RC 1913, ECR, March 2, 2024

Technical Possibilities of Photon-Counting CT

Marc Kachelrieß

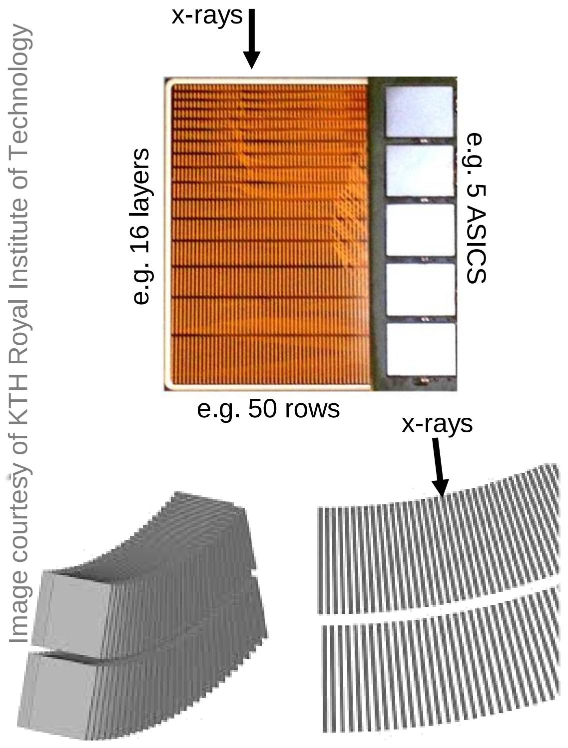
German Cancer Research Center (DKFZ)
Heidelberg, Germany
www.dkfz.de/ct

DEUTSCHES
KREBSFORSCHUNGSZENTRUM
IN DER HELMHOLTZ-GEMEINSCHAFT

Photon-Counting CT Availability

	Sensor material	Detector pixel size at iso	Pixel binning	FOM	Bins	FDA	Pubs	Installations
Canon	CdZnTe	210 µm	3×3, 1×1	50 cm	5	no	1	3 prototypes (Japan, Netherlands)
GE	Si, edge on	400 × 400 µm	?	?	?	no		1 experimental (Sweden), 2 prototypes (USA)
Philips	CdZnTe	274 × 274 µm	?	50 cm	5	no	≈22	1 experimental setup (France)
Siemens CounT	GOS/CdTe dual source	700 × 600 µm / 250 × 250 µm	2×2, 1×1	50 / 28 cm	4	no	≈50	3 experimental systems (Germany, USA)
Siemens CountPlus	CdTe	150 × 176 µm	2×2, 1×1	50 cm	4	no	≈11	3 prototypes (Czech, Sweden, USA)
Siemens Alpha	CdTe/CdTe dual source	2 · 150 × 176 µm	2×2, 1×1	50 / 36 cm	4	yes	≈40	more than 100 worldwide

Edge on design (Si only)



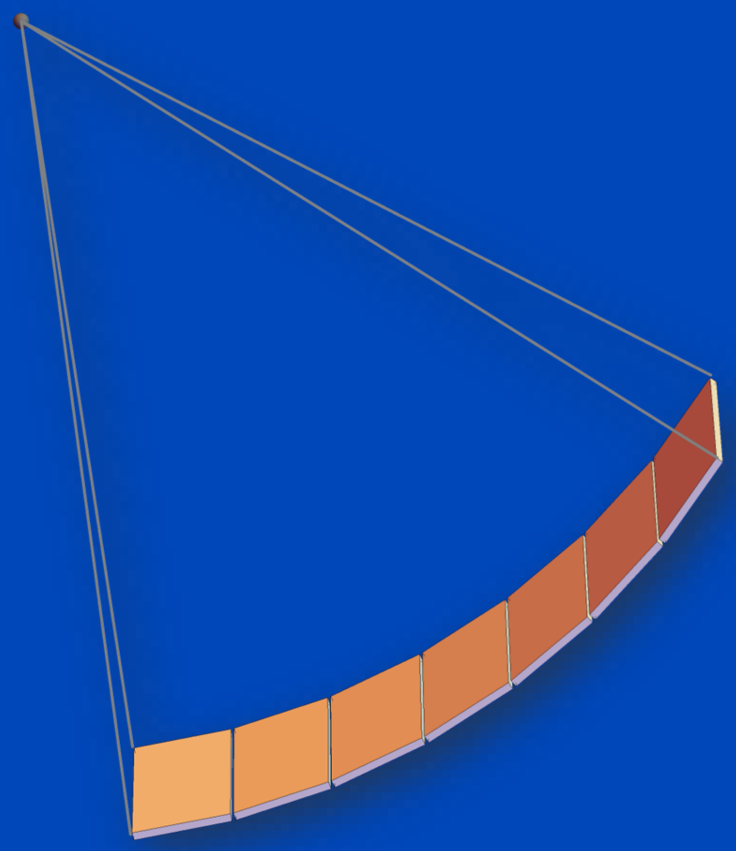
Face on design (all others)

Image courtesy of Siemens Healthineers

The additional factor 2 in the detector pixel size column indicates that some scan modes may use binning.

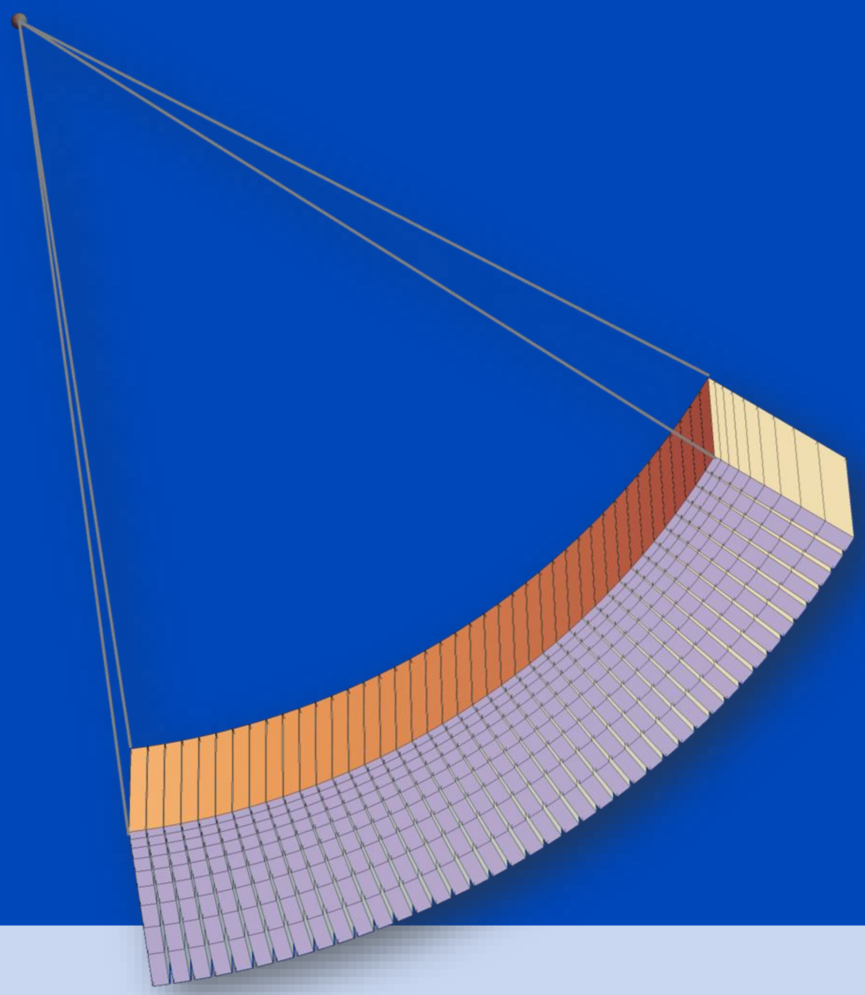
Face-on Design

- Sensor material: CdTe or CZT
- Sensor thickness as seen by the x-ray: millimeters
- E.g. 64×64 pixels per module
  and 16 modules
  to realize a 64-row detector with 1024 channels

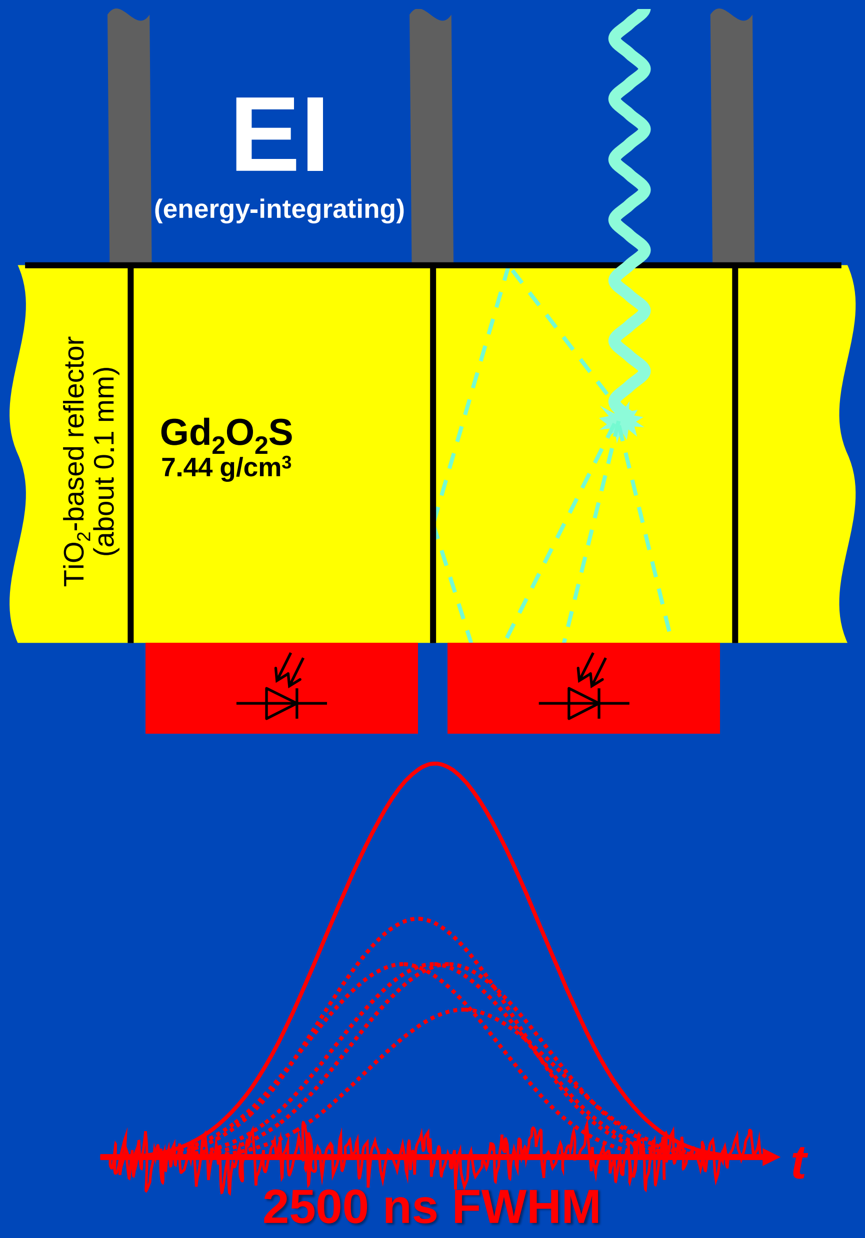


Edge-on Design

- Sensor material: Si
- Sensor thickness as seen by the x-ray: centimeters
- E.g. 64 pixels times 9 in depth per module
  and 1024 modules
  to realize a 64-row detector with 1024 channels

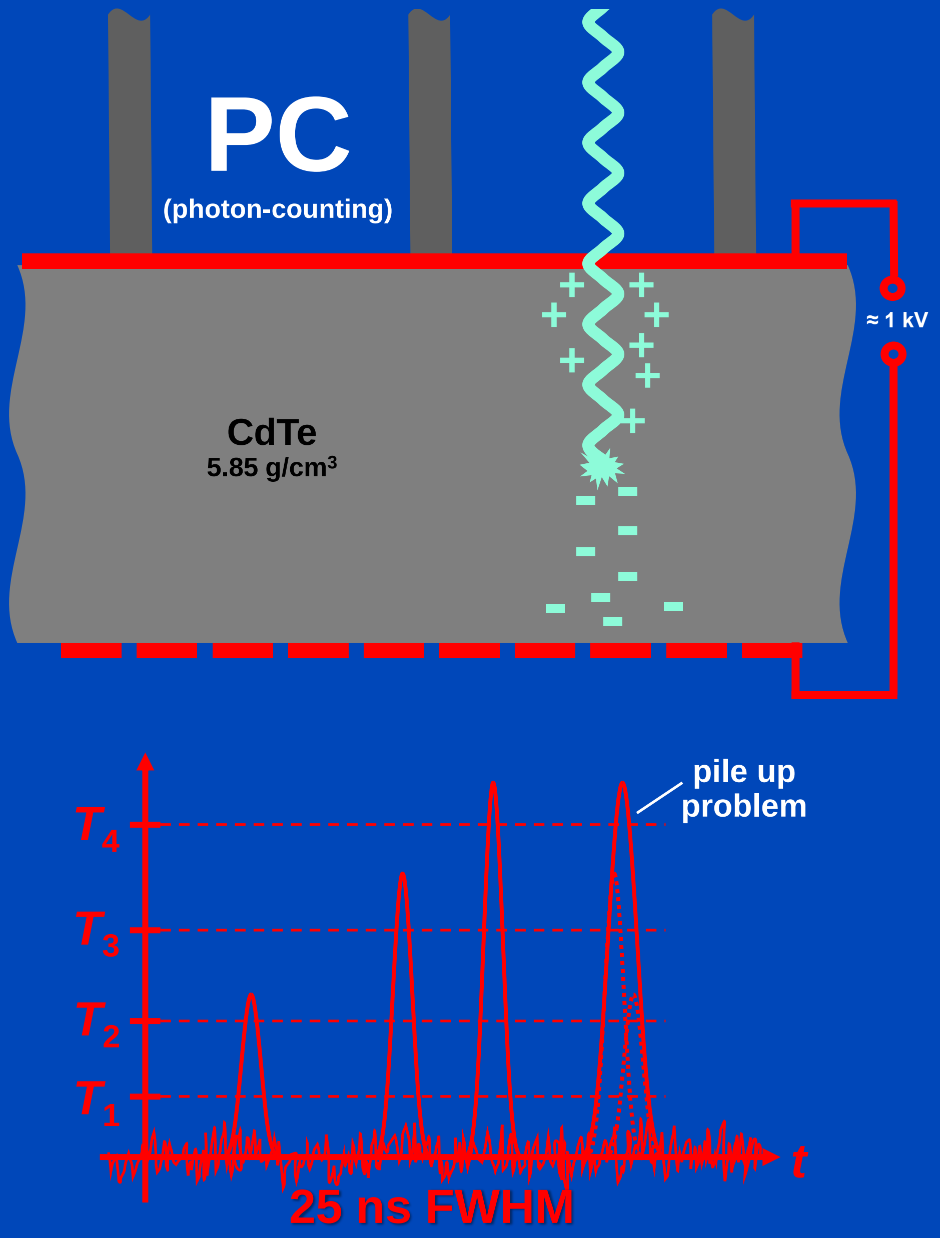


Indirect Conversion



i.e. max O(40·10^3) cps

Direct Conversion

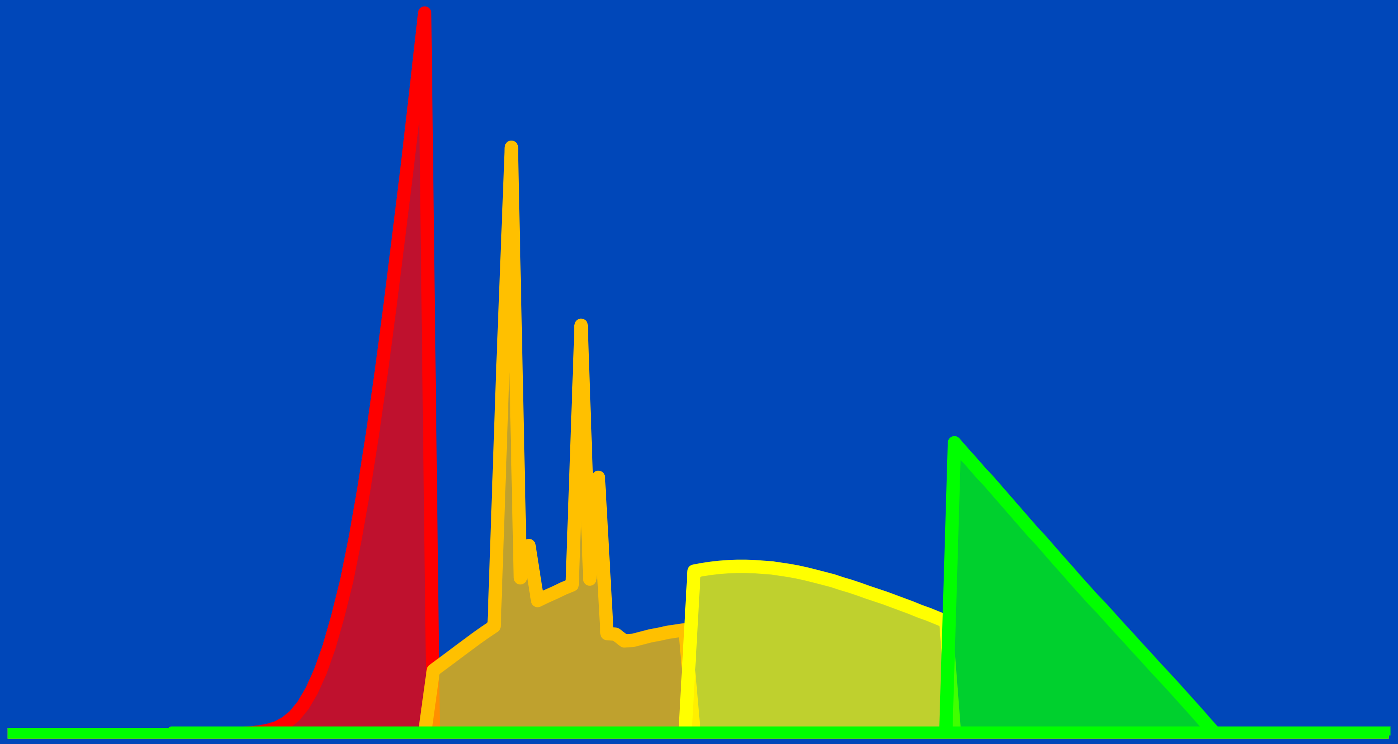


i.e. max O(40·10^6) cps

Requirements for CT: up to 10^9 x-ray photon counts per second per mm^2.
Hence, photon counting only achievable for direct converters.

Energy-Selective Detectors: Improved Spectroscopy, Reduced Dose?

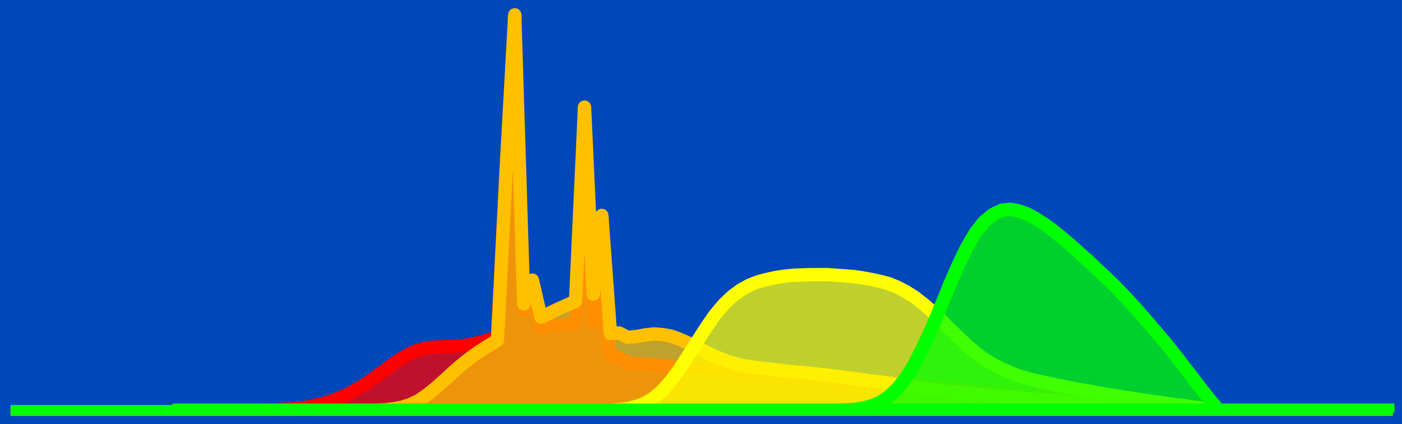
Ideally, bin spectra do not overlap, …



Spectra as seen with 4 bins after having passed a 32 cm water layer.

Energy-Selective Detectors: Improved Spectroscopy, Reduced Dose?

… realistically, however, they do!

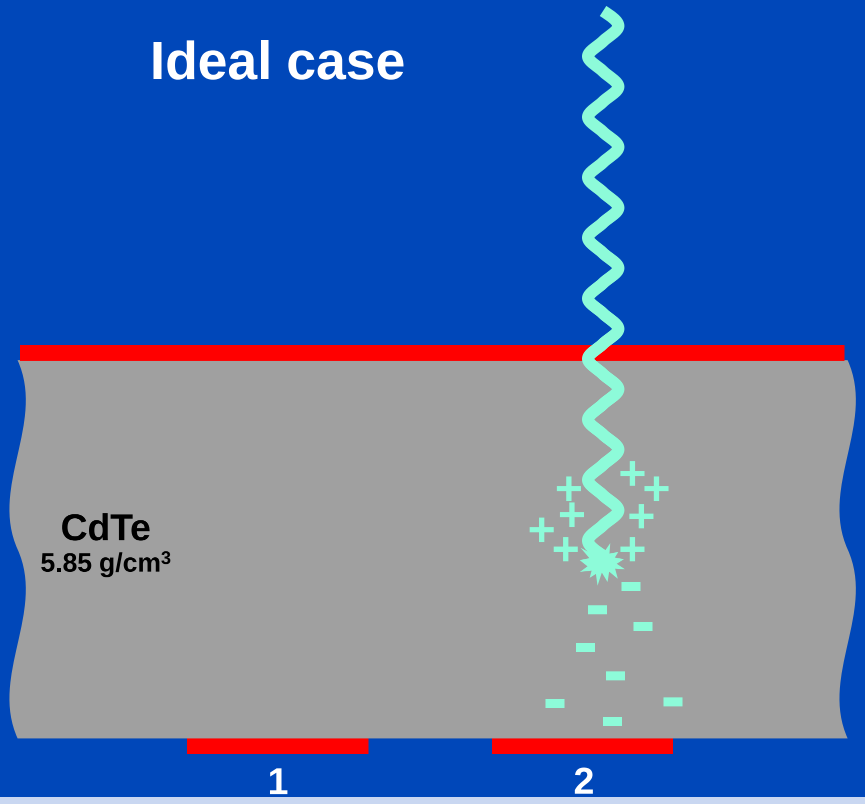


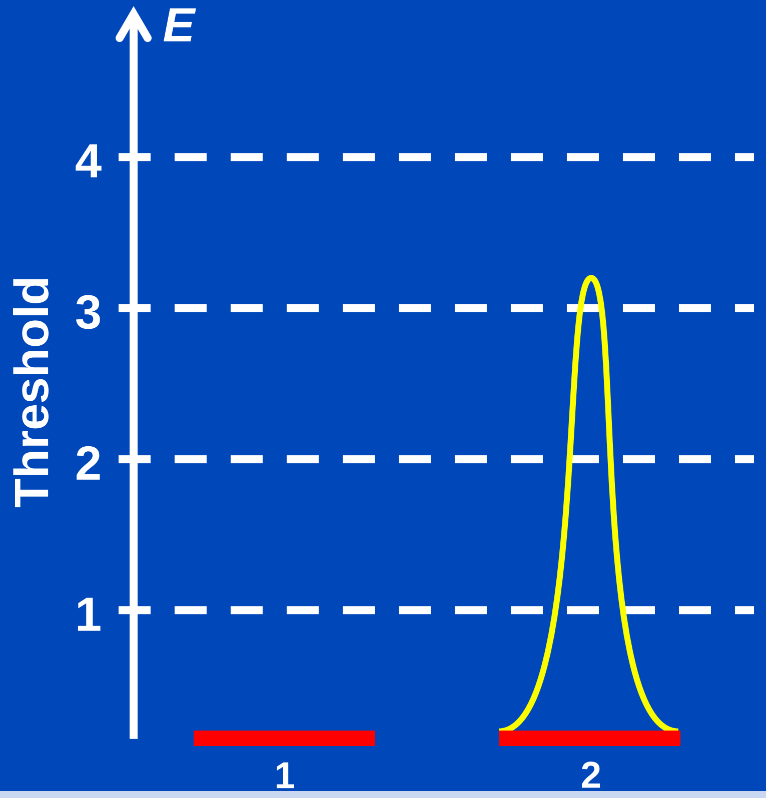
Spectra as seen with 4 bins after having passed a 32 cm water layer.

Photon Events

- Detection process in the sensor
- Photoelectric effect (e.g. 80 keV)

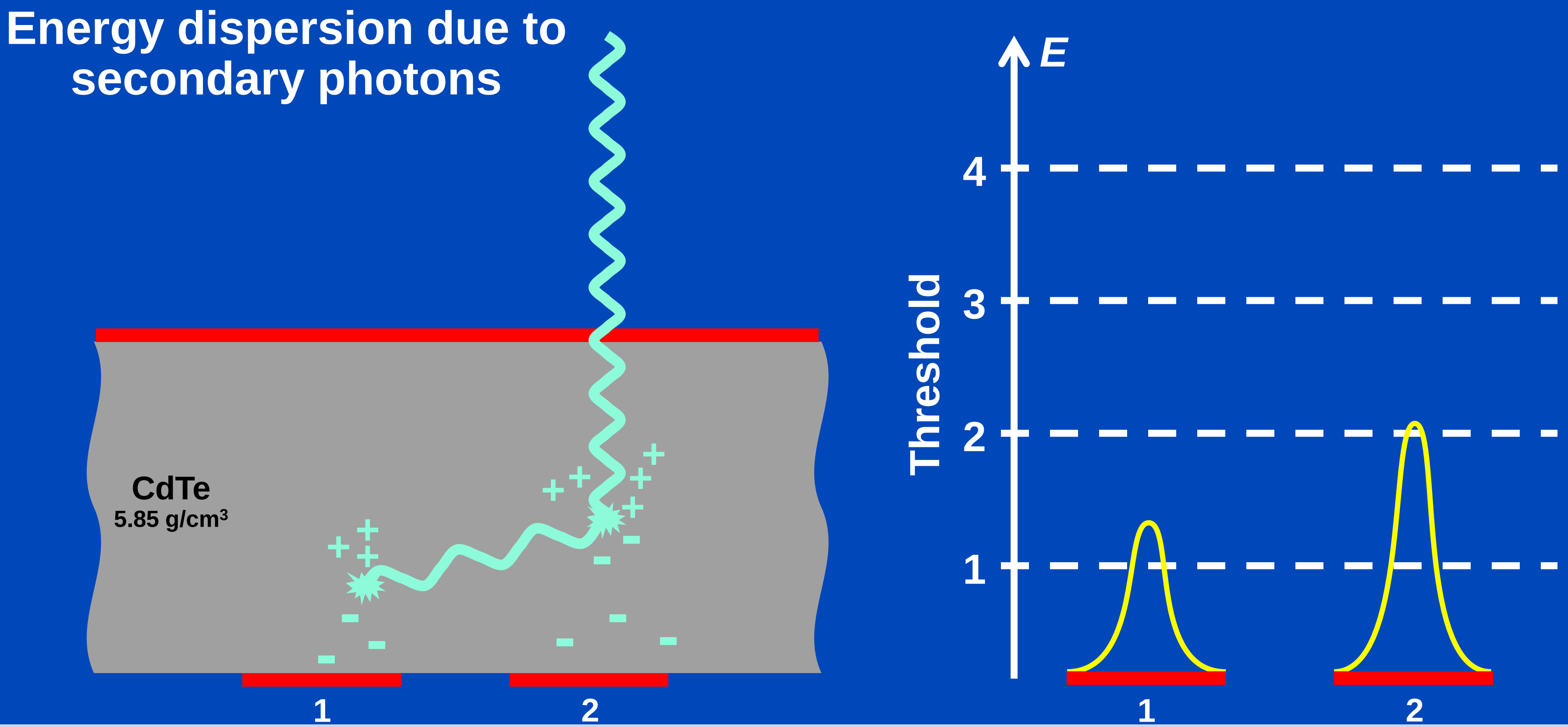
Ideal case





Photon Events

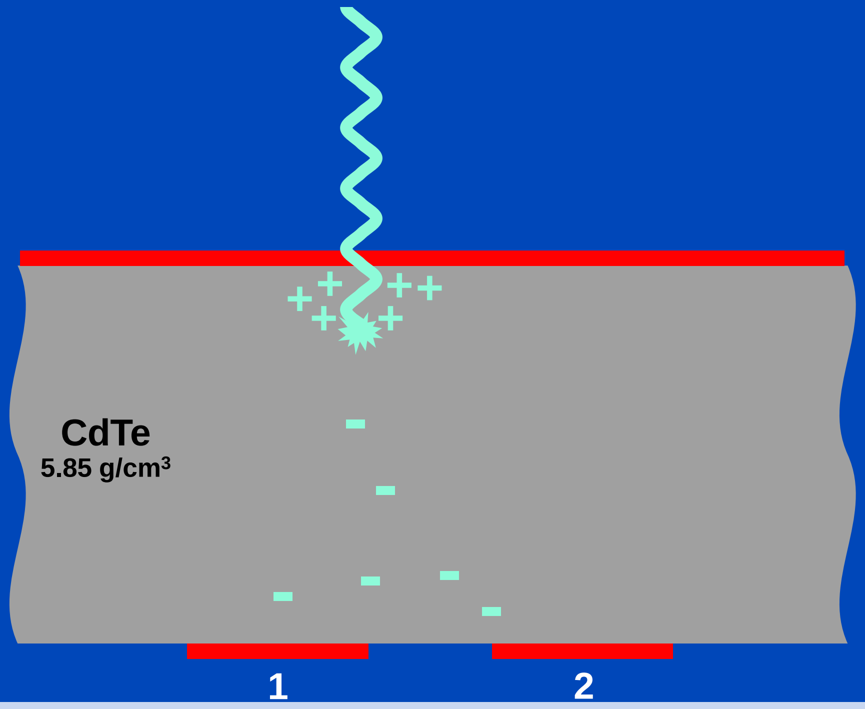
- Detection process in the sensor
- Compton scattering or K-fluorescence (e.g. 80 keV)

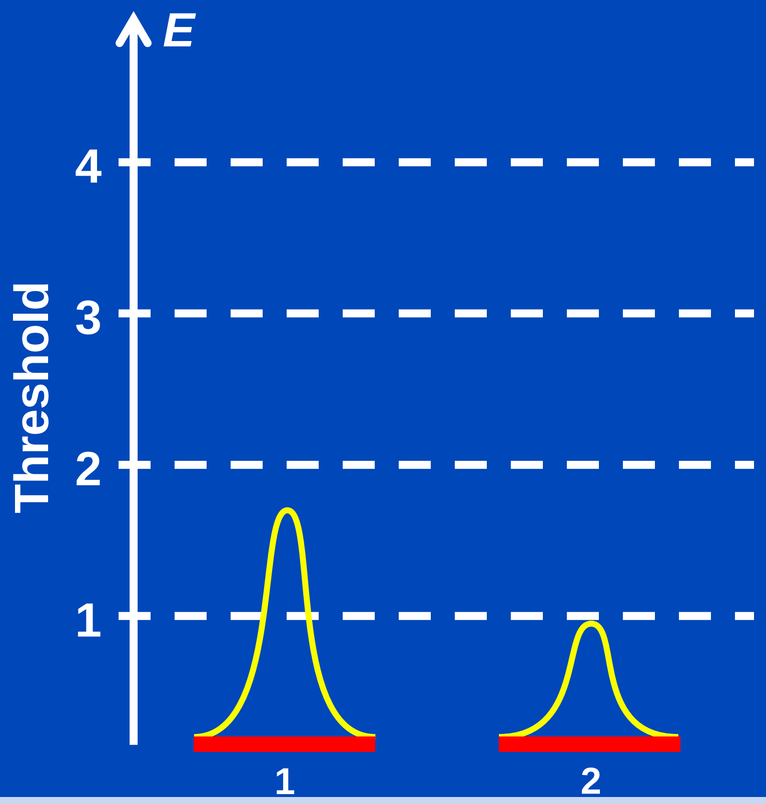


Photon Events

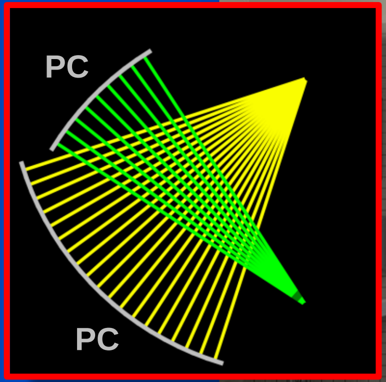
- Detection process in the sensor
- Photoelectric effect (e.g. 30 keV), charge sharing

Energy dispersion due to charge diffusion





Siemens Naeotom Alpha
The World‘s First Photon-Counting CT is a Dual Source PCCT

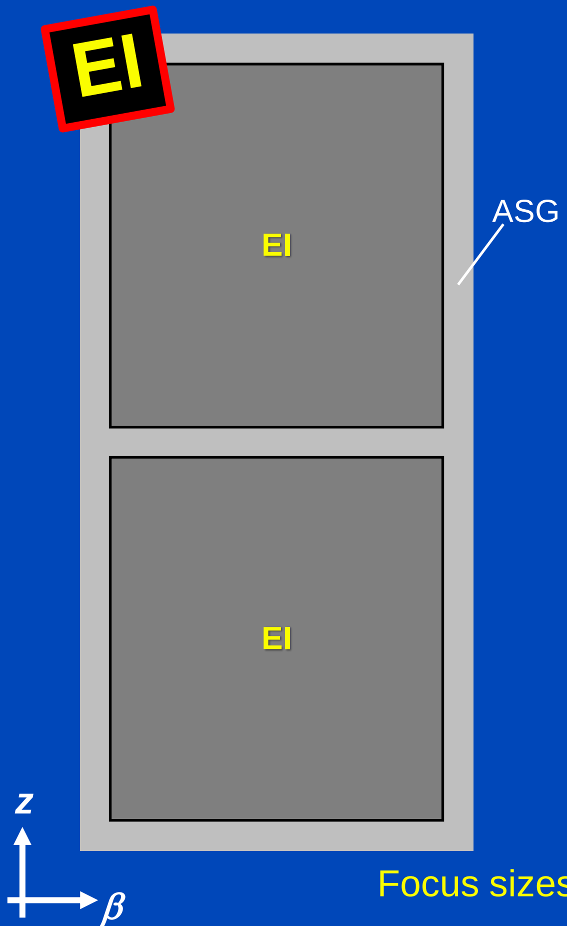


Alpha PCCT at University Medical Center Mannheim (UMM), Heidelberg University, Germany

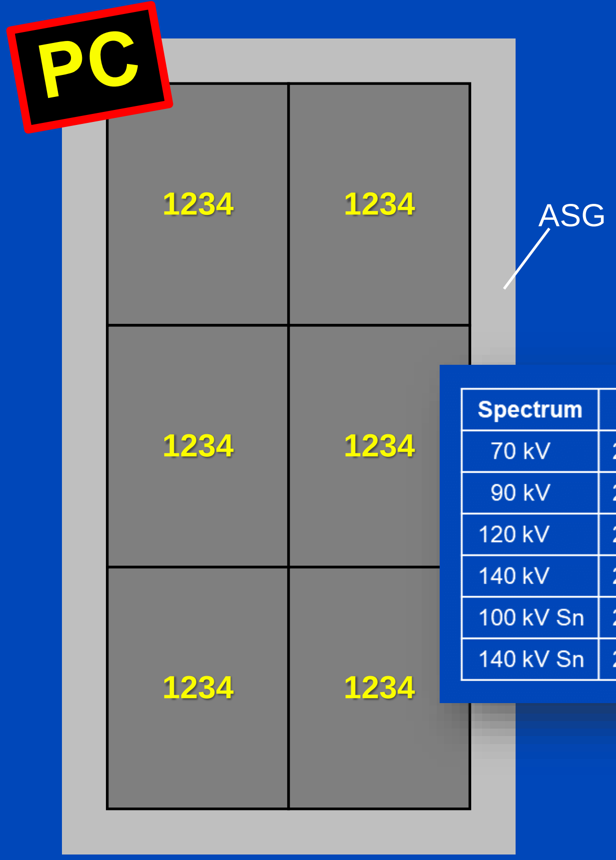
dkfz.

Detector Pixel Force vs. Alpha

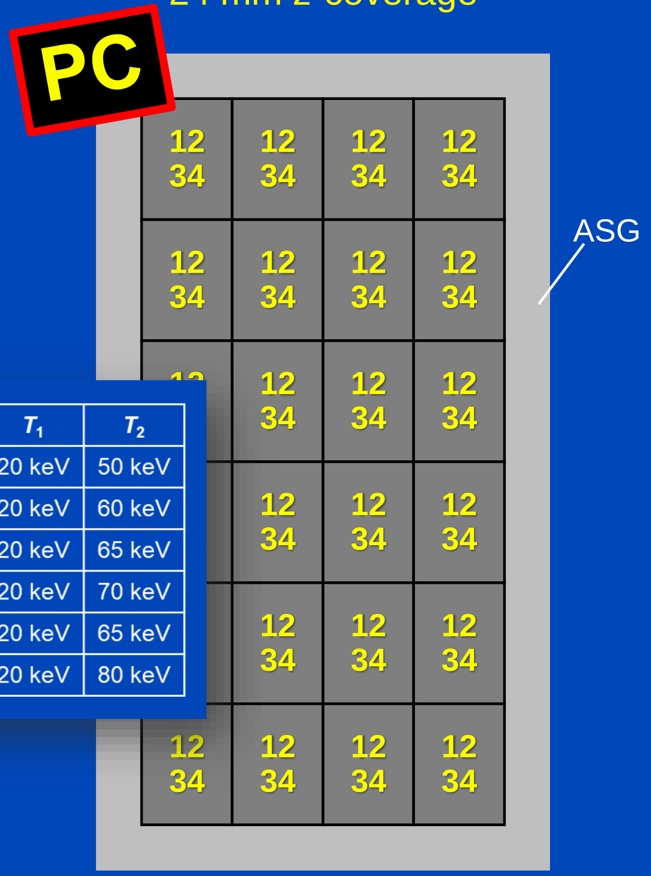
Force
920 × 96 detector pixels
pixel size 0.52 × 0.56 mm at iso
avg. sampling 0.56 × 0.6 mm at iso
57.6 mm z-coverage



Alpha (Quantum Plus)
1376 × 144 macro pixels
pixel size 0.3 × 0.352 mm at iso
avg. sampling 0.344 × 0.4 mm at iso
57.6 mm z-coverage



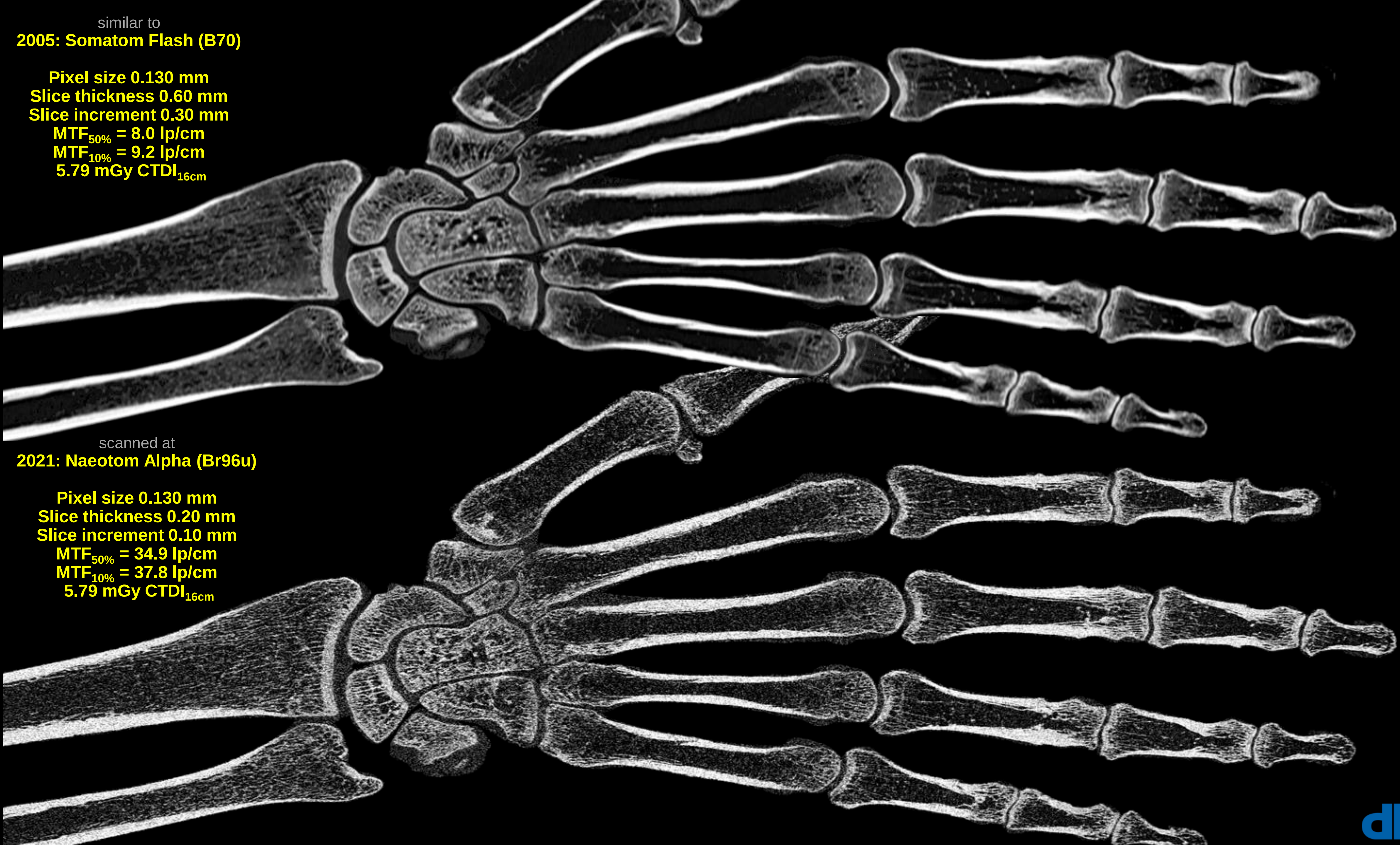
Alpha (UHR)
2752 × 120 pixels
pixel size 0.151 × 0.176 mm at iso
avg. sampling 0.172 × 0.2 mm at iso
24 mm z-coverage



Spectrum	T_1	T_2
70 kV	20 keV	50 keV
90 kV	20 keV	60 keV
120 kV	20 keV	65 keV
140 kV	20 keV	70 keV
100 kV Sn	20 keV	65 keV
140 kV Sn	20 keV	80 keV

Focus sizes (Vectron): 0.181×0.226 mm, 0.271×0.7316 mm, 0.362×0.497 mm at iso
which are 0.4×0.5 mm, 0.6×0.7 mm, 0.8×1.1 mm at focal spot

ASG information taken from [J. Ferda et al. Computed tomography with a full FOV photon-counting detector in a clinical setting, the first experience. European Journal of Radiology 137:109614, 2021]



similar to
2005: Somatom Flash (B70)

Pixel size 0.130 mm
Slice thickness 0.60 mm
Slice increment 0.30 mm
$MTF_{50\%}$ = 8.0 lp/cm
$MTF_{10\%}$ = 9.2 lp/cm
5.79 mGy $CTDI_{16cm}$

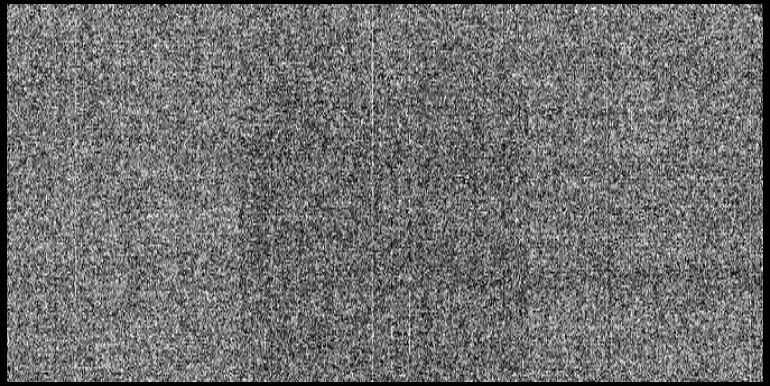
scanned at
2021: Naeotom Alpha (Br96u)

Pixel size 0.130 mm
Slice thickness 0.20 mm
Slice increment 0.10 mm
$MTF_{50\%}$ = 34.9 lp/cm
$MTF_{10\%}$ = 37.8 lp/cm
5.79 mGy $CTDI_{16cm}$

Advantages of Photon-Counting CT

- No reflective gaps between detector pixels
  - Higher geometrical efficiency
  - Less dose
- No electronic noise (every photon counts)
  - Less dose for infants
  - Less noise for obese patients
- Energy bins = spectral information
  - Lower dose/noise
  - Improved iodine CNR
  - Dual energy CT (DECT)
  - Potential for standardization
- Counting
  - Swank factor = 1 = maximal
  - “Iodine effect“ due to higher weights on low energies
- Smaller pixels (to avoid pileup)
  - Higher spatial resolution
  - “Small pixel effect” i.e. lower dose/noise at conventional resolution

EI (Dexela)



Readout noise only. Single events hidden!

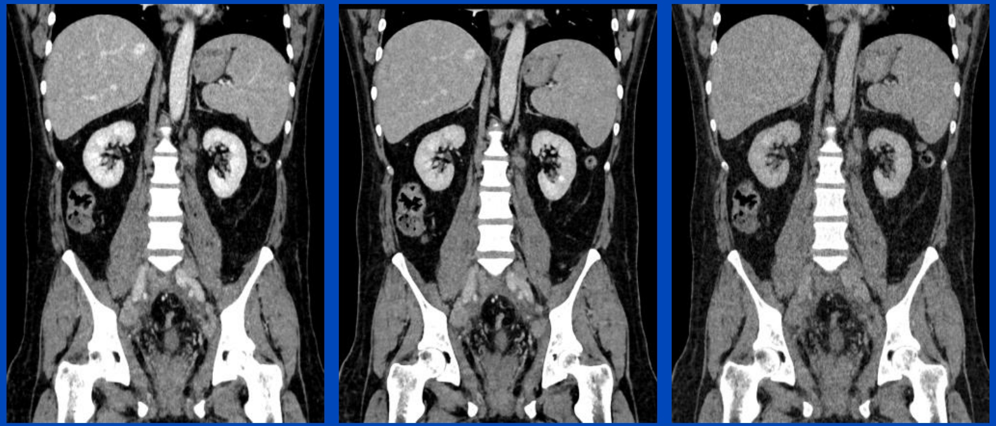
PC (Dectris)

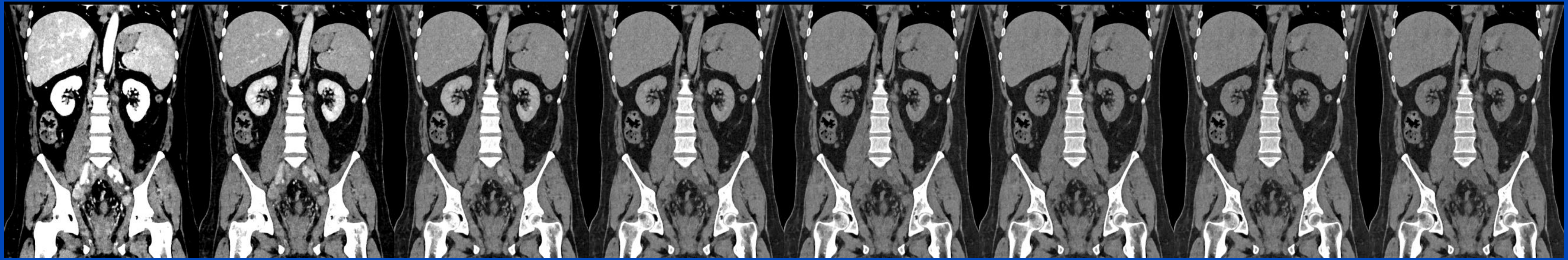
No readout noise. Single events visible!

18 frames, 5 min integration time per frame, x-ray off

Virtual Monochromatic Imaging (VMI)

- **Linear combination of Lo and Hi with noise reduction** (e.g. Siemens` Mono+)
- **Standardizes the gray values regardless of tube voltage**
  - **not only for water or soft tissue**
  - **but also for other materials (e.g. bone, iodine, …)**
- **Energy or "keV level"**
  - **optimum value depends on task (non-contrast, bone, contrast-enhanced, vasular …)**
  - **can be freely adjusted** (but then changes the gray values)
- **VMI images are displayed by default.**





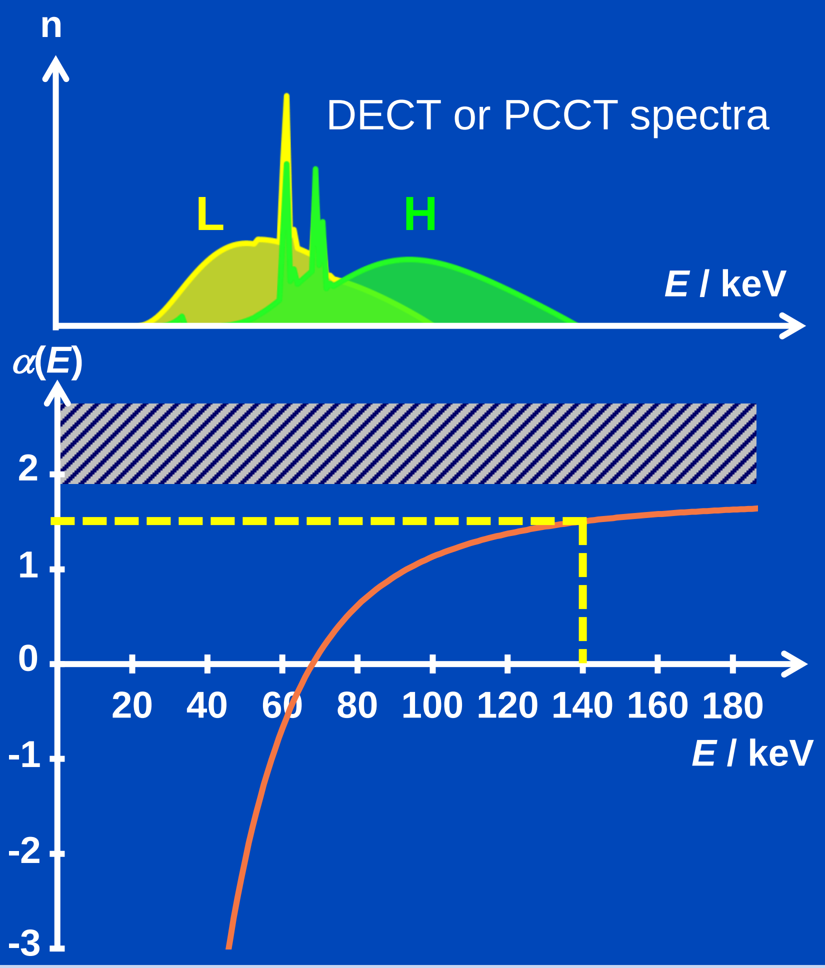
C = 60 HU, *W* = 360 HU

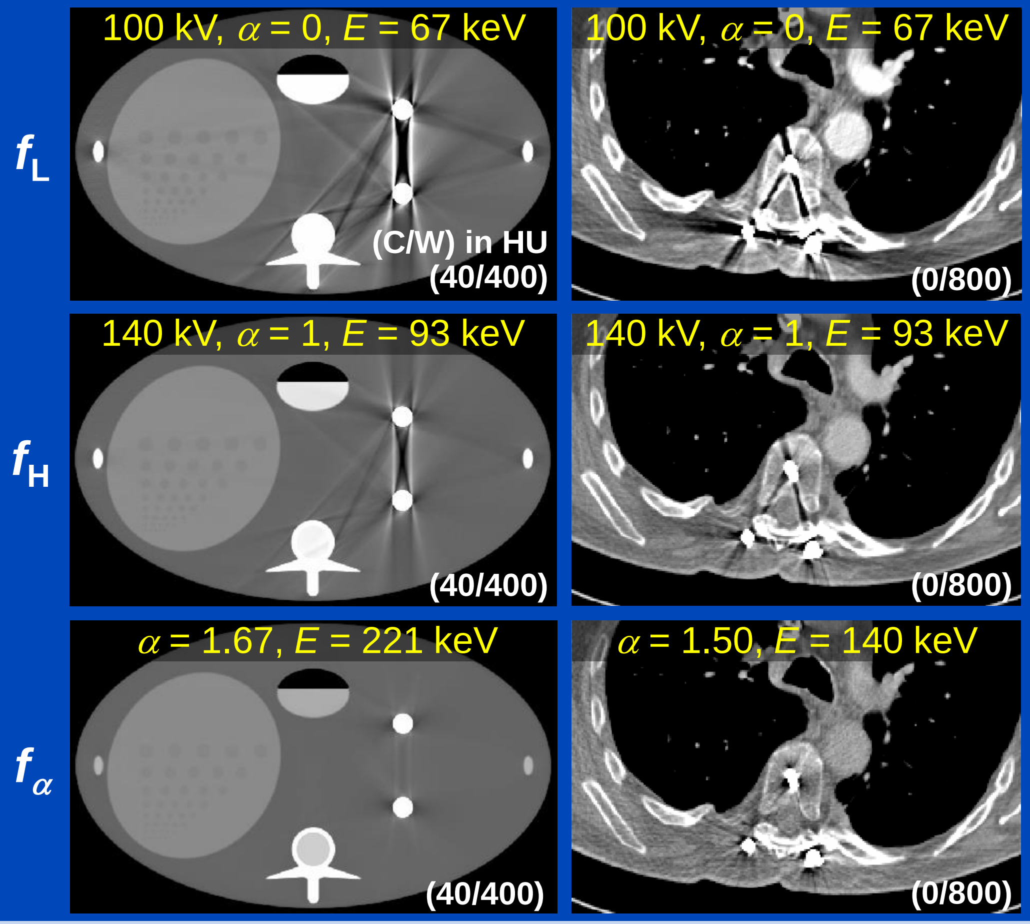
dkfz.

Spectral CT and Virtual Monoenergetic Images

VMIs are a linear combination of low and high energy images f_L and f_H:

$$f_\alpha = (1-\alpha)\, f_L + \alpha\, f_H$$

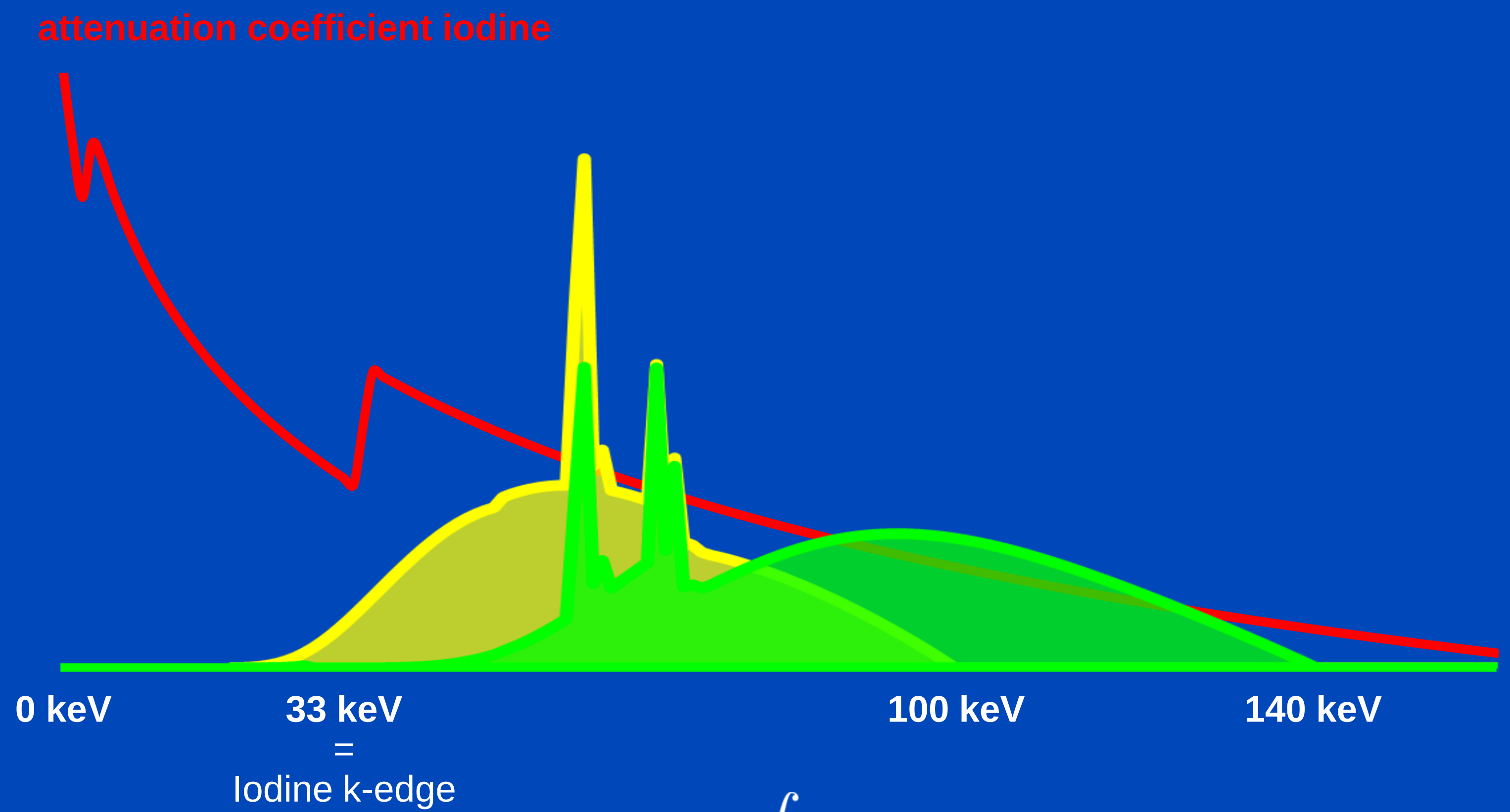




Kuchenbecker, Faby, Sawall, Lell, and Kachelrieß. Dual energy CT:
How well can pseudo-monochromatic imaging reduce metal artifacts? Med. Phys. 42(2), 2015

dkfz.

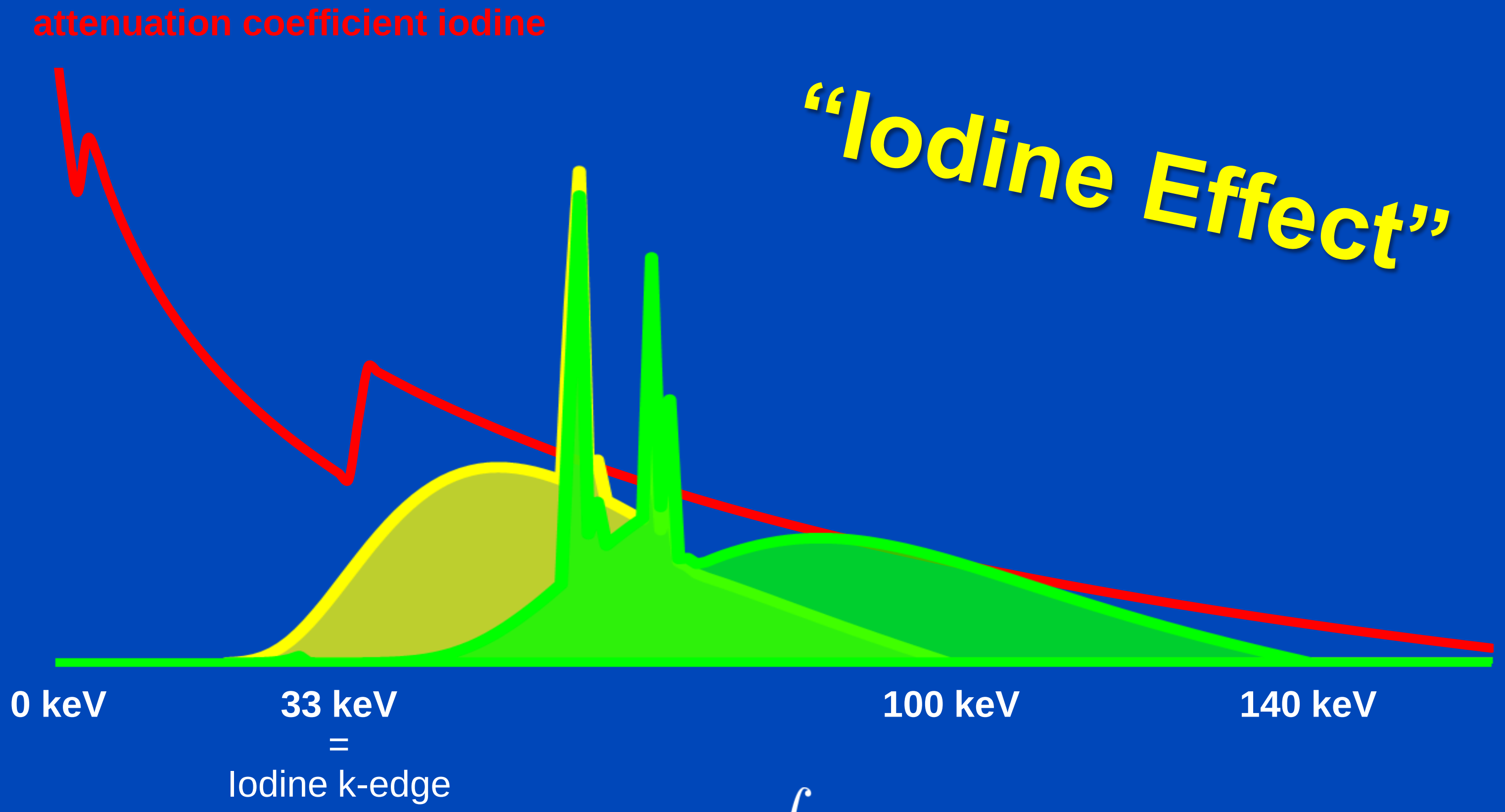
Energy Integrating
(Detected Spectra at 100 kV and 140 kV)



$$\text{Signal}_{\text{EI}} = \int dE\, E\;\; N(E)$$

100 kV and 140 kV EI spectra as seen after having passed 32 cm of water.

Photon Counting
(Detected Spectra at 100 kV and 140 kV)



$$\text{Signal}_{\text{PC}} = \int dE\, 1\ N(E)$$

100 kV and 140 kV PC spectra (one bin) as seen after having passed 32 cm of water.

dkfz.

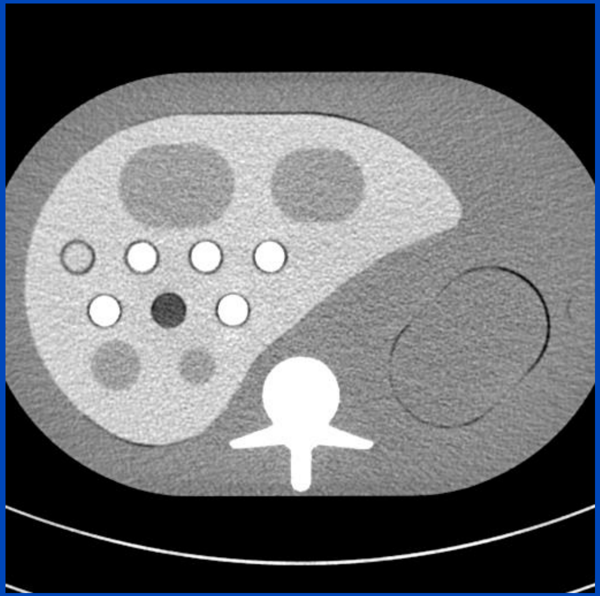
Iodine CNRD Assessment

- Images are acquired at **different tube voltages:**
  - 80 kV at 4.40 mGy ($CTDI_{vol\ 32\ cm}$) using 200 mAs_{eff}
  - 100 kV at 9.20 mGy ($CTDI_{vol\ 32\ cm}$) using 200 mAs_{eff}
  - 120 kV at 15.03 mGy ($CTDI_{vol\ 32\ cm}$) using 200 mAs_{eff}
  - 140 kV at 21.76 mGy ($CTDI_{vol\ 32\ cm}$) using 200 mAs_{eff}
- Pitch in all acquisitions was 0.6.
- Collimation for EI (32×0.6 mm) and PC (32×0.5 mm) was matched as close as possible, i.e. geometric efficiency is 80% vs. 82%
- Reconstruction is performed with **matched spatial resolution** using a D40f kernel onto a grid with a voxel spacing of 0.54 mm and a slice thickness of 1.2 mm.
- The **thresholds were fixed at 20 keV and 50 keV**, resulting in two bins: [20 keV, 50 keV] and [50 keV, *eU*].

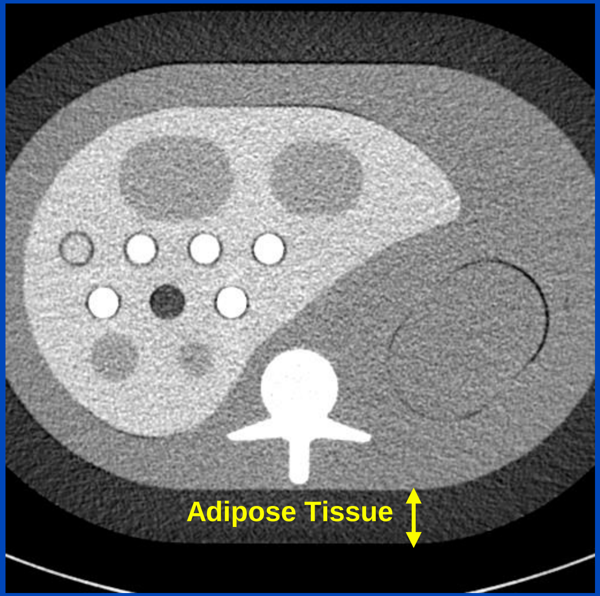
Iodine CNRD Assessment

Reconstruction Examples @ 80 kV

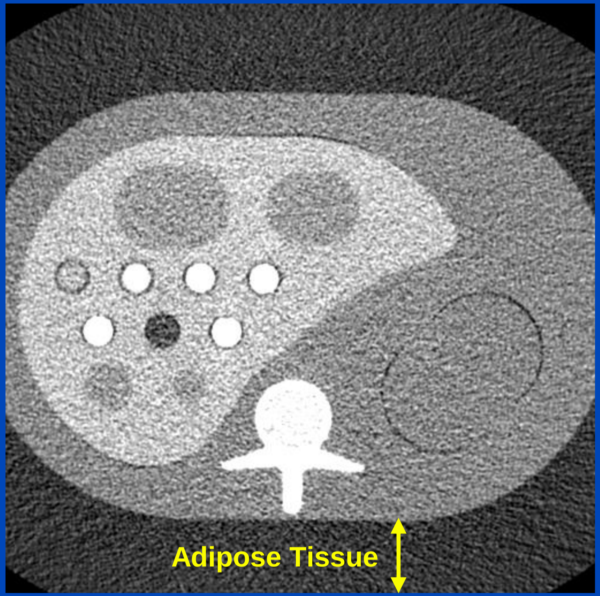
Small (200 × 300 mm)



Medium (250 × 350 mm)



Large (300 × 400 mm)

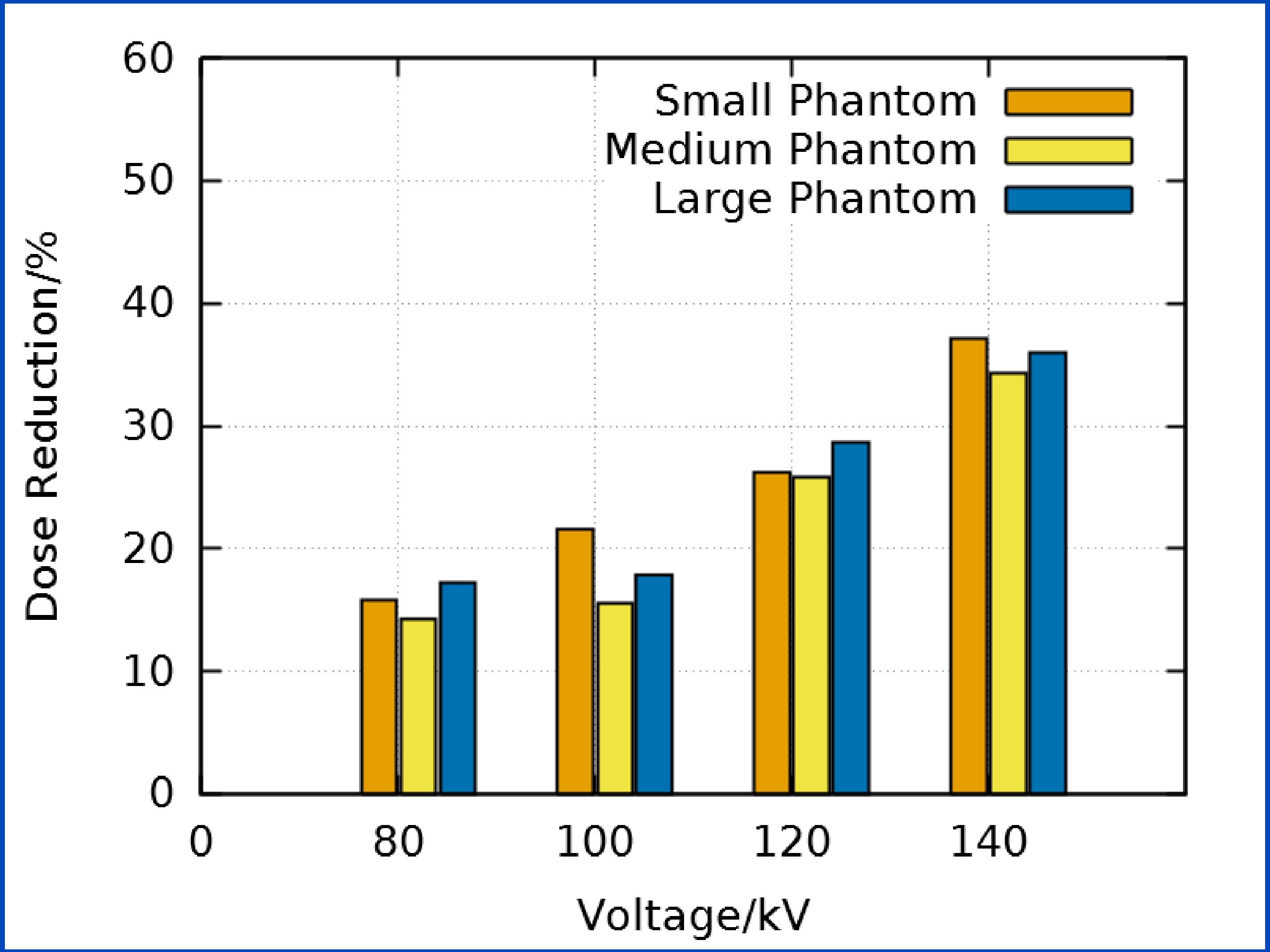


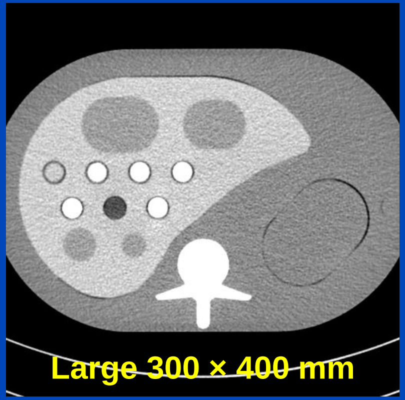
C = 0 HU, *W* = 400 HU

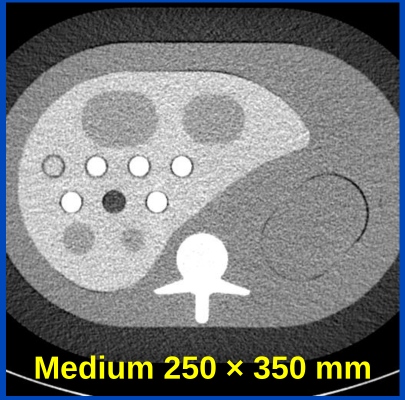
S. Sawall, M. Kachelrieß et al. Iodine contrast-to-noise ratio improvement at unit dose and contrast media volume reduction in whole-body photon-counting CT. Eur. J. Radiol. 126:108909, 2020.

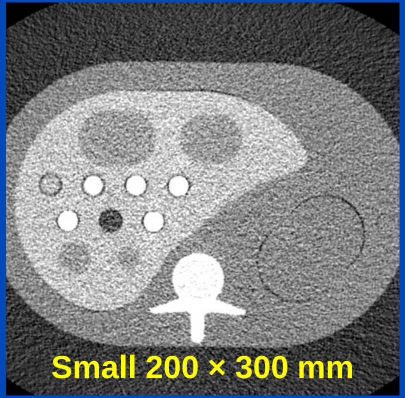
PC with 1 Bin vs. EI

Potential Dose Reduction also due to Iodine Effect







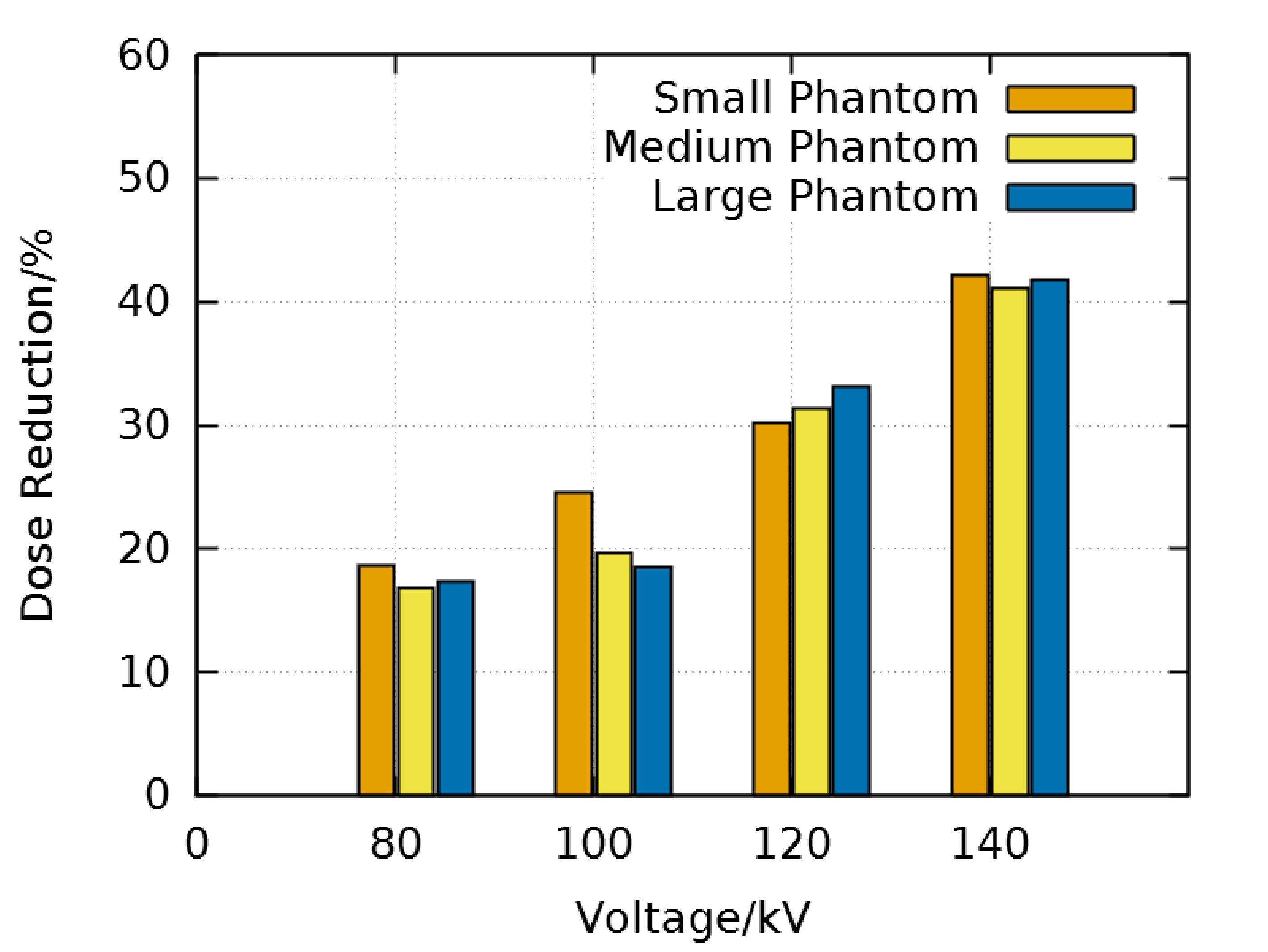


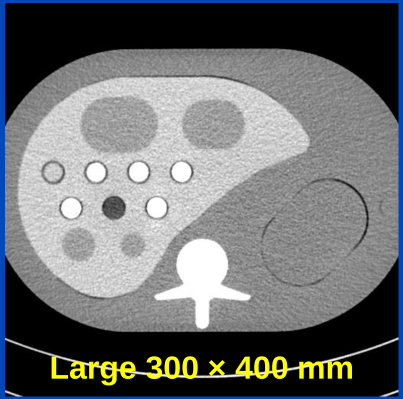
S. Sawall, M. Kachelrieß et al. Iodine contrast-to-noise ratio improvement at unit dose and contrast media volume reduction in whole-body photon-counting CT. Eur. J. Radiol. 126:108909, 2020.

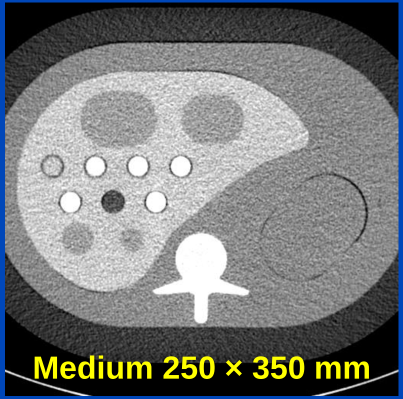
dkfz.

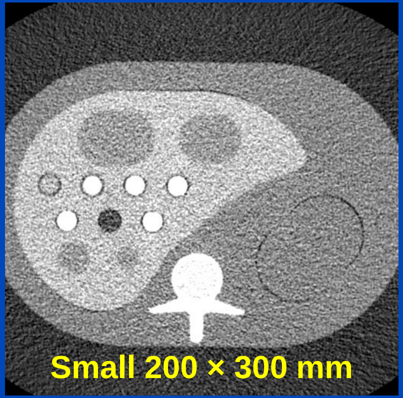
PC with 2 Bins vs. EI

Potential Dose Reduction also due to Iodine Effect



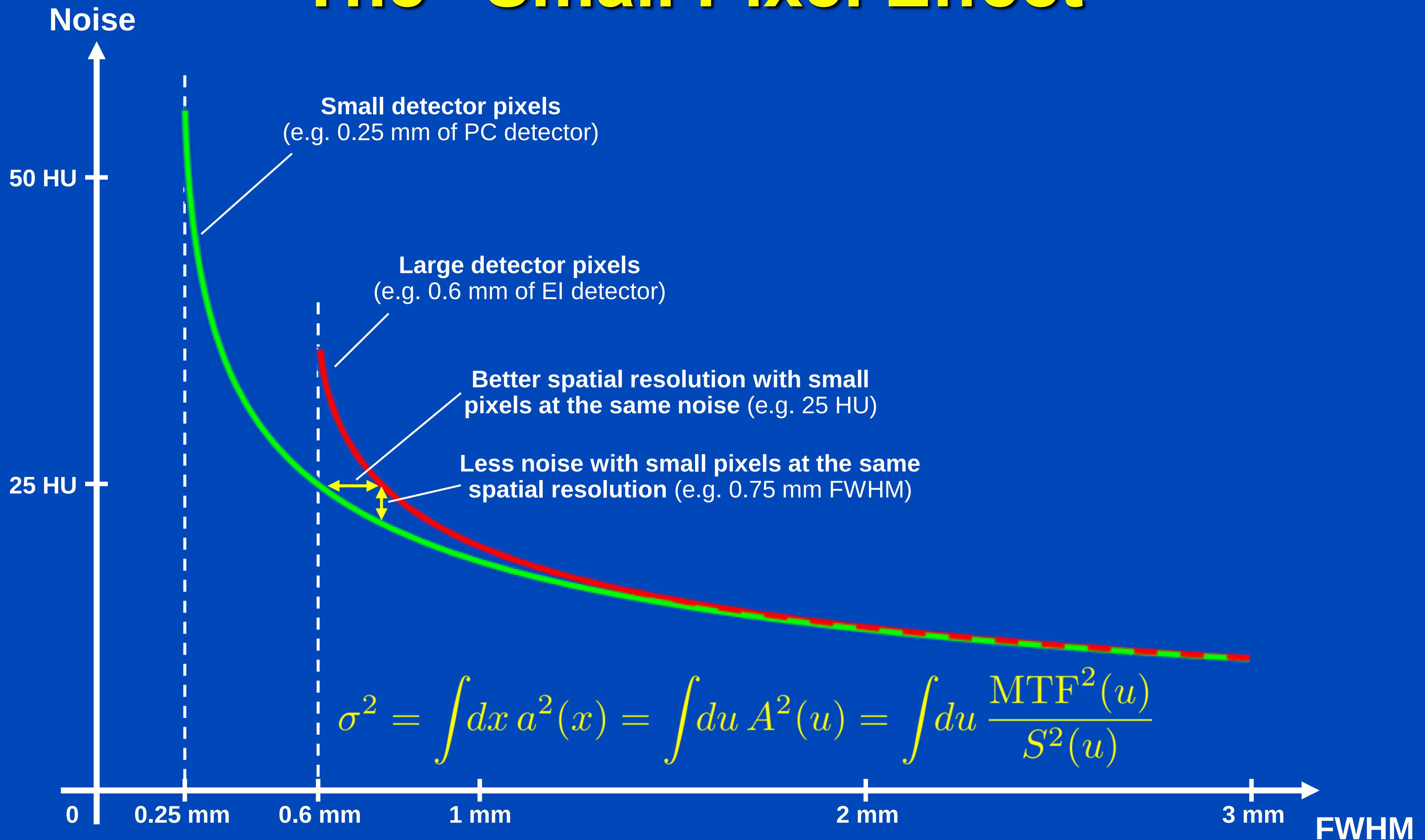






S. Sawall, M. Kachelrieß et al. Iodine contrast-to-noise ratio improvement at unit dose and contrast media volume reduction in whole-body photon-counting CT. Eur. J. Radiol. 126:108909, 2020.

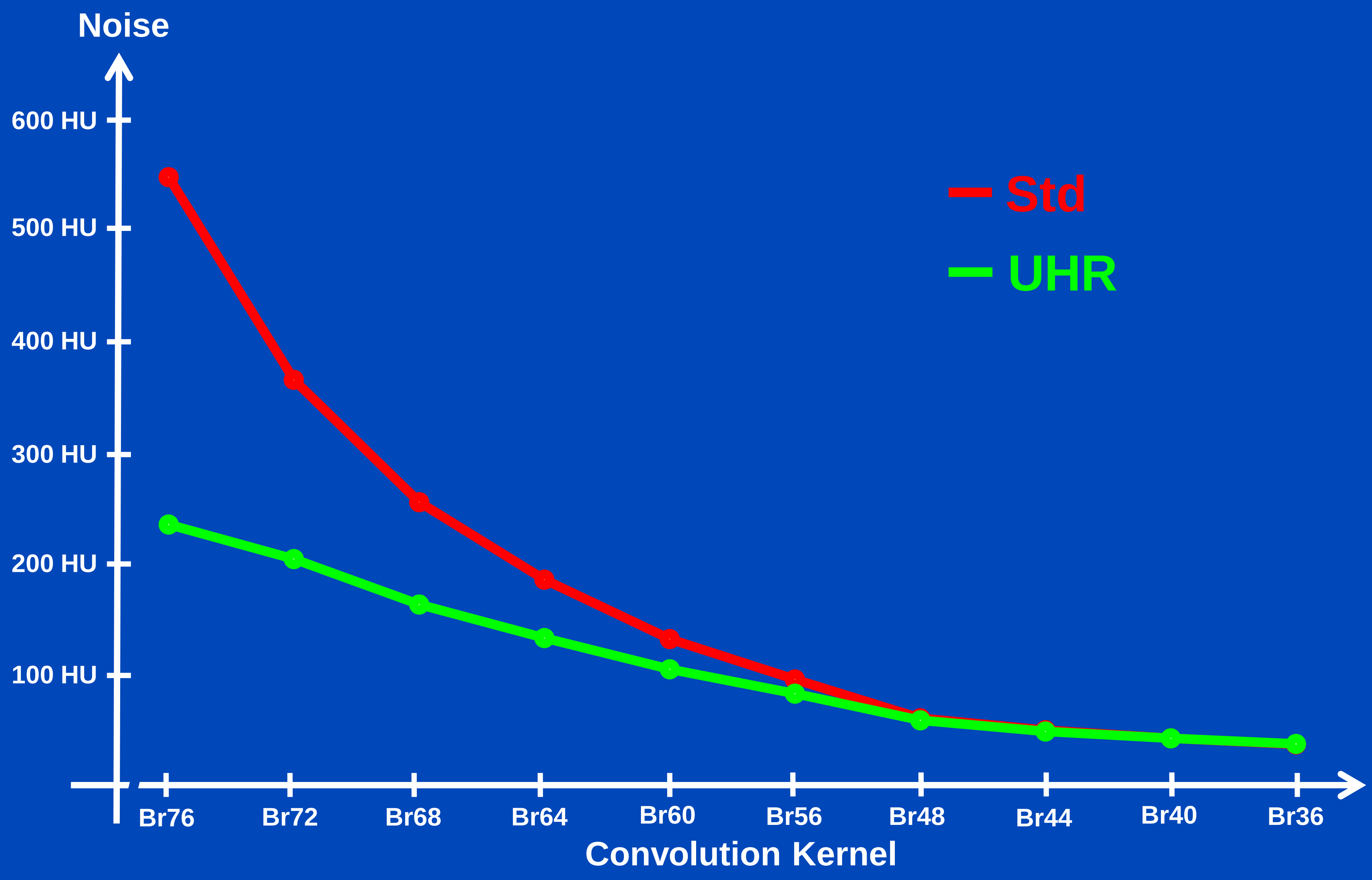
The "Small Pixel Effect"



$$\sigma^2 = \int dx\, a^2(x) = \int du\, A^2(u) = \int du\, \frac{\mathrm{MTF}^2(u)}{S^2(u)}$$

Small Pixel Effect at Naeotom Alpha

Medium Phantom, 4 mGy $CTDI_{32}$

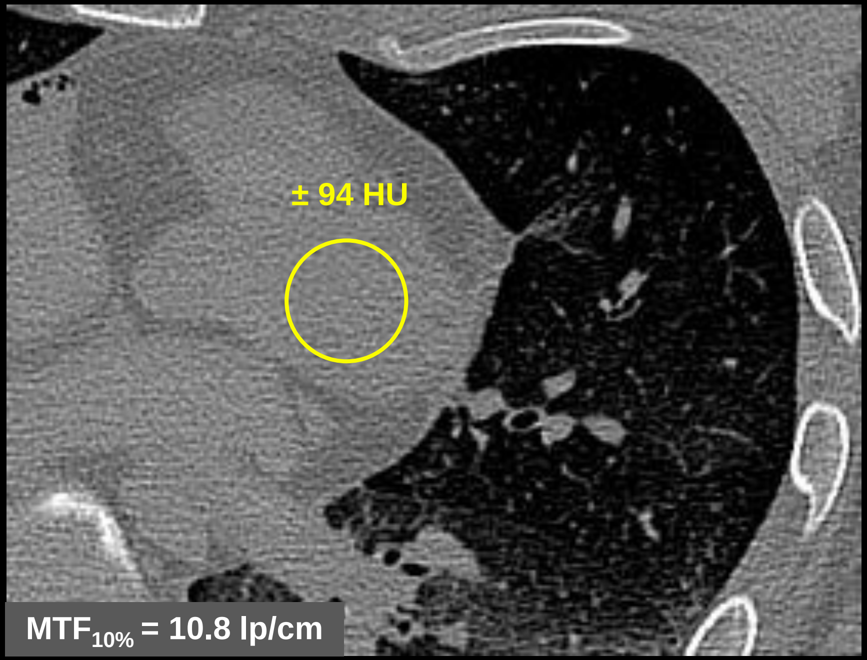


To disable the longitudinal small pixel effect, we reconstructed rather thick slices (1 mm thickness).

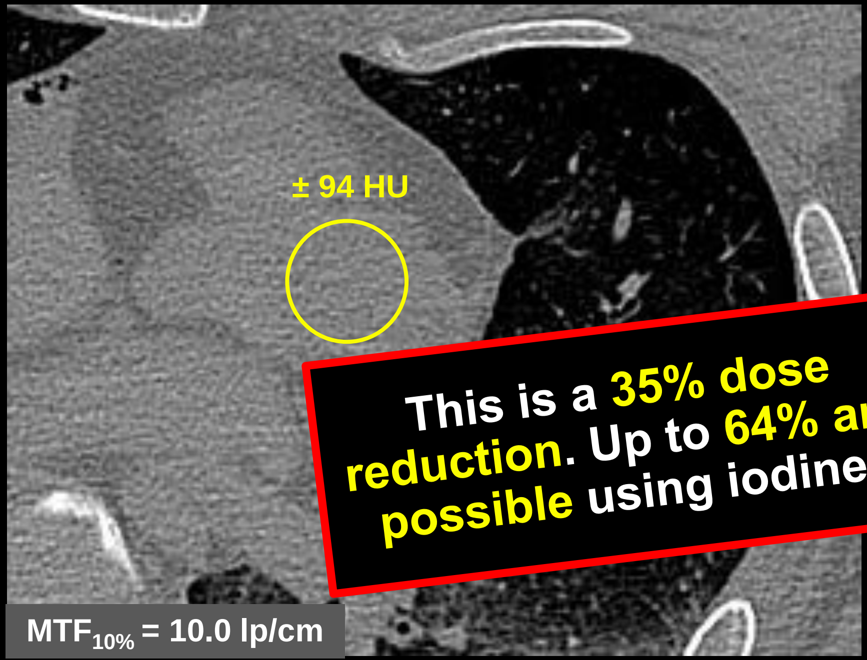
dkfz.

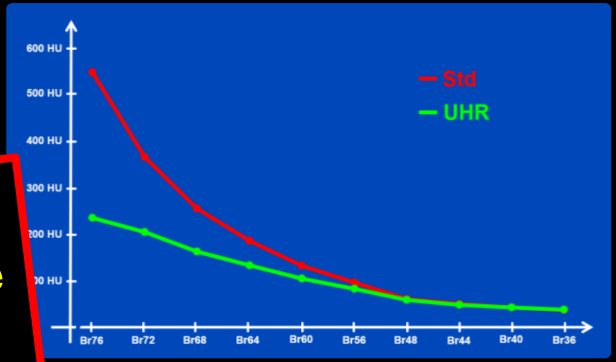
L. Klein, C. Amato, S. Heinze, M. Uhrig, H.-P. Schlemmer, M. Kachelrieß, and S. Sawall.
Effects of Detector Sampling on Noise Reduction in a Clinical Photon Counting Whole-Body CT. Investigative Radiology, vol. 55(2):111-119, February 2020.

Energy Integrating Detector (B70f)



Photon Counting Detector (B70f)





This is a 35% dose reduction. Up to 64% are possible using iodine.

Acquisition with EI:
- **Tube voltage of 120 kV**
- **Tube current of 300 mAs**
- **Resulting dose of $CTDI_{vol\ 32\ cm}$ = 22.6 mGy**

Acquisition with UHR:
- **Tube voltage of 120 kV**
- **Tube current of 180 mAs**
- **Resulting dose of $CTDI_{vol\ 32\ cm}$ = 14.6 mGy**

C = 50 HU, *W* = 1500 HU

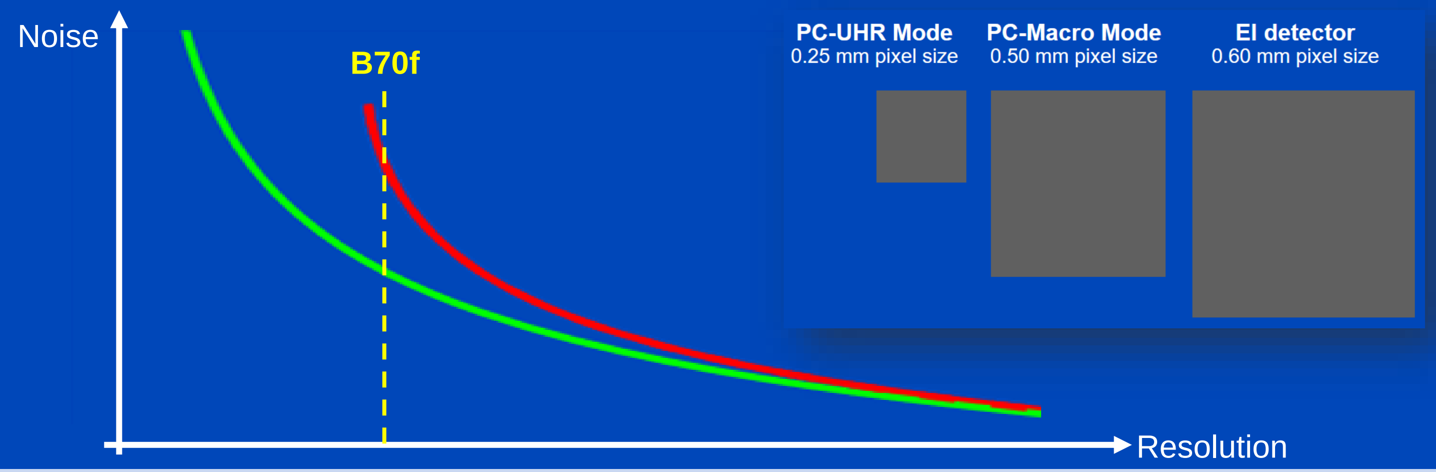
X-Ray Dose Reduction of B70f

PC vs. PC
(“small pixel effect only”)

UHR vs. Std	80 kV	100 kV	120 kV	140 kV
S	**23%** ± 12%	**34%** ± 10%	**35%** ± 11%	**25%** ± 10%
M	**32%** ± 10%	**32%** ± 8%	**35%** ± 8%	**34%** ± 9%
L	**35%** ± 10%	**29%** ± 15%	**27%** ± 9%	**31%** ± 11%

PC vs. EI
(“small pixel effect” and “iodine effect”)

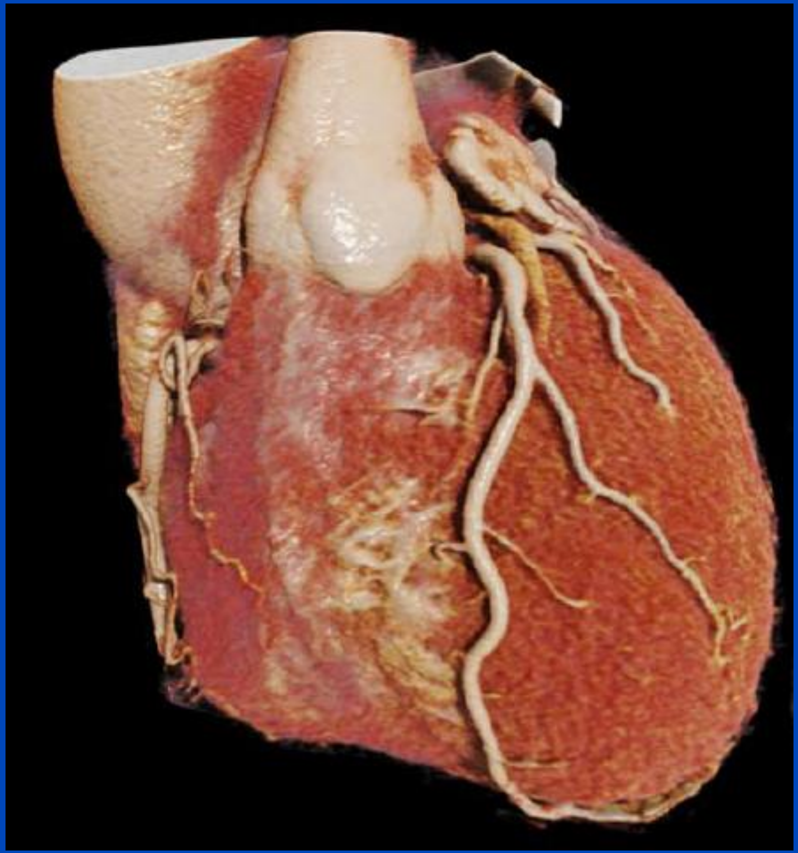
UHR vs. EI	80 kV	100 kV	120 kV	140 kV
S	**33%** ± 9%	**52%** ± 5%	**57%** ± 7%	**57%** ± 6%
M	**41%** ± 8%	**47%** ± 7%	**60%** ± 6%	**62%** ± 4%
L	**48%** ± 8%	**43%** ± 10%	**54%** ± 6%	**63%** ± 5%



Klein, Kachelrieß, Sawall et al. Invest. Radiol. 55(2), Feb 2020

Conclusions

- PCCT offers several technical advantages:
  - low dose
  - high spatial resolution
  - spectral information
  - more standardized CT values
- Thereby, it outperforms EICT systems.



Mergen et al. Ultra-high-resolution coronary CT angiography with photon-counting detector CT. Invest. Radiol. 57(12), 2022

Thank You!

- This presentation will soon be available at www.dkfz.de/ct.
- Job opportunities through DKFZ's international PhD or Postdoctoral Fellowship programs (marc.kachelriess@dkfz.de).
- Parts of the reconstruction software were provided by RayConStruct® GmbH, Nürnberg, Germany.

dkfz.