Development and characterization of hybrid photodetector based on MCP and an embedded Timepix4 ASIC anode

Riccardo Bolzonella on behalf of 4DPHOTON team

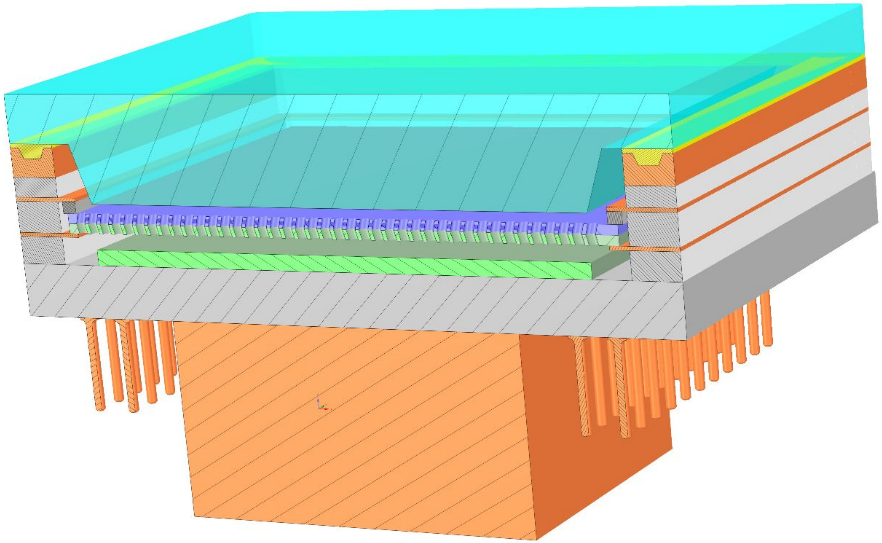
J. Alozy [1]
R. Ballabriga [1]
N.V. Biesuz [2]
R. Bolzonella [2,3]
M. Campbell [1]
V. Cavallini [2,3]
A. Cotta Ramusino [2]
M. Fiorini [2,3]
E. Franzoso [2]
X. Llopart Cudie [1]
G. Romolini [2,3]
A. Saputi [2]

1. CERN
2. INFN
3. University of Ferrara

25th iWoRiD - Lisbon, 3rd July 2024

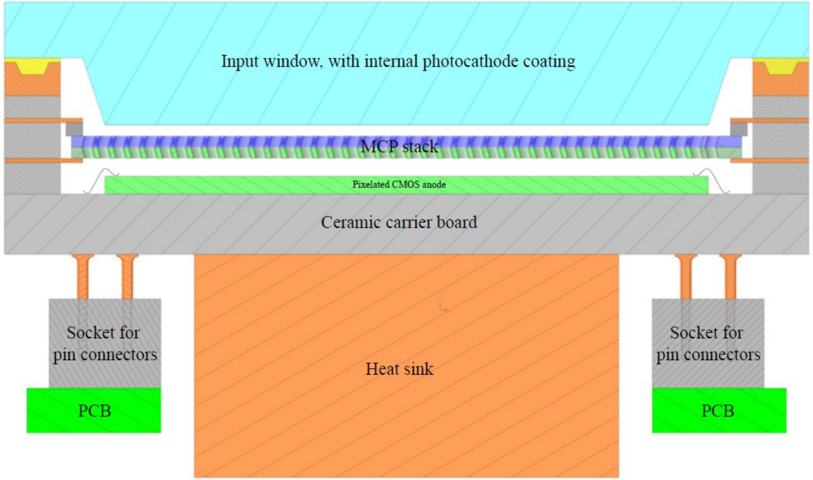
Overview

- Project overview
- The hybrid detector operating principle
- The Timepix4 ASIC
- DAQ and software
- Ceramic carriers quality tests
- MCP-PMT preliminary tests
  - gain measurements
  - timing measurements



Project recap - Novel hybrid photon detector

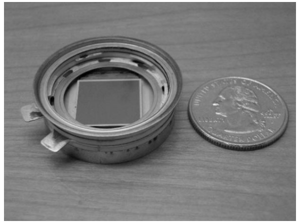
- ➢ **“Hybrid” assembly** based on tube kept under high vacuum
- ➢ Photocathode deposited in the inner part of the input window
- ➢ **MCP stack** (Chevron configuration)
- ➢ Pixelated CMOS anode: **Timepix4 ASIC**
- ➢ **Ceramic carrier board**
  - interface between inner/outer parts of the detector
  - custom Pin Grid Array for I/O signals
- ➢ **Heat sink** (ASIC power 5 W)
- ➢ **PCBs** to connect the detector to a FPGA-based DAQ system

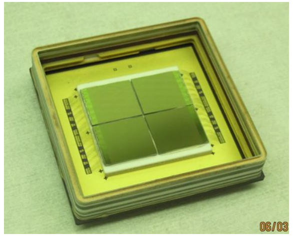


[M. Fiorini et al, JINST 13 (2018) C12005]

Proof of concept: use of a bare ASIC inside a vacuum tube with a microchannel plate (MCP) already demonstrated

- optical imaging tube based on Medipix2 ASIC [Proc. SPIE 7021 2008 (J. Vallerga, A. Tremsin et al.)]
- optical imaging tube with a quad Timepix readout [JINST 9 C05055 2014 (J. Vallerga, A. Tremsin et al.)]





Project recap - Detector operating principle

Photon conversion producing a photo-electron in a high Quantum Efficiency (QE) photocathode

⇩

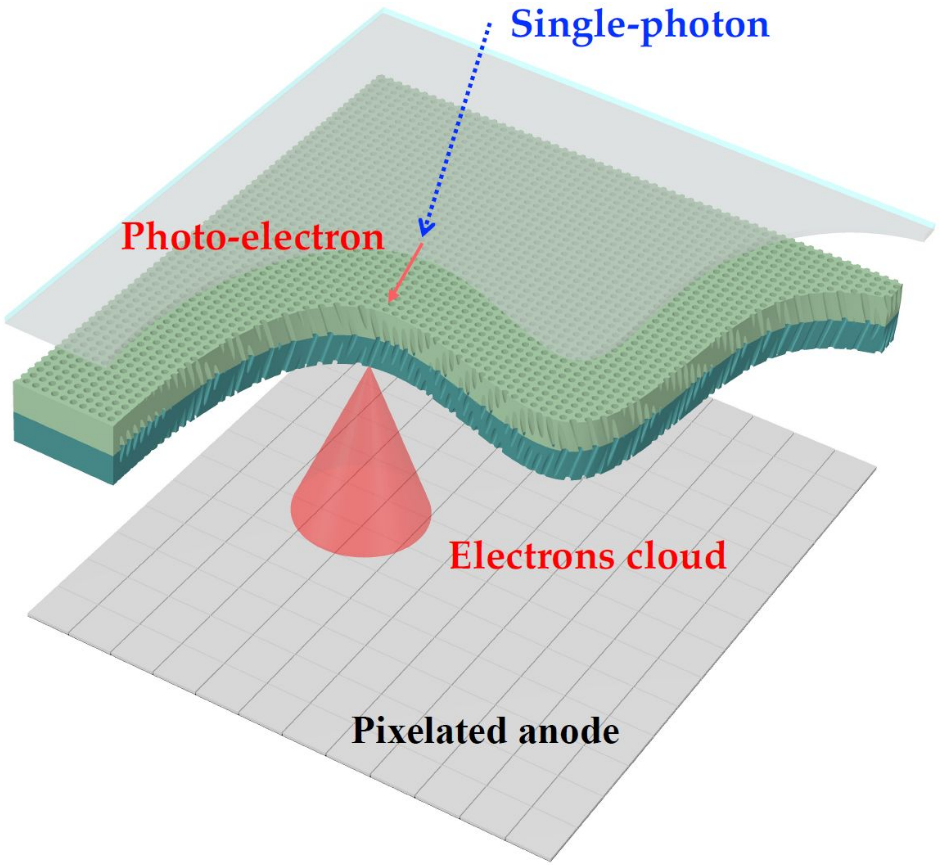
The photo-electron is transported by a drift electric field onto a microchannel plate (MCP) in Chevron configuration

⇩

The electrons cloud produced by the MCP is carried by another drift field onto the input (bump-bonding) pads of a bare Timepix4 ASIC, where it is sensed as a charge pulse by the read-out electronics

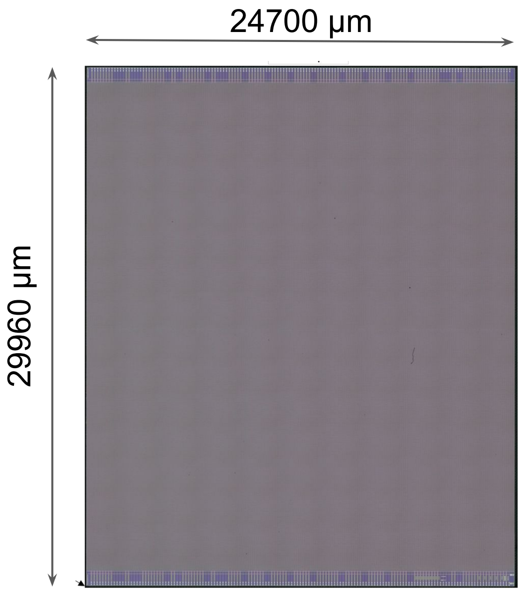
⇩

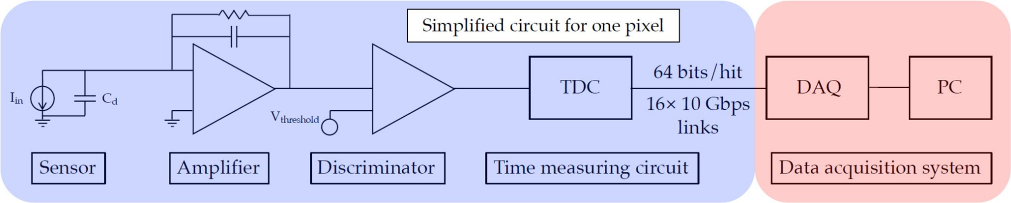
The Timepix4 ASIC will amplify, discriminate and digitize the MCP signal inside the vacuum tube



Pixelated anode: Timepix4 ASIC

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



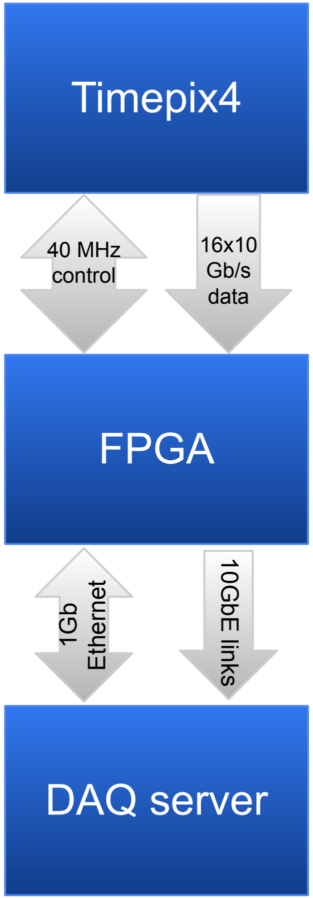


- ➢ Signal from MCP amplified and discriminated
- ➢ Time-stamp provided by Time-to-Digital Converter (TDC) based on Voltage-Controlled Oscillator (VCO)
  - ○ **195 ps** bin size (**~ 56 ps r.m.s. resolution**) for Time-of-Arrival (ToA) measurements
  - ○ **1.56 ns** bin size for Time-over-Threshold (ToT) measurements
- ➢ **High rate capability**:
  - ○ maximum bandwidth: **160 Gb/s**
  - ○ maximum hit rate: **2.5 Ghits/s/chip**
- ➢ Output:
  - ○ 64 bits of data per hit with 64b/66b encoding
  - ○ transmitted via 16 high-speed links up to 10.24 Gbps

[X. Llopart *et al* 2022 *JINST* **17** C01044]

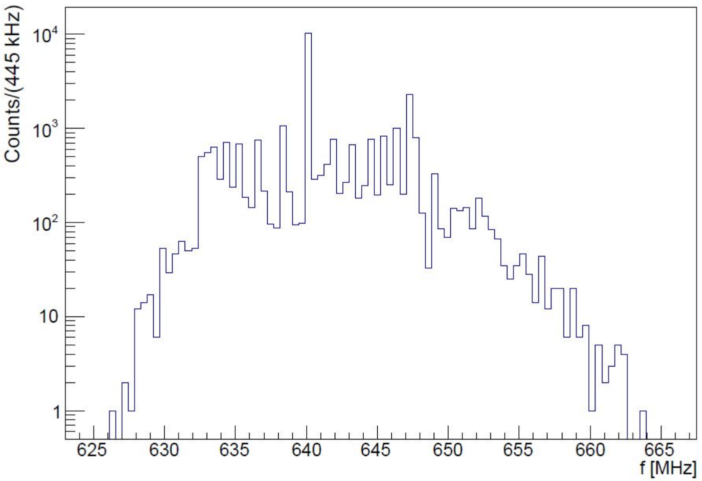
Data Acquisition (DAQ) system

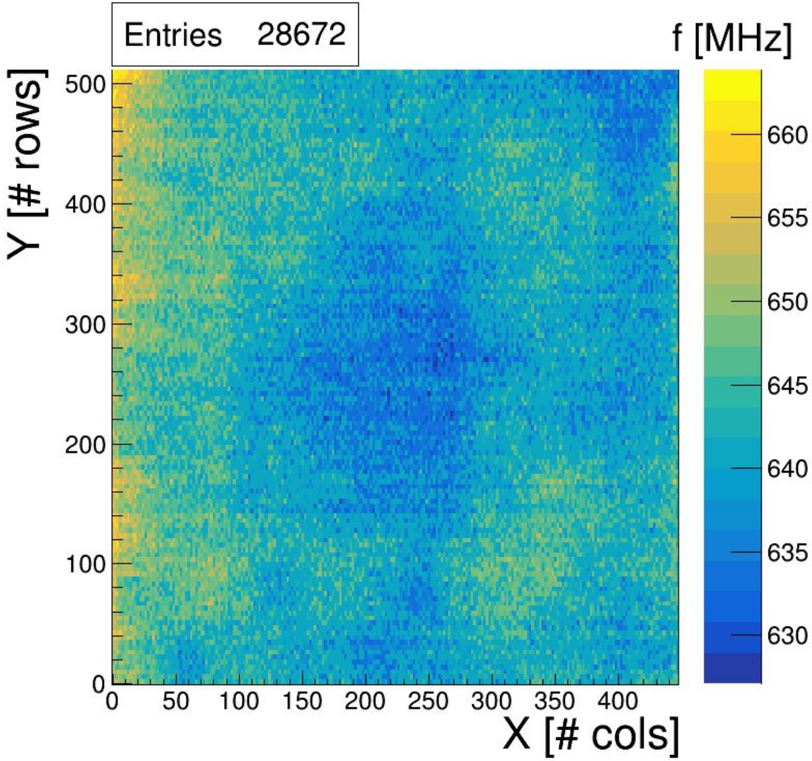
- **Data driven front-end electronics**
  - 64 bits for each pixel hit
  - **40 MHz slow control**
  - **16 x 10.24 Gb/s fast serial links**
- **FPGA-based control board**:
  - detector configuration
  - serial data decoding
  - sends pre-processed data to server to store them for post-processing
- **DAQ** server
  - receives and decodes data from control board
  - data analysis
  - data storage



Timepix4 characterization measurements - VCO calibration

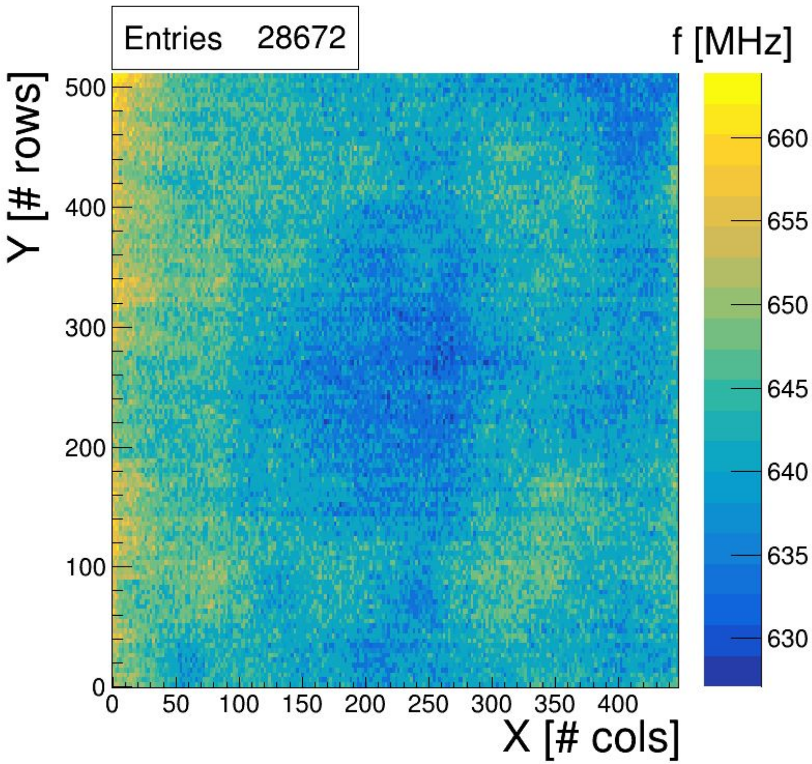
- On pixel VCO oscillation frequency controlled by a PLL at the center of the chip (@ 640 MHz nominal)
- It has been measured that on pixel VCO oscillate around 640 MHz with a spread of around 40 MHz





Timepix4 characterization measurements - VCO calibration

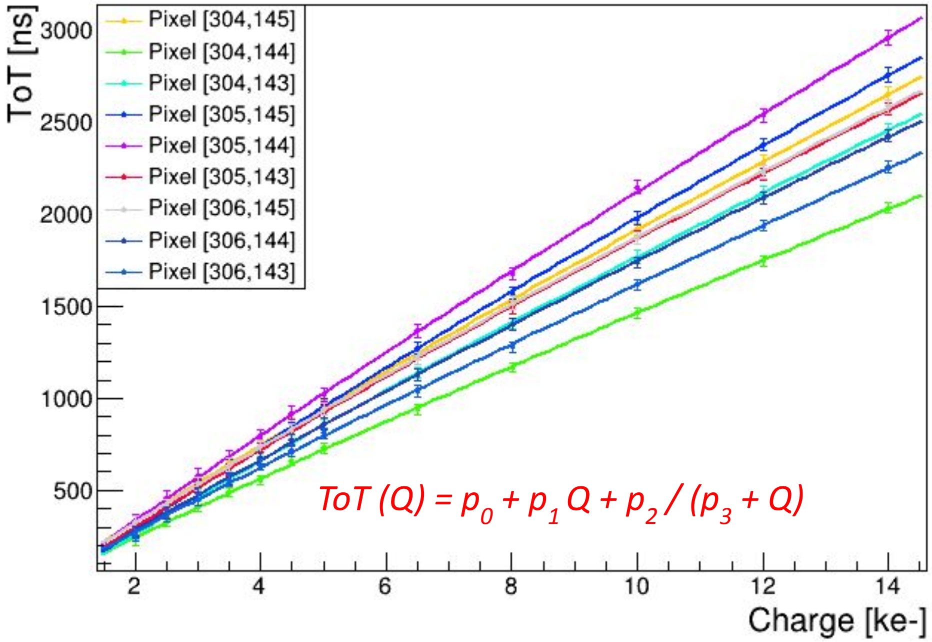
- On pixel VCO oscillation frequency controlled by a PLL at the center of the chip (@ 640 MHz nominal)
- It has been measured that on pixel VCO oscillate around 640 MHz with a spread of around 40 MHz
- Spread caused by power supply dispersion due to large size and wire bonds: large improvements expected with TSV
- Finer ToA bins generated with different width
- Timing performances heavily affected by this effect
- Internal test pulse tool exploited to **calibrate VCO frequencies for the whole matrix (28672 VCO)**



arXiv:2404.15499

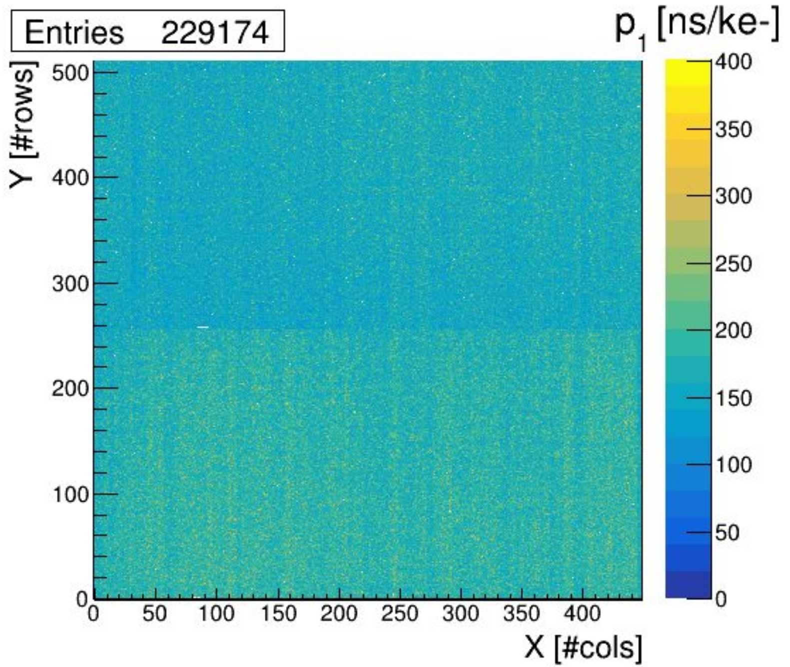
ToT vs Q calibration

- At fixed charge, large ToT spread across the matrix
- Analog testpulse
- **Non linear** calibration
- Threshold set to 1 ke^-



ToT vs Q calibration

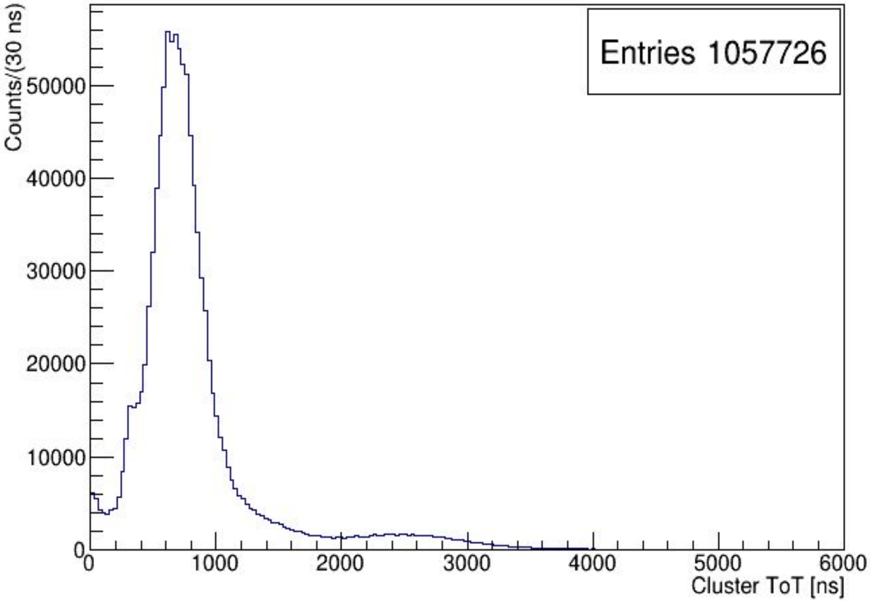
- At fixed charge, large ToT spread across the matrix
- Analog testpulse
- **Non linear** calibration
- Threshold set to 1 ke$^-$
- Per-pixel calibration done over the whole matrix
- Automatic algorithm exploiting fast read-out
- Calibration fit parameters distribution

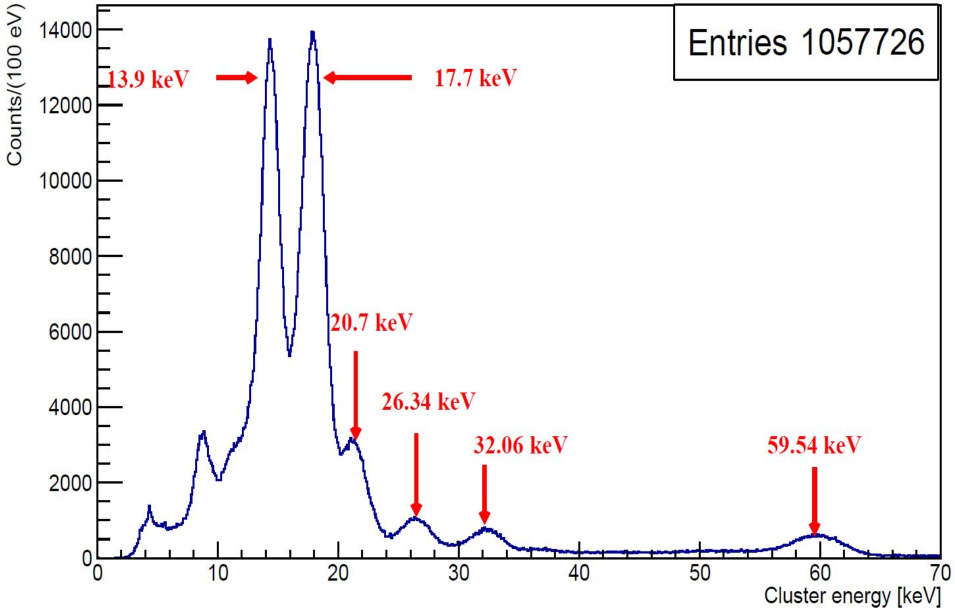


$ToT(Q) = p_0 + p_1 Q + p_2 / (p_3 + Q)$

ToT vs Q calibration

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



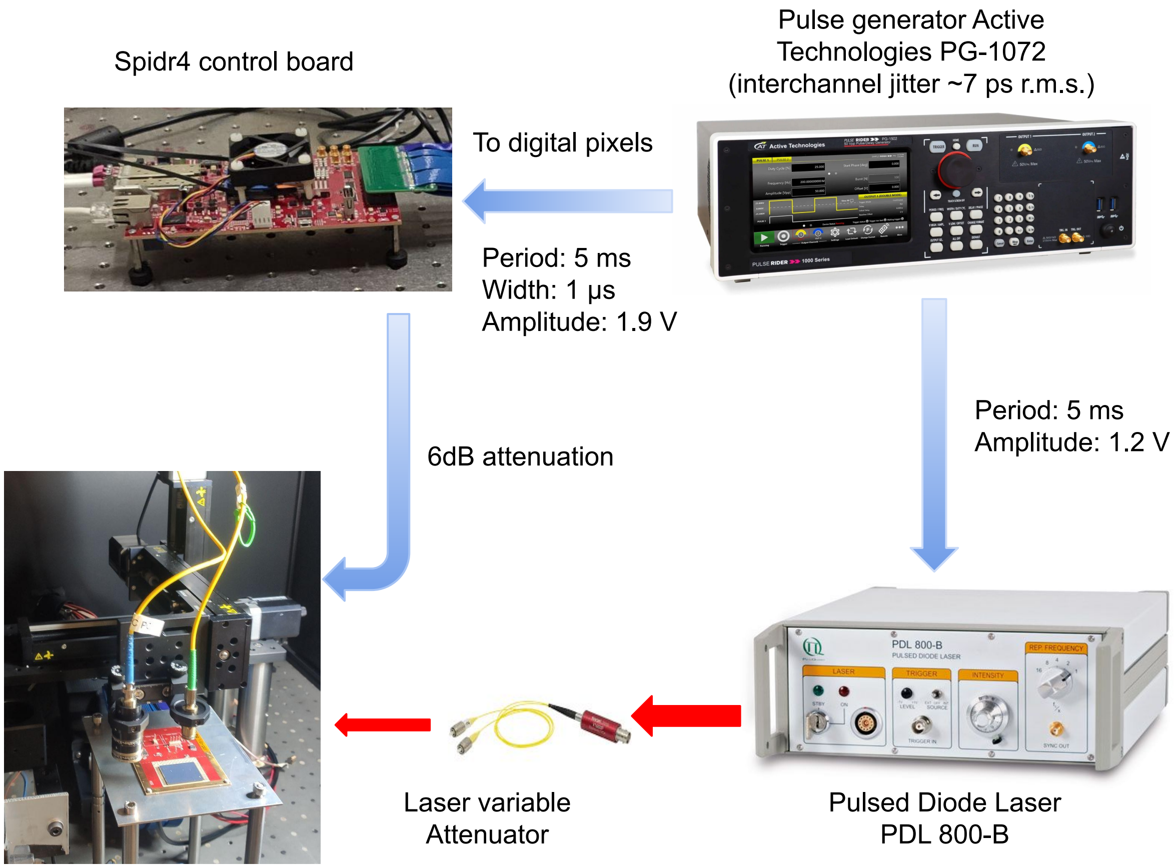


arXiv:2404.15499

- Up to 1.3 keV FHWM (@ 8 keV)
- Resolution up to 8% (@60 keV)
- ASIC bonded to 100 µm n-on-p Si detector

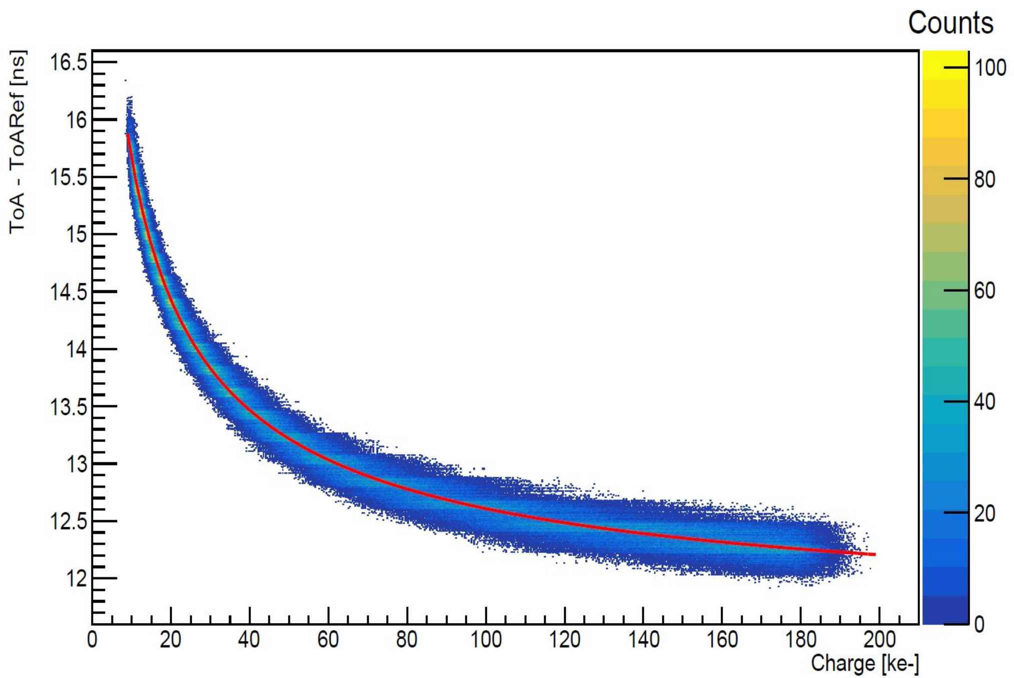
Timing resolution measurements - Laser measurements

- **Spidr4** control board
- **Timepix4v2**:
  - bonded to a 100 µm n-on-p Si detector biased at -150 V
  - metalization with holes pattern
  - Courtesy of CERN and NIKHEF Medipix4/VELO groups
- **Waveform generator**
  - input signal to digital pixels
  - laser trigger
- **Laser**:
  - 1060 nm
  - variable attenuator



Single pixel timing resolution

- **Laser focused using micro-collimator**:
  - spot size = 77 µm
- Laser spot in **fixed position** for all presented measurements
- Measurements using **variable laser attenuation**, populating a wide charge range on each pixel
- **Different time walk trends** on different pixels
- Time walk corrected separately on each pixel

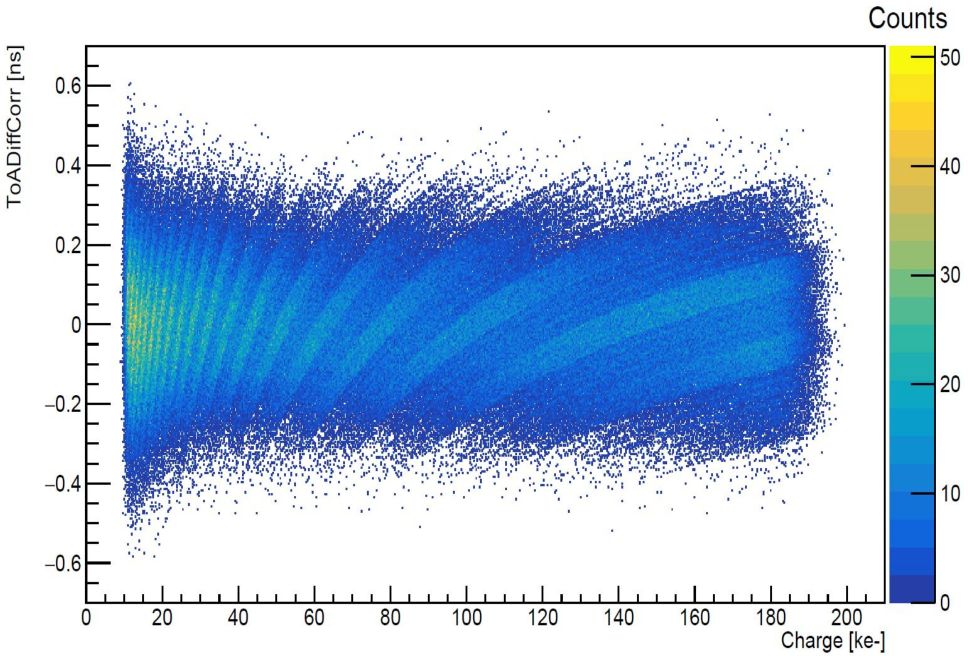


$$TW(Q) = \frac{p_0}{Q^{p_1} + p_2} + p_3$$

arXiv:2404.15499

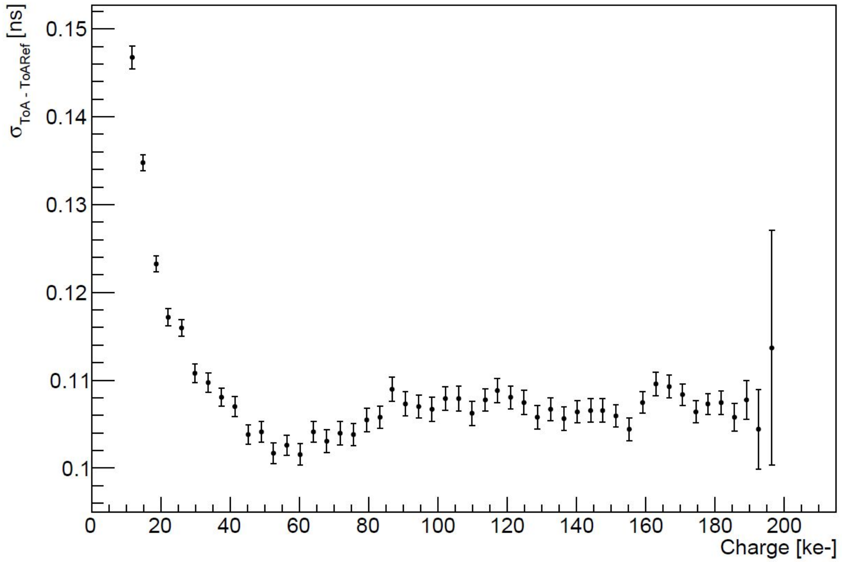
Single pixel timing resolution

- **Laser focused using micro-collimator**:
  - spot size = 77 µm
- Laser spot in **fixed position** for all presented measurements
- Measurements using **variable laser attenuation**, populating a wide charge range on each pixel
- **Different time walk trends** on different pixels
- Time walk corrected separately on each pixel



arXiv:2404.15499

Single pixel timing resolution

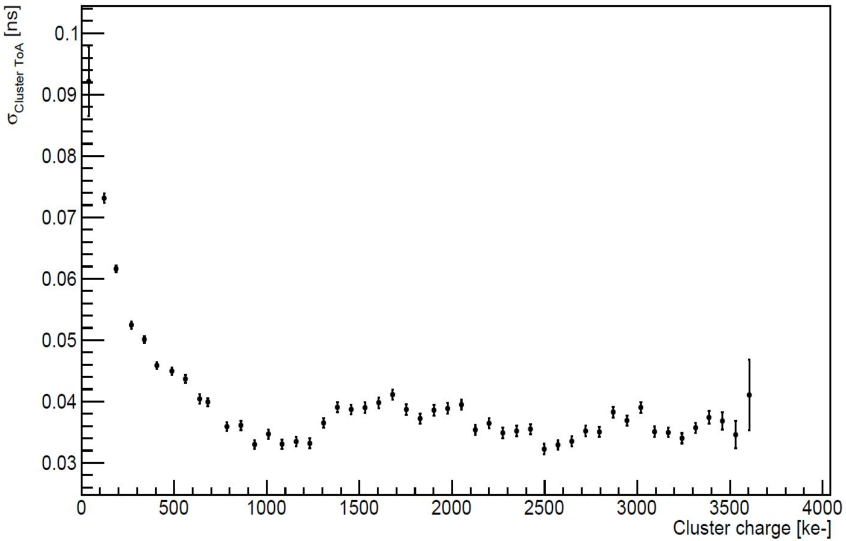


- ➢ Distribution of timing resolution as a function of injected charge
- ➢ For the pixel [305,144], where the laser is focused, the standard deviation saturates at 129±2 ps rms
- ➢ Subtracting the contribution of the reference signal (72 ps), a resolution of 107±3 ps rms is obtained

arXiv:2404.15499

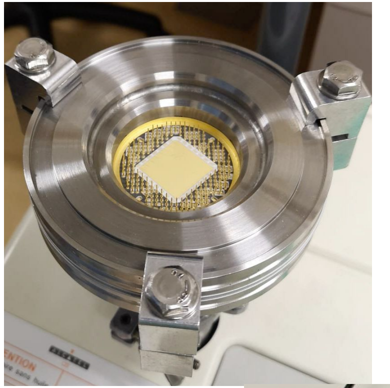
Cluster timing resolution

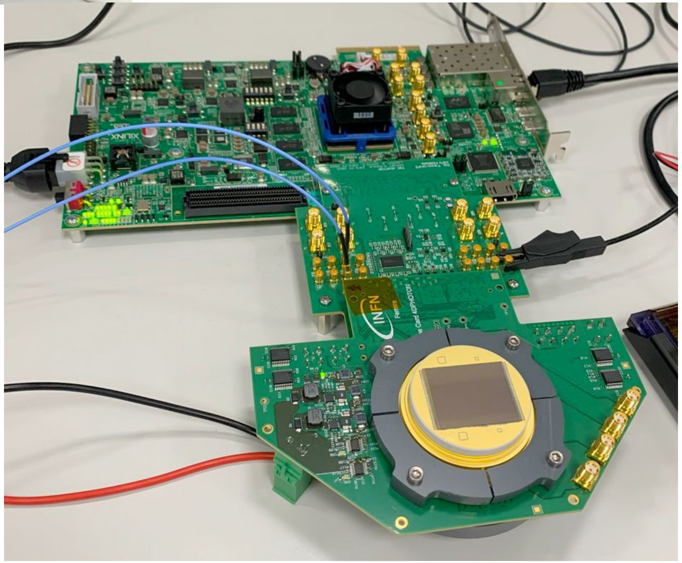
- For each cluster (~30 pixels):
  - **weighted average** of ToA using charge as weights
  - cluster charge computed
- Timing resolution dependency on cluster charge:
  - best result: $\sigma_{ToADiffAvg}$=79 ± 1 ps rms
    - timing resolution subtracting reference signal contribution: σ_{ToAAvg}=33 ± 3 ps rms



arXiv:2404.15499

Ceramic carrier

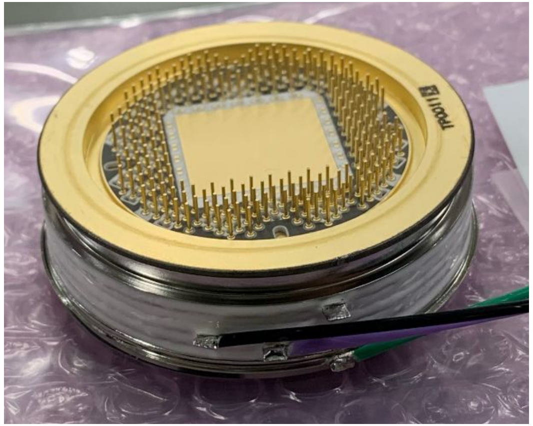




- ➢ Custom design and Pin Grid Array (PGA) by INFN and Kyocera
- ➢ Produced by Kyocera
- ➢ Timepix4 planarity measurements
- ➢ Electrical continuity measurements
- ➢ Ceramic characterization through Timepix4:
  - ○ Timepix4 diagnostic:
    - ■ per-pixel digital test
    - ■ DACs diagnostic
    - ■ power supply measurements
    - ■ DLL columns and ADBs check
  - ○ Test-pulses measurements, to verify both test-pulse and data-readout
  - ○ High-speed links configuration

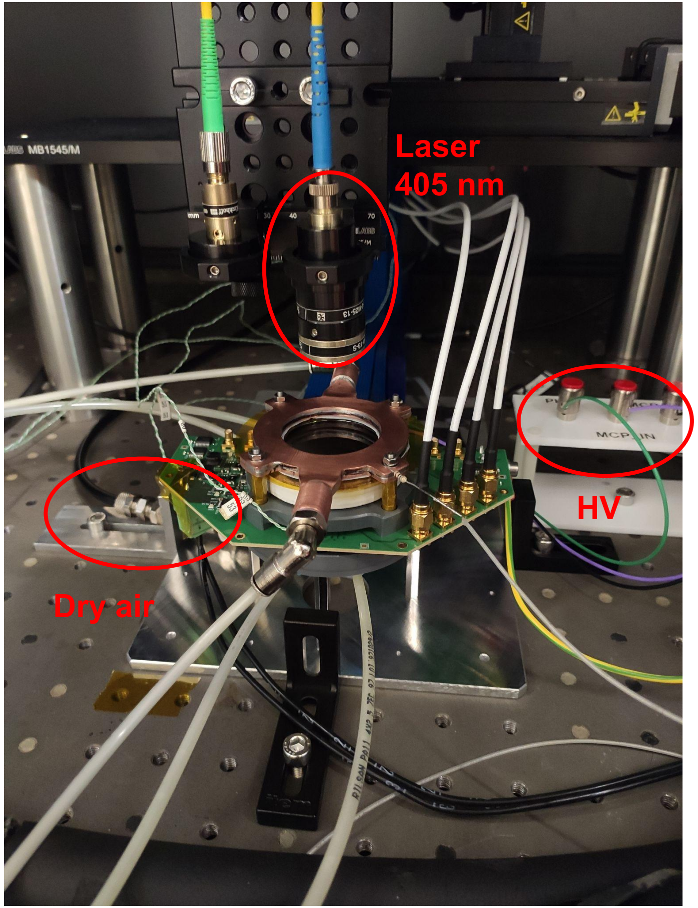
MCP-PMT prototype

- Prototype vacuum tube produced by Hamamatsu HPK
  - first prototypes received one month ago
- Main characteristics:
  - Multi-alkali S20 photocathode
    - peak QE > 30% at 380 nm
  - 6 µm MCP channel diameter (7.5 µm pitch)
- Several variants for complete characterization
  - 2-MCP stack and 3-MCP stack
  - 1d - 2d - 3d end-spoiling



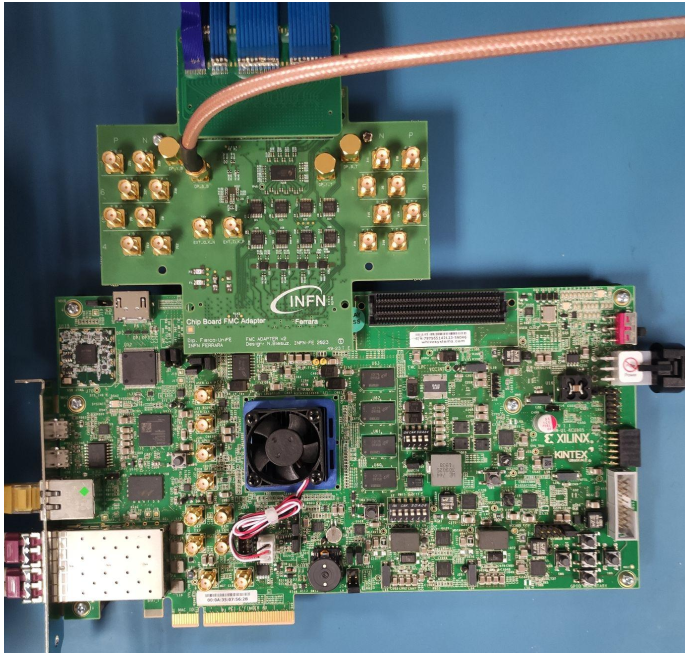
MCP-PMT characterization measurements - Setup

- Tube prototypes (2-MCP stack with 2d end-spoiling) received from Hamamatsu HPK mounted on custom carrier board within a **dark box**
- **Cooling system** to maintain stable temperature inside the tube
- **Dry air fluxed** in the dark box to decrease the internal dew point



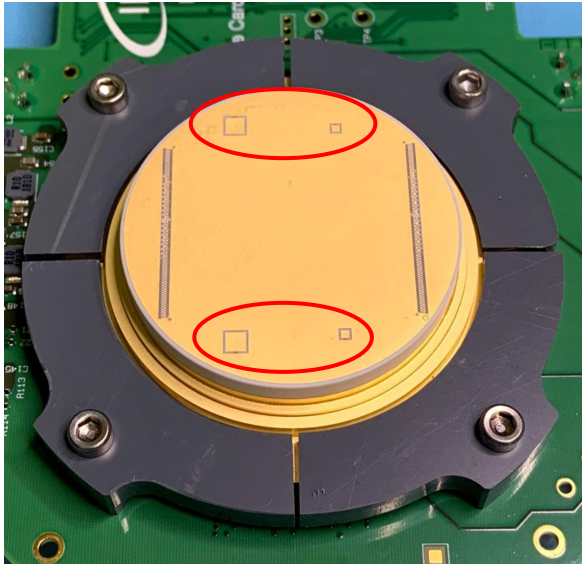
MCP-PMT characterization measurements - Setup

- Tube prototypes (2-MCP stack with 2d end-spoiling) received from Hamamatsu HPK mounted on custom carrier board within a **dark box**
- **Cooling system** to maintain stable temperature inside the tube
- **Dry air fluxed** in the dark box to decrease the internal dew point
- Control board and DAQ PC outside the box with 1 m flat FMC cable connection
  - Developed by INFN Ferrara:
  - based on commercial dev. kit Xilinx KCU105
  - firmware, FMC adaptor and carrier board
- **Remote monitoring and control of HV** and current values



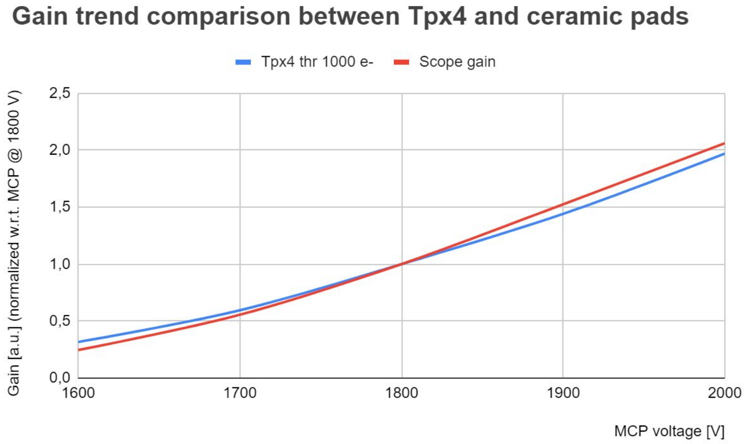
MCP-PMT characterization measurements - Dark conditions

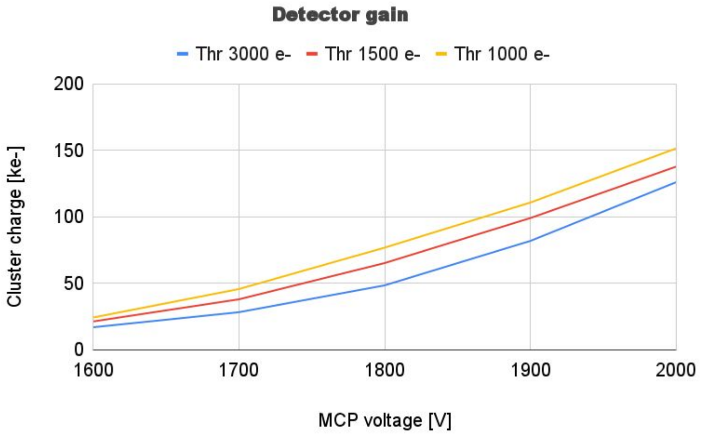
- ➢ Gain and dark count rate (DCR) measurements performed on dark noise acquisitions
- ➢ MCP_{out} - MCP_{in} scan with 100 V step
- ➢ Different threshold levels used (1000 e-, 1500 e-, 3000 e-)
- ➢ Per-pixel ToT calibration not done yet
  - ○ average calibration used
- ➢ Relative gain obtained both from **clusters charge** and **pads on ceramic carrier**
- ➢ Gain trend from clusters compatible with pads one



MCP-PMT characterization measurements - Dark conditions

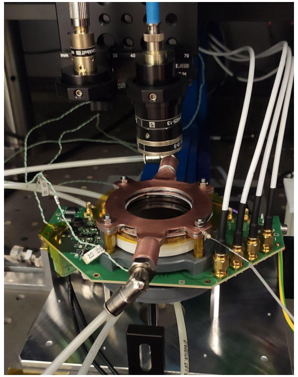
- Gain and dark count rate (DCR) measurements performed on dark noise acquisitions
- MCP_{out} - MCP_{in} scan with 100 V step
- Different threshold levels used (1000 e-, 1500 e-, 3000 e-)
- Per-pixel ToT calibration not done yet
  - average calibration used
- Relative gain obtained both from **clusters charge** and **pads on ceramic carrier**
- Gain trend from clusters compatible with pads one

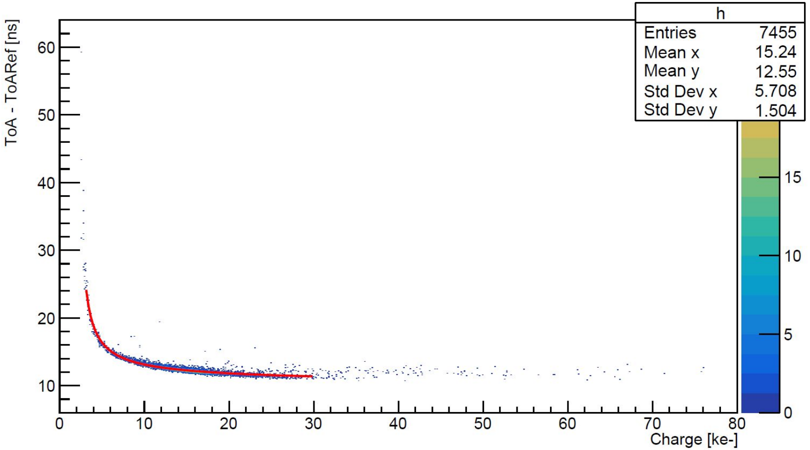




MCP-PMT characterization measurements - Timing resolution

- **Laser setup**:
  - 405 nm
  - variable attenuator
  - exploring both single photon and multiple photons regimes
- **Ongoing analysis**:
  - Time-walk correction procedure
  - Single-pixel timing resolution (exploring low-charge range)





Next steps

- Improvements of ceramic carrier and MCP-PMT quality tests:
  - fast links diagnostic
  - MCP-PMT measurements to be optimized for in-spec HV parameters
- Further studies on dark count rate and uniformity
- Timing resolution:
  - analysis to be completed for multiple and single photon measurements
  - cluster timing resolution analysis to be included
- Test-beam preparation with Cherenkov setup ongoing
  - Beam time allocated SPS H8 (October 2024)

Conclusions

We are developing a new detector for single photons in the visible range:

- ➢ Vacuum tube with MCP and Timepix4 CMOS ASIC as anode
- ➢ Funded by the European Research Council (G.A. No. 819627)
- ➢ Complete integration of sensor and electronics (internal data processing and data transmission)

Promising results characterizing Timepix4 bonded to Si sensor (arXiv:2404.15499):

- ➢ ToT vs Q per pixel calibration
- ➢ single pixel timing resolution: ***σ_{ToA} = 107 ± 3 ps rms***
- ➢ cluster timing resolution: ***σ_{ToA} = 33 ± 3 ps rms***

Preliminary measurements on MCP-PMT first prototypes:

- ➢ gain measurements through Timepix4 and oscilloscope
- ➢ expected gain dependance on MCP voltage
- ➢ dark count rate under study
- ➢ timing resolution through laser setup under study

Thanks for your attention

Thanks to the CERN for the support

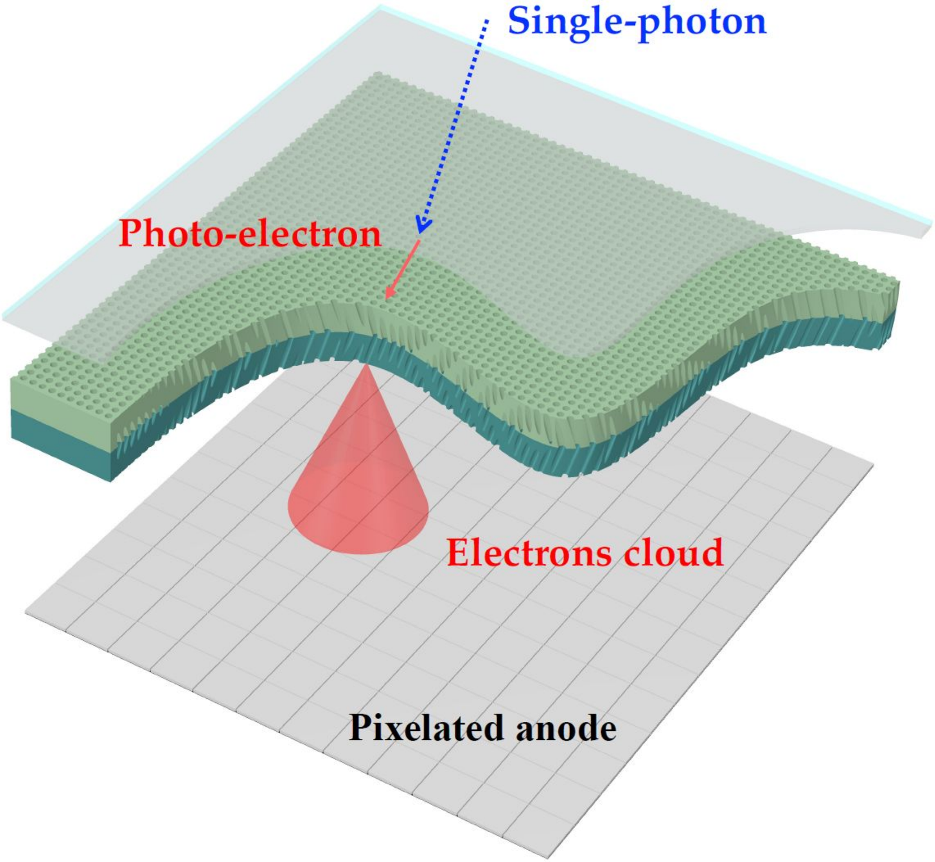
Backup

Detector operating principle: photocatode

Photon conversion producing a photo-electron in a high Quantum Efficiency (QE) photocatode

- ➢ high QE in blue-green region (for Cherenkov photons)
- ➢ low dark count rate (10^2-10^3 Hz/cm^2 @300K)
- ➢ large active area

Flexible design to use different photocatodes if needed for various applications



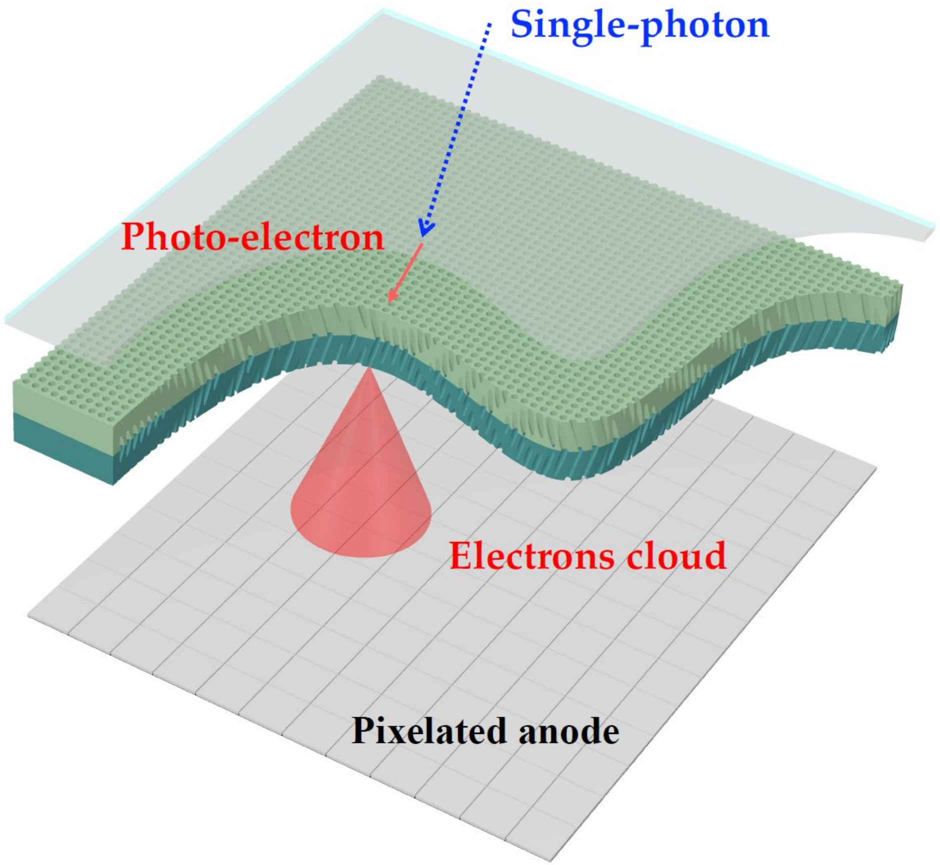
Detector operating principle: microchannel plate

Photon conversion producing a photo-electron in a high Quantum Efficiency (QE) photocatode

⇩

The photo-electron is transported by a drift electric field onto a microchannel plate (MCP) in Chevron configuration

- ➢ pore spacing of 5-10 μm to improve spatial and timing resolution, and hit rate
- ➢ short photocathode-to-MCP distance to improve spatial and timing resolution
- ➢ MCP-to-anode distance tuned for optimized spatial and timing resolution
- ➢ possible options to increase lifetime:
  - ○ MCP operated at low gain (10^4-10^5)
  - ○ Atomic Layer Deposition (ALD)



Detector operating principle: pixelated anode

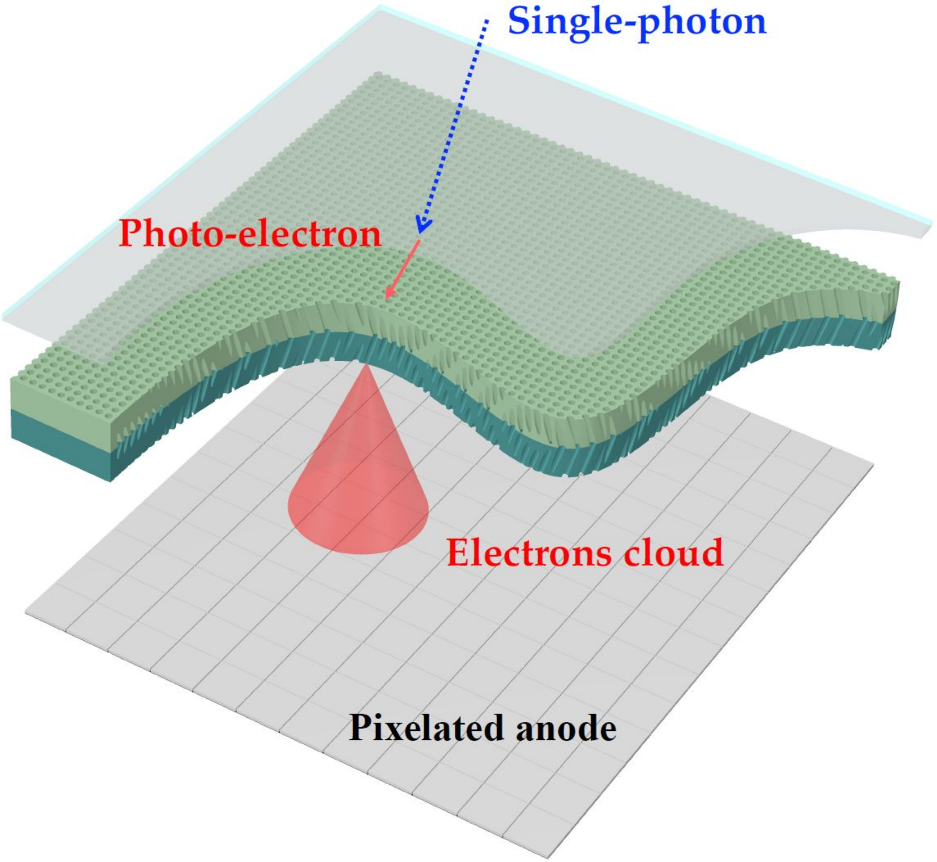
Photon conversion producing a photo-electron in a high Quantum Efficiency (QE) photocatode

⇩

The photo-electron is transported by a drift electric field onto a microchannel plate (MCP) in Chevron configuration

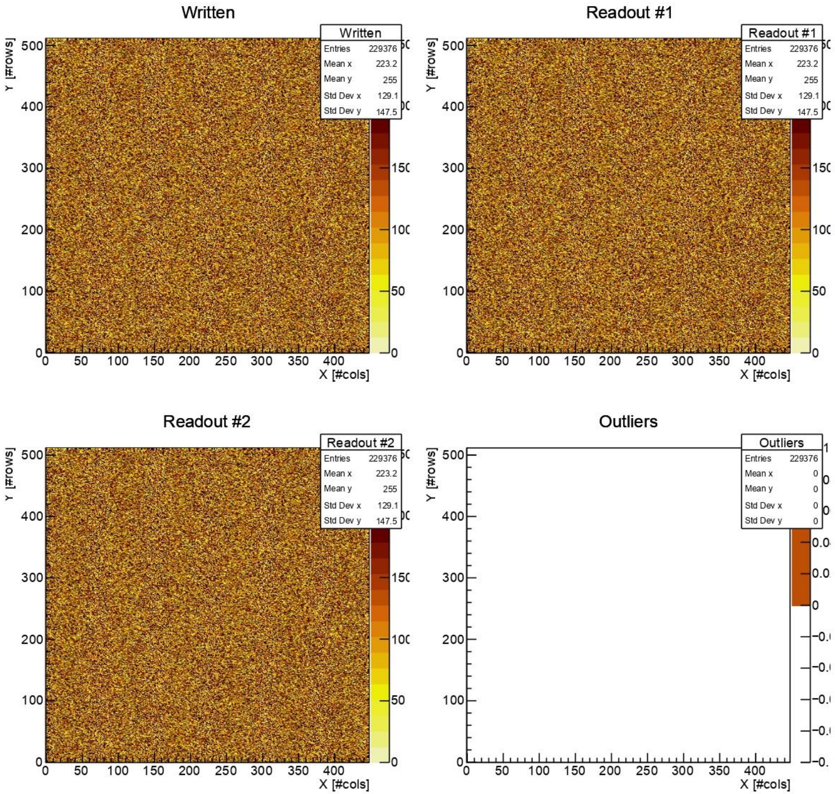
⇩

The electrons cloud produced by the MCP is carried by another drift field onto the input (bump-bonding) pads of a bare Timepix4 ASIC, where it is sensed as a charge pulse by the read-out electronics

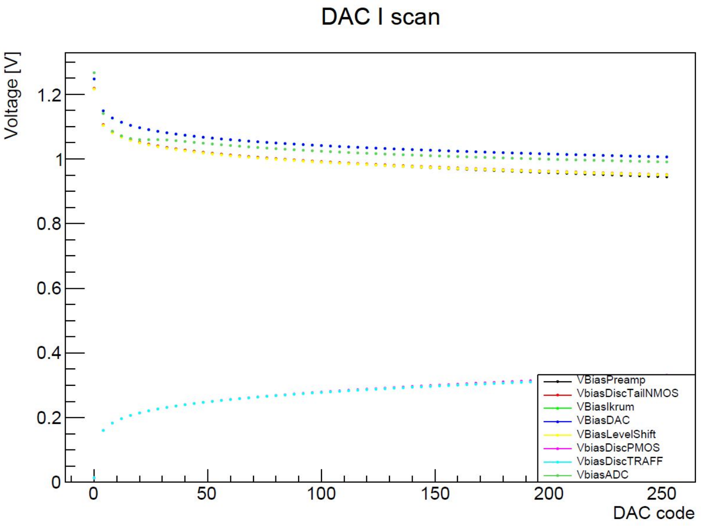


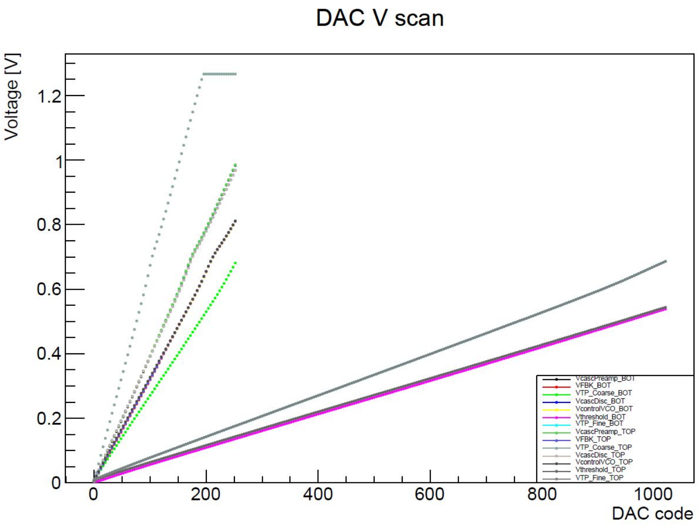
Ceramic carrier characterization

- Timepix4 planarity measurements
- Electrical continuity measurements
- Ceramic characterization through Timepix4:
  - Timepix4 diagnostic:
    - per-pixel digital test



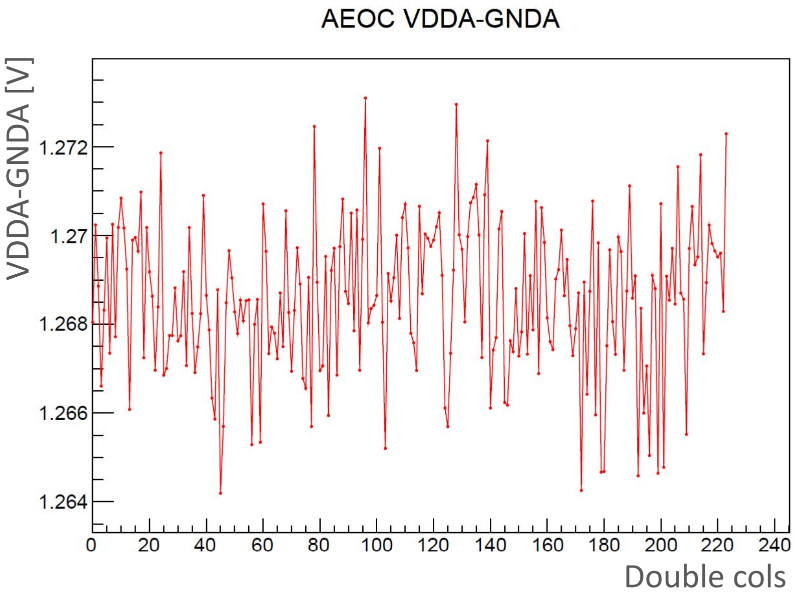
- ➢ Timepix4 planarity measurements
- ➢ Electrical continuity measurements
- ➢ Ceramic characterization through Timepix4:
  - ○ Timepix4 diagnostic:
    - ■ per-pixel digital test
    - ■ DACs diagnostic





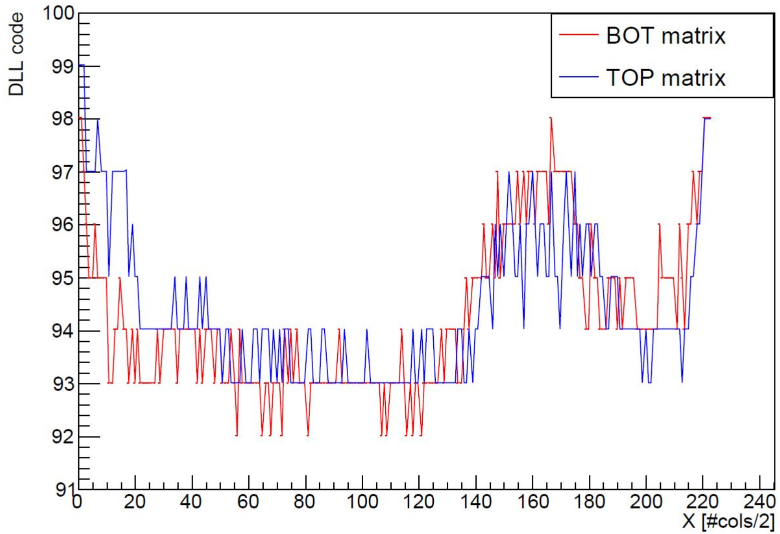
Ceramic carrier characterization

- Timepix4 planarity measurements
- Electrical continuity measurements
- Ceramic characterization through Timepix4:
  - Timepix4 diagnostic:
    - per-pixel digital test
    - DACs diagnostic
    - power supply measurements



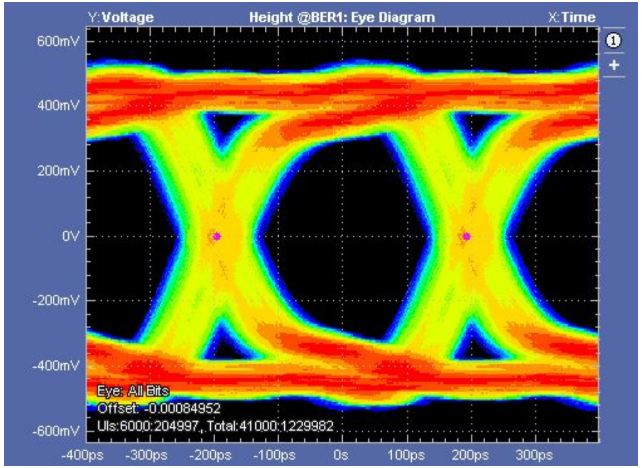
Ceramic carrier characterization

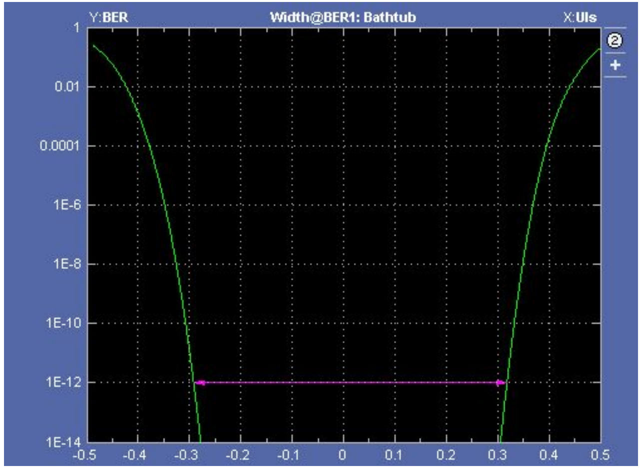
- ➢ Timepix4 planarity measurements
- ➢ Electrical continuity measurements
- ➢ Ceramic characterization through Timepix4:
  - Timepix4 diagnostic:
    - per-pixel digital test
    - DACs diagnostic
    - power supply measurements
    - DLL columns and ADBs check



Ceramic carrier characterization

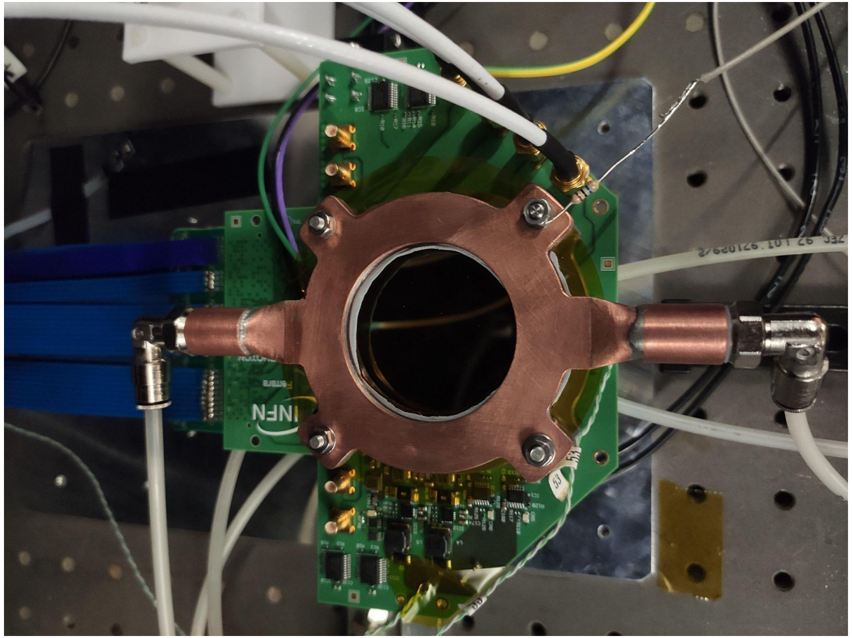
- ➢ Timepix4 planarity measurements
- ➢ Electrical continuity measurements
- ➢ Ceramic characterization through Timepix4:
  - ○ Timepix4 diagnostic:
    - ■ per-pixel digital test
    - ■ DACs diagnostic
    - ■ power supply measurements
    - ■ DLL columns and ADBs check
  - ○ Test-pulses measurements, to verify both test-pulse and data-readout
  - ○ High-speed links configuration





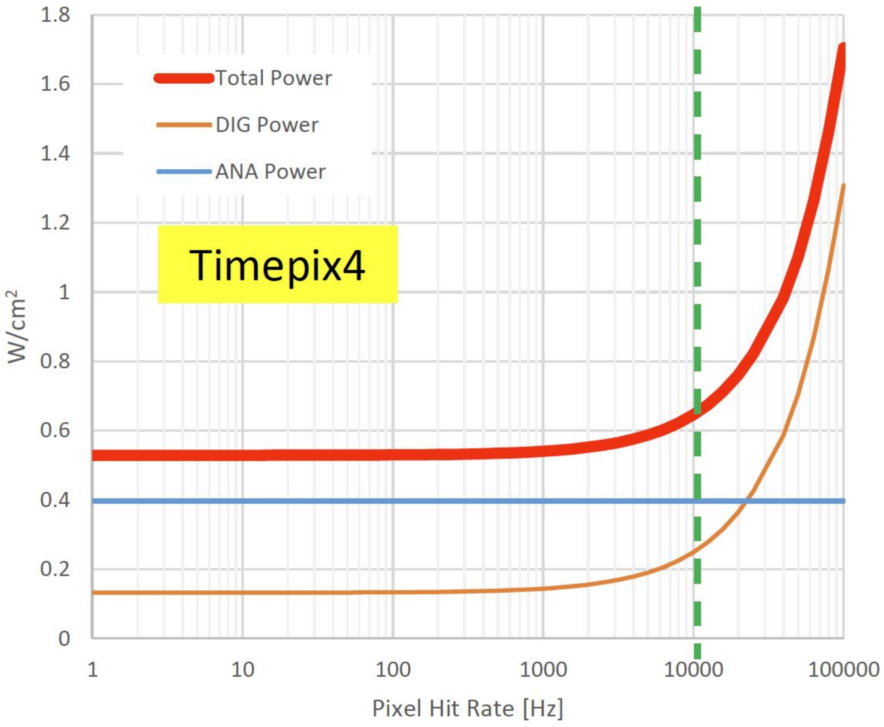
MCP-PMT characterization measurements - Cooling

- Previous cooling system: liquid cooling with a cold finger on the bottom face of the ceramic carrier
  - MCP and photocatode temperature still too high when Timepix4 operates
- Improved cooling system: **additional copper ring in thermal contact with quartz window** to extract heat from both tube sides
- More efficient cooling: tube temperature reaching about 5°C when thermal equilibrium is reached
- Increases of about 2°C on outer flange when Timepix4 reaches 5 W power consumption



Power consumption and cooling

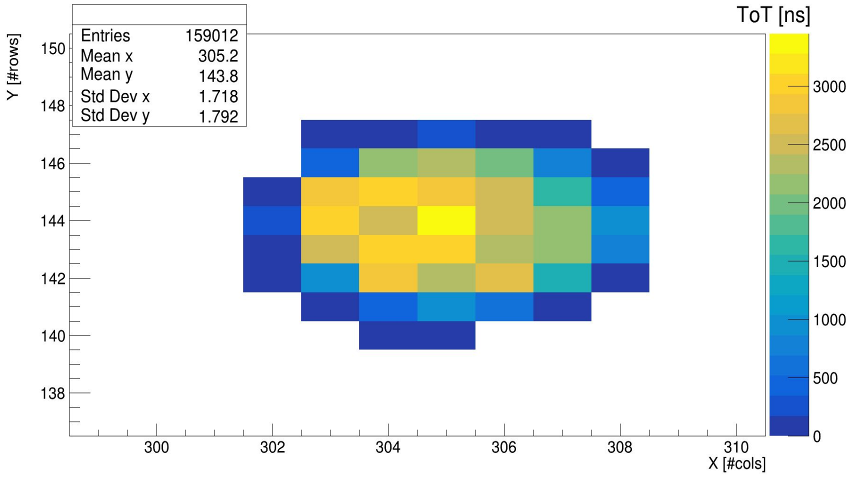
- ➢ Timepix4 power consumption∼ 5 W
- ➢ Goal: stable operation with 20°C inside the vacuum tube
  - ○ Cold finger attached to the ceramic carrier

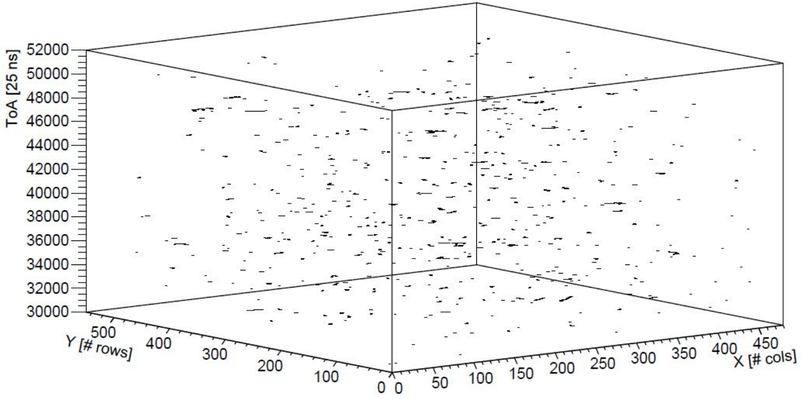


X. Llopart (CERN)

Analysis description

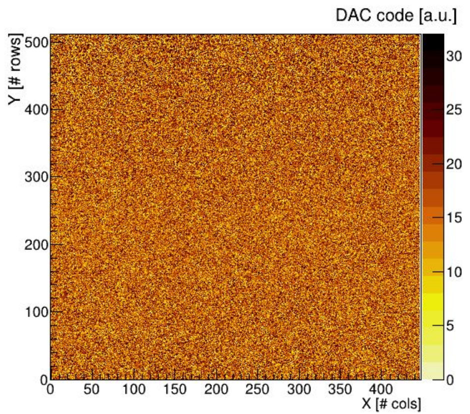
- ➢ **Packet decoding**
- ➢ **Clustering algorithm:**
  - ○ DBSCAN algorithm
  - ○ variable spatial and timing parameters to gather hits on the same cluster
- ➢ **ToA of each hit compared with the reference ToA of the associated digital pixel signal**

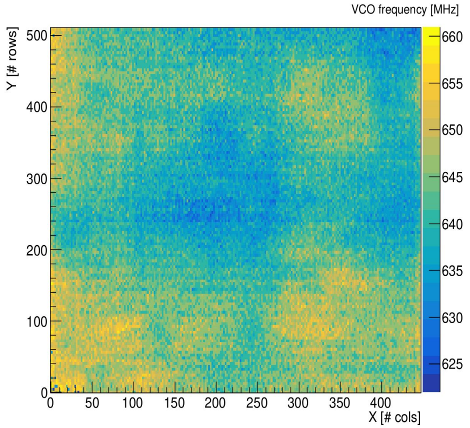




MCP-PMT characterization measurements - Preliminary procedures

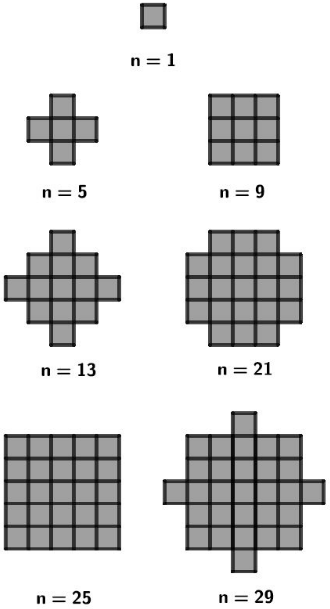
- Temperature inside dark box monitored through termo-couples in 4 points:
  - carrier PCB
  - tube flange (< 7°C when Timepix4 is acquiring)
  - chiller in branch and chiller out branch (about 3°C and 3.5°C)
- Humidity monitoring (about 5%)
- Timepix4 diagnostic repeated after MCP-PMT mounting, in vacuum conditions after phototube baking
- **Frame based threshold equalization**
- **VCO calibration** procedure

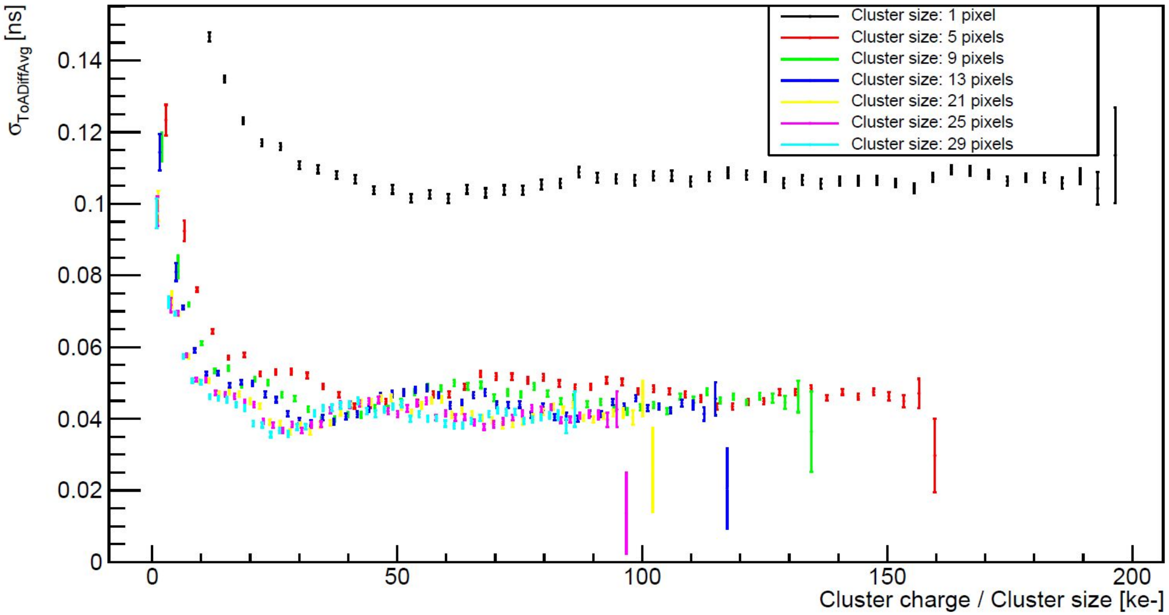




Cluster timing resolution selecting a shell of pixels

- ➢ **Large improvement in the resolution from 1-pixel clusters to 5-pixels clusters**
- ➢ Small or negligible improvement increasing further the cluster size

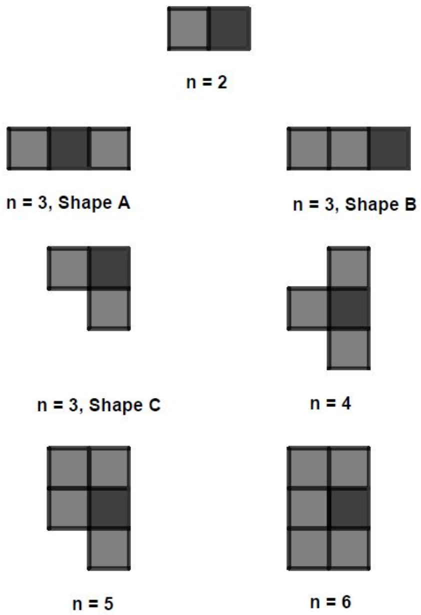


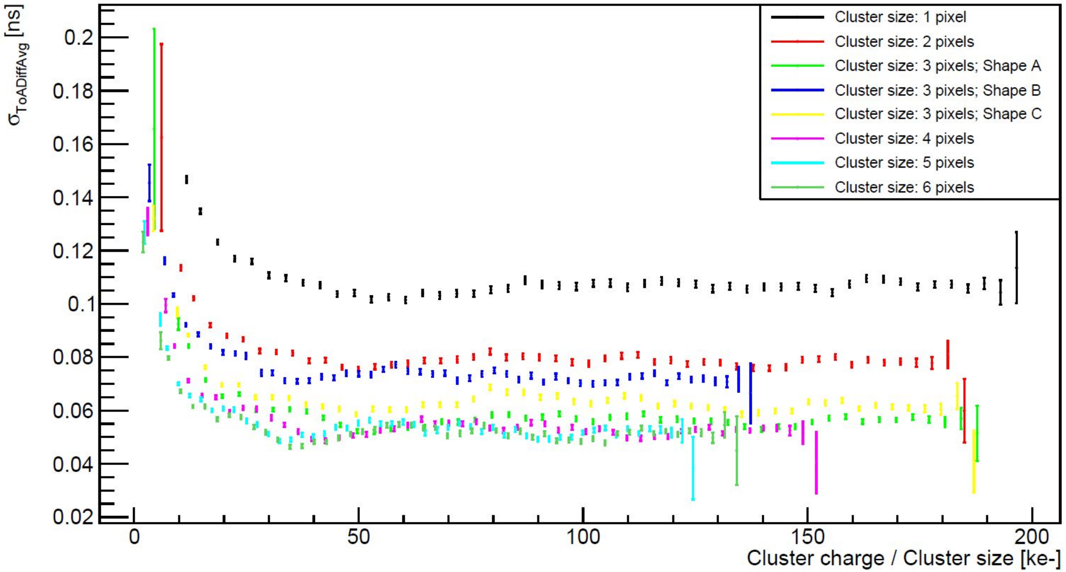


arXiv:2404.15499

Cluster timing resolution selecting a shell of pixels

- **Large improvement in the resolution from 1-pixel clusters to 5-pixels clusters**
- Small or negligible improvement increasing further the cluster size

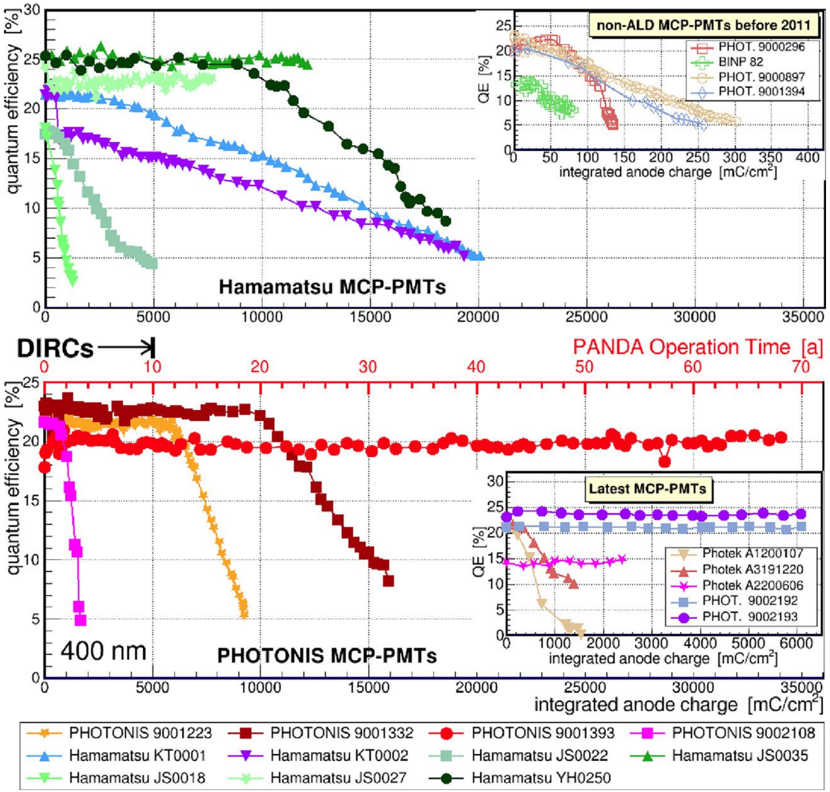




arXiv:2404.15499

MCP-PMT limitation

- MCP-PMT lifetime limited by the integrated anode charge, which leads to a strong QE reduction
  - From 0.2 C/cm^2 to >30 C/cm^2 in recent years thanks to ALD
- With the expected photon hit rate (~10 MHz/mm^2), assuming a 10^4 gain (very conservative), and an operation of 10 years with 25% duty cycle we have:
  - Total IAC ~120 C/cm^2
  - Anode current density ~2 μA/cm^2
- ALD coating is based on the deposition of resistive and/or secondary emissive layers (could tune MCP properties)
  - Reported adverse effects on saturation current on some model with ALD
- Strong R&D to find the best "recipe" is needed



[D. Miehling et al., NIM A 1049 (2023) 168047]