Pixelated Photodetector for Single-Electron Tracking

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IOTA/FAST Collaboration Meeting

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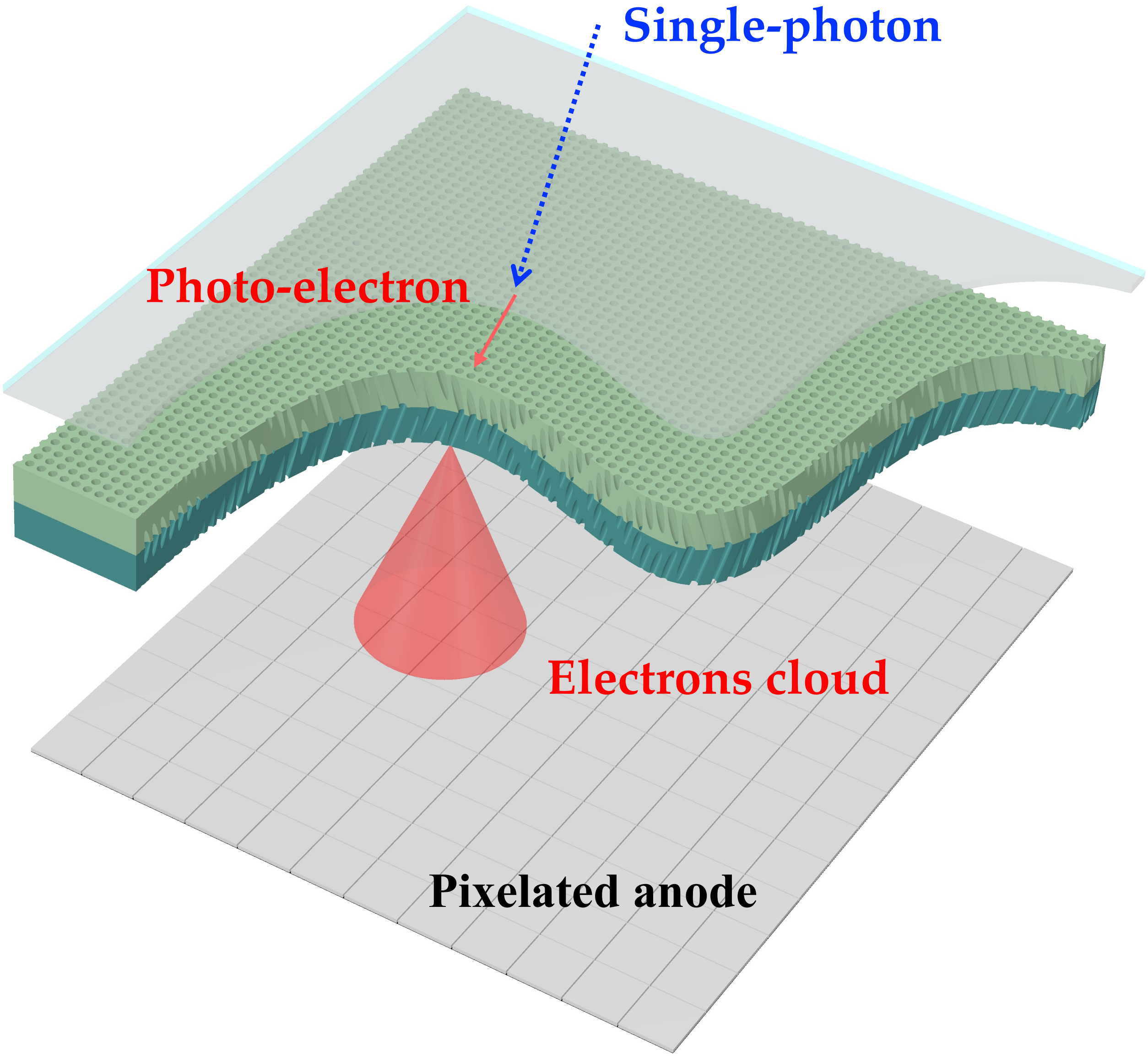
Hybrid photodetector development

- Large active area single-photon detector with simultaneous excellent timing and spatial resolution, with low noise level at room T
- Detector based on a "hybrid" concept:
  - Vacuum detector; photocathode with high QE in the region of interest
  - Proximity-focusing geometry; Micro-channel plate (MCP) amplification
  - Silicon ASIC embedded inside vacuum tube
  - Reference: JINST 13 C12005 2018
- Funded by ERC Consolidation Grant (P.I. M. Fiorini)

European Research Council

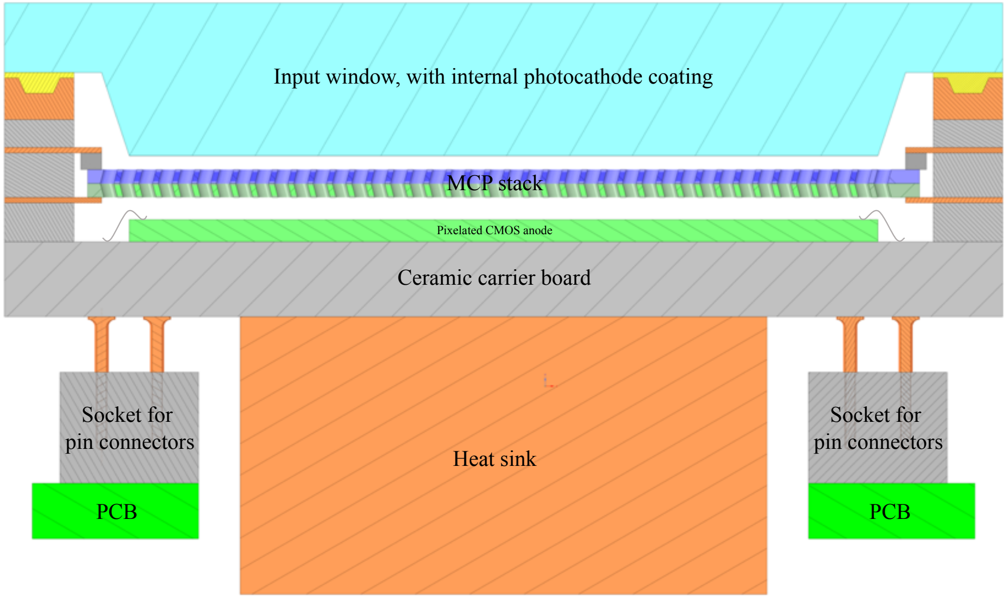
Target time resolution	<100 ps r.m.s.
Position resolution	5-10 μm
High-rate capability	10^9 hits/s
Low dark count rate at room T	~10^2-10^3 counts/s
Large active area	7 cm^2
High channel density	0.23 millions

Detector concept



- Entrance window + photocathode
- Microchannel plate stack (chevron)
- Pixelated anode
  - Electron cloud spread over a number of pixels
  - **55μm × 55μm** pixel size
  - **0.23 M pixels** measuring arrival time and duration of input signals
  - **7 cm^2** active area
  - Up to **2.5 Ghits/s**
  - Local signal processing

Detector geometry



- Vacuum-based detector
  - High-speed connections through pins in ceramic carrier board
  - Heat sink for stable detector operation (~5 W heat removal) needed
  - PCB with socket for detector pins connected to FPGA-based read-out and DAQ via 16 × 10 Gbps links
- Optimized geometry
  - Short photocathode-to-MCP distance preserves impact position information
  - MCP-to-anode distance spreads the electron cloud over a number of pixels

Pixelated anode

- Timepix4 ASIC in 65 nm CMOS **silicon pixel technology**
  - Developed and produced by the Medipix4 Collaboration for hybrid pixel detectors
- Charge sensitive amplifier, single threshold discriminator and TDC based on Voltage Controlled Oscillator
  - 4-side buttable (TSV)
  - Data-driven and frame-based read-out

<table>
<tr><td colspan="3">Technology</td><td>CMOS 65 nm</td></tr>
<tr><td colspan="3">Pixel Size</td><td>55 μm × 55 μm</td></tr>
<tr><td colspan="3">Pixel arrangement</td><td>4-side buttable
512×448 (0.23 Mpixels)</td></tr>
<tr><td colspan="3">Sensitive area</td><td>6.94 cm^2 (2.82 cm × 2.46 cm)</td></tr>
<tr><td rowspan="3">Read-out Modes</td><td rowspan="3">Data driven</td><td>Mode</td><td>TOT and TOA</td></tr>
<tr><td>Event Packet</td><td>64-bit</td></tr>
<tr><td>Max rate</td><td>358 Mhits/cm^2/s</td></tr>
<tr><td colspan="3">TDC bin size</td><td>195 ps</td></tr>
<tr><td colspan="3">Readout bandwidth</td><td>≤163.84 Gbps (16× @10.24 Gbps)</td></tr>
<tr><td colspan="3">Equivalent noise charge</td><td>50-70 e$^-$</td></tr>
<tr><td colspan="3">Target global minimum threshold</td><td><500 e$^-$</td></tr>
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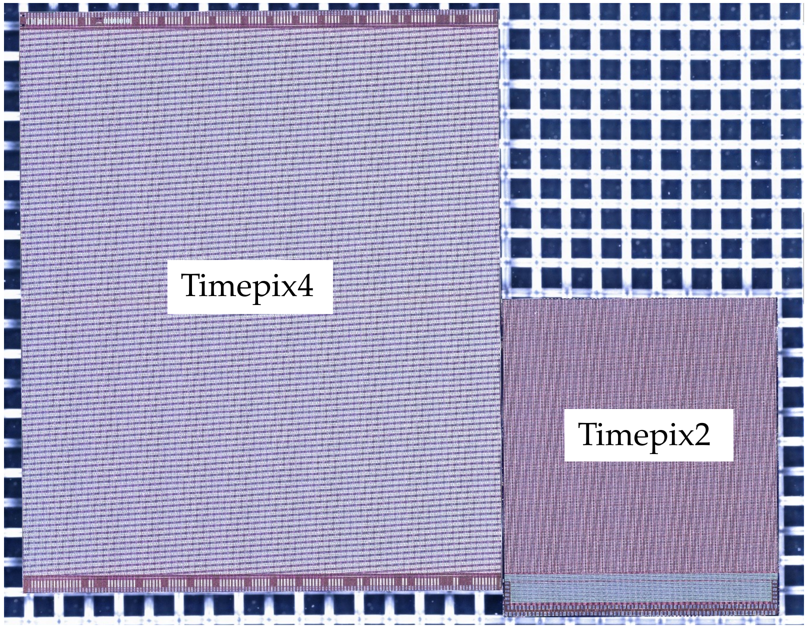
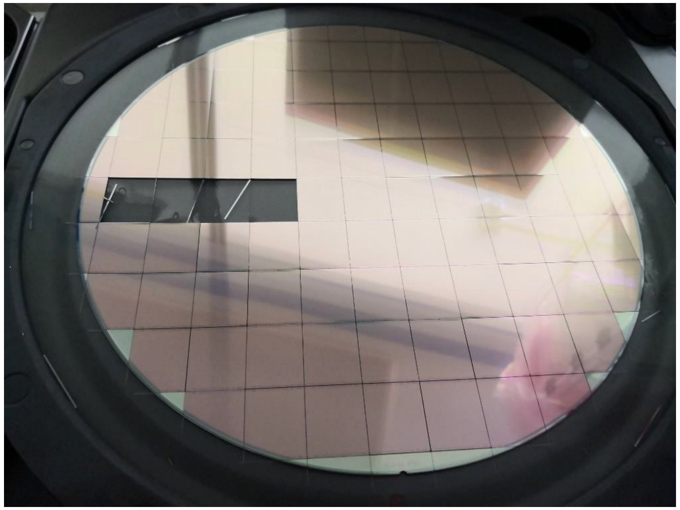
X. Llopart (CERN)

The Timepix4 ASIC





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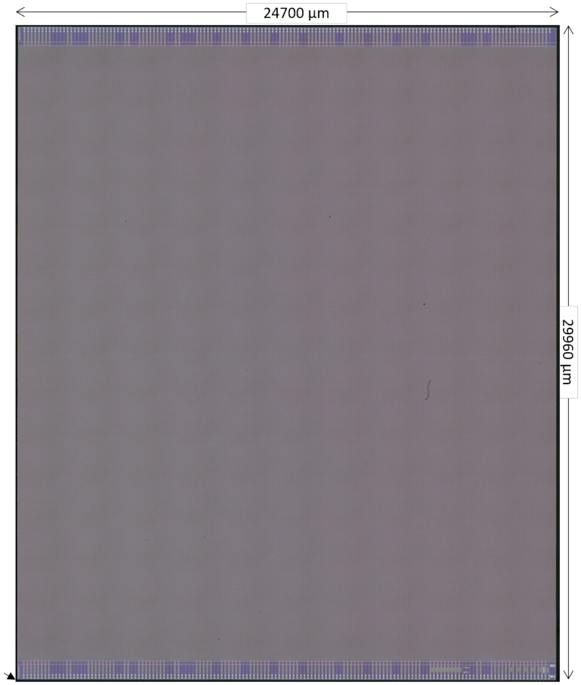
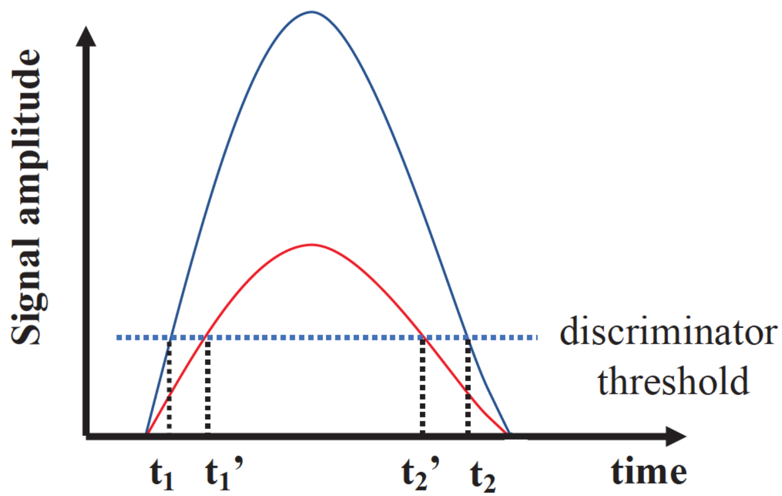
- 65 nm CMOS (TSMC)
- ASIC productions:
  - Timepix4_v0 (Q1 2020)
  - Timepix4_v1 (Q4 2020)
  - Timepix4_v2 (Q4 2021)
  - Timepix4_v3 (Q1 2023)



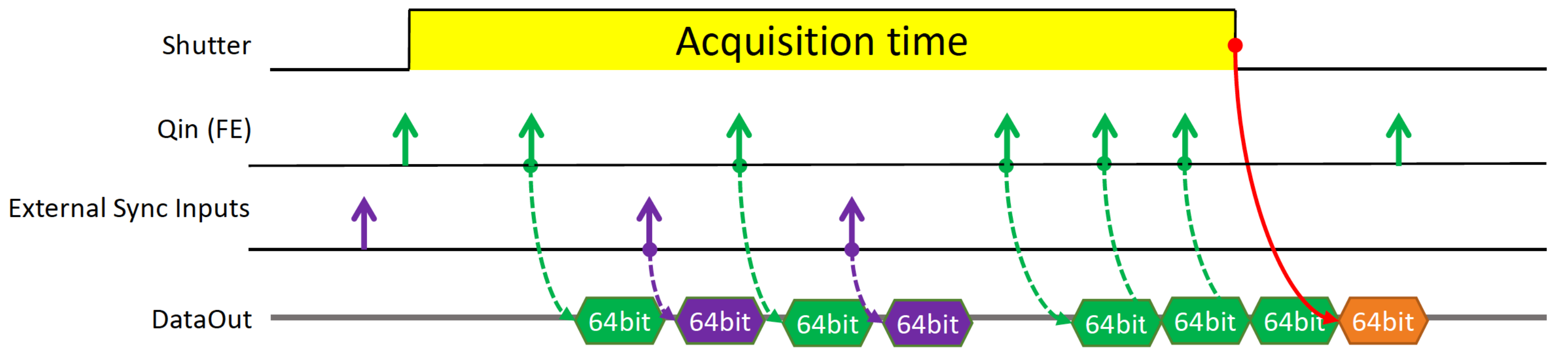
Timepix4 hit measurements

- Measure Time-of-Arrival (ToA=t_1) and Time-over-Threshold (ToT=t_2-t_1)
  - TDC bin size: 195 ps (**56 ps r.m.s. TDC resolution** per pixel)
- Electron cloud spread over a number of pixels → cluster
- Use ToT information (proportional to the charge in a pixel) to:
  - Correct for time-walk effect in every pixel
  - Improve **position resolution** by centroid algorithm
    - Go from $55\mu m/\sqrt{12}$~16μm down to **5-10 μm** (pore spacing)
  - Improve **timing resolution** by multiple sampling
    - Many timing measurements for the same photon → **50-100 ps**



Timepix4 data-driven read-out

- Zero-suppressed continuous data-driven
  - 64-bit words for each hit
  - 16 programmable serial links: total bandwidth from 40 Mbps (2.6 Hz/pixel) to 160 Gbps (10.8 KHz/pixel)
- 4 external inputs to synchronize/align external signals with data



SPEC: Packet specifications ToA/ToT				
Name	**Width**	**MSB**	**LSB**	**Bits**
Top	1	63	63	[63:63]
EoC	8	62	55	[62:55]
SP	6	54	49	[54:49]
Pixel	3	48	46	[48:46]
ToA	16	45	30	[45:30]
ufToA_start	4	29	26	[29:26]
ufToA_stop	4	25	22	[25:22]
fToA_rise	5	21	17	[21:17]
fToA_fall	5	16	12	[16:12]
ToT	11	11	1	[11:1]
Pileup	1	0	0	[0:0]

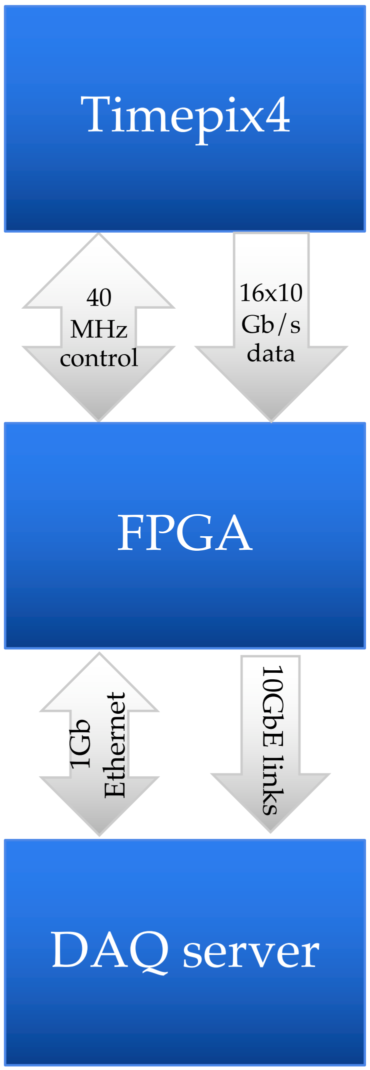
Address: 18 bits (Top, EoC, SP, Pixel)

Time: 29 bits (ToA, ufToA_start, ufToA_stop, fToA_rise, fToA_fall)

Energy: 21 bits (fToA_rise, fToA_fall, ToT)

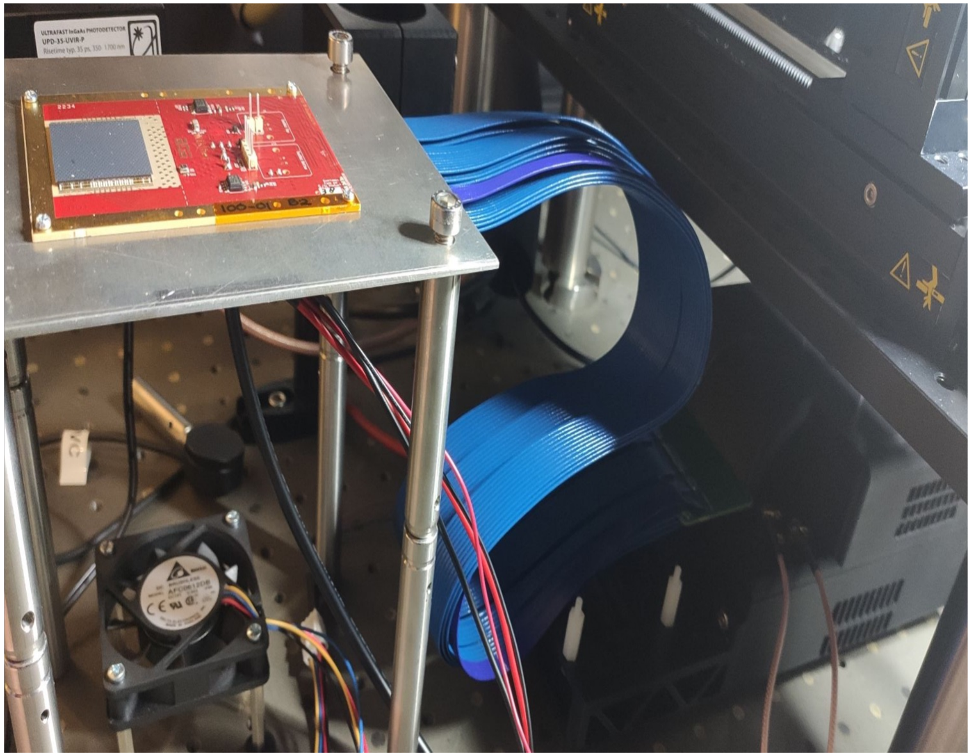
Electronics and DAQ

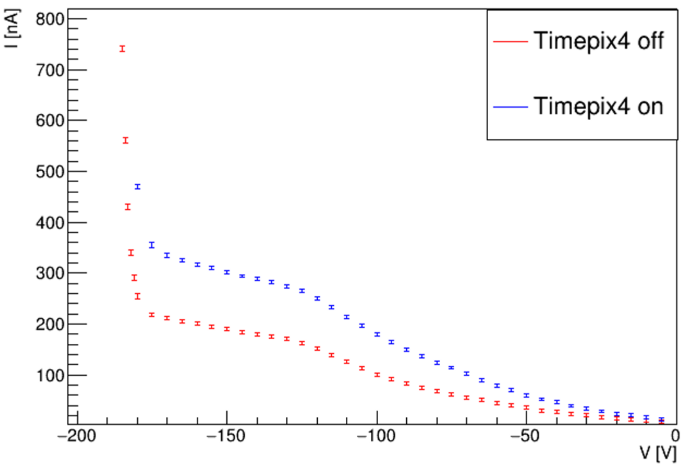
- On-detector electronics
  - Timepix4 ASIC
  - Electro-optical transceivers link the ASIC to an FPGA-based board for the exchange of configuration (slow control) and the collection of event data
  - Regulators, etc.
- Off-detector electronics
  - FPGA far from detector
- The FPGA performs serial decoding and sends the data to a PC for data analysis and storage using fast serial data links



Timepix4 characterization: setup

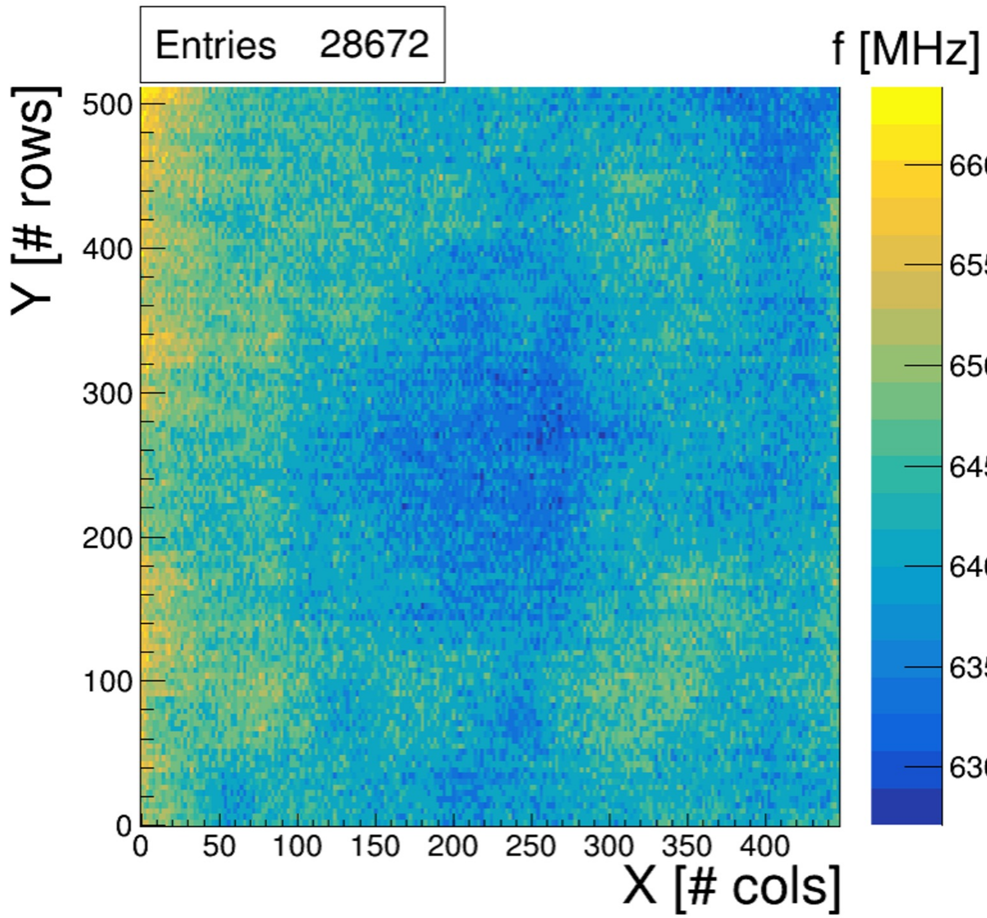
- SPIDR4 control board, developed by NIKHEF
- Timepix4 bonded to a 100 μm n-on-p Si detector biased at -150 V
  - Metallization with holes pattern
  - Courtesy of the CERN and NIKHEF Medipix4/VELO groups





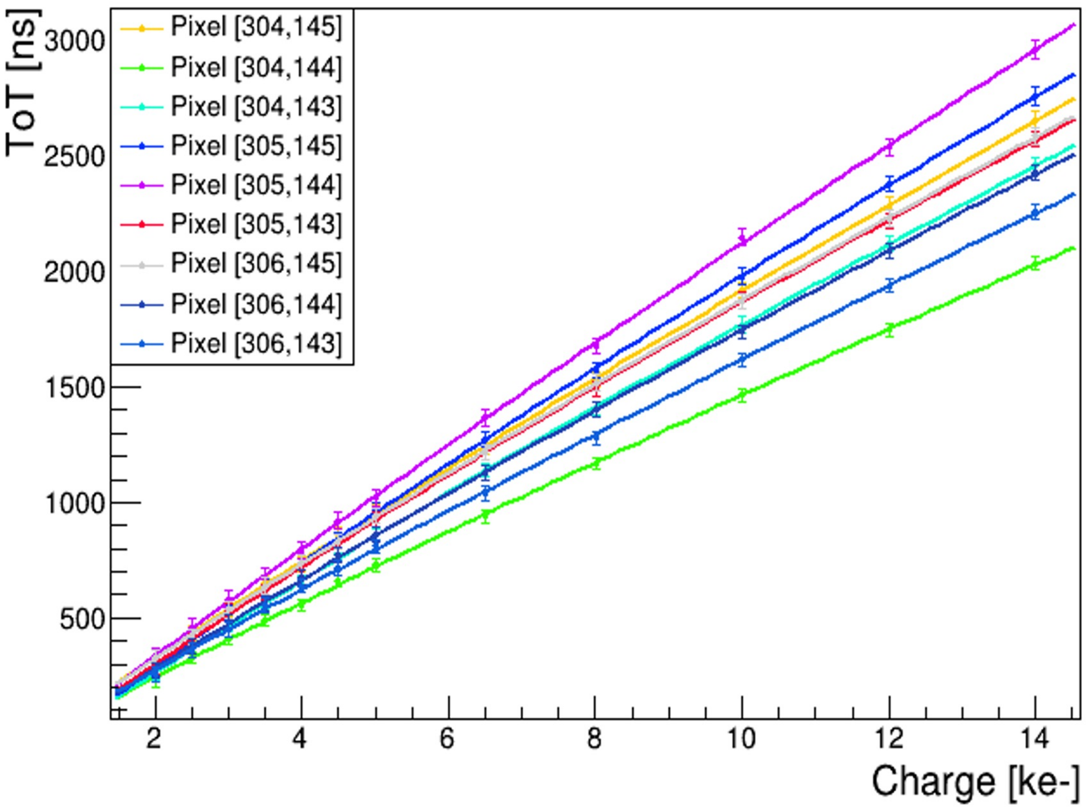
VCO calibration

- VCO of different pixels oscillate with different frequencies
- Finer ToA bins generated with different width
- ToA and ToT measurements heavily affected by this effect
- Internal test pulse tool exploited to calibrate VCO frequencies for the whole matrix
  - ~29 k TDCs based on VCO



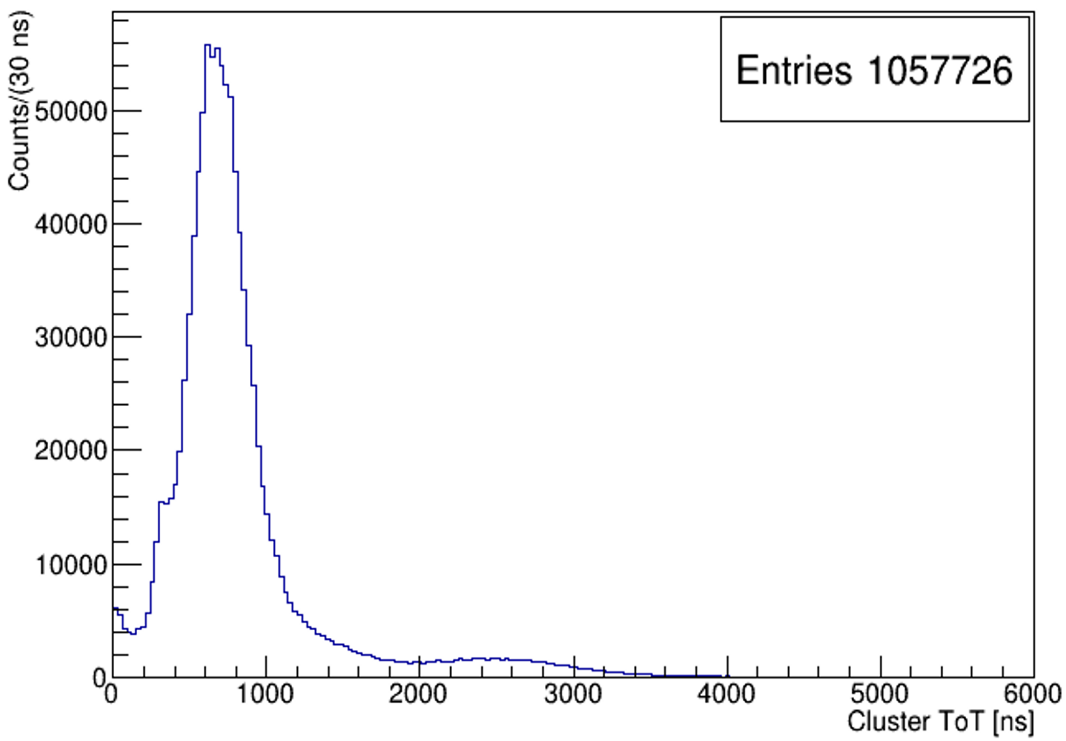
ToT vs Q calibration (1)

- Analog testpulse
  - Non-linear calibration
  - Threshold set to 1 ke-
- Per-pixel calibration done over the whole matrix



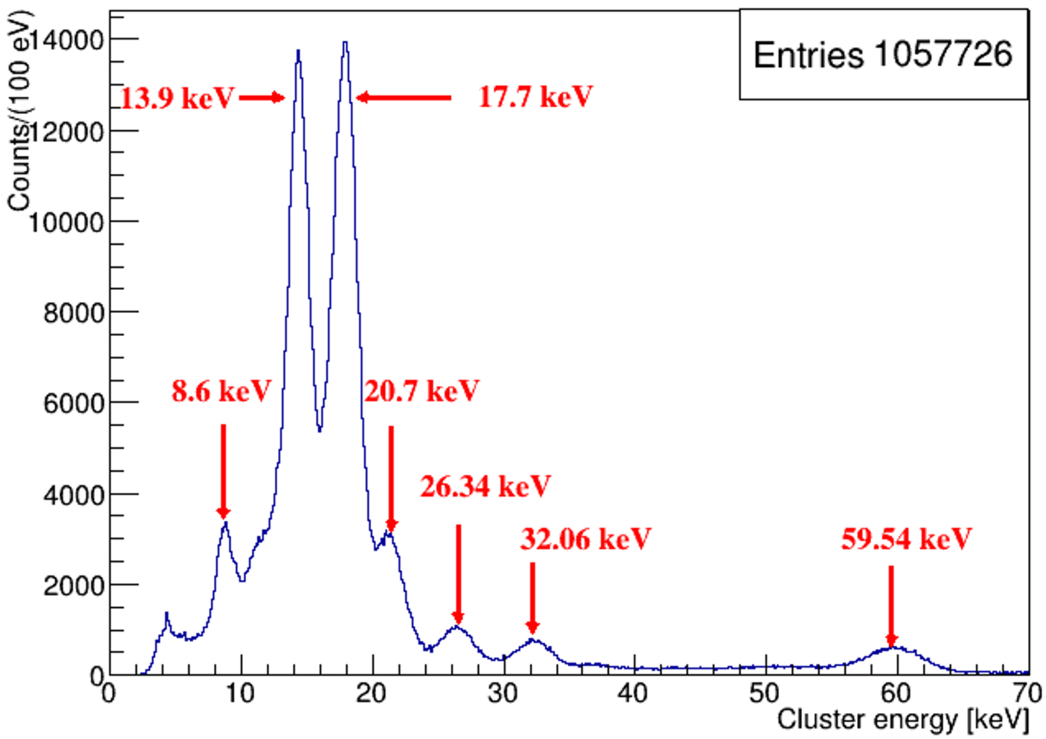
ToT vs Q calibration (2)

- Validation with radioactive sources (^{137}Cs and ^{241}Am superimposed spectra)



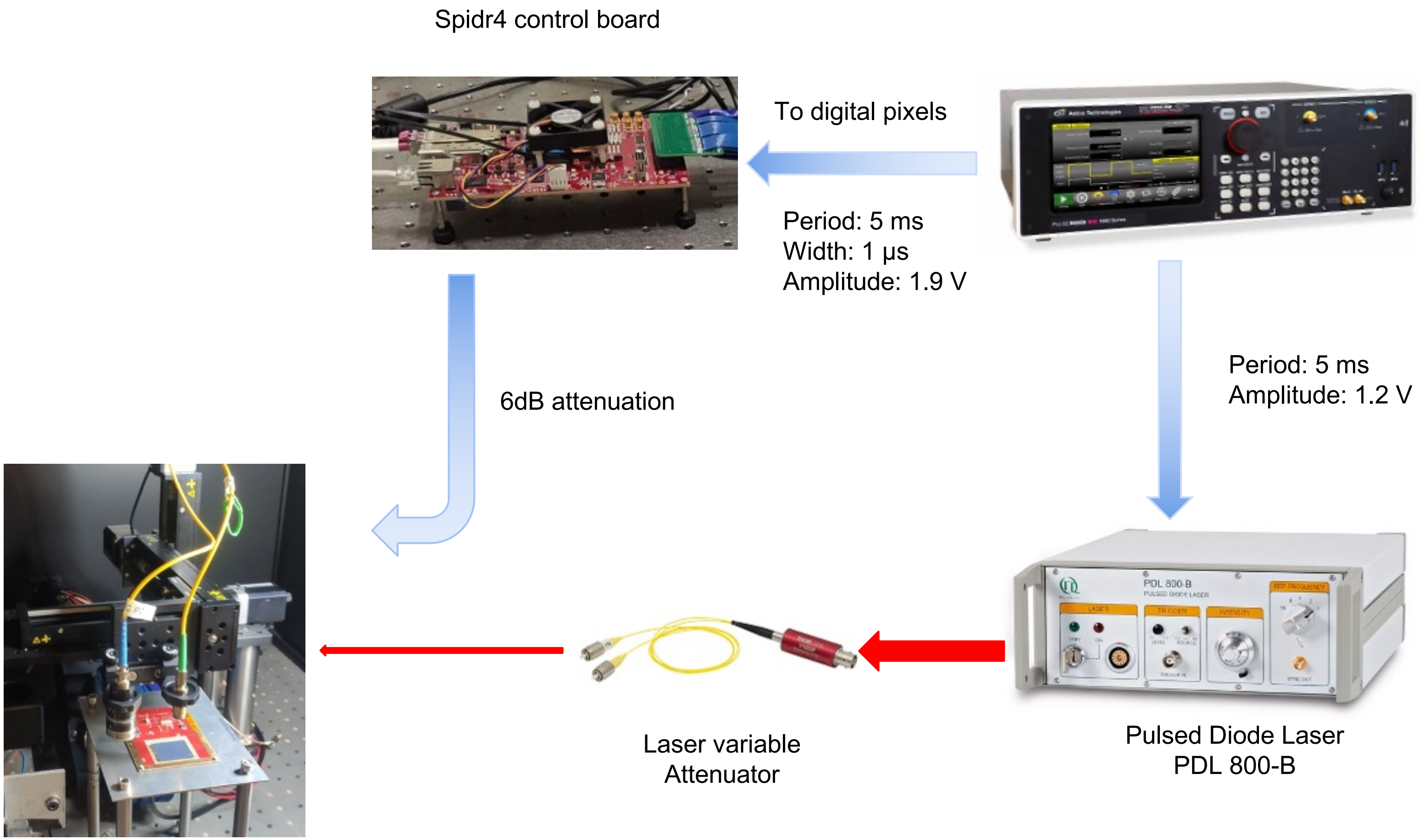
ToT vs Q calibration (3)

- Validation with radioactive sources (^{137}Cs and ^{241}Am superimposed spectra)



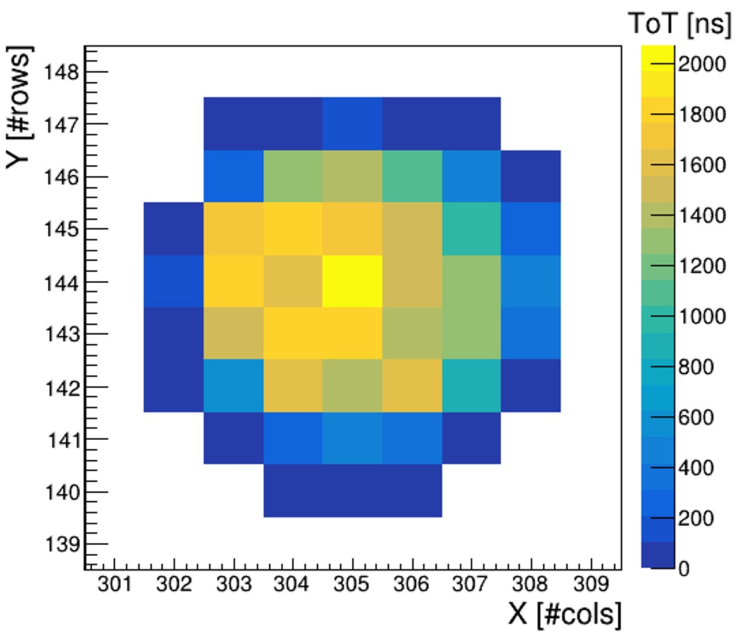
Timing resolution measurement (1)

- Waveform generator: input signal to digital pixels + laser trigger
- Picosecond laser: 1060 nm + variable attenuator
- Linear translation stages: 3D position regulation with μm precision



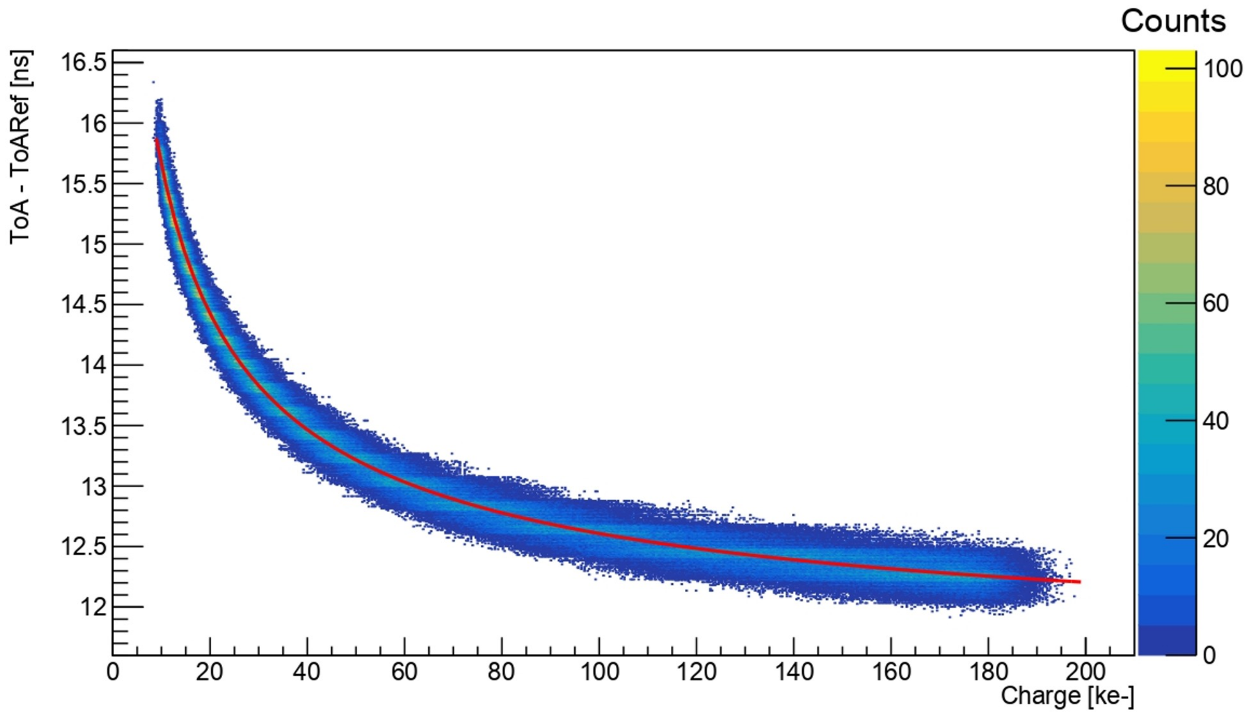
Timing resolution measurement (2)

- Laser focused using micro-collimator:
  - $\sigma = 1.4$ pixel = 77 μm
  - Large cluster (tens of pixels)
- Laser spot in fixed position for all presented measurements



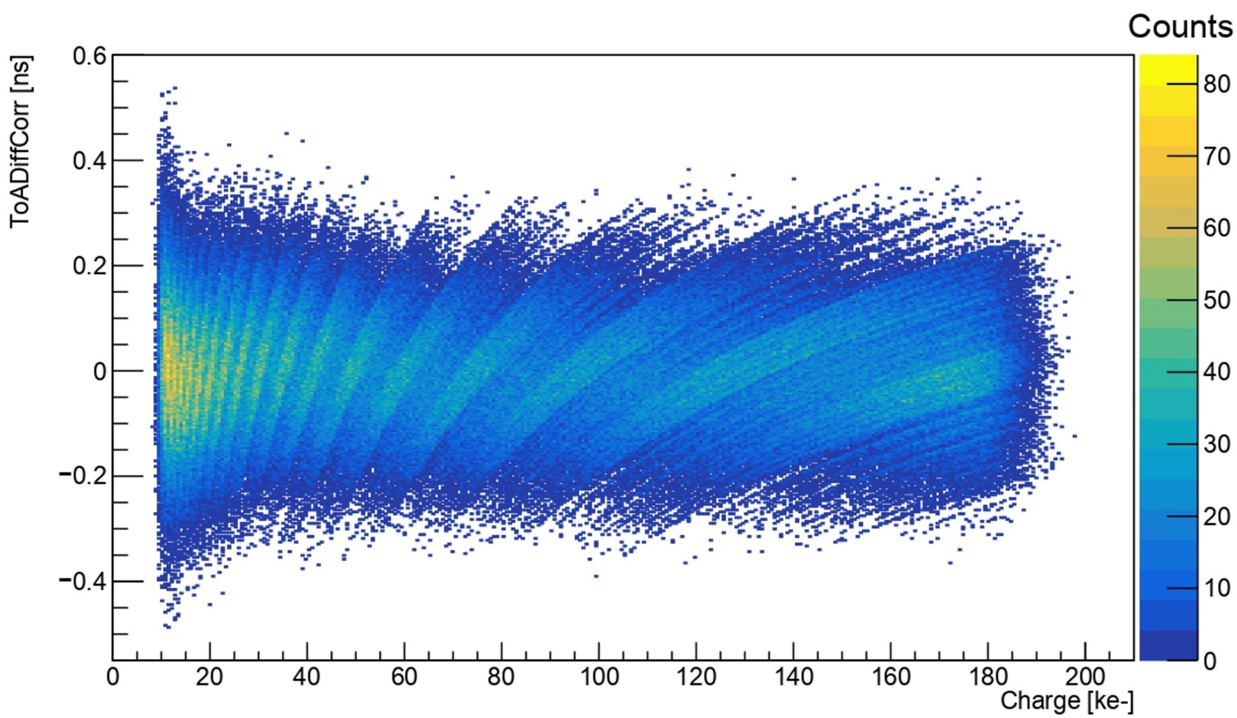
Timing resolution measurement (3)

- Single pixel timing resolution
- Measurements using variable laser attenuation, populating a wide ToT range on each pixel
- Different time walk trends on different pixels
- Time walk corrected separately on each pixel



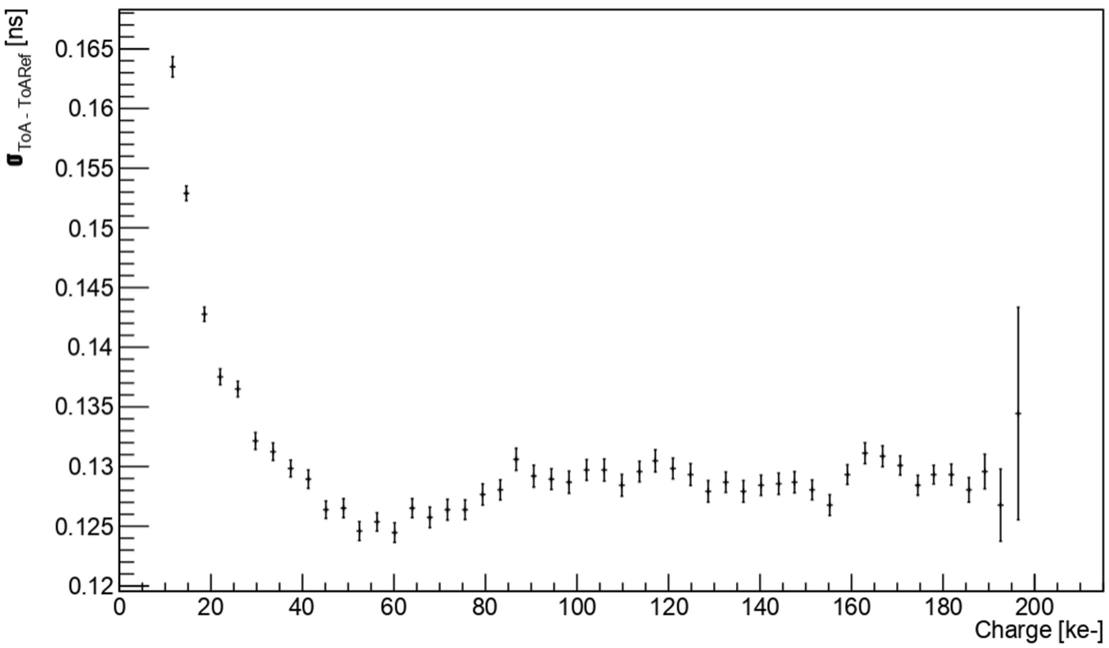
Timing resolution measurement (4)

- Single pixel timing resolution
- Measurements using variable laser attenuation, populating a wide ToT range on each pixel
- Different time walk trends on different pixels
- Time walk corrected separately on each pixel



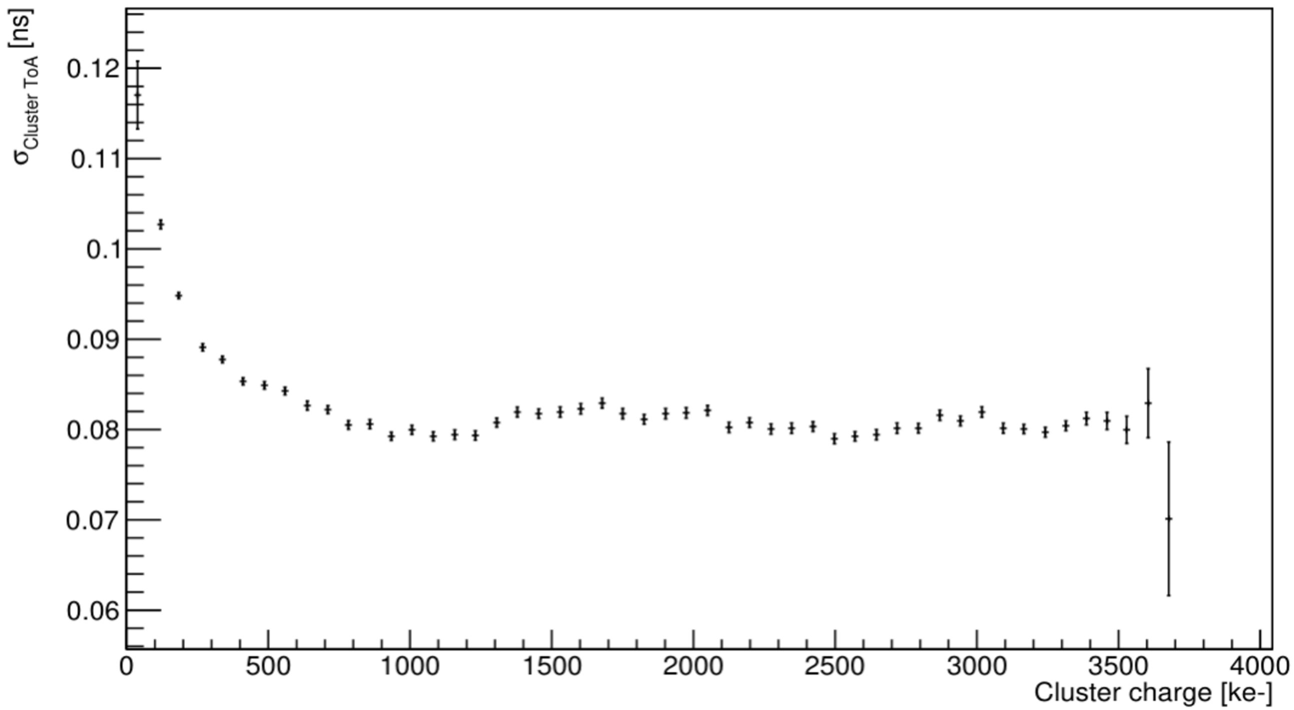
Single pixel timing resolution

- ToT vs charge calibration applied to each pixel
- Distribution divided into "vertical" slices (narrow range of charges)
- Timing resolution values extracted for each slice
- Distribution of timing resolution as a function of injected charge
- For **single pixel** [305,144], where the laser is focused, the standard deviation saturates at 129±1 ps r.m.s. → subtracting the contribution of the reference TDC (60 ps), a resolution of **113±1 ps r.m.s.** is obtained



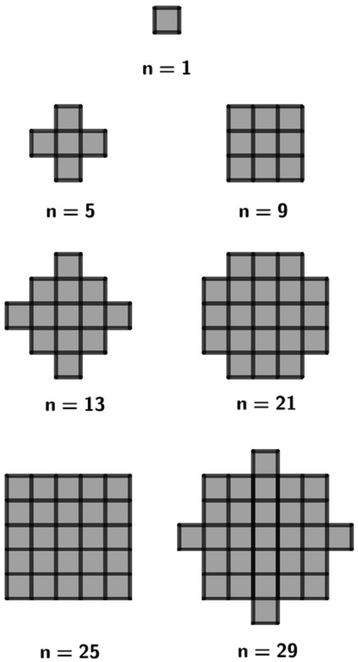
Cluster timing resolution

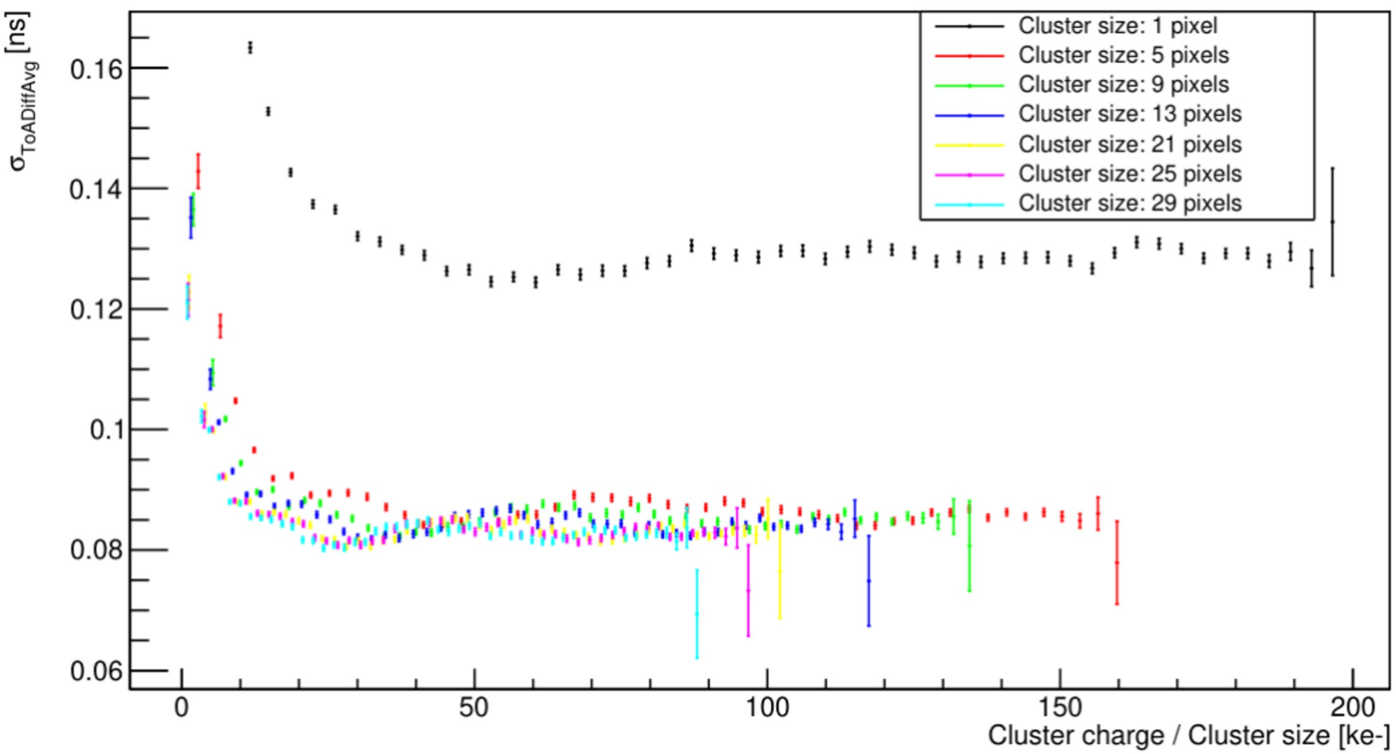
- For each cluster, the weighted average of ToA (using charge as weight) plus cluster charge are computed
- Timing resolution dependence on cluster charge:
  - Best result: 79 ± 1 ps r.m.s.
  - **Cluster timing resolution** is obtained subtracting the contribution of the reference TDC (60 ps): **49 ± 1 ps r.m.s.**



Timing dependence on cluster size

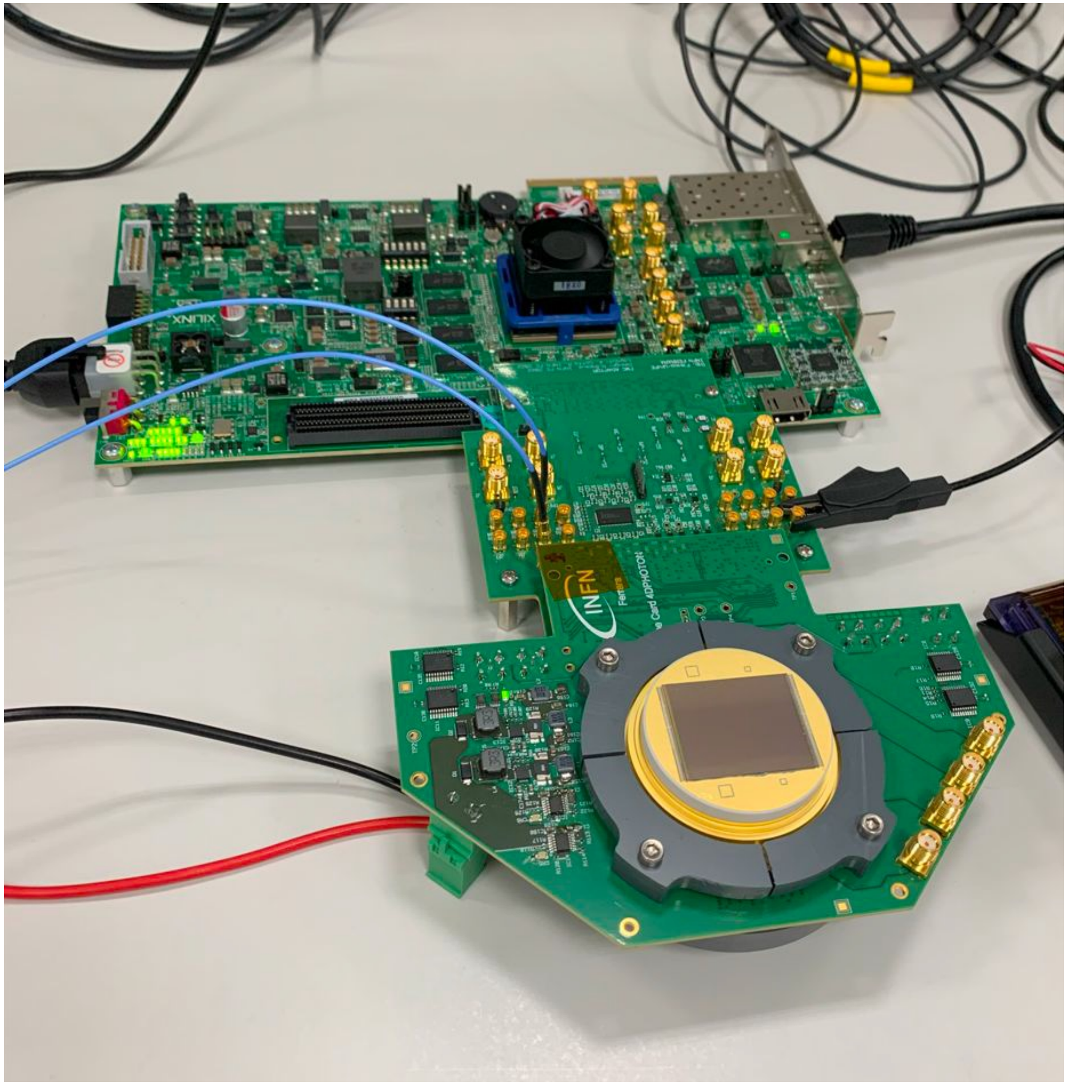
- Artificial selection of variable cluster size by excluding external pixels from the analysis
  - Large improvement going from 1-pixel clusters to 5-pixels clusters (oversampling)
  - Small or negligible improvement increasing further the cluster size (optimal cluster dimension for MCP detector: tuning of parameters)





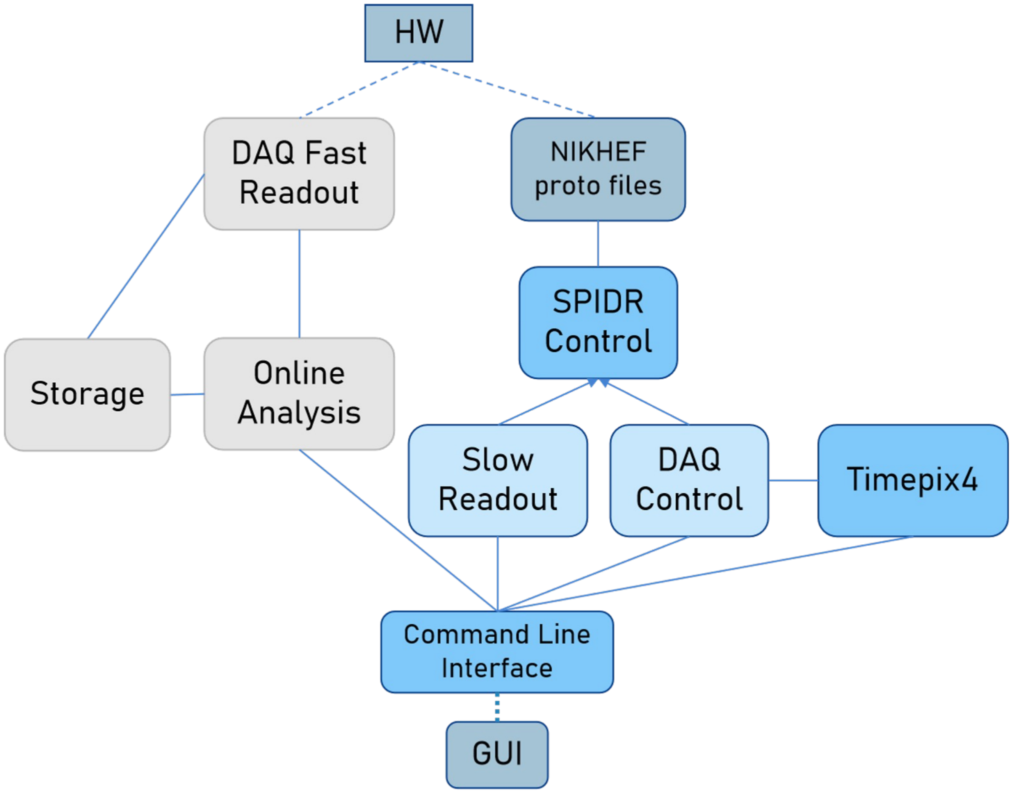
Ceramic carrier and DAQ system

- DAQ system developed at INFN Ferrara based on Xilinx FPGA dev. kit KCU105
  - Slow control (1 GbE)
  - 2x 2.56 Gbps fast links readout (10 GbE) under development
  - Chipboard to dev. kit adapter produced
- Ceramic carrier produced
  - Multi-layer ceramic PCB produced by Kyocera
  - Timepix4 glued and wire-bonded
- Complete system commissioned



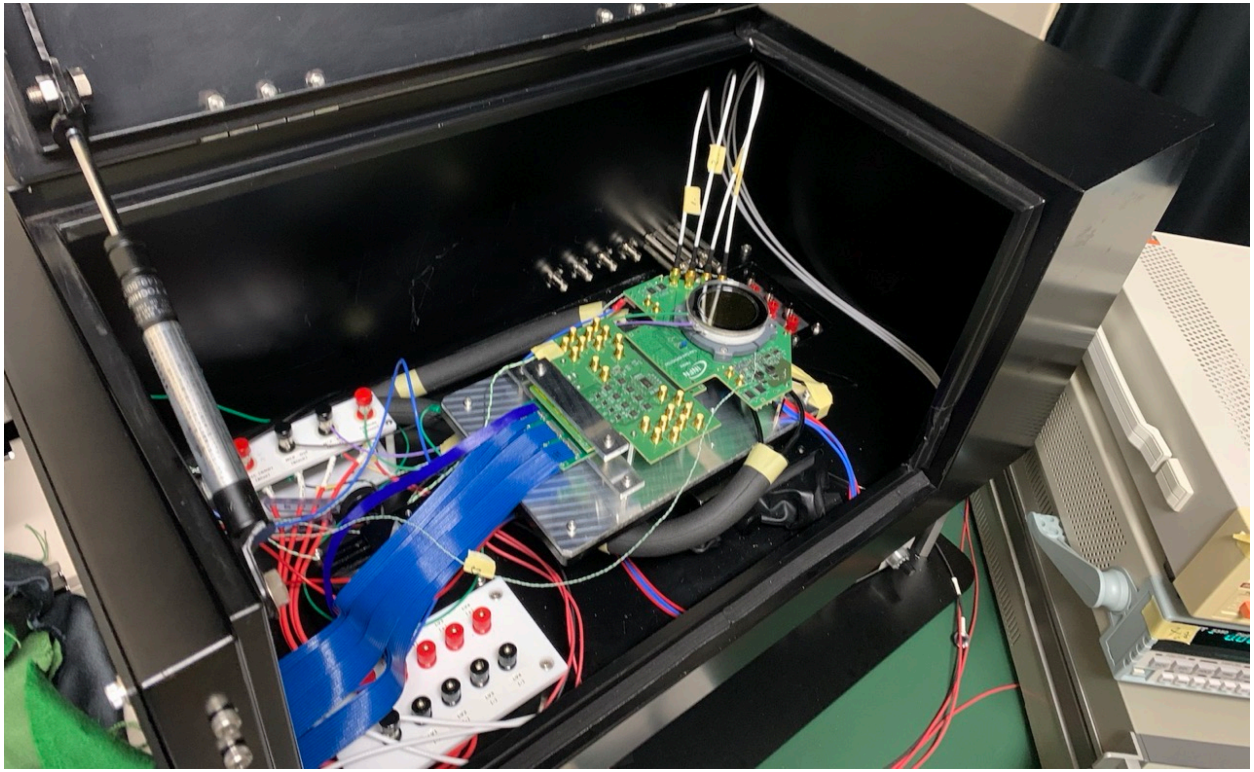
Software

- Dedicated software developed at INFN Ferrara
- C++ based
  - Low-level
  - Object-oriented
- Readout and Control in unique CLI
- Read and Write register functions
- Application Programming Interfaces for Timepix4
- Packets decoder



First 4DPHOTON prototype

- Production of 4DPHOTON prototypes at Hamamatsu Photonics
  - Syntetic silica window; 2-stage MCP stack (6 μm channel diam.)
  - S-20 multialkali photocathode
    - ~30% QE at 380 nm and DCR of ~300 cps/cm^2 expected
  - Systematic characterization starting next week in INFN Ferrara



Plans for IOTA/FAST (1)

- Create a beam diagnostics and monitoring system for IOTA/FAST enabling multiple experiments within the IOTA experimental program
  - Photodetector installed in dark box on top of one IOTA dipole magnet to measure synchrotron radiation emitted by the circulating electron beam
- The detector can provide simultaneously the X-Y coordinates of each individual photon and its time of arrival with respect to a reference time and shutter
  - Precise position resolution of 5-10 μm will allow precise measurement of transverse beam profile
  - Photon arrival time (ToA) measured with expected time resolution of 50-100 ps over extended time intervals
  - Time measurement with respect to the beam revolution marker can yield precise information on longitudinal beam profile and turn number

Plans for IOTA/FAST (2)

- Short term goals:
  - Installation, commissioning and operation of detection system using single electron beam, to validate performance as beam diagnostic tool
  - Beam parameters (such as transversal and longitudinal profile and turn number) will be measured offline
  - Study of complete single electron dynamics (in 6 dimensions)
  - Online measurement of beam parameters
    - Prototype online monitoring system developed and tested (see animated GIF attached to Indico --> measurement done at Trieste Elettra Synchrotron using monochromatic X-ray beam onto a 300 μm thick Si assembly with Timepix4)
- Medium term goals:
  - Interfacing the online beam information with ACNET
  - Measurements using many electrons per bunch
- Our interest in other specific measurements
  - Study of angular correlation in dipole and undulator radiation
  - Study of single electron interference pattern (e.g. using Mach-Zehnder inter.)
  - Measure transversal and longitudinal beam profiles before and after OSC

Conclusion

- A hybrid MCP-PMT based on the Timepix4 ASIC is proposed to be used in IOTA as beam monitoring system providing simultaneuos transversal and longitudinal beam profile
- Advantages of proposed detector compared to state-of-the-art:
  - Simultaneous measurement of single photons with 5-10 r.m.s. μm position resolution and 50-100 r.m.s. ps timing resolution, over large area (7 cm^2) with small noise and large hit-rate capabilities
  - Complete integration of sensor and electronics: on-detector signal processing, digitization and data transmission with large number of active channels (~230 k active pixels in 7 cm^2), with limited number of external interconnections (~200)
- Letter of Intent for IOTA will be submitted soon

This project receives funding from the FARE 2020 initiative (Prot. R20AJ4BNAM) of the Italian Ministry of University and Research (MUR), and from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (Grant agreement No. 819627).

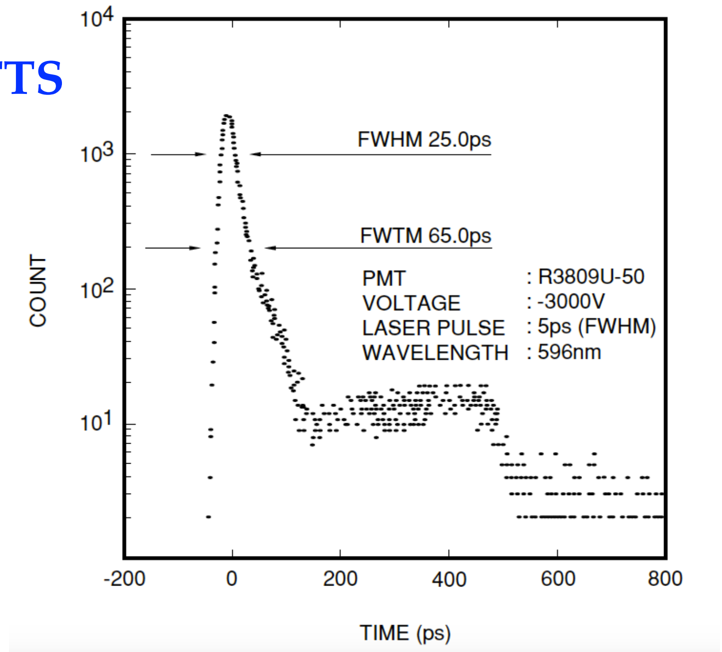

THANK YOU
FOR YOUR ATTENTION

Time resolution contributions

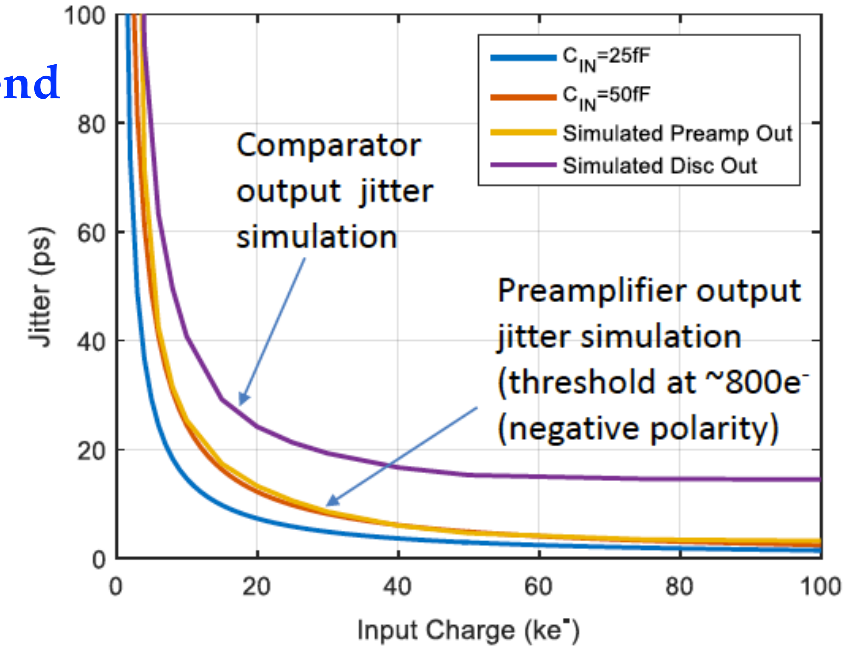
$$\sigma_{time} = TTS \oplus \sigma_{front-end} \oplus \sigma_{TDC}$$

- Contributions:
  - TTS (Transit Time Spread) of electrons: 25 ps FWHM
  - Front-end: <30 ps for input charge >10^4 e^-
  - TDC contribution: 56 ps (195 ps bin size/√12)
- Time resolution for **1 pixel**: **70 ps**

TTS

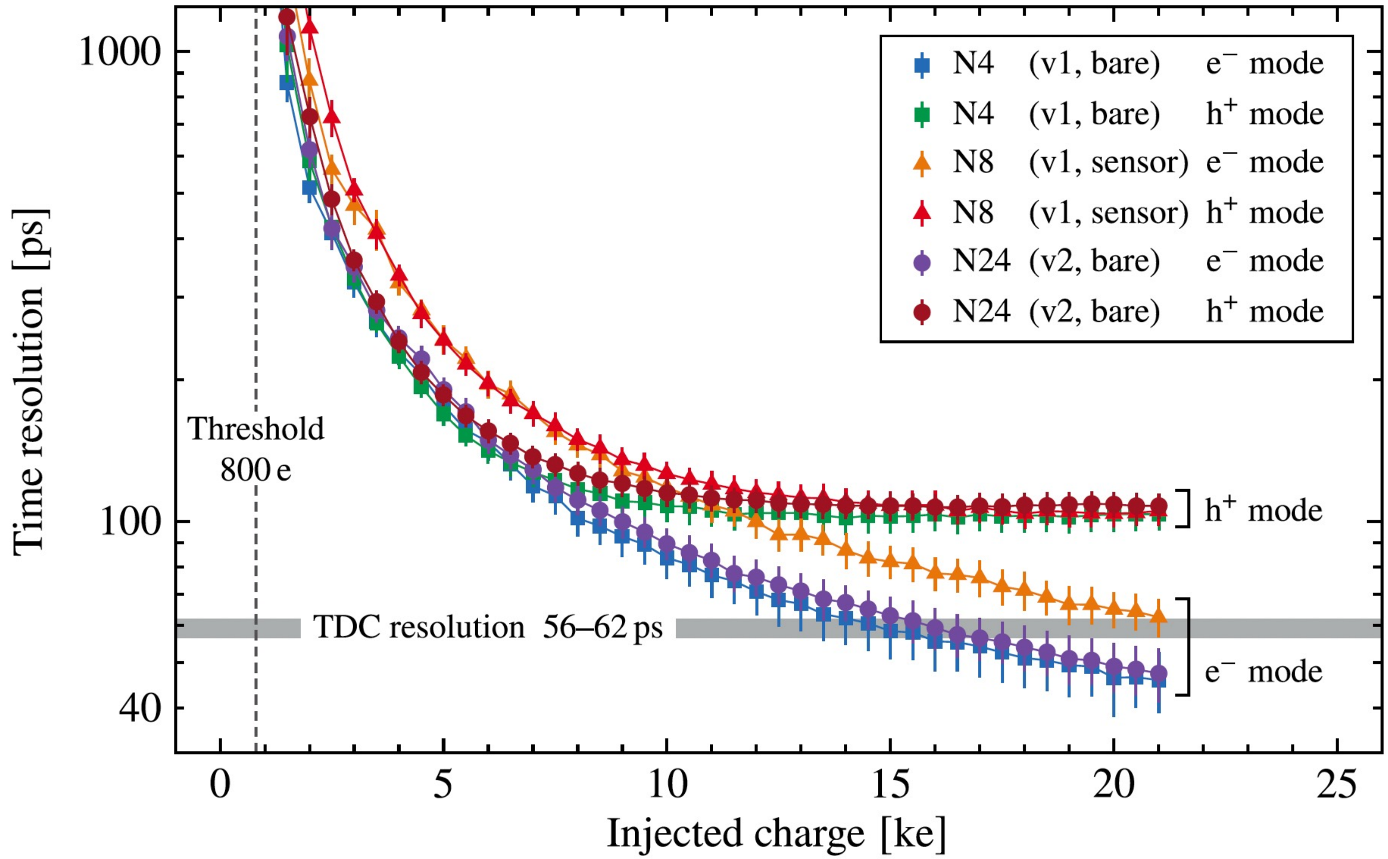


Front-end



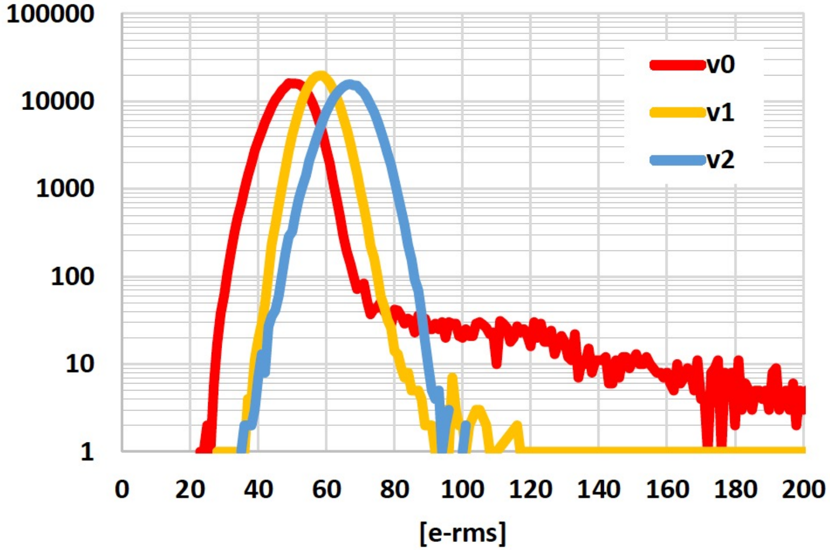
Analog front-end time resolution

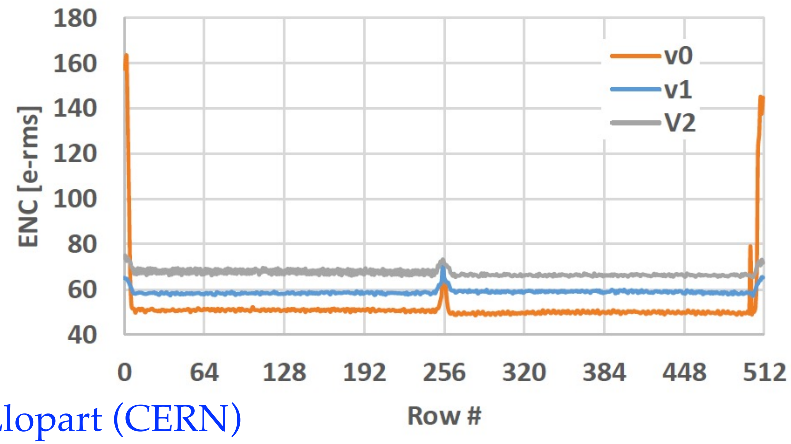
- Measurement of mean time resolution of the analog front-end as a function of injected charge for various devices and both polarity modes
  - K. Heijhoff et al., "Timing performance of the Timepix4 front-end", JINST 17 P07006 (2022)

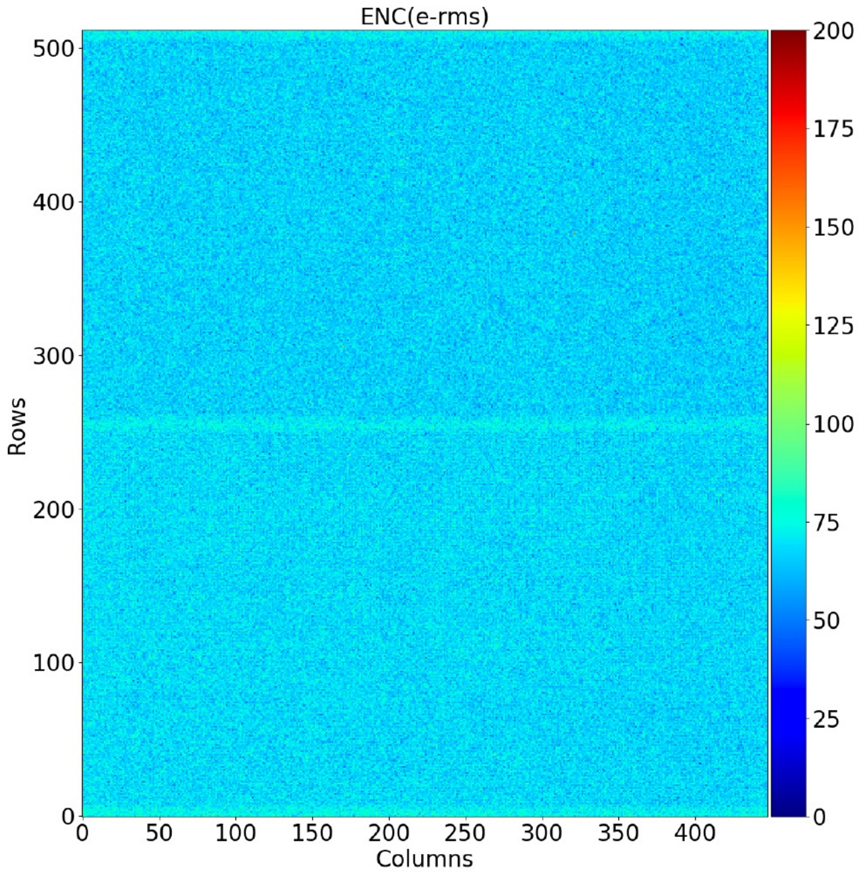


Timepix4 noise

- Equivalent Noise Charge (ENC) for v0, v1 and v2





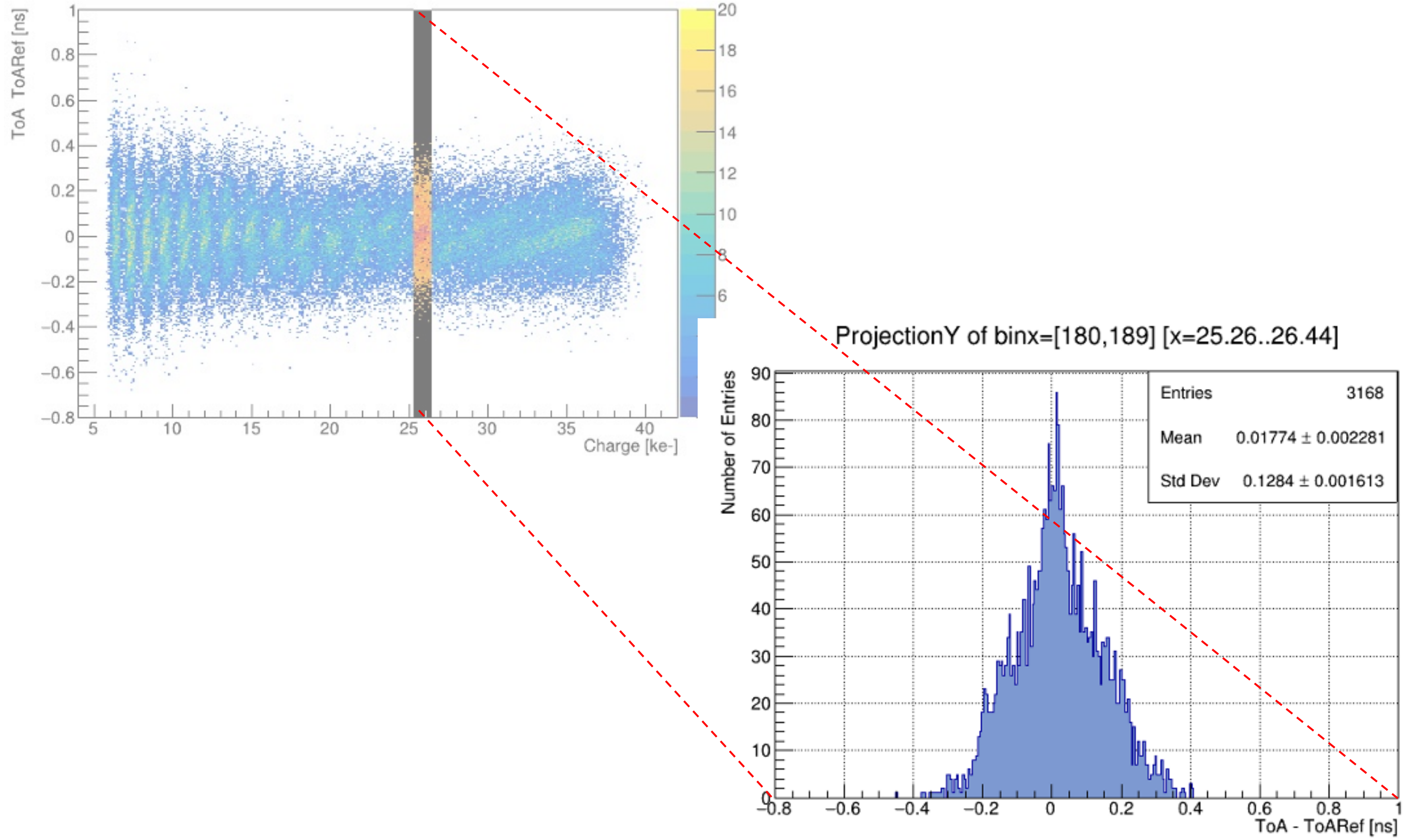


X. Llopart (CERN)

With a Si sensor the noise slightly increase ~3e$^-$ / pixel

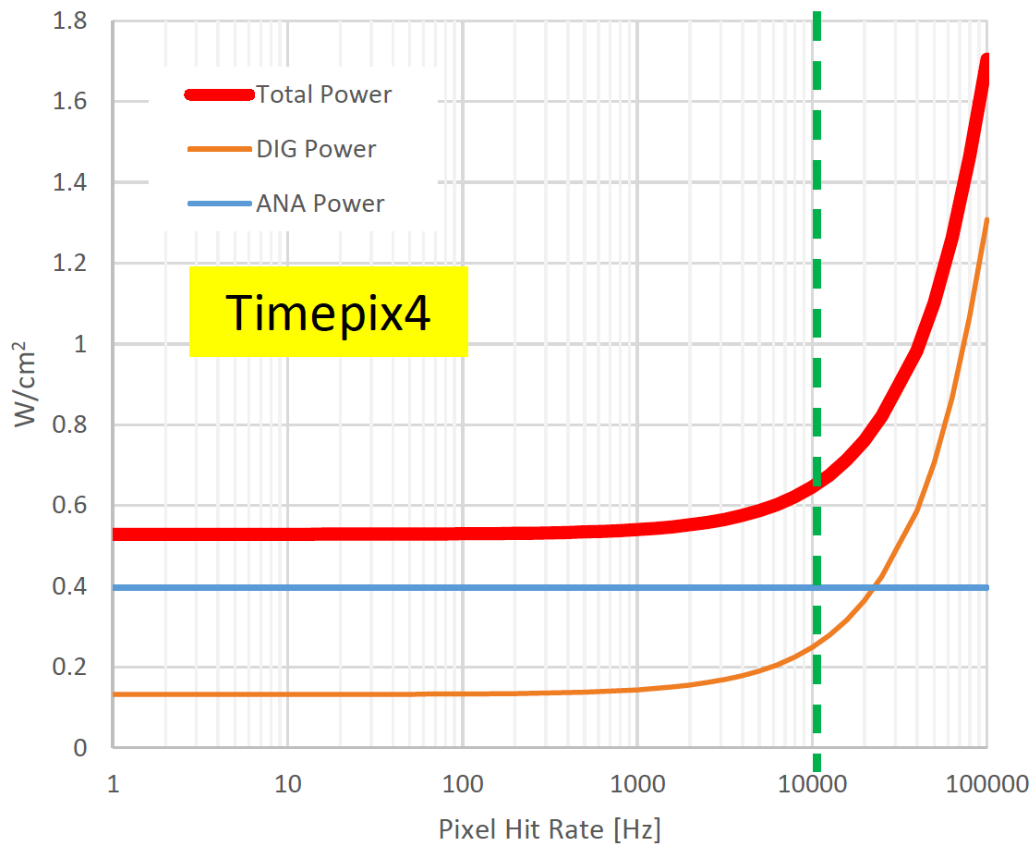
Timing resolution: time slices

- ToT vs charge calibration applied to each pixel
- Distribution divided into “vertical” slices, each one selecting a narrow range of charge
- Timing resolution values extracted for each slice



Power consumption and cooling

- Timepix4 power consumption (~5 W)
- Goal: stable operation with 20 °C inside the vacuum tube
  - Cold "finger" attached to ceramic carrier



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