Timepix4 Characterization with Monochromatic X-Ray Synchrotron Beam

Feruglio A., Biesuz N., Bolzonella R., Brombal L., Brun F., Cardarelli P., Cavallini V., Delogu P., Fiorini M., Longo R., Rosso V.

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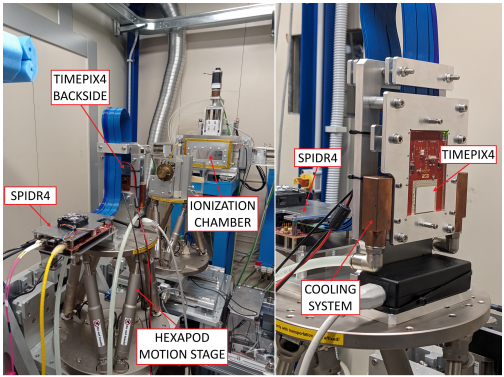
Timepix4

- Last Application-Specific Integrated Circuit (ASIC) of the Timepix family (Medipix4 collaboration)
- Different materials and thicknesses sensors connected to the ASIC via bump-bonding
- Hybrid pixelated detection system: 448x512 pixels with a 55 µm pitch (24.64 mm x 28.16 mm)

Operating Modes

- Frame-based photon counting
- Data-driven photon counting
- ToA-ToT data-driven mode:
  - Time-of-Arrival (**ToA**) measured with a bin width of 195 ps
  - Time-over-Threshold (**ToT**) measured with a bin width of 1.56 ns
  - Max rate: $3.6 \cdot 10^6$ hits/$mm^2 \cdot s$ (16 x10 Gbps fast link)

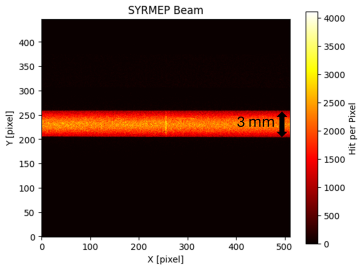
Data Acquisition System

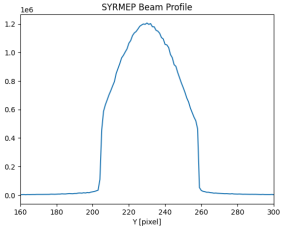


- **Timepix4-v2** assembly:
  - 300 µm p-on-n Si sensor
  - ToA-ToT data-driven mode
  - Thr: 1000 e^- (3.6 keV)
  - Bias: 100 V
- **SPIDR4** control board (2x2.56 Gbps fast link)
- **Custom software**: acquisitions with online monitor and analysis
- Custom **cooling system** to keep Timepix4 at 15 $^\circ C$
  - Chiller
  - Copper heat exchanger
- **2 Hexapod Motion Station**:
  - Timepix4 and SIPDR4
  - Lead edge (spatial response measurements)
- **Ionization chamber** to monitor the beam intensity

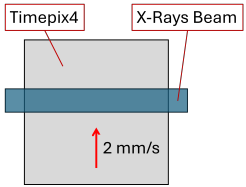
The Monochromatic Beam

- **Monochromatic X-rays laminar beam** of SYRMEP beamline at ELETTRA Synchrotron in Trieste
- **Beam energy** selected by acting on the orientation of the two crystals monochromator (8.5 - 40 keV)
- **Beam intensity** set by varying the relative angle of the crystals (rocking fraction) and applying Al filters
- **Beam geometry**: 3.0 mm x 28.6 mm cross section on the detector (tungsten slits), Gaussian profile





Timepix4 Energy Calibration

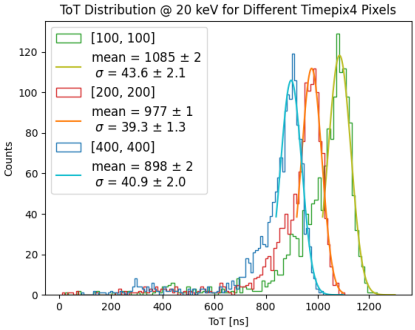


Data Acquisitions

- **Full-matrix monochromatic acquisitions** obtained by moving the Timepix4 at a constant speed of 2 mm/s along the fixed X-rays beam:
  - 18 energies in the range 8.5 keV - 40 keV
  - $\sim$ 4000 hits/pixel

Data Analysis

- Hits clusterization: only cluster size = 1 events used in the calibration
- Pixel by pixel analysis: gaussian fit on the ToT spectra



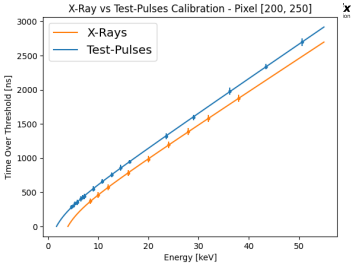
Timepix4 Energy Calibration

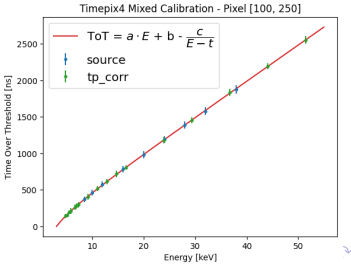
Test-Pulses Acquisitions and Analysis

- Timepix4 calibration curve non-linear in the low energy region
- **Internally generated test-pulses acquisition**
  - 17 energies in the nominal range 4.7 keV- 50.7 keV (500 hits/pixel)
- Test-pulses and X-rays: different calibration curves in ToT vs Energy plots
- Test-pulses acquisitions corrected introducing two parameters:
  - **Slope Correction**: $E_{TP} \rightarrow E_{TP} \cdot g_{i,j}$
  - **ToT Offset Correction**: $ToT_{TP} \rightarrow ToT_{TP} + h_{i,j}$

Timepix4 Calibration Curve

- Pixel per pixel fit of the Timepix4 calibration function on the ToT vs Energy plot: $$ToT = a \cdot E + b - \frac{c}{E - t}$$
- ToT to Energy conversion parameters: $a_{i,j}$, $b_{i,j}$, $c_{i,j}$ and $t_{i,j}$



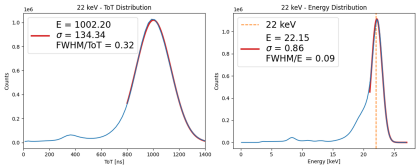


Timepix4 Energy Calibration

Calibration Results

- Full matrix **ToT spectra** → **Energy spectra** (all cluster size)
  - Energy peaks are systematically narrower than ToT peaks
- Photopeaks characterization via Gaussian fit:

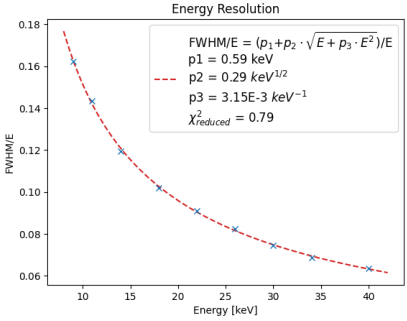
X-Rays Energy [keV]	$E_{measured}$ [keV]	FWHM/$E_{measured}$
9	9.0	0.16
22	22.1	0.09
30	30.1	0.07
40	40.0	0.06



Energy Resolution Function

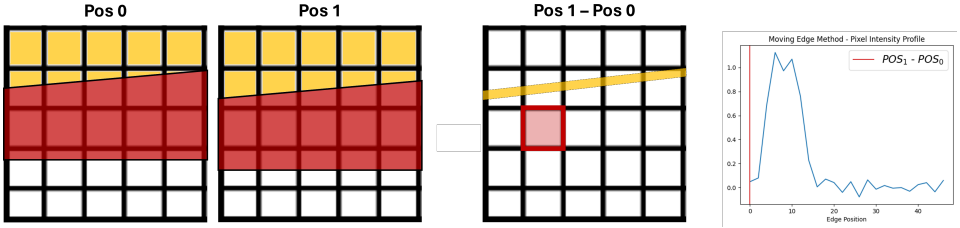
- **Energy resolution** evaluated by fitting the FWHM/E vs Energy points with the Gaussian energy broadening function:

$$\frac{\Delta E}{E} = \frac{p_1 + p_2 \cdot \sqrt{E + p_3 \cdot E^2}}{E}$$



Timepix4 Spatial Response: Moving Edge Method

- **Multiple acquisitions of an edge** shifted by a fixed step (shorter than pixel pitch)
- **ESF** $\rightarrow$ **LSF**: difference between each image and the one acquired in the previous position
- In each pixel, the intensity as a function of the slit position is measured
- Different pixel results combined to improve the statistics



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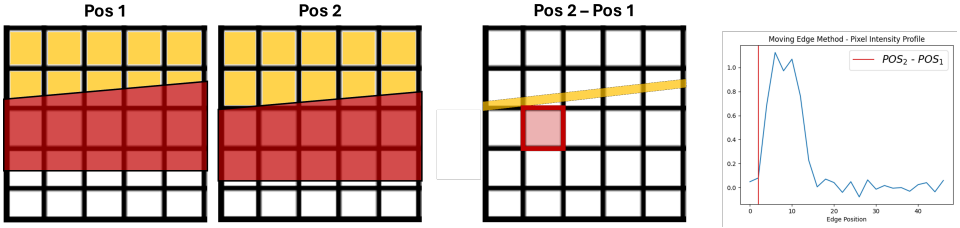

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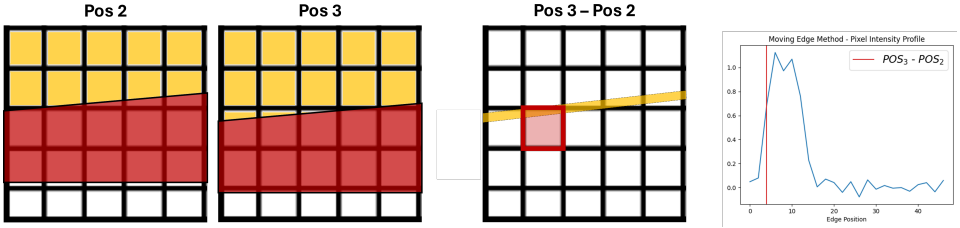

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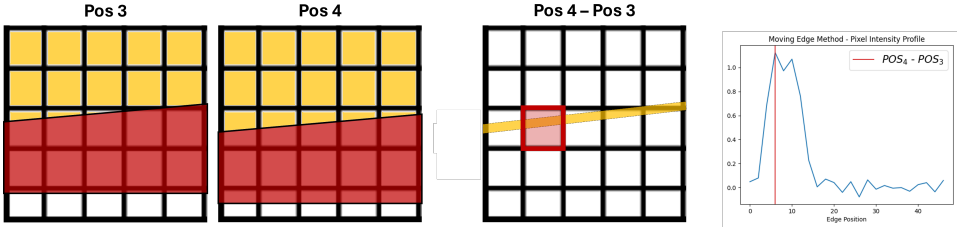
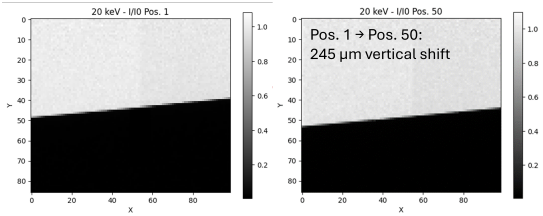


Timepix4 Spatial Response

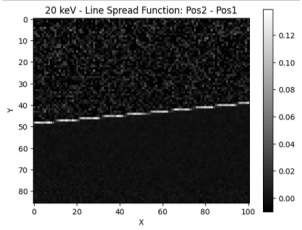
Data Acquisitions

- **Lead edge** in front of the detector (5.5° tilt)
- 5 µm steps vertical shift
- 50 position: 245 µm total shift
- Energies: 10 keV, 20 keV



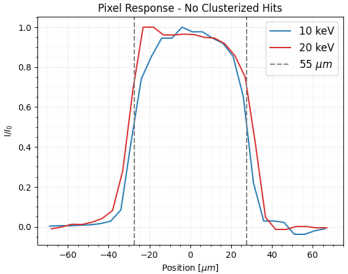
Data Analysis

- Four images for each position:
  - **No clusterized events**
  - **Clusterized events**
  - **Cluster size = 1 events**
  - **Cluster size = 2 events**
- Flat-field correction for each image
- Moving Edge Analysis: **ESF** → **LSF**



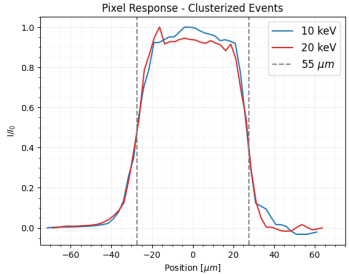
Timepix4 Spatial Response: Normalized LSF (thr = 3.6 keV)

No Clusterized Events



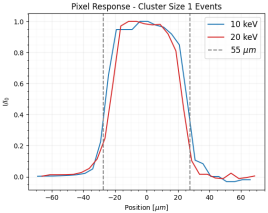
- $FWHM_{10keV}$ = 58 µm
- $FWHM_{20keV}$ = 61 µm
- FWHM larger than pixel pitch (55 µm) → charge sharing

Clusterized Events

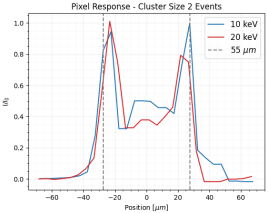


- $FWHM_{10keV}$ = 55 µm
- $FWHM_{20keV}$ = 55 µm
- FWHM match with pixel pitch → charge sharing corrected by clusterization

Cluster Size = 1



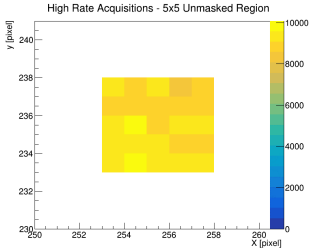
Cluster Size = 2



High Rate Measurements

Data Acquisitions

- **High rate acquisitions** → few pixels unmasked (5x5 pixel region) to avoid readout bandwidth saturation (2x2.56 Gbps fast link)
- Photon rate monitored using a ionization chamber
- Energies:
  - **11 keV:** 2.7 $\cdot 10^4$ - 1.7 $\cdot 10^8$ absorbed photon $mm^{-2}s^{-1}$
  - **20 keV:** 1.9 $\cdot 10^6$ - 3.2 $\cdot 10^7$ absorbed photon $mm^{-2}s^{-1}$



Paralyzable and Non-Paralyzable Models

Fit of the electronics paralyzable and non-paralyzable model on pixel counts:

- **Paralyzable Model**:

$$m = n \cdot e^{-n \cdot \tau} = I_{IOC} \cdot A \cdot e^{-I_{IOC} \cdot A \cdot \tau}$$

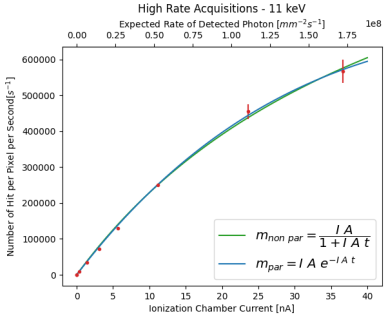
- **Non Paralyzable Model**:

$$m = \frac{n}{1 - n \cdot \tau} = \frac{I_{IOC} \cdot A}{1 - I_{IOC} \cdot A \cdot \tau}$$

m: measured hits rate per pixel [hits s^{-1}]
n: expected hits rate per pixel [hits s^{-1}]
I_{IOC}: Ionization chamber current [nA]
A: conversion factor
τ: pixel dead time

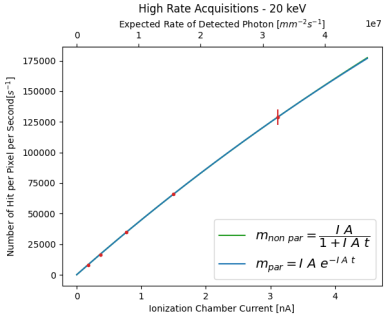
High Rate Measurements - Results

11 keV



- $\tau_{paralyzable} = 544 \pm 16$ ns
- $\tau_{non\ paralyzable} = 746 \pm 54$ ns
- $ToT_{11\ keV} \simeq 388$ ns

20 keV



- $\tau_{paralyzable} = 760 \pm 56$ ns
- $\tau_{non\ paralyzable} = 817 \pm 67$ ns
- $ToT_{20\ keV} \simeq 662$ ns

Timepix4 Characterization with Monochromatic Synchrotorn X-Ray Beam - Conclusions

Energy Characterization

- Timepix4 energy resolution after calibration (6 % at 40 keV) is compatible with literature results (Timepix assembly with 300 µm Si sensors)

Spatial Response

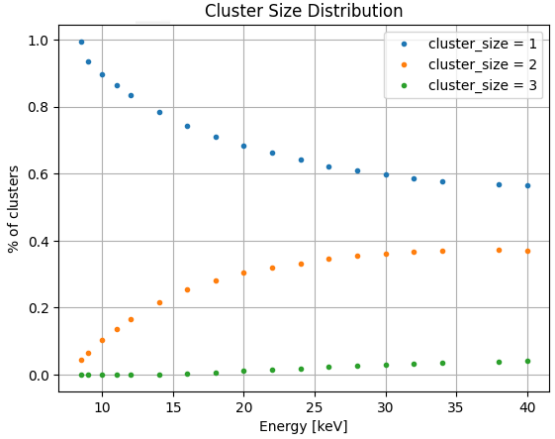
- Event clusterization: $FWHM_{20\ keV}$: 61 µm $\rightarrow$ 55 µm

High Rate Acquisitions

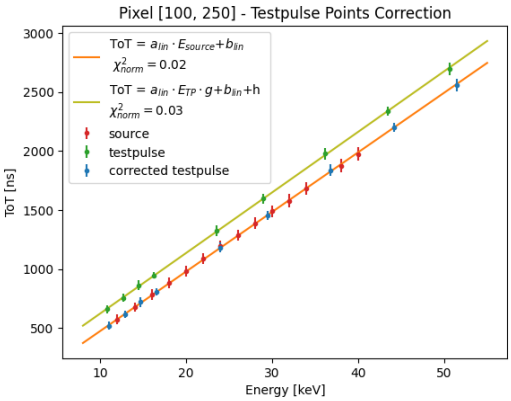
- Pixel count is linear up to high photon rate ($\sim 4{\cdot}10^7$ hits $\cdot mm^{-2}s^{-1}$ at 11 keV)
- More investigation are needed to study the pixel dead time dependence on photon energy and on the Timepix4 configuration parameters (Ikrum)

Thanks for your Attention!

Cluster Size Distribution



Testpulse Points Correction



- E $>$ 10 keV - Linear region of the calibration curve
- For each pixel, a linear fit was performed on source points:

$$ToT = a_{lin} \cdot E_{source} + b_{lin}$$

- For each pixel, the fit of function:

$$ToT = a_{lin} \cdot E_{testpulse} \cdot g + b_{lin} + h$$

was performed on testpulse points

- For each pixel, parameters g and h to correct the points acquired via testpulse