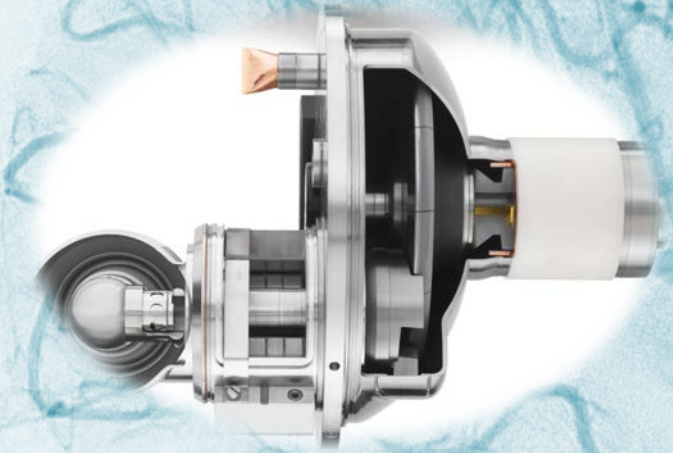
History and Future of the X-Ray Tube:

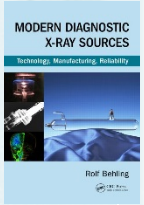
Can We Do It Better?



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

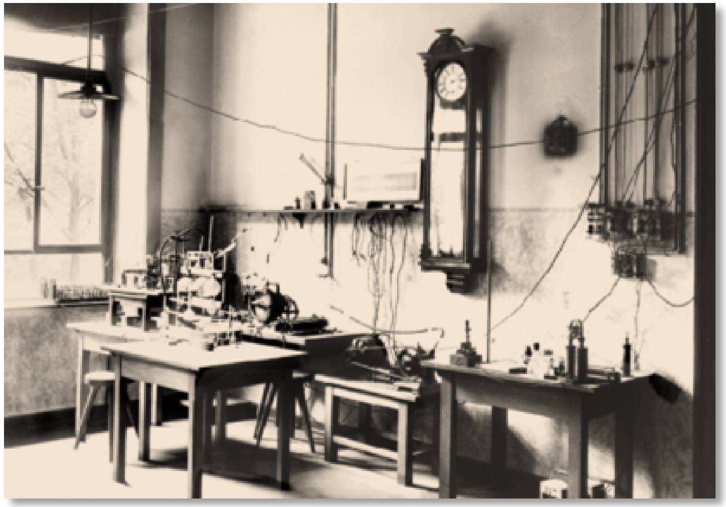


MODERN DIAGNOSTIC
X-RAY SOURCES
Technology, Manufacturing, Reliability
Rolf Behling

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."*

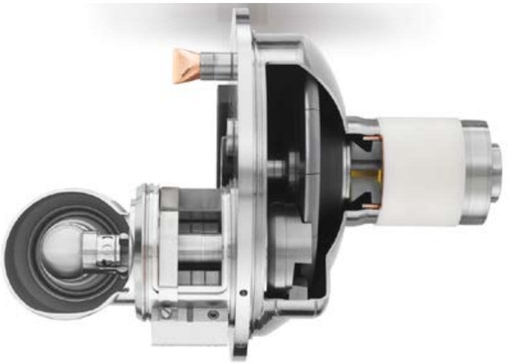
Prof. Dr. C.W. Röntgen, Jan 1897.
Translated from [7]



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

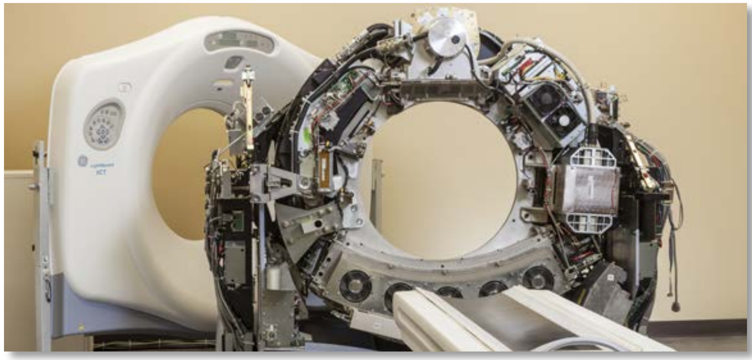
*) 2 atto (10^{-18}) \$ (good CT tube), 6 atto \$ (average CT tube)

**) yocto = 10^{-24}

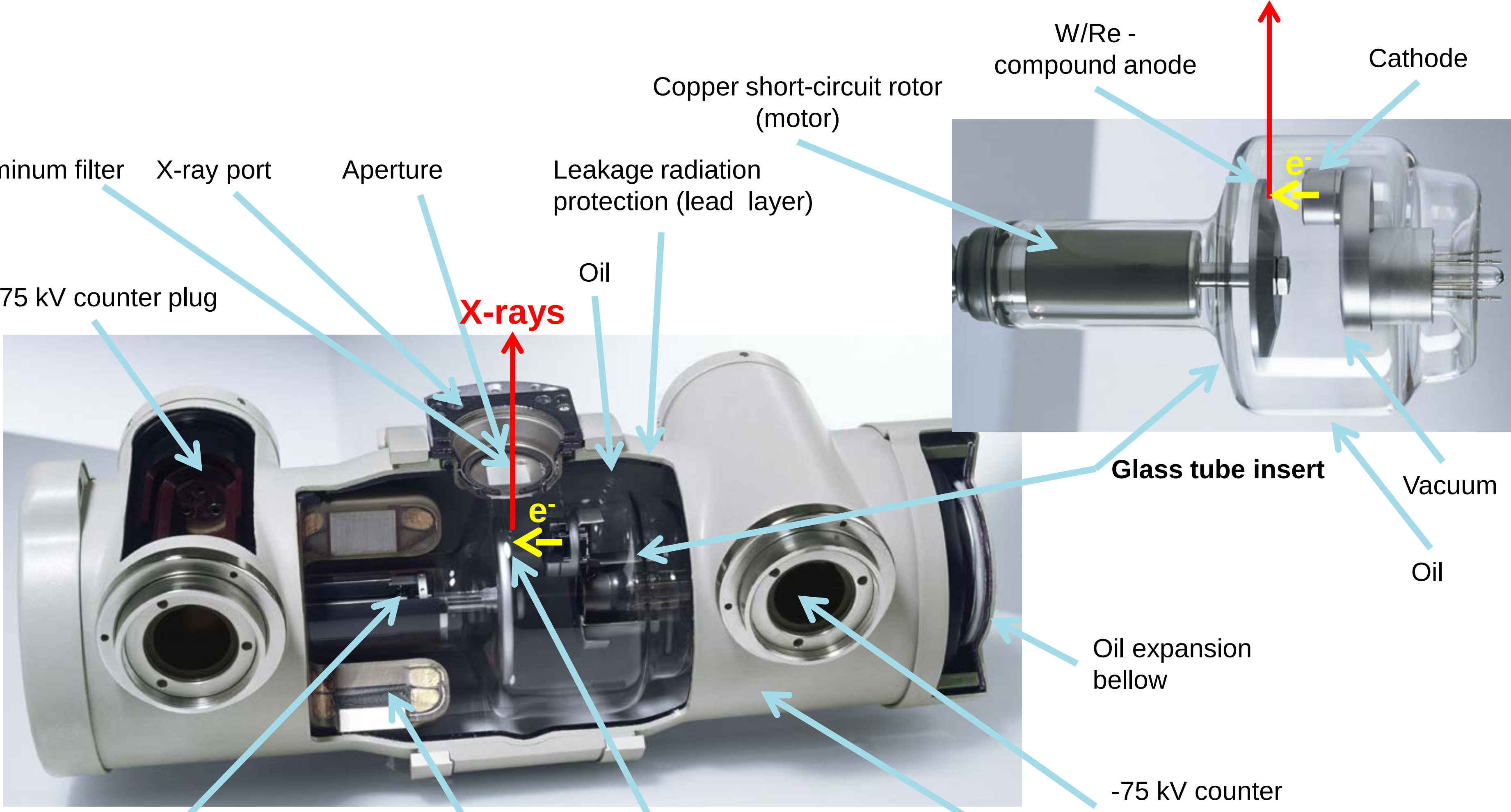
The Modalities

- 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



X-rays

W/Re - compound anode

Cathode

Copper short-circuit rotor (motor)

Aluminum filter

X-ray port

Aperture

Leakage radiation protection (lead layer)

Oil

+75 kV counter plug

X-rays

e$^-$

e$^-$

Glass tube insert

Vacuum

Oil

Oil expansion bellow

-75 kV counter plug

Bearings in vacuum

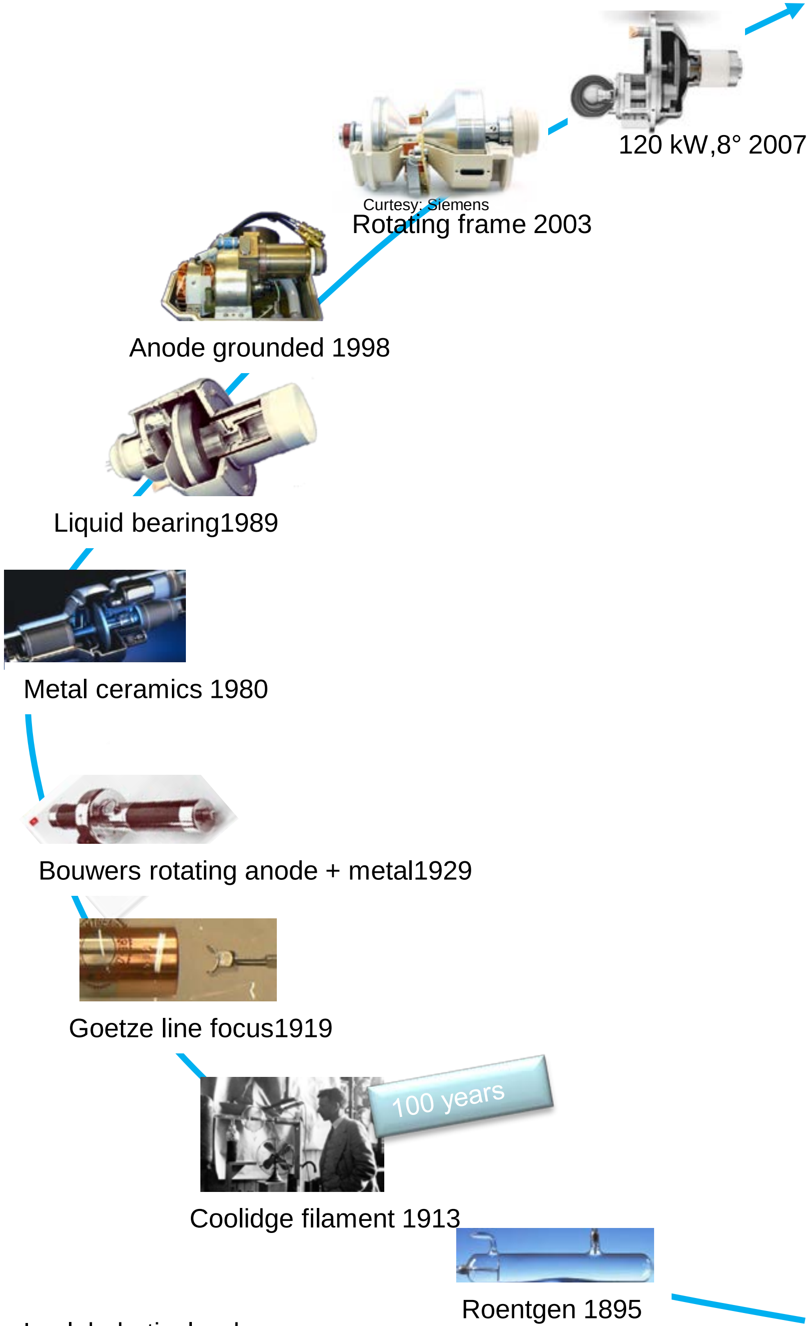
Stator coils (motor)

Origin of X-rays (focal spot)

X-ray tube housing 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



120 kW,8° 2007

Curtesy: Siemens

Rotating frame 2003

Anode grounded 1998

Liquid bearing1989

Metal ceramics 1980

Bouwers rotating anode + metal1929

Goetze line focus1919

100 years

Coolidge filament 1913

Roentgen 1895

In alphabetical order

X-Rays for Diagnostic Imaging

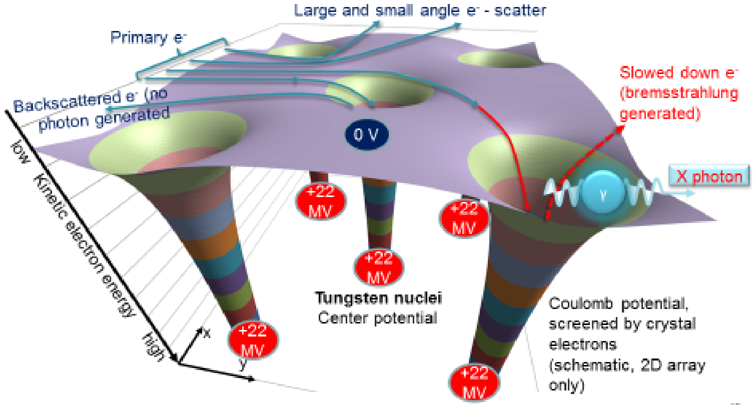
Lamor formula

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

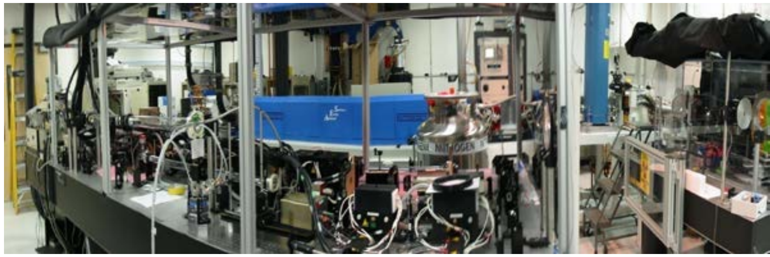
P_{light}: Light intensity; $\left|\ddot{X}\right|$: Particle acceleration

- Humans transparent for Photons ca. >16 keV
- Bremsstrahlung (electron brake-radiation)
  - – Electrons accelerated in strong nuclear E-fields (22 MV nuclei)
  - → Continuous spectrum
  - → Re-fill of voids in e^- - shells adds characteristic lines
  - → e^--scatter at free electrons in the bulk (e.g. plasmons) → heat
  - → Energetic conversion efficiency (input→ used beam) 10^{-4}
- Spatial resolution Δx limited: X-ray dose $\propto (1/\Delta x)^{3\ldots4}$
  - → Source width and length ~ 0.2…2 mm
- Alternative sources costly, not (yet?) practical
  - – Inv. Compton scatter (electrons → photons): M$ laser costs
  - – Undulators (fast electrons zig-zag in magnets): large (>>10m)
  - – Synchrotrons (circular electron tracks): large, 100’s M$
  - – Nuclear decay, not controllable
  - – …
- No X-ray LED
  - – Semicon band gap 3 eV instead of required 30 keV

→ Vacuum electronics / bremsstrahlung will remain



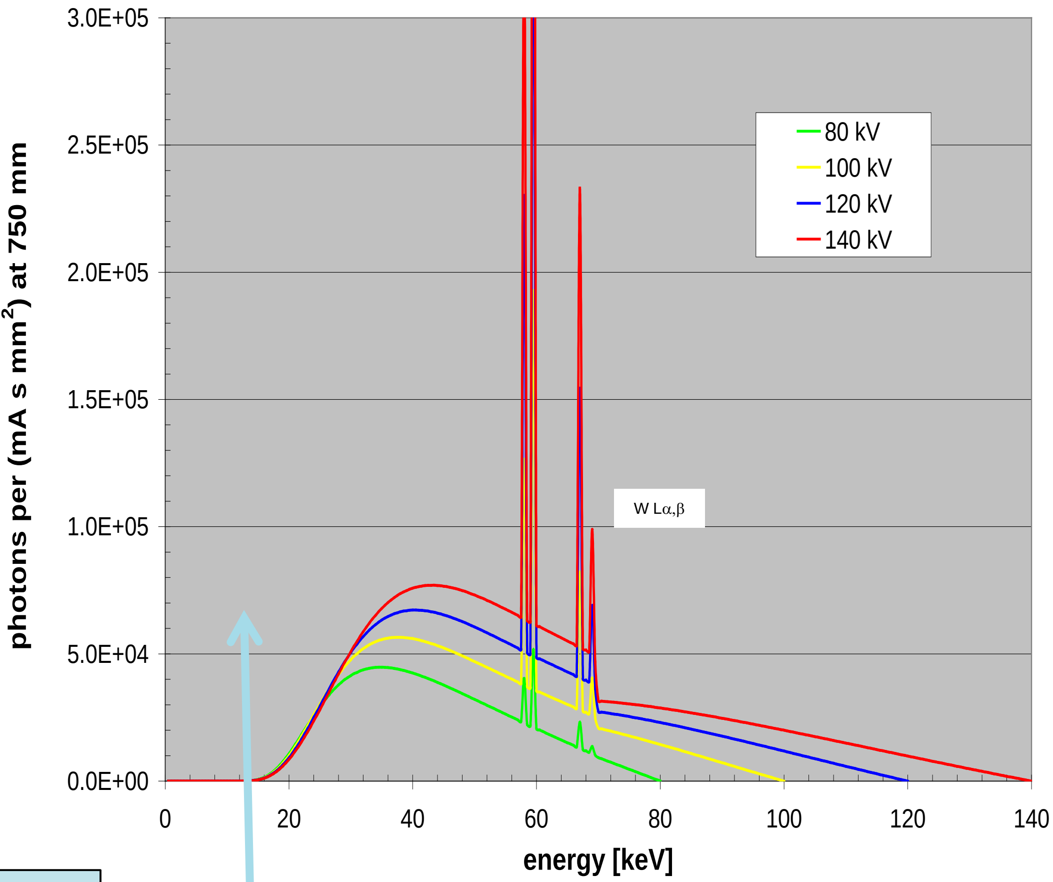
2D representation of electron acceleration and decelleration at atomic nuclei and production of bremsstrahlung photons



Inv. Compton scatter source, petawatt / femtosecond laser

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)

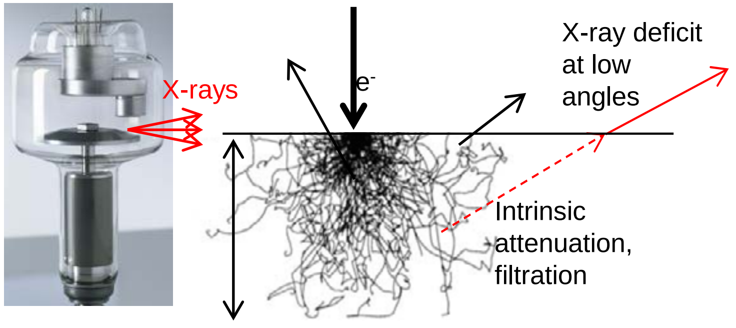


Spectrum vs. tube voltage. W-anode, 2 mm Al filter

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

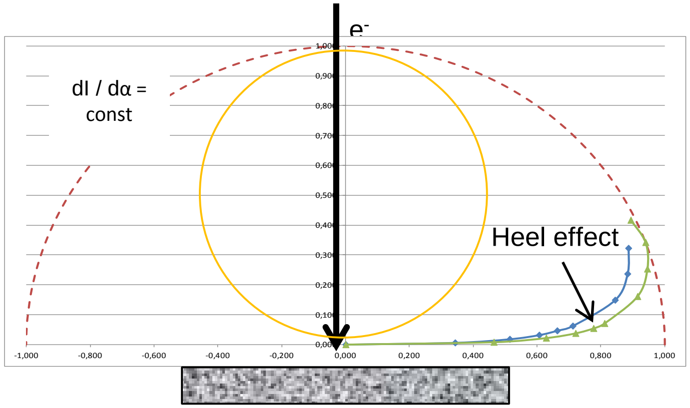
→ Fine tuning high-voltage and filtration defines the bremsstrahlung spectrum

Reflection Targets



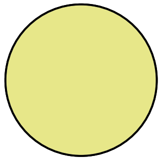
Ca 5 µm for 100 keV

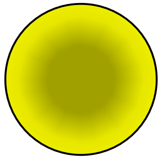
- X-rays taken off “backwards”
  - 5x…10x intensity gain with reflection target and Goetze line focus. Good for typical small take-off angle.
  - Thin targets feature relativistic forward intensity enhancement, but..
    - Enhancement is in the “wrong” direction
    - Would be good for large coverage >>40° only
    - Electron interaction <<100%
    - Cooling difficult
- X-ray and heat generated 2-10 µm deep
  - Depth of electronic interaction zone $\propto V_{tube}^{3/2}$
  - Primary electrons quickly “forgetting” their origin
  - → Polar Intensity diagram is about a half sphere
  - (other than Lambert’s law of heat radiation)
  - Heel effect (intrinsic attenuation) = reduced intensity near anode shadow



Nearly isotropic X-ray intensity from a reflection target (red, half sphere). Measured Philips SRO 2550 tube, blue: aged, green: new.
Bown: Lambert’s law of heat radiation for comparison

→ Reflection target optimal for diagnostic imaging of humans. Low take-off angle


Sun


X-ray sun
(electrons from space)

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

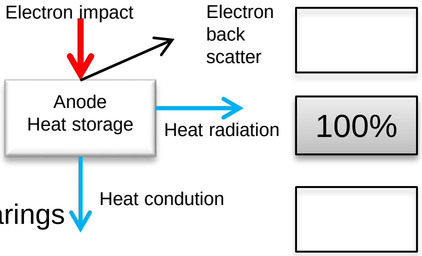
20% 4. No additional filter is needed, the target filters intrinsically

20% 5. X-ray deflection enhances the brilliance

10

Bulk Anode Cooling

Glass tube, ball bearings



Electron impact

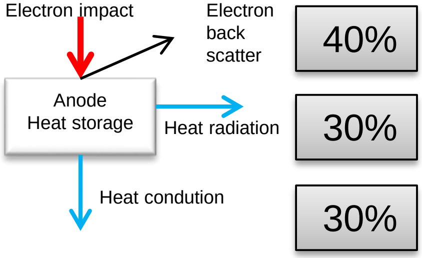
Anode
Heat storage

Electron back scatter

Heat radiation: 100%

Heat condution

Single polar, liquid bearing



Electron impact

Anode
Heat storage

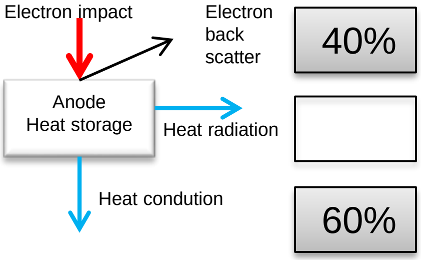
Electron back scatter: 40%

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?

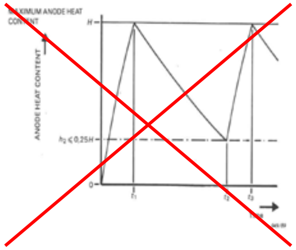
20%	1.	It is simpler to manage
20%	2.	Heat radiation is not effective at high temperatures
20%	3.	The anode can be made smaller while maintaining high performance
20%	4.	Scattered electrons provide “heat conduction”
20%	5.	Improved image processing allows using stationary target tubes in most cases

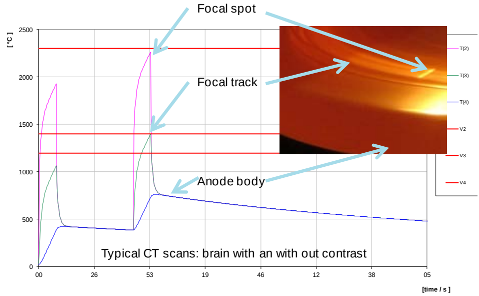
10

Historic “Mega Heat Units” are Out

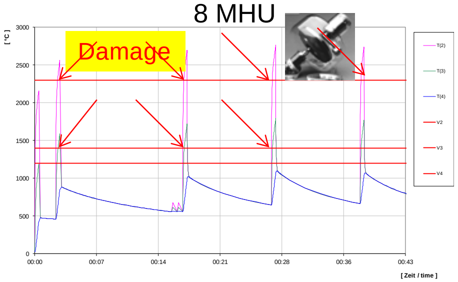
- In 2010 IEC **cancelled MAXIMUM ANODE HEAT CONTENT** (“Mega Heat Units”)
  - Misleading metric
  - For historic technology

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





Typical CT scans: brain with an with out contrast



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

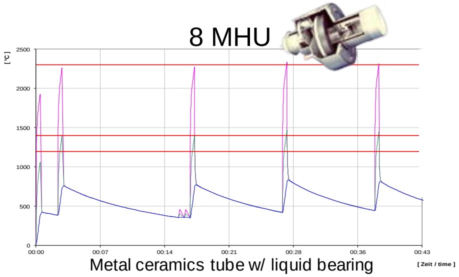
3.16 NOMINAL CT ANODE INPUT POWER

…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 $= \frac{1}{(t_{max} - t_{min})} \int_{t_{min}}^{t_{max}} P(t)\, dt$

IEC®

NEW



Metal ceramics tube w/ liquid bearing

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

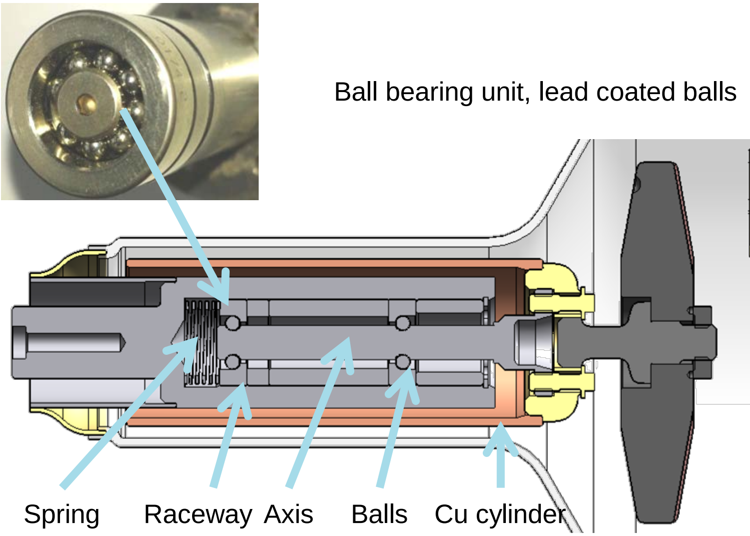
- Ball bearings
  - Hard steel, would freeze immediately w/o inter-layers

  → 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

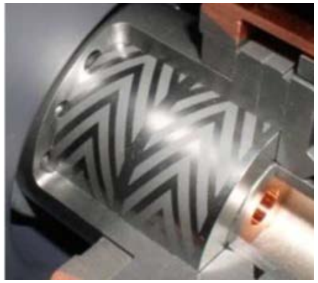
  → Continuous rotation (zero prep time)
  - Noiseless, stable, scaled to load & speed
  - Four bearings in one (2 x radial, 2 x axial),
  - Latest: dual suspended for CT (32 g)

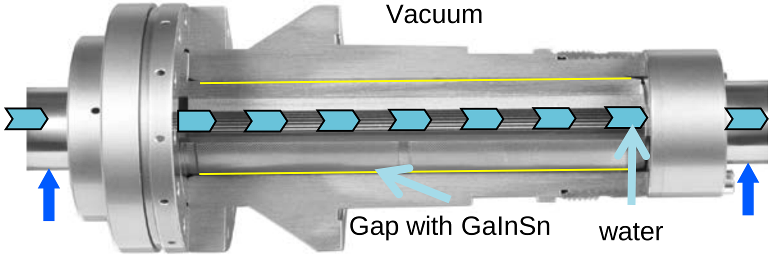
(Rotating frame tubes have well lubricated ball bearings in oil)

→ 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

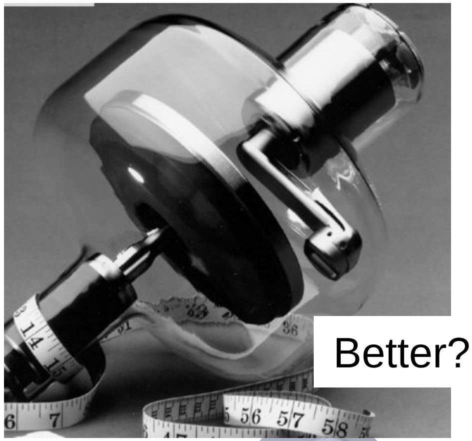
10

Product Selection: Cheaper Might be Better

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

$$I_{rotor} \propto \varnothing_{anode}^{4}$$

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



Better??

I_{rotor} : Momentum of inertia
$\varnothing_{anode}$: 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

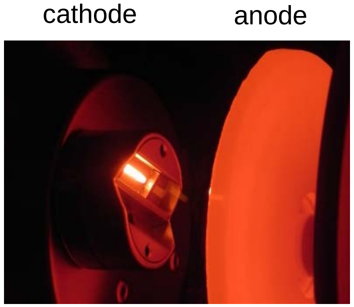
Cathode

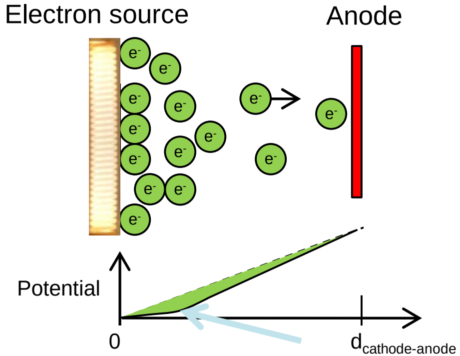
- Thermionic **emission** (e^- boiled off W-emitter)

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

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

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

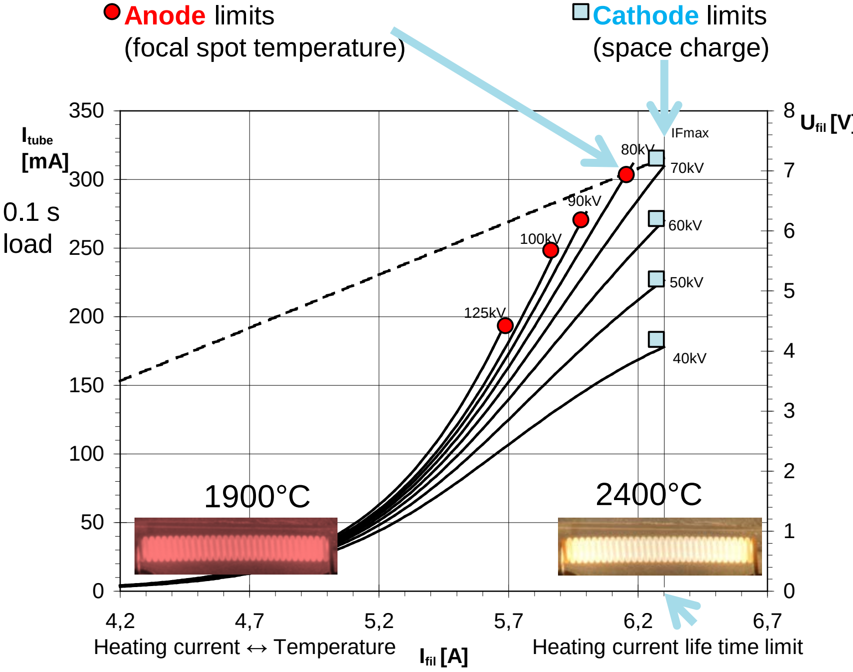




Space charge deviation, reduced pull-field at the emitter

- "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)

$d_{cathode-anode}$: 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 …

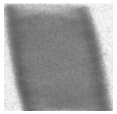
20%	1.	…good cathode performance. Space charge is minimal
20%	2.	…poor cathode performance. Space charge is maximal
20%	3.	…good anode performance
20%	4.	…a low conversion factor for electrical to X-ray energy
20%	5.	…having a poor X-ray high voltage generator

10

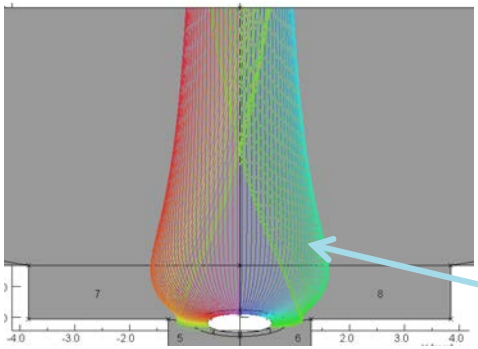
Focusing

- 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

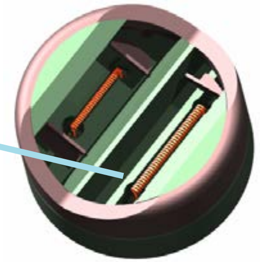
→ **Electrostatic focusing is simpler, magnetic focusing is more effective and versatile**



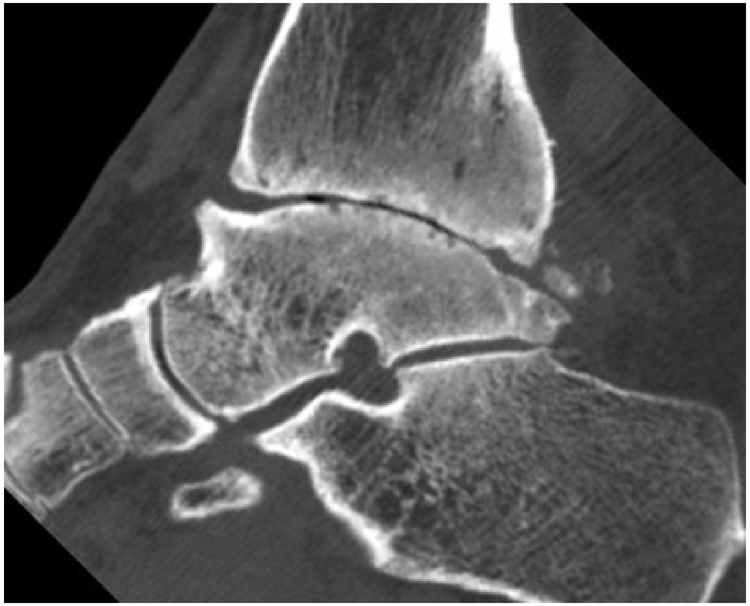
Current density profile at the anode (focal spot exposure)



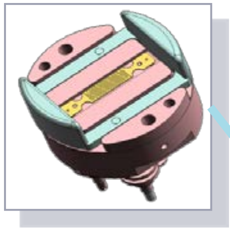
Electron beam tracing around one of the filaments. Geometry defines E-field for electrostatic focusing



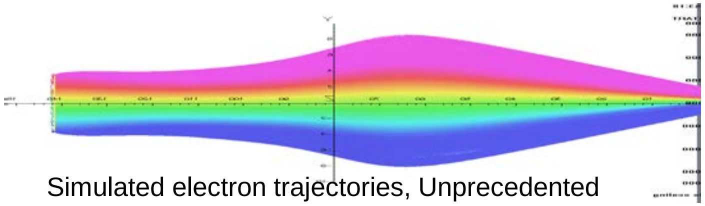
Dual filament cathode



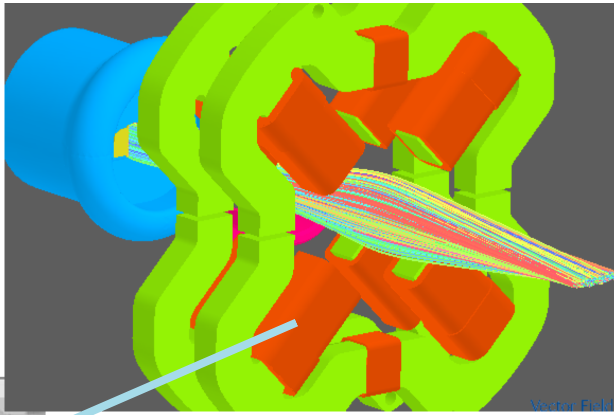
Latest: Flat Emitter+Magnetic Focusing+Deflection



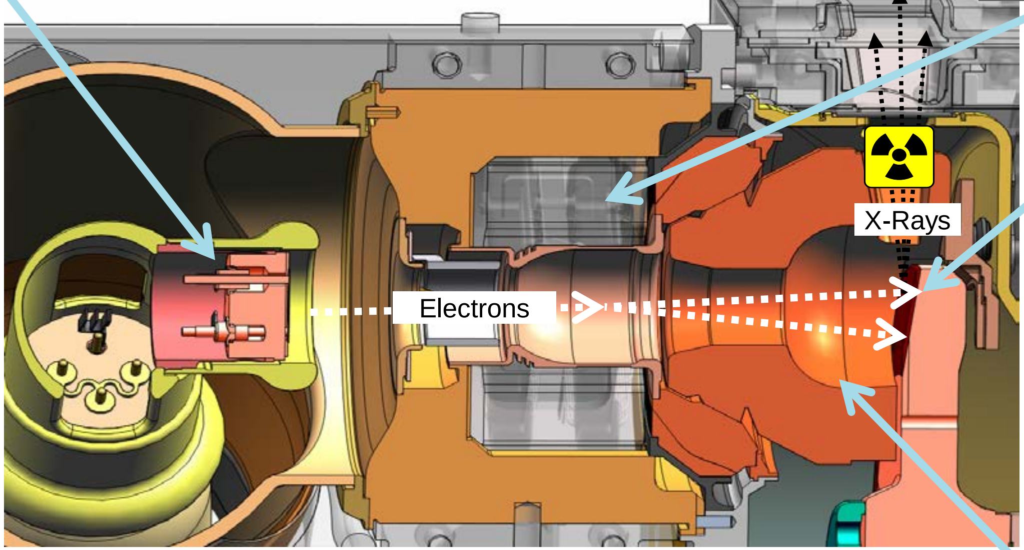
Cathode with tungsten flat emitter



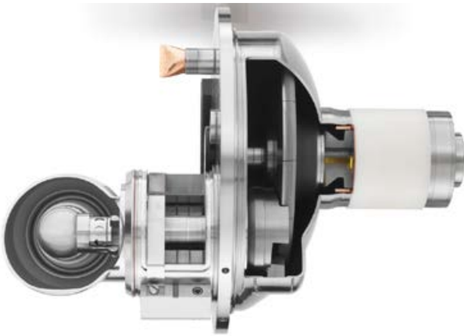
Simulated electron trajectories, Unprecedented compression, lowest isowatt point.



Double quadrupole and dipole

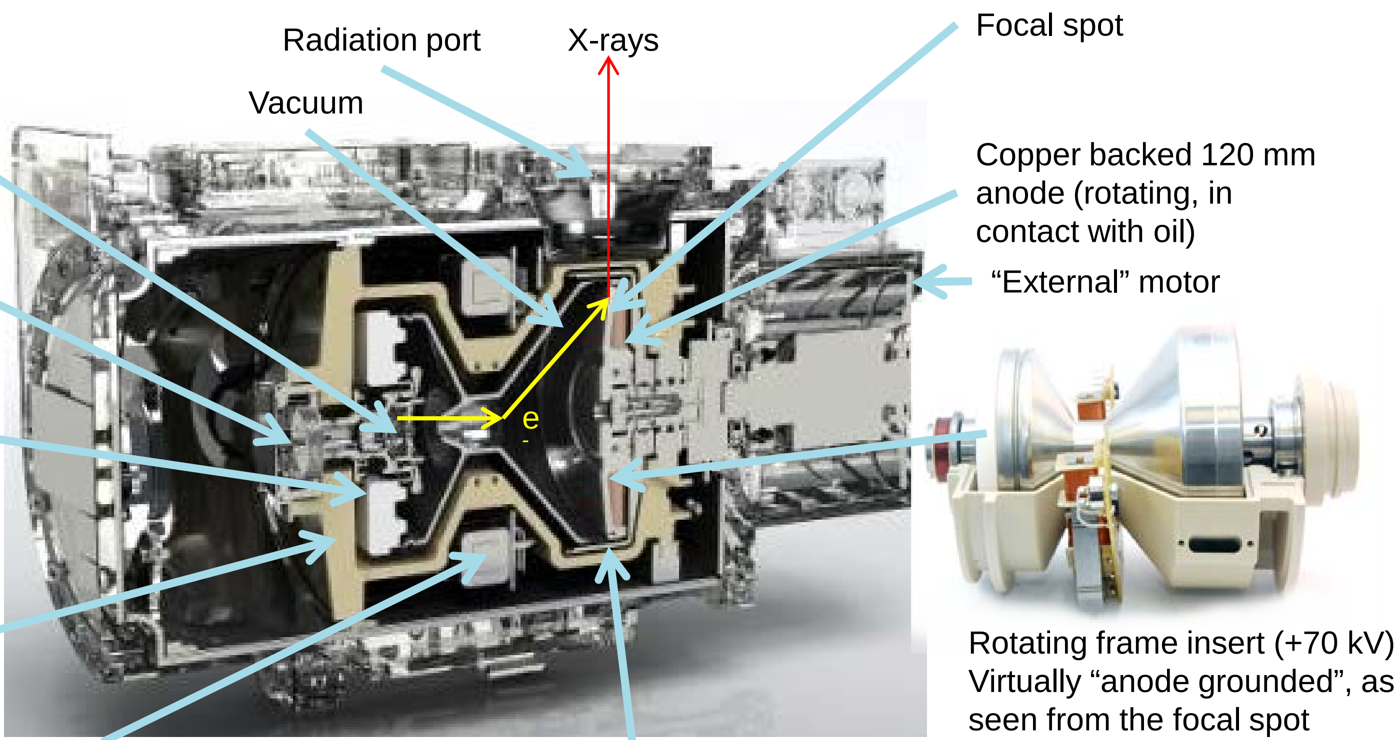


Z-deflection



Scattered Electron Collector collects 40% of the primary electron energy

A Rotating Frame CT Tube Assembly



Radiation port

X-rays

Focal spot

Vacuum

Rotating circular
cathode
(-70 kV)

Copper backed 120 mm
anode (rotating, in
contact with oil)

Rotor bearing (in oil)

“External” motor

Ceramics insulator
(rotating)

Plastics insulator

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

Yoke of the magnetic quadrupole focusing and dipole deflection unit

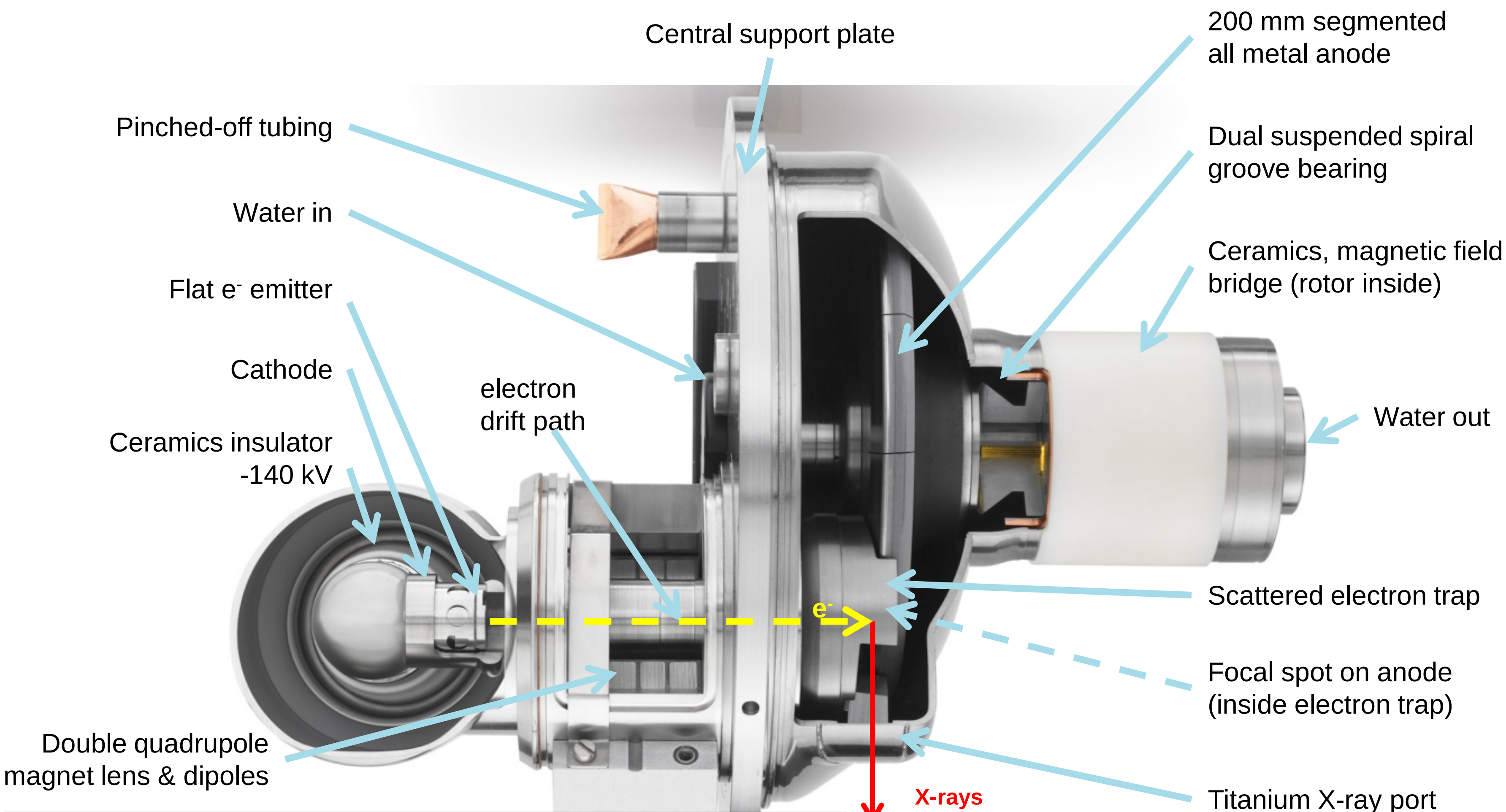
Courtesy: Siemens

Oil

→ Rotating frame = Compact

Type: Siemens Straton

A CT Tube with the Highest Power Density



→ Latest: Top CT performance, reliable

Type: Philips iMRC

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.

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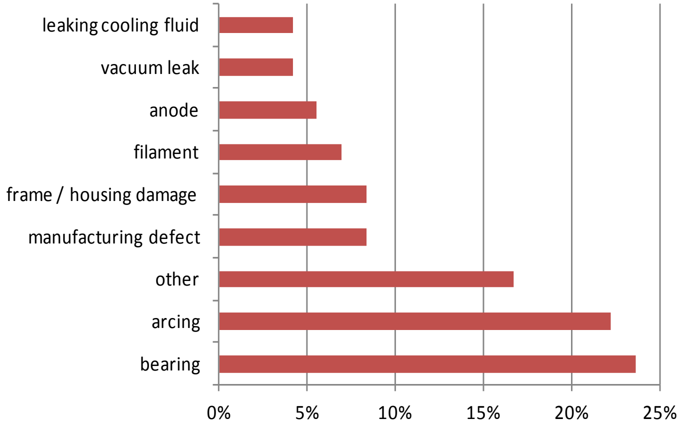
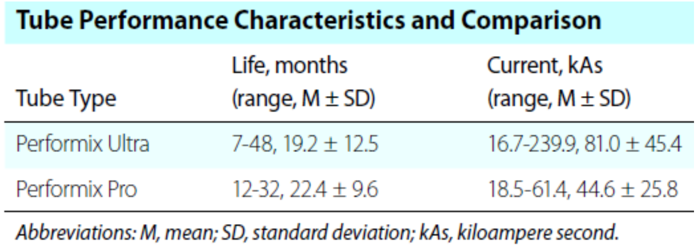
Tube Failures

- 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.

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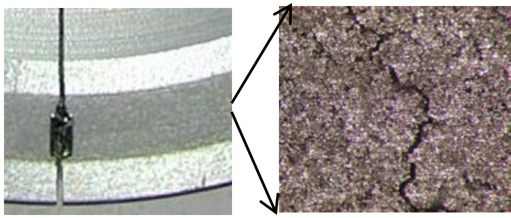
Tube life time statistics of GE CT tubes in 13 CT systems in the Sloan Kettering Center, NYC



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

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

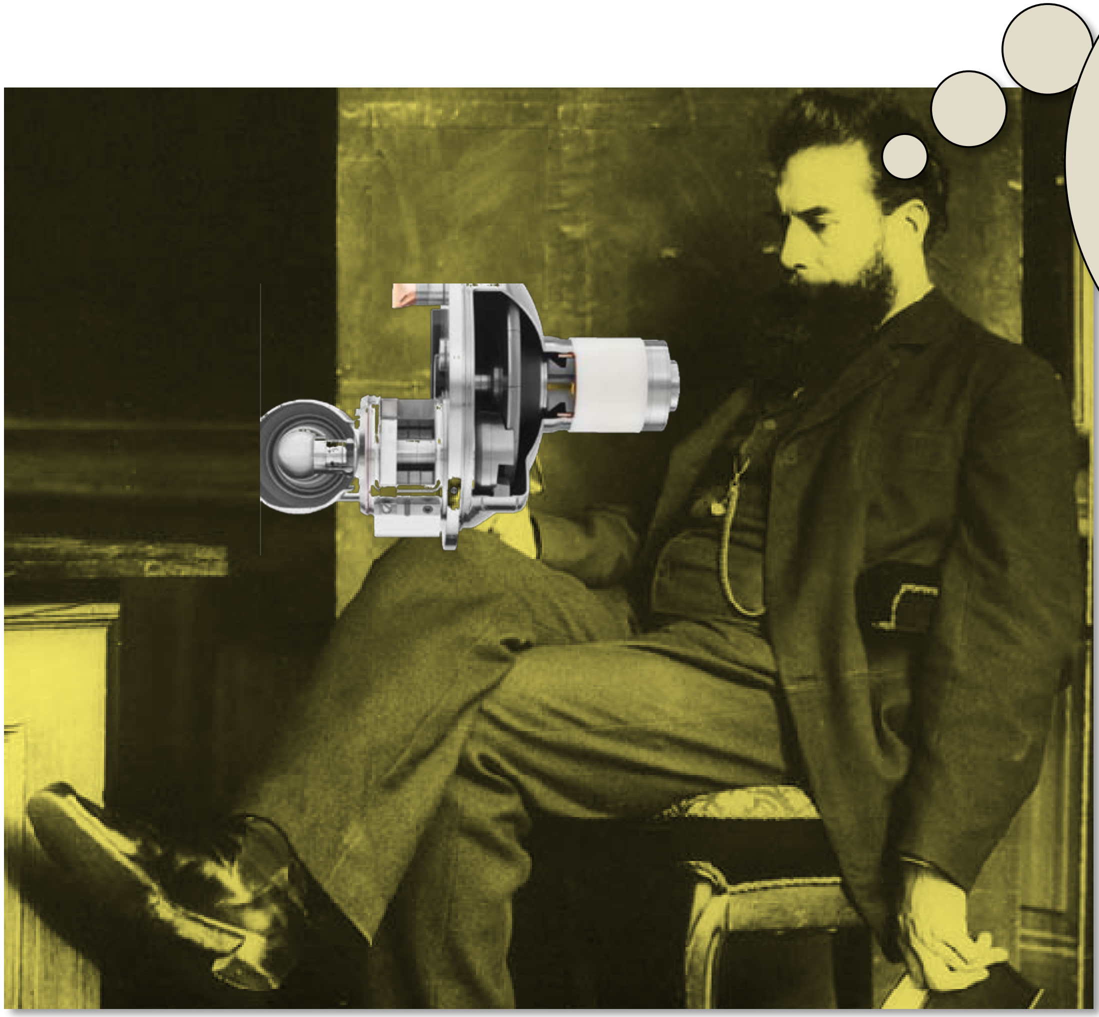
→ Broad failure distribution over time

What can Clinicians do Better?

- Selection of 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

→ Remember, how you would be driving your own car

Röntgen 2016 …



”I am amazed,

quite a few 21st century tubes are indeed excellent!

Thank You for Listening