Refresher Course RC113, ECR 2021, Vienna, Austria

Updates and Future Perspectives to CT

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DEUTSCHES KREBSFORSCHUNGSZENTRUM IN DER HELMHOLTZ-GEMEINSCHAFT

Part 1: CT Hardware

Canon Aquilion ONE Genesis

GE Revolution Apex

Philips IQon Spectral CT

Siemens Somatom Force

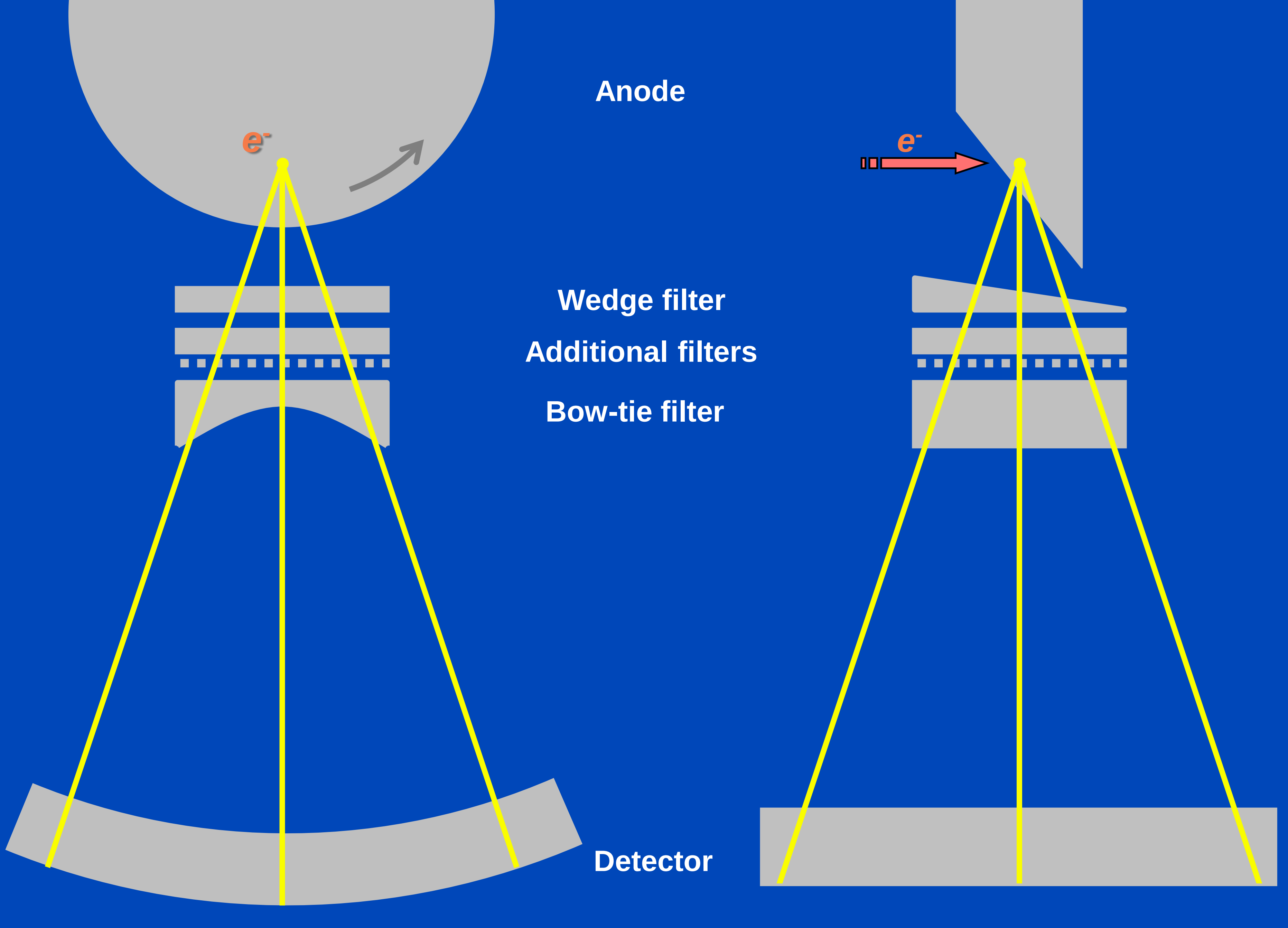
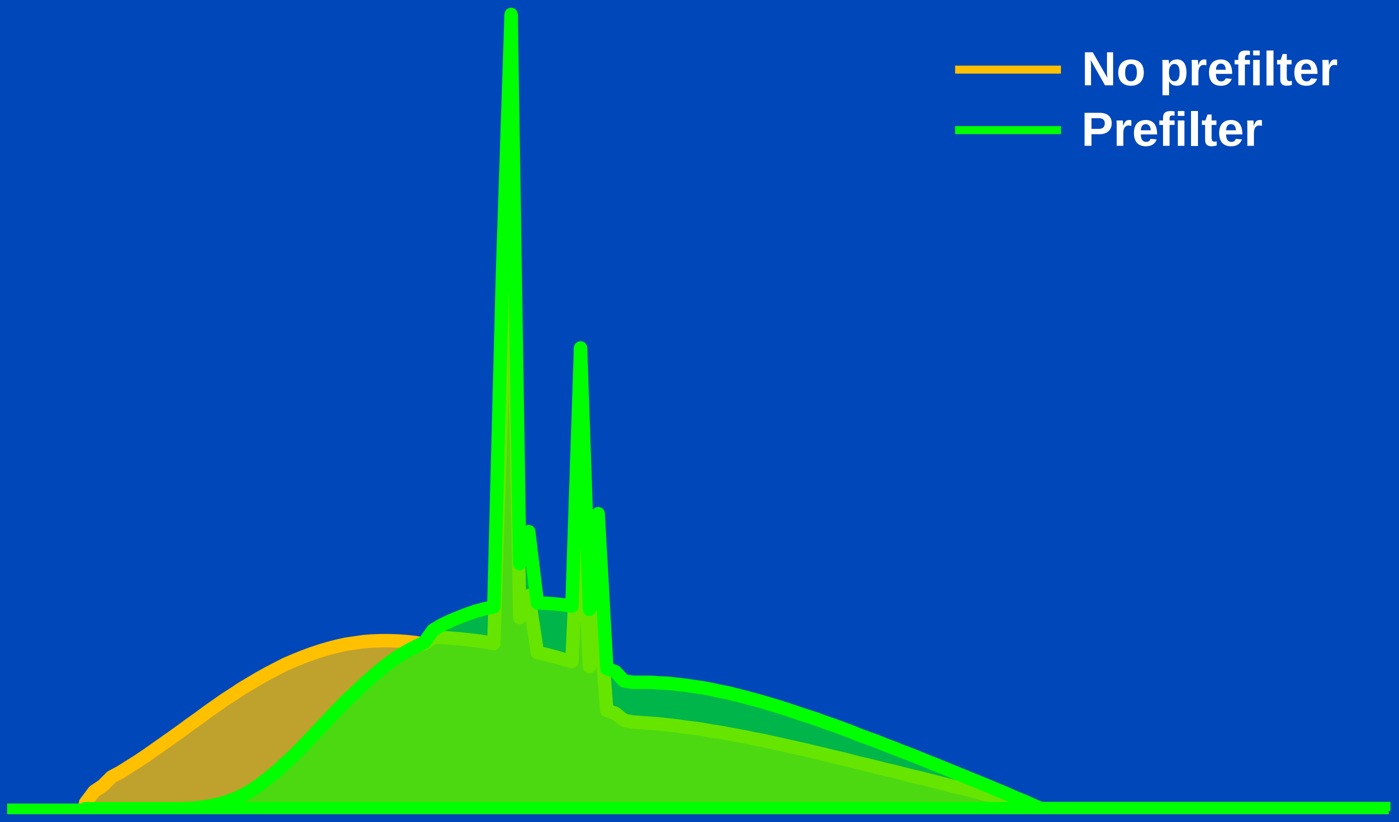
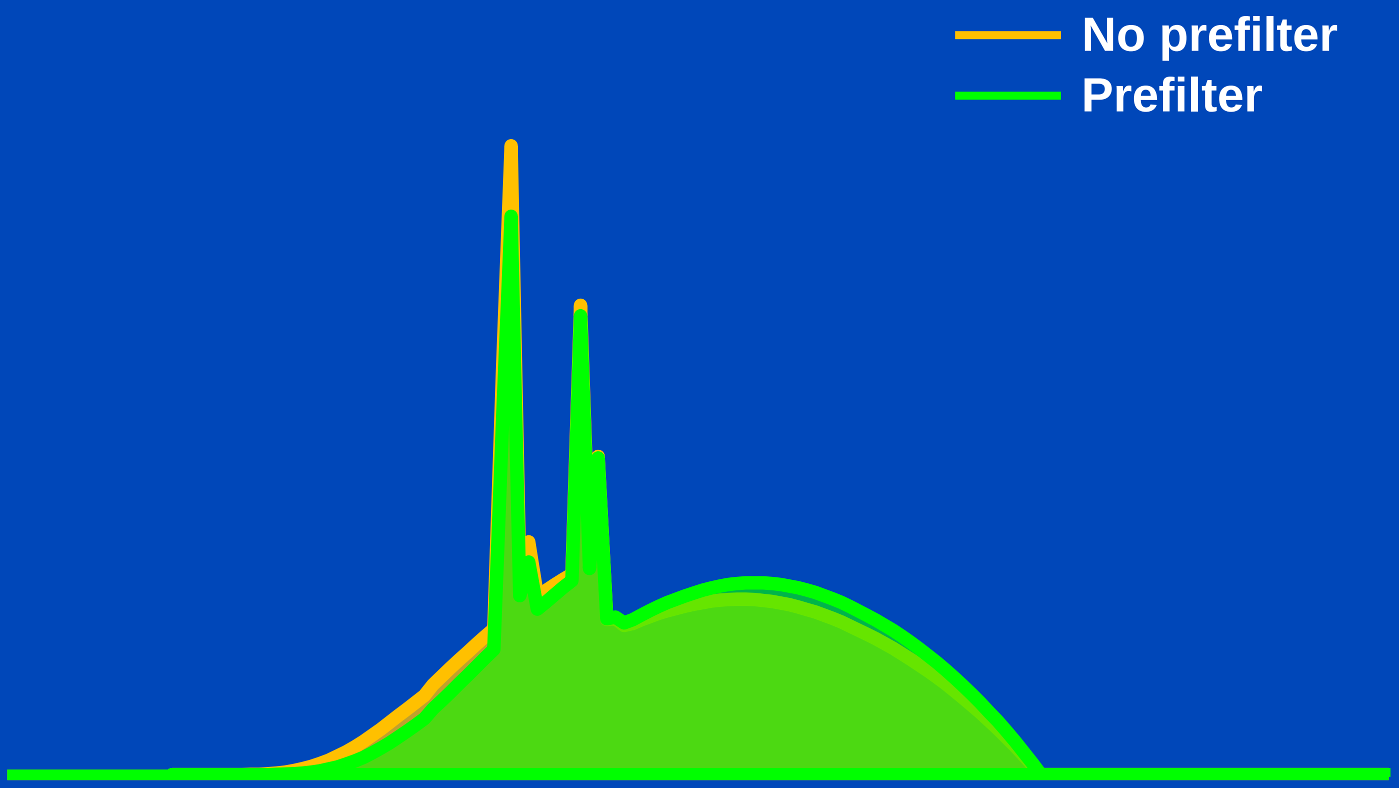


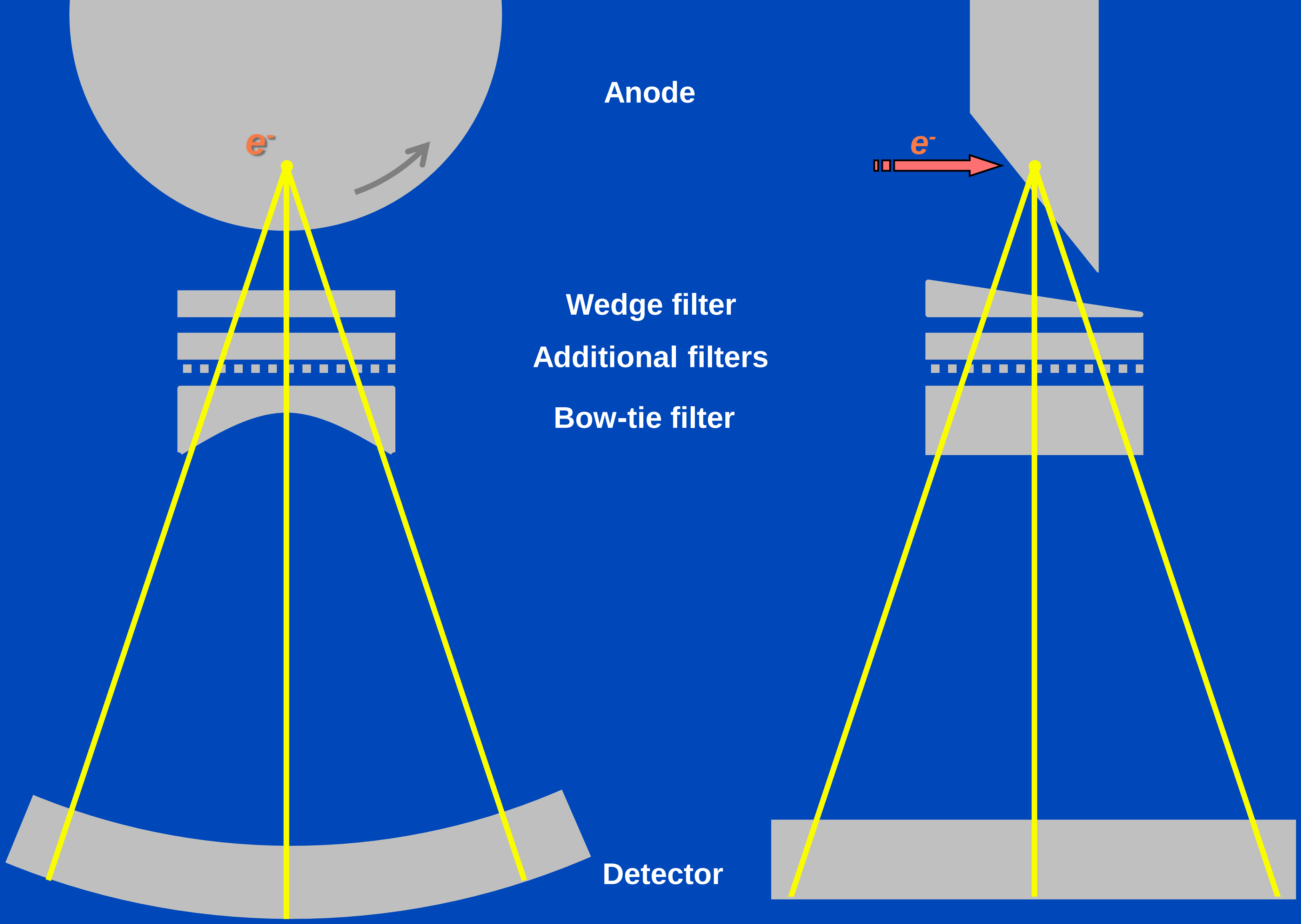
Figure not drawn to scale. Type and order of prefiltration may differ from scanner to scanner.
Depending on the selected protocol filters are changed automatically (e.g. small bowtie for pediatric scans).

120 kV + 0 mm water with and without prefilter



120 kV + 320 mm water with and without prefilter





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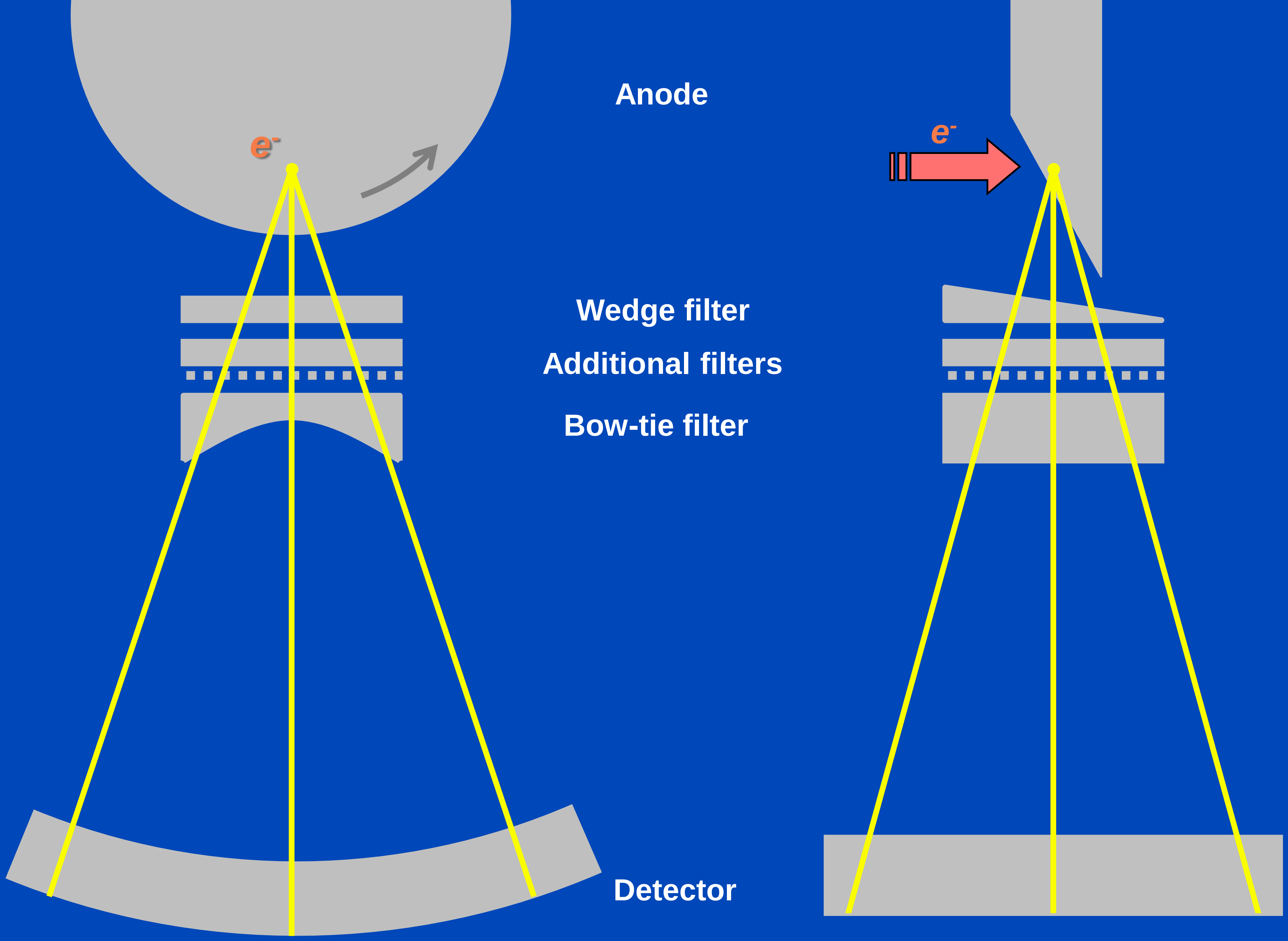

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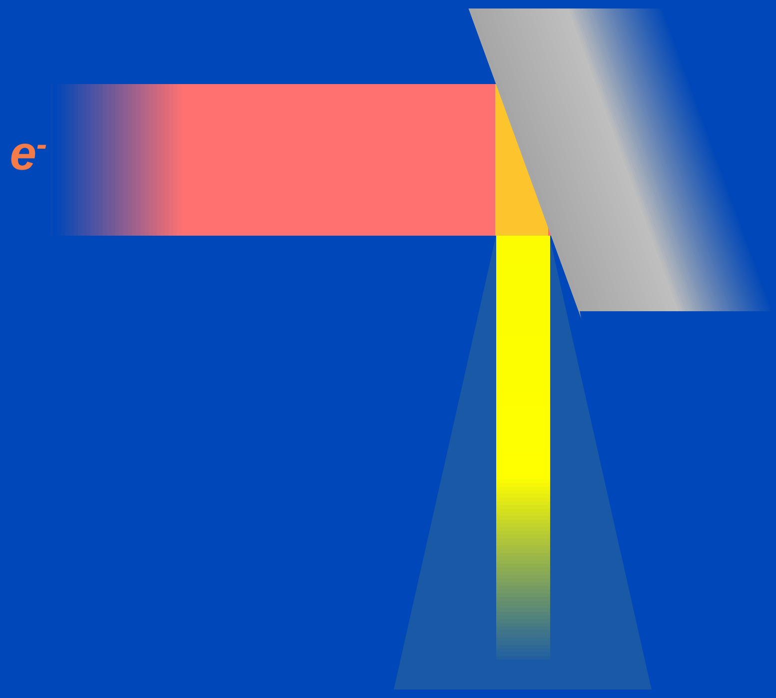
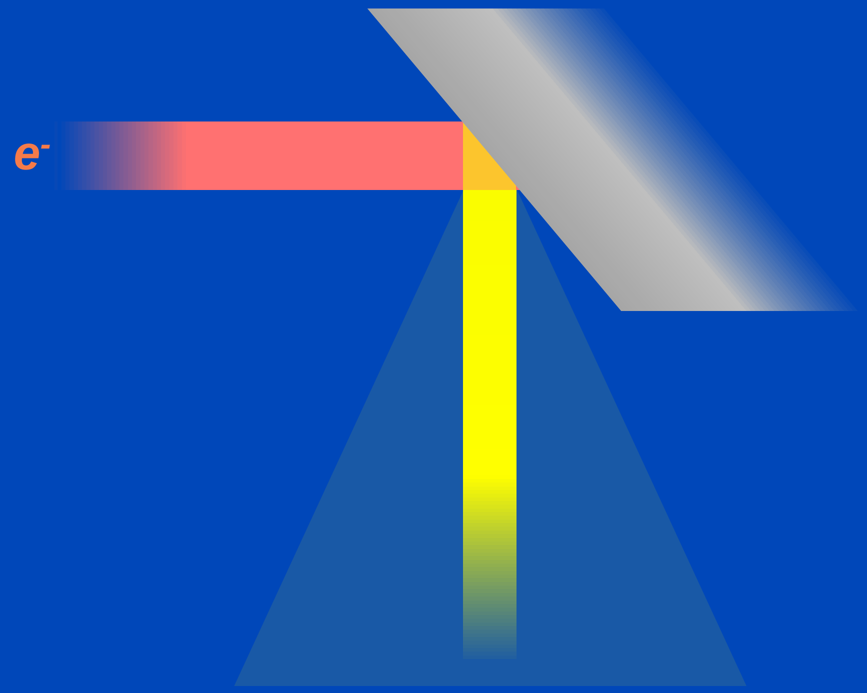
Narrow Cone = High Tube Power



Wide Cone = Low Tube Power

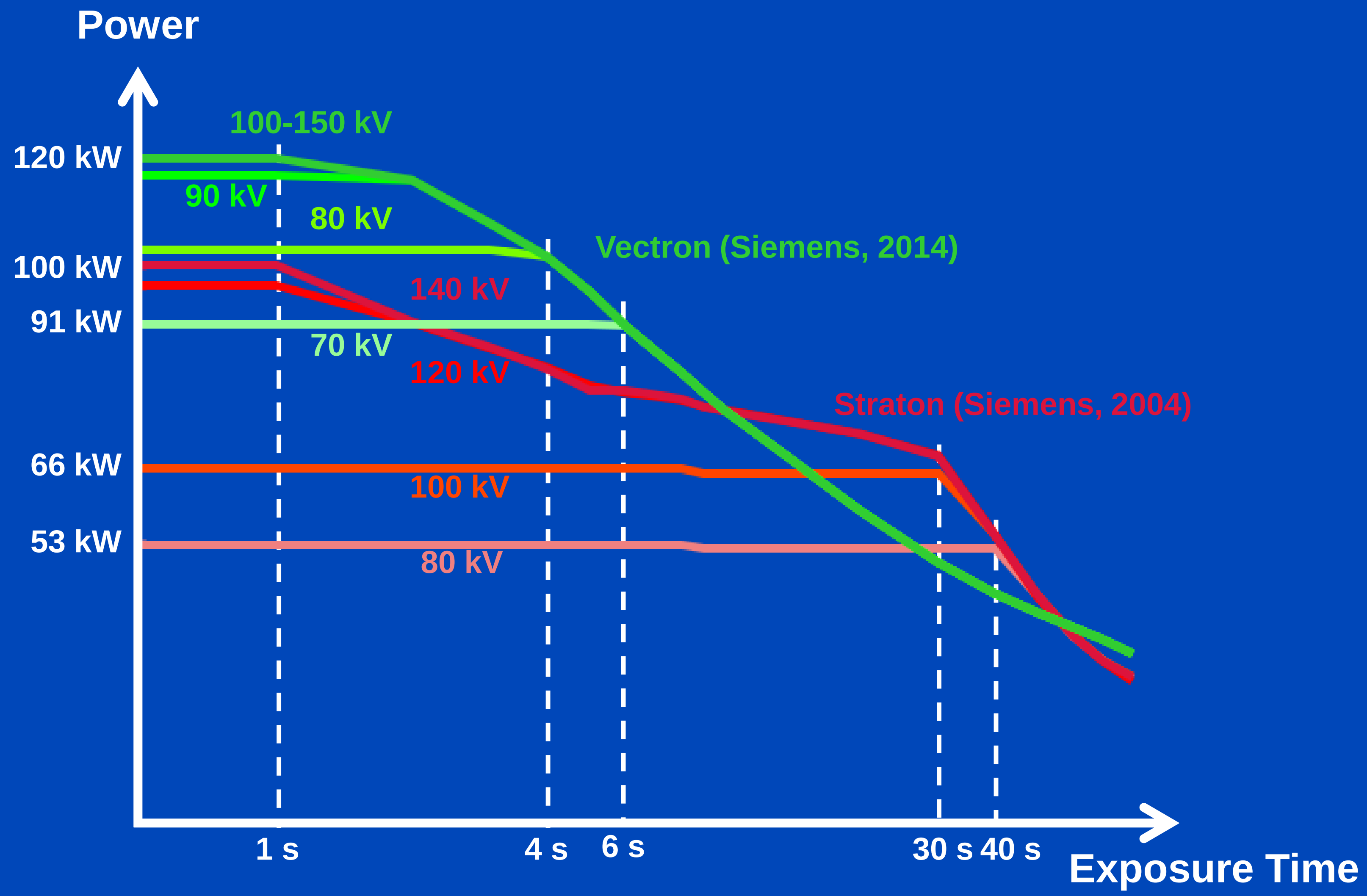


… at the same spatial resolution

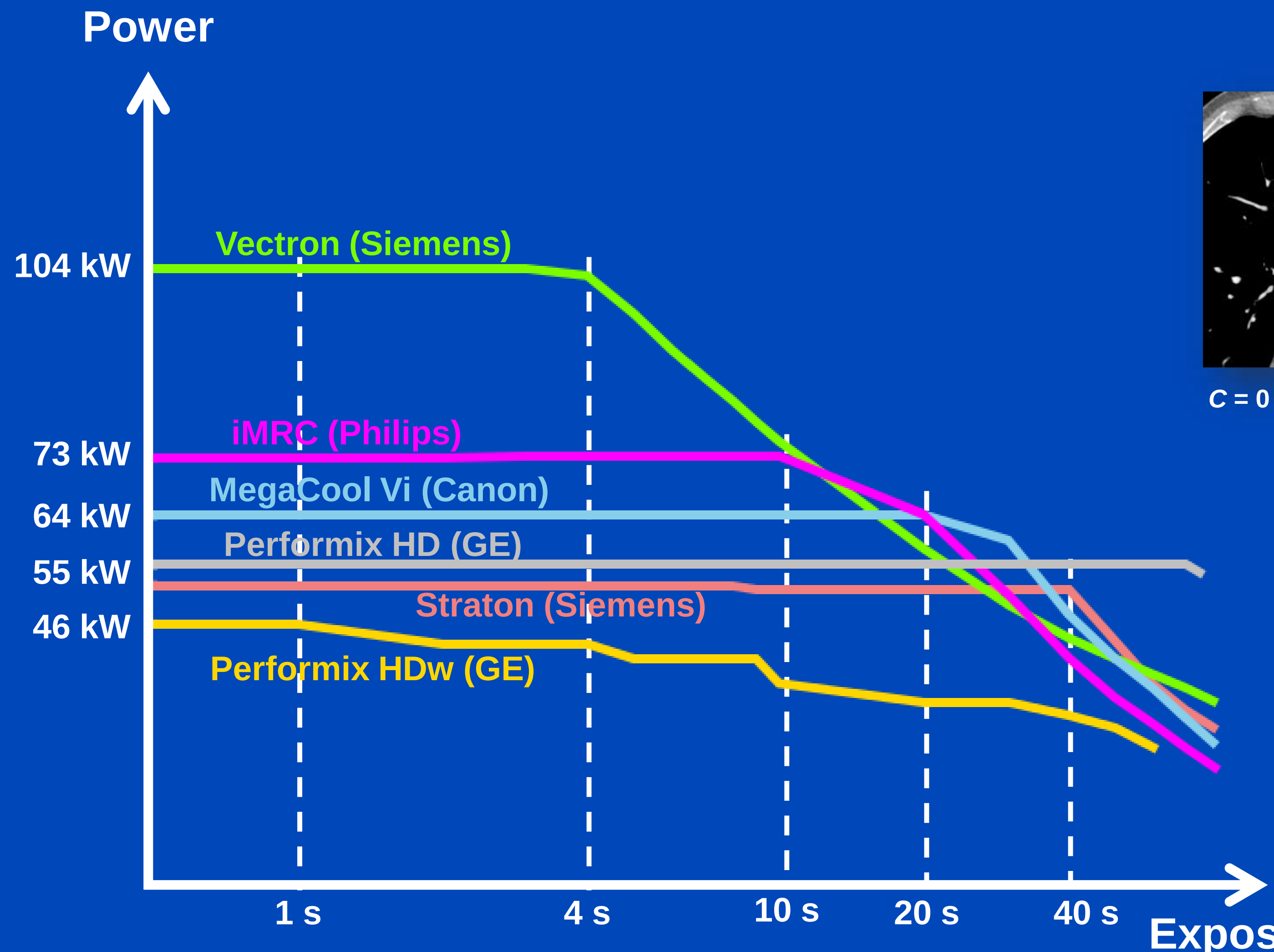
Onset of target melting (rule of thumb)[1]: 1 W/µm

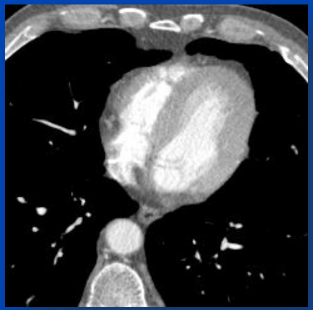
[1] D.E. Grider, A. Writh, and P.K. Ausburn. Electron Beam Melting in Microfocus X-Ray Tubes. J. Phys. D: Appl. Phys 19:2281-2292, 1986

Straton vs. Vectron at all kV



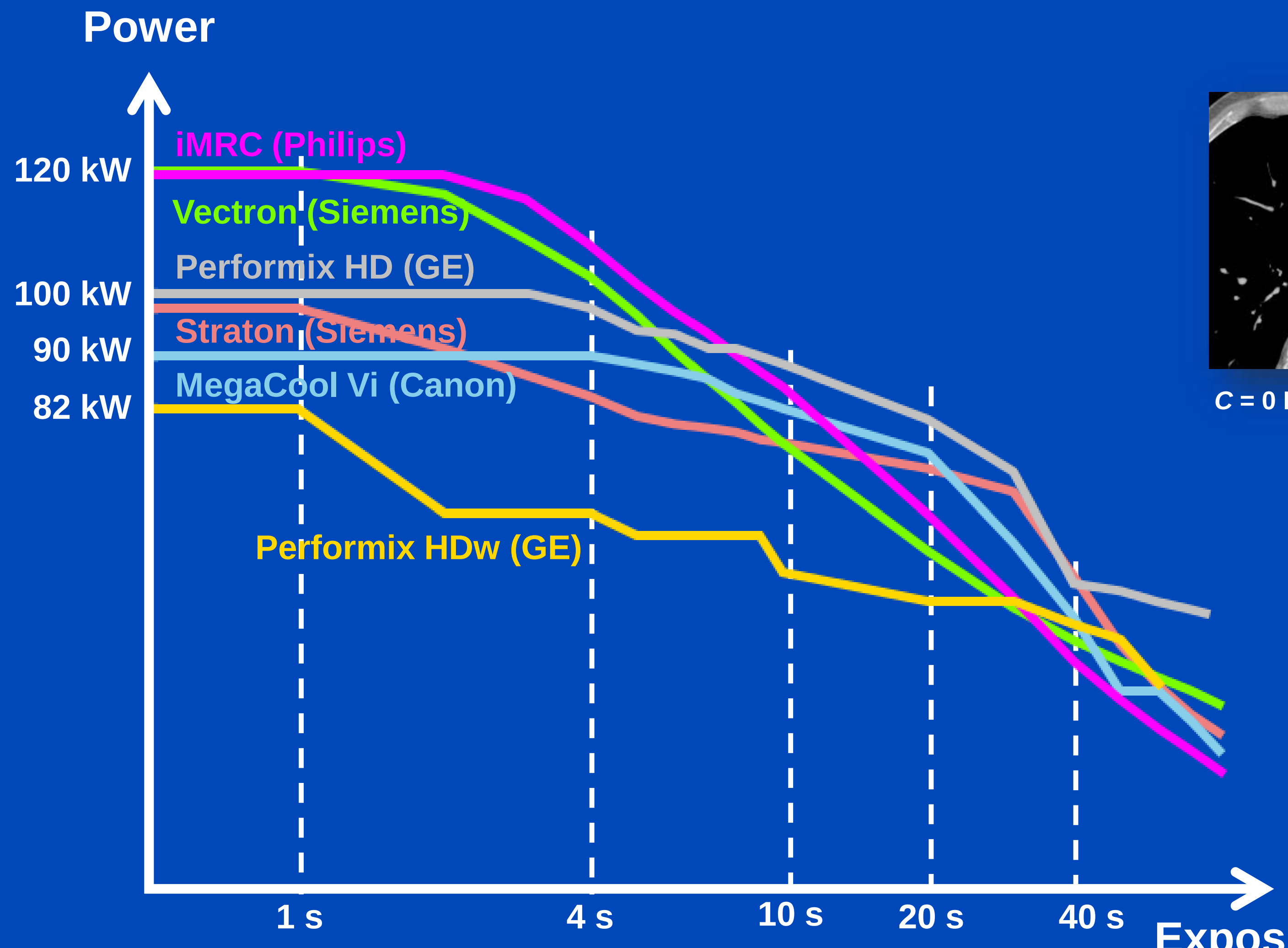
Tube Voltage 80 kV





C = 0 HU, *W* = 700 HU

Tube Voltage 120 kV



C = 0 HU, *W* = 700 HU

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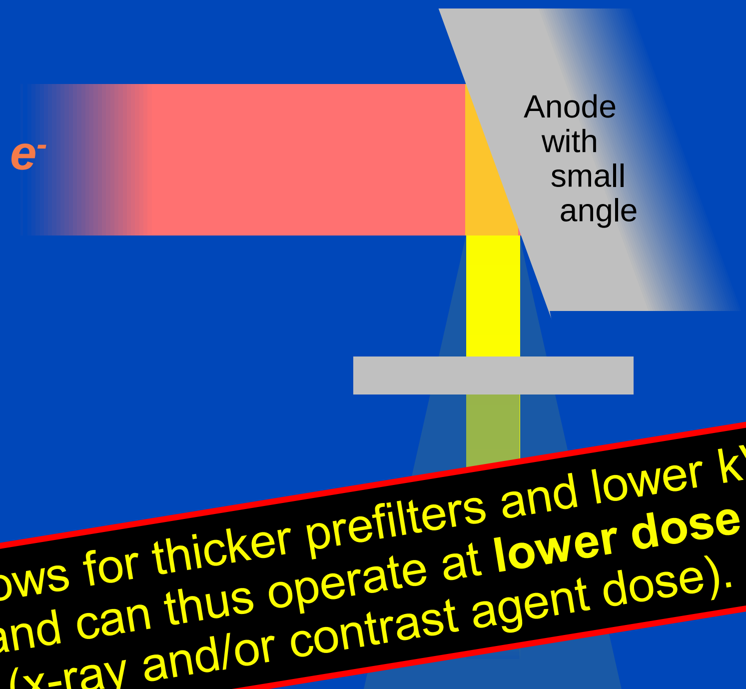
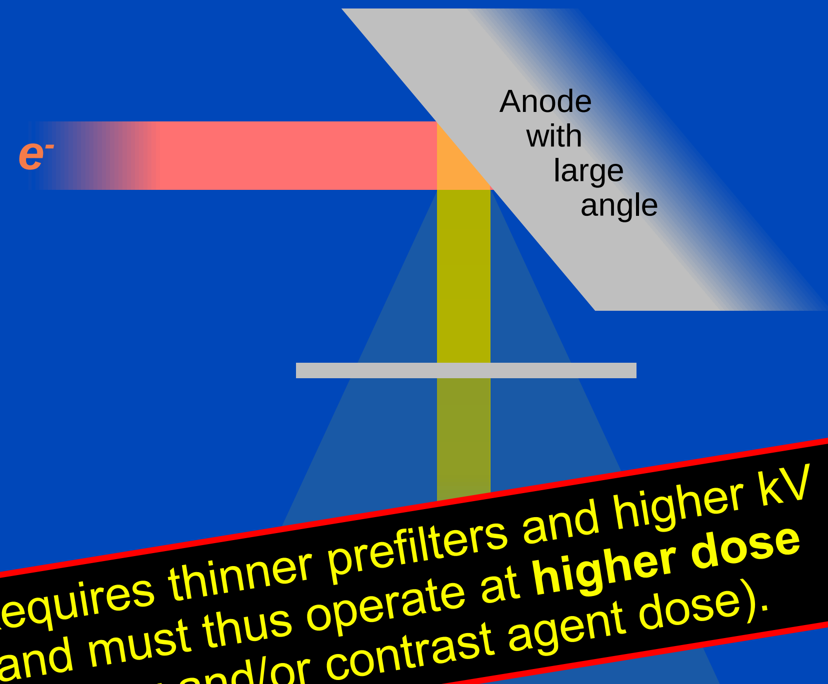
Narrow Cone = High Tube Power

Wide Cone = Low Tube Power



Allows for thicker prefilters and lower kV and can thus operate at **lower dose** (x-ray and/or contrast agent dose).



Requires thinner prefilters and higher kV and must thus operate at **higher dose** (x-ray and/or contrast agent dose).

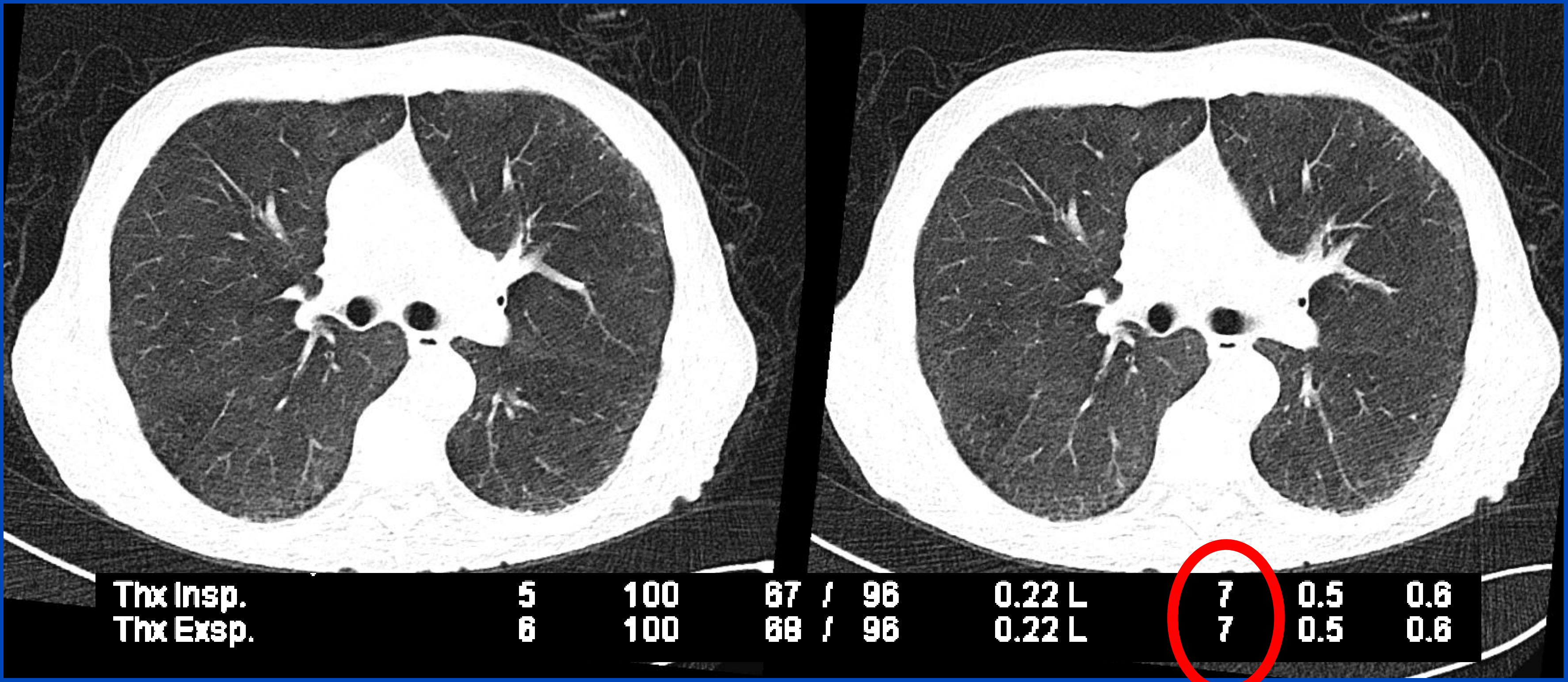
… at the same spatial resolution

Onset of target melting (rule of thumb)[1]: 1 W/µm

[1] D.E. Grider, A. Writh, and P.K. Ausburn. Electron Beam Melting in Microfocus X-Ray Tubes. J. Phys. D: Appl. Phys 19:2281-2292, 1986

Somatom Force: Ultra Low Dose Lung Imaging

- Atypical pneumonia in inspiration and expiration
- Turbo Flash mode, 737 mm/s, 100 kV Sn
- DLP = 7 mGy·cm ≈ 0.1 mSv per scan



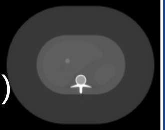
Courtesy of University Hospital Mannheim

Removable Prefilters

- Thicker prefilters
  - improve the dose efficiency
  - require higher x-ray tube power
- Thus, patient-specific filters are advantageous
  - filter changer
  - filter thicknesses for a variety of patient sizes and anatomical regions
  - tube should operate close to its maximum power
- Systems that use patient-specific filtration today:
  - 0.4 mm Sn for Siemens‘ Somatom Flash, Drive, go.Now, go.Up and go.all
  - 0.6 mm Sn for Siemens‘ Somatom Force, Edge Plus, go.Top and Definition Edge
  - 0.4 mm and 0.7 mm Sn for Siemens‘ Somatom X.cite

Dose Reduction by Patient-Specific Tin or Copper Prefilters[1,2] 1000 mAs Limit

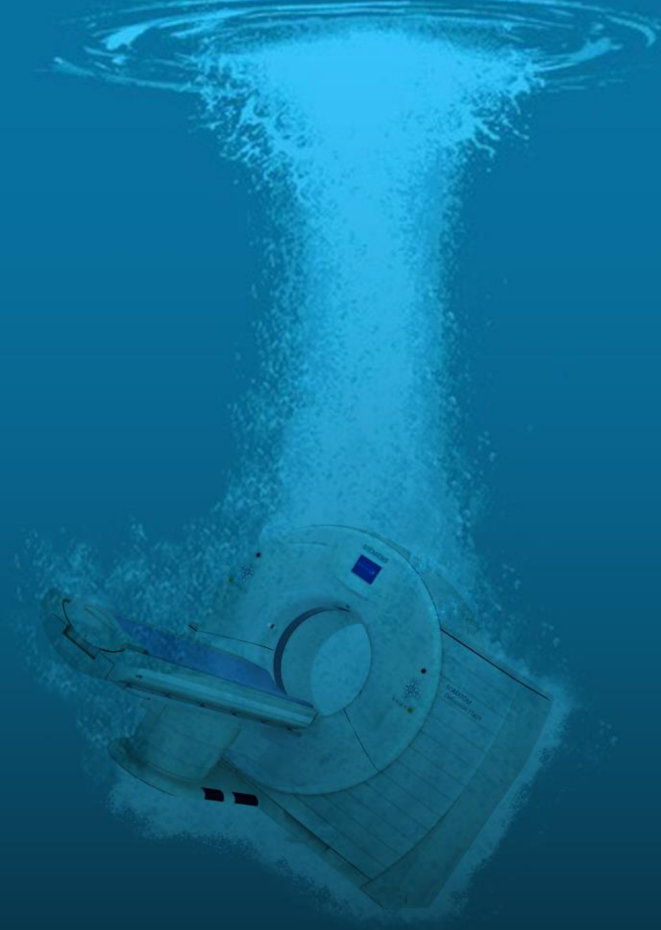
K-edges:
Iodine at 33 keV
Hafnium at 65 keV

	Child (15 cm × 10 cm) 	**Adult** (30 cm × 20 cm) 	**Obese** (50 cm × 40 cm) 
Soft tissue (basis)	30 mAs, 90 kV	100 mAs, 130 kV	600 mAs, 150 kV
Soft tissue, Sn	0.6 mm, 1000 mAs, 75 kV **15%** → 19%	1.0 mm, 1000 mAs, 120 kV **32%** → 36%	0.2 mm, 1000 mAs, 150 kV **25%** → 57%
Soft tissue, Cu	1.6 mm, 1000 mAs, 70 kV **17%** → 19%	3.4 mm, 1000 mAs, 125 kV **31%** → 36%	0.8 mm, 1000 mAs, 150 kV **29%** → 57%
Iodine (basis)	50 mAs, 70 kV	120 mAs, 90 kV	720 mAs, 120 kV
Iodine, Sn	0 mm, 210 mAs, 50 kV **39%**	0.1 mm, 1000 mAs, 70 kV **40%** → 53%	0.0 mm, 1000 mAs, 105 kV **39%** → 81%
Iodine, Cu	0.4 mm, 1000 mAs, 50 kV **57%** → 67%	0.2 mm, 1000 mAs, 65 kV **49%** → 68%	0.0 mm, 1000 mAs, 105 kV **39%** → 89%
Hafnium, no filter	0.0 mm, 25 mAs, 100 kV **-29%**	0.0 mm, 100 mAs, 100 kV **55%**	0.0 mm, 860 mAs, 115 kV **80%**
Hafnium, Cu	3.3 mm, 1000 mAs, 85 kV **43%** → 53%	2.3 mm, 1000 mAs, 95 kV **79%** → 86%	0.3 mm, 1000 mAs, 120 kV **83%** → 94%

[1]Steidel, Maier, Sawall, Kachelrieß. Tin or Copper Prefilters for Dose Reduction in Diagnostic Single Energy CT? RSNA 2020.
[2]Steidel, Maier, Sawall, Kachelrieß. Dose Reduction through Patient-Specific Prefilters in Diagnostic Single Energy CT. RSNA 2020.

Premium CT Systems 2020/2021

Vendor	CT-System	Configuration	Collim, Cone	Rotation, FOM	Max. Power, Anode Angle	Max. mA @ low kV, patient-specific filters	Matrix	DECT
Canon	Aquilion ONE Genesis	320 × 0.5 mm PUREViSION	160 mm, 15°	0.275 s, 50 cm	100 kW, 10° MegaCool Vi	600 mA @ 80 kV, none	512	2 scans
Canon	Aquilion Precision	160 × 0.25 mm PUREViSION	40 mm, 3.9°	0.35 s, 50 cm	72 kW, 7° MegaCool	600 mA @ 80 kV, none	512, 1024, 2048	2 scans
GE	Revolution Apex	256 × 0.625 mm GemStone Clarity	160 mm, 15°	0.28 s, 50 cm	108 kW, 10° Quantix 160	1300 mA @ 70+80 kV, none	512	fast TVS or 2 scans
GE	CardioGraphe	192 × 0.73 mm (focused FOM)	140 mm, 17°	0.24 s, 25 cm	72 kW, 13° Dual MCS-2093	600 mA @ 80 kV, none	512	2 scans
Philips	Brilliance iCT	2 · 128 × 0.625 mm NanoPanel 3D	80 mm, 7.7°	0.27 s, 50 cm	120 kW, 8° iMRC	925 mA @ 80 kV, none	512, 768, 1024	2 scans
Philips	IQon	2 · 64 × 0.625 mm NanoPanel Prism	40 mm, 3.9°	0.27 s, 50 cm	120 kW, 8° iMRC	925 mA @ 80 kV, none	512, 768, 1024	sandwich
Siemens	Somatom X.cite	2 · 64 × 0.6 mm Stellar	38.4 mm, 3.7°	0.3 s, 50 cm	105 kW, 8° Vectron	1200 mA @ 70+80+90 kV, {0, 0.4, 0.7} mm Sn	512, 768, 1024	split filter or 2 scans
Siemens	Somatom Force	2 · 2 · 96 × 0.6 mm Stellar	57.6 mm, 5.5°	0.25 s, 50/36 cm	2 · 120 kW, 8° Vectron	2 · 1300 mA @ 70+80+90 kV, {0, 0.6} mm Sn	512, 768, 1024	DSCT
Siemens experimental	Somatom CounT	32×0.5/24×0.25 mm (photon counting)	16 mm, 1.5°	0.5 s, 50/28 cm	77 kW, 7° Straton MX P	500 mA @ 70 kV {0, 0.4} mm Sn	512, 768, 1024, 2048	4 bin PC

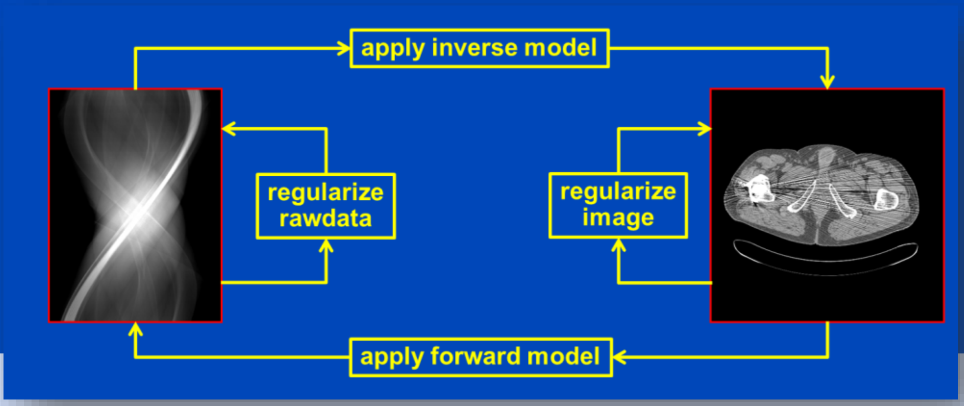


Part 2: Deep Image Formation Software

Premium Recon Algorithms 2020/2021

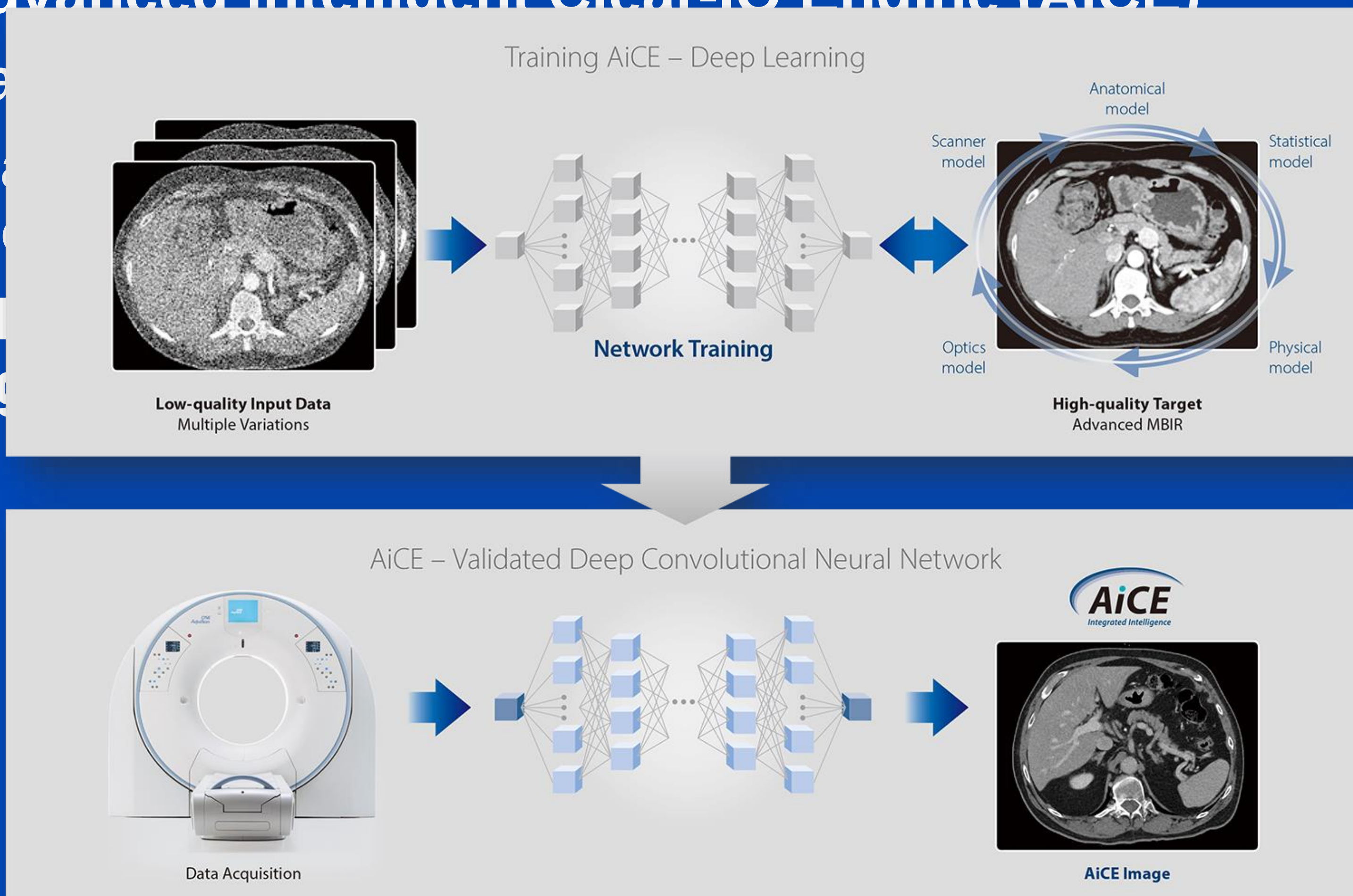
Vendor	Algorithm	Additional parameters	Sinogram restoration	Image restoration	Full iterations	Deep learning
all	FBP	-	✓	-	-	-
Canon	AIDR-3D enhanced FIRST AiCE	Body, Bone, Brain, Cardiac, Lung each with Mild, Standard, or Strong	✓ ✓ ?	✓ ✓ ✓	- ✓ -	- - ✓
GE	ASIR, ASIR-V True Fidelity	0 – 100% (e.g. ASIR 30%) ???	✓ ?	✓ ✓	- -	- ✓
Philips	iDose IMR	Levels 1 – 7 Soft, Routine, or SharpPlus	✓ ?	✓ ?	- ?	- -
Siemens	IRIS SAFIRE ADMIRE	Strength 1 – 5 Strength 1 – 5 Strength 1 – 5	✓ ✓ ✓	✓ ✓ ✓	- ✓ ✓	- - -

= deep learning-based image restoration so far



Noise Removal Example 2
Canon's AiCE

- Advanced intelligent Clear-IQ Engine (AiCE)
- Ba
- Tr
  pr .
- FI n a
  hi



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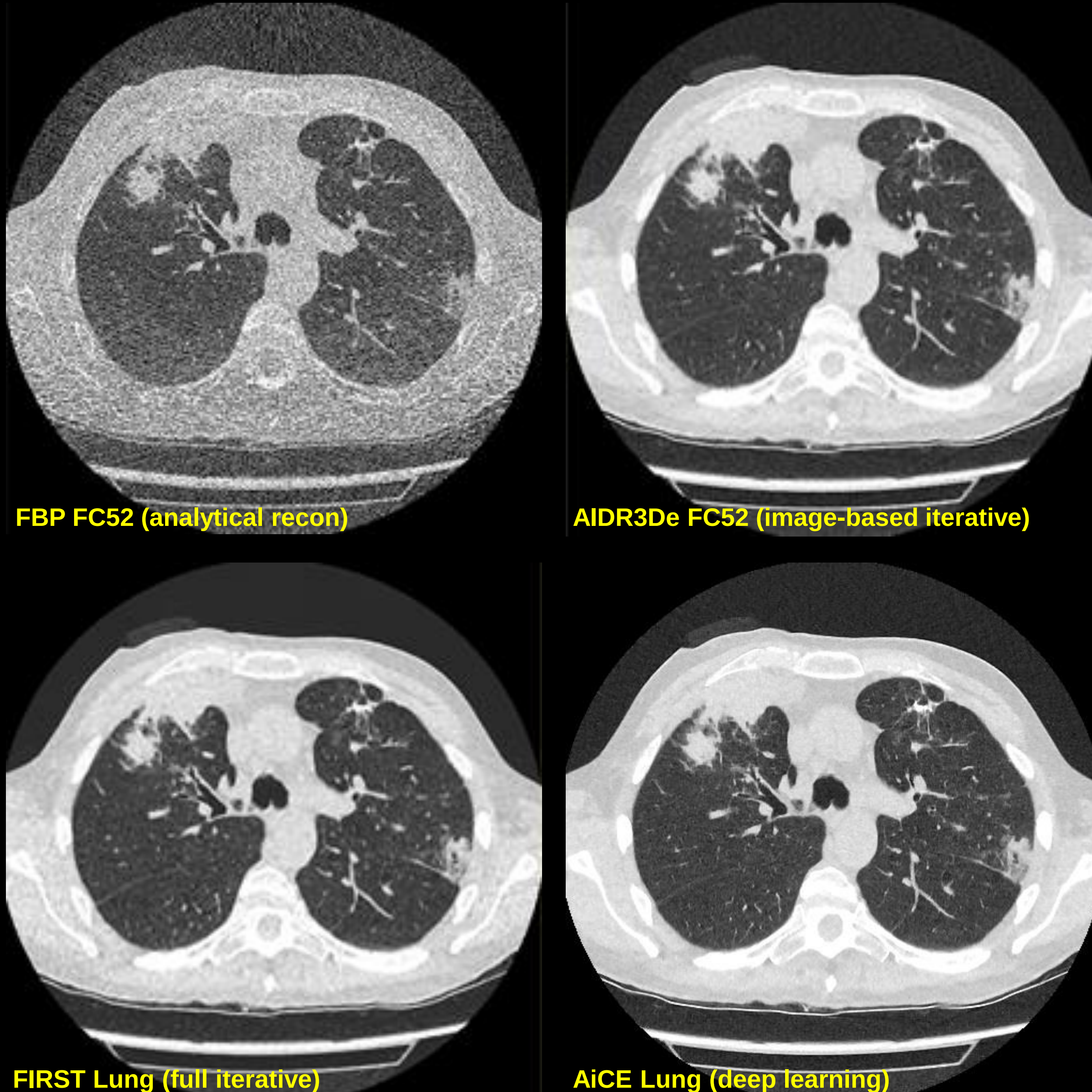
U = 100 kV
CTDI = 0.6 mGy
DLP = 24.7 mGy·cm
D_{eff} = 0.35 mSv



Courtesy of
Radboudumc,
the Netherlands

Noise Removal Example 3
GE's True Fidelity

- Based on a deep CNN
- Trained to restore low-dose CT data to match the properties of Veo, the model-based IR of GE.
- No information can be obtained in how the training is conducted for the product implementation.

2.5D DEEP LEARNING FOR CT IMAGE RECONSTRUCTION USING A MULTI-GPU IMPLEMENTATION

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Jean-Baptiste Thibault[‡], *Charles A. Bouman*[⋆]

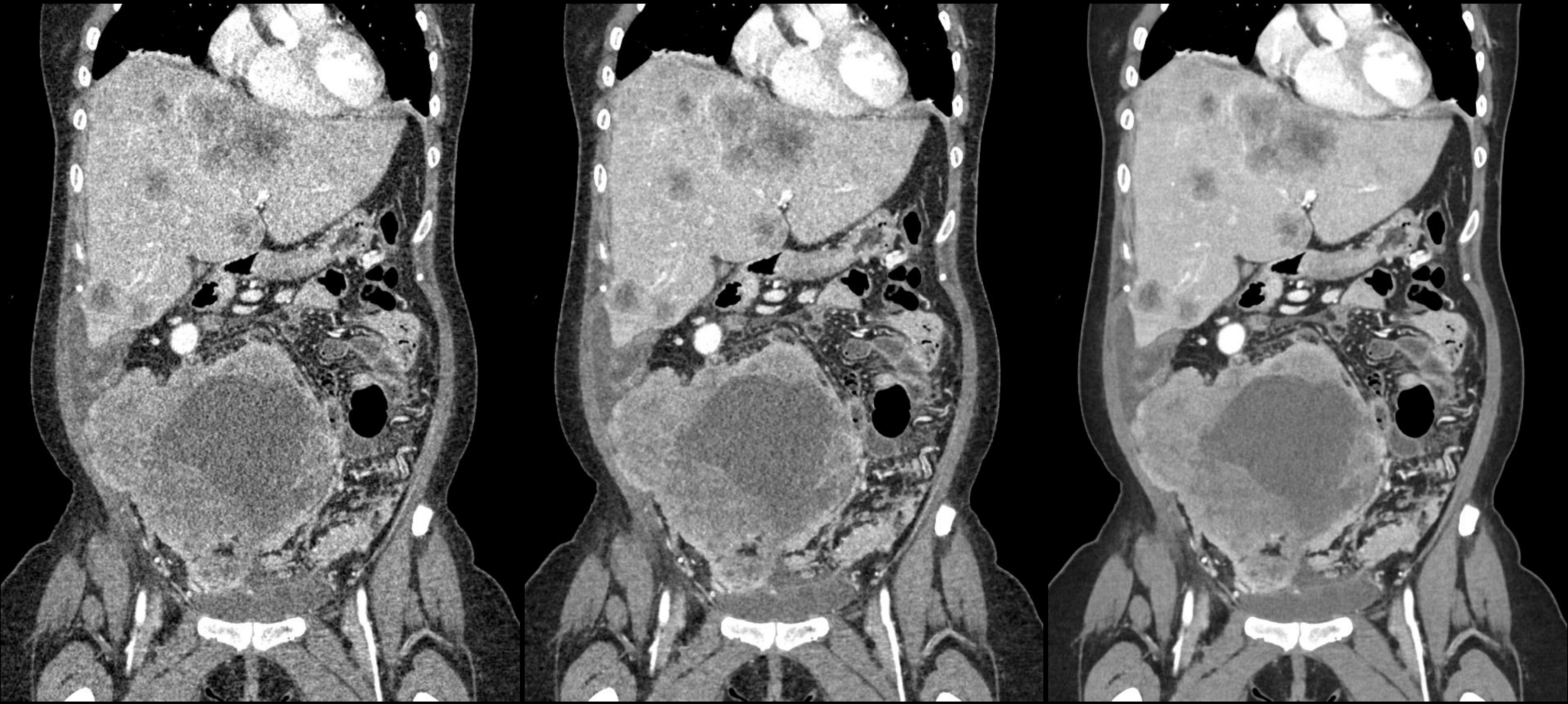
[⋆] Electrical and Computer Engineering at Purdue University
[†] Electrical and Computer Engineering at Marquett University
[‡] GE Healthcare
[⊕] Electrical Engineering at University of Notre Dame

ABSTRACT

While Model Based Iterative Reconstruction (MBIR) of CT scans has been shown to have better image quality than Filtered Back Projection (FBP), its use has been limited by its high computational cost. More recently, deep convolutional neural networks (CNN) have shown great promise in both denoising and reconstruction applications. In this research, we propose a fast reconstruction algorithm, which we call Deep

streaking artifacts caused by sparse projection views in CT images [8]. More recently, Ye, et al. [9] developed method for incorporating CNN denoisers into MBIR reconstruction as advanced prior models using the Plug-and-Play framework [10, 11].

In this paper, we propose a fast reconstruction algorithm, which we call Deep Learning MBIR (DL-MBIR), for approximately achieving the improved quality of MBIR using a deep residual neural network. The DL-MBIR method is trained to



FBP

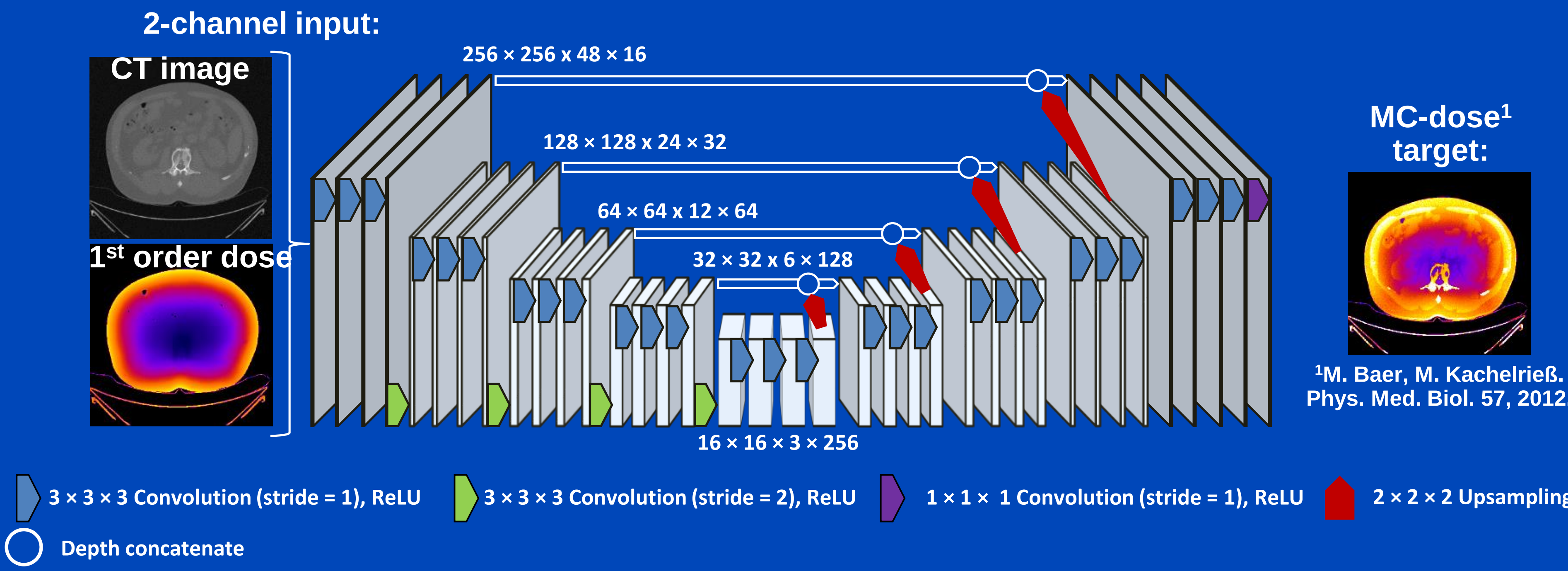
ASIR V 50%

True Fidelity

Courtesy of GE Healthcare

Deep Dose Estimation (DDE)

- Combine fast and accurate CT dose estimation using a deep convolutional neural network.
- Train the network to reproduce MC dose estimates given the CT image and a first-order dose estimate.

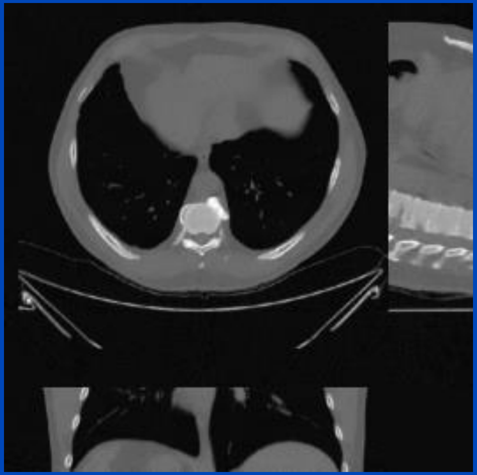


J. Maier, E. Eulig, S. Sawall, and M. Kachelrieß. Real-time patient-specific CT dose estimation using a deep convolutional neural network, Proc. IEEE MIC 2018 and ECR Book of Abstracts 2019. *Best Paper within Machine Learning at ECR 2019!*

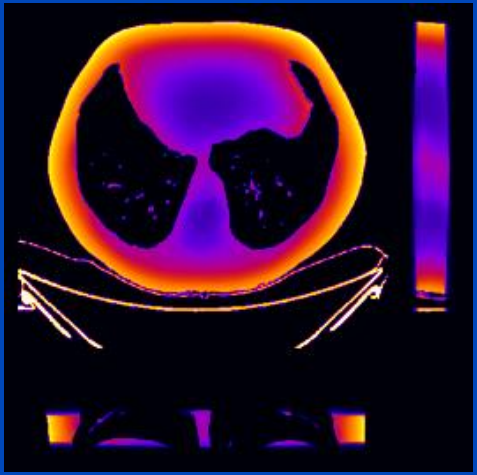
Deep Dose Estimation (DDE)

Thorax, tube A, 120 kV, no bowtie

CT image



First order dose

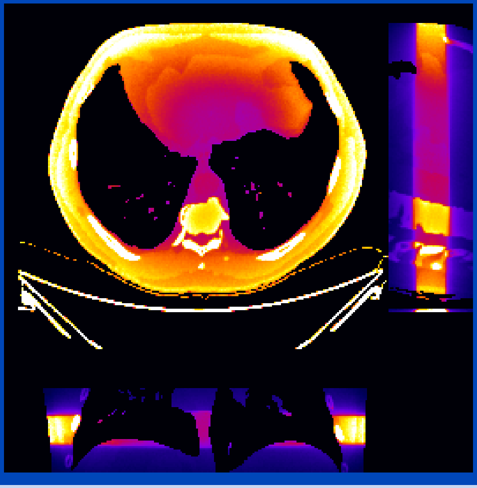


	MC	DDE
48 slices	1 h	0.25 s
whole body	20 h	5 s

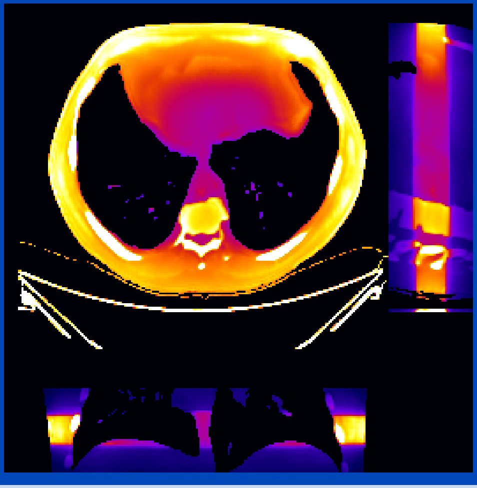
MC uses 16 CPU kernels
DDE uses one Nvidia Quadro P600 GPU

DDE training took 74 h for 300 epochs, 1440 samples, 48 slices per sample

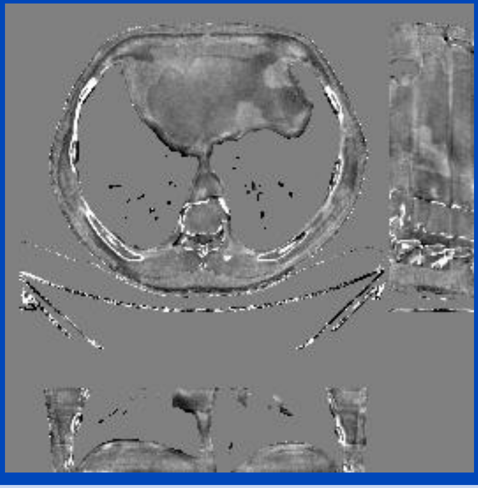
MC ground truth



DDE



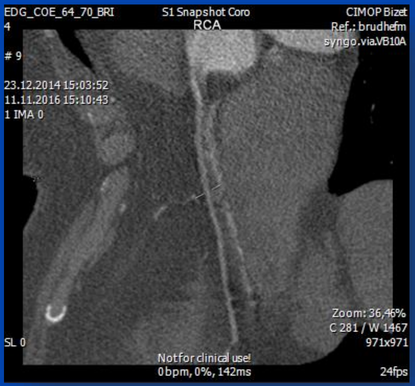
Relative error



C = 0%
W = 40%

J. Maier, E. Eulig, S. Sawall, and M. Kachelrieß. Real-time patient-specific CT dose estimation using a deep convolutional neural network, Proc. IEEE MIC 2018 and ECR Book of Abstracts 2019. *Best Paper within Machine Learning at ECR 2019!*

Deep Cardiac Motion Compensation



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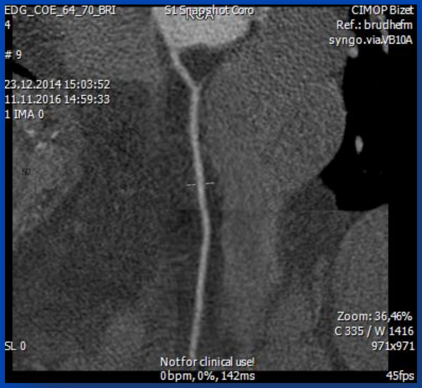

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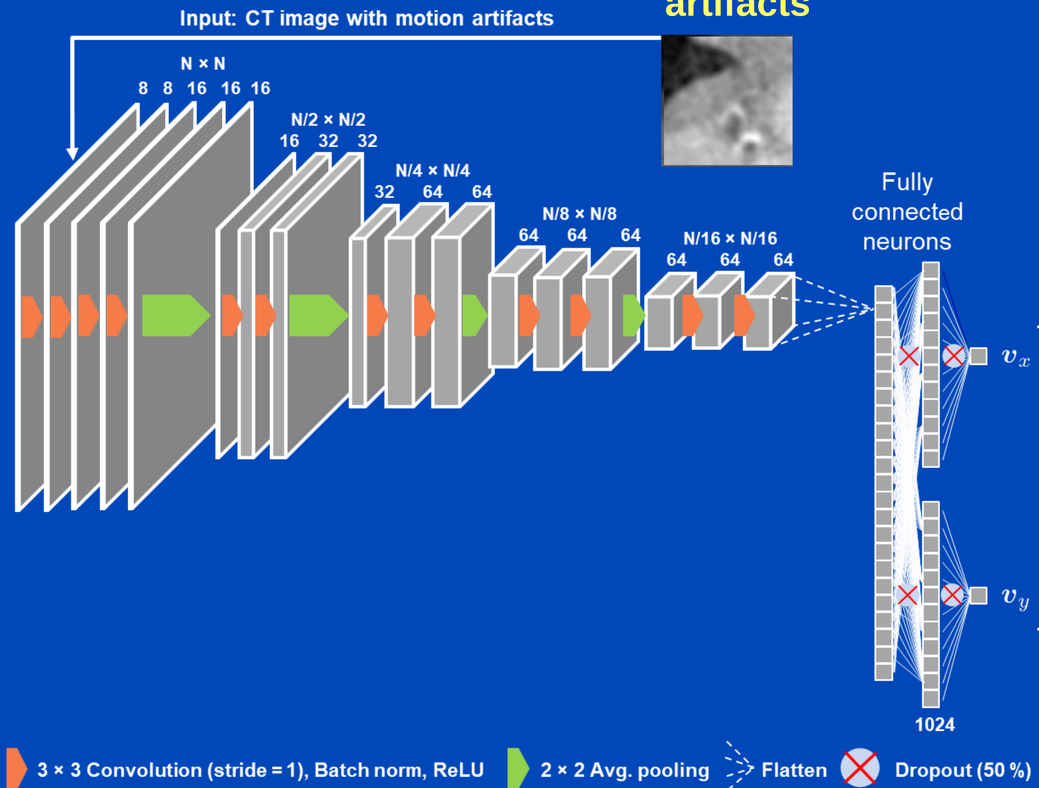
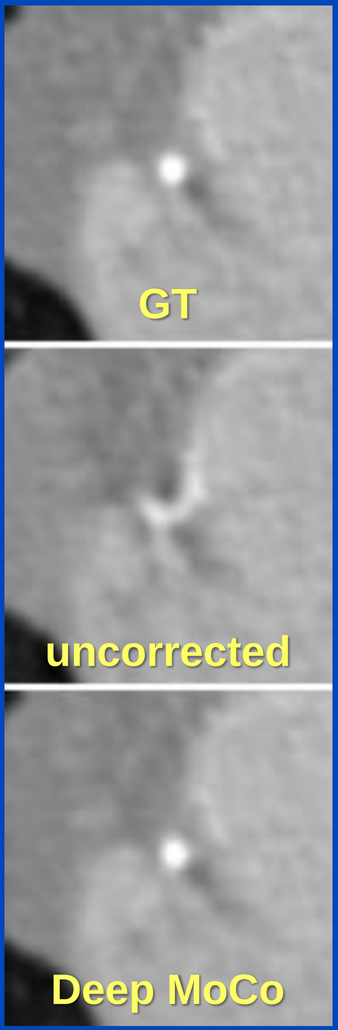
Motion Compensation for Cardiac CT

Input: CT image with motion artifacts

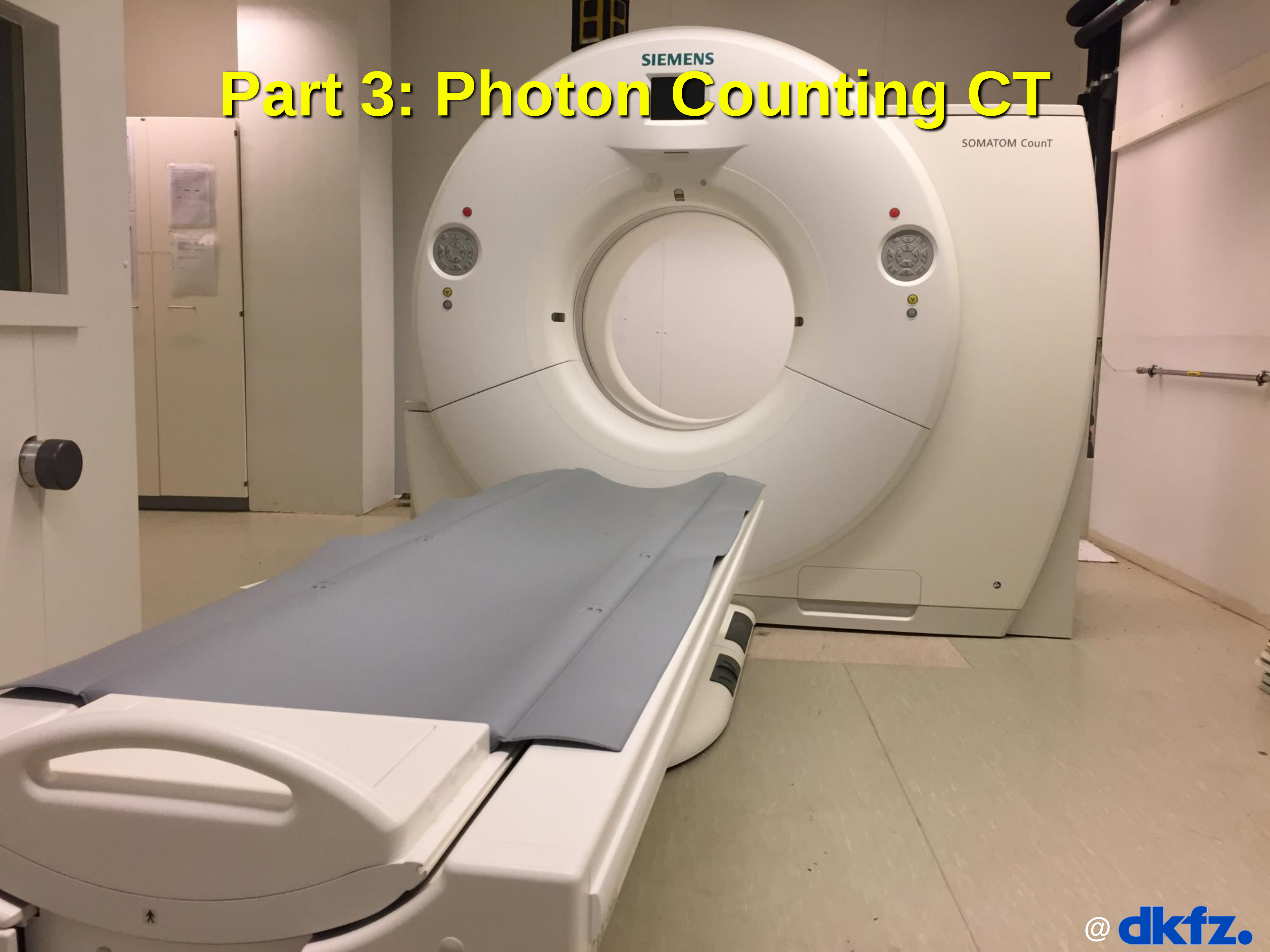


Output: motion direction (to be used by MoCo recon)



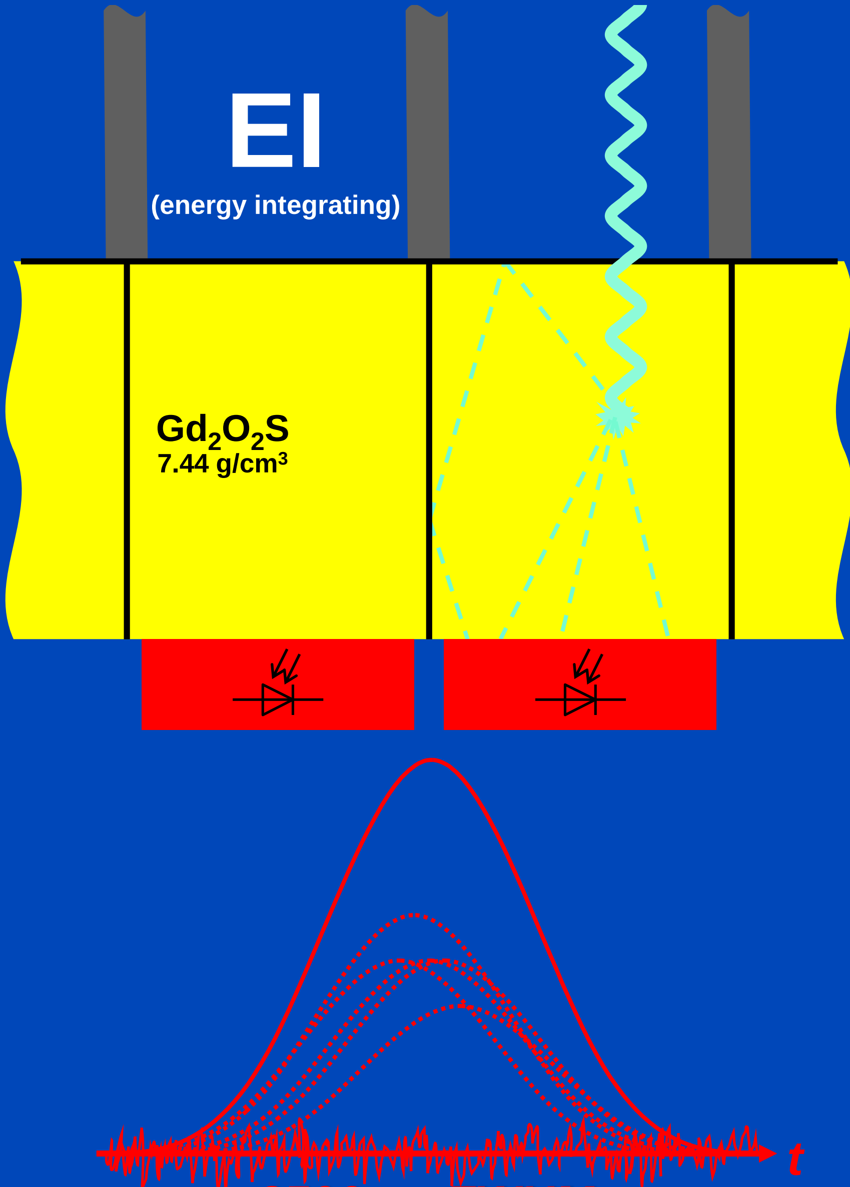
J. Maier, S. Lebedev, E. Eulig, S. Sawall, E. Fournié, K. Stierstorfer, and M. Kachelrieß .Coronary artery motion compensation for short-scan cardiac CT using a spatial transformer network. Conference Program of the 6th International CT-Meeting, August 2020.

Part 3: Photon Counting CT



@ dkfz.

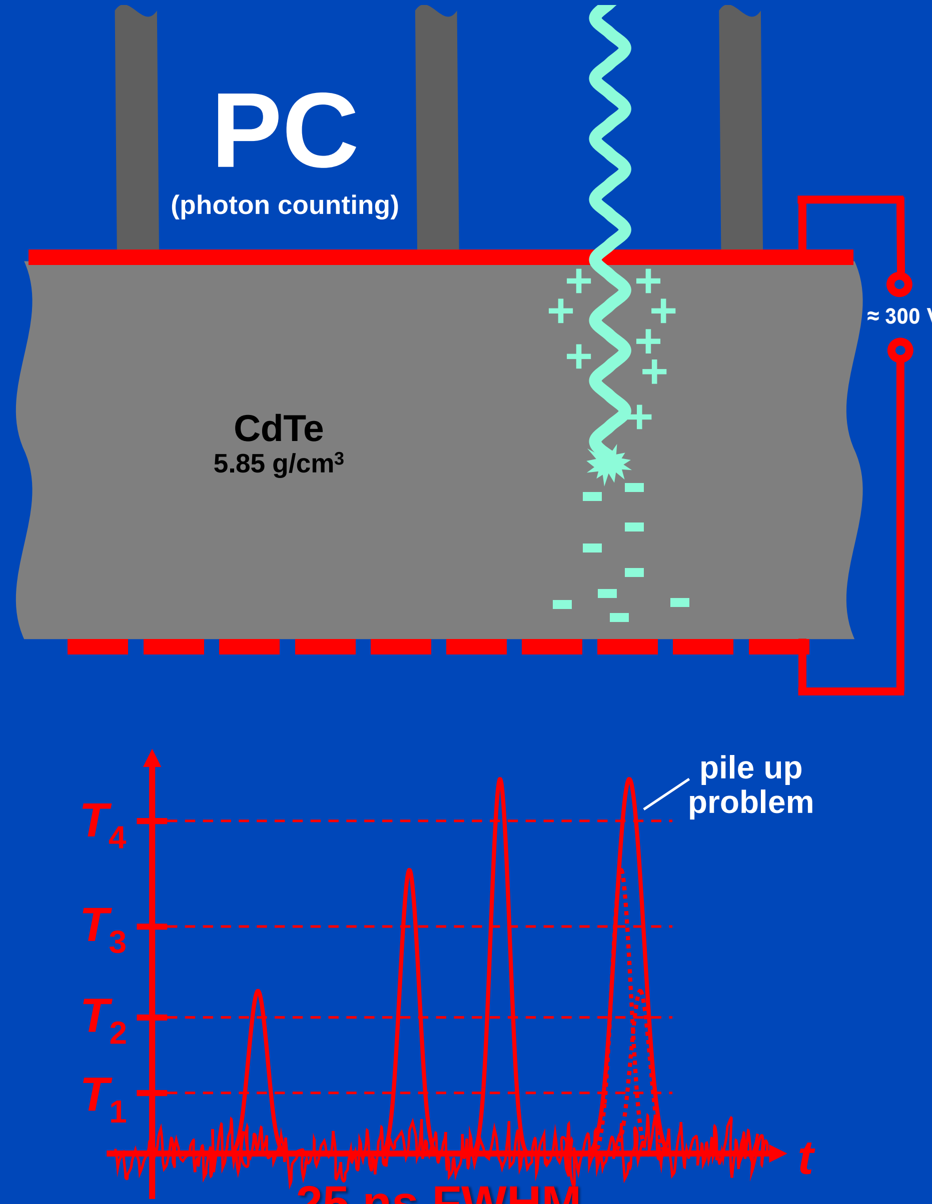
Indirect Conversion (Today)



2500 ns FWHM

i.e. max $O(40\cdot10^3)$ cps

Direct Conversion (Future)



25 ns FWHM

i.e. max $O(40\cdot10^6)$ cps

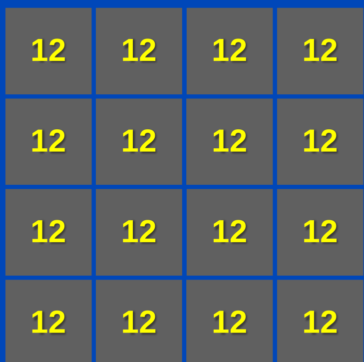
Requirements for CT: up to 10^9 x-ray photon counts per second per mm^2.
Hence, photon counting only achievable for direct converters.

Existing Systems 2020

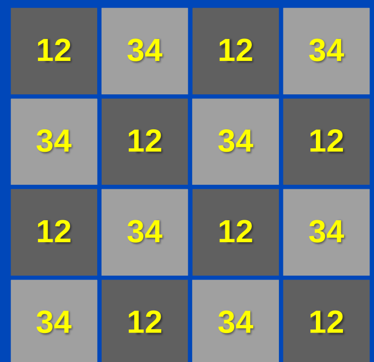
	Setup	Detector	Pixel size (mm^2)	FOV	Thresholds	Acquisition rate info	Extra
Philips Healthcare (preclinical) [1, 2, 3]	Preclinical	CdZnTe	0.5 × 0.5	16.8 cm	5 (30-98 keV)	Frame rate: 2400 Hz	
MARS Bioimaging (preclinical) [4, 5]	Preclinical MARS orthopaedic imaging-cooming soon	2 mm CdZnTe; 5 medipix3RX chips in a row (70 mm × 14 mm)	0.11 × 0.11	10 cm	8 (10-120 keV)	Scan time: 8 minutes for a sample with 30 mm diameter and 15 mm length	Charge summing mode
Siemens Somaton CounT [6]	**Clinical, whole body**	Dual-source CT with one PC detector of 1.6 mm CdTe	0.225 × 0.225 or 0.45 × 0.45 or 0.9 × 0.9	**27.5 cm**	4 (20-90 keV)	4 kHz	
KTH Royal Institute of Technology, Stockholm [7]	Table-top Translating detector	30 mm Silicon strip	0.4 × 0.5	0.93 cm (need to translate the detector several times)	8	Count rate: 300 $Mcps/mm^2$	Edge-on design
Center for In Vivo Microscopy, Duke University, Durham (preclinical) [8, 9]	Preclinical Table-top	1 mm CdTe	0.15 × 0.15	~6.5 cm	4		
DKFZ	Preclinical	1 mm CdTe	0.15 × 0.15	~15 cm	4 (9-90 keV)	Frame rate 200 Hz Count rate 100 $Mcps/mm^2$	

Readout Modes of the Siemens CounT

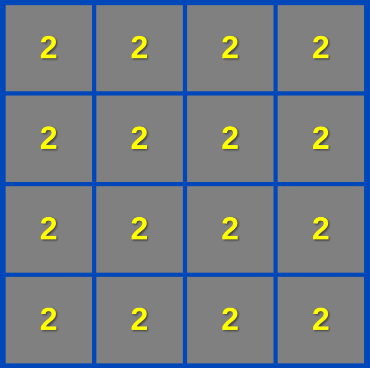
Macro Mode
0.9 × 1.1 mm focus
2 readouts
16 mm z-coverage



Chess Mode
0.9 × 1.1 mm focus
4 readouts
16 mm z-coverage



Sharp Mode
0.9 × 1.1 mm focus
5 readouts
12 mm z-coverage



UHR Mode
0.7 × 0.7 mm focus
8 readouts
8 mm z-coverage

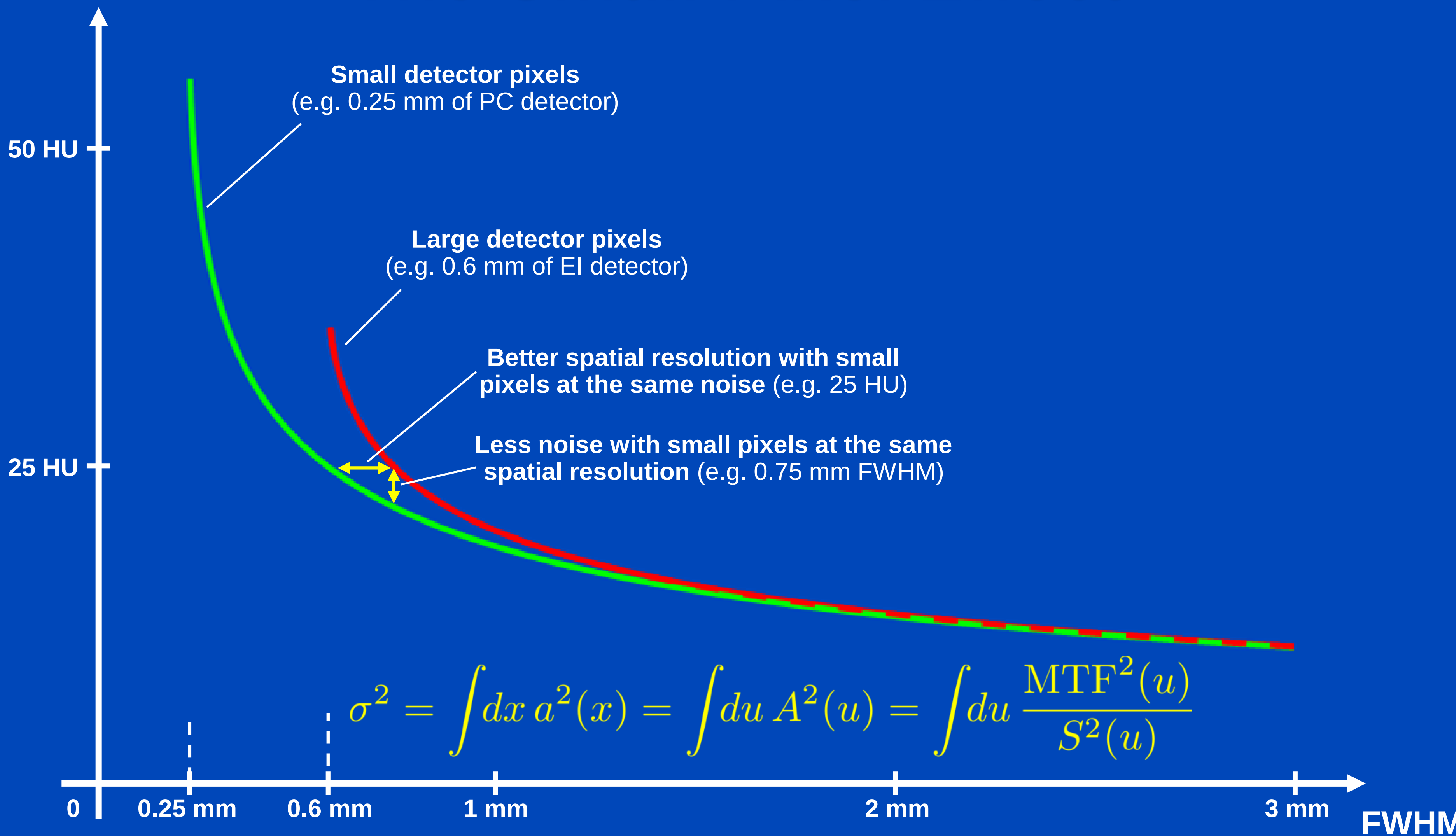
1.6 mm CdTe sensor. No FFS on detector B (photon counting detector). 4×4 subpixels of 225 µm size = 0.9 mm pixels (0.5 mm at isocenter). An additional 225 µm gap (e.g. for anti scatter grid) yields a pixel pitch of 1.125 mm.The whole detector consists of 128×1920 subpixels = 32×480 macro pixels.

This photon-counting whole-body CT prototype, installed at the Mayo Clinic, at the NIH and at the DKFZ is a DSCT system. However, it is restricted to run in single source mode. The second source is used for data completion and for comparisons with EI detectors.

Potential Advantages of Photon Counting CT

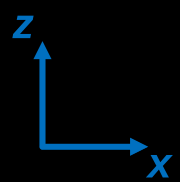
- No electronic noise
  - Less dose for infants
  - Less noise for obese patients
- Counting
  - Swank factor = 1 = maximal
  - Higher weights on low energies = good for iodine contrast
- Energy bin weighting
  - Lower dose/noise
  - Improved iodine CNR
- Smaller pixels (to avoid pileup)
  - Higher spatial resolution
  - Lower dose/noise at conventional resolution
- Spectral information on demand

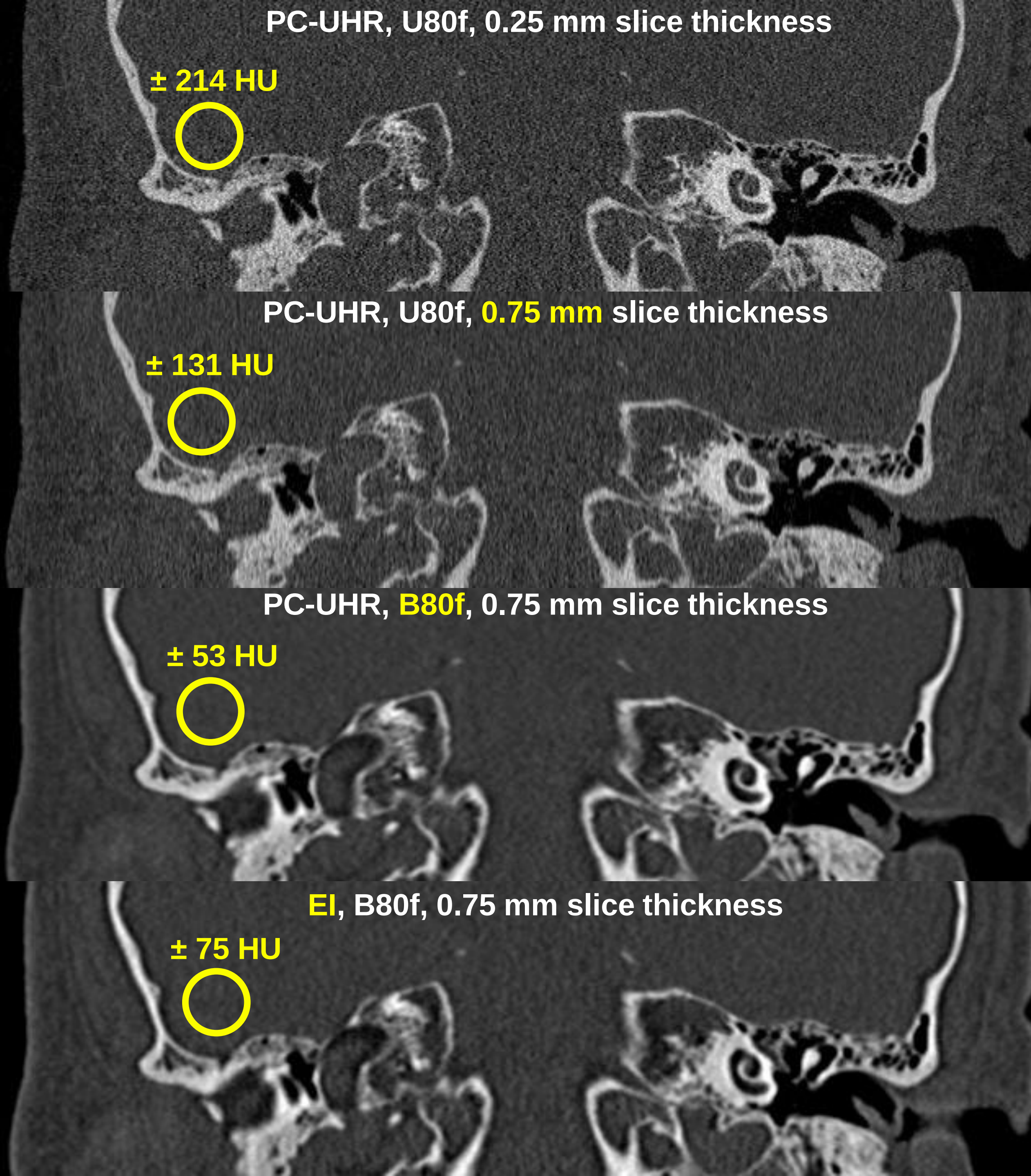
The Small Pixel Effect



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

All images reconstructed with 1024^2 matrix and 0.15 mm slice increment.
***C* = 1000 HU**
***W* = 3500 HU**





PC-UHR, U80f, 0.25 mm slice thickness
10% MTF: 19.1 lp/cm
10% MTF:17.2 lp/cm
xy FWHM: 0.48 mm
z FWHM: 0.40 mm
$CTDI_{vol}$: 16.0 mGy

PC-UHR, U80f, 0.75 mm slice thickness
10% MTF: 19.1 lp/cm
10% MTF:17.2 lp/cm
xy FWHM: 0.48 mm
z FWHM: 0.67 mm
$CTDI_{vol}$: 16.0 mGy

PC-UHR, B80f, 0.75 mm slice thickness
10% MTF: 9.3 lp/cm
10% MTF:10.5 lp/cm
xy FWHM: 0.71 mm
z FWHM: 0.67 mm
$CTDI_{vol}$: 16.0 mGy

EI, B80f, 0.75 mm slice thickness
10% MTF: 9.3 lp/cm
10% MTF:10.5 lp/cm
xy FWHM: 0.71 mm
z FWHM: 0.67 mm
$CTDI_{vol}$: 16.0 mGy

Data courtesy of the Institute of Forensic Medicine of the University of Heidelberg and of the Division of Radiology of the German Cancer Research Center (DKFZ)

dkfz.

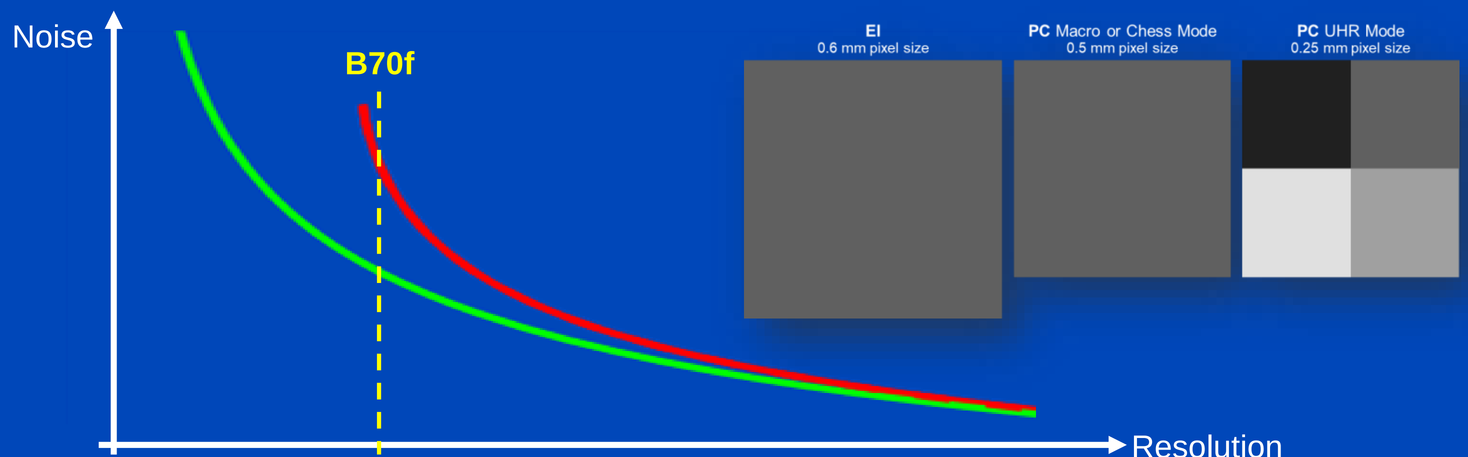
X-Ray Dose Reduction of B70f

PC vs. PC (“pixel effect only”)

UHR vs. Macro	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 (“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

Summary

- **CT dose efficiency and image quality will significantly improve**
  - Patient-specific prefilters
  - Deep learning-based image formation
  - Photon counting detectors
- **Less artifacts**
  - Iterative reconstruction
  - Deep learning-based image formation
- **Higher spatial resolution will become routinely available**
  - Conventional detectors with smaller pixels
  - Photon counting CT systems
- **Spectral information will be available on demand**
  - Photon counting detectors

Thank You!

This presentation is 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.