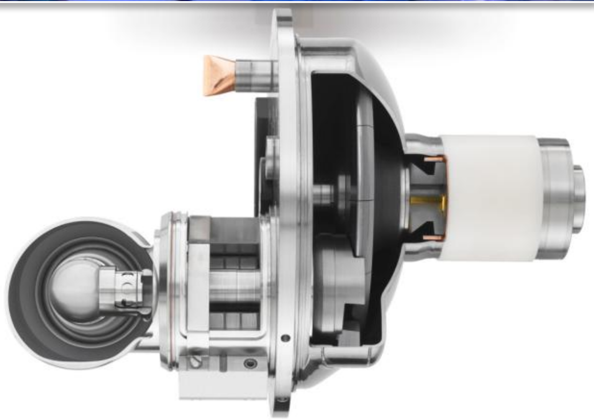
X-Ray Tubes for Medical Imaging

AAPM 2013



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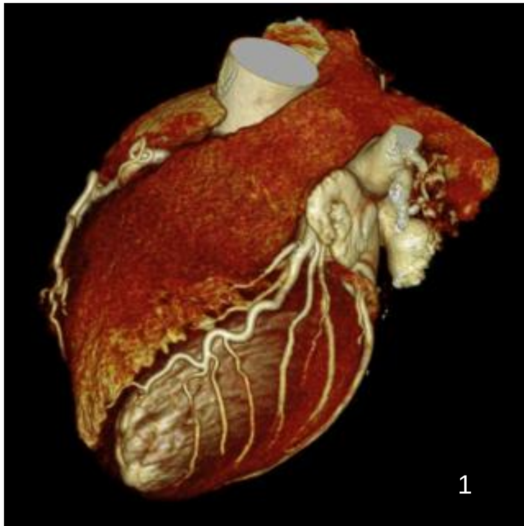

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Abstract

Why do we find 500+ types of X-ray tubes on the market? 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.

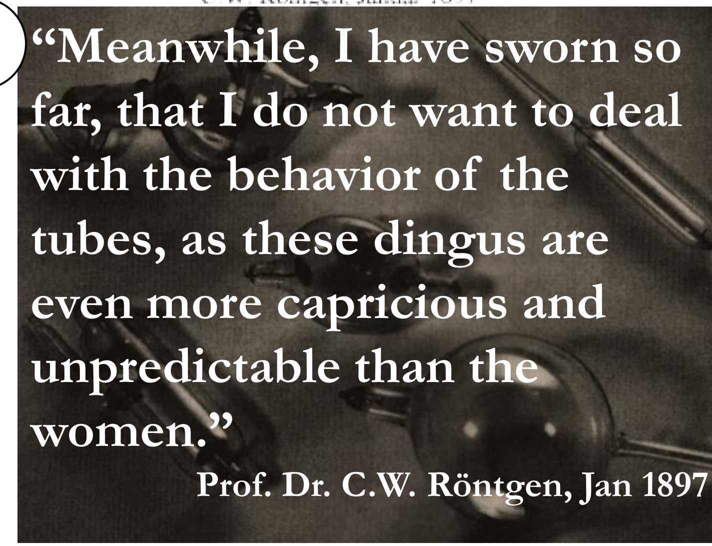
Learning Objectives:

1. Understand design concepts of glass and metal frame, single ended and dual polar tubes with reflection targets.
2. Understand the principle of rotating anode tubes, their bearings, anode discs, motors, cooling, heat balance, electron emitters and beam focusing, focal spot characteristics.
3. Understand the impact of focal spot MTF, off-focal radiation, focal spot deflection on image quality
4. Understand the trade-offs of tube type specification and selection.

Röntgen’s Early Tubes

„Indessen habe ich vorläufig geschworen, mit dem Verhalten der Röhren nichts zu tun haben zu wollen, denn diese Dinger sind noch launischer und unberechenbarer als die Weiber“

C.W. Röntgen, Januar 1897

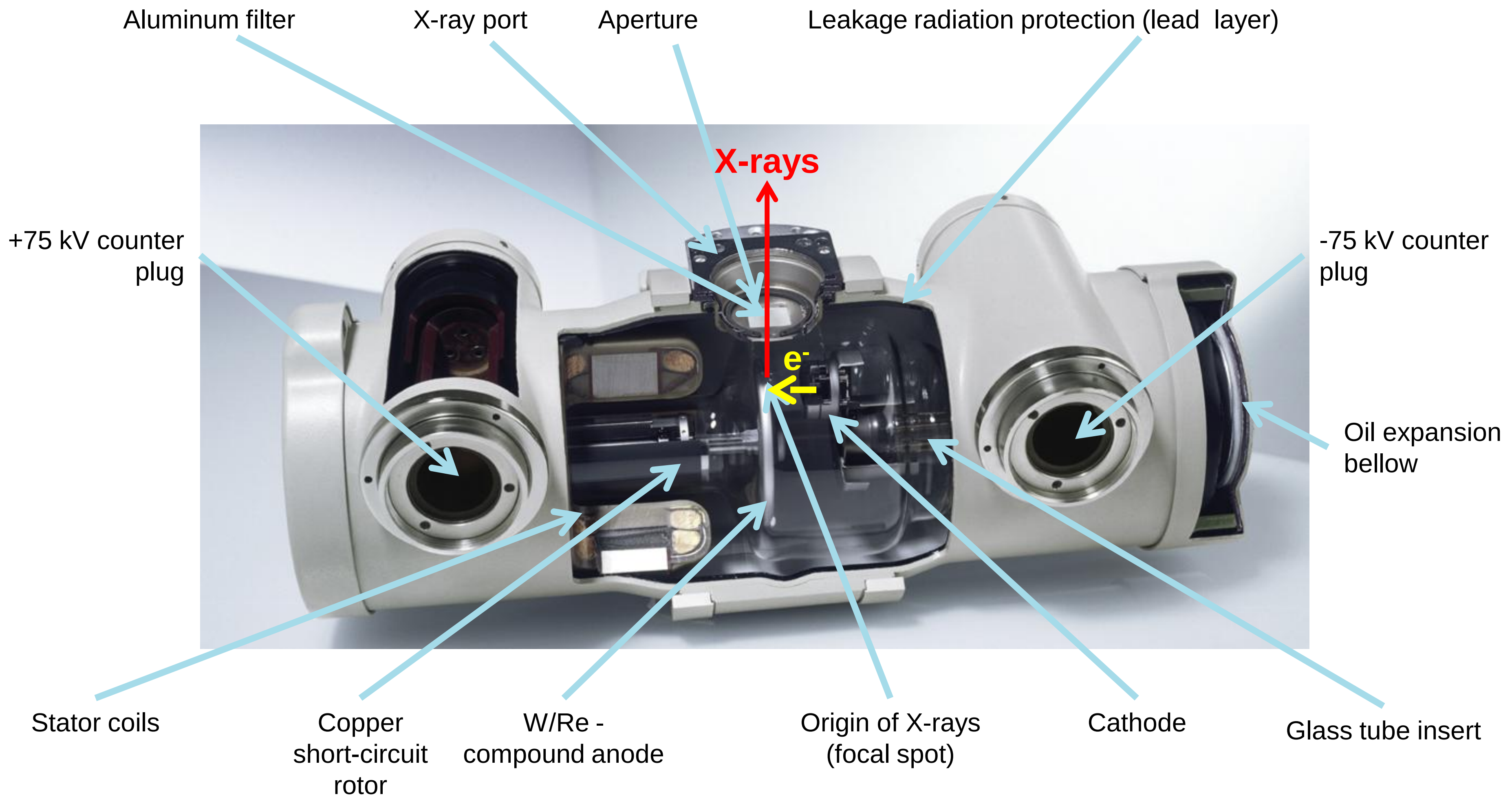


Applications

- CT
  - 70…140 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)
- Hardly any multi purpose tubes

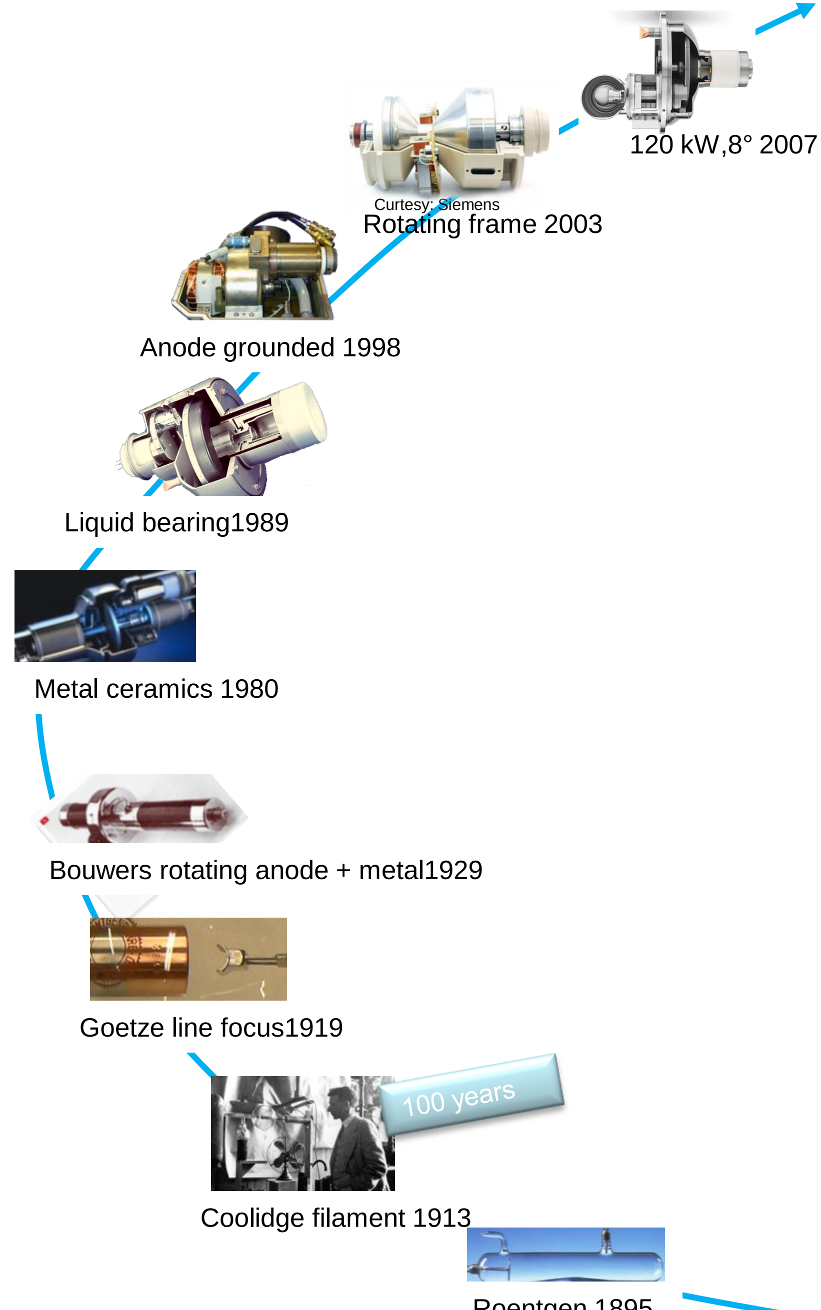
→ ~500 tube types on the market

Standard Rotating Anode Tube Assembly (1970)



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 trapping, anode end grounded tube (1998)
- Other vendors

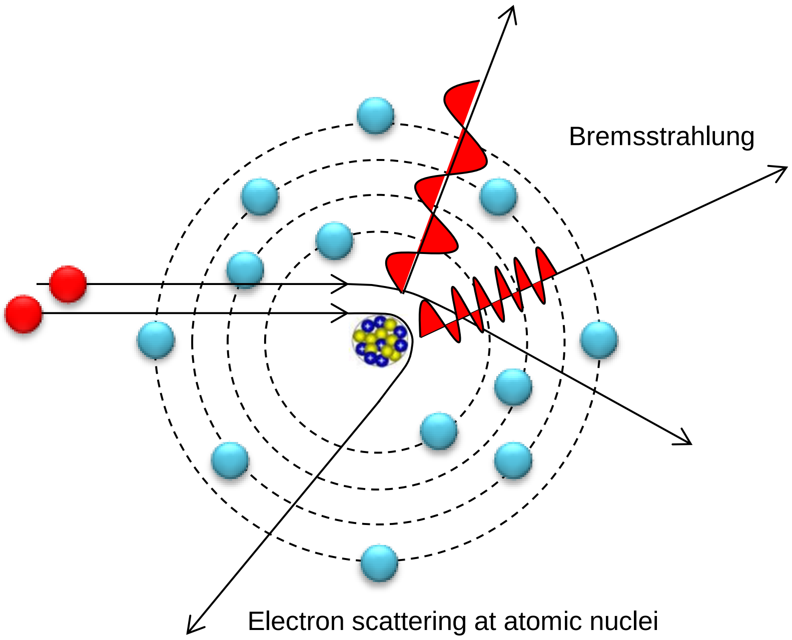


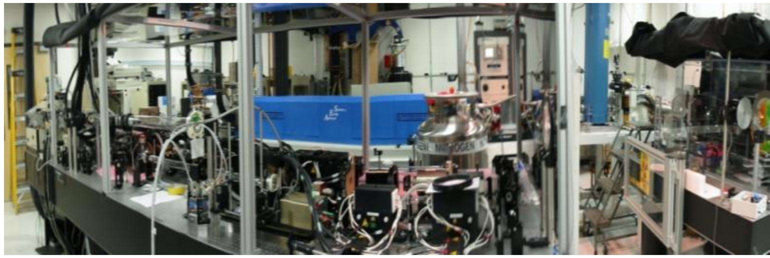
In alphabetical order

X-Ray Generation

- Human body transparent for E_{photon} ca. >20 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 generates heat
- Other sources costly, not (yet?) practical
  - – Thomson scatter (electrons → photons), high laser costs
  - – Undulators (fast electrons zig-zag in magnets), large
  - – Synchrotrons(electrons travel in circles), large, expensive
  - – Nuclear decay, not controllable
  - – …
- No X-ray LED on the horizon
  - – Semiconductors band gap too small (eV instead of keV)

→ Vacuum Technology will remain




Thomson scatter source, petawatt laser

Laws of Bremsstrahlung

- Kramer’s linear **Intensity** law

$$I_\gamma = const_1 * Z * (\gamma_{max} - \gamma)$$

(in photon energy intervals, unfiltered)

- Total **power**

$$P_X = const * I_{tube} * Z * V_{tube}^{2}$$

- Low conversion **efficiency**

$$P_X/P_e \approx 10^{-6} * Z * V_{tube} / [kV]$$

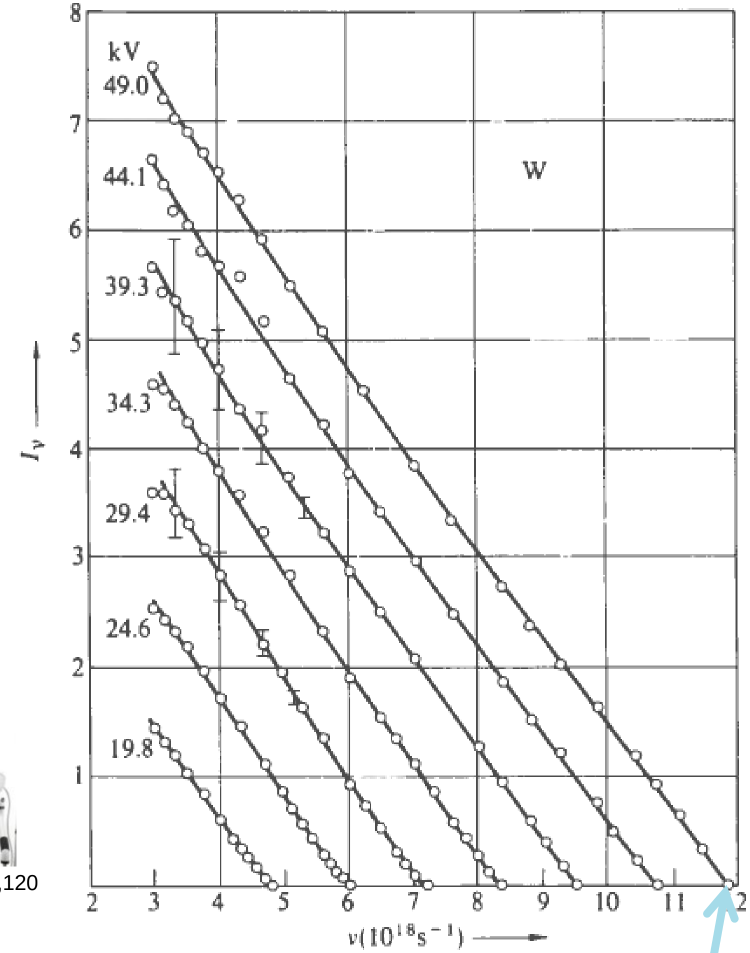
$$\approx 0{,}9\ \%$$

(W reflection target, 120 kV, unfiltered, half space)

(50° x 8 cm fan in iso-center,120 kV, incl. X-ray filter)

- **CT: 100 kW input → ≈ 2 W useful X-rays**

X-ray intensity = X-ray energy per unit electron energy interval



Frequency γ ~photon energy

Duane-Hunt-limits

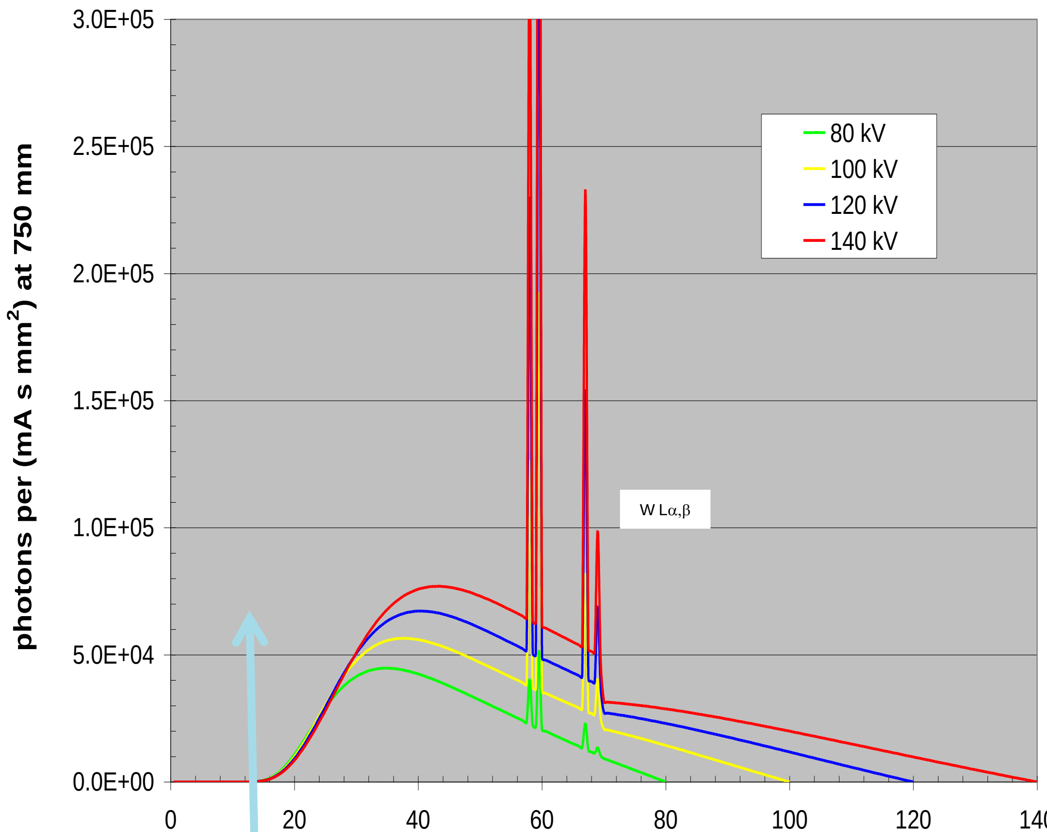
I_{tube} = Tube current
I_γ: X-ray Intensity per unit freq.
P_X: X-ray power
P_e: electrical power
V_{tube}: tube voltage
Z: atomic number
γ: X-ray frequency

Tungsten-Spectra

- Continuous
- **Max photon energy is e^{-}*V_{tube}**
- Spectrum alternating with tube voltage
  - E.g. for source controlled dual energy imaging

- Soft X-rays taken out by filter
- Filter is key for patient safety
  - Eliminate non-imaging photons
  - FDA: minimum 2,5 mm Al equiv.
  - Skin dose further down by additional up to 1 mm Cu
    - Requires powerful tube

→ Never remove the X-ray filter

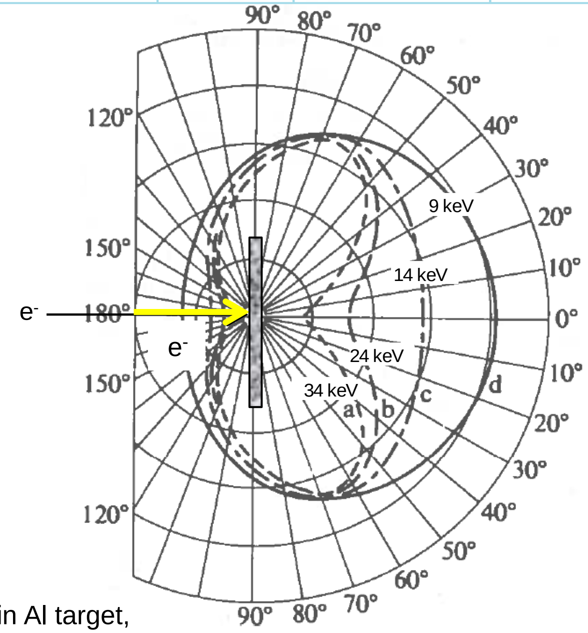


Spectrum vs. tube voltage. W-anode, 2 mm Al filter

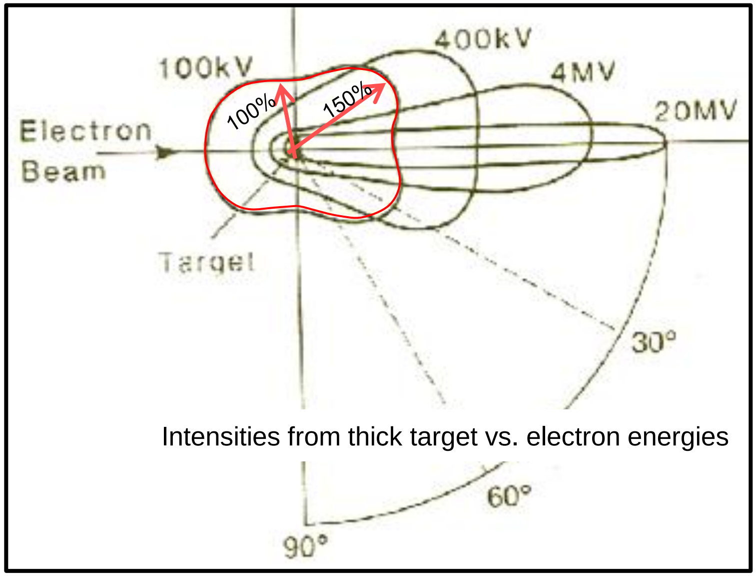
Radiation taken out by the X-ray filter

X-Ray Intensity Profiles

- **Thin target** (gas, ions, nm thin layers)
  - Electrons hit ~single nucleus (→ low X-intensity)
  - → Polarized dipole radiation @ 90°
  - → Minima forward and backward
  - → Enhanced forward intensity for relativistic electrons
- **Thick transparent target** (e^- opaque & X-transparent)
  - Strong forward intensity for relativistic electrons
  - → Used for high energy radiation therapy



Thin Al target,
(Doffin and Kuhlenkampf, 1957 , Z. Phys. 148, 496)



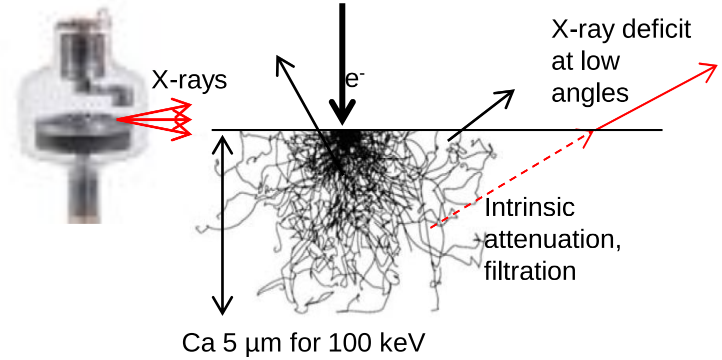
Intensities from thick target vs. electron energies

Intensities from Faiz M. Khan, “The Physics of Radiation Therapy”

→ Forward enhancement for “Linacs” (MeV)

→ Imaging done with reflection targets (keV)

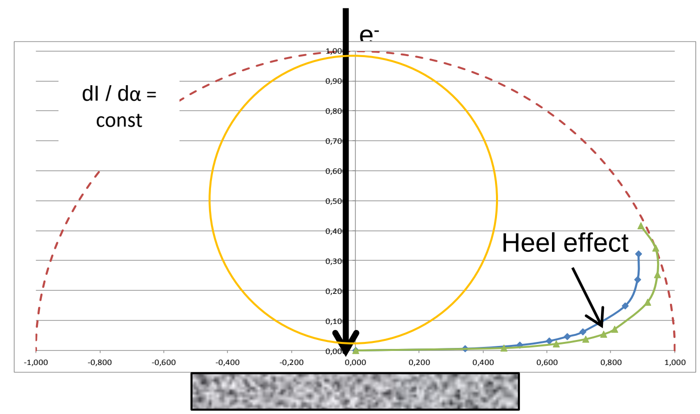
Reflection Targets for Imaging



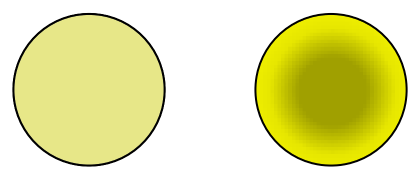
- X-rays taken off "backwards"
  - 5x…10x intensity benefit of using reflection target with a Goetze line focus at small take-off angle (next slide)
  - The forward intensity enhancement @ 100 keV, 40° off center, would not justify the use a thin target. The rate of electron interaction is less than 100%, cooling is more difficult.
- X-ray and heat generated 2-10 µm deep
  - Primary electrons quickly "forget" 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
- Electron target penetration

$$d_p \approx \text{const} * V_{tube}^{3/2}$$

- **Reflection target is best for imaging**



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



Line Focus (Goetze)

- The **Projected** focal spot is key
  - Not the physical FS
  - Projection on plane orthogonal to viewing direction
  - X-ray fan usually narrow 8° (CT) … 35° (mammo)

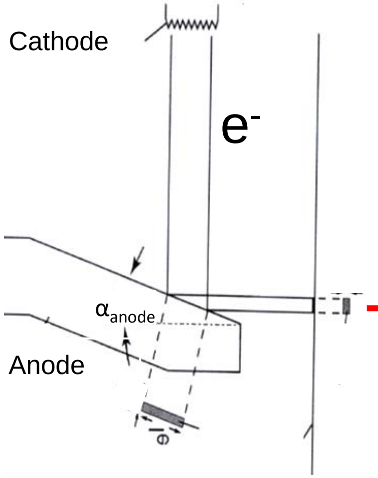
→ Large *physical* focal spot length

- $L_{physical} = L_{projected} / \sin(\alpha_{anode})$

→ **5…10 x gain of power**

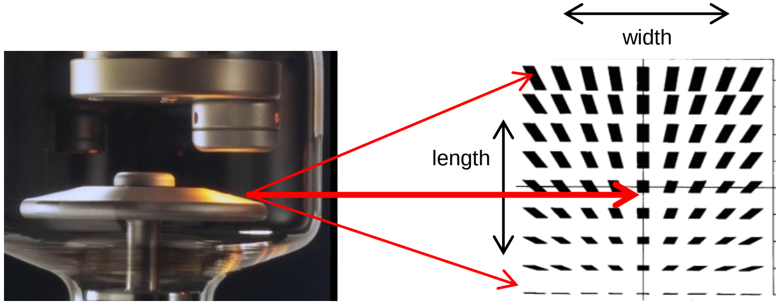
- → is proportional to physical focal spot length
- → high intensity, high tube current (avoids cathode limits)
- → High z-resolution close to anode shadow

→ Minimize the anode angle α_{anode}



Projection of the FS is key for sharpness, not the real length

$L_{physical}$ ≈ **5…10** x $L_{projected}$



Apparent focal spot shape: Projections in axial (length) and tangential (width) orthogonal to directions of viewing. Note the high z-resolution (short apparent focal spot) near the anode shadow. Focal spots look distorted from edges of the field of view.

Power and Temperature

- Good conversion by **Tungsten**
  - z=74, ρ = 19 g/cm3
  - melting Temp >3400°C, low vapor pressure
  - decent heat conduction, capacity
- Focal spot (FS) temperature $T_{FS} = \Delta T_{FS} + T_{body}$
- Focal spot temperature swing (Oosterkamp)

$$\Delta T_{FS} = const * P_e / \left(L_{physical} * \sqrt{V_{focal\ track} * W_{FS}} \right)$$

- **Power rating,** with given material limits

$$P_e = const * L_{projected} * \sqrt{V_{focal\ track} * W_{FS}} / \alpha_{anode}$$

T_{FS} < 2700 °C, ΔT_{FS} < 1500 K, T_{body} < 1500 °C (varies by simulation model)

→ **Power proportional to 1/ α_{anode} and (FS size)$^{3/2}$**

→ **4x anode speed needed to double the power density**

Rotating anode yellow glowing focal spot area (thin radial rectangle) on red glowing bulk material.

FS: Focal spot
$L_{projected}$: projected focal spot length
P_e: electrical input power
T_{body}: focal track temperature
T_{FS}: focal spot temperature
ΔT_{FS}: focal spot temperature swing
$V_{focal\ track}$: focal track speed
W_{FS}: focal spot width (tangential to anode disk)
α_{anode} : anode angle

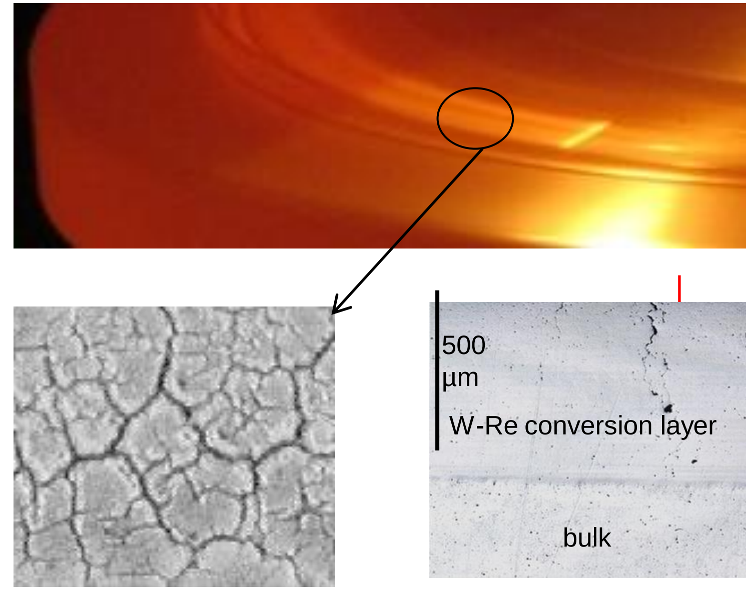
Dose Stability

- ~10^8 hot-cold cycles → cracks
- → Target intrinsic X-ray attenuation

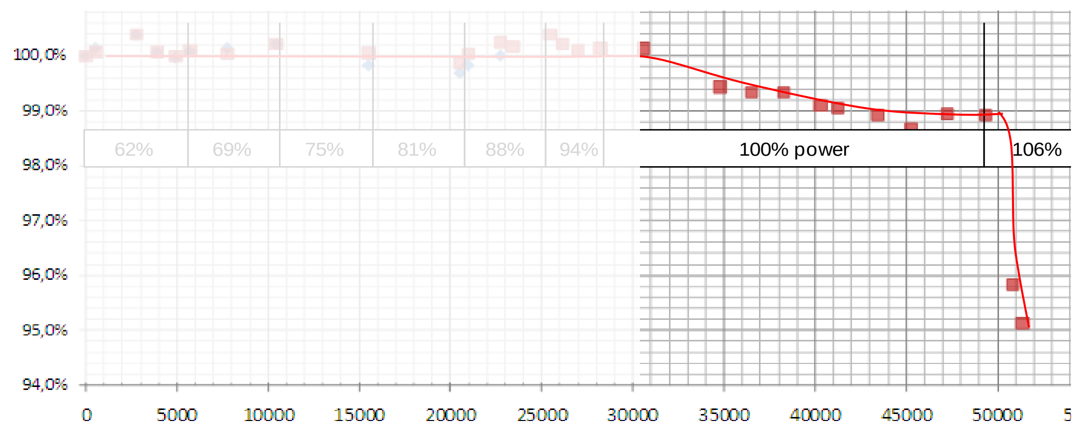
- % measured dose drop depends on technique factors
  - -40 % measured degradation @ 40 kV, 2.5 mm Al filter

  …from the same anode reveals

  -10 % measured degradation @ 140 kV, 1 mm Cu filter



Left: µ-cracks, top view. Right: cut view



Relative dose output over number of cycles.
77 kV, 2 mm Aluminum filter

→ Do not overload the target

Bulk Anode Cooling

Glass tube, ball bearings

Electron impact
Electron back scatter
Anode Heat storage
Heat radiation 100%
Heat condution

Single polar, liquid bearing

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

Curtsey: Siemens

Rotating frame tube

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

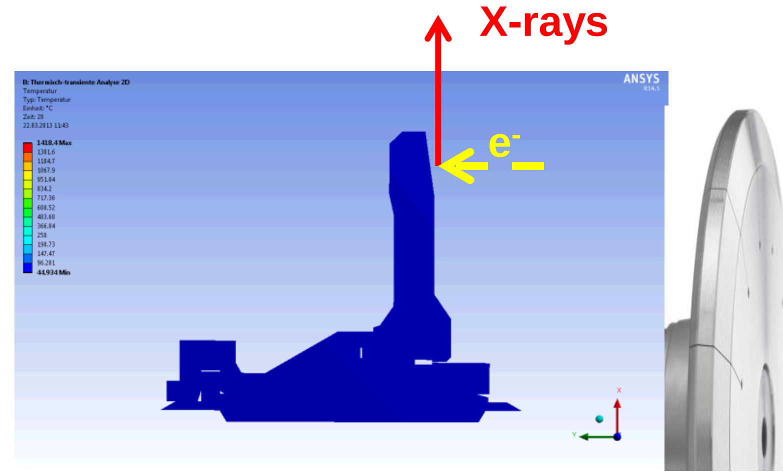
→Radiation cooling leaves heat in the anode

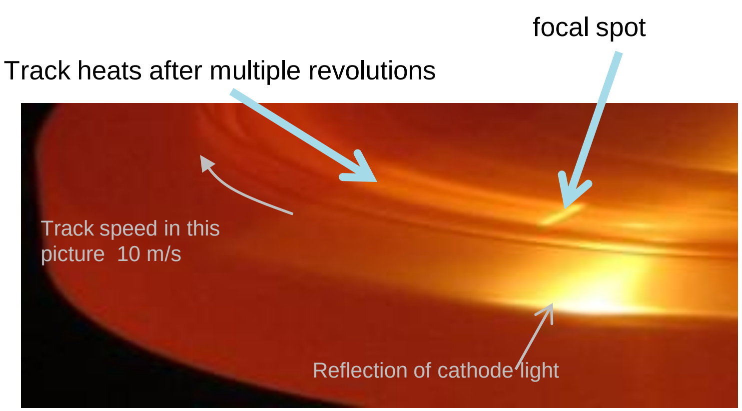
Glass tube with ball bearings. Multiple exposures.
Cooling:
Heat radiation is strong at the beginning of the pause. But, as the anode cools down and becomes invisible (< 400 °C), heat radiation ceases (T^4). The anode remains at elevated temperature. The next patient gets a pre-heated tube, the performance of which is limited. Heat conduction is more effective for removal of residual heat.

Heat Waves

- Source of thermal energy is the focal spot
- Distribution into spot track by fast rotation
- Radial heat flow
- Propagation of the heat wave
  - Focal spot → next sub-layer ~ µs
  - Sub-layer → focal spot track ~ ms
  - Focal spot track → anode body ~10 s
  - Steady-state temperature after ~ minutes

→ Only outer target rim is hot after a CT scan





Focal spot of a rotating target under e^- bombardment

Anode Bearings in Vacuum

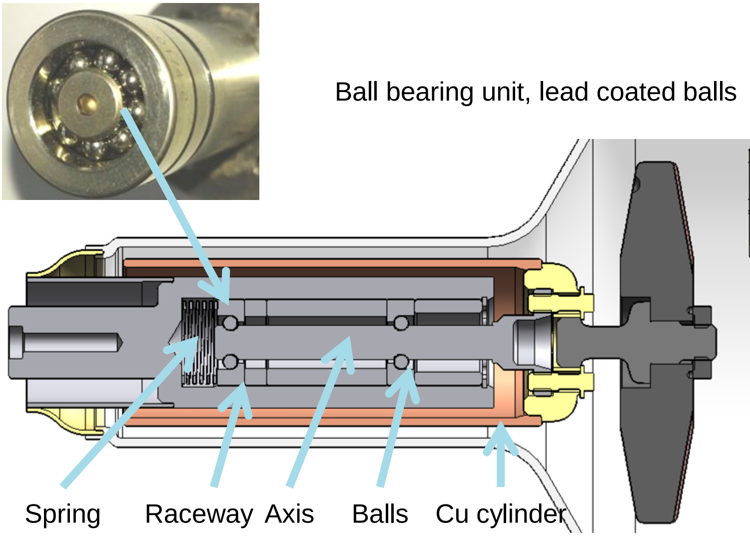
- Ball bearings
  - Hard steel, would freeze immediately w/o inter-layers

  → 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

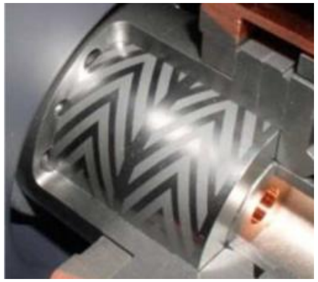
  → Continuous rotation (zero prep time)
  - Noiseless, stable, scaled to load & speed
  - Four bearings in one (2 x radial, 2 x axial),
  - Latest: dual suspended for CT (32 g)

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

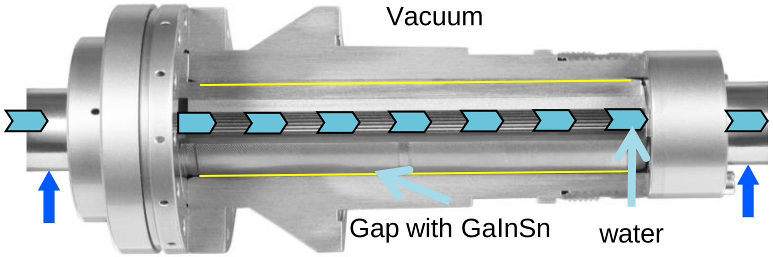
→ The type of bearing is key for tube life and practical use (prep time, cooling)



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.

Cathode

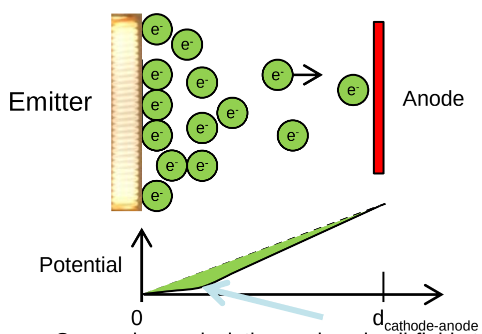
- Thermionic **emission** (e^- boiled off W-emitter)

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

  Max. 2 A/cm² for a flat emitter for 10^6 scan seconds cathode life

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

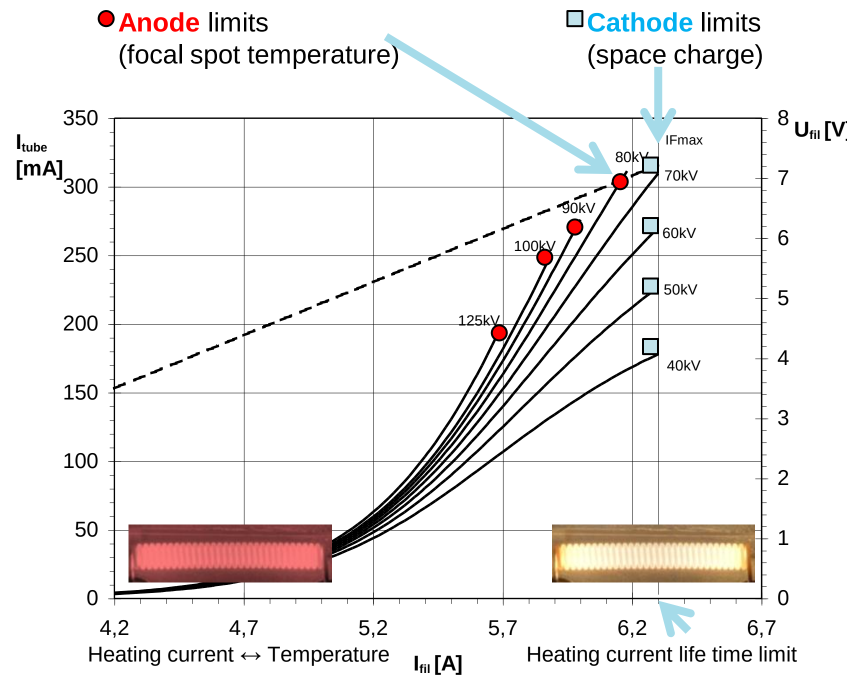
  $$J = const * V_{tube}^{3/2} / d_{cathode\text{-}anode}^{2}$$



Space charge deviation, reduced pull-field at the emitter

- "**isowatt point**": space charge limit = anode limit

> **→ The cathode may limit tube performance as well as the anode**



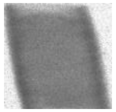
Emission characteristics of a 0,4 (IEC 60336) focal spot (11° anode angle, 108 mm anode Ø). Isowatt point 72 kV. Observe the $V_{tube}^{3/2}$ law in the space charge regime (right, hot emitter)

$d_{cathode\text{-}anode}$: 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)

Focusing

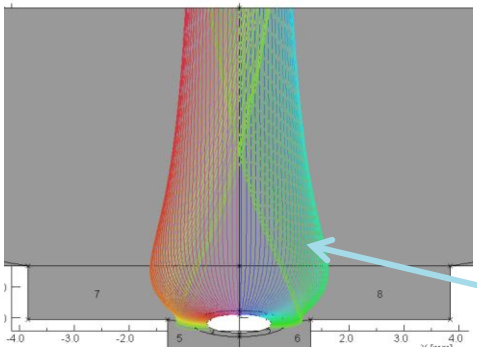
- Electrostatic focusing (shape of cathode cup)
  - FS size independent of U_{tube} (except w/ space charge)
- Recent: Magnetic focusing
  - magnetic quadrupoles
  - Magnetic fields to be adapted to U_{tube}
- MTF = modulation transfer function
  - Fourier transform of the projected intensity profile
  - Measure of resolution capability
- 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

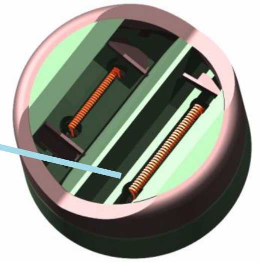


Current density profile at the anode (focal spot exposure)

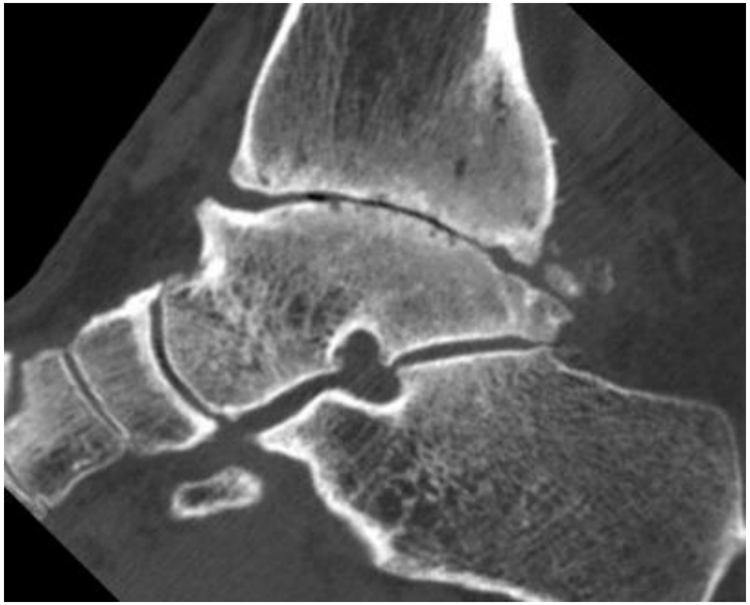
Anode



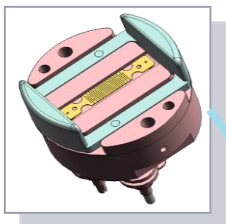
Electron beam tracing around one of the filaments. Geometry defines E-field for electrostatic focusing



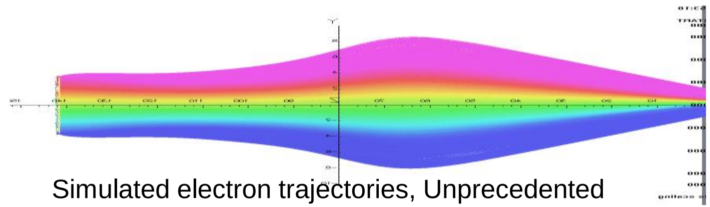
Dual filament cathode



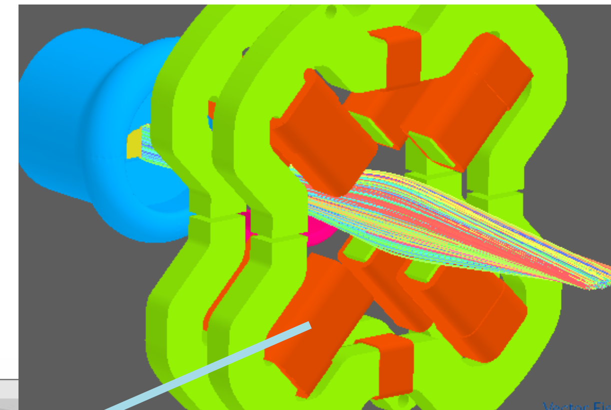
Latest: Flat Emitter+Magnetic Focusing+Deflection



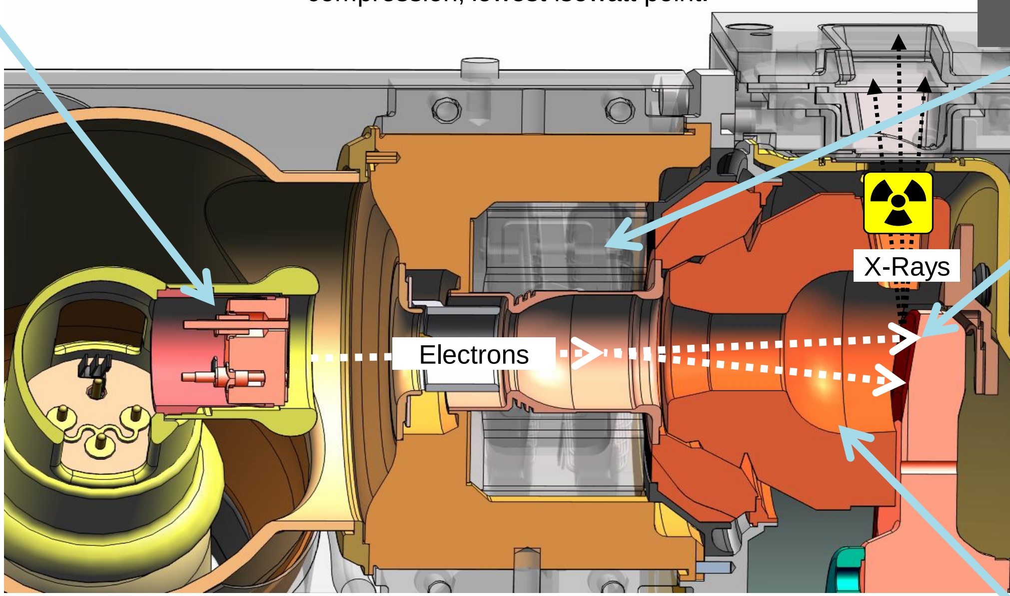
Cathode with tungsten flat emitter



Simulated electron trajectories, Unprecedented compression, lowest isowatt point.



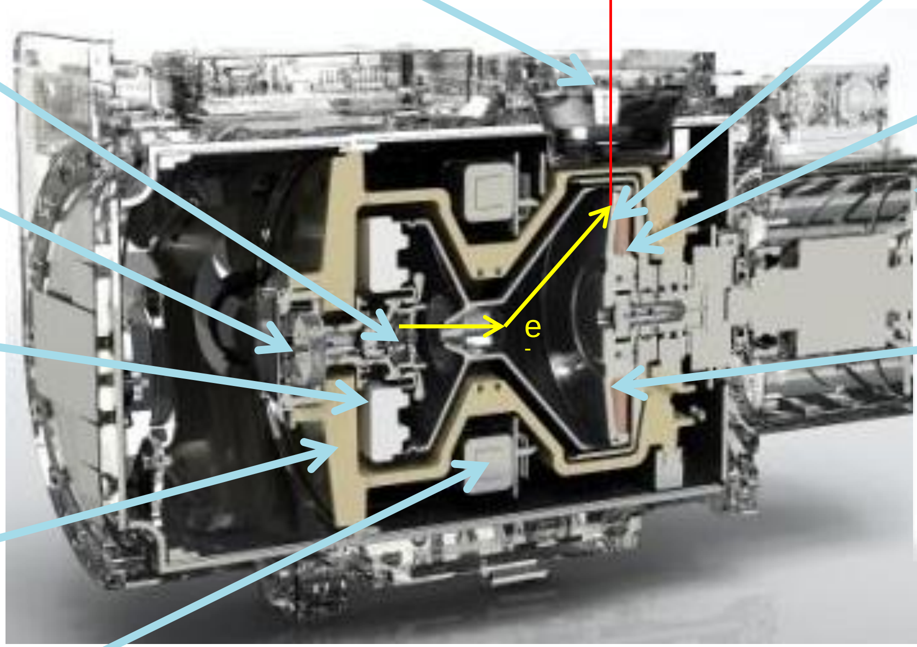
Double quadrupole and dipole



Z-deflection

Scattered Electron Collector collects 40% of the primary electron energy

A Rotating Frame CT Tube Assembly



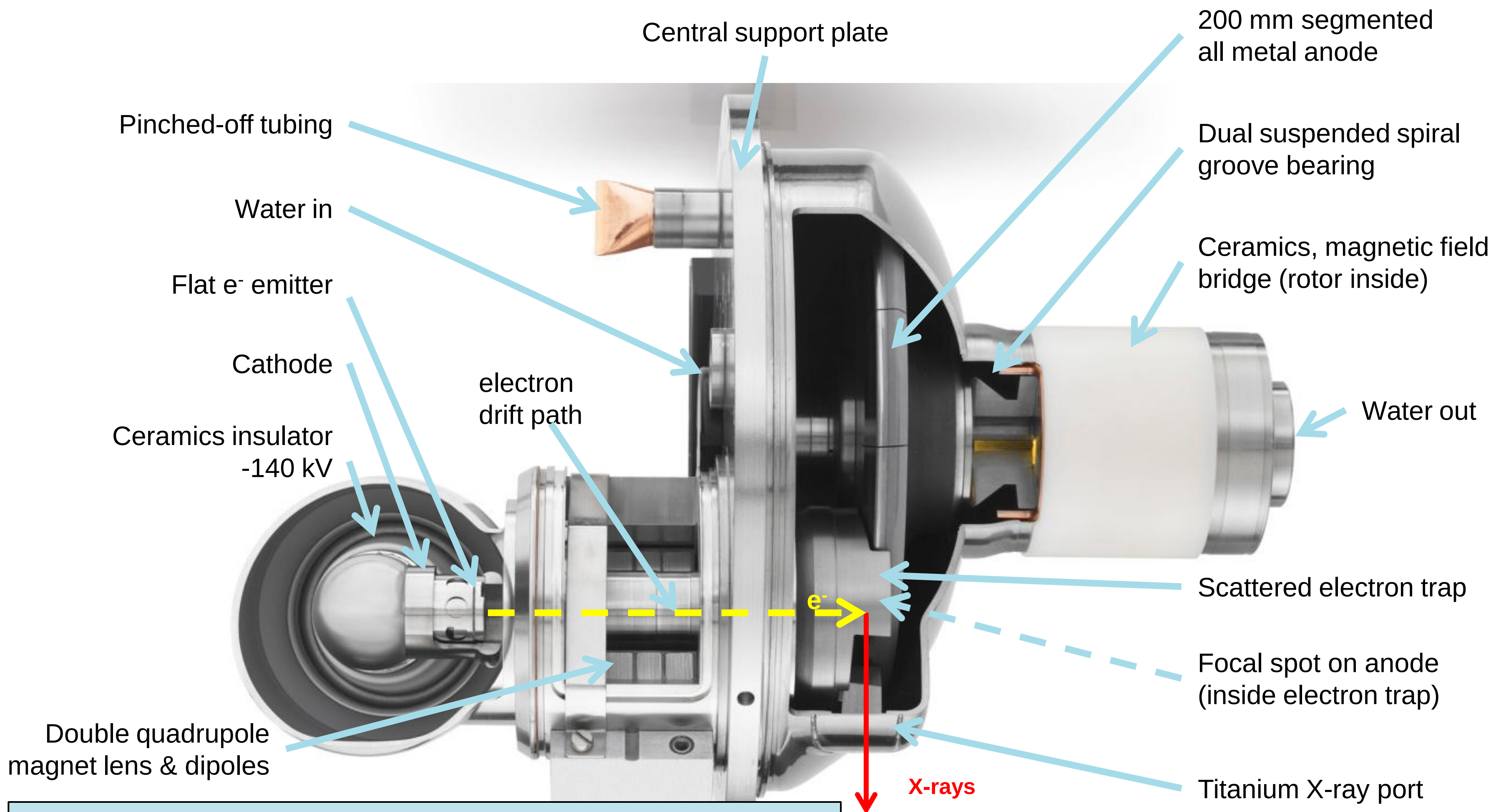
Courtesy: Siemens

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

Compact, high CT performance

Type: Siemens Straton

A CT Tube with the Highest Power Density



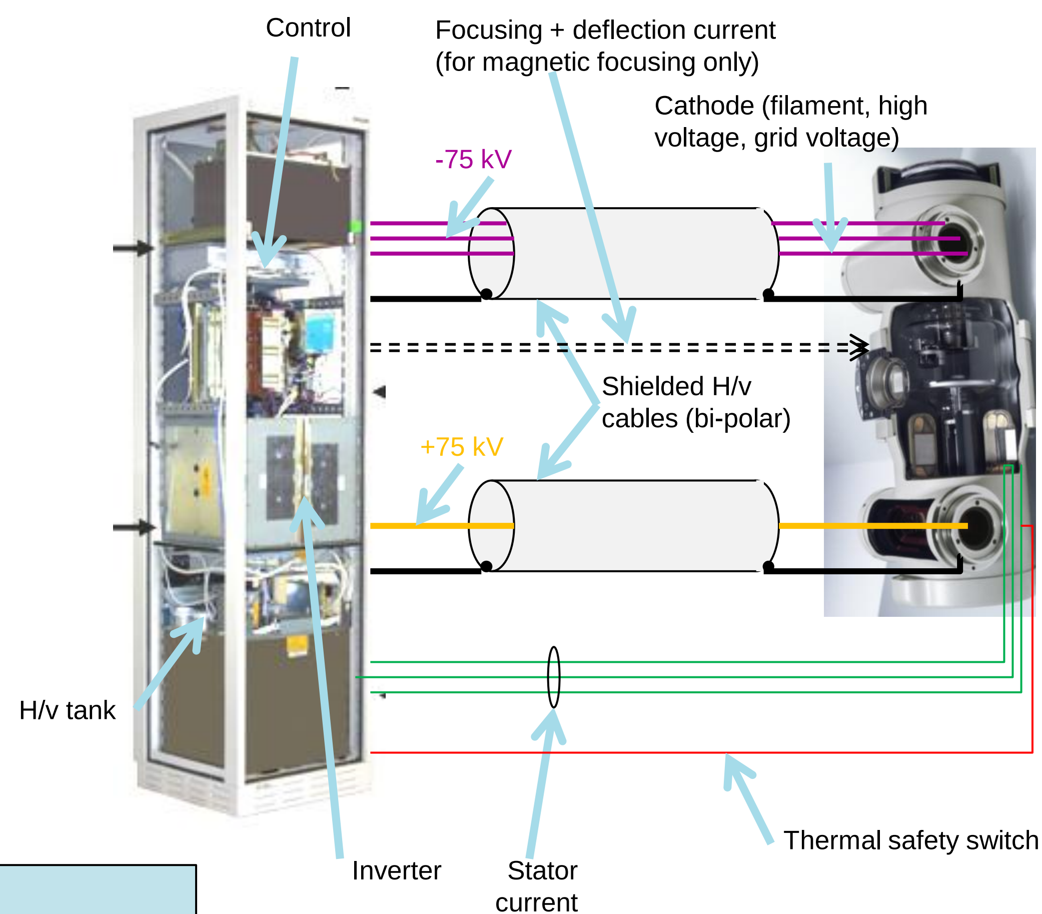
Top CT performance, reliable

Type: Philips iMRC

High Voltage from the Generator

- Up to 150 kV, 120 kW
- Mono- or bi-polar
- Ripple smoothening, arc recovery
- Emitter heating current
- Grid supply for grid switched tubes
- Stator supply (motor)
- Currents for magnetic focusing
- Mains adaptation
- Interface to the X-ray system
- Dose rate, power, h/v control
- User interface
- Safety functions
- Service functions, remote access

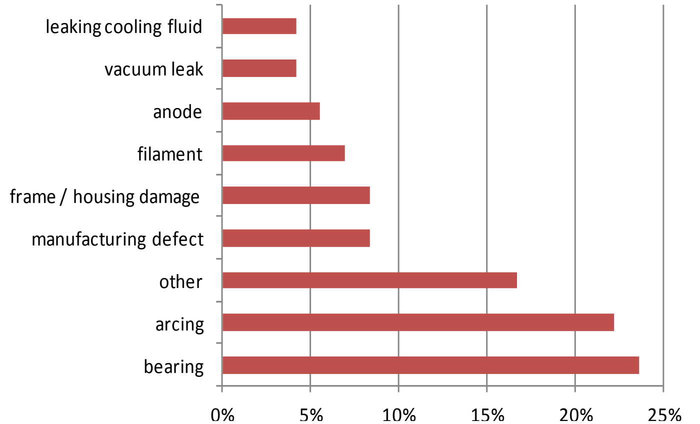
→ **Complex control center & interface**



X-ray segment: generator (left) and tube combination)

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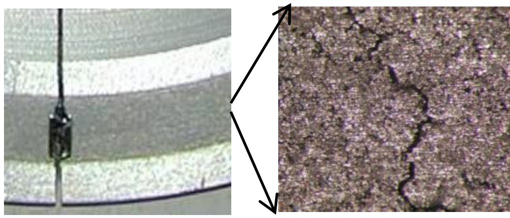
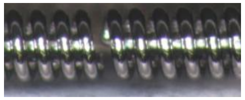
Tube life time statistics of GE CT tubes in 13 CT systems in the Sloan Kettering Center, NYC



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

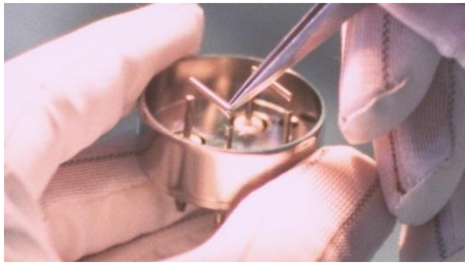
→ Tube life time depends on concept, system type, usage, service, manufacturer

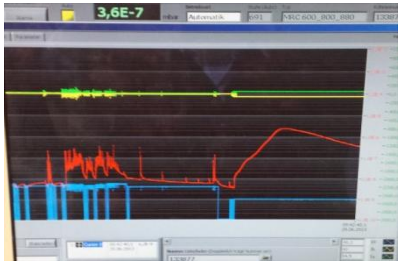
→ Broad failure distribution over time

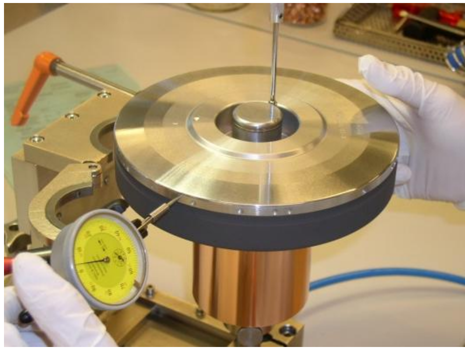
Manufacturing and Costs

- Assembly, exhaust, break-in, testing
  - Material prep., machining, coating, brazing, cleaning
  - Dust-free assembly, spacey (human factor)
  - ca. 8 hours baking, component heating, UHV
  - H/v break-in, remove irregularities and gas pockets
  - Testing on arcing, focal spot, vibration, 100% leakage radiation
- Well-refined processes
  - FDA etc. compliant
  - Experience, strict quality control

- **Key cost drivers**
  - **Anode**
  - **Ceramics**
  - **Bearing**
  - **Housing**
  - **Production yield**

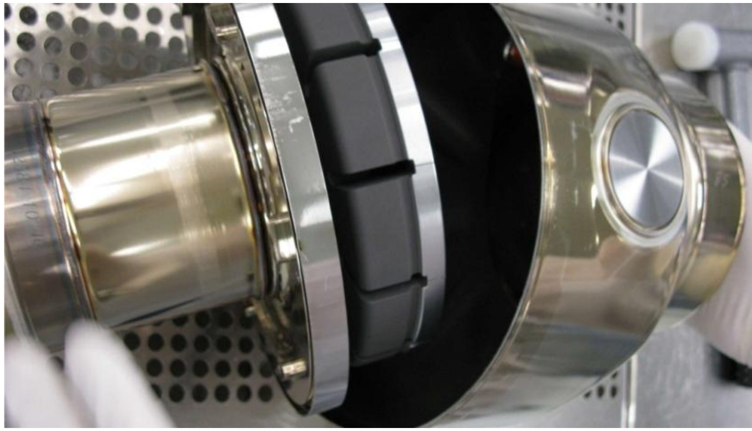






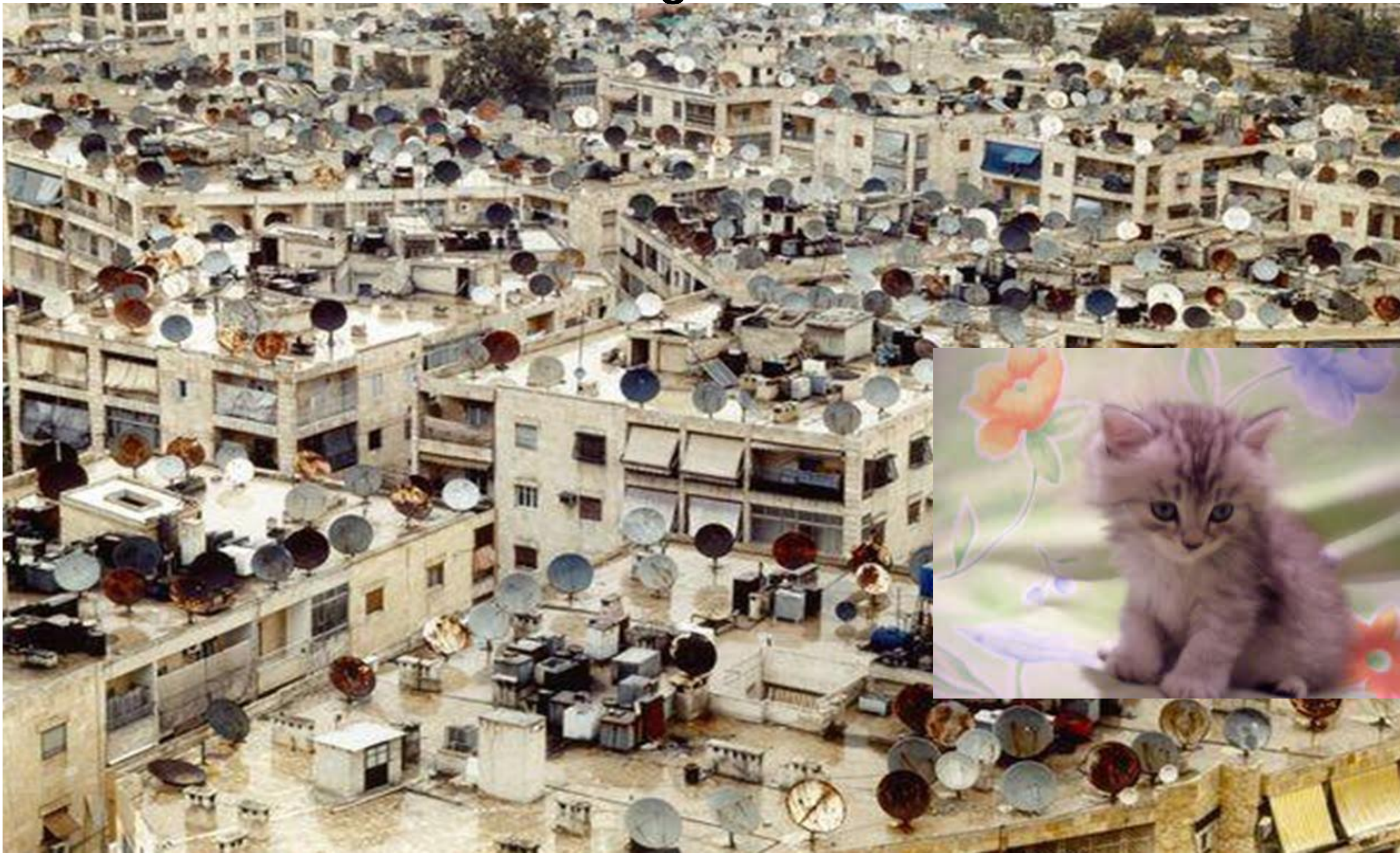
Recycling

- Recycling is a must
  - Harmful materials (Be, Pb,…)
  - Recycling of housings established
  - Recycling of metal tube parts gaining importance
  - Tube construction needs to enable this
- Same or better performance and life time compared with new material
  - Several years “vacuum cleaning”
  - Proven stability
- Cost saving



→ Manufacturers differentiate by recycling rate and environmental impact

Thank You for Listening



Suggested Reading

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