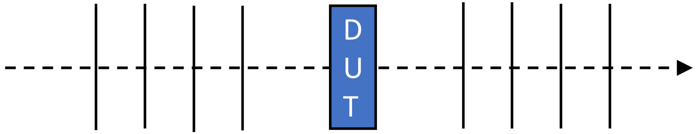
First tracks and initial timing results with Timepix4 detectors

Martin van Beuzekom

27 June 2022

Riva del Garda

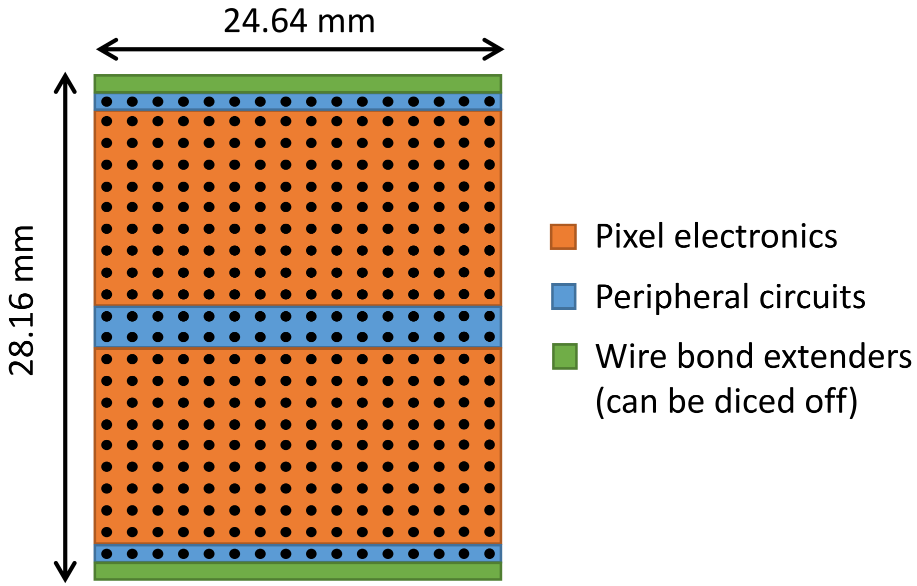
Introduction & Motivation



- Beam telescopes will be used for characterization of novel sensors, in view of LHC upgrades
- After successful Timepix3 beam telescope, upgrade based on Timepix4
- Main improvement (and challenge) is a better track time resolution
  - Timepix3 telescope achieved 236 ps after long and careful tuning
- Aim for (about) 20 ps track time resolution
  - If using fast sensors and reference timing layer
- Maintain excellent pointing resolution of (about) 2 μm
- Operation at 'high' rate (> 1 Mtracks/s)
- Timepix4 is an excellent candidate chip for a beam telescope
  - Large area, high resolution time stamping, large design team and user community
- This work shows the first testbeam results; step-1 on the way to a full telescope

medipix collaboration

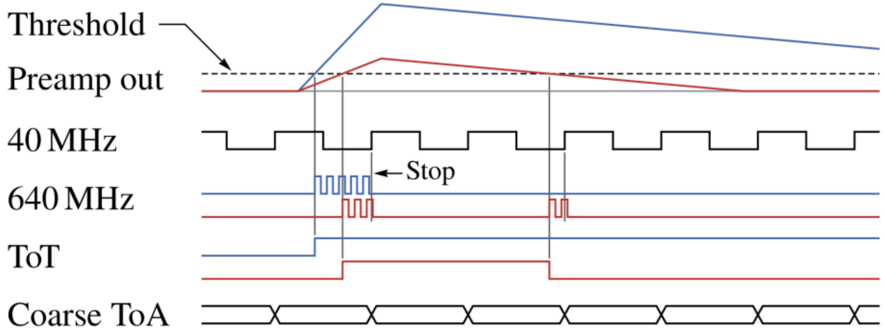
Timepix4 main specifications

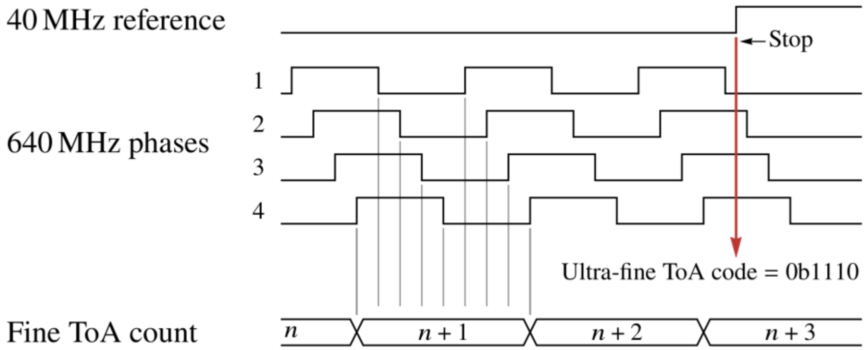


- 65 nm CMOS
- Matrix of 512 x 448 pixels
- 55 x 55 um^2 pixels
  - Electronics in 55 x 51.4 um^2
- Active area 6.94 cm^2
- 4-side buttable, using redistribution layer
- Many modes, for telescope: simultaneous Time-Of-Arrival and Time-Over-Threshold
- 195 ps TDC bins
- Data driven readout: 16 x 10.24 Gbps
- Min. threshold: ~500 e-

X. Llopart et al. 2022 JINST 17 C01044

Timepix4 time measurement





- Base clock of 40 MHz
- Hit starts 640 MHz oscillator
  - 1.56 ns bins
  - Count #clock cycles (like in Tpx3)
  - Oscillator shared by 8 pixels in superpixel
- Oscillator is stopped by first rising edge of 40 MHz clock
- In addition the internal state of ring oscillator (VCO) is captured –> 195 ps bins
- Back edge of Time-over-Threshold signal is measured with a high time resolution
  - Improved ToT measurement

Timepix4 versions

Q4 2019

Timepix4v0

Full mask engineering run

6 wafers received

Chip is operational

1) Excess noise coupling from peripheries to FE
2) 640 MHz clock in edge peripheries
3) VCO not oscillating at nominal frequency

Q3 2020

Timepix4v1

4 BEOL masks changed

Small test VCO chip

6 wafers received

1) Improved RDL shielding in peripheries
2) 640MHz in peripheries recovered

1) VCO not oscillating at nominal frequency

Q2 2021

Timepix4v2

4 FEOL + 4 BEOL masks changed

19 wafers received

1) TDC and High speed links working as expected
2) Further improvement in RDL shielding in peripheries

Chip at its final version

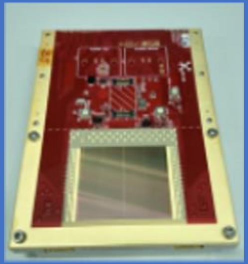
- Version1 with sensor used in testbeam
  - Voltage Controlled Oscillator running 25% too fast
  - And not properly locked to its reference oscillator
- Version2 (still) without sensor used for lab measurements

More Timepix4 info in Xavi Llopart's seminar: https://indico.cern.ch/event/1121147/

SPIDR4 readout

External clock/timing (optional)

Timepix4 chipboard

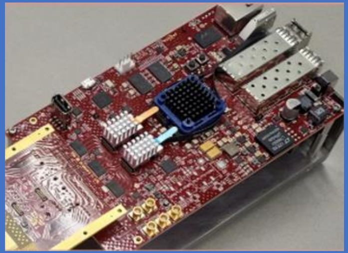


Clock / Timing

Config. / status

Pixel data

Control board



Config. / Control

gRPC, 1 Gb Ethernet

Data

10 Gb Ethernet

Off–the-shelf computer

Raw data (64b/66b)
160 Gbit/s

Optional DAQ server

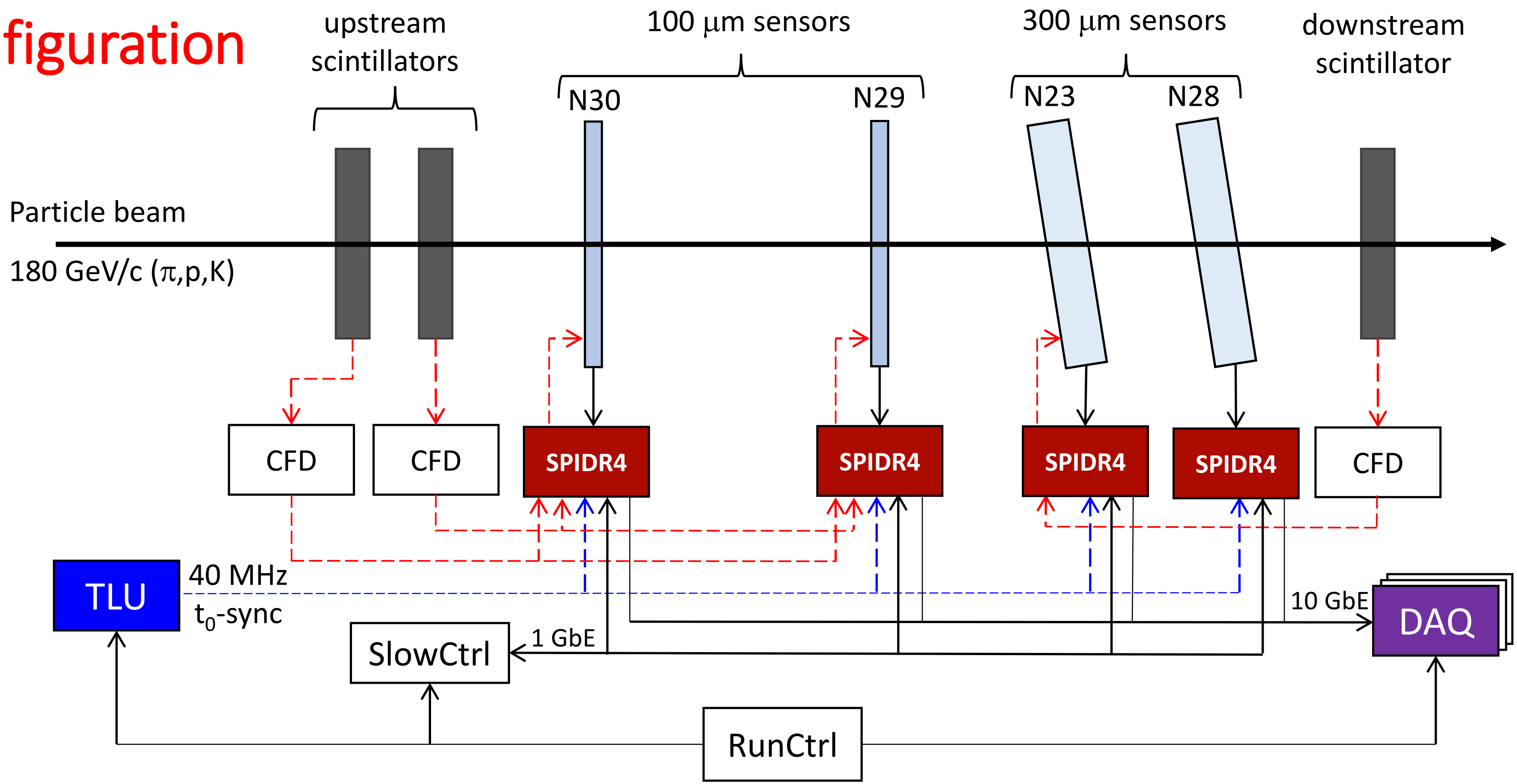
Config. / Control

Data access

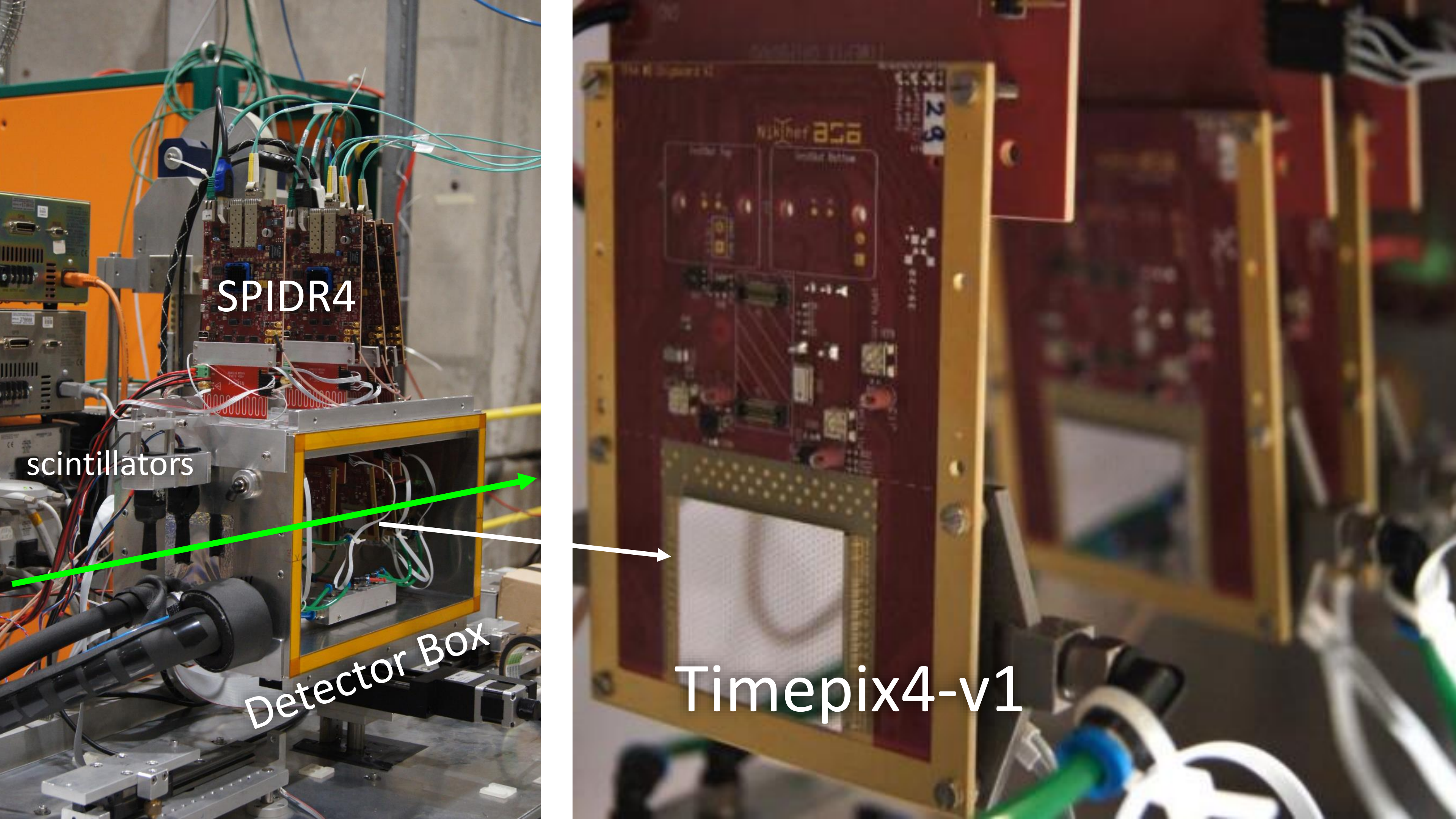
- Readout specifically for Timepix4
- Default: 10 Gbits/s readout
  - More than sufficient for typical testbeam
- Supports full bandwidth of chip (160 Gbit/s) with optional DAQ server

AMSTERDAM SCIENTIFIC INSTRUMENTS

Configuration



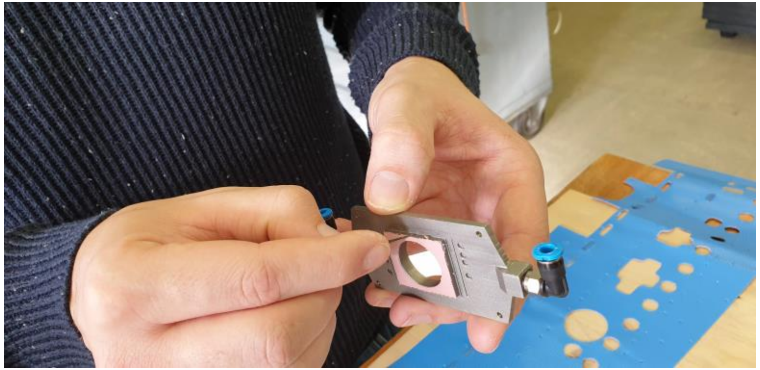
All sensors are n-on-p (e- collecting)

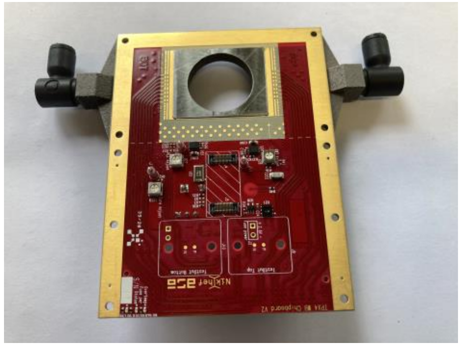


SPIDR4
scintillators
Detector Box
Timepix4-v1

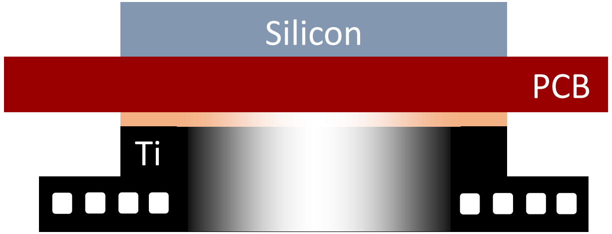
Cooling

- Power consumption of few Watts per Timepix4
- All chips/PCBs attached to 3D printed titanium cooling block
- Glycol used to cool chips to about room temperature
- Ready to go colder

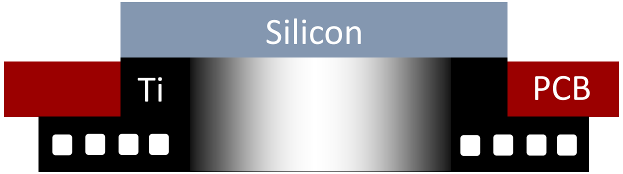




Current cooling



Envisioned cooling

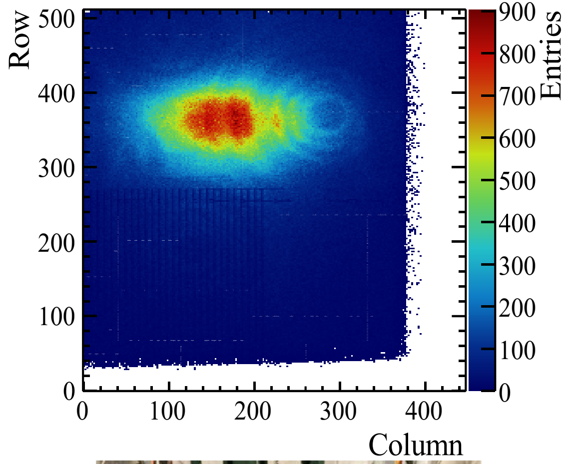


First beam on Timepix4

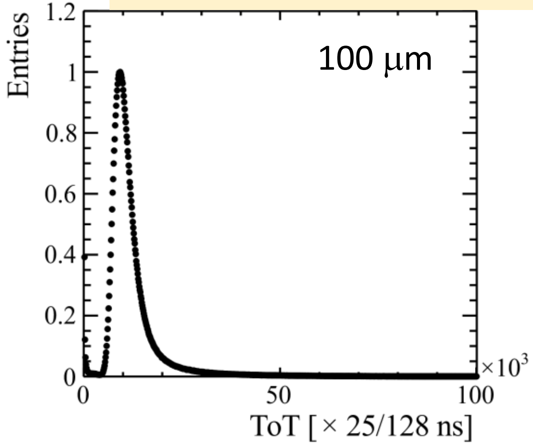
- ✔ DAQ and synchronization works
- ✔ Online monitoring works
- ✔ Offline analysis using the LHCb's Kepler framework works

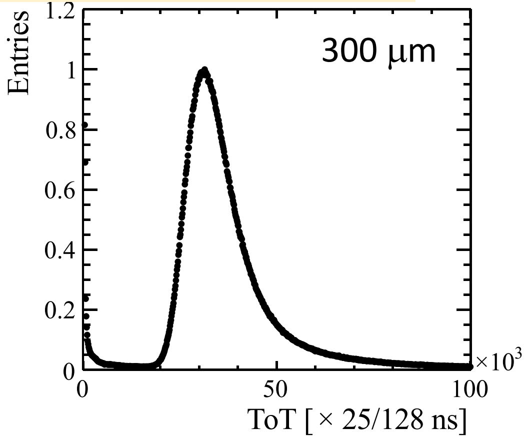
-> ToT and hitmap look as expected

Hitmap of associated clusters to a track on a single plane

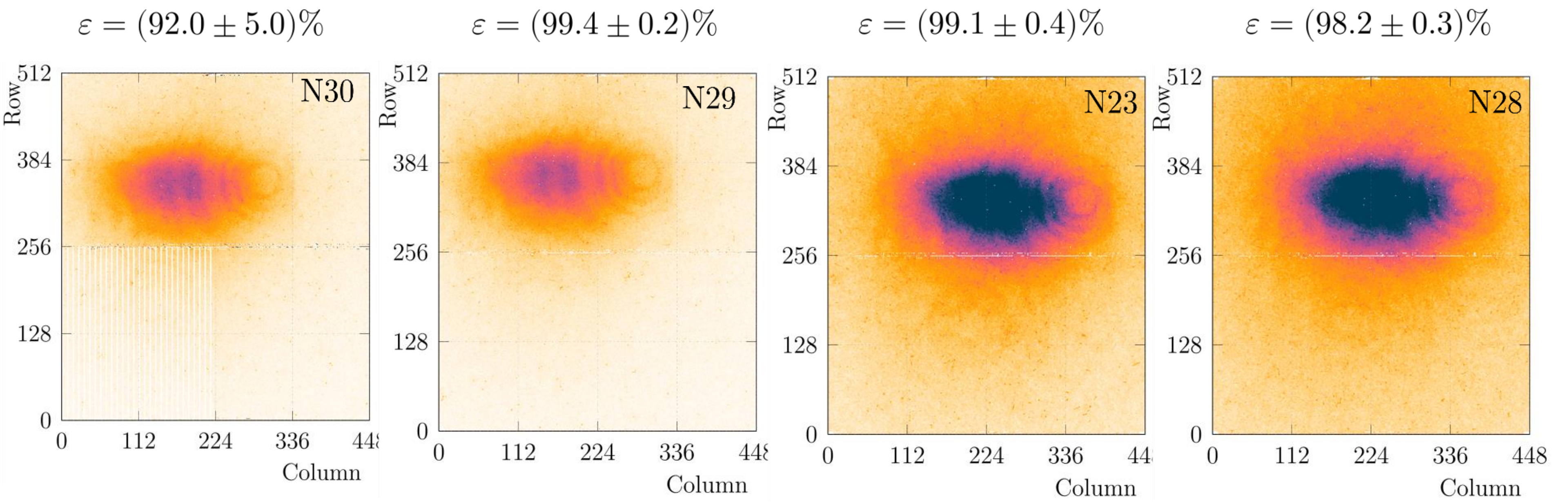


TOT/Charge distribution for the two sensor variants



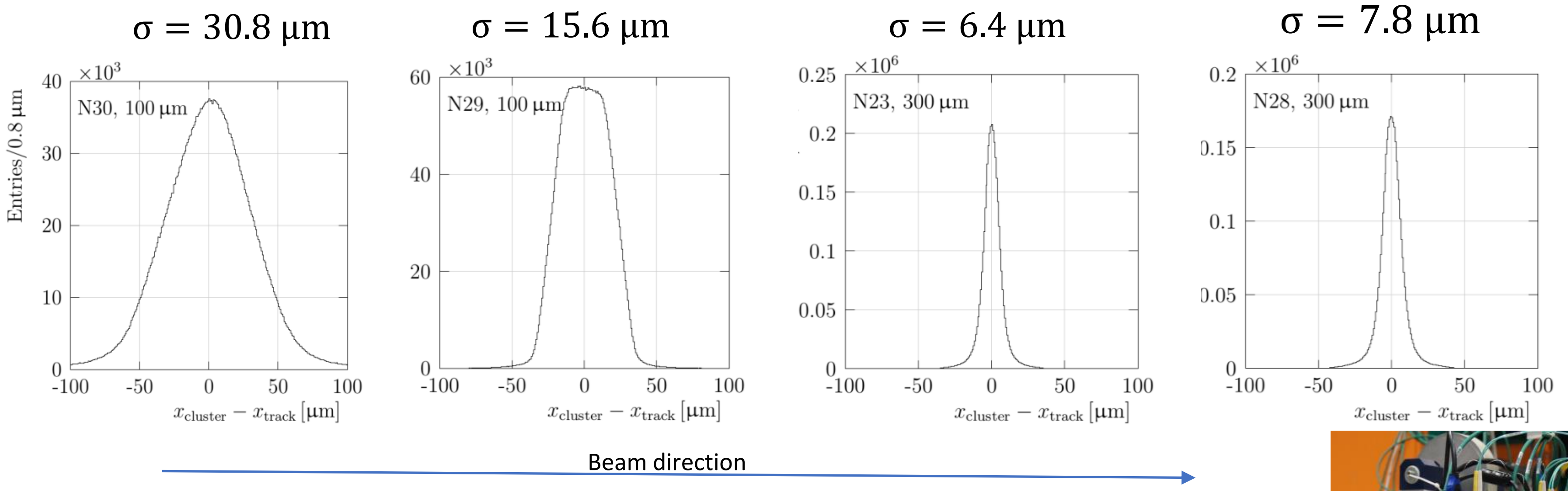


Efficiencies

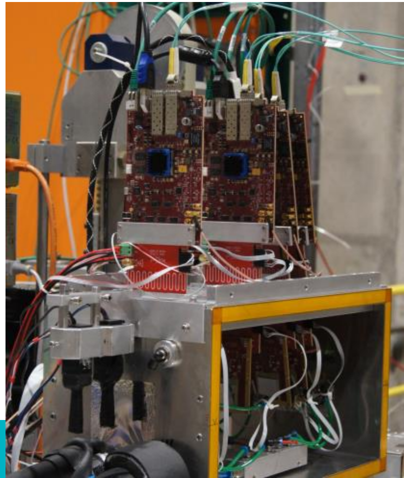


- ”Out of the box” efficiencies
- Not yet optimized (but anyhow, >> 90% sufficient for telescope)

Spatial residual distributions

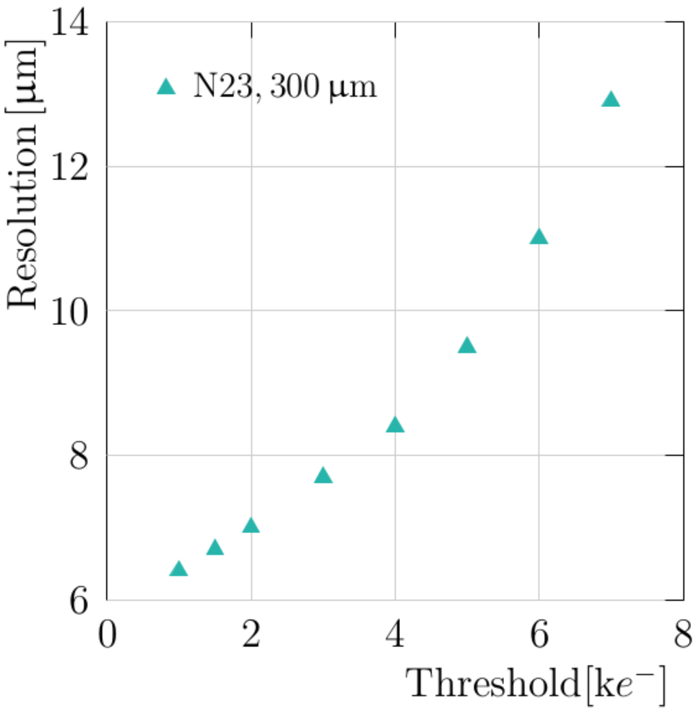


- Unbiased residuals, measured by extrapolating tracks made with the other 3 detectors
- The pointing resolution is not subtracted from these values, hence the huge variation between similar planes
- Results in line with expectation

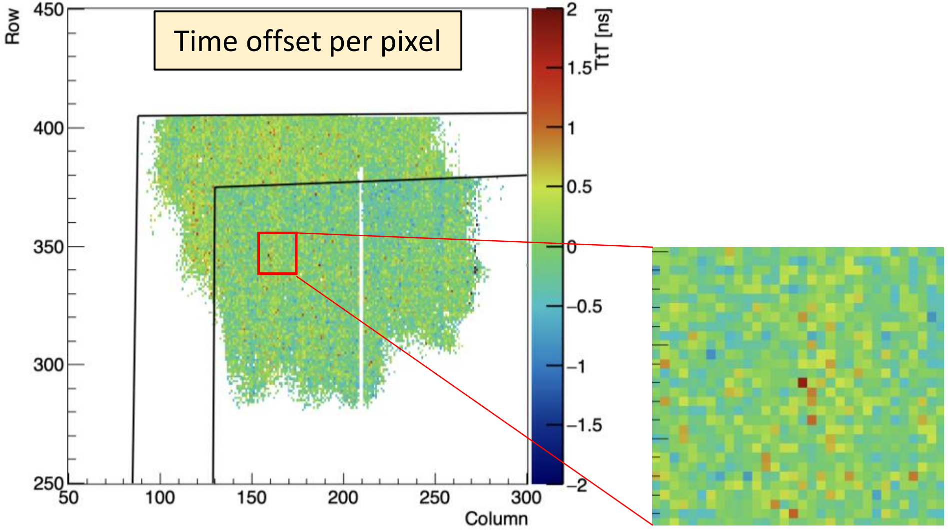


Optimizing for spatial resolution

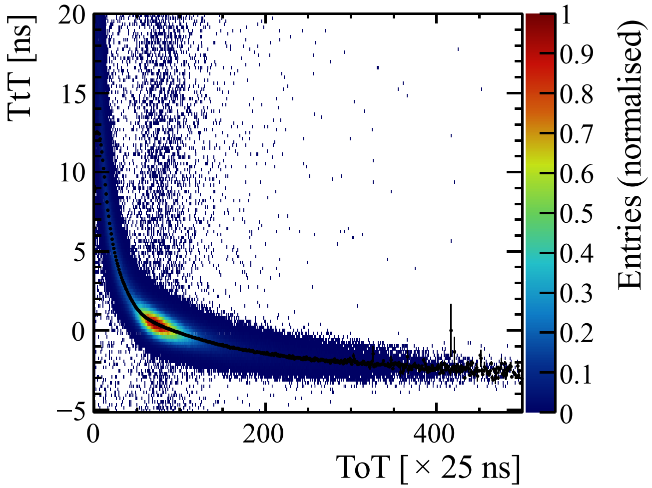
- The 300 μm sensors are placed at a 9° pitch and yaw angle w.r.t. beam
- Improves spatial resolution to ~ 6 μm
  - Binary resolution 55 μm / sqrt(12) = 15.9 μm
- Low threshold operation is beneficial for spatial resolution
  - ~600 e- seems feasible with careful tuning
- Find balance between optimization for spatial resolution and for timing



Optimization for timing



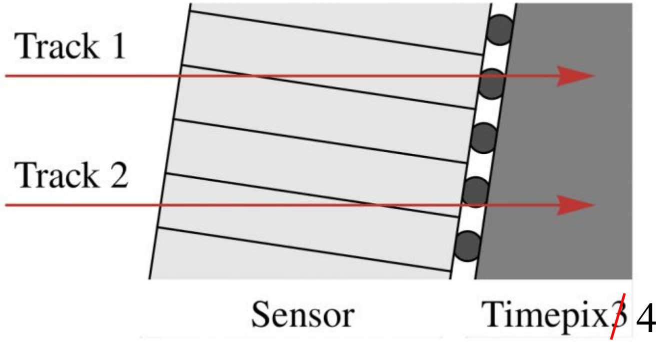
- ‘Standard’ time-walk correction for thin perpendicular sensors
- Currently using Time-over-Threshold, accurate charge calibration not yet available

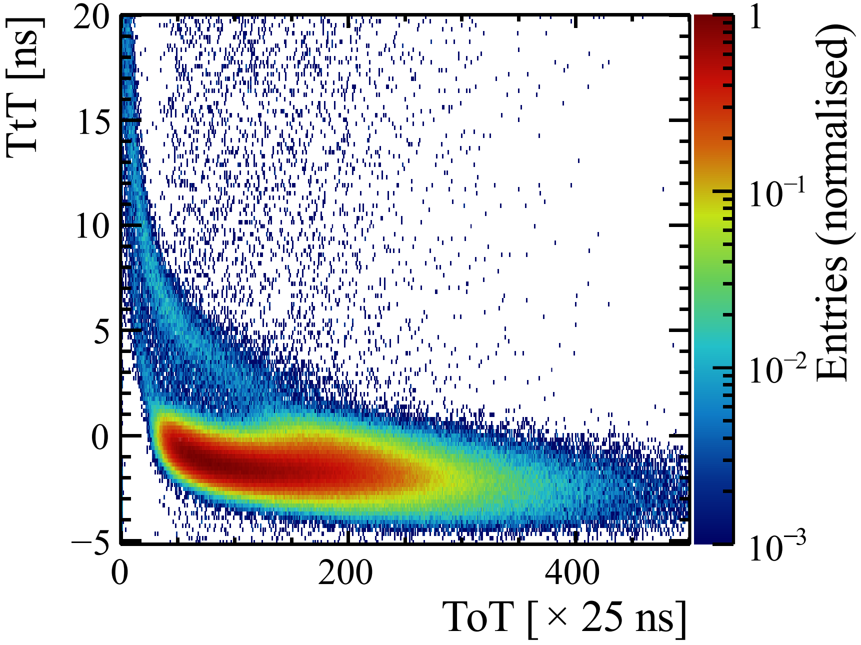


- Time offset per pixel determined via time-to-threshold measurement
- Planned for final telescope: per-TDC-bin offset correction
  - Requires substantial statistics

Timewalk correction for thick tilted planes

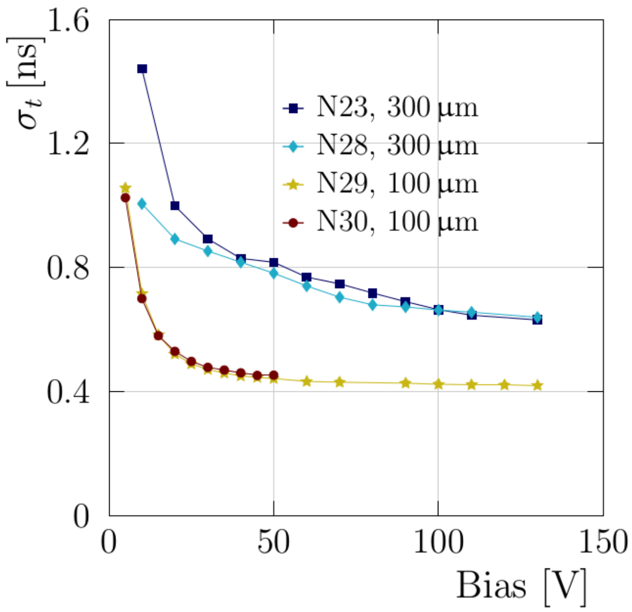
- Tilting sensors is beneficial for spatial resolution, but affects time resolution
- Timewalk plot for tilted thick sensor shows multi-band structure
- Requires timewalk correction based on track topology, currently limited by statistics

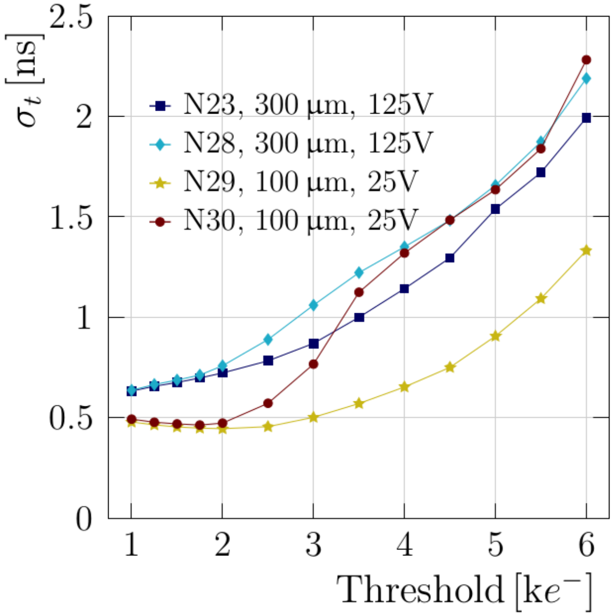




More details: K. Heijhoff https://doi.org/10.1088/1748-0221/15/09/P09035

Temporal resolution of individual planes





- Limited by bias voltage on sensor
- Lower threshold for 300 µm sensors might improve time resolution

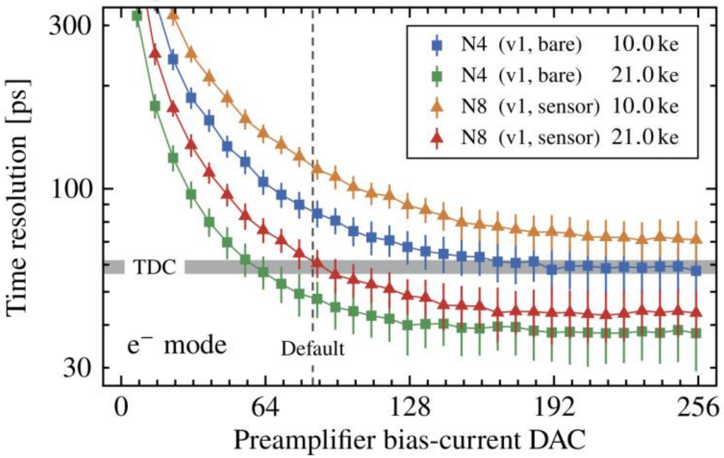
Track time resolution

- Current track time resolution is (‘only’) 340 ps

- Improvements expected from:
  - More layers: at least 8, maybe 10 or 12
  - Operation at higher bias voltage
  - Timepix4v2, with locked TDC oscillators
  - Higher preamplifier current
  - Cluster time instead of hit time
  - Better track topology based timewalk correction (suffering from limited statistics)

- Major improvement will come from faster sensors: LGAD, (trench) 3D

Time resolution of TPX4 analog front-end, with testpulse



K. Heijhoff: arXiv:2203.15912 (accepted by JINST)

Summary and outlook

- Reconstructed first tracks through Timepix4 !
- Successful first testbeam, many things tested/learnt:
  - Mechanics and cooling
  - Slow control and online monitoring
  - Synchronisation
  - Track reconstruction
  - Experience with Timepix4, SPIDR4 etc.
- Performance in line with expectation
- Track time resolution so far: 340 ps
- Many 'knobs' we can turn to improve time resolution
  - Tuning, corrections, and more corrections

- Next testbeam in about 3 weeks from now
  - 8 layers: 4 x Timepix4v2, 4 x Timepix4v1

Thank you