Istituto Nazionale di Fisica Nucleare
SEZIONE DI FERRARA

International Workshop 27th iWoRiD on Radiation Imaging Detectors

27th iWoRID | June 30th 2026 | Ghent

Characterization of CdTe and GaAs Timepix4 detectors with monochromatic X-rays at SOLEIL synchrotron

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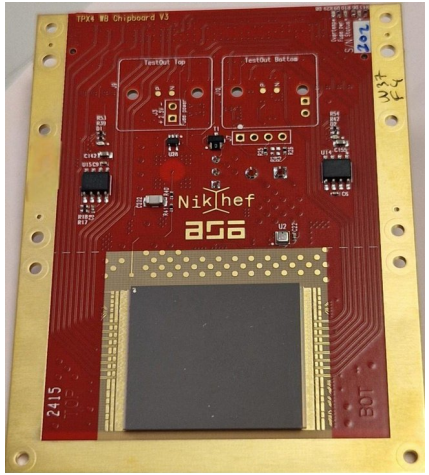
Timepix4

- Medipix4 collaboration → development of read-out chips for hybrid pixel detectors: Medipix4 and Timepix4

- Timepix4 features:
  - Small pixel size: 55 µm
  - Large single-sensor area: 512 x 448 pixel (28.2 x 24.6 mm^2)
  - TSV compatible → gapless tiling possible
  - Hybrid technology Si, GaAs, CdTe sensors → application optimization
  - 2 readout modes: data-driven and frame-based

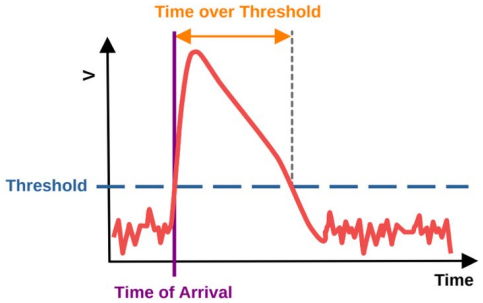


Timepix4
Calibration
SOLEIL setup
CdTe results
GaAs results
Conclusions

Timepix4 operation modes

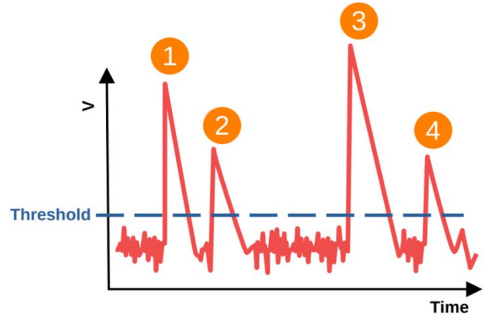
Data-driven

- **Event-based** readout
- Pixel **position**
- **Time-of-arrival**, <200 ps timestamp binning
- **Time-over-threshold**, 11-bit dynamic range, ~ 200 e^- rms resolution
- Rate up to 3.6 Mhit s^{-1} mm^{-2} @ 160 Gb/s Readout bandwidth (16×10.24 Gbps)



Frame-Based

- **Single energy-threshold** photon-counting mode
- **Full-frame readout** with continuous read-write
- 8-bits or 16-bits counter depth
- Rate up to 5 Ghit s^{-1} mm^{-2} @ 160 Gb/s Readout bandwidth (16×10.24 Gbps)



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Timepix4 X-ray imaging application

- Application to **X-ray imaging** (~10-100 keV)
- Thick high-Z sensor (CdTe, GaAs) for efficiency

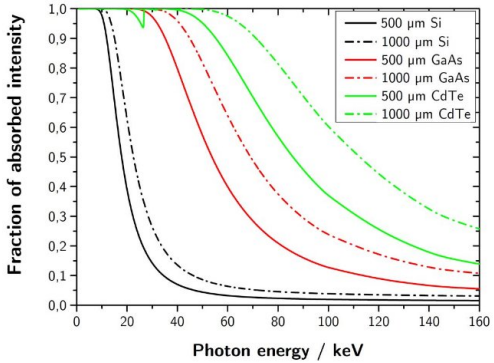
- **Frame-based** mode (single-threshold PC detector)

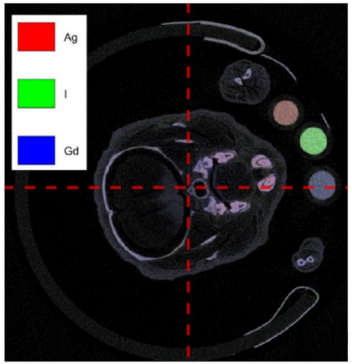
  → morphological information

- **Data-driven** mode

  → high spatial-resolution, full-spectral information

  → Spectral imaging





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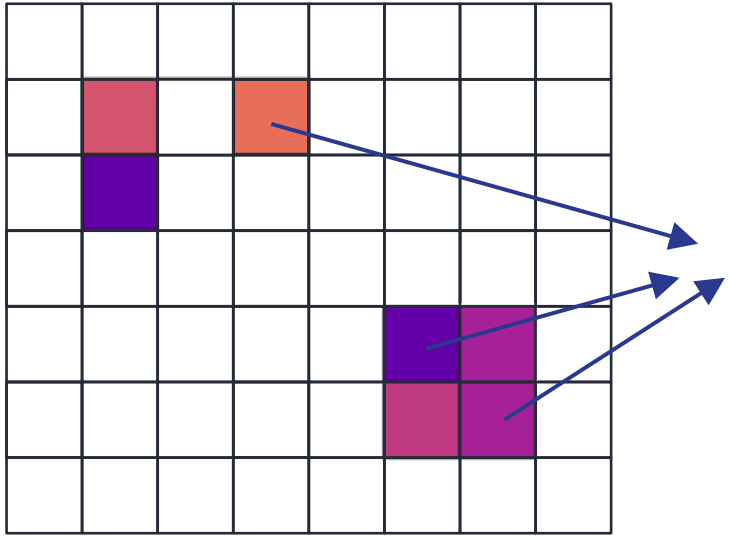
Data-driven acquisition mode



$[\ \text{ToA, x, y, ToT}\ ]_i$ For each pixel hit

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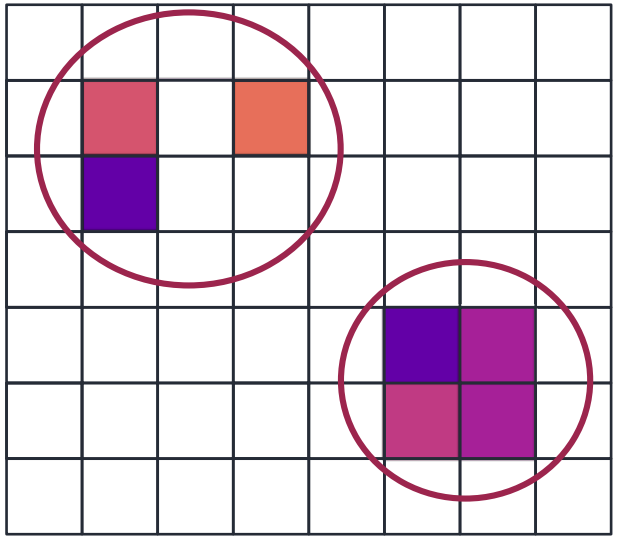
Data-driven acquisition mode



Time and position coincidence window
→ **Clustering** → event reconstruction

$[\ \text{ToA}, x, y, \text{ToT}\ ]_i$ For each pixel hit

Time over Threshold
→ Charge collected
→ energy deposited

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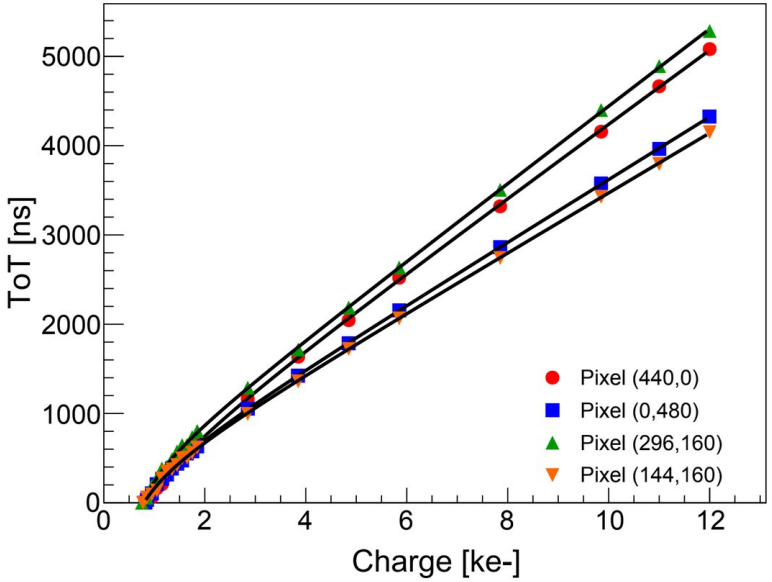
Calibration with test pulse

- Timepix4 calibration curve non-linear in the low energy region
- Internally generated test-pulse acquisition sequence
- 20 charge points [0.5 ke- → 12 ke-]

- Each pixel response fit with the function*:

$$ToT = aE + b - \frac{c}{E - t}$$



*J. Jakubek et al. (2007) IEEE Nuclear Science Symposium Conference Record, Vol. 3

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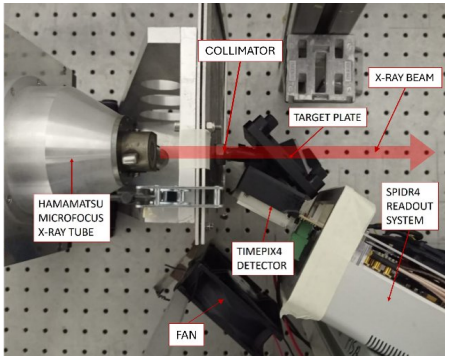
Calibration with radiation

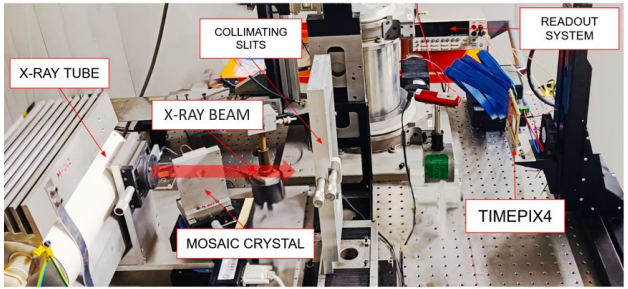
- Test pulse calibration → pixel-based ToT vs Charge response curve → not reliable for absolute quantitave measure of energy deposit by radiation in sensor
- Calibration with radiation at accurately known energies is required

X-ray fluorescence



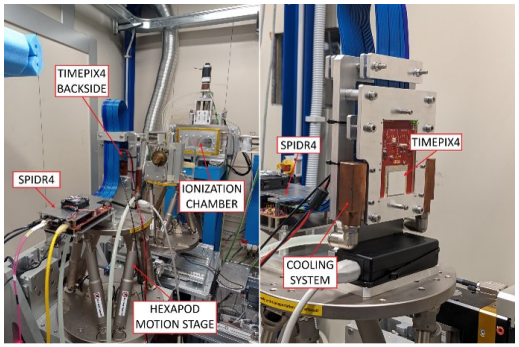
Feruglio et al. (2024) Nuovo Cimento C 47

X-ray tube beam bragg diffraction



Velardita et al. (2025), J. Instrum. 20, T05003.

Synchrotron radiation



Delogu et al. (2024) NIM A 1068, 169716

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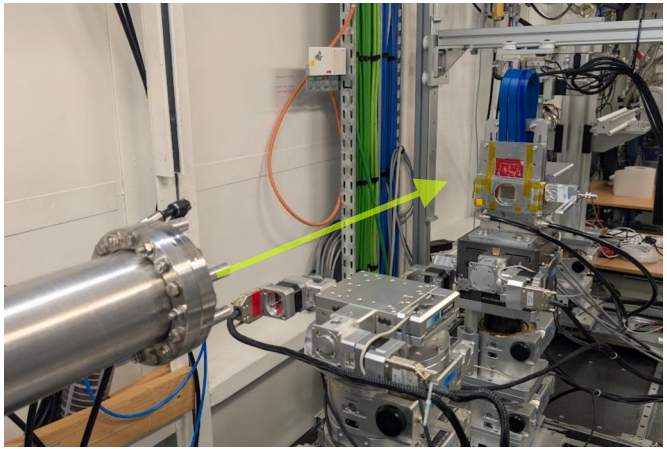
SOLEIL beamline and goals

- SOLEIL Synchrotron (Paris, France)
- METROLOGIE beamline
- Hard X-ray branch ~100 eV – 40 keV (monochromatic)
- Few 10^9 photons/s/mm^2 in monochromatic



Acquired datasets for several Timepix4 assemblies:

- 3x CdTe (1 mm)
- 1x GaAs (0.5 mm)

→ energy calibration
→ pixel spectral response
→ energy resolution

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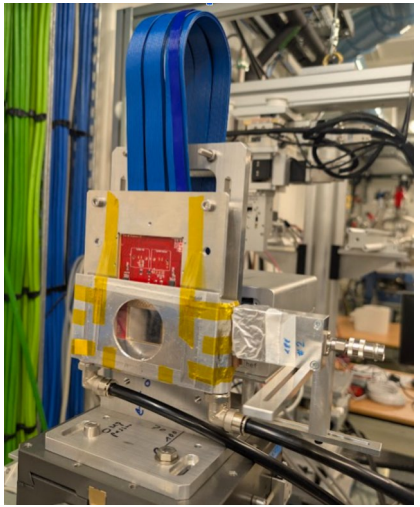
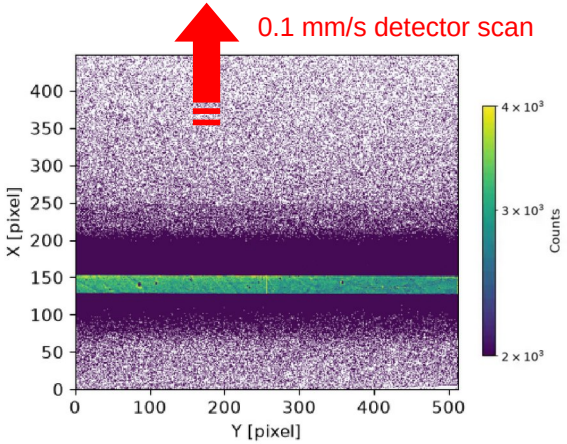
SOLEIL setup and goals

- **Timepix4** CdTe / GaAs assemblies
- SPIDR4 readout system (Nikhef) 2x 5.12 Gbs
- DataPix4 software (INFN)
- $V_{bias} = 500$ V
- Liquid cooling (back of carrier board) at 15°C





X-ray beam

- X-ray beam heigth ~ 1.4 mm
- Rate adjusted to ~ 600 hits/pix/s
- Scan time to integrate $>10^4$ events/pix

Timepix4
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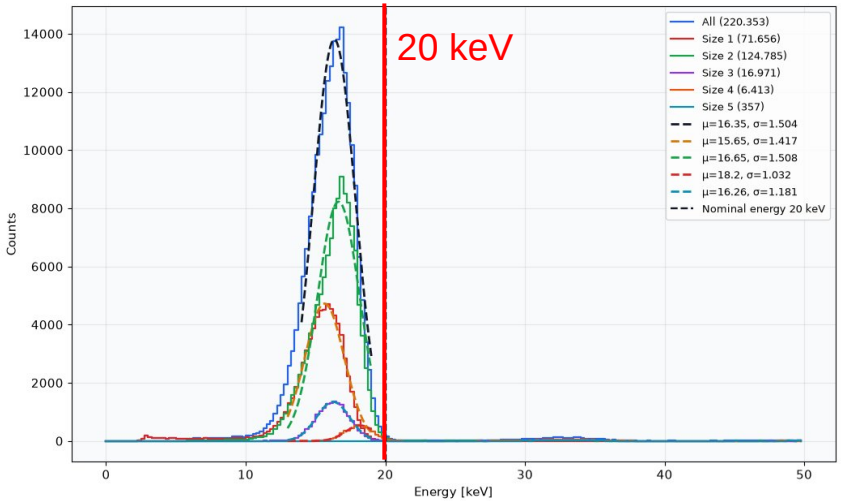
SOLEIL energy calibration methods

- After test-pulse calibration mismatch of energy evaluated (cluster-size dependent)

Test-pulse calibration only



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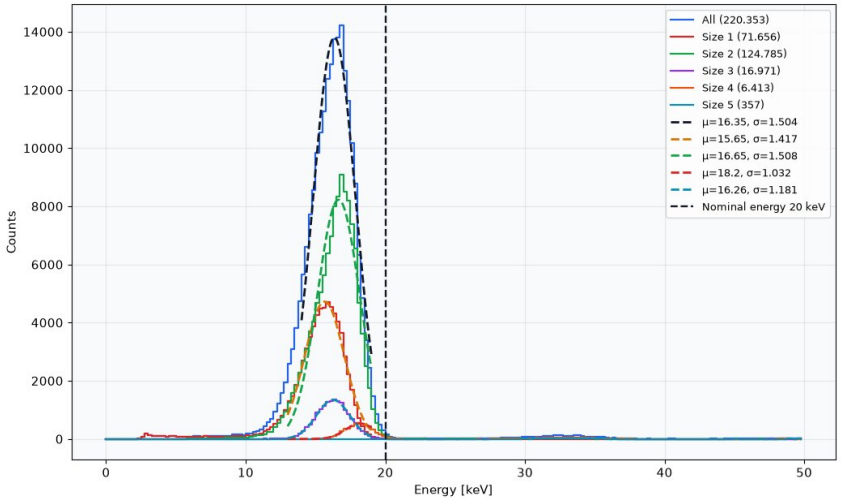
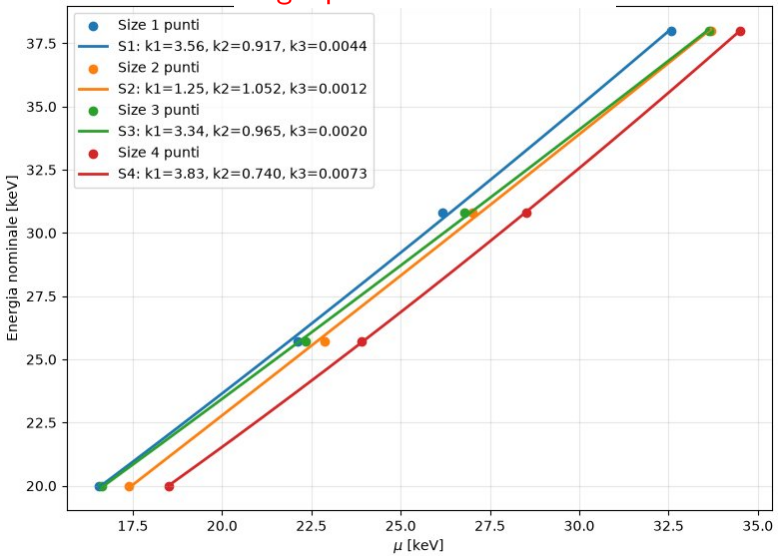
SOLEIL energy calibration methods

- After test-pulse calibration mismatch of energy evaluated (cluster-size dependent)
- cluster-size dependent energy correction for each pixel



Single pixel calibration curve



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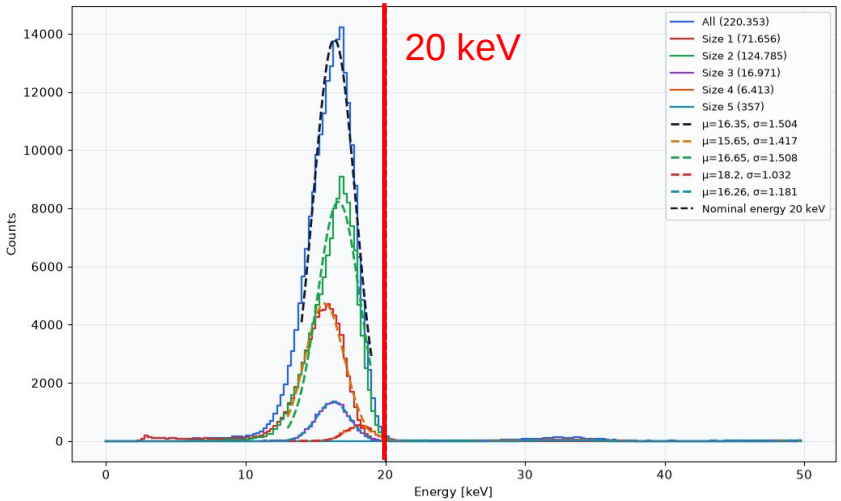

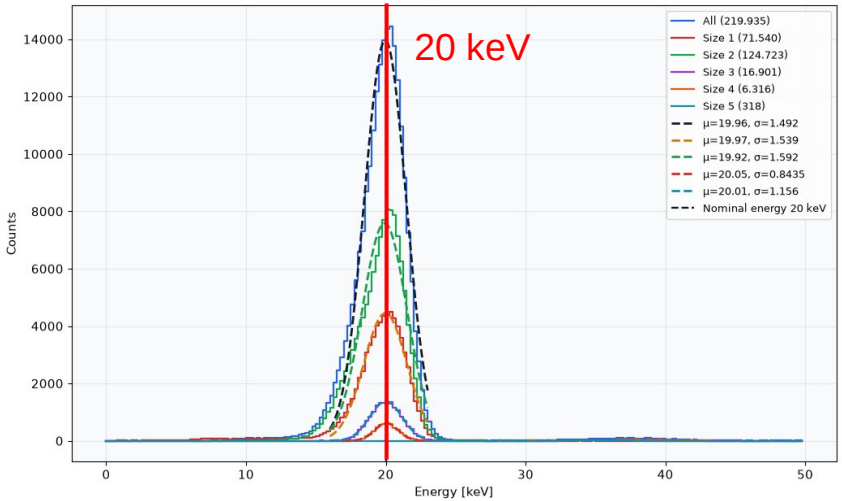

Timepix4 Calibration
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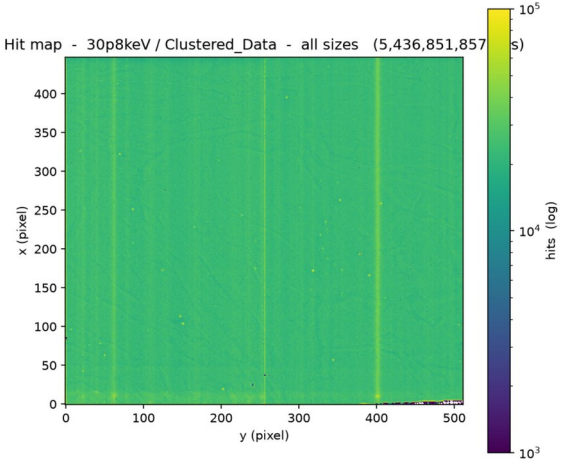
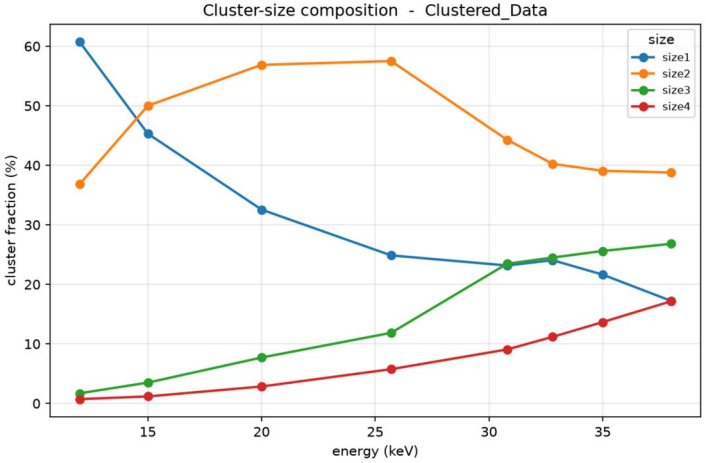
Results CdTe assembly

- CdTe 1mm-thick sensor
- Beam energies acquired : 12, 15, **20**, **25.7**, 27.7, **30.8**, 32.8, 35, **38** keV
- Pixel based calibration calculated and applied





5 pixel radius, 250 ns time window

Cd **48**
cadmium

26711	23173	26093
4018	3400	3365
3727	3315	3715
3538	3133	3526
405		
112.414		+2

Te **52**
tellurium

31814	27473	30993
4939	4118	4068
4612	4029	4570
4341	3768	4299
573	573	583
127.6		-2, +2, +4, +6

Timepix4
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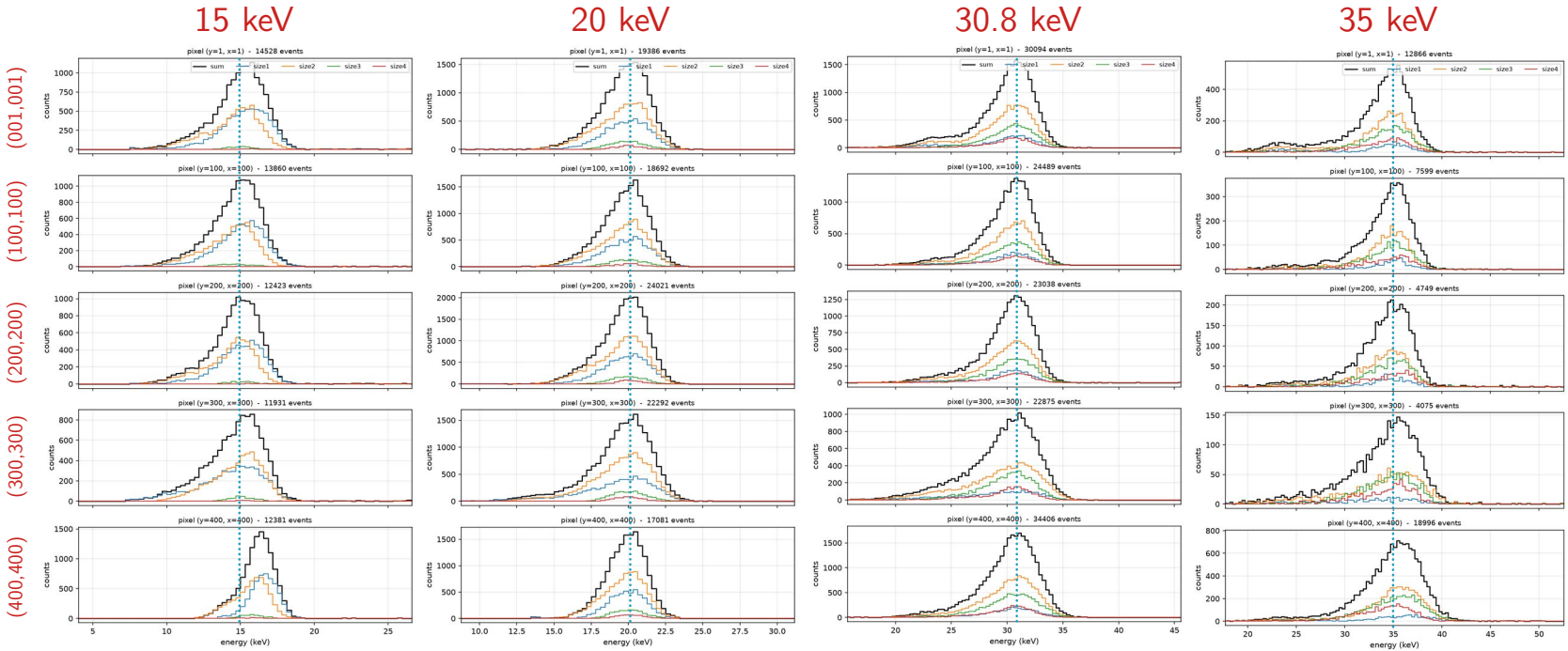
CdTe – single-pixel spectra

- Sample single pixel spectra at different energies after calibration



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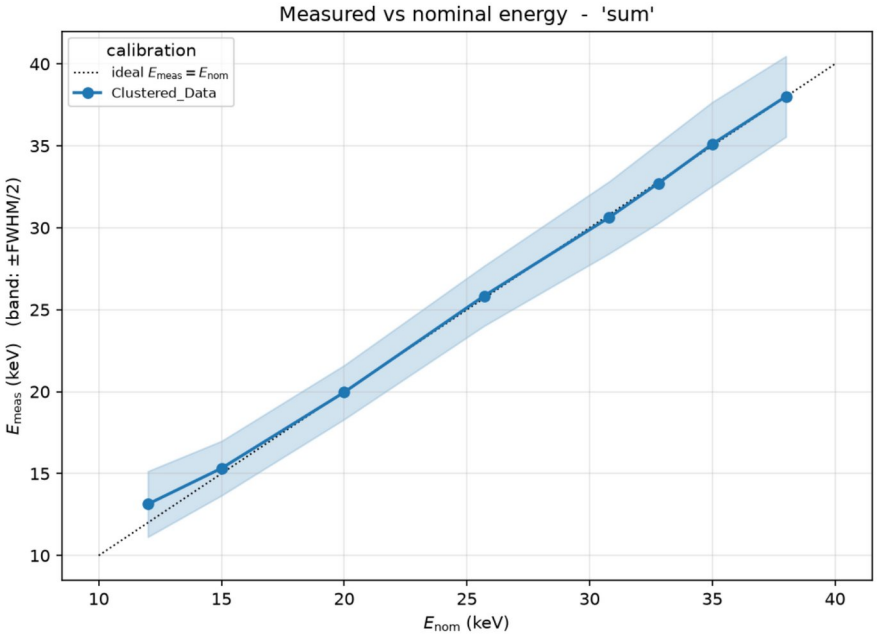
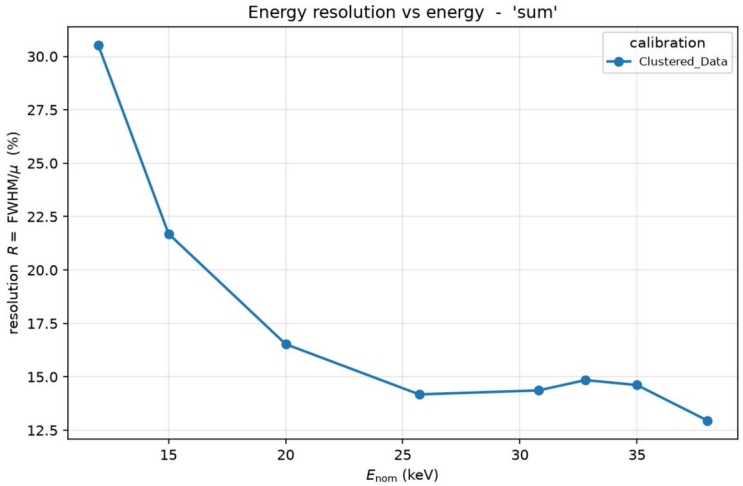
Results CdTe assembly





- Resolution FWHM (sum all cluster size) 4 keV → 4.75 keV (30% → 12.5%)

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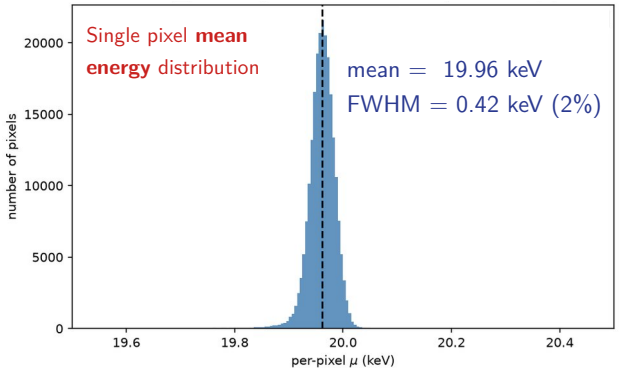
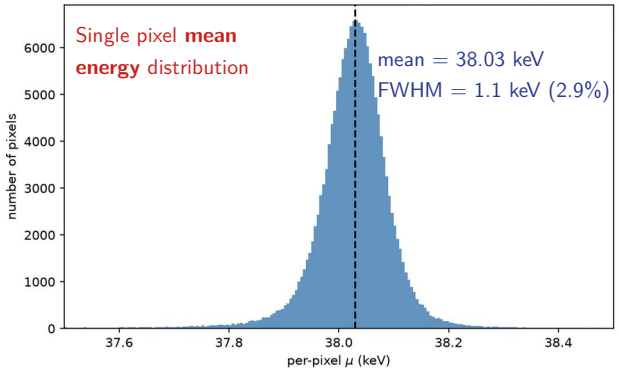
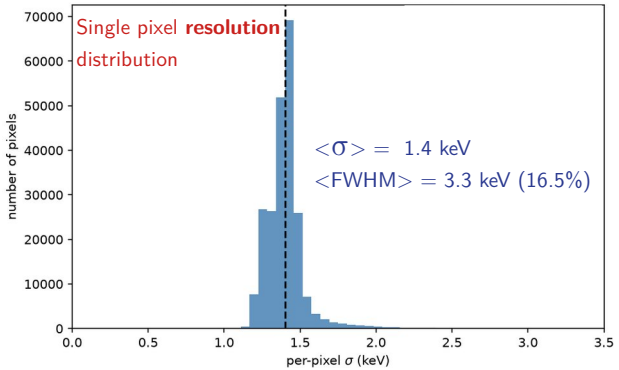
CdTe – pixel spectra distribution

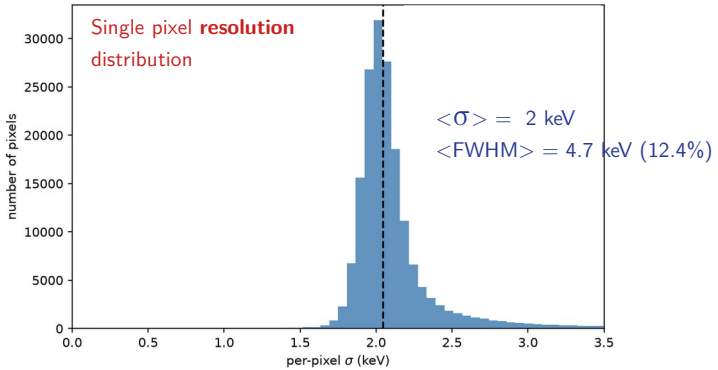
20 keV



38 keV







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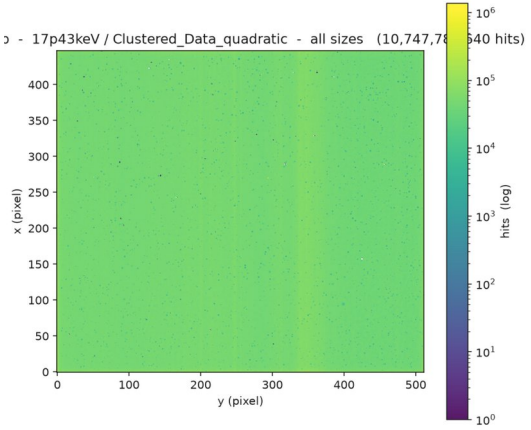
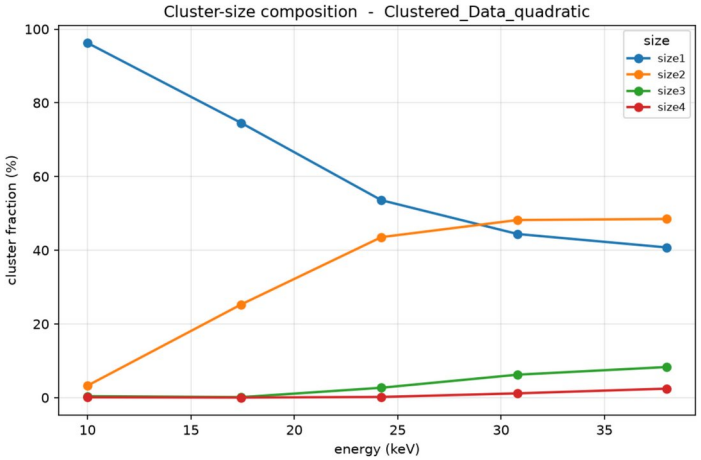
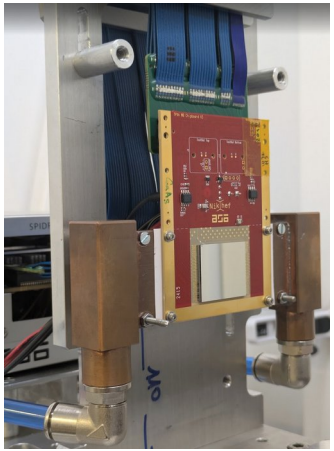
GaAs assembly

- GaAs 0.5 mm-thick sensor
- Beam energies: 10, **17.43**, **24.21**, **30.8**, **38** keV







Ga	31	As	33
gallium		arsenic	
10367	9251	10267	11867	10543	11726
1299	1199	1196	1527	1386	1381
1143	1124		1359	1317	
1116	1098		1324	1282	
19			42		
69.72		+3	74.9216		-3, +3, +5

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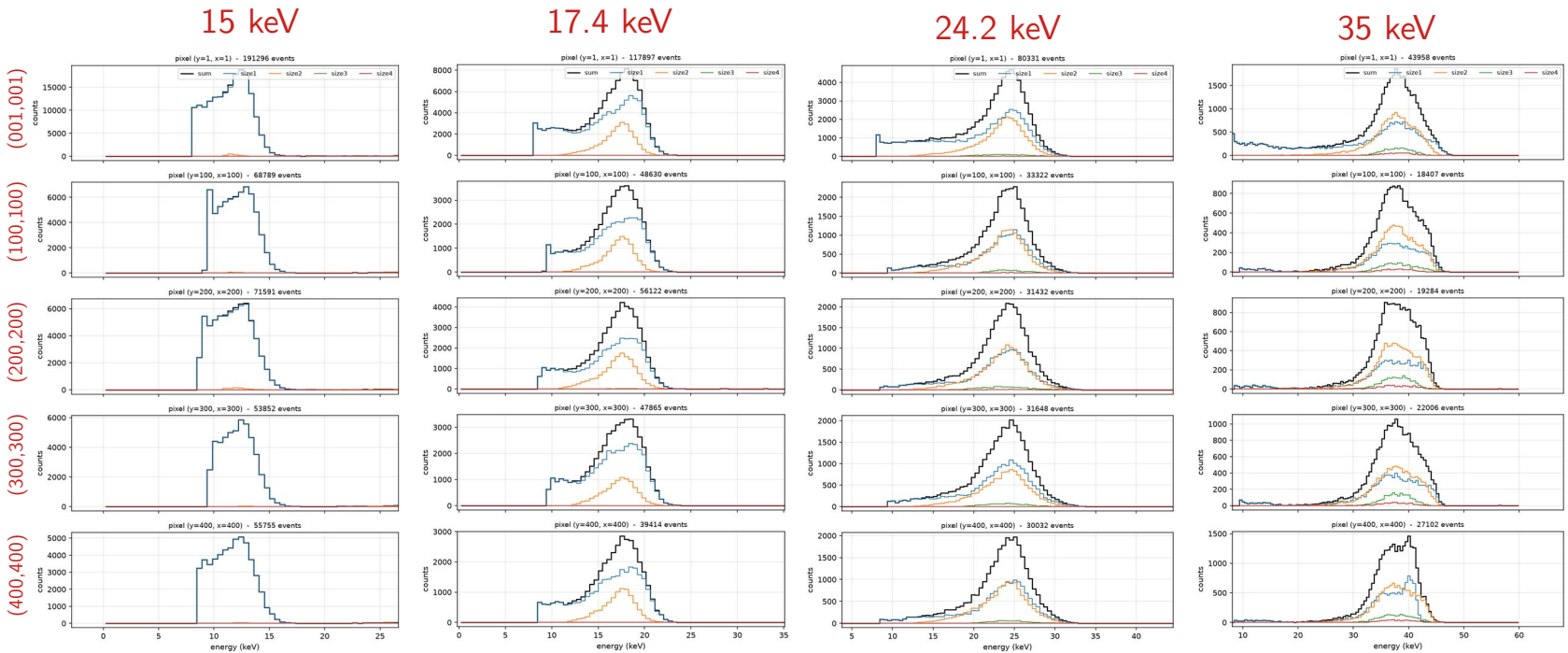
GaAs – single-pixel spectra

- Sample single pixel spectra at different energies



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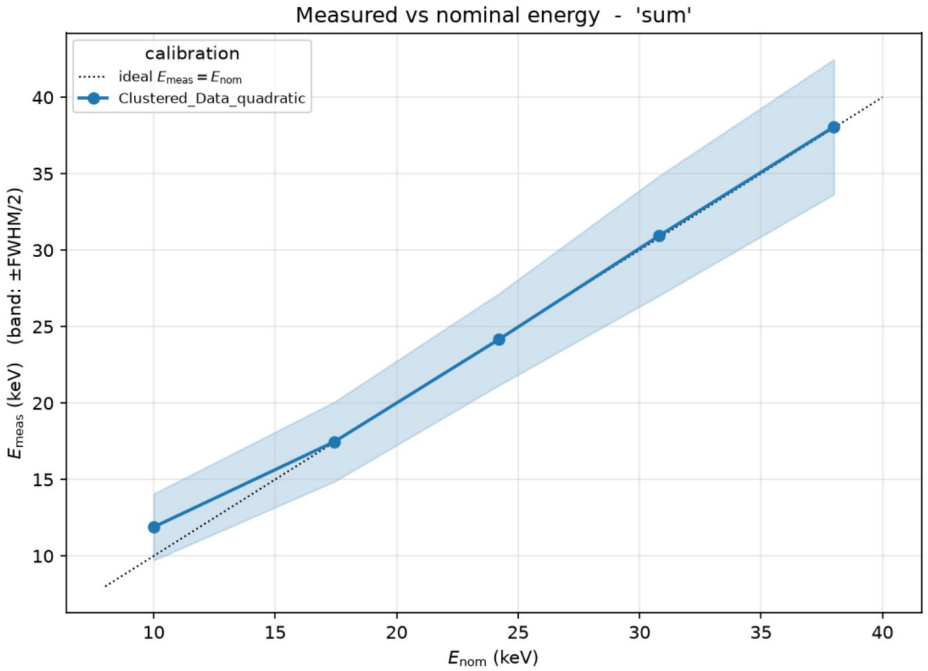
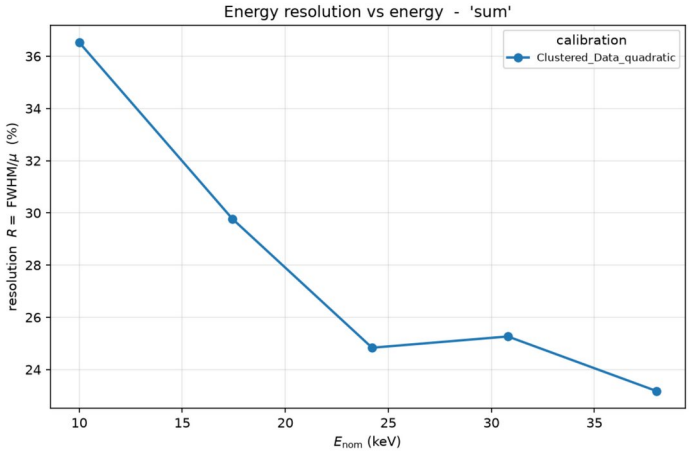
Results GaAs assembly





- Resolution FWHM (sum all cluster size) 3.6 keV $\rightarrow$ 8.7 keV (36% $\rightarrow$ 23%)
- Pixel mean energy distribution $\sigma < 1\%$

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Summary

- Energy response calibration aimed at high-resolution spectral X-ray imaging applications
- Timepix4 assemblies with CdTe (1 mm) and GaAs (0.5 mm)
- Measurement at METROLOGIE beamline (SOLEIL) energy range 10 - 40 keV
- Energy response calibrated pixel-by-pixel on clustered events

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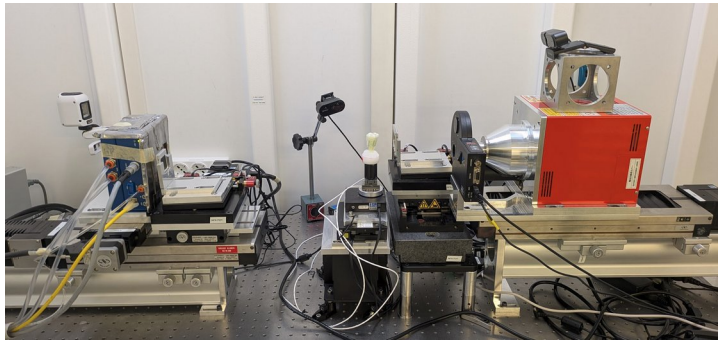
Outlook

- **Expand energy range** of calibration with lab-based sources (XRF and K-edge absorption)
- Monitor calibration stability and reliability with lab measurement
- Application to **high-resolution micro tomographic spectral imaging**

  → **Simone Velardita's talk on Thursday at 9:50**
- Refinenment of the calibration based on single pixel test-pulse response alignemnt

  (Delogu et al. (2024) NIM A 1068, 169716)



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CdTe – single-pixel spectra

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cadmium			tellurium		
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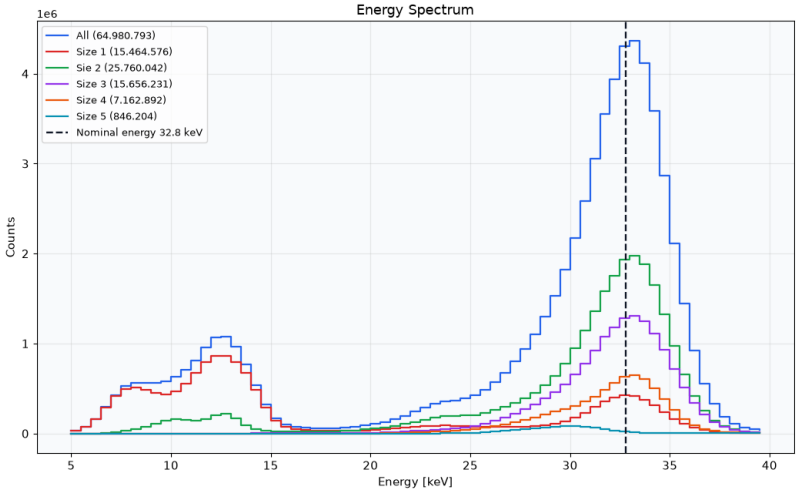
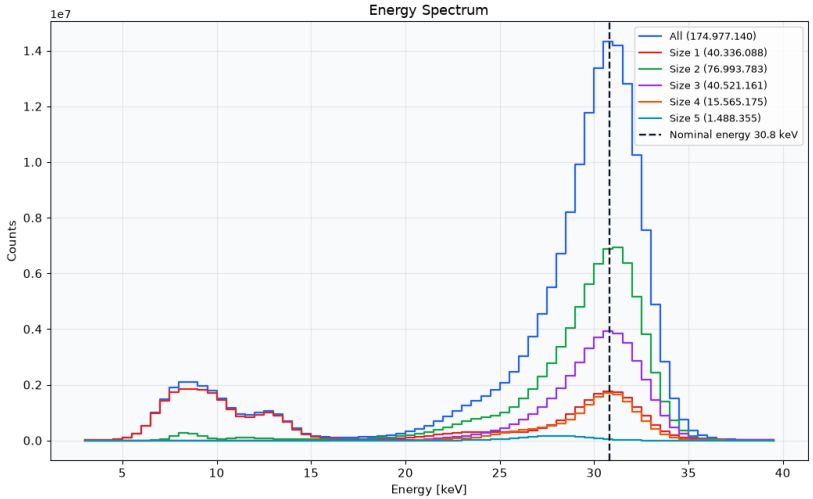
405			573	573	583
112.414		+2	127.6		-2, +2, +4, +6





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Mixed calibration pixel-to-pixel

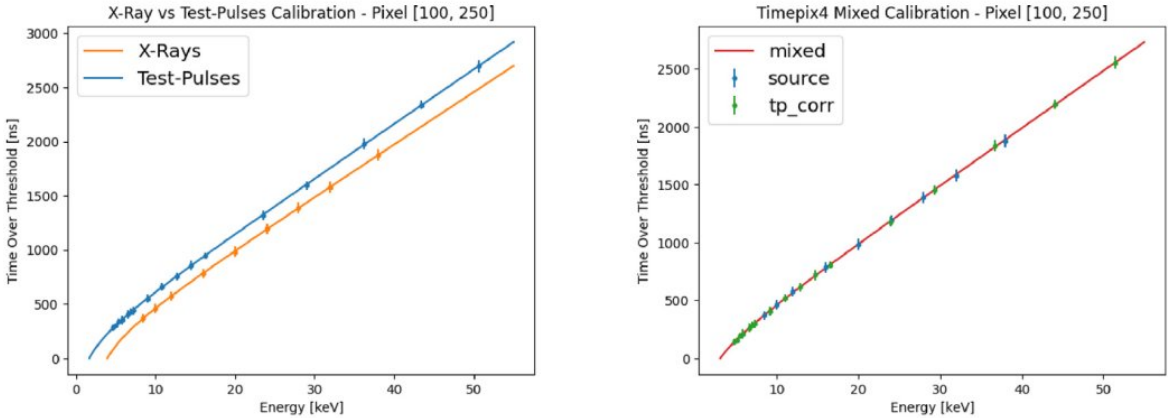

Fig. 5. Left: comparison between the calibration curves obtained using the X-ray acquisitions and the test-pulses acquisitions. Right: fit of the calibration curves on both the X-ray points and test-pulses corrected points. The two plot refers to the same pixel [100, 250].

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Full Length Article

Validation of Timepix4 energy calibration procedures with synchrotron X-ray beams

P. Delogu [a,b], N.V. Biesuz [c,d], R. Bolzonella [c,d], L. Brombal [e,f], V. Cavallini [c,d], F. Brun [g,f], P. Cardarelli [c,d], A. Feruglio [h,b,*], M. Fiorini [c,d], R. Longo [e,f], V. Rosso [h,b]

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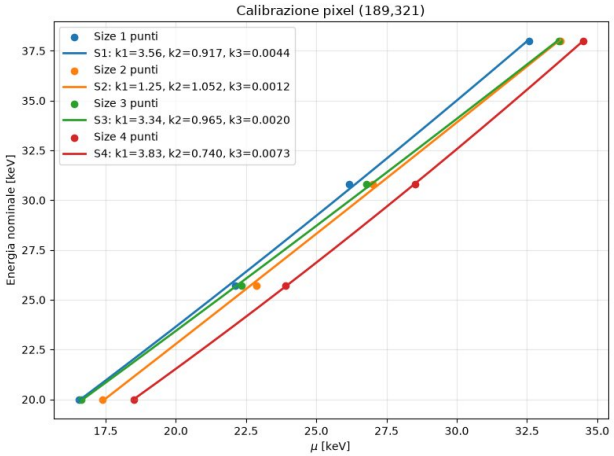
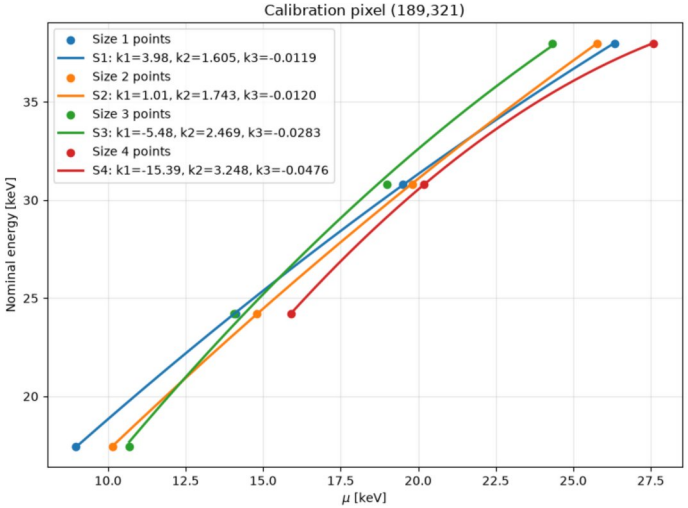
Calibration





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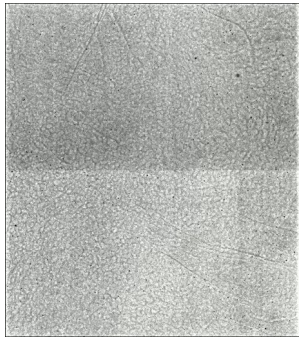
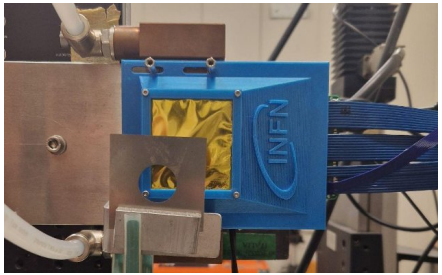
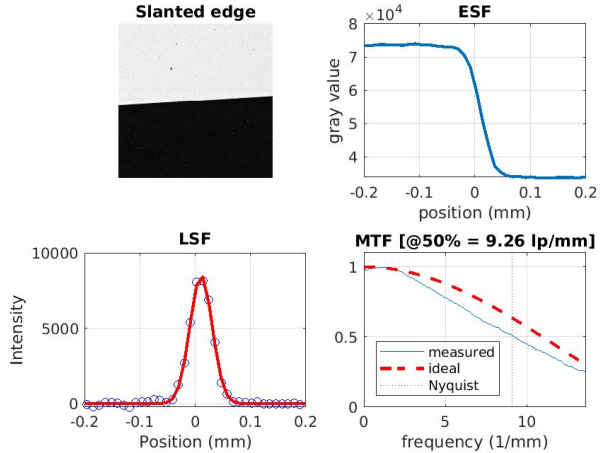
Previous activities on GaAs assembly at INFN

- flat-field stability (frame-based)
- spatial resolution (frame-based)
- preliminary energy calibration and cluster formation (data-driven)







Presented at iWORID Workshop (July 2025), proceedings:
Velardita S. et al. “First characterization of a GaAs-based Timepix4 detector assembly for X-ray imaging applications”

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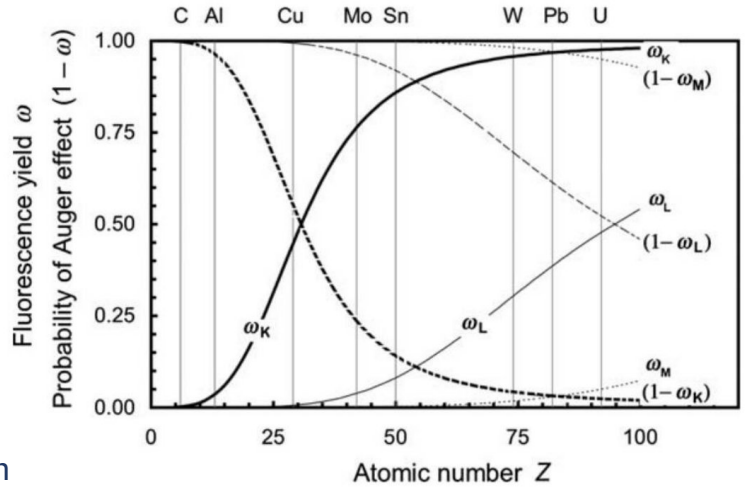
Semiconductor materials

Material	Atomic Numbers (Z)	Density (g/cm³)	K_α Energy (keV)
Si	14	2.33	Si 1.74 keV
GaAs	Ga: 31, As: 33	5.32	Ga 9.25 keV As 10.53 keV
CdTe	Cd: 48, Te: 52	6.2	Cd 23.17 keV Te 27.47 keV
CZT	Cd: 48, Zn: 30, Te: 52	~5.78	Cd 23.17 keV Zn 8.64 keV Te 27.47 keV

MFP~60 μm

MFP ~110 μm