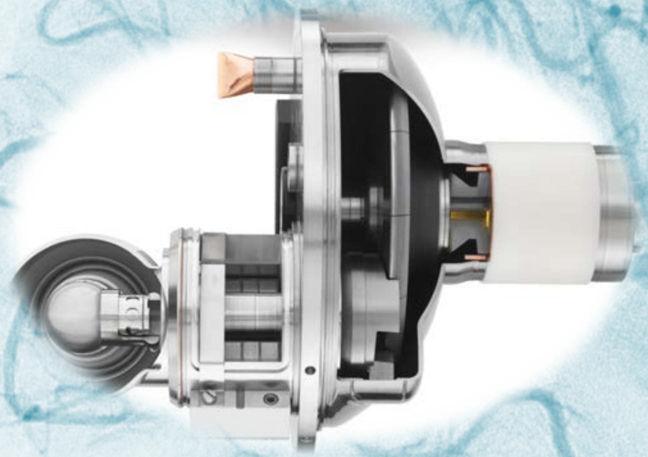
History and Future of the X-Ray Tube:

Can We Do It Better?

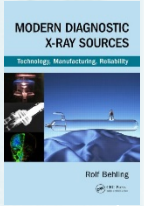


AAPM Spring Clinical Meeting, SLC, 2016

Rolf Behling

Royal Philips, Hamburg, Germany

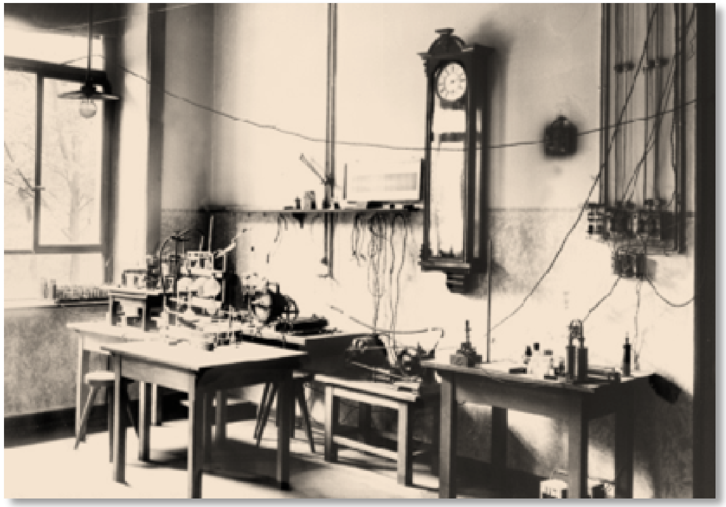
New book: R. Behling. 2016. *Modern Diagnostic X-Ray Sources: Technology, Manufacturing, Reliability*. CRC Press, T&F, USA



Tubes – The Year After… Roentgen Frustrated

*"Meanwhile,
I have sworn so far, that
I do not want to deal with the behavior of the tubes, as these dingus are even more capricious and unpredictable than the women."*

**Prof. Dr. C.W. Röntgen, Jan 1897.
Translated from [7]**



Roentgen's lab in Würzburg, Germany
Discovery of the X-rays: Nov 8th 1895.
Curtesy of the German Röntgen Museum, Remscheid-Lennep, Germany

Questions Which You Have Never Asked

- How hot is a diagnostic X-ray beam?

  About 10 million Kelvin. That‘s why it is bio-destructible & difficult to produce.

- How much is a typical diagnostic X-ray photon?

  Two atto $ *)

- Isn‘t this cheap?

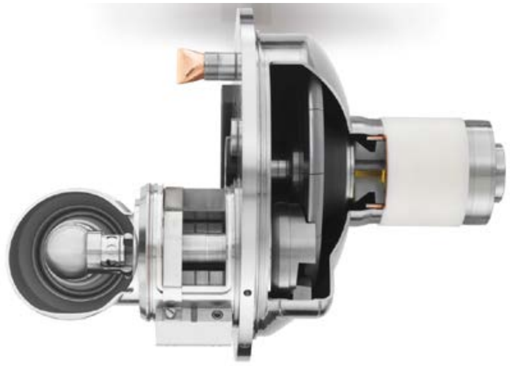
  No, extremely expensive

- How much does an LED photon cost, then?

  A yocto cent **)

- Will we produce X-rays in LED‘s ?

  No, X-ray tubes will remain



→ If so, let‘s talk about better X-ray tubes

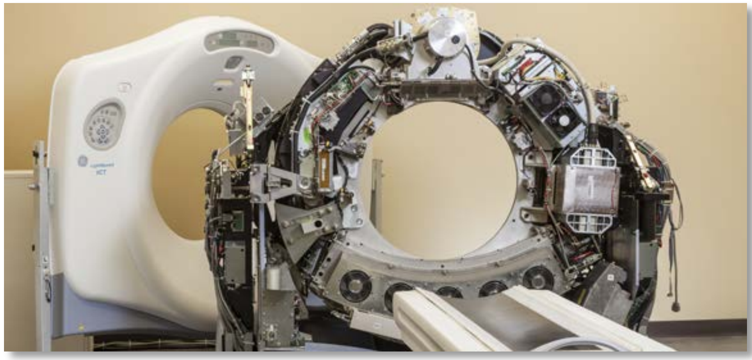
*) 2 atto (10^{-18}) $ (good CT tube), 6 atto $ (average CT tube)

**) yocto = 10^{-24}

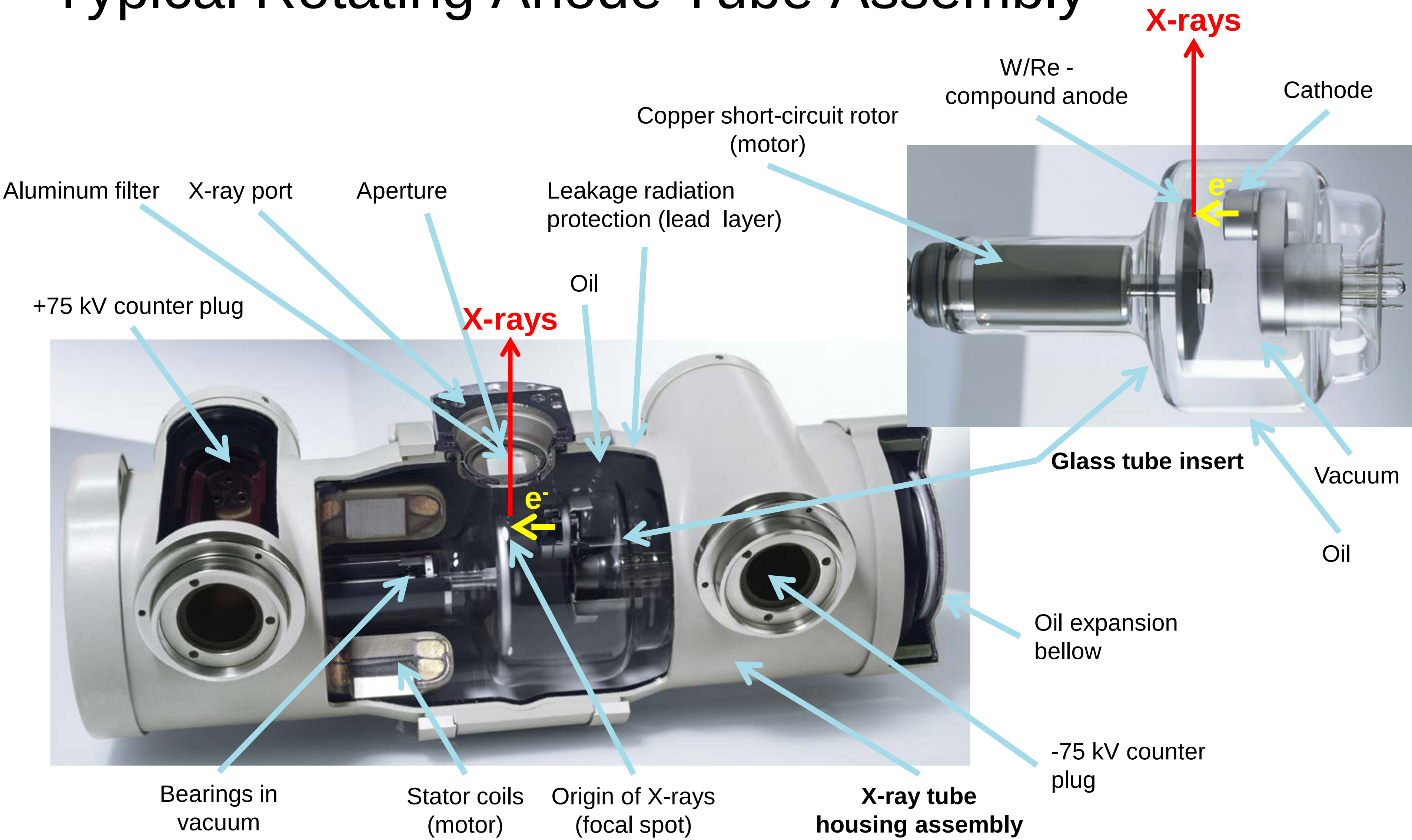
The Modalities

- Computed Tomography (CT)
  - 70…150 kV, ~ 4 s scans, up to 120 kW, ~2 MJ
  - Gantry: centrifugal acceleration 30+ g
  - focal spot deflection
- Interventional
  - 60…125 kV
  - Minute-long pulse series, e.g. 20..80 kW, 5 ms @ 7,5 Hz
  - High tube current @ low tube voltage
  - Gyro forces
- General radiology
  - 40…150 kV, e.g. 80 kW, 3 ms every minute
- Mammo
  - 20…40 kV, small focal spots (0,1 … 0,3 mm)

→ ~500 tube types on the market

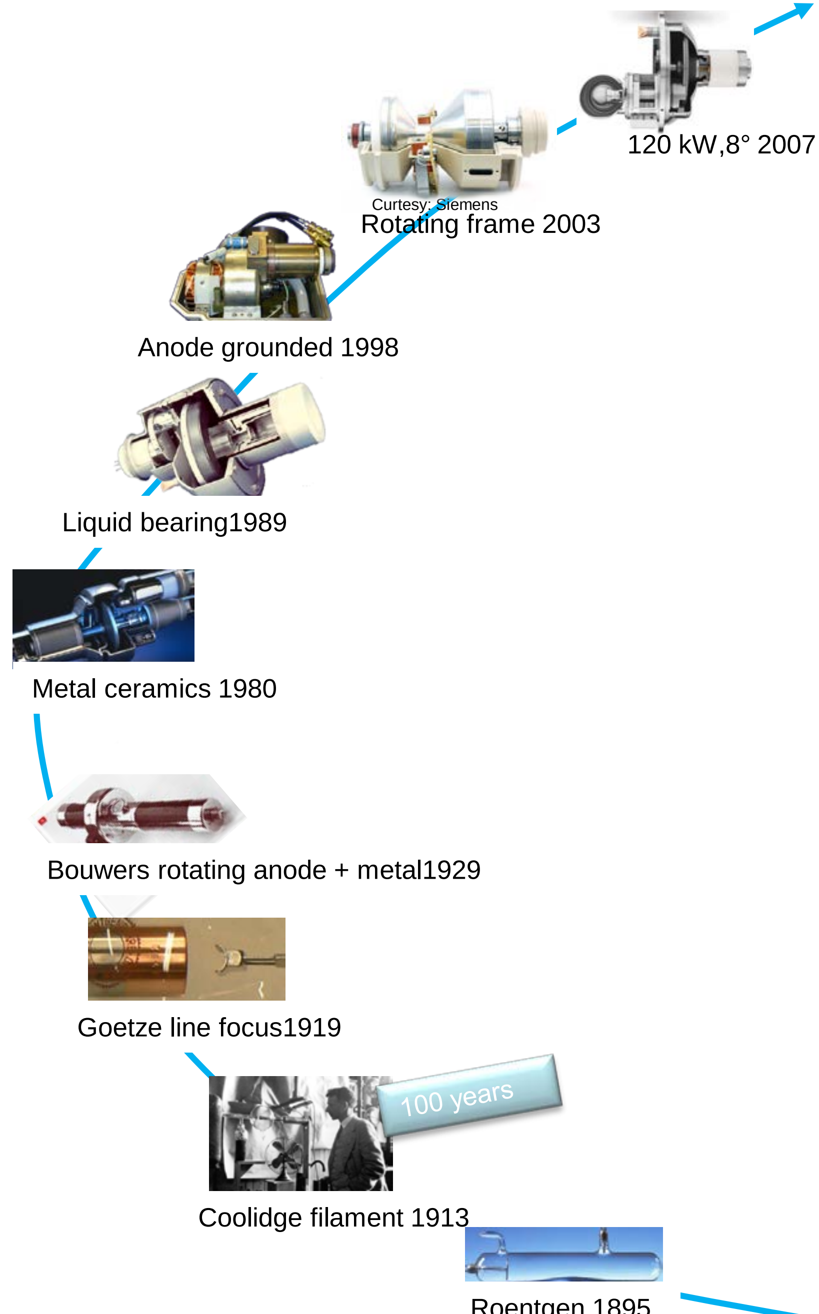


Typical Rotating Anode Tube Assembly



Who is Best in Class?

- GE
  - **Thermo-ionic electrons (Coolidge, 1913)**
  - Graphite anodes (CGR, later GE, 1967)
  - Largest anode (238 mm, 2005)
- Philips
  - **Line focus (Goetze, 1919)**
  - Metal frame + **rotating anode (Bowers, 1929)**
  - All metal ceramics (1980)
  - **Spiral groove bearing (1989), dual suspended (2007)**
  - **Double quadrupole (2007)**
- Siemens
  - Graphite backed anodes (1973)
  - Flat electron emitter (1998)
  - **Rotating frame tube (2003)**
  - Magnetic quadrupole, z-deflection (2003)
- Varian
  - Metal frames, largest anode heat capacity (1980ies)
  - Finned rotating anodes (1998)
  - **Electron trap, anode end grounded tube (1998)**
- Other vendors



In alphabetical order

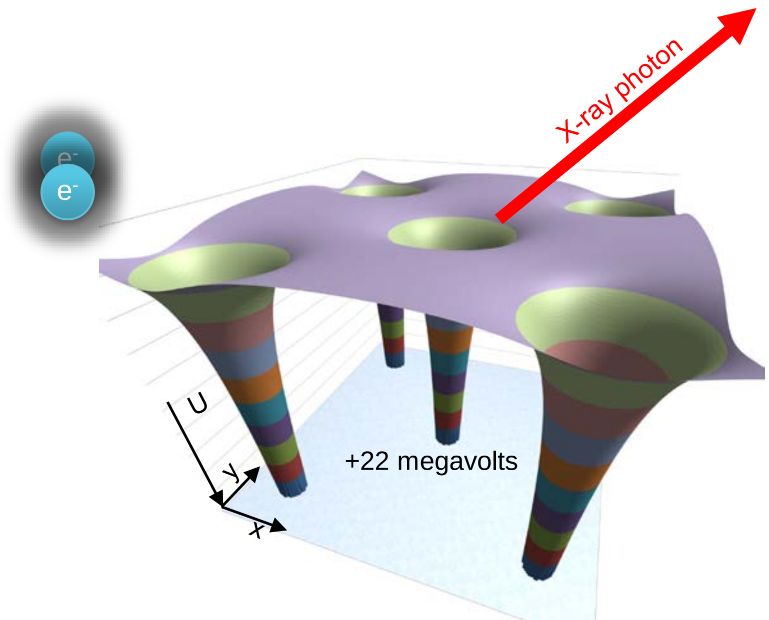
Diagnostic Imaging

Lamor formula

$$P_{light} = \frac{e^2}{6\pi\varepsilon_0 c^3}\left|\ddot{X}\right|^2$$

P_{light}: Light intensity; $|\ddot{X}|$: Particle acceleration

- Photons: energy > 16 keV
- Bremsstrahlung (electron brake-radiation)
  - Electrons accelerated in nuclear E-fields
  - → Continuous spectrum
  - → Re-fill of e^- - shells adds characteristic lines
  - → e^--scatter at free electrons (plasmons) → heat
  - → Conversion efficiency 10^{-4}
- Spatial resolution Δx limited (dose penalty):
  - X-ray dose $\propto (1/\Delta x)^{3 \ldots 4}$
  - → Source size ~ 0.2…2 mm

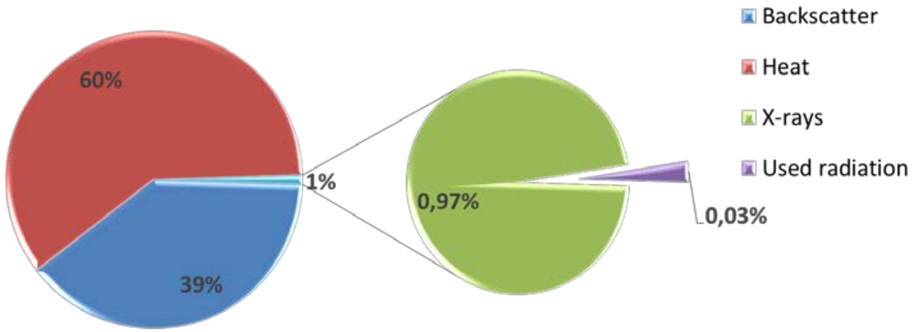


Nuclear Cloulomb potential in tungsten plane (schematic). Animation:

1. Photon created upon hard inelastic electron scatter
2. Strong elastic scatter (→ angular diffusion)

→Bremsstrahlung, limited brilliance

Efficiency of Generation of Bremsstrahlung

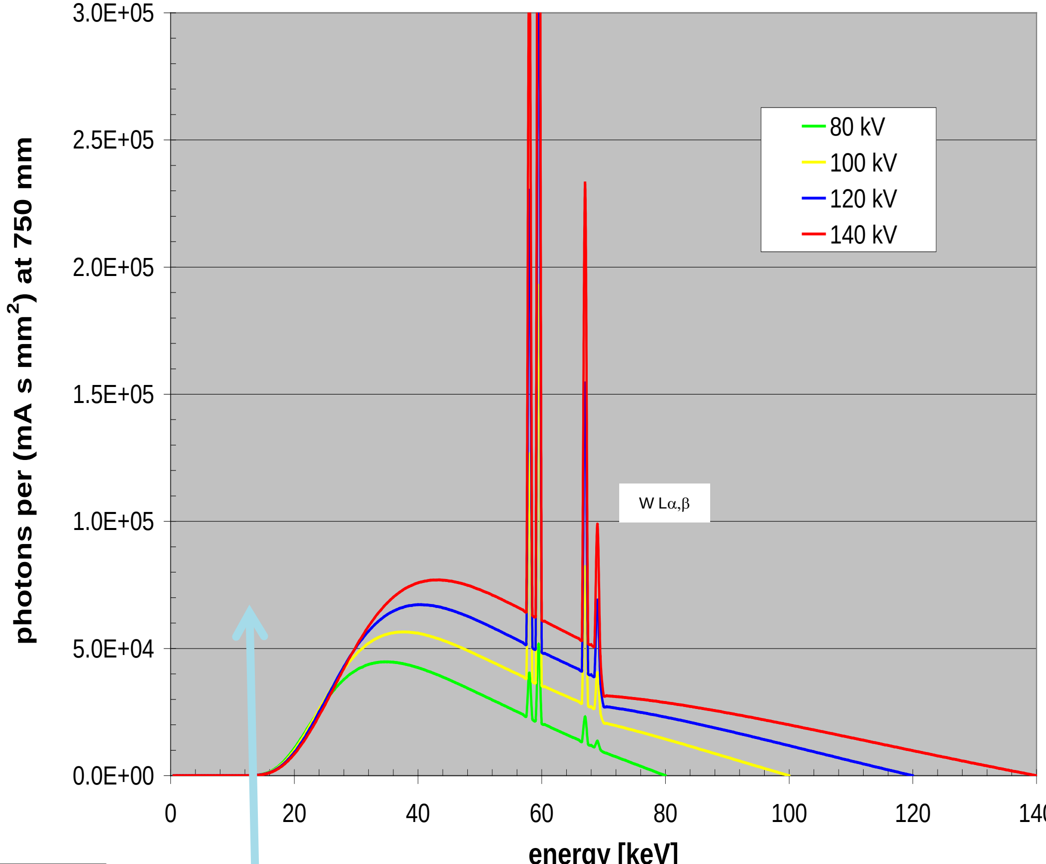


- Good energy conversion by tungsten: atomic number 74, melts @ >3400°C
- Waste of electron energy through
  - inelastic low energy scatter,
  - Plasmon creation (electron cloud polarization, ~25 eV quanta)
  - Eventually energy transfer to phonons (heat)

→ Conversion efficiency ~10^{-4}

Tungsten-Spectra

- Continuum of frequencies
- Max photon energy = $|e^{-}|\ V_{tube}$
- Tube voltage defines spectrum
- Soft X-rays cancelled by filter
  - Eliminating non-imaging photons
  - Key for patient safety
  - FDA: minimum 2,5 mm Al equiv.
  - Skin dose further down by additional up to 1 mm Cu
  - Strong filtration requires powerful tube
    - e.g. interventional X-ray
    - TwinBeam CT)



Spectrum vs. tube voltage. W-anode, 2 mm Al filter

Soft radiation removed from the used beam by the X-ray filter

→ Fine tuning high-voltage and filtration defines the bremsstrahlung spectrum

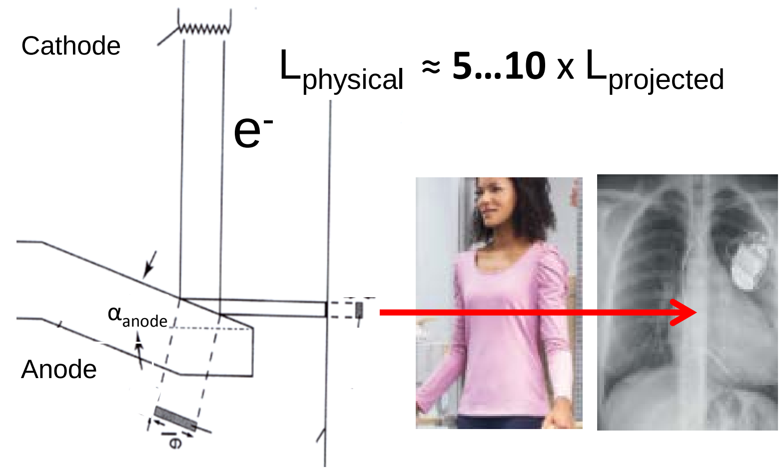
Line Focus (Goetze) Resolution

- Projected spot size counts
  - Projection on plane ⊥ central beam
  - X-ray fan usually narrow: 8° to 35°
  - High z-resolution @ anode shadow)

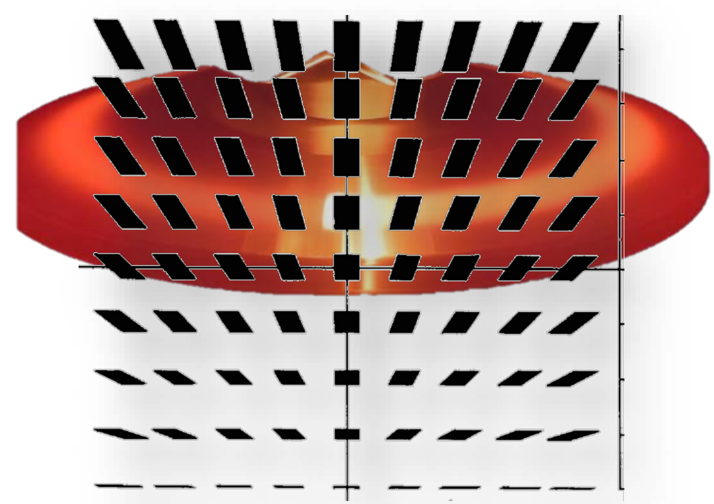
→ Long physical spot $L_{physical} = \frac{L_{projected}}{\sin(\alpha_{anode})}$

→ 5 x…10 x gain of power and current
- → Power $\propto$ physical spot length
- → Low current density (reduced space charge)

→ Minimize the anode angle α_{anode}
→ But: Observe heel effect, notably for CT



Projected FS defines sharpness



Focal spot appears distorted, in the periphery of the field of view

Why are reflection targets used for medical imaging instead of transparent targets?

20%	1.	A.Reflection of electrons reduces target heating
20%	2.	The X-ray intensity is highest, given a small X-ray fan angle
20%	3.	There is backward enhancement of the X-ray intensity
20%	4.	No additional filter is needed, the target filters intrinsically
20%	5.	X-ray deflection enhances the brilliance

10

Bulk Anode Cooling

Glass tube, ball bearings

- Electron impact → Anode Heat storage
- Electron back scatter:
- Heat radiation: 100%
- Heat condution:

Single polar, liquid bearing

- Electron impact → Anode Heat storage
- Electron back scatter: 40%
- Heat radiation: 30%
- Heat condution: 30%

Courtesy: Siemens

Rotating frame tube

- Electron impact → Anode Heat storage
- Electron back scatter: 40%
- Heat radiation:
- Heat condution: 60%

→Radiation cooling: residual heat in the anode

Glass tube with ball bearings. Multiple exposures. Cooling:

- Heat radiation starts strong at the beginning of the pause.
- But, as the anode cools down (invisible, < 400 °C), heat radiation ceases (T^4).
- Anode remains at elevated temperature.
- The next patient faces a pre-heated tube →limited performance
- Solution: Heat conduction (dissipating residual heat)..

Why is heat conduction cooling used in modern high performance X-ray tubes?

20%	1.	It is simpler to manage
20%	2.	Heat radiation is not effective at high temperatures
20%	3.	The anode can be made smaller while maintaining high performance
20%	4.	Scattered electrons provide "heat conduction"
20%	5.	Improved image processing allows using stationary target tubes in most cases

Historic “Mega Heat Units” are Out

- In 2010 IEC **cancelled MAXIMUM ANODE HEAT CONTENT** (“Mega Heat Units”)
  - Misleading metric
  - For historic technology

- IEC introduced new practical terms
  - Relevant in clinical use
  - Can be validated by the user

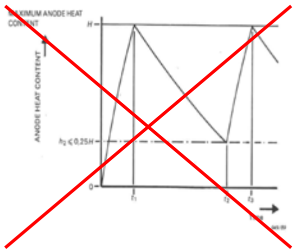
3.15 NOMINAL RADIOGRAPHIC ANODE INPUT POWER

…POWER which can be applied for a single X-RAY TUBE LOAD with a LOADING TIME of 0,1 s and a CYCLE TIME of 1,0 min, for an indefinite number of cycles

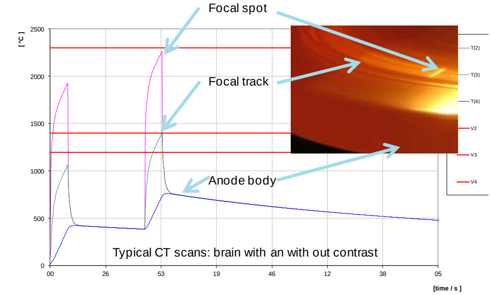
3.16 NOMINAL CT ANODE INPUT POWER

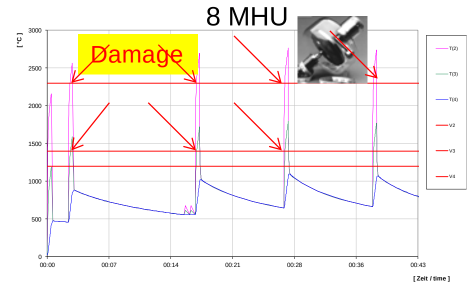
…POWER which can be applied for a single X-RAY TUBE LOAD with a LOADING TIME of 4 s and a CYCLE TIME of 10 min, for an indefinite number of cycles

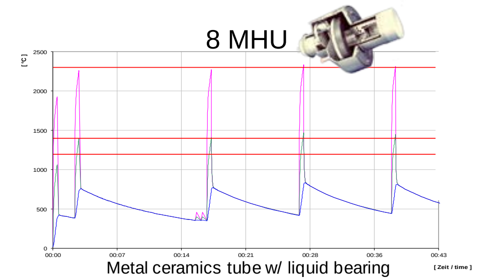
3.20 CT SCAN POWER INDEX CTSPI $= \frac{1}{(t_{max} - t_{min})} \int_{t_{min}}^{t_{max}} P(t)\, dt$



NEW







Same x-ray output + „MHU‘s“, but:
• ball bearing glass tube (center) breaks: 1st scan ok, anode stays hot.
•Tube with conduction cooling (SGB, bottom) survives. Cool at 2nd patient.

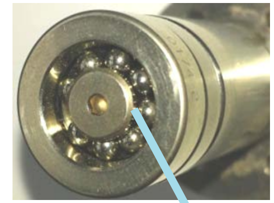
→ Please apply new IEC terminology

Anode Bearings in Vacuum

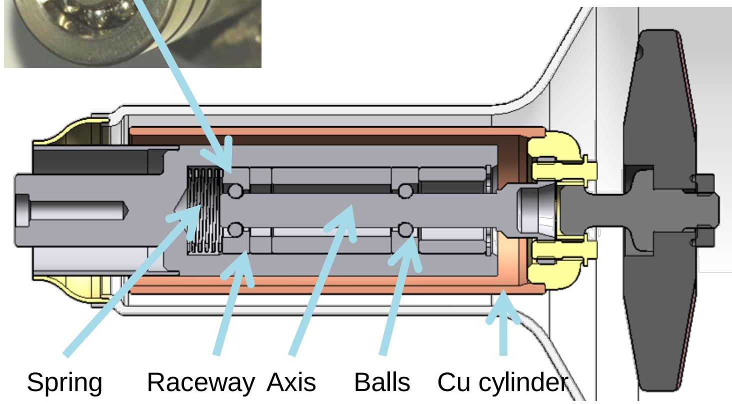
- Ball bearings
  - Hard steel, would freeze immediately w/o inter-layers
  - → Ag or Pb coating of balls
  - ~1 Watt heat conduction → heat radiation cooling only
  - Limited life → Start-stop needed
  - Deterioration by high speed, load, temperature
- Spiral groove bearing system (SGB)
  - Kilowatt heat conduction
  - ~10…50 µm gaps filled with liquid GaInSn
  - Infinite rotation life, little wear at start & landing
  - → Continuous rotation (zero prep time)
  - Noiseless, stable, scaled to load & speed
  - Four bearings in one (2 x radial, 2 x axial),
  - Latest: dual suspended for CT (32 g)

(Rotating frame tubes have well lubricated ball bearings in oil)

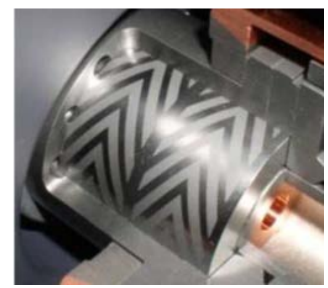
→ Bearing type is key for tube life and practical experience (prep, cooling)



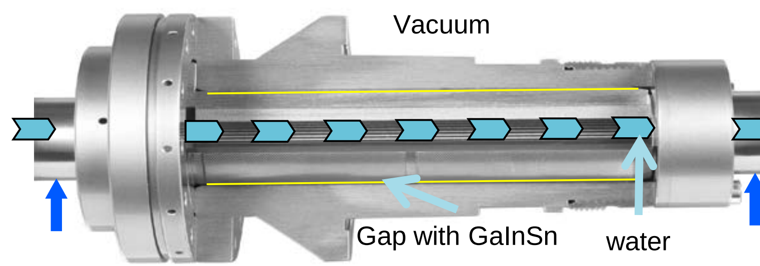
Ball bearing unit, lead coated balls



Ball bearing system in a glass tube



Two radial bearings of a liquid metal lubricated SGB.



Dual suspended SGB for high centrifugal forces in CT.

Spiral groove bearings…

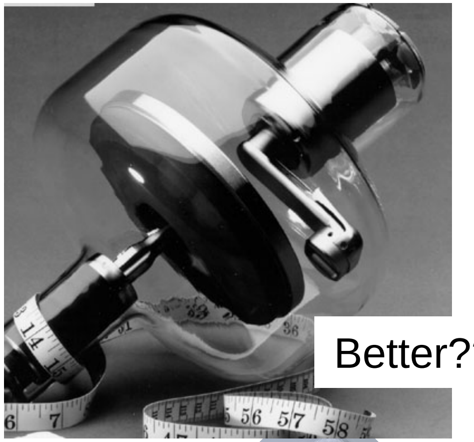
20%	1.	A.are lubricated by cooling oil and thus enable heat dissipation by convection
20%	2.	B.allow for heat conduction even at low anode temperatures
20%	3.	C.cannot withstand high g-forces
20%	4.	D.dissipate heat at stand-still and not when rotating
20%	5.	E.Need to stop between patients to conduct heat out

Product Selection: Cheaper Might be Better

- Momentum of inertia I_{rotor} of the anode rotor

$$I_{rotor} \propto Ø_{anode}^{4}$$

→ Disadvantage for larger tubes with ball bearings
  - More prep time (pediatrics, interventional)
  - More heat for start / stop (air cooling)
  - Bearing failure
  - Costs



I_{rotor} : Momentum of inertia
$Ø_{anode}$: Anode diameter

→ Select the right tube, not always the largest

Larger anodes are always beneficial for tubes with ball bearings, right?

20%	1.	Yes. All major characteristics are superior, including prep time and average power available for X-ray generation
20%	2.	No. The momentum of inertia is higher, and with it prep time and heat from start-stop operation
20%	3.	Yes, a large mass reduces bearing noise
20%	4.	Yes, a large momentum of inertia stabilizes the high rotor speed
20%	5.	Yes. More X-ray intensity can be produced while the overall heat dissipation stays the same.

10

Cathode

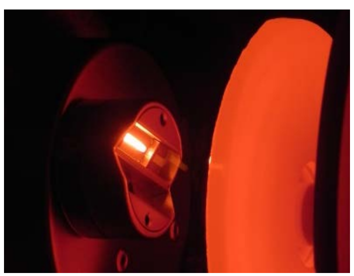
- Thermionic **emission** (e^- boiled off W-emitter)

  $$J = const * T^2 * \exp(-e\phi / kT)$$

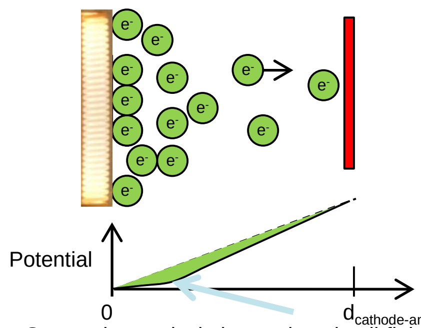
- Child's law: e^- **space charge** in front of emitter

  $$J = const * V_{tube}^{3/2} / d_{cathode\text{-}anode}^{2}$$

cathode anode



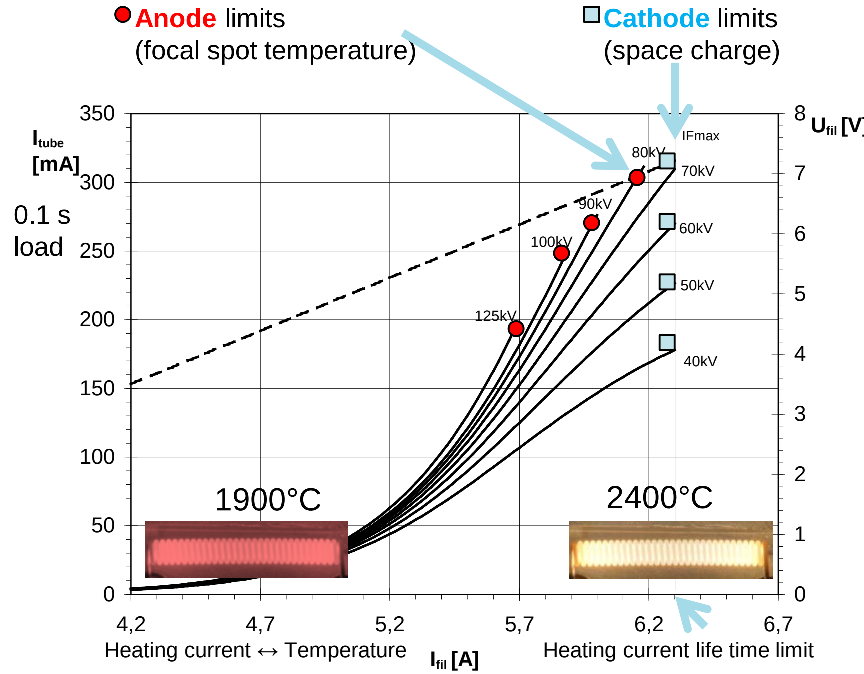
Electron source Anode



Space charge deviation, reduced pull-field at the emitter

- "isowatt point: tube voltage where space charge limit = anode limit (75 kV for the sample tube)

→ Cathode may be limiting tube performance



Emission characteristics

of a 0,4 (IEC 60336) focal spot (11° anode angle, 108 mm anode Ø). Isowatt point 72 kV. Observe the $V_{tube}^{3/2}$ law in the space charge regime (right, hot emitter)

$d_{cathode\text{-}anode}$: distance emitter – anode (e.g. 2 cm)
I_{fil}: Emitter heating current
J: Emitter current density (e.g. max 2 A/cm²)
k: Boltzmann's constant
T: Emitter temperature (e.g. max 2500 °C)
U_{fil}: Emitter heating voltage
V_{tube}: Tube voltage (< isowatt point → space charge limit)
ϕ: Work function of the emitting surface (e.g. 4,5 eV for W)

A low Isowatt Point, where cathode and anode limitations of the tube current meet, indicates …

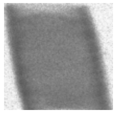
20%	1.	…good cathode performance. Space charge is minimal
20%	2.	…poor cathode performance. Space charge is maximal
20%	3.	…good anode performance
20%	4.	…a low conversion factor for electrical to X-ray energy
20%	5.	…having a poor X-ray high voltage generator

10

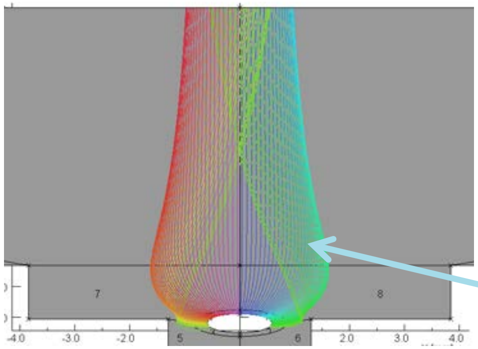
Focusing

- Electrostatic focusing (shape of cathode cup)
  - FS size independent of U_{tube} (except w/ space charge)
- Recent: Magnetic focusing
  - magnetic quadrupoles
  - Magnetic deflection → more projections → less artifacts
  - Magnetic fields to be adapted to U_{tube}
- MTF = modulation transfer function
  - Fourier transform of the projected intensity profile (point spread function)
  - Measure of resolution capability (bandwidth of spatial frequencies)
- Design goals
  - Focal spot independent of tube current (space charge)
  - Focal spot independent of tube voltage
  - Max. emitter size (tube life)
  - Minimal off-focal intensity

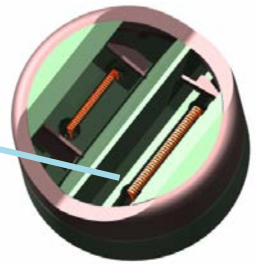
→ Electrostatic focusing is simpler, magnetic focusing is more effective and versatile



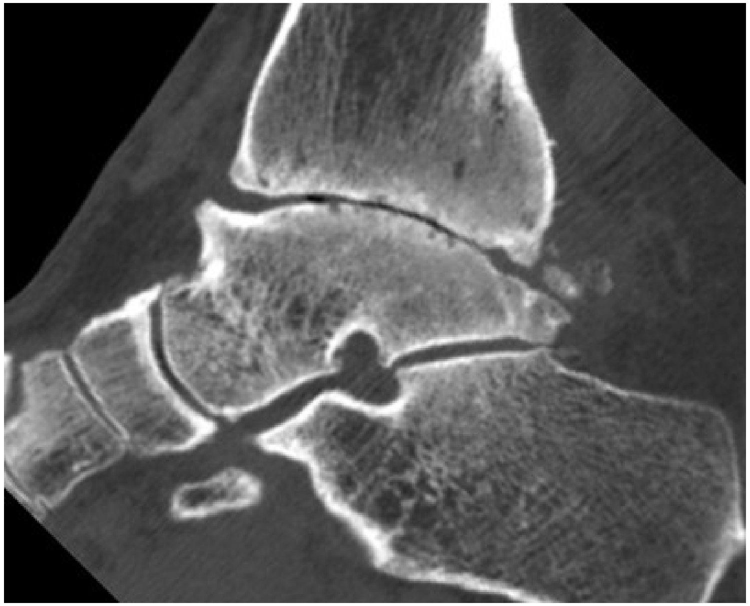
Current density profile at the anode (focal spot exposure)



Electron beam tracing around one of the filaments. Geometry defines E-field for electrostatic focusing

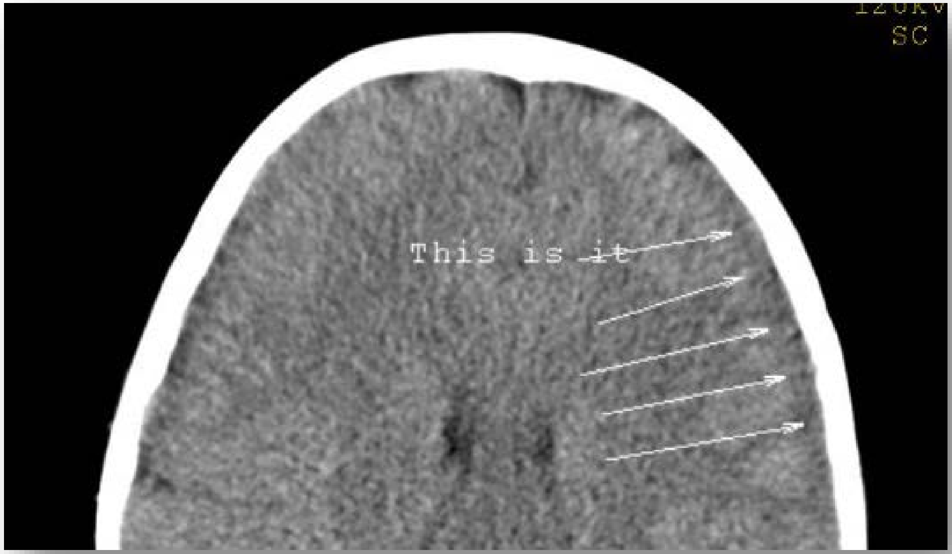


Dual filament cathode

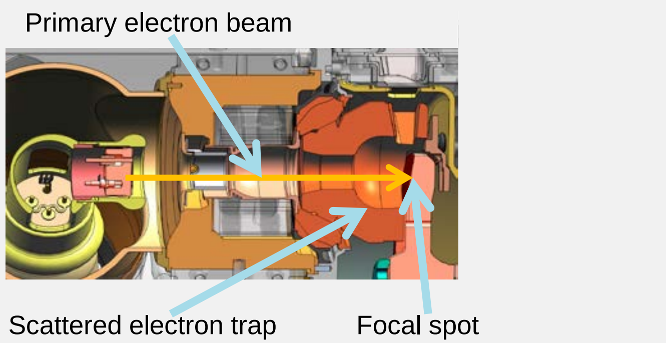


Off-Focal Radiation

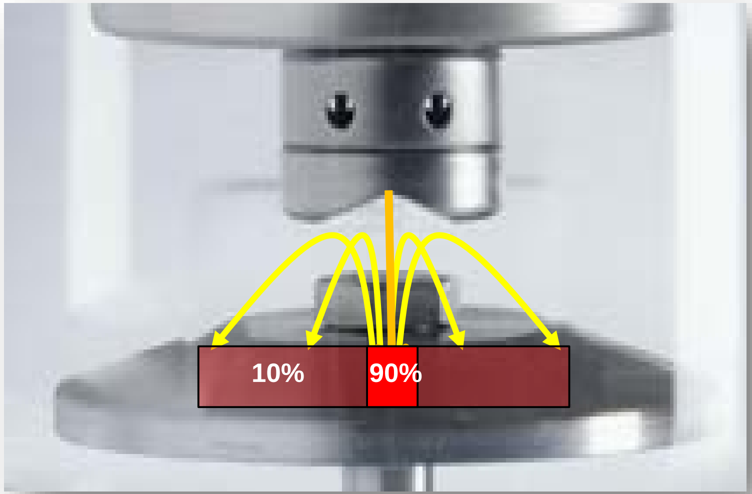
- 2[nd] impact of back-scattered electrons
- Artifacts @ hard contrast
  - May mimic bleeding (stroke)
  - Shadows
- Remedy: electron trap, avoid mirroring



Artifact: Over-compensated off-focal



Anode grounded tube. Scattered electrons are captured

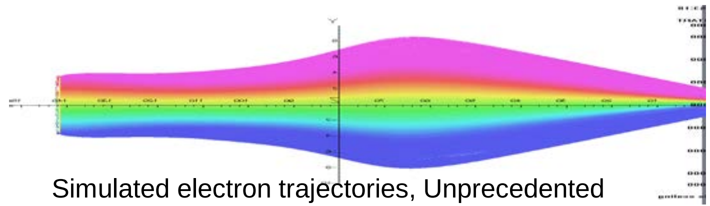


~10% off-focal (softer than primary)

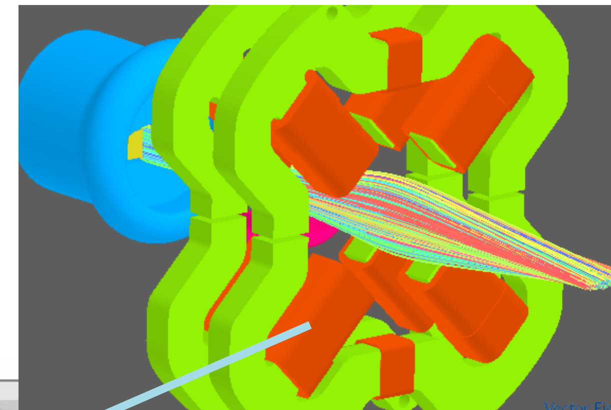
→ Anode grounded, drift space, electron trap

Latest: Flat Emitter+Magnetic Focusing+Deflection

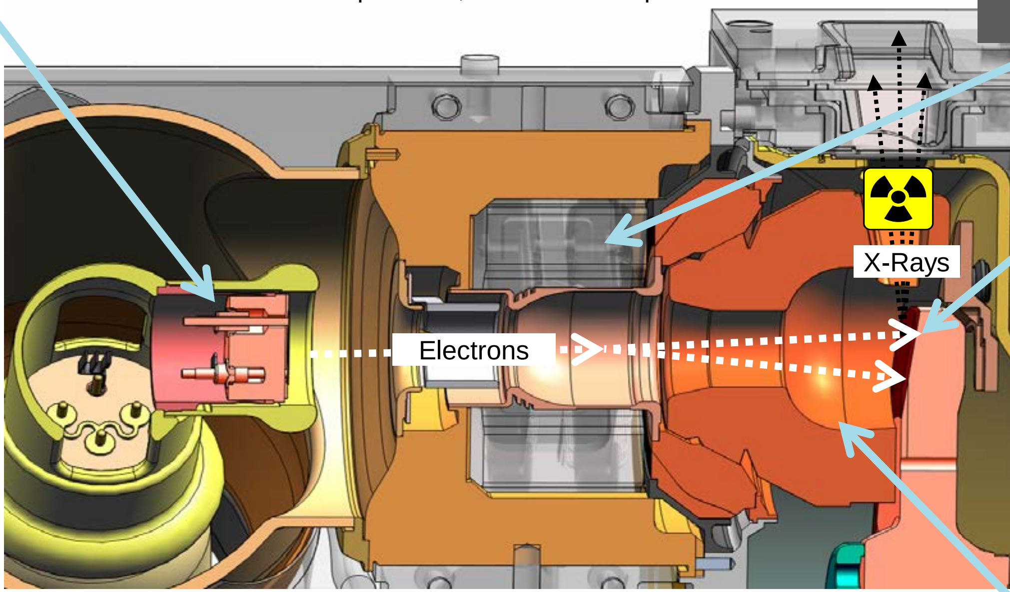
Cathode with tungsten flat emitter



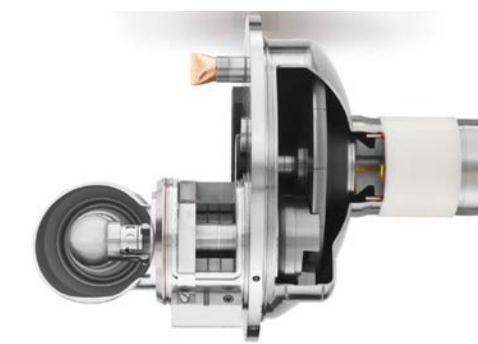
Simulated electron trajectories, Unprecedented compression, lowest isowatt point.



Double quadrupole and dipole

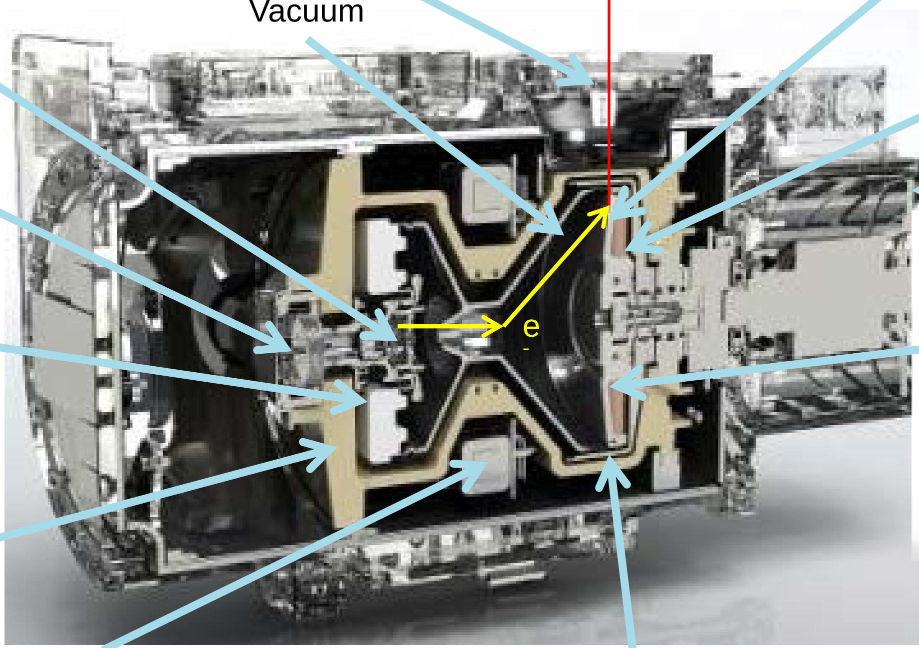


Z-deflection



Scattered Electron Collector collects 40% of the primary electron energy

A Rotating Frame CT Tube Assembly



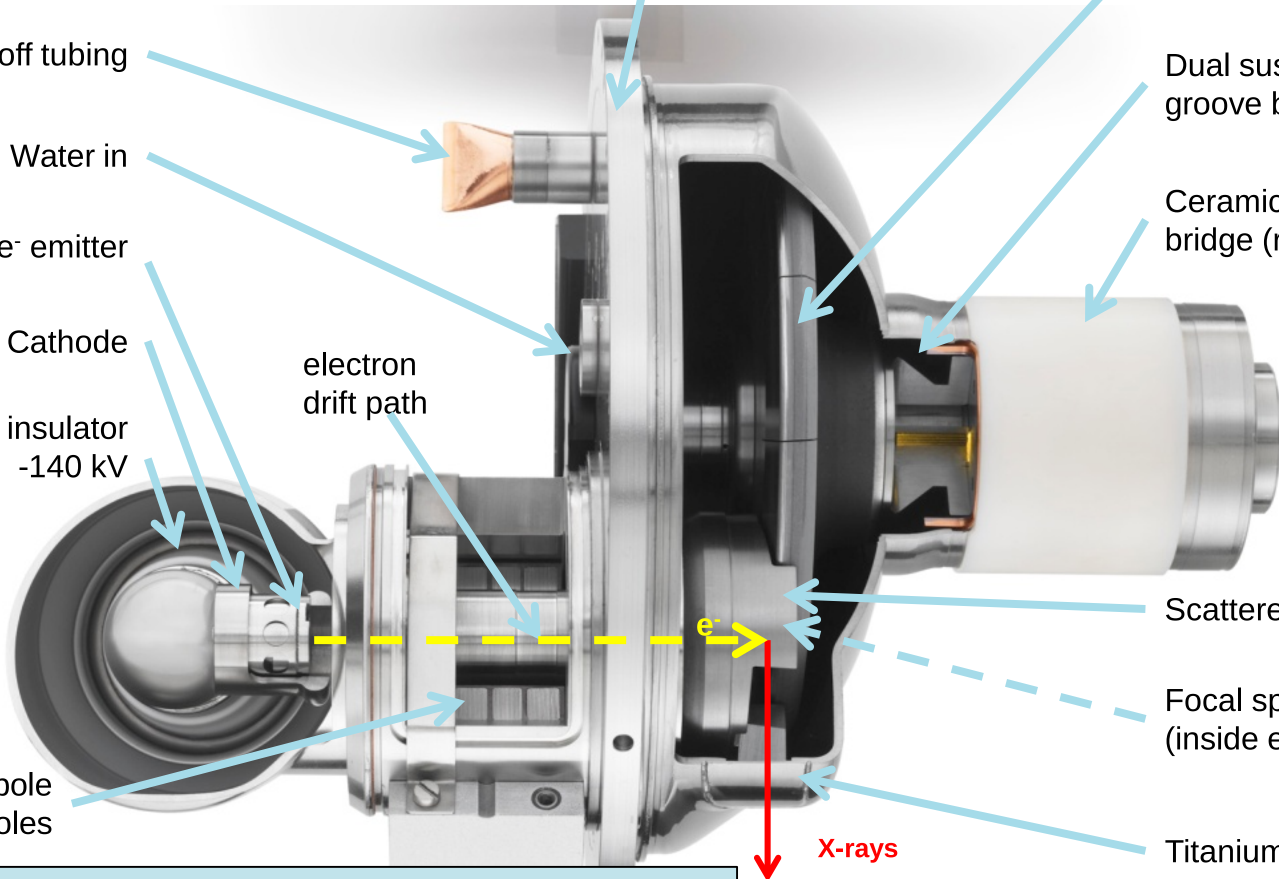
Courtesy: Siemens

Rotating frame insert (+70 kV)
Virtually "anode grounded", as seen from the focal spot perspective

→ Rotating frame = Compact

Type: Siemens Straton

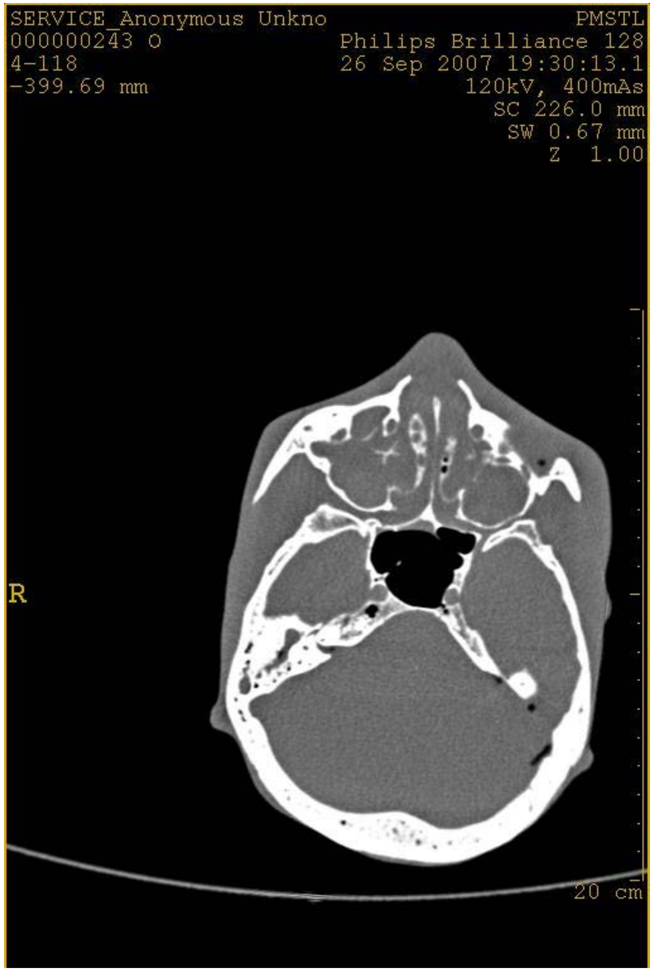
A CT Tube with the Highest Power Density



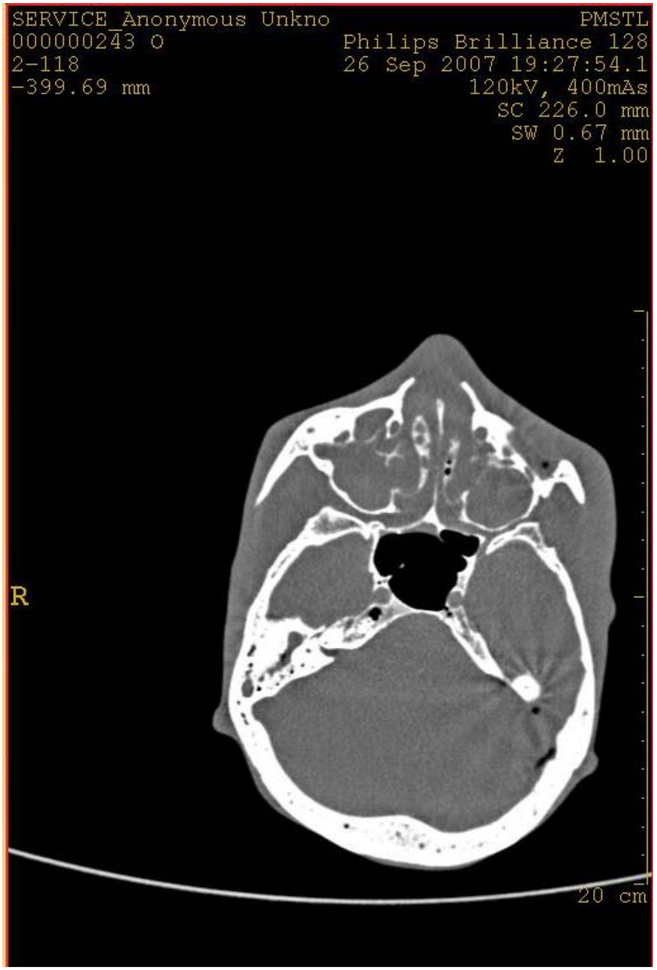
→ Latest: Top CT performance, reliable

Type: Philips iMRC

Artifact Reduction by z/x FS Deflection

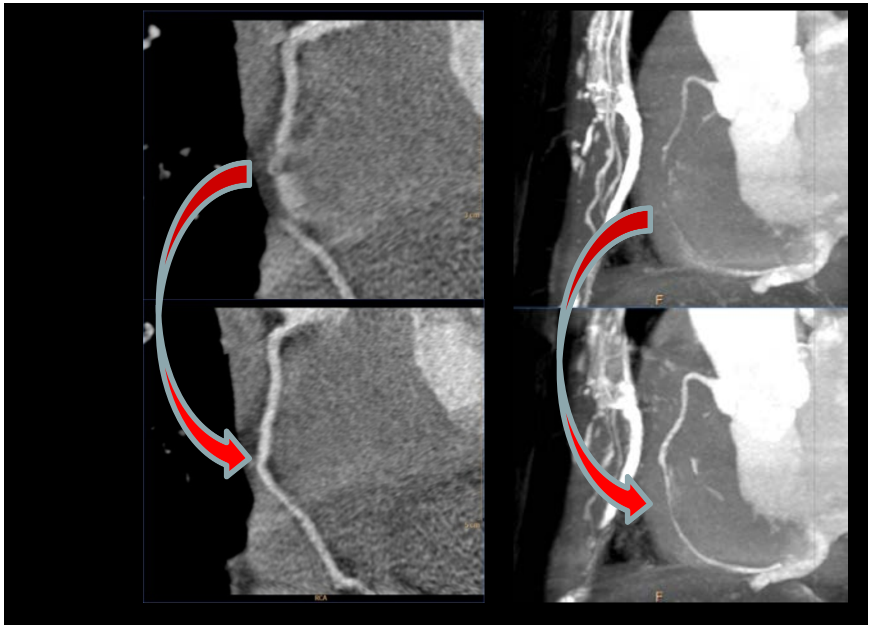


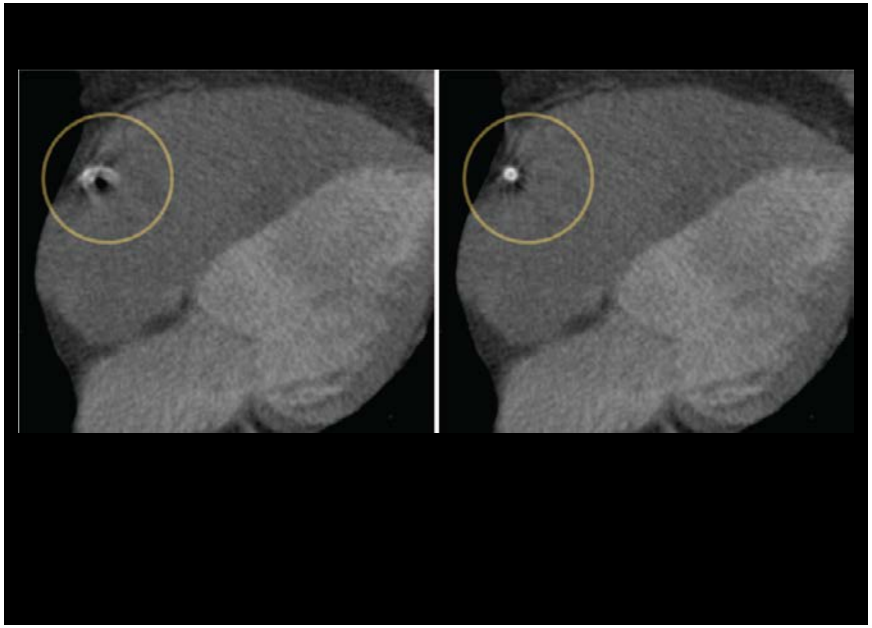
z-DFS



w/o z-DFS

Lack of Power, Gantry Speed → Motion Artifacts





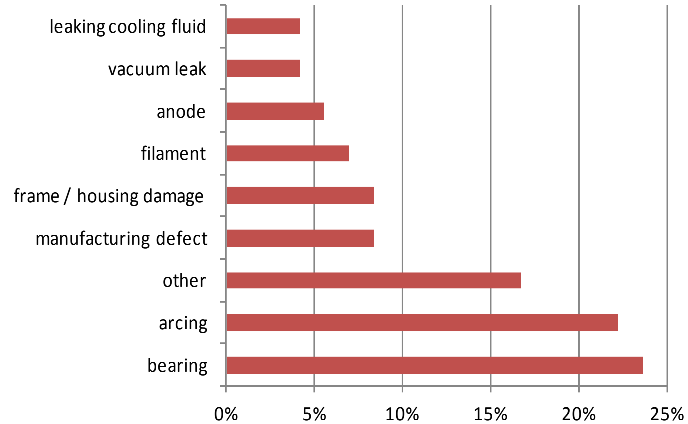
Lack of Power → Image Noise

Why has the IEC canceled Maximum Anode Heat Content (slang: “Heat Units”) in 2010?

20%	1.	IEC wanted to render the standard leaner
20%	2.	The terminology was accurate, but too complicated to communicate
20%	3.	The historic metric is misleading for current high-tier tubes.
20%	4.	It has not been used in practice anymore
20%	5.	The physics was faulty.

Tube Failures

- Arcing
- Low dose output
- Beam hardening
- Vibration / noise
- Rotor frozen
- Electron emitter fails
- Implosion
- Run-away arcing
- Field emission >~50 µA
- Heat exchanger error
- Fluid leakage
- Anode broken
- Stator burn-out
- Mechanical damage
- other



Typical failure distribution of CT tubes, av. over tube types

Tube Performance Characteristics and Comparison

Tube Type	Life, months (range, M ± SD)	Current, kAs (range, M ± SD)
Performix Ultra	7-48, 19.2 ± 12.5	16.7-239.9, 81.0 ± 45.4
Performix Pro	12-32, 22.4 ± 9.6	18.5-61.4, 44.6 ± 25.8

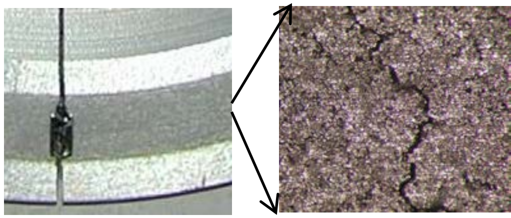
Abbreviations: M, mean; SD, standard deviation; kAs, kiloampere second.

RADIOLOGIC TECHNOLOGY, *July/August 2013, Volume 84, Number 6*

Tube life time statistics of GE CT tubes in 13 CT systems in the Sloan Kettering Center, NYC

→ Tube life time depending on concept, system type, usage, service, manufacturer

→ Broad failure distribution over time

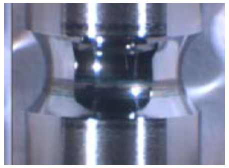
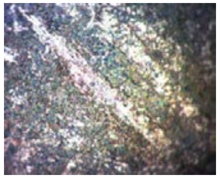

Anode crack (left), eroded focal spot track


Broken filament


Heat exchanger un-plugged → compressed


Glass coated→arcing


Arcing, craters

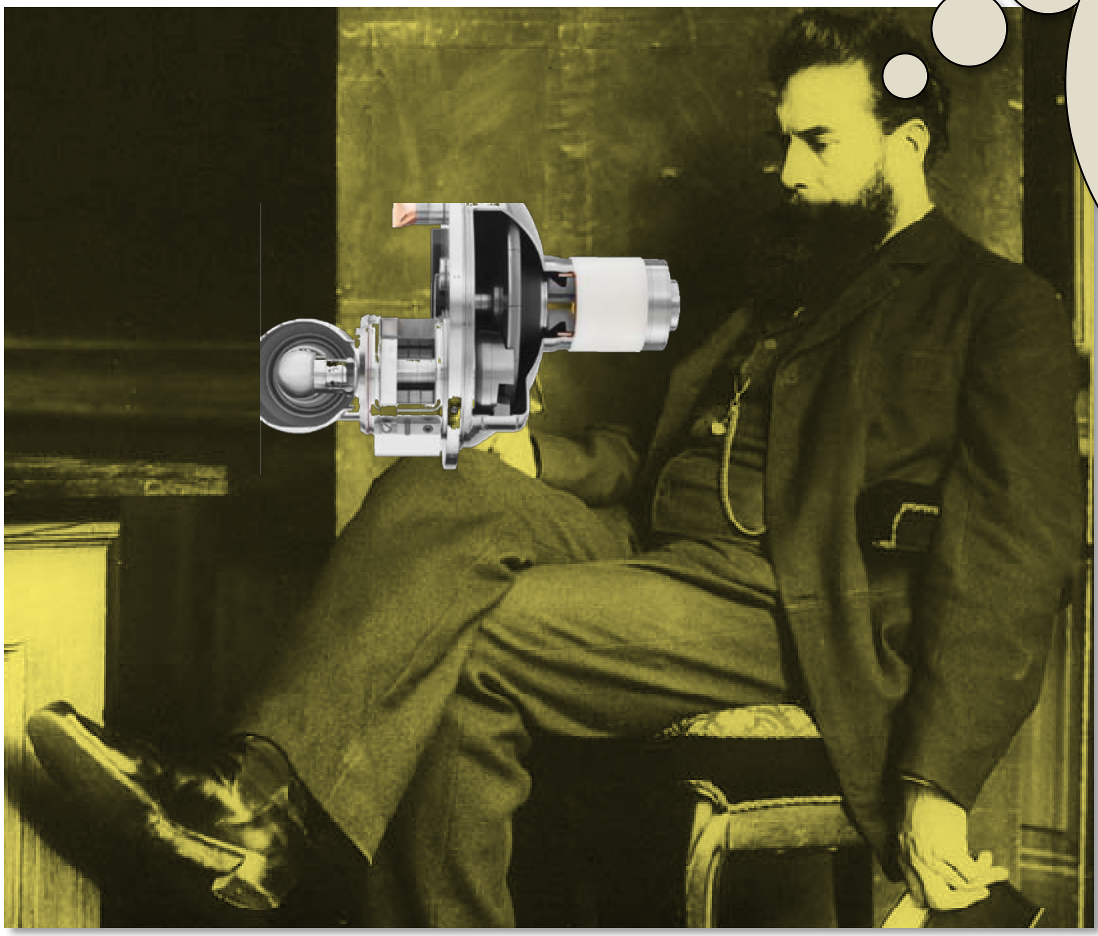


Worn-out ball raceway and ball

What can Clinicians do Better?

- Select the right equipment
  - State-of-the art metrics (no Heat Units anymore)
- Minimize tube costs
  - Single tube or multiple tubes systems?
  - Select long-life supplier (major differences)
  - Tube-included service contracts. Purchase photons, not iron
- Clinical application
  - Apply state-of-the-art de-noising technologies (power down)
  - Avoid cold-start @ high power
  - Avoid high tube current in angiography and mammography
  - Minimize fluoro time

→ How would you be driving your own car?

Röntgen 2016 …



"I am amazed,

quite a few 21st century tubes are indeed excellent!

Thank You for Listening