Energy dependent imaging properties of the Medipix2 X-ray-detector

Vertex 2007
Lake Placid
September 28, 2007

Thilo Michel

Institute of Physics
University of Erlangen-Nuremberg, Germany

Outline

The Medipix2 detector

- Medipix2: a detector for x-ray imaging
- The working principle
- Processes in the sensor layer

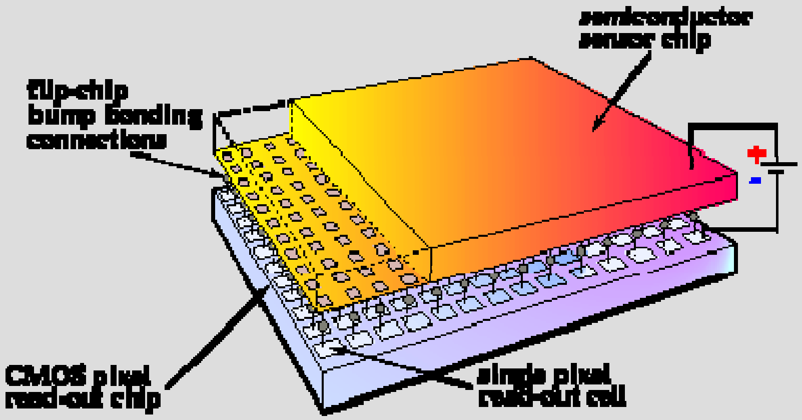
Imaging properties

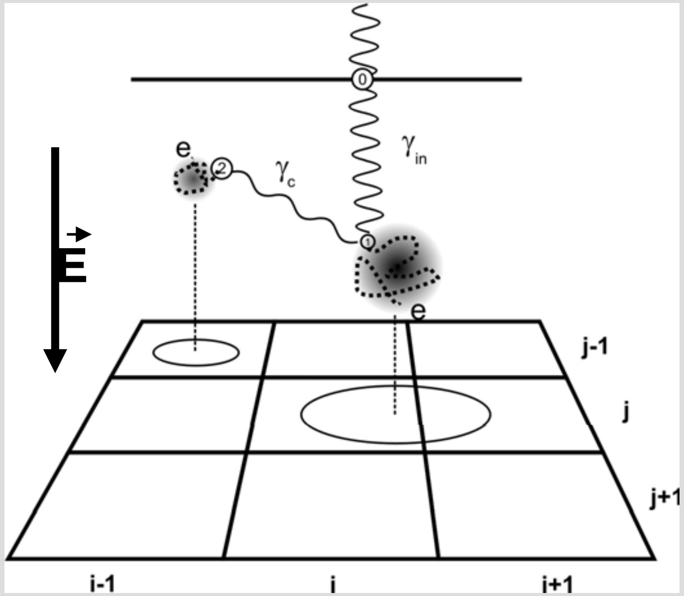
- Spatial resolution
- Detective-Quantum-Efficiency
- Energy response function

Using the energy resolution

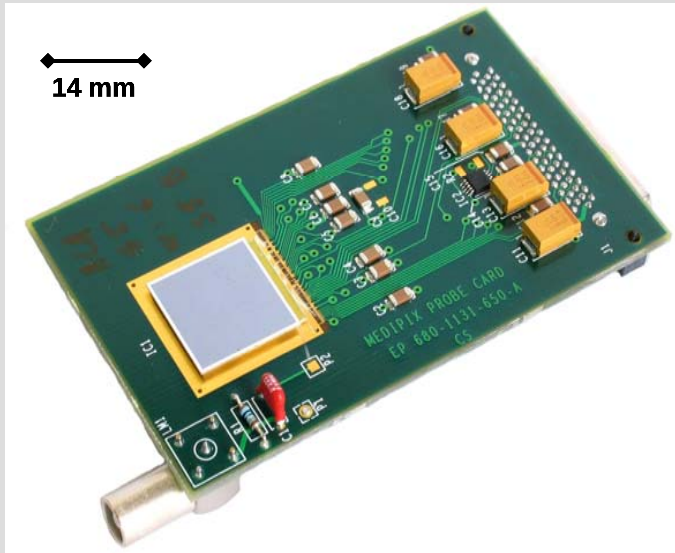
- Reconstruction of incident x-ray spectra
- Material decomposition
- Outlook: Medipix3

The Medipix2-Detector: a direct-converting, hybrid photon counting pixel detector



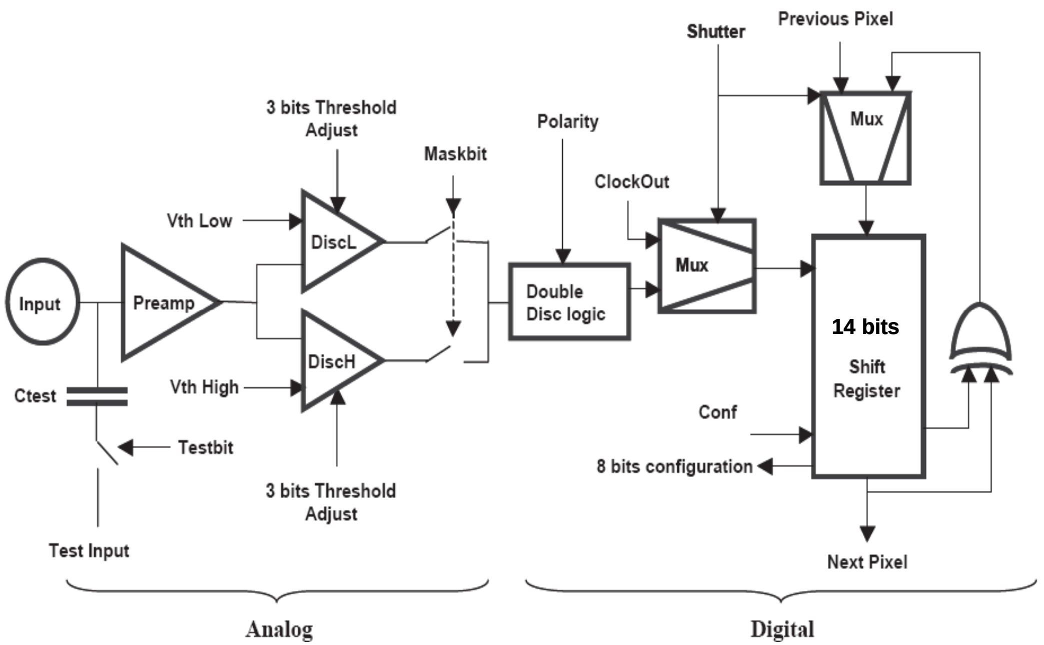


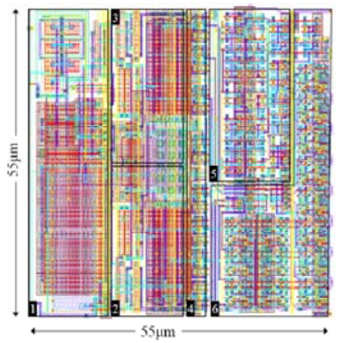
- **ASIC/Sensor:**
  - Development: International Collaboration with seat at CERN
  - Bump-bonded with Pb/ Sn
  - 65536 pixels in 256 columns and 256 rows
  - Pixel pitch: 55 µm
  - Size of the matrix: 14 mm
  - 0.25 µm CMOS
- **Sensor:**
  - Materials: Si, GaAs, CdTe
  - Bias voltage: 150 V (300 µm Si)
  - 2x2-version



Medipix2: a photon counting ASIC

Pixel electronics





Working principle

- **Idea:**
  - –Counting of each photon with energy deposition above threshold or in energy window
  - –Counting is noiseless
- **Analog part:**
  - –Charge sensitive pre-amplifier
  - –2 discriminators per pixel (window mode, single threshold mode)
- **Digital part:**
  - –1 counter
  - –Max. 800 million photons per image
  - –Pseudo-random counters act as shift registers during readout
  - –Read out times: 9 msec (serial), approx. 265 µsec (parallel)

Outline

The Medipix2 detector

- Medipix2: a detector for x-ray imaging
- The working principle
- Detecting X-ray photons

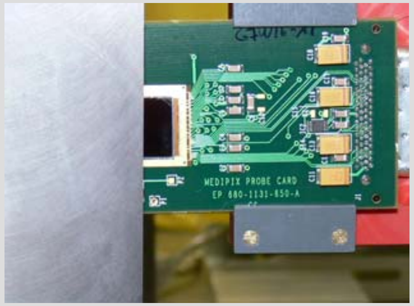
Imaging properties

- Spatial resolution
- Detective-Quantum-Efficiency
- Energy response function

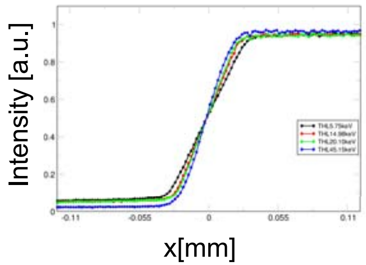
Using the energy resolution

- Reconstruction of incident x-ray spectra
- Material decomposition
- Outlook: Medipix3

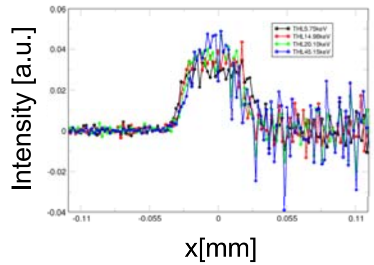
Measurement of the Modulation-Transfer-Function (MTF) with the edge method



Edge spread function



Line spread function (lsf)

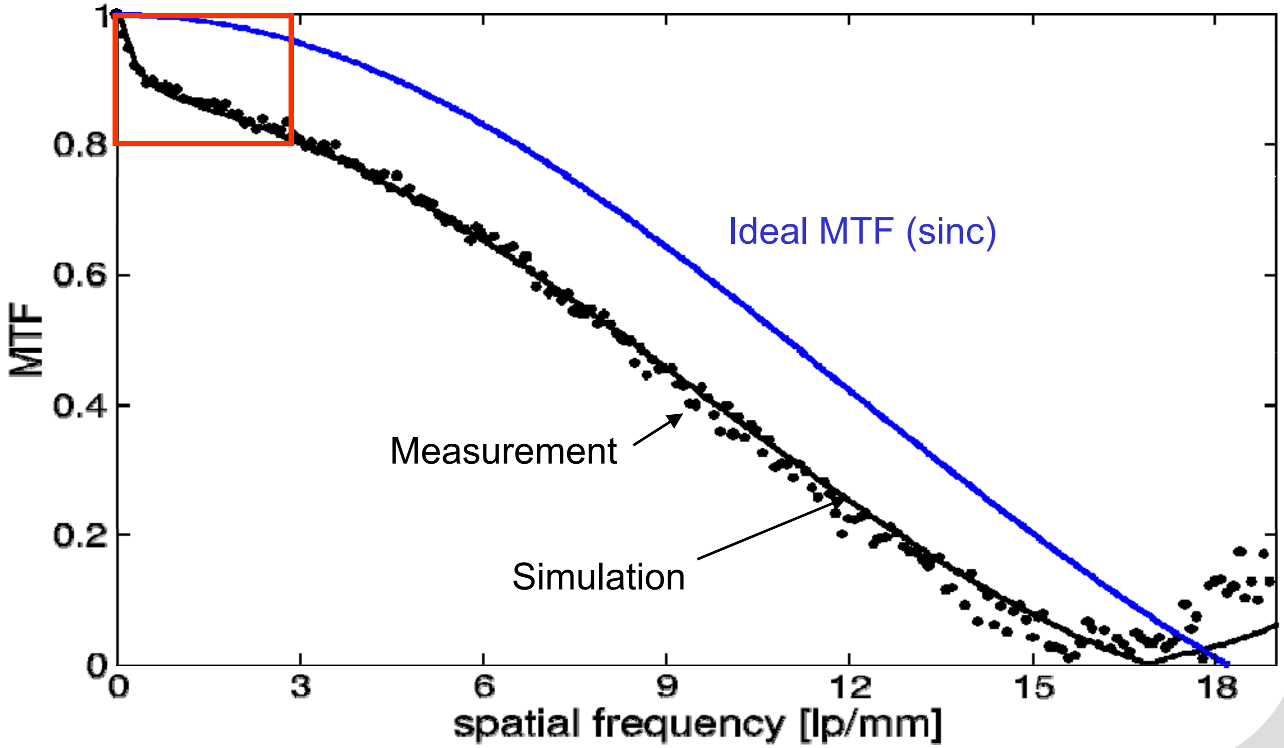


$$MTF(f) = \frac{\left|[FT(lsf)](f)\right|}{[FT(lsf)](0)}$$

$$MTF(f) = \frac{C_{out}(f)}{C_{in}(f)}$$

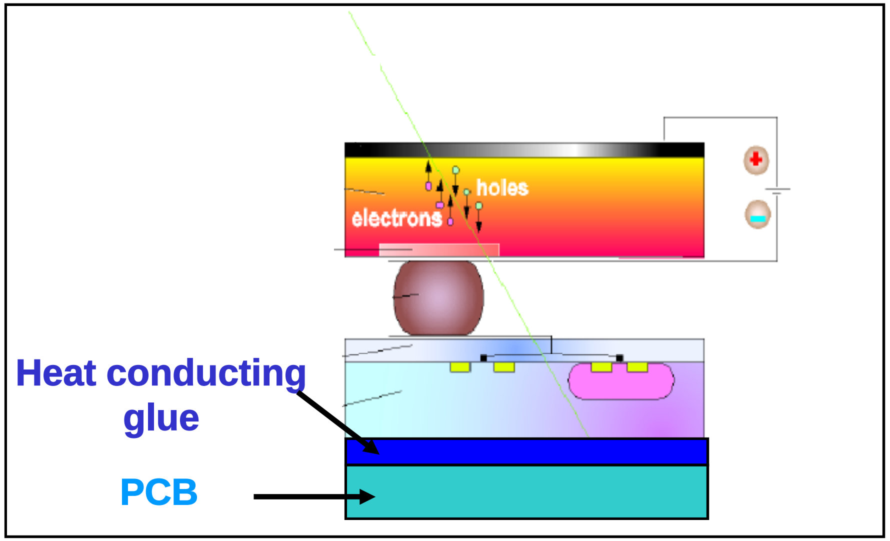
$$C = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

MTF (90 kVp, E_{thr}=6 keV)

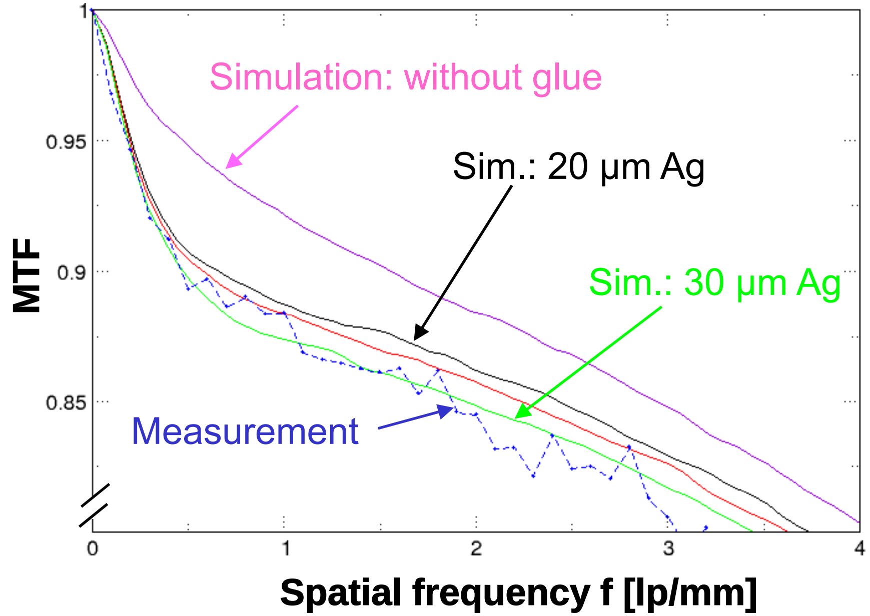


The Low-Frequency-Drop in the MTF

Schematic of the detector assembly

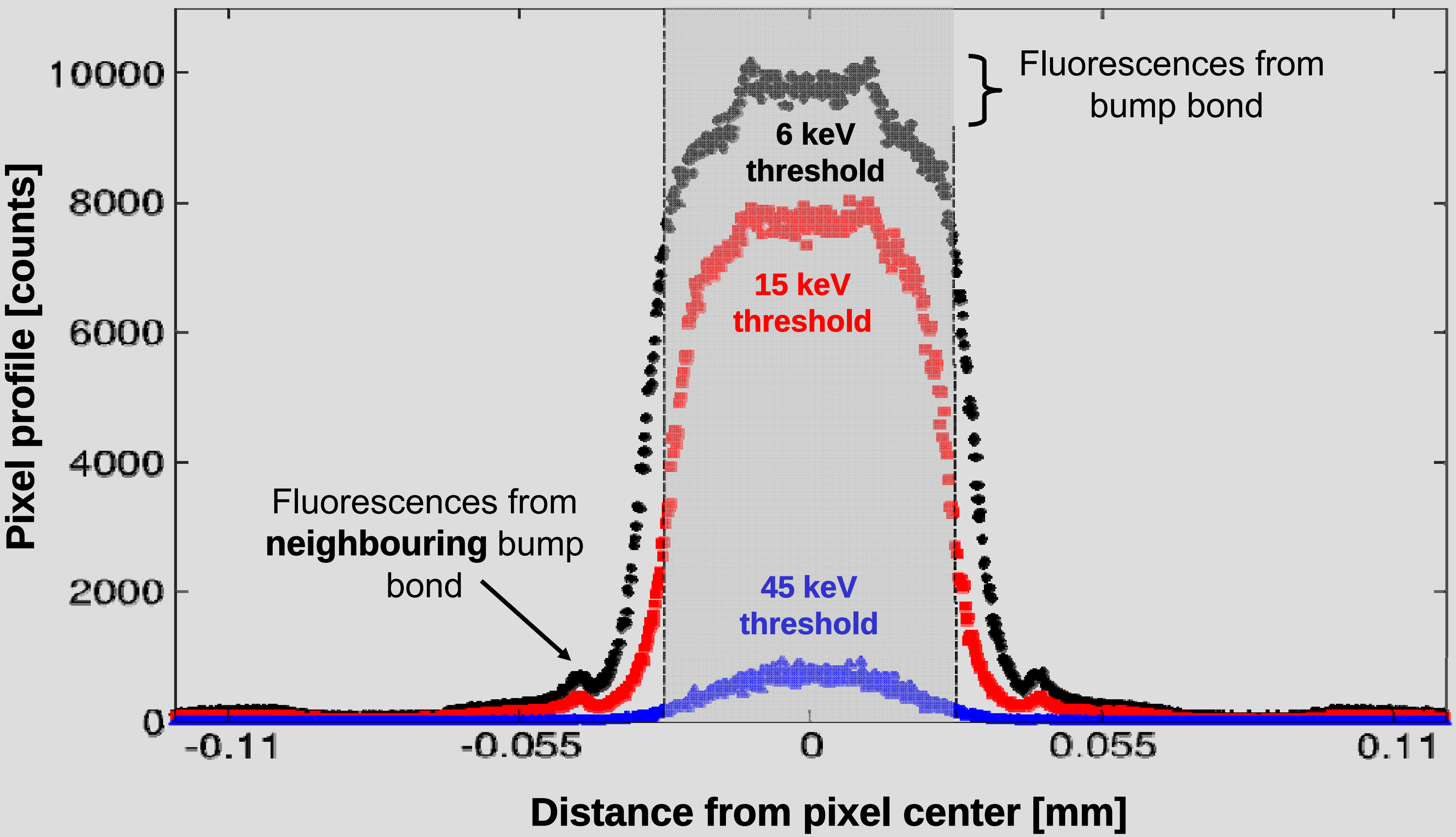


MTF for low spatial frequencies



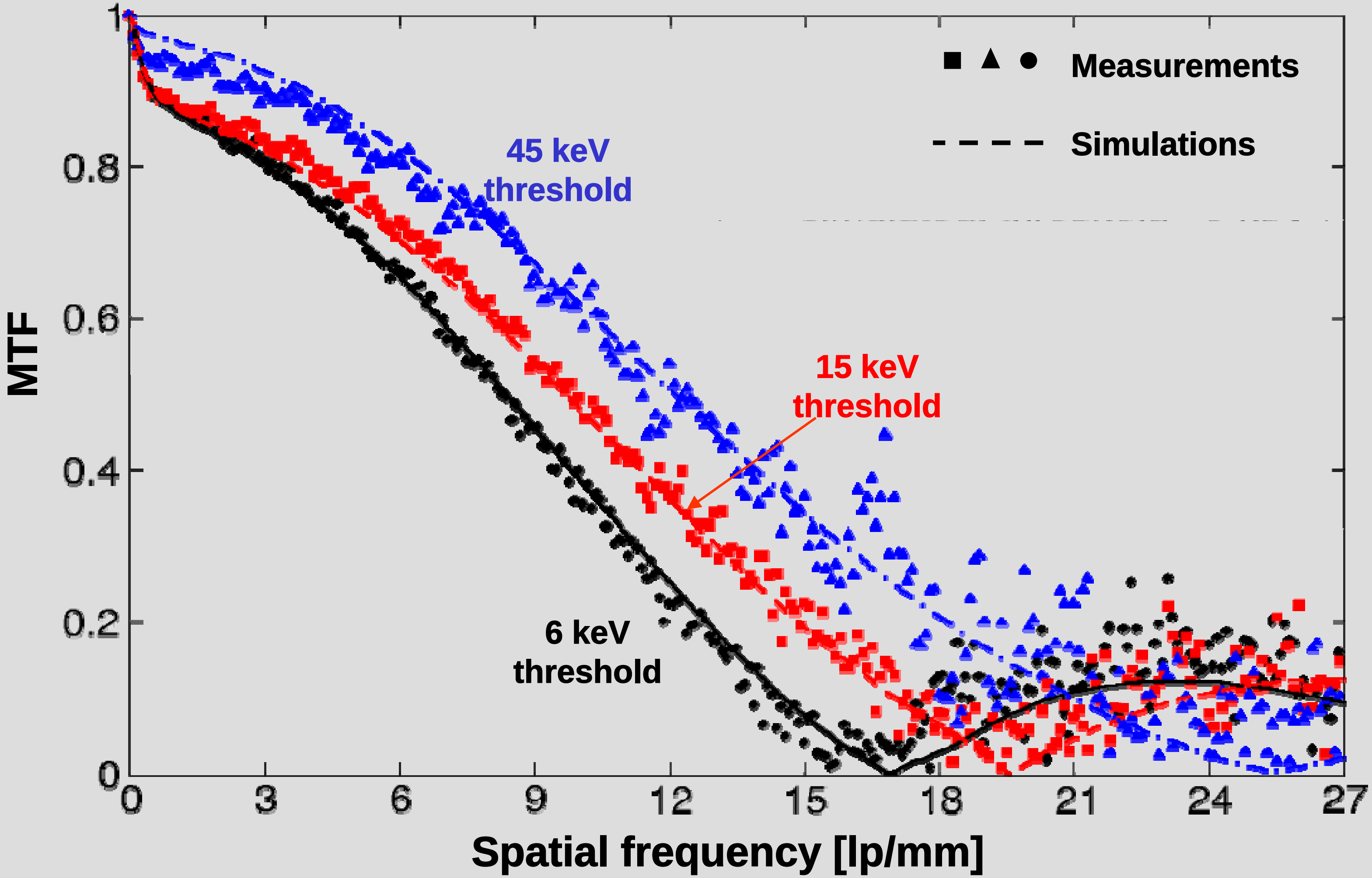
- Production of fluorescence photons in the silver containing glue between ASIC and PCB
- Triggering of pixels sometimes far away from the production vertex of the fluorescence photons
- This long range effect leads to a reduction of MTF at low spatial frequencies

Simulation: The pixel profile (response to line source) in dependence on the discriminator threshold



Tube voltage: 90 kVp, tungsten anode

The dependency of the MTF on the discriminator threshold: higher spatial resolution at higher discriminator thresholds



Excellent agreement of simulation and measurement

Tube voltage: 90 kVp, tungsten anode

Outline

The Medipix2 detector

- Medipix2: a detector for x-ray imaging
- The working principle
- Detecting X-ray photons

Imaging properties

- Spatial resolution
- Detective-Quantum-Efficiency
- Energy response function

Using the energy resolution

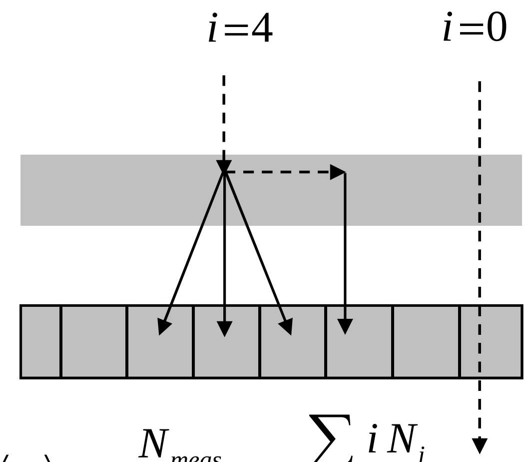
- Reconstruction of incident x-ray spectra
- Material decomposition
- Outlook: Medipix3

A model to describe the Detective-Quantum-Efficiency (DQE) of a photon counting pixel detector

Problem:
Multiple counting affects the image noise

- Number of counts in one pixel varies according to Poisson-statistics
- Charge-Sharing:
  Numbers of counts in different pixels are not independent random variables
- Image noise is depending on fraction of multiple counts
- Therefore: Influence on the DQE

The (average) multiplicity



$N_{in}=2$

$N_{true}=1$

$N_{meas}=4$

$N_4=1$

$\langle m\rangle=4$

$\varepsilon=0.5$

$$\langle m\rangle = \frac{N_{meas}}{N_{true}} = \frac{\sum i\,N_i}{\sum N_i}$$

$$\langle m^2\rangle = \frac{\sum i^2\,N_i}{\sum N_i}$$

$$SNR_{out} = \frac{N_{meas}}{\sigma_{N_{meas}}} = \frac{\langle m\rangle N_{true}}{\sqrt{\sum_i i^2 N_i}} = \frac{\langle m\rangle N_{true}}{\sqrt{\langle m^2\rangle N_{true}}} = \frac{\langle m\rangle}{\sqrt{\langle m^2\rangle}}\sqrt{\varepsilon\cdot N_{in}}$$

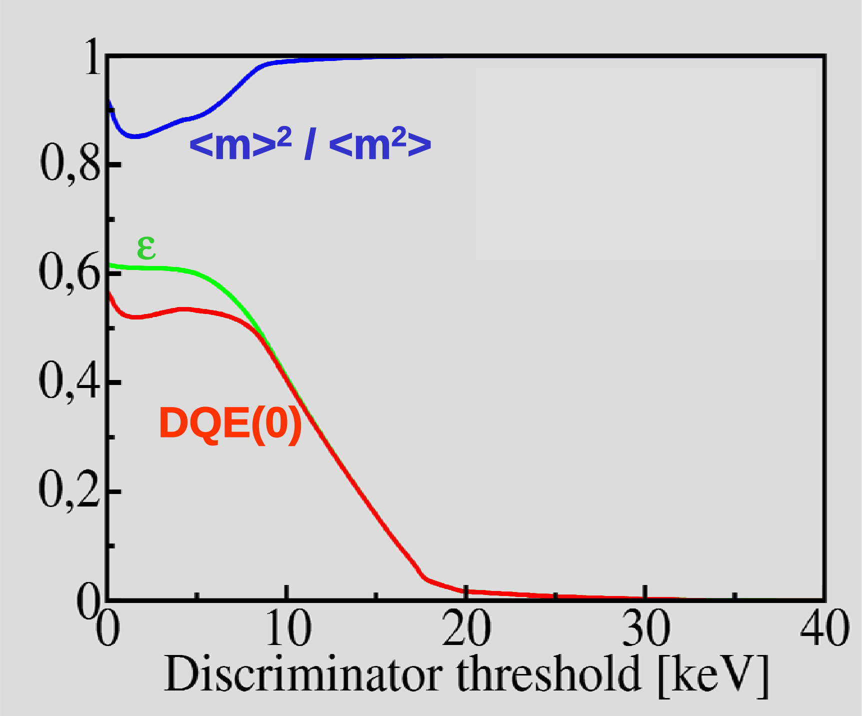
$$SNR_{in} = \frac{N_{in}}{\sigma_{N_{in}}} = \sqrt{N_{in}}$$

$$DQE(0) = \frac{SNR_{out}^{\;2}}{SNR_{in}^{\;2}} = \frac{\langle m\rangle^2}{\langle m^2\rangle}\varepsilon$$

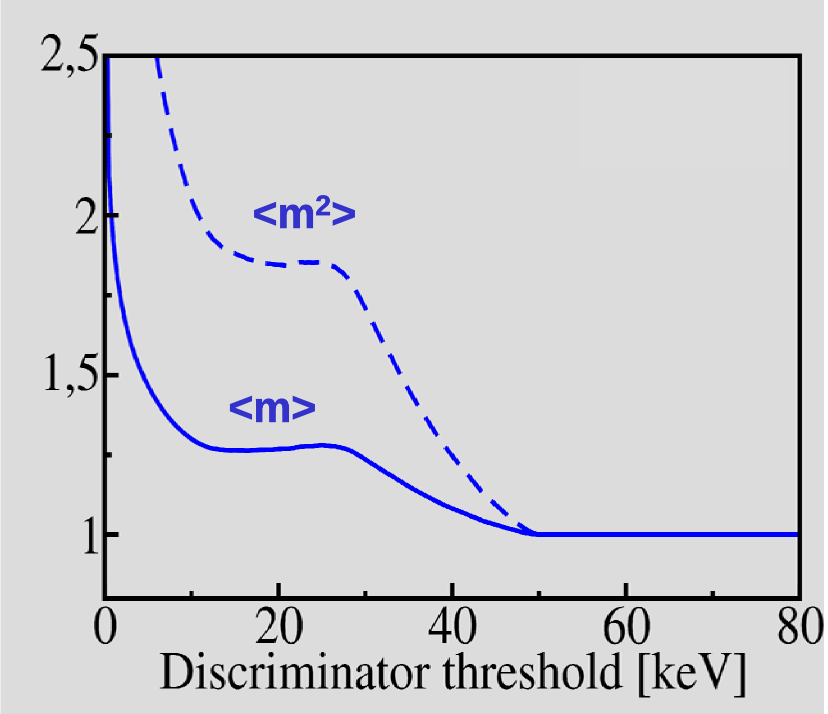
T. Michel et al., „A fundamental method to determine the signal-to-noise ratio (SNR) and detective quantum efficiency (DQE) for a photon counting pixel detector“, Nuclear Instruments and Methods A, Volume 568, Issue 2, p. 799-802 (2006)

Simulations of the average multiplicity and the DQE(0)

40 kV spectrum, Mo-Anode



100 keV



Outline

The Medipix2 detector

- Medipix2: a detector for x-ray imaging
- The working principle
- Detecting X-ray photons

Imaging properties

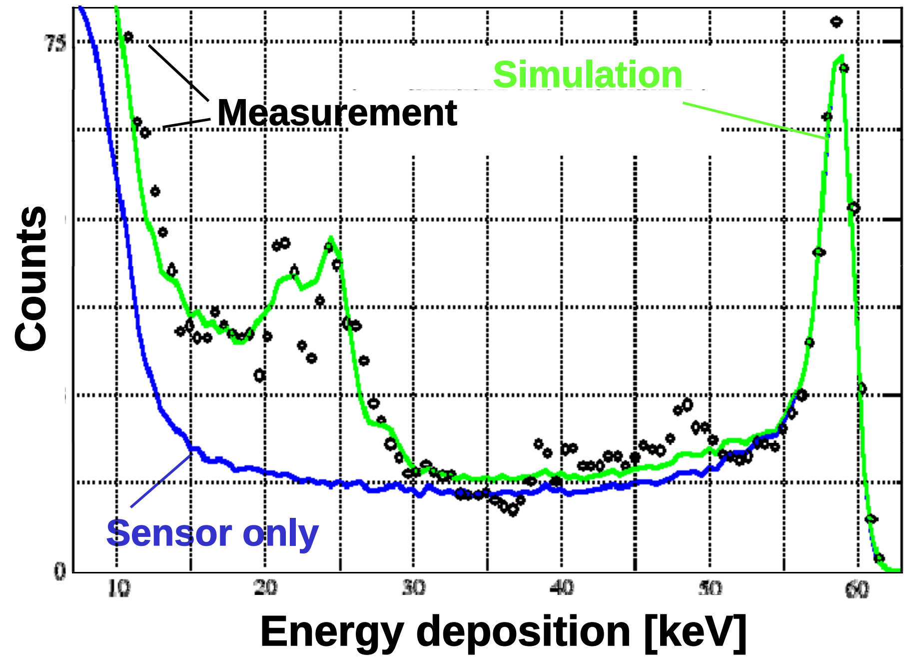
- Spatial resolution
- Detective-Quantum-Efficiency
- Energy response function

Using the energy resolution

- Reconstruction of incident x-ray spectra
- Material decomposition
- Outlook: Medipix3

Simulations and measurements of the energy response

Energy response at 59.3 keV (tungsten Kα1)



- Response function R depends on various parameters: $R = R(E', E_{\gamma}, V_{bias}, d_{Sensor}, p, \text{sensormaterial})$
- But: Can be described very well with our simulations
- Validation of simulation code in measurements

Physikalisches Institut Universität Erlangen-Nürnberg

Outline

The Medipix2 detector

- Medipix2: a detector for x-ray imaging
- The working principle
- Detecting X-ray photons

Imaging properties

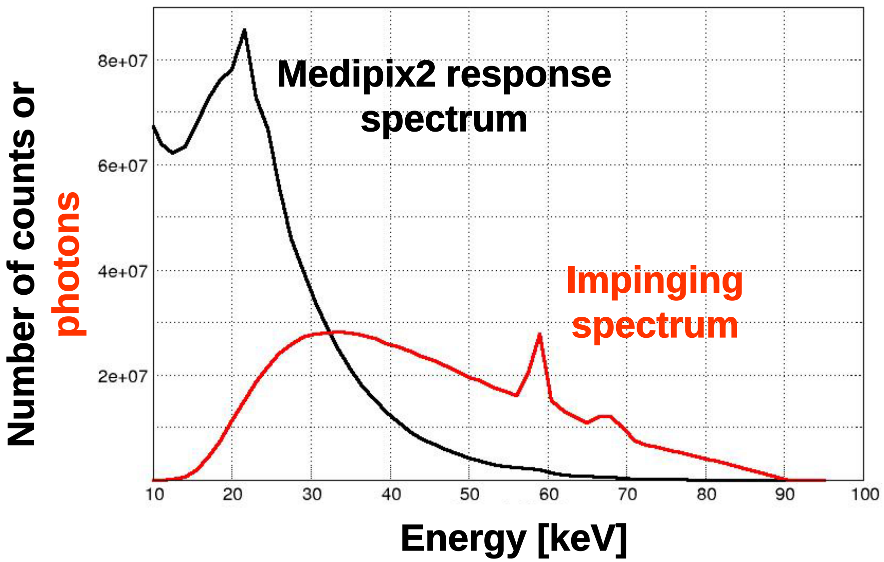
- Spatial resolution
- Detective-Quantum-Efficiency
- Energy response function

Using the energy resolution

- Reconstruction of incident x-ray spectra
- Material decomposition
- Outlook: Medipix3

Methods for the reconstruction of incident x-ray spectra with high flux

Response spectrum of polychromatic irradiation



$R(E_i^|, E_j)$: the probability that a photon of energy E_j causes an energy deposition of $E_i^|$

$$M(E_i') = \sum_{j=1}^{N} R(E_i', E_j) \cdot S(E_j)$$

$$\vec{M} = R \cdot \vec{S}$$

Spectrum-Stripping-Method

Subtract the monoenergetic response functions successively:

$$S_N = \frac{M_N}{R_{NN}} \qquad S_{N-1} = \frac{M_{N-1} - R_{N-1,N} \cdot S_N}{R_{N-1,N-1}}$$

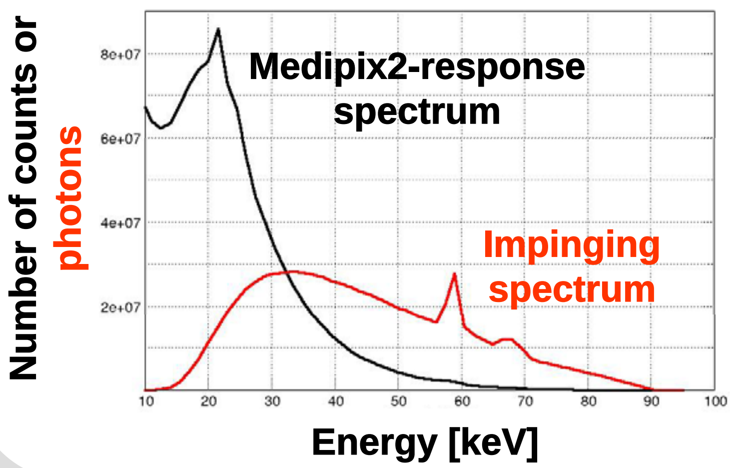
Matrix-Inversion-Method

Best estimate for impinging spectrum $\vec{S}$ is given by:

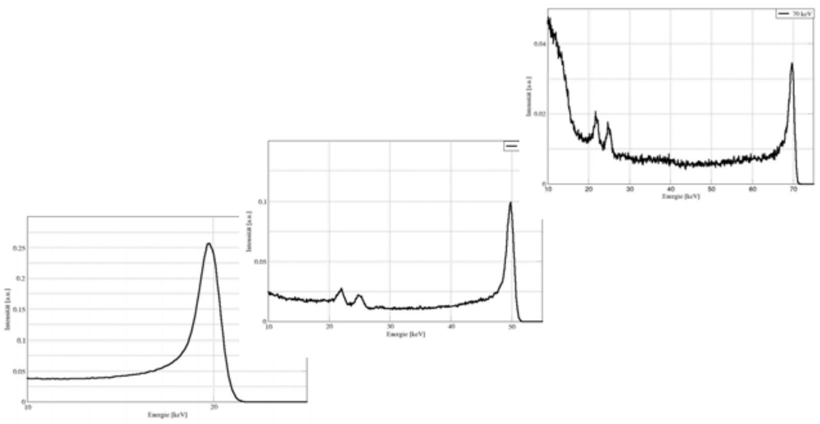
$$\vec{S} = (R^T R)^{-1} R^T \cdot \vec{M}$$

Results of the spectrum reconstruction methods

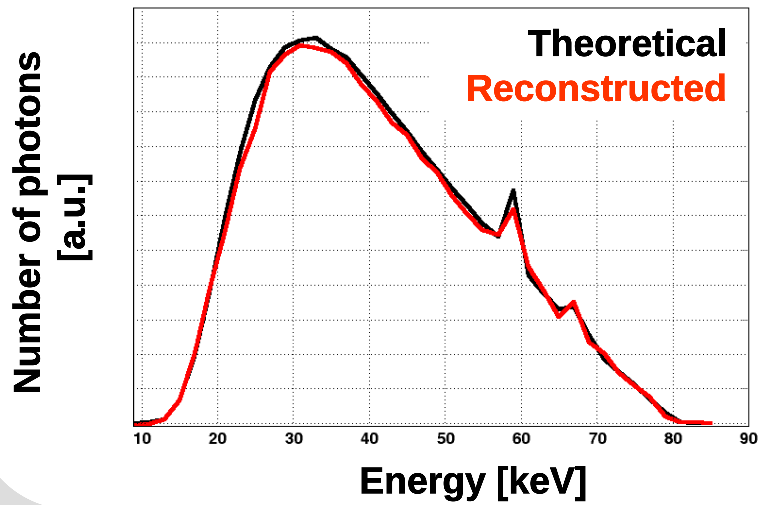
Measured energy deposition spectrum



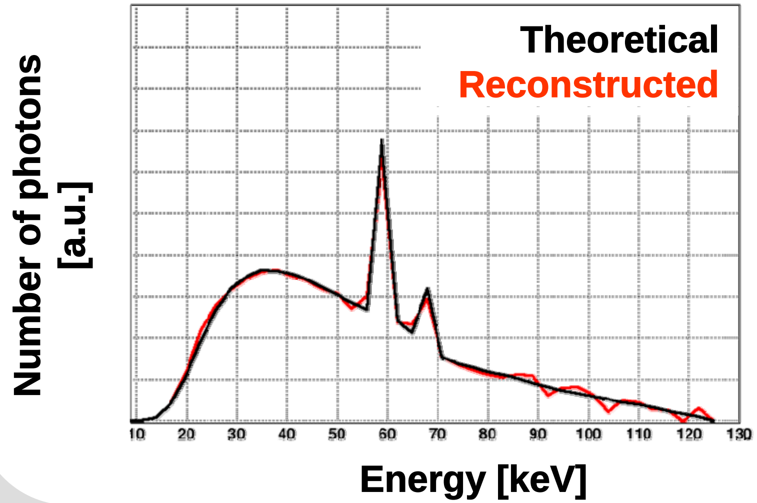
Simulated response functions



80 kVp with spectrum stripping



120 kVp with matrix inversion



Outline

The Medipix2 detector

- Medipix2: a detector for x-ray imaging
- The working principle
- Detecting X-ray photons

Imaging properties

- Spatial resolution
- Detective-Quantum-Efficiency
- Energy response function

Using the energy resolution

- Reconstruction of incident x-ray spectra
- Material decomposition
- Outlook: Medipix3

Application of reconstruction methods: Quantitative determination of the material composition of irradiated objects

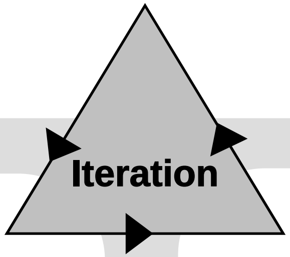
Transmission for different incident x-ray energies E_i

$$t(E_i) = -\ln T(E_i) = -\ln \frac{N(E_i)}{N_o(E_i)} = \sum_{j=1}^{m} \left[\frac{\mu(E_i)}{\rho}\right]_j \cdot p_j$$

Mass attenuation coeffizient M_{ij}

Areal density of material j $p_j = (\rho d)_j$

$$\vec{t} = M \cdot \vec{p}$$



Application of the pseudo-inverse matrix M gives best estimate of areal densities p of the involved materials

$$\vec{p} = \left[(M^T M)^{-1} M^T\right] \cdot \vec{t}$$

The materials-matrix

$$M = \begin{pmatrix} \left(\frac{\mu}{\rho}\right)_{H_2O_{E_1}} & \left(\frac{\mu}{\rho}\right)_{Gd_{E_1}} & \left(\frac{\mu}{\rho}\right)_{I_{E_1}} \\ \left(\frac{\mu}{\rho}\right)_{H_2O_{E_2}} & \left(\frac{\mu}{\rho}\right)_{Gd_{E_2}} & \left(\frac{\mu}{\rho}\right)_{I_{E_2}} \\ \left(\frac{\mu}{\rho}\right)_{H_2O_{E_3}} & \left(\frac{\mu}{\rho}\right)_{Gd_{E_3}} & \left(\frac{\mu}{\rho}\right)_{I_{E_3}} \\ \left(\frac{\mu}{\rho}\right)_{H_2O_{E_4}} & \left(\frac{\mu}{\rho}\right)_{Gd_{E_4}} & \left(\frac{\mu}{\rho}\right)_{I_{E_4}} \end{pmatrix}$$

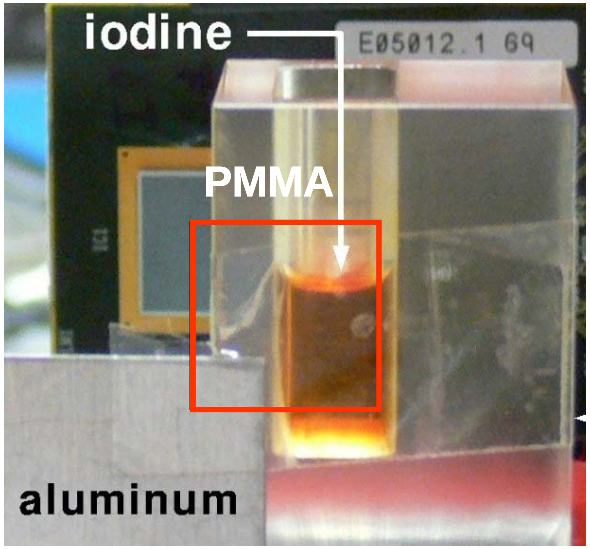
Energy

Material

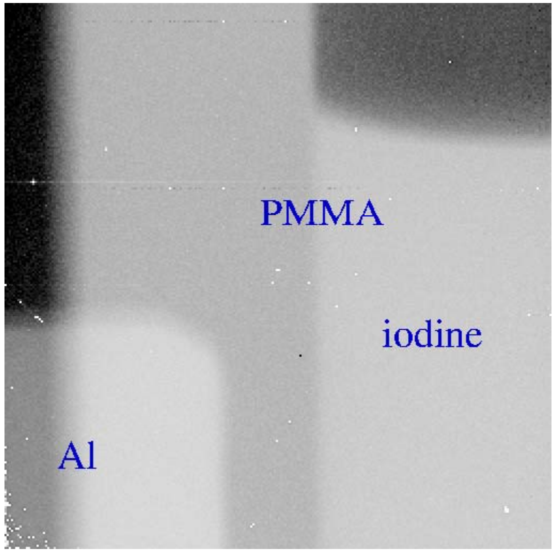
First experimental try of material reconstruction with iodine, plastics (PMMA) and alumunium

- 50 kVp, tungsten anode
- Threshold scan
- 450 mAs/image charge in tube
- 200.000 counts per pixel at lowest threshold in directly irradiated ROI

The phantom: view from tube



Projective photon counting image

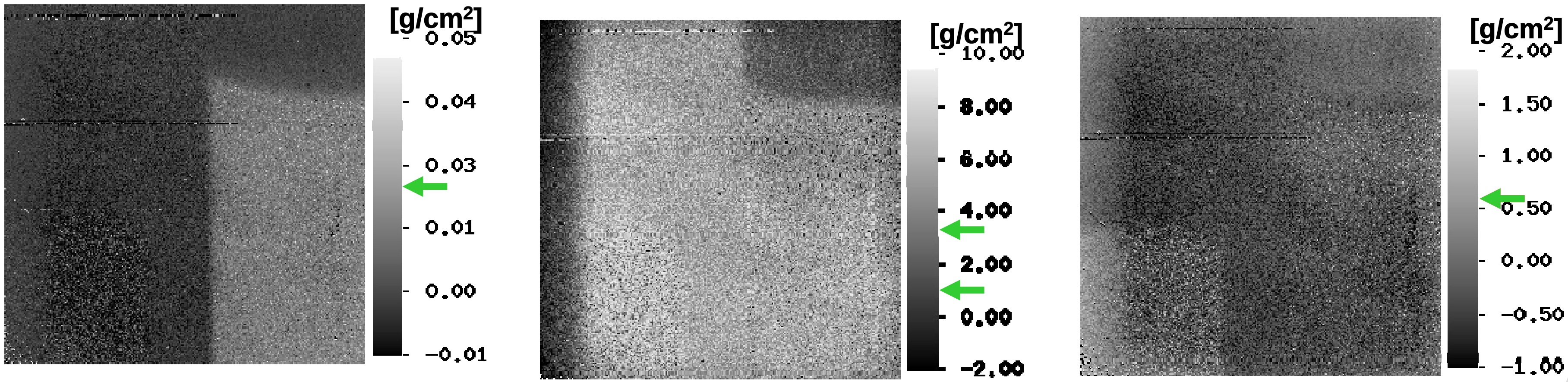


Physikalisches Institut Universität Erlangen-Nürnberg

Material reconstructed images for each base material obtained with simulated energy response functions

Expected images

Material reconstructed images



Reconstruction: energy deposition range: 20-50 keV; energy bin size: 2 keV

Outline

The Medipix2 detector

- Medipix2: a detector for x-ray imaging
- The working principle
- Detecting X-ray photons

Imaging properties

- Spatial resolution
- Detective-Quantum-Efficiency
- Energy response function

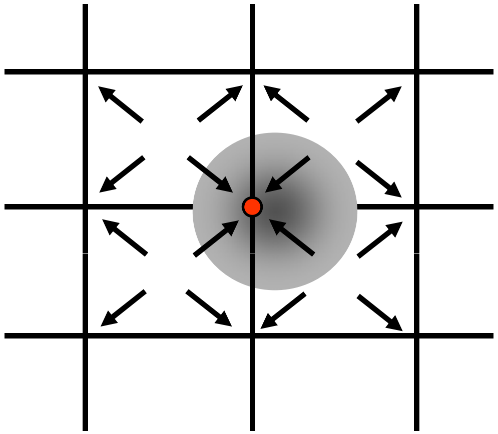
Using the energy resolution

- Reconstruction of incident x-ray spectra
- Material decomposition
- Outlook: Medipix3

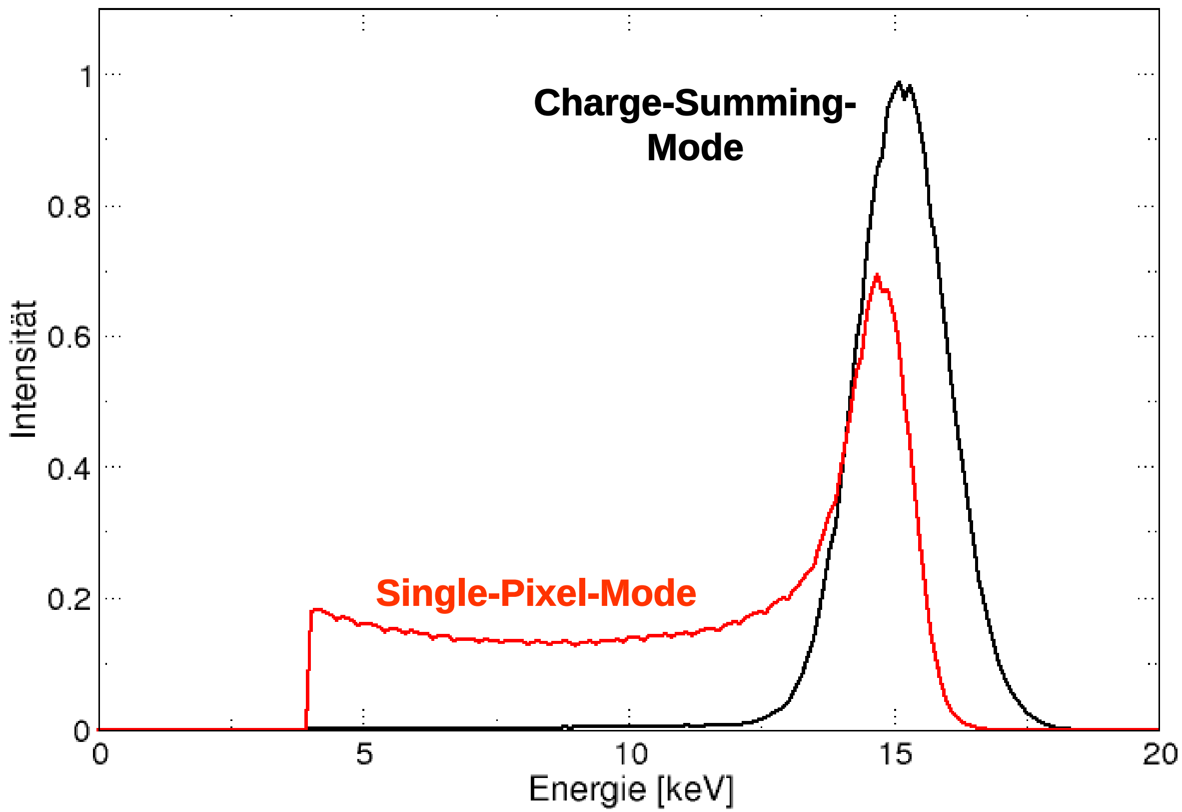
Medipix3 will have a high potential for applications of the material reconstruction method

Charge-Summing

- Real-time communication in each 2x2 neighbourhood
- Detection of the total released charge in **one** node (●)

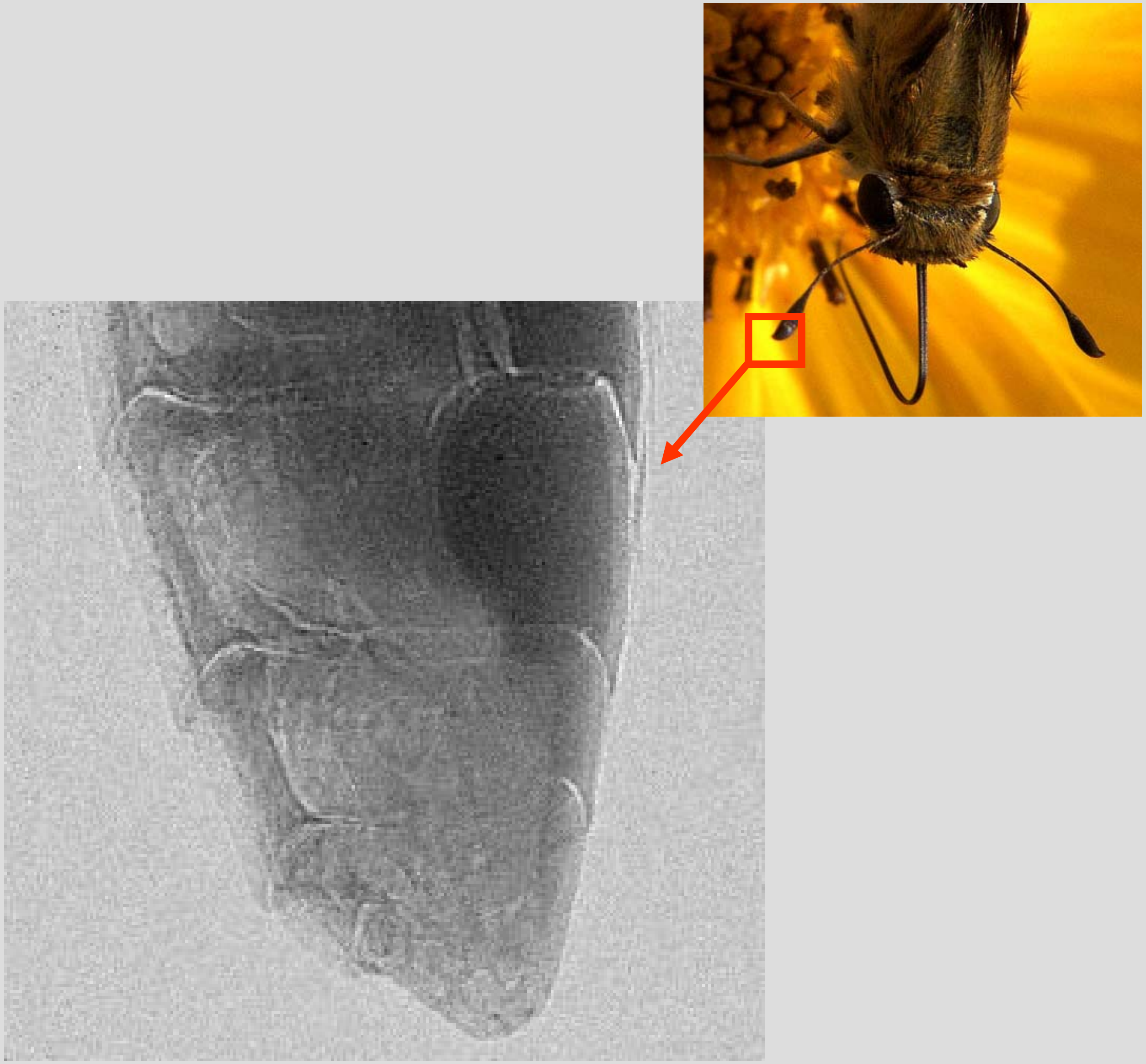


Simulated energy response for 15 keV



Combined with true color mode (110 µm pixel pitch in the sensor): this spectroscopic detector is very good for material reconstruction

High resolution images taken in collaboration with the Univeristy of Gent will be shown in the talk of Bert Masschaele



Summary

- **Simulations predict behaviour of Medipix2 very well**

- **Image quality**
  - Spatial resolution (MTF) is reduced by fluorescence photons, diffusion and range of electrons
  - Image noise is correlated due to multiple counting which reduces DQE

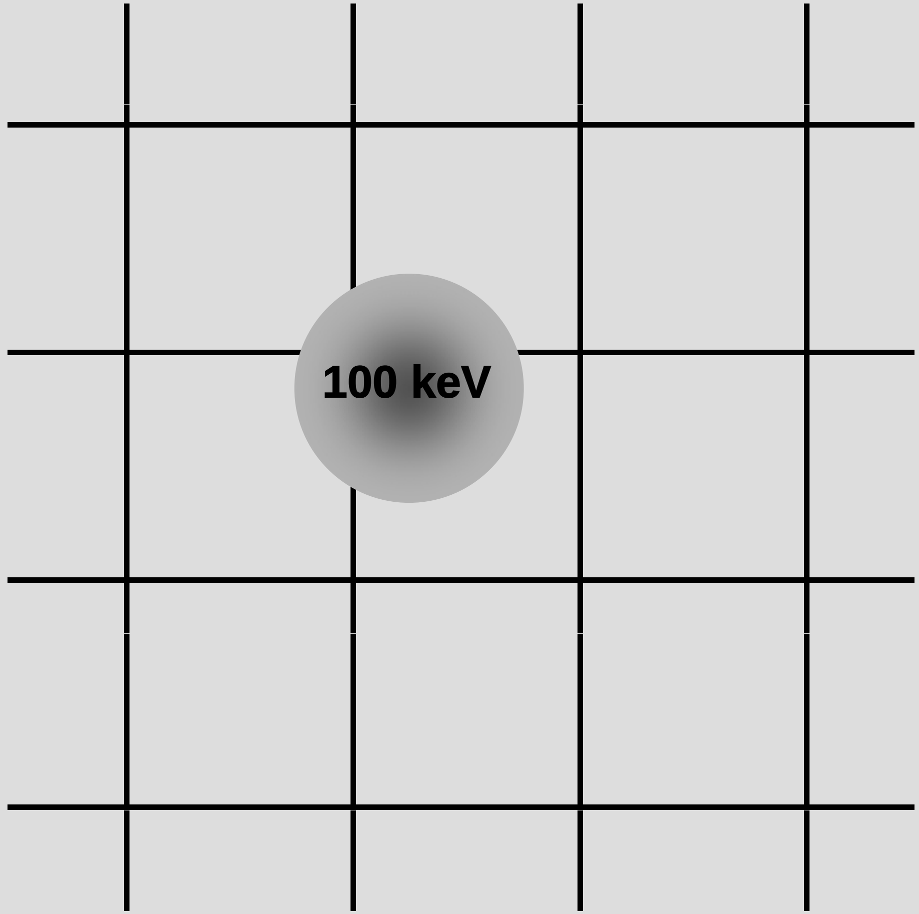
- **Spectral information**
  - Incident x-ray spectrum at high fluxes can be measured
  - Selective images of materials can be calculated from images taken at different thresholds
  - First experiments of material reconstruction have been successful
  - Medipix3: high potential for applications of the material reconstruction

Backup

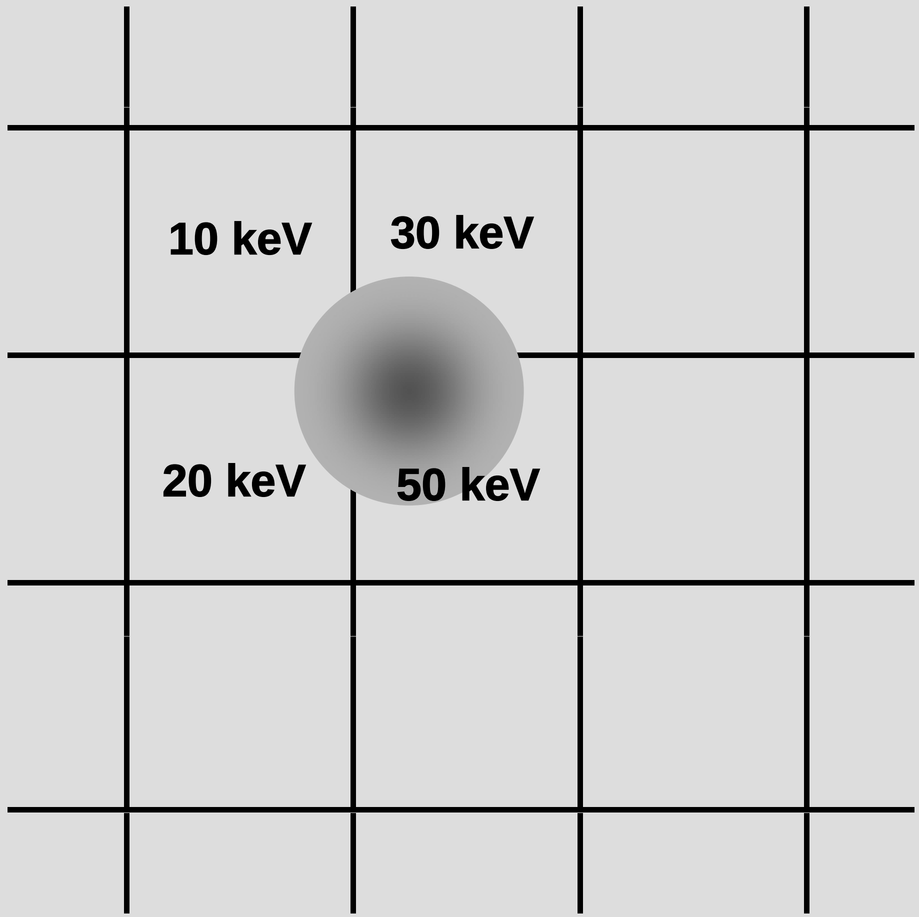
Advantages and disadvantages of the Medipix2 in x-ray imaging applications

Advantages	Disadvantages
• Noise free dark image	• Small size
• No read out noise	• Tiling to large arrays without dead zones or large edge pixels not yet done
• No blooming	• Charge-Sharing
• No after glow	• Multiple counting: reduction of DQE
• Exact linearity at low rates	• Rate limitation at very high rates
• High spatial resolution	
• High framerate	
• **Energy sensitive**	

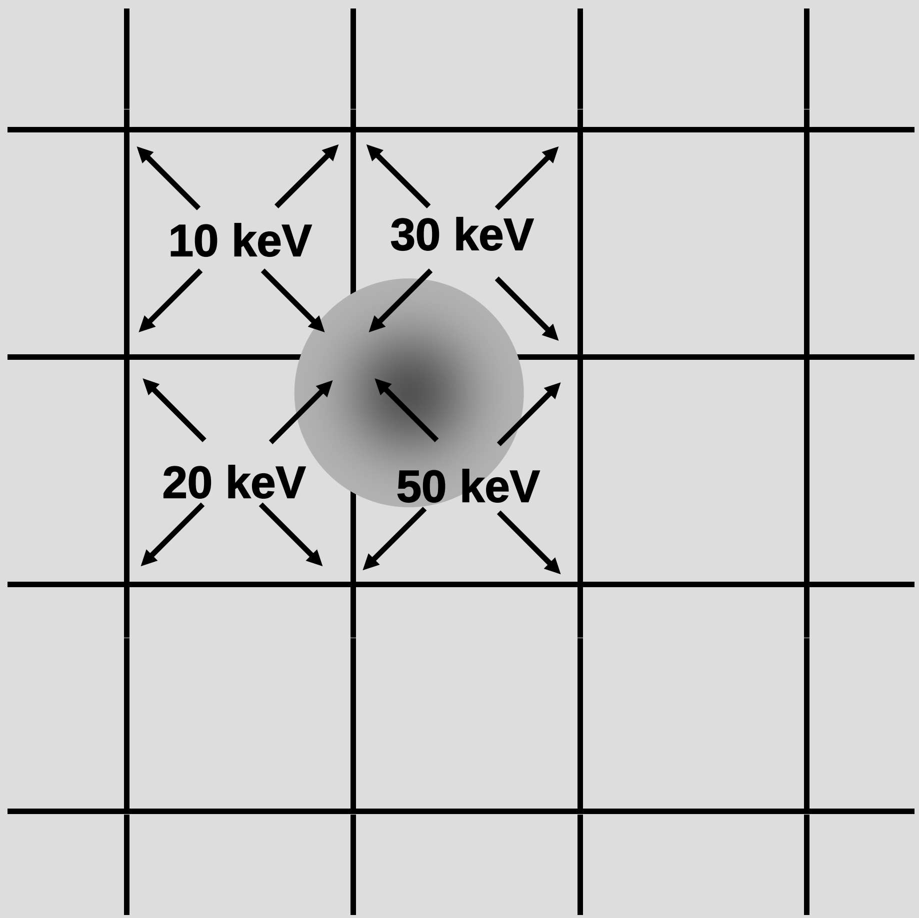
The reacting photon deposits 100 keV in four neighbouring pixels



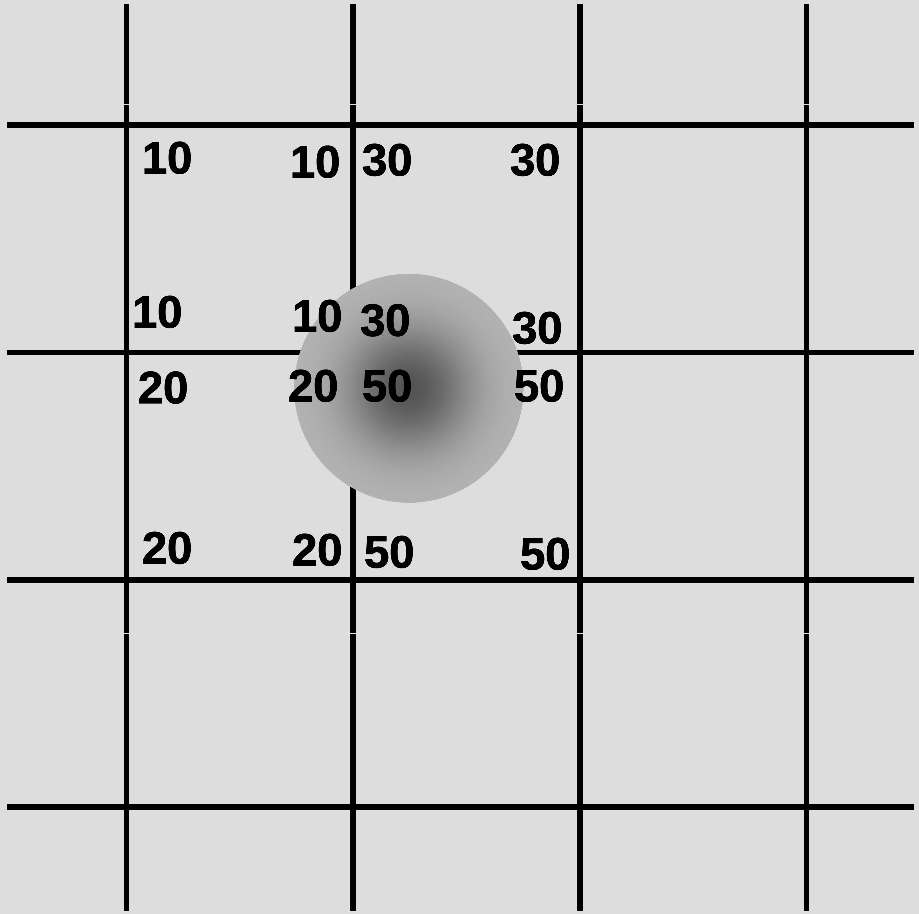
Each charge sensitive preamplifier generates a current signal that is proportional to the collected charge



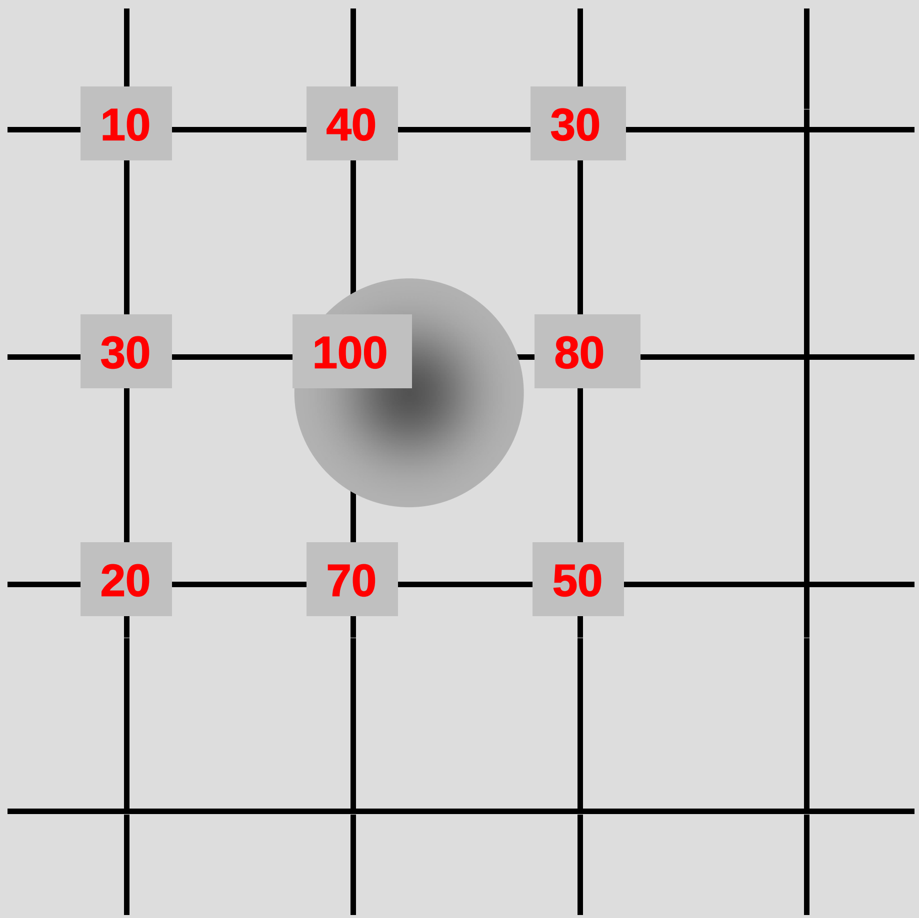
4 current signal copies are generated and sent to the corners (nodes)



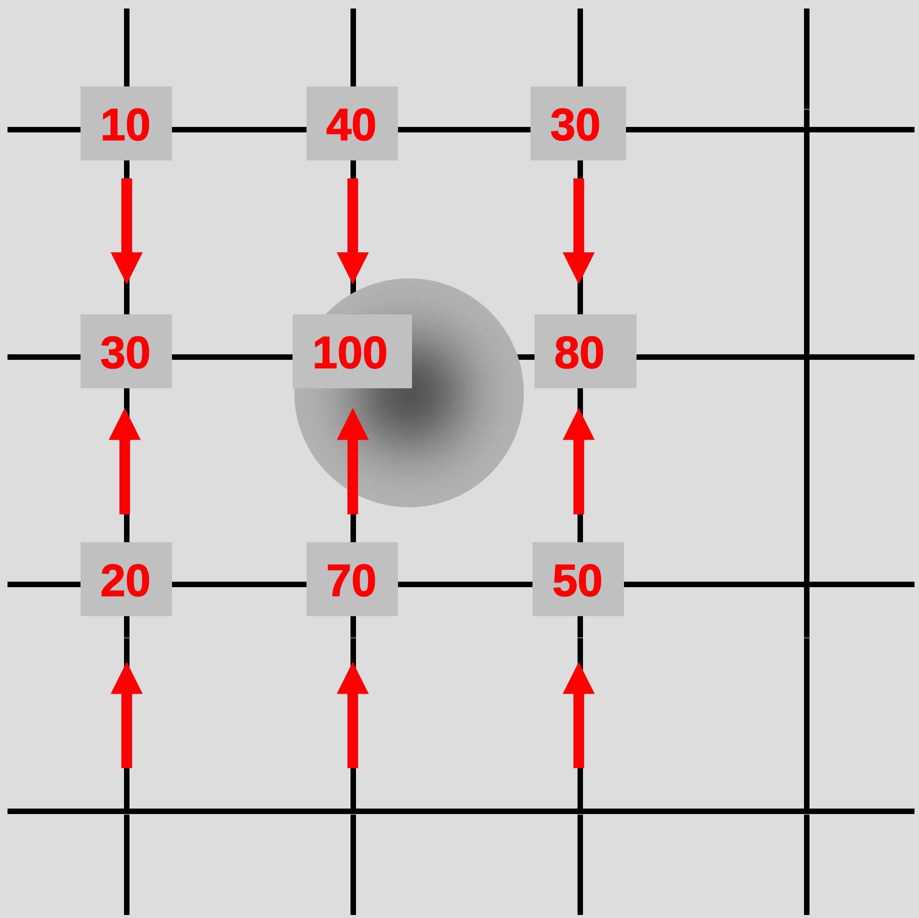
The 4 current signals reach the nodes and there …



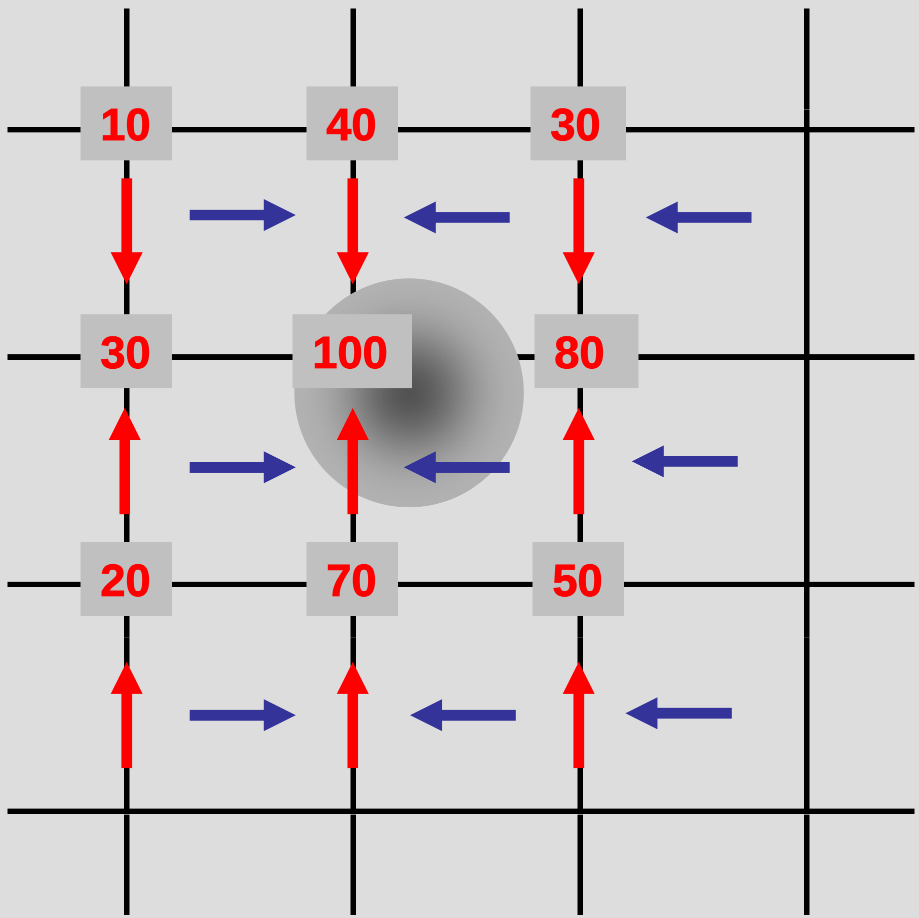
… they are summed



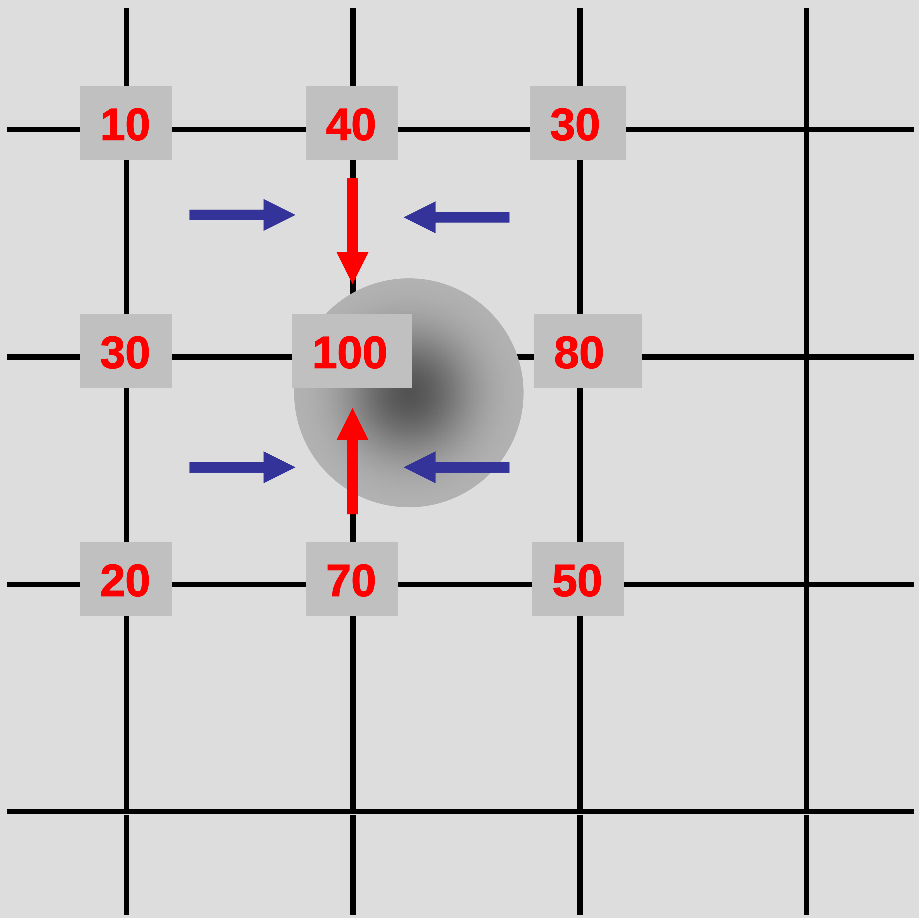
The vertical arbiters point to the vertical node with the higher sum signal



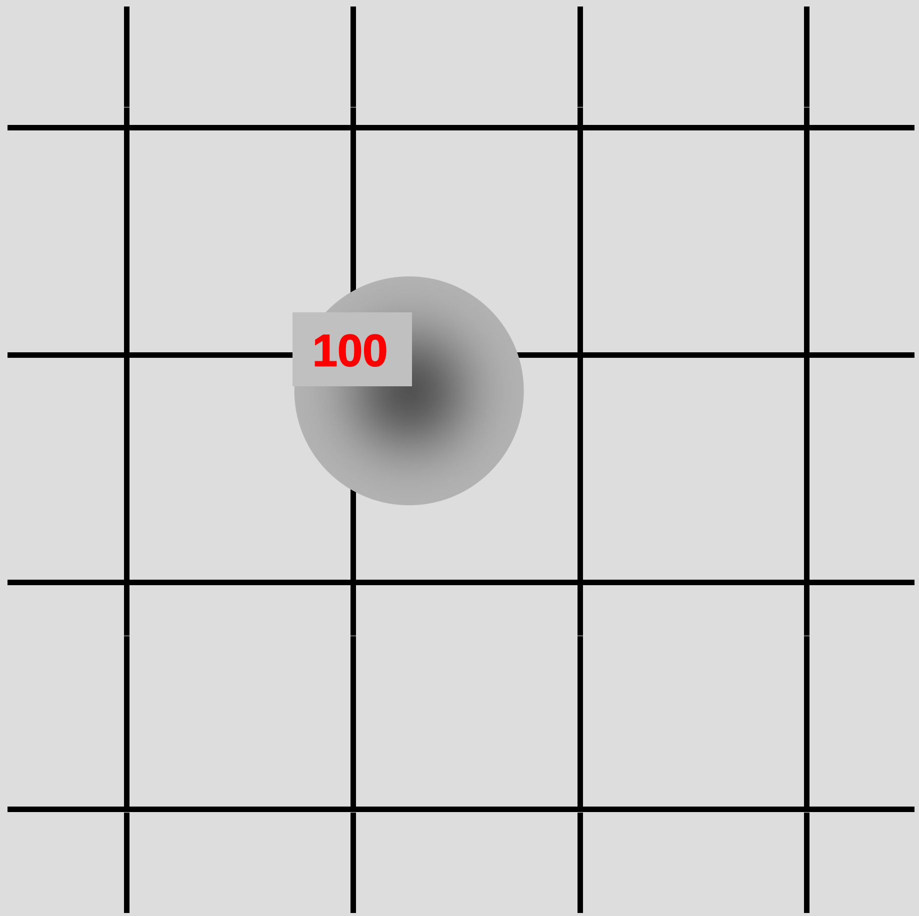
The horizontal arbiter compare the maximum on one side with the maximum on the other side



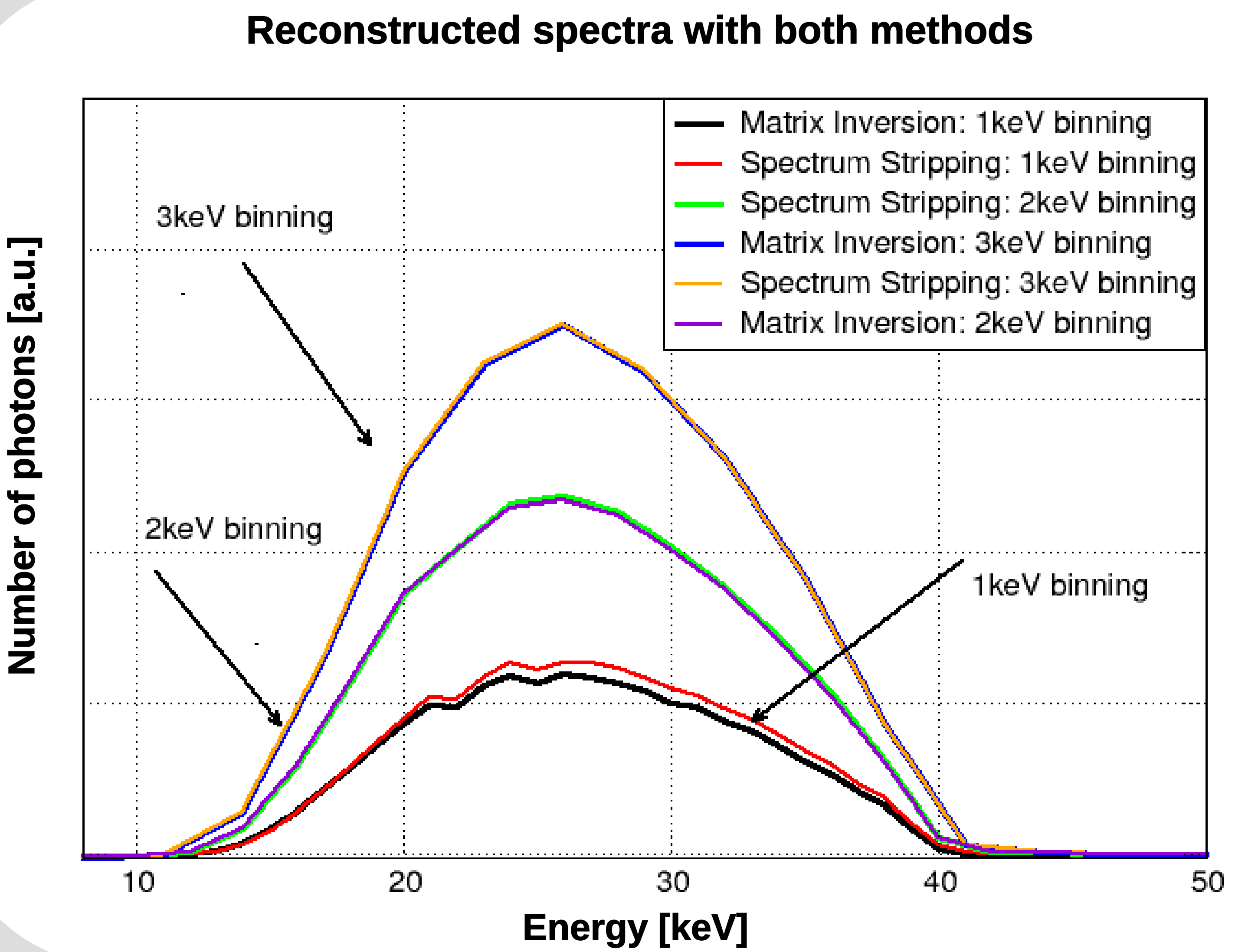
There is only one node with all the surrounding arbiters pointing to it and …



… this node counts the photon if the threshold is exceeded



Differences occur if the bin size for reconstruction comes closer to the noise level of the detector

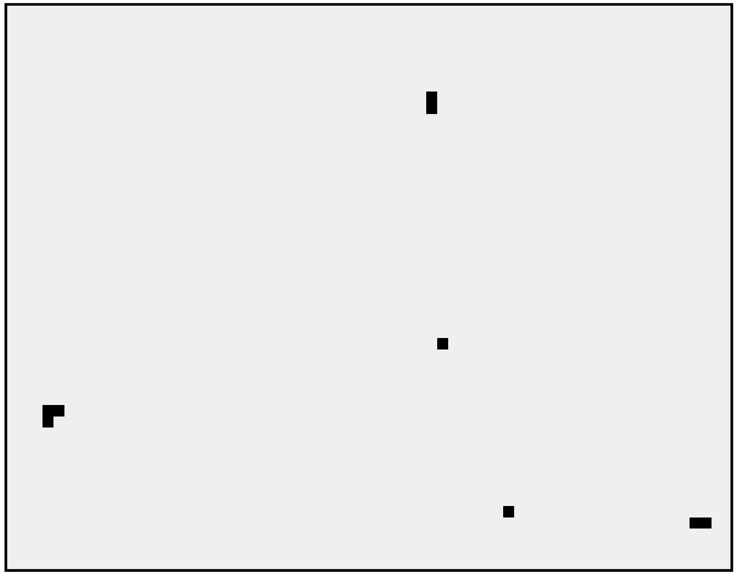


Physikalisches Institut Universität Erlangen-Nürnberg

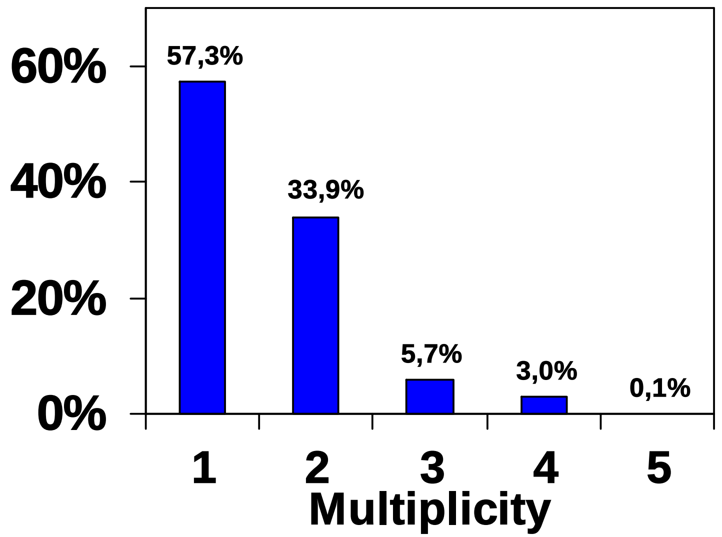
Measurement of the average multiplicity

Measurement

- Monochromator setup for 59 keV, 8 keV threshold, 700 µm Si sensor
- Framerate of 20 Hz
- Cluster analysis determines multiplicity of each event



Distribution of event multiplicities

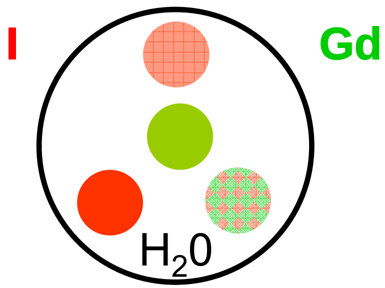


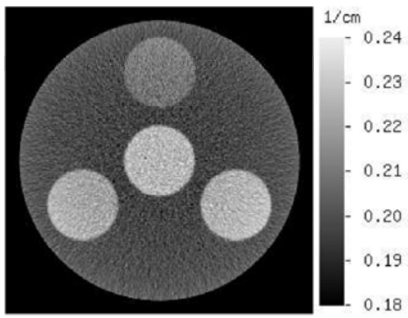
Comparison: simulation and experiment

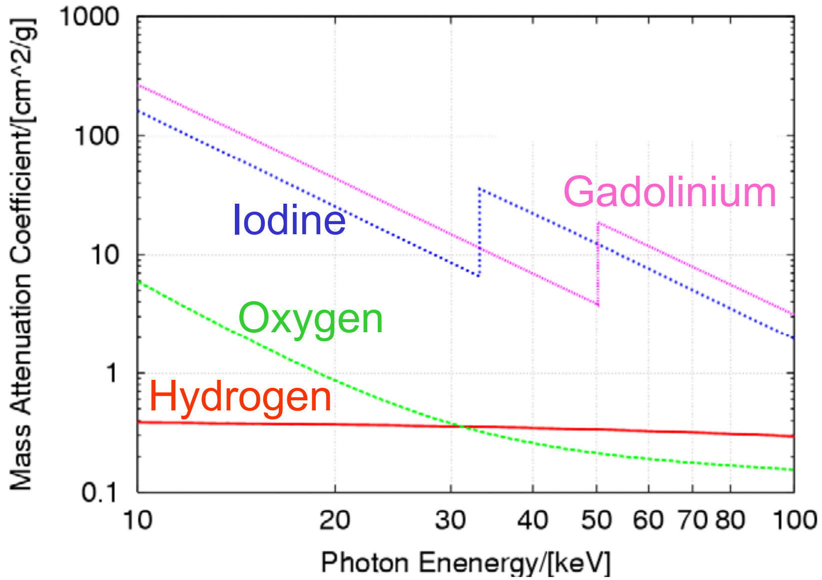
$$\langle m \rangle_{measurement} = 1.55 \pm 0.04$$

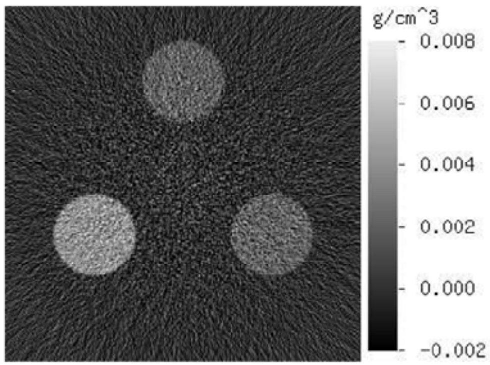
$$\langle m \rangle_{simulation} = 1.57 \pm 0.01$$

Material reconstruction in simulated CT with an ideal photon counting detector and „friendly“ materials (K-edges)

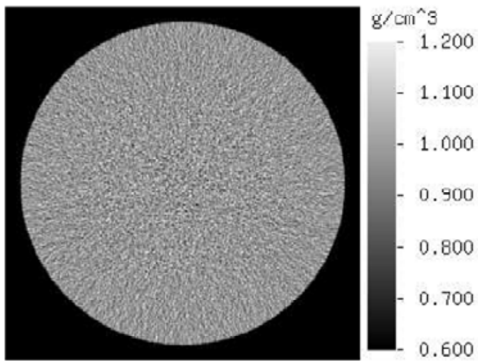




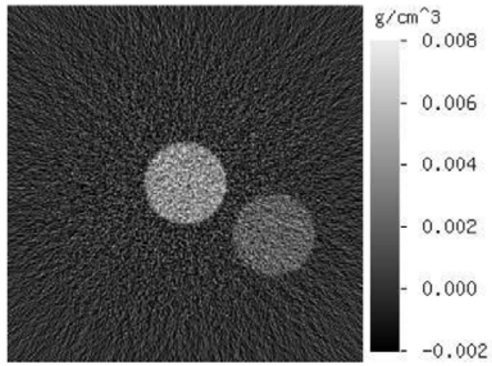




Iodine

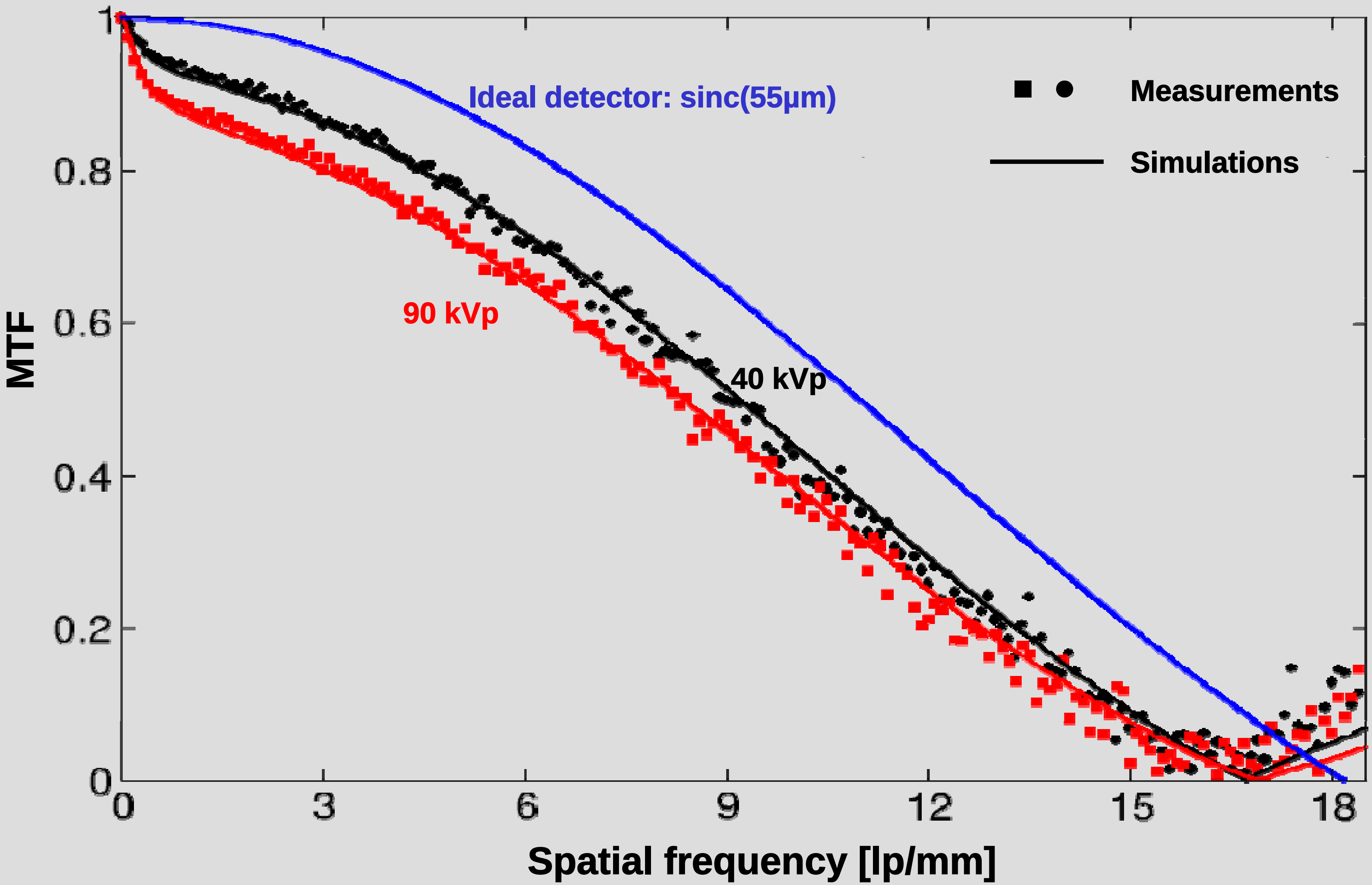


Water

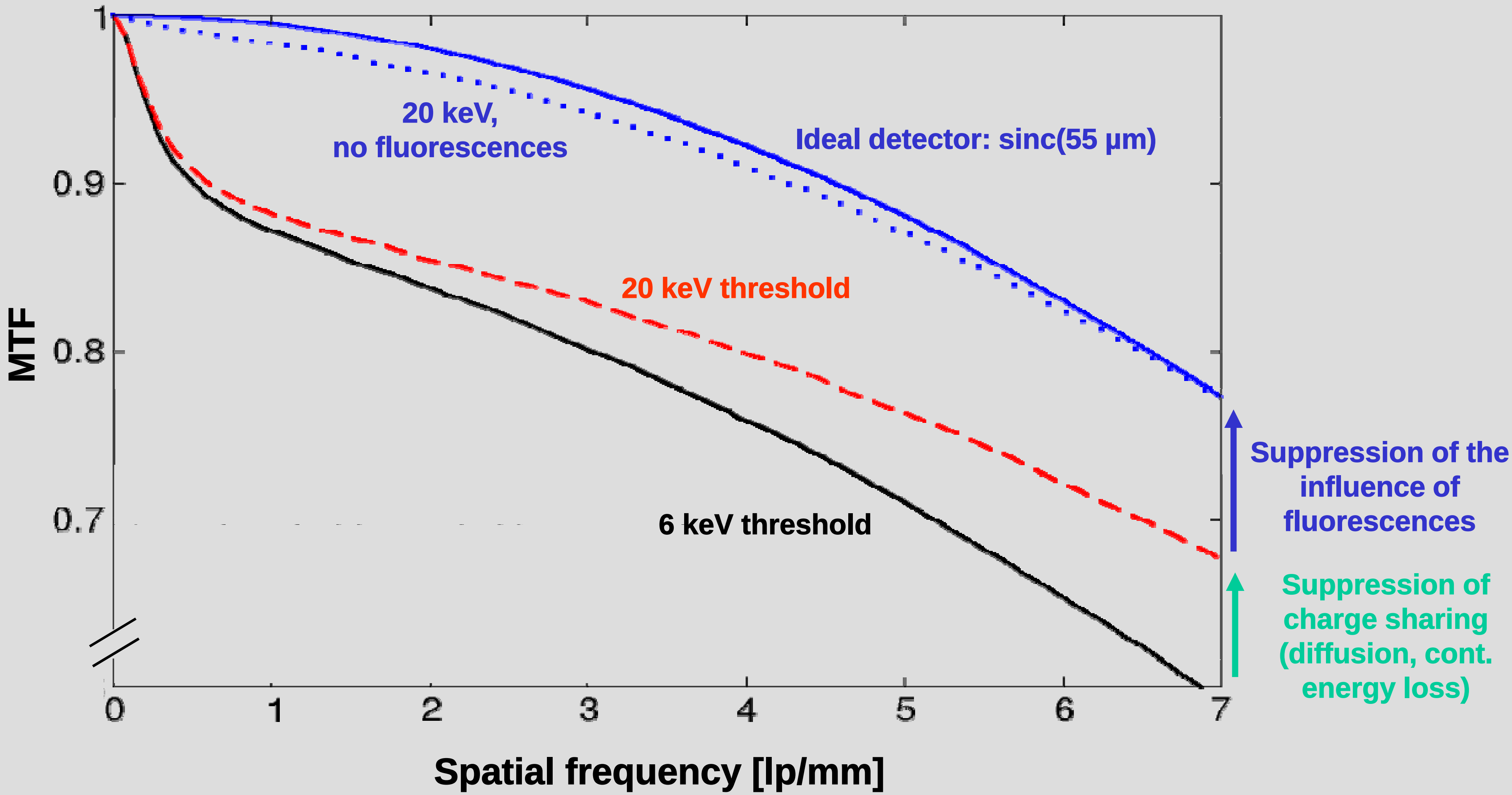


Gadolinium

The MTF also depends on the impinging spectrum: higher spatial resolution at lower energies



Fluorescence photons and charge sharing have strong impact on the MTF

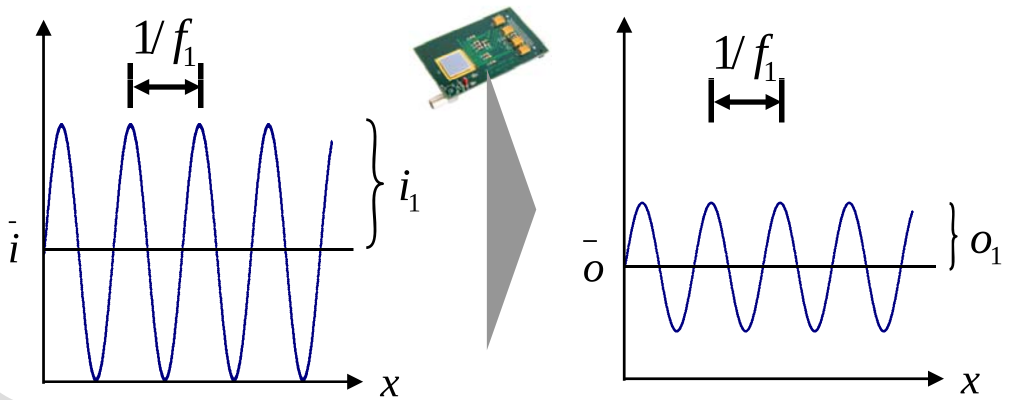


Tube voltage: 90 kVp, tungsten anode

The modulation transfer function (MTF): a key performance indicator of an imaging detector

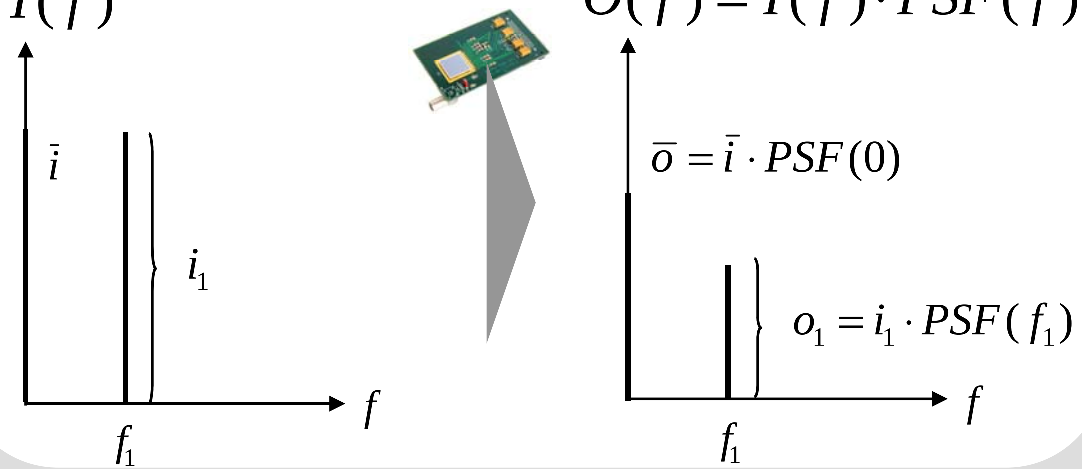
Spatial domain

$$o(x) = i(x) \otimes psf(x)$$



Spatial frequency domain

$$O(f) = I(f) \cdot PSF(f)$$



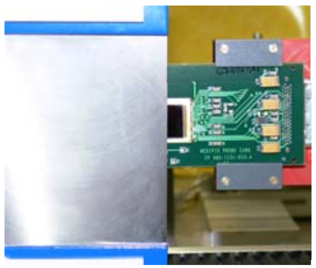
$$\bar{o} = \bar{i} \cdot PSF(0)$$

$$o_1 = i_1 \cdot PSF(f_1)$$

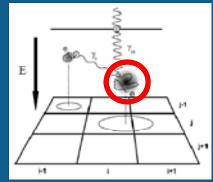
Modulation-Transfer-Function (MTF)

$$C = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

$$MTF(f_1) = \frac{C_o(f_1)}{C_i(f_1)} = \frac{|PSF(f)|}{PSF(0)}$$



First interaction of an x-ray photon with sensor



$$I(E) = I_0(E) \cdot e^{-\mu(E) \cdot x}$$