New Results from GridPixes

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Improving Micromegas: GridPix

Standard charge collection:
- Pads of several mm²
- Long strips (l~10 cm, pitch ~200 µm)

Instead: Bump bond pads are used as charge collection pads.

Could the spatial resolution of single electrons be improved?

Ar:CH₄ 90:10 → $D_T = 208 \mu m/\sqrt{cm}$
→ $\sigma = 24 \mu m$
Ar:iButane 95:5 → $D_T = 211 \mu m/\sqrt{cm}$
→ $\sigma = 24 \mu m$

Smaller pads/pixels could result in better resolution!

At Nikhef the GridPix was invented.
Timepix3

- Number of pixels: 256 × 256 pixels
- Pixel pitch: 55 × 55 µm²
- ENC: ~ 60 e⁻
- Charge (ToT) and time (ToA) available for each hit
- Timing resolution: 1.56 ns for duration of ~410 µs
- Zero suppression on chip (sparse readout)
- Multi-hit capable (pixels sensitive after \( t_{ToT} + 475 \) ns)
  
  Super-pixels store hits for some time
- Output rate up to 5.12 Gbps
- Power pulsing possible (800 ns for start up)
Production at IZM

Production was set up at the Fraunhofer Institut IZM at Berlin. This process is wafer-based → batches of up to 4 wafers (105 chips each) at a time.

1. Formation of $\text{Si}_x\text{N}_y$ protection layer (to protect chip from discharges)
2. Deposition of SU-8
3. Pillar structure formation
4. Formation of Al grid
5. Dicing of wafer
6. Development of SU-8

The process will be transferred to the FTD at Bonn in 2020.
Magnet is pointed to the Sun. Axions and chameleons produced in the Sun convert into X-ray photons. Detector requirements:

- Radiopure materials
- Good background separation (distinguish round X-rays and longer tracks)
- Good energy resolution
- Very low dead time

=> Detector optimized for spatial and energy resolution:

- Gas mixture
  \[(\text{Ar:iC}_4\text{H}_{10}: 97.7:2.3)\]
- Electric fields
  \[(E_{\text{drift}} = 500 \text{ V/cm})\]
- Gas gain (G~ 2500) and
- Analysis (pixel counting).

During the study energy resolutions of \(\sigma_E/E = 3.95\%\) for the photopeak of \(^{55}\text{Fe}\) could be reached.
International Linear Collider (ILC) is a linear $e^+e^-$ collider with $\sqrt{s}$ up to 500 GeV – 1TeV

**International Large Detector**
- Standard HEP detector
- TPC as main tracker

**TPC Requirements:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$r_{\text{in}}$</th>
<th>$r_{\text{out}}$</th>
<th>$z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometrical parameters</td>
<td>329 mm</td>
<td>1808 mm</td>
<td>$\pm$ 2350 mm</td>
</tr>
<tr>
<td>Solid angle coverage</td>
<td>up to $\cos \theta$ $\approx 0.98$ (10 pad rows)</td>
<td></td>
<td></td>
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<tr>
<td>TPC material budget</td>
<td>$\approx 0.05 X_0$ including outer field cage in $r$</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>$&lt; 0.25 X_0$ for readout endcaps in $z$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of pads/timebuckets</td>
<td>$\approx 1-2 \times 10^6/1000$ per endcap</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pad pitch/ no. padrows</td>
<td>$\approx 1 \times 6$ mm$^2$ for 220 pads</td>
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</tbody>
</table>

- $\sigma_{\text{point}}$ in $r\phi$ $\approx 60$ $\mu$m for zero drift, $< 100$ $\mu$m overall
- $\sigma_{\text{point}}$ in $rz$ $\approx 0.4 – 1.4$ mm (for zero – full drift)
- 2-hit resolution in $r\phi$ $\approx 2$ mm
- 2-hit resolution in $rz$ $\approx 6$ mm
- dE/dx resolution $\approx 5\%$
- Momentum resolution at $B=3.5$ T $\delta(1/p_t) \approx 10^{-4}$/GeV/c (TPC only)

**Benefits of GridPix readout:**
- Lower occupancy $\to$ better track finding
- Identification/removal of $\delta$-rays/kinks
- Improved dE/dx $\to$ primary $e^-$ counting

**But** to readout the TPC with GridPixes:
- $\approx 100-120$ chips/module 240 module/endcap (10 m²)
- $\to$ 50k-60k GridPixes
**Test Beam with Single GridPix**

- Test beam in July 2017 at ELSA, Bonn
- 2.5 GeV electrons at up to 10 kHz
- Tracks referenced by 6 layers of Mimosa telescope in front of detector
- Gas: Ar/CF$_4$/iC$_4$H$_{10}$ 95/3/2 (T2K)
- Electrons: ~100 e/cm
- $E_d = 280$ V/cm, $V_{\text{grid}} = -350$ V

*Results published in: Nuclear Inst. and Methods in Physics Research, A 908 (2018) 18–23*
Transverse Spatial Resolution

Single hit resolution in pixel plane:

\[ \sigma_y^2 = \sigma_{y0}^2 + D_T^2(z-z_0) \]

Depends on:
- pixel size → \( \sigma_{y0} = \text{pixel size}/\sqrt{12} \)
- diffusion coefficient \( D_T \) from fit

Deformations in pixel plane:
- 7 µm (RMS) in selected area

\[ D_T = 306 \text{ µm}/\sqrt{\text{cm}} \]

(318 ± 7 µm/√cm expected)
Time Walk Correction

Time walk error: time of arrival depends on signal amplitude

Correction using Time over Threshold (ToT) as a measure of signal strength

\[ \delta Z_{\text{timewalk}} = \frac{c_1}{t_{\text{ToT}} + t_0} \]

Residual distribution improved

Higher order corrections did not yield further improvements
Single hit resolution in pixel plane:

$$\sigma_z^2 = \sigma_{z_0}^2 + D_L^2(z-z_0) + \text{time bin size}$$

Additional selection cuts:

ToT cut (>0.60 µs) was applied to avoid large time walk errors

Deformations in z-direction: 21µm (RMS) in selected area

$$D_L = 226 \, \mu m/\sqrt{cm}$$

(201 ± 5 µm/√cm expected)
dE/dx Measurements

- dE/dx resolution with truncated mean
  - From the single chip tracks 1 m long tracks are made;
  - \( n_r \) of electrons counted in slices of 20 pixel and reject 10% highest slices
  - Distances along track are scaled by 1/0.7 to get an estimation for the dE/dx of a MIP
  - Resolution is 4.1% for a 2.5 GeV electron and 4.9% for a MIP
- Separation \( S = (N_e - N_{MIP})/\sigma_e \rightarrow 8\sigma \) MIP-e separation for a 1m track

A pixel readout can in principle within the resolution (diffusion) separate primary from secondary clusters. dE/dx can be measured by cluster counting and performance separation enhanced.
Construction of a QUAD

- Four-Timepix3 chips
- All services (signal IO, LV power) are located under the detection surface
- The area for connections was squeezed to the minimum → QUAD has an sensitive area of 68.9%
- Very high precision 10 μm mounting of the chips and guard
- 14 QUADs have been assembled of these 12 are working fine.
- DAQ by SPIDR

series of QUADs

39.6 x 28.38 mm
Test Beam with QUAD

- Test beam in October 2018 at ELSA, Bonn
- 2.5 GeV electrons at up to 10 kHz
- Typical beam height above the grid: ~1 cm
- Tracks referenced by 6 layers of Mimosa telescope with DUT in the middle
- Gas: Ar/CF₄/iC₄H₁₀ 95/3/2 (T2K)
- \( E_d = 280 \text{ V/cm}, V_{\text{grid}} = -330 \text{ V} \)
- Longer drift distance (4 cm) with field cage
Global Distortion Correction

Gap between GridPixes is grounded. This leads to field distortions.

At borders larger residuals.
→ 1.) reduce fiducial volume
2.) - project residuals on x-axis
   - fit analytic function
   - correct for deviations
→ RMS 16/9 µm

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Local Distortion Correction

3.) - Split data in slices along the y-axis
   - fit analytical function to distribution
   - correct slicewise

Correction improves corners but not the central regions. → RMS 12/9 µm
Spatial Resolutions

Both distributions show small bumps at the beginning from tracks scattered of the guard.

**Transverse spatial resolution**

Fit gives $D_T = 398 \, \mu m/\sqrt{cm}$

Magboltz: $D_T = (273\pm3) \, \mu m/\sqrt{cm}$

Corrections with y-dependence (slices) are applied.

**Longitudinal spatial resolution**

Fit gives $D_L = 212 \, \mu m/\sqrt{cm}$

Magboltz: $D_L = (201\pm3) \, \mu m/\sqrt{cm}$

Same corrections are applied in drift direction.
Distance of all QUAD hits to Telescope Track

Gauß fit yields a width of $\sigma = 42 \, \mu m$

Background of coincidental tracks estimated to 3 % by introducing a time delay of 115 ms.
Module made of QUADs

- Module with 8 functional QUADs is finished.
- Test detector with field cage assembled and tested (gas tight, stands HV, low gas contamination)
- Quads are individually tested
- Firmware to readout complete module with one SPIDR is being developed.
- Adding a guard electrode (wire) set on correct voltage to reduce field distortions between GridPixes.
Timepix3 Readout for SRS

- Firmware had been developed on ML650 Xilinx development board
- Important functions are available
- Hardware for SRS is available now
- Firmware has been transported on FECv6
- Tests and detailed studies are ongoing

![A-Card](image)

![picture of $^{55}$Fe source](image)

![track of $\alpha$](image)
Summary

- GridPixes based on Timepix3 are available since ~3 years
- Intense program to go to larger areas
  - Single chip detectors tested in 2017
  - QUAD detector constructed and tested in 2018
  - 8 QUAD modules constructed, tests ongoing, test beam scheduled for September
- 2 Test beams have been performed showing excellent performance
- Observed field distortions currently mitigated during analysis, a hardware remedy is tested.
- Additional applications (e.g. IAXO) are planned and new designs will be implemented soon.