X-Ray Sources in Diagnostic CT

Marc Kachelrieß

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

DEUTSCHES
KREBSFORSCHUNGSZENTRUM
IN DER HELMHOLTZ-GEMEINSCHAFT

Canon Aquilion ONE Vision

GE Revolution CT

Philips IQon Spectral CT

Siemens Somatom Force

In-plane resolution: 0.4 … 0.7 mm

Nominal slice thickness: S = 0.5 … 1.5 mm

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

Effective tube current: mAs_{eff} = 10 mAs … 1000 mAs

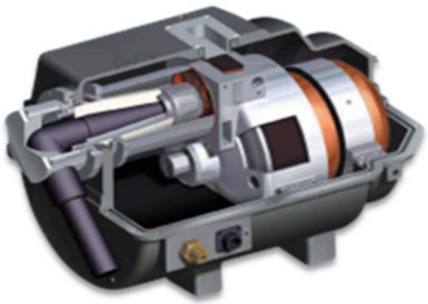
Rotation time: T_{rot} = 0.25 … 0.5 s

Simultaneously acquired slices: M = 16 … 320

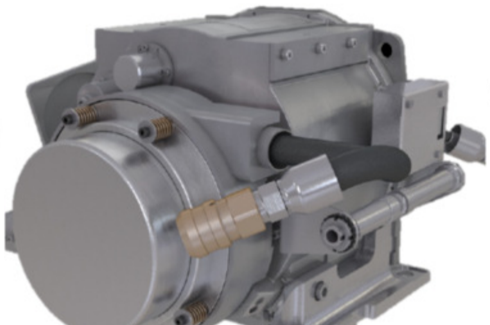
Table increment per rotation: d = 1 … 183 mm

Scan speed: up to 73 cm/s

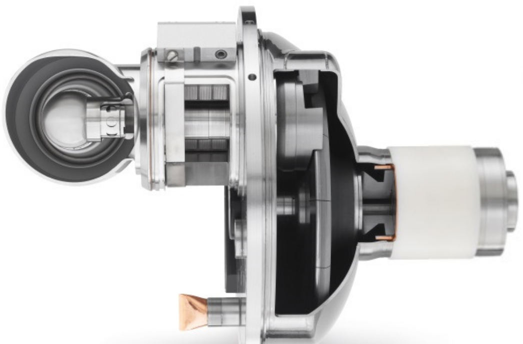
Temporal resolution: 50 … 250 ms



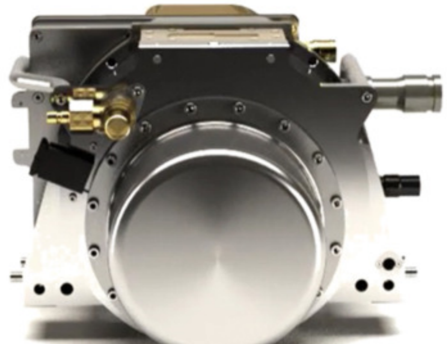
Canon Megacool Vi



GE Performix HDw

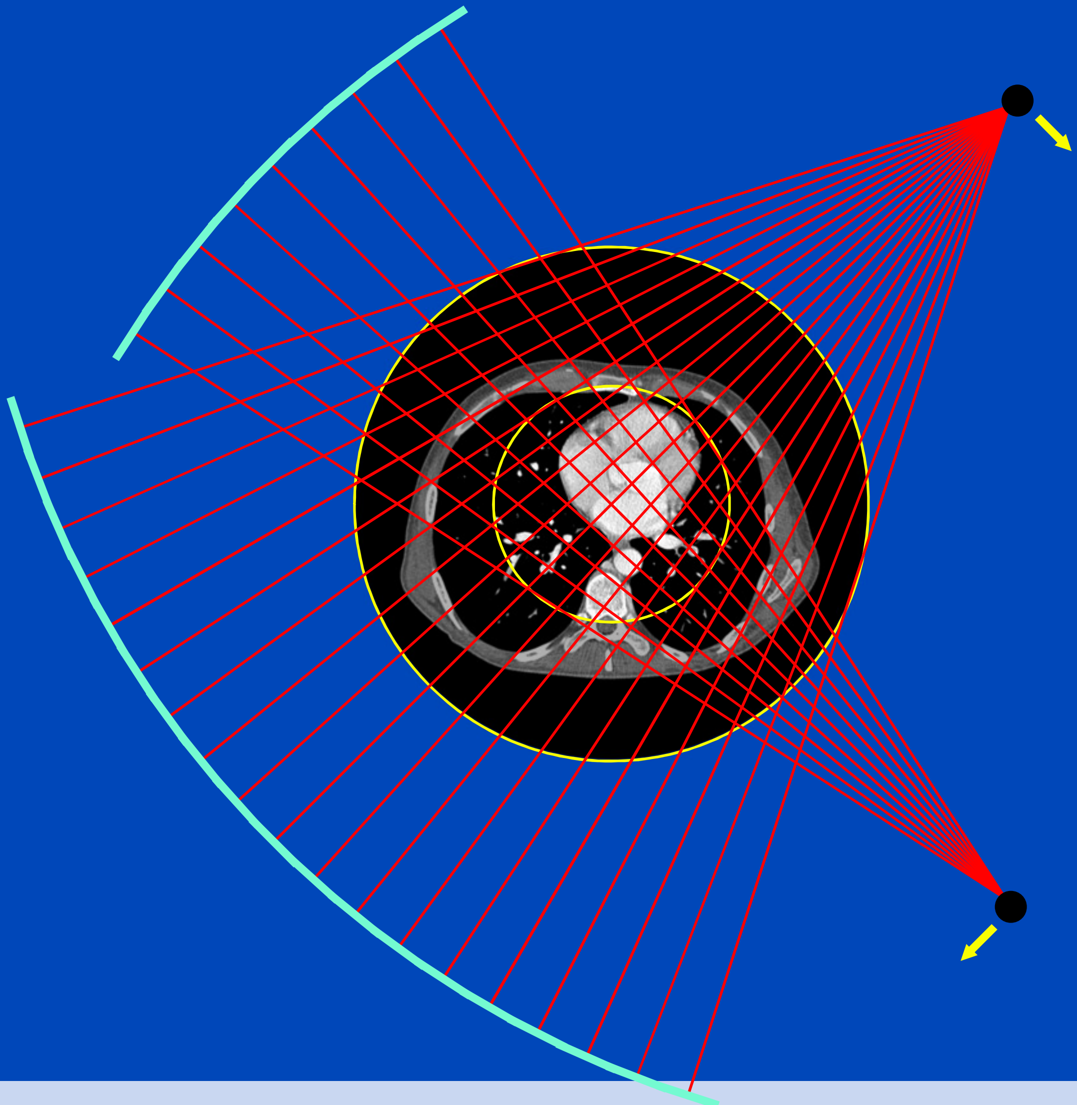


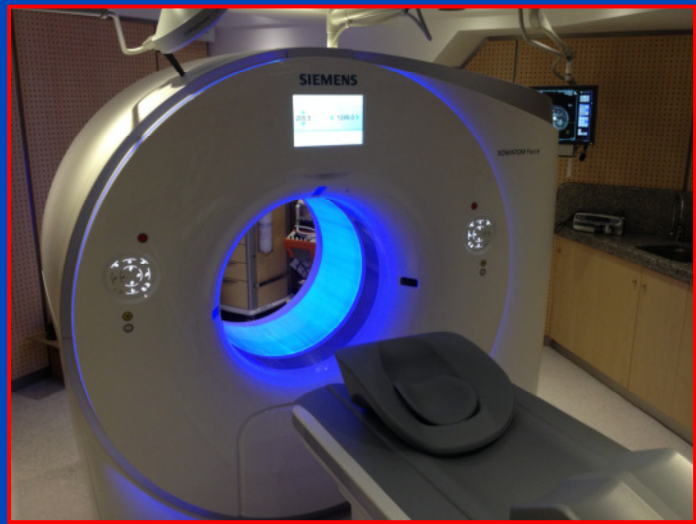
Philips iMRC



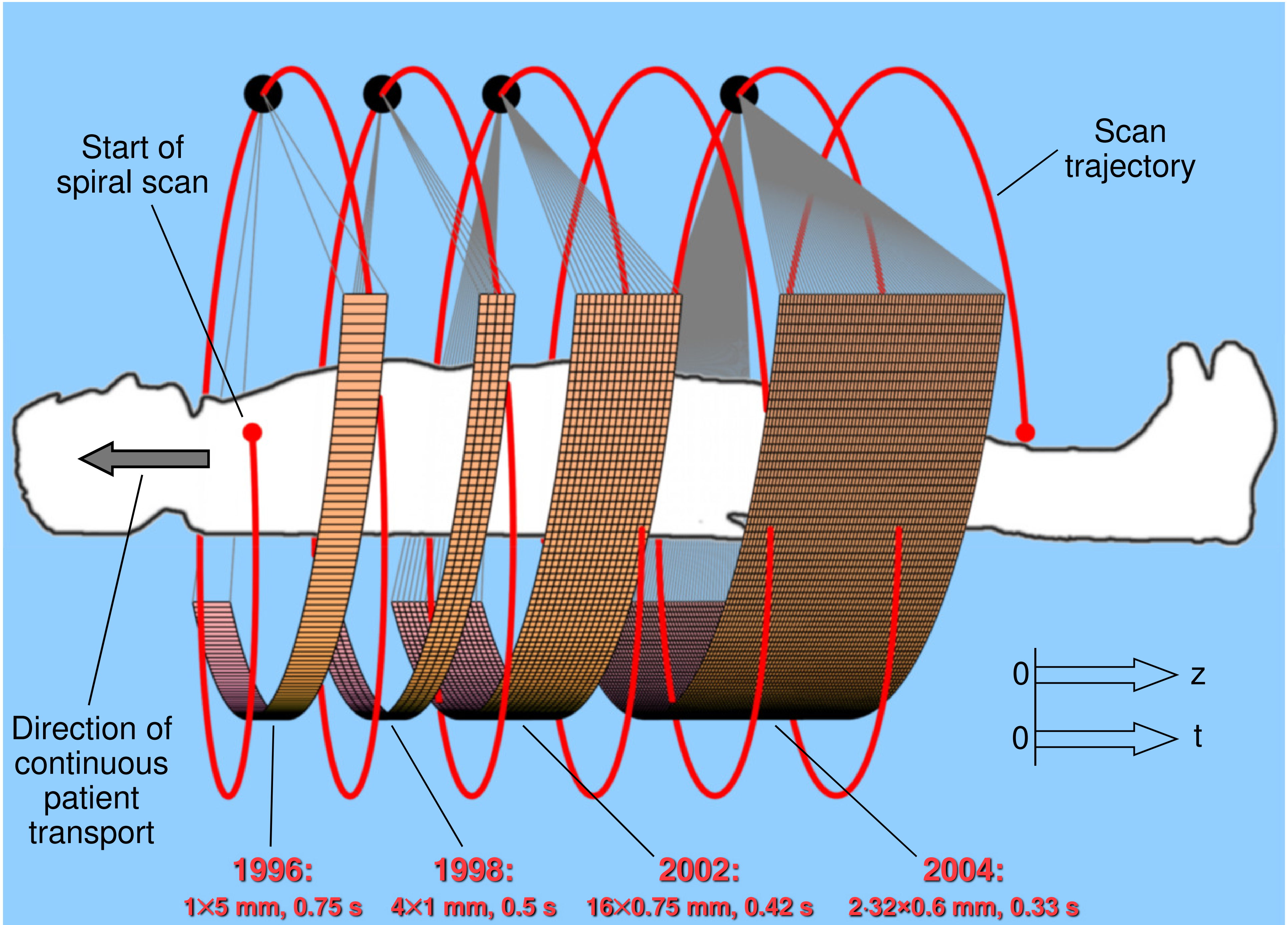
Siemens Vectron

CT is Fast!





Siemens SOMATOM Force
dual source cone-beam spiral CT



Kalender et al., Radiology 173(P):414 (1989) and 176:181-183 (1990)

Very Fast Scanning (Somatom Force)

Procedure:
Transcatheter aortic valve implantation (TAVI)

Patient age: 80 years

Tube voltage: 80 kV
Current: 340 ref mAs/rot

Rotation time: 0.25 s
Pitch: 3.2
Slice thickness: 0.75 mm
Scan length: 557 mm
Scan time: 0.76 s
Scan speed: 737 mm/s

Kernel : B40
Recon: ADMIRE 3

CTDIvol: 2.7 mGy
DLP: 162 mGy·cm
Effective dose: 2.3 mSv

Case information

Axial slices, *C* = 0 HU, *W* = 1500 HU

Volume rendering

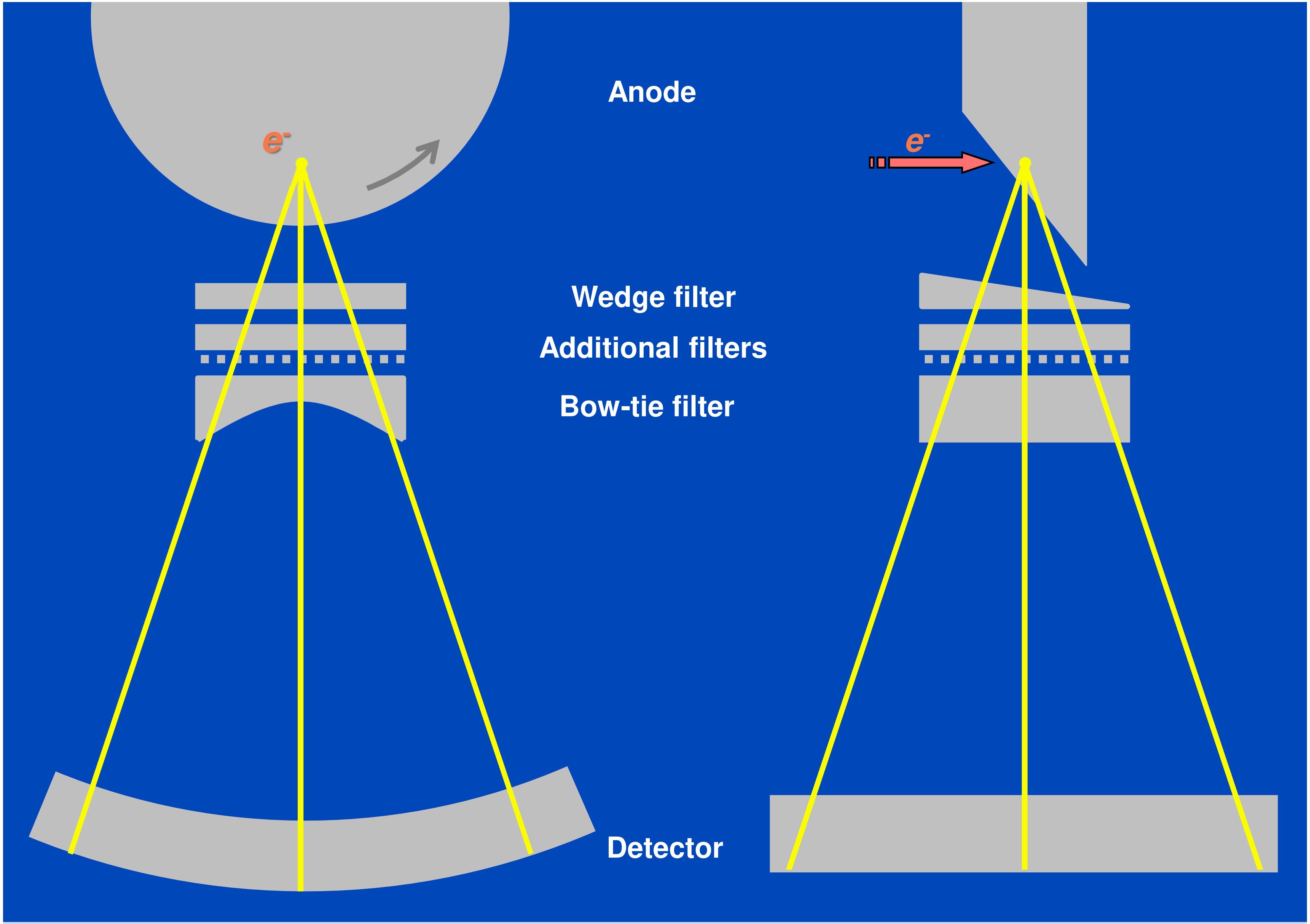
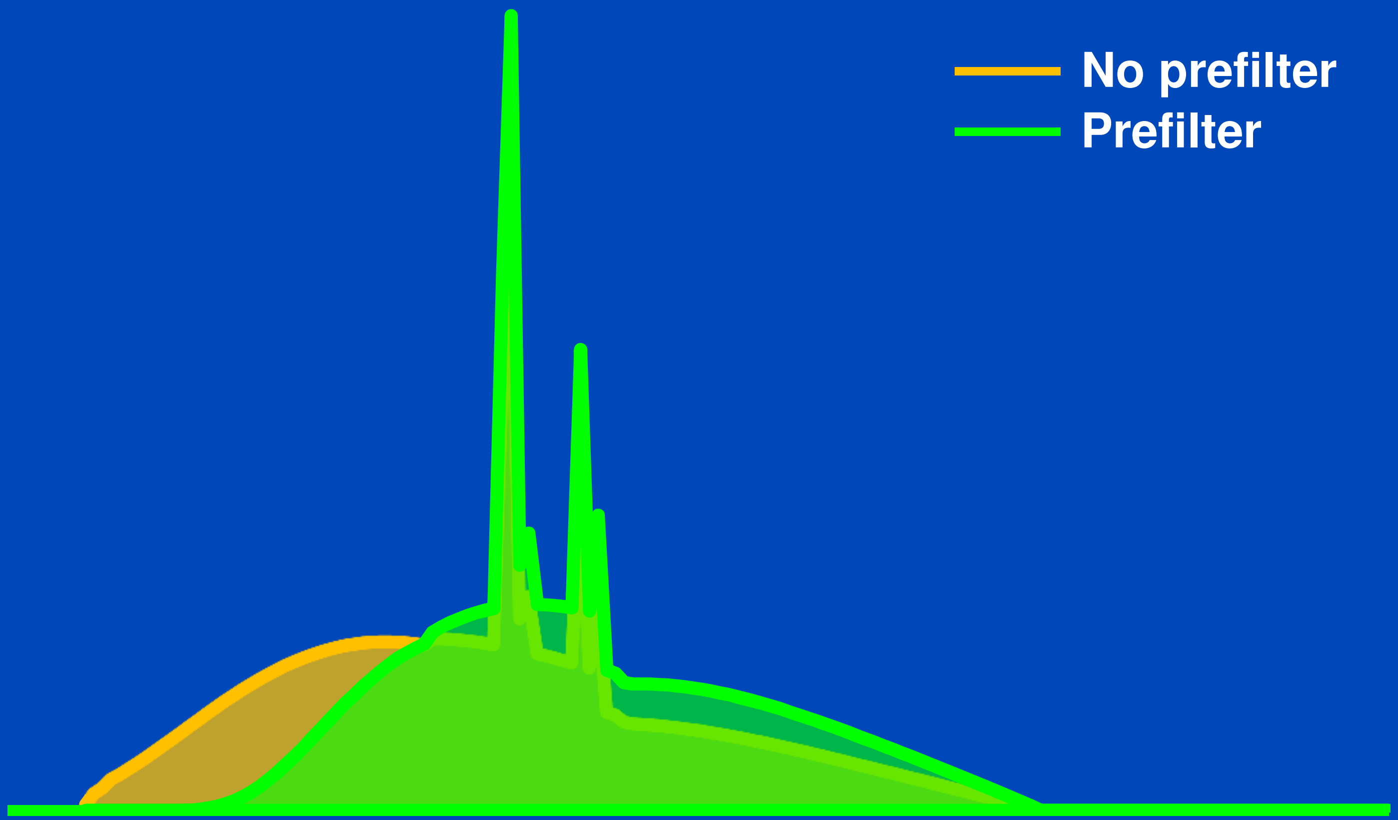


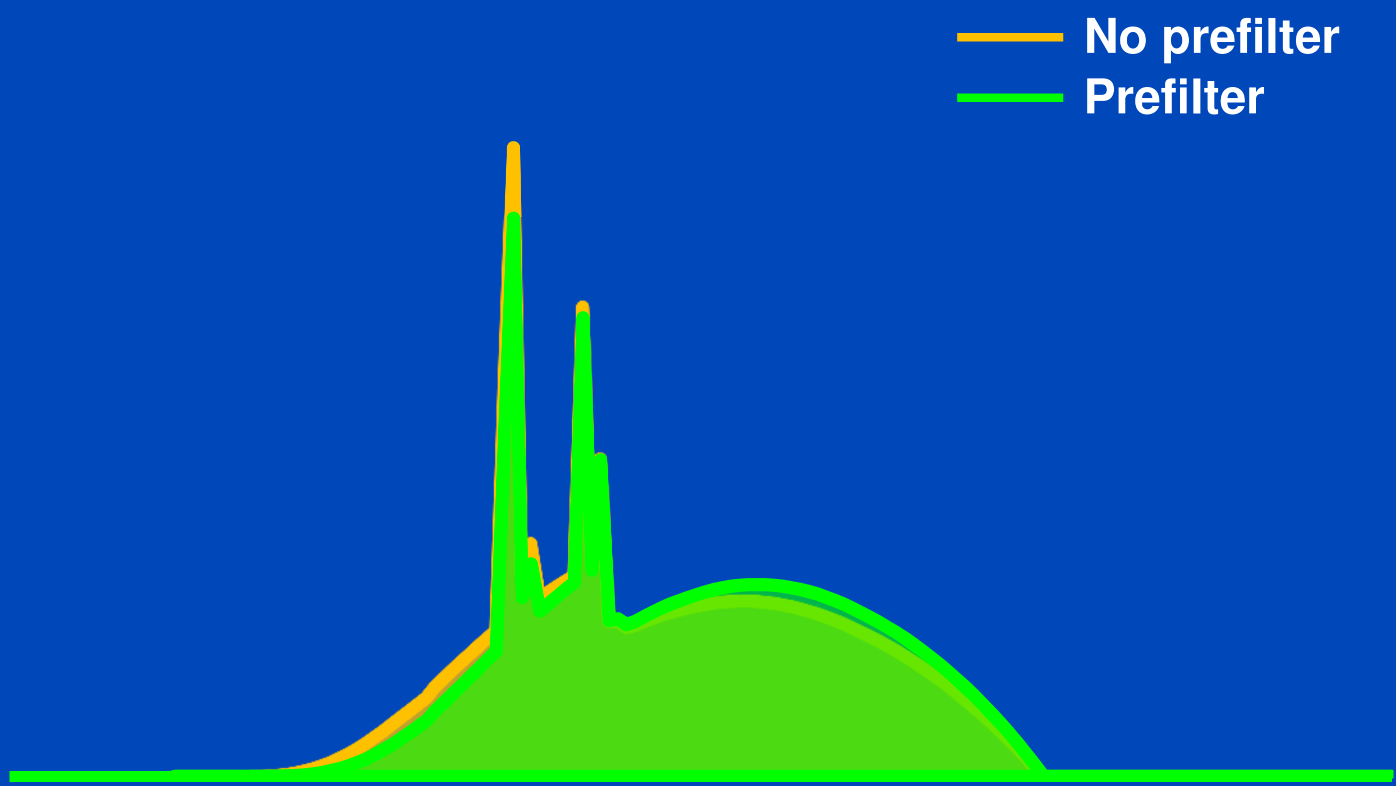
Figure not drawn to scale. Type and order of prefiltration may differ from scanner to scanner.
Depending on the selected protocol filters are changed automatically (e.g. small bowtie for pediatric scans).

dkfz.

120 kV + 0 mm water with and without prefilter

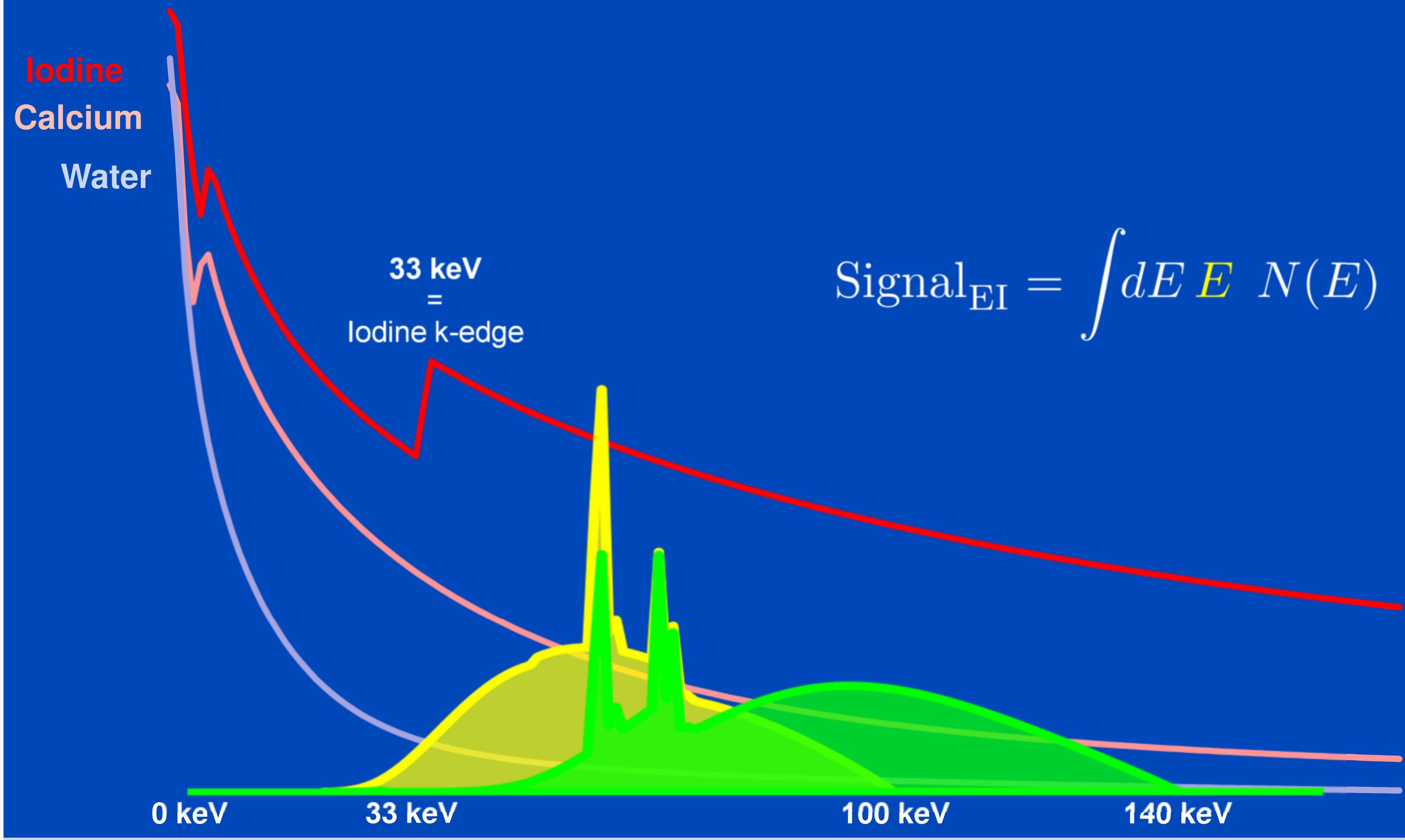


120 kV + 320 mm water with and without prefilter



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

Iodine Contrast is Good at Low kV
(Detected Spectra at 100 kV and 140 kV)



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

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

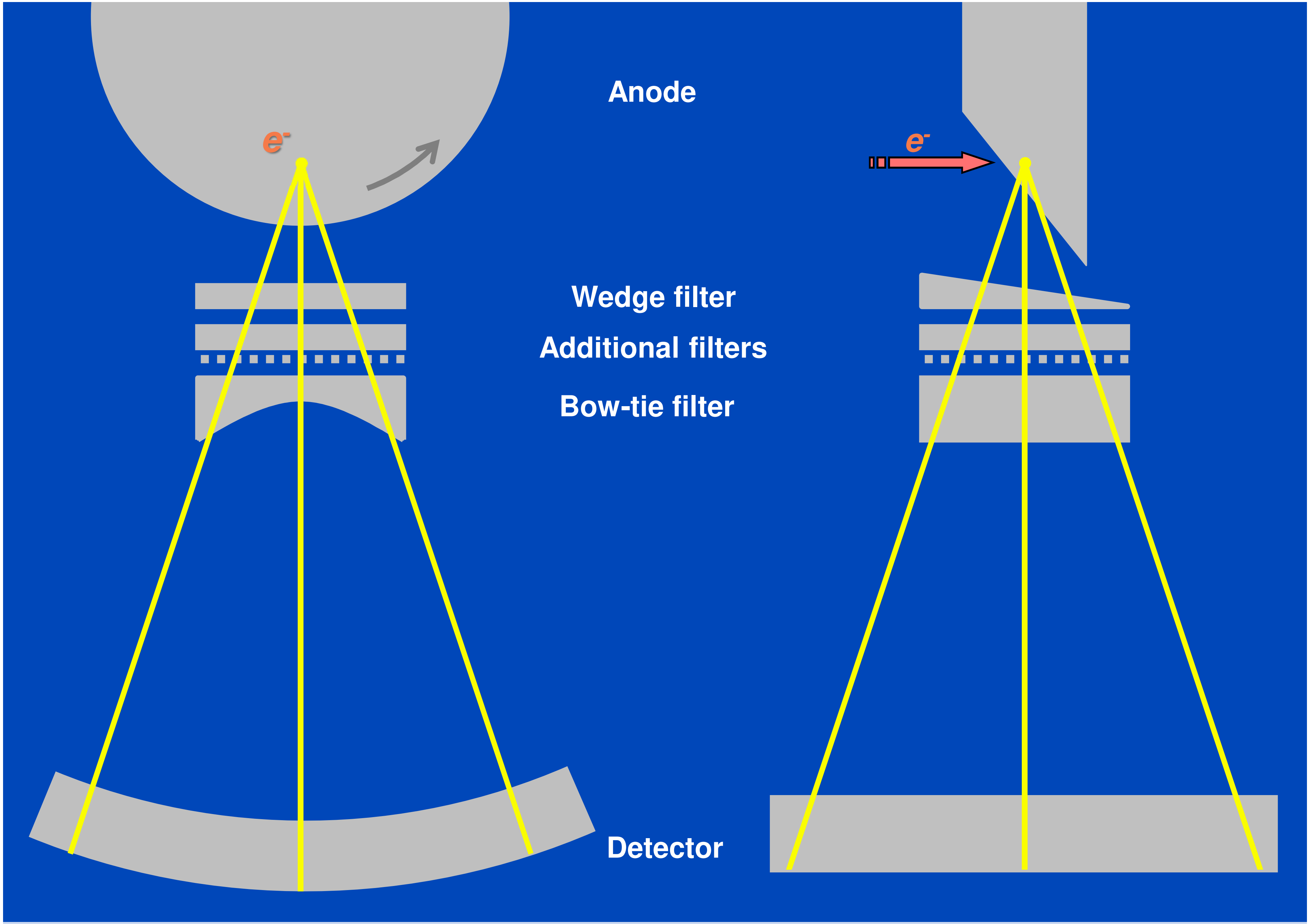


Figure not drawn to scale. Type and order of prefiltration may differ from scanner to scanner.
Depending on the selected protocol filters are changed automatically (e.g. small bowtie for pediatric scans).

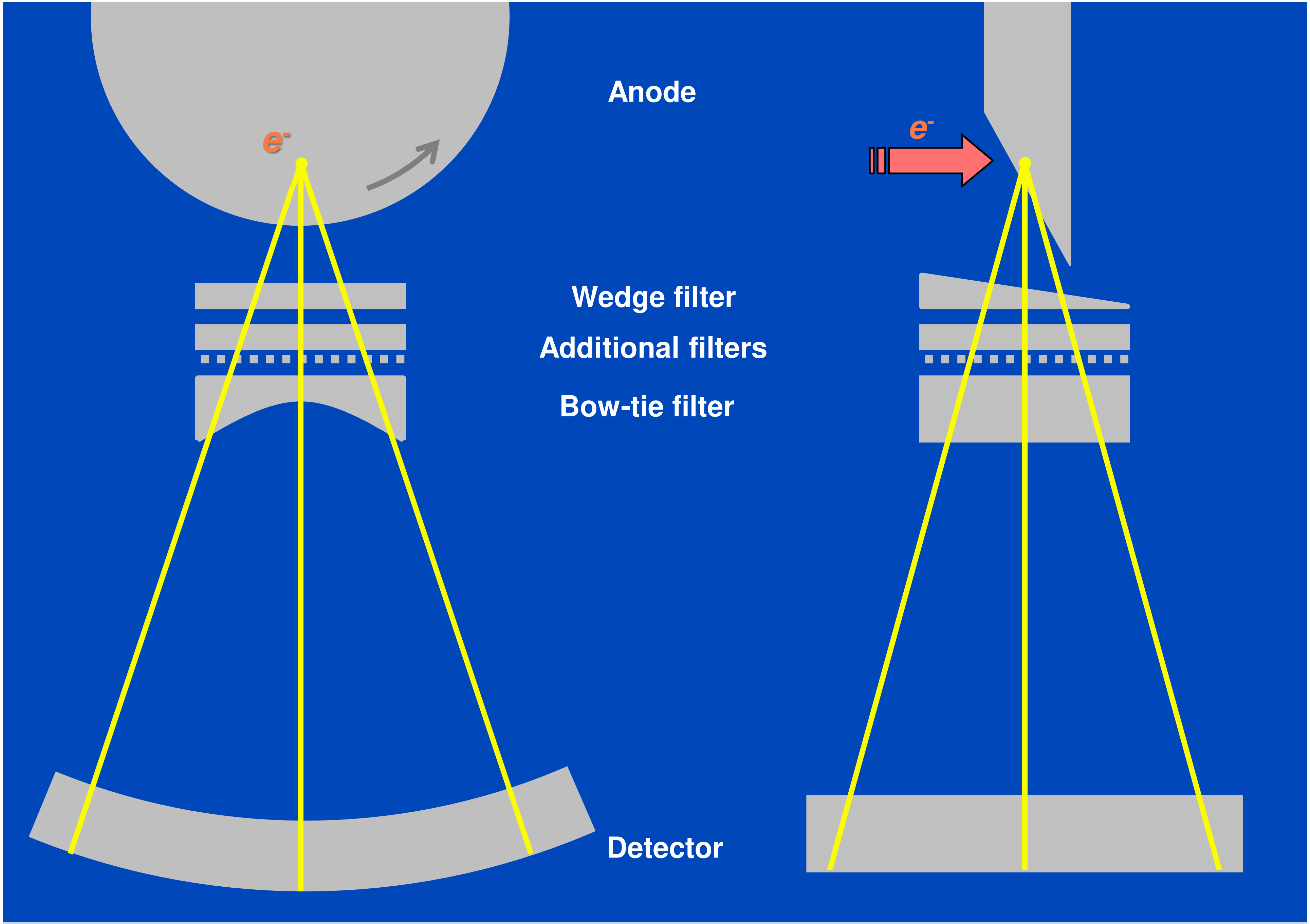
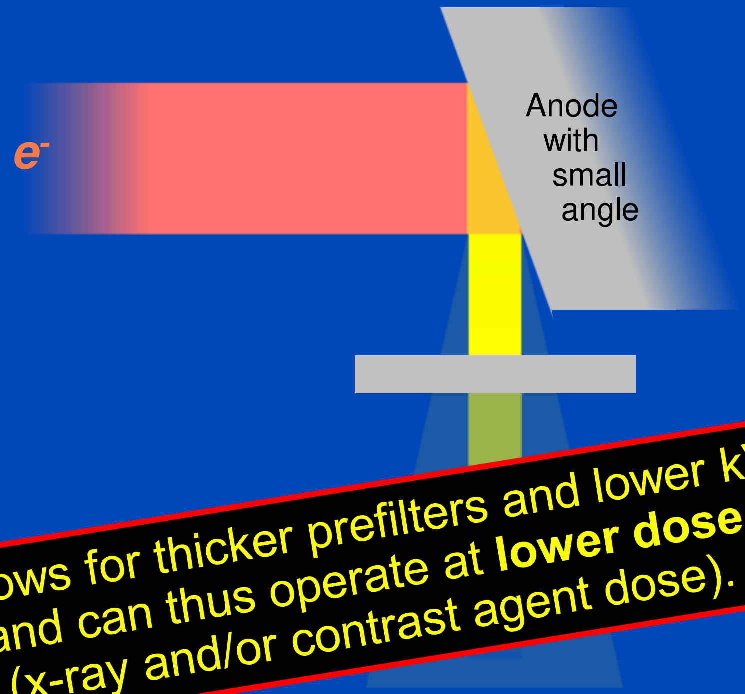
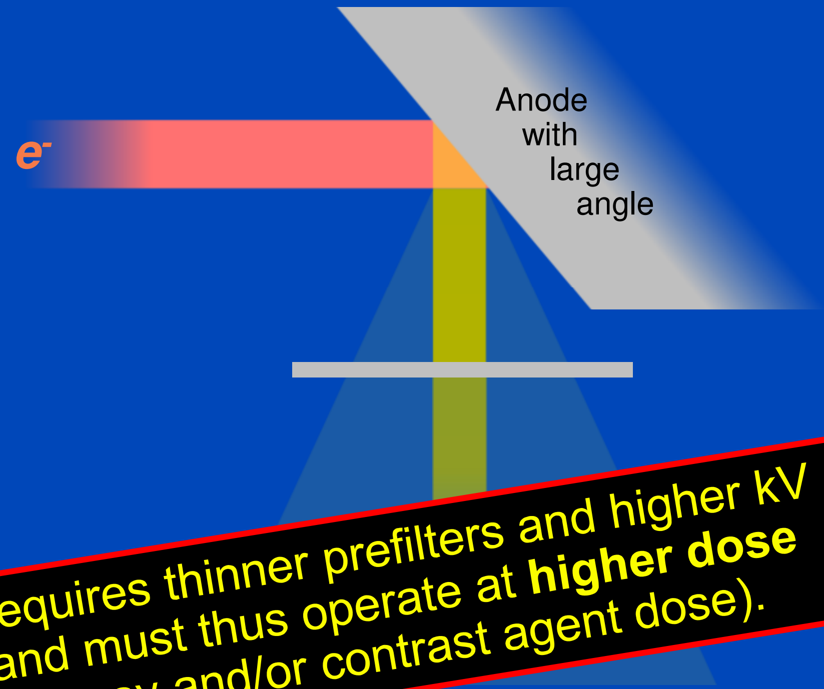


Figure not drawn to scale. Type and order of prefiltration may differ from scanner to scanner.
Depending on the selected protocol filters are changed automatically (e.g. small bowtie for pediatric scans).

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).

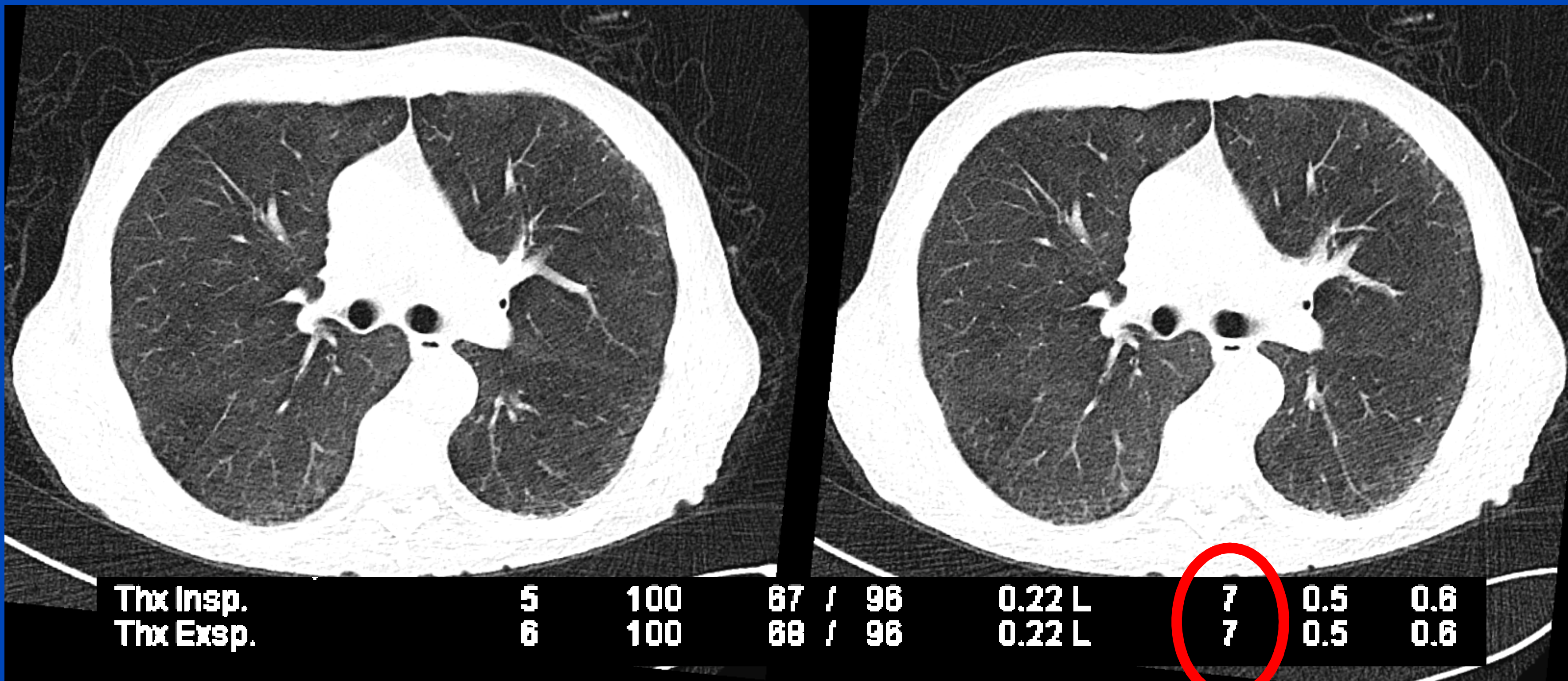
… at the same spatial resolution

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

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 (good for Iodine contrast)
- High continuous power levels (typ. > 5 kW)
- High cooling rates (typ. about 25 kW ≈ 1 MHU/min*)
- High tube current variation (low inertia)
- Must withstand centrifugal forces
  - 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: $a = 55\,g$
- Two focal spot sizes
- Compact and robust design
- Long service intervals
  - Ball bearings cannot be lubricated and wear out early
  - Liquid bearings to be preferred (also due to good heat conduction)

* 1 MHU = $\sqrt{2}$ MJ

Tube Technology

conventional tube
(rotating anode, helical wire emitter)

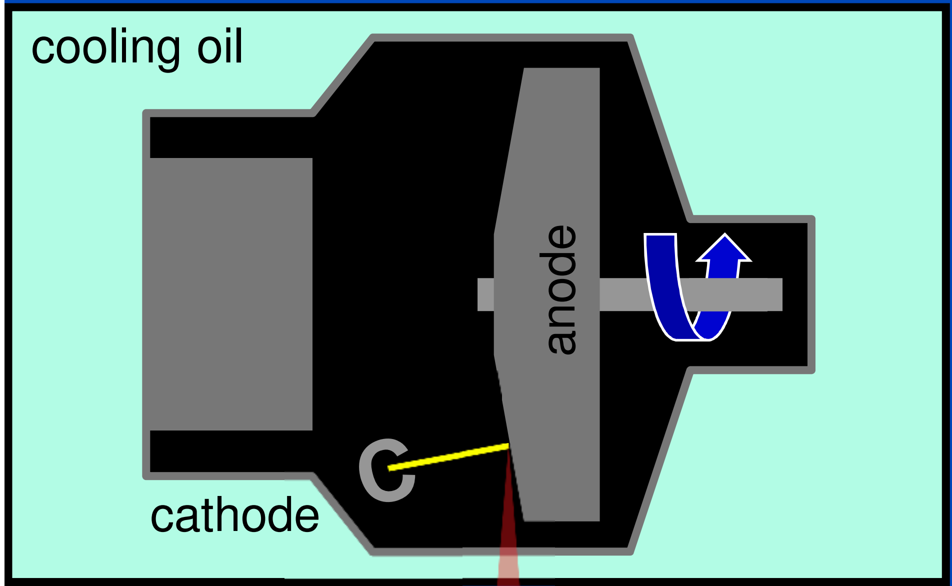


Photo courtesy of GE

Anode at high temperature ($\gg$ 1000 °C)

Radiative cooling ($\propto T^4$) is dominant

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

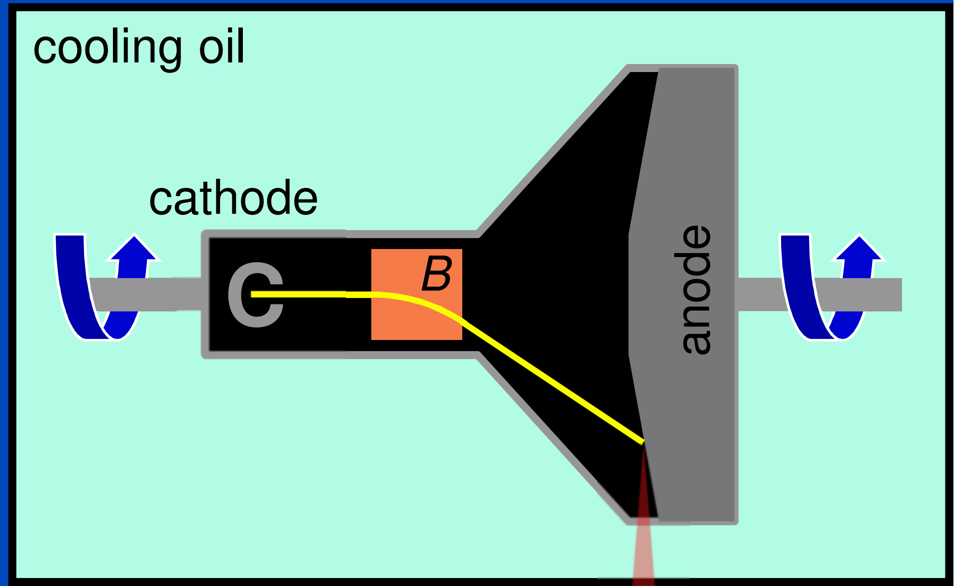
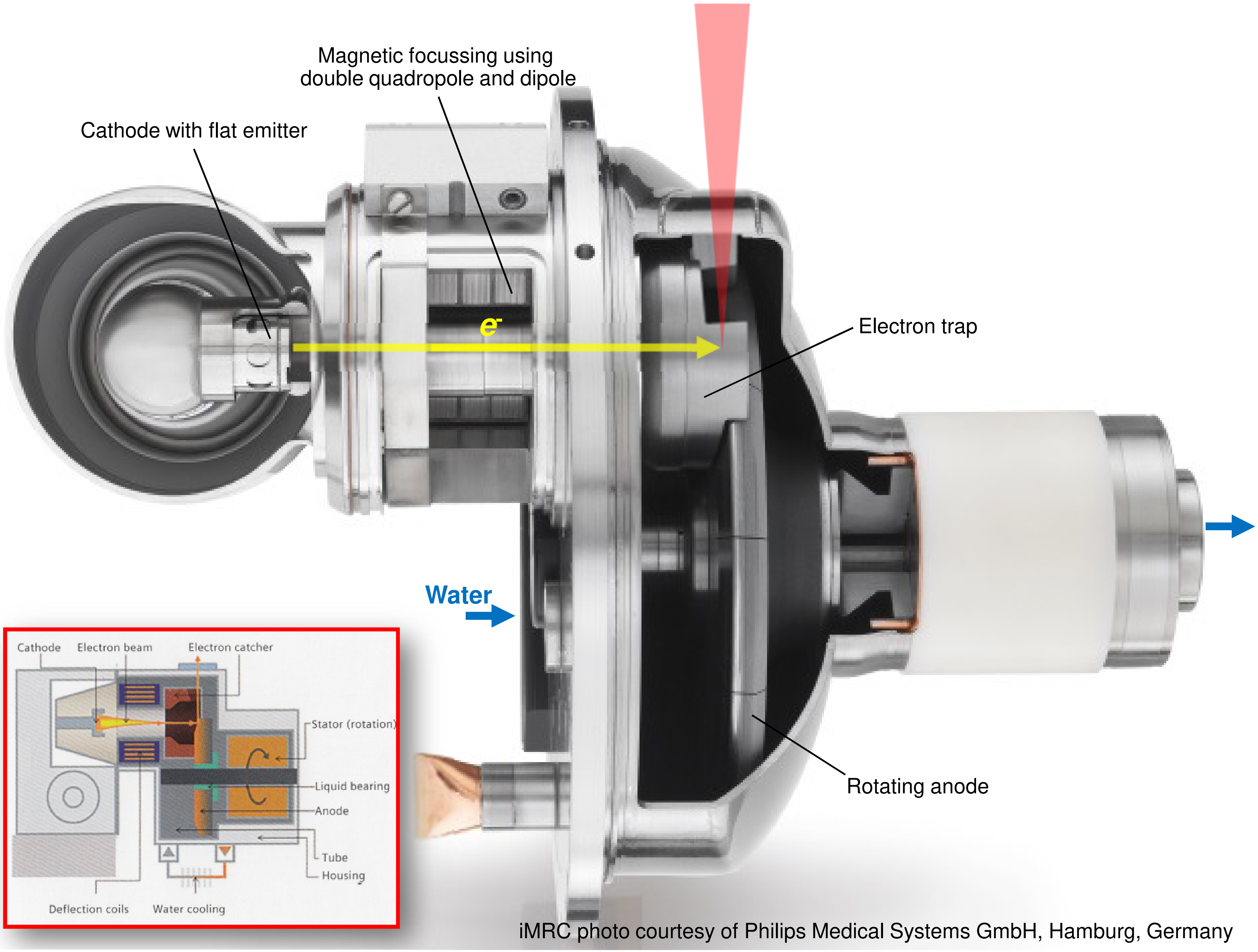


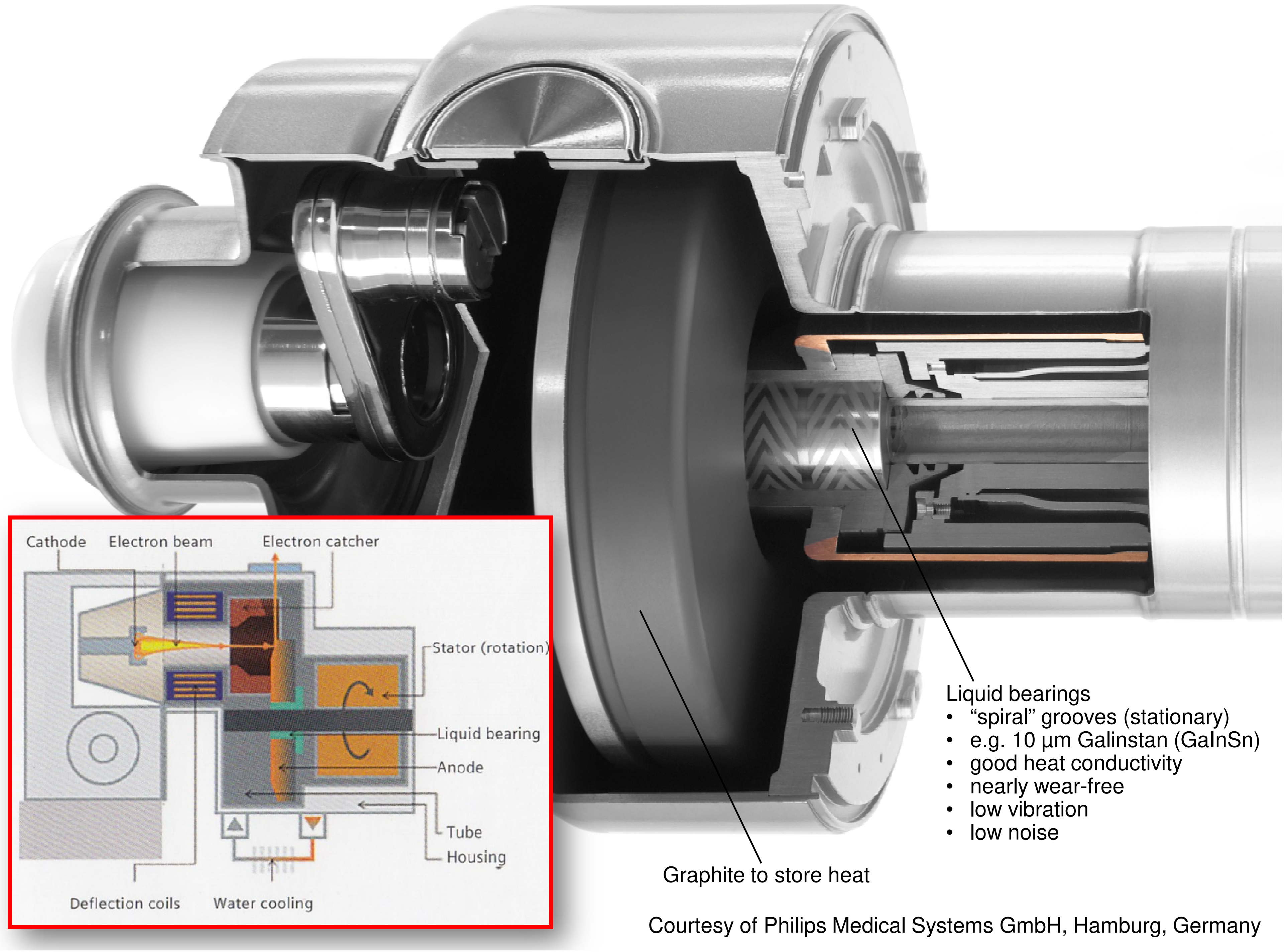
Photo courtesy of Siemens

Anode at low temperature ($\ll$ 1000 °C)

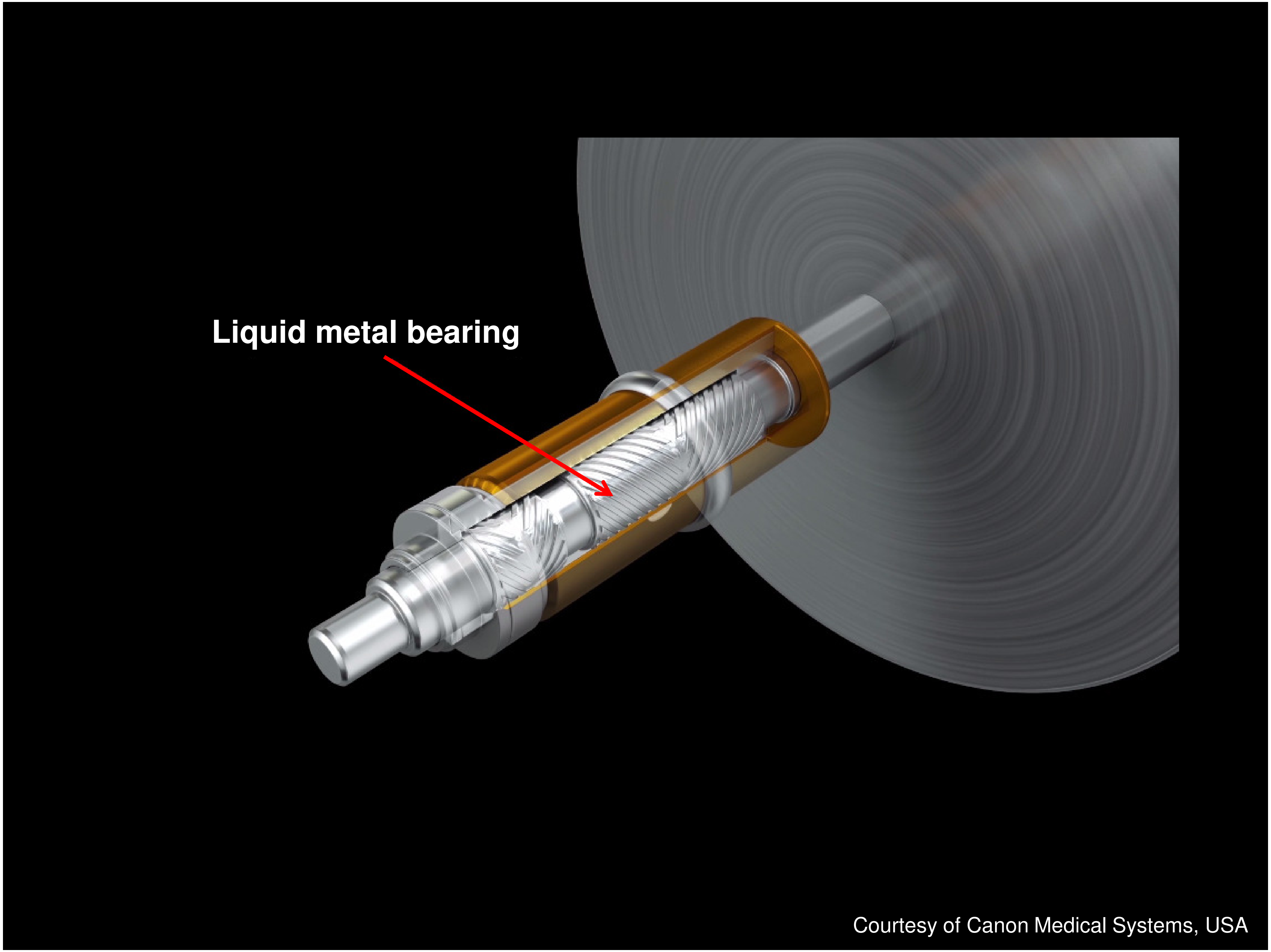
Conductive cooling ($\propto T$) is dominant



iMRC photo courtesy of Philips Medical Systems GmbH, Hamburg, Germany



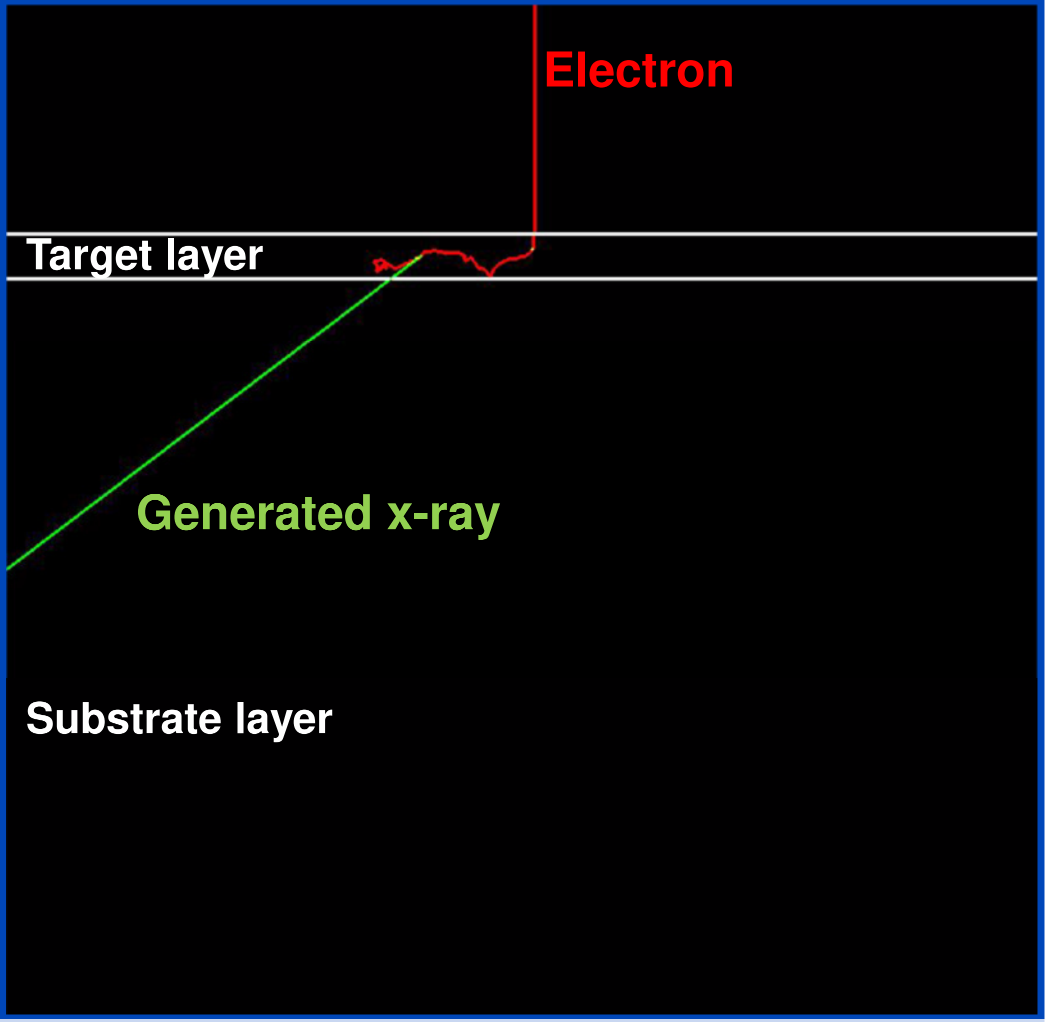
Courtesy of Philips Medical Systems GmbH, Hamburg, Germany



Courtesy of Canon Medical Systems, USA

Estimation of the X-Ray Spectrum

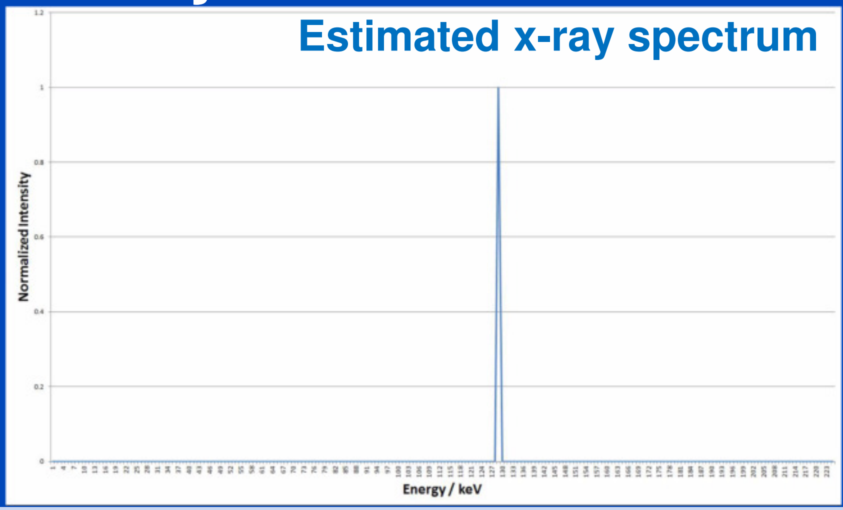
- Monte-Carlo simulation of single electron tracks through target[1]
- Target configuration of the industrial CT system

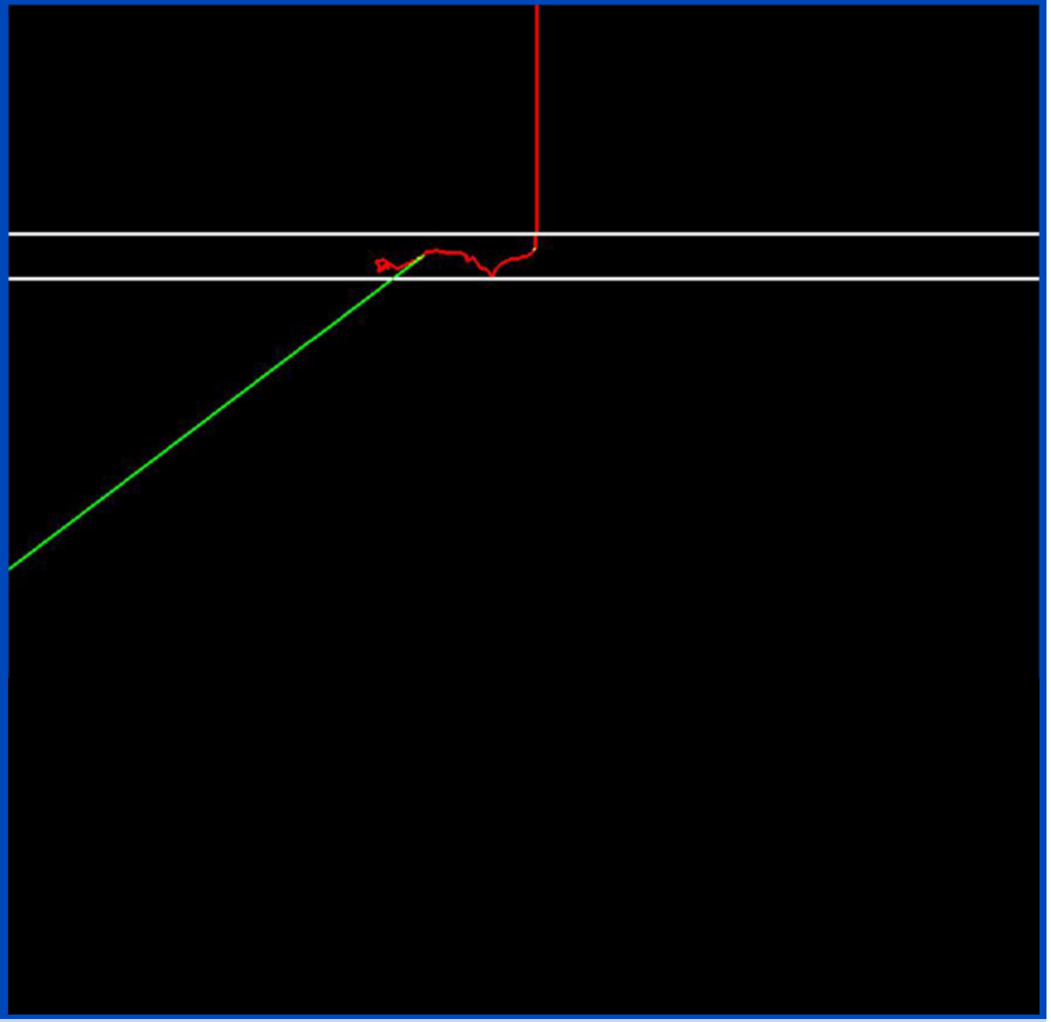


[1]S. Agostinelli et al, "Geant4—a simulation toolkit", Nucl. Instrum. Meth. A. 506(3), 250-303 (2003)

Estimation of the X-Ray Spectrum

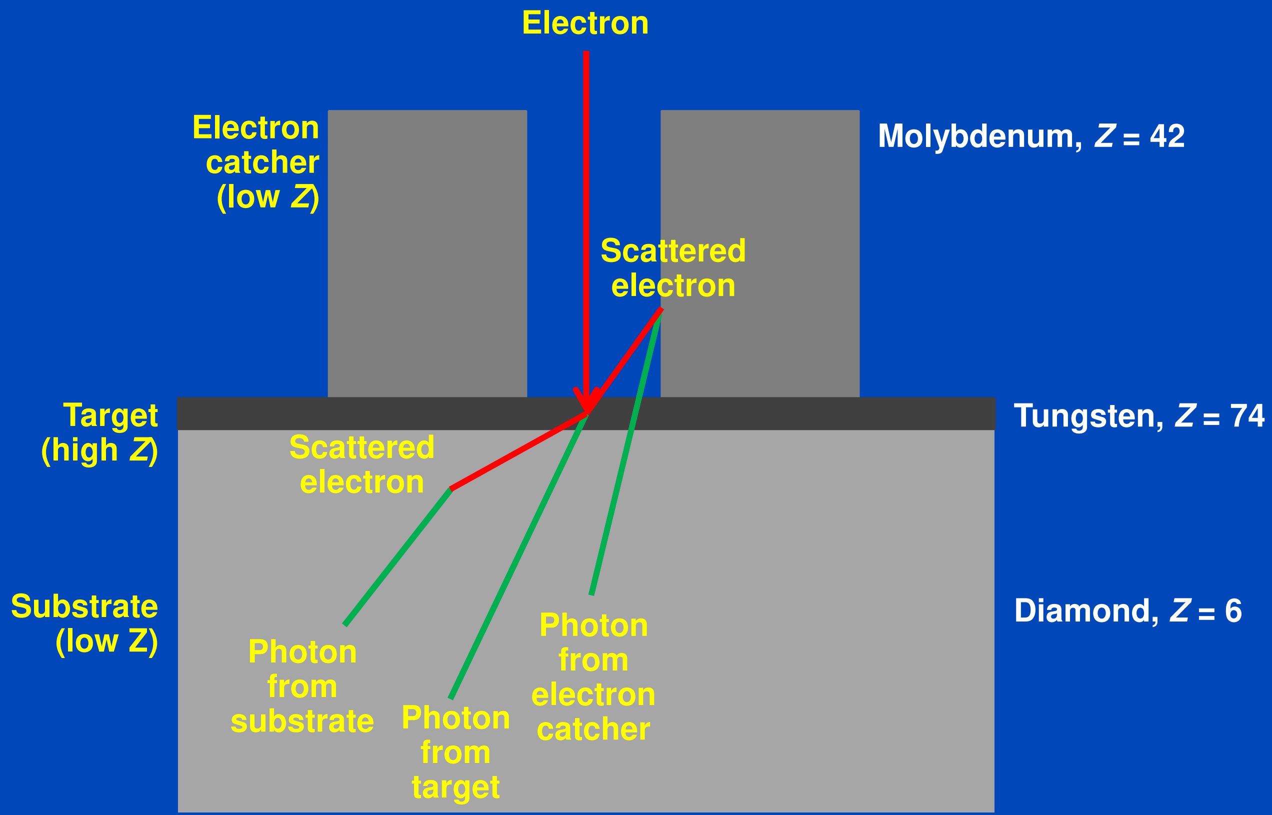
- Monte-Carlo simulation of single electron tracks through target[1]
- Target configuration of the industrial CT system

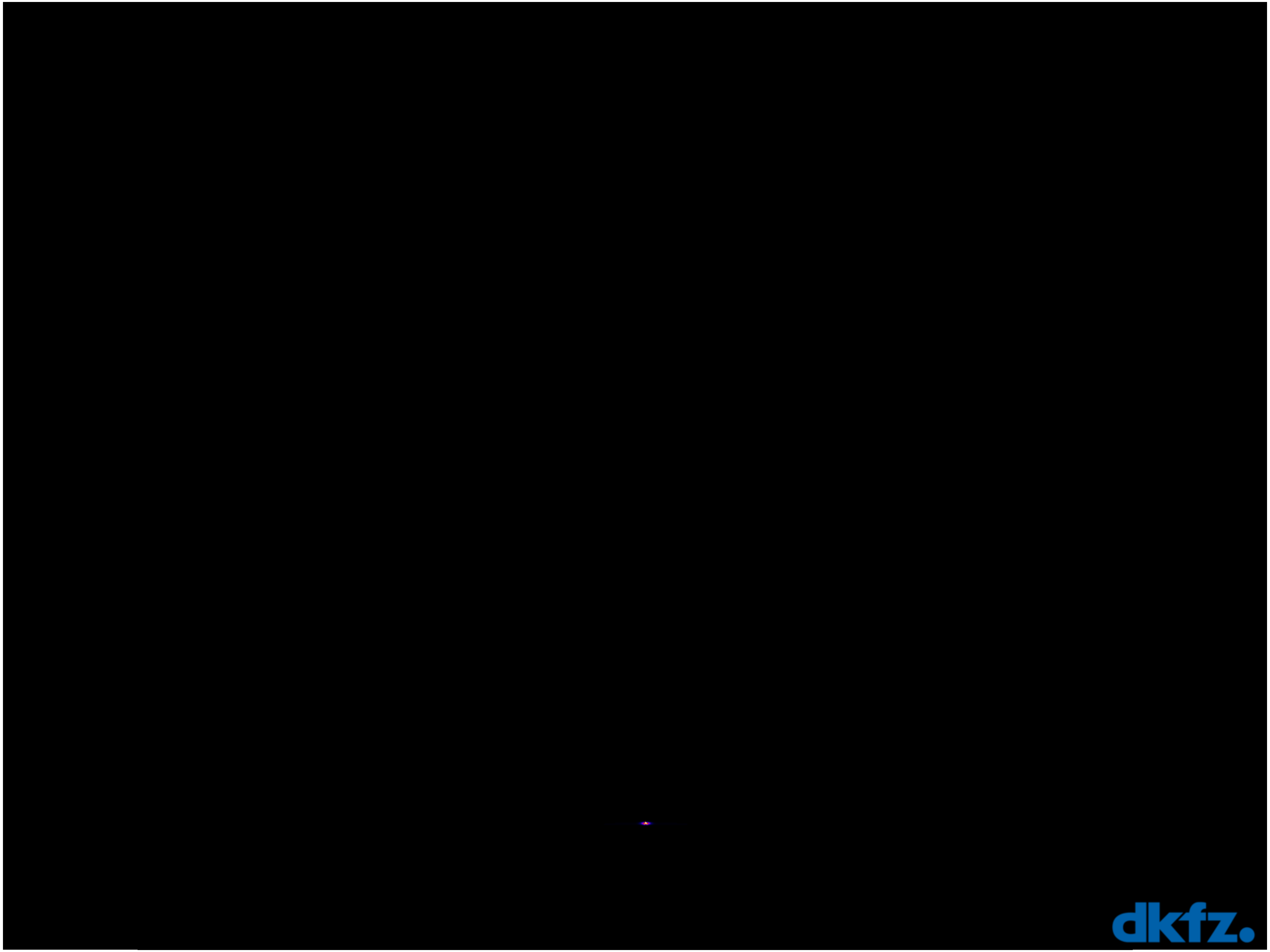


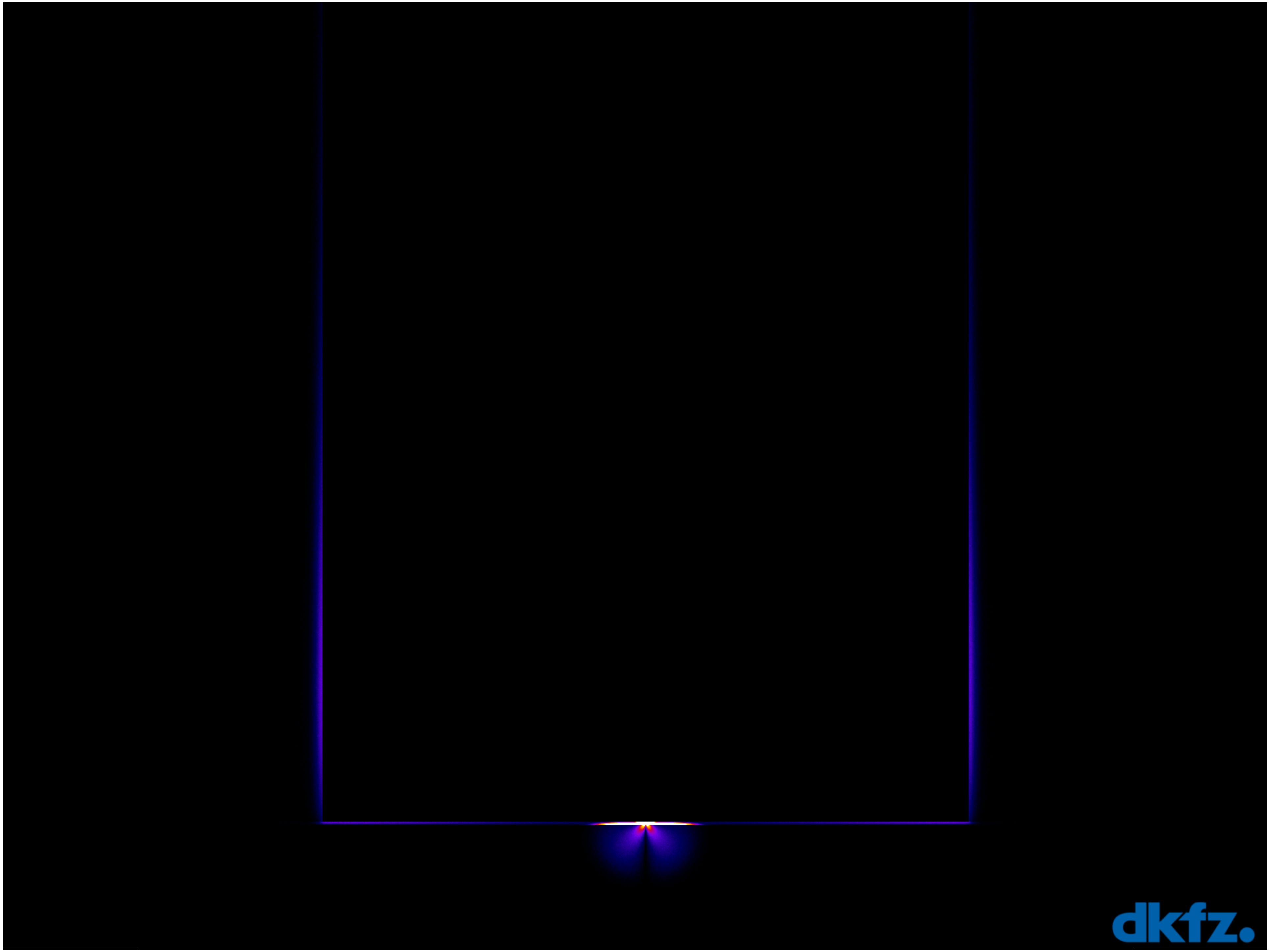


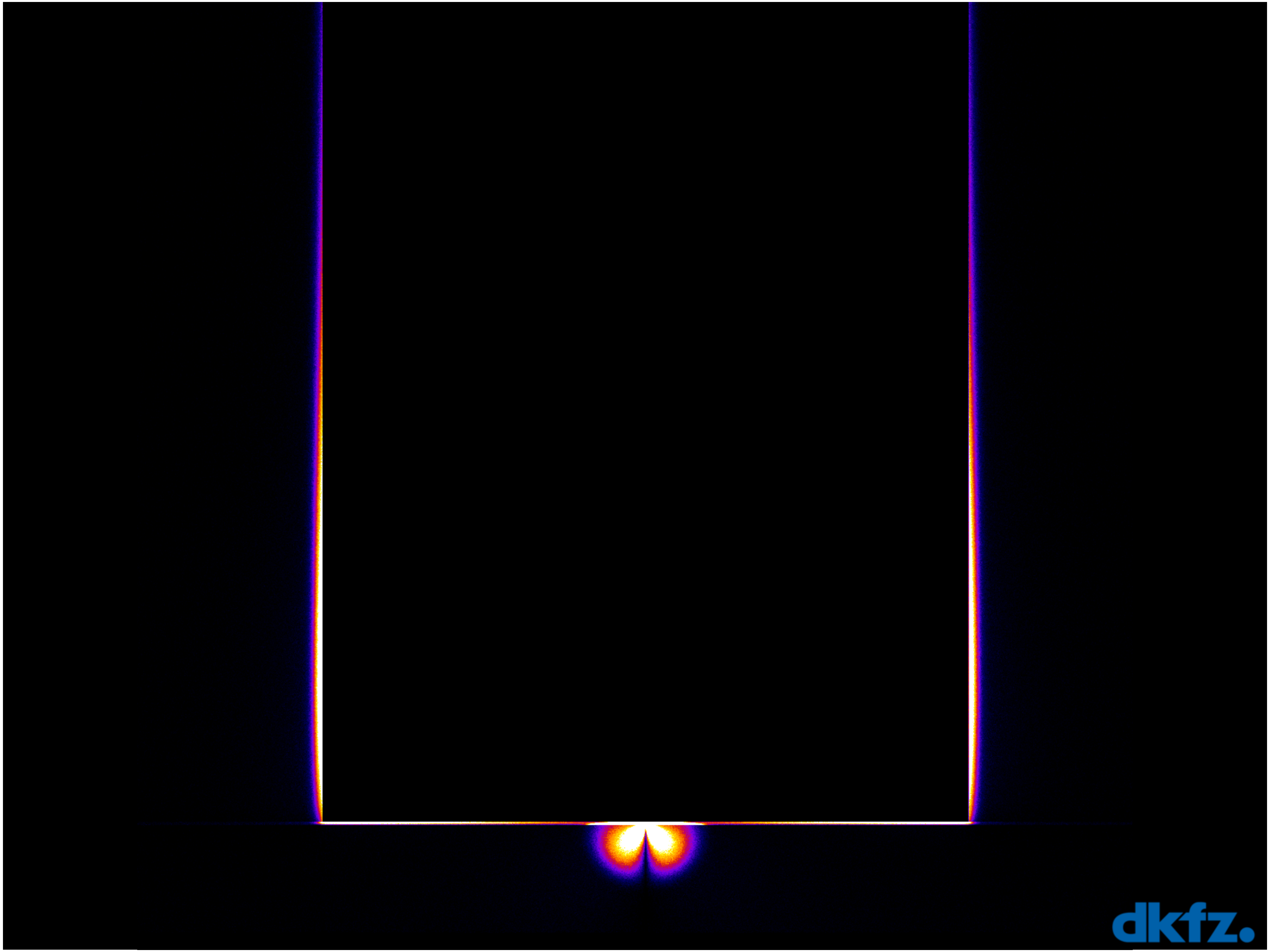
Geant4 Monte Carlo computation time: O(1 day)

Estimation of Off-Focal Radiation by MC Simulation of the X-Ray Tube

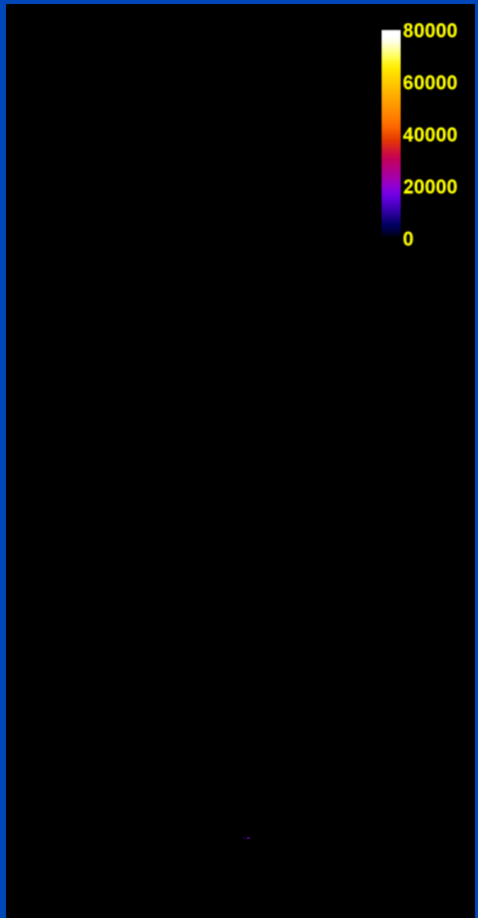


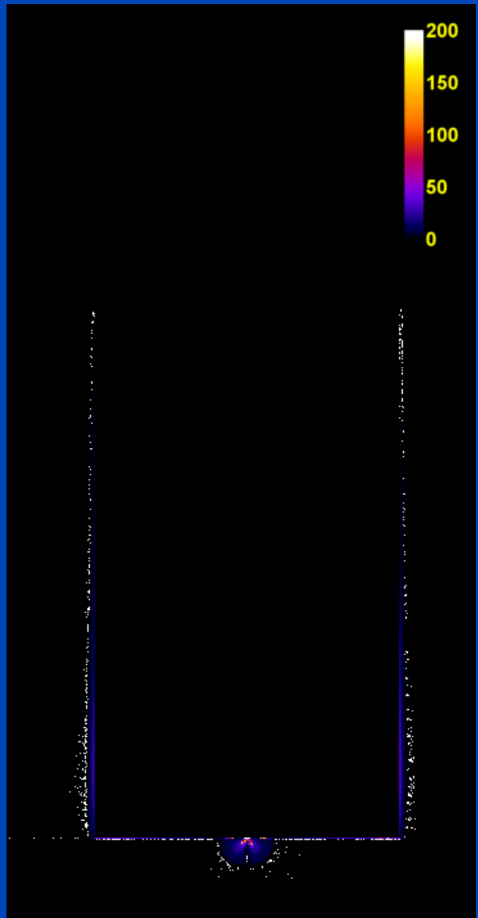


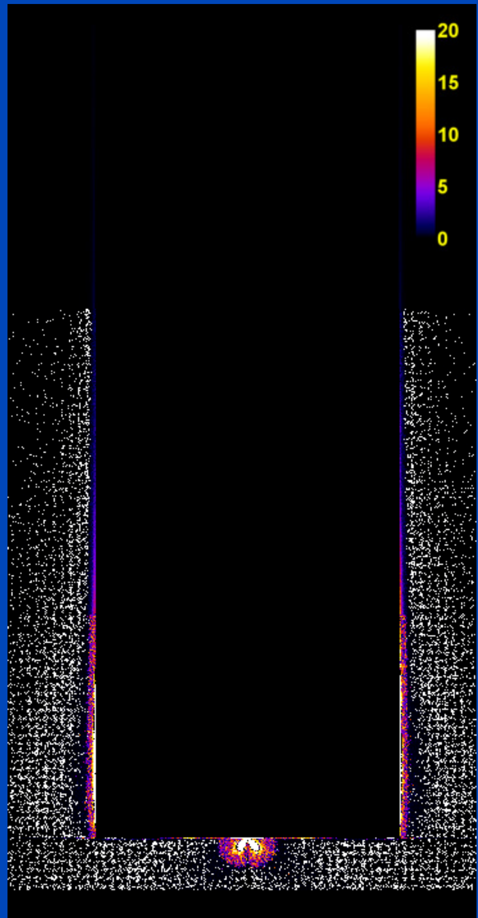




Off-Focal Radiation of a Micro Focus Transmission Source

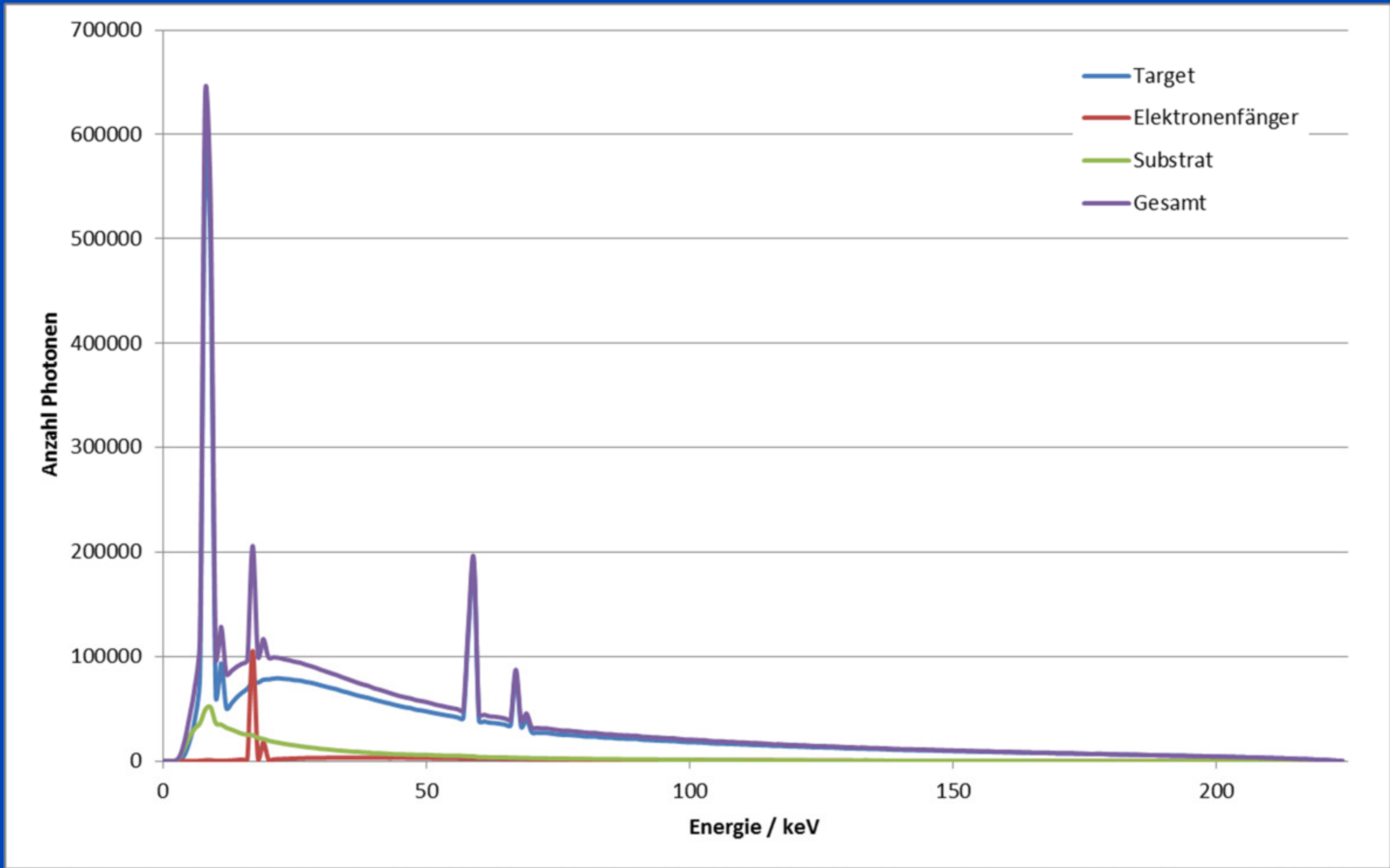


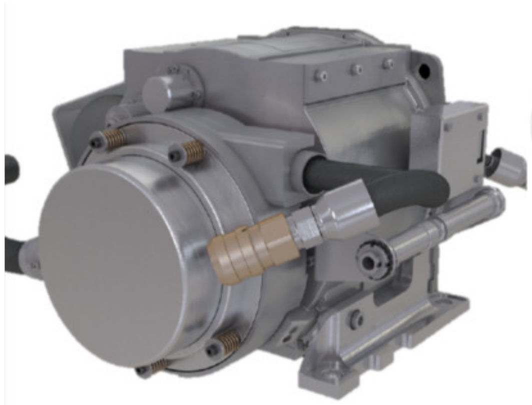




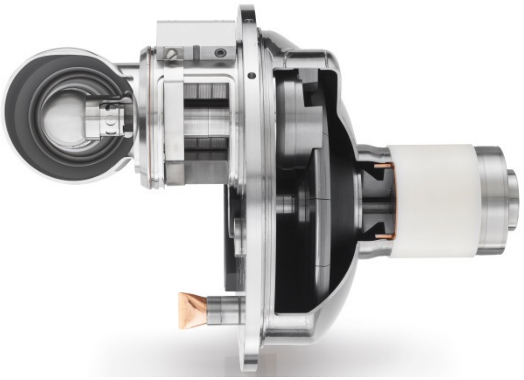
The three images are identical up to their window center and width. We simulated a needle beam of electrons.

Spectral Distribution of On- and Off-Focal Radiation



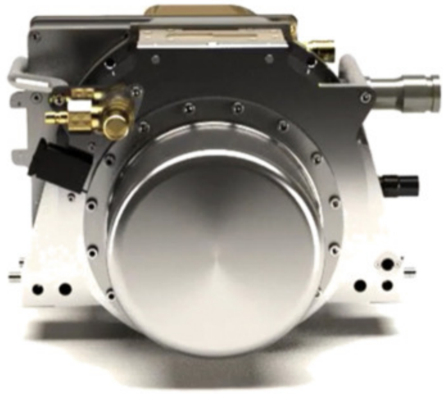


Performix HDw (GE)



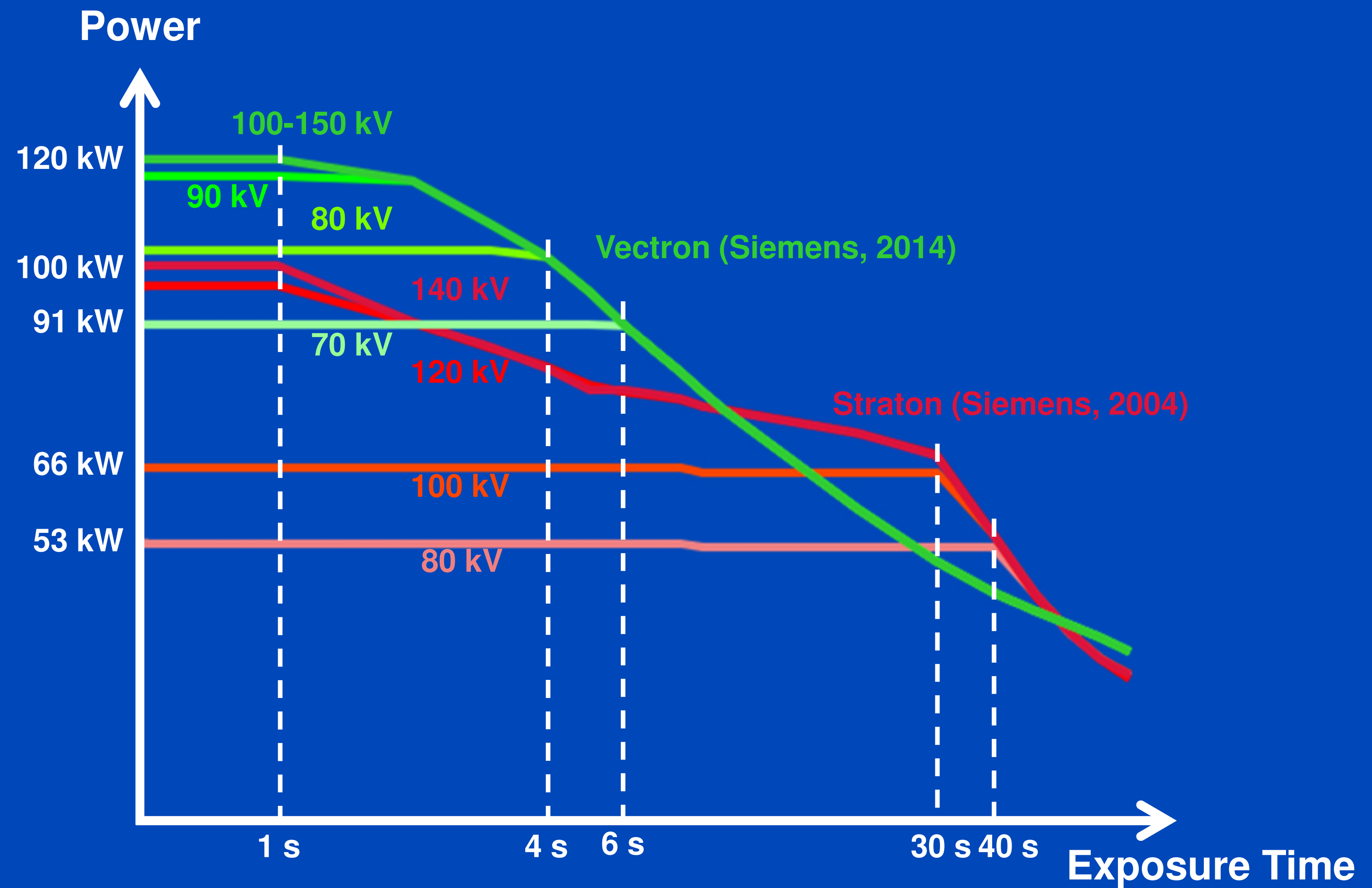
iMRC (Philips)

Straton (Siemens)

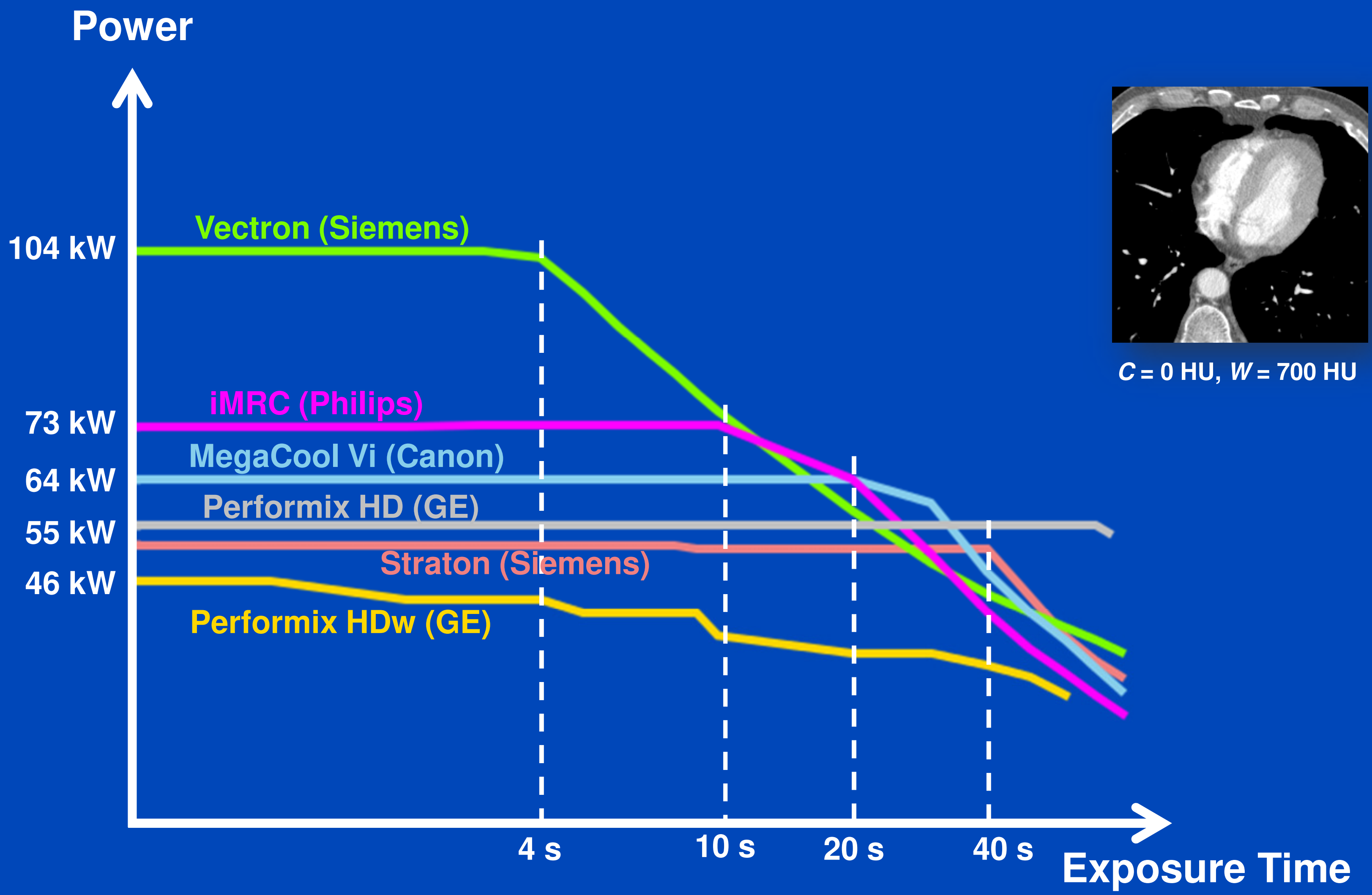


Vectron (Siemens)

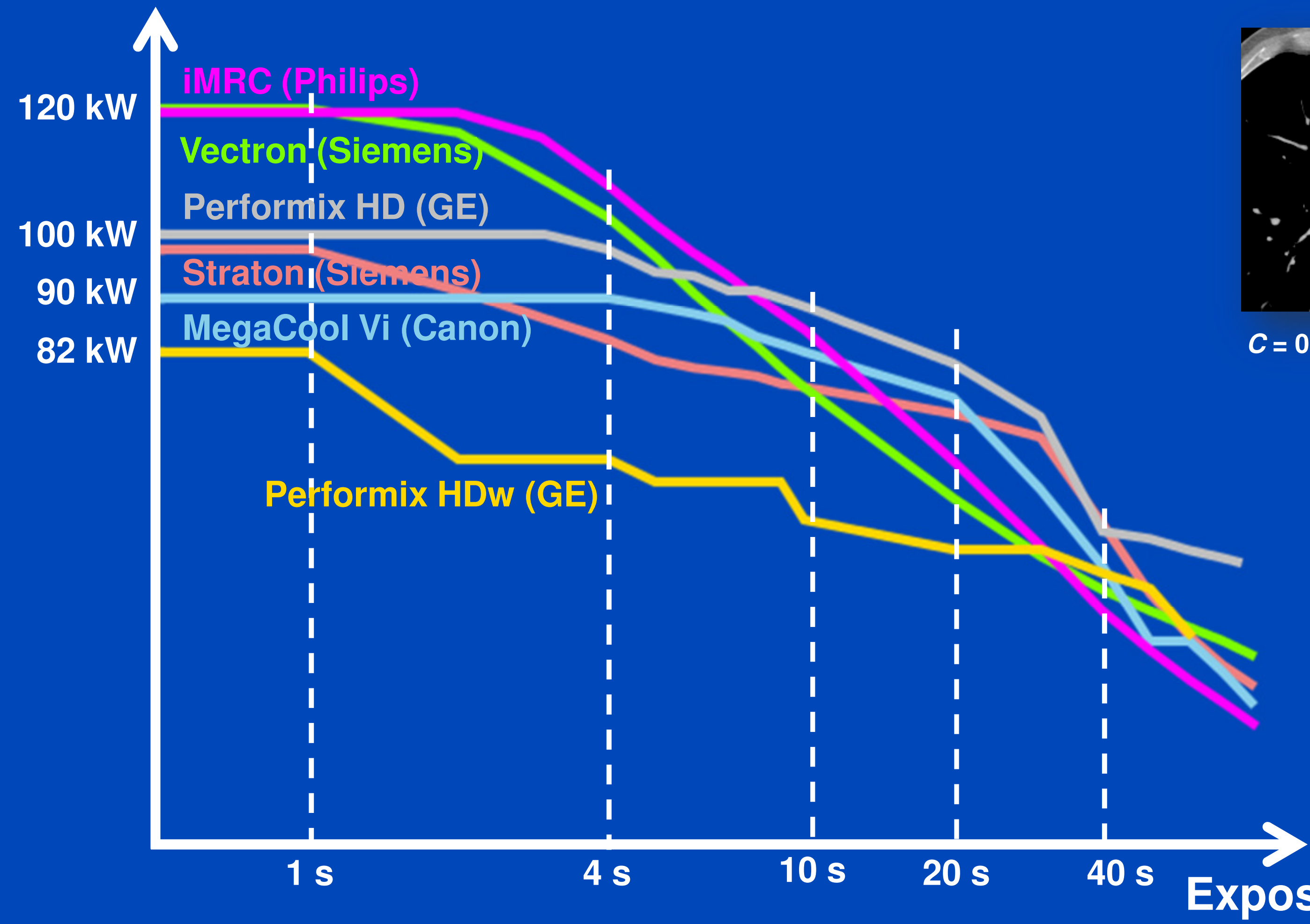
Straton vs. Vectron at all kV

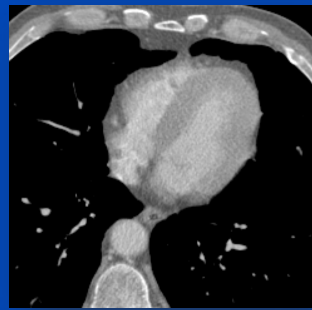


Tube Voltage 80 kV



Tube Voltage 120 kV

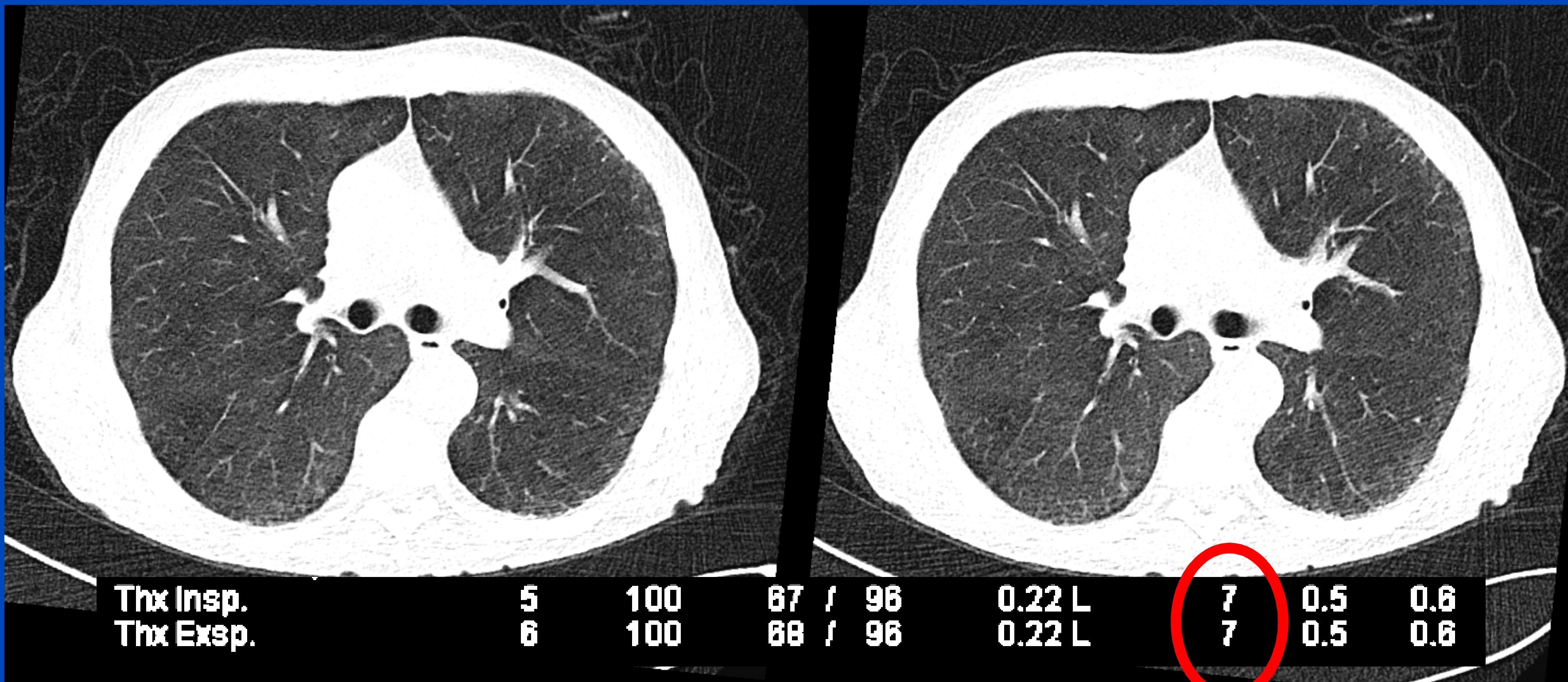




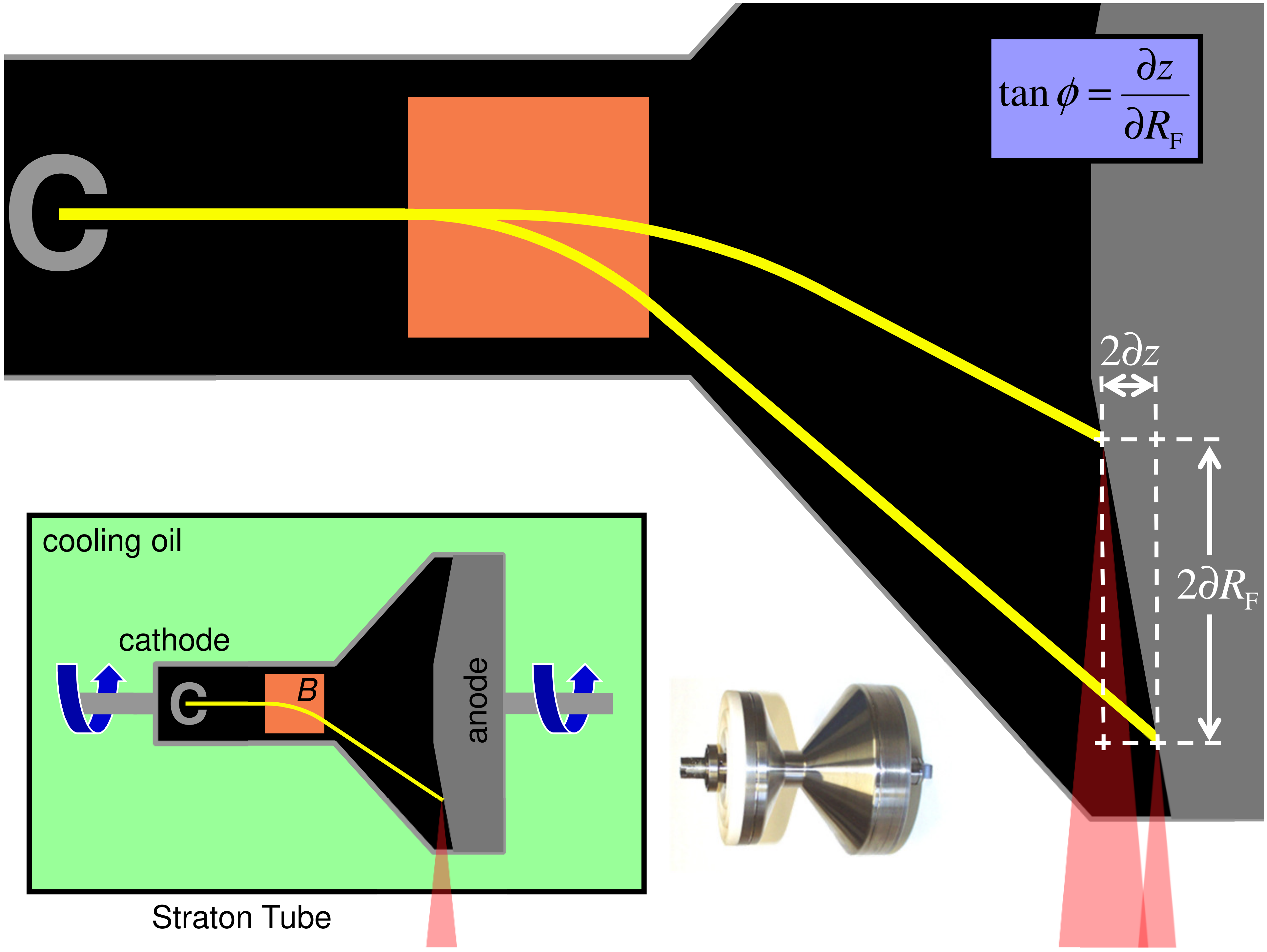
C = 0 HU, W = 700 HU

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



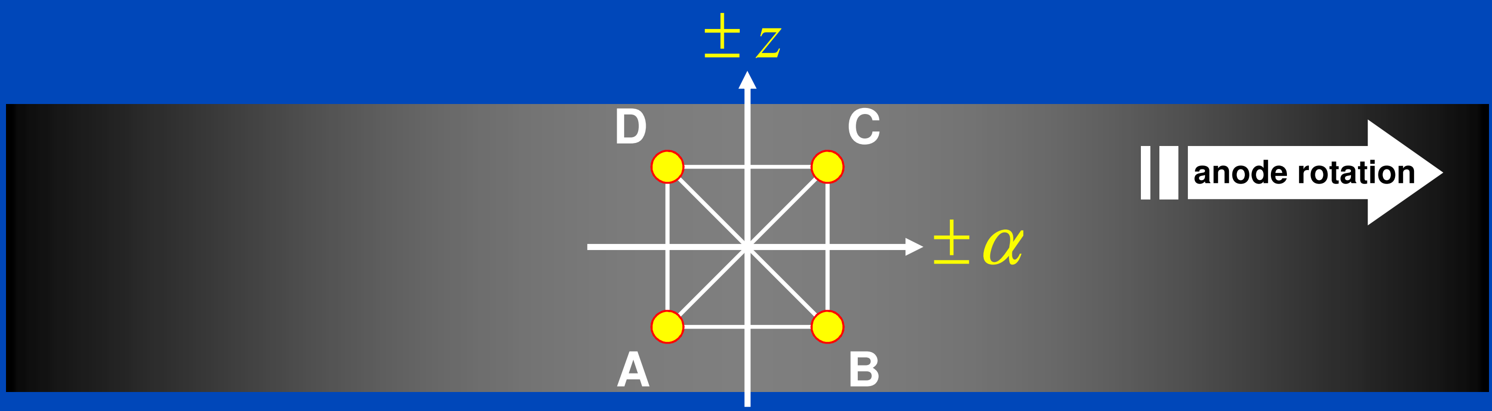
Courtesy of University Hospital Mannheim



$\tan\phi = \frac{\partial z}{\partial R_F}$
$2\partial z$
$2\partial R_F$
cooling oil
cathode
B
anode
Straton Tube

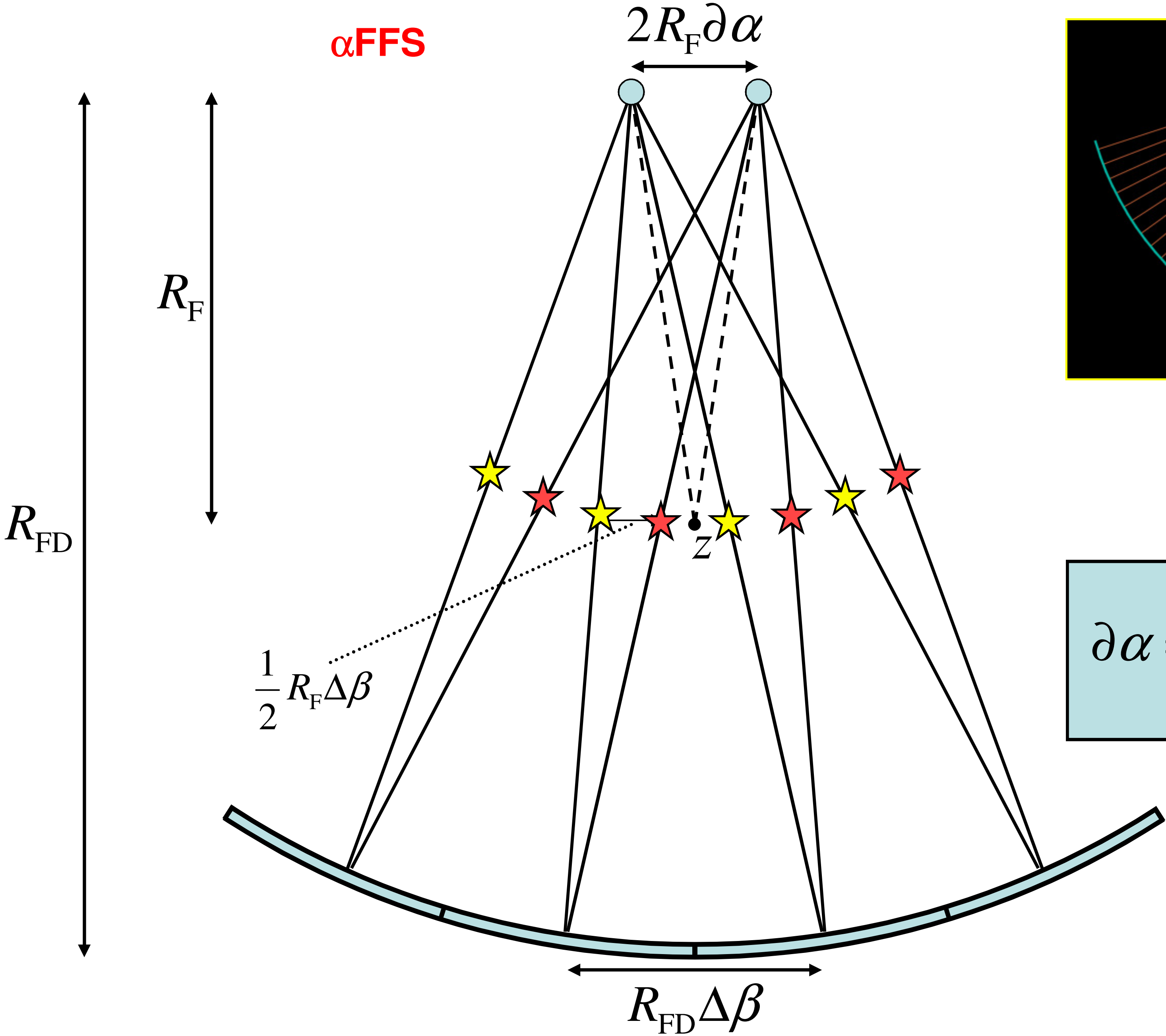
αFFS and zFFS

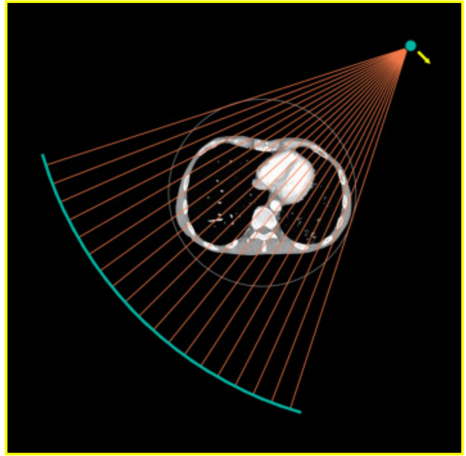
- The flying focal spot (FFS) can be used to improve the in-plane (lateral) sampling as well as the through-plane (longitudinal) sampling.



Anode as viewed from the isocenter

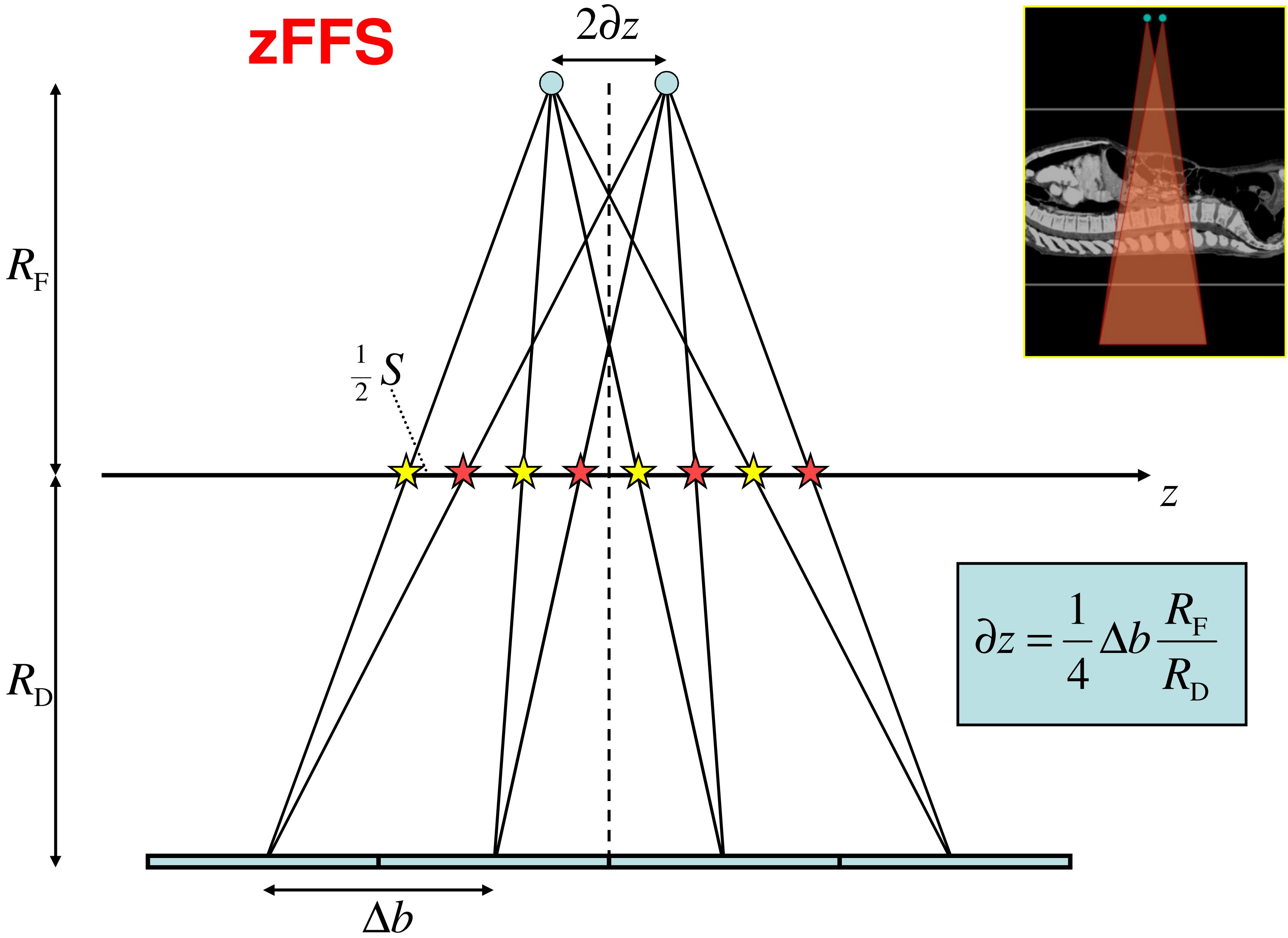
αFFS





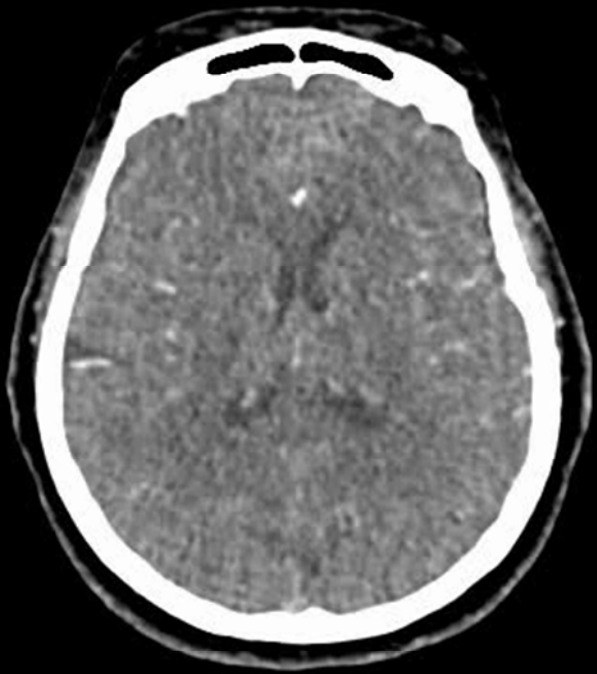
$$\partial\alpha = \frac{1}{4}\Delta\beta\frac{R_{FD}}{R_D}$$

zFFS

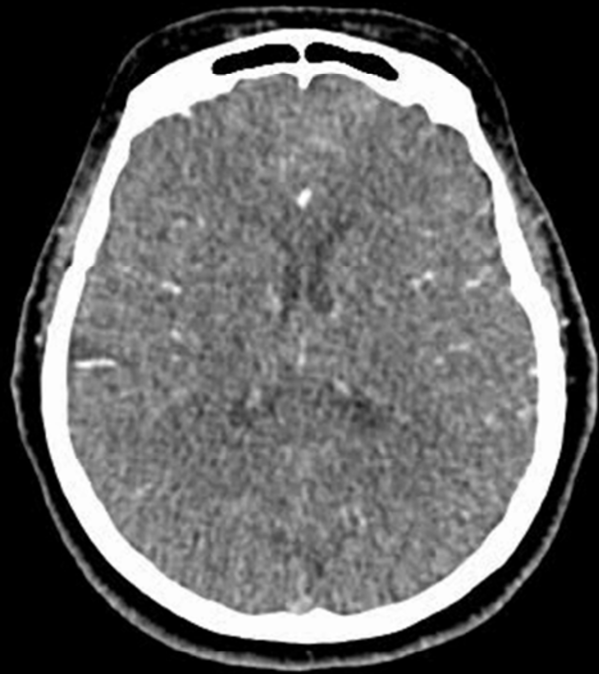


$$\partial z = \frac{1}{4}\Delta b \frac{R_F}{R_D}$$

Windmill Artifacts and their Removal



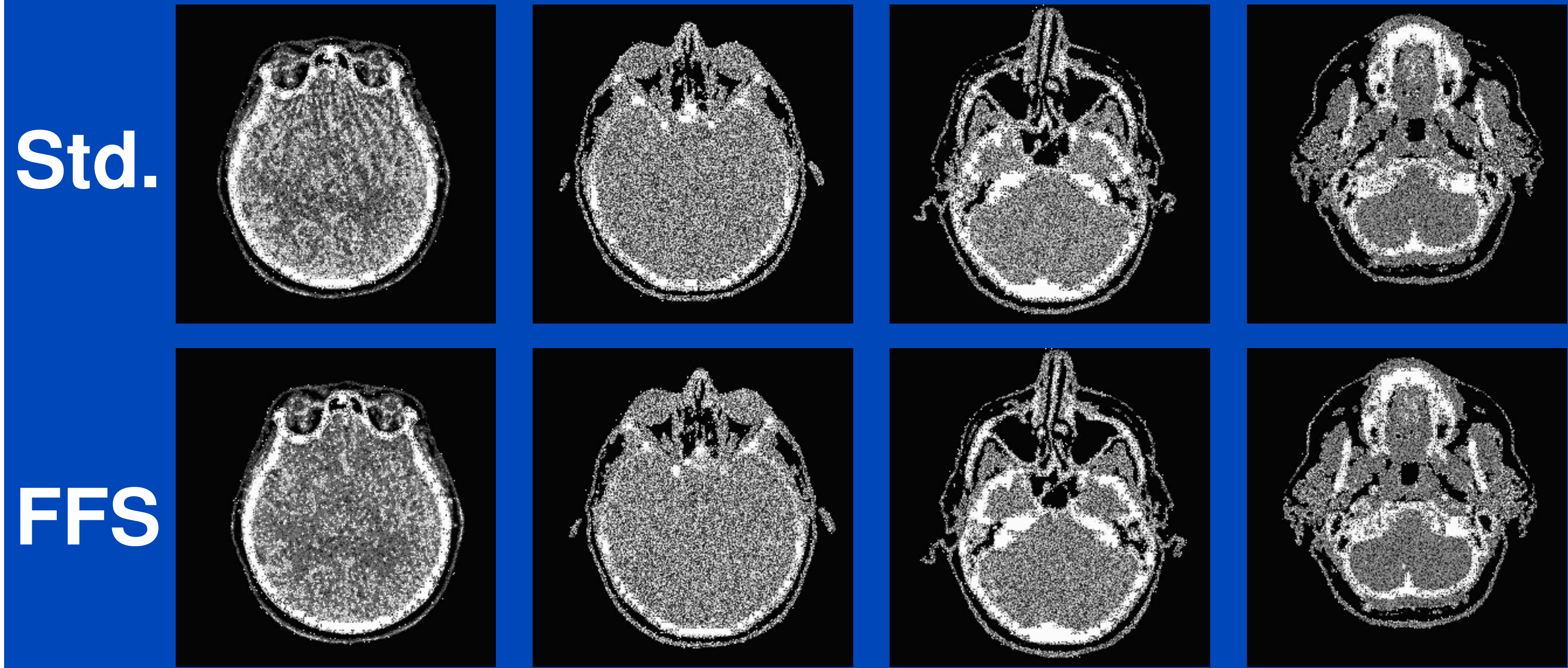
Standard (no FFS)

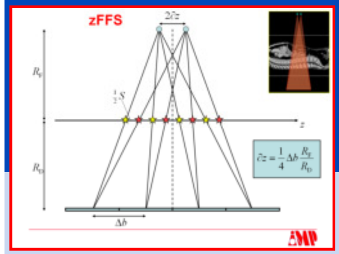


Double z-Sampling (zFFS)

ASSR reconstruction, p = 1.0, (C = 0 HU, W = 200 HU)

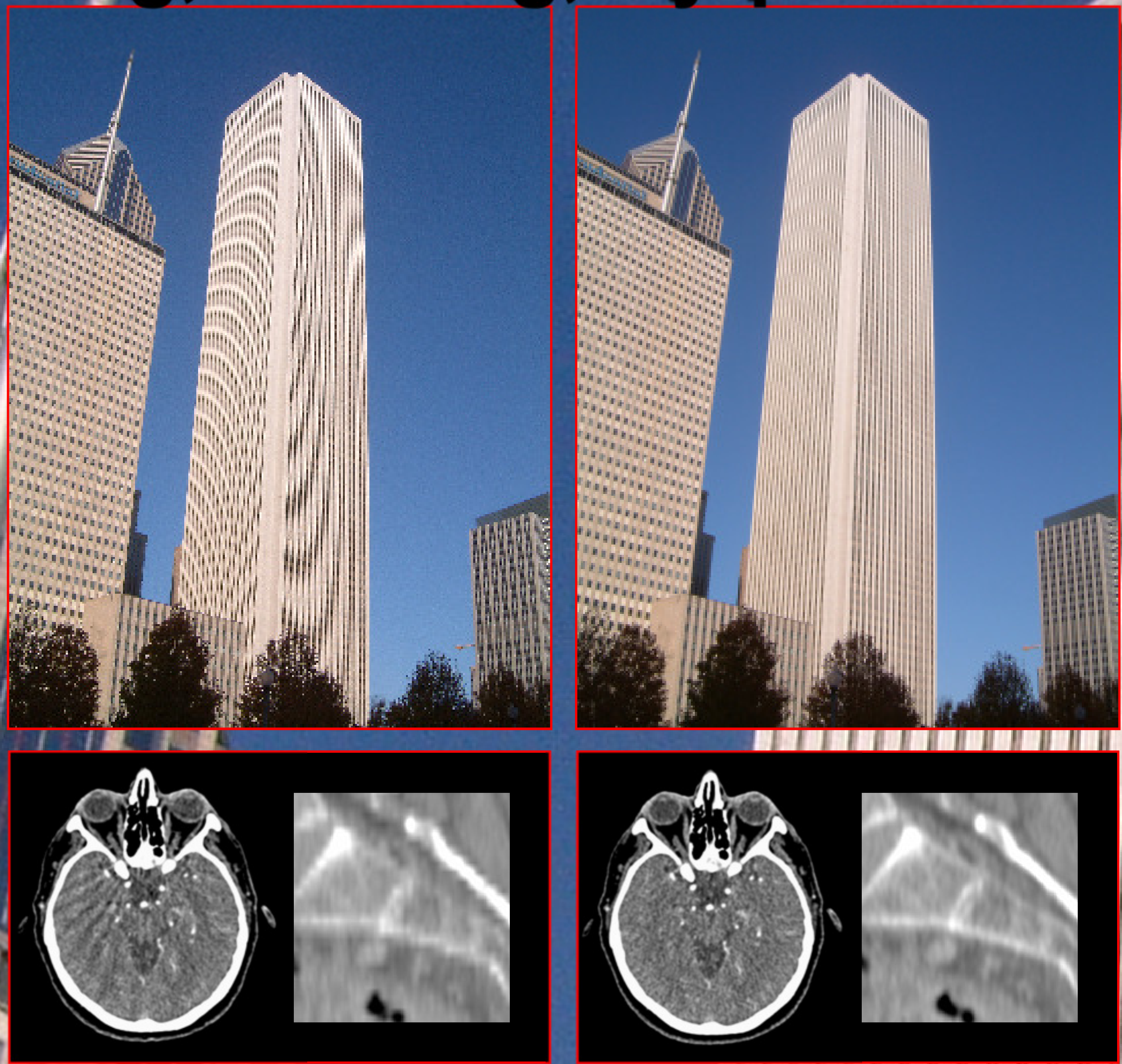
Sampling Effects during Acquisition





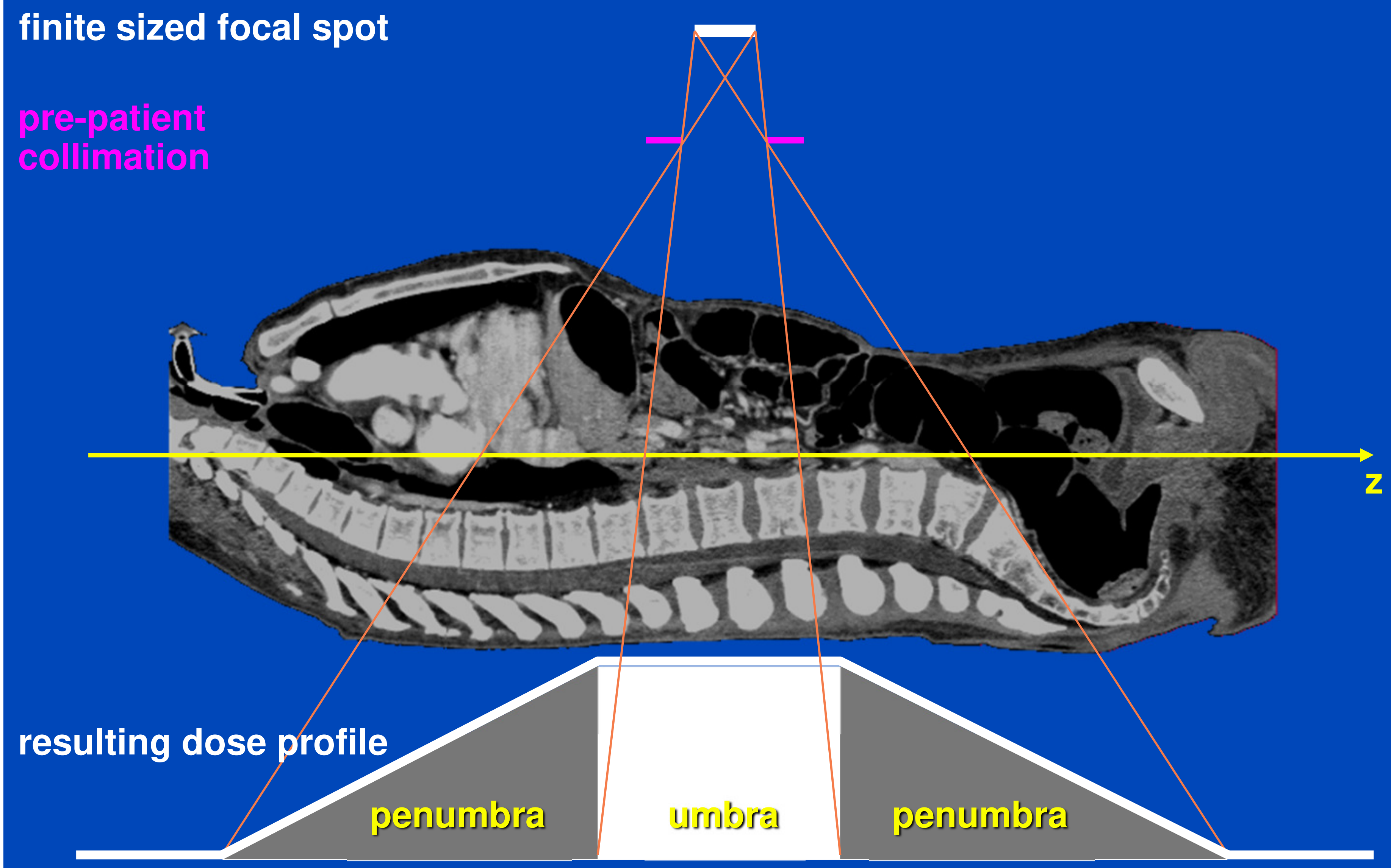
Kyriakou, Kachelrieß, Knaup, Krause, Kalender. European Radiology, 2006.

Sampling, Aliasing, Nyquist-Condition

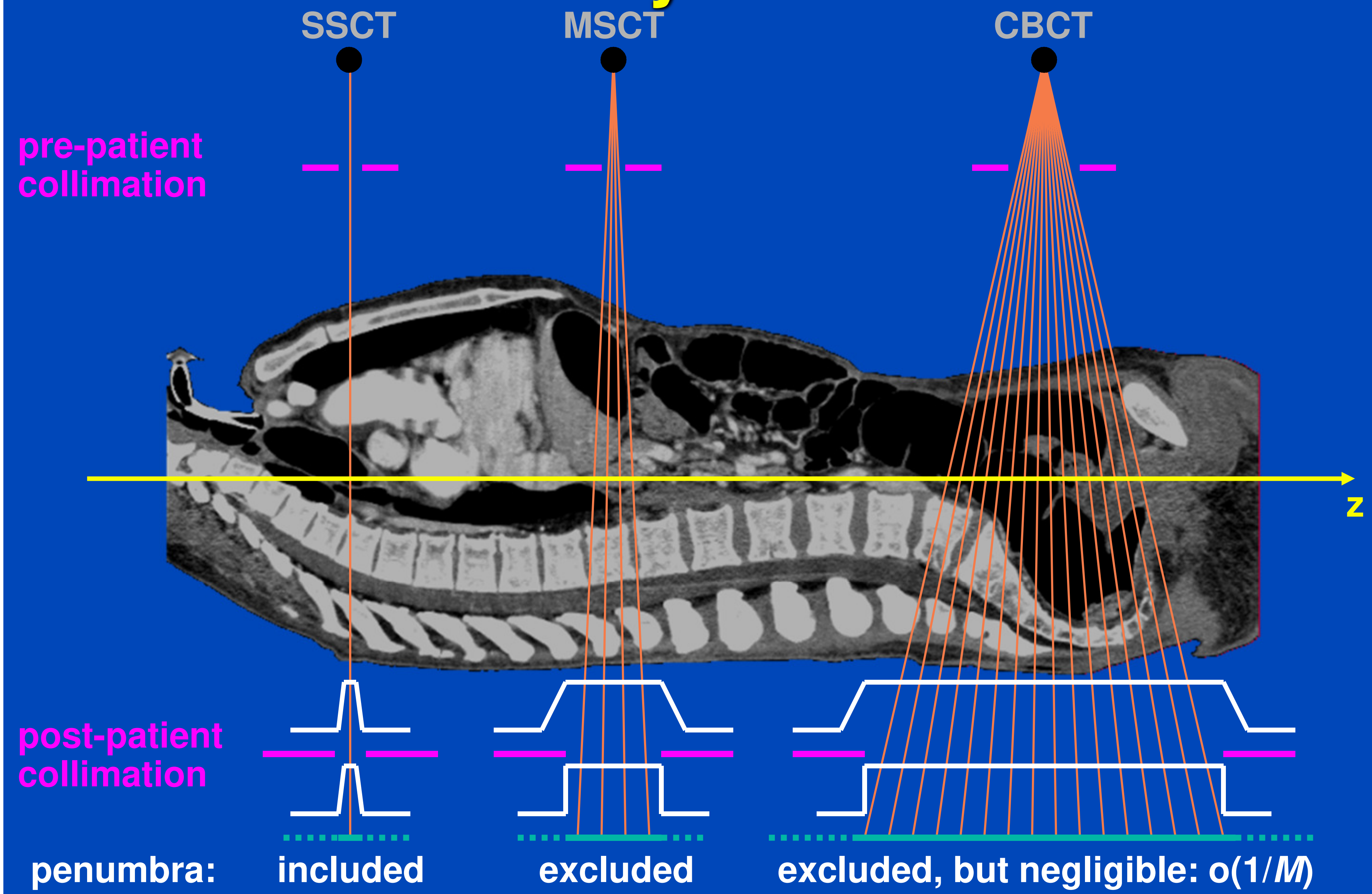


Edward Durell Stone, Amoco building, Chicago, 1973

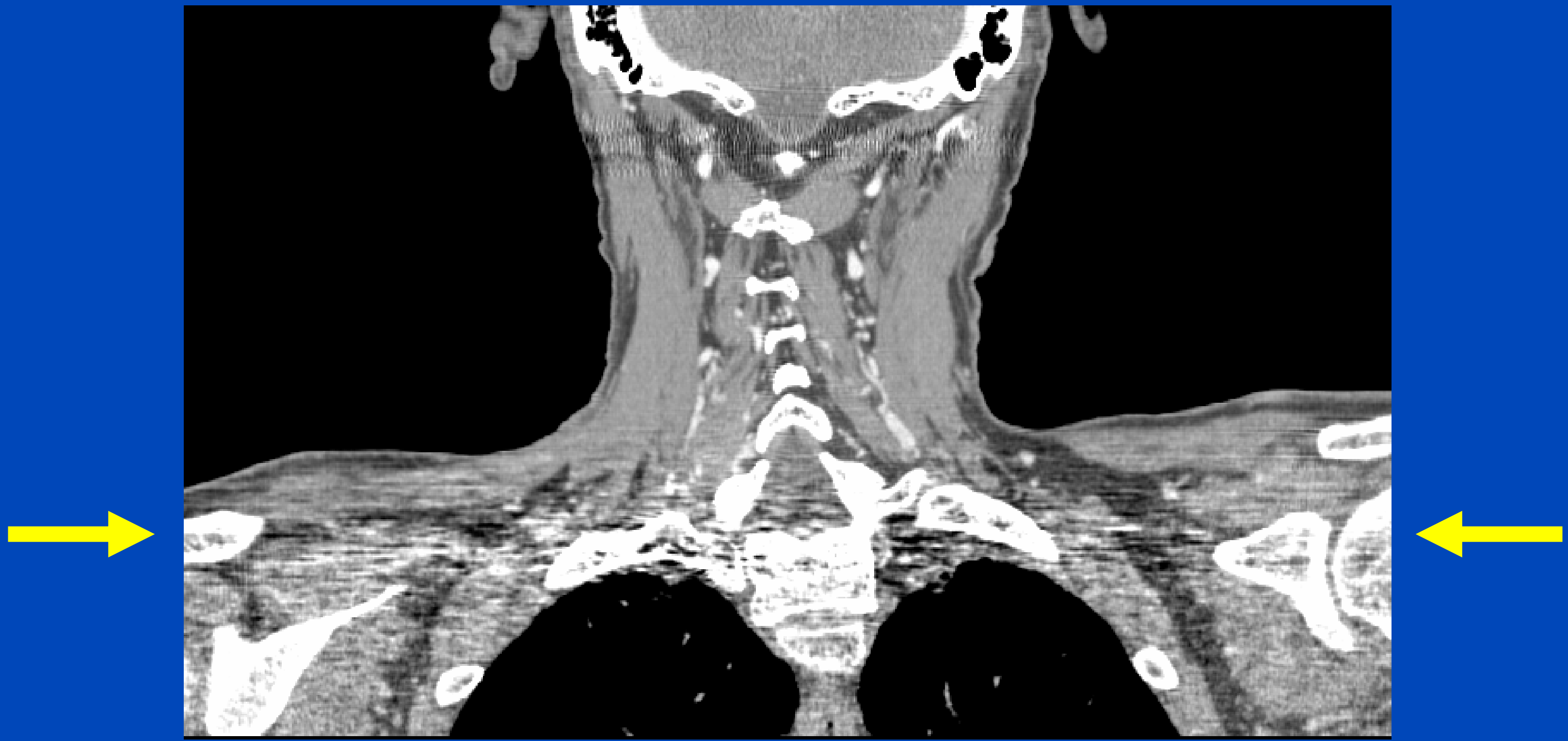
Dose Profile: Penumbra



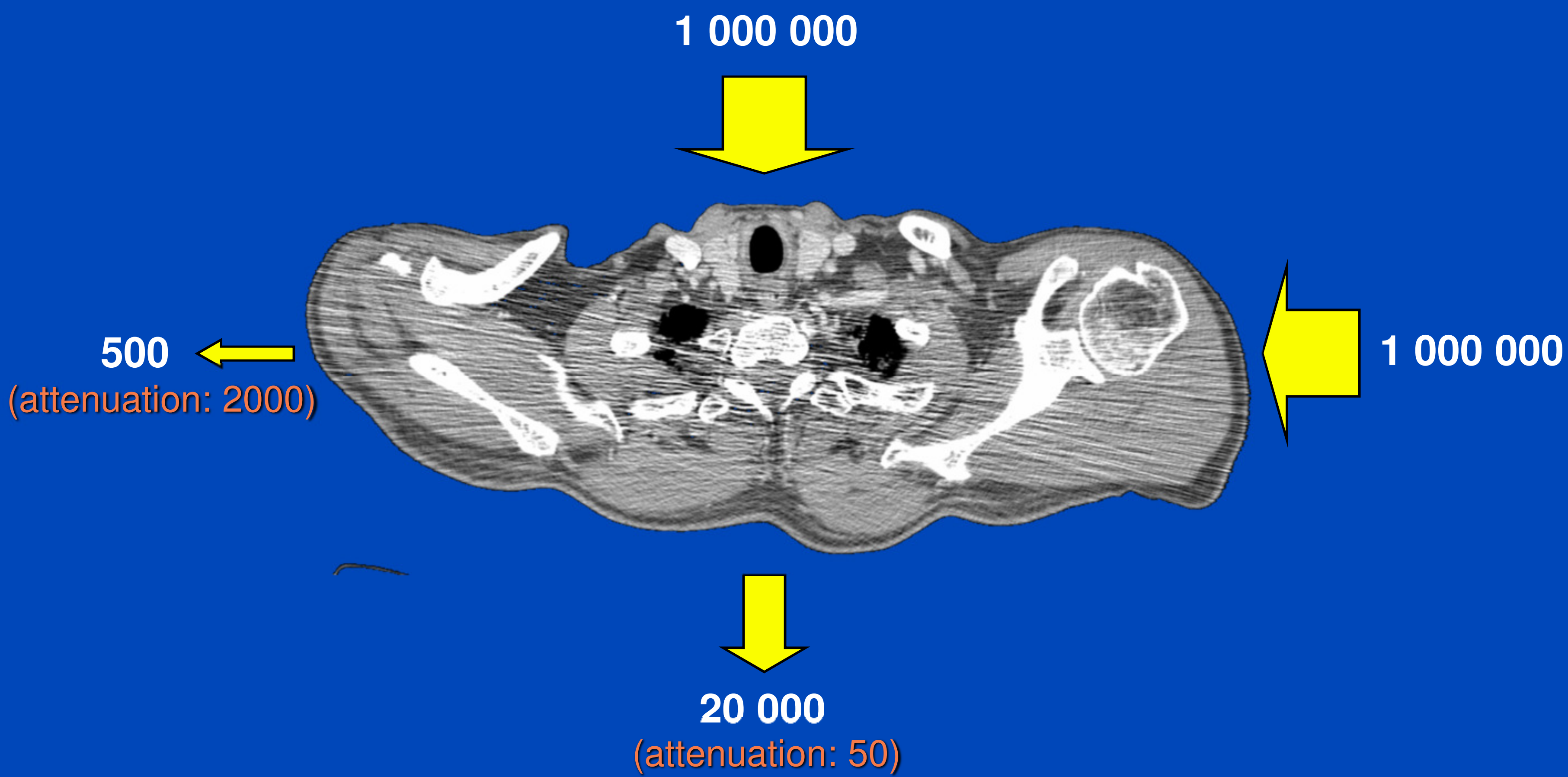
Dose Efficiency in the z-Direction



Photon Starvation



Tube Current Modulation



Constant tube current: High, inhomogeneous noise.

$$\sigma^2_{\text{pixel}} \propto \sum_n \sigma^2_{\text{projection } n}$$

Theory of DOM, TCM, AEC …

$$\int d\alpha \left(\underbrace{\operatorname{Var} p(\alpha)}_{\text{minimize noise}} + \underbrace{\lambda D(I(\alpha))}_{\text{keep dose constant}} \right) = \min$$

$$\int d\alpha \left(\underbrace{D(I(\alpha))}_{\text{minimize dose}} + \underbrace{\lambda \operatorname{Var} p(\alpha)}_{\text{keep noise constant}} \right) = \min$$

$$p = p(q)$$

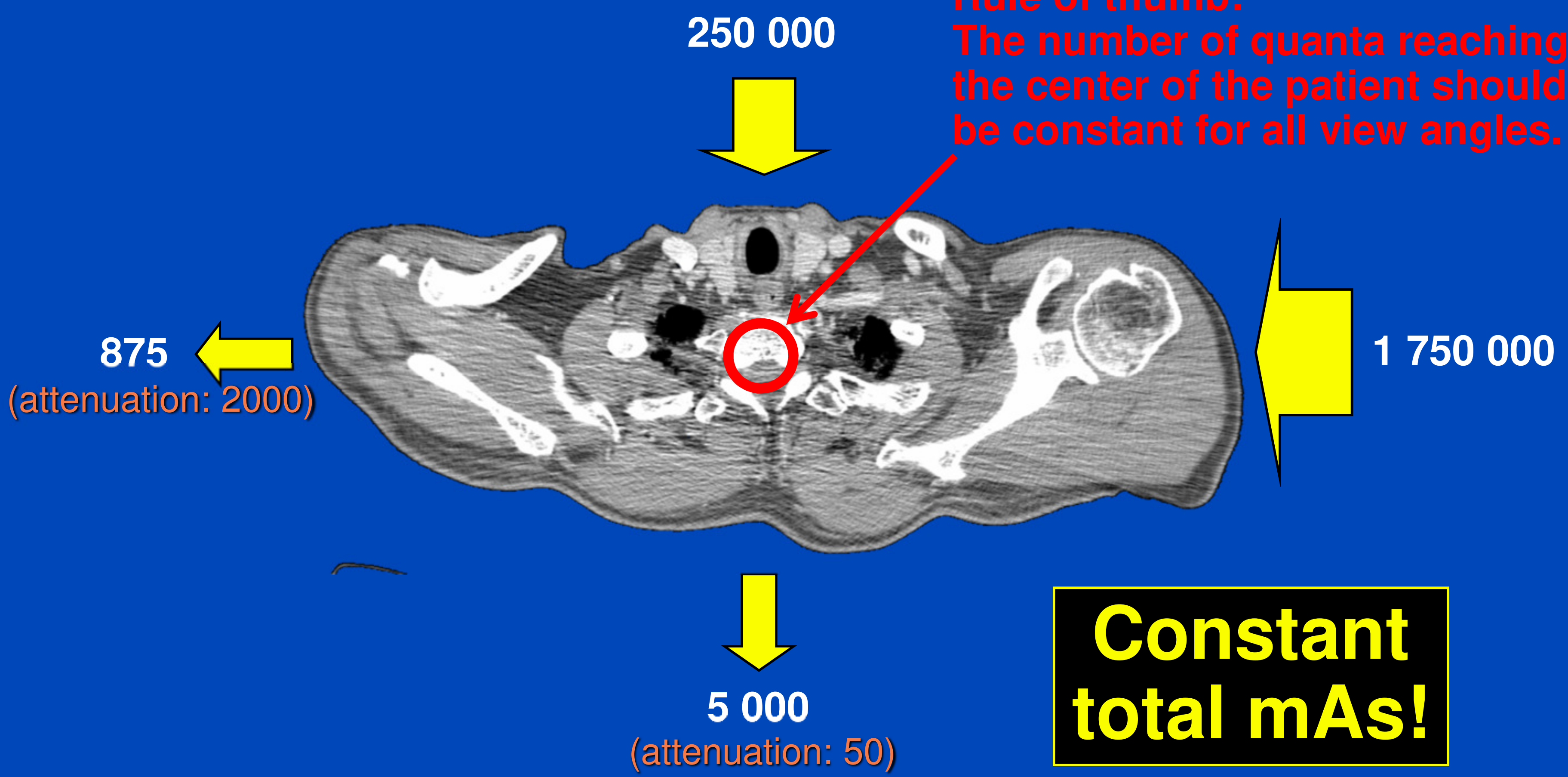
$$\operatorname{Var} q = \gamma \frac{e^q}{I}$$

$$D = \kappa I$$

$$I^2(\alpha) \propto \left(\frac{\partial p}{\partial q} \right)^2 \gamma \frac{e^q}{\kappa}$$

Tube Current Modulation

Rule of thumb:
The number of quanta reaching the center of the patient should be constant for all view angles.



Constant total mAs!

Modulated tube current: Low, homogeneous noise.

Dose Reduction by Tube Current Modulation

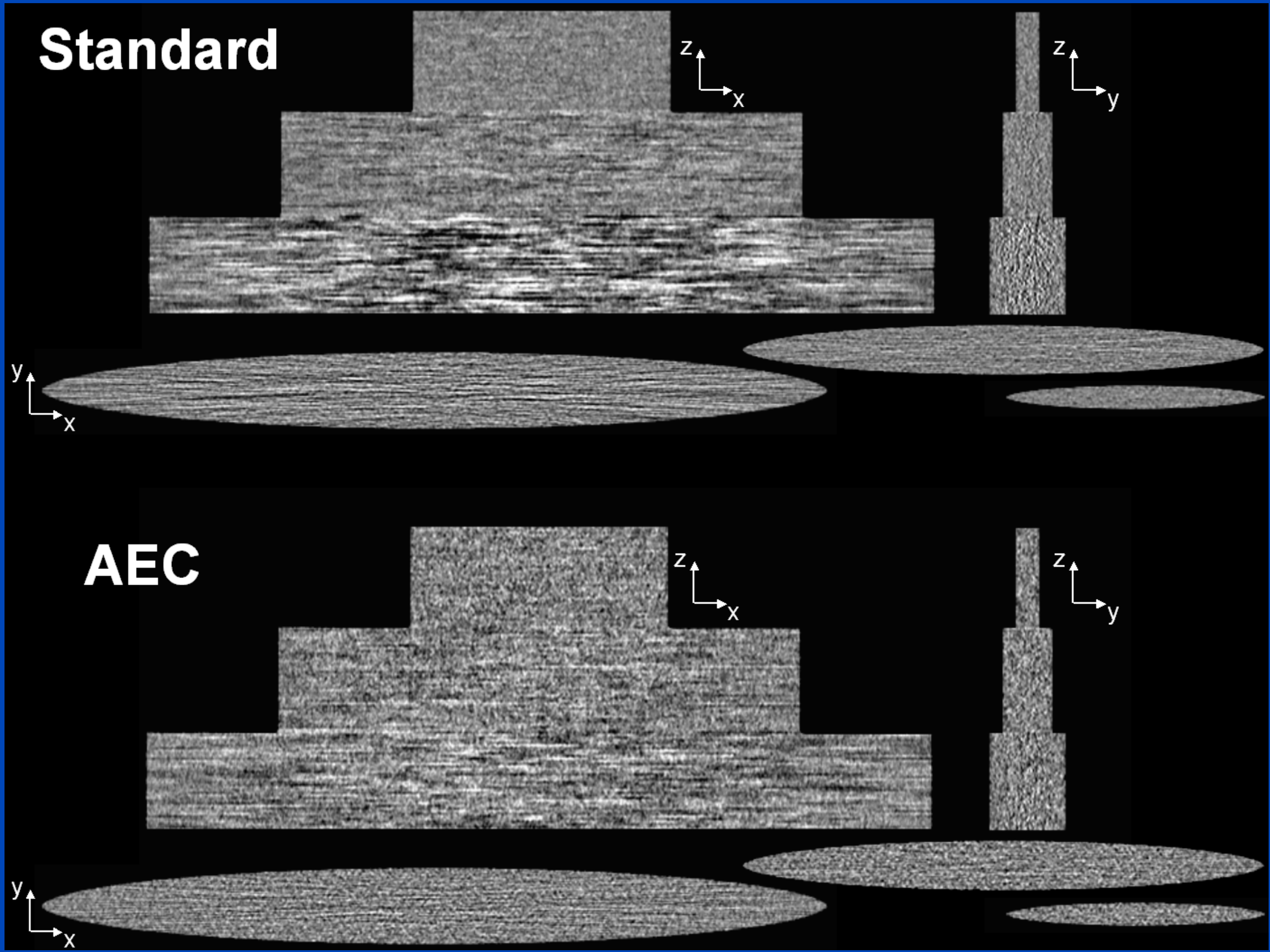
Conventional scan: 327 mAs

Online current modulation: 166 mAs

53% dose reduction on average for the shoulder region
49% dose reduction in this case

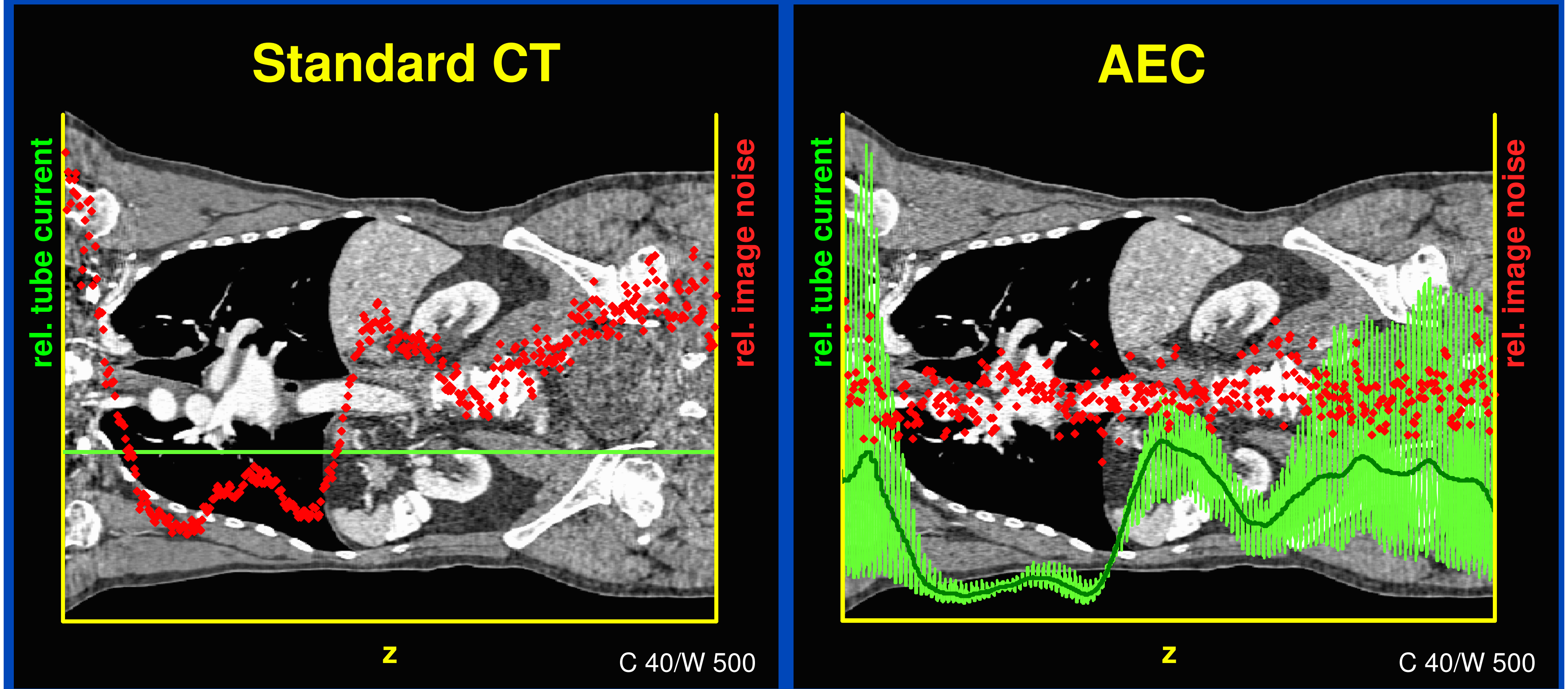
Kalender WA et al. Med Phys 1999; 26(11):2248-2253

Automatic Exposure Control



Kachelrieß, Schaller, Kalender. In: CT of the Chest, Springer 2003

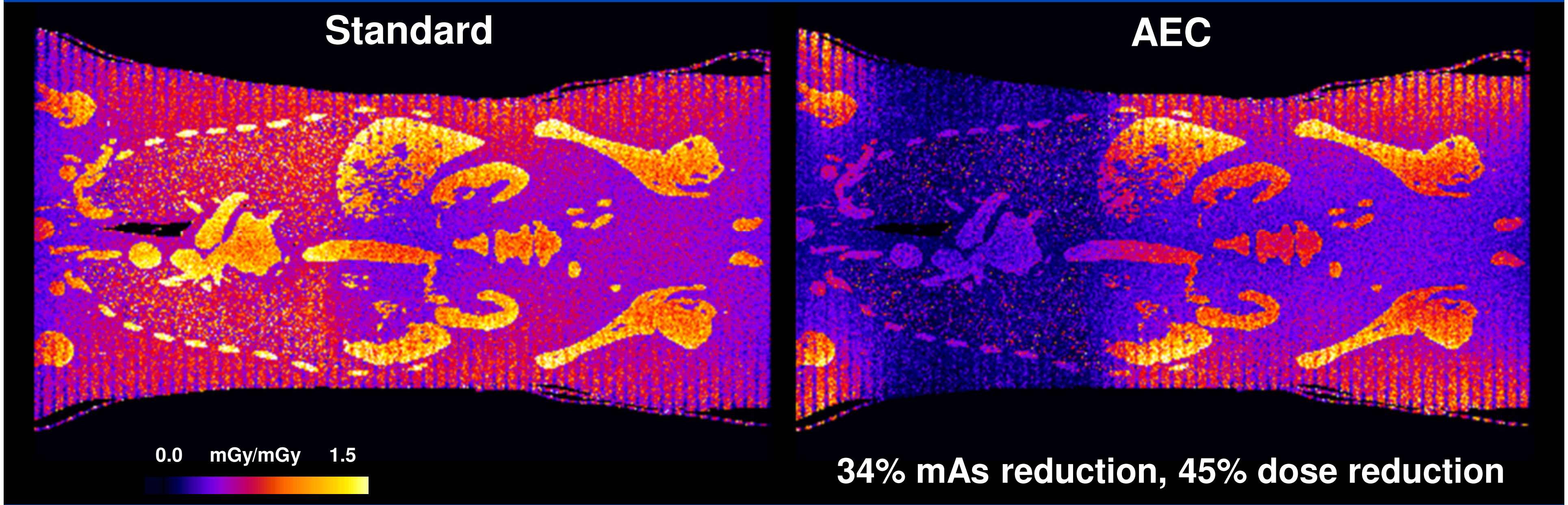
Automatic Exposure Control (AEC)
(z-dependent + angular dependent tube current modulation)



34% mAs reduction with AEC at constant image quality for that specific case

Dose Modulation: DOM, TCM, AEC, …

- Better dose usage
- ECG pulsing
- Avoiding organs of risc
- Specification of image quality $\sigma(z)$



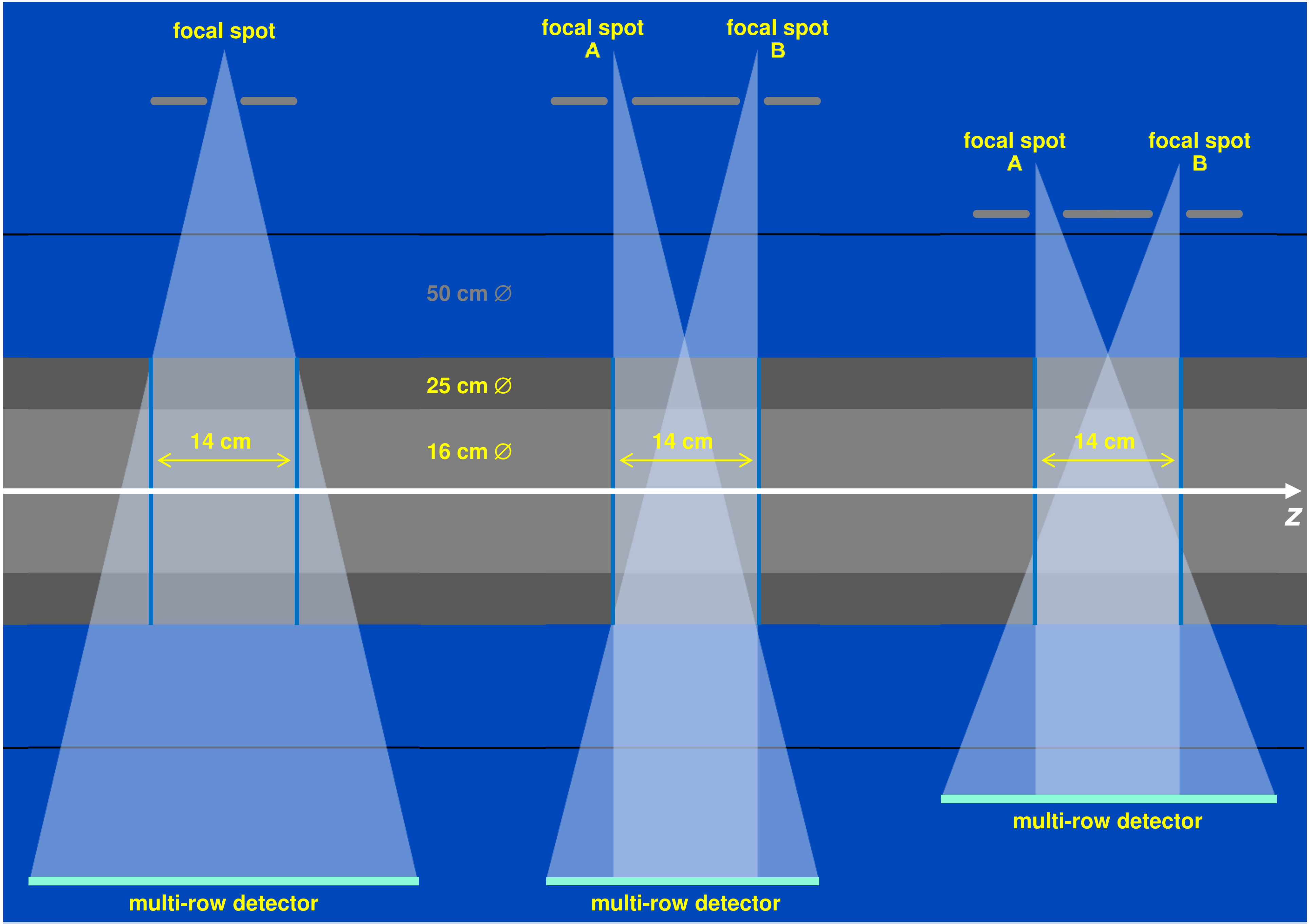
34% mAs reduction, 45% dose reduction

Wishlist

- Tube voltages from 50 to 150 kV in fine steps
- Much more power (>> 120 kW)
- Higher tube currents at low kV
- High cooling rates
- Higher tube current variation (low inertia)
- Flying focal spot
- Special tubes for special purposes
  - DECT
  - Cardiac CT
  - ...

GE's CardioGraphe

- Dedicated cardiac CT (but rather low temporal resolution)
- Manufactured by Arineta (Israel), distributed by GE
- 0.24 s rotation time, 120 ms temporal resolution
- 16 cm or 25 cm FOV (user-selectable, realized by prefilter)
- 14 cm z-coverage for circle scan
- 0.73 mm slice tickness with 0.28 mm recon increment (or larger)
- Runs GE's snapshot freeze and ASIR-CV (= undefined)
- Lowres detector outside the 25 cm to avoid truncation artifacts.
- Dose reduced outside the 25 cm (similar to bowtie filter)
- RF = 45 cm is smaller than the typical 60 cm
  - Less centrifugal forces
  - Better flux usage
- Two focal spots with fast focal spot switching to enable two parallel acquisition circles and thereby increase z-coverage and reduce cone-beam artifacts


focal spot
focal spot A
focal spot B
focal spot A
focal spot B
50 cm ∅
25 cm ∅
16 cm ∅
14 cm
14 cm
14 cm
z
multi-row detector
multi-row detector
multi-row detector

dkfz.

Thank You!

The 6th 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.
Job opportunities through DKFZ's international Fellowship programs (marc.kachelriess@dkfz.de).
Parts of the reconstruction software were provided by RayConStruct® GmbH, Nürnberg, Germany.