First results from the Timepix4 Telescope

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HSTD13 — 4 December 2023
People involved

Testbeam crew

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University of Birmingham: Dan Johnson, Marcus Jonathan Madurai
University of Glasgow: Naomi Cooke, Aleksandrina Docheva

And acknowledgements to everyone making this possible, including

Richard Bates, Vincent van Beveren, Henk Boterenbrood, Paula Collins, Maarten van Dijk, Martin Fransen, Abraham Gallas Torreira, Vladimir Gromov, Bas van der Heijden, Malcolm John, Xavi Llop, Loris Martinazolli, and Heinrich Schindler
Successor to the LHCb VELO Timepix3 Telescope (2013–2019)

Timepix3 telescope:
• 1.6 µm pointing resolution

Timepix4 telescope goal:
• Study prototype sensors for 4D trackers at high rate
• < 50 ps track-time resolution at high rate

K. Akiba et al 2019 JINST 14 P05026 [DOI: 10.1088/1748-0221/14/05/P05026]
K. Heijhoff et al 2020 JINST 15 P09035 [DOI: 10.1088/1748-0221/15/09/P09035]
E. Buchanan et al 2022 JINST 17 P06038 [DOI: 10.1088/1748-0221/17/06/P06038]
Timepix4: Hybrid pixel detector readout ASIC

- Developed by CERN, Nikhef, and IFAE
- 65 nm CMOS
- 448×512 pixels, 55×55 µm² pitch
- Simultaneous measurement of time and charge deposition (by measuring time over threshold)
- Time-bin size of 25 ns/128 = 195 ps
  (Timepix3: 1.56 ns)
- Max rate: 360×10⁶ hits/cm²/s (160 Gb/s for single chip)

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X. Llopart et al 2022 JINST 17 C01044 [DOI: 10.1088/1748-0221/17/01/C01044]
### Timepix3 → Timepix4

**Dimensions:**
- Timepix3: W x H = 16.21 mm x 29.96 mm
- Timepix4: W x H = 24.7 mm x 53 mm

**Technology:**
- Timepix3 (2013): 130nm – 8 metal

**Pixel Size:**
- 55 x 55 µm

**Pixel arrangement:**
- 3-side buttable: 256 x 256
- 4-side buttable: 512 x 448

**Sensitive area:**
- Timepix3: 1.98 cm²
- Timepix4: 6.94 cm²

**Readout Modes**

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Data driven (Tracking)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Event Packet</td>
<td>48-bit</td>
<td>64-bit</td>
</tr>
<tr>
<td>Max rate</td>
<td>0.43x10⁶ hits/mm²/s</td>
<td>3.58x10⁶ hits/mm²/s</td>
</tr>
<tr>
<td>Max Pix rate</td>
<td>1.3 KHz/pixel</td>
<td>10.8 KHz/pixel</td>
</tr>
<tr>
<td>Frame based (Imaging)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mode</td>
<td>PC (10-bit) and iTOT (14-bit)</td>
<td>CRW: PC (8 or 16-bit)</td>
</tr>
<tr>
<td>Frame</td>
<td>Zero-suppressed (with pixel addr)</td>
<td>Full Frame (without pixel addr)</td>
</tr>
<tr>
<td>Max count rate</td>
<td>~0.82 x 10⁹ hits/mm²/s</td>
<td>~5 x 10⁹ hits/mm²/s</td>
</tr>
</tbody>
</table>

**TOT energy resolution:**
- Timepix3: < 2KeV
- Timepix4: < 1Kev

**TOA binning resolution:**
- Timepix3: 1.56ns
- Timepix4: 195ps

**TOA dynamic range:**
- Timepix3: 409.6 µs (14-bits @ 40MHz)
- Timepix4: 1.6384 ms (16-bits @ 40MHz)

**Readout bandwidth:**
- Timepix3: ≤5.12Gb (8x SLVS@640 Mbps)
- Timepix4: ≤163.84 Gbps (16x @10.24 Gbps)

**Target minimum threshold:**
- Timepix3: <500 e⁻
- Timepix4: <500 e⁻
Time measurement in Timepix4

- Nominal TDC resolution: $195\text{ ps}/\sqrt{12} = 56\text{ ps}$
- Time over threshold (ToT) measures signal charge

Coarse and fine time measurement – 40 MHz and 640 MHz

- Threshold
- Preamp out
- 40 MHz
- 640 MHz
- ToT
- Coarse ToA

Ultrafine time measurement – 195 ps

- 40 MHz reference
- 640 MHz phases

Ultra-fine ToA code = 0b1110
Speedy Pixel Detector Readout 4 (SPIDR4)
Telescope configuration

Upstream scintillators

Planes 1–4
100 µm 300 µm

DUT

Planes 5–8
300 µm 100 µm

Downstream scintillator

MCPs

Beam

CFD

SPIDR4

SPIDR4

SPIDR4

CFD

PicoTDC

CFD

HPTC

t₀-sync/shutter

TLU

clock

DAQ

data

Run control

start/stop
Micro channel plate detectors

- Time reference to study telescope timing
- Considering installing Timpix4 plane to VETO events with nuclear interactions
- Current time resolution: 17 ps (single MCP)
- Combined MCP resolution: 12 ps

\[ \sigma_G = 24 \text{ ps} \]
Plane assemblies (all Timepix4v2)

- Eight telescope planes with n-on-p planar silicon sensors:
  - 4 x 300 µm sensors for spatial resolution (angled)
  - 4 x 100 µm sensors for time resolution (perpendicular)
  - Sensor upgrades are anticipated (LGAD, 3D, …)

- Several DUT assemblies:
  - 50 µm, 100 µm, and 200 µm n-on-p planar silicon
  - 300 µm p-on-n
  - 2 x 250 µm iLGAD sensor 55 and 110 µm pitch (Tpx3 sized)
Assembly cooling

- All assemblies have a 3D-printed titanium cooling block
- Cooled using glycol at 20 °C
- Could go to –20 °C in the future
- Plan to mill PCB to have direct thermal contact with Timepix4

Current thermal interface

Future thermal interface
Spatial resolution

- Pixel size 55 µm × 55 µm
- Four innermost planes rotated 9° around x and y to induce charge sharing between pixels
- Charge-weighted mean gives cluster position
- Single plane resolution: 4.3 µm
- Resolution depends on detection threshold
Track pointing resolution

- Pointing resolution at DUT: 2.7 μm (Mixed hadron beam 180 GeV/c)
- PCB adds 1.8 % $X_0$ (ASIC + sensor adds 0.8–1.0 %$X_0$)
- Milling out PCB would improve resolution to 2.2 μm
- Investigating “eta corrections” for nonlinear charge sharing
- Other possible improvements:
  - Move telescope arms further inward when possible
  - Operate 300 μm planes at lower detection threshold
  - Add additional planes

\[\text{Scattering proportional to } \sqrt{x/X_0} \left[1 + 0.038 \log \frac{x}{X_0}\right]\]
Time resolution

- Thin sensors reduce time errors due to Landau fluctuations
- Perpendicular to beam to maximise signal charge in single pixel
- Reduced signal size reduces analog front-end performance

**Analog front-end resolution**

- N24 (v2, bare) $e^-$ mode
- N24 (v2, bare) $h^+$ mode
- N24 (v2, bare) $e^-$ mode Modified DACs
- N24 (v2, bare) $h^+$ mode Modified DACs

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**References**

- K. Heijhoff et al 2022 JINST 17 P07006
  [DOI: 10.1088/1748-0221/17/07/P07006]
Timewalk

- Time measurement depends on signal size
- Preamplifier output has a fixed risetime
- Reduced signal size makes timewalk corrections crucial
Time resolution

- Working on per-pixel timewalk corrections
- Current cluster-time resolution: ~250 ps
- Expected track-time resolution with 4 planes: ~130 ps
- Working on clock corrections to improve further

\[
\Delta t = \frac{a}{(ToT + b)^d} + c
\]

\[\sigma = 250 \text{ ps}\]
Inverted LGAD on Timepix4 as DUT

- Low-gain avalanche diodes (LGADs) use charge multiplication to deliver larger input signals
- Small pixel size cannot be achieved in standard LGAD technology (without losing efficiency)
- Inverted LGADs (iLGADs) solve this by placing the gain layer on the backside
- Sensors produced by Micron and provided by Glasgow

![Diagram of Standard LGAD and Inverted LGAD](image-url)
Inverted LGAD on Timepix4 as DUT (first glance)

- Analysis not yet started
- Large cluster size at perpendicular beam incidence
- Cluster have skirt of low-ToT hits (< 25 ns)
- We suspect due to bipolar signals in neighbouring pixels
Grazing angle measurements

- Grazing angle measurements probe different depths of the sensor
- Can be used to determine thickness by measuring cluster length at various angles
- Sensors are thin, but not flat

N161, Pixel pitch 55um, Thickness 100um, Run 5196

Cluster length

\[\sigma_1 = 0.92 \pm 0.01\]
\[\text{peak}_1 = 119.94 \pm 0.02\]
\[\sigma_2 = 1.06 \pm 0.03\]
\[\text{peak}_2 = 130.19 \pm 0.04\]

Bias = 50.000V
Stage angle = 89.50°
Conclusion

- First stable operation of complete telescope
- Current pointing resolution: 2.7 µm
- Current cluster-time resolution: 250 ps
- Expected track-time resolution: 130 ps
- Plenty of data to be analysed (Better corrections/understanding of chip)
- Ready to move on to faster sensor technologies
Backup slides
Timepix4 front-end

Analog Front-end
- Leakage Current compensation
- Preamp
- 2.5fF
- tp_enable
- 3fF
- power_enable
- global threshold
- Analog test pulses
- Input pad

Digital Front-end
- Counters & Latches
- Synchronizer & Clock-gating
- Digital pixel input for external signals
- Time stamp
- OP Mode
- Control voltage
- Data out to EOC
- VCO @640MHz
- 40MHz

Super pixel
- SPixel
- 8 pixels
- SPGroup
- 32 pixels

Digital pixel input for external signals
- Time stamp
- OP Mode
- Control voltage
- Data out to EOC
- VCO @640MHz

1 pixel

K. Heijhoff
HSTD13
4 December 2023
Clock distribution – Column digital locked look (DLL)

- The column DLL distributes the clock along the columns
- The adjustable delay buffers (ADBs) precisely define the clock phase in each pixel group
- Controller tunes the total delay to 25 ns
- Possible to set the delay manually
- Individual ADB stations can be bypassed

~22.7 mW/cm² to distribute a 40 MHz clock with a 100 ps<sub>rms</sub>
- Time resolution in $h^+$ mode limited to 75–105 ps depending on DAC settings
- Pixel capacitance decreases the time resolution

(see R. Ballabriga et al NIM A 1045 (2023) 167489 [DOI: 10.1016/j.nima.2022.167489])
Variation in the VCO frequency over the pixel matrix observed:
  Bottom half: 1.547 ns ± 20 ps
  Top half: 1.583 ns ± 14 ps

Structure in ultra-fine time bins has a small impact on TDC resolution (few %)

We have tried to predict the TDC resolution for correction methods of increasing complexity

Fine time bins (640 MHz)

Ultra-fine time bins

Phase shifted 640 MHz clocks

Ultra-fine time bin: 0 1 2 ...

Fine time bin: 0 1 2 ...

No correction: 111 ± 33 ps
Chip-wide: 111 ± 32 ps
Per matrix half: 80 ± 22 ps
Per VCO: 61.9 ± 1.3 ps
Per VCO, uToA: 60.3 ± 1.0 ps
Best possible: 58.3 ± 0.9 ps
Ideal bins: 56.4 ps
MCP time reference

- Two MCPs provide precise time references to study timing performance of telescope
- Placed at end to not hinder other groups in same beam area
- CFDs suffered from large signals due to nuclear interactions
Correlations between time measurements

Clock phase variation

Timing systematics in the LHCb VELO Timepix3 Telescope

**Single-hit time:**

- Time offset $-240$ ns
- Time in 1.6 μs period

$\sigma_t = 1$ ns

**Track time:**

- Mean of 8 hits
- Correlations between time measurements

$\sigma_t = 438$ ps

K. Heijhoff et al 2020 JINST 15 P09035 [DOI: 10.1088/1748-0221/15/09/P09035]
- Time bins measured using digital pixel inputs
- Timepix4v2

**Timepix4 TDC bins**

![Timepix4 TDC bins diagram](image-url)
Timepix4 – Jitter vs threshold

- Jitter depends on threshold
- Tail at high thresholds in electron-collecting mode not understood

Jitter vs threshold (hole collecting)

- ~25 ps
- ~30 ps

Jitter vs threshold (electron collecting, 10 ke)

- W7E2 (bare)
- W8?? (with sensor)
Timepix3 telescope

- Eight planes with Timepix3 + sensors
- Planes rotated to optimise spatial resolution
- Scintillators provide a reference time
- Constant fraction discriminators (CFDs) reduce timewalk effects
- All planes run on a common 40 MHz clock
Timewalk and intercept correction

- Use both track intercept and charge to find correction in a lookup table
- Simultaneously corrects for timewalk and signal induction variations
- Improves track time resolution: $\sigma_{\text{track}} = 438 \text{ ps} \rightarrow 385 \text{ ps}$

**Time corrections throughout a pixel**

Correction depends on track location!

**Intercept relative to first hit**

Pixel with first hit

First hit
DUT charge distributions

- MIPs going through electrodes of 3D sensor only generate charge in small region
Intrapixel time delay

Timepix3 pixel ASIC + sensor

3D sensor technology

Thin planar sensor

K. Heijhoff et al 2021 JINST 16 P08009 [DOI: 10.1088/1748-0221/16/08/P08009]