TRAINING COURSE ON RADIATION DOSIMETRY:

Instrumentation 2 – Solid state detectors

Hybrid pixel detectors and their applications

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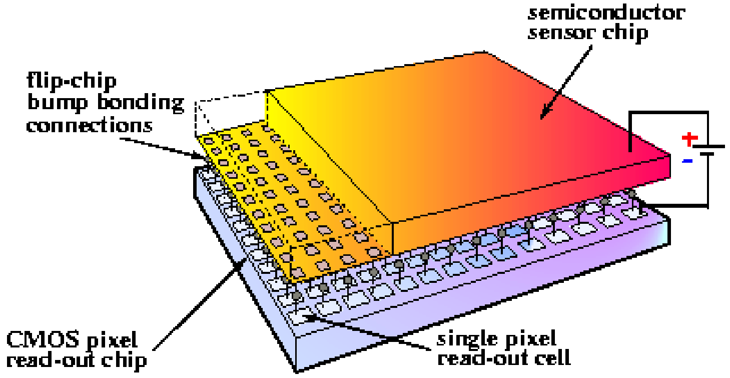
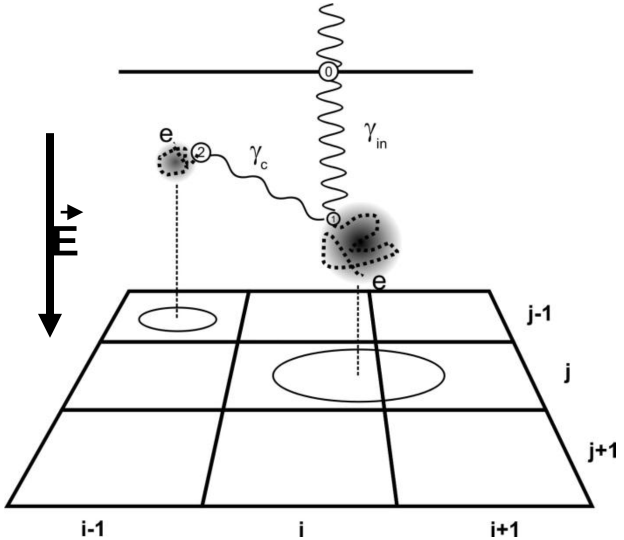
Thu. 22/11/2012, 10:00 – 11:00 am

Agenda

- **The Medipix/Timepix detector**
- Energy response
- Application: Imaging spectroscopy at high flux
- Application: Material resolved imaging
- Application: Dosimetry

The Medipix2/3 and Timepix detectors: hybrid photon counting pixel detectors



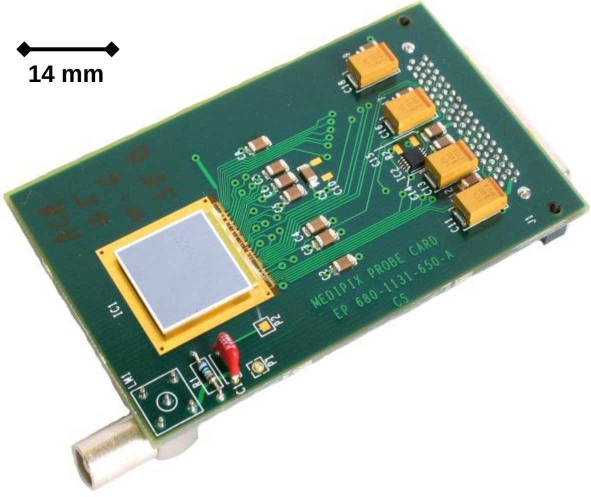


ASIC/Sensor:

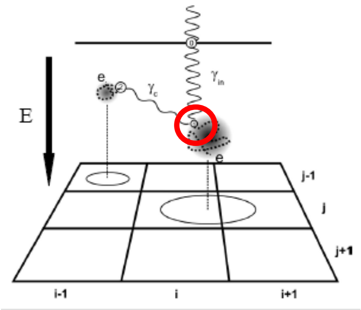
- Development: International Collaboration with seat at CERN
- Bump-bonded with Pb/ Sn
- 65536 pixels in 256 columns and 256 rows
- Pixel pitch: 55 µm
- Size of the matrix: 14 mm (2 cm^2)
- 0.25 µm CMOS

Sensor:

- Materials: Si, GaAs, CdTe
- Bias voltage: 150 V (300 µm Si)
- 2x2-version (Quad)



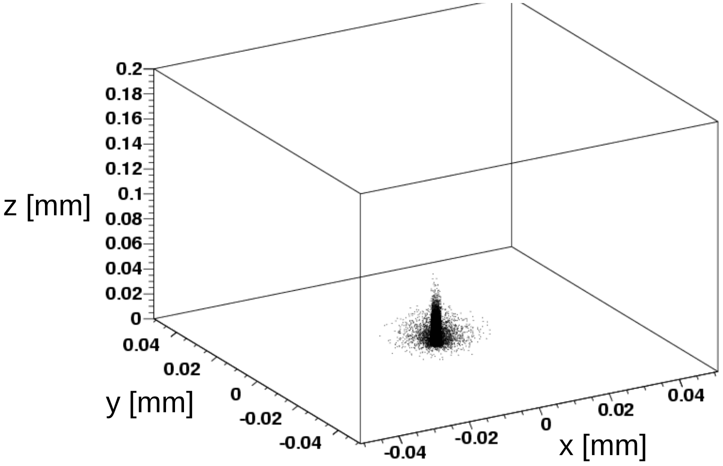
Step 1a: photoabsortion + relaxation



GaAs (Z=31, 33)

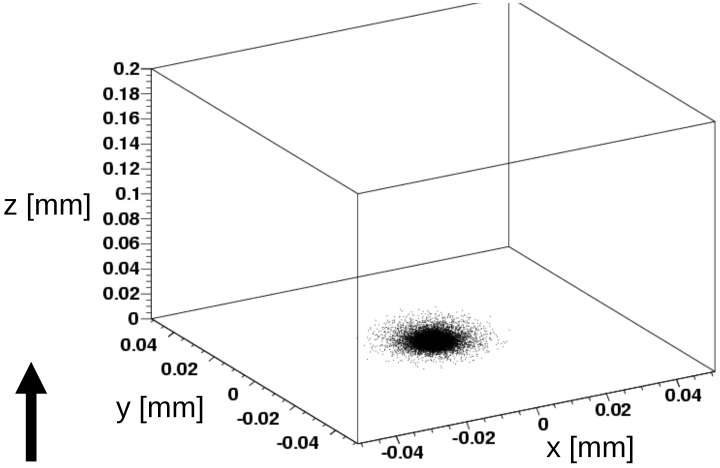
$E_g < E_{K\text{-}shell}$

10 keV



$E_g > E_{K\text{-}shell}$

12 keV

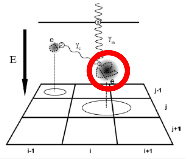


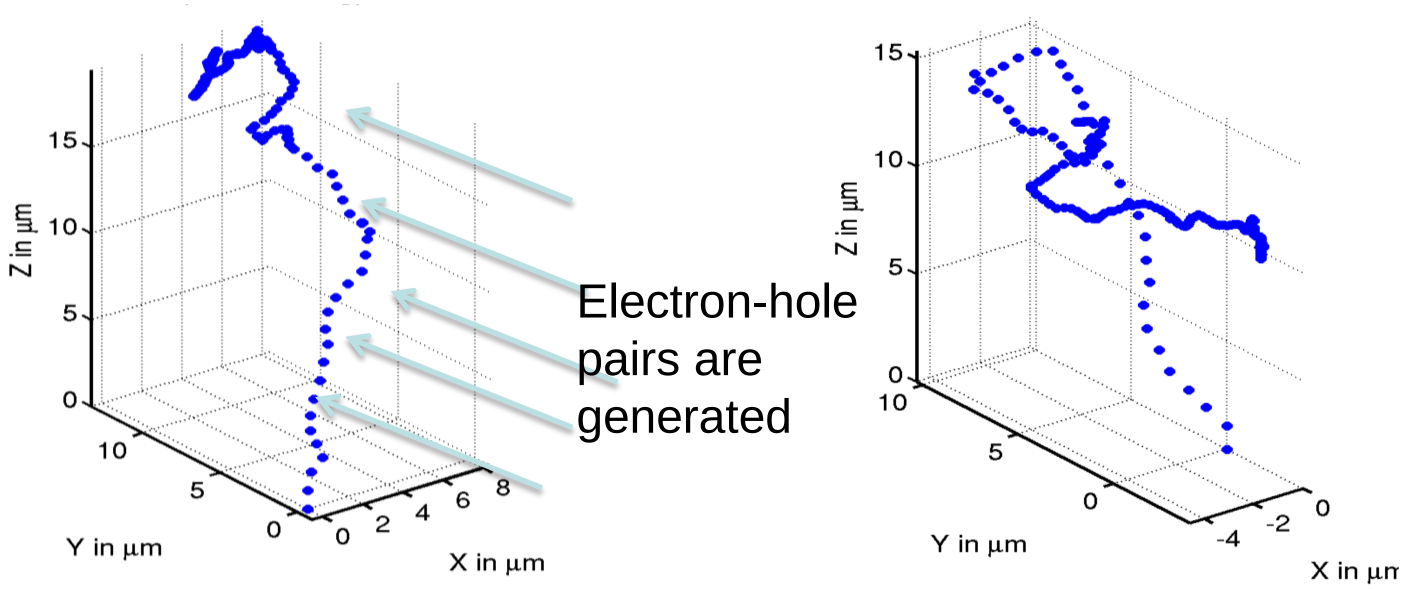
Photon

- Energy not suffcient to remove e- from K-shell
- Longer penetration depth

- Production and detection of fluorescence photons and Auger electron emission
- Smaller penetration depth
- Broader transversal profile

Step 1b: Continuous energy loss of electrons





Electron-hole pairs are generated

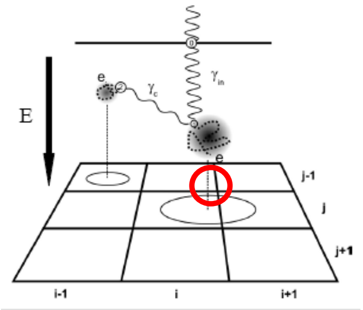
- **Contiouous energy loss: Bethe-Bloch-Fomula**

$$-\left\langle \frac{dE}{dx} \right\rangle = Kz^2 \rho \frac{Z}{A} \frac{1}{\beta^2} \left[\ln \frac{2m_0 c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - 2\beta^2 - \delta - c\frac{C}{Z} \right]$$

- **For silicon: electron path length approximately**

$$l[\mu m] = \left(\frac{E[keV]}{10} \right)^{1.75}$$

Step 2: Drift and diffusion of released charge carriers in semiconductor



Transport of charge carriers described by differential equation

Charge carrier density change

Diffusion term

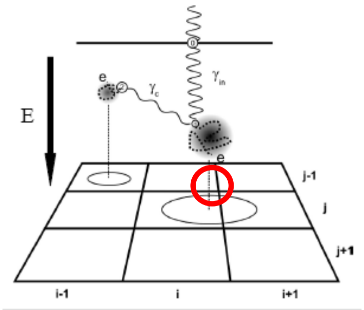
$$G = \frac{\partial n(\vec{x},t)}{\partial t} - \vec{\nabla}(n \cdot m \vec{E}) - \vec{\nabla}(D \cdot \vec{\nabla} n) + \frac{1}{t} \cdot n$$

Charge generation term

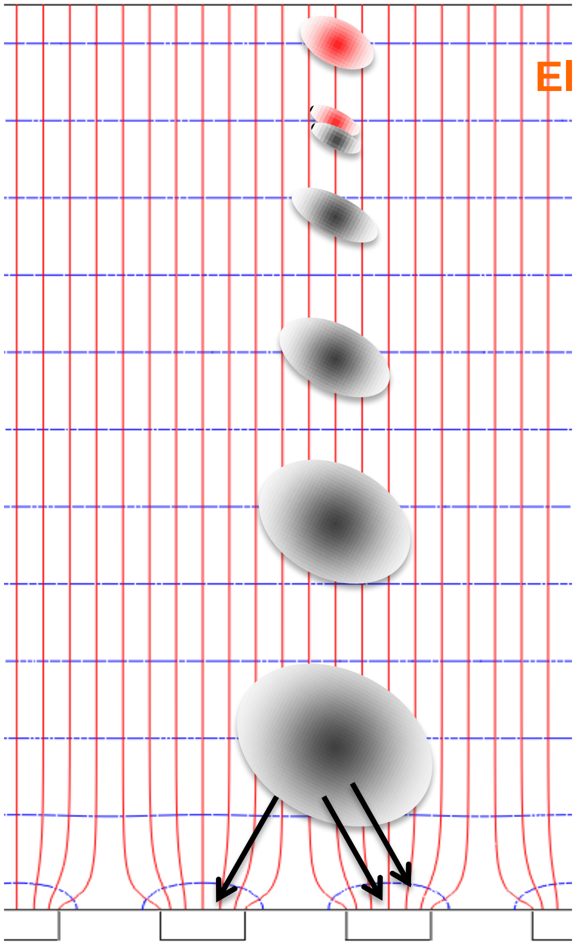
Drift term

Limited lifetime term

Step 2: Drift and diffusion of charge carriers



+ 150 V (for example)



Electric field lines

● Electrons for example

● Holes for example

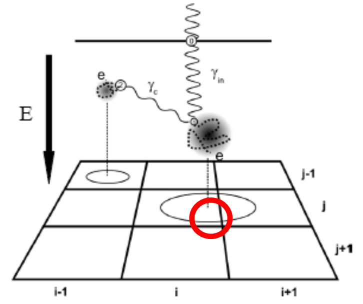
Electric potential

Pixel electrodes at approx. 0 V

Charge might be shared between several pixels (charge sharing, charge splitting)

Attention: Do not forget the second charge carrier type

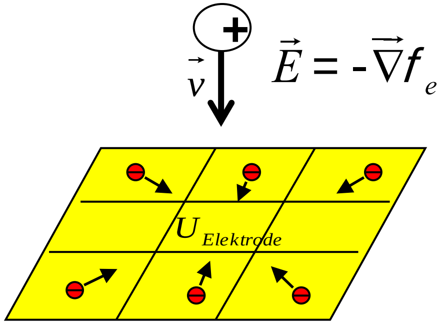
Step 3: signal generation in pixel electrode



Influenced current

- Charge above electrode influences mirror charge in all pixel electrodes
- Charge carrier moves -> mirror charge changes
- A current flows in or out the pixel electrode

$$I = q \cdot \vec{v} \cdot \underbrace{\vec{\nabla} \overbrace{\frac{\partial F_{electric}}{\partial U_{Electrode}}}^{f_{Weighing}}}_{\vec{W}}$$



$$\vec{E} = -\vec{\nabla} f_{electric}$$

Weighting potential

- Pixelelectrode at $\vec{x}_j$ is put to norm weighting potential

$$f_{Weighting}(\vec{x}_j) := 1$$

- Other electrodes to 0:

$$f_{Weighting}(\vec{x}_{i^1 j}) := 0$$

- Solve Laplace equation:

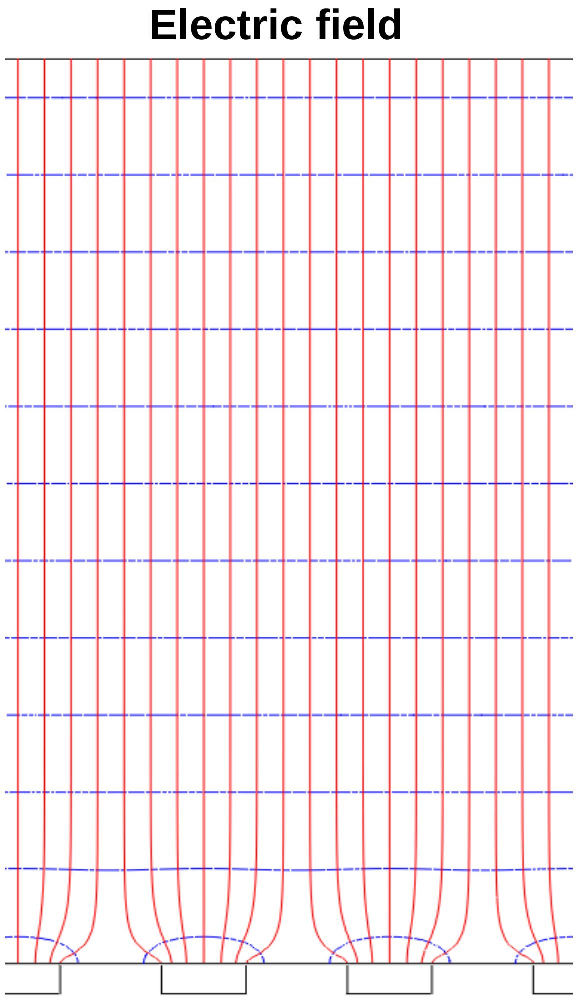
$$D f_{Weighting} = 0$$

- Obtain weighting-Field:

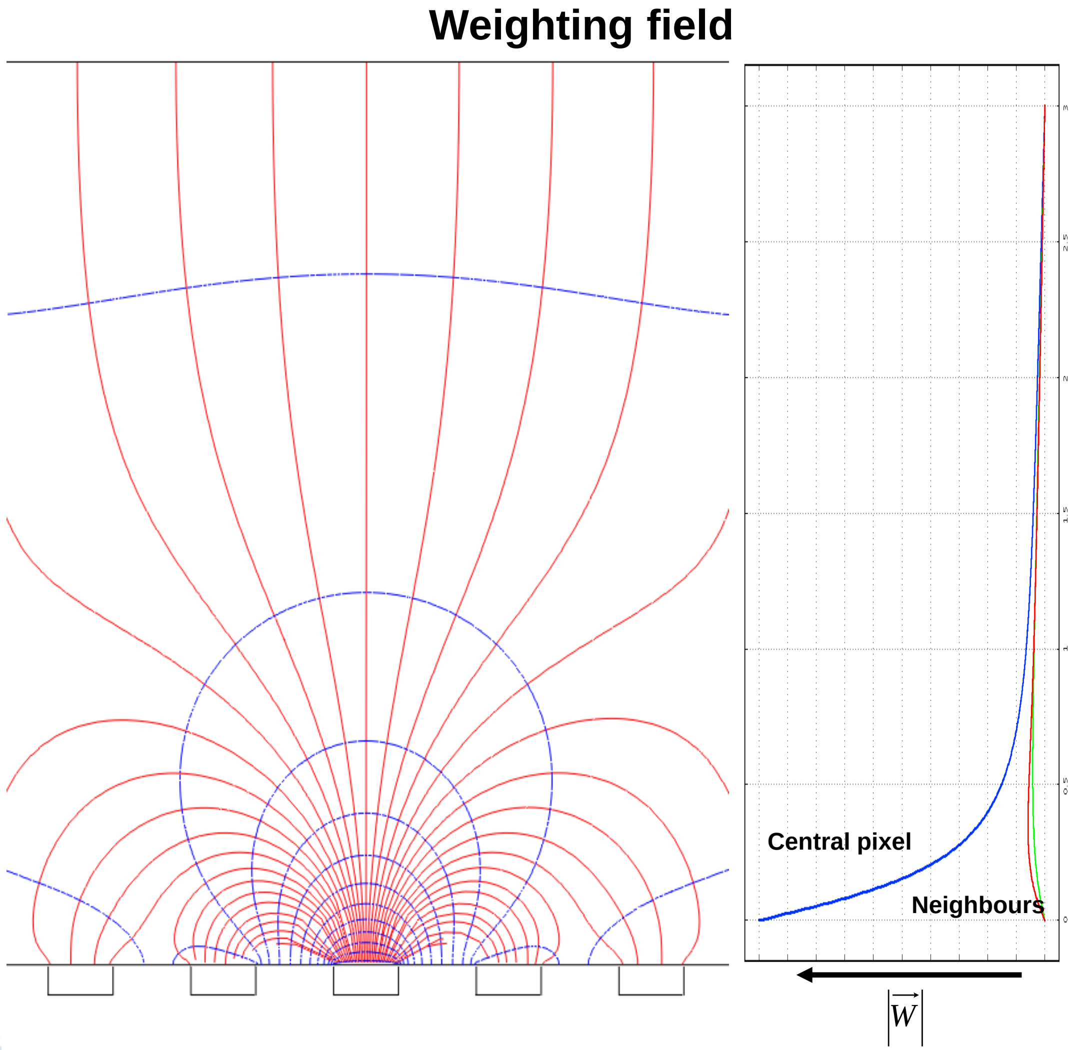
$$\vec{W} = \vec{\nabla} f_{Weighting}$$

Attention: electrons AND holes influence both a current with same polarity!!!

Step 3: The weighting field above a pixel electrode



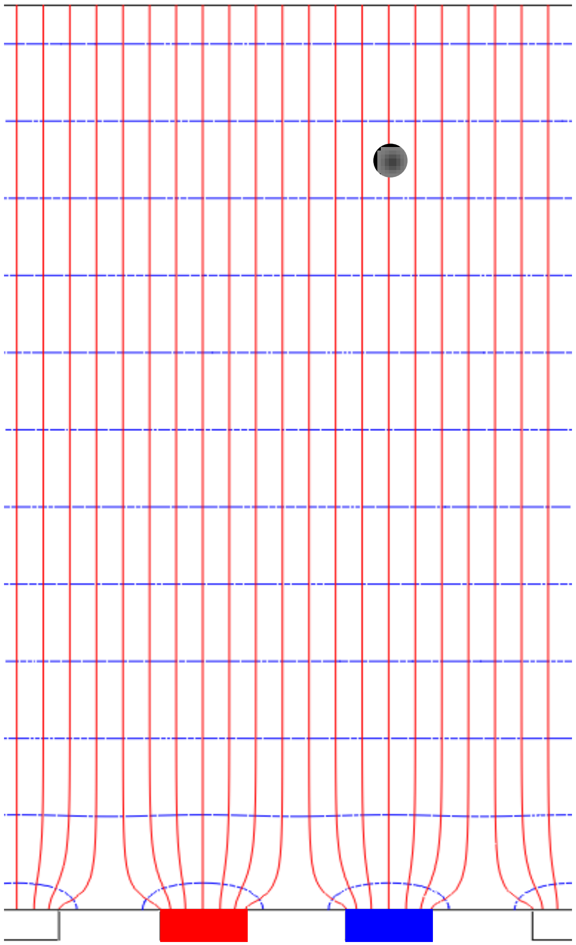
Electric field



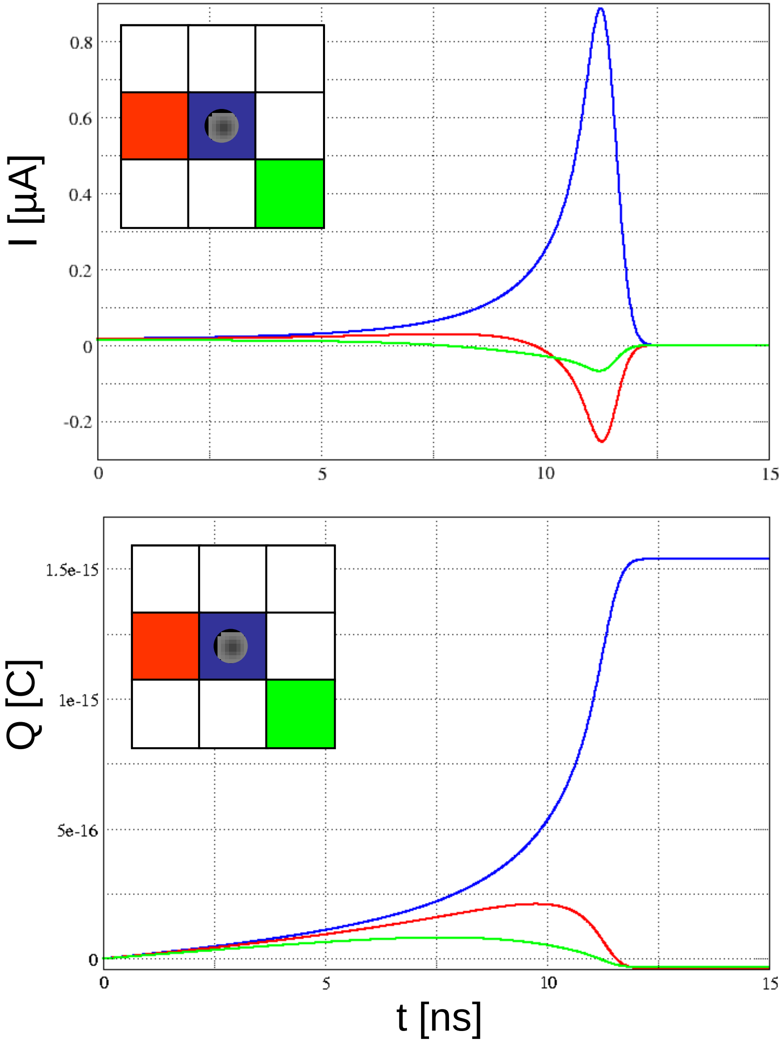
Weighting field

Attention: The charge carrier type drifting to pixels contributes most!!!

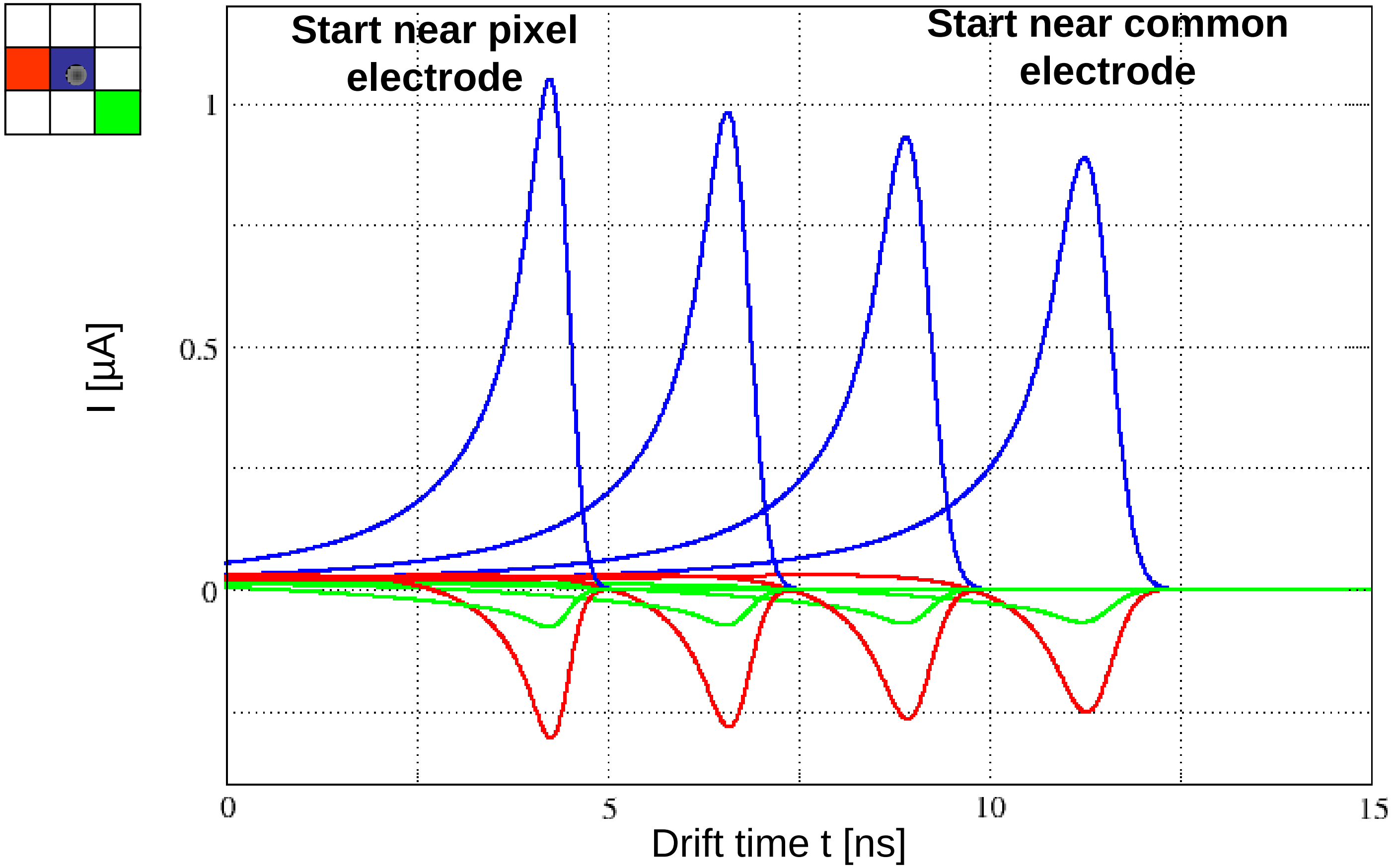
Step 3: the pulse-forms of the influenced currents



Electric field

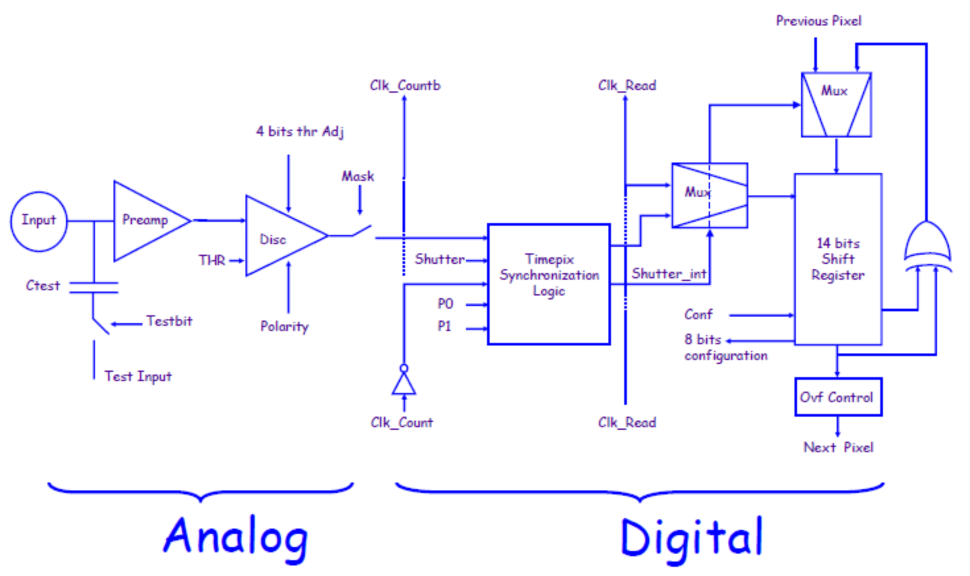


Step 3: Pulseform depends on point of generation of charge carriers

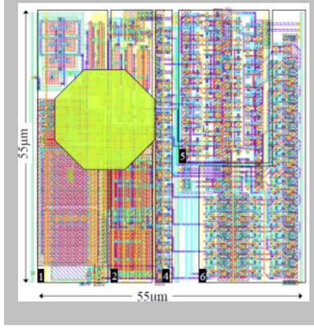


Step 4: integrate current and process digitally

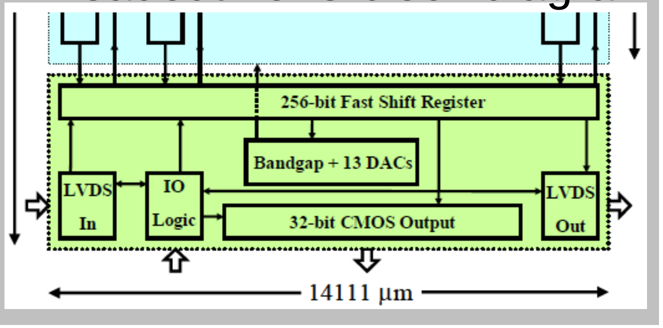
Pixel electronics



Pixel cell



Readout zone block diagram



Principle

- **Pixel electronics**
  - Charge-Sensitive Preamplifier
  - 1 discriminator (minimum threshold approx. 1000 e- = 3.6 keV in Si and 4.4 keV in CdTe)
  - 1 counter per pixel
- **Operation modes**
  - Counting
  - Time-Over-Threshold
  - Time-Of-Arrival

Advantages and disadvantages of the Medipix detector in X-ray imaging

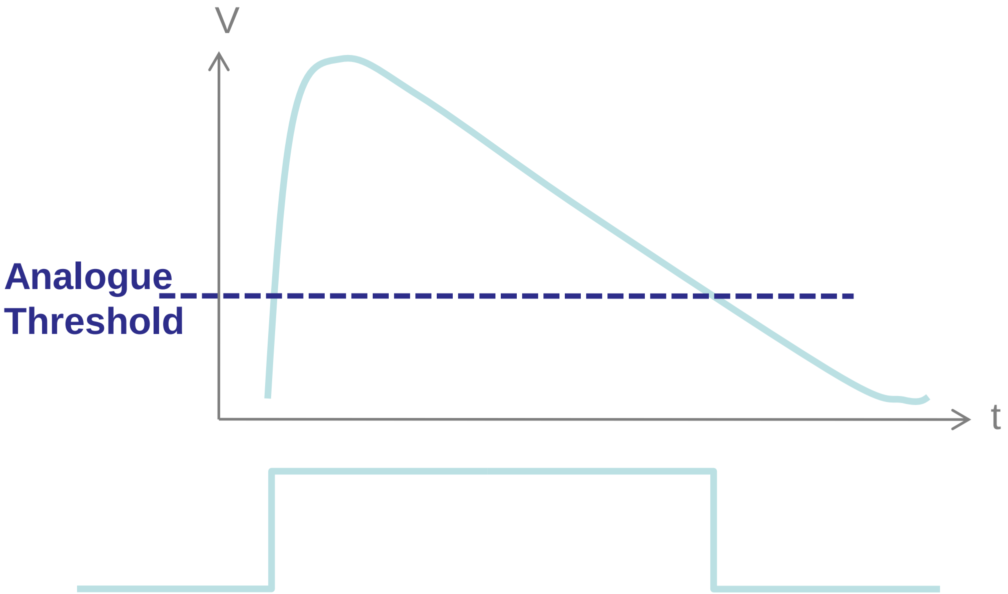
Advantages

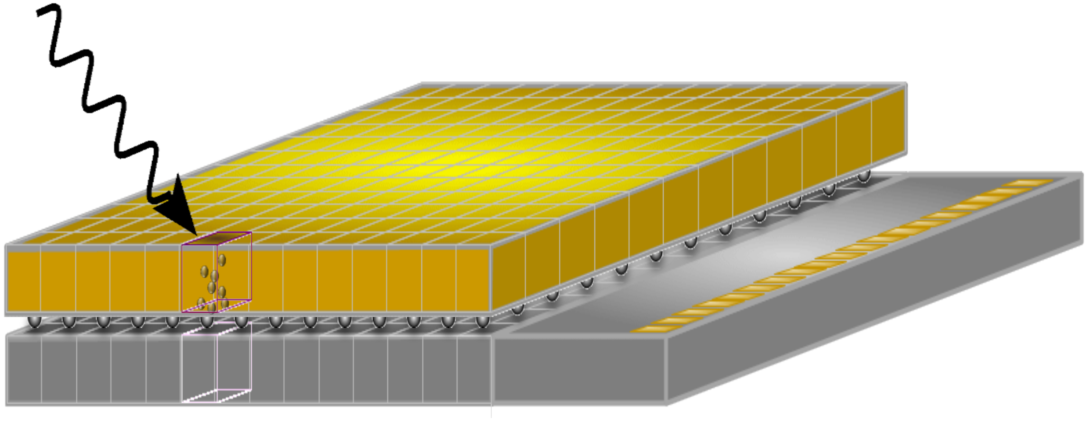
- Noiseless dark field image
- No readout noise
- No blooming
- No afterglow
- Very linear at low rates
- High position resolution
- High frame rate
- **Energy sensitive**

Disadvantages

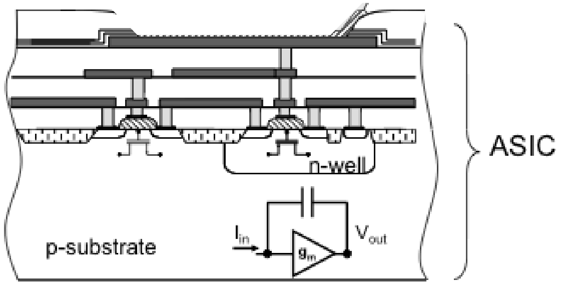
- Small size
- Charge-Sharing
- Multiple counting reduces DQE
- Rate limitations at high flux (10^{10} photons/cm^2/sec)

Working principle

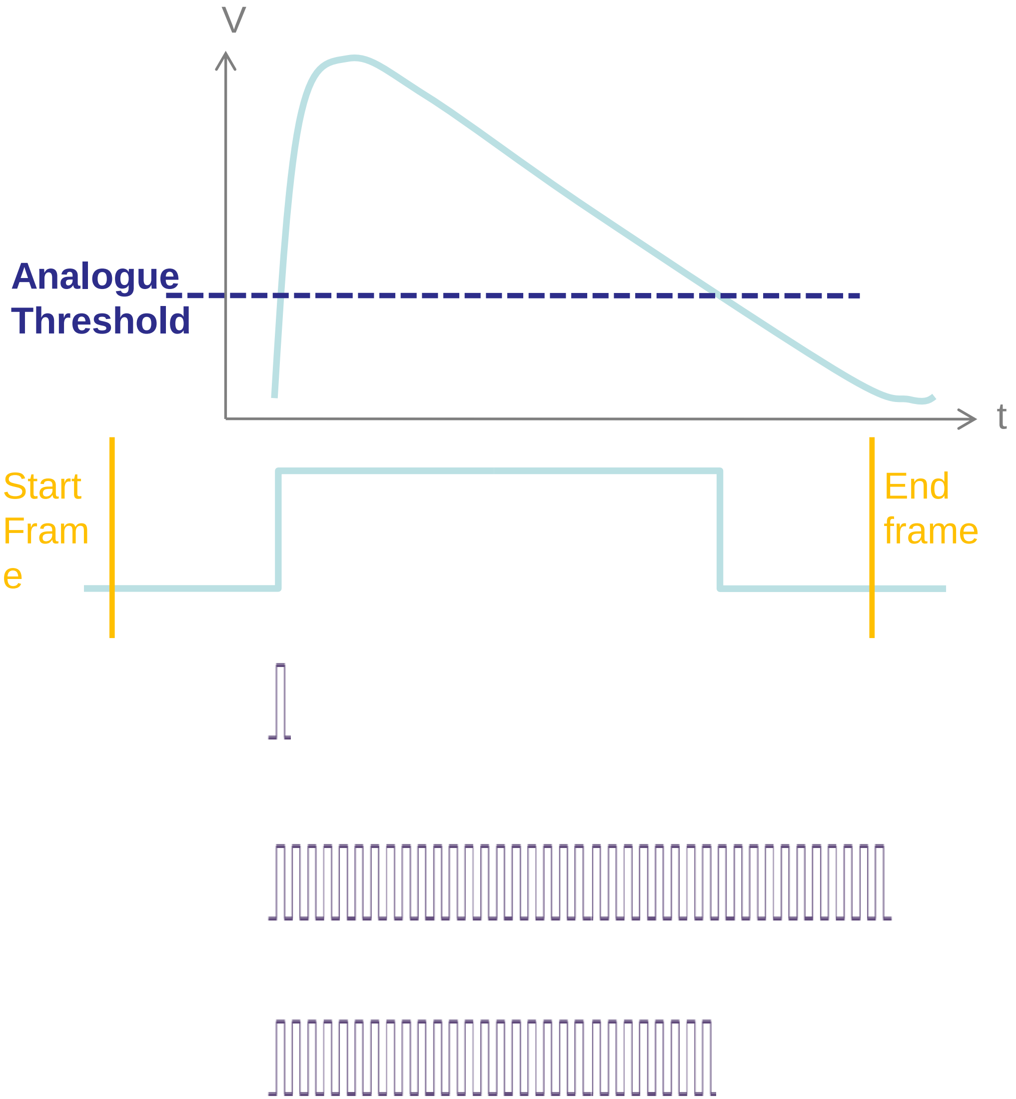




*by Winnie Wong



Working principle

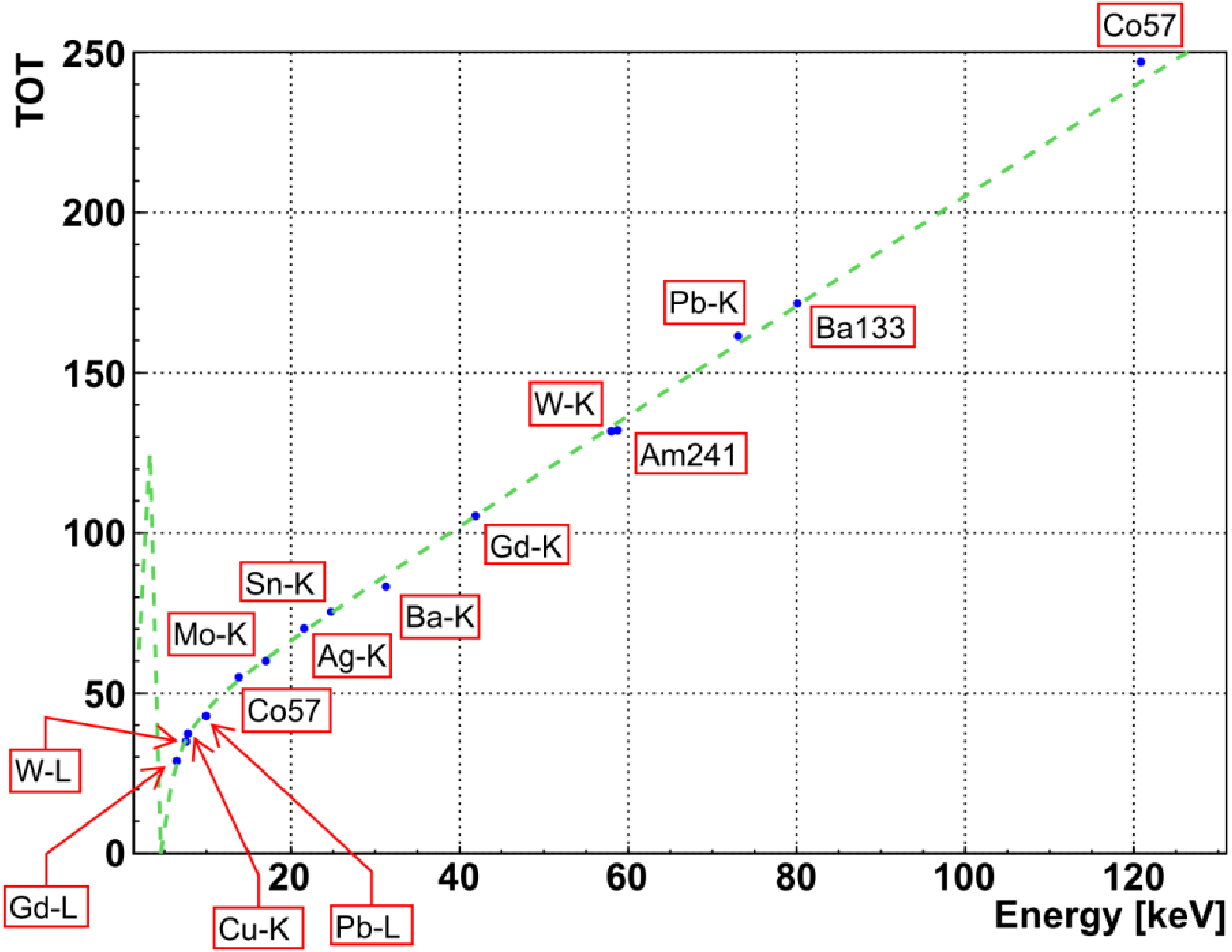


Counting (Medipix2,3 & Timepix)

Time of Arrival (ToA) (Timepix)

Time over Threshold (ToT) (Timepix)

Pixelwise energy calibration for ToT mode necessary



Agenda

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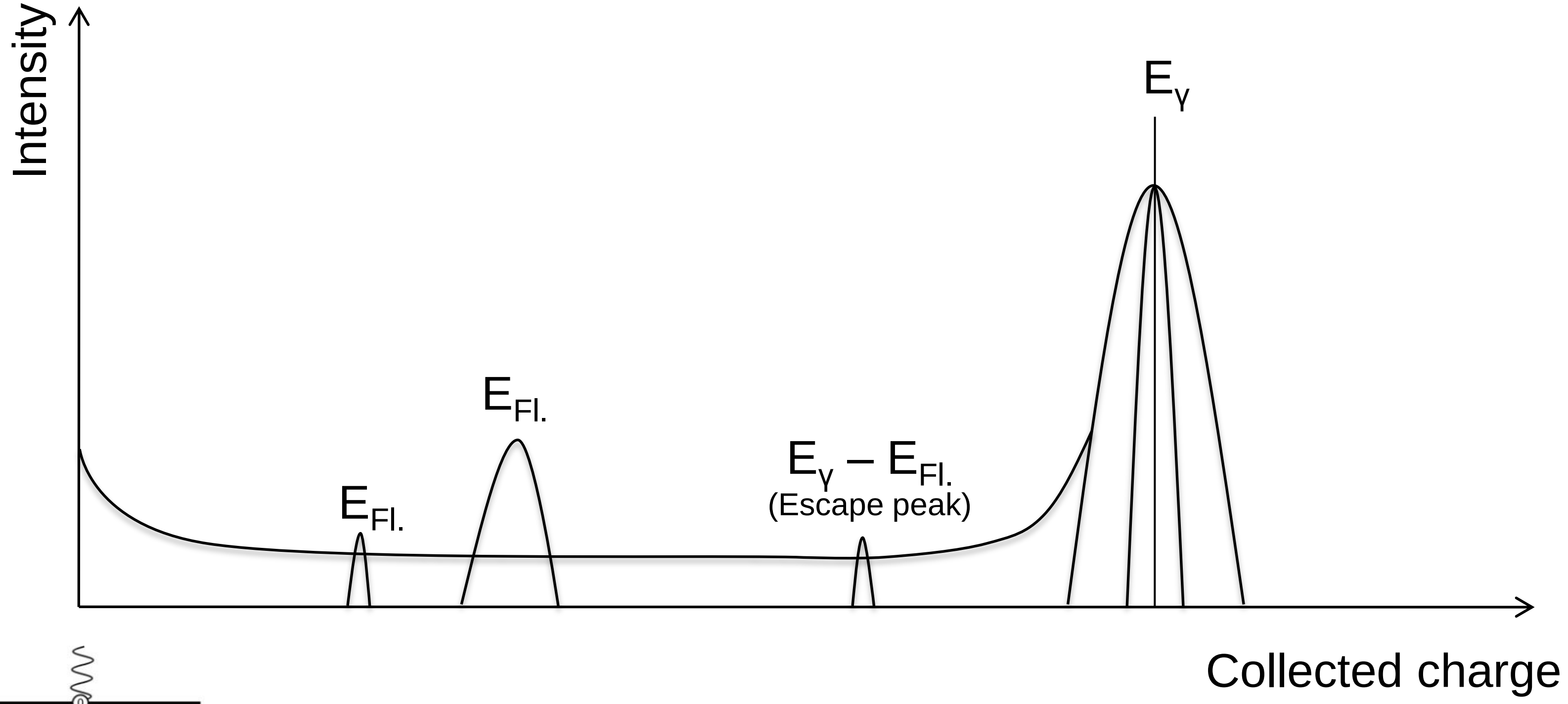
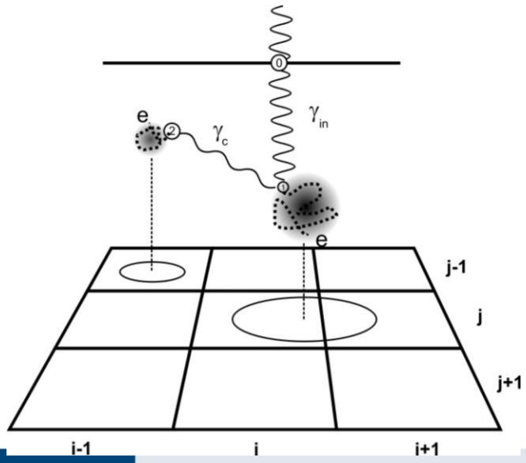
- **Energy response**
- Application: Imaging spectroscopy at high flux
- Application: Material resolved imaging
- Application: Dosimetry

Does it measure the impinging photon energy ?

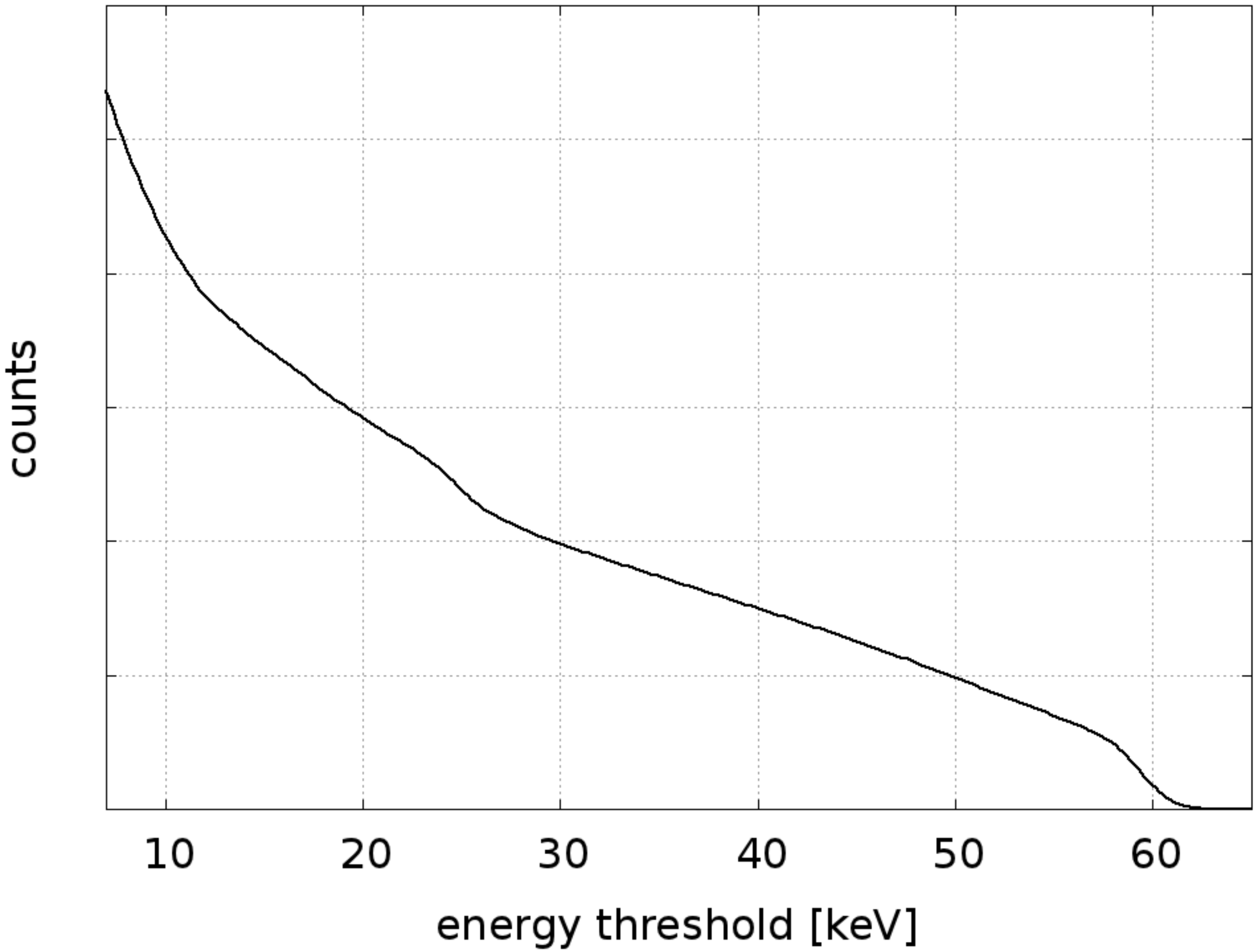




Detector response affected by

- Electronic noise
- Fluorescence photon production
- Charge Sharing
- Compton scattering

Threshold scan for 60 keV photons onto silicon sensor



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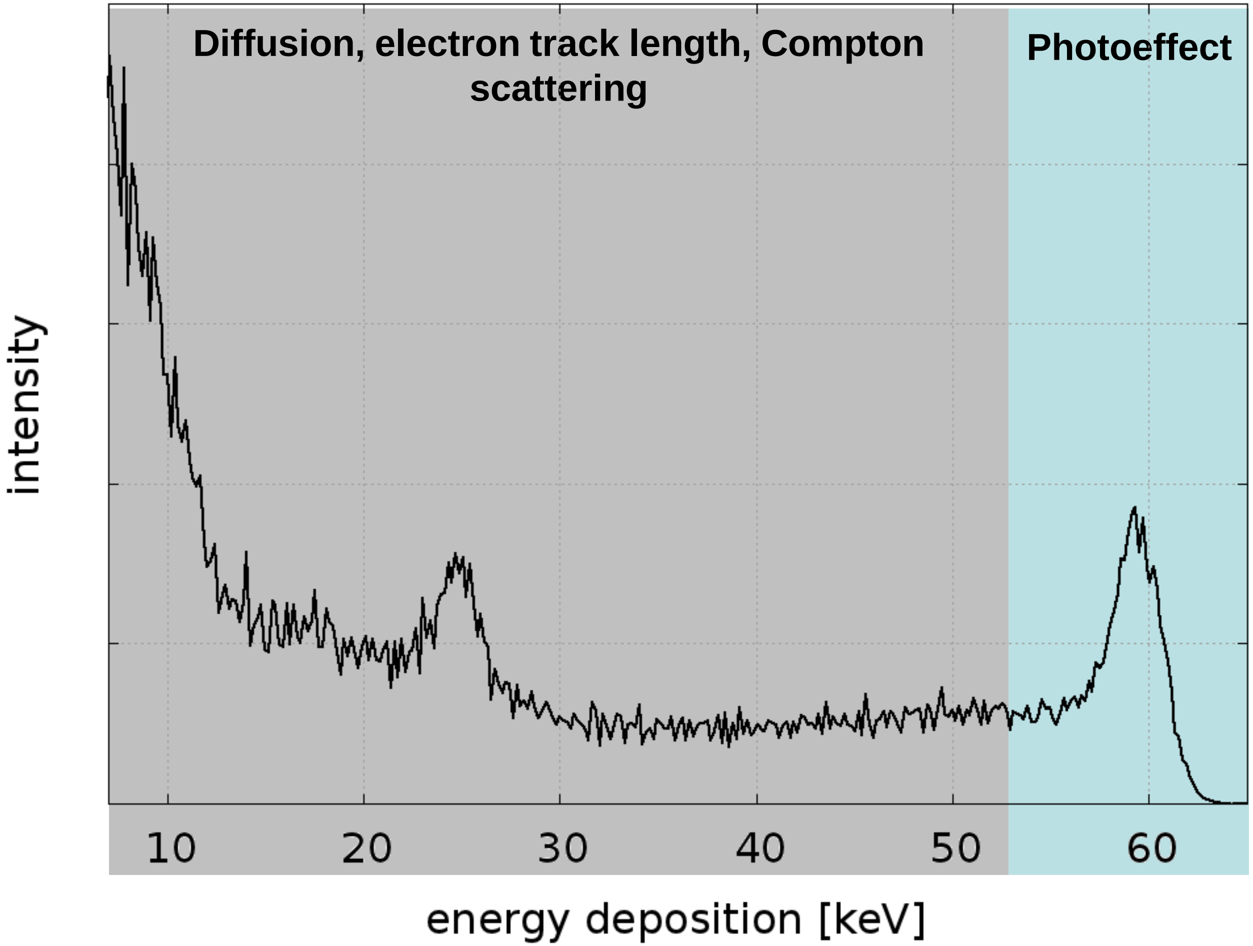
Differentiated threshold-scan = response function



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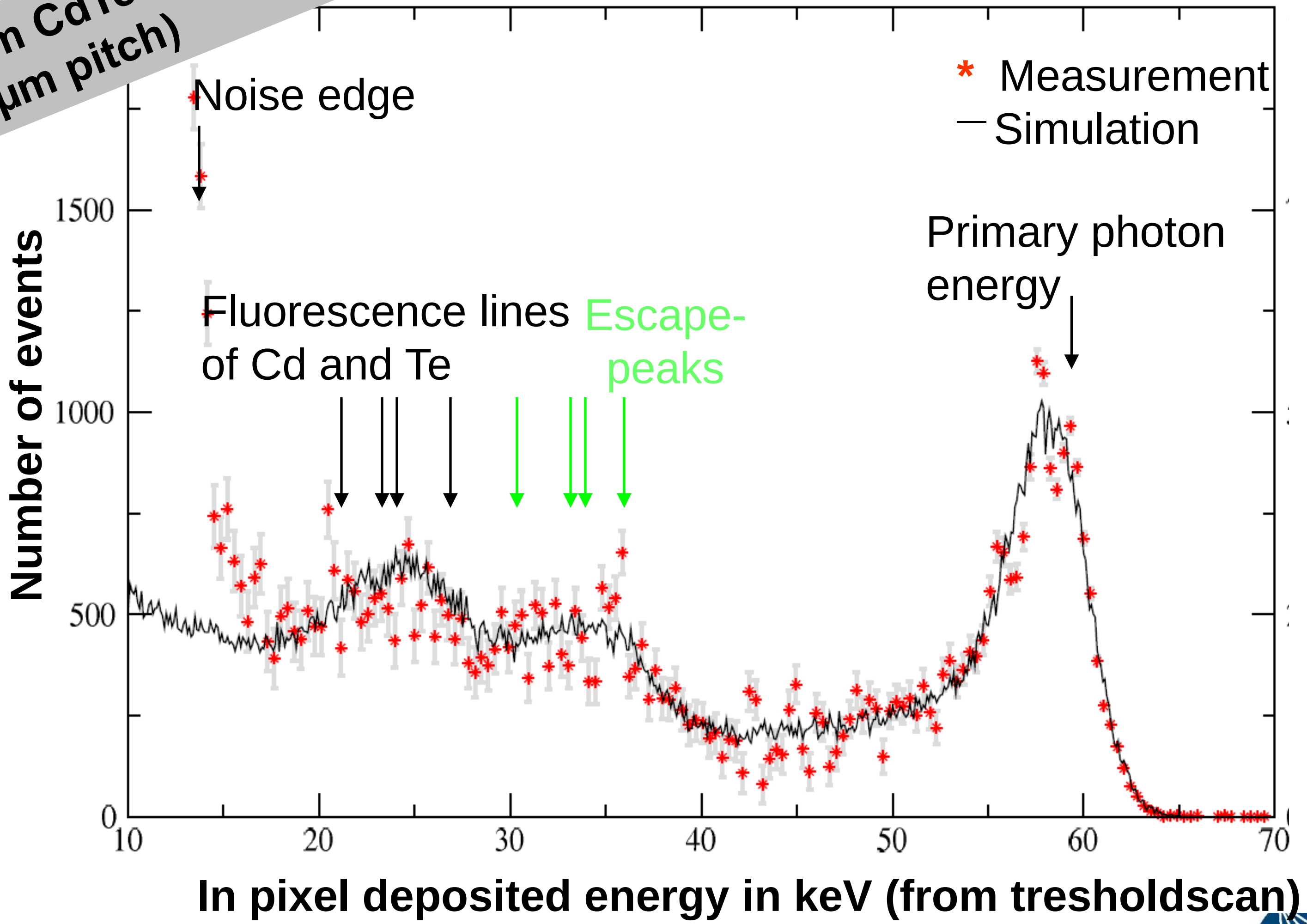
Response of a CdTe Medipix to X-rays

1.6 mm CdTe sensor (220 µm pitch)



Noise edge

Fluorescence lines of Cd and Te

Escape-peaks

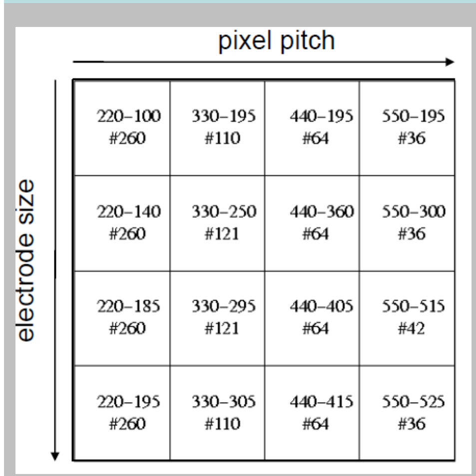
Primary photon energy

Simulation of response has to take many effects into account

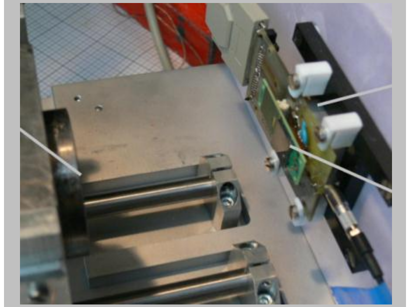
Physics models needed for:

- Elektromagnetic interactions
- Secondary radiation (fluorecences)
- Tracking on µm-scale
- Fano-Noise
- Charge-Carrier respulsion
- Isotropic diffusion during drift
- Limited charge carrier lifetime
- Electron+hole signal contribution
- Electric field in doped CdTe
- Electrode size, pitch (Weighting potential)
- Electronics noise
- Threshold dispersion

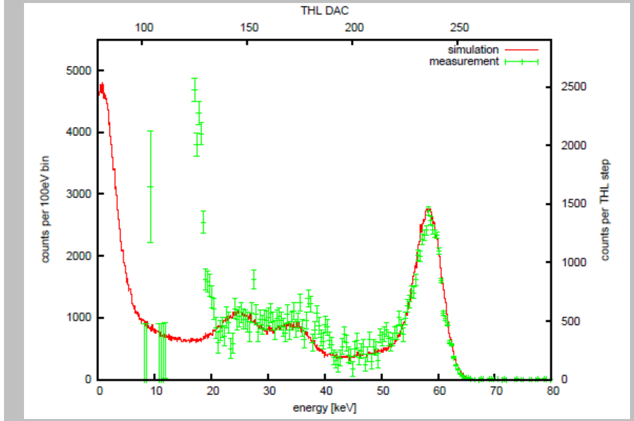
Experiments* / Simulations



220–100 #260	330–195 #110	440–195 #64	550–195 #36
220–140 #260	330–250 #121	440–360 #64	550–300 #36
220–185 #260	330–295 #121	440–405 #64	550–515 #42
220–195 #260	330–305 #110	440–415 #64	550–525 #36

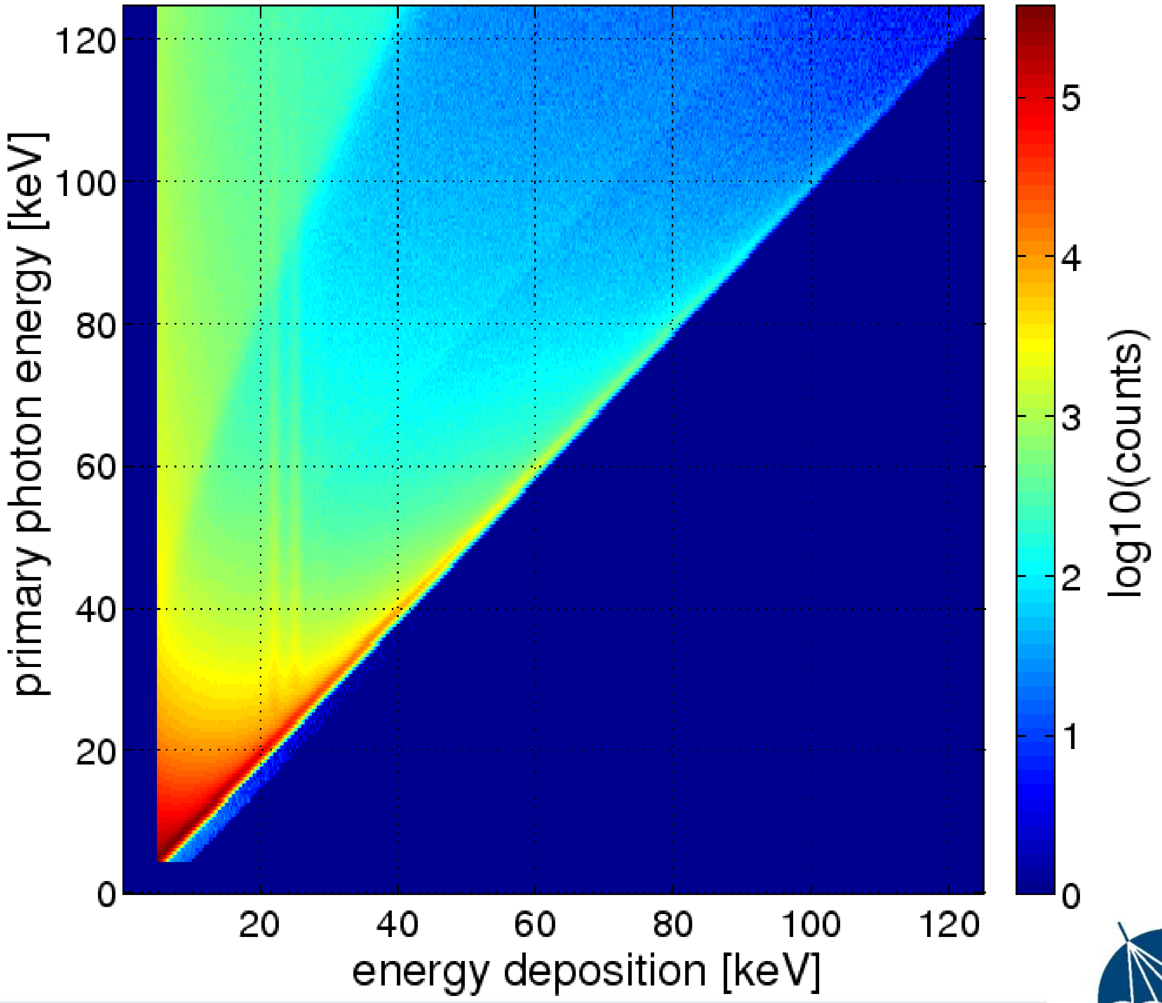


1.6 mm CdTe, 700 V



*) Experiments are performed with a CdTe detector made by the Freiburger Materialforschungszentrum

Response matrix for silicon sensor



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- The Medipix/Timepix detector
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- **Application: Imaging spectroscopy at high flux**
- Application: Material resolved imaging
- Application: Dosimetry

Spectrum of deposited energies is a convolution of response with impinging spectrum

Impinging spectrum

$$M\left(E'_k\right)=\sum_i R\left(E'_k, E_i\right)\cdot T\left(E_i\right)$$

Measurement (Threshold scan)

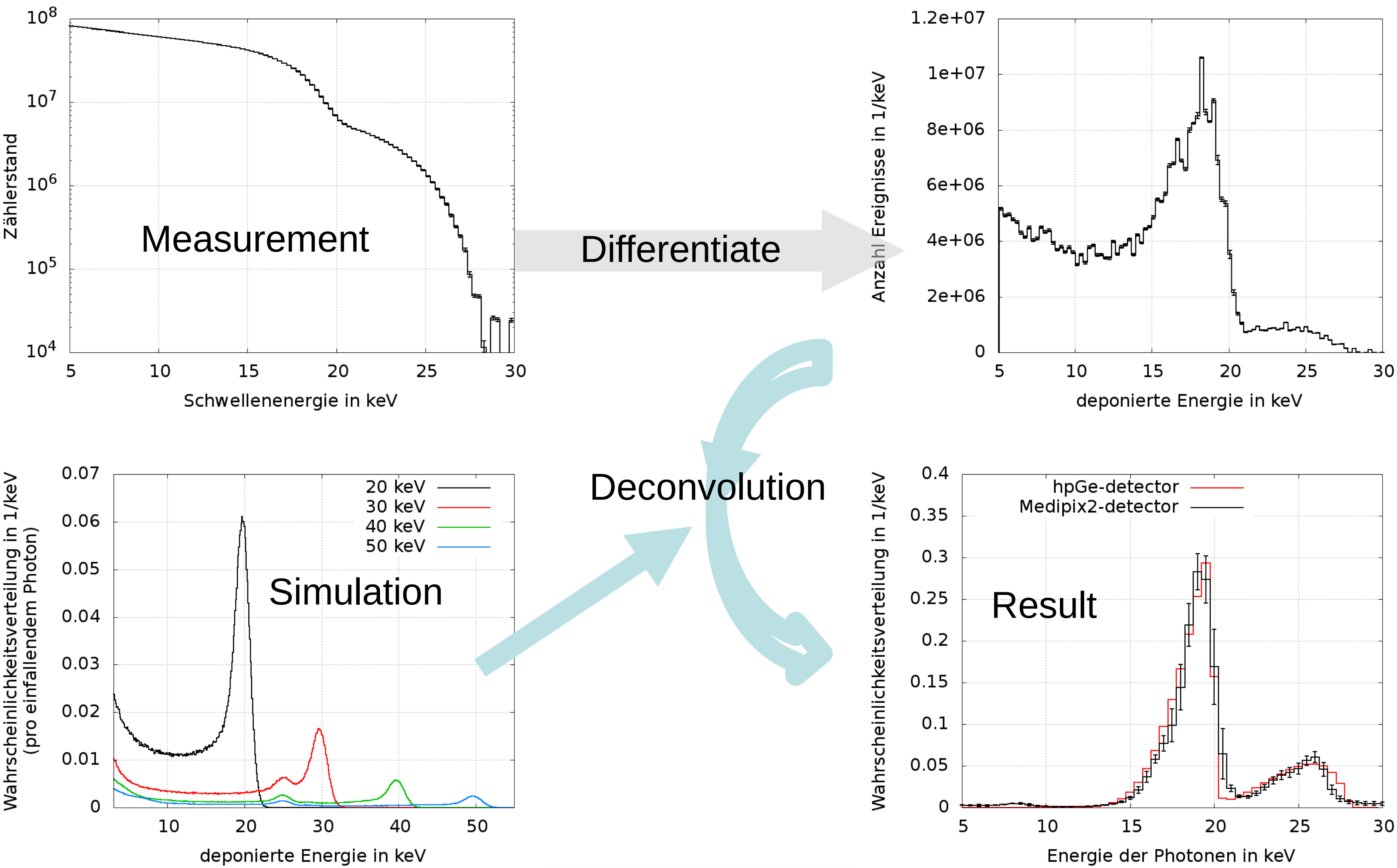
Response-Matrix

Possibilities to get impinging spectrum:

- Pseudo Inverse Matrix
- Spectrum-Stripping
- Bayesian deconvolution

Courtesy: Peter Sievers (Physikalisch Technische Bundesanstalt PTB)

Differentiated threshold scans can be used for deconvolution, BUT ...



Measurement

Differentiate

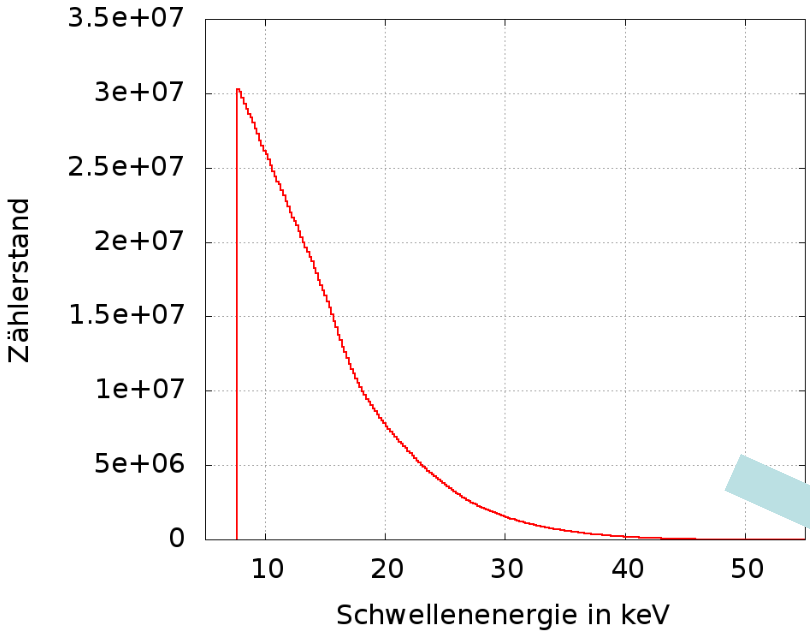
Deconvolution

Simulation

Result

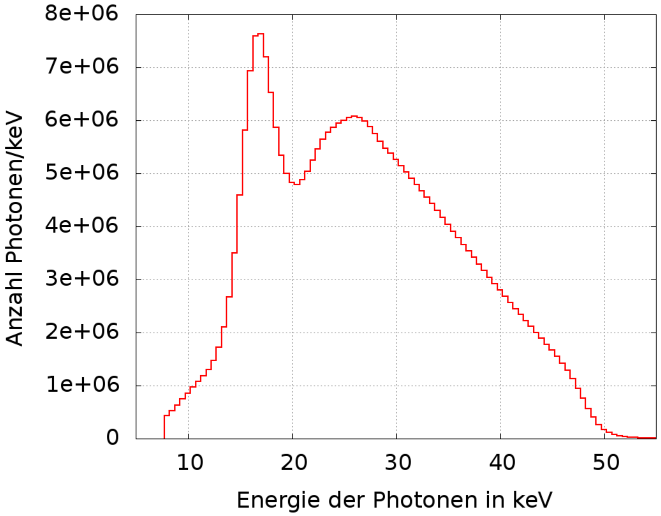
Courtesy: Peter Sievers (Physikalisch Technische Bundesanstalt PTB)

…it is statistically better to use threshold scans directly in Bayesian deconvolution



$$T_i^{n+1} = \frac{1}{\varepsilon_i} T_i^n \sum_k \frac{R_{ki} \cdot M_k}{\sum_j R_{kj} \cdot T_j^n}$$

with $\varepsilon_i = \sum_k R_{ki}$



Courtesy: Peter Sievers (Physikalisch Technische Bundesanstalt PTB)

A difficulty: threshold dispersion among pixels

Measurement (N40 X-ray quality)

Global Kalibration of thresholds

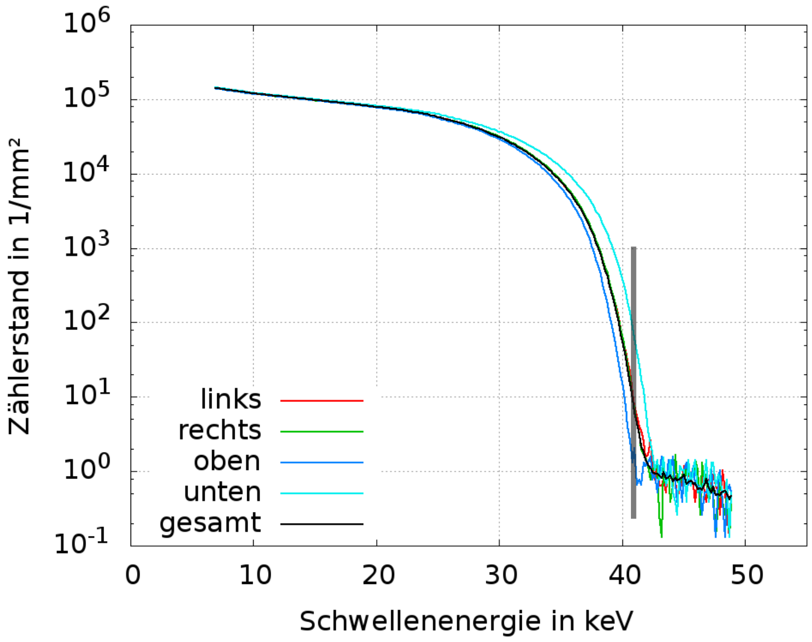
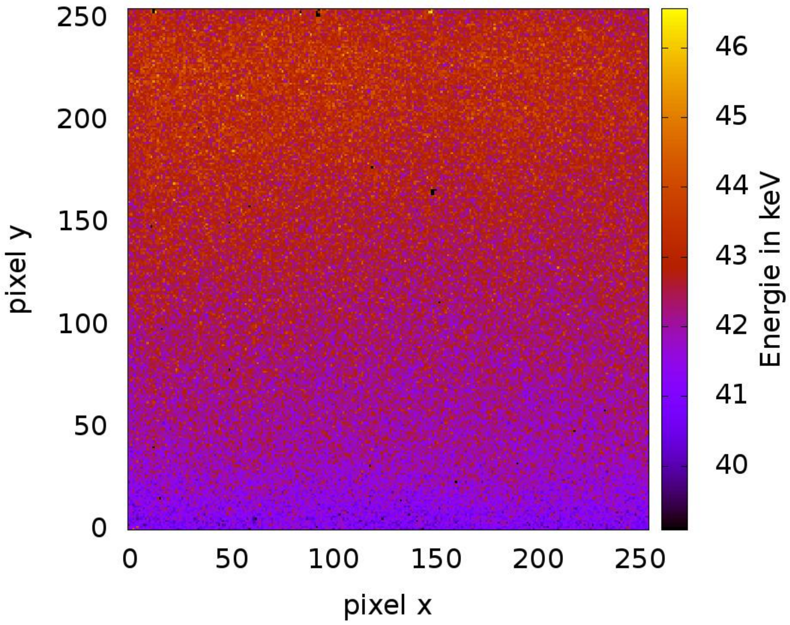


Image at 42,5 keV threshold

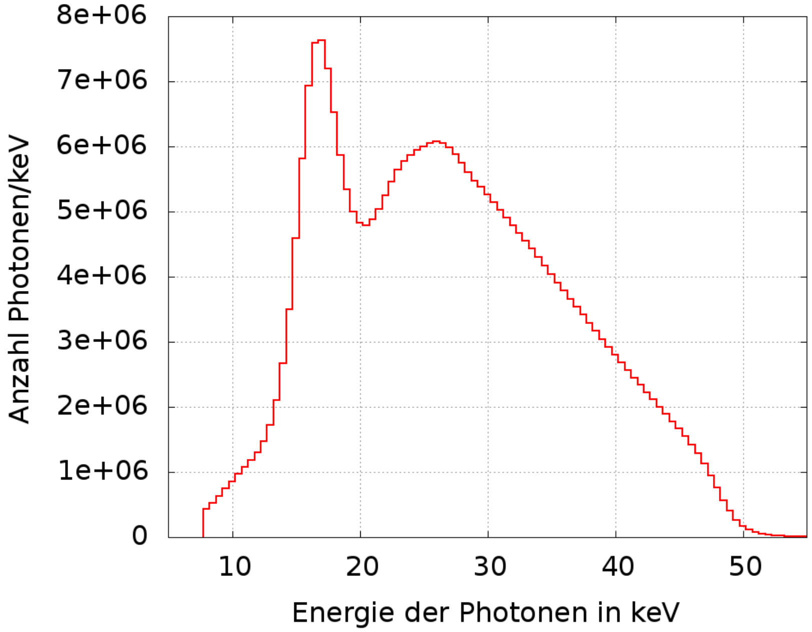


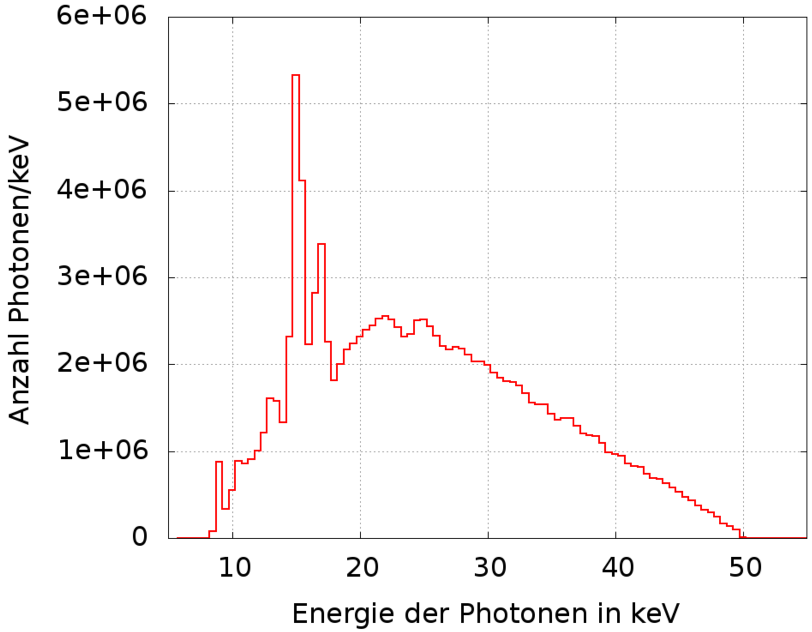
Courtesy: Peter Sievers (Physikalisch Technische Bundesanstalt PTB)

Improvement by pixelwise threshold calibration

Global calibration
(64k pixels and 1 calibration)

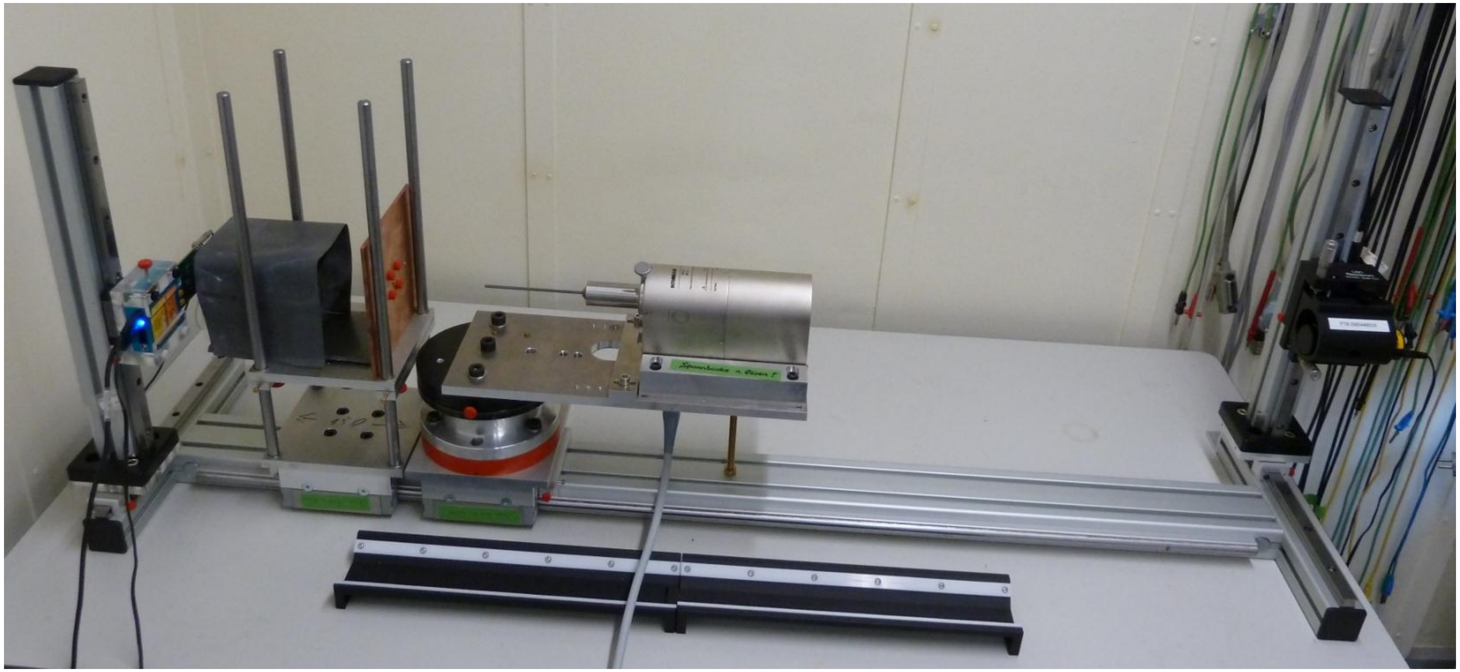
Pixelwise calibration
(64k calibrations)





Courtesy: Peter Sievers (Physikalisch Technische Bundesanstalt PTB)

Spectral imaging with a brachytherapy X-ray tube



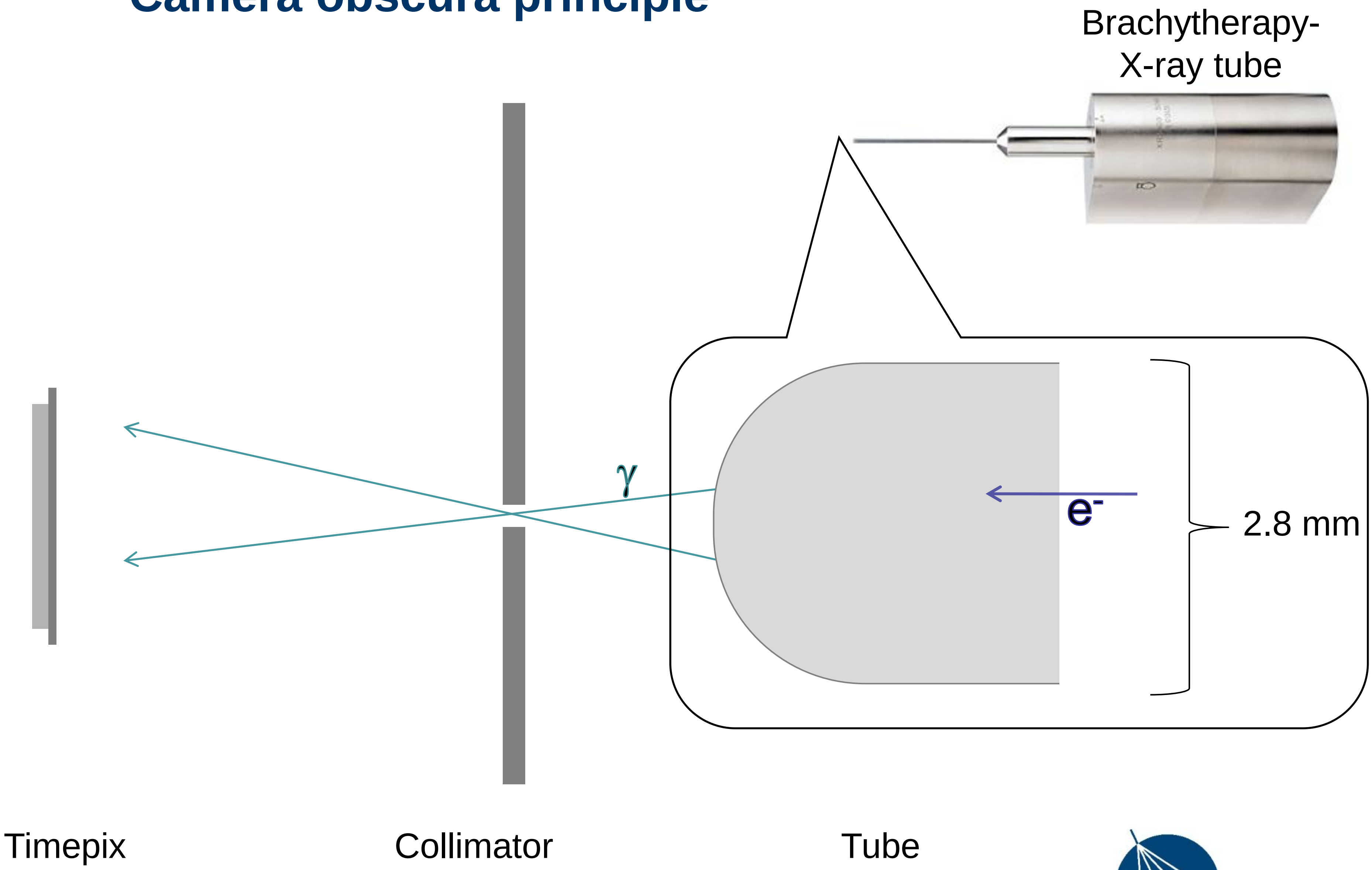
- Tube-collimator: 10 cm
- Collimator-detector: 30 cm
- Hole in collimator: 50 µm
- Collimator thickness: 1 mm

=> Magnification: 2.99

- Acc. voltage: 50 kV
- Current: 40 µA
- Measurement time:
  per threshold: 60 s
  overall: 4,4 h

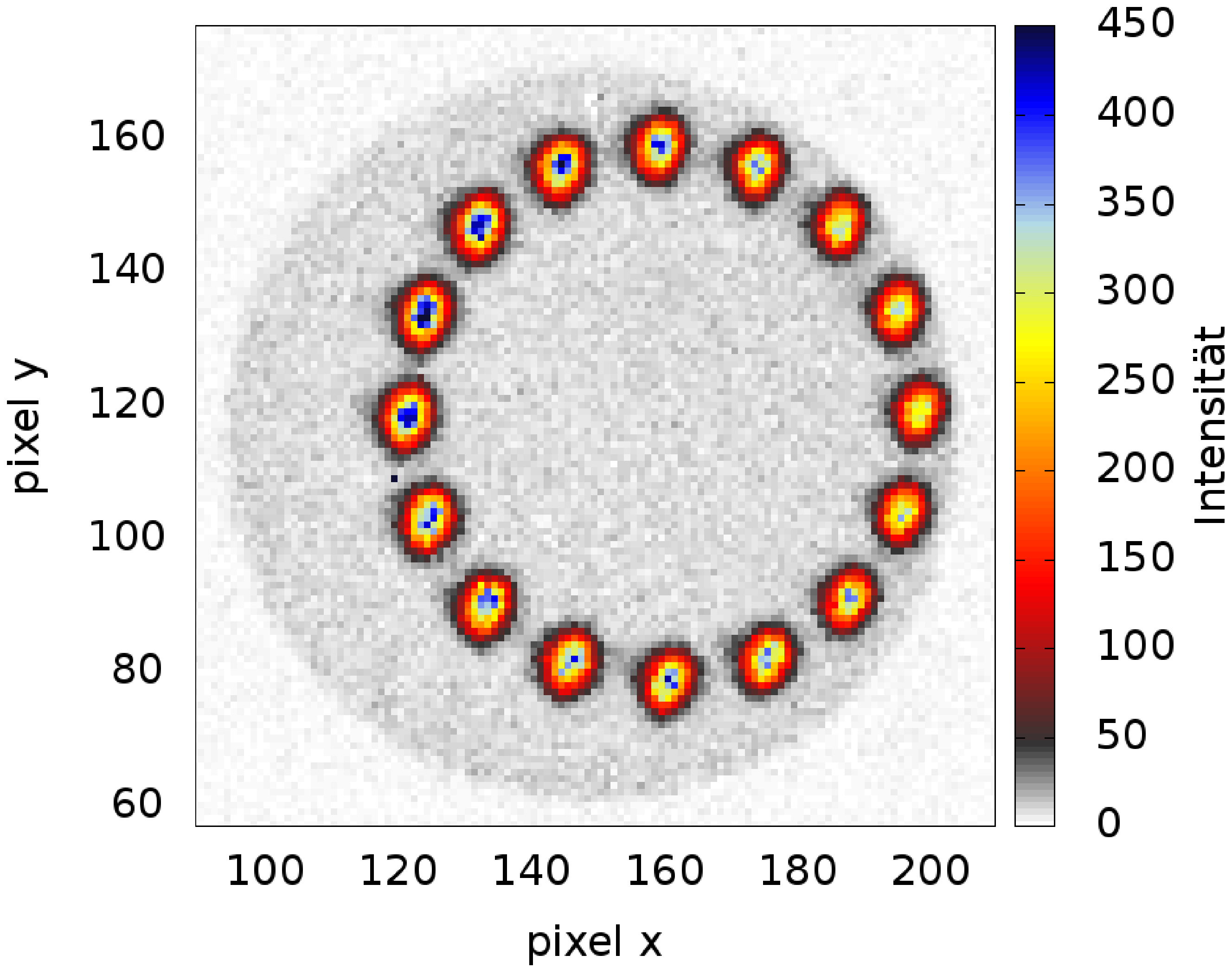
Courtesy: Peter Sievers (Physikalisch Technische Bundesanstalt PTB)

Camera obscura principle



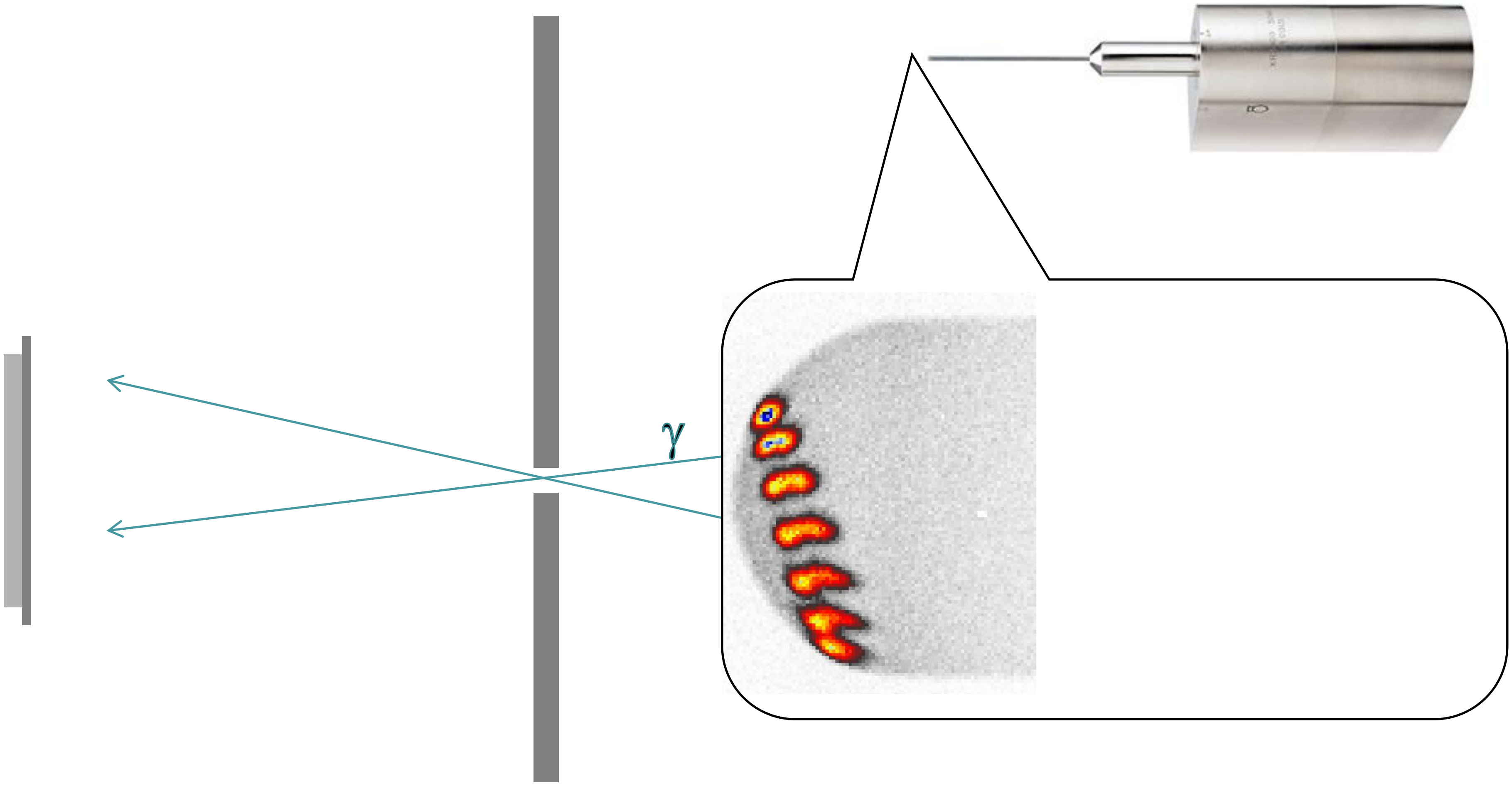
Courtesy: Peter Sievers (Physikalisch Technische Bundesanstalt PTB)

The electron beam moves around



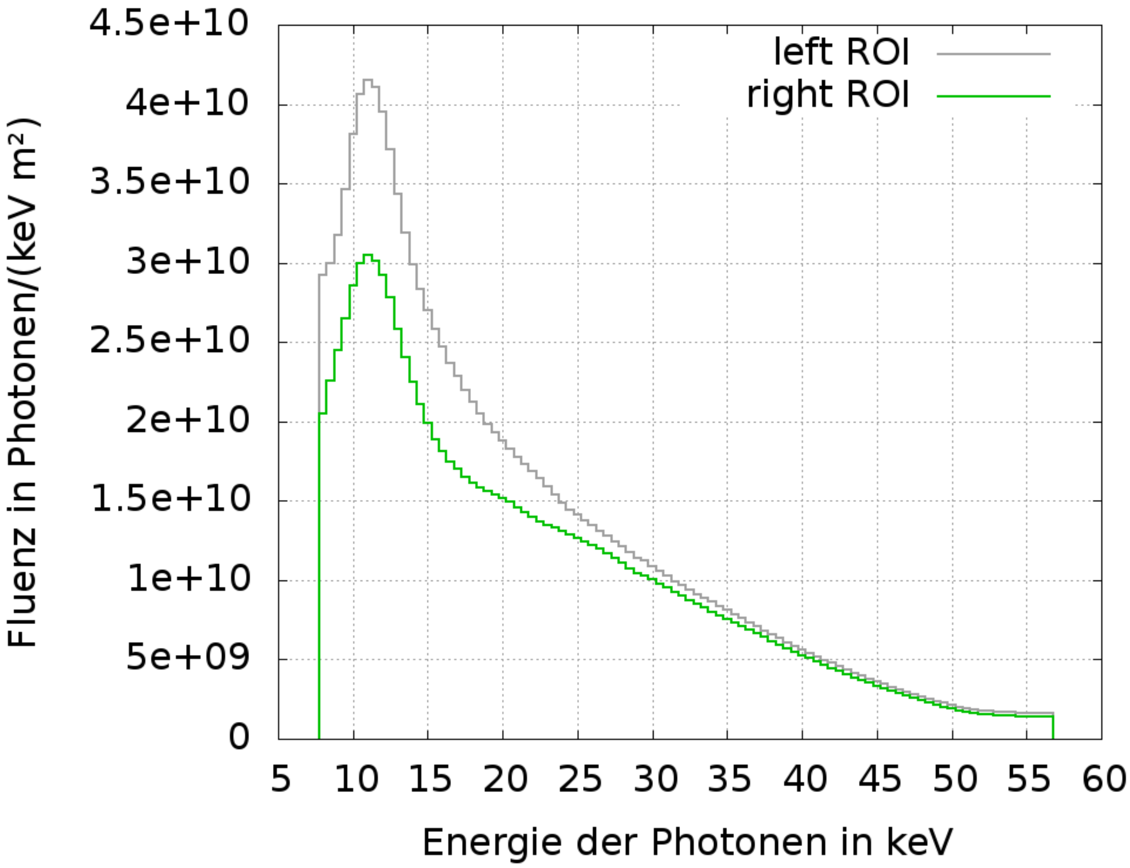
Courtesy: Peter Sievers (Physikalisch Technische Bundesanstalt PTB)

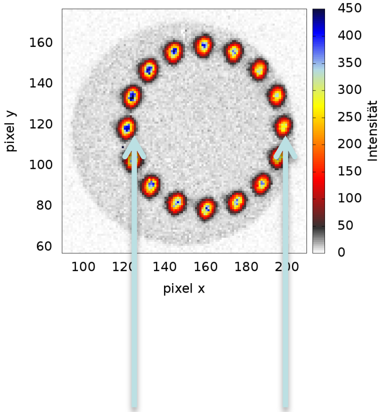
Look from the side: Misalignment of the target …



Courtesy: Peter Sievers (Physikalisch Technische Bundesanstalt PTB)

… causes differences in the spectrum





left ROI right ROI

Courtesy: Peter Sievers (Physikalisch Technische Bundesanstalt PTB)

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Principle of Material Reconstruction

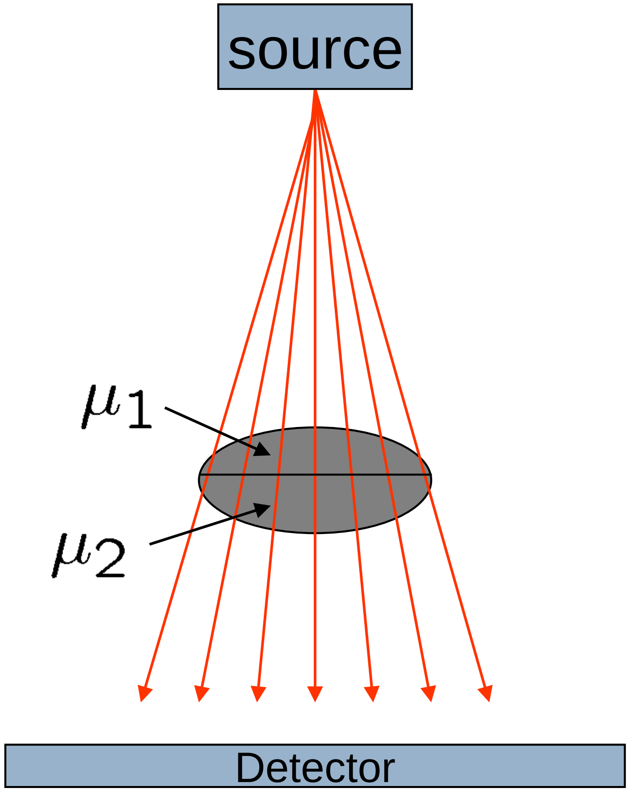
X-Ray transmission through a compound object

$$I(E) = I_0(E)\,\mathrm{e}^{-\sum_j \boxed{\mu'_j(E)} m_j}$$

μ': mass attenuation coefficient

m_j: areal density

j: index for basis materials



A method of material reconstruction without explicit spectrum reconstruction

Number of counts in energy deposition interval

Sum over energy depositions in interval

Sum over primary energies in spectrum

Sum over materials

$$\overbrace{I_{0_i} \cdot \mathrm{e}^{-\sum_j \mu'_{ij} m_j}}^{\text{transmitted spectrum}}$$

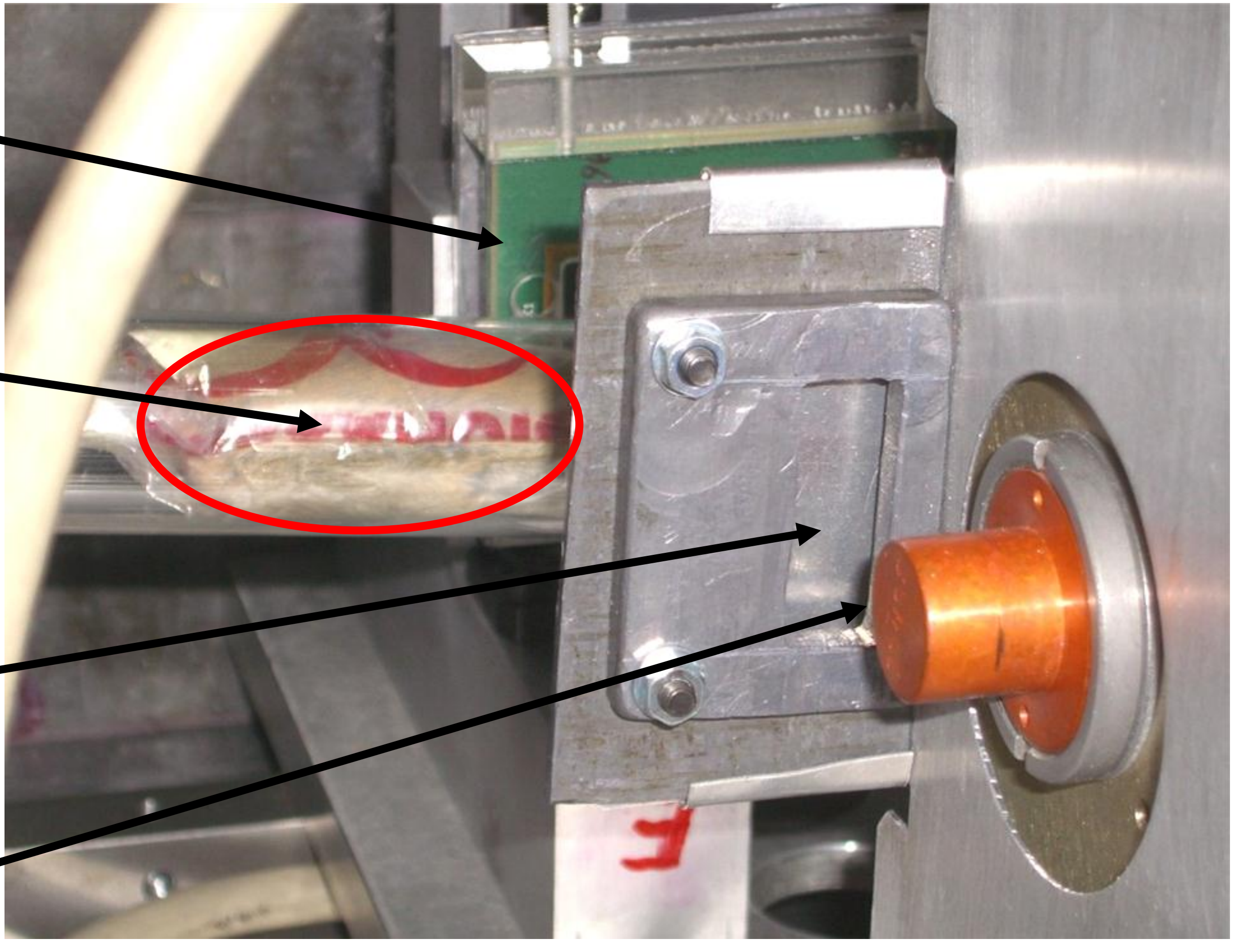
Vary to get best agreement of M_b and measurement

Measurement details

- Tested with the MARS scanner together with the University of Canterbury, Christchurch, New Zealand
- Medipix2 MXR, 300 µm Si sensor
- Energy calibration with ^{241}Am, Gd- and Mo K-edges
- Threshold equalisation mask generated with flatfield at THL approx. 35keV and not at the noise floor

- Source: 0.1mA @75kV tungsten anode X-Ray tube
- Acquisition at 4 THL values: 8, 20, 33 and 45keV with 2, 3, 4 and 5s duration respectively
- 3 detector positions and 180 projections (360 degrees)

Experimental setup



Medipix2 MXR

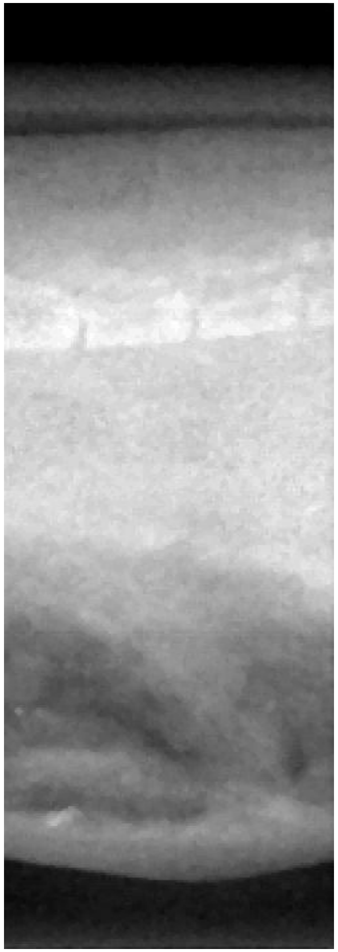
Mouse inside Perspex tube

0.5mm Al Filter

X-Ray source

Material Reconstruction: Projections

Photon counting image

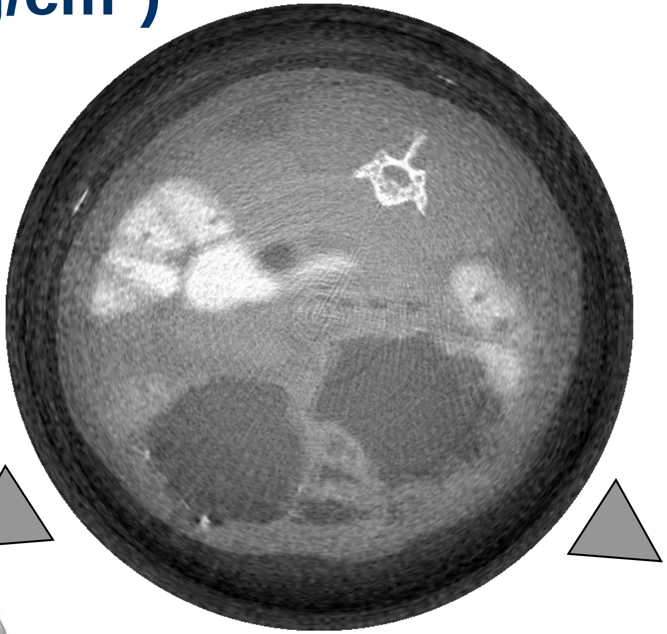


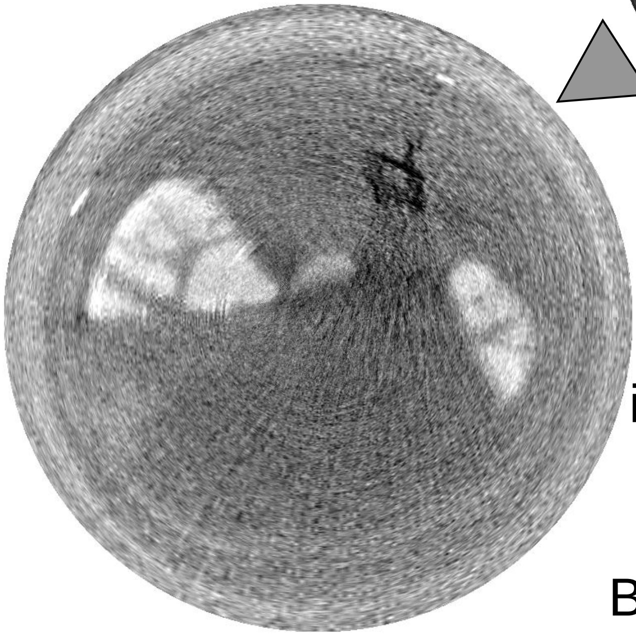
Non-iodine (water) image

Iodine image

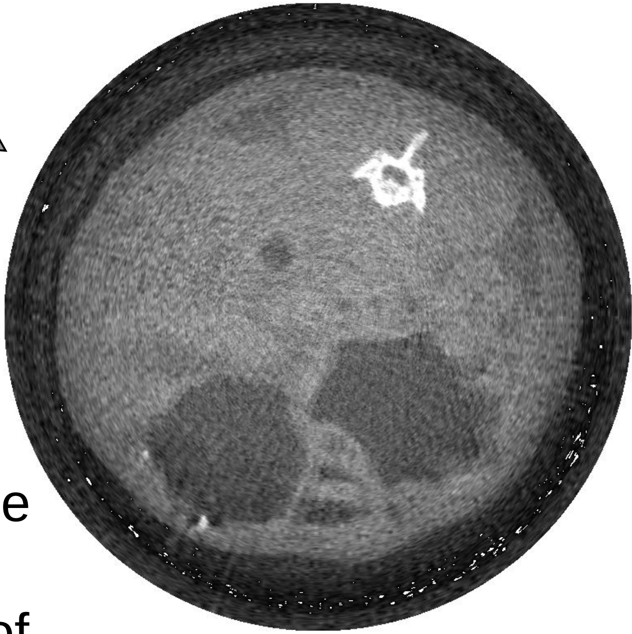
Material Reconstruction in CT: Brightness = density of base materials (g/cm³)

Photon counting at
8 keV threshold





iodine



water /
non iodine

Brightness = areal density of materials

Agenda

- The Medipix/Timepix detector
- Energy response
- Application: Imaging spectroscopy at high flux
- Application: Material resolved imaging
- **Application: Dosimetry**

The personal dose equivalents Hp(10) and Hp(0.07)

Definition of the personal dose equivalents

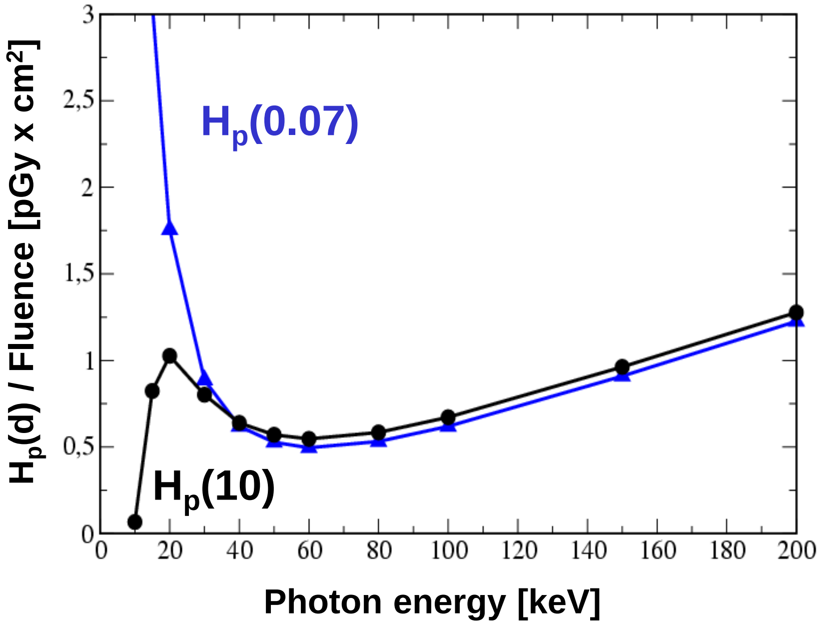
- Dose:

$$H = \lim_{\Delta V \to 0} \frac{\Delta E}{\rho \cdot \Delta V}$$

- $H_p(d)$: dose in soft tissue in a certain depth d [mm] of the ICRU slab phantom
(30 x 30 x 15 cm^3 PMMA)

- To be measured with
an active personal dosemeter:
  - $H_p(10)$: Deep dose
  - $H_p(0.07)$: Surface dose

Photon energy dependence of personal dose equivalents [1]



Example: $H_p(0.07)$ = 1 nSv
- 10 keV: 140 photons/cm^2
- 60 keV: 2000 photons/cm^2
- 200 keV: 800 photons/cm^2

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[1] Data compiled from ICRU-Report 57, 1998

Table 4 – Radiation characteristics of $H_p(10)$ dosemeters for X and gamma radiation

Line	Characteristic under test or influence quantity	Minimum rated range of influence quantity	Limit of variation of instrument parameter or relative response for whole rated range	Sub-clause
1	Variation of the response due to the non-linearity of the response itself	Four orders of magnitude for personal dose equivalent	±15 % [a)] dose equivalent meter	9.3
2	Statistical fluctuation, v: dose equivalent $H_p(10)$	$H < 1$ µSv 1 µSv $\leq H <$ 11 µSv $H \geq$ 11 µSv	15 % (16 – H/(1 µSv)) % 5 %	9.3.5
3	Statistical fluctuation, v: dose equivalent rate $\dot{H}_p(10)$	$\dot{H} <$ 10 µSv h^{-1} 10 µSv h^{-1} $\leq \dot{H} <$60 µSv h^{-1} $\dot{H} \geq$ 60 µSv h^{-1}	20 % (21 – $\dot{H}$/(10 µSv h^{-1})) % 15 %	9.3.5
4	Radiation energy and angle of incidence	80 keV to 1,5 MeV or 20 keV to 150 keV and 0° to 60° from reference direction under consideration	–29 % to +67 % [b)]	9.5.2
5	Gamma radiation energy and angle of incidence for use in the vicinity of nuclear reactor installations	1,5 MeV to 6,6 MeV and 0˚ to 60° from reference direction under consideration	–50 % to +100 % [b)]	9.5.2
6	As in line 4 and 5 but new reference direction opposite to that one used	See line 4 and 5, if no statement concerning wrong orientation is given by the manufacturer	See line 4 and 5, if no statement concerning wrong orientation is given by the manufacturer	7.7
7	Dose rate	0,5 µSv h^{-1} to 1 Sv h^{-1} [c)]	±20 % [a) d)]	9.4
8	Overload	10 times maximum range, but for dose rate not more than 10 Sv h^{-1}	Indication to be off-scale on the high side or dose equivalent(rate) meter to indicate overload (for 10 min)	9.9
9	Response time for dose equivalent rate indication and alarm functions	$\dot{H}_p(10) \geq$ 100 µSv h^{-1} and 10 s maximum waiting time	±20 % and any delay of more than 1 s in the alarm responding shall not result in the receipt of a dose in excess of 10 µSv	9.10.2
10	Effects of radiation not intended to be measured	—	Response to be stated by the manufacturer	6.8
11	Response due to natural background radiation	—	To be stated by the manufacturer	9.4.2

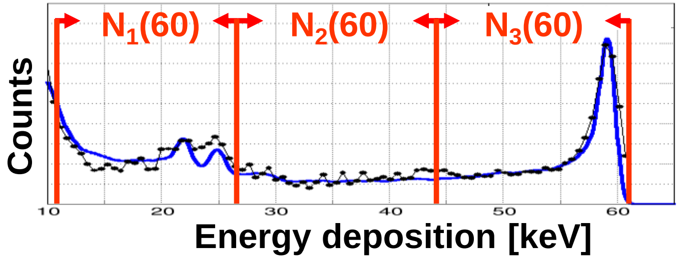
Solution: estimation of the dose equivalent with the measured number of counts in energy intervals

Monochromatic irradiation with E_j

$$H_p(E_j) = \alpha_i \cdot N_i(E_j) \qquad \forall i$$

$$H_p(E_j) = \frac{1}{i_{\max}} \sum_{i=1}^{i_{\max}} \alpha_i \cdot N_i(E_j)$$

Measure/simulate the number of counts in energy deposition intervals



Calibrate with $j_{\max}$ different photon energies

$$\begin{pmatrix} H_p(E_1) \\ \ldots \\ H_p(E_{j_{\max}}) \end{pmatrix} = \begin{pmatrix} N_1(E_1) & \ldots & N_{i_{\max}}(E_1) \\ \ldots & \ldots & \ldots \\ N_1(E_{j_{\max}}) & \ldots & N_{i_{\max}}(E_{j_{\max}}) \end{pmatrix} \cdot \begin{pmatrix} \alpha_1 \\ \ldots \\ \alpha_{i_{\max}} \end{pmatrix}$$

Known doses

Number of counts in each energy deposition bin

Unknown calibration factors from counts to dose

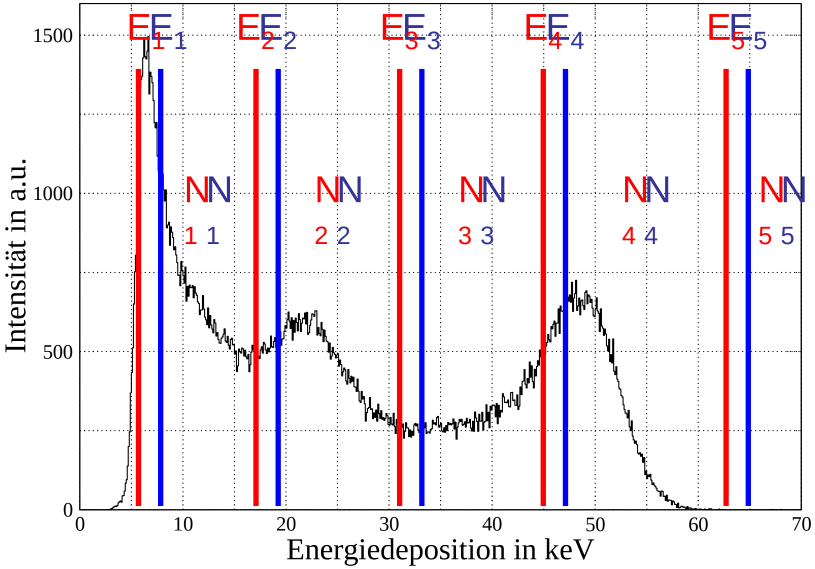
Apply pseudoinverse of the „counts matrix“

$$\vec{\alpha} = \left[\left(N^T N \right)^{-1} \cdot N^T \right] \cdot \vec{H}_p$$

Best estimation (maximum-likelihood) of the calibration factors

Calculation of conversion factors and energy bins

Collection of monoenergetic responses



Coupled set of equations

$$\begin{pmatrix} D_1 \\ D_2 \\ \vdots \\ D_n \end{pmatrix} = \begin{pmatrix} N_{11} & \cdots & N_{1i_{max}} \\ \vdots & \ddots & \vdots \\ N_{n1} & \cdots & N_{ni_{max}} \end{pmatrix} \cdot \begin{pmatrix} k_1 \\ k_2 \\ \vdots \\ k_{i_{max}} \end{pmatrix}$$

Apply pseudoinverse matrix

$$\vec{k} = \left(\hat{N}^T \hat{N}\right)^{-1} \hat{N}^T \vec{D}$$

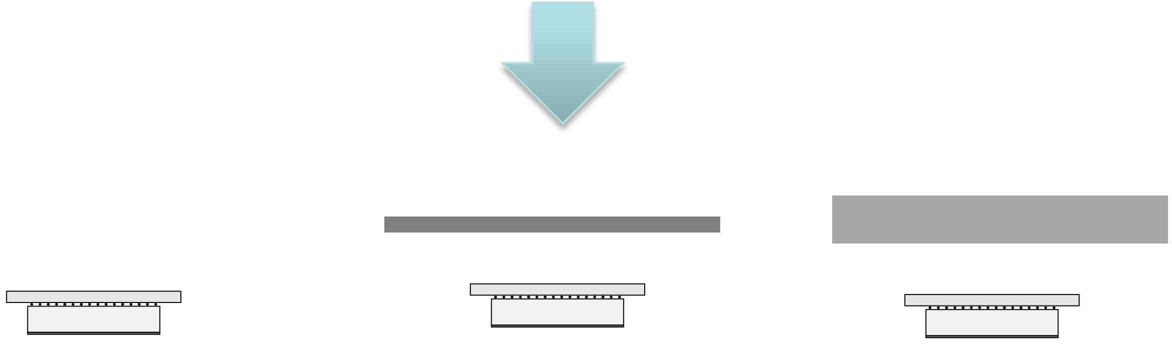
$$D_{rekon} = \sum_{i=1}^{i_{max}} k_i \cdot N_i$$

Assess quality of dose reconstruction on test spectra

Iterate

Extension of energy range beyond 200 keV only possible with filters above pixel detector,

Reason: energy deposition spectra look the same for higher energies due to dominance of Compton scattering in silicon



Uncovered

Filter 1

Filter 2

low energies

medium energies

high energies

$$H_p(10) = \sum_{i=1}^{16} a_i^{nofilter} \cdot N_i^{nofilter} + \sum_{i=1}^{16} a_i^{filter1} \cdot N_i^{filter1} + \sum_{i=1}^{16} a_i^{filter2} \cdot N_i^{filter2}$$

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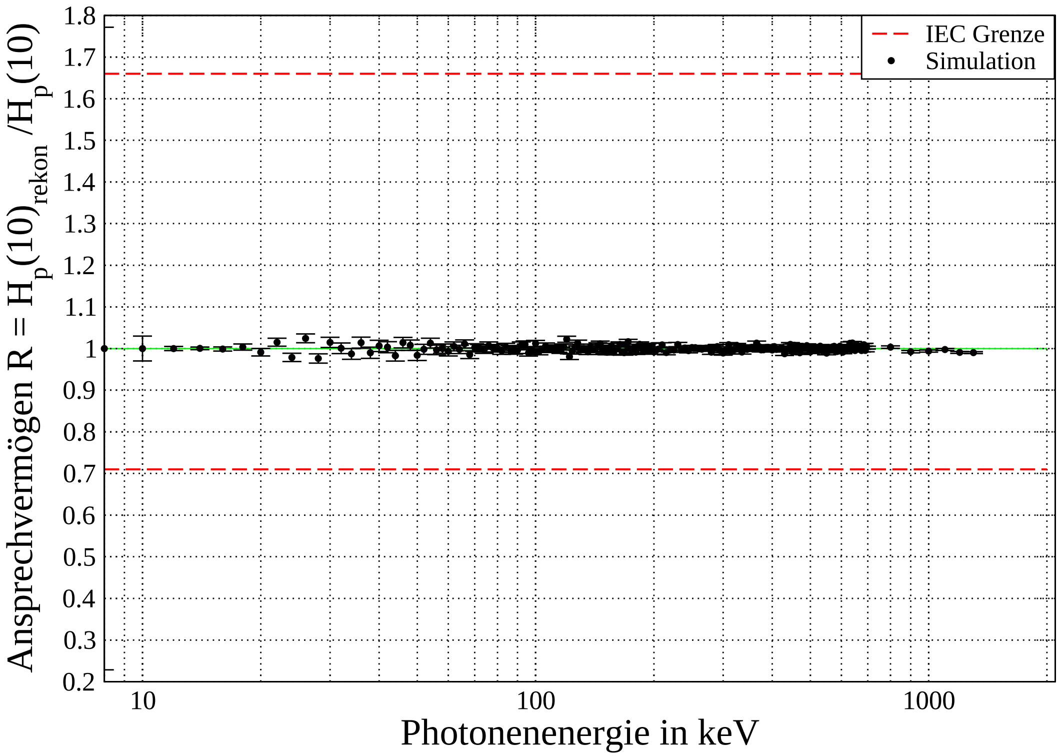
FOR ASTROPARTICLE
PHYSICS

Response to perpendicular irradiation

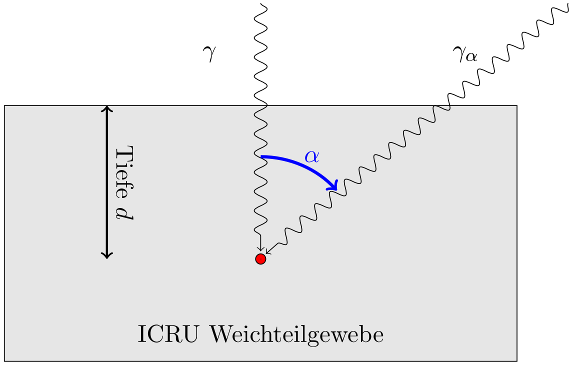
3 detectors with 2 filters and 3 x 16 energy bins



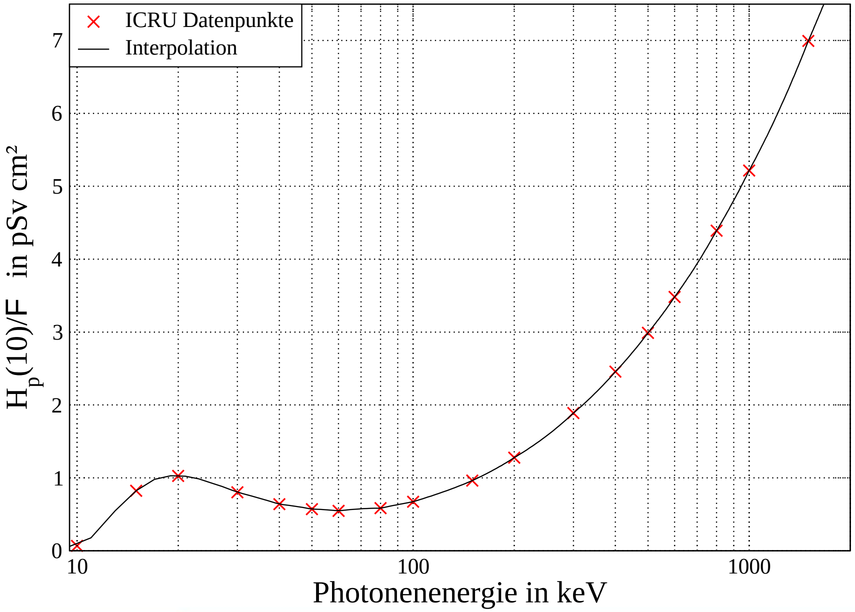
IEC limit (+67%)

IEC limit (-29%)

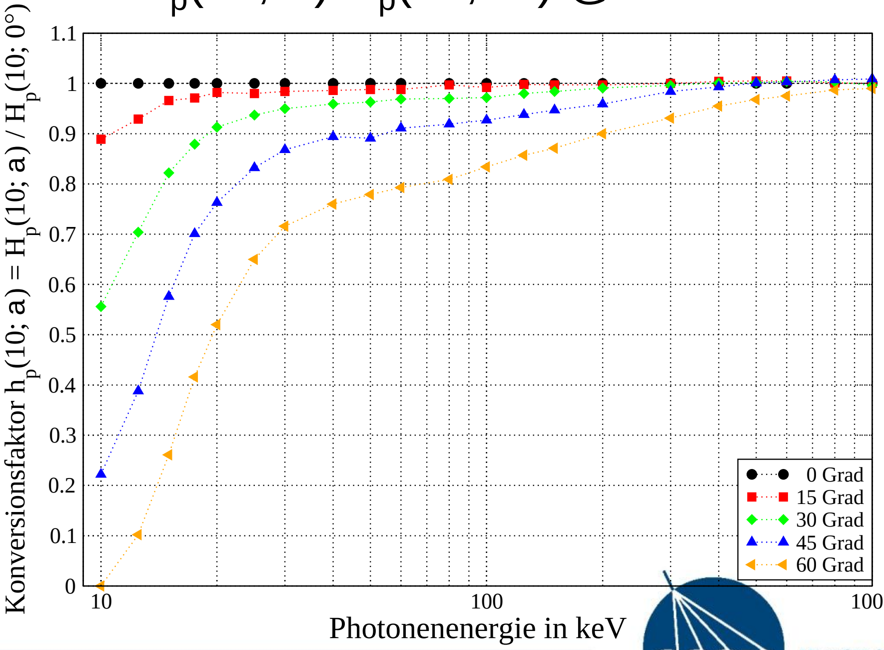
Angular dependence of deep dose $H_p(10; \alpha)$



$H_p(10,0°)$/Fluence in pSv*cm²



$H_p(10, \alpha)/H_p(10, 0°)$ @fixed fluence



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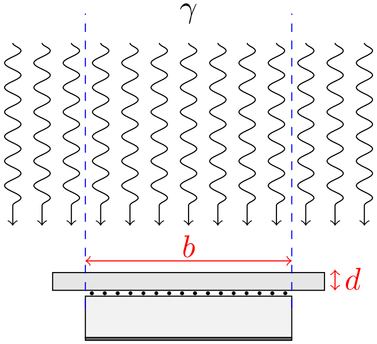
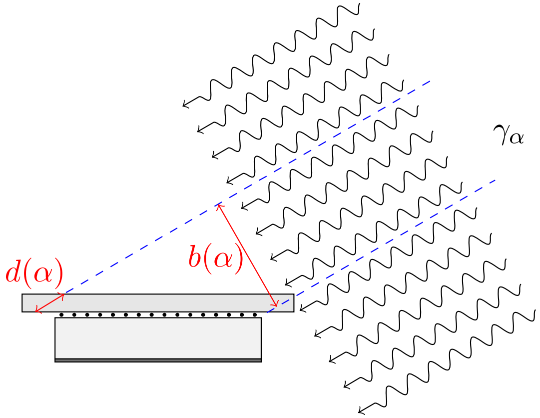
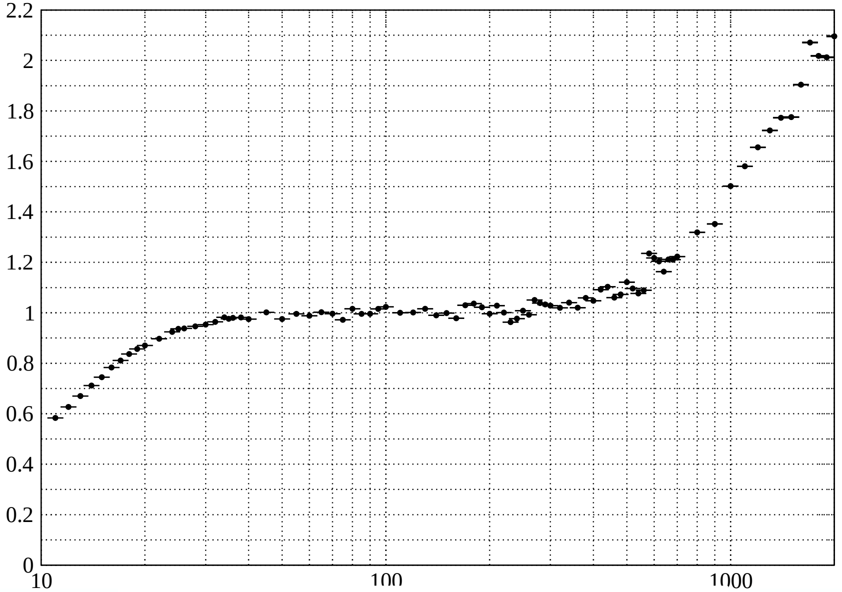
Under angle of incidence the sensor effectively becomes thicker and smaller





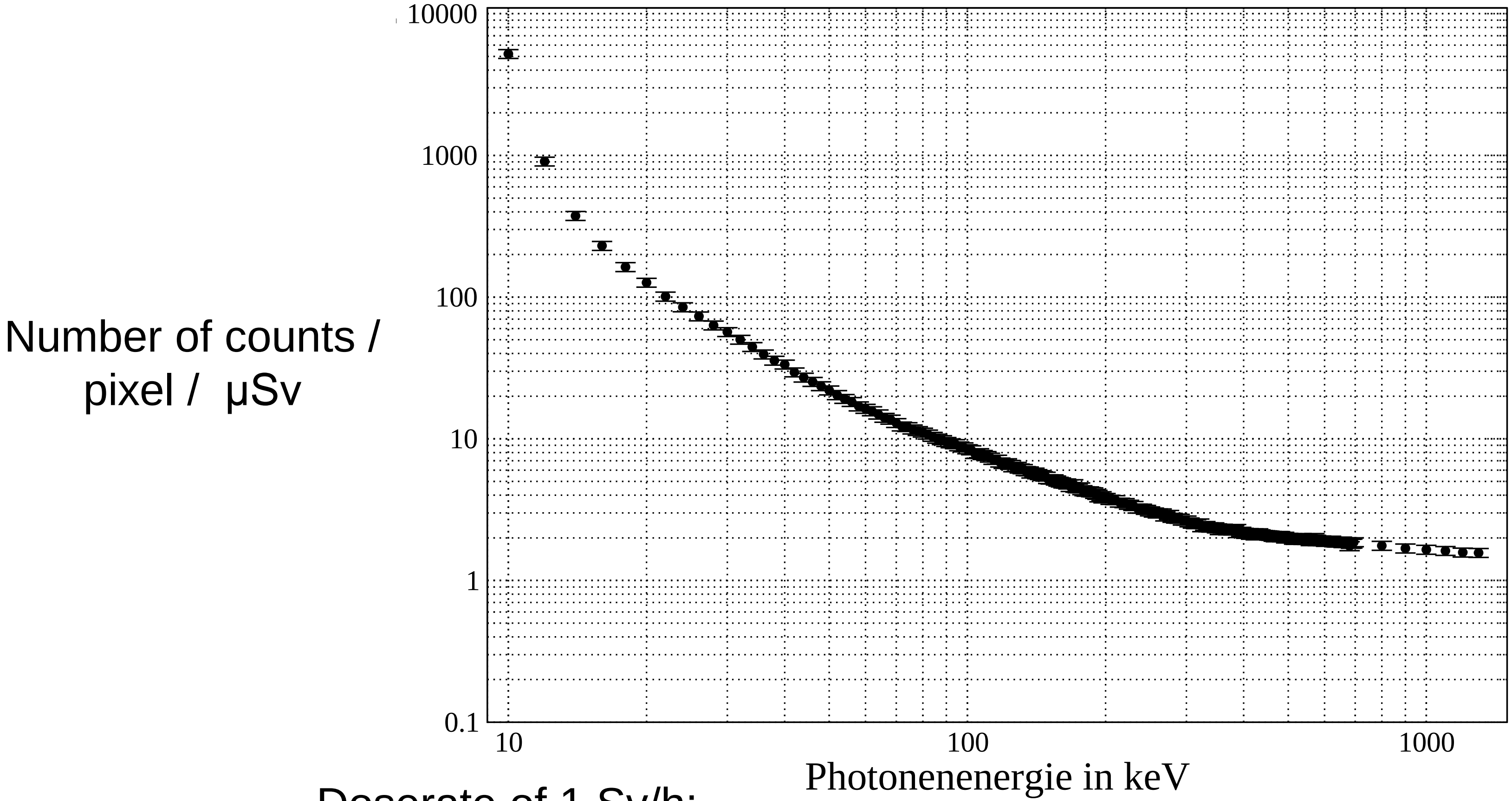
$$b(\alpha) = b \cdot \cos(\alpha)$$
$$d(\alpha) = d / \cos(\alpha)$$

Number of counts at 60 degrees / Number of counts at 0 degrees



Photon energy in keV

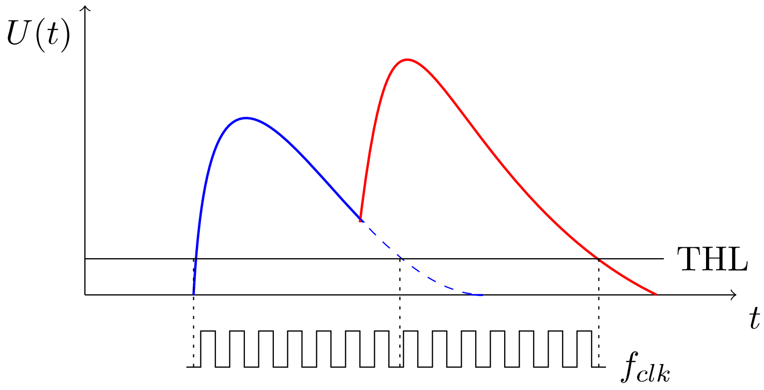
Dose reconstruction with 220 micron pixel at high dose rates



Doserate of 1 Sv/h:

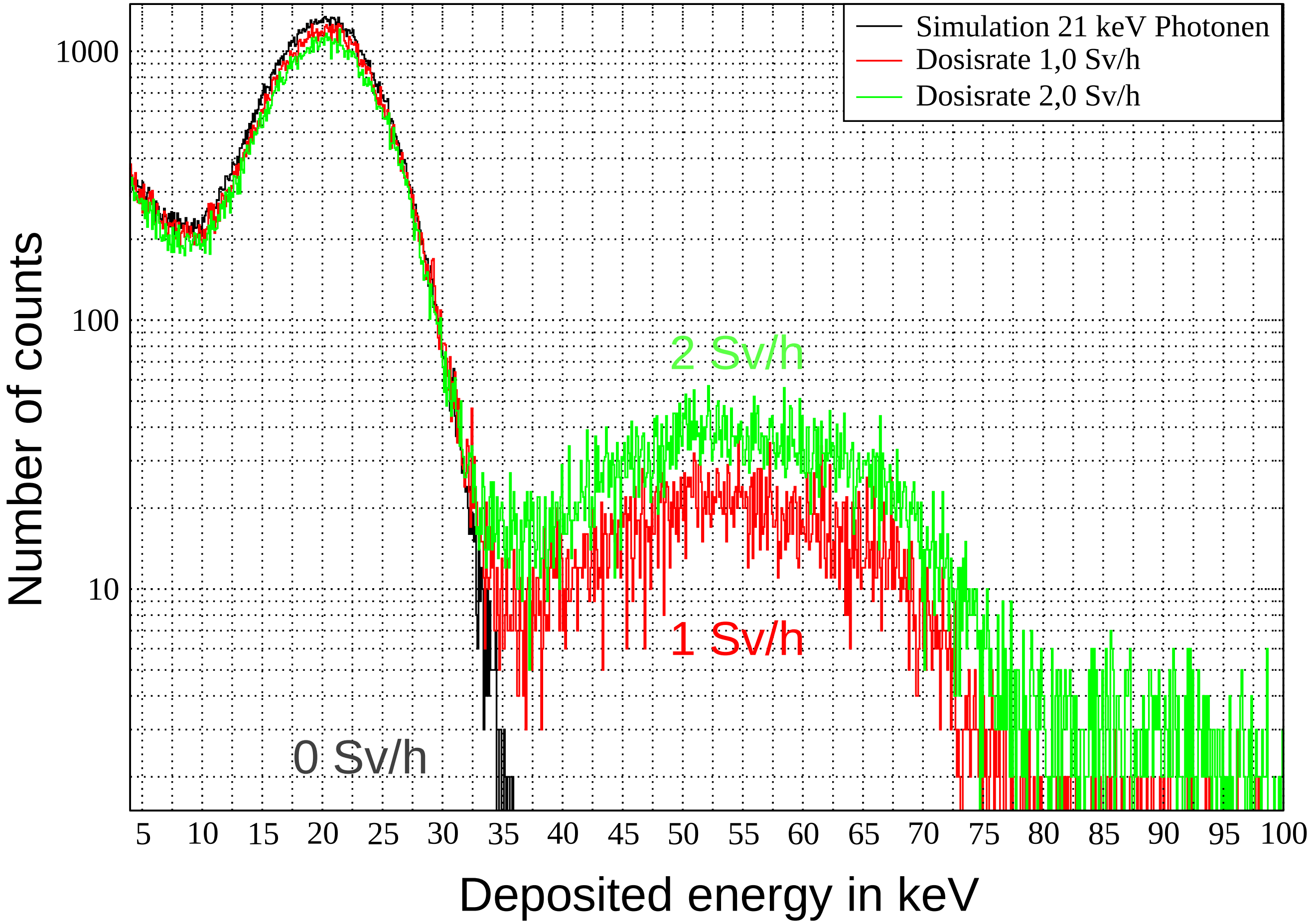
- 111 kHz @14 keV -> Δt_{mean} = 9 µs
- ToT-duration@14 keV = 1.4 µs
- -> significant pile up expected

Pile-up in preamplifier (analog side of electronics)



- Two events above threshold are recorded as one event but with higher energy
- Two events originally below threshold are detected by coincidence

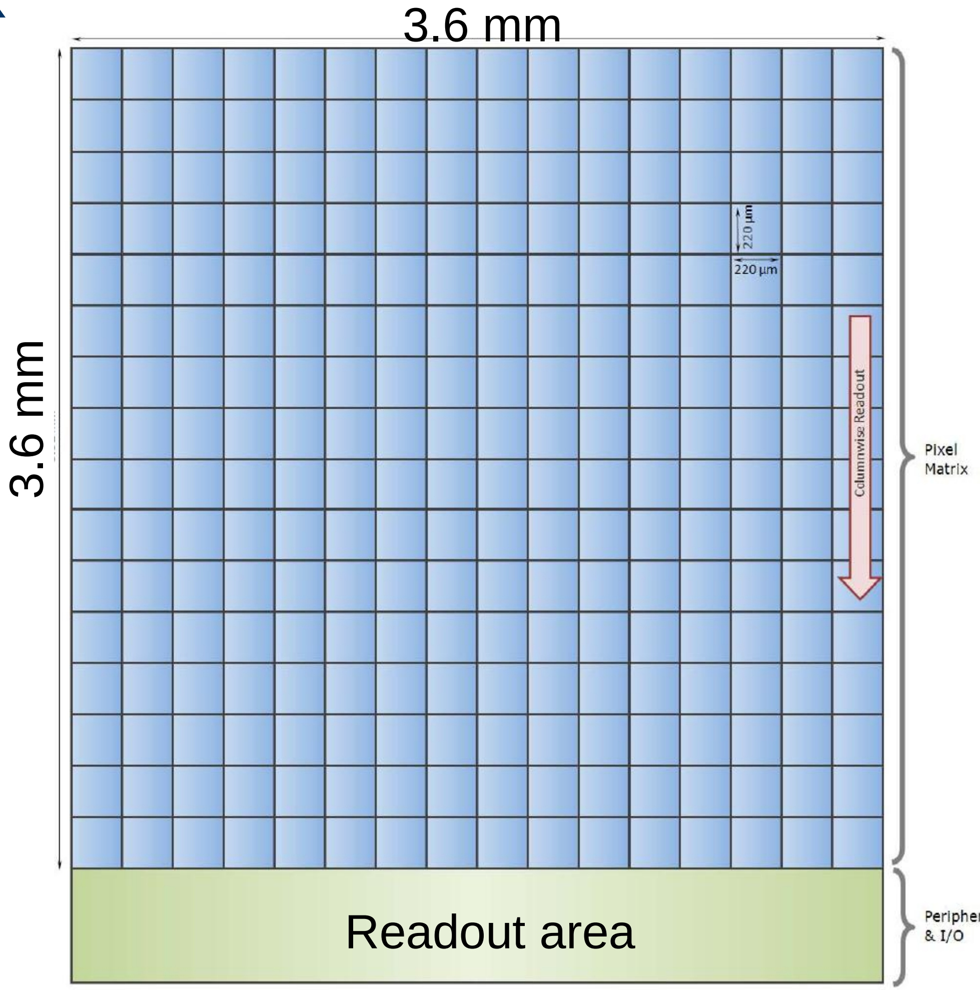
How does pile-up influence the measured spectrum ?



New pixel detector Dosepix

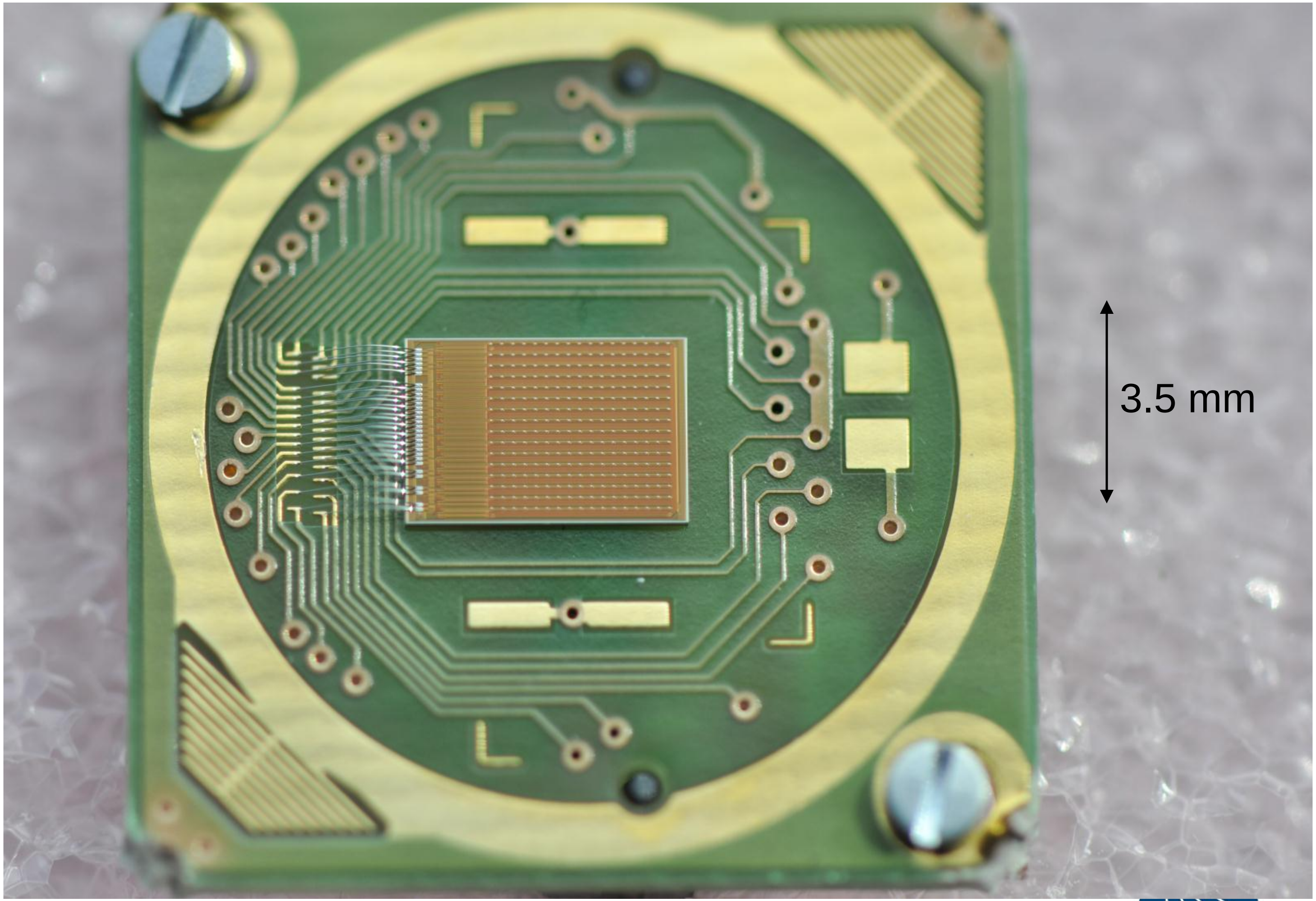
Disadvantages Timepix for dosimetry

- Non-linear ToT(E)
- Feedback from digital to analog pixel electronics
- Dynamic range of test pulsers too small
- Sensitive to temperature changes
- Power consumption too high
- Pixel suffer from charge sharing (too small)
- More functionality needed in pixel
- Dead time during readout



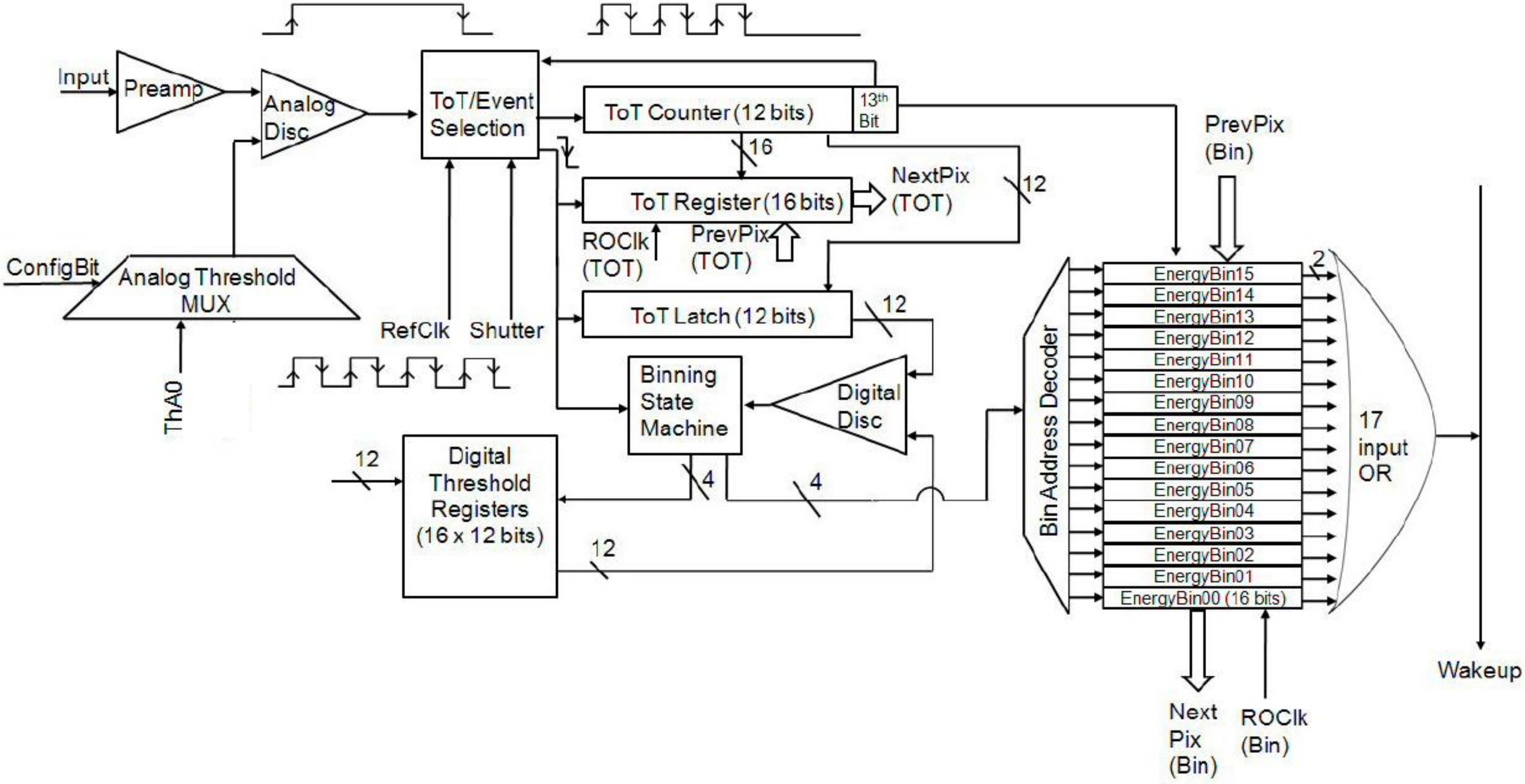
New detector:
16 x 16 Pixel with 220 µm x 220 µm area

May 2011: the first sample without sensor



3.5 mm

Pixel electronics (CERN, IBA, Uni Erlangen)



Patent: M. Campbell (CERN), W. Wong (CERN), X. Llopart-Cudie (CERN), R. Ballabriga-Sune (CERN), T. Michel, G. Anton, M. Böhnel, : „Radiation Monitoring Device", EP 07114122.0 (2007)

Hybrid photon counting pixel detectors

- **... have their roots in high energy physics (e.g. ATLAS, CMS, ALICE,...)**
- **... can have intelligent pixel cell electronics**
- **... are used in combination with Si, CdTe, GaAs sensor layers**
- **... can measure energy and time of arrival**
- **... can have high position resolution**
- **... can process events in high flux individually**
- **... allow spectrometry in high flux fields**
- **... allow identification of particle types by track signature**