New results from GridPix Detectors

Y Bilevych, K Desch, J-P Fransen, H van der Graaf, M Gruber, F Hartjes, B van der Heijden, K Heijhoff, C Ietswaard, D John, J Kaminski, P Kluit, N van der Kolk, A Korporaal, C Ligtenberg, O van Petten, G Raven, J Rövekamp, T Schiffer, S Schmidt and J Timmermans

1 Rheinische Friedrich-Wilhelms-Universität Bonn, Physikalisches Institut, Nussallee 12, 53115 Bonn, Germany
2 Nikhef, Science Park 105, 1098 XG Amsterdam, The Netherlands

E-mail: kaminski@physik.uni-bonn.de

Abstract. GridPix structures combine the high resolution of a pixel readout chip with a Micromegas as gas amplification stage. This detector has shown excellent performance before with the Timepix ASIC, but has been improved by using the successor ASIC, the Timepix3. This new version of the GridPix detectors has been used in test beams at the ELSA accelerator at Bonn, where 2.5 GeV electrons are available for tracking studies. It could be demonstrated that the spatial resolution in both transverse and longitudinal direction follows the diffusion function.

Structures made of four GridPixes have been designed and constructed to cover larger areas. Also these devices called quads have been successfully tested with the electron beam giving similarly good results as the single GridPix detector.

1. Introduction
The development of the GridPix devices was driven by the aim of reaching the best possible resolutions with gaseous detectors. The structures used in micropattern gaseous detectors (MPGDs) have a spacing between the active regions which corresponds to typical distances between electrons in a charge cloud. The charge collection areas, however, have significantly larger sizes ranging from several square millimeters for pads to tens of centimeters for long strips. To match the feature sizes of both the gas amplification stage and the charge collection, the GridPix detector uses a readout ASIC for pixel detectors where the bump bond pads serve as charge collection pads. A resistive layer made of silicon-rich silicon-nitride protects the ASIC from rare discharges. Finally a Micromegas is built on top of the ASIC with photolithographic postprocessing techniques [1], which allow for very precise alignment. The grid is made of a 1 µm thick aluminum layer in which 30 µm wide holes are etched. The pitch of the holes corresponds to the 55 µm^2 pitch of the Timepix pixels [2] and the alignment has been measured to be better than 1 µm.

Because of the low equivalent noise charge (ENC) of about 90 electrons, the Timepix can be operated basically noise-free at thresholds of about 700-900 electrons. So, if single primary electrons undergo an amplification process with an average gas gain of 2500 to 3000, the detection efficiency is much better than 90 percent. Assuming sufficient diffusion for reducing the probability of collecting 2 primary electrons in one hole almost every primary electron can
be detected allowing to study an event such as a photon conversion of an X-ray or a charged particle track in unprecedented detail.

We have applied the GridPix technology in several experiments already. Most prominent is the CAST experiment [3], where axions or chameleons coming from the Sun are searched for by pointing a strong magnet towards the Sun. The axions can convert into X-ray photons and are focused by telescopes into X-ray detectors. A GridPix-based detector [4] has been used in 2014-2015 to set a new limit for chameleons [5] and in 2018-2019 for another data run, which is still analyzed. We are also suggesting GridPixes as a possible readout for a time projection chamber at the International Large Detector (ILD) [6]. We have therefore, built a prototype readout comprising of 160 GridPixes and operated this detector in a test beam [7]. Also, applications in a detector for thermal neutrons have been tested [8].

2. GridPix based on Timepix3
The GridPix detectors based on Timepix showed very good performance and central properties like spatial resolution or energy loss measurements could be performed. However, several limitations of the chip were identified and were preventing the GridPix from new applications. In particular the fact that only the charge or the time of arrival can be measured for each signal makes a timewalk correction impossible. Also, the non-zero suppressed slow readout of all pixels, the frame-based readout without any multi-hit capability and the slow clock frequency of less than 100 MHz restricts the rate capability of the detector.

To overcome these limitations a successor ASIC Timepix3 [9] was developed. It features a continuous readout mode where only pixels above threshold are read out and several different settings including the simultaneous readout of precise time and charge information. Also a phase-locked loop (PLL) increasing the counting frequency from 40 MHz to 640 MHz was included to improve the time measurement down to a granularity of 1.56 ns. A multi-hit capability is implemented by grouping 8 pixels to a super-pixel with additional memory cells.

In preparation for the new GridPixes also the design of the supporting structure of the amplification grid has been changed. With the new layout only 2.3 percent of the pixels are covered with the photoresist SU8, while in the old design 8.7 percent were left inactive. The production process performed at the Fraunhofer Institut IZM at Berlin remained the same as before.

3. First test beam with GridPixes based on Timepix3
A series of tests was initiated to validate the performance of the new GridPixes and to develop a design which allows for a high percentage of active area on a larger scale. The tests were done first with a laser in the lab. After establishing the full functionality, a test beam with high energetic particles is planned at the end of each stage. For these tests the ELSA accelerator at Bonn was chosen. Here a test beam area with 2.5 GeV electrons is available for tests. The electron rate was set to 1-10 kHz and individual tracks can be recorded by the 6 layers of the EUDET telescope [10] based on Mimosa silicon pixel detectors giving a very precise path of the electrons.

During the first test beam in July 2017 a small detector with a single GridPix was placed behind the 6 layers of the telescope. The detector had a maximum drift length of 2.8 cm and was flushed with Ar:CF$_4$:iC$_4$H$_{10}$ 95:3:2, which is the gas mixture currently envisioned for the ILD-TPC. The electric drift field was put to $E_{\text{drift}} = 280$ V/cm. The readout of the ASIC was performed by the SPIDR system and the related software [11].

The results of the analysis are published in [12] and here only a few important ones are shortly summarized. First the hits recorded by the Timepix3 are converted into 3D positions and hits with the same drift time are combined to a track. Then a track was reconstructed from the 6 layers of the EUDET telescope and the track was extrapolated into the gas volume of the
detector. An alignment procedure was necessary to take into account the 5 angles and 4 \( \times 2 \) shifts of the telescope planes. Then the telescope information was merged into one super-point with small errors. Finally all track points of the GridPix were fitted together with the super-point giving the most precise track estimate. After applying several selection criteria, the resolution of the hits in the pixel plane (transverse spatial resolution) is determined with respect to the fitted track.

This is plotted in figure 1, where the function

\[
\sigma_y^2 = \frac{d_{\text{pixel}}^2}{12} + D_T^2 (z - z_0)
\]  

was fitted to the data. In this equation a degradation caused by the pixel pitch \( d_{\text{pixel}} = 55 \mu m \) is considered as well as one term caused by the diffusion. Here the diffusion coefficient \( D_T \) and the grid position \( z_0 \) are important parameters. The result is in good agreement with this equation and also the measured diffusion coefficient \( D_T = 306 \mu m/\sqrt{\text{cm}} \) is slightly lower than the expected value of \((318 \pm 7) \mu m/\sqrt{\text{cm}} \).

The residuals in the drift direction are significantly worse, which is because of the timewalk effect: signals of higher pulse height are passing a constant threshold earlier than signals of lower pulse height. If the charge of a signal is known, this effect can be corrected for and the resulting residuals shown in figure 2 improve significantly. Still a degradation of the residual from lower pulse heights was observed as the correction function is only known to a certain precision. The residuals of pulses with more charge were fitted with the function

\[
\sigma_z^2 = \frac{\tau^2 v_{\text{drift}}^2}{12} + \sigma_{z0}^2 + D_L^2 (z - z_0).
\]  

Here \( \tau \) is the minimal clock cycle of 1.56 ns, \( v_{\text{drift}} \) the drift velocity of electrons in the gas mixture, \( \sigma_{z0} \) a time jitter and \( D_L \) the longitudinal diffusion coefficient. The measured value of the diffusion coefficient \( D_L = 226 \mu m/\sqrt{\text{cm}} \) is slightly higher than the expected value of \((201 \pm 5) \mu m/\sqrt{\text{cm}} \).

In all cases, the statistical uncertainty of the fits to the experimental data are negligible, while the expected values are quoted with their statistical spread given by Magboltz [13].
Figure 3. The left side shows an explosion view of the quad, while the right side shows a photograph of a final quad without the guard.

4. Quad Design
The design of the quad was driven by the necessity to have small units of four GridPixes, which can be tiled seamlessly to larger areas. The design can be seen in figure 3, where an explosion view is shown on the left side. The basic unit of the quad is the COld CArrier which is only slightly larger than the footprint of the four GridPixes. These are placed with a robot with a precision of 10 µm and then are electrically connected with wirebonds to a PCB at the center between the four ASICs. The PCB can be seen on the photograph at the right side of figure 3. It connects the chip to a first stage of the readout, which is then connected via Kapton™ flexes to further stages. The COld CArrier can be mounted on a detector providing gas tightness and cooling of the ASICs. The grids are connected with insulated magnet wires to an HV board, which regulates and filters the high voltage. The complete quad has an active area of 68.9 percent.

14 quads have been assembled of which 12 are working fine and can be used in experiments. As a readout the SPIDR system is foreseen.

5. First test beam with a quad
A second test beam was performed in October 2018, when the first quad had been finished and could be tested in the electron beam. The setup was slightly modified. In particular a new detector with a drift length of 4 cm was constructed, where the electrical field is kept homogeneous by a field cage made of a series of wires connected to a resistor chain. This detector is placed in the middle of the EUDET telescope to reduce the effect of multiple scattering between the last layer of the telescope and the GridPixes. The electric drift field was put to $E_{\text{drift}} = 400 \text{ V/cm}$. The remaining parameters such as gas mixtures and gas gain were kept similar to the ones of the first test beam.

The analysis of the data is still ongoing, but some preliminary results shall be discussed here. The general sequence of the analysis is the same as for the single GridPix analysis. However, the small gaps between the GridPixes on the quad lead to field non-uniformities close to the GridPixes, as the ground potential can be seen through those gaps. Reconstructing the tracks as described above gives deficits in many variables. For example the occupancy shows lower values close to the sides adjacent to the gaps and the residuals also give dissenting values. In a first attempt a fiducial area at the center of the GridPixes was defined, where the field homogeneities had only very little impact. While this obviously gives better results and is used for figures 4 and 5, it also reduces the active area and still degrades the performance. Therefore, a correction function was derived by projecting the residuals on an axis perpendicular to the gaps and fitting a function made of four Cauchy distributions to the data. The correction function was applied to the data and a significant improvement was found on large parts of the detector except for the corners. To further improve the result a third approach was taken by slicing the axis along
the gaps in 16 strips repeating the second approach for each strip individually but using a fourth order polynomial with some fixed values leaving only the overall magnitude free. This gives the best values for the local deviations, but does not improve the final result significantly, which is shown in figure 4 for the residuals in the pixel plane. The same function as described in equation 1 is fitted to the data. The current value for the diffusion coefficient $D_T = 398 \, \mu m/\sqrt{cm}$ is significantly higher than expected ($270 \pm 3 \, \mu m/\sqrt{cm}$). This result is still being scrutinized as the origin of the additional degradation is unknown. In figure 5 the residuals in the drift direction are given and here the measured value $D_L = 212 \, \mu m/\sqrt{cm}$ is in good agreement with the expected one ($212 \pm 3 \, \mu m/\sqrt{cm}$). In both cases small deviations from the fit curve are seen at around 0.3 mm, because these electrons are being scattered from the guard electrode, which is mounted above the readout PCB.

6. Preparation of a new detector with 8 quads
As a next step towards increasing the area, a detector made of 8 quads is prepared for a test beam campaign. As mentioned above, a sufficient number of quads has been built and tested...
to be functional. Also a new detector casing with a cathode, field cage and mounting area has been finished (see figure 6).

In figure 7 the base plane with 8 mounted quads is shown. To decrease the field distortions on and between the quads wires will be strung along the gaps and connected to the correct electric potential.

Currently the readout is done with a SPIDR system for one quad at a time. In this configuration each quad is tested individually with the laser setup. For the final detector a data concentrator is foreseen, which allows to read out the 8 quads by a single SPIDR system.

Acknowledgments

The authors would like to thank the ELSA team for the smooth operation of the test beam and the support during the test beam campaign. We would also like to thank H. Blank, D. Pohl and Y. Dieter for their help in the preparation of the setup.

References

[1] Chefdeville M et al. 2006 Nucl. Instr. and Meth. A556, 490-4
[2] Llopart X et al. 2007 Nucl. Instr. and Meth. A581, 485-94; Erratum ibid 2008 585, 106-8
[3] Zioutas K et al. 1999 Nucl. Instr. Meth. A425 480-7
[4] Krieger C, Kaminski J, Lupberger M and Desch K 2017 Nucl. Instr. Meth. A867 101-7
[5] Anastassopoulos V et al. 2019 J. Cos. and Astrop. Phys. 01 032
[6] Behnke T et al., ILC TDR, Volume 4: Detectors arXiv:1306.6329
[7] Lupberger M et al. 2017 IEEE Trans. Nucl. Sci. 64 1159-67
[8] Köhli M, Desch K, Gruber M, Kaminski J, Schmidt F P and Wagner T 2018 Physica B: Cond. Matter 551 517-22
[9] Poikela T et al. 2014 J. of Instr. 9 C05013
[10] Rubinskiy I et al. 2012 Phys. Procedia 37 923-31
[11] Visser J et al. 2015 J. of Instr. 10 C12028
[12] Ligtenberg C et al. 2018 Nucl. Instr. Meth. A908 18-23
[13] Biagi S 1999 Nucl. Instr. and Meth. A421, 234-40