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detecting the future

IBEX based CdTe Detectors for Spectral Applications at High X-ray Energies

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The IBEX ASIC

Feature	Value	Remarks
Number of pixels	256 x 256	65k pixel
Counter size	16 / 32 bit	2 x 2 x 16 bit counters for continuous readout or high dynamic range and 2 thresholds
Continuous readout	☑	16 bits mode
Count rate [Mcps/pixel]	10	Instant Retrigger technology
Signal carriers	holes	For Si sensors
	electrons	For CdTe sensor

High Resolution Mode	
Pixel size [μm^2]	75 x 75
Energy thresholds	2

Spectral Mode	
Pixel size [μm^2]	150 x 150
Energy thresholds	4

Bochenek, M. et al. (2018), IBEX: Versatile Readout ASIC with Spectral Imaging Capability and High Count Rate Capability. IEEE Trans. Nucl. Sc., doi: 10.1109/TNS.2018.2832464.

Part I

Spectral Efficiency as a Figure of Merit for Spectral Applications

Trueb, P., Zambon, P. and Broennimann, C. (2017), Assessment of the spectral performance of hybrid photon counting x-ray detectors. Med. Phys., 44: e207-e214. doi:10.1002/mp.12323.

Zambon, P. et al. (2018) Spectral response characterization of CdTe sensors of different pixel size with the IBEX ASIC. NIMA, Volume 892, 106-113. doi: 10.1016/j.nima.2018.03.006.

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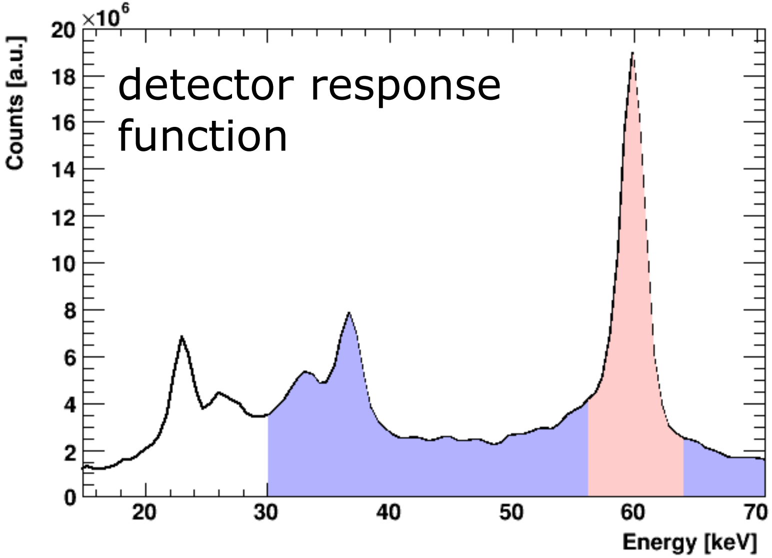
Spectral Efficiency

$$\frac{\text{photons measured with correct energy}}{\text{number of incoming photons}}$$



blue photons contributing to quantum efficiency

red photons contributing to spectral efficiency

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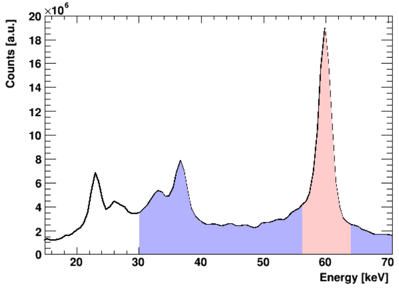
Spectral Efficiency

Formal definition

$$SE(E_\gamma, \Delta E) = \int_{E_\gamma - \Delta E}^{E_\gamma + \Delta E} DR(E_\gamma, E)\,\mathrm{d}E$$

$$= QE(E_\gamma, E_\gamma - \Delta E) - QE(E_\gamma, E_\gamma + \Delta E)$$



detector response function

SE spectral efficiency
E_γ photon energy
ΔE energy window of the order of the energy resolution
DR normalised detector response
QE quantum efficiency as function of photon energy and energy threshold

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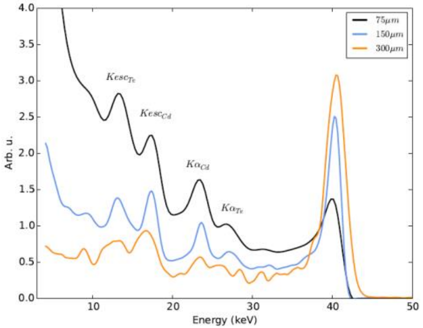
Discussion

Advantages

Well defined even for response functions distorted by

- charge sharing
- fluorescence effects
- pulse pile-up

Simple comparison of different detector designs



detector response function

Disadvantages

Measurement requires determination of incoming flux

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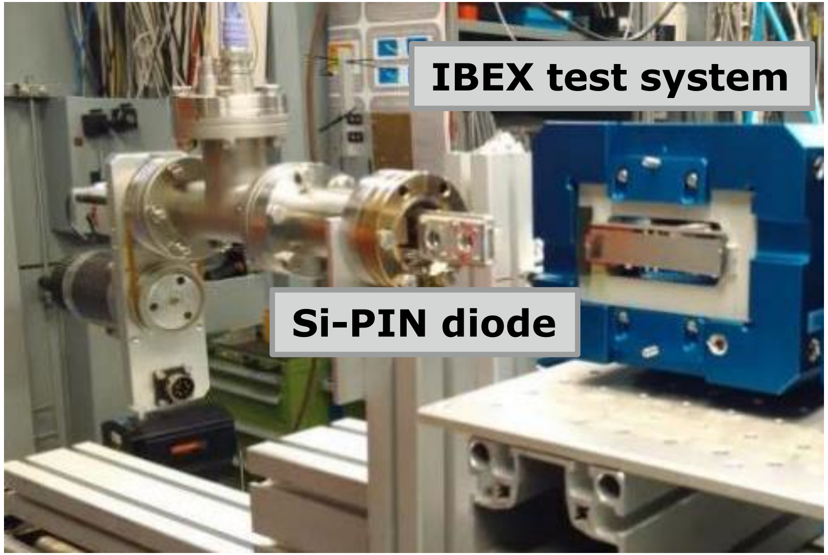
Measurements at Synchrotron (BESSYII)

In collaboration with the Physikalische Technische Bundesanstalt (PTB) group at the BAMLine

IBEX test systems with pixel sizes of
- 75µm
- 150µm
- 300µm

CdTe sensors of 750µm, 1000µm thickness

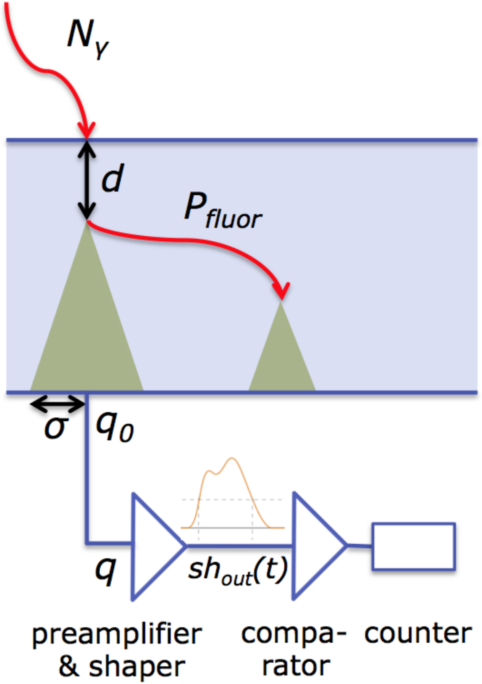
Energy Range of 10 – 60 keV



Monte-Carlo Simulation

Simulated effects

photon statistics
absorption depth
k-edge fluorescence
charge diffusion
preamplifier noise
pulse pileup



$$P(N_\gamma, \bar{N}) = \frac{\bar{N}^{N_\gamma} e^{-\bar{N}}}{N_\gamma !}$$

$$P(d) \propto e^{-\mu d}$$

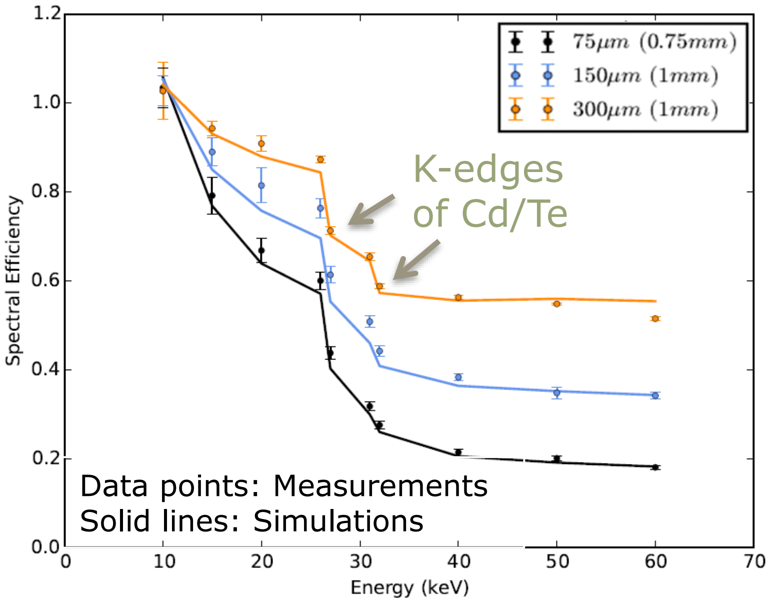
$$P_{fluor} = P_{fluor}(E_\gamma, Cd\,|\,Te)$$

$$\sigma^2 = \sigma_0^2 + \frac{2Ddk_B T}{qV_B}$$

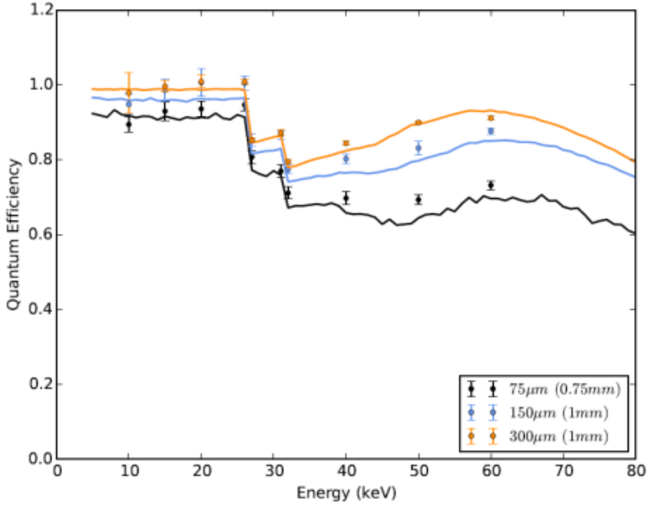
$$q = q_0 \times \mathrm{Gauss}(1, ENC)$$

$$sh_{out}(t) = \sum_i q_i(t') \times \mathrm{sh}(t - t')$$

Spectral Efficiency vs Photon Energy



Spectral Efficiency $SE(E_\gamma, \Delta E = 6$ keV$)$



Quantum Efficiency
$QE(E_\gamma, E_{th} = E_\gamma / 2)$

Larger pixels have less charge sharing and fluorescence effects!

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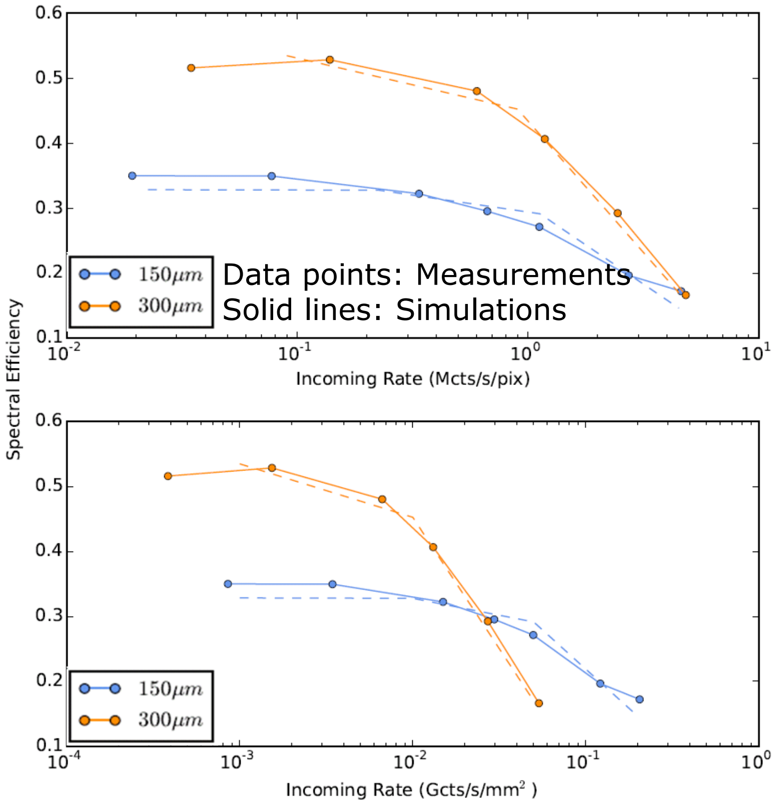
Spectral Efficiency vs Photon Flux



Spectral Efficiency vs Count Rate

Photon energy 60 keV
Reduction at high count rates due to pulse pile-up

Spectral Efficiency vs Photon Flux

300μm pixel performs better at low flux
150μm pixel performs better at high flux

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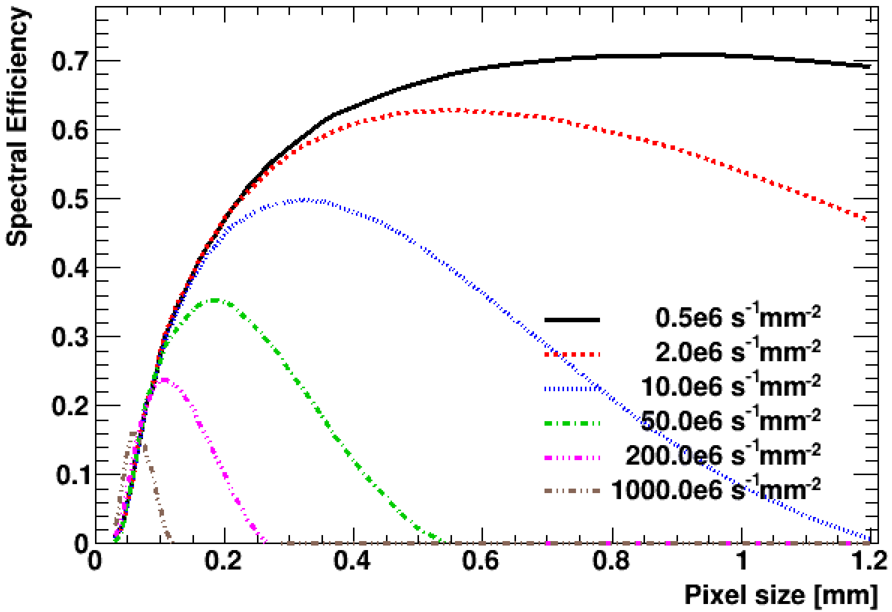
Pixel Size Optimisation



Simulated spectral efficiency
vs pixel size for different fluxes

Small pixels

Charge sharing
Fluorescence effects

Large pixels

Pulse pile-up

Simulation parameters

Photon energy 60 keV
CdTe thickness 750 µm
Pulse width 76 ns
ENC 700 eV

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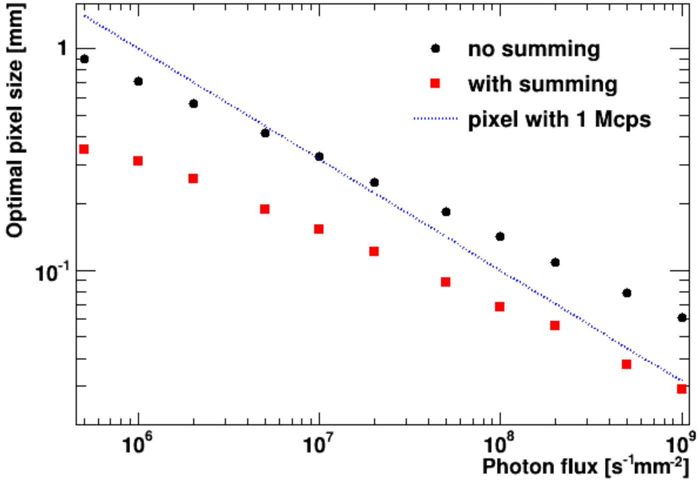
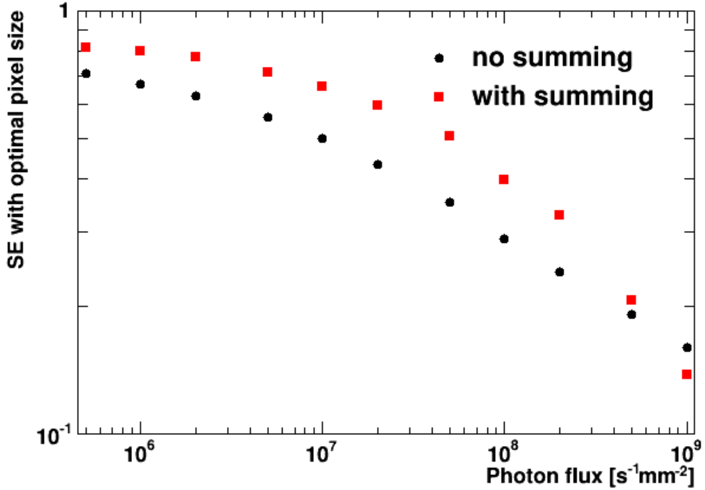
Large Pixels or Charge Summing?

Spectral Efficiency as a tool to quantify the benefits of a simulated charge summing architecture



Optimal pixel size vs photon flux



Spectral efficiency with optimal pixel size vs photon flux

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Part II

Threshold Equalisation up to 150 keV with a Bremsstrahlung Spectrum

High-Energy Calibration

X-ray energy references

K and L fluorescence lines up to Pb (75 keV)

K-edges in transmission spectrum up to Pb (90 keV)

Radioactive decay lines (^{241}Am, ^{99}Tc, ^{57}Co, …)

End-point of X-ray tube spectrum

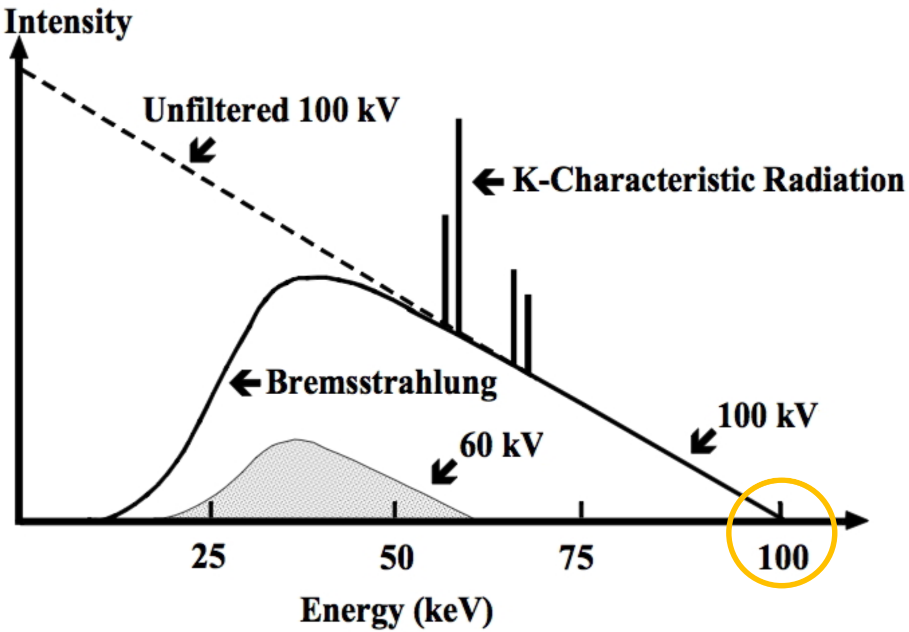
End-point of X-ray tube spectrum

+ Usability / Safety

+ Sufficient photon flux

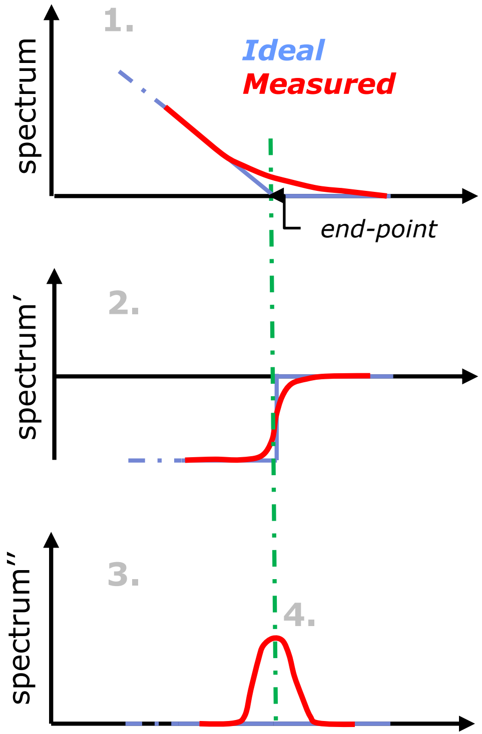
- End-point smeared out by energy resolution

Duane-Hunt Law



Bremsstrahlung spectrum of X-ray tube with linear decrease up to peak acceleration voltage of the tube (kVp).

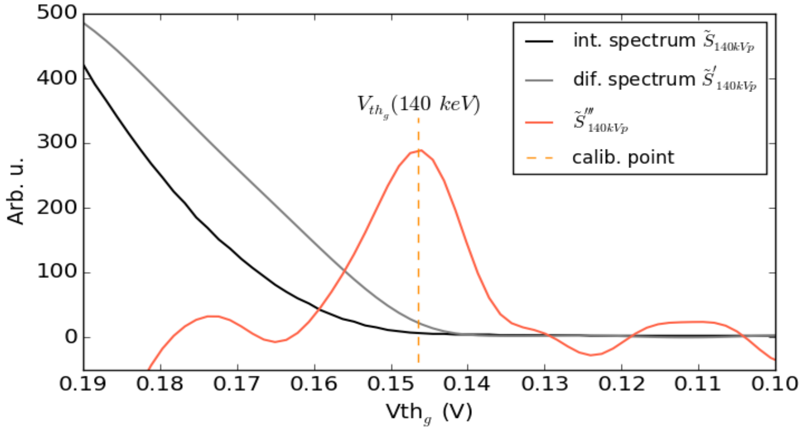
Extraction of Spectrum End-point



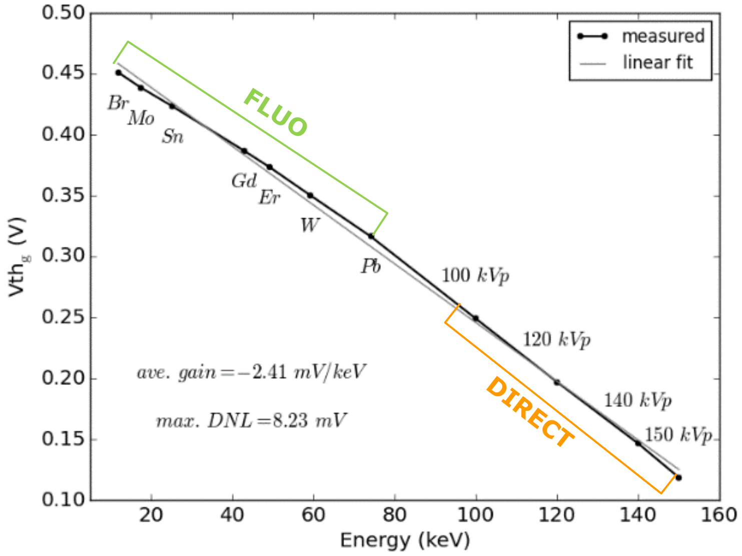
1. Spectrum = derivative of threshold = ramp function convoluted with a Gaussian energy resolution
2. Spectrum' = step function convoluted with a Gaussian
3. Spectrum'' = delta function convoluted with a Gaussian = Gaussian.
4. The peak is the calibration point

Global Threshold Calibration

IBEX CdTe with 150 µm pixel



140 kVp end-point



Global calibration curve

^{99m}Tc Measurement at Kantonsspital Baden

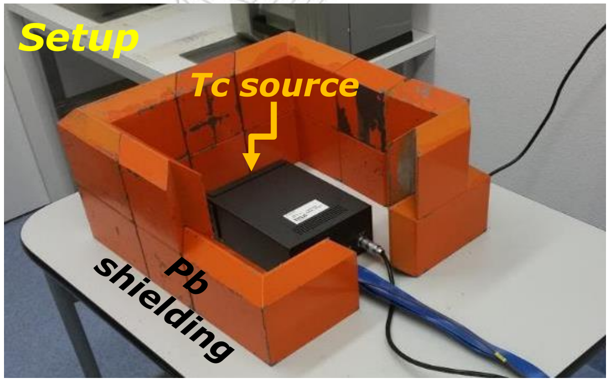
Source

Metastable nuclear isomer of Tc-99

Most used medical radioisotope

γ = 140.5 keV (98%) + 142.6 keV (1.4%)

T = 6.0058 h → 93.7% decay after 24 h

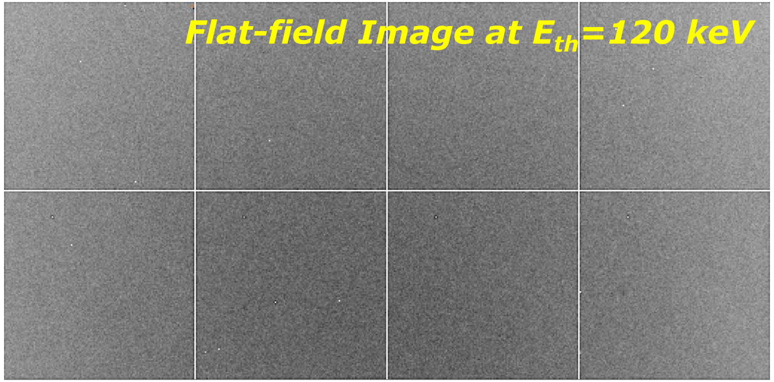


Detector

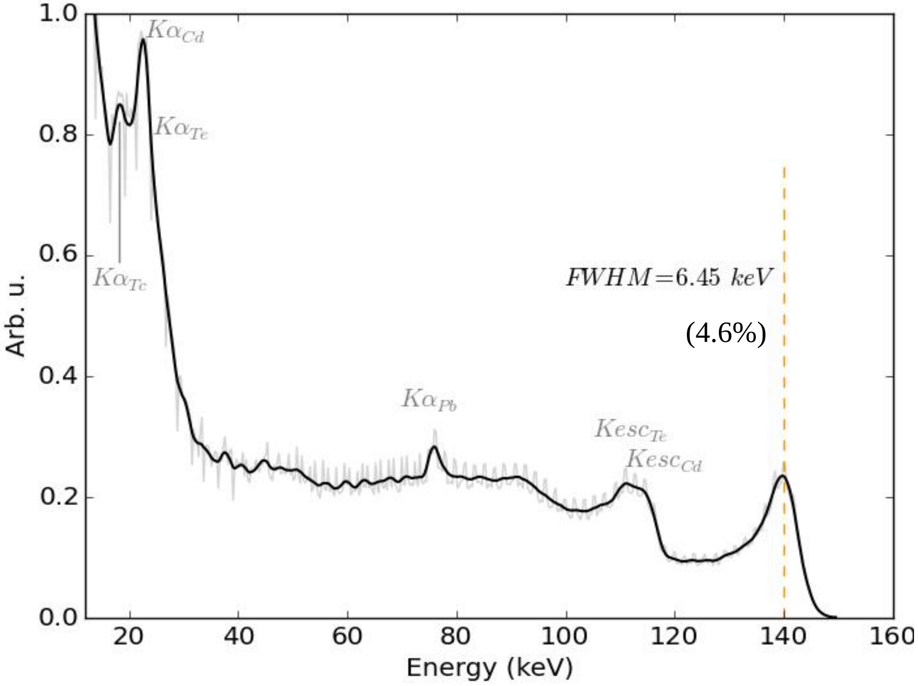
IBEX 150 µm pixel size

1 mm CdTe

Calibration range: 25 – 140 keV



^{99m}Tc Spectrum



Global spectrum

Global Offset

≤ 0.5 keV

≤ 1%

Threshold Dispersion

~ 1.7 keV (rms)

~ 40% of energy resolution

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Summary

*Of making many books
there is no end*

Ecclesiastes

IBEX based CdTe detectors **evaluated** for spectral applications

Spectral efficiency **defined** as useful figure of merit for spectral performance of counting detectors

Spectral efficiency **measured** and **simulated** as function of X-ray energy and flux

IBEX based CdTe detector **calibrated** in the energy range 100 - 150 keV with end-point peak in second derivative of bremsstrahlung spectrum

Calibration **validated** with ^{99}Tc at 140 keV to accuracy of 0.5 keV and precision of 1.7 keV

Acknowledgement

If I have seen further than others,
it is by standing upon the
shoulders of giants

Isaac Newton

Research & Physics group (DECTRIS)

ASIC design group (DECTRIS)

L. Cibik, S. Schreiber and M. Krumrey, PTB Synchrotron Radiometry department (HZB)

C. Ludwig, Nuclear Medicine Department (KSB)

DECTRIS Workshop 2018

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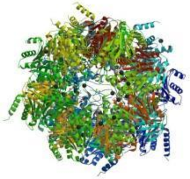
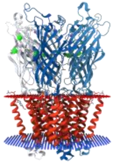
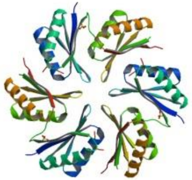
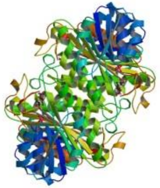
Thank you for your attention!

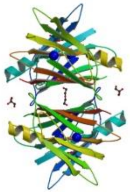

5LF0

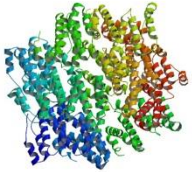

5F2W


4HFC


4RBT


5JO9


4TLK


4YO5

7 protein structures (out of >10^4) solved with PILATUS detectors

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