Hybrid single-photon detector based on microchannel plate and the Timepix4 ASIC as pixelated anode

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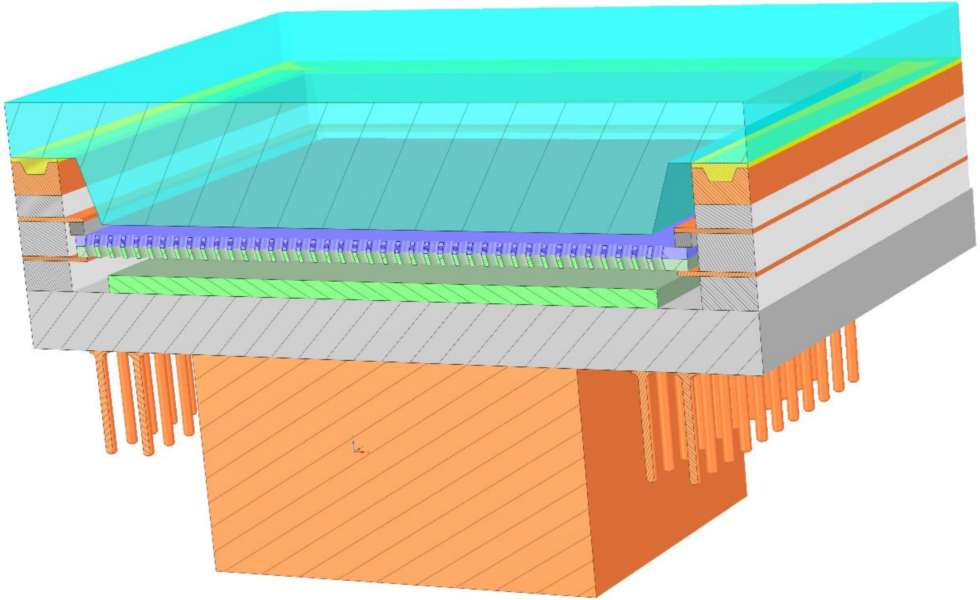
Overview

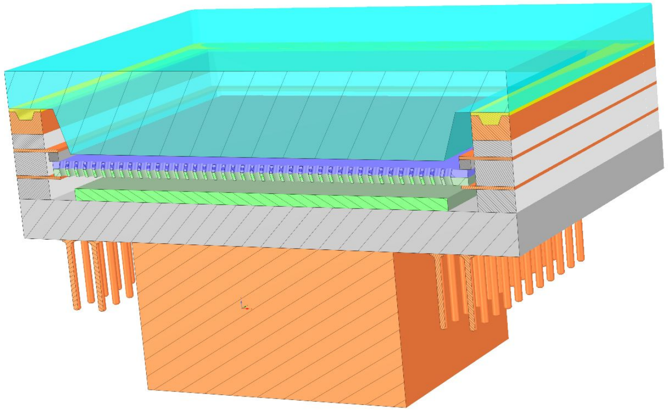
- Detector concept
- The Timepix4 ASIC
- Expected performance
- DAQ system
- Results on detector components



The ‘hybrid’ detector [M. Fiorini et al. JINST 13 (2018) C12005]

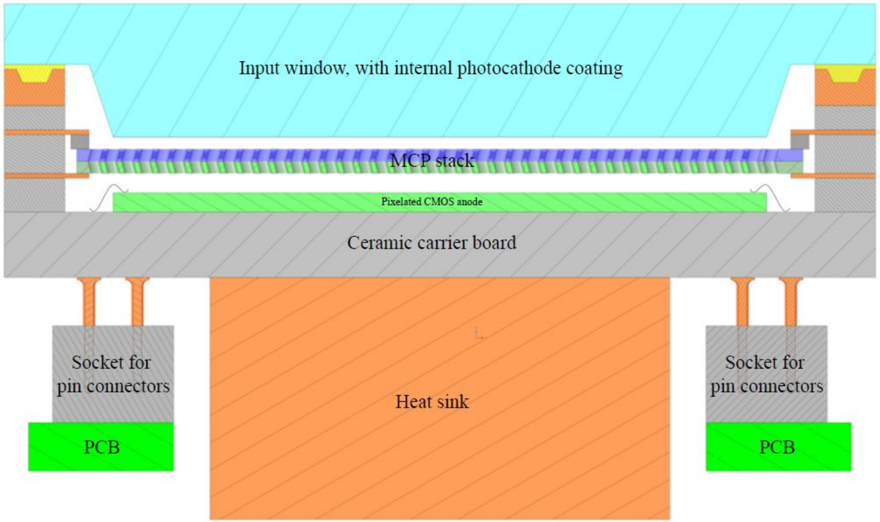
We are developing a single-photon detector:

- based on a vacuum tube
- transmission photocathode with high QE in the spectral region of interest
- micro-channel plate stack
- a pixelated CMOS read-out anode with integrated front end electronics



Timing resolution	few 10 ps
Position resolution	5-10 µm
Maximum rate	10^9 hits/s
Dark count rate	10^2 counts/s
Active area	~7 cm^2
Channel density	0.23 M channels

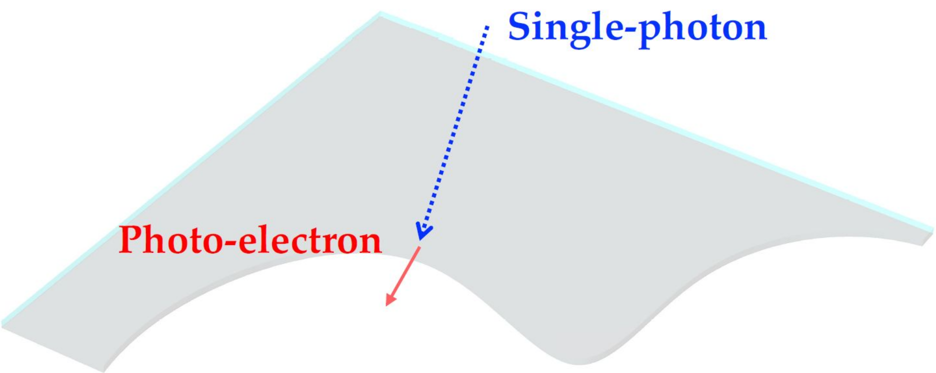
The detector assembly



On the left: cross-section of the detector assembly

- Vacuum-tube based detector
  - Assembly under high vacuum
  - Assembly and bonding to minimize distance between components
- High-speed connections through pins in ceramic carrier board
  - custom PGA - 2.54 mm pitch
- Socket for detector I/O and low voltage
- Heat sink under AISC
  - Assembly < 20° C with ASIC @ peak power
- PCB allows connection to FPGA-based DAQ system

The hybrid detector: entrance window + photocathode

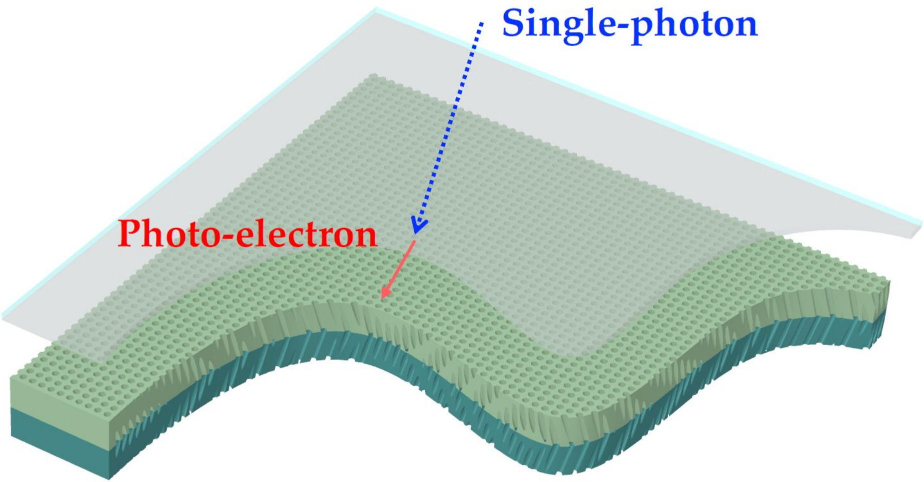


Photon conversion using high Quantum Efficiency (QE) Photocathode

- E.g. bialkali photocathode
  - 30-50% QE
  - ~10^2 Hz dark count rate @300 K
  - Best for timing
- Flexible design allows to use different photocathodes

The hybrid detector: MCP stack

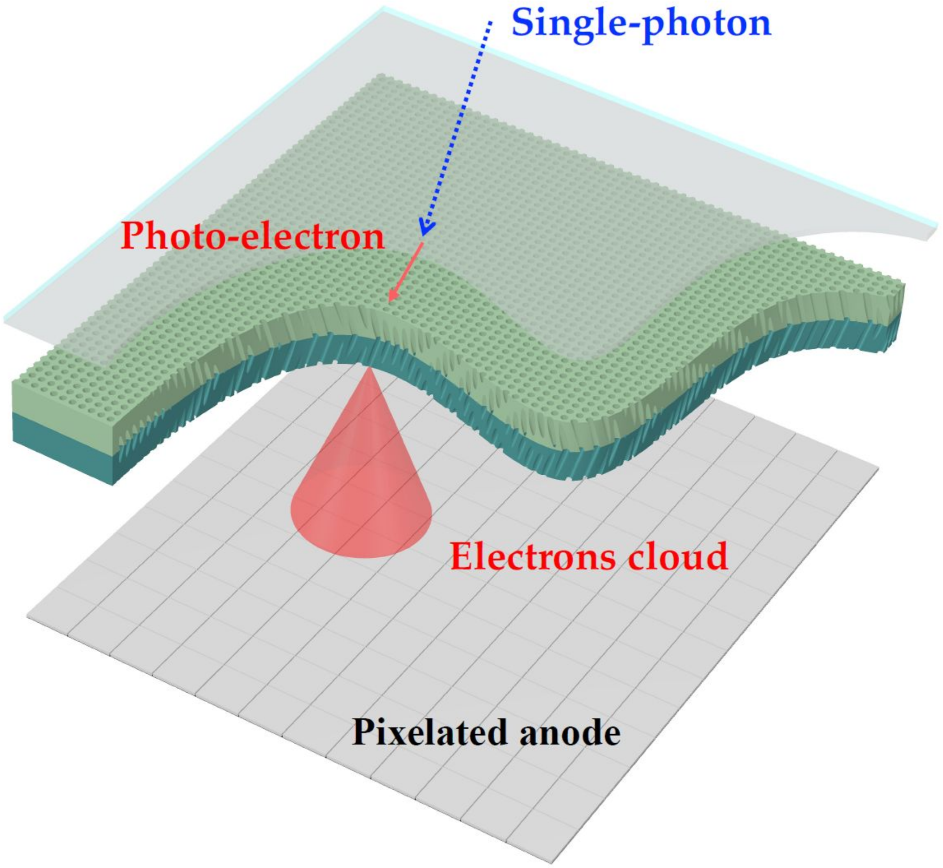
- Microchannel plate stack (chevron)
  - dual or triple stack
    - > 10^4 gain
  - 5-10 μm pore size
- Possibility of atomic layer deposition for increased lifetime:
  - >30 C/cm^2
- Proximity focus
  - Short distance from MCP to cathode and anode for best time and position resolution



The hybrid detector: active anode

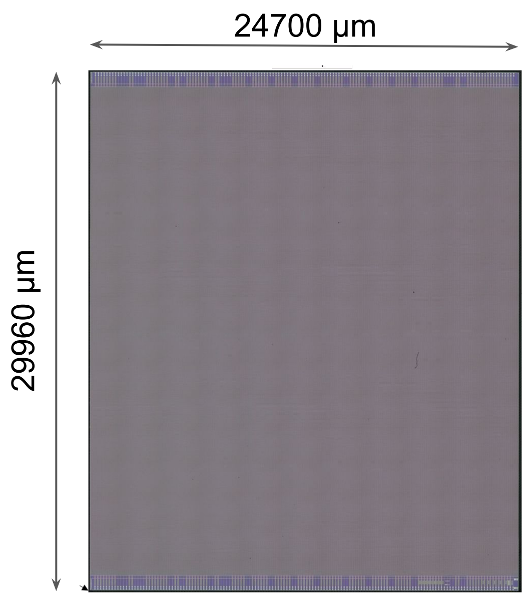
Pixelated anode:

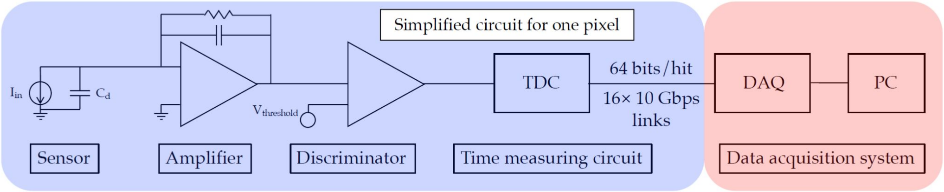
- Electron cloud spread over a number of pixels
- Anode is an ASIC that integrates digital and analog front-end
  - pixels coordinates
  - pixels Time of Arrival (ToA)
  - pixels Time over Threshold (ToT)



The hybrid detector: active anode [X. Llopart et al 2022 JINST 17 C01044]

- Timepix4 ASIC in 65 nm CMOS
  - Developed by Medipix4 collaboration
- 512 ✕ 448 pixels (55 μm ✕ 55 μm pitch)
- Large active area: 7 cm^2
- Bump pads used as anode





Signal from MCP amplified and discriminated

- Time-stamp provided by Time-to-Digital Converter (TDC)
  - 195 ps bin size for ToA
    - ~ 56 ps r.m.s. resolution
  - 1.56 ns bin size for ToT
- High rate capability:
  - maximum bandwidth: 160 Gb/s
  - maximum hit rate: 2.5 Ghits/s
- Output:
  - 64 bits of data per hit with 64b/66b encoding
- transmitted via 16 high-speed links up to 10.24 Gbps

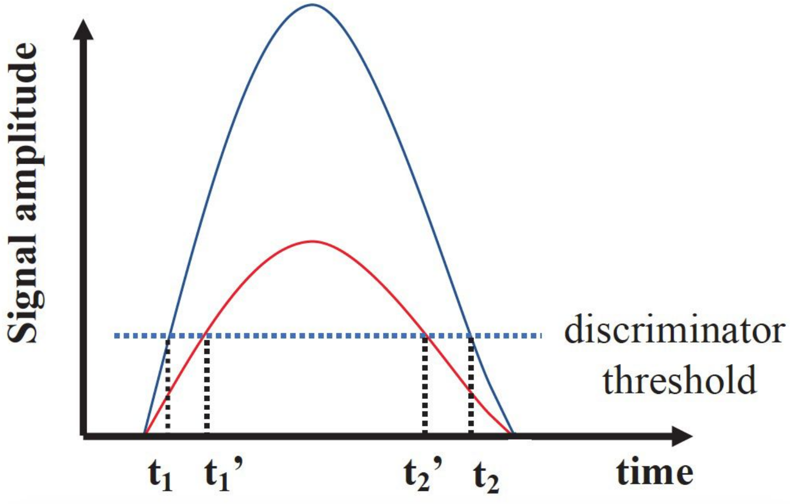
Improving the Timepix4 resolution

For each pixel, it provides combined measure of:

- Time-of-Arrival [t1]
- Time-over-Threshold [t2 - t1]

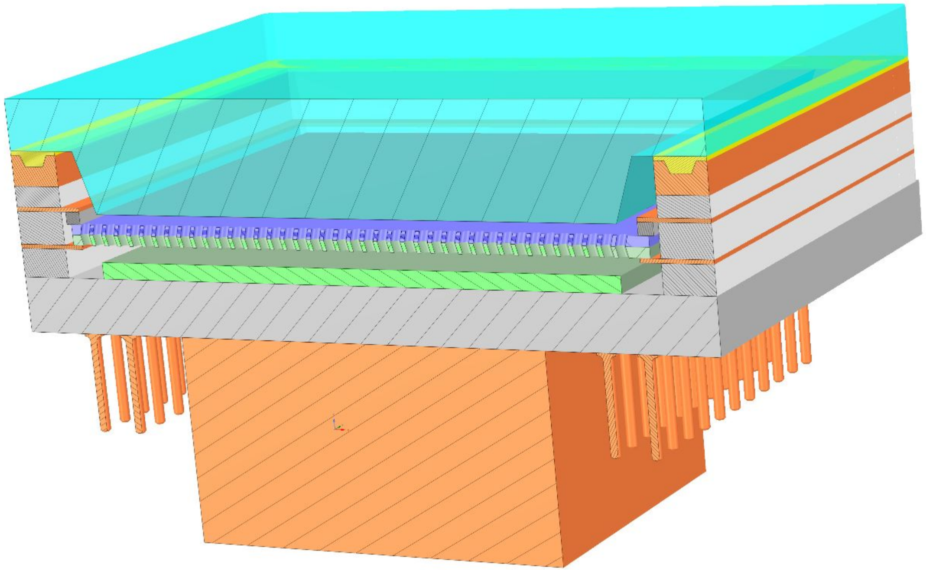
Time over Threshold used to:

- Correct for time-walk effect [t1- t1']
- Improve resolution on cluster centroid
  - ~16µm → ~5µm
- 3D clustering (space and time)
  - Improve timing resolution by multiple sampling
  - Cluster Time of Arrival Resolution few 10s ps

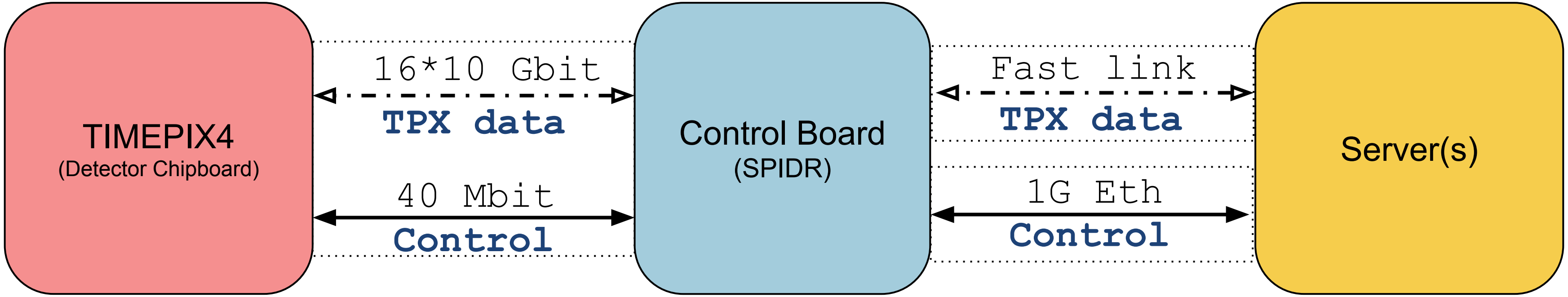


Design status

- Thinned (300 μ) Timepix4 v2 ASIC available:
  - Behaviour well understood
  - CERN working on single chip probing
- Ceramic carrier
  - First prototypes received in July 2023
  - Fully characterised
  - Already integrated with Timepix4 v2
- Tube design ongoing
  - estimated production 2024



The Data AcQuisition (DAQ) system



DAQ system composed by:

- **Detector and Front-End** (Timepix4) **Signal collection** and **digitization**
- **Control Board** (SPIDR) **Data-handling**, interface to DAQ servers
- **Server(s)** **System control** (master), **data storage** and **post-processing**

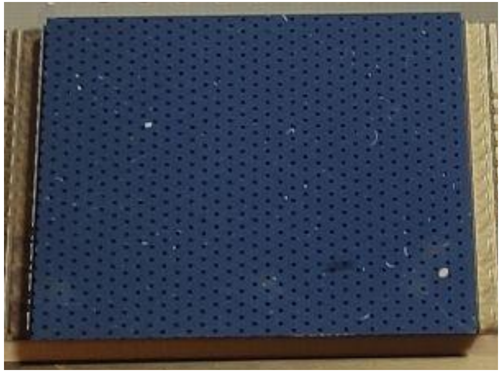
Timepix4 characterization - Setup

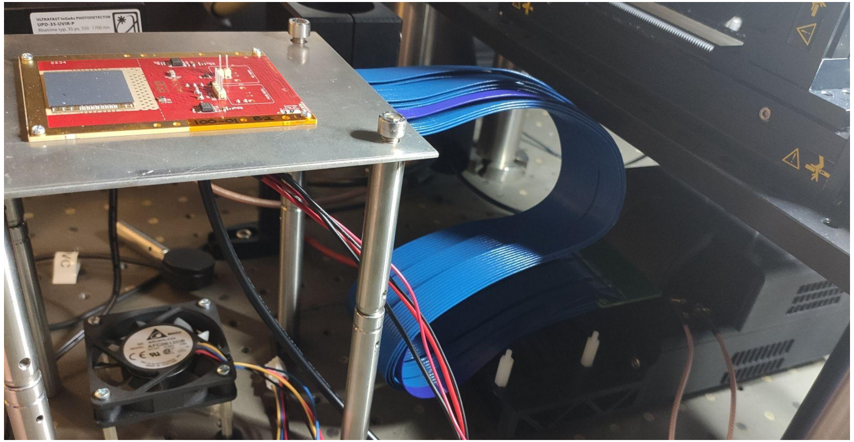
Control board:

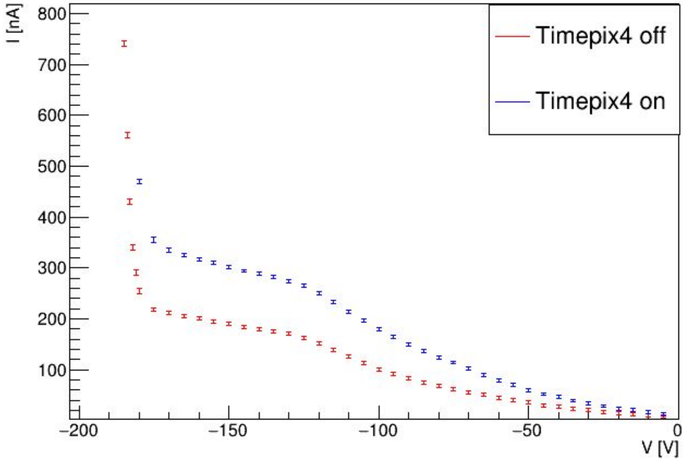
- SPIDR4 control board, developed by NIKHEF

Timepix4_v2:

- 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



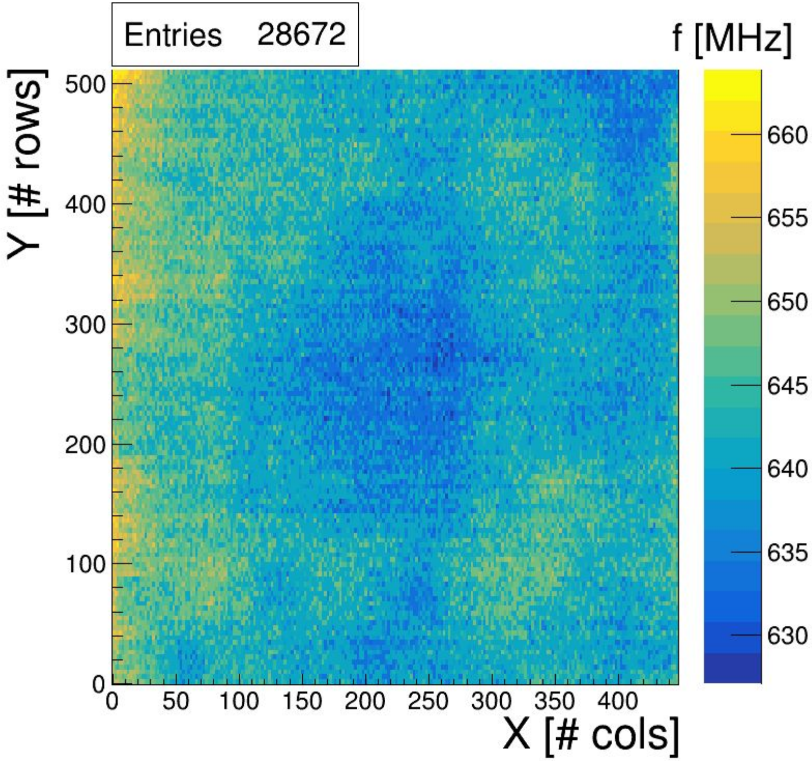




Timepix4 characterization - VCO calibration

The TDC is based on a DLL

- One per pixel group (8pixels)
- It uses a Voltage Controlled Oscillator (VCO)
- Ideally all pixels are locked to the same clock
  - Reality: different VCOs → different frequencies
- Finer ToA bins generated with different width
- ToA and ToT heavily affected by VCO drift
- Use internal test pulse to calibrate VCO
  - the whole matrix (~28.7k VCO)



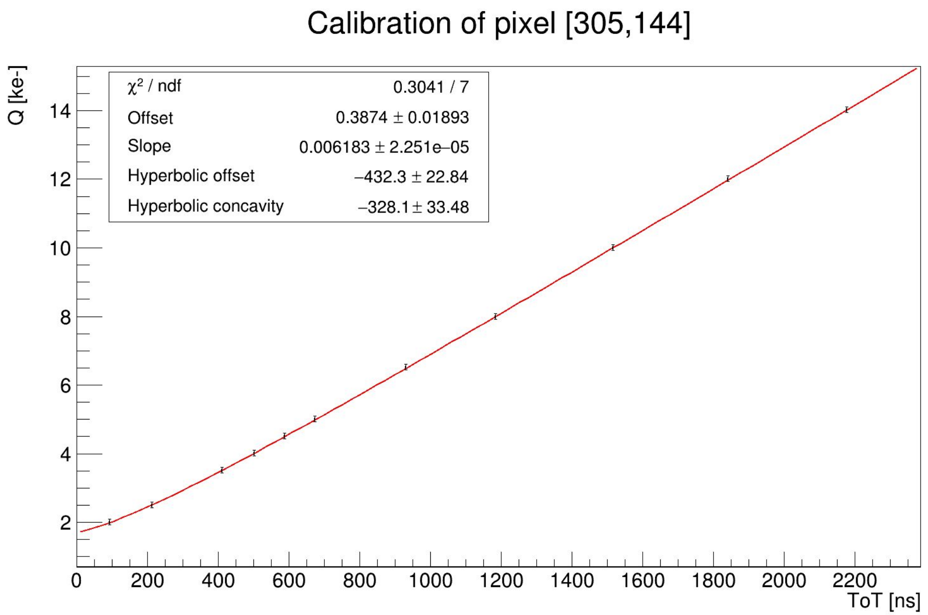
Timepix4 characterization - ToT vs Q calibration

Procedure:

1. Set threshold to 1K e^-
2. **Send pulse to the pixel input**
   - signal amplitude is known
   - signal generated by the Timepix4
     - Analog test-pulse
3. Observe Timepix4 response
4. Plot injected charge against ToT
5. Repeat from 2 changing the signal amplitude
6. Repeat for all pixels in the matrix
   - ~230k pixels

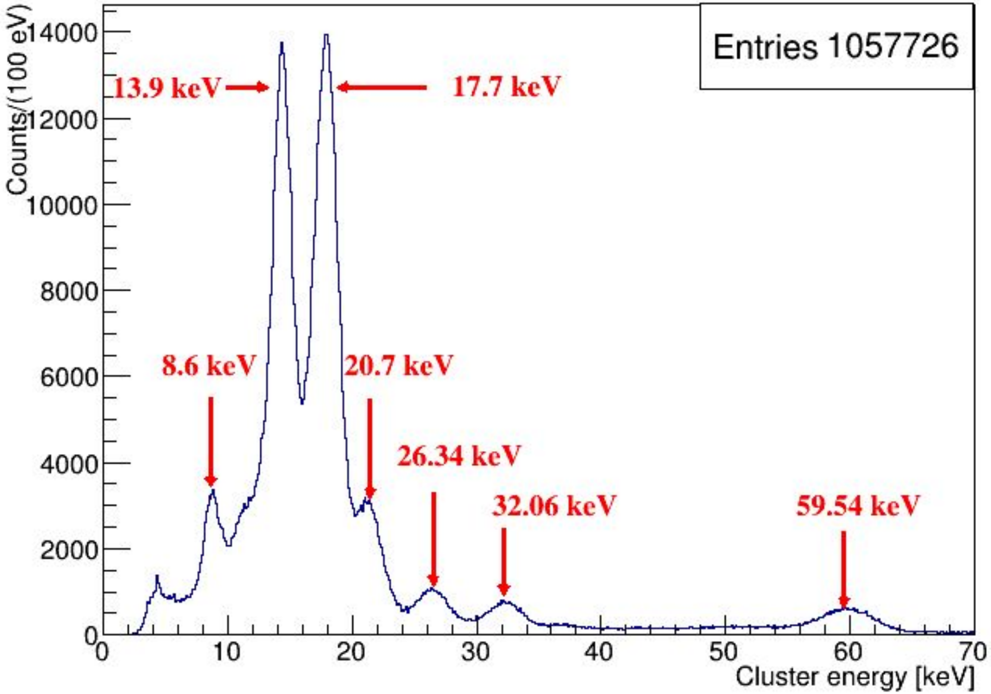
Results:

- Non linear calibration



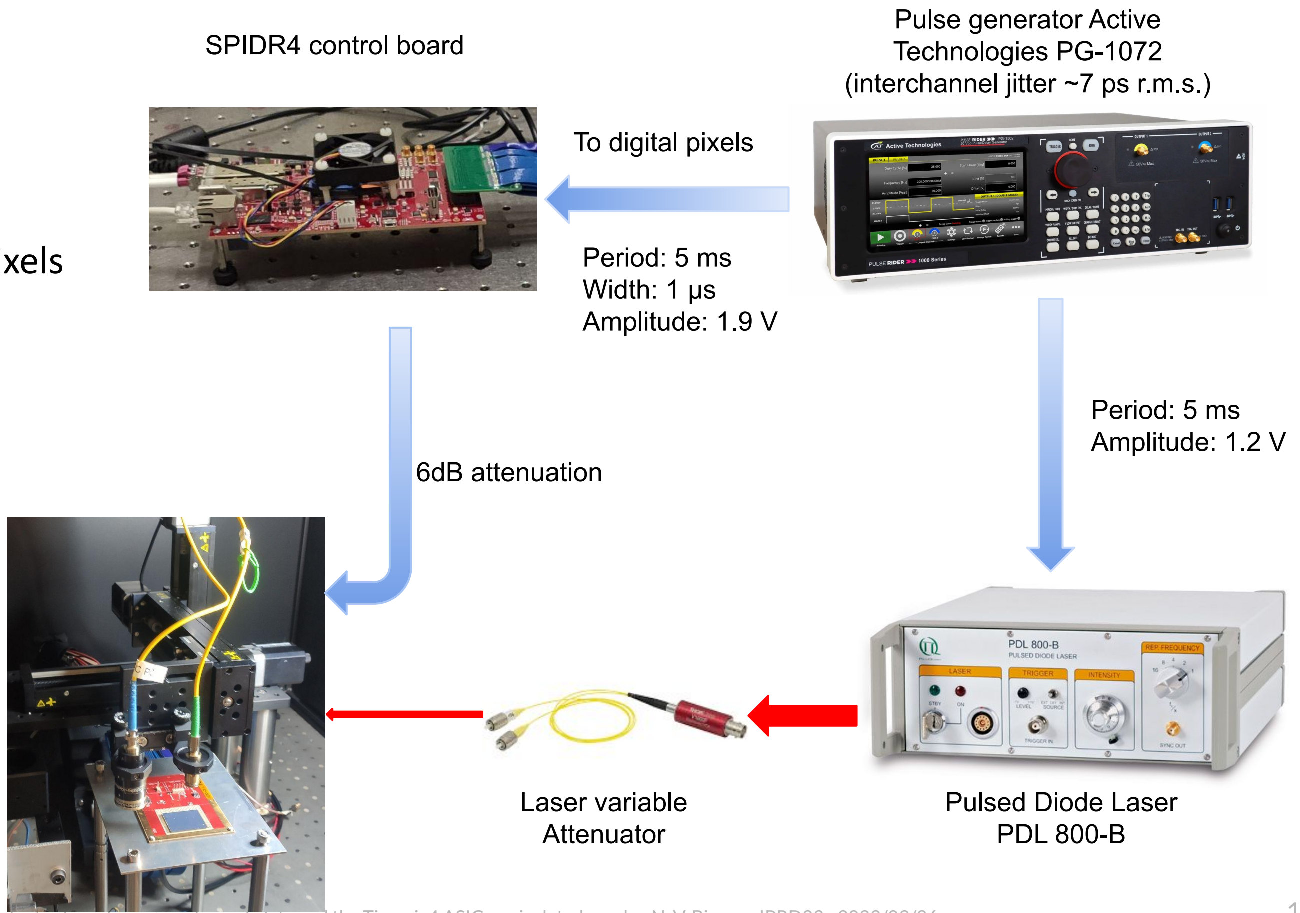
Timepix4 characterization – calibration validation

Calibration validated using radioactive sources (^{137}Cs and ^{241}Am superimposed spectra)



Timepix4 characterization - Timing resolution setup

- **Waveform generator**
  - input signal to digital pixels
  - laser trigger
- **Laser**:
  - 1060 nm
  - variable attenuator
- **Zaber** motion setup
  - 3D position regulation
  - µm precision

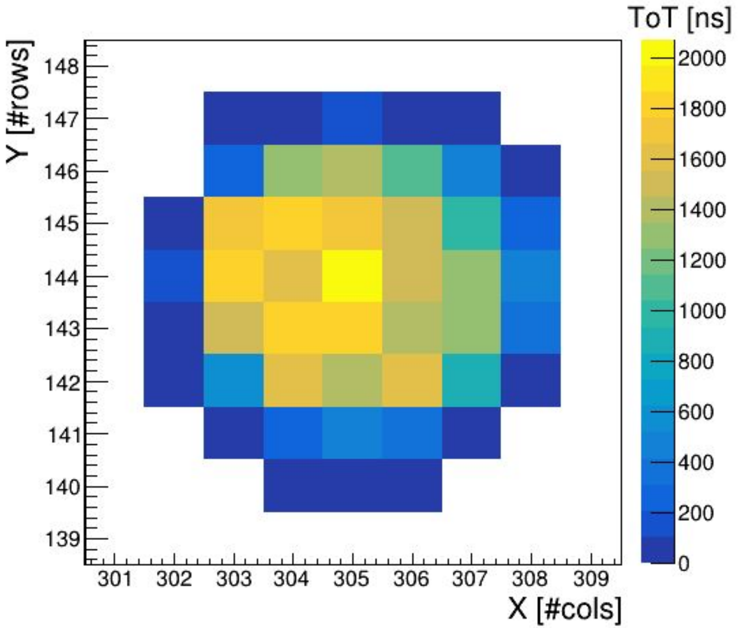


Timepix4 characterization - Timing resolution

Laser focused using micro-collimator:

- σ = 1.4 pixel = 77 µm

Laser spot in fixed position for all presented measurements



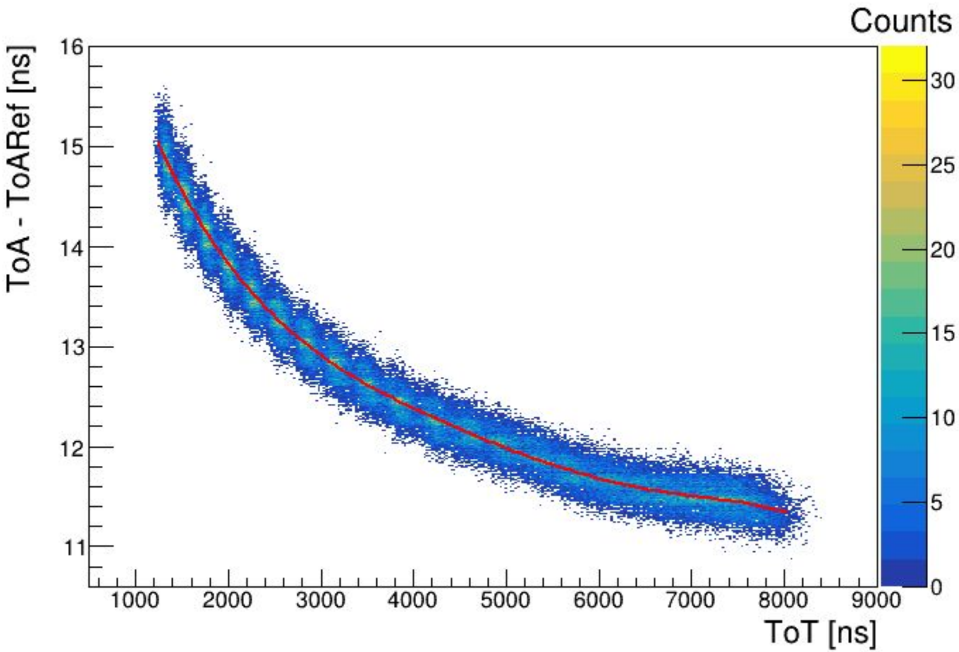
Timepix4 characterization - Time walk correction

Measurements using variable laser attenuation

- populate a wide ToT range

Different time walk trends on different pixels

- Time walk corrected separately on each pixel



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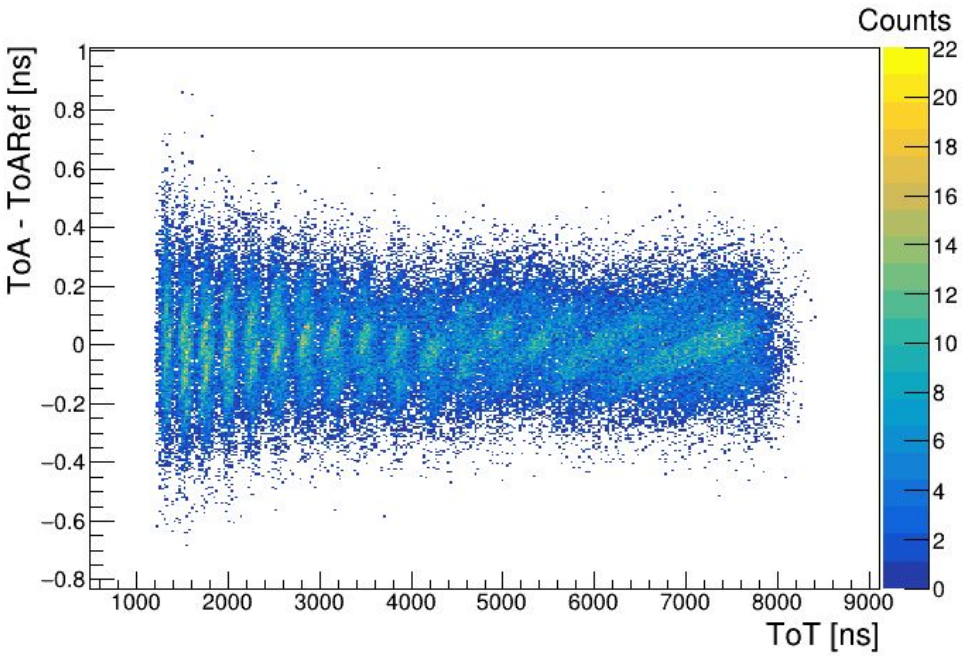
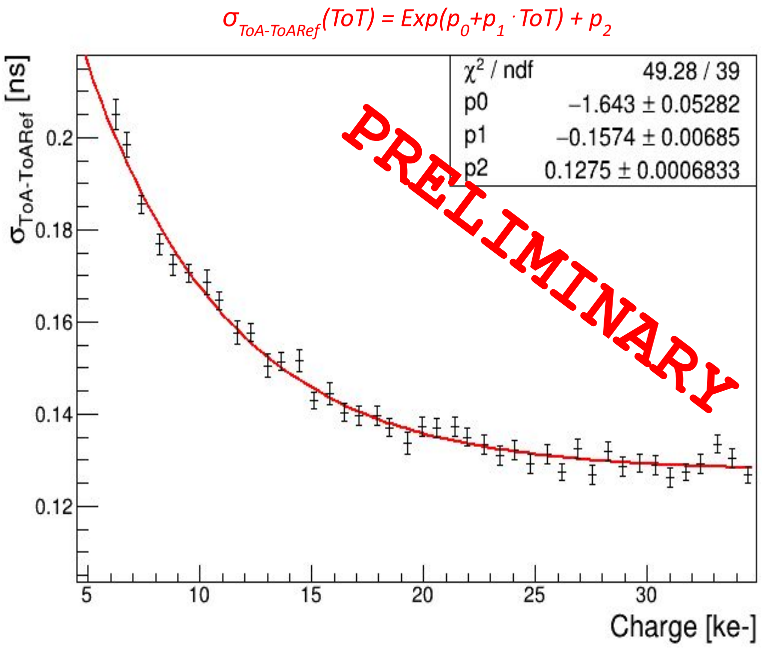
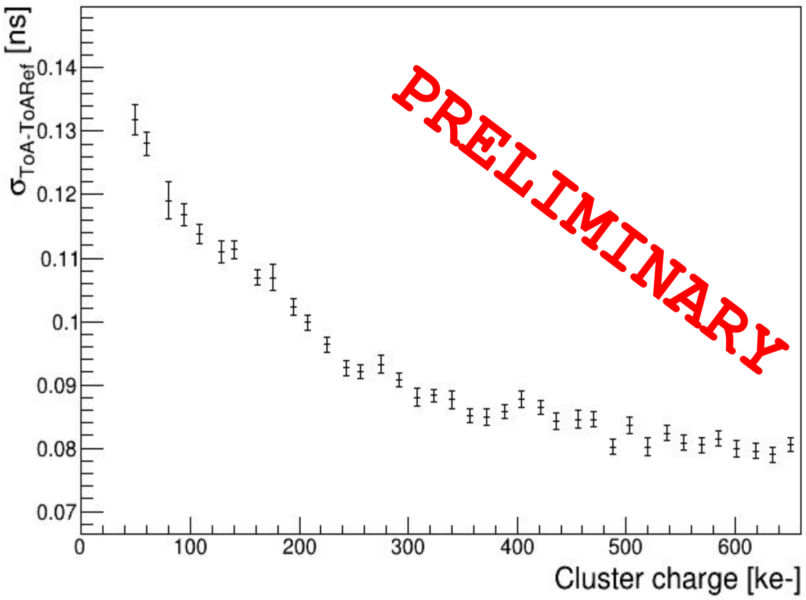


Timing resolution





Single-pixel best resolution:

- 128±1 ps rms
- **111±1 ps rms** (W/O ToA_{ref} contribution)

Multi-pixel cluster best resolution:

- 79 ± 1 ps rms
- **49 ± 1 ps rms** (W/O ToA_{ref} contribution)

Summary

We are developing a detector for visible single photons:

- based on a vacuum tube
- a bare Timepix4 CMOS ASIC (anode)
- a Micro Channel Plate stack

This detector will allow the detection of up to 10^9 photons/s with simultaneous measurement of time and position with excellent resolutions

- Fully exploit both timing and position resolutions of a MCP
- High-performance data acquisition (up to ~160 Gbps)

The first tests on the Timepix4 ASIC are encouraging

- ToT vs Q per pixel calibration
- single pixel timing resolution: → σToA = 111 ± 1 ps rms
- cluster timing resolution: → σToA = 49 ± 1 ps rms