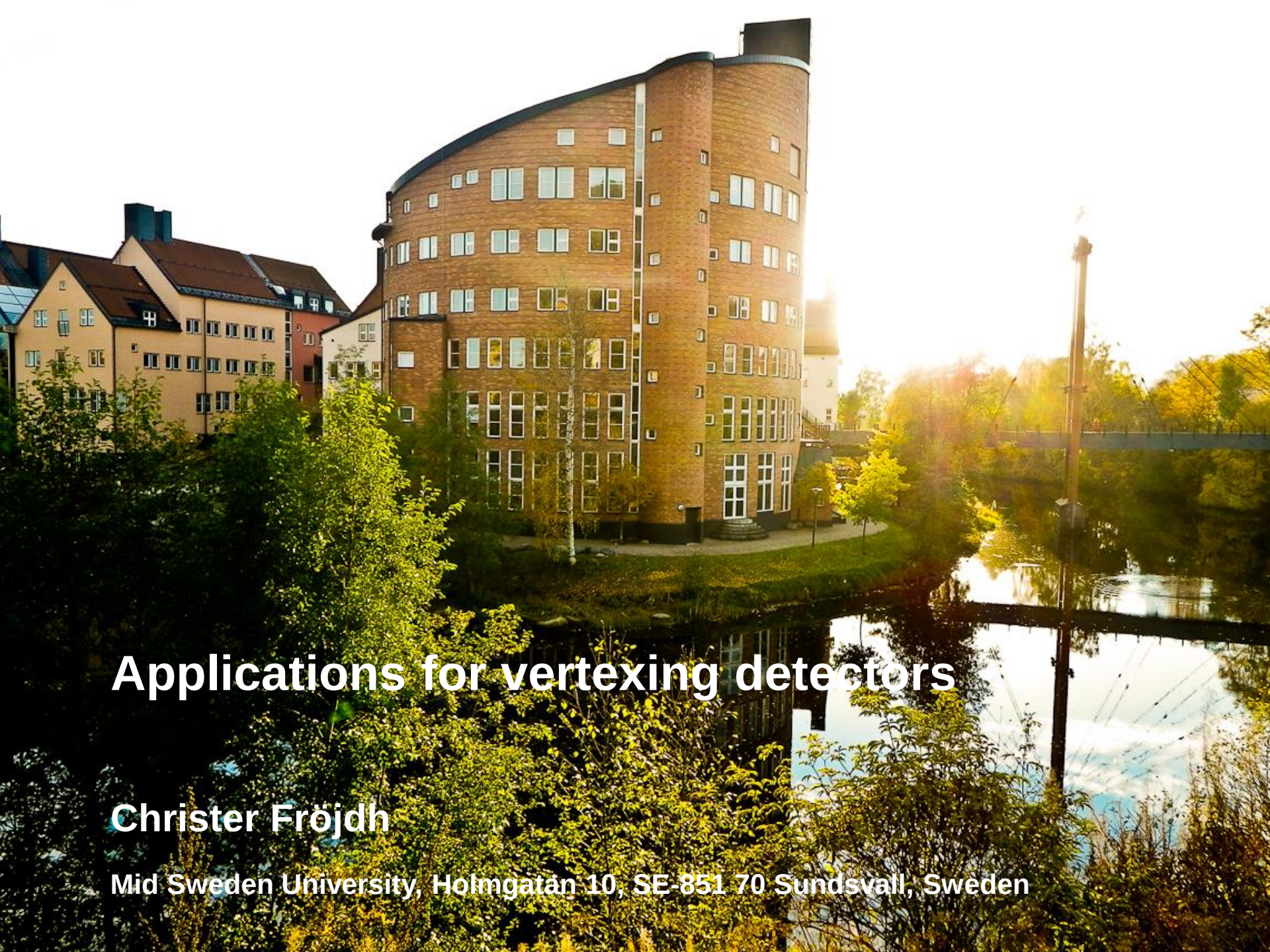

Applications for vertexing detectors

Christer Fröjdh

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Pixel detectors for single particle processing

- This presentation will focus on the MEDIPIX family of detectors
  - All measurements were done using MEDIPIX3/TIMEPIX(3) devices developed by the MEDIPIX collaboration
  - MEDIPIX3 was operated using the FITPIX readout system and the Pixelman software developed by IEAP Prague
  - The readout system for TIMEPIX3 - SPIDR, and its control software was developed by NIKHEF
- Similar detectors exist from other collaborations
  - PSI/DECTRIS developed Pilatus, Eiger and other detectors mainly for use with synchrotrons.
  - XPAD, AGIPD …

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OUTLINE

- The MEDIPIX/TIMEPIX family of chips
- Special features of TIMEPIX3
- Spectral X-ray imaging
  - Spectral resolution
  - The charge sharing problem
- Charged particle detection
- Applications
  - Medical imaging
  - Materials research
  - Radiation monitoring and dosimetry
  - Neutron imaging
- Summary and conclusions

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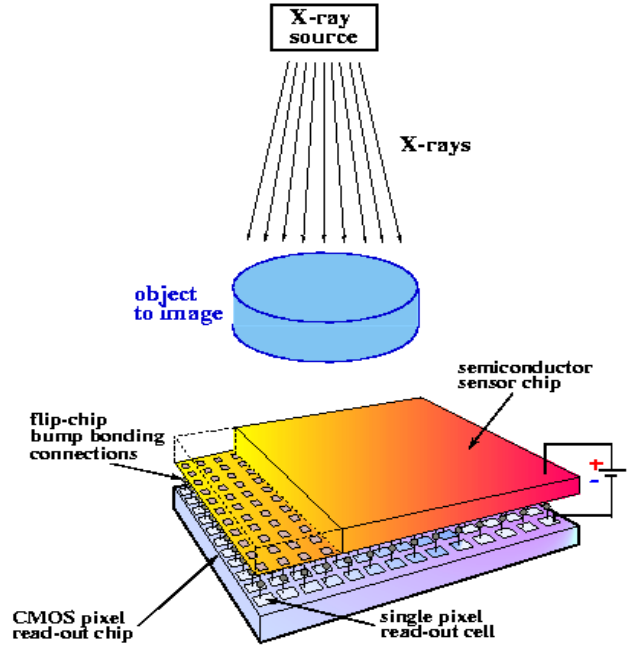
The MEDIPIX/TIMEPIX family of chips

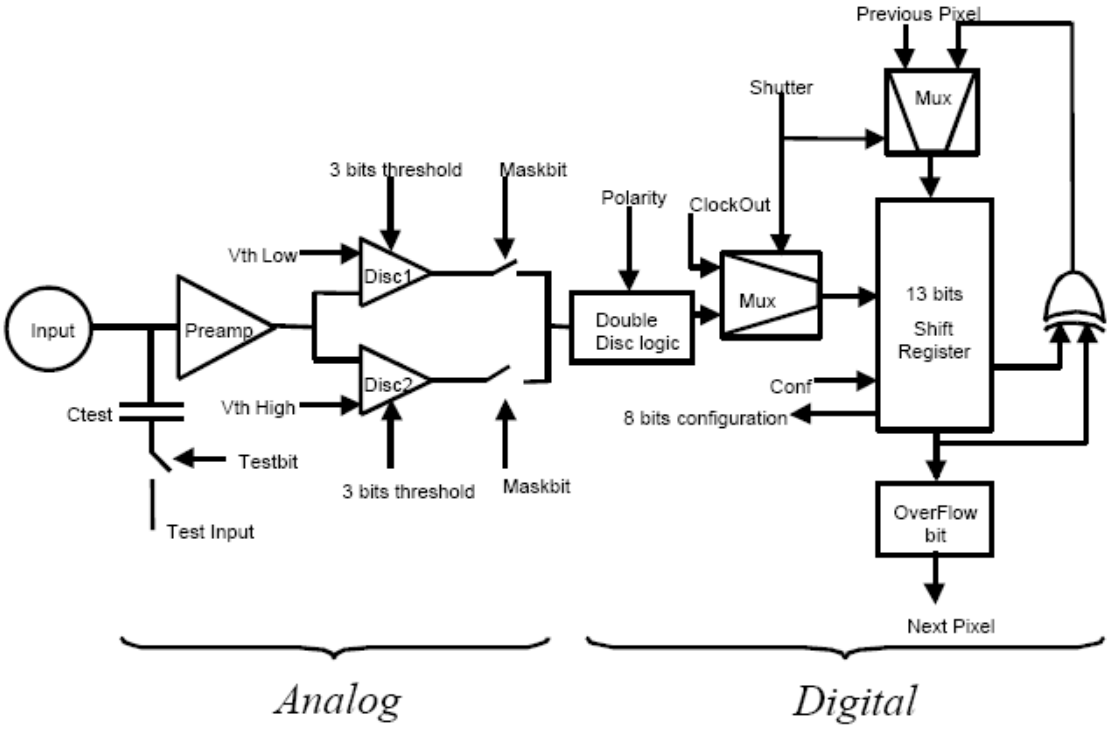
The MEDIPIX collaboration

- Development of hybrid pixel detectors for single photon processing
  - Coordinated by CERN
  - Around 20 member institutes
  - MEDIPIX1
    - 64 x 64 pixels, 170 um
  - MEDIPIX2
    - 256 x 256 pixels, 55 um
    - Window mode
  - TIMEPIX
    - Time-over- threshold
  - MEDIPIX3
    - 256 x 256 pixels, 55 um
    - Spectral mode
    - Charge summing
  - TIMEPIX3
    - Time-over-threshold
    - Time-of-arrival



The MEDIPIX2 chip

- Two thresholds – operating in window mode.
- Three adjustment bits
- Serial or parallel readout



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MEDIPIX3

- Analog charge summing on chip
- Configuration for ”color” imaging with several thresholds per pixel
- Variable counter depth
- Simultaneous counting and readout
- Selectable gain for operation in different energy regions

MEDIPIX3RX

- Configuration modes of the MEDIPIX3RX chip

Matrix configuration	Pixel Operating Modes	Thresholds
Fine Pitch Mode (55µm)	Single Pixel Mode	2
	Charge Summing Mode	1+1
Spectroscopic Mode (110µm)	Single Cluster Mode	8
	Charge Summing Mode	4+4
Front-end gain mode	**Linearity**	**Thresholds**
Super High Gain Mode	~5 ke^-	2
High Gain Mode	~9 ke^-	
Low Gain Mode	~12.5 ke^-	
Super Low Gain Mode	~18 ke^-	
Pixel Counter Modes	**Dynamic range**	**Counters**
1-bit	1	2
6-bit	63	2
12-bit	4095	2
24-bit	16777215	1
Pixel readout mode	**Active Counters**	**Dead Time**
Sequential Read-Write	2	Yes
Continuous Read-Write	1	No

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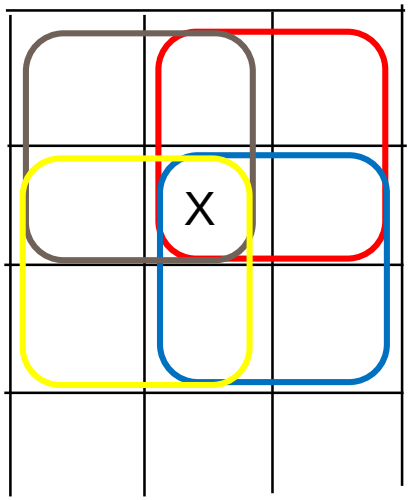
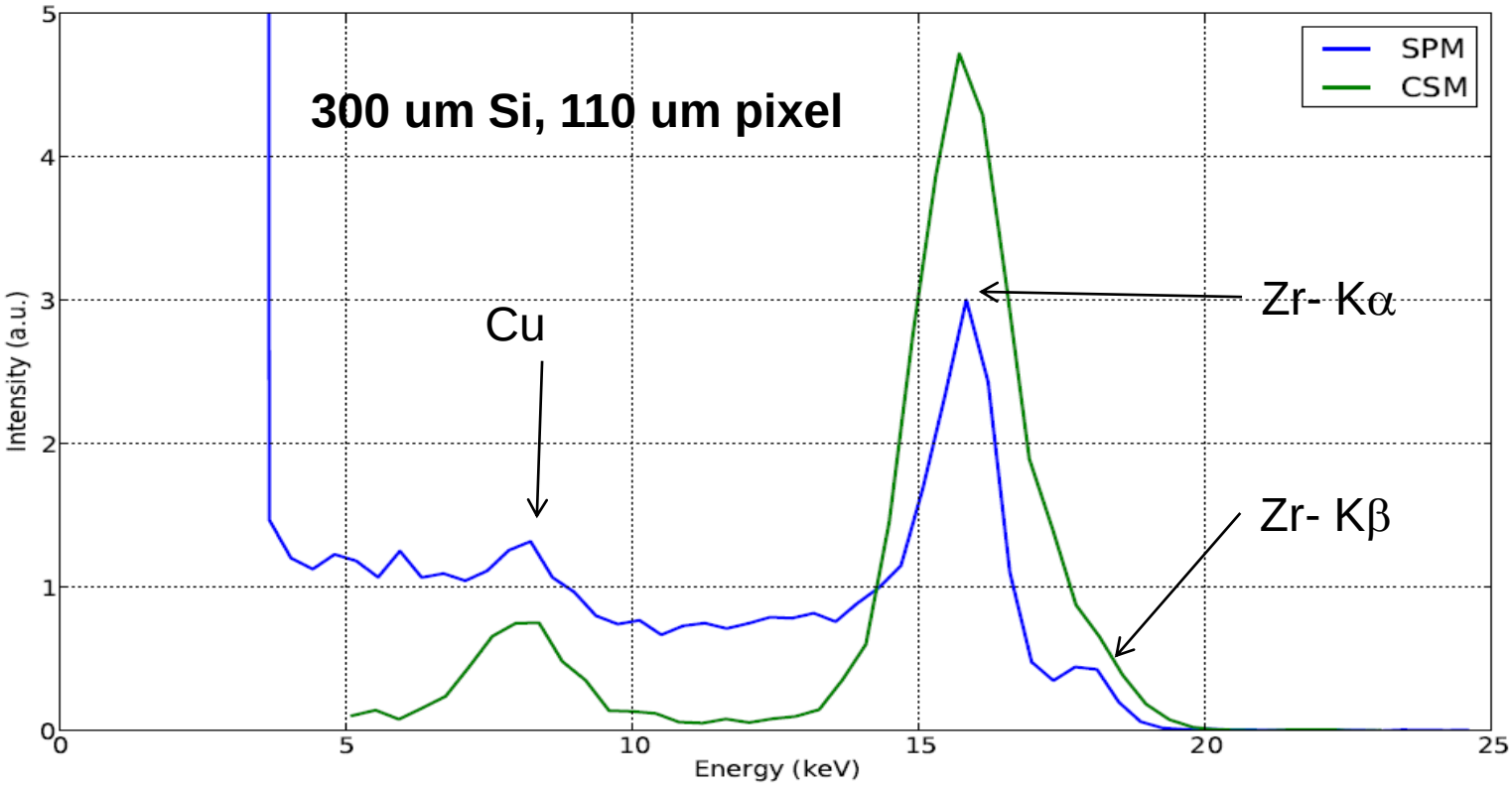
MEDIPIX3RX - charge summing

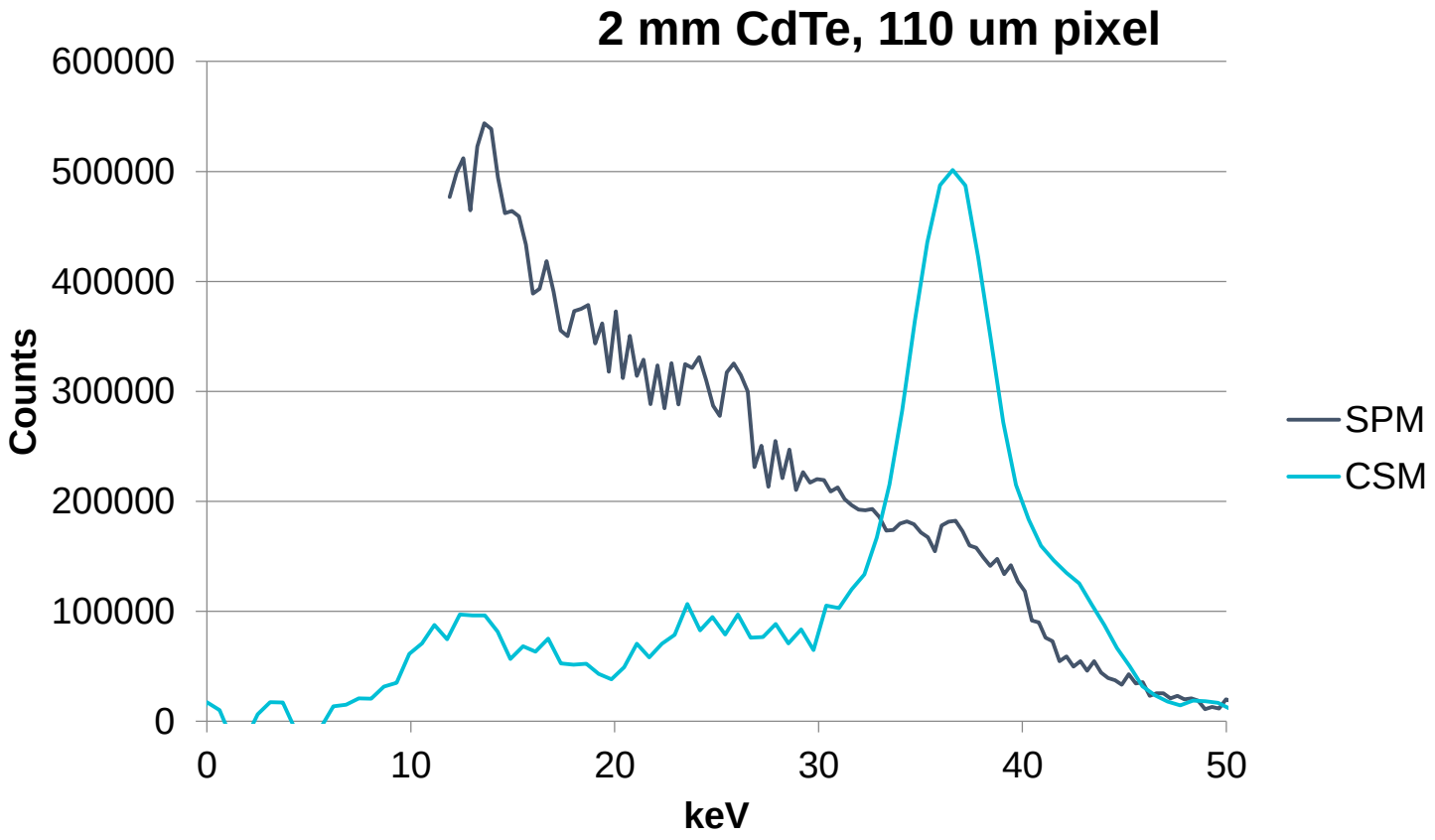
- The charge summing algorithm in MEDIPIX3RX dynamically checks the charge generated in any four pixel matrix. The charge is allocated to the pixel with the highest signal
- Significantly reduced charge sharing
- Increased noise
- Reduced count rate



Zr fluorescence in SPM and CSM



Pr fluorescence in SPM and CSM



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TIMEPIX – derived from MEDIPIX2

- Same geometry as MEDIPIX2
- Single threshold
- Improved threshold adjustment
- New operation modes
  - Time-over-threshold
  - Time-of-arrival

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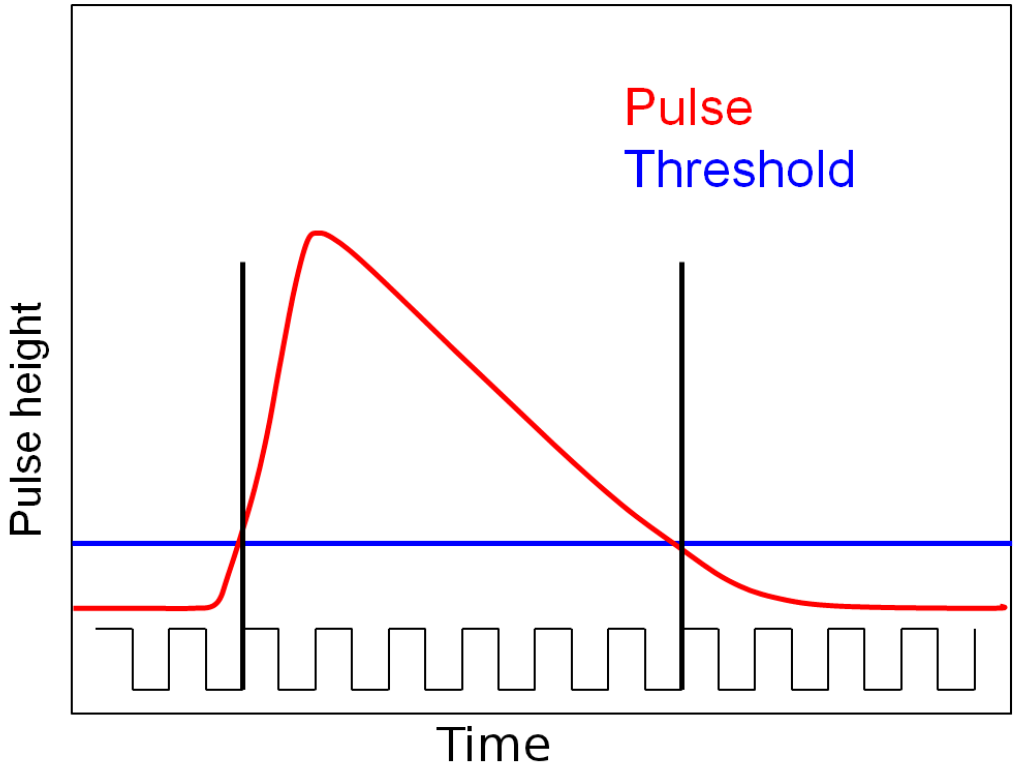
Timepix in ToT mode

- Time over threshold mode – an ADC in each pixel



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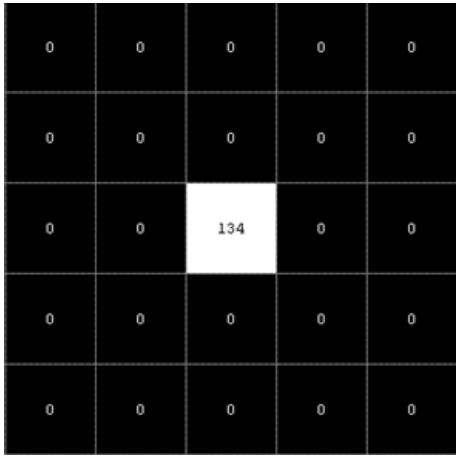
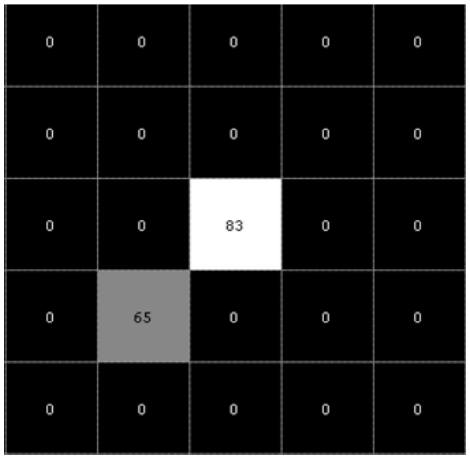
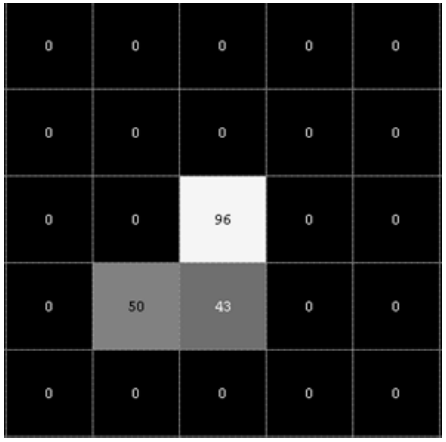
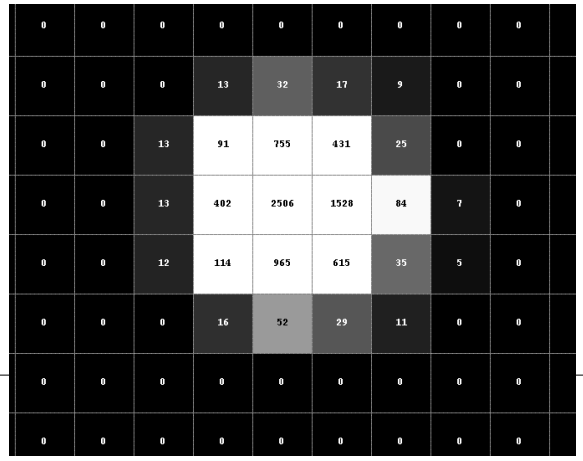
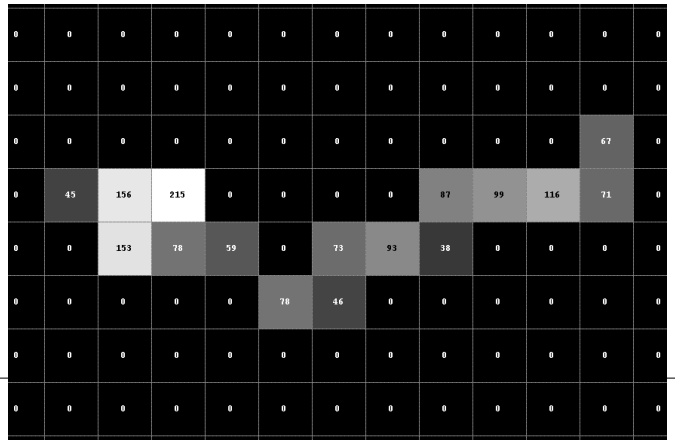
Cluster processing with Timepix











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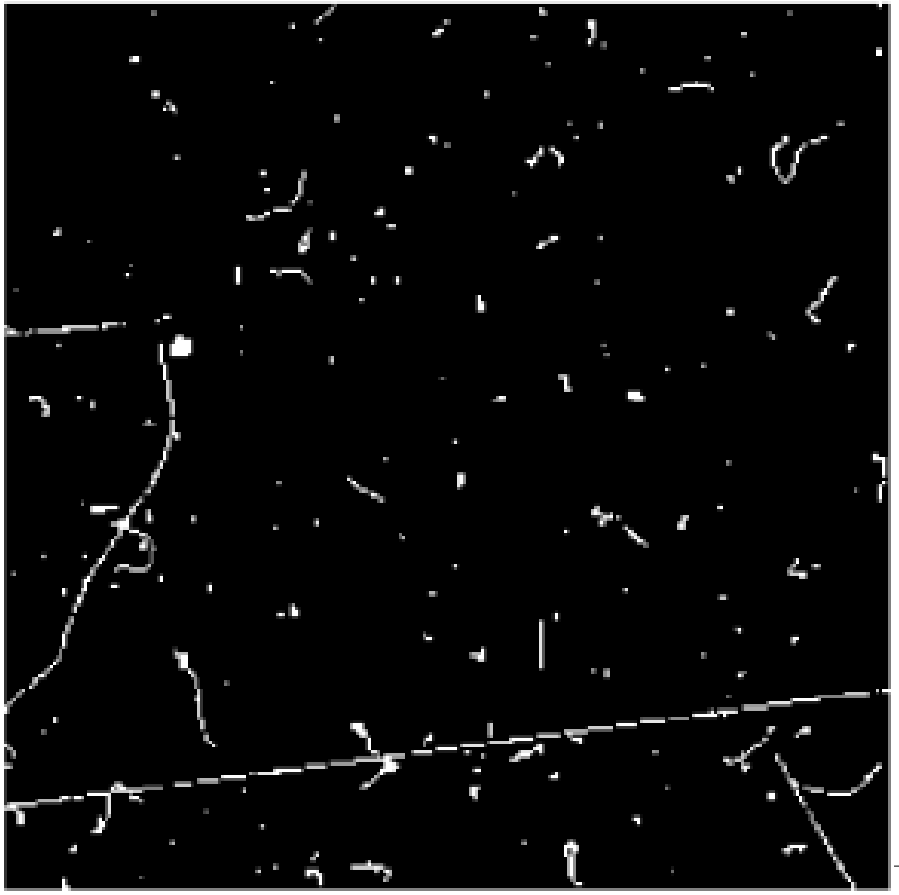
Identification of radiation



Measurements of natural background radiation with a Medipix2-USB device equipped with a 700 mm thick silicon sensor (10 min exposure time). Various traces and tracks of X-ray photons, electrons and some α–particles are displayed. A rare cosmic muon track is clearly seen traversing the sensor horizontally.

Study of the charge sharing in a silicon pixel detector by means of α-particles interacting with a Medipix2 device
M. Campbell, E. Heijne, T. Holy , J. Idarraga, J. Jakubek, C. Lebel, C. Leroy, X. Llopart, S. Pospısil, L. Tlustos, Z. Vykydal, NIM-A 591, 2008

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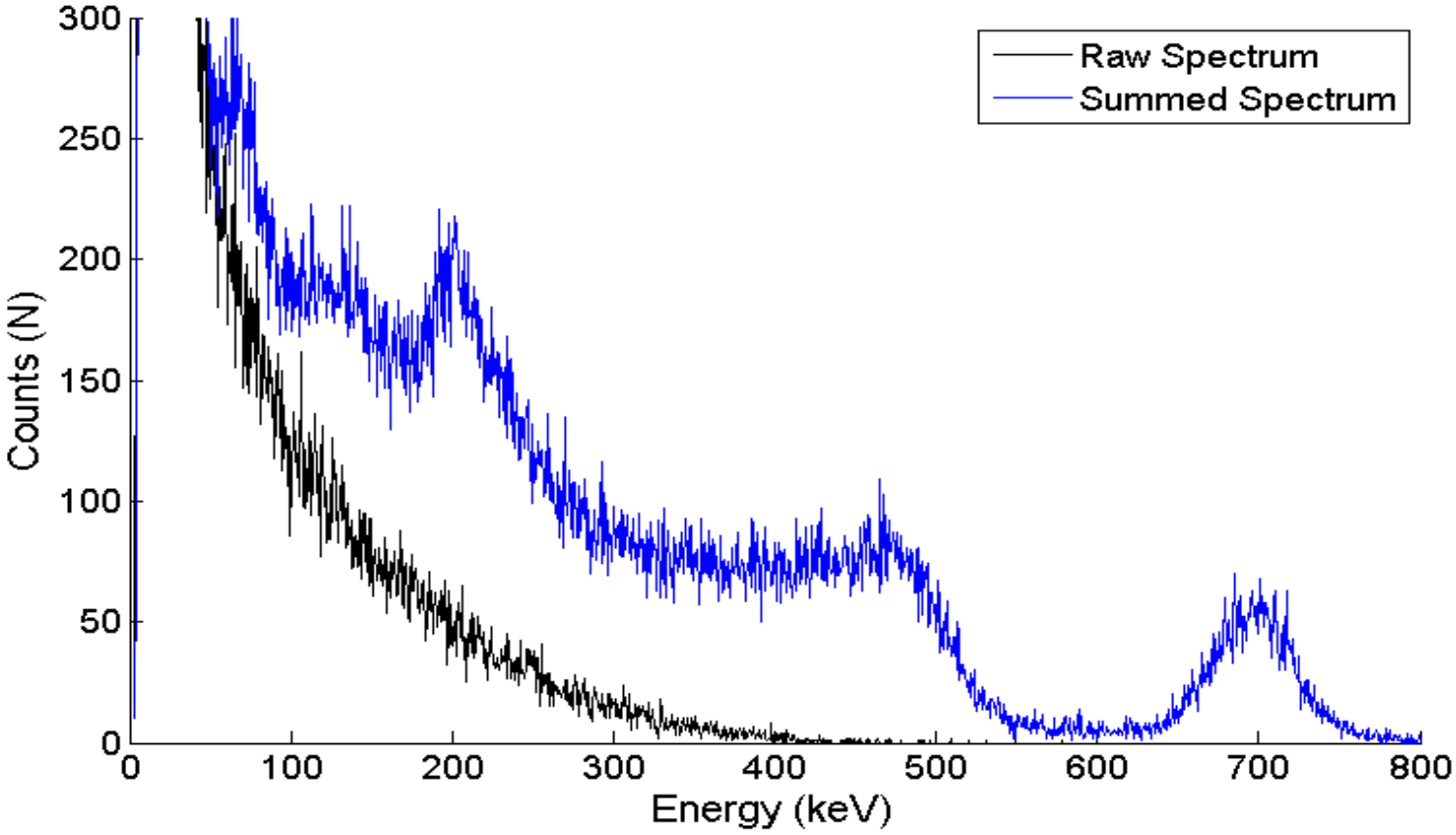
^{137}Cs spectrum taken with a 1 mm thick CdTe sensor



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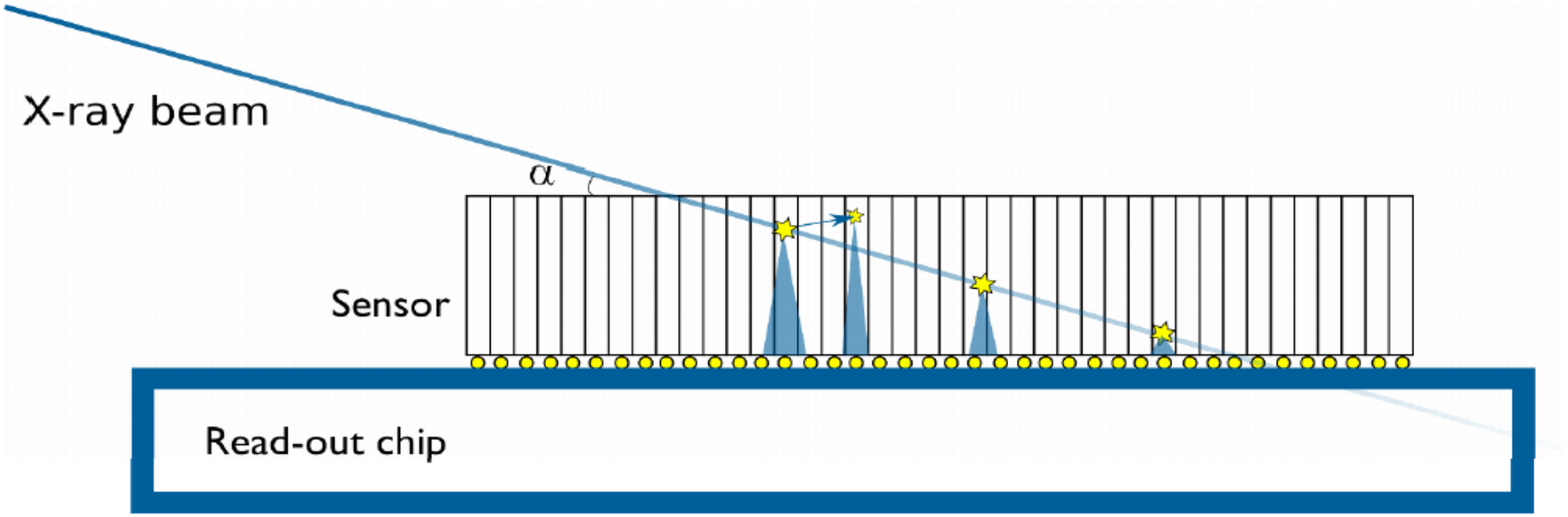
Depth of interaction measurements

- Experiments at DIAMOND light source with a monoenergetic pencil beam. 1 mm thick CdTe sensor with 110 um pixels



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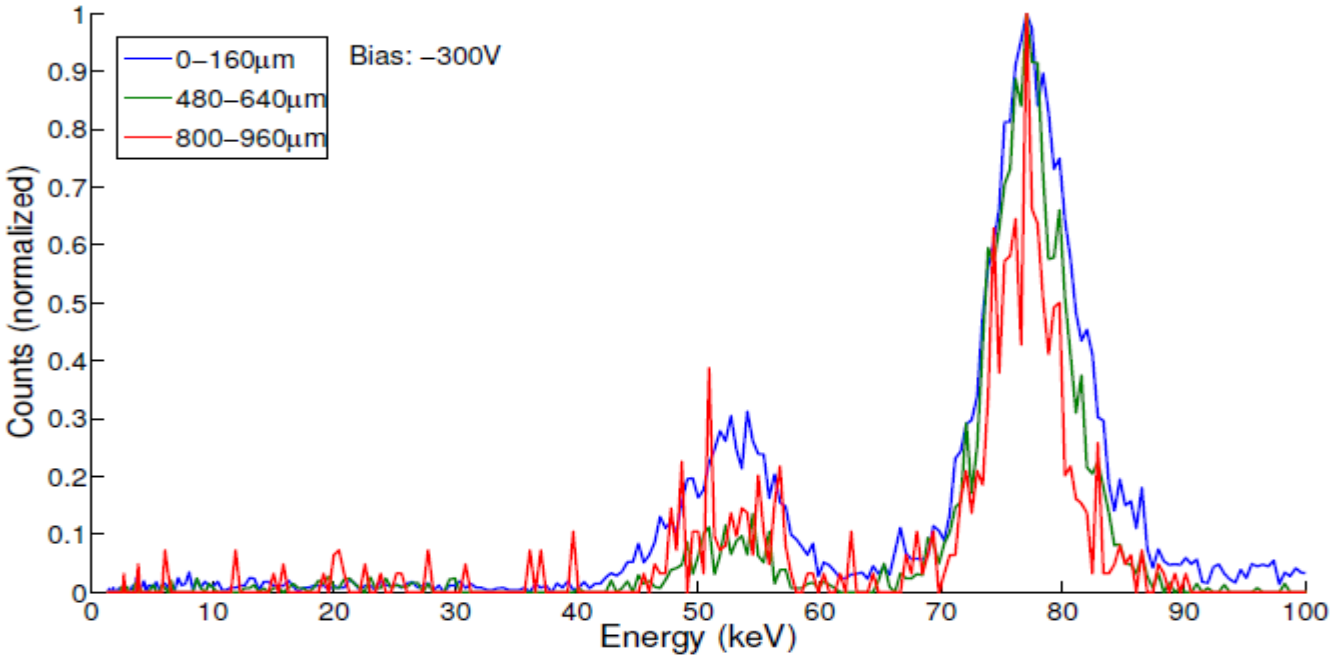
Depth of interaction

- The signal is independent of depth of interaction – Small pixel effect



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Special features of TIMEPIX3

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Timepix and Timepix3 – what is the difference?

- TIMEPIX
  - TOT or TOA
  - Frame readout – limited occupancy required to decode data
  - 25 ns time resolution
- TIMEPIX3
  - TOT and TOA
  - Event driven readout – much faster than TIMEPIX
  - 1.56 ns time resolution

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Timepix3

Pixel matrix	256 x 256
Pixel size	55 x 55 μm^2
Technology	CMOS 130 nm
Measurement modes	• Simultaneous 10 bit TOT and 14 + 4 bit TOA • 14 + 4 bit TOA only • 10 bit PC and 14 bit integral TOT
Readout type	• Data driven • Frame based (both modes with zero suppression)
Dead time (pixel, data driven)	>475 ns (pulse processing + packet transfer)
Output bandwidth	40 Mbits/s – 5.12 Gbits/s
Maximum count rate	0.4 Mhits/mm^2/s (data driven mode)
TOA Precision	1.56 ns
Front end noise	60e- RMS
Minimum threshold	~500 e-

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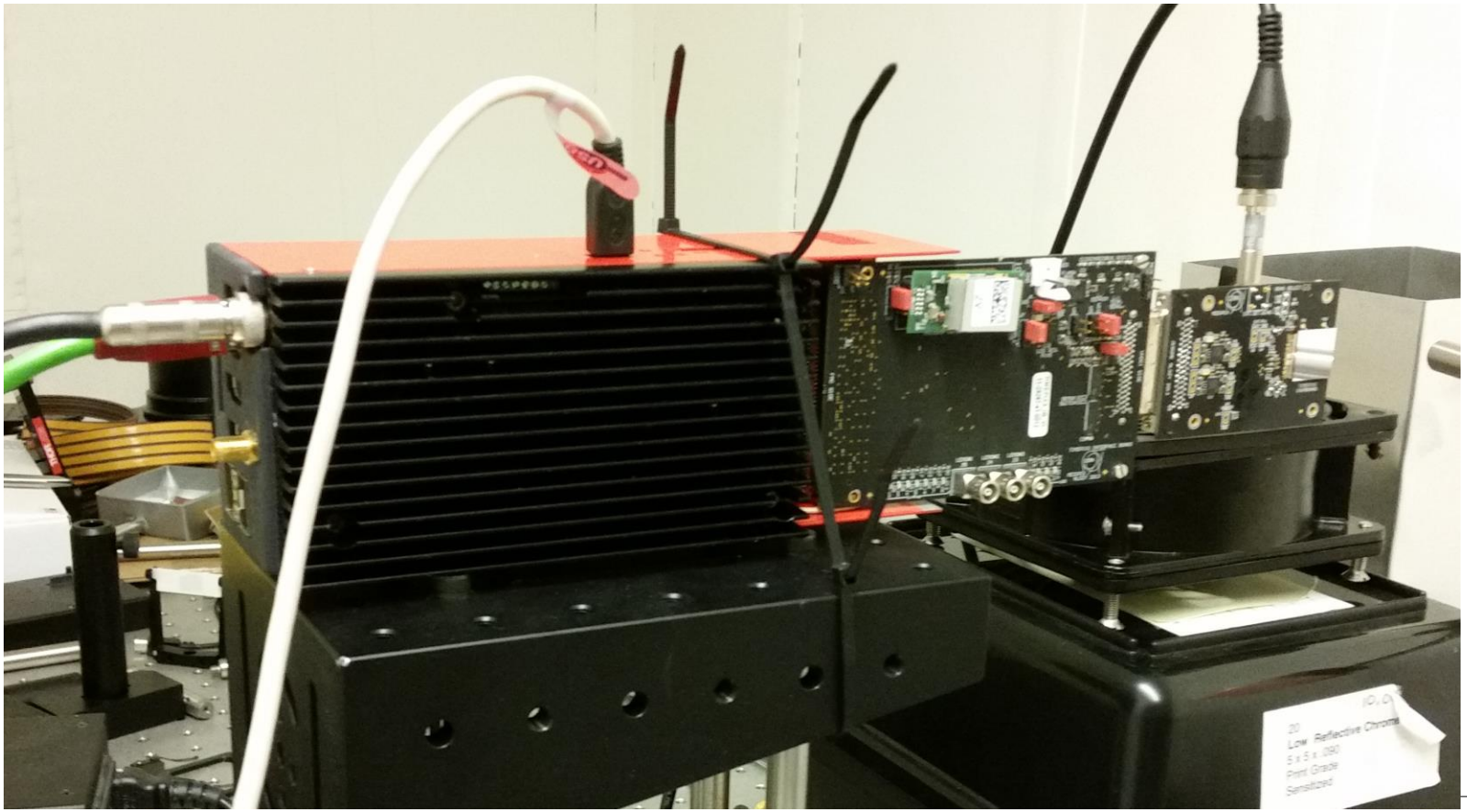
SPIDR readout system – developed by NIKHEF



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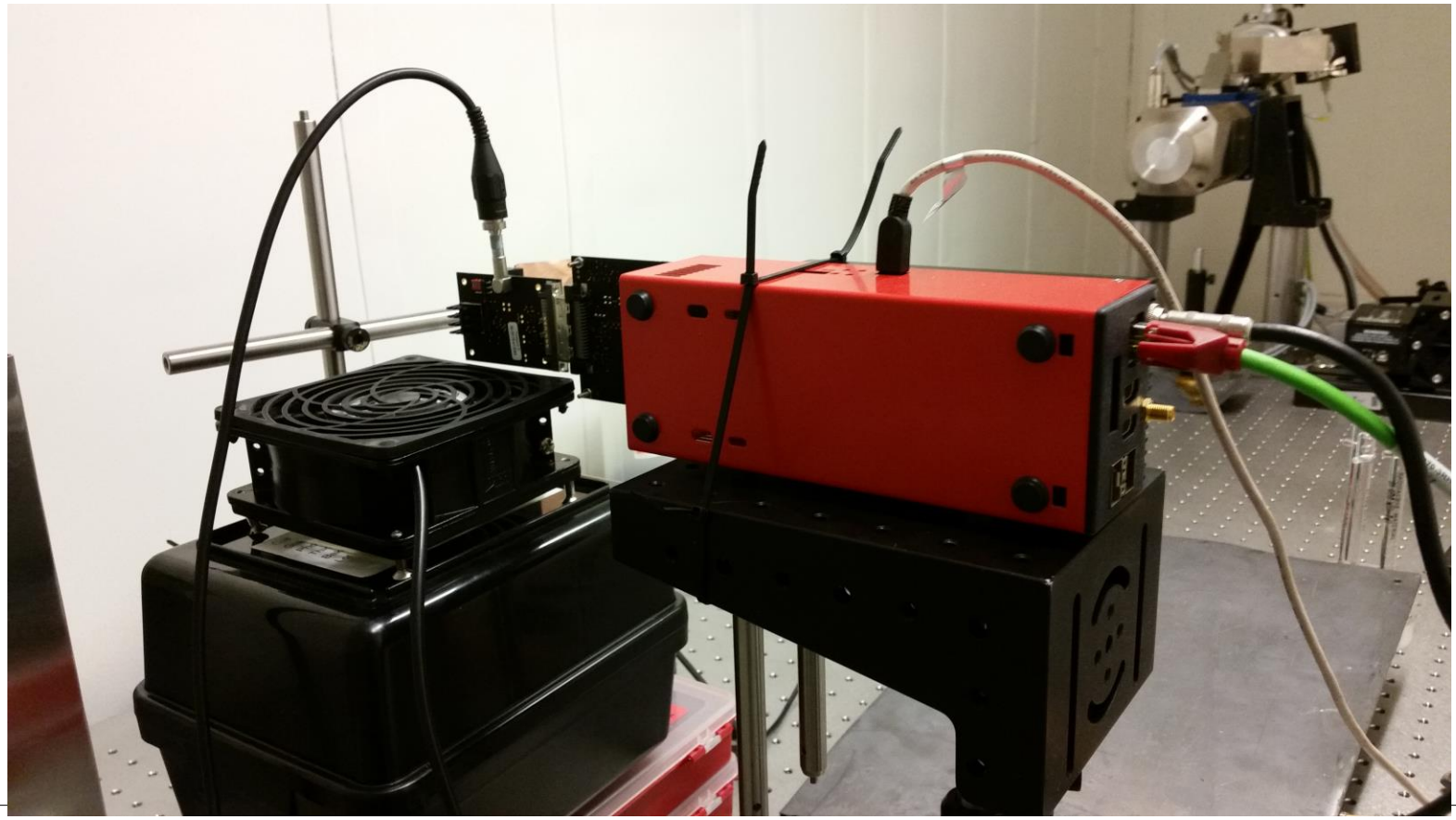
… from the opposite side



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TIMEPIX3 data format

- The original data packet is a 48 bit unit. Another 16 bits of timing information is added by the SIPDR readout system.

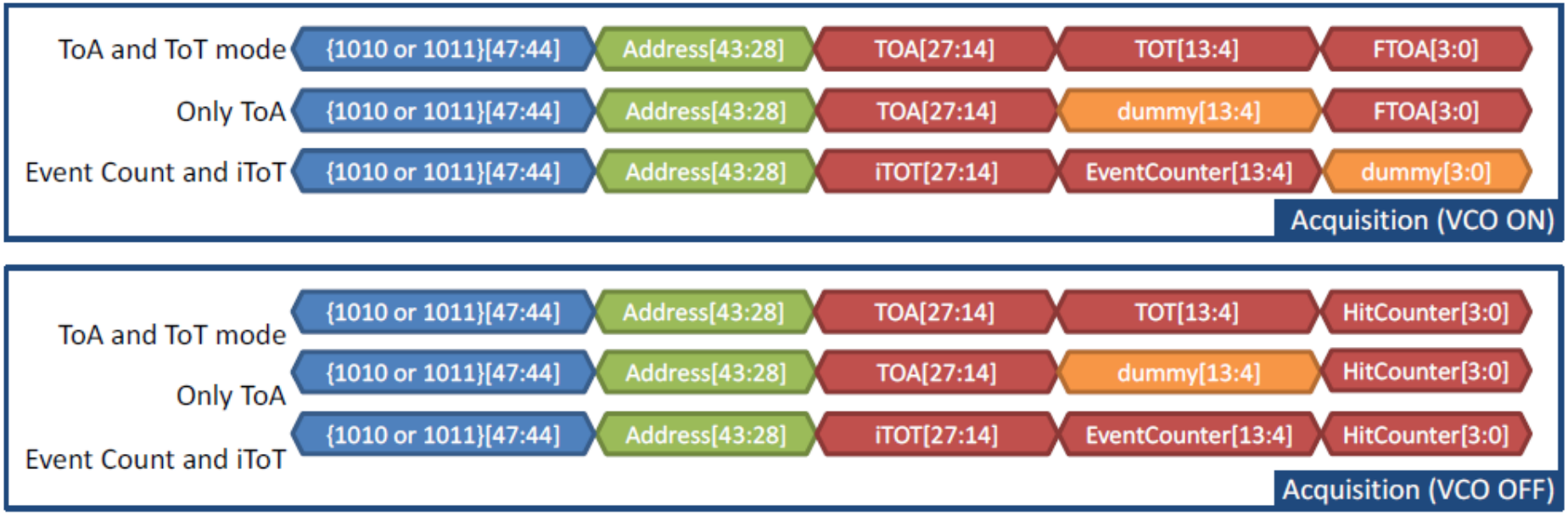

Figure 1. Acquisition packet depending of the acquisition mode and the superpixel VCO.

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Decoded data packets from TIMEPIX3

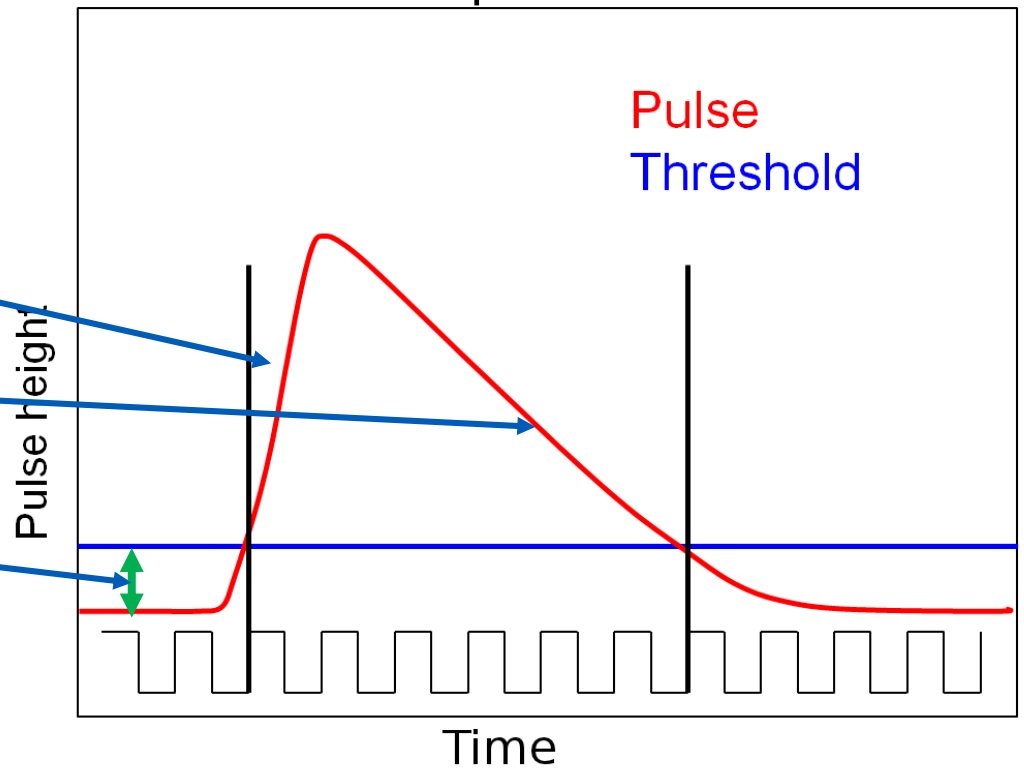
Time	Row	Col	ToT
11157735820	163	73	24
11157736762	203	99	18
11157736843	112	189	1
11157735622	227	41	13
11157737239	1	1	14
11157737672	178	93	23
11157736719	112	188	14
11157737963	113	172	28
11157738419	43	186	26
11157740227	186	239	11
11157739919	2	241	9

Timepix in ToT mode

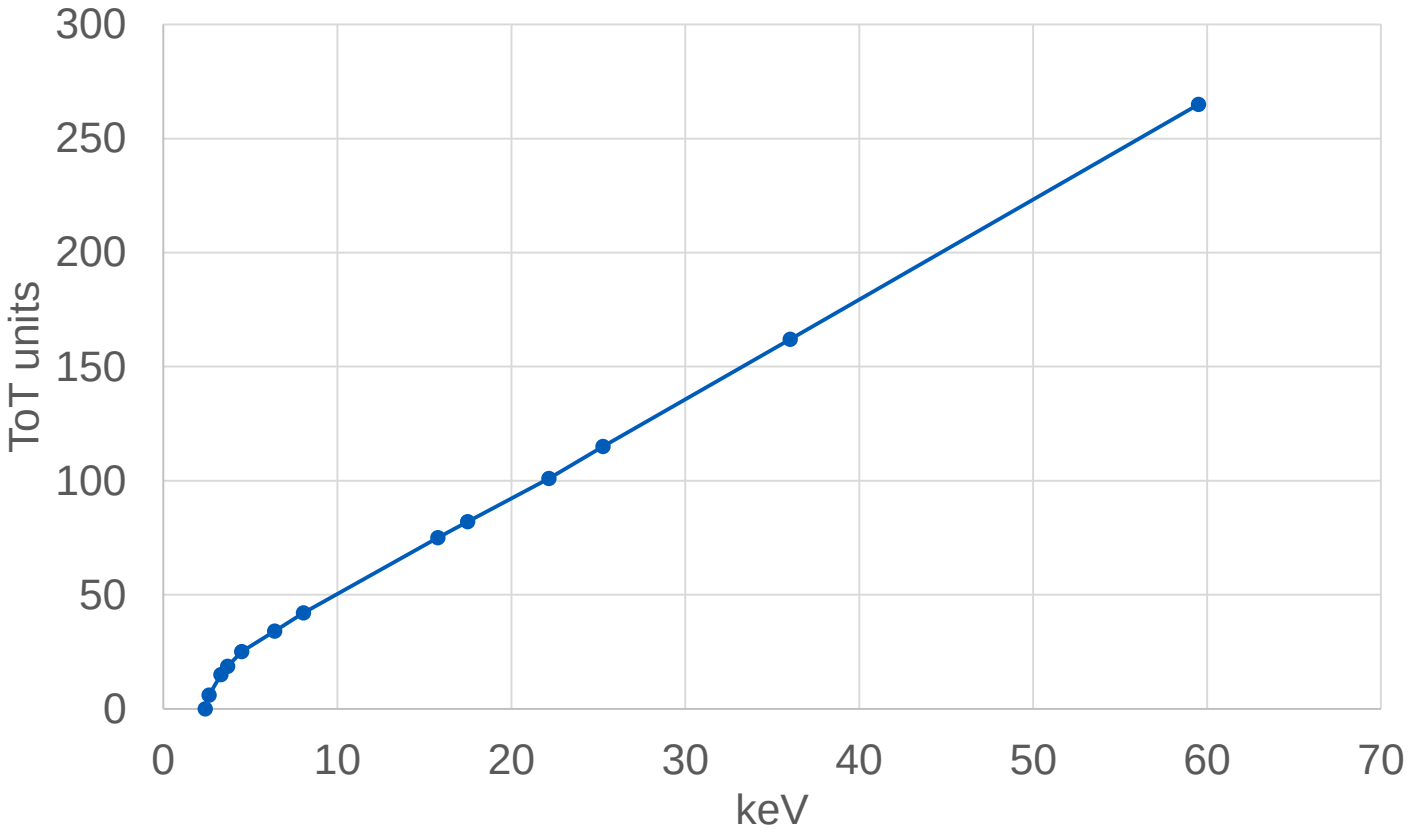
- Time over threshold mode – an ADC in each pixel

Calibration required for:

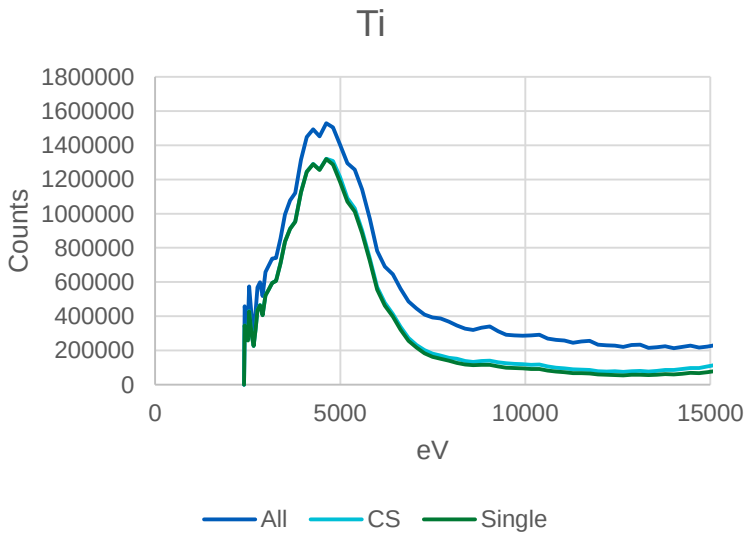
- The finite risetime of the analog electronics
- The slope of the return to zero (controlled by I_{krum}
- The offset of the threshold from zero

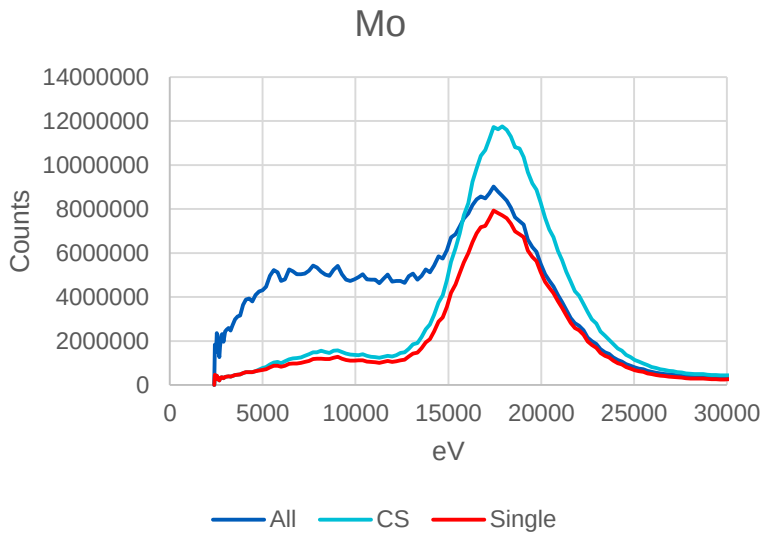


TIMEPIX3 calibration curve



Two energies used for calibration





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Spectral X-ray imaging

Spectral resolution

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Factors affecting the spectral resolution

- Noise
  - Fano limited noise – *fundamental property*
  - Electronic noise – *around 60e- RMS for Timepix3*
  - Incomplete charge collection – *usually not a problem for silicon*
- Threshold dispersion
  - Corrected by offset adjustment – *four bits in Timepix3*
- Gain dispersion
  - Could be corrected by adjusting the feedback capacitance – *not implemented in Timepix3, anyway I_{krum} is more important*

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Spectral X-ray imaging

The charge sharing problem

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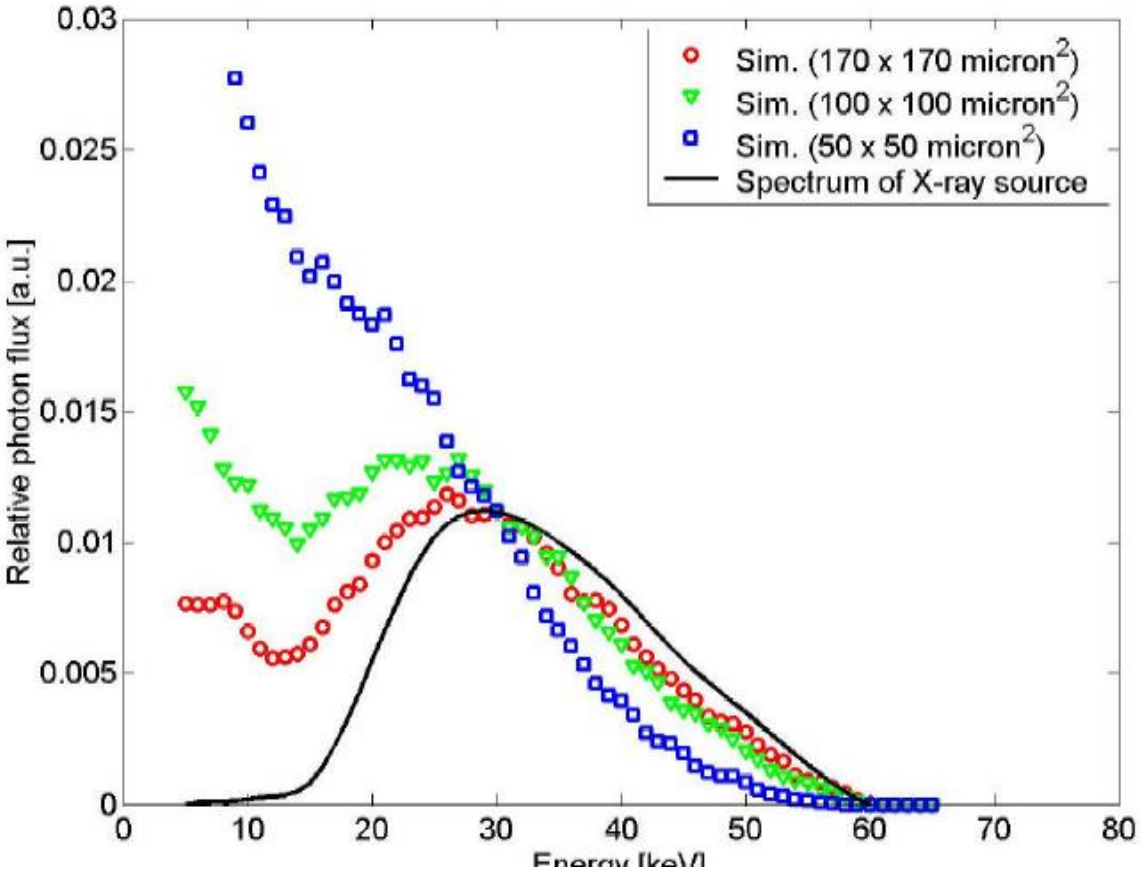
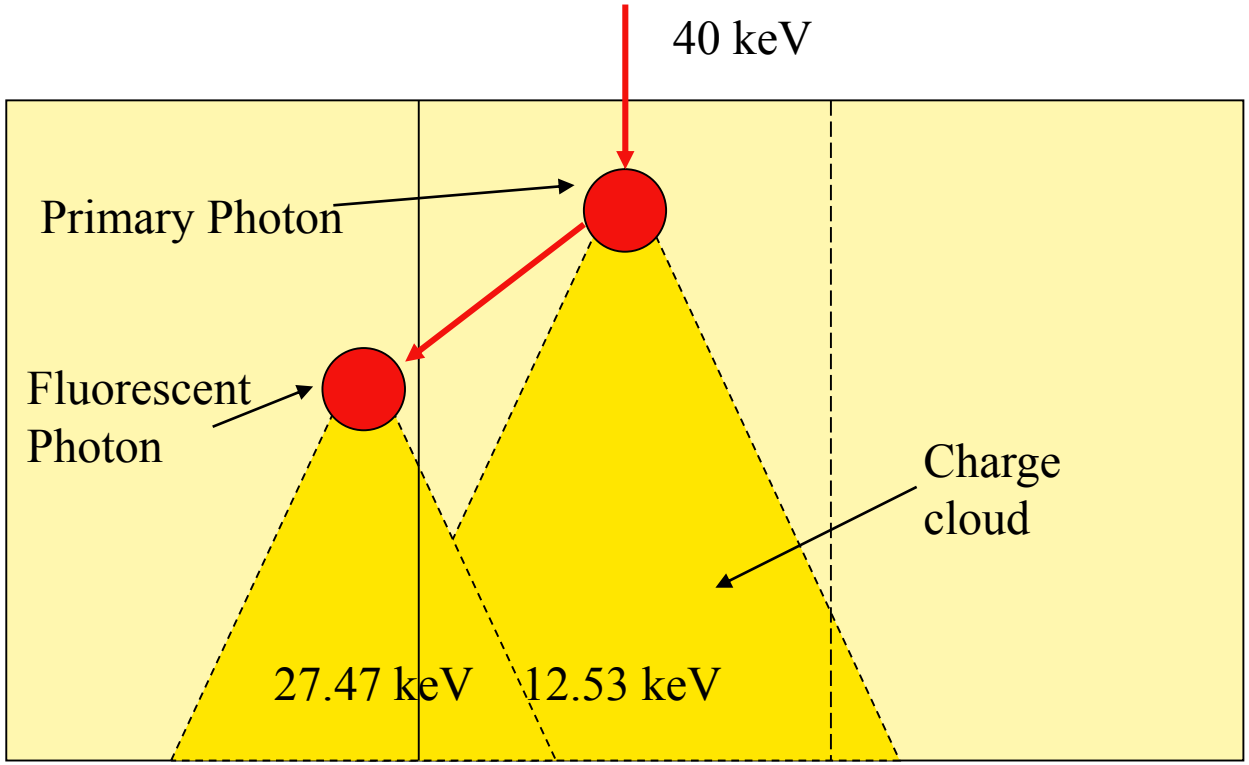
Charge sharing

- Charge sharing distorts the spectrum and makes any pulse height measurements unreliable.
- The figure shows a simulation of the charge sharing as a function of pixel size.



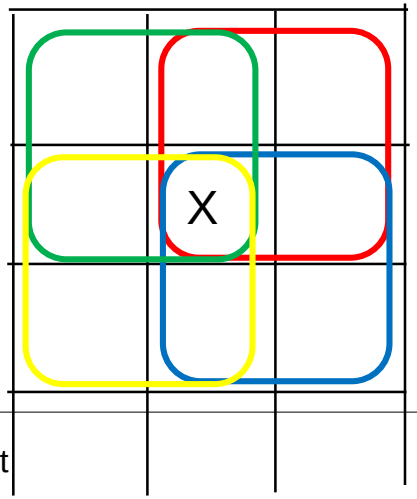
Charge sharing

- Charge sharing in high-z materials is a combination of fluorescence and diffusion



Charge sharing correction in MEDIPIX3 and TIMEPIX3

- MEDIPIX3 - Analog charge summing on chip
  - Sum over four neighboring pixels
  - Noise from four pixels added
  - Final result compared against predefined threshold



- TIMEPIX3 – digital charge summing off line
  - Sum over any range possible
  - Digitization noise added to the result
  - Charge from pixels below threshold lost
  - Possibility to adjust for threshold and gain variation

5818122348 , 236 , 234 , 7
5818123961 , 119 , 76 , 7
5818127245 , 87 , 101 , 8
5818126999 , 12 , 98 , 15

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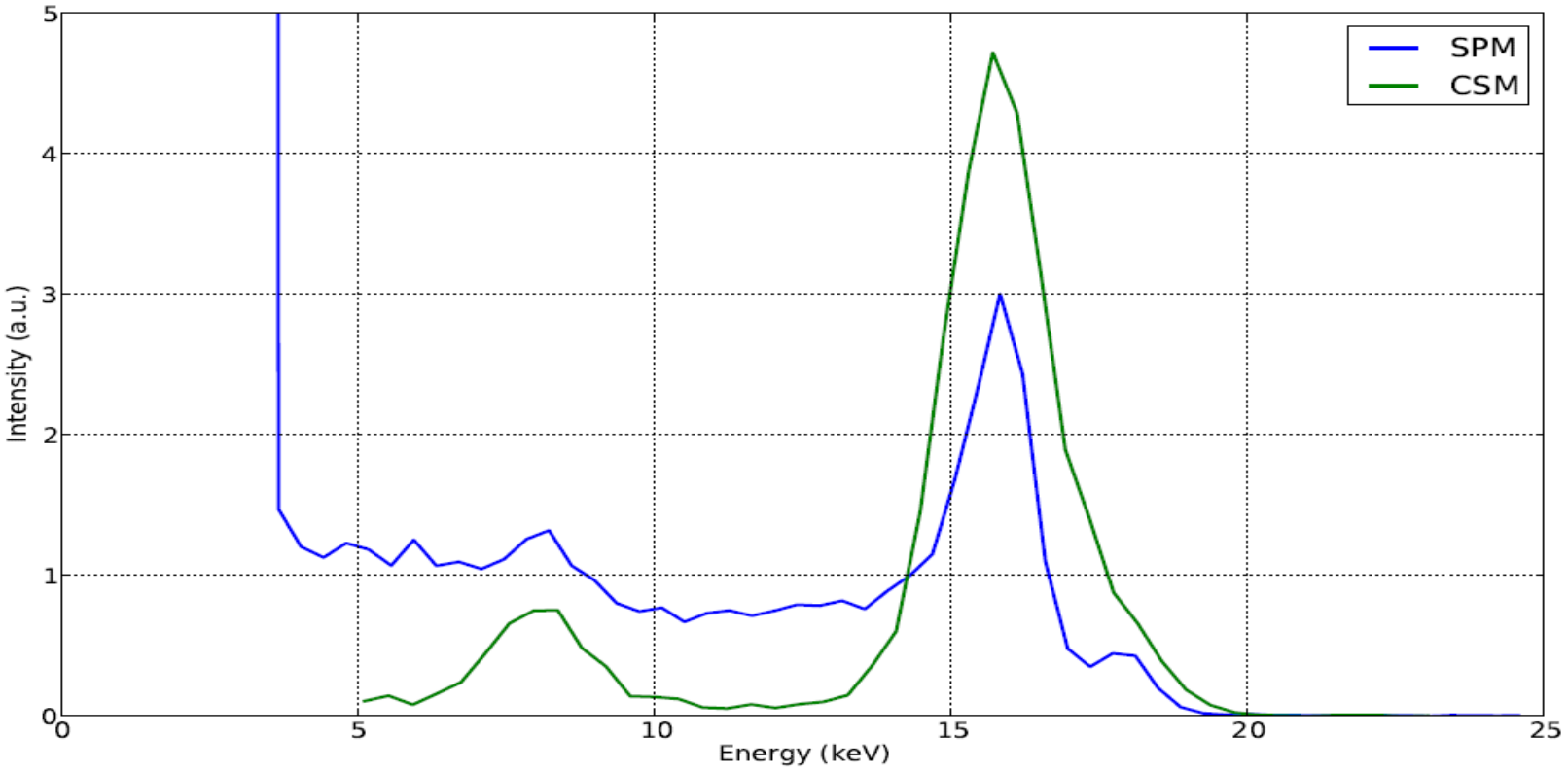
Zr spectrum taken with MEDIPIX3



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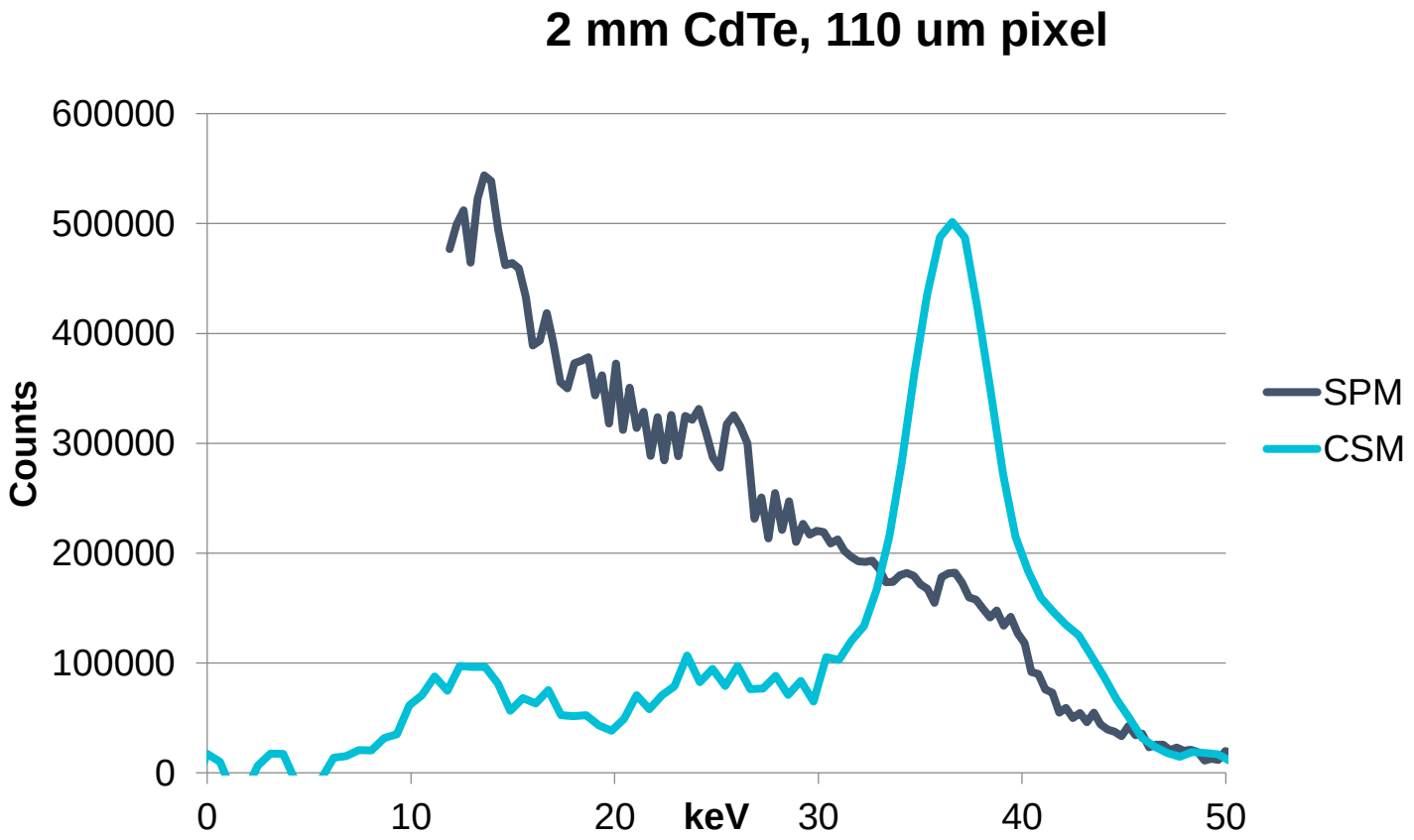
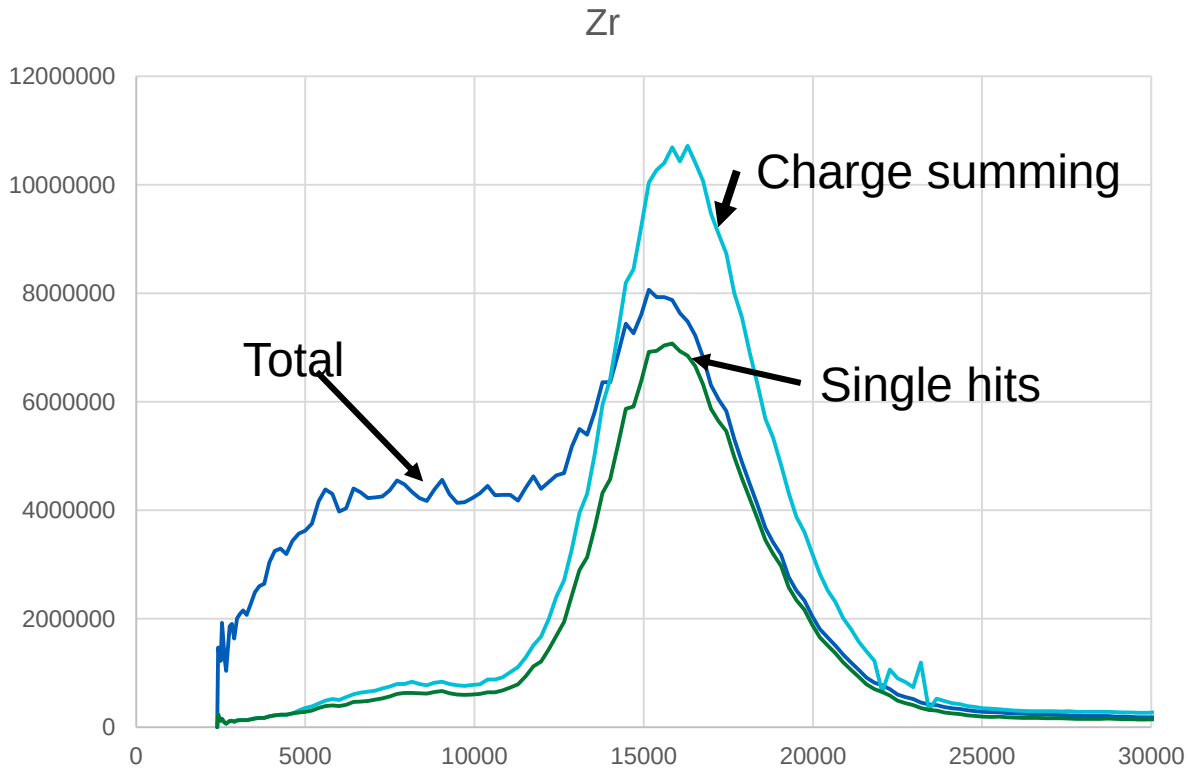
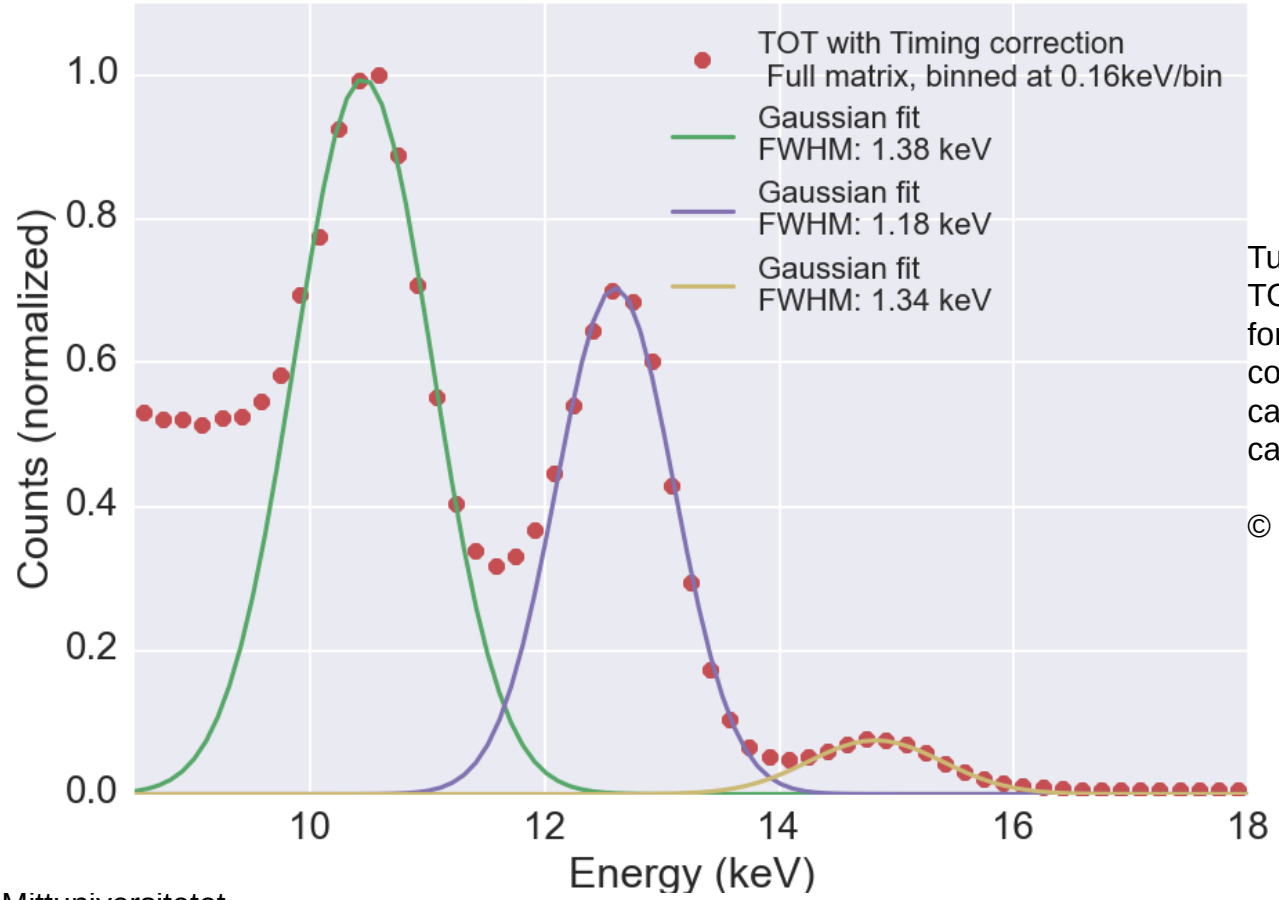
Pr fluorescence in SPM and CSM



Zr spectrum taken with TIMEPIX3



Optimized Energy Resolution (Si)



Turing off the distribution of the TOA clock and using the VCO for fine energy binning in combination with a source calibration the energy resolution can be improved

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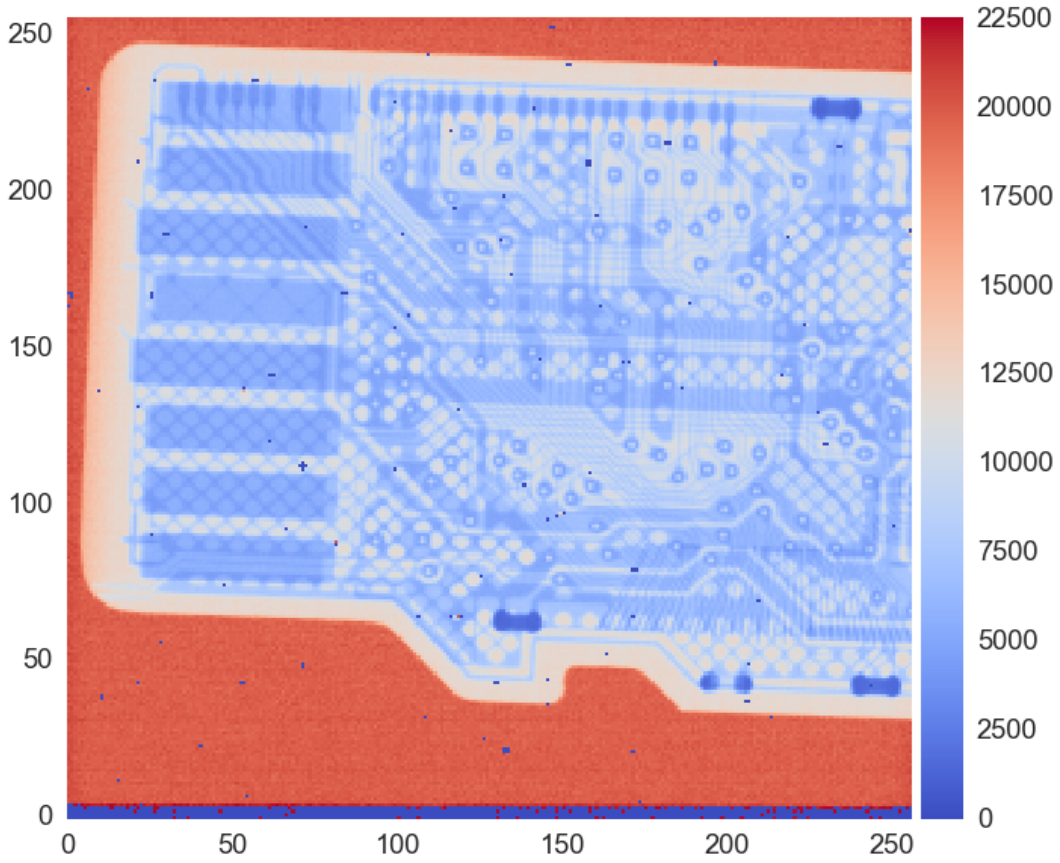
Image of an SD-card

- Nanofocus X-ray source at 60kVp and 10 uA
- Integration time 100 s
- File size: 8 Gb
- Charge sharing correction off line
- Masked (noisy) pixels not processed



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Charged particle detection

3D image of a cosmic muon

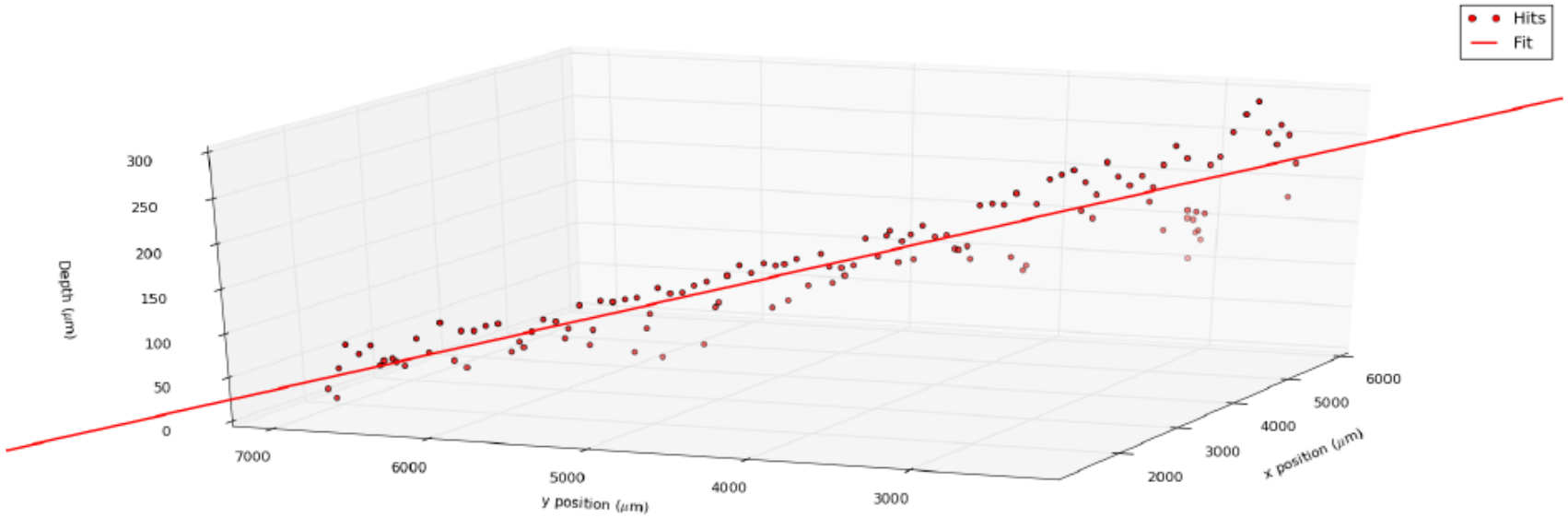
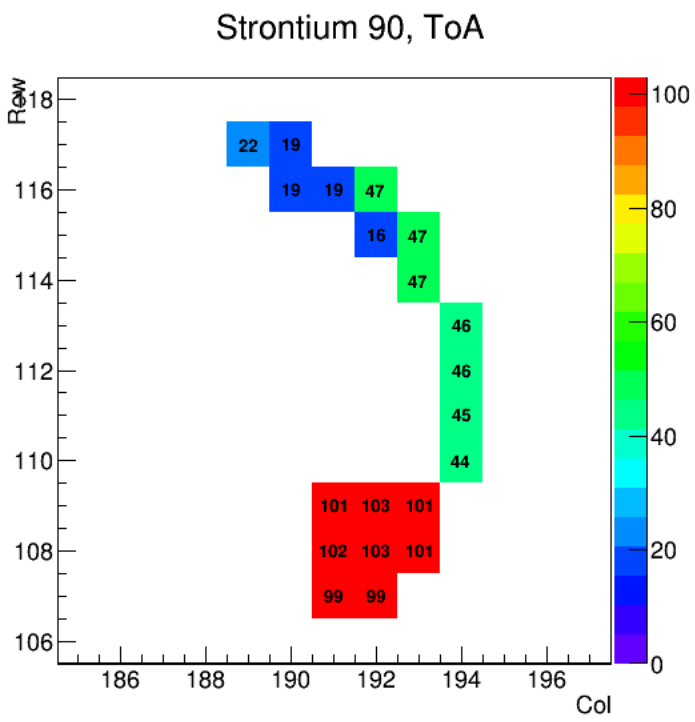
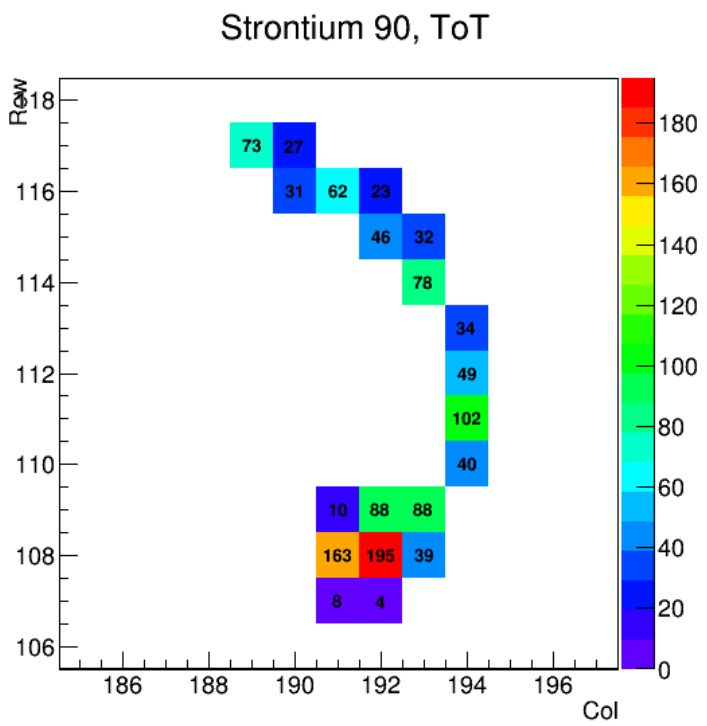


Figure 10: Track from a MIP going trough the silicon sensor. The z-dimension is magnified to increase the visibility.

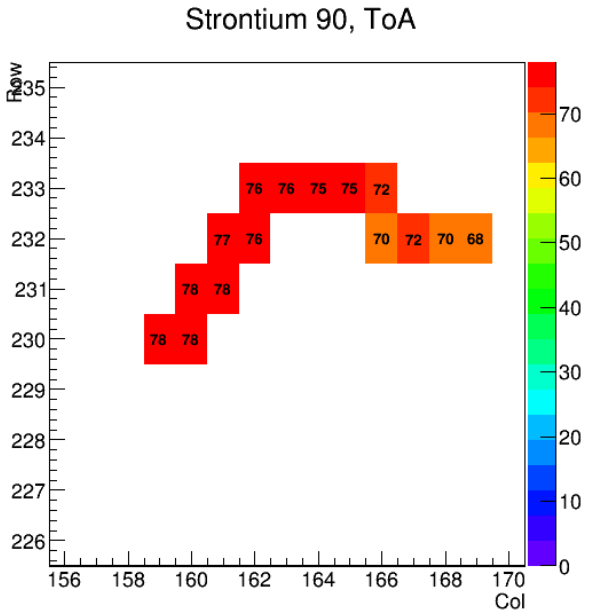
Frojdh, E. et.al. Timepix3: First measurements and characterization of a hybrid pixel detector working in event driven mode, JOURNAL OF INSTRUMENTATION Volume: 10 Article Number: C01039 Published: JAN 2015

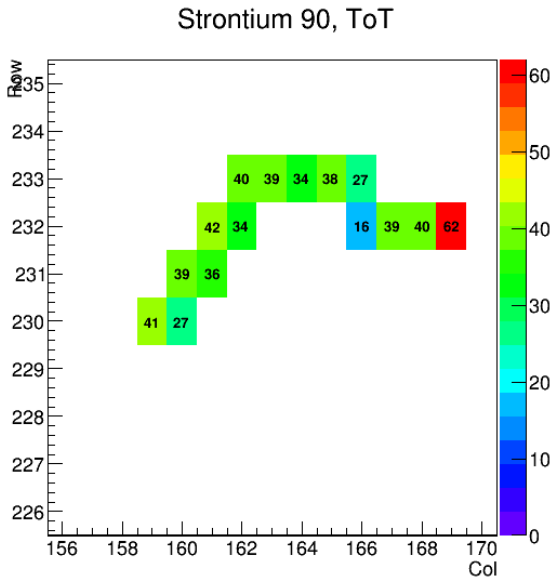
^{90}Sr images


Strontium 90, ToA
Row
Col
22 19
19 19 47
16 47
47
46
46
45
44
101 103 101
102 103 101
99 99


Strontium 90, ToT
Row
Col
73 27
31 62 23
46 32
78
34
49
102
40
10 88 88
163 195 39
8 4

^{90}Sr images


Strontium 90, ToA
Row
Col
76 76 75 75 72
77 76
70 72 70 68
78 78
78 78


Strontium 90, ToT
Row
Col
40 39 34 38 27
42 34
16 39 40 62
39 36
41 27

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Applications

- Medical Imaging

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Challenges in medical imaging

- Area!!!
- Diagnostic value of the information
- Will spectral imaging increase dose?
- Masking of spectral information by the body
- Doctors are conservative

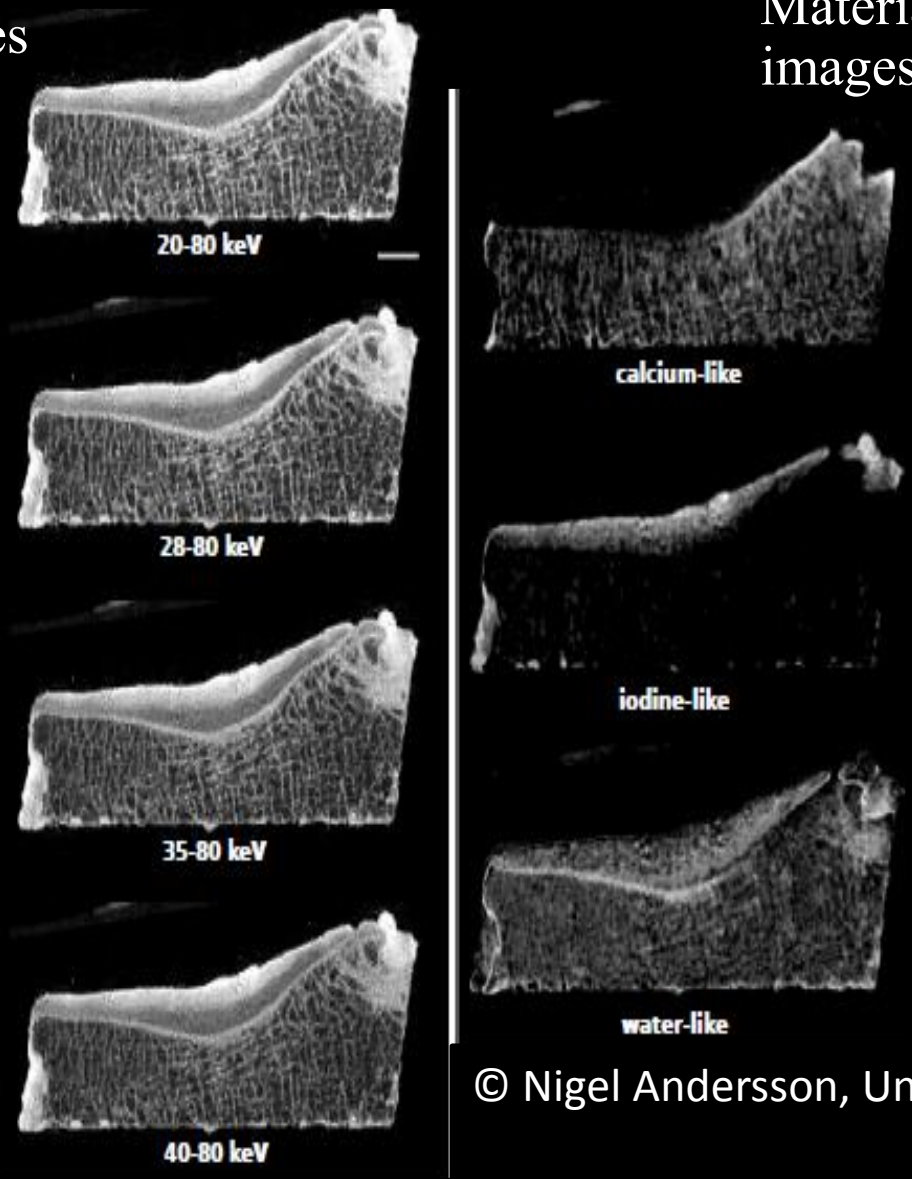
Advantages in medical imaging

- Better contrast between different substances
- Multiple contrast agents in one examination
- Reduced doses of the contrast agent.
  - Barium, Iodine, Gold nanoparticles…

MARS Applications - Orthopaedics

Multi-energy images

Material decomposition images



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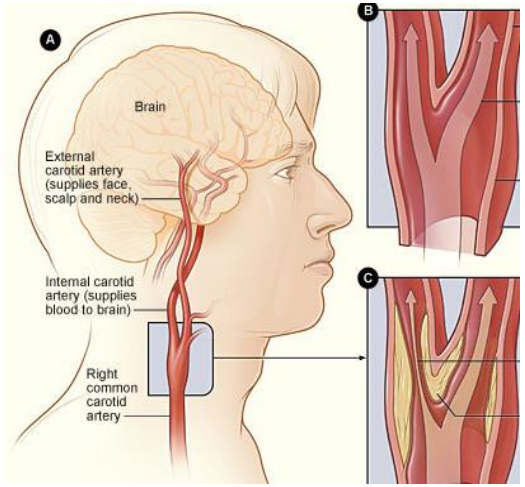
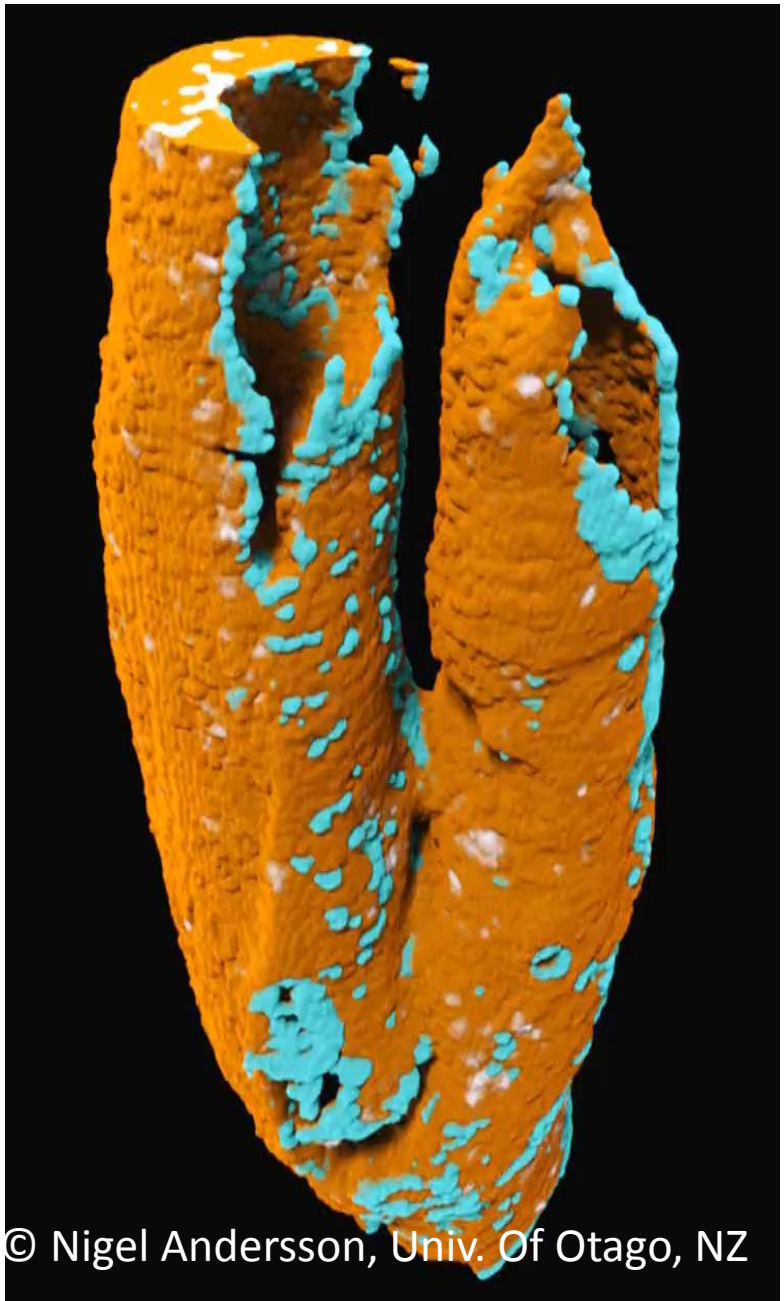
Atherosclerosis



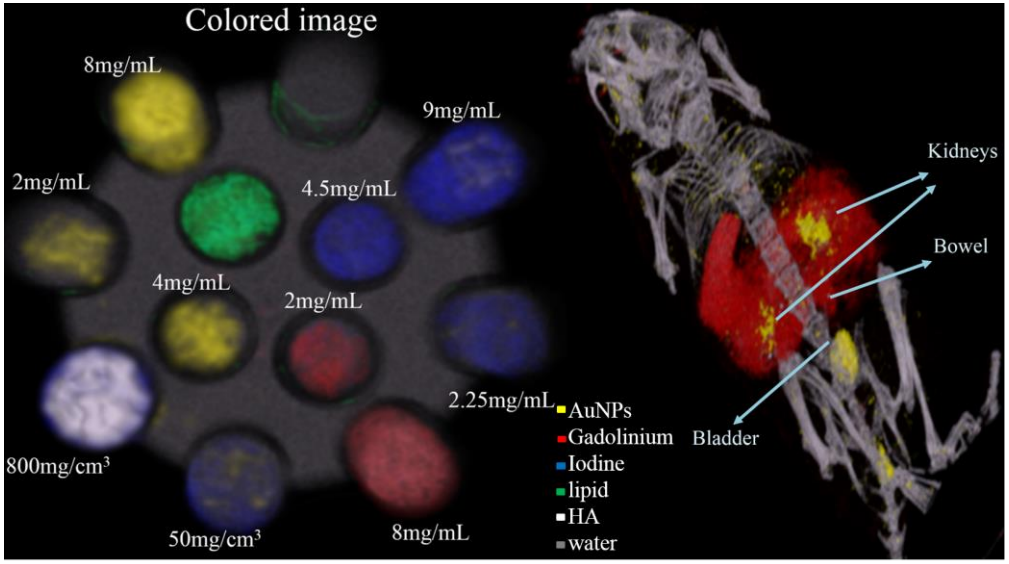


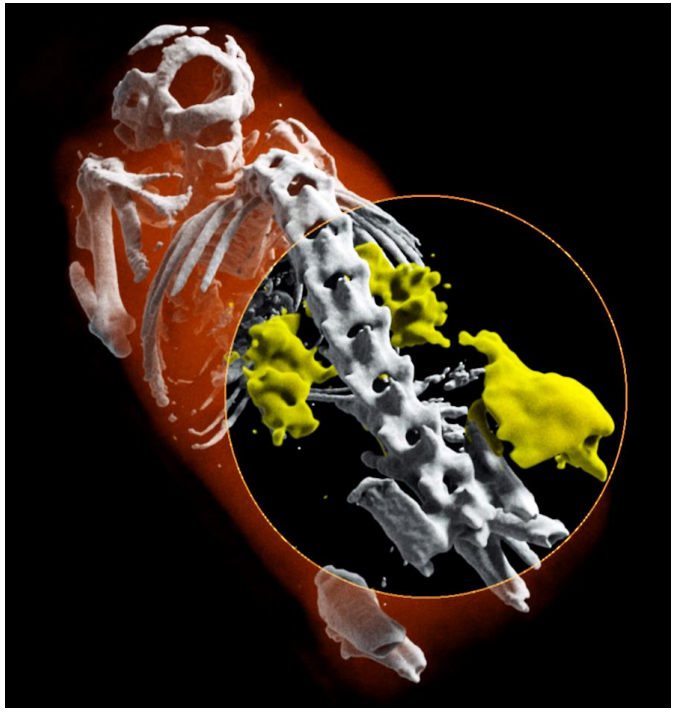
Water-like

Calcification

Lipid

Multiple contrast materials - mouse





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Applications

- materials research

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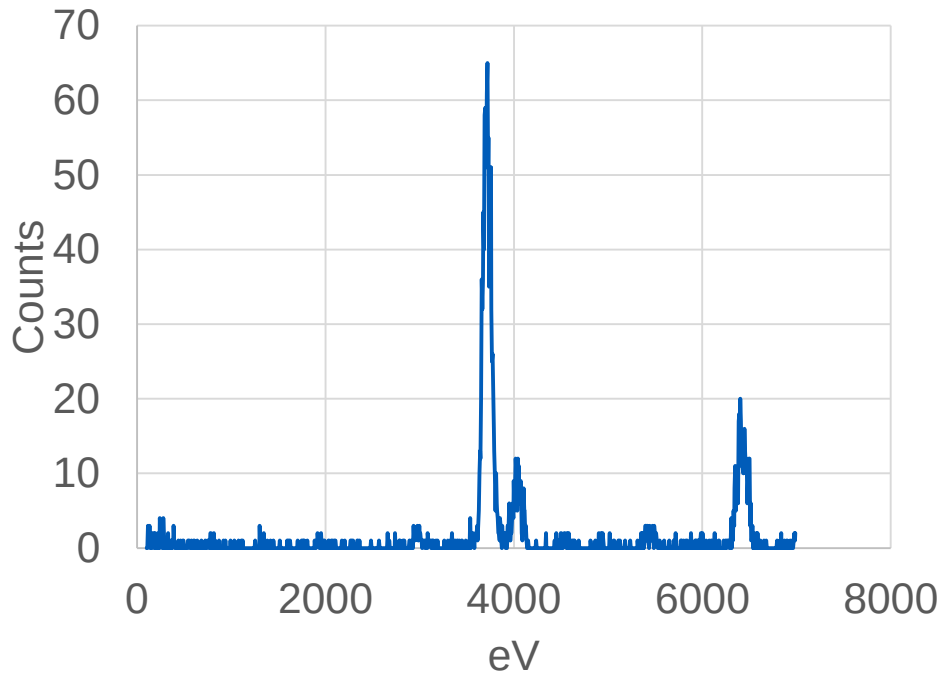
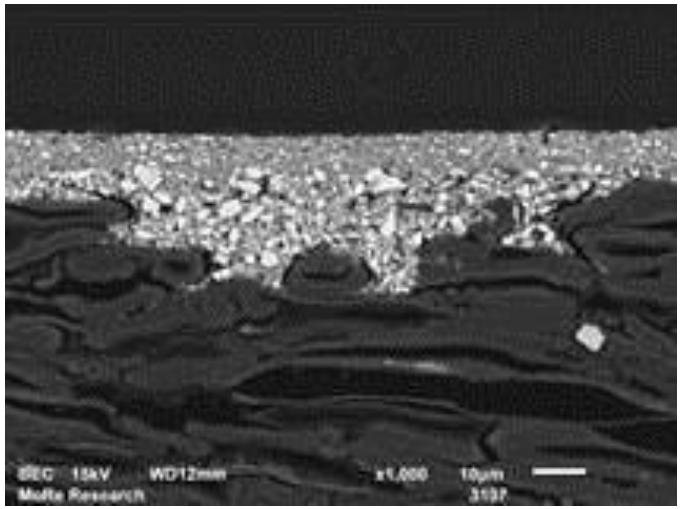
Materials research

- XRD/XRF – energy dispersive detectors for structural analysis
  - Panalytical uses MEDIPIX detectors in their XRD units

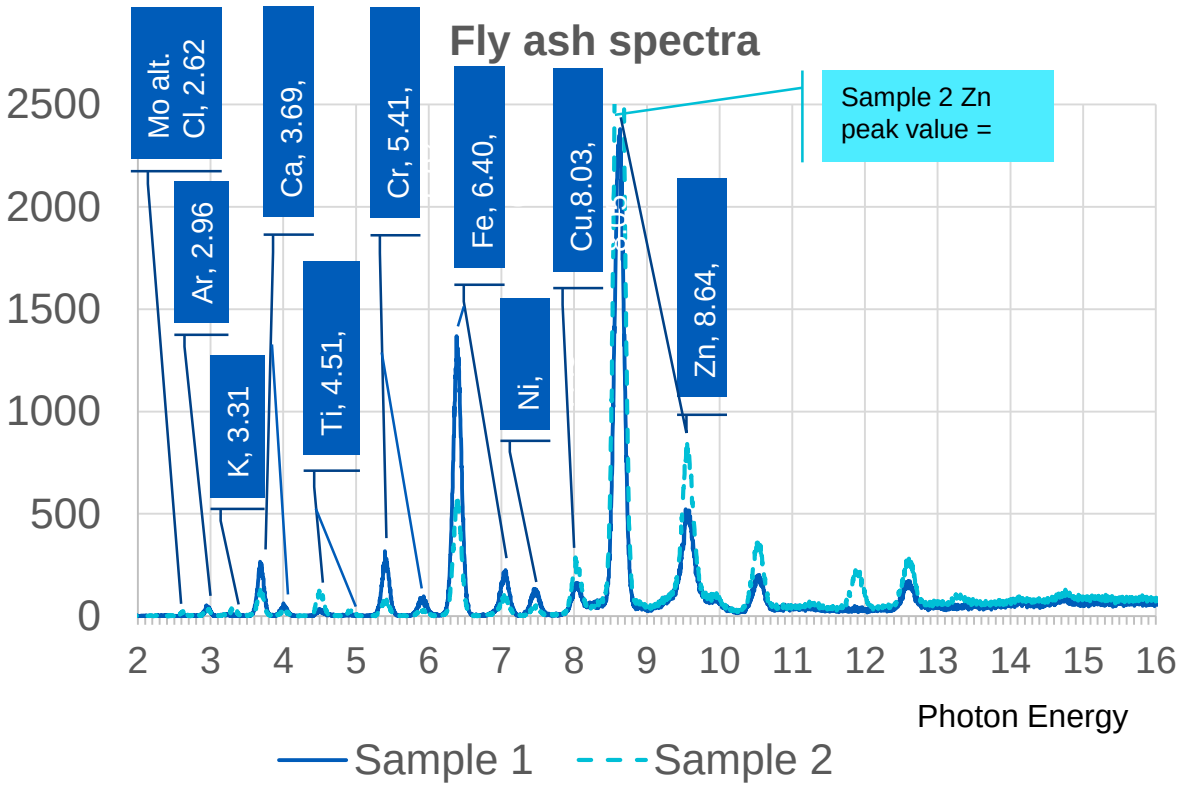
XCOAT – measuring the structure of coated paper

- Coating uniformity, $CaCO_3$





ASKA – measuring the composition of ashes



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Application

- radiation monitoring and dosimetry

Radiation monitoring at the International Space Station

Summary of the First Year of Medipix-Based Space Radiation Monitors on the ISS
By: Pinsky, Lawrence; Hoang, Son Minh; Idarraga-Munoz, John; et al.
Book Group Author(s): IEEE
Conference: IEEE Aerospace Conference Location: Big Sky, MT Date: MAR 01-08, 2014
Sponsor(s): IEEE
2014 IEEE AEROSPACE CONFERENCE Published: 2014

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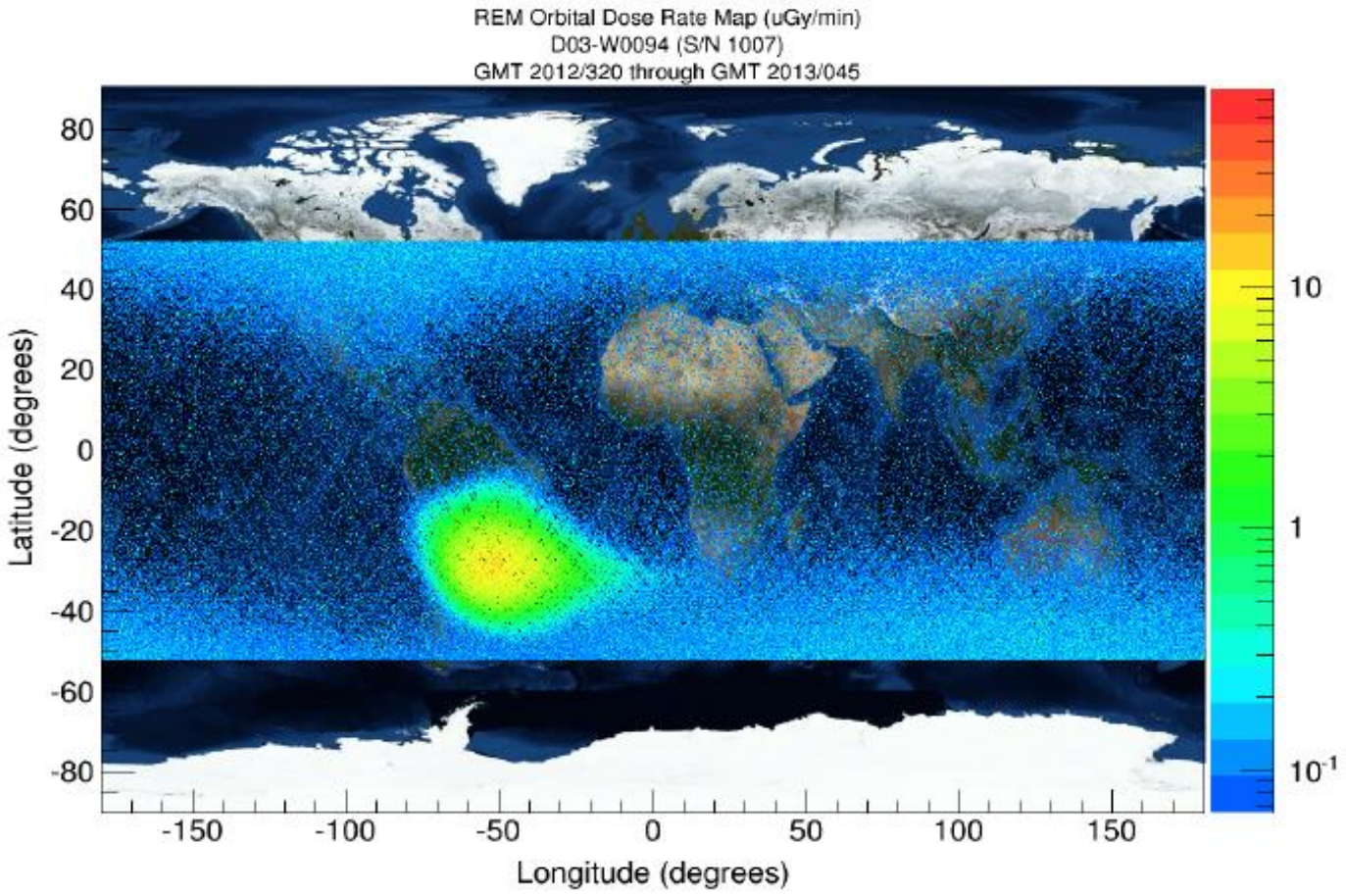
ISS – the South Atlantic Anomaly



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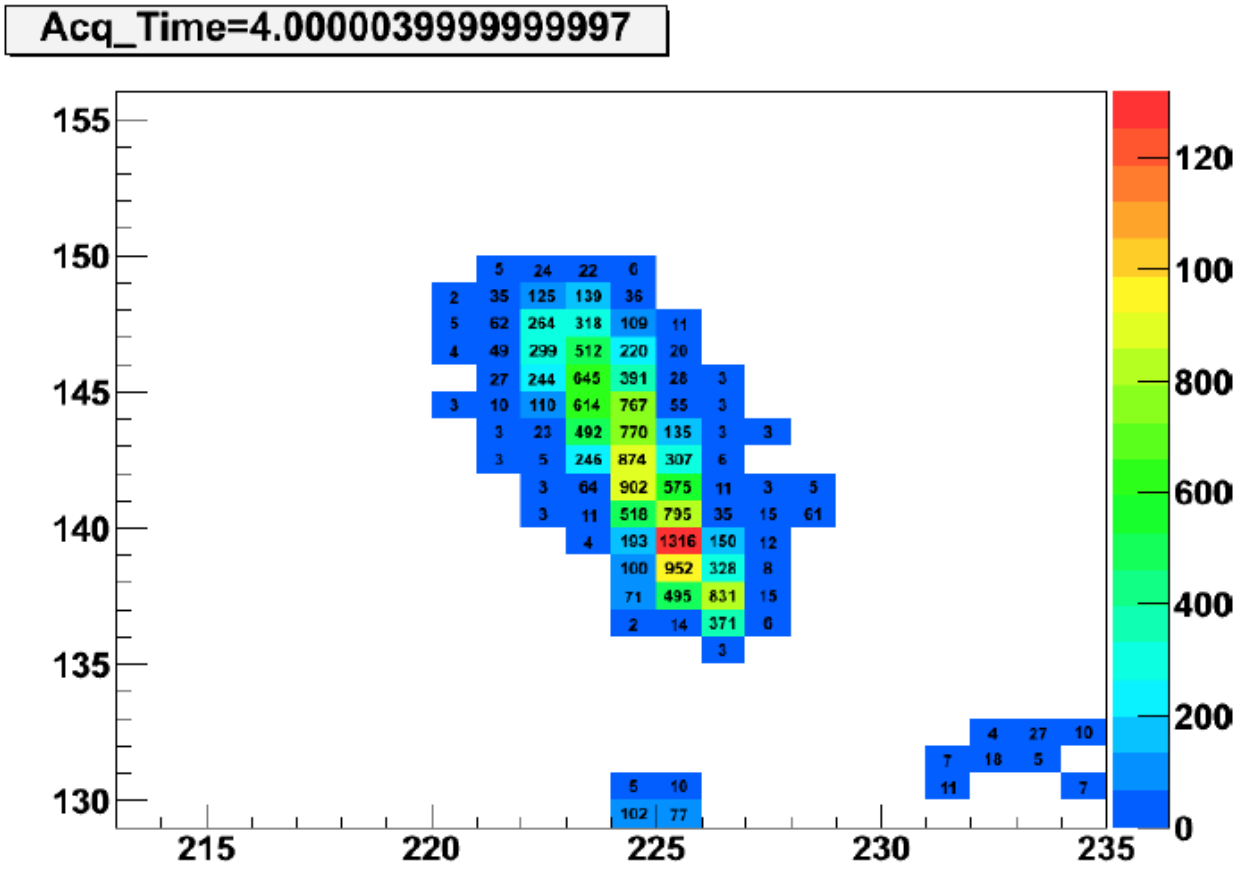
ISS – radiation



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Neutron imaging

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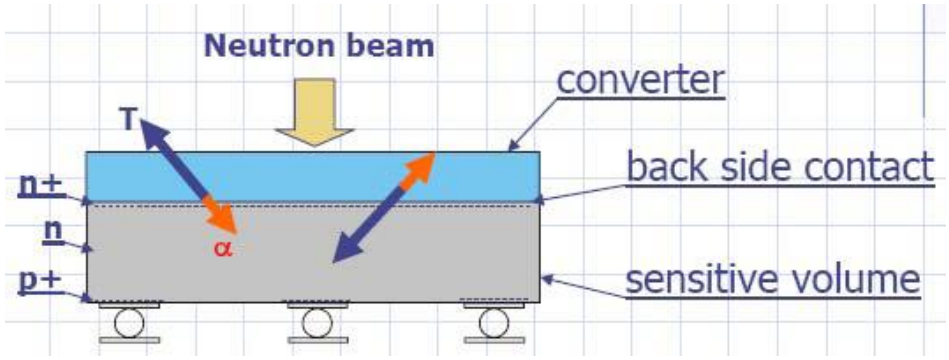
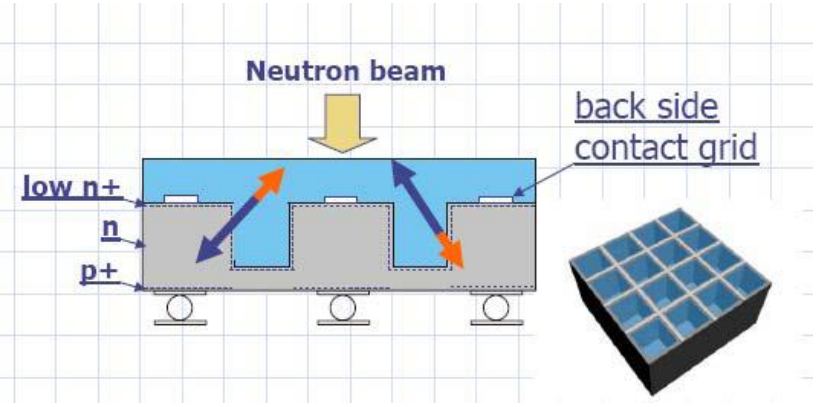
Neutron converters

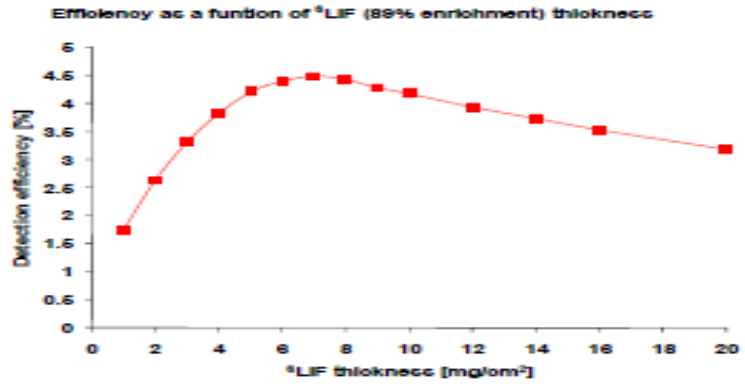
- Common materials
  - $^{3}He + n \rightarrow {}^{3}H + {}^{1}H + 0.764$ MeV
  - $^{6}Li + n \rightarrow {}^{4}He + {}^{3}H + 4.79$ MeV
  - $^{10}B + n \rightarrow {}^{7}Li + {}^{4}H + 2.31$ MeV + $\gamma(0.48$ MeV)
  - $\rightarrow {}^{7}Li + {}^{4}H + 2.79$ MeV

- Additional materials
  - ^{113}Cd
  - ^{155}Gd, ^{157}Gd

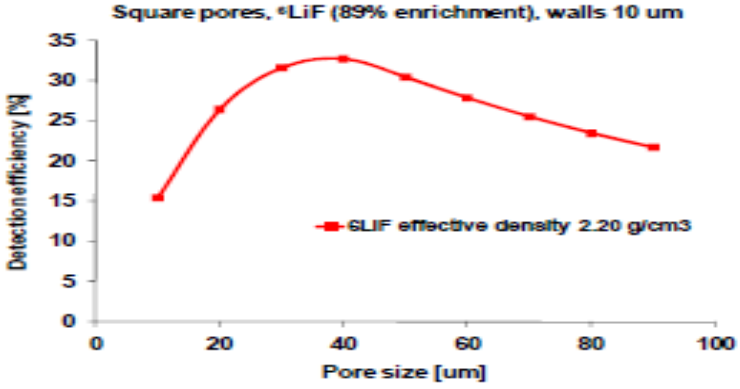
Structured neutron detector





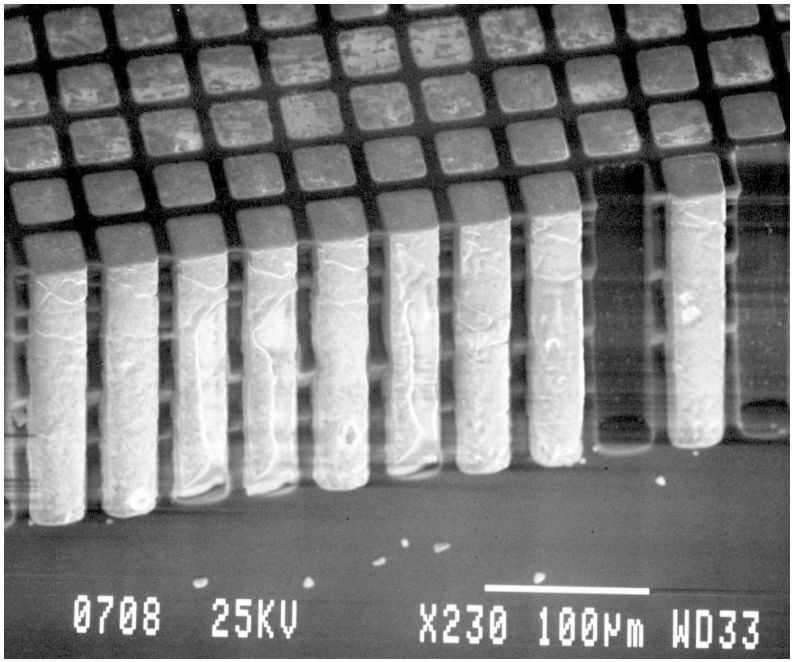


a)



b)

Converter filled silicon matrix



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Neutron response of Gadolinium

- High energy gamma photons
- Internal conversion electrons

IC electron energy (keV) from $^{158}Gd^*$	Yield per neutron	IC electron energy (keV) from $^{156}Gd^*$	Yield per neutron
29	0.0982	39	0.0419
71	0.268	81	0.0497
78	0.0617	88	0.0116
131	0.0341	149	0.0084
173	0.0146	191	0.003
180	0.0031	198	0.0006
228	0.004	246	0.0002
Total yield	0.4837	Total yield	0.1154

Measurement of internal conversion electrons from Gd neutron capture P. Kandlakunta, L.R.Cao, P.Mulligan, Nuclear Instruments and Methods in Physics Research A 705 (2013) 36–41

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New neutron converters

- Semiconducting $^{6}LiInSe_2$
- Epitaxial ^{10}BN
- Li or B loaded plastic scintillators
- …

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Back to HEP

ATLAS-MPX Network

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- 16 Medipix2MXR detectors with neutron convertors
- Placed in the ATLAS experimental cavern
- Installed in 2008 before the first LHC beam
- Proposed upgrade to Timepix detectors

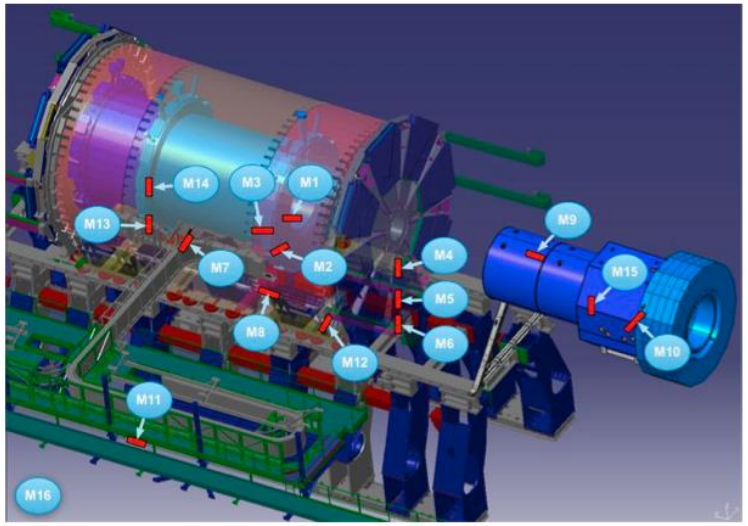
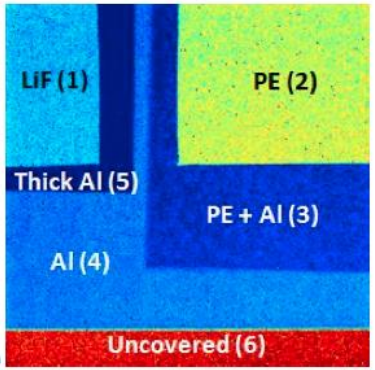


Figure 34. The network of ATLAS-MPX detectors in ATLAS.



Work done by Z. Vykydal [1]

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What's next?

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MEDIPIX4/TIMEPIX4

- Four side buttable
  - TSV technology
  - Distributed pixel matrix
- Target timing resolution: 160 ps
- Target energy resolution: 1 keV FWHM
- Pixel size might be smaller for TIMEPIX4
- Cost to join the consortium: 250.000 CHF distributed over four years

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Summary and conclusions

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Summary and conclusions

- Pixel detectors with single photon processing find applications in various fields
  - Medical imaging
  - Materials research
  - Dosimetry
  - …
- Future challenges concern
  - Area
  - Power consumption
  - Energy resolution
  - Speed
  - …

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Thank you for your attention!