed runs for the $B = 0$ T data set were runs 6916, 6934 and 6935 and for the $B = 1$ T data set runs 6969 and 6983.

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

Table 2: Measured mean ToT 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]	[10^3hits/s]	[10^3hits/s]
6916	0	0.628	0.653	16.8	5.81	6.25	13.1	2.9	1.08	2.26
6934	0	-	0.651	73.4	0.60	-	20.5	121.7	-	33.92
6935	0	0.620	-	73.9	0.60	6.95	-	122.5	11.51	-
6969	1	0.650	0.666	7.94	3.45	1.93	2.16	2.3	0.56	0.62
6983	1	0.657	0.678	67.9	0.70	11.6	14.1	96.2	16.44	19.94

The results for the measured average ToT for different runs and hit rates are summarised in Table 2. ToT1(2) denotes the mean ToT for upper and lower 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 in runs 6934, 6935 and 6983 taken at 5 GeV/c is 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 chip. 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 chip.

The relative change in the mean ToT can be related to the relative change in the single-electron efficiency $\delta\epsilon/\epsilon$ by:

$$\delta \mathrm{ToT}/\mathrm{ToT} = \mathrm{d}\ \delta\epsilon/\epsilon. \qquad (2)$$

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 inFig. 4.7 of [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 3.3 (5.7) kHz per chip. To conclude, running at hit rates up 5.7 kHz per chip gives a reduction of at most 0.6% in the relative efficiency.

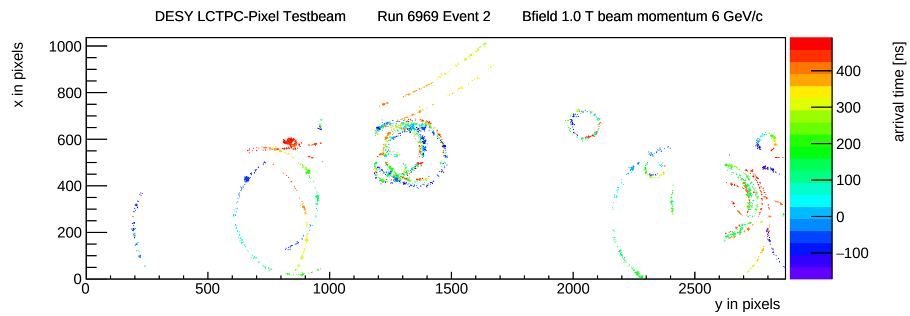

Figure 2: An event display for run 6969 event 2 taken at a 5 GeV/c beam momentum in a $B = 1$ T field. The hits are shown in the xy plane, in colour the time of arrival is shown.

4. Characterisation of hit bursts

In event displays hit burst caused by highly ionising particles (e.g. alpha particles or delta electrons) can be observed. An example event is shown in Fig. 2. A large variety of hit patterns can be observed: large radii (open) circles, smaller size radius circles from low momentum particles, curlers and more confined bursts. 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 hit bursts, the data of run 6969 - taken at a 5 GeV/c beam momentum in a $B = 1$ T field - were analysed. Bursts were 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 bursts were characterised by the number of associated hits, the radius in which 90% of the

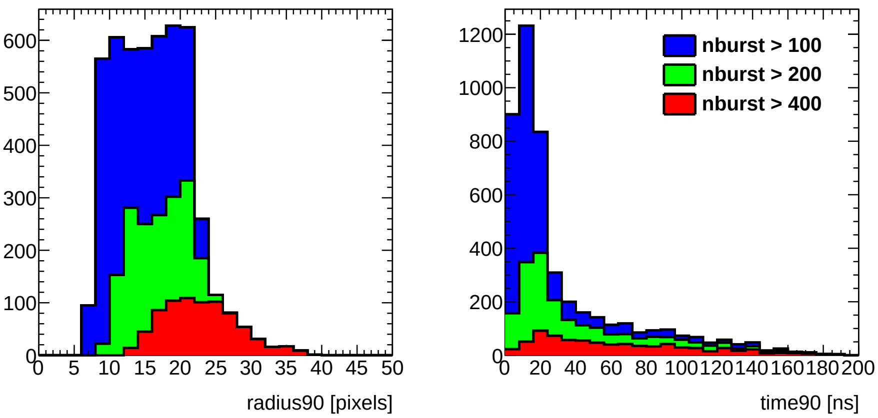

Figure 3: The stacked distributions for radius90 and time90, for bursts with more than 100 (blue), 200 (green) and 400 (red) hits, in run 6969.

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. 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 the burst may remain 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 the run used in Fig. 3 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. Therefore in future pattern recognition software one could run a 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. Track resolution as function of the local track angle

The resolution in the precision plane as a function of the local 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 local track angle see e.g. [5]. The resolution is best 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. In order to test experimentally this hypothesis, reconstructed circle tracks were selected. Examples of circle tracks can be observed in the event display shown in Fig. 2. For circles, 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 residuals in the xy plane, it is possible to measure the resolution of the hits as a function of the local track angle.

A dedicated pattern recognition program was written to find and fit multiple circles in an event. To find candidate circles, a Hough transform was used to find the centre of the circle in the xy plane. In the circle fit, the resolution in xy was estimated to be about 4 pixels and in z it was 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 $\chi^2_{xy}/d.o.f.$ 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

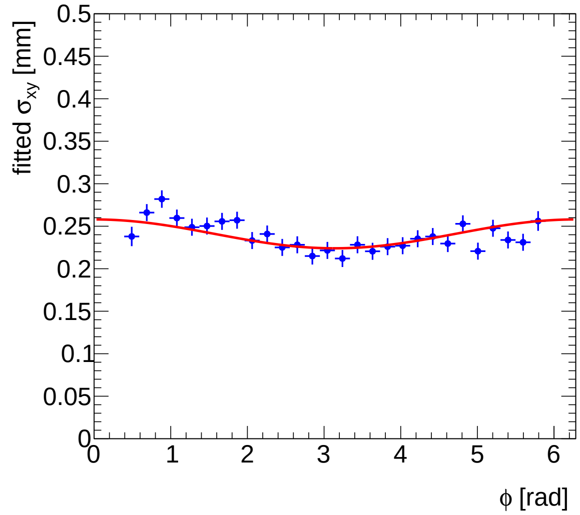

Figure 4: The fitted resolution in xy as a function of the local track angle ϕ for the hits on the circle. The fitted curved in red is given in Eq. 3.

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.

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 (i.e. the momentum) and small radii span a large ϕ range, the data were re-weighted as a function of the circle radius. 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. 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 $\sigma_0 = 0.241$ mm and $\sigma_1 = 0.016$ mm and describes the modulation observed in the data.

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

5.1. 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 expected electron PID resolution in the ILD TPC is then 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 ($\mathrm{tlength}_0$) of 1441 mm. The PID resolution for different particles can be written as:

$$\sigma_i = \sigma_e \sqrt{\mathrm{tlength}_0 \ . \ E_e} / \sqrt{\mathrm{tlength} \ E_i}, \tag{4}$$

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 PID resolution will be reached for the largest track length, which corresponds to $\cos\theta = 0.85$ in ILD.

The ILD parametrisations of the energy loss for different particles as a function of the momentum were used as given in [6]. 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

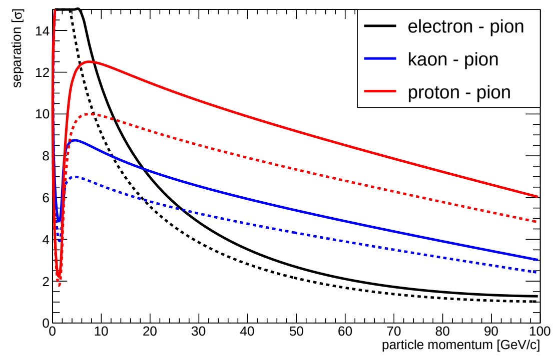

Figure 5: The projected PID separation for a GridPix TPC in ILD for electrons, kaons and protons w.r.t. pions at $\cos\theta = 0$. The continuous lines correspond to an electron PID resolution of 2.4% and the dashed to 3%.

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. 5, 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.

6. Conclusions 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 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 efficiency at high hit rates was studied. For hit rates up 5.7 kHz per chip a reduction of at most 0.6% in the relative efficiency was measured.

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

The resolution in the precision plane as a function of the local track angle was measured in the $B = 1$ T data using reconstructed circle 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 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 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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