EFOMP Workshop, ECR, March 1, 2023

Technical Possibilities of Photon-Counting CT

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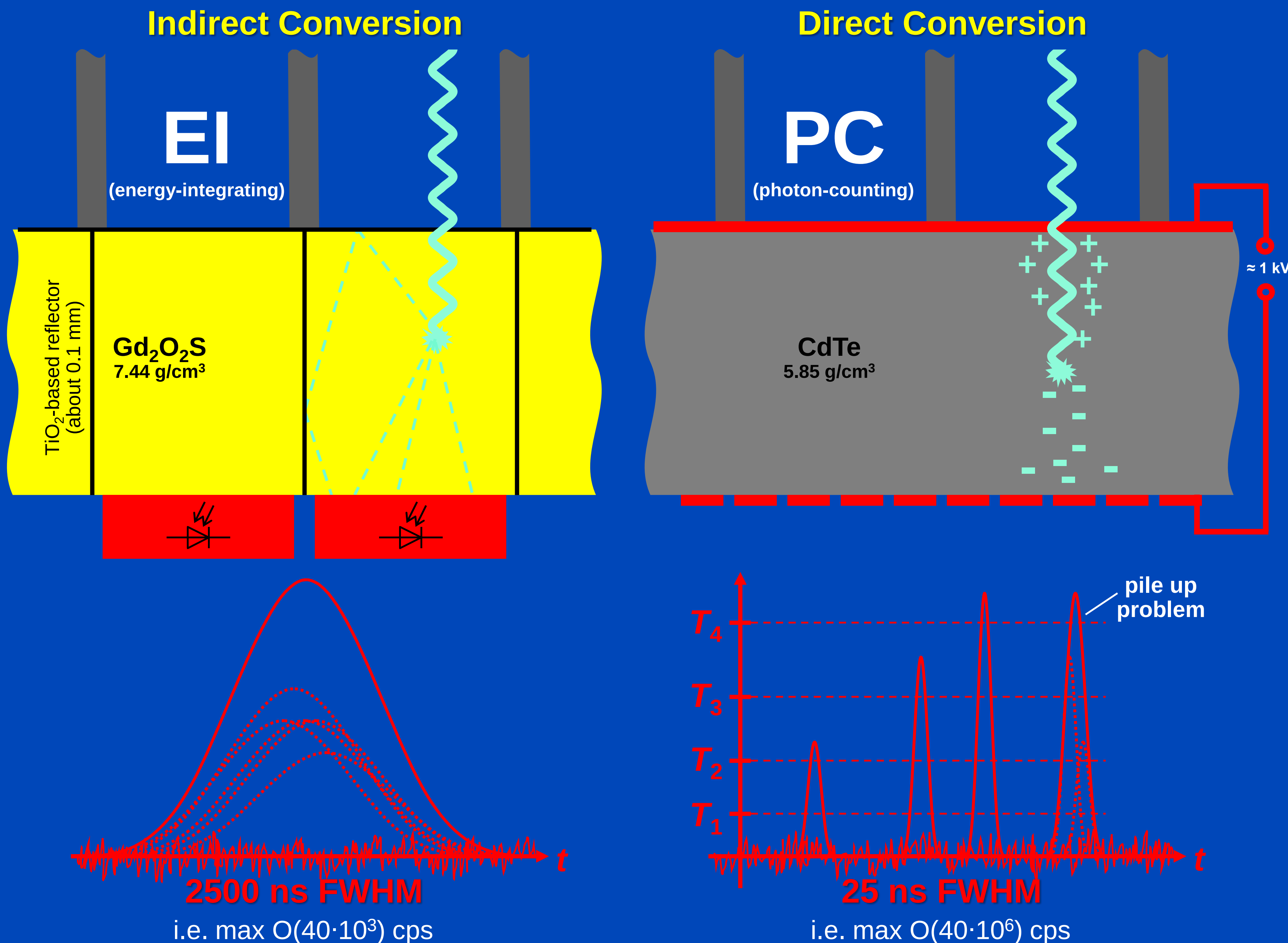
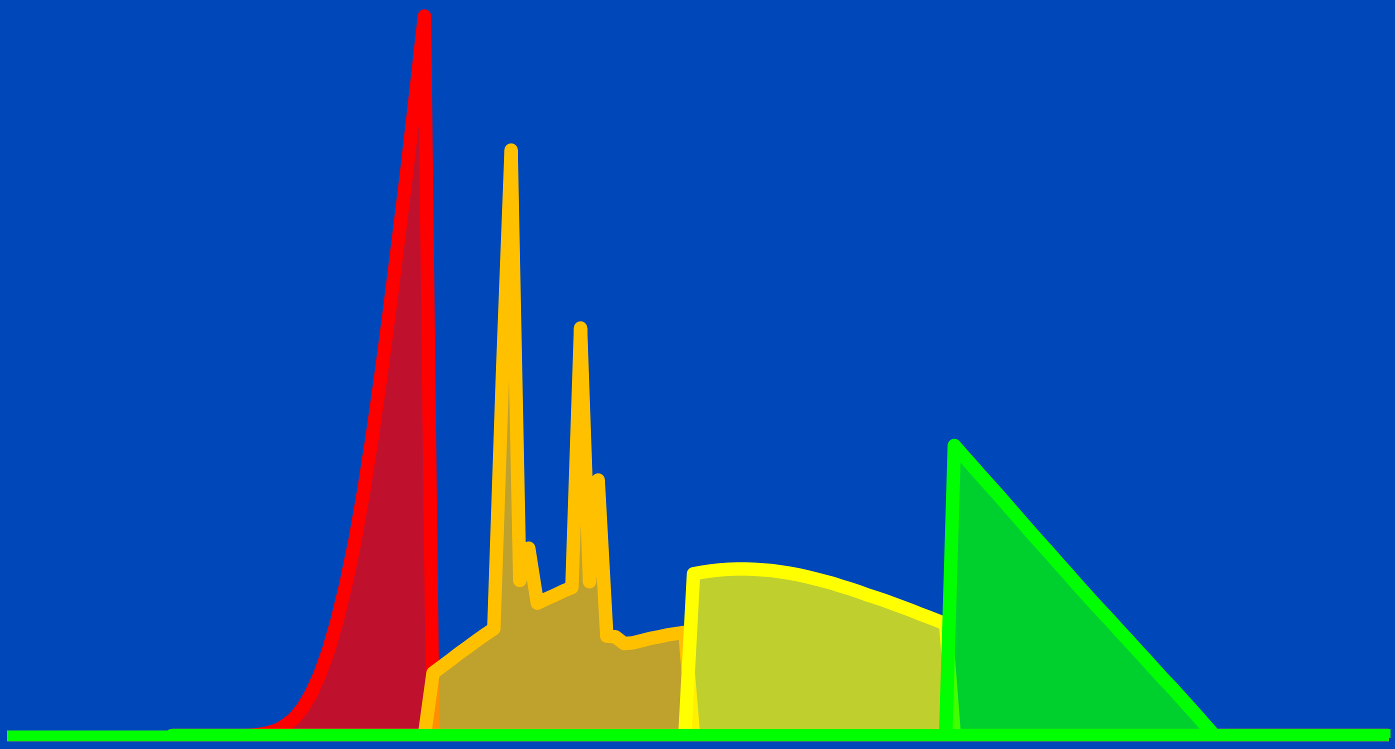
DEUTSCHES KREBSFORSCHUNGSZENTRUM IN DER HELMHOLTZ-GEMEINSCHAFT



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?

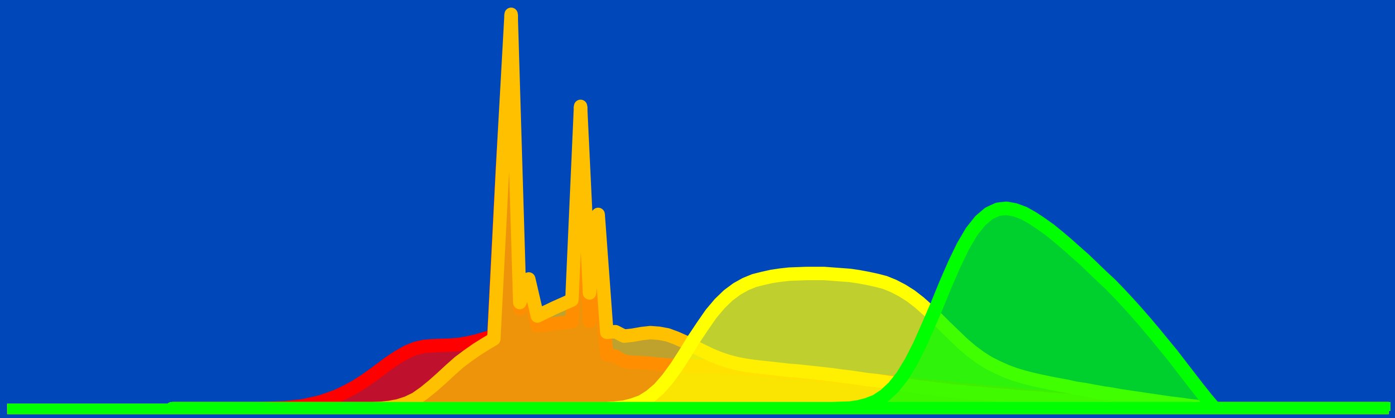
Ideally, bin spectra do not overlap, …



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 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	1 prototype (Japan)
GE	Si, edge on	400 × 400 µm	?	?	?	no		2 experimental setups (Sweden, 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	about 100 worldwide

Edge on design (Si only)

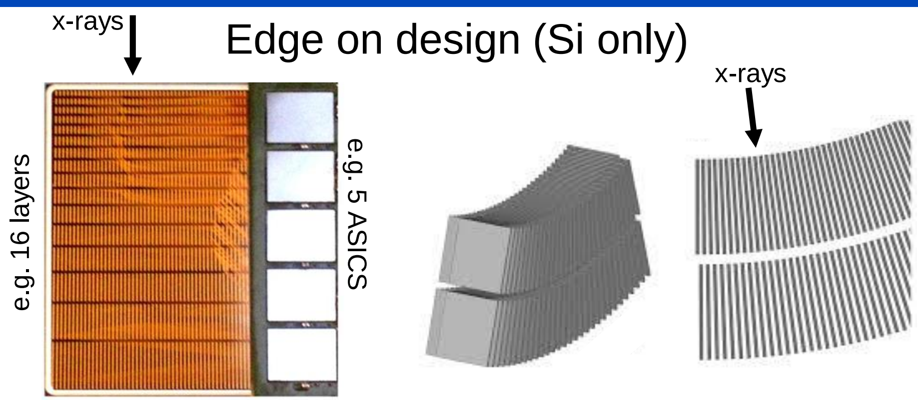


Image courtesy of KTH Royal Institute of Technology

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.

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

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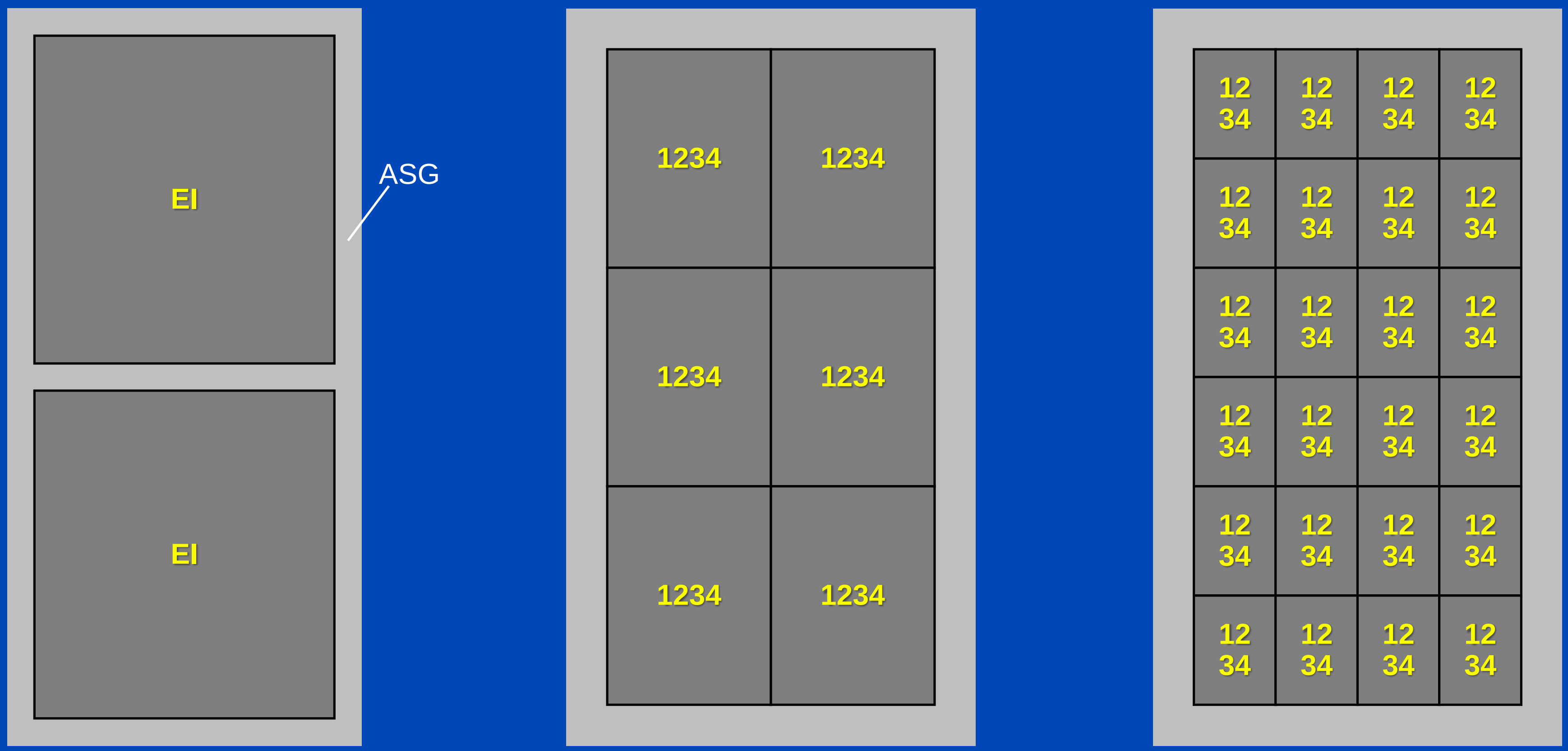
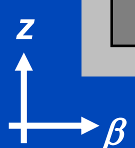
Detector Pixel Force vs. Alpha

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 0.15 × 0.176 mm at iso
avg. sampling 0.172 × 0.2 mm at iso
24 mm z-coverage





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

Evolution of Spatial Resolution

similar to
Energy-integrating CT (B70)

Pixel size 0.181 mm
Slice thickness 0.60 mm
Slice increment 0.30 mm
$MTF_{50\%}$ = 8.0 lp/cm
$MTF_{10\%}$ = 9.2 lp/cm

10 mm

scanned at
PCCT (Naeotom Alpha, Br98u)

Pixel size 0.181 mm
Slice thickness 0.20 mm
Slice increment 0.10 mm
$MTF_{50\%}$ = 39.0 lp/cm
$MTF_{10\%}$ = 42.9 lp/cm

All measurements at Naeotom Alpha, Siemens Healthineers. QIR Reconstructions such that the maximum spatial resolution of Flash, CounT and Alpha is demonstrated on the same sample. *C* = 1200 HU, *W* = 4000 HU

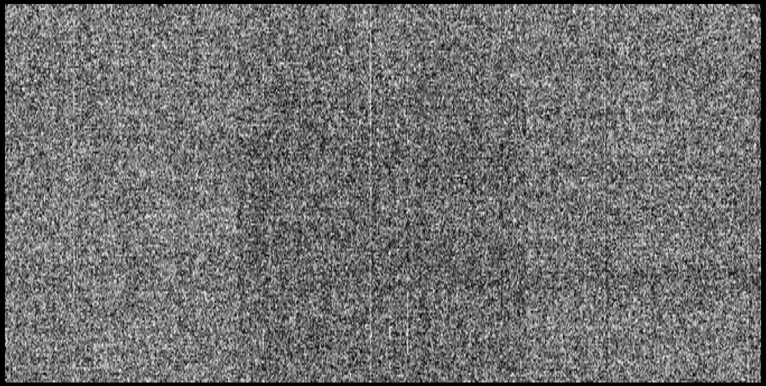
Advantages of Photon Counting CT

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

No Electronic Noise!

- Photon counting detectors have no electronic noise.
- Extreme low dose situations will benefit
  - Pediadric scans at even lower dose
  - Obese patients with less noise
  - …

EI (Dexela)



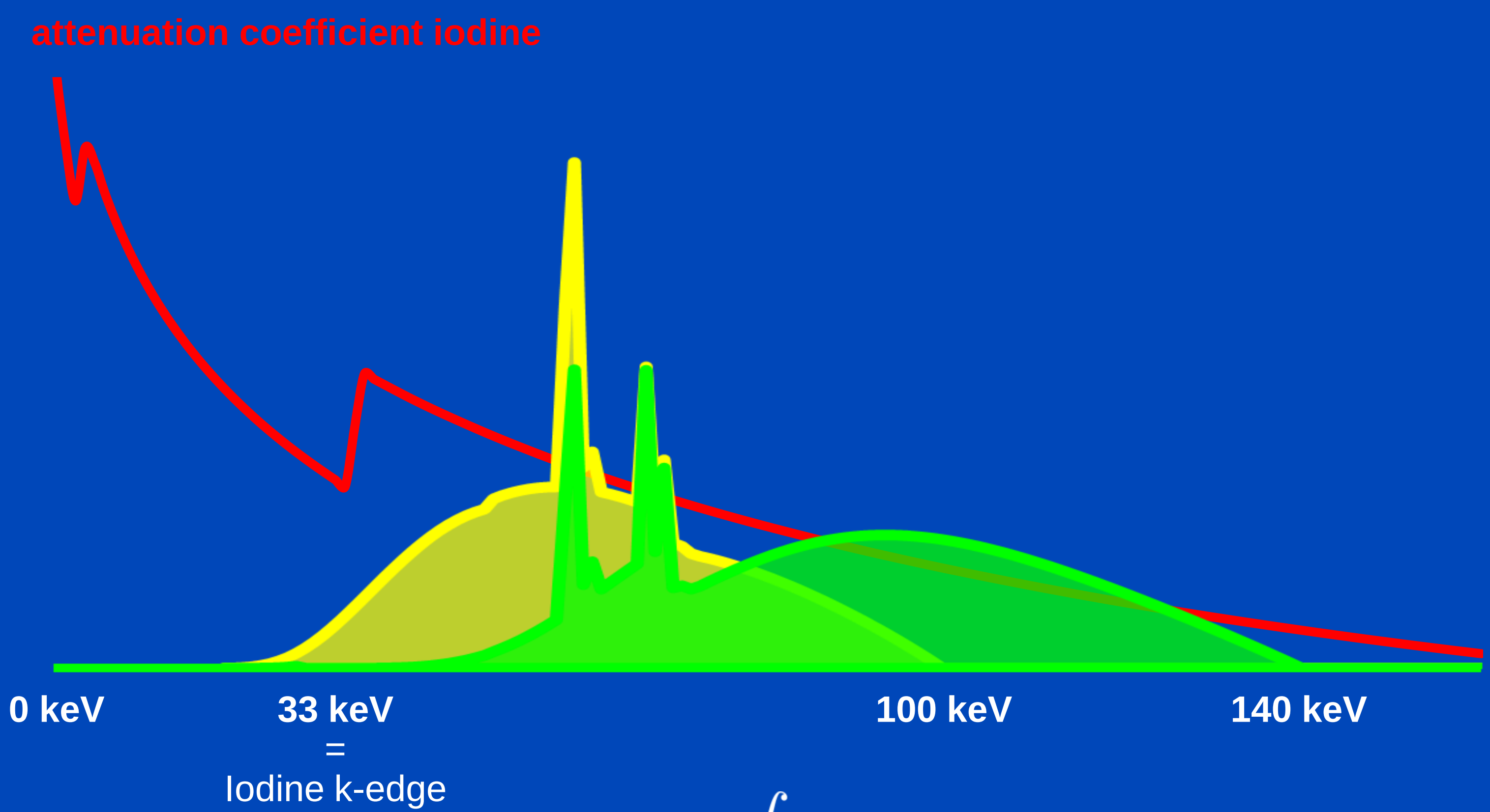
Readout noise only. Single events hidden!

PC (Dectris)

No readout noise. Single events visible!

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

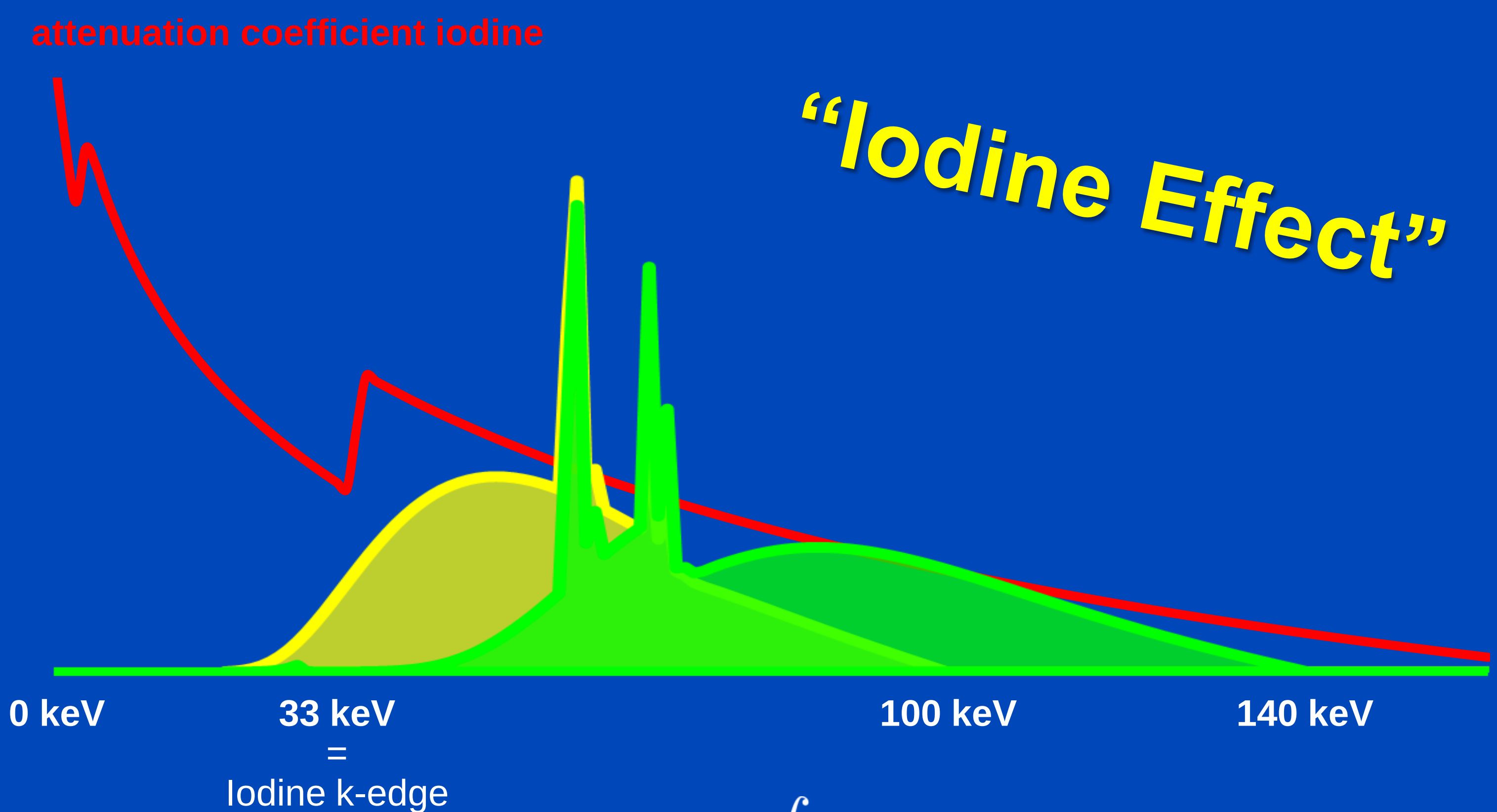
Energy Integrating
(Detected Spectra at 100 kV and 140 kV)



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

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)

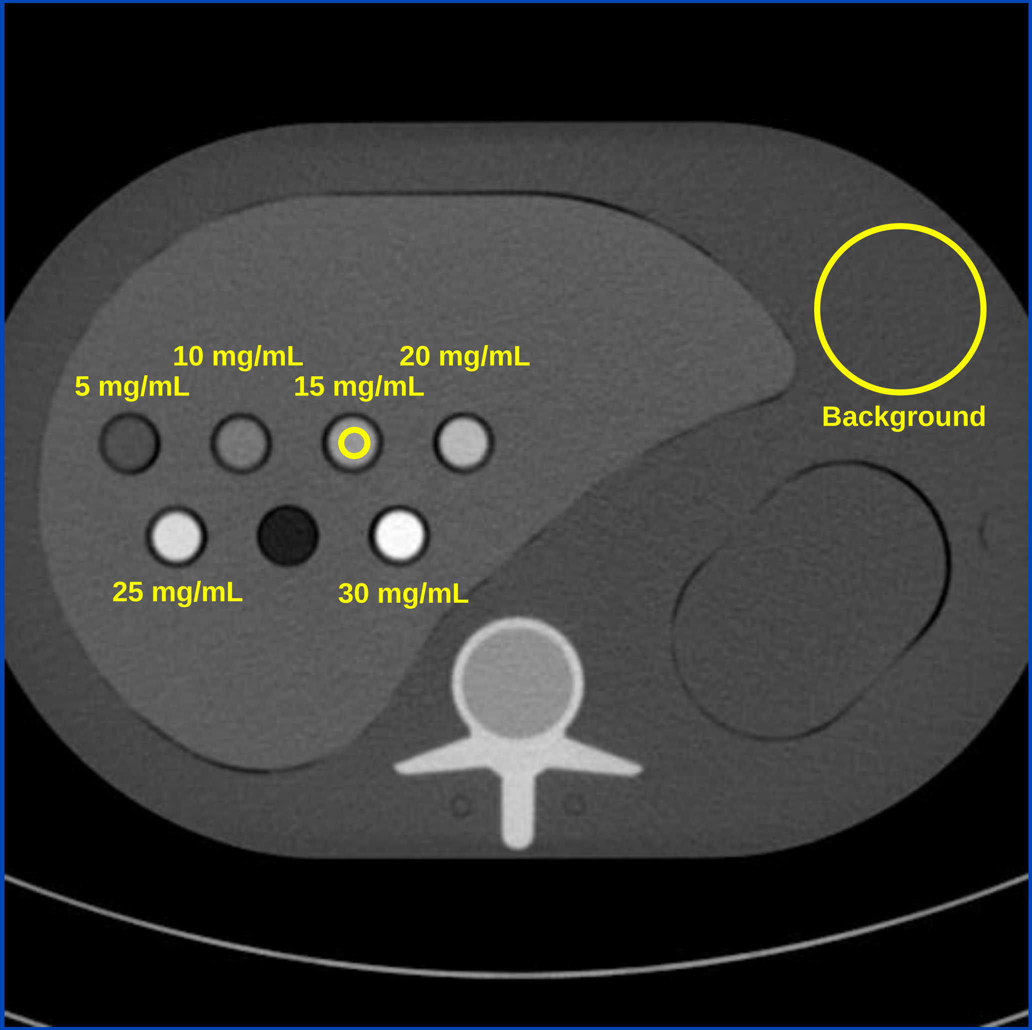


$$\mathrm{Signal}_{\mathrm{PC}} = \int dE\, 1\;\; N(E)$$

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

Iodine CNRD Assessment

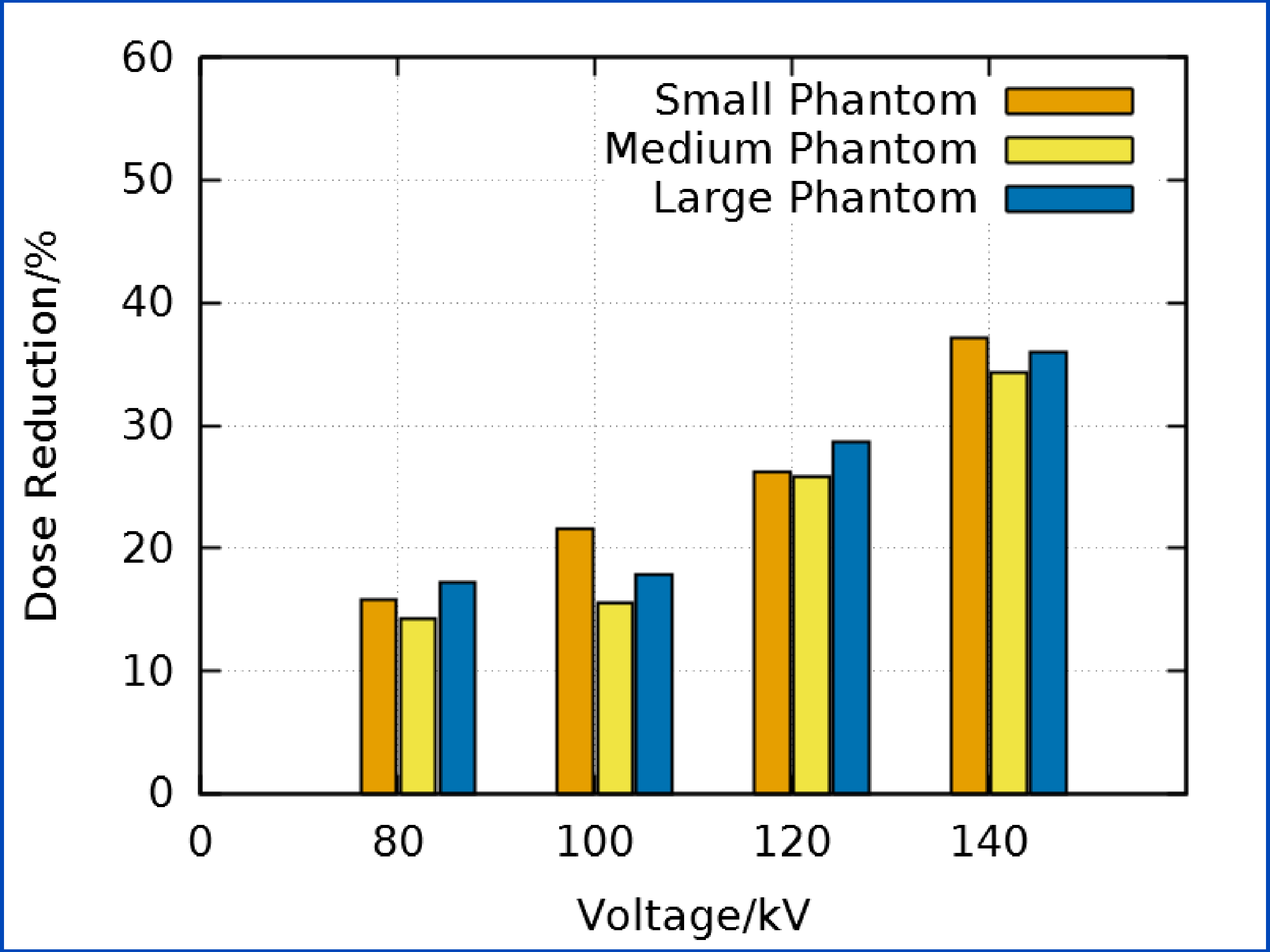
Regions of Interest



C = 180 HU, W = 600 HU

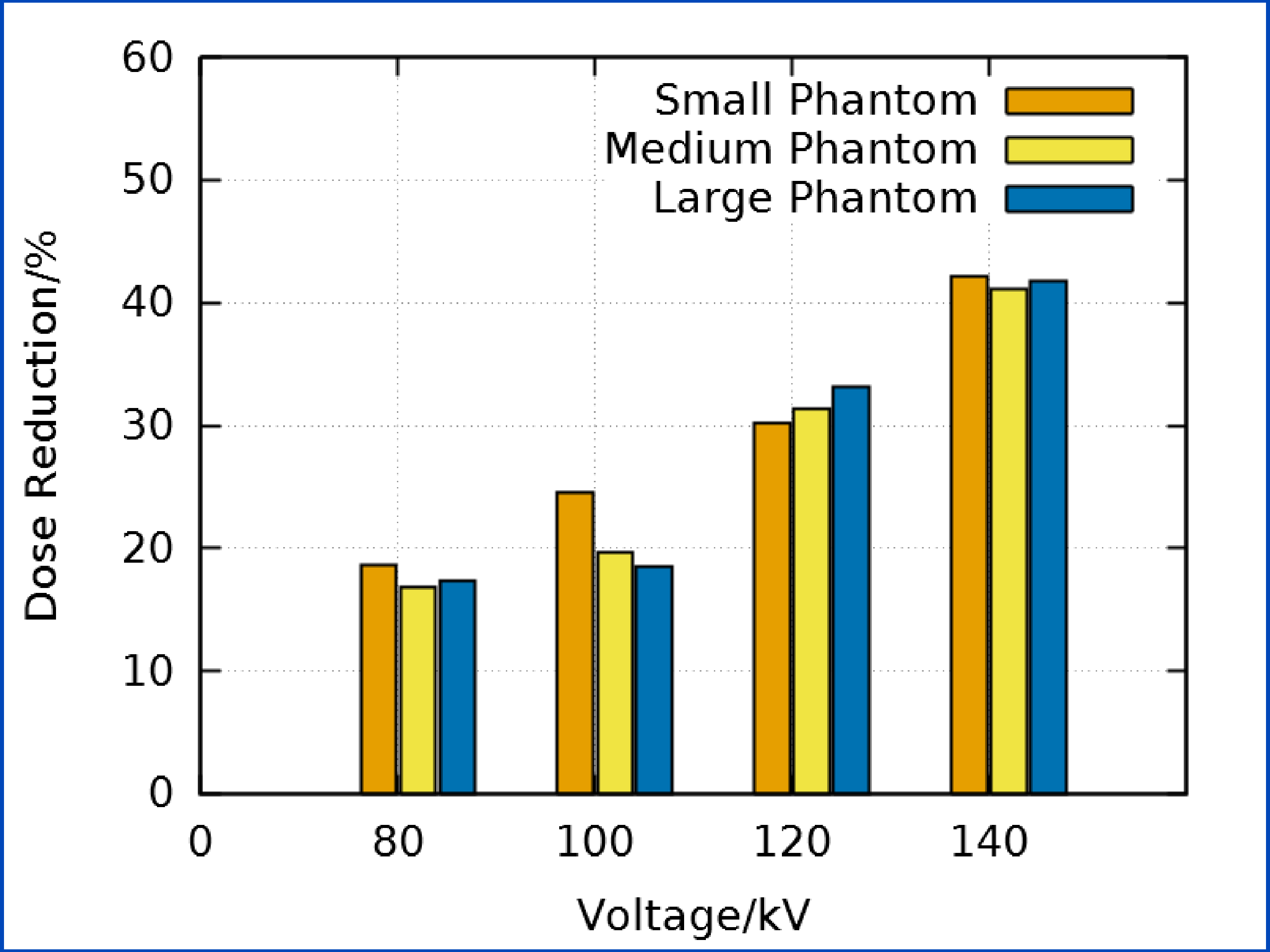
PC with 1 Bin vs. EI

Potential Dose Reduction



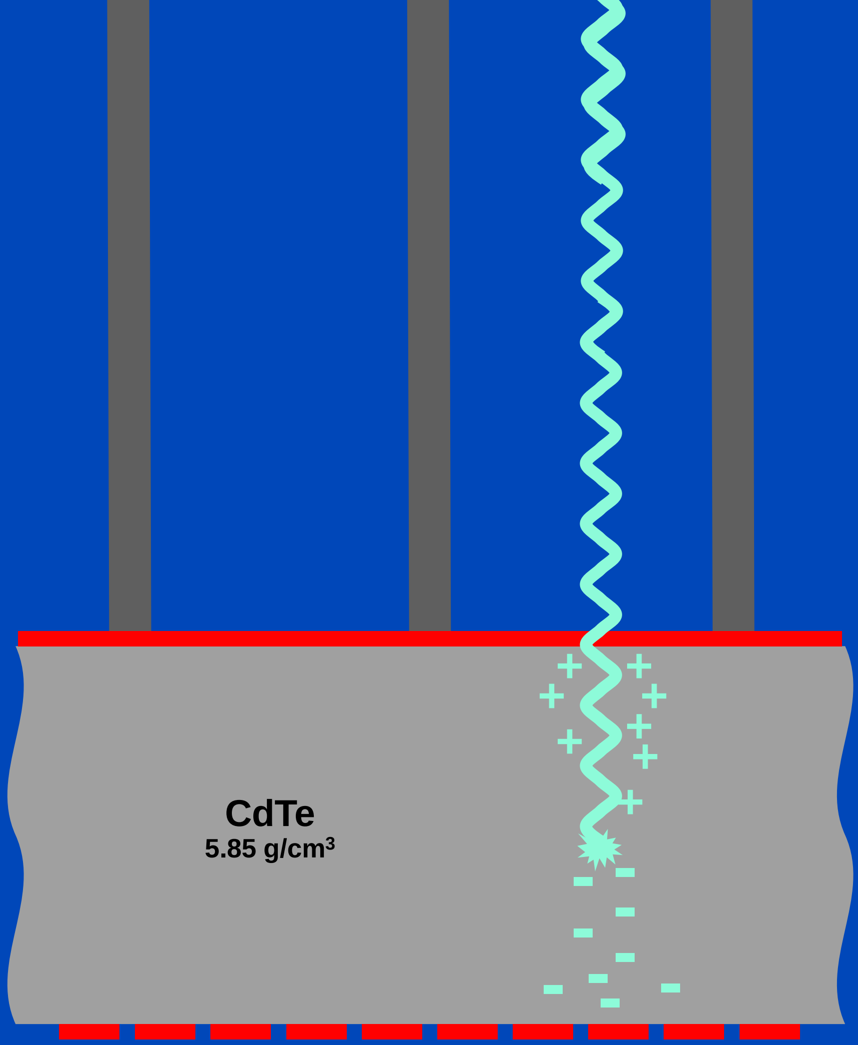
PC with 2 Bins vs. EI

Potential Dose Reduction

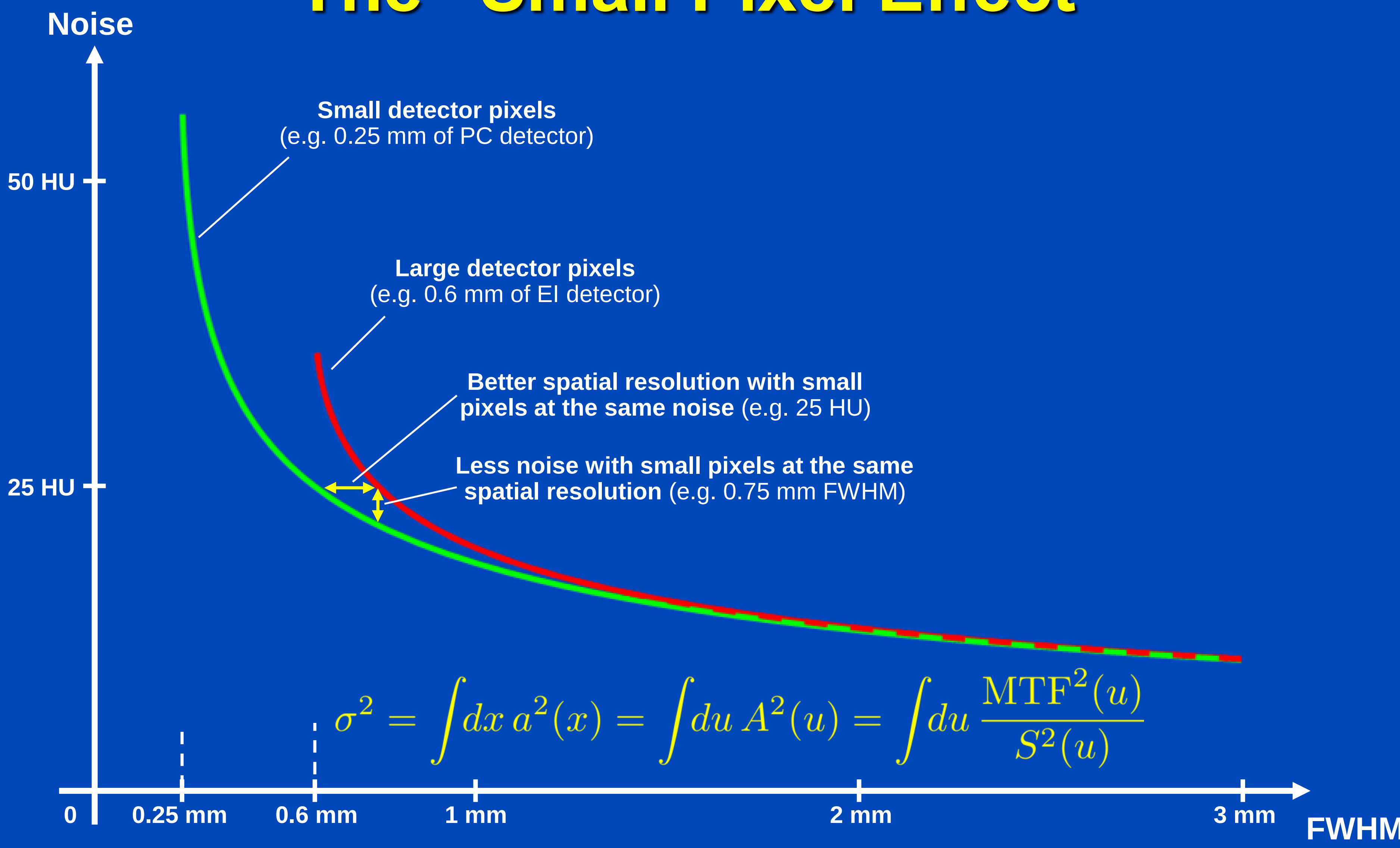


Ultra-High Spatial Resolution on Demand!

- Small electrodes are necessary to avoid pile-up.
- High bias voltages (around 300 V) limit charge diffusion and thus blurring in the non-structured semiconductor layer.
- Thus, higher spatial resolution is achievable.



The “Small Pixel Effect”

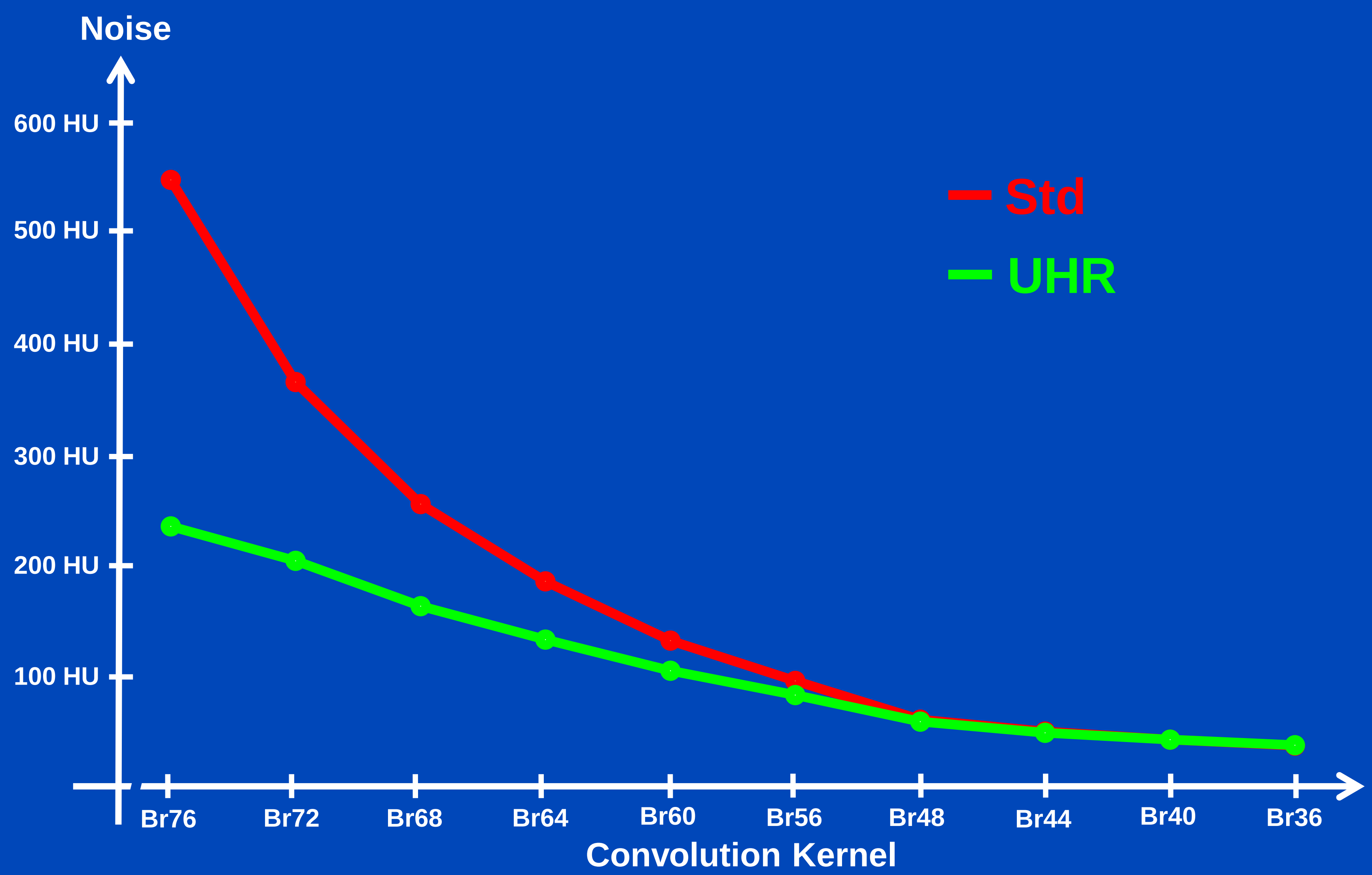


$$\sigma^2 = \int dx\, a^2(x) = \int du\, A^2(u) = \int du\, \frac{\mathrm{MTF}^2(u)}{S^2(u)}$$

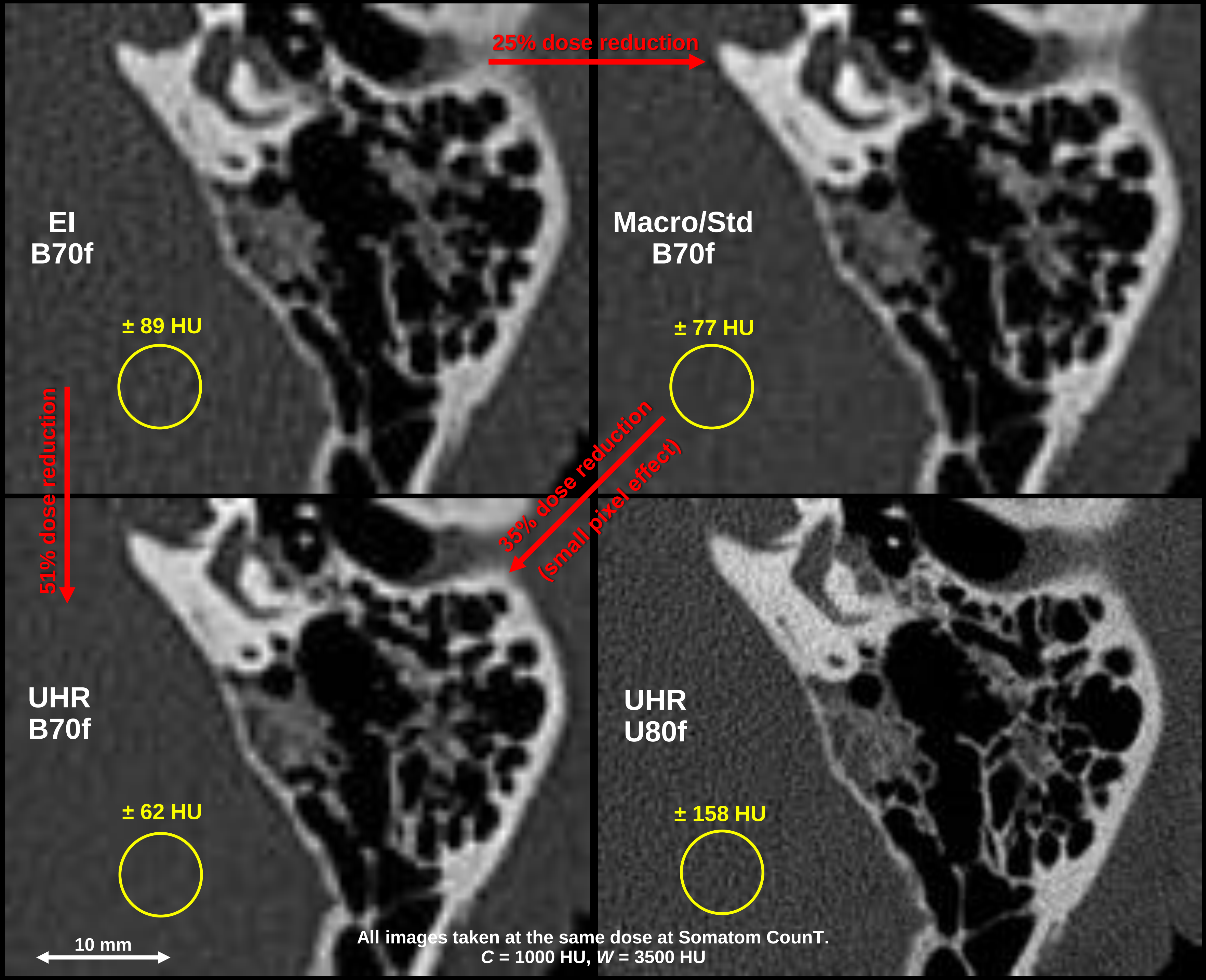
Kachelrieß, Kalender. Med. Phys. 32(5):1321-1334, May 2005

Small Pixel Effect at Naeotom Alpha

Medium Phantom, 4 mGy $CTDI_{32}$



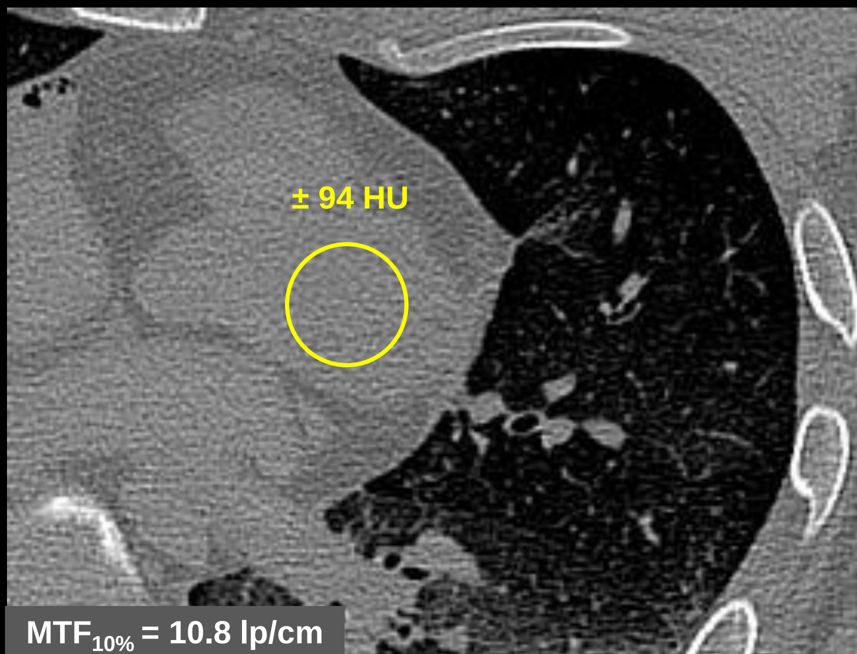
To disable the longitudinal small pixel effect, we reconstructed rather thick slices (1 mm thickness).



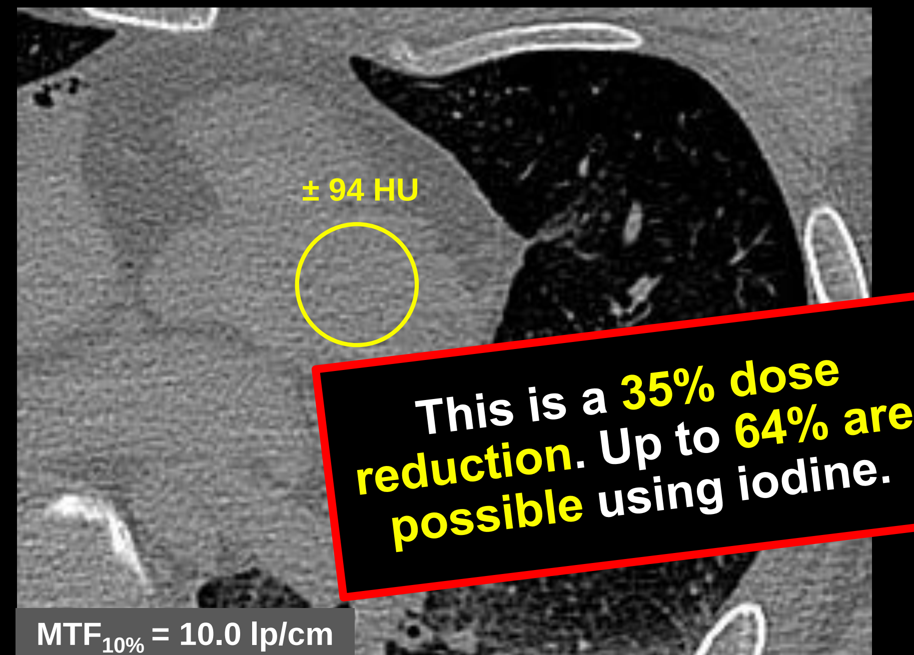
25% dose reduction
EI
B70f
Macro/Std
B70f
± 89 HU
± 77 HU
51% dose reduction
35% dose reduction
(small pixel effect)
UHR
B70f
UHR
U80f
± 62 HU
± 158 HU
10 mm
All images taken at the same dose at Somatom CounT.
C = 1000 HU, W = 3500 HU

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)



Acquisition with EI:

- **Tube voltage of 120 kV**
- **Tube current of 300 mAs**
- **Resulting dose of $\mathrm{CTDI}_{\mathrm{vol\ 32\ cm}}$ = 22.6 mGy**

Acquisition with UHR:

- **Tube voltage of 120 kV**
- **Tube current of 180 mAs**
- **Resulting dose of $\mathrm{CTDI}_{\mathrm{vol\ 32\ cm}}$ = 14.6 mGy**

C = 50 HU, W = 1500 HU

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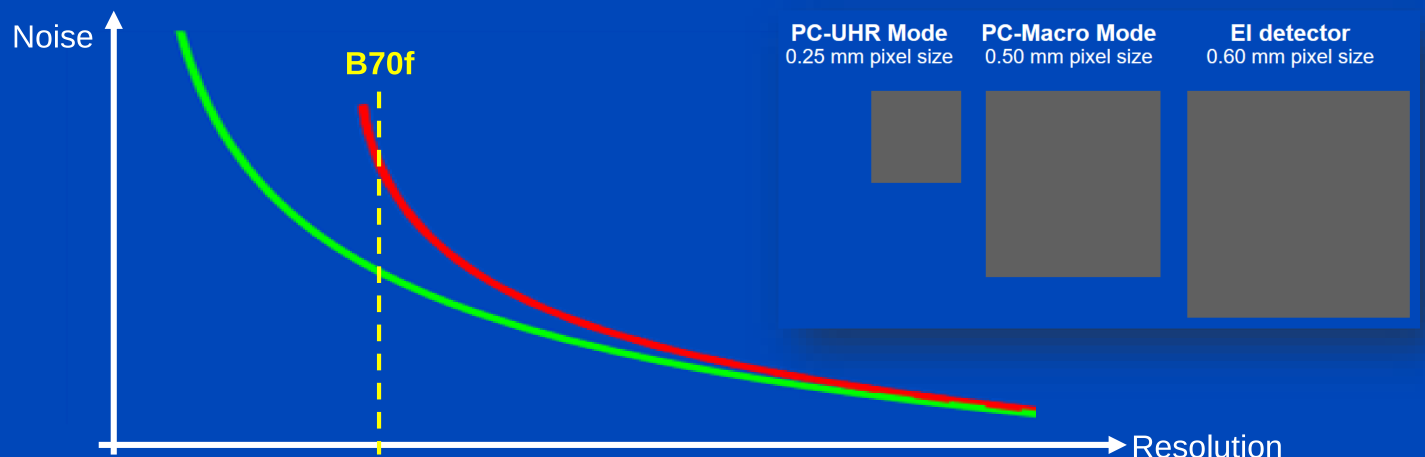
X-Ray Dose Reduction of B70f

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%

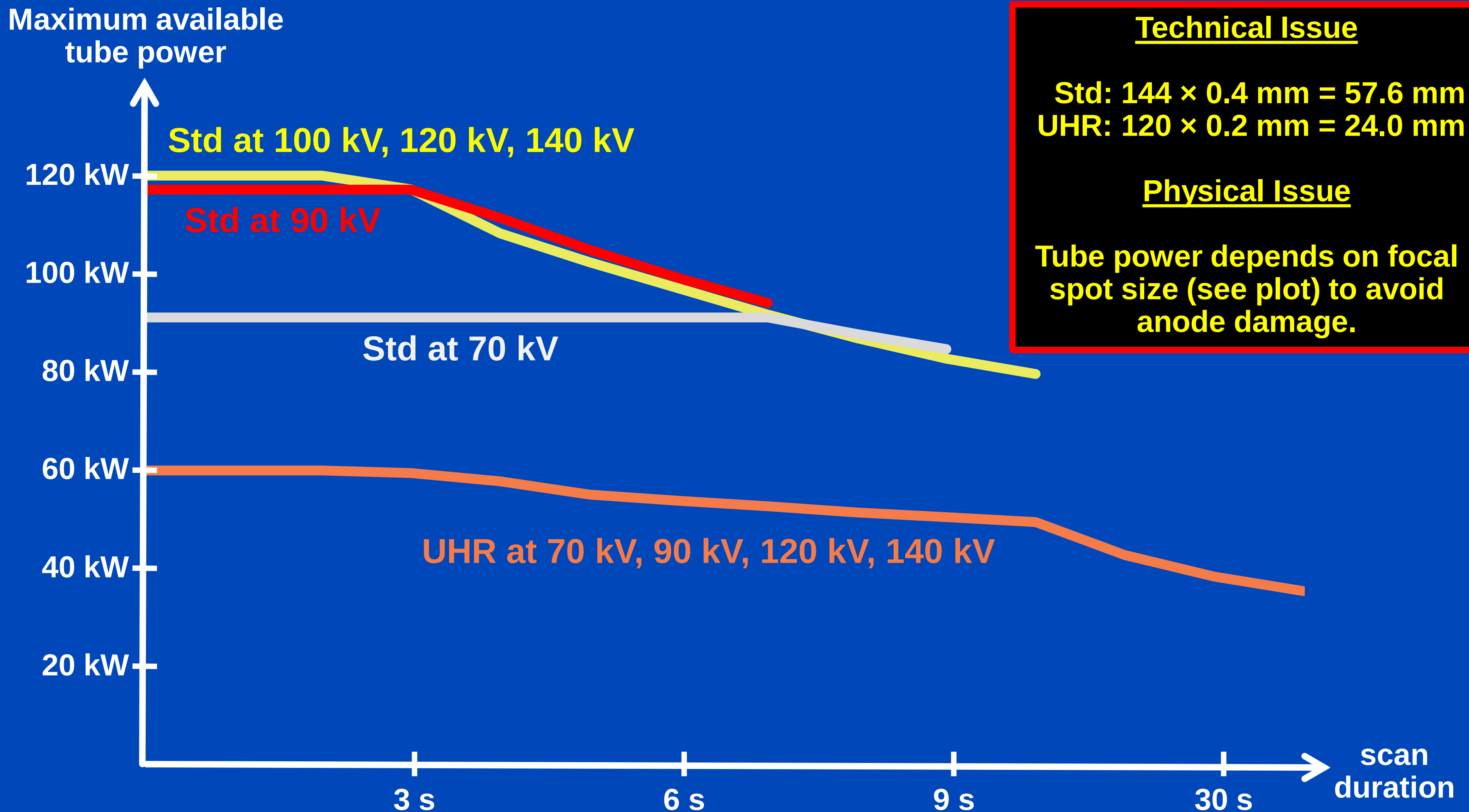
PC vs. EI
("small pixel effect"
and "iodine effect")

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%



Drawbacks of UHR?

Power of Vectron X-Ray tube in Naeotom Alpha



Technical Issue

Std: 144 × 0.4 mm = 57.6 mm
UHR: 120 × 0.2 mm = 24.0 mm

Physical Issue

Tube power depends on focal spot size (see plot) to avoid anode damage.

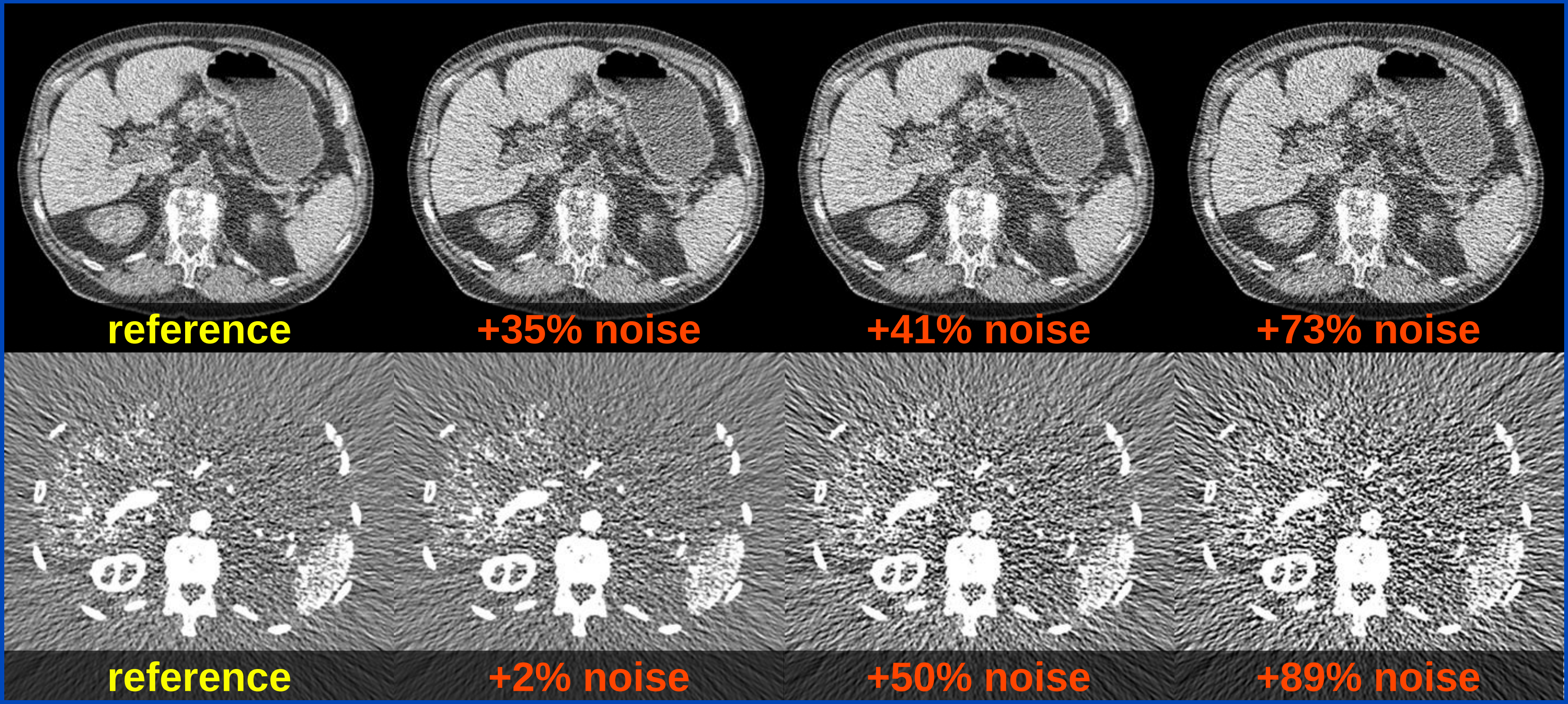
What About the Spectral Performance of PCCT?

Results – Different DECT Techniques

DS 100 kV / Sn 140 kV | TVS 80 kV / 140 kV | Sandwich 140 kV | Split detector 120 kV

VNC

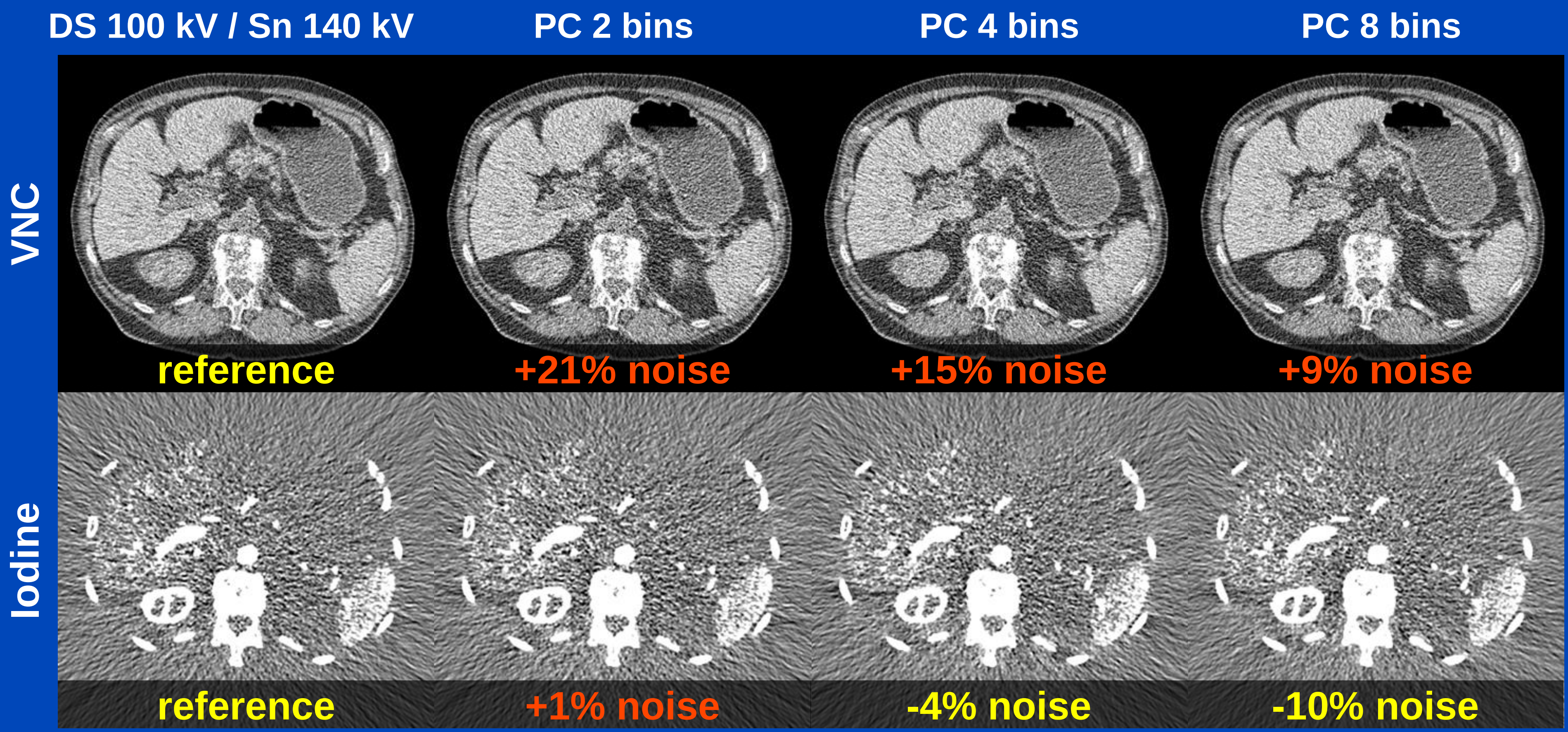
Iodine



Faby and Kachelrieß, MedPhys 42(7):4349-4366, July 2015.

Water: *C* = 0 HU / *W* = 400 HU
Iodine: *C* = 0 mg/mL / *W* = 6 mg/mL

Results – PC (Realistic PC Model)



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Water: *C* = 0 HU / *W* = 400 HU
Iodine: *C* = 0 mg/mL / *W* = 6 mg/mL

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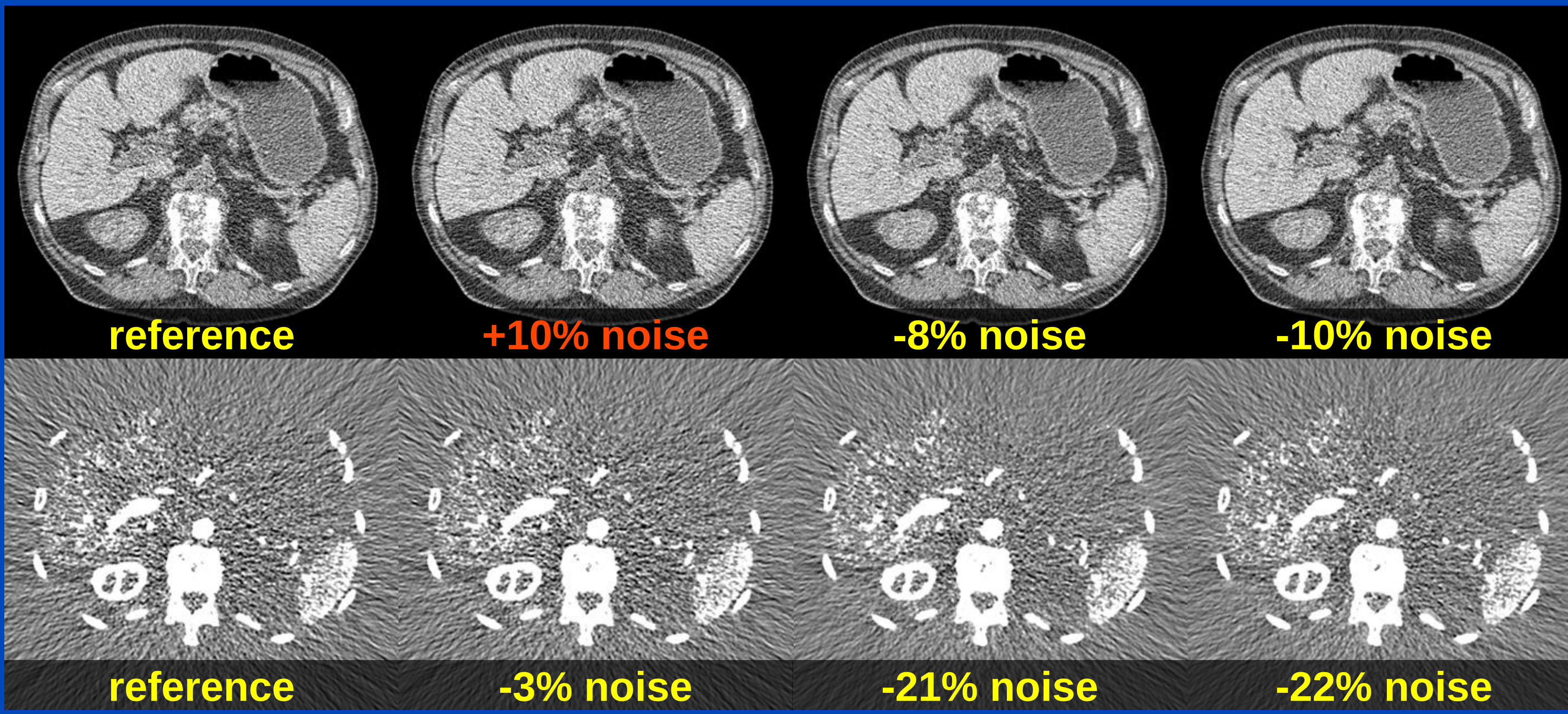
Results – PC/PC (Realistic PC Model)

PC 100 kV / PC Sn 140 kV

	DS 100 kV / Sn 140 kV	DS PC 1 bin	DS PC 2 bins	DS PC 4 bins

VNC

Iodine

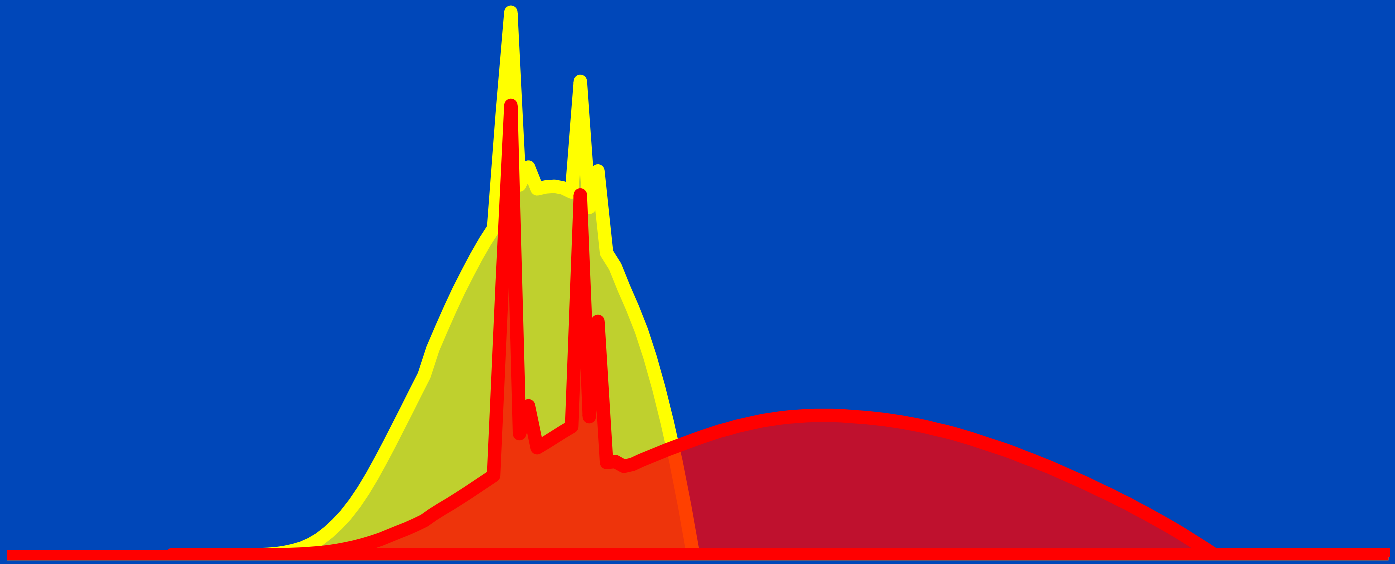


Faby and Kachelrieß, MedPhys 42(7):4349-4366, July 2015.

Water: *C* = 0 HU / *W* = 400 HU
Iodine: *C* = 0 mg/mL / *W* = 6 mg/mL

80 kV / 140 kV

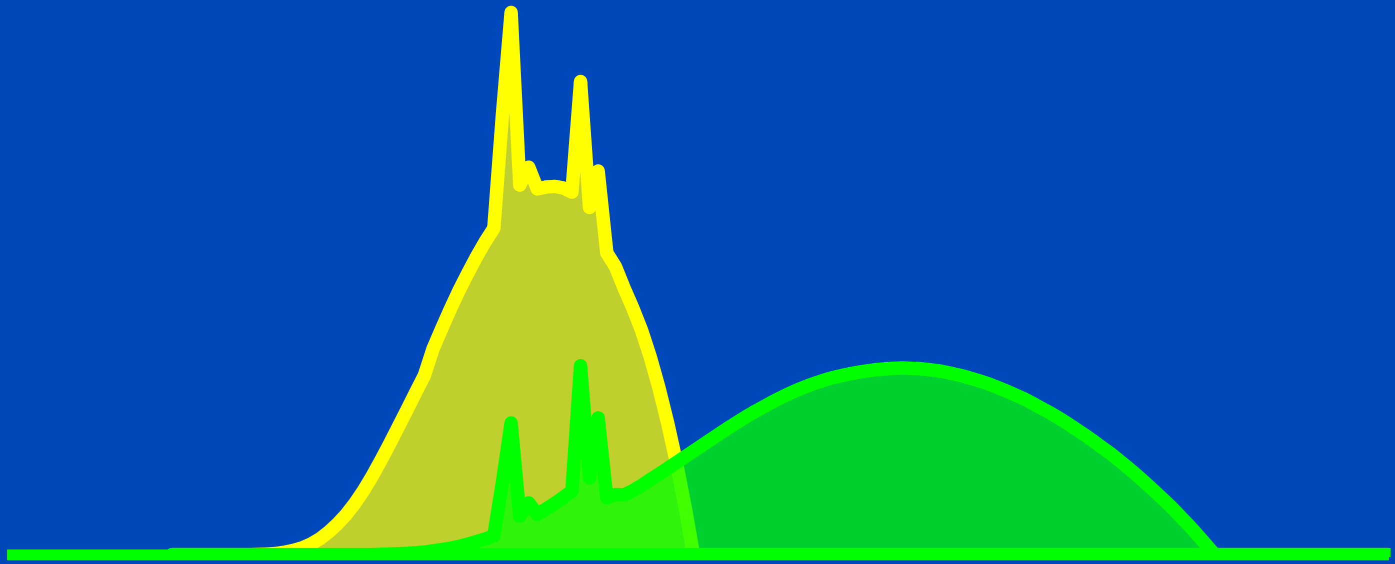
Used in
- Siemens‘ 1st generation DSCT



DSCT spectra as seen with one bin after having passed a 32 cm water layer.

80 kV / 140 kV $Sn_{0.4\ mm}$

Used in
- Siemens‘ 2nd generation DSCT



DSCT spectra as seen with one bin after having passed a 32 cm water layer.

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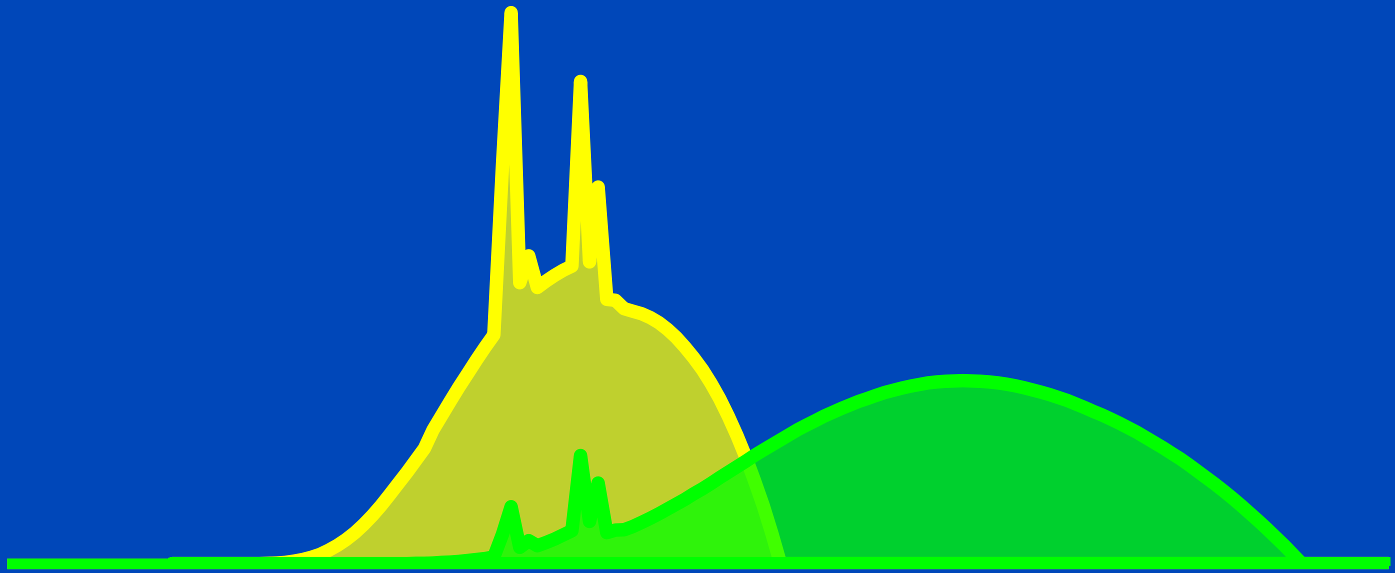
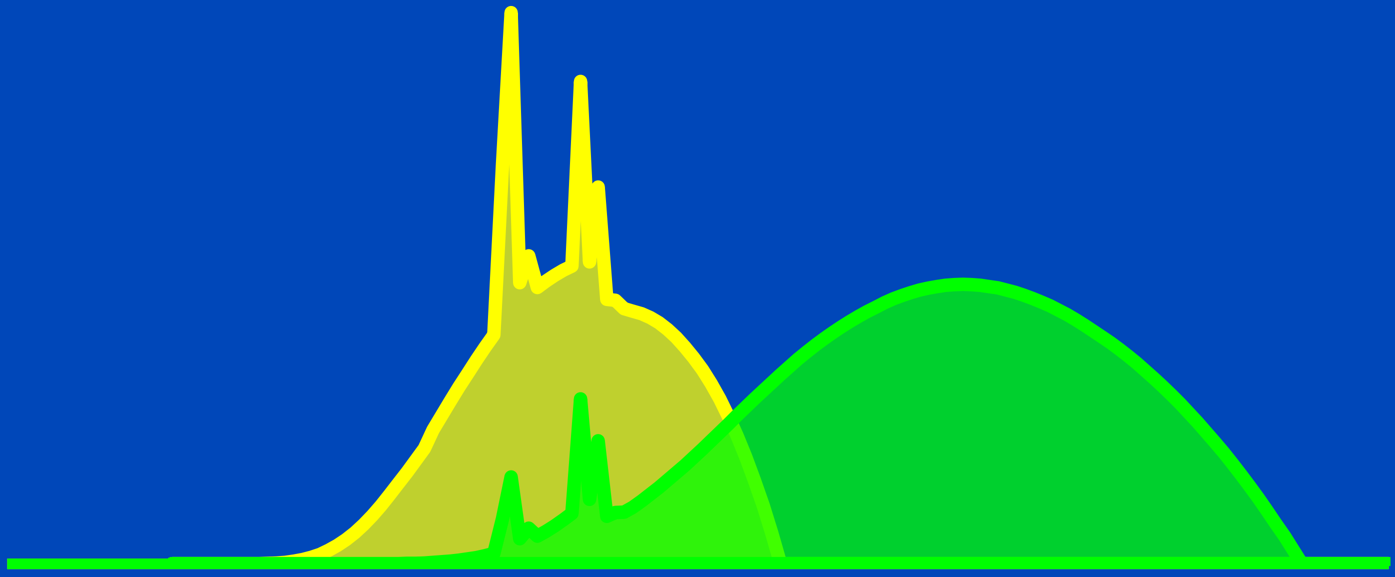
90 kV / 150 kV $Sn_{0.6\ mm}$

Used in
- **Siemens‘ 3rd generation DSCT**



DSCT spectra as seen with one bin after having passed a 32 cm water layer.

90 kV / 150 kV $Sn_{0.6\ mm}$



Used in
- Siemens‘ 3rd generation DSCT

DSCT spectra as seen with one bin after having passed a 32 cm water layer.

90 kV / 150 kV $Sn_{0.6\ mm}$

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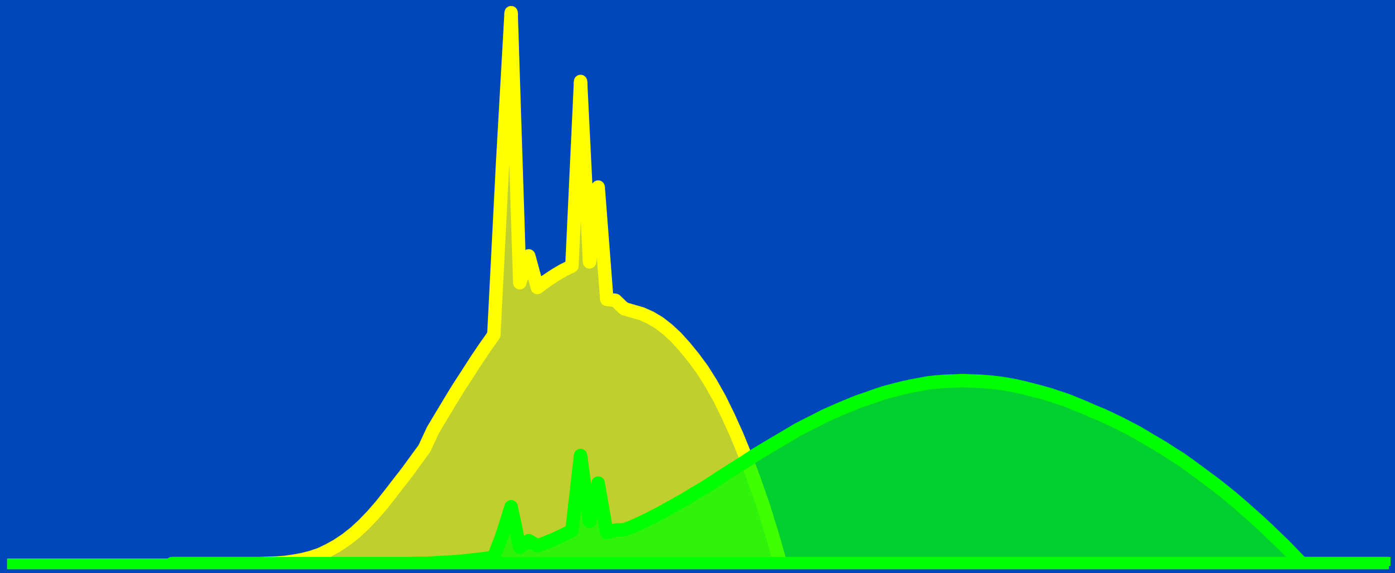

DSCT spectra as seen with one bin after having passed a 32 cm water layer.

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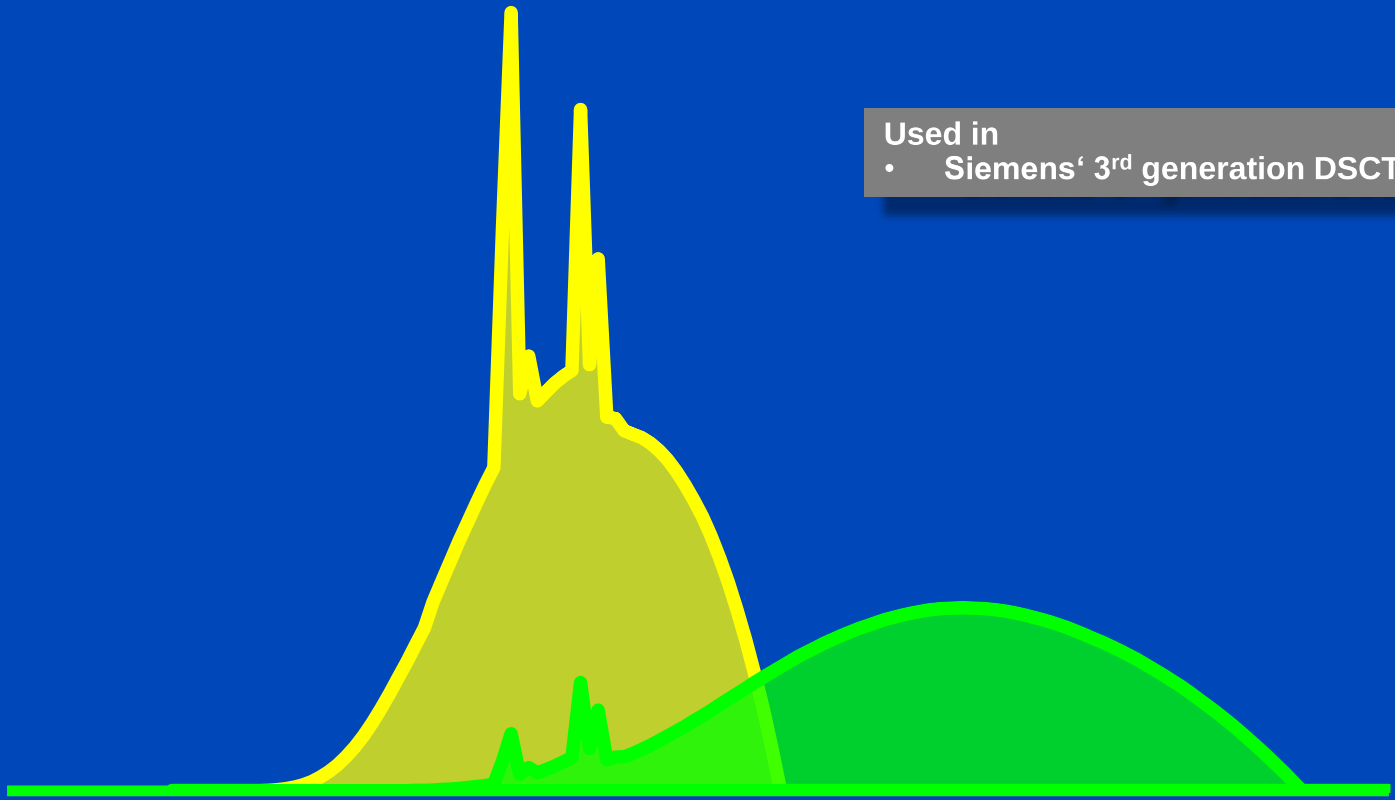
90 kV / 150 kV $Sn_{0.6\ mm}$



Used in
- Siemens' 3rd generation DSCT

DSCT spectra as seen with one bin after having passed a 32 cm water layer.

Conclusions

- PCCT offers several advantages: low dose, high spatial resolution, spectral information on demand.
- Thereby, it outperforms all EI CT systems by far.
- PCCT further outperforms all DECT implementations other than dual source CT (DSCT).
  - Fast tube voltage switching, sandwich detectors, or split filter DECT implementations are inferior compared with PCCT.
  - DSCT, cannot be outperformed by single source PCCT. The reason is that DSCT marginalizes the spectral overlap by using a selective prefilter on the high kV tube.
  - To outperform DSCT in terms of spectral performance it is necessary to have a DS-PCCT system with a prefilter on the high kV tube.

Thank You!

This presentation will soon be available at www.dkfz.de/ct.

Job opportunities through DKFZ's international Fellowship programs (marc.kachelriess@dkfz.de).

Parts of the reconstruction software were provided by RayConStruct® GmbH, Nürnberg, Germany.