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 localized hit bursts from low energetic curling electrons were characterised.

The single-electron resolution in the xy precision plane as a function of the

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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 $\cos\theta = 0$ 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. The GridPixes 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 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 gas of $Ar/CF_4/iC_4H_{10}$ (by volume) with a small amount of oxygen and water vapour.

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 localized hit bursts caused by from 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 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 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.

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 number of hits of different GridPixes were weighted to give the same mean number of hits per GridPix. 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 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 full 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. The long Landau tail in the dE/dx distribution is coming from the multi-electron clusters that will peak at low distances and are smeared out by the diffusion

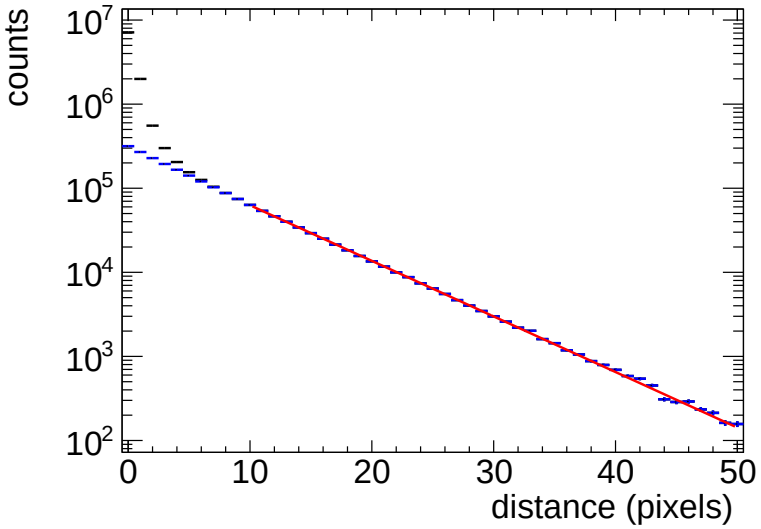

Figure 1: Distribution of the number of selected hits as a function of the distance d_y in pixel unitsi for the B= 1T data is show in black. The weighted distribution is shown with blue points and the exponential fit result with a red line.

proces.

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. 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 1 for the B= 1T 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 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 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 30% of the hits associated to the track, the response of a MIP defined 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, 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 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. 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

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 %

85-150 μm.

The results for the 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.

In order 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 the mean electron response divided by 0.7. Clearly, one wants to use an algorithm for which the linearity is close to 1. E.g. a value of 1.2 would imply that the MIP-electron separation is 20In 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 1. The PID performance can be corrected for by scaling the expectation 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.

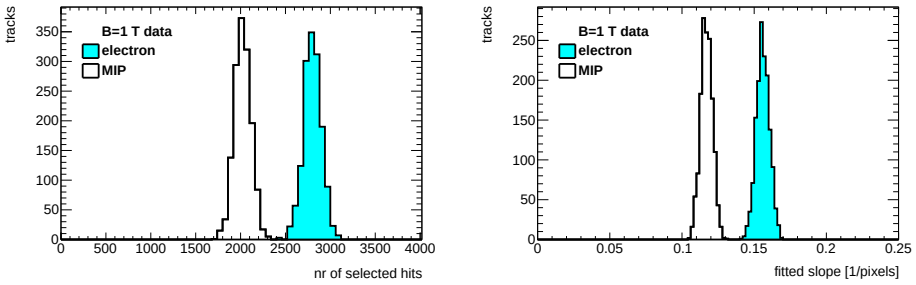

Figure 2: Distribution of the number of selected hits per track for the dE/dx truncation method (left) and the fitted slope for the template fit method (right) for an electron (light blue shaded) and for a MIP, using 1 m long tracks with 60% coverage, for the $B = 1$ T data.

3. Single-electron efficiency at high hit rates

The single-electron efficiency of 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 ToT is related to the deposited charge on the pixel and the single-electron efficiency of the detector. The relative change in the single-electron efficiency $\delta\epsilon/\epsilon$ can be related to the relative change in the mean ToT by

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

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 Fig. 4.7 of [2]. By measuring the mean ToT in a high (low) rate environment runs at B fields of 0 and 1 T, the relative change in single-electron efficiency is extracted.

In order 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 runs 6934 and 6935 and 6983 have a high hit rate and were taken at a beam momentum of 5 GeV/c. Runs 6916 and 6969 were taken at a beam momentum of 6 GeV/c and have a low hit rate. 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 [T]	ToT1 [μs]	ToT2 [μs]	triggers 10^3	run time [10^3s]	Hits1 10^6	Hits2 10^6	trig rate [Hz]	Rate1 [10^3hits/s]	Rate2 [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 mean 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 the high rate runs 6934, 6935 and 6983 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 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 efficiency $\delta\epsilon/\epsilon$ 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 GridPix. To conclude, running at hit rates up 5.7 kHz per GridPix gives a reduction of at most 0.6% in the relative efficiency.

4. Characterisation of large localized hit bursts

In event displays large localized 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. 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 localized hit bursts, the data of run 6969 - taken at a

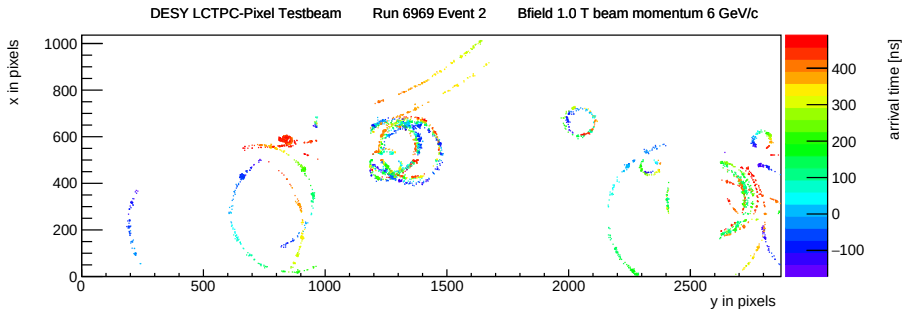

Figure 3: An event display for run 6969 event 2 taken at a 6 GeV/c beam momentum in a $B = 1$ T field. The hits are shown in the xy plane, in colour the time of arrival is shown.

6 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 large localized 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

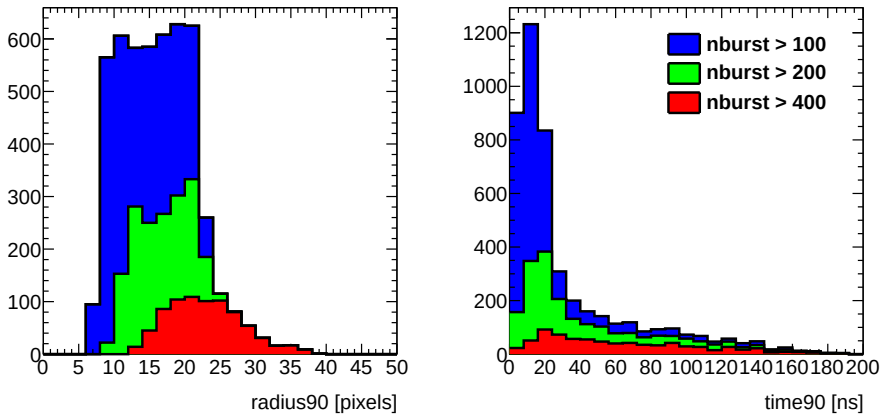

Figure 4: The stacked distributions for radius90 and time90, for large localized hit bursts with more than 100 (blue), 200 (green) and 400 (red) hits, in run 6969.

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 has been measured in run 6969 of the $B = 1$ T data set taken at a beam momentum of 6 GeV/c. For a pad based readout system the resolution has a strong dependence on the local track angle see e.g. [5]. 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. In order 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 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 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

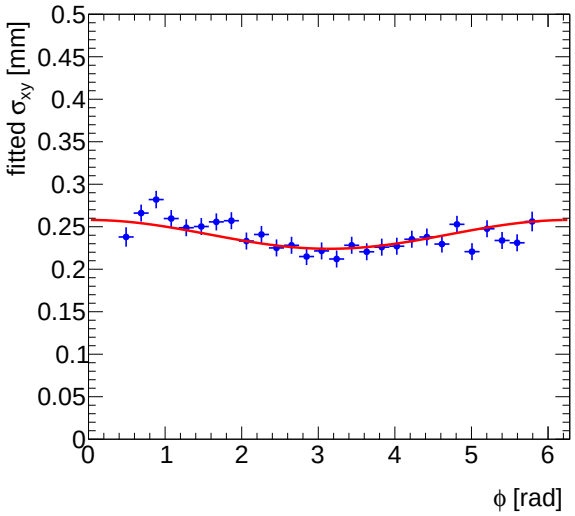

Figure 5: The fitted single-electron resolution in xy as a function of the local track angle ϕ for the hits on the circle. The fitted curve in red is given in Eq. 3.

- 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 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 (tlength_0) of 1441 mm. The PID resolution for different particles can be written as:

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

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). [1]

The ILD parametrisations of dE/dx for different particles as a function of the momentum were used as given in [7]. 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:

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

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

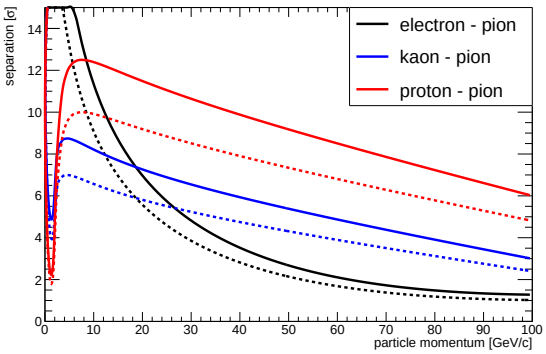

Figure 6: The projected PID separation for a GridPix TPC in ILD for electrons, kaons and protons w.r.t. pions at $\cos\theta = 0$. The continuous lines correspond to an electron PID resolution of 2.4% and the dashed to 3%.

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.

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 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 localized 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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