Basics of X-Ray-Based Tomographic Imaging for IGRT 1:
Diagnostic CT and Flat Detector CT

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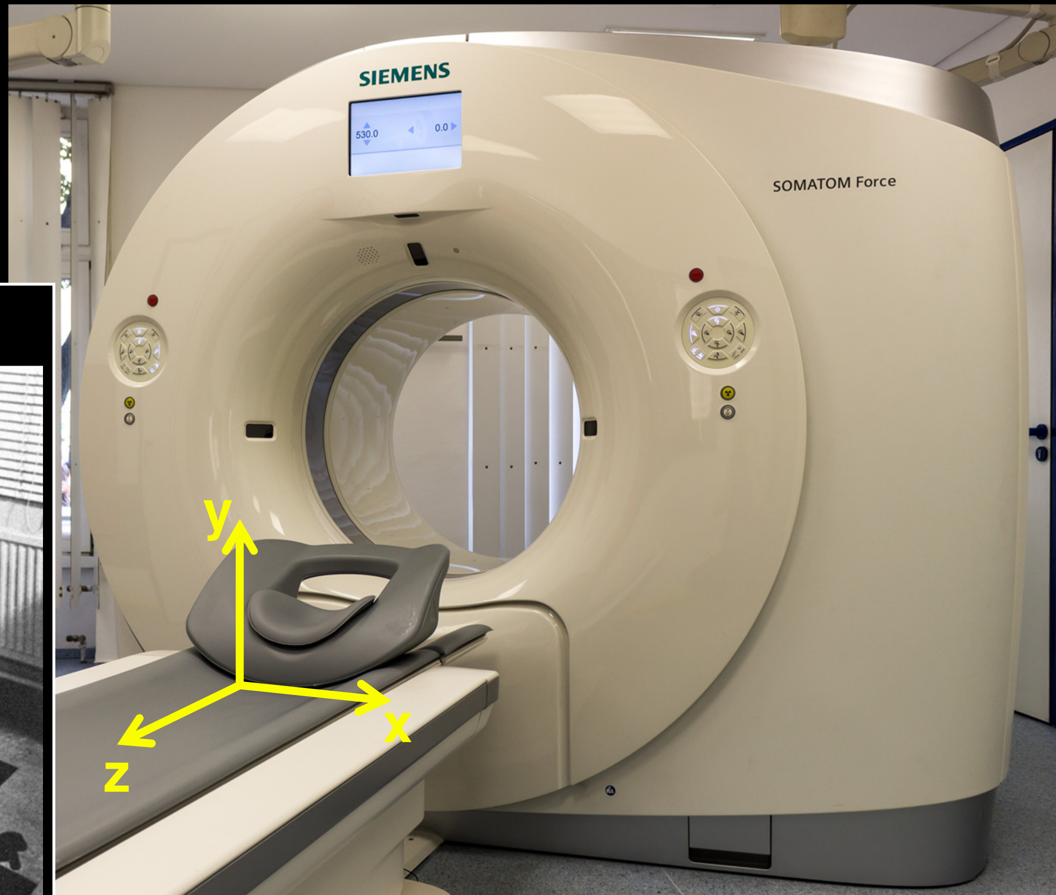
DEUTSCHES
KREBSFORSCHUNGSZENTRUM
IN DER HELMHOLTZ-GEMEINSCHAFT

Siemens 2·2·96=384-slice dual source cone-beam spiral CT(2013)



525 views (1050 readings) per rotation in 0.25 s

2·96×(920+640) two-byte channels per view

1,200 MB/s data transfer rate

up to 4 GB rawdata, 2 GB volume size typical

EMI parallel beam scanner (1972)

180 views per rotation in 300 s

2×160 positions per view

384 B/s data transfer rate

113 kB data size

dkfz.

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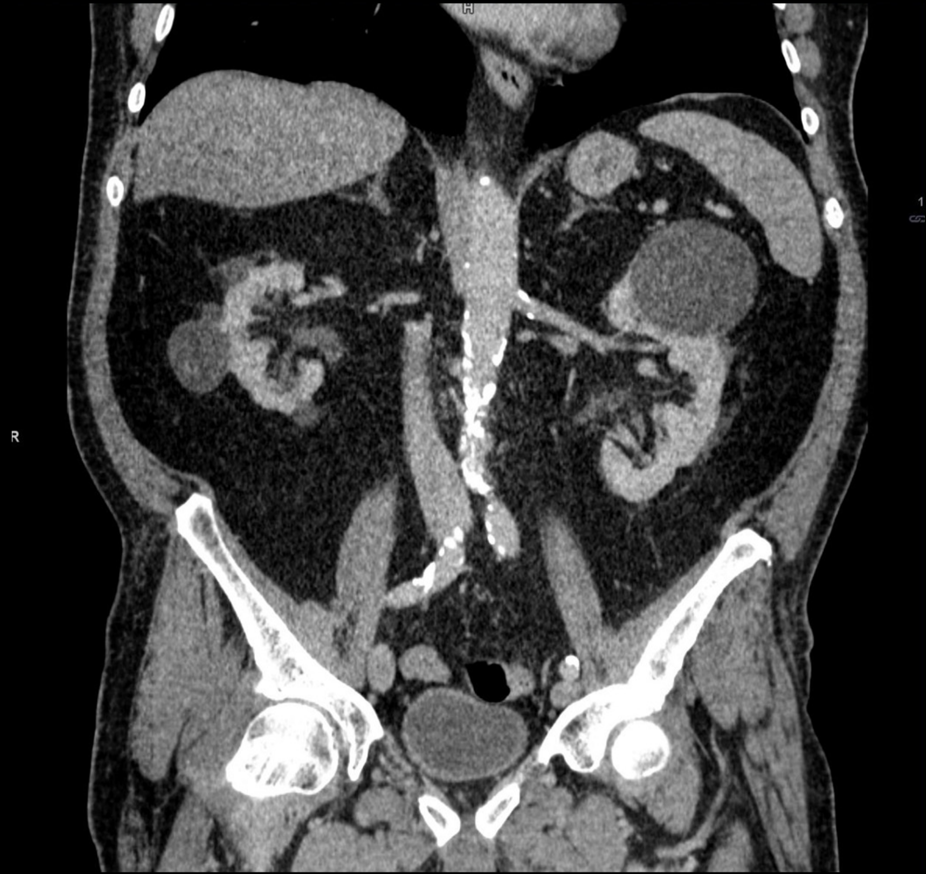

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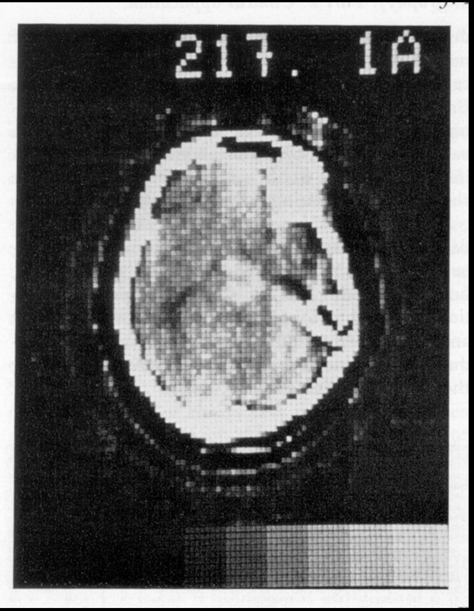

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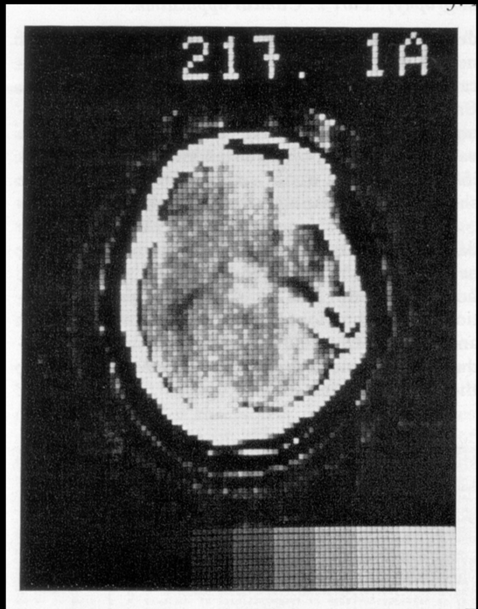

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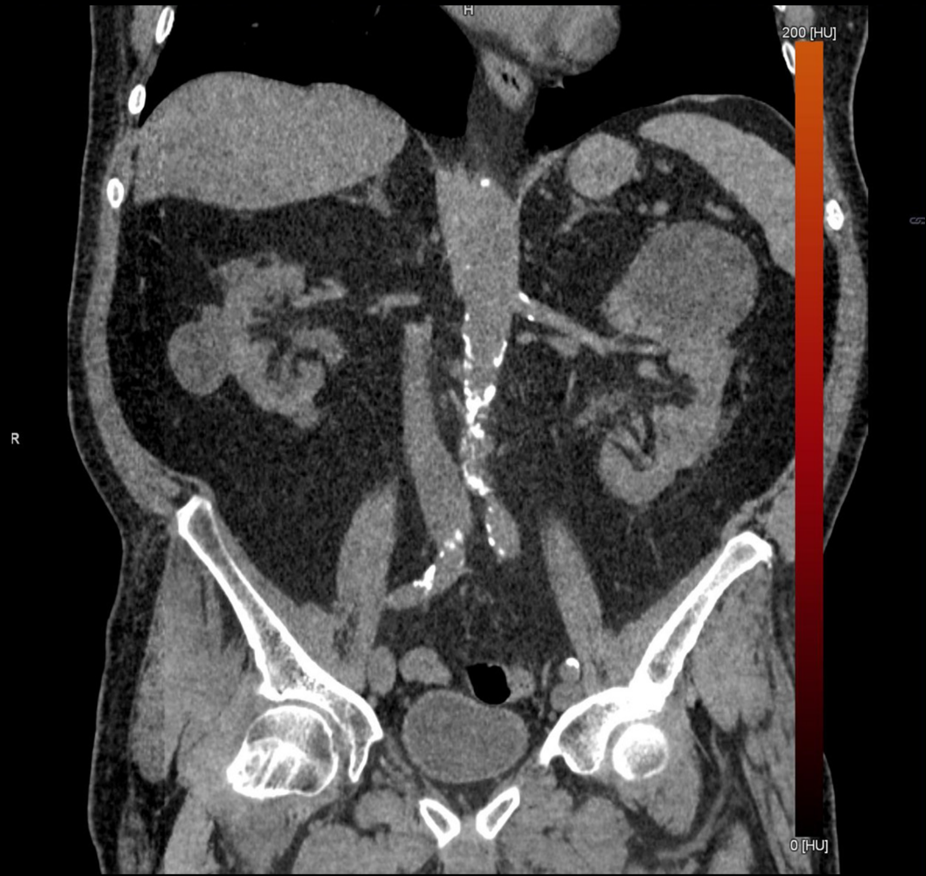

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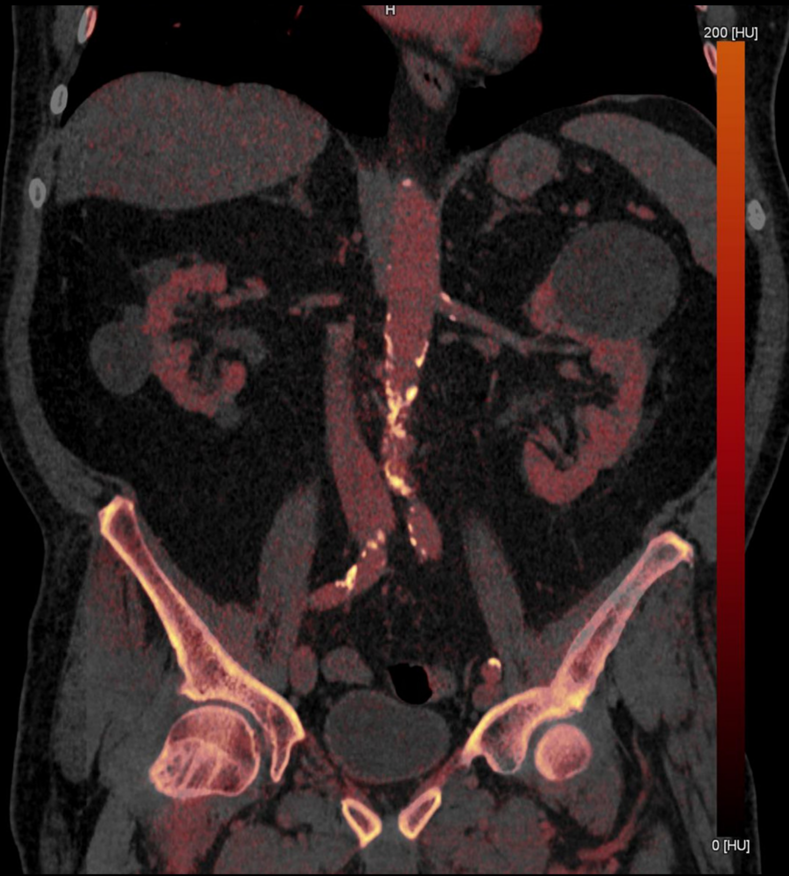

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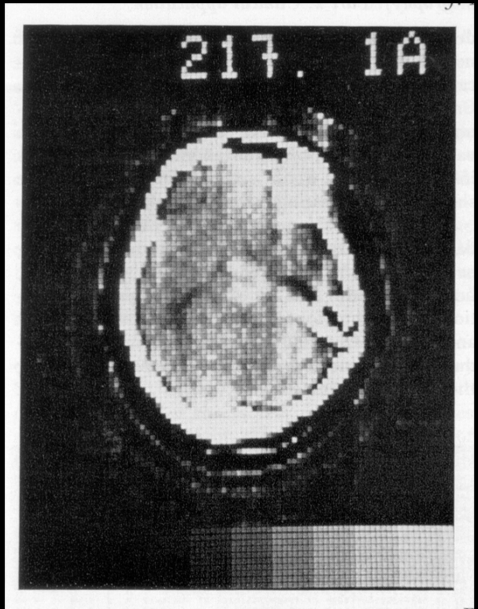

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GE Revolution CT

Philips IQon Spectral CT

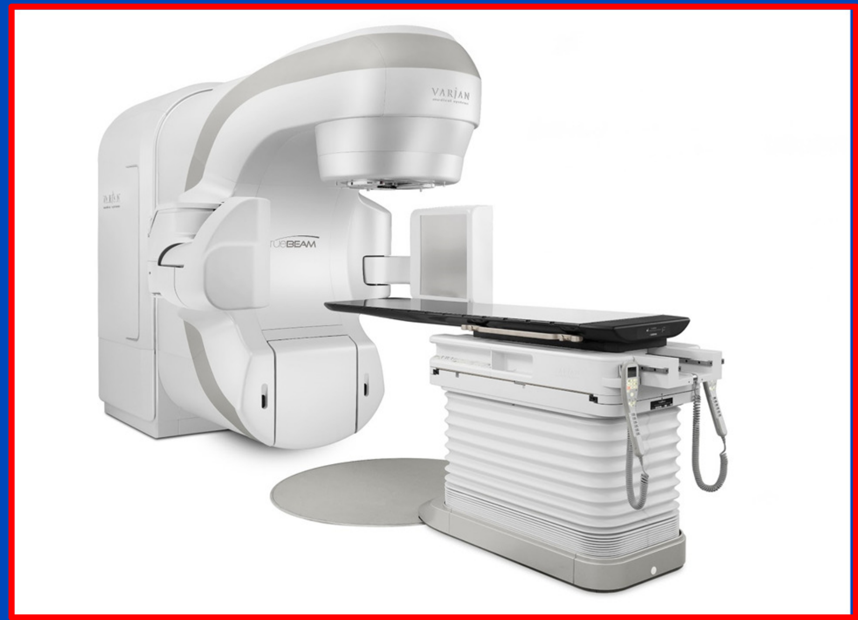
Siemens Somatom Force

Toshiba Aquilion ONE Vision

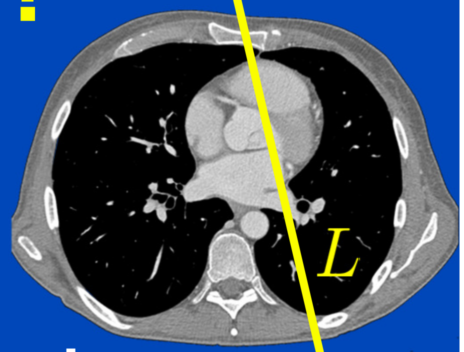
Clinical vs. Flat Detector CT

Clinical CT

Flat Detector CT



What does CT Measure?



- X-rays are generated in an x-ray tube.
- The polychromatic radiation is attenuated in the patient. X-ray photon attenuation is dominated by the photo and the Compton effect.
- Detectors measure the x-ray intensity after the rays have passed through the patient along several lines *L*.
- The log intensity is the so-called x-ray transform:

$$q(L) = -\ln \frac{I(L)}{I_0} = -\ln \int dE\, w(E) e^{-\int dL \mu(\boldsymbol{r}, E)}$$

- Often, the follwing monochromatic approximation is used:

$$q(L) \approx p(L) = \int dL \mu(\boldsymbol{r}, E_{\text{eff}})$$

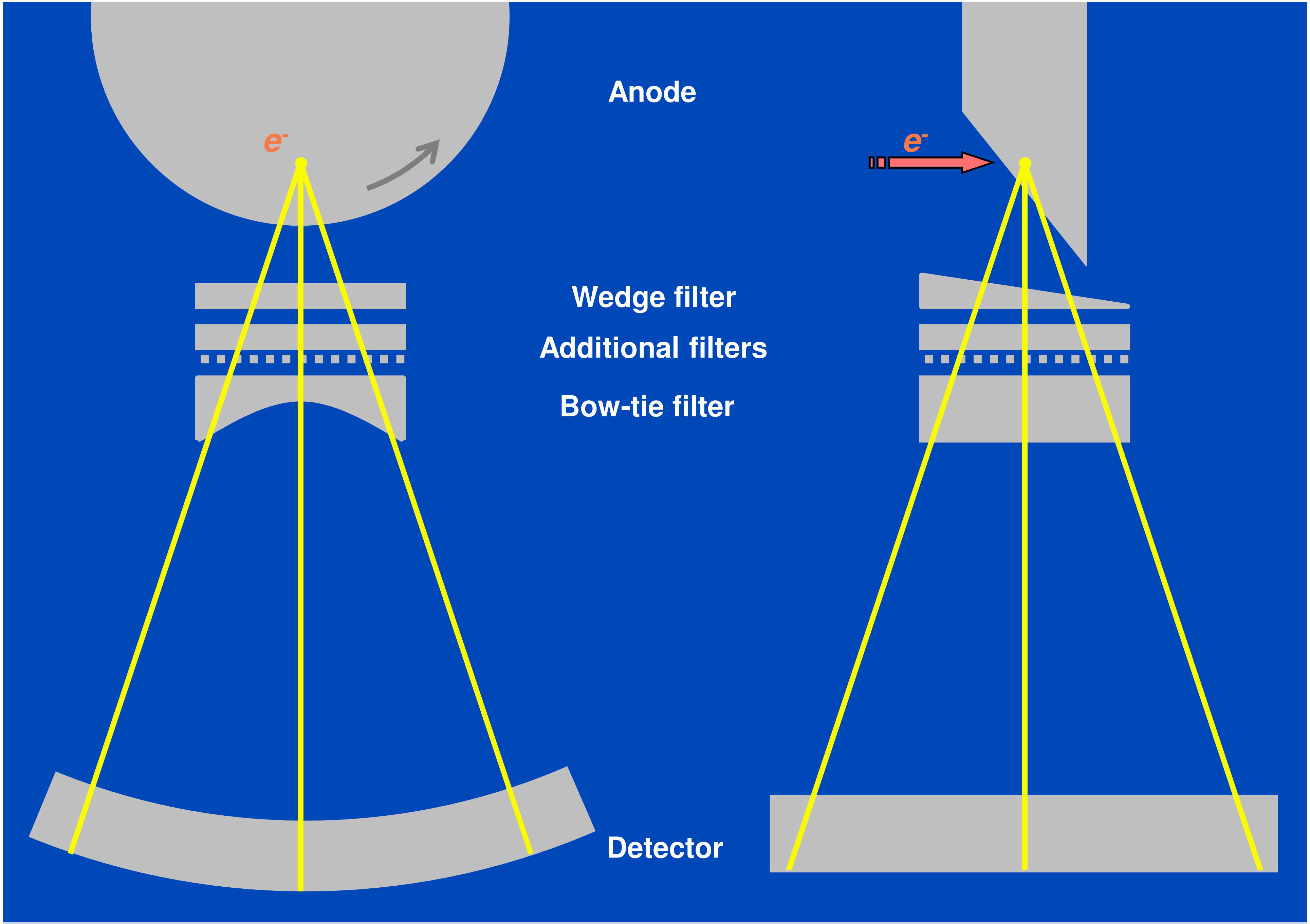
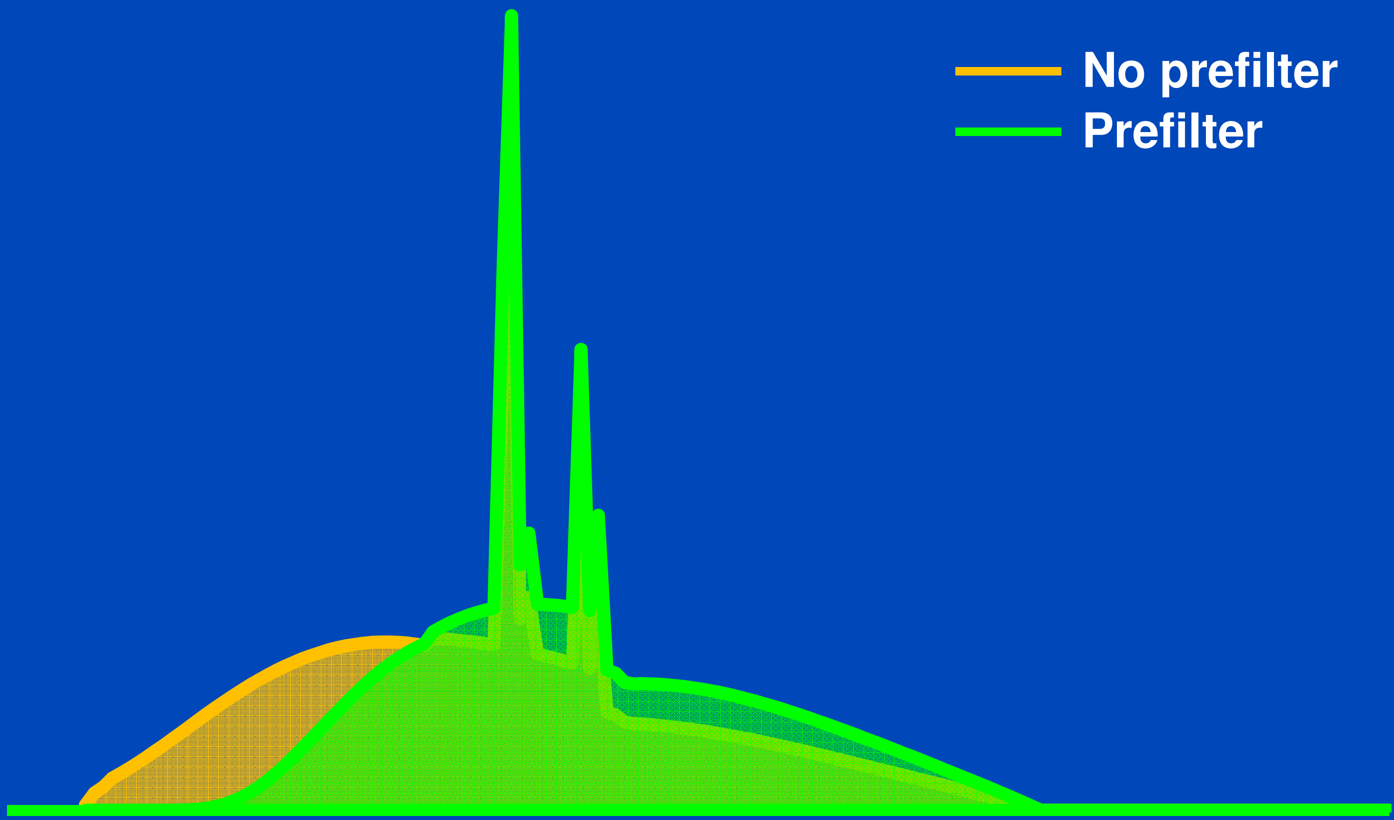
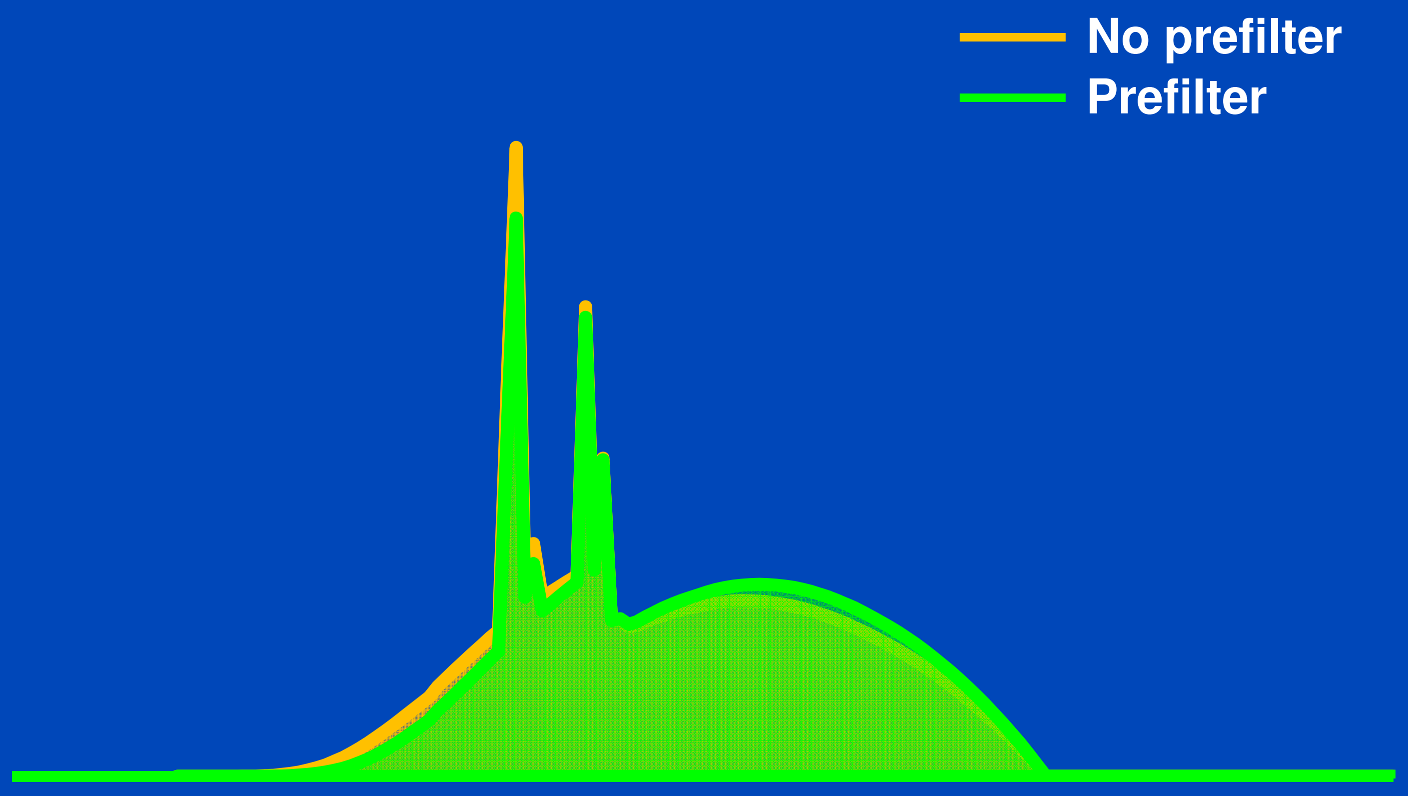


Figure not drawn to scale. Order of prefiltration may differ from scanner to scanner.

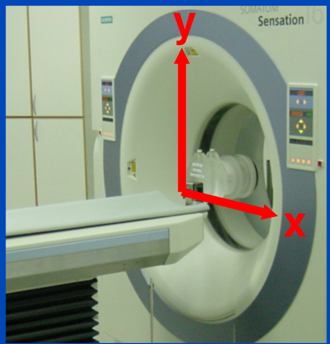
120 kV + 0 mm water with and without prefilter

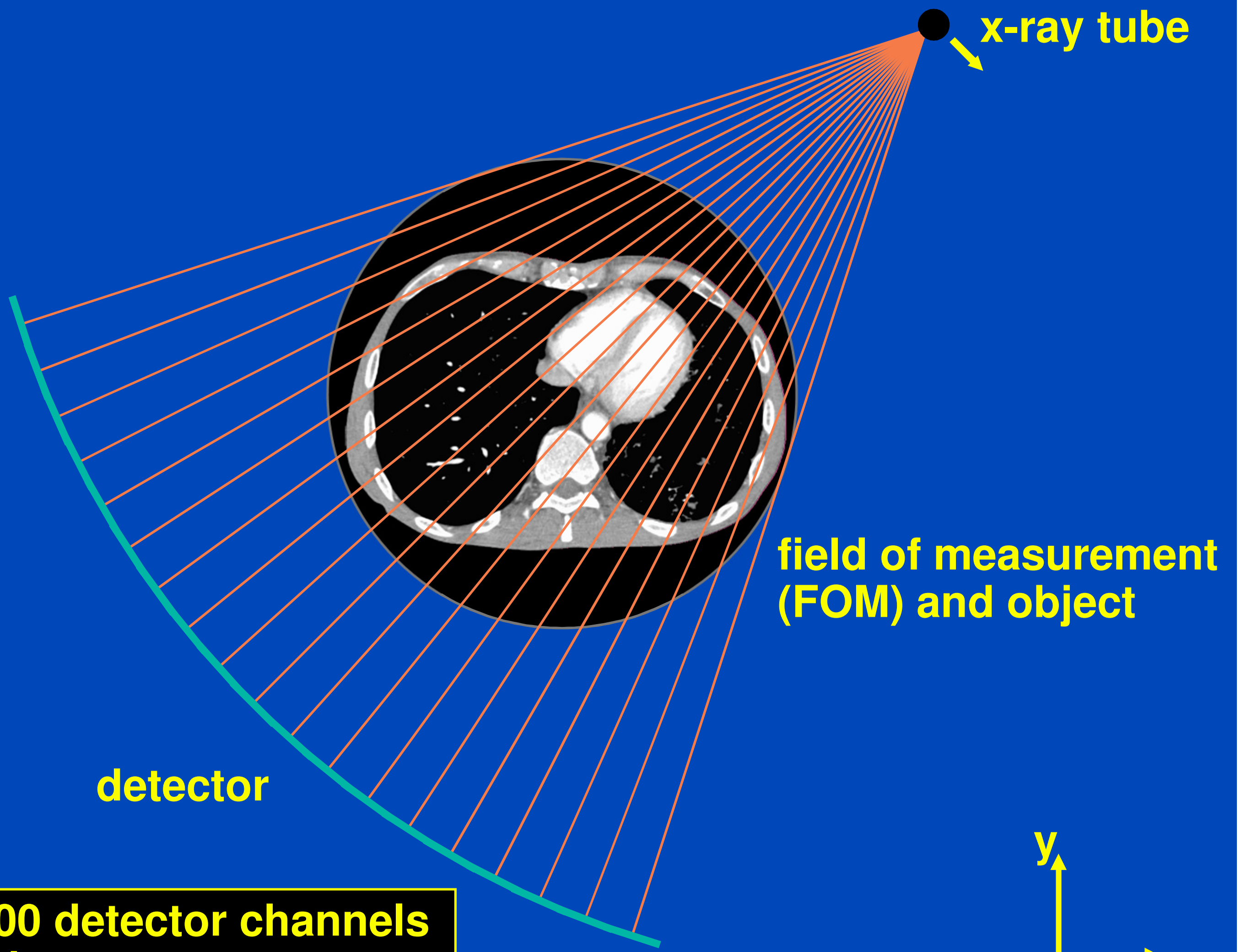


120 kV + 320 mm water with and without prefilter

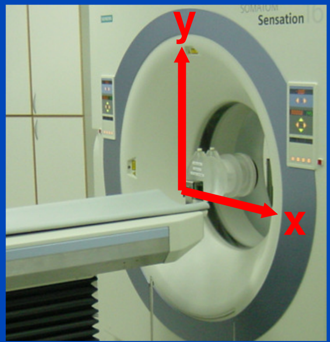


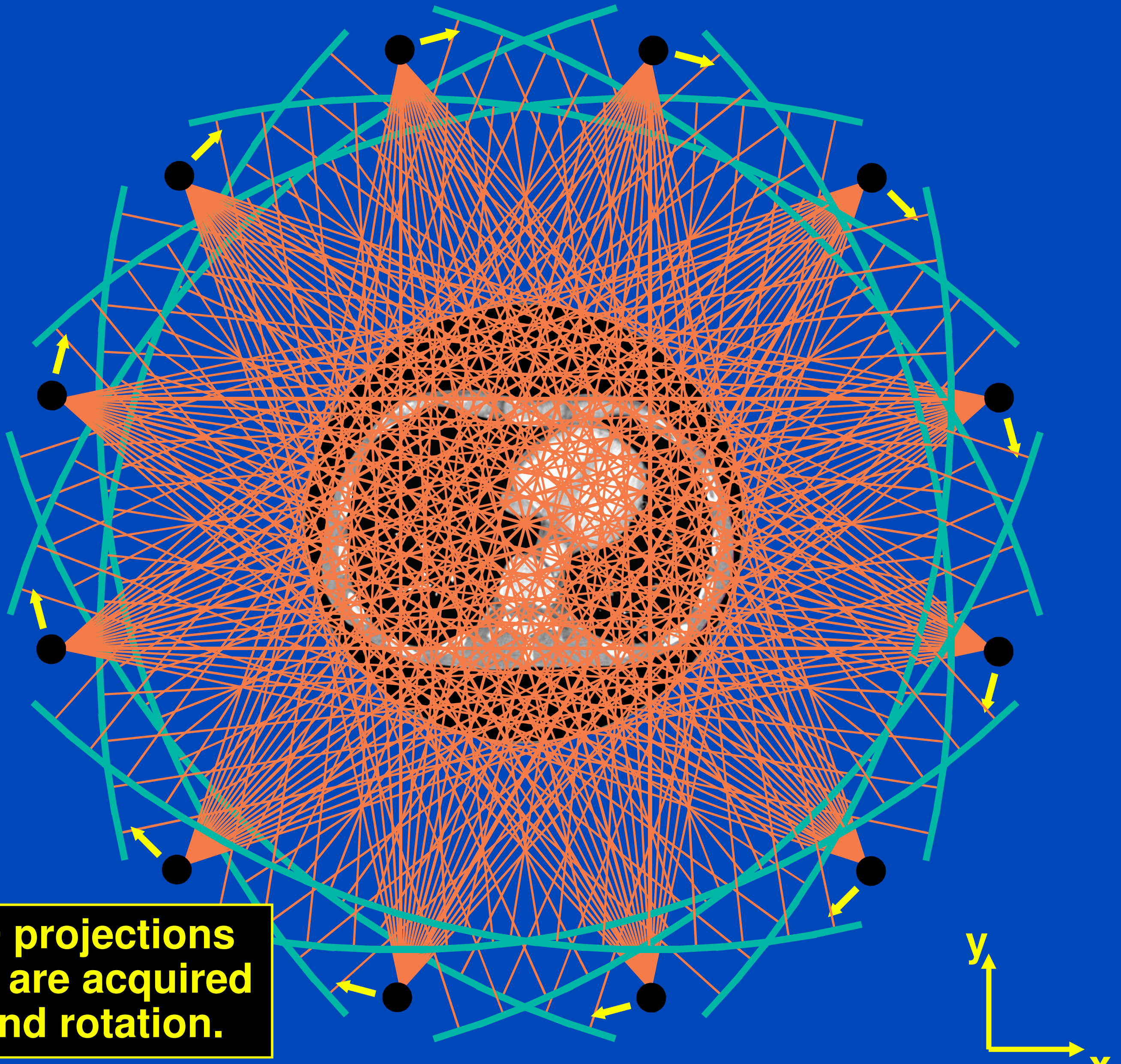
Fan-Beam Geometry (transaxial / in-plane / x-y-plane)





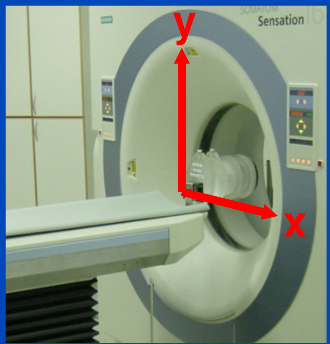
In the order of 1000 detector channels are available per detector row.

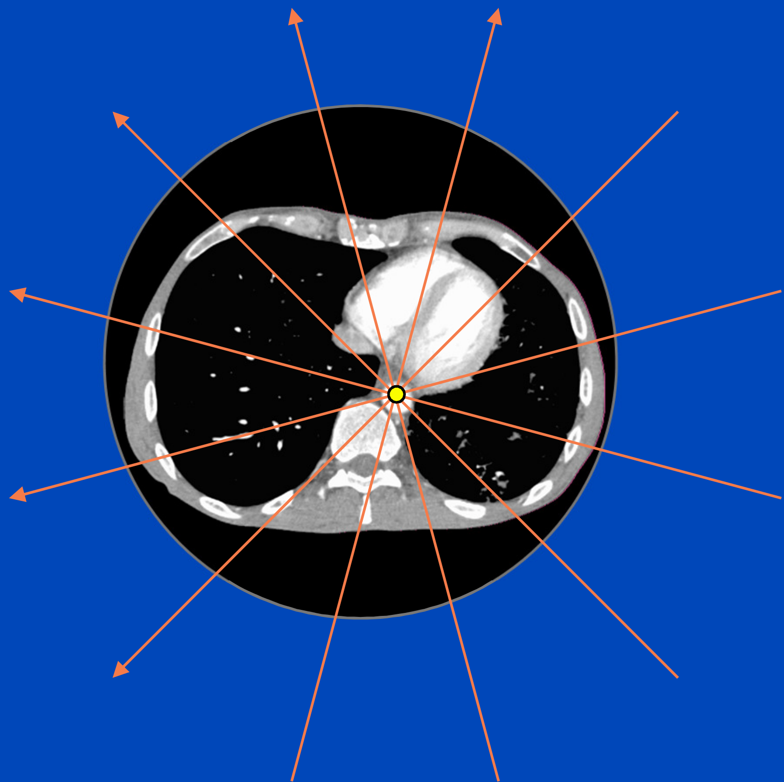




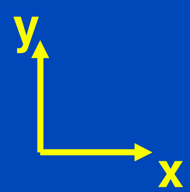
In the order of 1000 projections with 1000 channels are acquired per detector slice and rotation.

Data Completeness

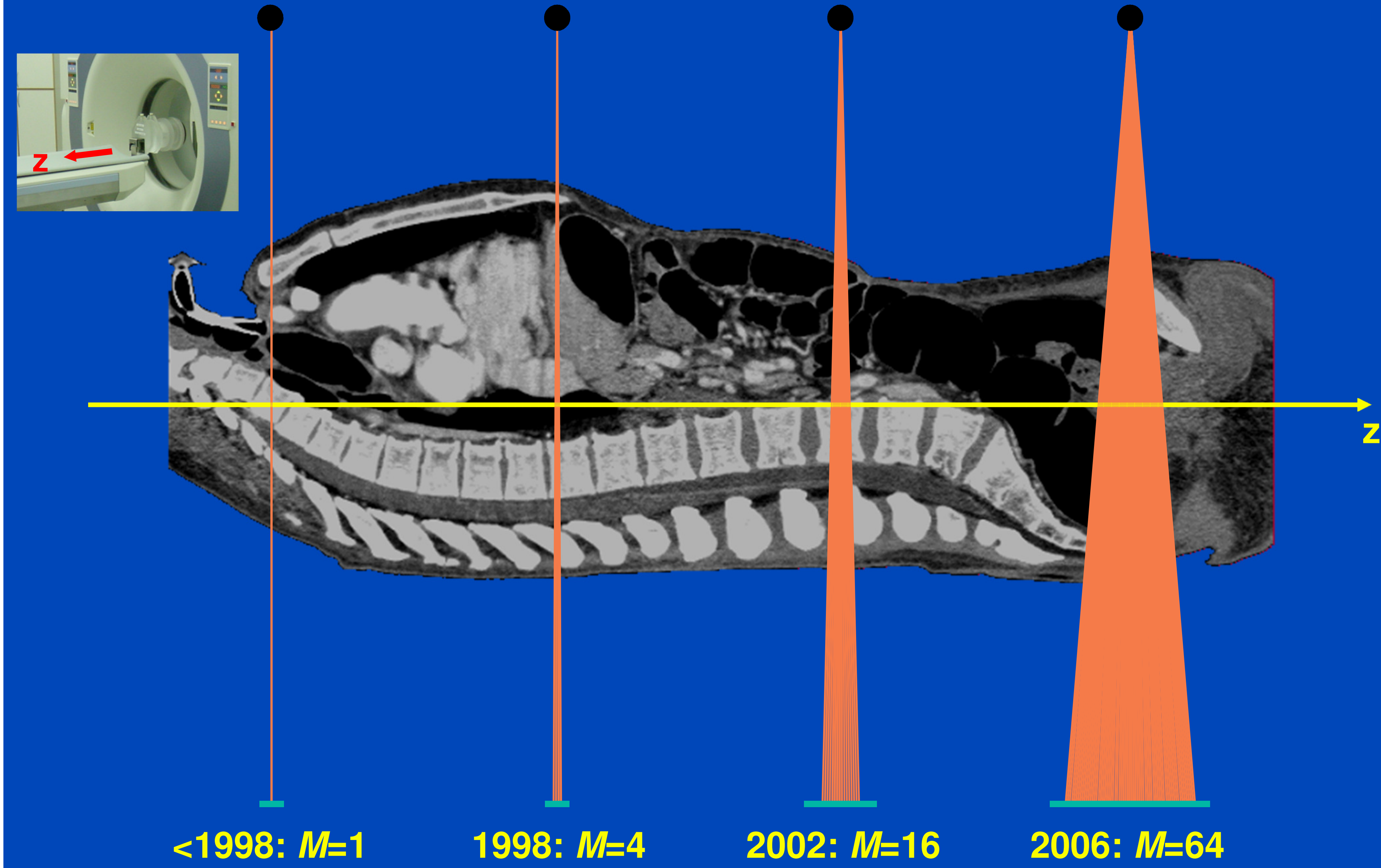




Each object point must be viewed by an angular interval of 180° or more. Otherwise image reconstruction is not possible.



Axial Geometry (z-Direction)



Equipment Technology

GE Revolution CT

Philips IQon Spectral CT

Siemens Somatom Force

Toshiba Aquilion ONE Vision

In-plane resolution: 0.4 … 0.7 mm

Nominal slice thickness: $S = 0.5 \ldots 1.5$ mm

Tube (max. values): 120 kW, 150 kV, 1300 mA

Effective tube current: $\mathrm{mAs}_{\mathrm{eff}} = 10$ mAs … 1000 mAs

Rotation time: $T_{\mathrm{rot}} = 0.25 \ldots 0.5$ s

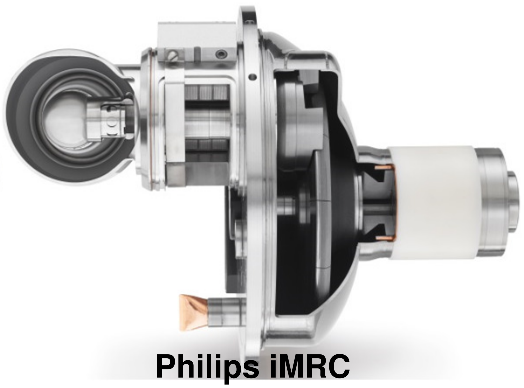
Simultaneously acquired slices: $M = 16 \ldots 320$

Table increment per rotation: $d = 1 \ldots 183$ mm

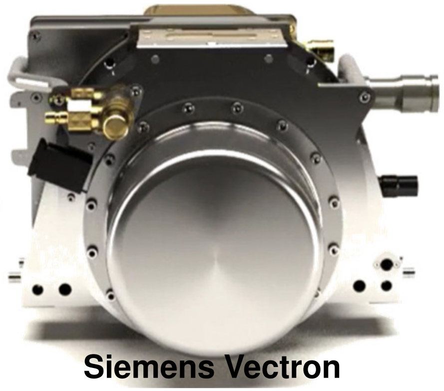
Scan speed: up to 73 cm/s

Temporal resolution: 50 … 250 ms

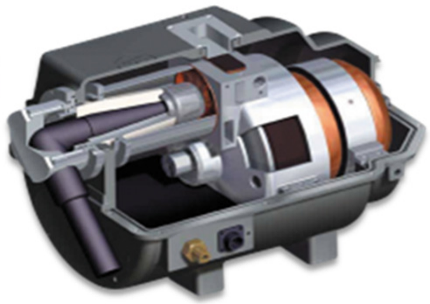
GE Performix HDw



Philips iMRC



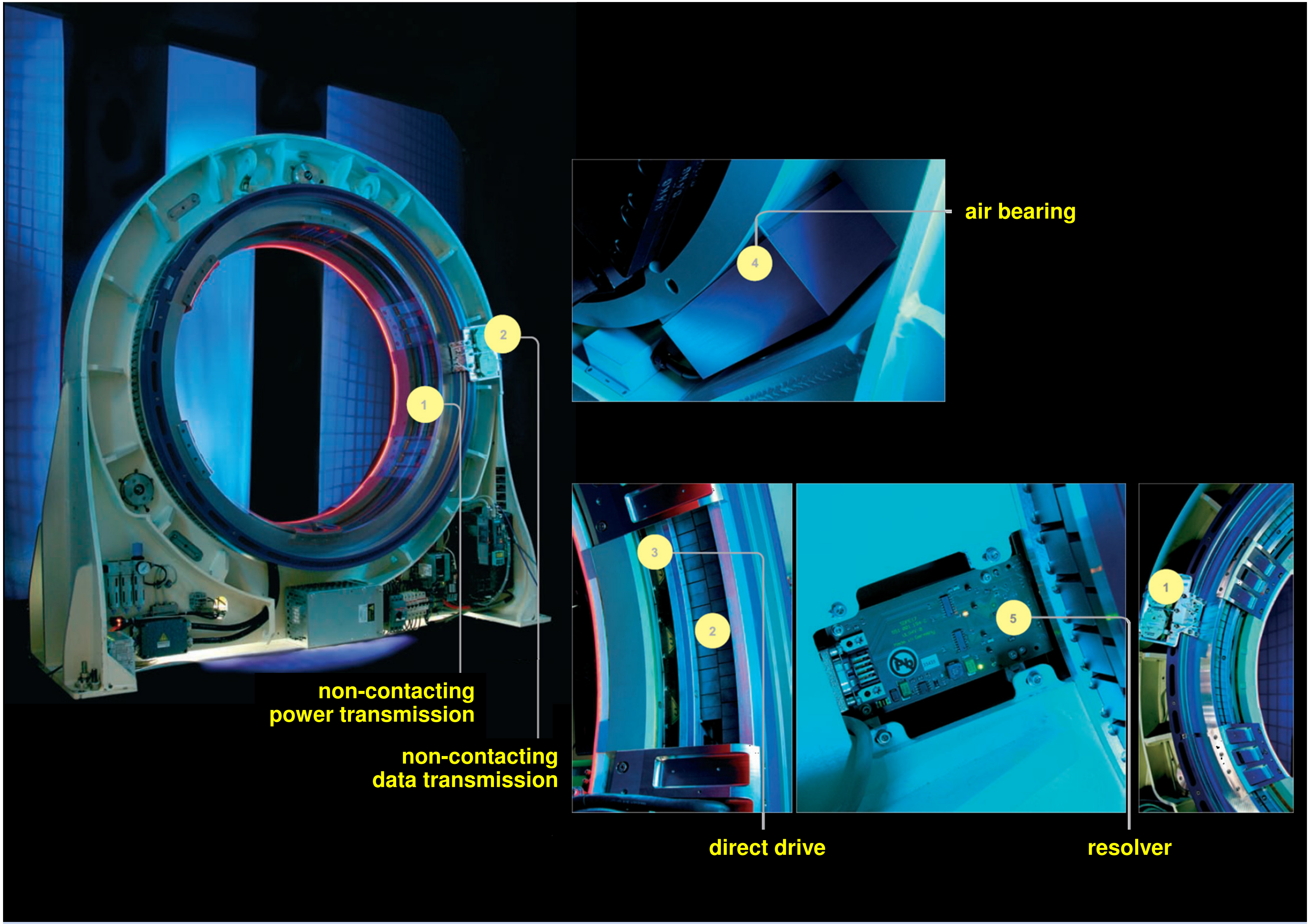
Siemens Vectron



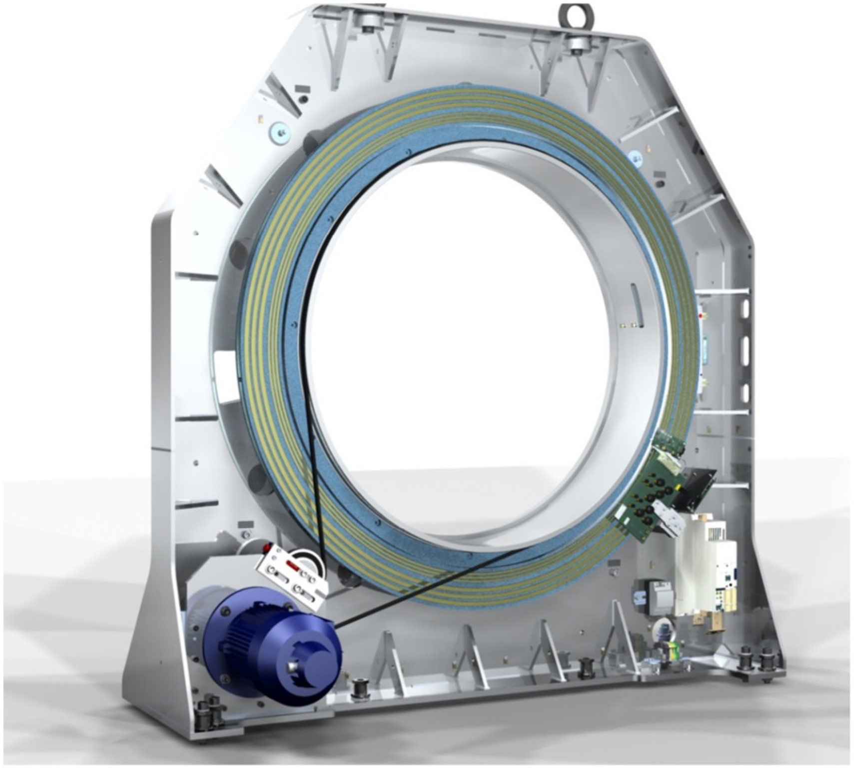
Toshiba Megacool Vi

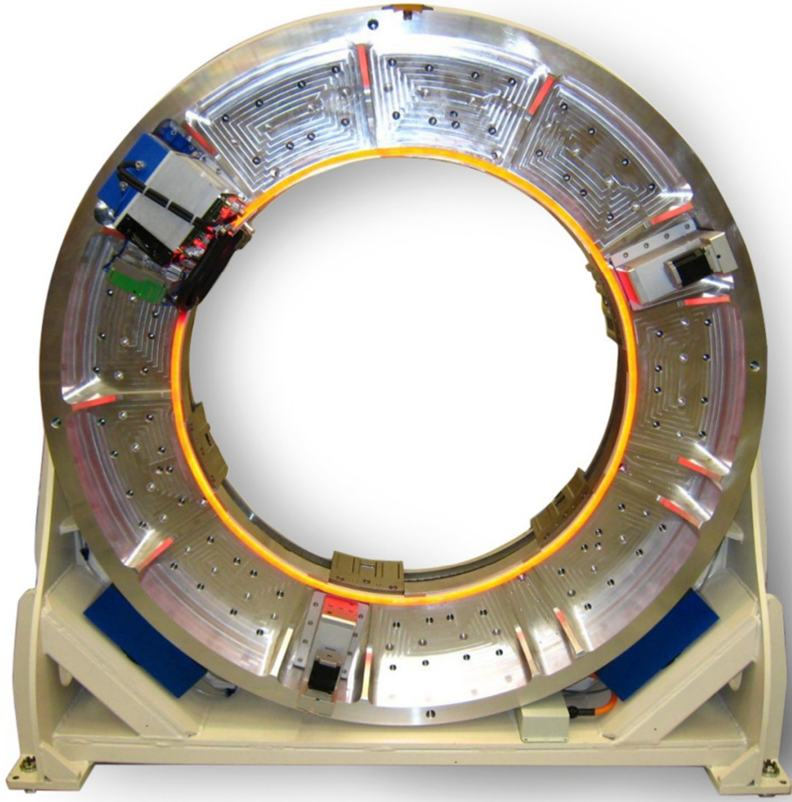
Demands on the Mechanical Design

- Continuous data acquisition (spiral, fluoro, dynamic, …)
- Able to withstand very fast rotation
  - Centrifugal acceleration at 550 mm with 0.5 s: $a = 9\ g$
  - with 0.4 s: $a = 14\ g$
  - with 0.3 s: $a = 25\ g$
  - with 0.2 s: $a = 55\ g$
- Mechanical accuracy better than 0.1 mm
- Compact and robust design
- Short installation times
- Long service intervals
- Low cost



Data courtesy of Schleifring GmbH, Fürstenfeldbruck, Germany
and of rsna2011.rsna.org/exbData/1678/docs/Gantry_Subsystem.pdf





Courtesy of Schleifring GmbH, Fürstenfeldbruck, Germany

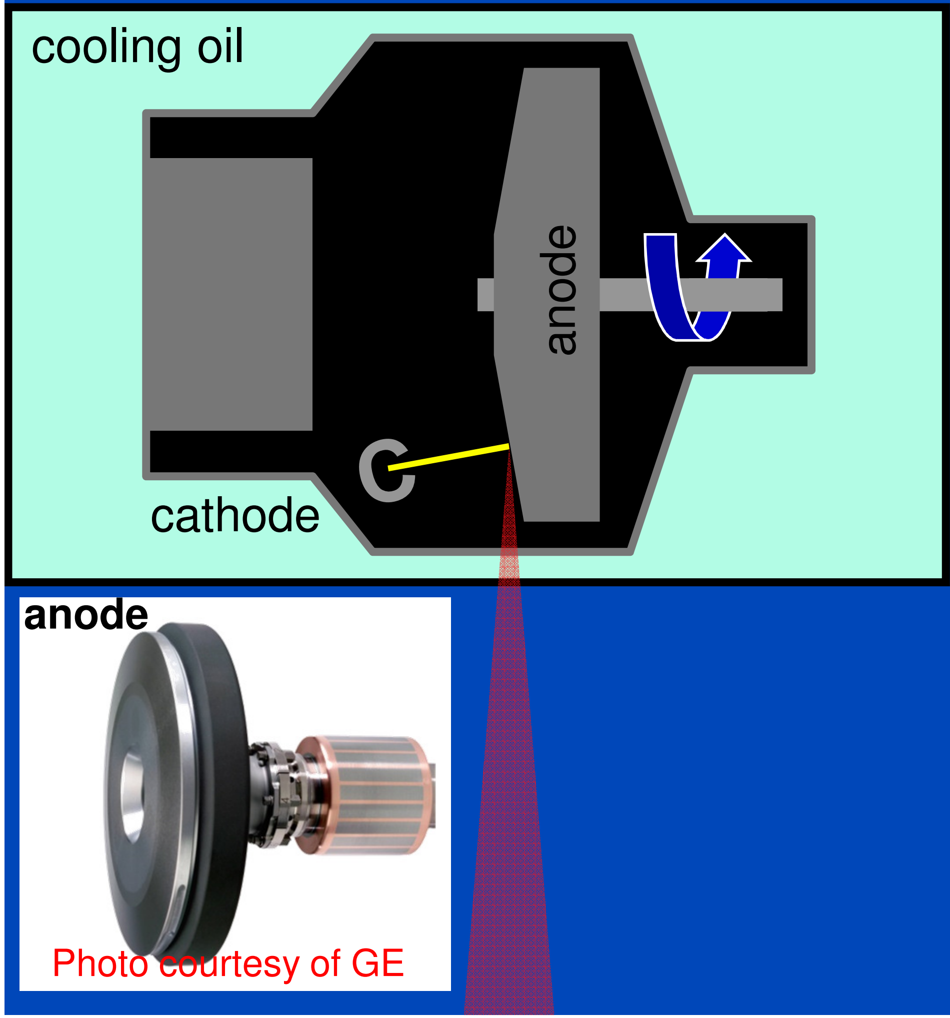
Demands on X-Ray Sources

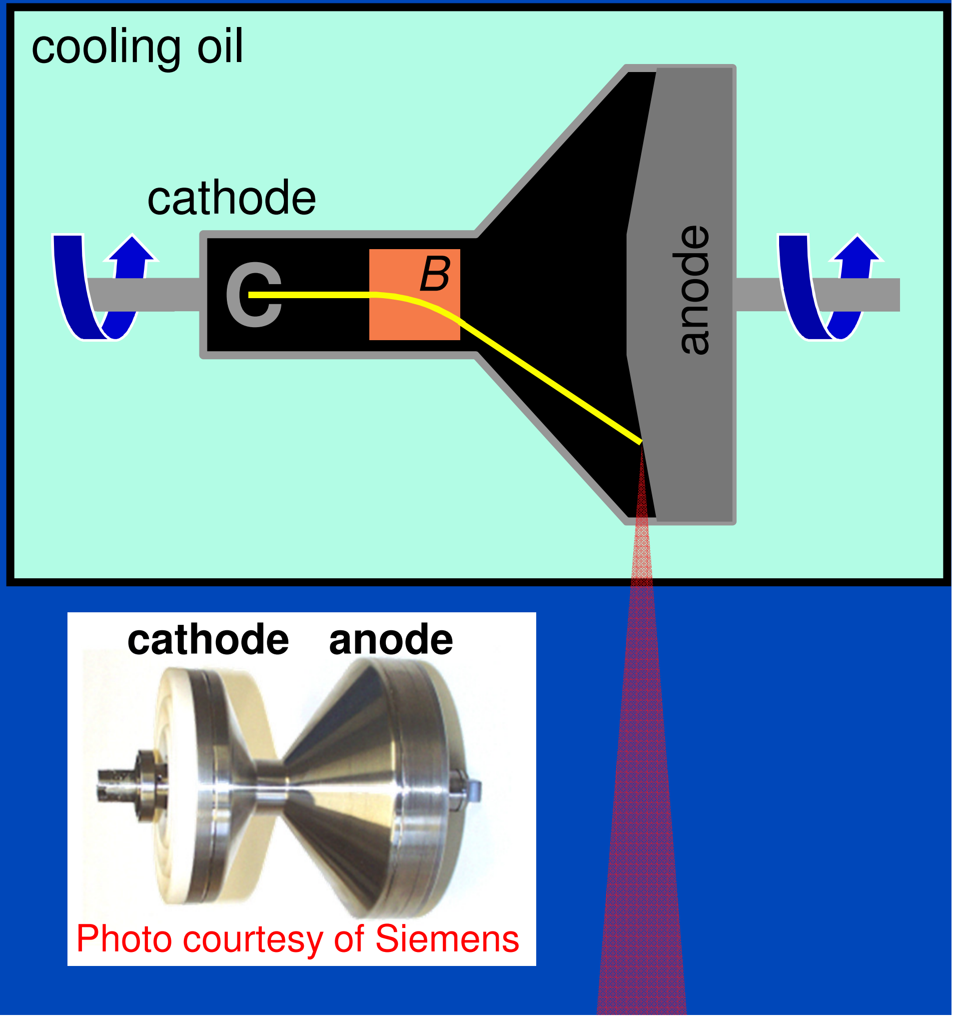
- Tube voltages from 70 to 150 kV in steps of 10 kV
- High instantaneous power levels (typ. 50 to 120 kW)
- High tube currents at low kV
- High continuous power levels (typ. > 5 kW)
- High cooling rates (typ. > 1 MHU/minute)
- High tube current variation (low inertia)
- Must withstand centrifugal forces
- Compact and robust design

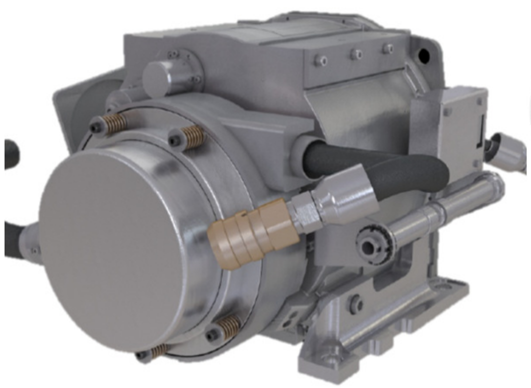
Tube Technology

conventional tube
(rotating anode, helical wire emitter)

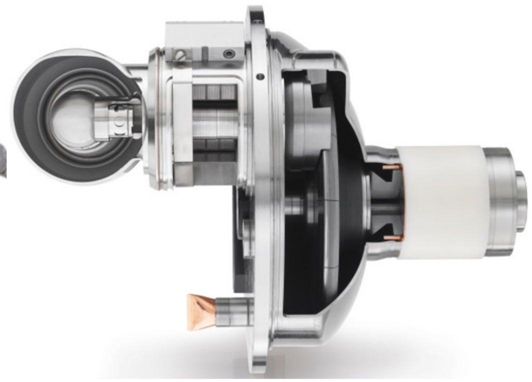
high performance tube
(rotating cathode, anode + envelope, flat emitter)





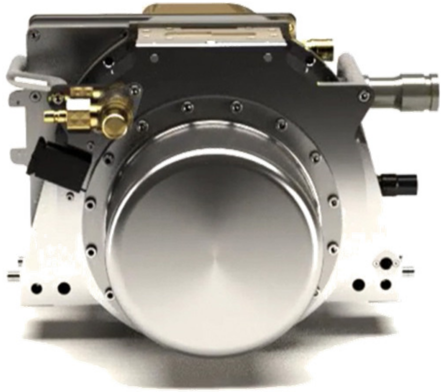


Performix HDw (GE)



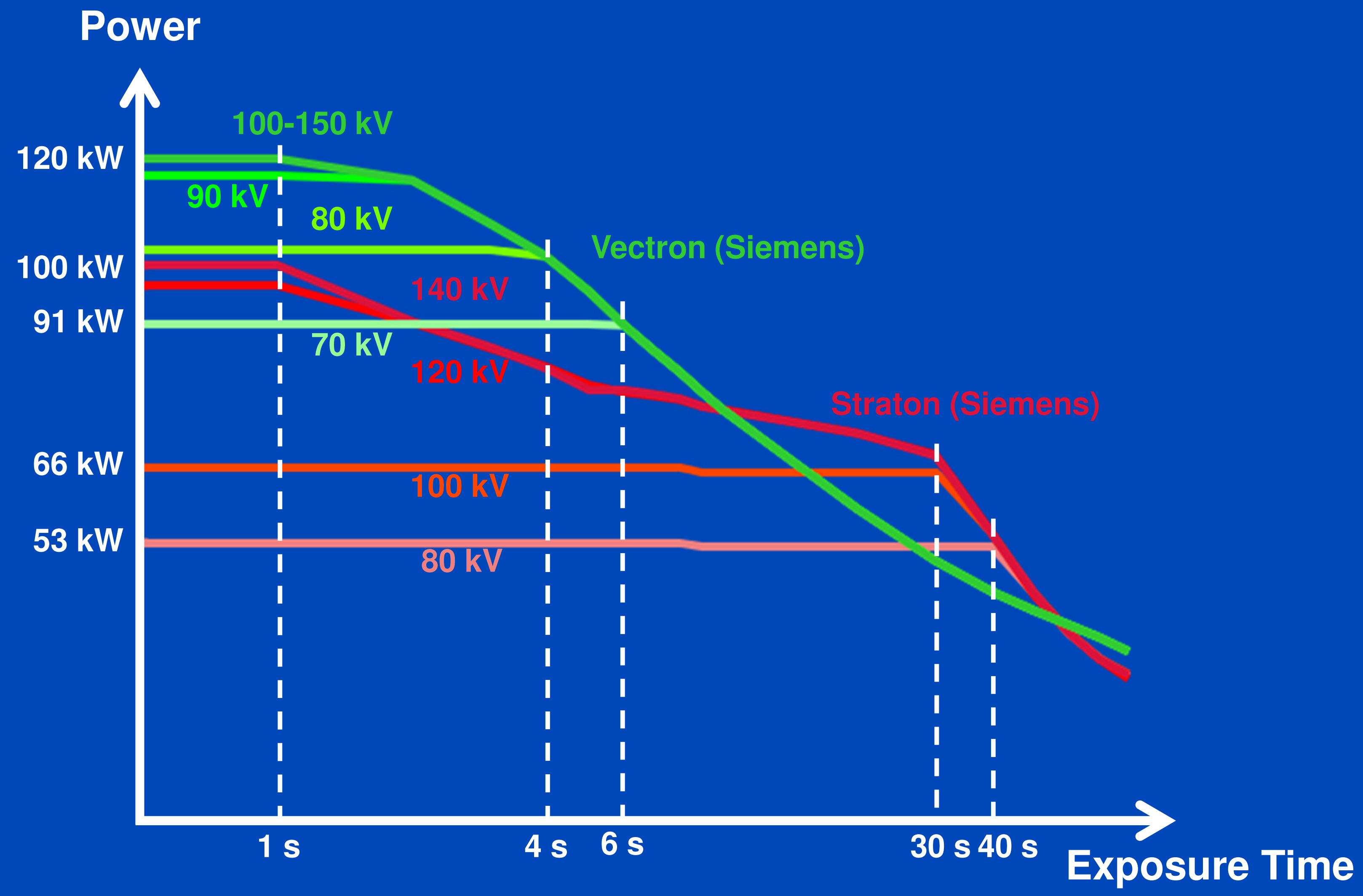
iMRC (Philips)

Straton (Siemens)



Vectron (Siemens)

Straton vs. Vectron at all kV



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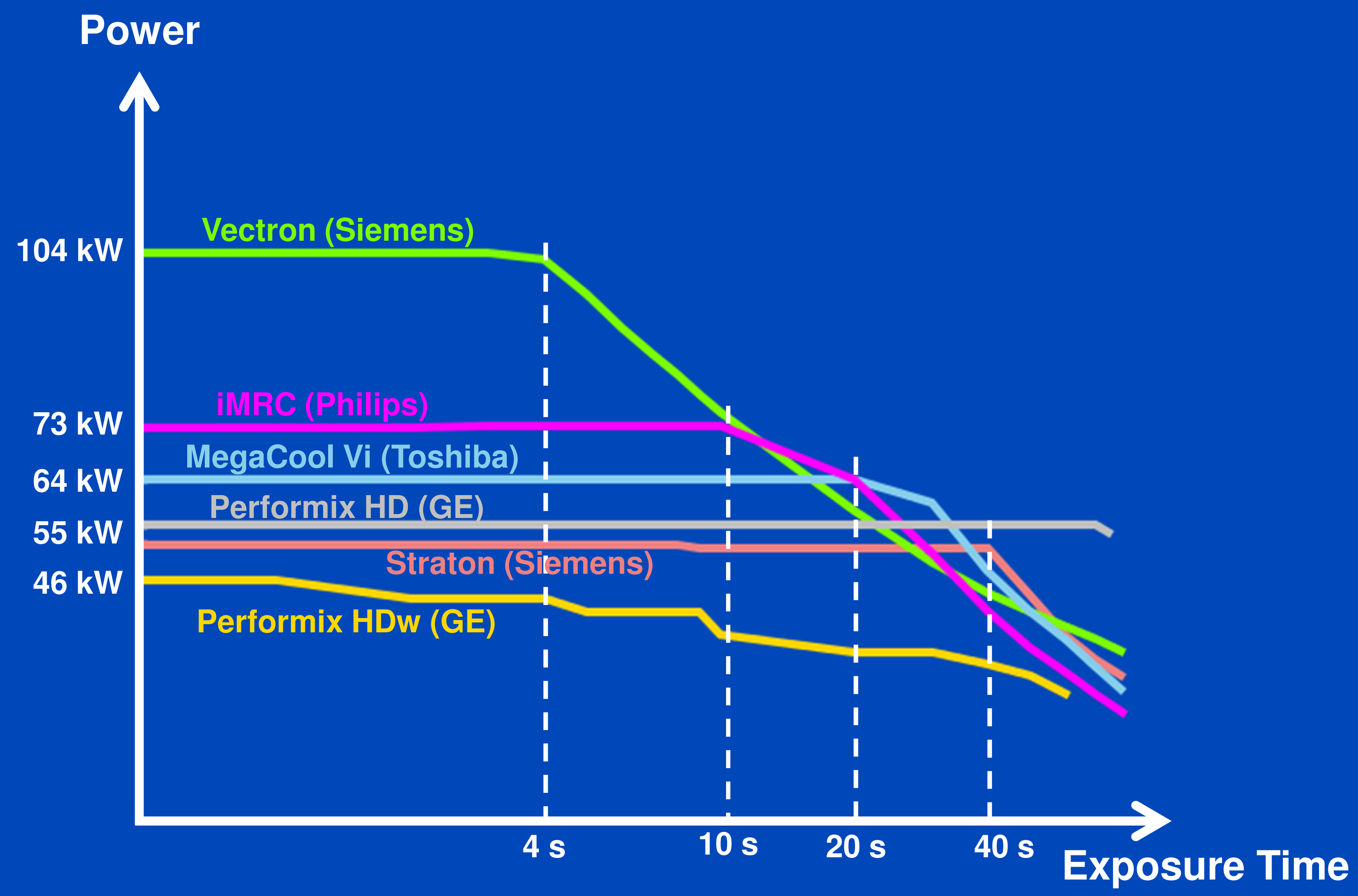
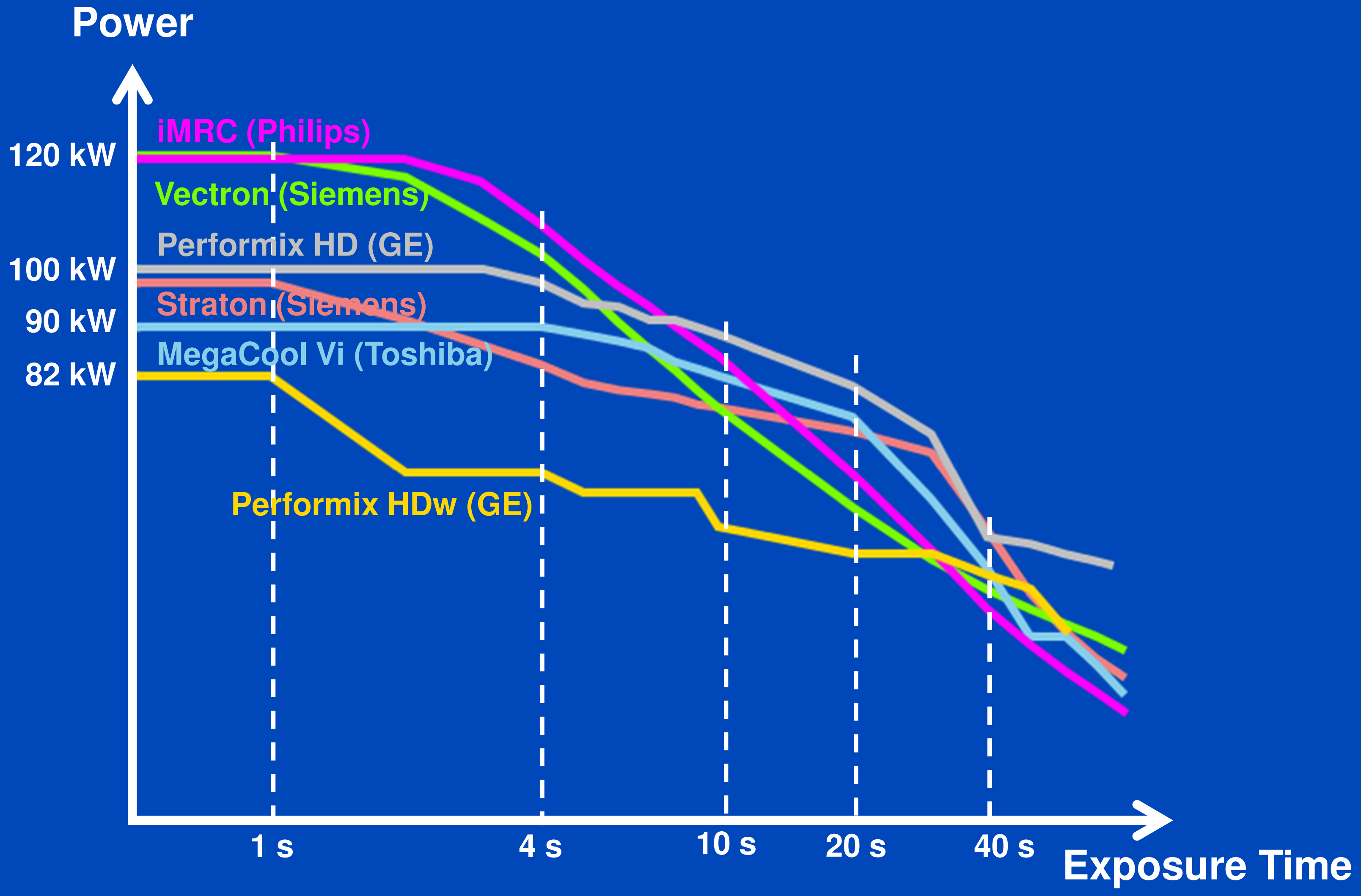
Tube Voltage 80 kV

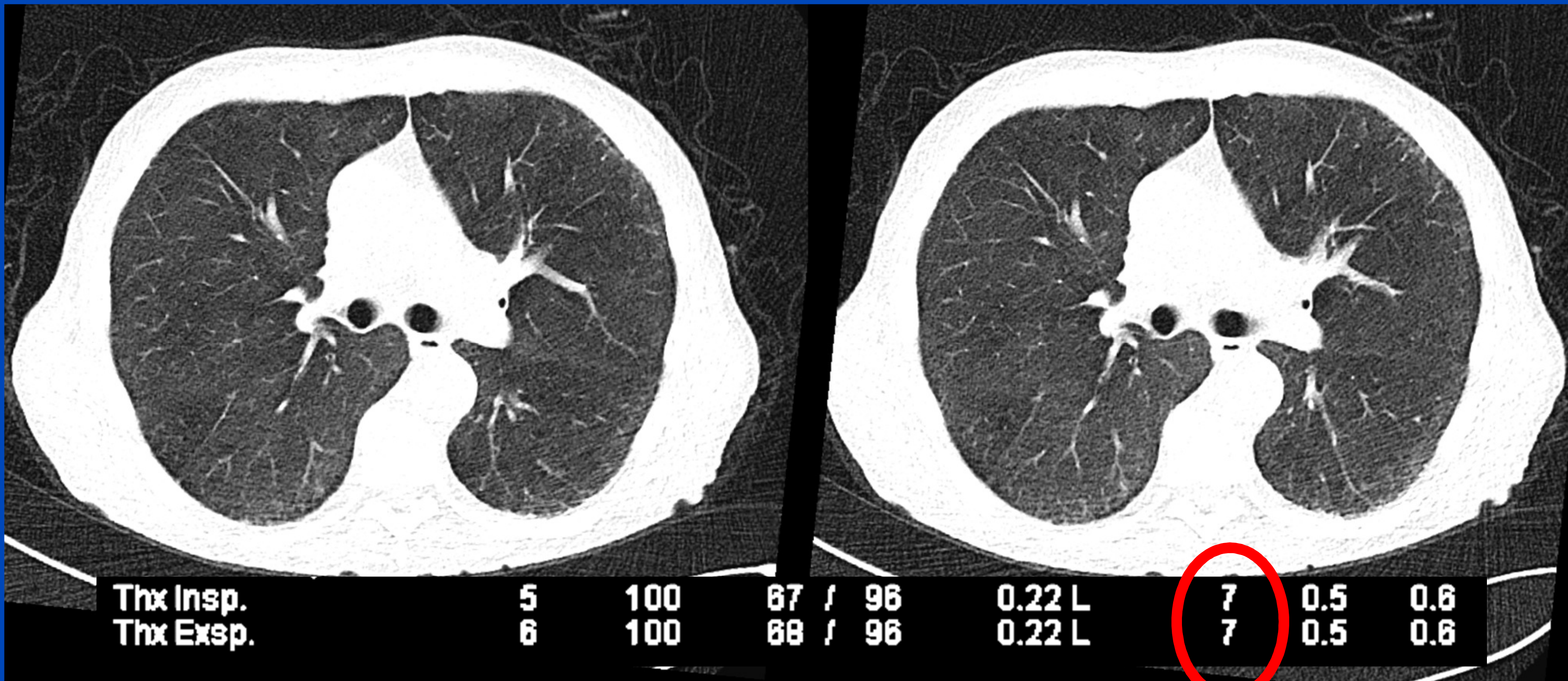


Tube Voltage 120 kV



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



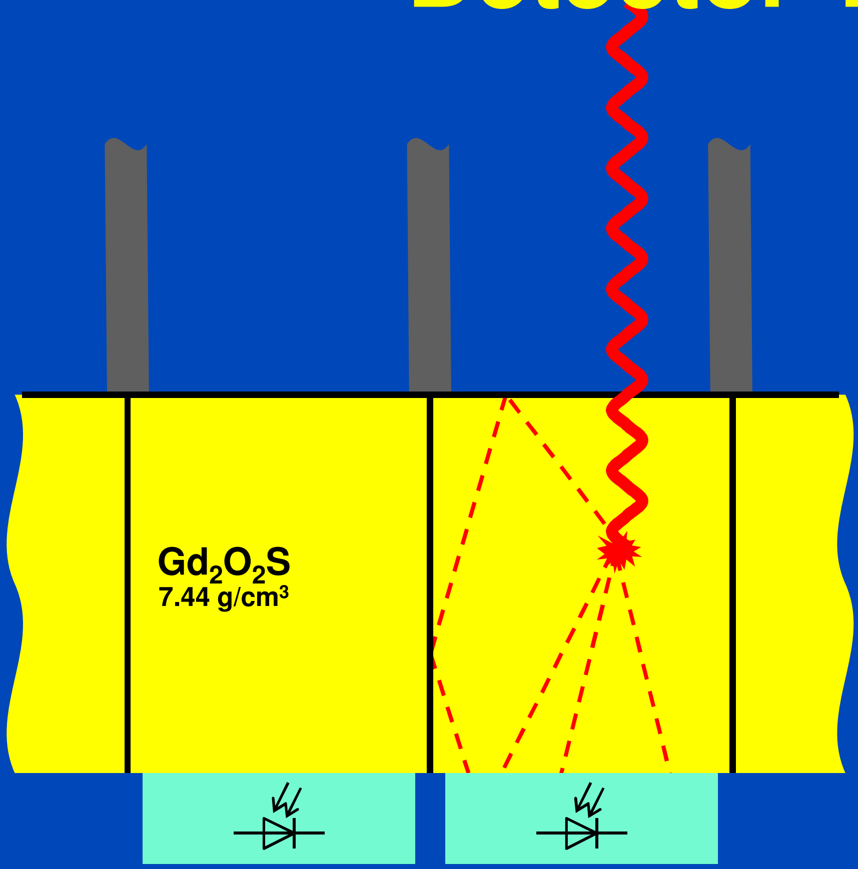
Courtesy of University Hospital Mannheim

Demands on CT Detector Technology

- **Available as multi-row arrays**
- **Very fast sampling (typ. 300 µs)**
- **Favourable temporal characteristics (decay time < 10 µs)**
- **High absorption efficiency**
- **High geometrical efficiency**
- **High count rate (up to 10^9 cps*)**
- **Adequate dynamic range (at least 20 bit)**

* in the order of 10^5 counts per reading and 10^4 readings per second

Detector Technology



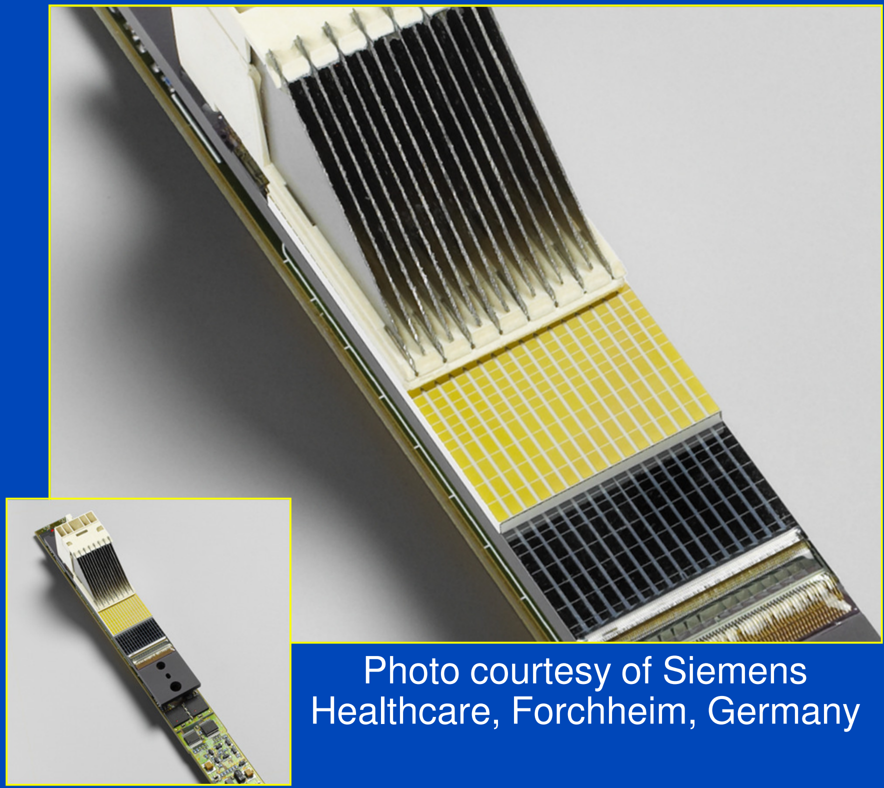
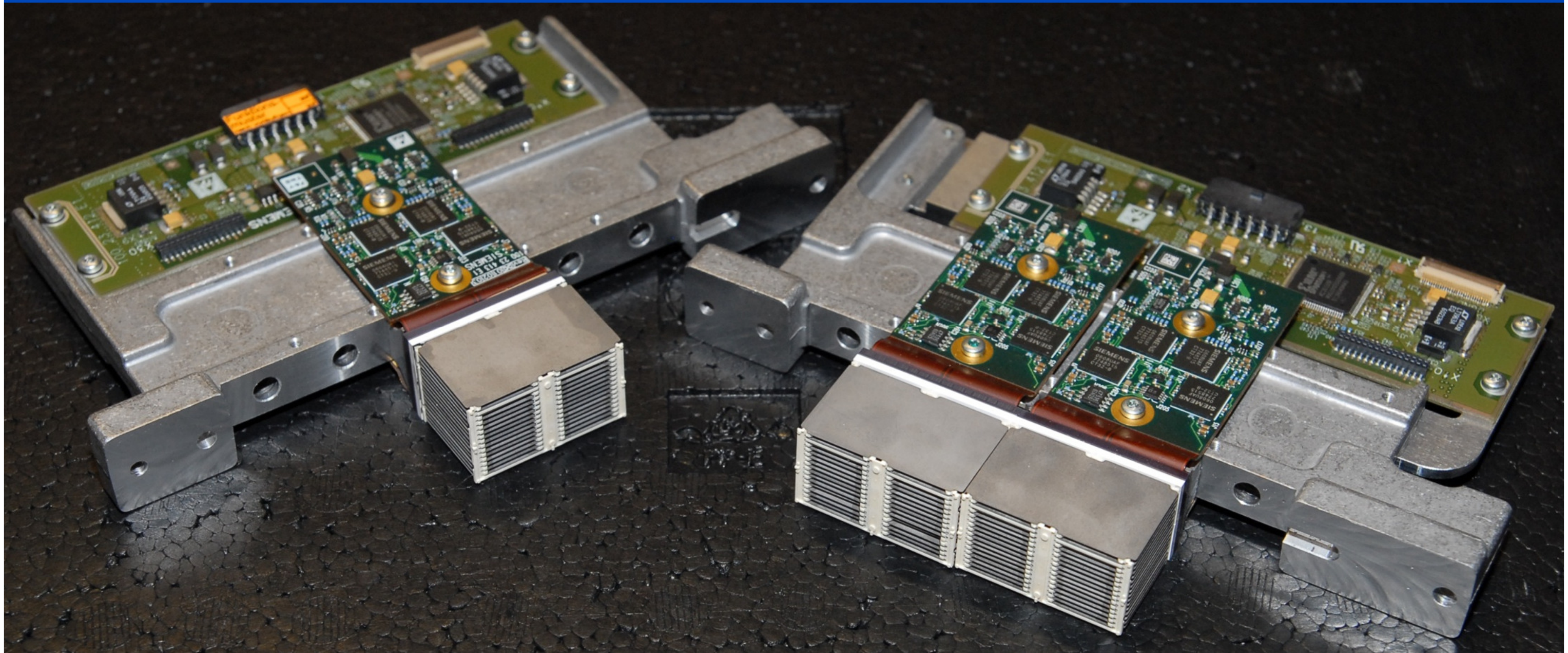
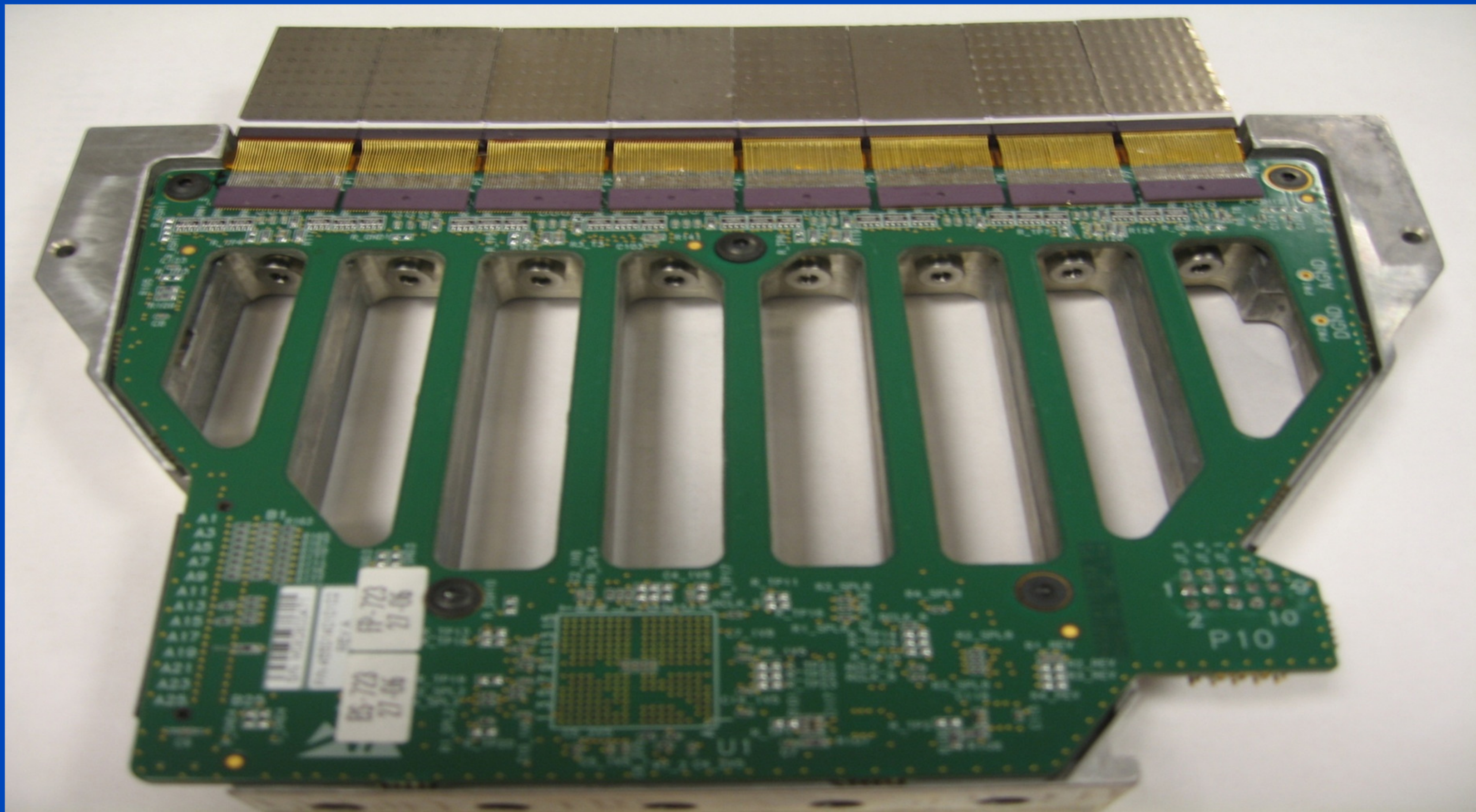


Photo courtesy of Siemens Healthcare, Forchheim, Germany



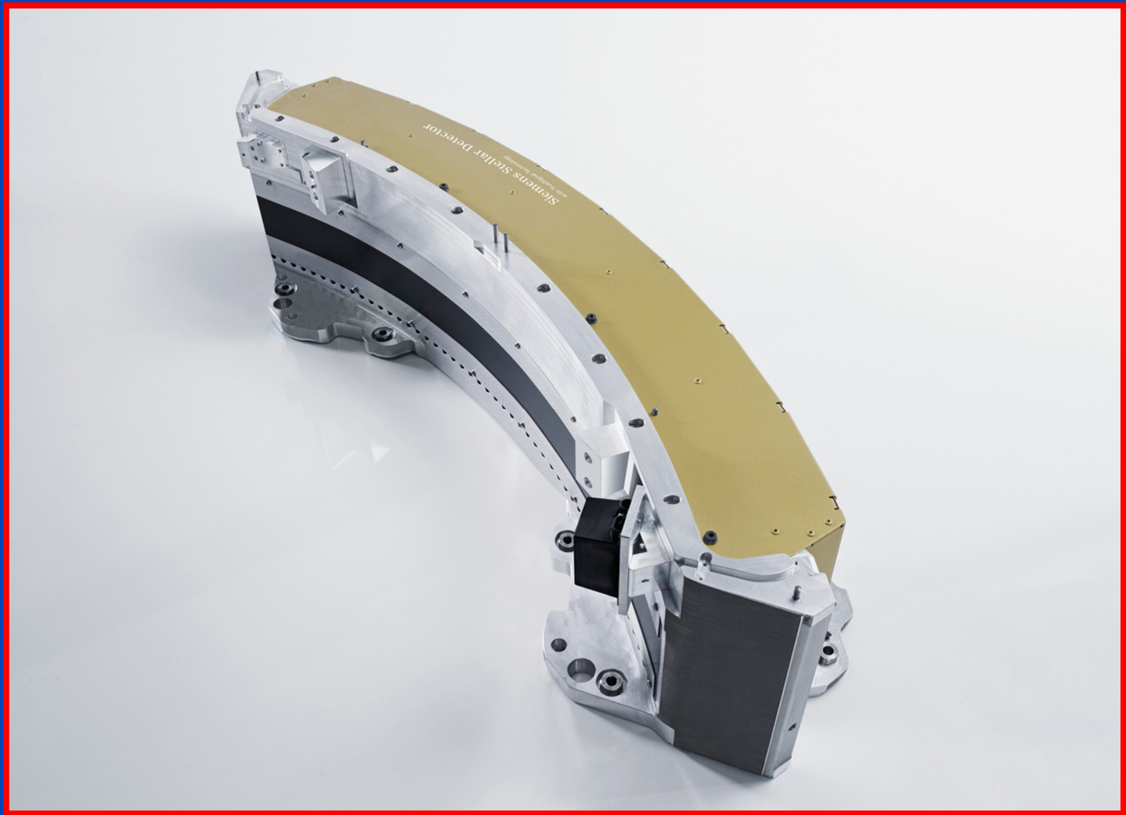
modular and 2D tileable, 1D anti-scatter grid, modules arranged on the surface of a cylinder segment (Photo courtesy by Siemens)

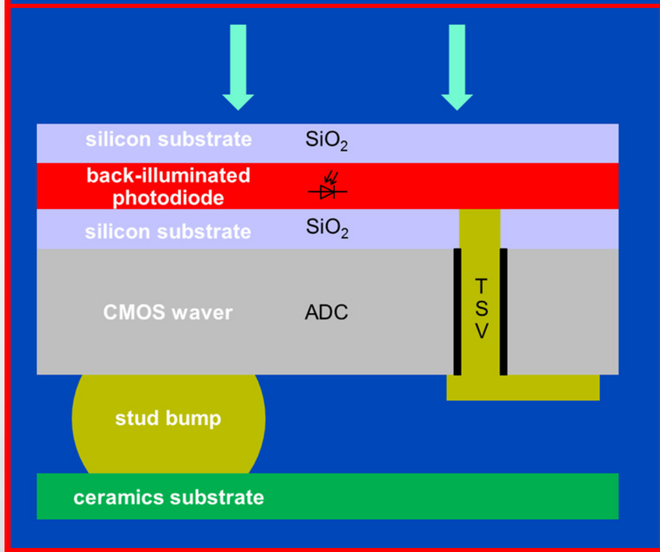


“Nano-panel detectors”, modular and 2D tilable, focussed 2D anti scatter grid (Photo courtesy by Philips)

Premium Systems 2014-2016

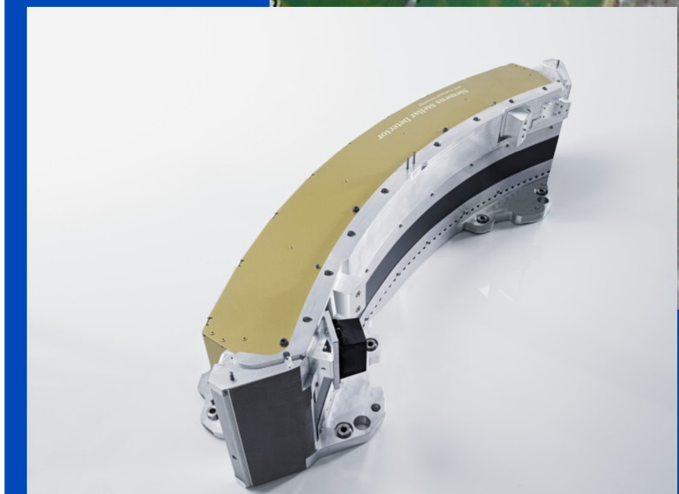
CT-System	Vendor	Configuration	Collimation	Cone	Rotation	Max. Power
Revolution CT	GE	256 × 0.625 mm GemStone Clarity	160 mm	15°	0.28 s	103 kW Performix HDw
Brilliance ICT	Philips	2 · 128 × 0.625 mm NanoPanel 3D	80 mm	7.7°	0.27 s	120 kW iMRC
IQon	Philips	2 · 64 × 0.625 mm NanoPanel Prism	40 mm	3.9°	0.27 s	120 kW iMRC
Definition Edge	Siemens	2 · 64 × 0.6 mm Stellar	38.4 mm	3.7°	0.28 s	100 kW Straton
Definition Flash	Siemens	2 · 2 · 64 × 0.6 mm Stellar	38.4 mm	3.7°	0.28 s	2 · 100 kW Straton
Somatom Force	Siemens	2 · 2 · 96 × 0.6 mm Stellar	57.6 mm	5.5°	0.25 s	2 · 120 kW Vectron
Aquilion ONE Vision	Toshiba	320 × 0.5 mm Quantum	160 mm	15°	0.275 s	100 kW MegaCool Vi

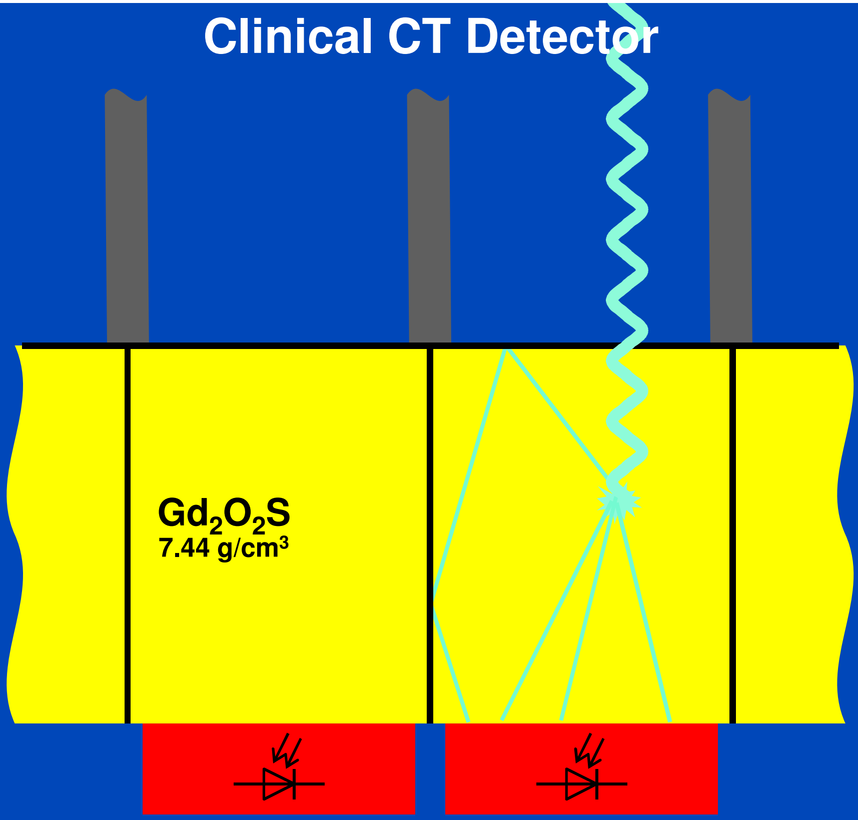


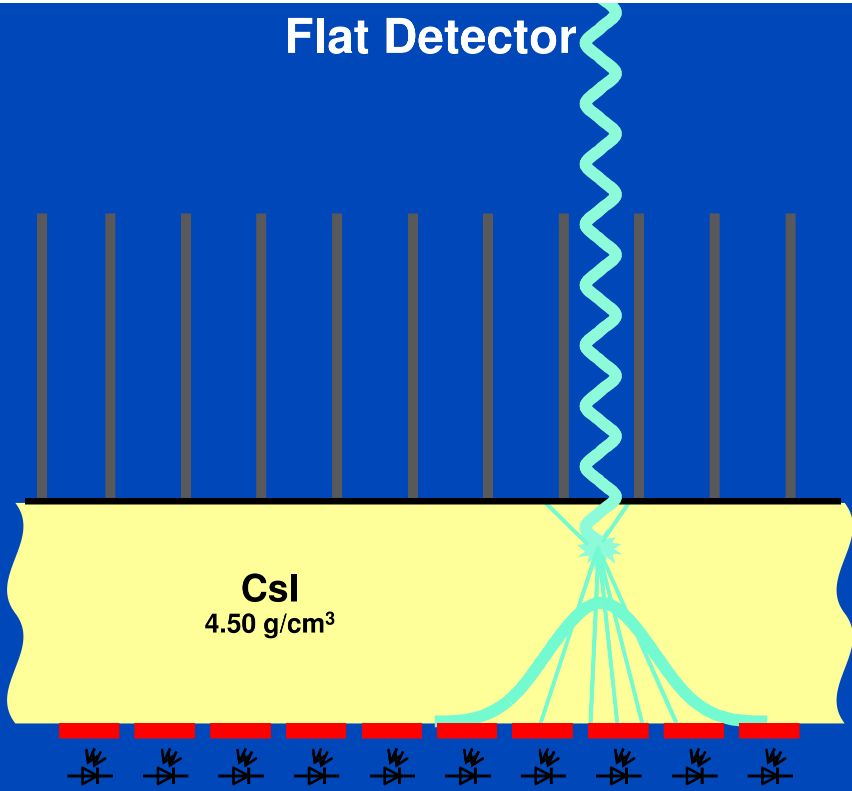


"Stellar detector", modular and 2D tilable, focussed 1D anti scatter grid (Photo courtesy by Siemens)


A
B
C

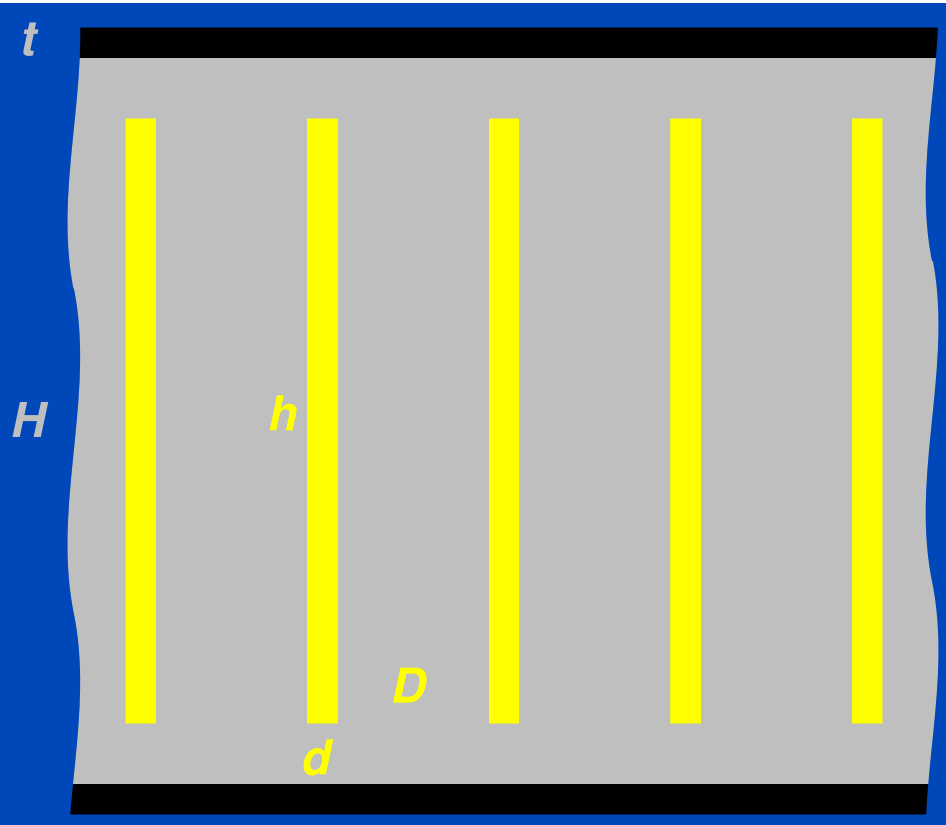


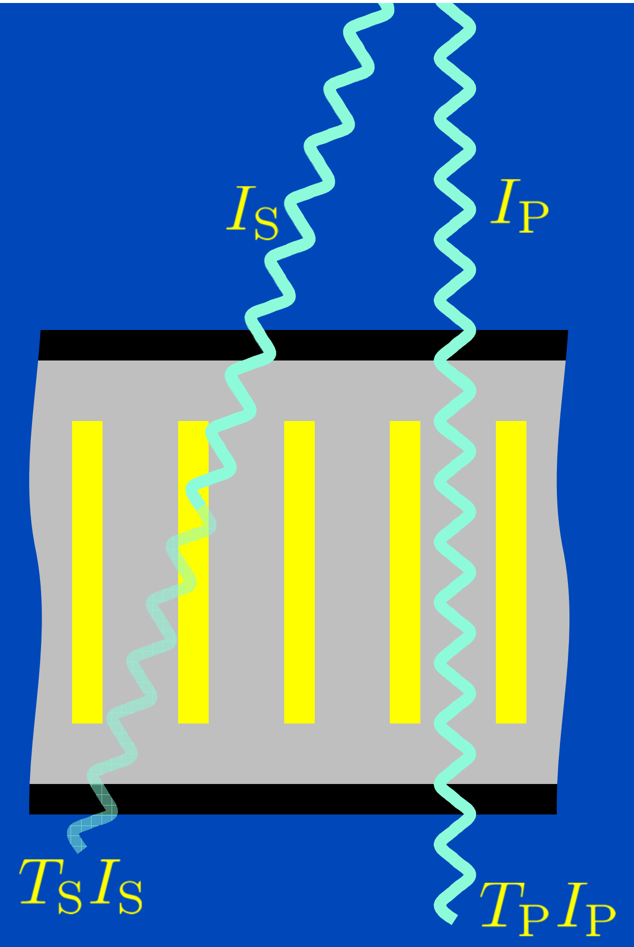




- Anti-scatter grids are aligned to the detector pixels
- Anti-scatter grids reject scattered radiation
- Detector pixels are of about 1.2 mm size
- Detector pixels are structured, reflective coating maximizes light usage and minimizes cross-talk
- Thick scintillators improve dose usage
- Gd_2O_2S is a high density scintillator with favourable decay times
- Individual electronics, fast read-out (5 kHz)
- Very high dynamic range (10^7) can be realized

- Anti-scatter grids are not aligned to the detector pixels
- The benefit of anti-scatter grids is unclear
- Detector pixels are of about 0.2 mm size
- Detector pixels are unstructured, light scatters to neighboring pixels, significant cross-talk
- Thick scintillators decrease spatial resolution
- CsI grows columnar and suppresses light scatter to some extent
- Row-wise readout is rather slow (25 Hz)
- Low dynamic range ($<10^3$), long read-out paths





Cover thickness: *t*, e.g. 0.2 mm Al or 0.25 mm C
Height of strips: *h*
Thickness of strips: *d*, e.g. 0.04 mm Pb
Gap between strips: *D*, e.g Al or C-fiber
Grid ratio: *h*/*D, e.g. 8 or 15*
Grid frequency: 1/(*D*+*d*), e.g. 40/cm
Geometrical efficiency: *D*/(*D*+*d*)
Height of interspace material: *H*

Primary intensity: I_P
Scatter intensity: I_S
Primary transmission: $T_P < 1$, e.g. 75%
Scatter transmisstion: $T_S > 0$, e.g. 30%

No grid: $T_P = T_S = 1$
Ideal grid: $T_P = 1$, $T_S = 0$

Flat detector grids. Drawn to grid ratio 4:1 and infinite focus.

To Grid or not to Grid?

- Only primary counts for the signal, but primary and scatter count for noise. Thus,

$$\mathrm{SNR} = \frac{T_\mathrm{P} I_\mathrm{P}}{\sqrt{T_\mathrm{P} I_\mathrm{P} + T_\mathrm{S} I_\mathrm{S}}}$$

- SNR improvement factor (SNR with grid / SNR no grid)

$$\mathrm{SNR}_\mathrm{if} = T_\mathrm{P} \frac{\sqrt{I_\mathrm{P} + I_\mathrm{S}}}{\sqrt{T_\mathrm{P} I_\mathrm{P} + T_\mathrm{S} I_\mathrm{S}}}$$

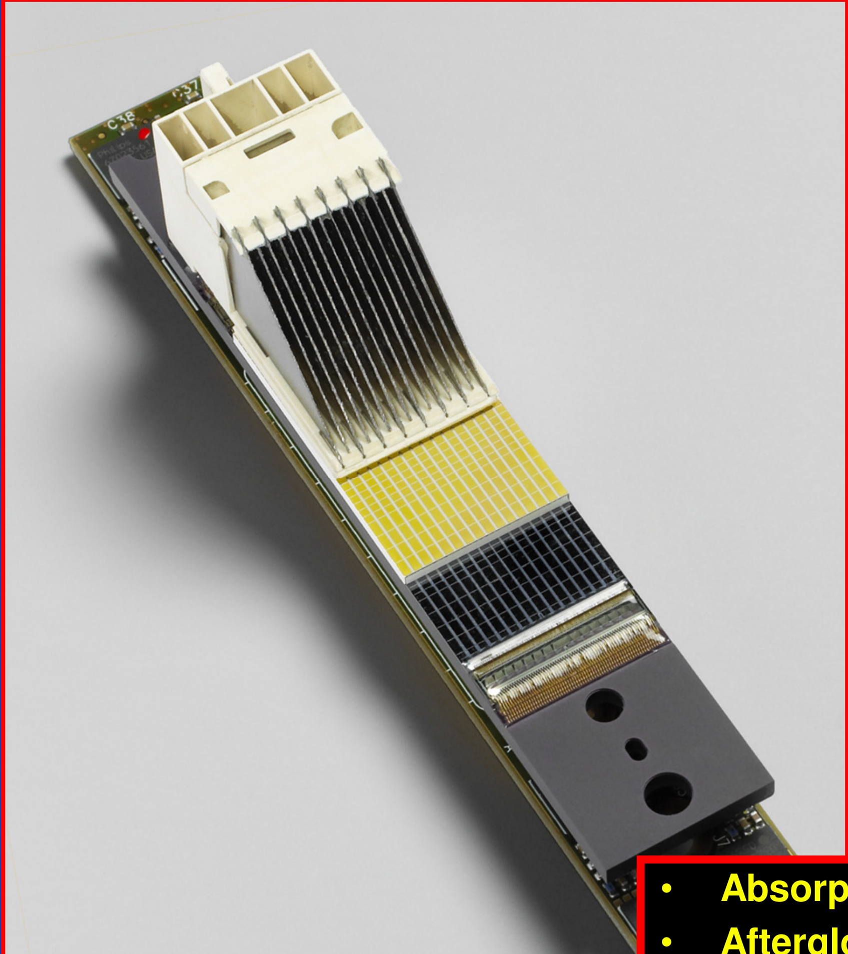
- The case $T_\mathrm{S} = 0$ is interesting and yields

$$\mathrm{SNR}_\mathrm{if} \le \sqrt{T_\mathrm{P}}\sqrt{1 + \mathrm{SPR}}$$

  with SPR being the scatter-to-primary ratio.
- Use a grid only for cases with $\mathrm{SNR}_\mathrm{if} \geq 1$.
- Additional scatter correction algorithms are to be used complementary and not as an alternative to grids.

Detector Technology

Clinical CT Detector



Flat Detector

- Absorption efficiency
- Afterglow
- Dynamic range
- Cross-talk
- Framerate
- Scatter grid

Sensor Dose Efficiency

	Clinical CT (120 kV)			Flat Detector CT (120 kV)			Photon Counting CT (120 kV)		
Material	Gd_2O_2S			CsI			CdTe		
Density	7.44 g/cm^3			4.5 g/cm^3			5.85 g/cm^3		
Thickness	1.4 mm			0.6 mm			1.0 mm		
Manufacturer	Siemens			Varian			Dectris		
Water Layer	0 cm	20 cm	40 cm	0 cm	20 cm	40 cm	0 cm	20 cm	40 cm
Photons absorbed	96.2%	92.7%	89.8%	73.5%	59.2%	50.9%	88.6%	77.9%	70.4%
Energy absorbed	94.3%	90.7%	87.9%	66.4%	53.9%	46.6%	83.2%	73.0%	66.1%

Absorption values are relative to a detector of infinite thickness.

The energy absorption coefficient μ_{en} was used to estimate the absorption values.

X-Ray Exposure Dynamic Range D

- D = saturation exposure / quantum-limited exposure
  - Saturation exposure N_{max}: Exposure where the detector runs into saturation
  - Quantum-limited exposure N_{min}: Exposure where the x-ray quantum noise equals the detector‘s electronic noise.
- Measurements[1]
  - Saturation signal: Increase exposure until you obtain $E(S_{max})$ in the offset-corrected reading.
  - Relation $S = k \cdot N$: Evaluate an offset-corrected medium level exposure to obtain a pair of values $\mathrm{Var}(S_{med})$ and $E(S_{med})$. Now, use the relation $\mathrm{Var}(N_{med}) = E(N_{med})$ with $\mathrm{Var}(S_{med}) = k^2 \cdot \mathrm{Var}(N_{med})$ and $E(S_{med}) = k \cdot E(N_{med})$ to find $k = \mathrm{Var}(S_{med}) / E(S_{med})$.
  - Electronic noise: Determine $\mathrm{Var}(S_{min})$ from the subtraction of two dark images.
- X-ray exposure dynamic range

$$D = \frac{\mathrm{E}(N_{\mathrm{max}})}{\mathrm{E}(N_{\mathrm{min}})} = \frac{\mathrm{E}(S_{\mathrm{max}})/k}{\mathrm{Var}(S_{\mathrm{min}})/k^2} = \frac{\mathrm{E}(S_{\mathrm{max}})\mathrm{Var}(S_{\mathrm{med}})}{\mathrm{E}(S_{\mathrm{med}})\mathrm{Var}(S_{\mathrm{min}})}$$

[1]Instead of doing this very simple procedure one may want to use statistically optimal estimates. One may use many readings, and many exposure levels. One may further determine D on a pixel-by-pixel basis.

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Dynamic Range in Flat Detectors

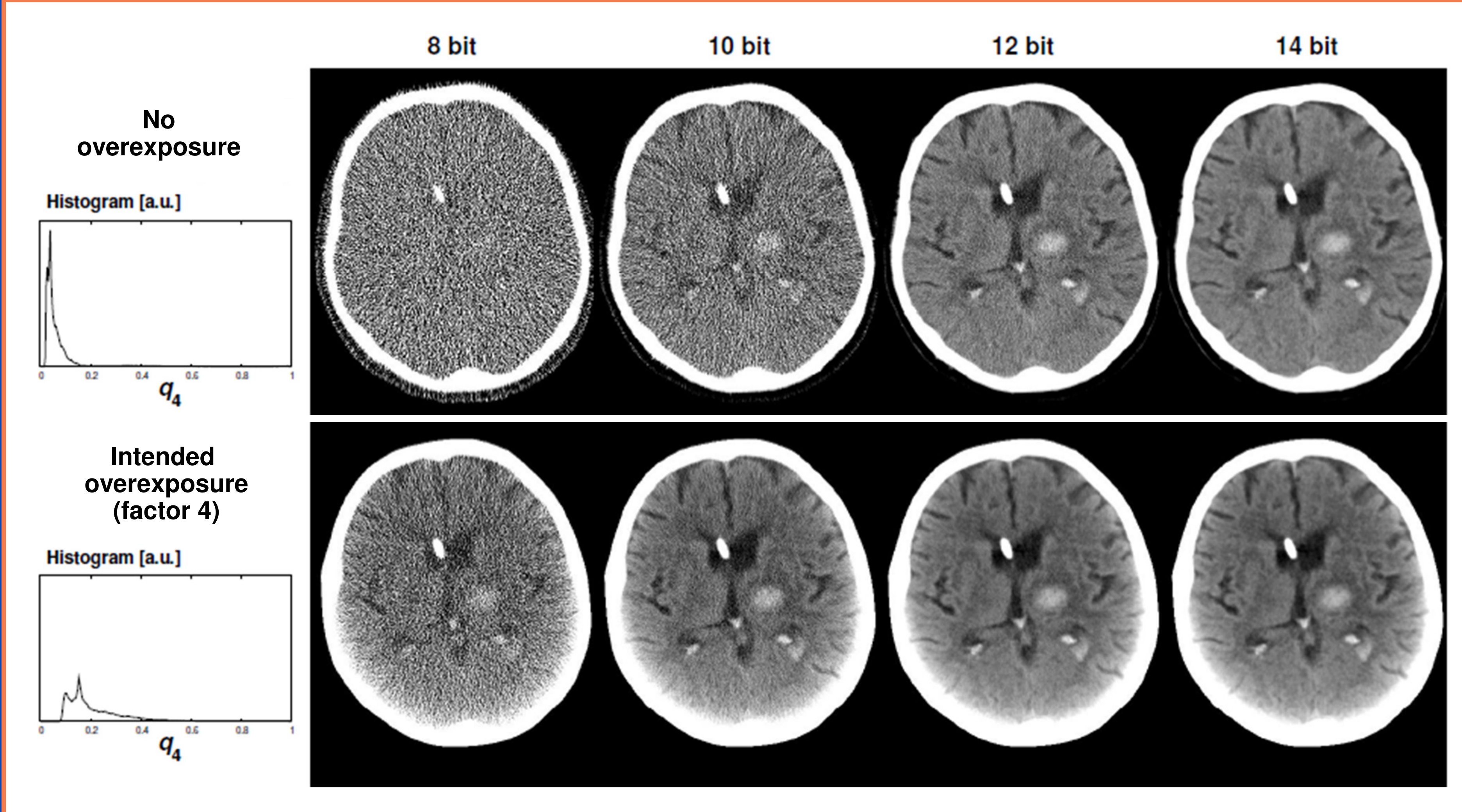
	Saturation-to-noise range			X-ray exposure range				Digital range	
	Electronic noise (ADU)	Saturation signal (ADU)	Dynamic range	Quantum limited exposure (μR)	Saturation exposure (μR)	Dynamic range	Eff. bit depth (bits)	Quantization range	Eff. bit depth (bits)
No binning, gain 2	A1	B1	B1/A1	A2	B2	C2=B2/A2	D2=lb(C2)	B1:1	lb(B1)
Dynamic gain switching	5.32	80500	15100	2.75	3550	**1291**	**10.3**	80500:1	16.3
0.5 pF fixed	5.32	14500	2700	2.75	595	**216**	**7.8**	14500:1	13.8
4 pF fixed	3.57	14800	4150	35.7	4200	**118**	**6.9**	14800:1	13.8
2x2 binning, gain 1									
Dual gain readout	4.33	80100	18500	1.00	1800	**1800**	**10.8**	80100:1	16.3
Dynamic gain switching	4.37	84200	19300	1.03	2062	**2002**	**11.0**	84200:1	16.4
0.5 pF fixed	4.37	14300	3300	1.03	311	**302**	**8.2**	14300:1	13.8
4 pF fixed	3.14	14800	4700	15.6	2104	**135**	**7.1**	14800:1	13.8
0.5 pF fixed, gain 2 (fluoroscopy mode)	7.25	12900	1700	0.71	125	**176**	**7.5**	12900:1	13.6

Table 2 4030CB dynamic range in available imaging modes

A2 is defined as the exposure where QuantumNoise=ElectronicNoise.

$$D = \frac{80500/k}{5.32^2/k^2} = 1291 \quad \text{if} \quad k = 0.45$$

Table taken from [Roos et al. “Multiple gain ranging readout method to extend the dynamic range of amorphous silicon flat panel imagers,” *SPIE Medical Imaging Proc.*, vol. 5368, pp. 139-149, 2004]. Additional values were added, for convenience.


8 bit
10 bit
12 bit
14 bit
No overexposure
Histogram [a.u.]
0 0.2 0.4 0.6 0.8 1
q4
Intended overexposure (factor 4)
Histogram [a.u.]
0 0.2 0.4 0.6 0.8 1
q4

Dynamic Range Required for Diagnostic Image Quality

- **Soft tissue μ = 0.0192/mm object of diameter *D* between $D_{\min}$ = 200 mm and $D_{\max}$ = 500 mm with a lesion of diameter *d* = 5 mm and contrast δ = 5 HU = 0.005.**
- **Number of photons to be registered at the detector:**

$$I(D,\delta d) = I_0 e^{-\mu D - \mu\delta d}$$

- **Minimal signal difference to be detected:**

$$I(D_{\max},\delta d) - I(D_{\max},0) \approx \mu\delta d I(D_{\max},0)$$

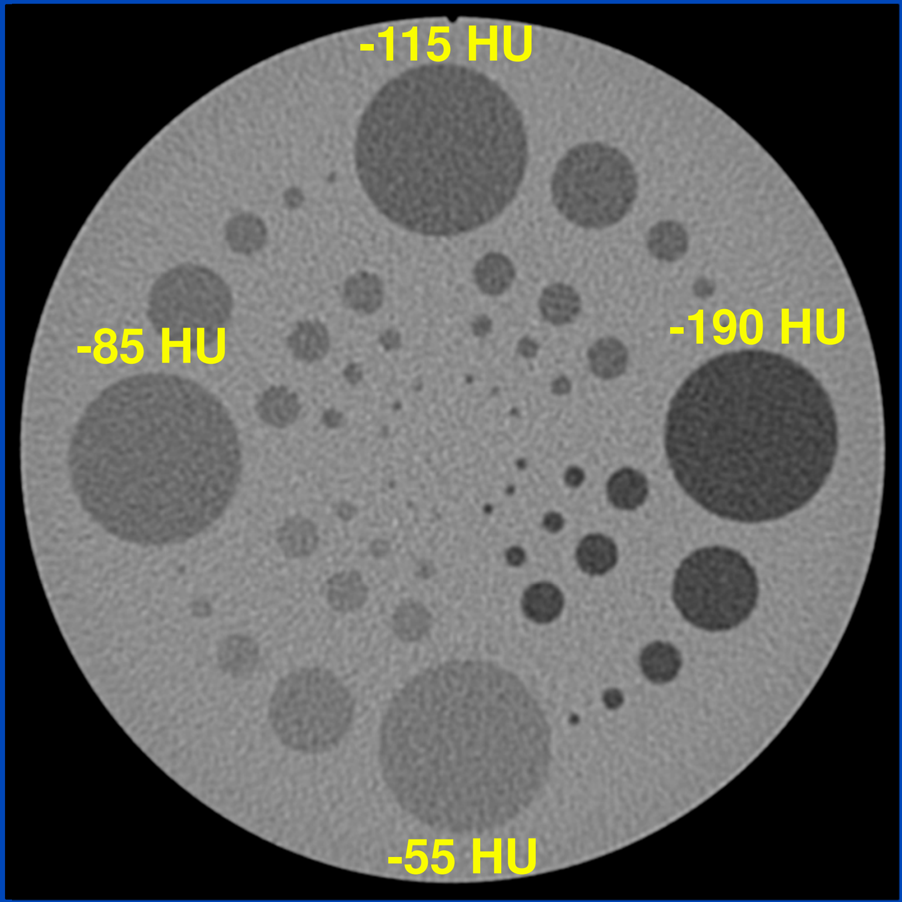
- **Maximum signal to be detected:**

$$I(D_{\min},0)$$

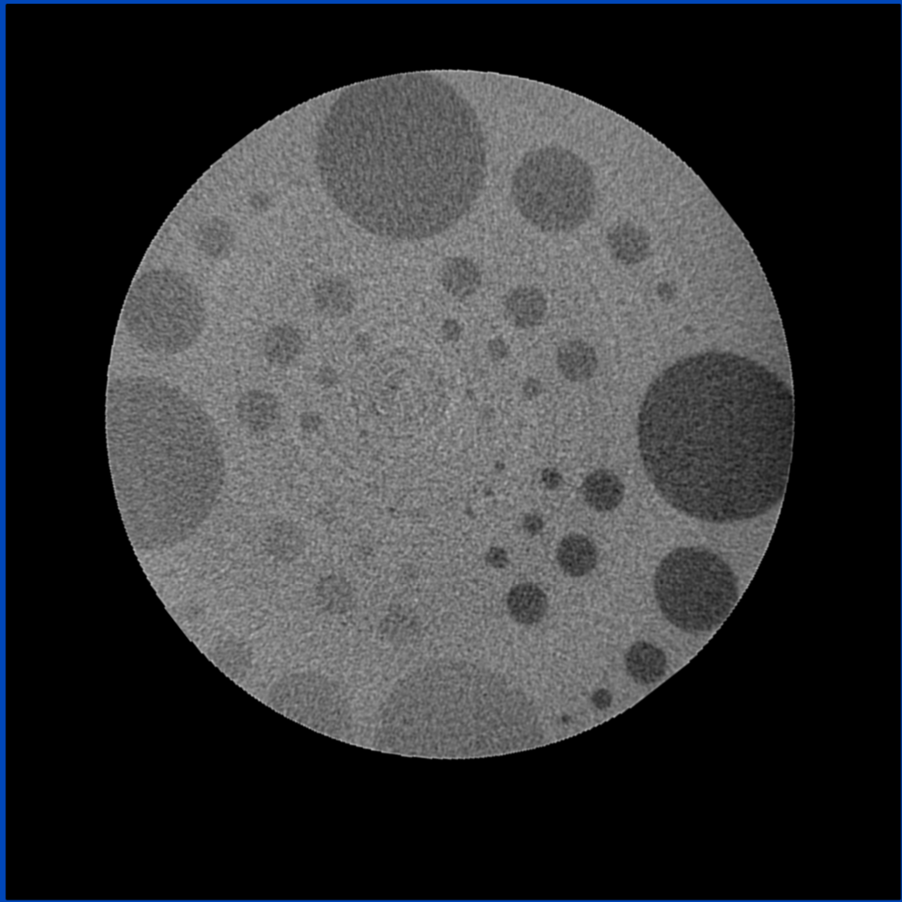
- **Thus, the dynamic range required in diagnostic CT is in the order of**

$$\frac{I(D_{\min},0)}{\mu\delta d\, I(D_{\max},0)} \approx 10^6 \approx 2^{20}$$

Clinical CT vs. Flat Detector CT

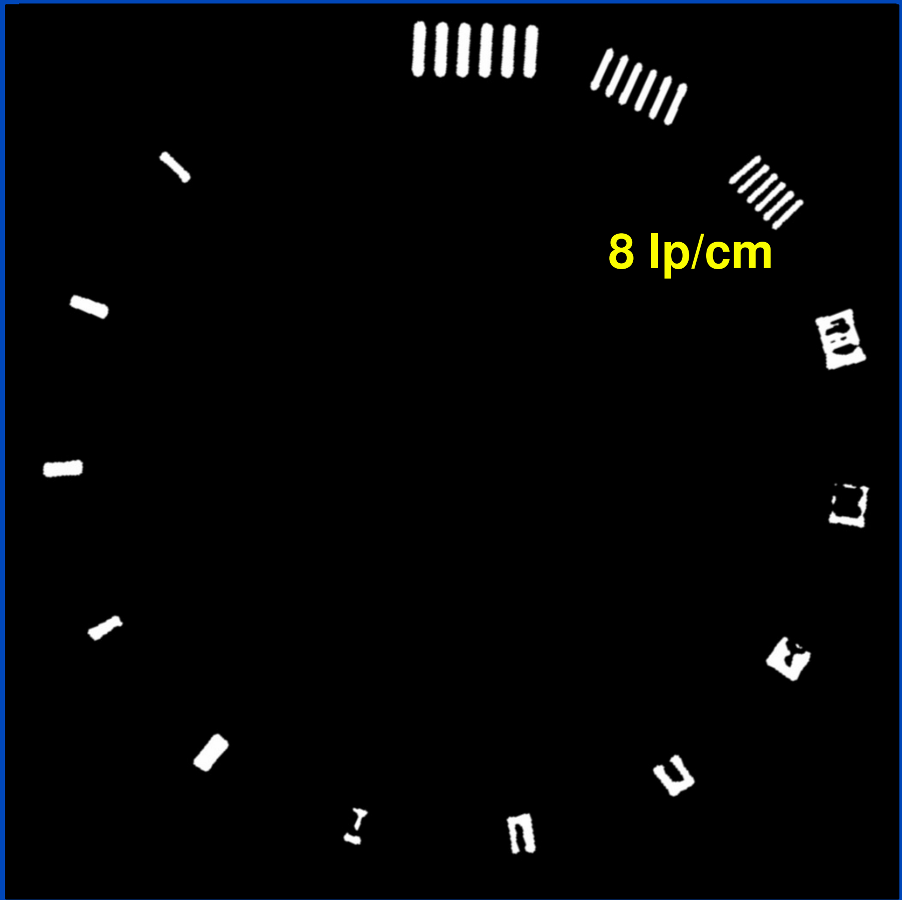


Clinical CT, Standard Kernel
C = 0 HU, *W* = 700 HU

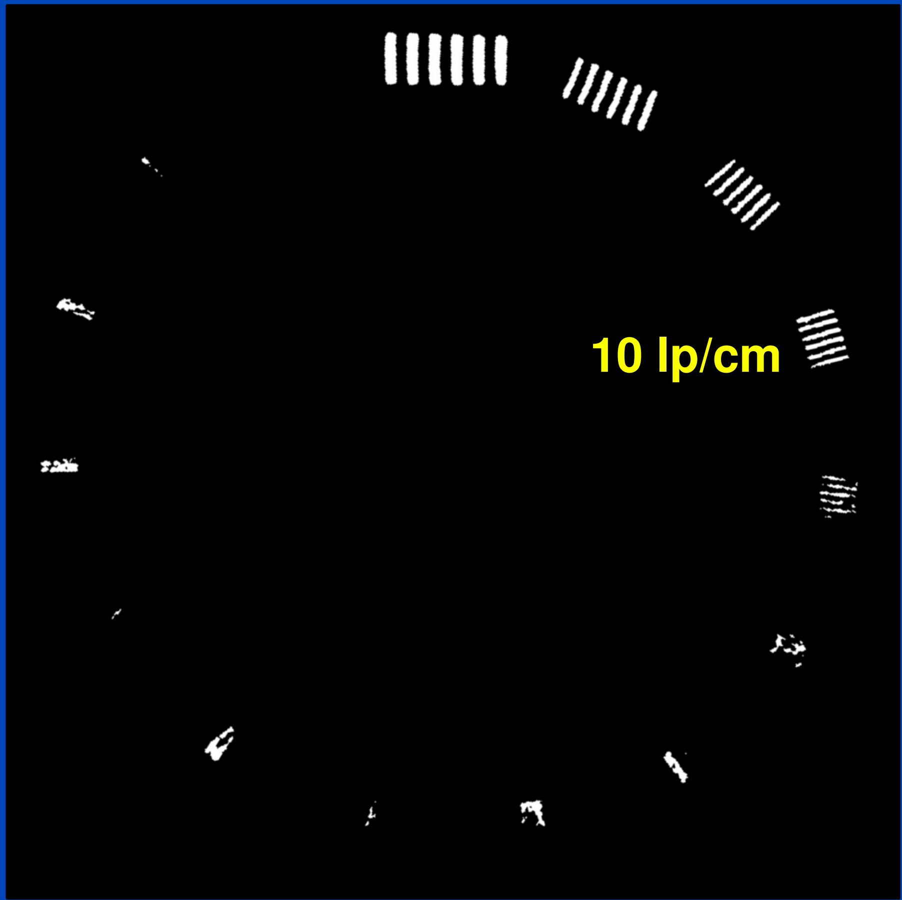


Flat Detector CT, 2×2 Binning

Clinical CT vs. Flat Detector CT

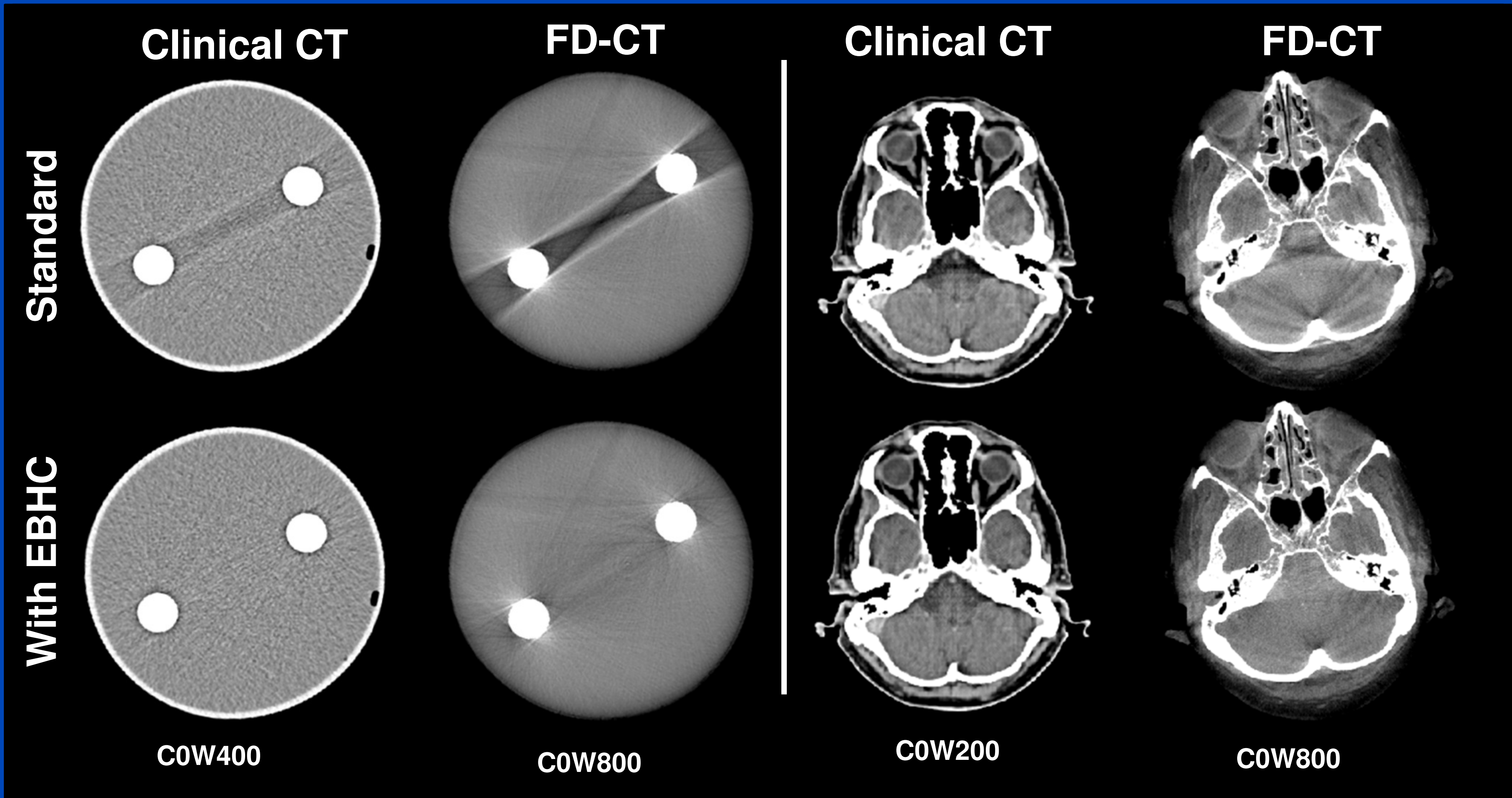


Clinical CT, Standard Kernel



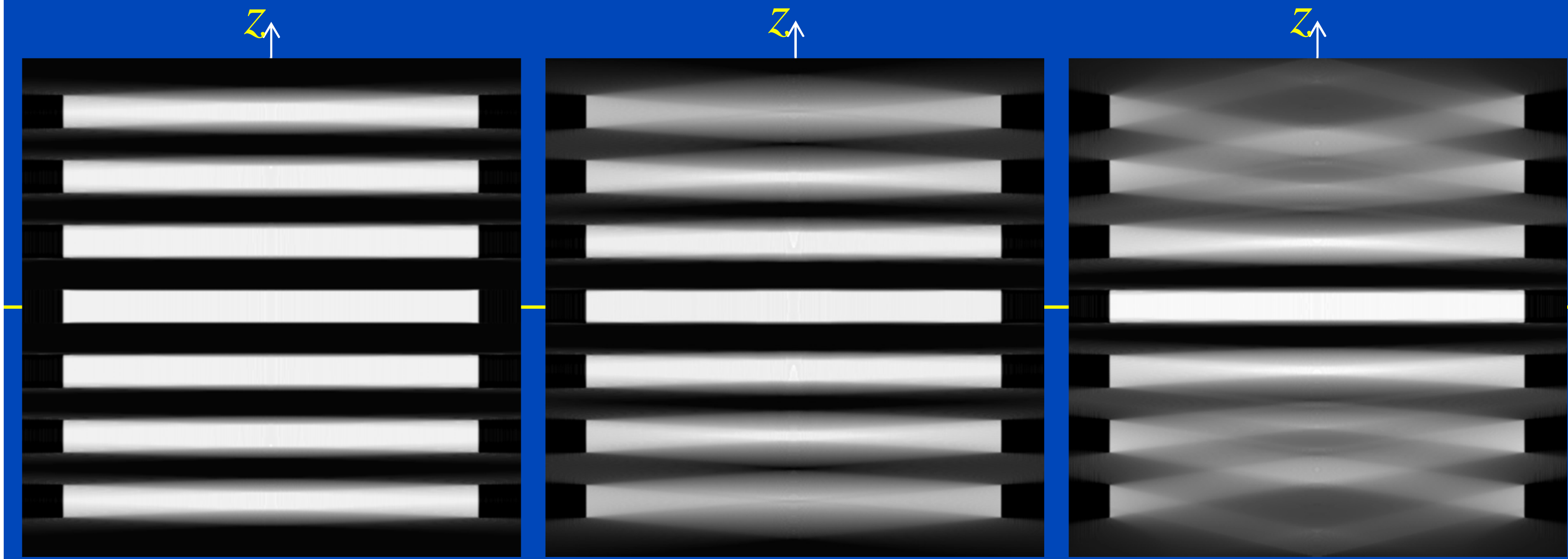
Flat Detector CT, 2×2 Binning

Clinical CT vs. FD-CT

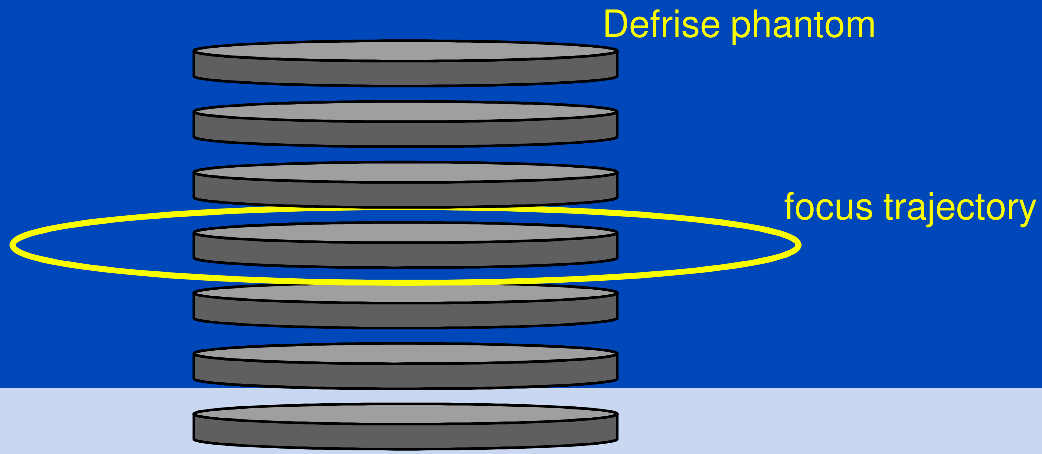


Siemens Somatom Definition vs. Siemens Axiom Artis

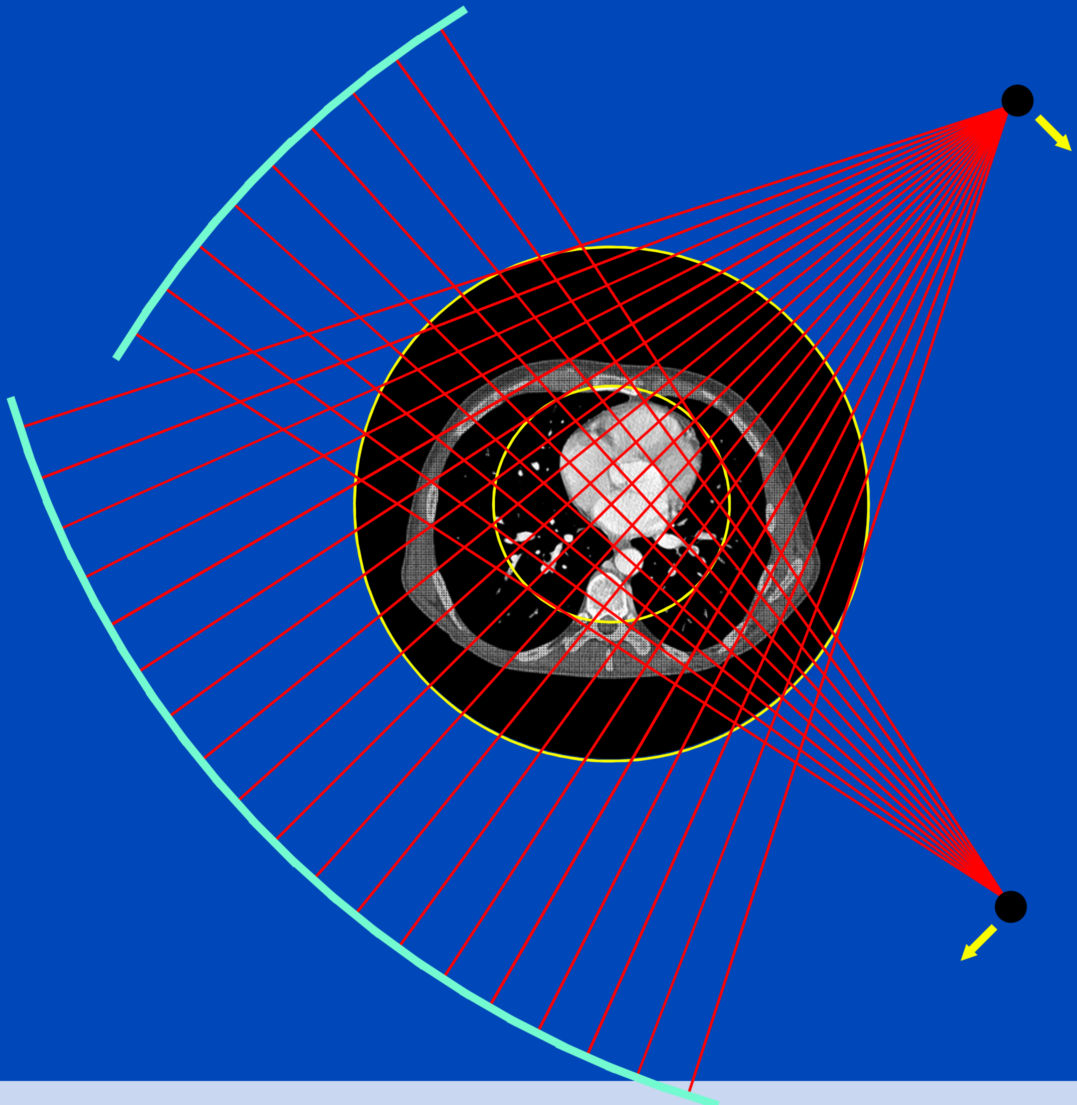
Cone-Beam Artifacts

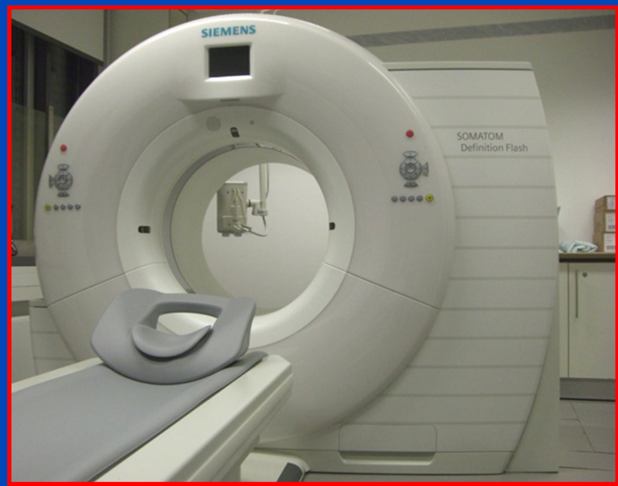


Cone-angle Γ = 6°   Cone-angle Γ = 14°   Cone-angle Γ = 28°



Multi-Threaded CT Scanners and Dual-Source-CT





Siemens SOMATOM Definition Flash
dual source cone-beam spiral CT scanner


SIEMENS
300.0
-2000.0
SOMATOM Force

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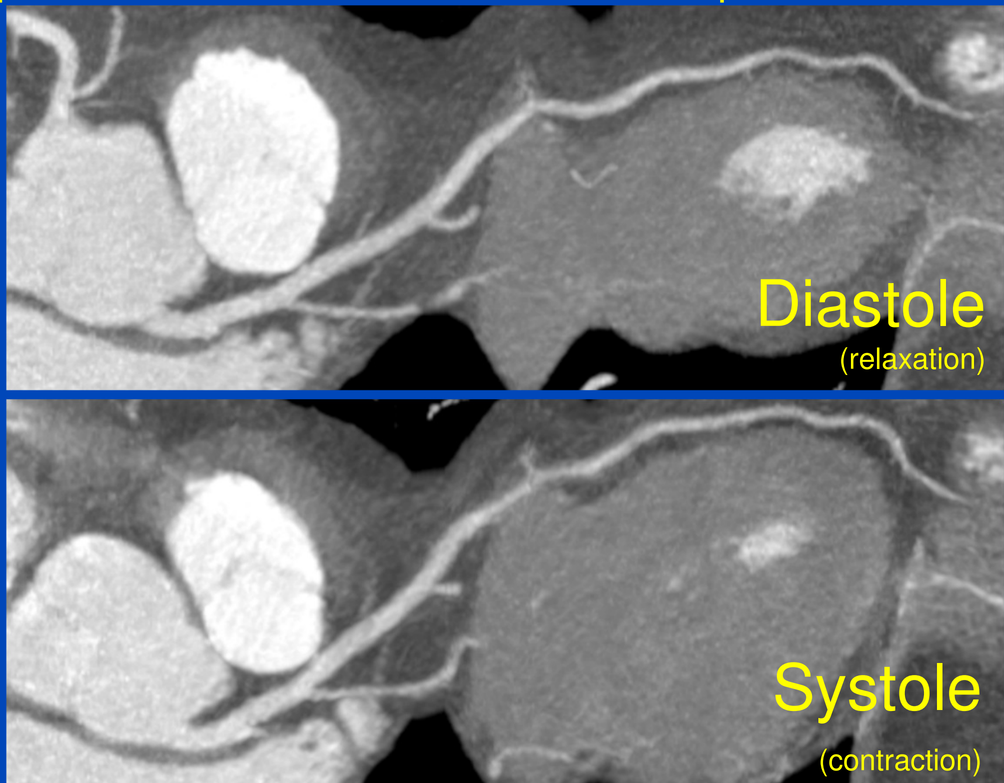
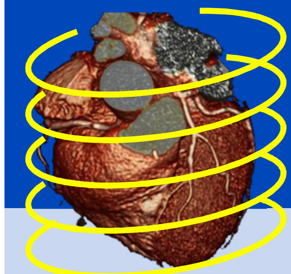
Dual Source CT = Best Possible Cardiac CT

- **Extremely high temporal resolution**
- **Nearly free of motion artifacts**

dual source CT, 330 ms rotation,
partial scan reconstruction, 83 ms temporal resolution

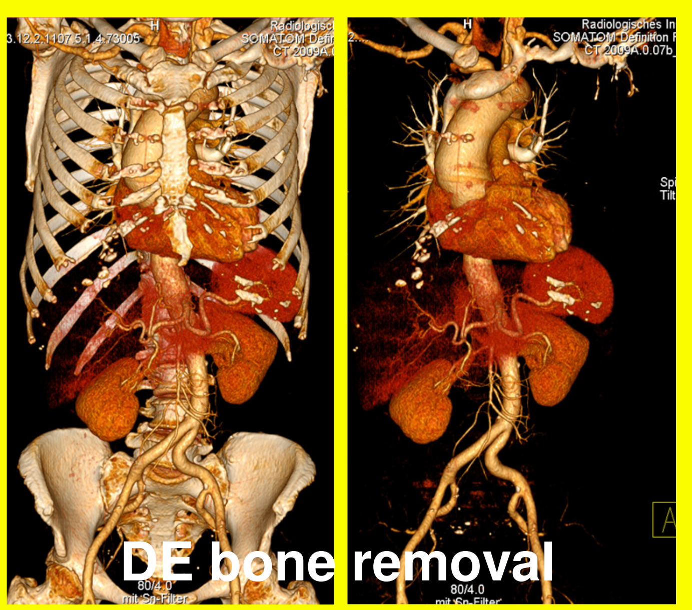


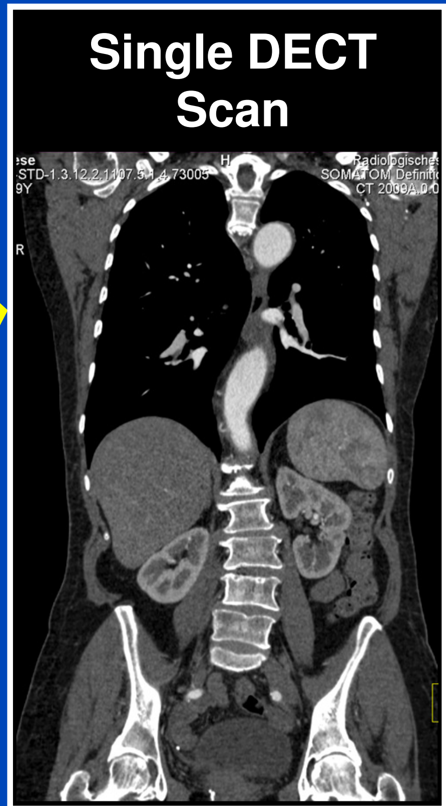


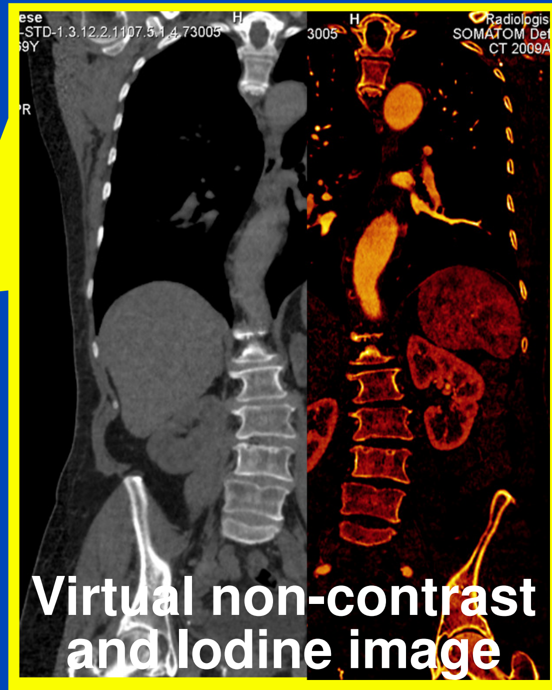
Data courtesy of Stephan Achenbach

Dual Source CT =
Best Possible Dual Energy CT

- Tube currents can be selected and modulated for each thread independently
- Prefiltration can be optimized for each thread independently
- Optimal sampling







Dual Energy whole body CTA: 100/140 Sn kV @ 0.6mm

Clinical vs. Flat Detector CT

	Clinical CT (MDCT)	Flat Detector CT (CBCT)
Spatial resolution	0.5 mm	0.2 mm
Contrast	3 HU	30 HU
Dynamic range	≈ 20 bit	≈ 10 bit
Dose efficiency	≈ 90%	≈ 50%
Lowest rotation time	0.25 s	3 s
Temporal resolution	0.07 s	3 s
Frame rate	≈ 5000 fps	≈ 25 fps
X-ray power	100 – 120 kW	5 – 25 kW
Bow tie	optimized for patient	optimized for detector
AEC (for mAs and kV)	optimized for patient	optimized for detector
Advanced dose reduction techniques	IR, DOM, task-specific kV, organ and ECG specific AEC, dynamic collimation, …	few, if any

Thank You!

The 4th International Conference on

Image Formation in X-Ray Computed Tomography

Conference Chair

Marc Kachelrieß, German Cancer Research Center (DKFZ), Heidelberg, Germany

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

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