

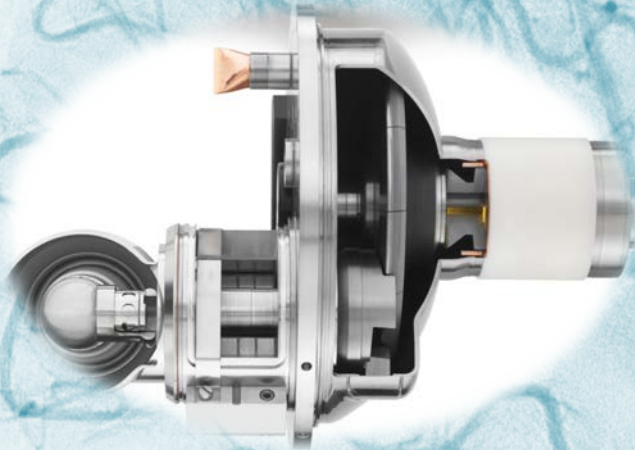
History and Future of the X-Ray Tube:

Can We Do It Better?

AAPM Clinical Spring Meeting, SLC, 2016

Rolf Behling

Royal Philips, Hamburg, Germany



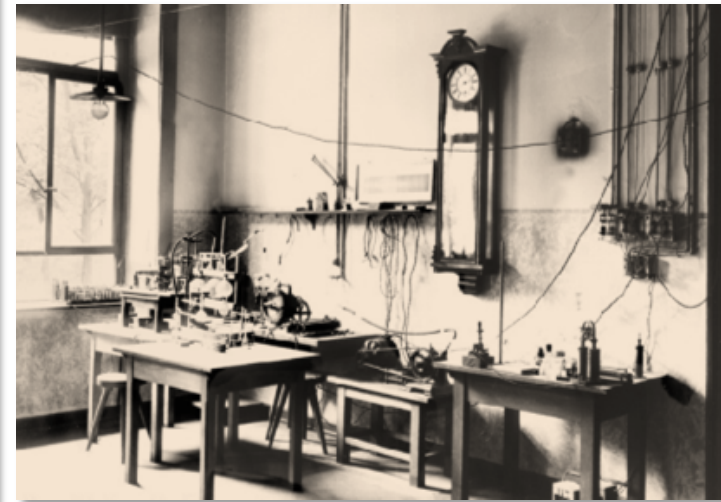
Tubes – The Year After... Roentgen Frustrated



*“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.

Courtesy of the German Röntgen Museum, Remscheid-Lennep, Germany

Questions Which You Have Never Asked

- How hot is a diagnostic X-ray beam?
- How much is such a diagnostic X-ray photon?
- Isn't this cheap?
- How much does an LED photon cost, then?
- Will we produce X-rays in LED's ?

→ 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}



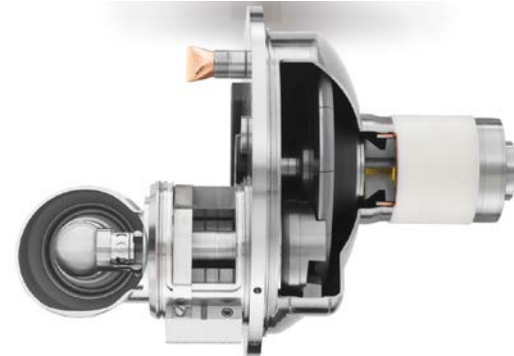
About 10 million Kelvin. That's why it hurts and is so difficult to produce.

Two atto \$ *)

No, extremely expensive

A yocto cent **)

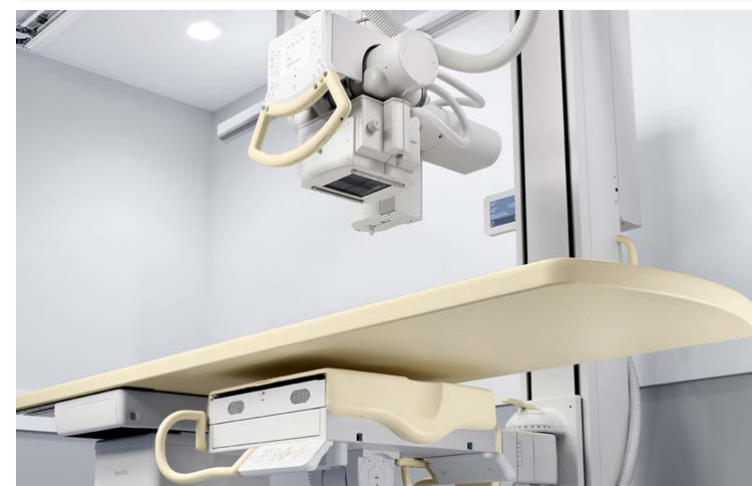
No, X-ray tubes will remain



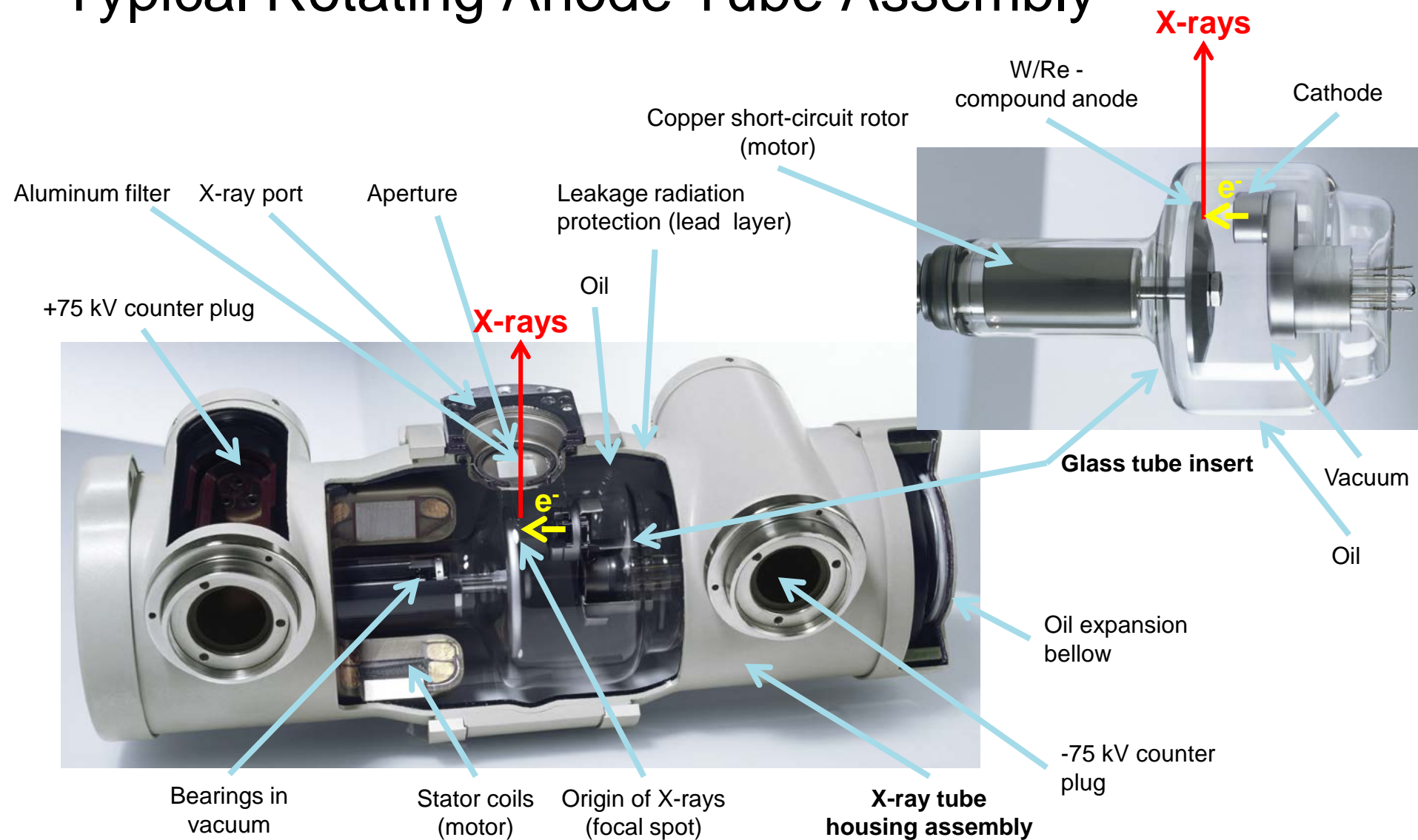
The Modalities

- 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

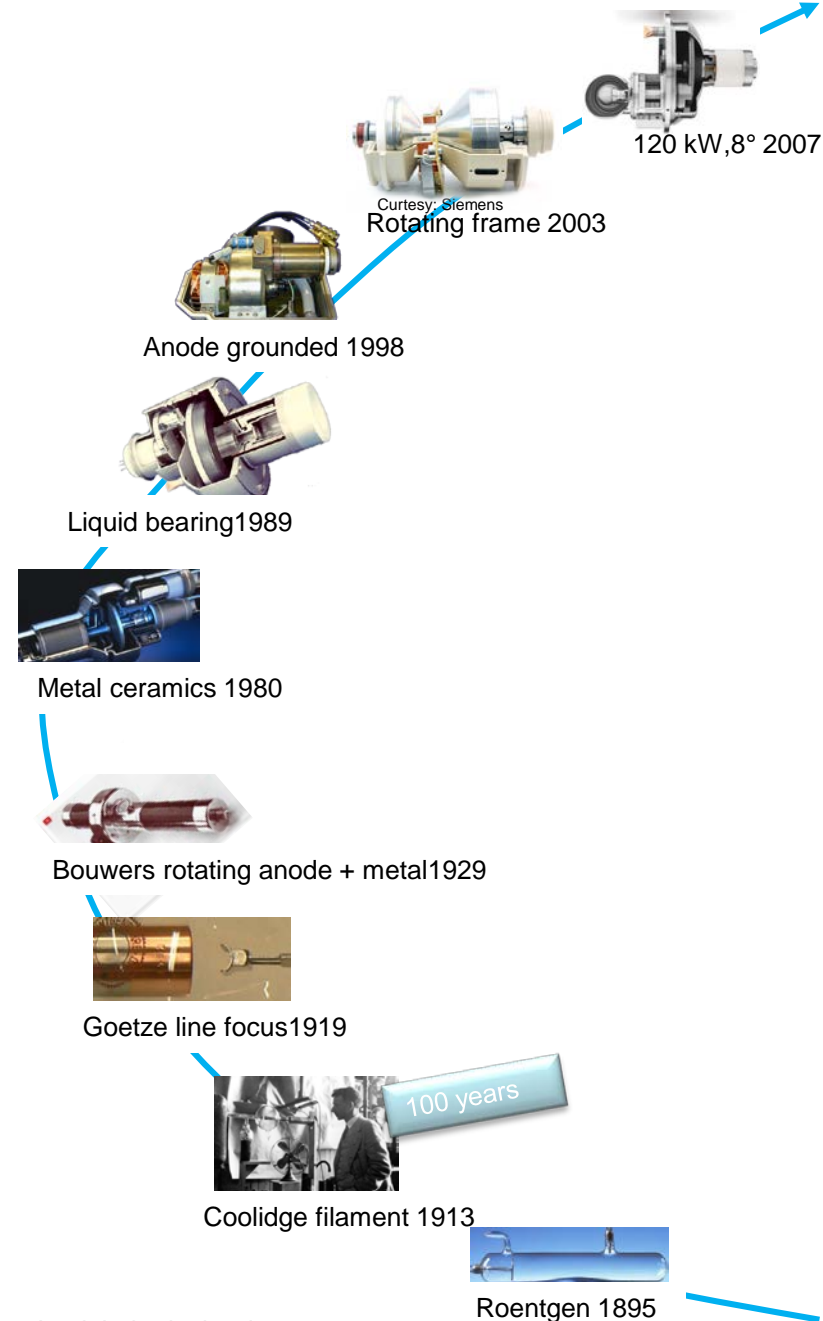


Typical Rotating Anode Tube Assembly



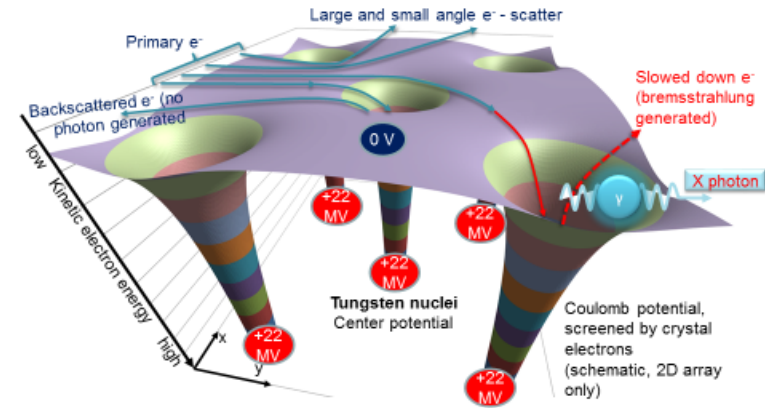
Who is Best in Class?

- 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

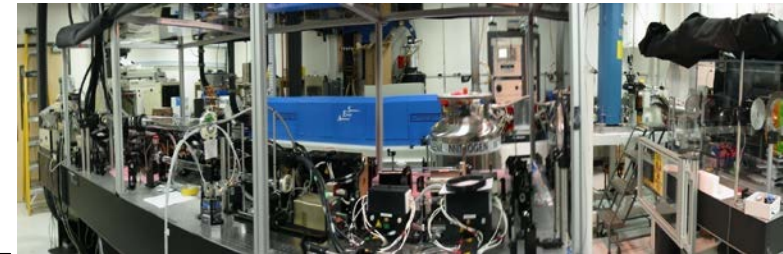


X-Rays for Diagnostic Imaging

- Humans transparent for Photons ca. >16 keV
- Bremsstrahlung (electron brake-radiation)
 - Electrons accelerated in nuclear E-fields (22 MV nuclei)
 - Continuous spectrum
 - Re-fill of e^- - shells adds characteristic lines
 - e^- -scatter at free electrons (e.g. plasmons) → heat
 - Spatial resolution limited on purpose (dose penalty $(1/\Delta x)^{3...4}$)
- Alternative sources costly, not (yet?) practical
 - Inv. Compton scatter (electrons → photons): M\$ laser costs
 - Undulators (fast electrons zig-zag in magnets): large ($>>10$ m)
 - Synchrotrons (circular electron tracks): large, 100's M\$
 - Nuclear decay, not controllable
 - ...
- No X-ray LED
 - Semiconductors band gap too small (3 eV instead of 30 keV)



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



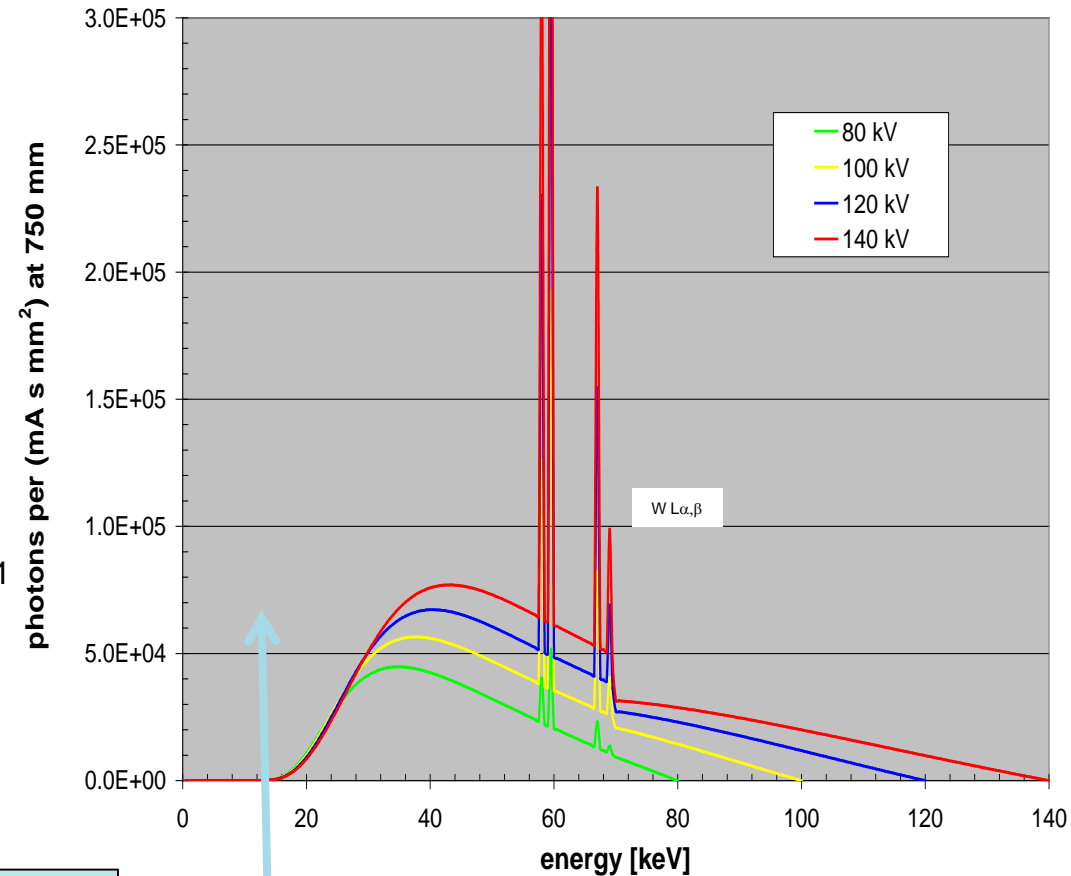
Inv. Compton scatter source, petawatt / femtosecond laser

→ Vacuum electronics / bremsstrahlung will remain

Tungsten-Spectra

- Continuum of frequencies
- Max photon energy = $|e^-| V_{\text{tube}}$
- 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)

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

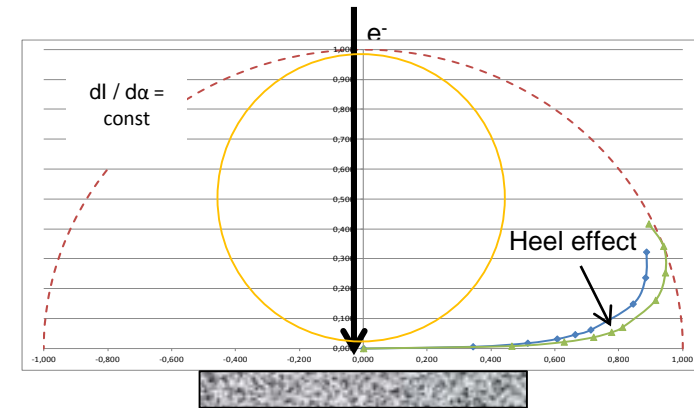
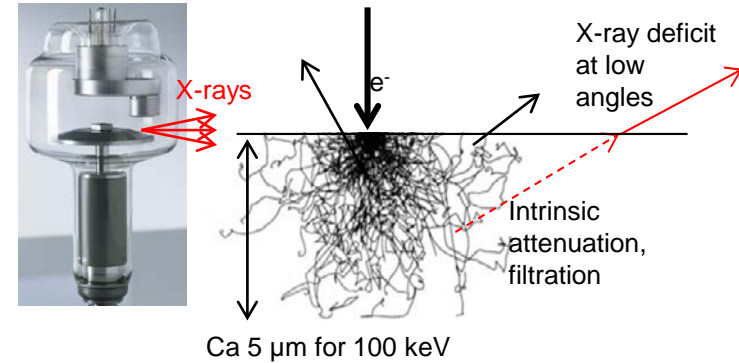


Spectrum vs. tube voltage. W-anode, 2 mm Al filter

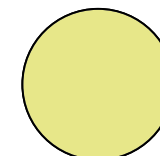
Soft radiation removed from the used beam by the X-ray filter

Reflection Targets

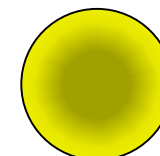
- X-rays taken off “backwards”
 - 5x...10x intensity gain with reflection target and Goetze line focus. Good for typical small take-off angle.
 - Thin targets feature relativistic forward intensity enhancement, but..
 - Enhancement is in the “wrong” direction
 - Would be good for large coverage $\gg 40^\circ$ only
 - Electron interaction $\ll 100\%$
 - Cooling difficult
- X-ray and heat generated 2-10 μm deep
 - Depth of electronic interaction zone $\propto V_{\text{tube}}^{3/2}$
 - 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



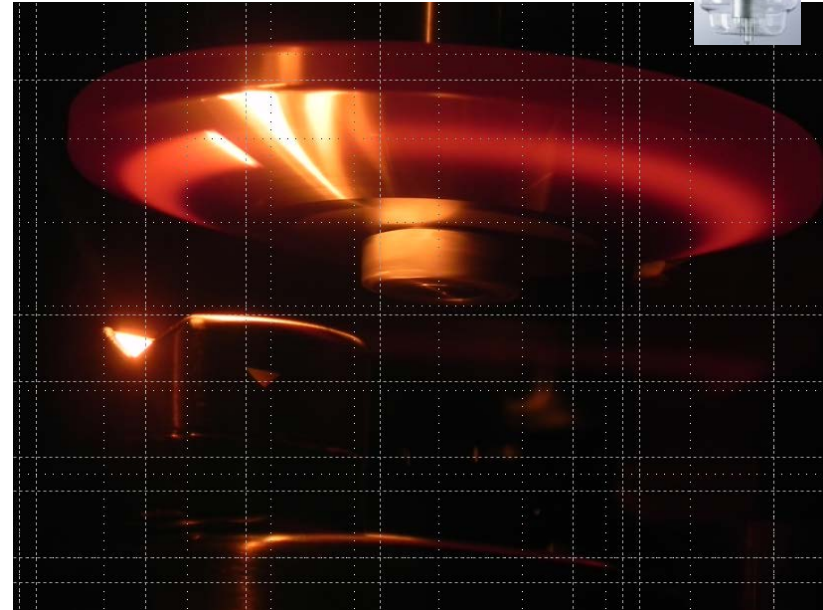
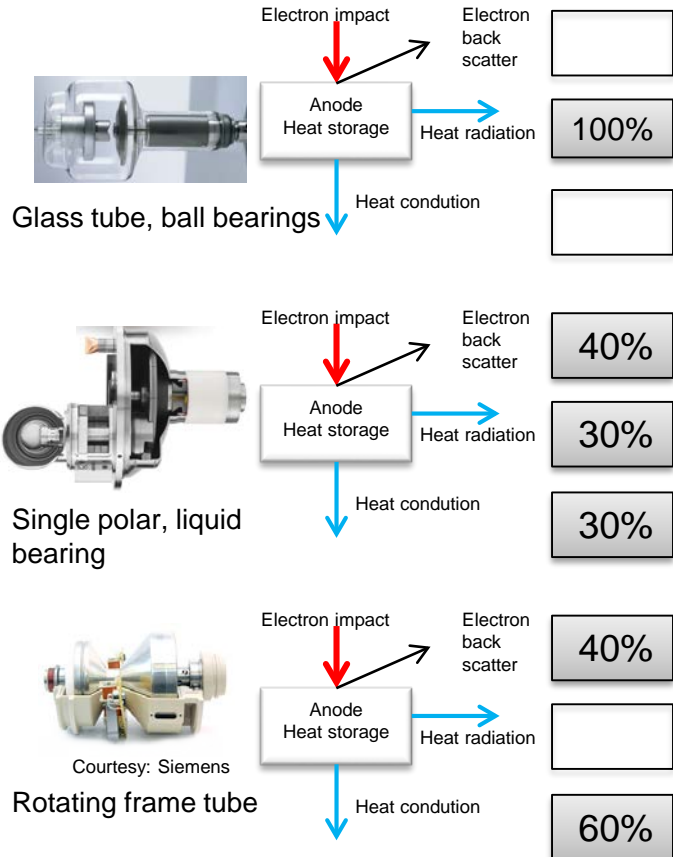
Sun



X-ray sun
 (electrons from space)

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

Bulk Anode Cooling



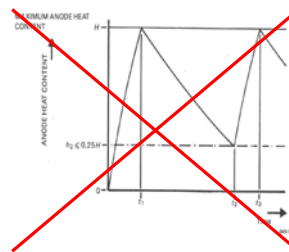
→Radiation cooling: residual heat in the anode

- 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 gets a pre-heated tube, the performance of which is limited.
 - Solution: Heat conduction (dissipating residual heat)..

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



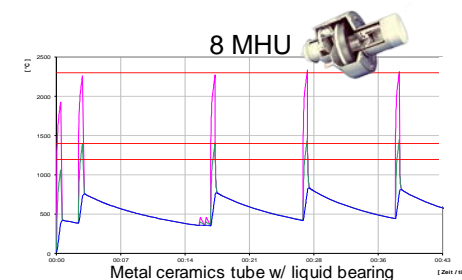
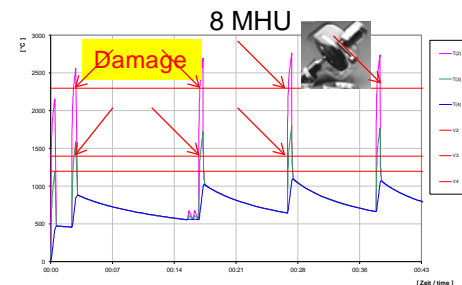
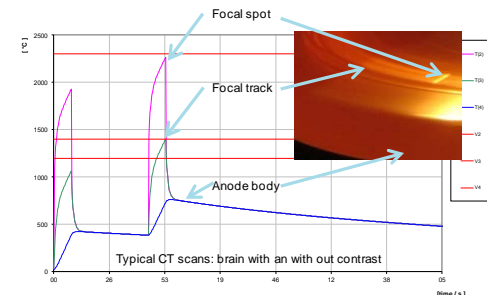
3.15 NOMINAL RADIOGRAPHIC ANODE INPUT POWER

...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

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



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

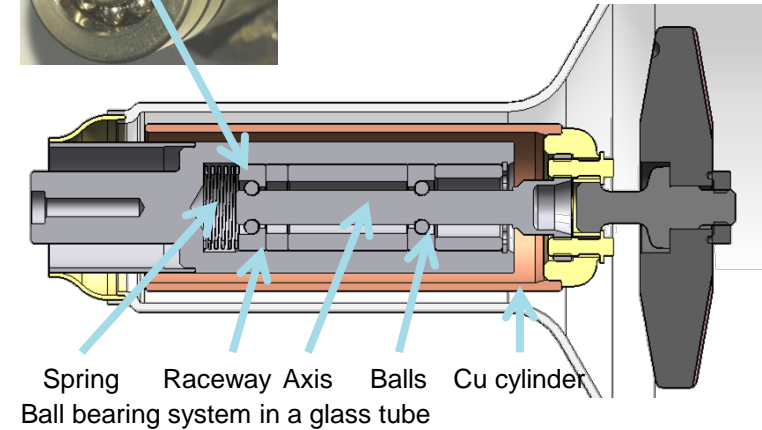
- Ball bearings
 - Hard steel, would freeze immediately w/o inter-layers
 - Ag or Pb coating of balls
 - ~1 Watt heat conduction → heat radiation cooling only
 - Limited life → Start-stop needed
 - Deterioration by high speed, load, temperature
- Spiral groove bearing system (SGB)
 - Kilowatt heat conduction
 - ~10...50 μm gaps filled with liquid GalnSn
 - 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)

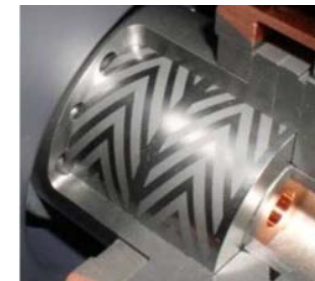
→ **Bearing type is key for tube life and practical experience (prep, cooling)**



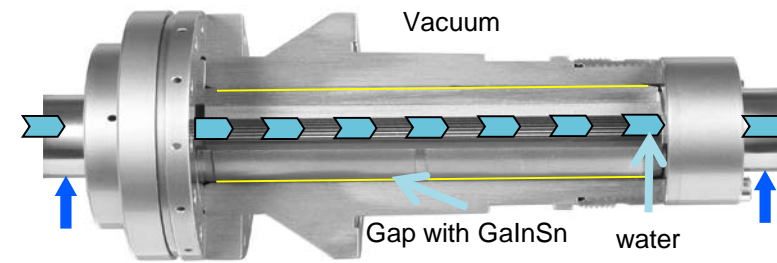
Ball bearing unit, lead coated balls



Ball bearing system in a glass tube



Two radial bearings of a liquid metal lubricated SGB.



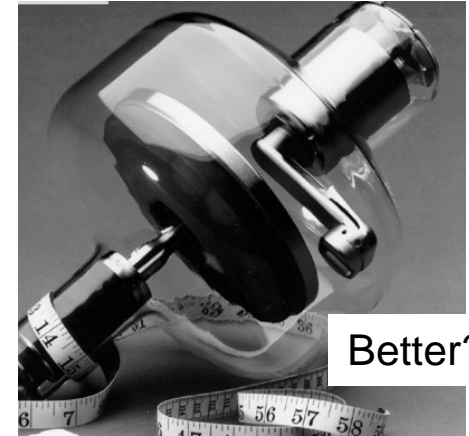
Dual suspended SGB for high centrifugal forces in CT.

Product Selection: Cheaper Might be Better

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

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

- 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
 $\varnothing_{\text{anode}}$: Anode diameter

→ Select the right tube, not always the largest

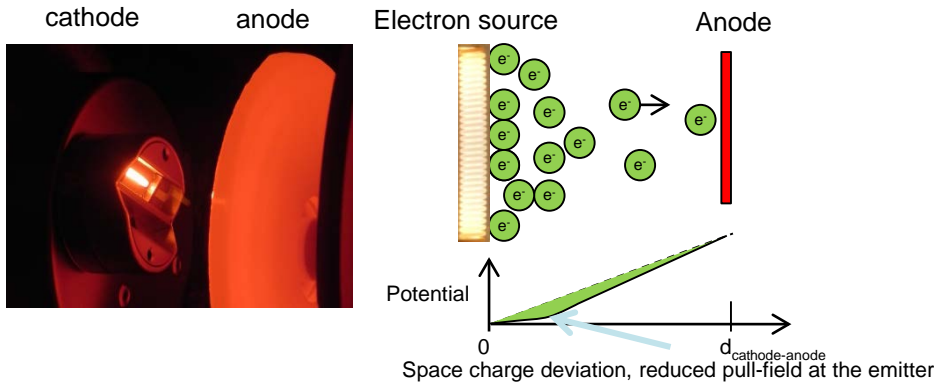
Cathode

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

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

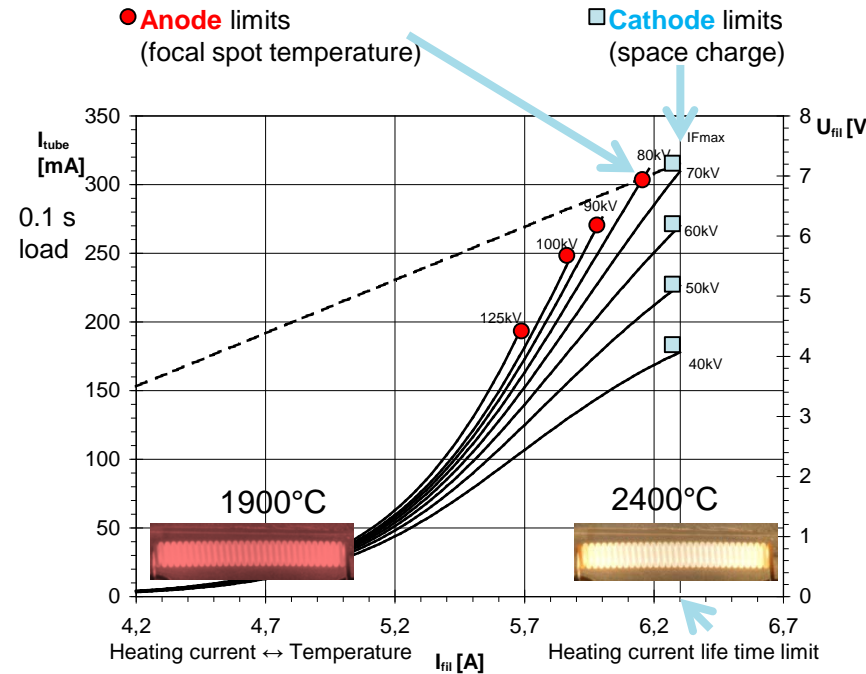
- Child's law: e⁻ **space charge** in front of emitter

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



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

→ Cathode may be limiting tube performance



Emission characteristics

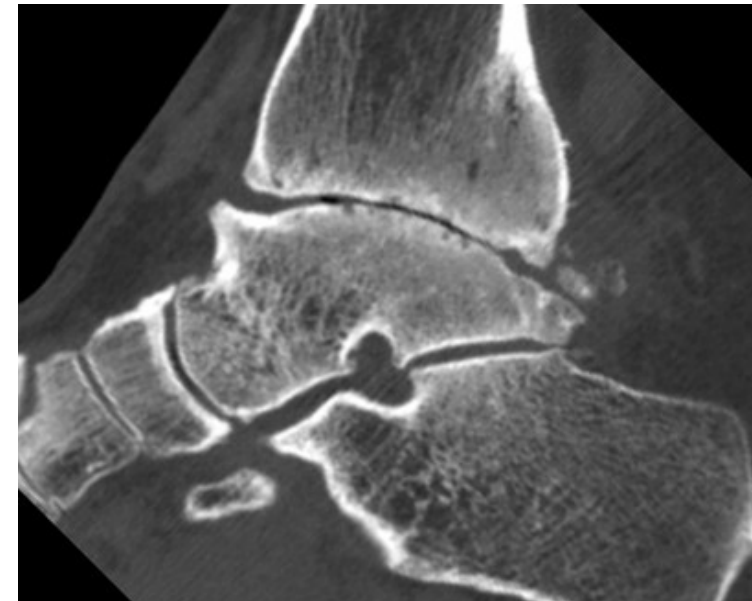
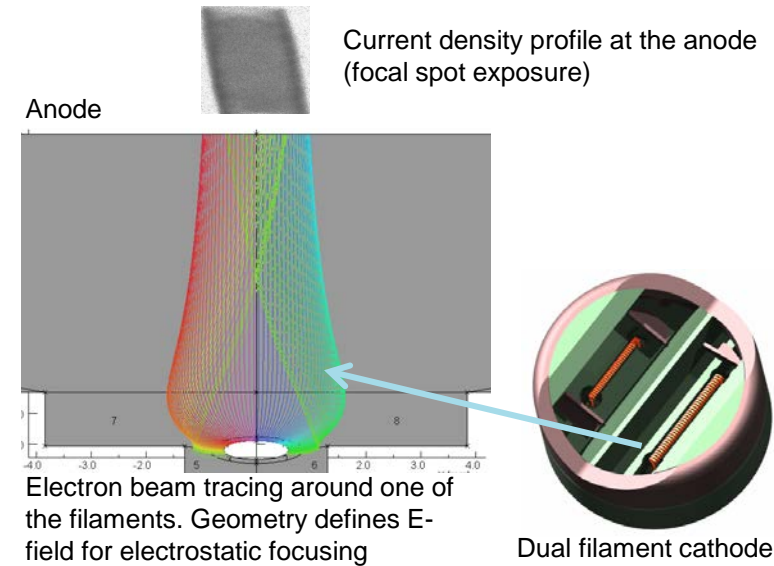
of a 0,4 (IEC 60336) focal spot (11° anode angle, 108 mm anode Ø). Isowatt point 72 kV. Observe the $V_{\text{tube}}^{3/2}$ law in the space charge regime (right, hot emitter)

$d_{\text{cathode-anode}}$: distance emitter – anode (e.g. 2 cm)
 I_{hi} : 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_{hi} : 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)

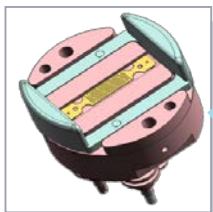
Focusing

- Electrostatic focusing (shape of cathode cup)
 - FS size independent of U_{tube} (except w/ space charge)
- Recent: Magnetic focusing
 - magnetic quadrupoles
 - Magnetic deflection \rightarrow more projections \rightarrow 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

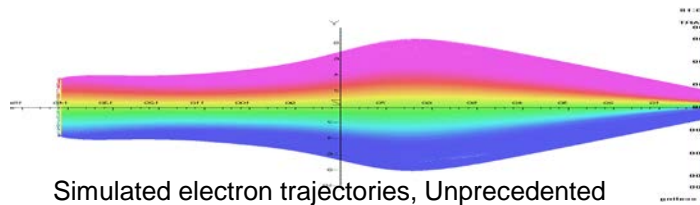
\rightarrow Electrostatic focusing is simpler, magnetic focusing is more effective and versatile



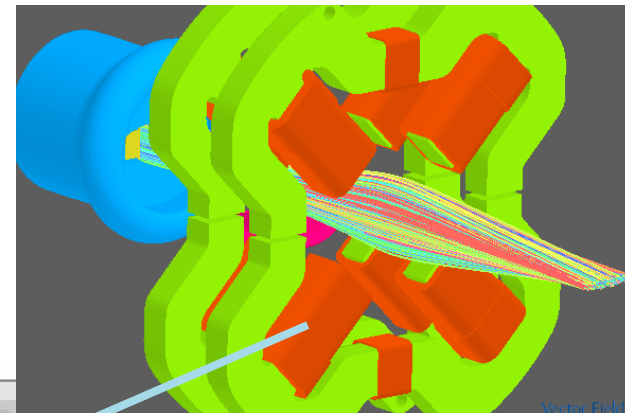
Latest: Flat Emitter+Magnetic Focusing+Deflection



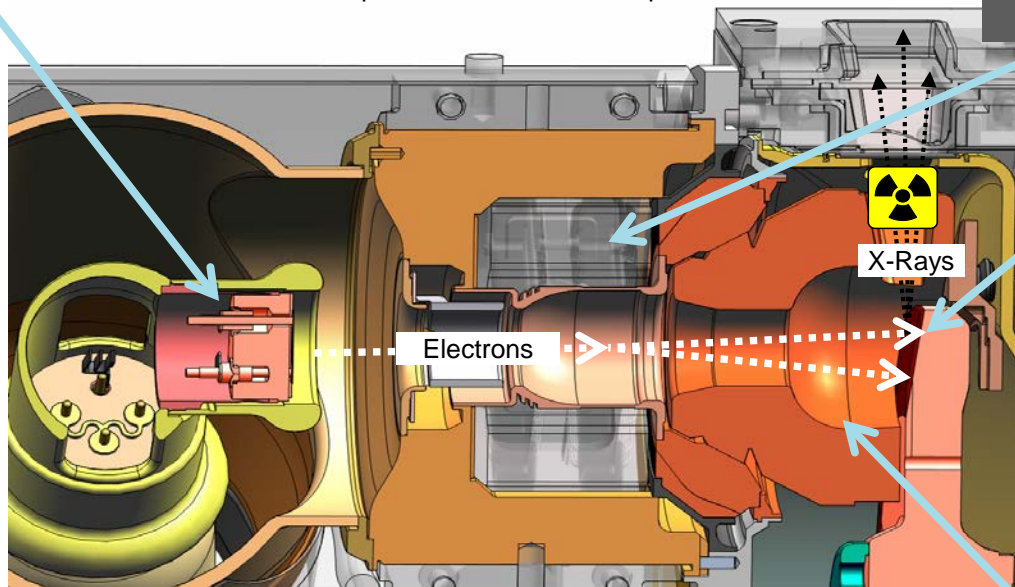
Cathode with tungsten flat emitter



Simulated electron trajectories, Unprecedented compression, lowest isowatt point.



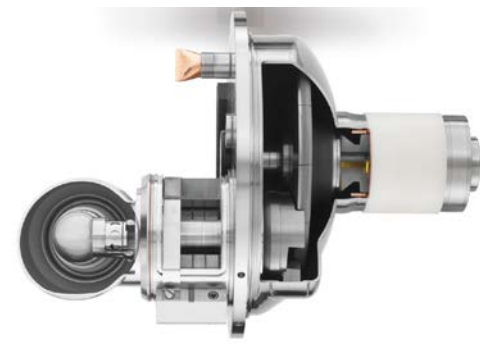
Double quadrupole and dipole



Electrons

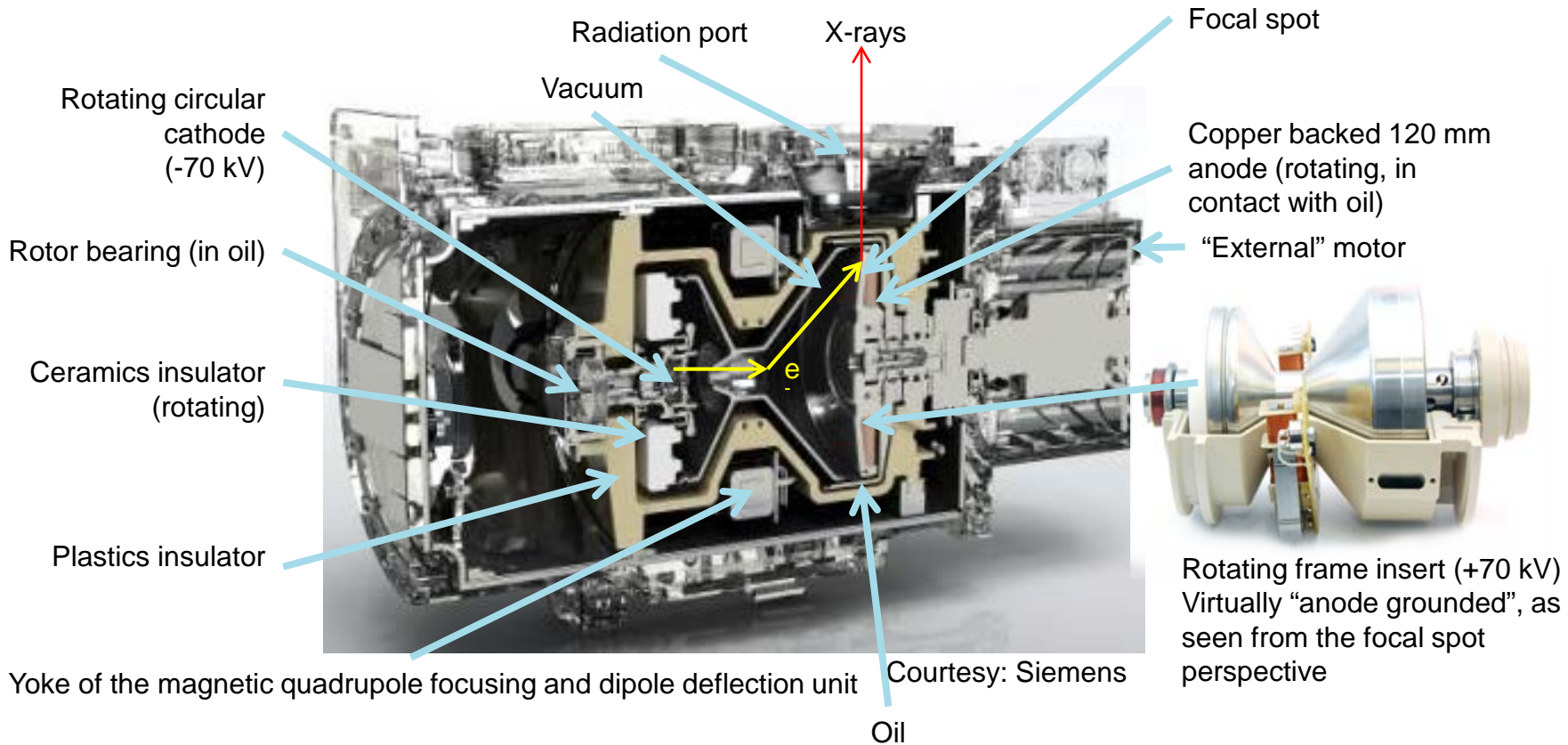
X-Rays

Z-deflection



Scattered Electron Collector collects 40% of the primary electron energy

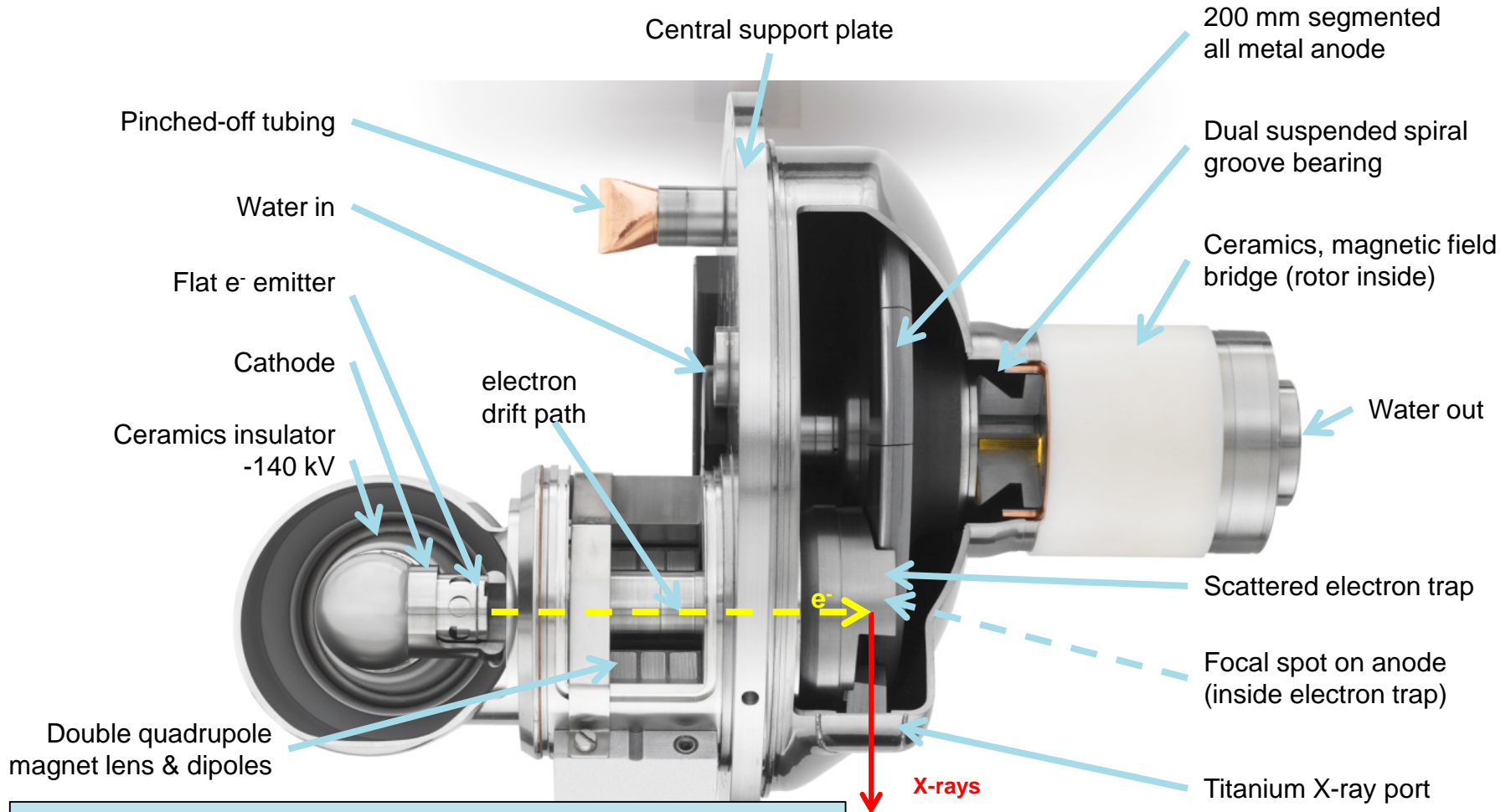
A Rotating Frame CT Tube Assembly



→ Rotating frame = Compact

Type: Siemens Straton

A CT Tube with the Highest Power Density

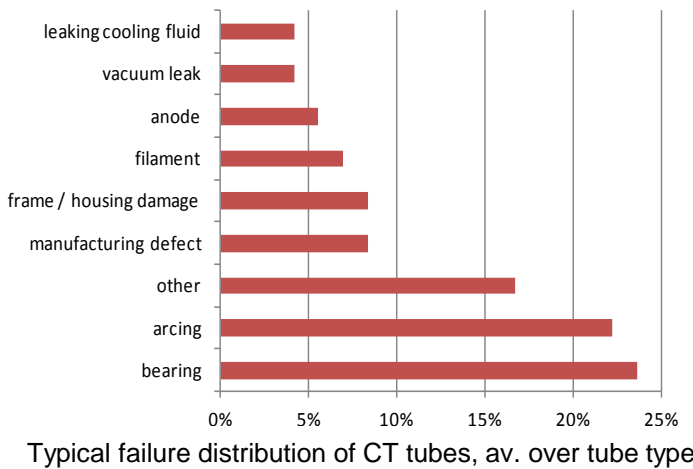


→ Latest: Top CT performance, reliable

Type: Philips iMRC

Tube Failures

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



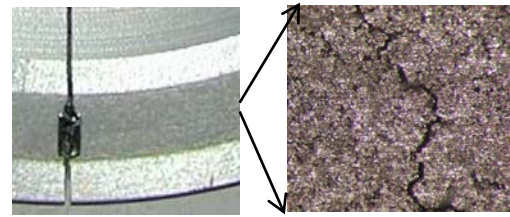
Tube Performance Characteristics and Comparison

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

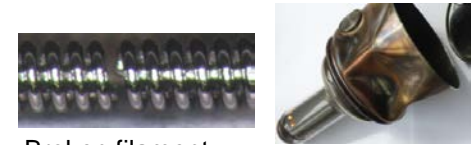
Abbreviations: M, mean; SD, standard deviation; kAs, kiloampere second.

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

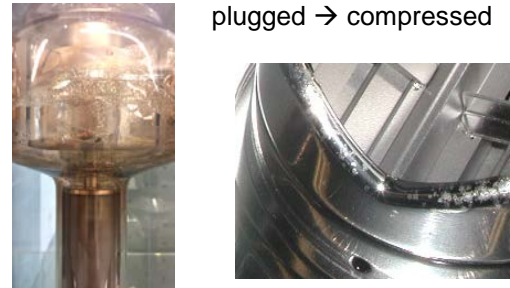
→ Tube life time depending on concept, system type, usage, service, manufacturer
 → Broad failure distribution over time



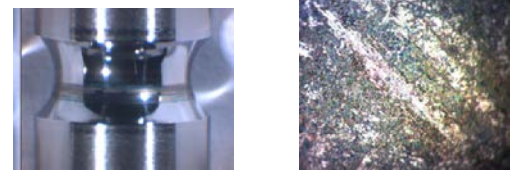
Anode crack (left), eroded focal spot track



Broken filament Heat exchanger unplugged → compressed



Glass coated → arcing Arcing, craters



Worn-out ball raceway and ball

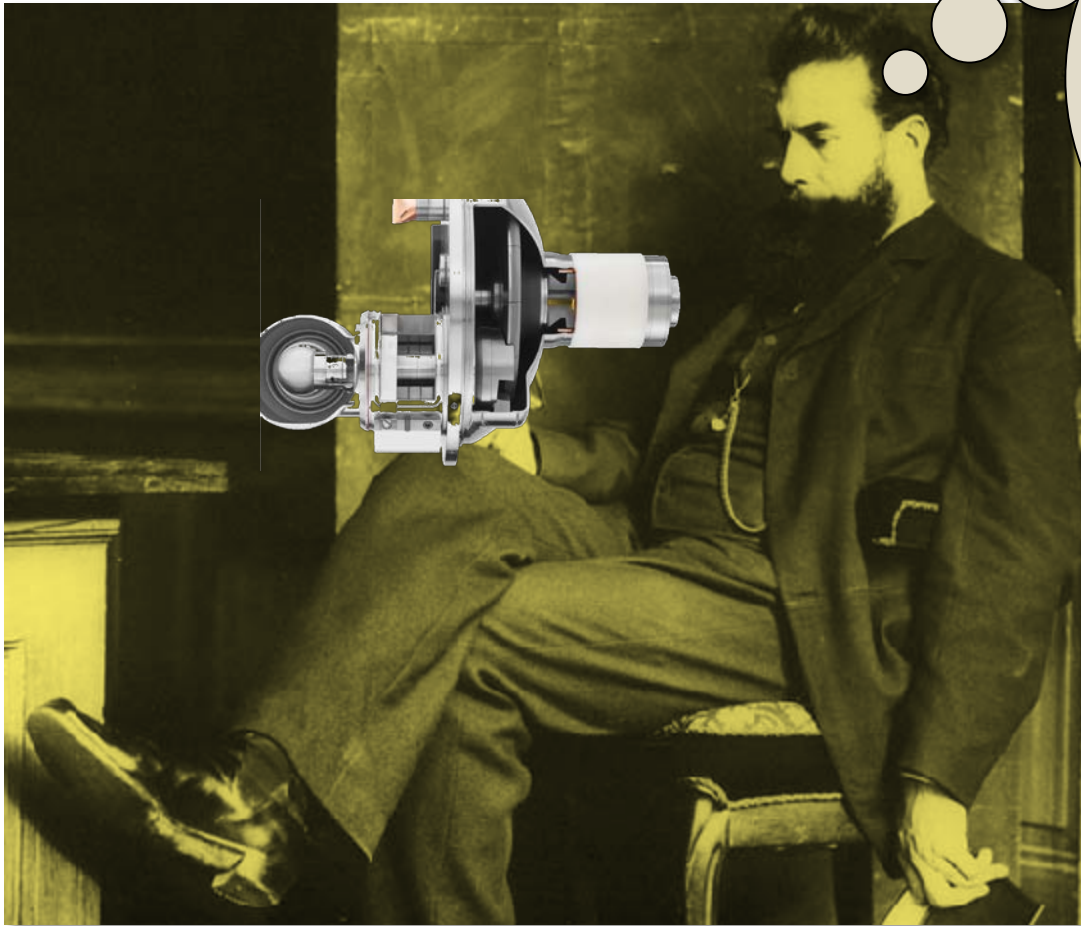
What can Clinicians do Better?

- 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



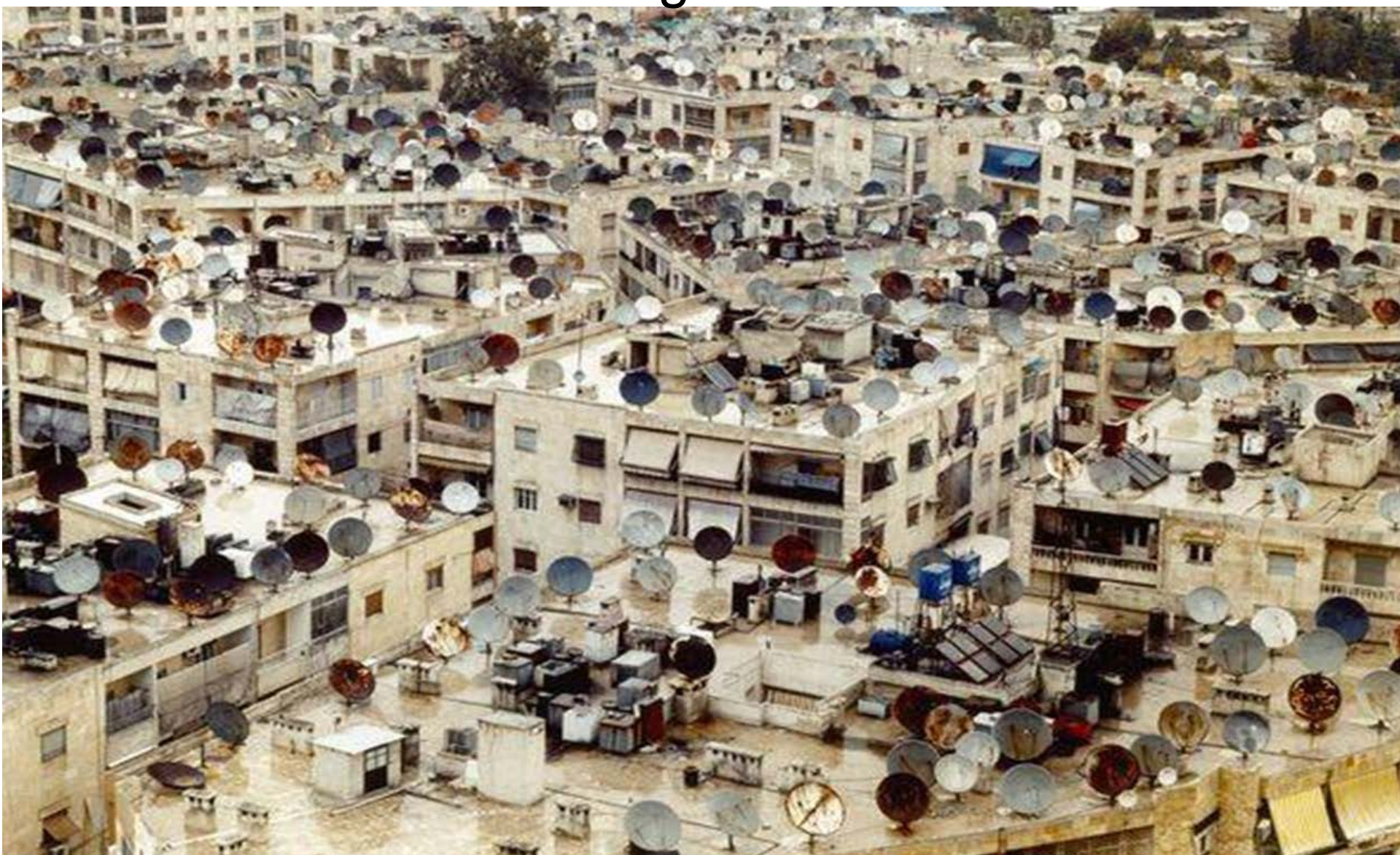
→ Remember, how you would be driving your own car

Röntgen 2016 ...



*"I am amazed,
quite a few 21st century
tubes are indeed excellent!*

Thank You for Listening



Abstract

Why still vacuum technology to generate Bremsstrahlung, ca. 120 years after Conrad Roentgen's discovery? How do X-ray tubes function and look like? What's next? (When...?) Will we see the X-ray LED's, compact X-ray Lasers or flat panel sources in medical imaging? These and more questions will be answered in this lecture. We will shortly dive into physics of X-ray generation, study key characteristics, material boundary conditions, manufacturing technology. We will identify the quality parameters, which allow us to compare and select the proper source.

Learning objectives:

- X-Ray physics
- Tube design concepts, sub-components, interfacing
- Quality parameters, costs, reliability

Suggested Reading and References

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