Pitfalls: Reliability and Performance of Diagnostic X-Ray Sources

AAPM Annual Meeting 2016
Washington DC

Rolf Behling
Philips, Hamburg, Germany

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

Röntgen 1897 - Frustrated

"Meanwhile I have sworn, 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."

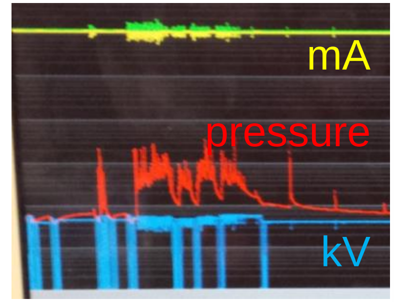
Prof. Dr. C. W. Röntgen, Jan 1897.
Translated from Zehnder (1935)

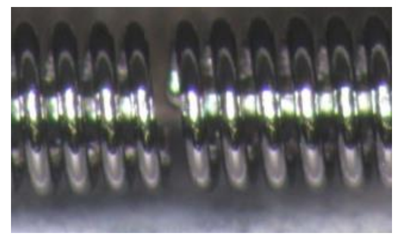
Röntgen dearly loved his wife: Picture of Anna Bertha on his desk with a bowl of chocolate which she always kept filled for him.

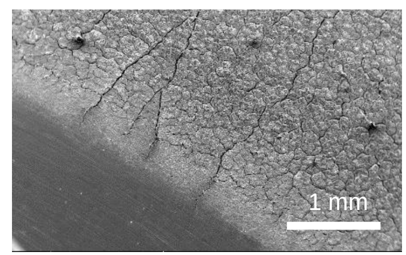
(German Röntgen Museum, Remscheid-Lennep)

Typical Tube Failures

- Computed Tomography (CT)
  - Vacuum discharges
  - Tube rotor
- Interventional
  - Cathode, emitter burn-out
  - Dose degradation
- General radiology / Mammo
  - Cathode, emitter burn-out
  - Tube rotor / bearing noise and vibration
  - X-ray dose degradation
  - beam hardening (contrast)

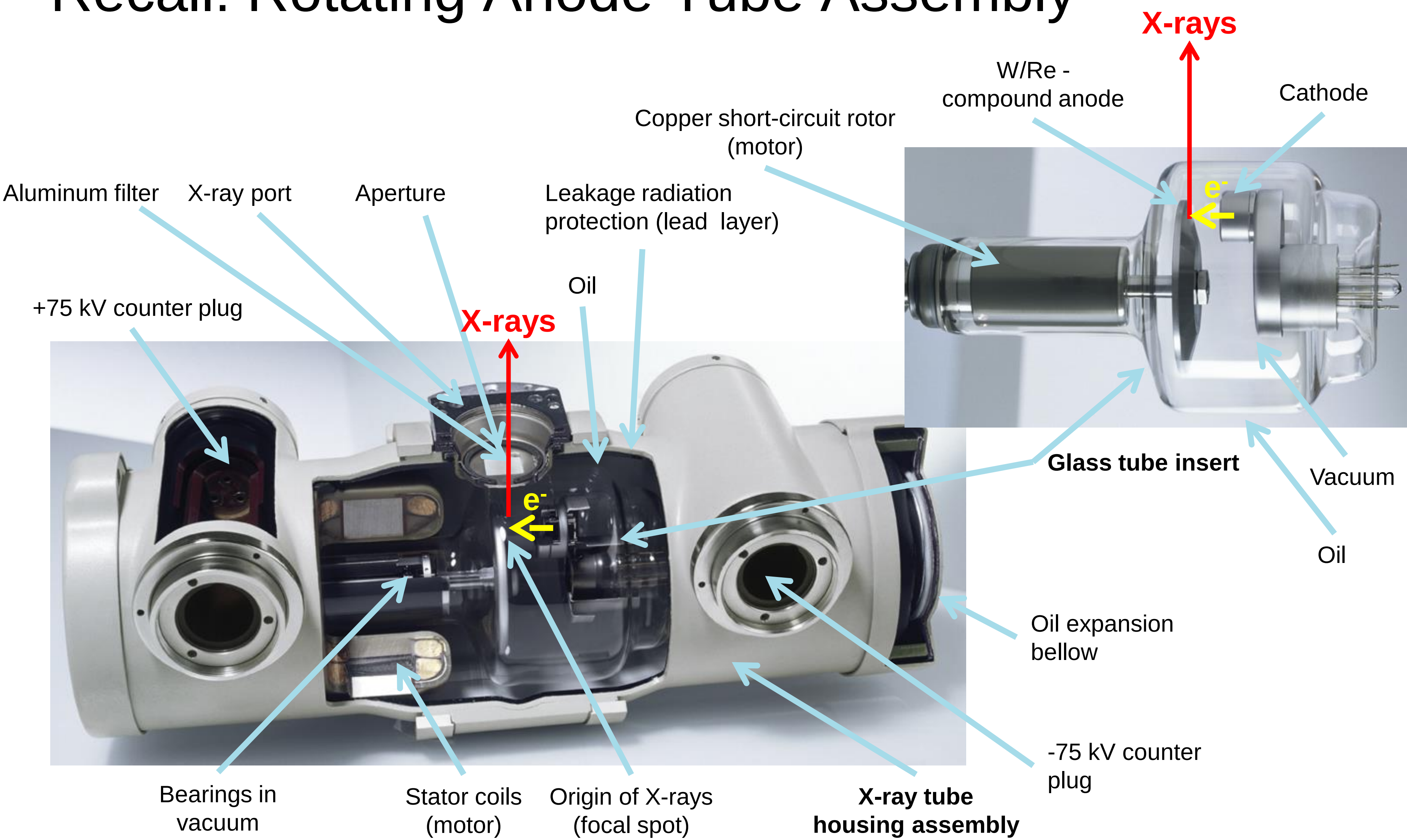






Pitfall: X-ray tubes are consumables

Recall: Rotating Anode Tube Assembly



Improvements Over Ti

(alphabetical)

- **GE**
  - **Thermionic cathode (Coolidge, 1913)**
  - Graphite anodes (CGR, 1967)
  - Largest anode (2005)
- **Philips**
  - **1st clinic (Hamburg, Germany, Müller, 3/20/1896)**
  - **Line focus (Goetze, 1919)**
  - **Metal frame + finned rotating anode (Bowe**
  - All metal ceramics (1980)
  - **Liquid bearing (1989), dual suspended (2007)**
  - **Double quadrupole (2007)**
- **Siemens**
  - Graphite backed anodes (1973)
  - Flat electron emitter (1998)
  - **Rotating frame (2003)**
  - Magnetic quadrupole, **z-deflection** (2003)
- **Varian**
  - Largest anode heat capacity (1980s)
  - **Liquid cooled e^- - trap (1998)**
- Others

No off focal, FS deflection, 32+ g, …

Compactness (DSCT)

Siemens: Hell, rotating frame 2003

No waiting times in CT w/ ball bearings

Varian: Runnoe, anode grounded 1998

No wait times intervention. – 3 x tube life

Philips: Hartl, liquid bearing 1989

50% less waiting times for interventional

Philips: Hartl, all metal ceramic 1980

10 x speed of imaging

Philips: Bouwers, rotating finned anode + metal shield 1929

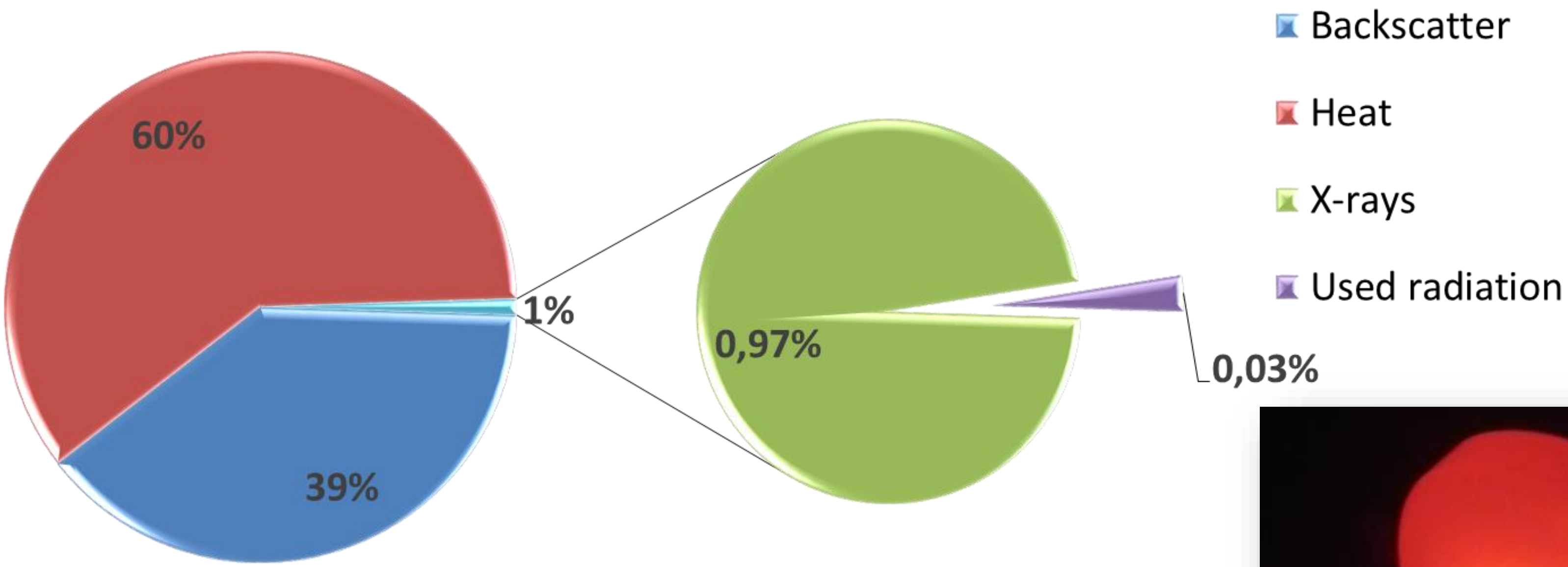
10 x speed of imaging

Contrast independent of brightness

GE: Coolidge filament 1913

Röntgen 1895 – ion tubes

Energy Conversion in Practice

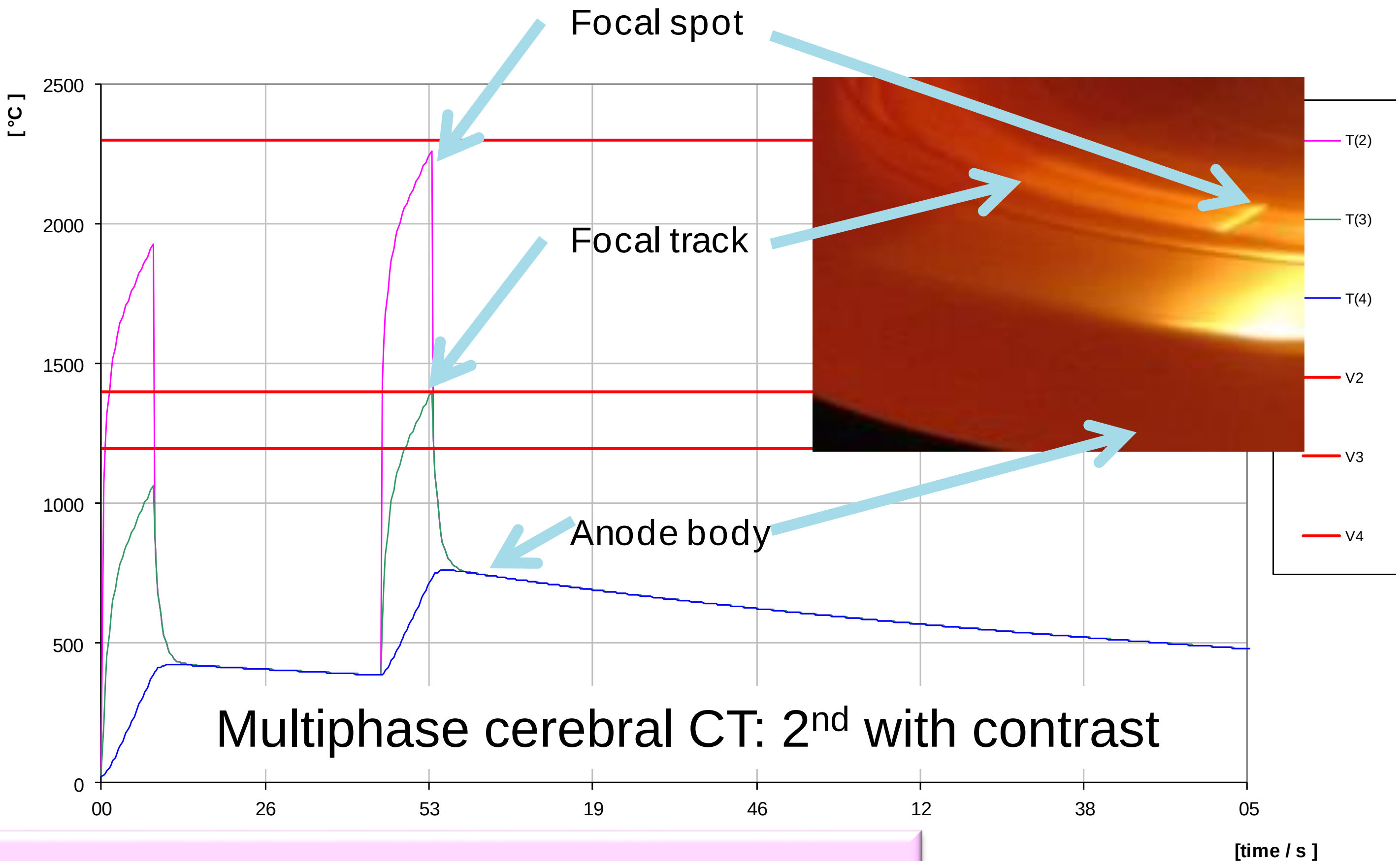


Total efficiency ~10^{-4}

Tube technology means heat management

Thermal picture of a rotating anode in operation

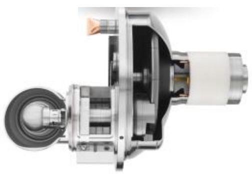
Temperatures in the Anode



Pitfall: Overheat may hamper workflow

Bulk Anode Cooling

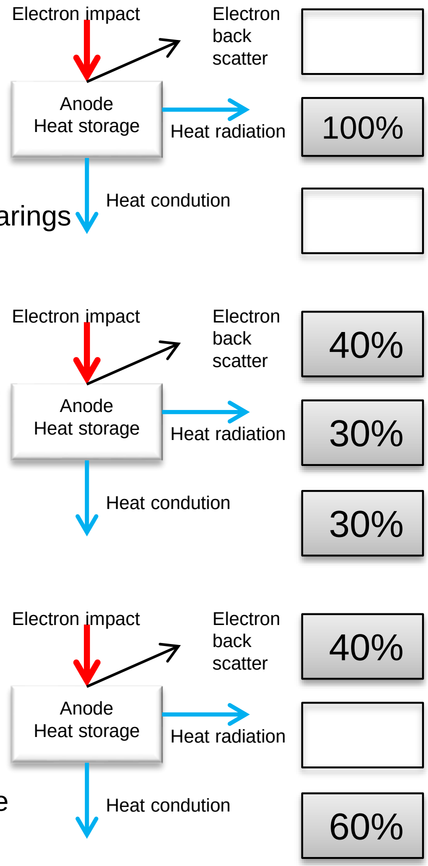
Glass tube, ball bearings



Single polar, liquid bearing

Courtesy: Siemens

Rotating frame tube



- Glass tube with ball bearings.
- Multiple exposures.
- Heat radiation needs visible glow
- Stefan-Boltzmann T^4 - law
- Glow ceases at about 400°C

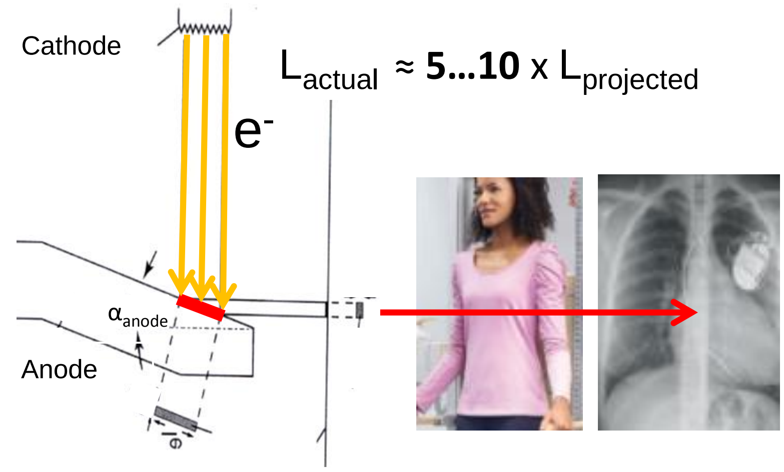
Pitfall: T^4 → Residual heat in the anode

Line Focal Spot

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

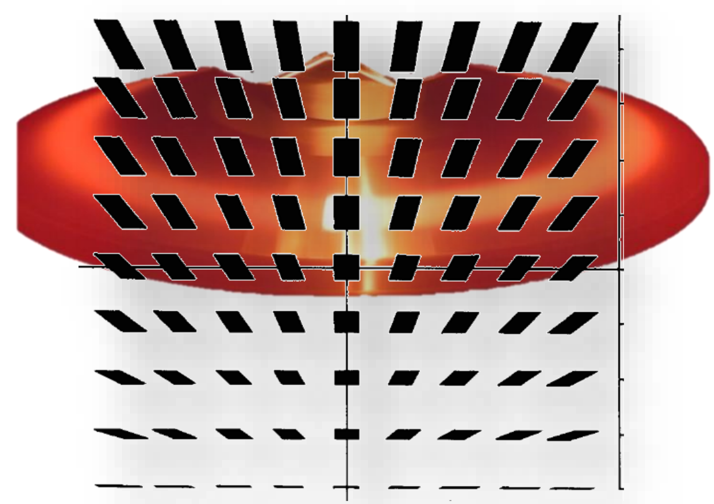
→ 5 x …10 x power rating (anode performance)

→ 5 x …10 x tube current (cathode performance)



Projected FS defines sharpness

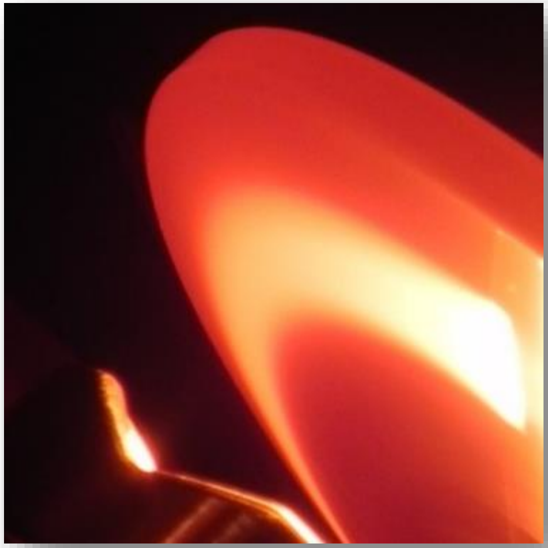
Pitfall: Resolution depends on organ position



Distorted FS projection in the periphery of the field of view

Target Issues

Focal track roughened during thermal cycling

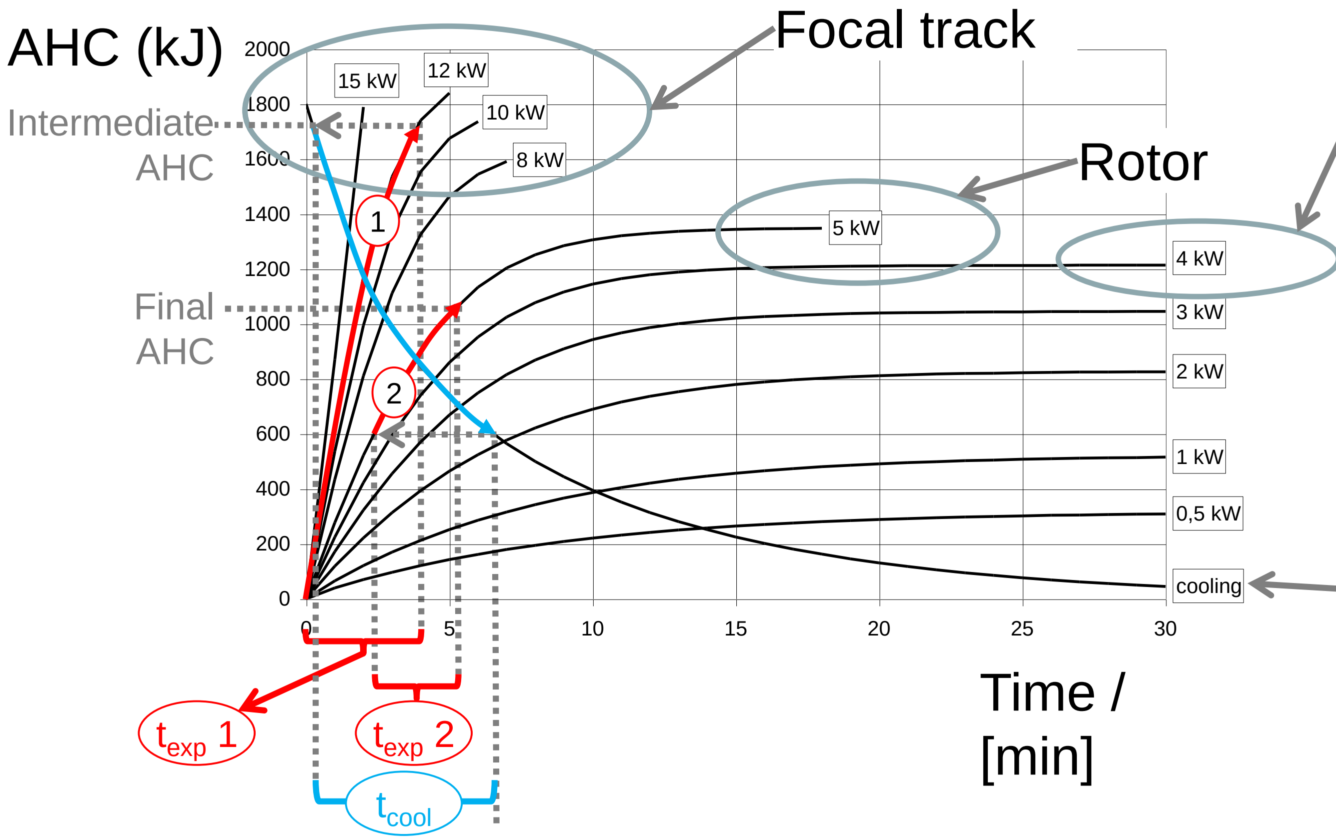


Thermal gradient

Crack relaxing excessive residual tensile stress

Pitfalls: Cold start cracking, gas desorption

Outdated Metric – Anode Heat Content (AHC)



Pitfall: Misleading metric, old technology

Example:
Two exposures t_{exp1} and t_{exp2} with a break t_{cool} in between

“Heat Units” are Out

- IEC: MAXIMUM ANODE HEAT CONTENT cancelled
  - outdated technology
- new terms:

3.15 NOMINAL RADIOGRAPHIC ANODE INPUT POWER

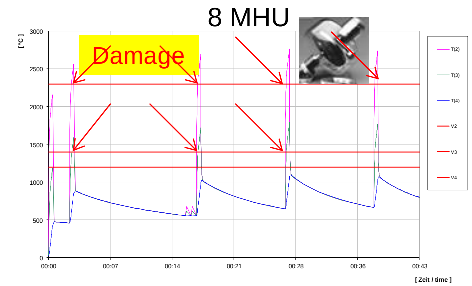
…POWER which can be applied for a single X-RAY TUBE LOAD with a LOADING TIME of 0,1 s and a CYCLE TIME of 1,0 min, for an indefinite number of cycles

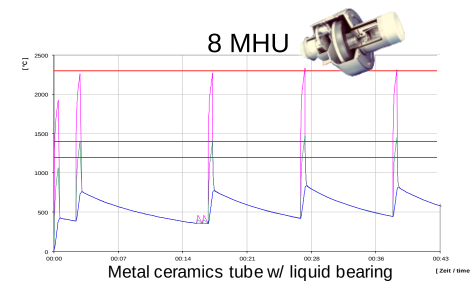
3.16 NOMINAL CT ANODE INPUT POWER

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

Pitfall: MHU’s confuse → Use new metric





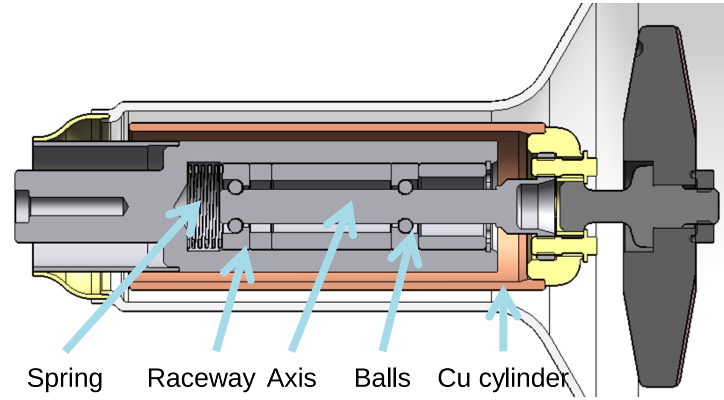
Same # of „MHU‘s“ but

- Ball bearing glass tube (top) damaged
- Tube with conduction cooling (SGB, bottom) survives.

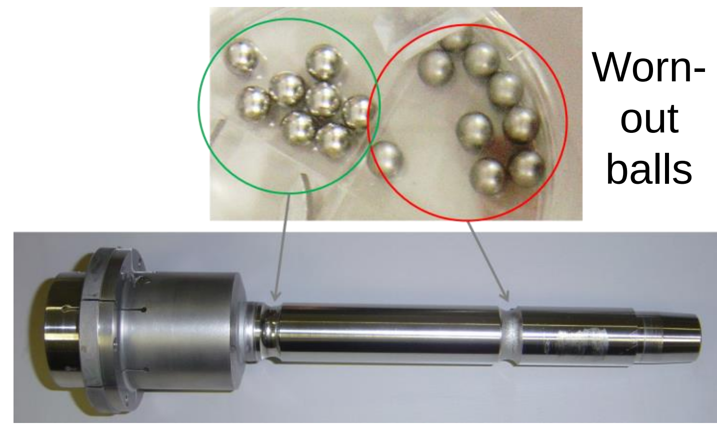
Ball Bearings in Vacuum

- Steel
- Would pit or freeze immediately without silver or lead coating
- Subject to wear
- Start-expose-brake required
  - Prep time
  - Additional heat input
- Limited load and speed capacity
- Essentially no heat conduction

Pitfalls: Wear. Prep time. Load limit.



Ball bearing system in a glass tube



Worn-out balls

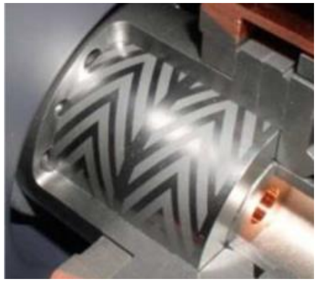
Manual assembly for a CT tube

Hydrodynamic Bearings in Vacuum
(Liquid bearings, spiral groove bearings SGB)

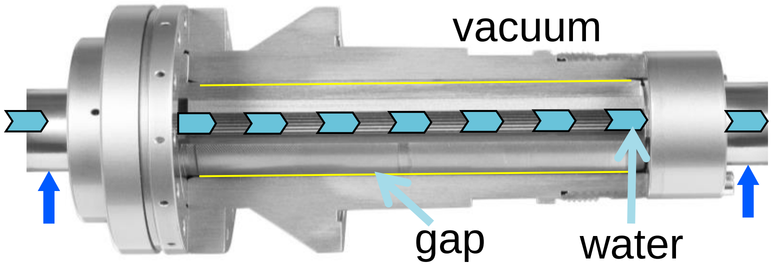
- ~10…50 µm gaps filled with liquid GaInSn
- Four in one (2 x radial, 2 x axial)
- Latest: dual suspended for CT
- Kilowatt heat conduction
- Minor wear, only during start & landing

→ Continuous rotation (zero prep time)

- Noiseless, stable, scalable to load



The two radial bearings of an SGB.



Dual suspended SGB for high centrifugal forces in CT.

Pitfall: Difficult to produce

Remark: rotating frame tubes (Siemens Straton) operate well lubricated ball bearings in oil

Cheaper all Bearing Tubes Might Perform Better

- Momentum of inertia of the anode

$$I_{rotor} \propto Ø_{anode}^{4}$$

→ Downside of heavy anodes
  - Extended prep time
  - More heat input during start / brake
  - Reduced cooling budget for X-ray production
  - Early bearing failure
  - Costs

→ Tade-off w/ heat balance advised

→ Pitfalls: Long prep time, overheat, costs

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

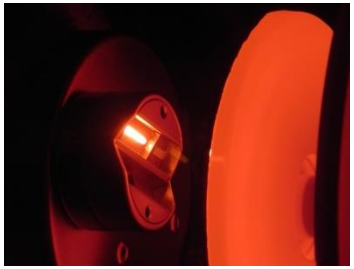
Cathode

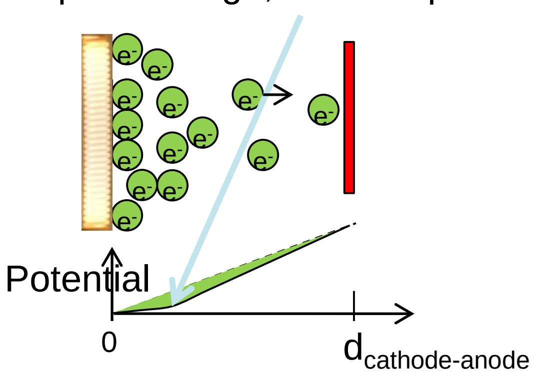
- Thermionic emission (high kV)

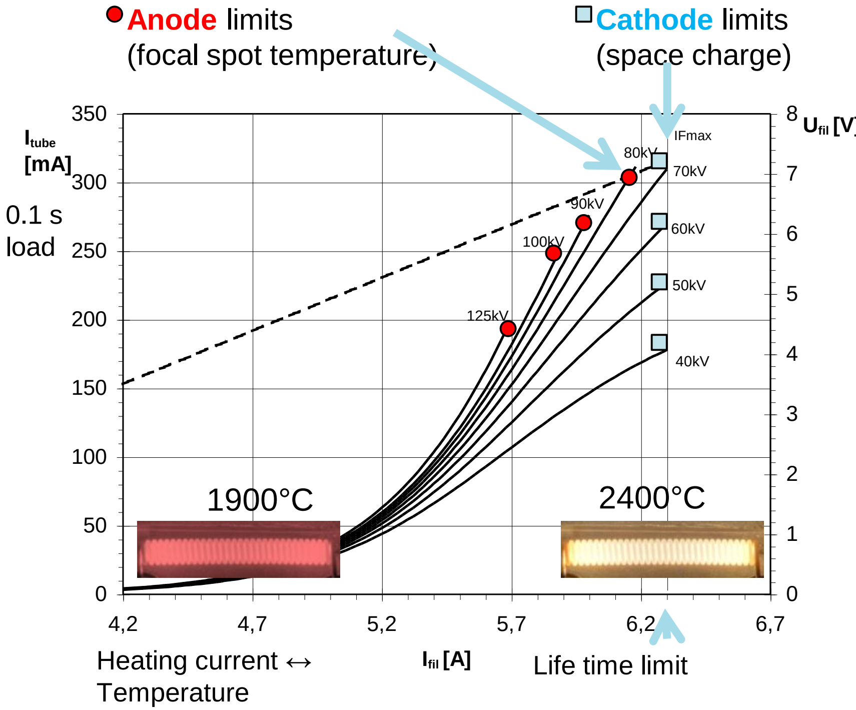
  $J = const * T^2 * \exp(-e\phi / kT)$

- Electronic space charge (low kV)

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







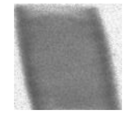
Sample Emission characteristics

→ Pitfall: Insufficient tube current

Electrostatic Focusing

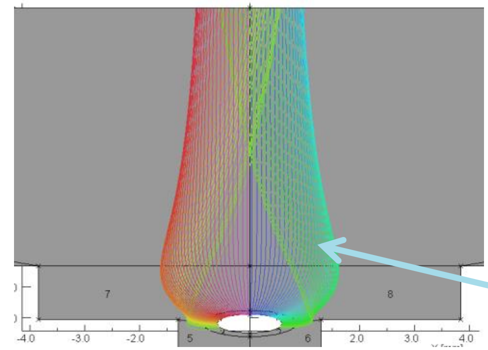
- Shape of cathode cup defines focusing electric field
- Simple: FS size nearly independent of tube voltage
- FS blooming (breathing) due to space charge. Electric potential depends on tube current

Pitfalls: FS blooming. Limited current

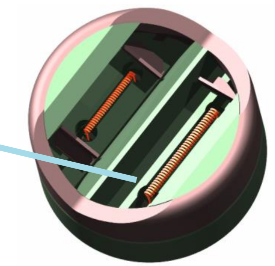


Current density at the anode (X-ray FS)

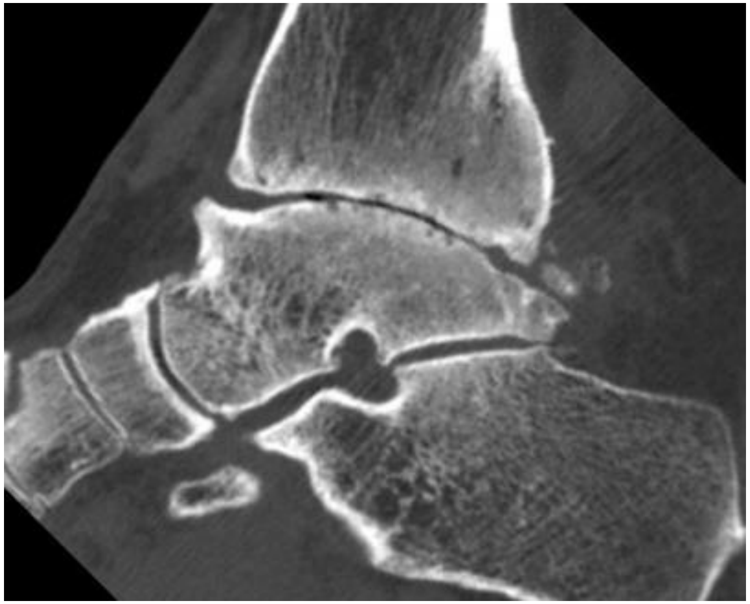
Anode



Electron beam tracing

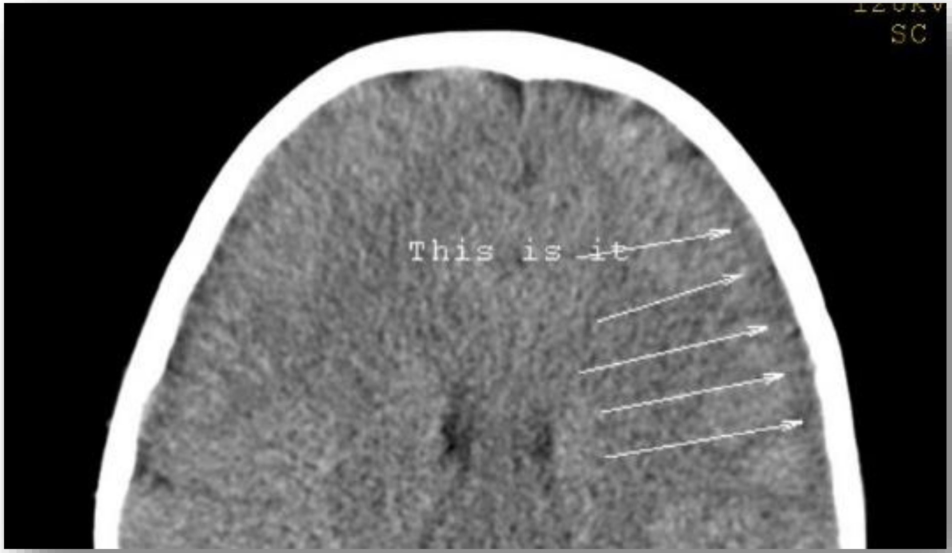


Dual filament cathode

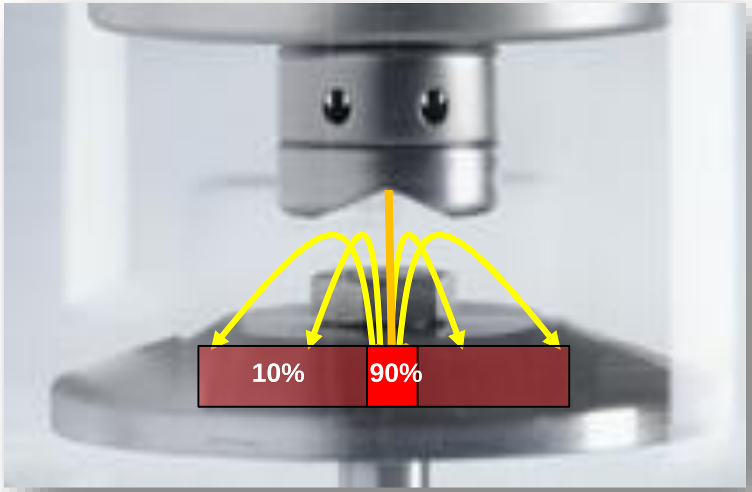


Off-Focal Radiation

- Form 2nd impact of back-scattered electrons
- Causes artifacts @ strong contrast
  - Mimics bleeding (stroke)
  - Shadow artifacts
  - Grey image
- Remedies
  - Electron trap
  - Avoid electron mirroring
  - Aperture closest to the focal spot



Sample artifact: Over-compensated off-focal



~10% off-focal (softer than primary)

Pitfalls: Off focal artifacts, extra dose

Compact Rotating Frame CT Tube Assembly

Radiation port

X-rays

Deflectable focal spot (azimuthal and radial = axial)

Vacuum

Rotating circular cathode (-70 kV)

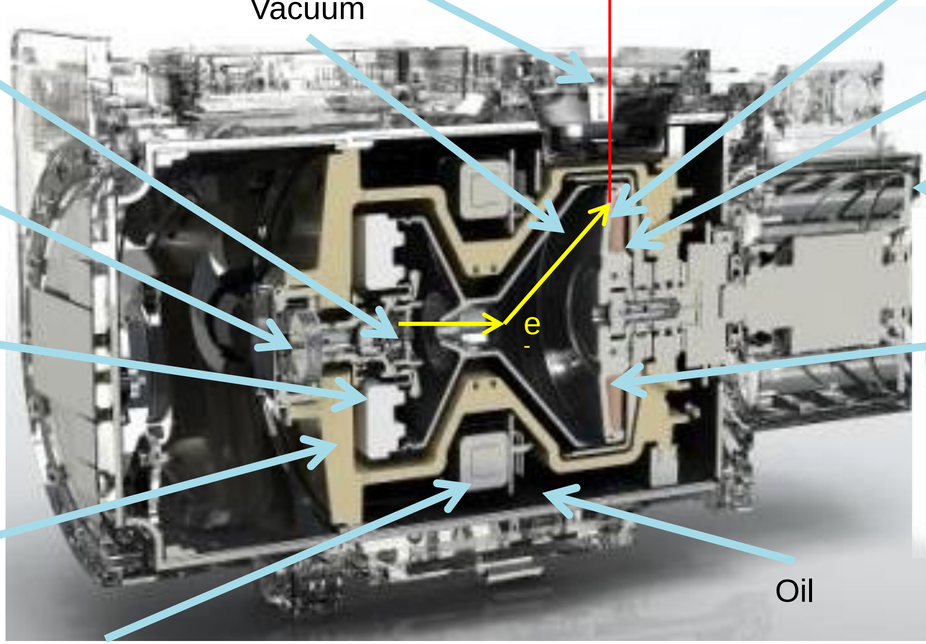
Copper backed 120 mm anode (in touch with oil)

Rotor bearing (in oil)

"External" motor

Ceramics insulator (rotating)

Plastics insulator



Oil

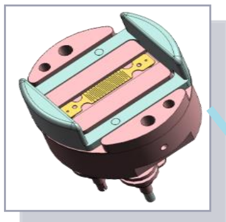
Rotating frame insert (+70 kV) Virtually "anode grounded", as seen from the focal spot perspective

Yoke of the magnetic quadrupole focusing and dipole deflection unit

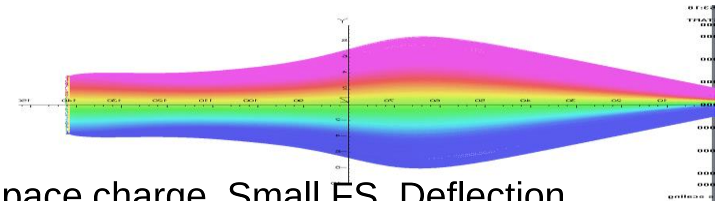
Pitfall: Limited X-ray flux

Type: Siemens Straton
Adapted from Behling (2016)

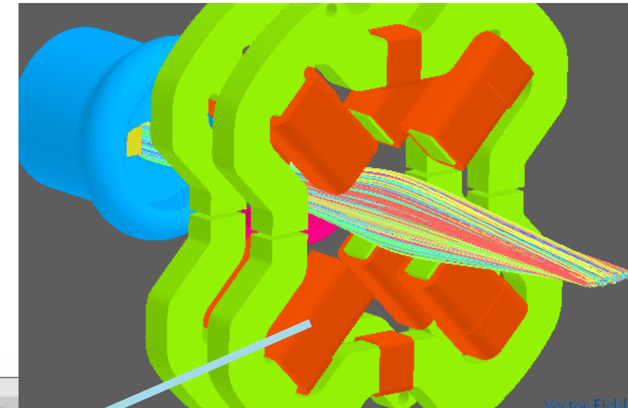
Flat Emitter and Magnetic Focusing / Deflection



Cathode with tungsten flat emitter

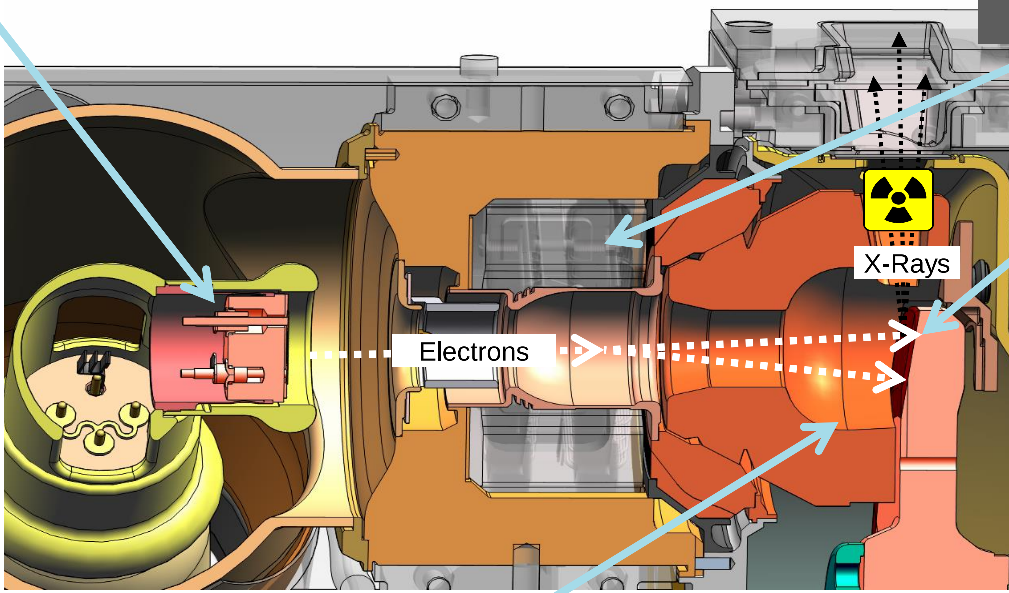


No space charge. Small FS. Deflection

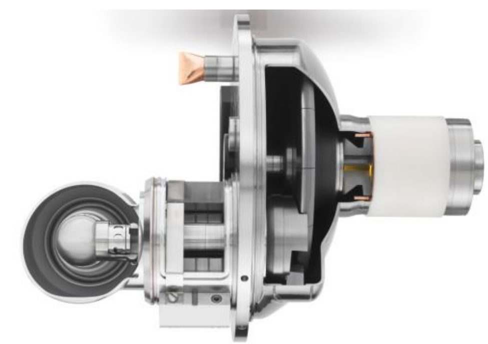


Magn. 2 x quadrupole + dipole

Z-deflection

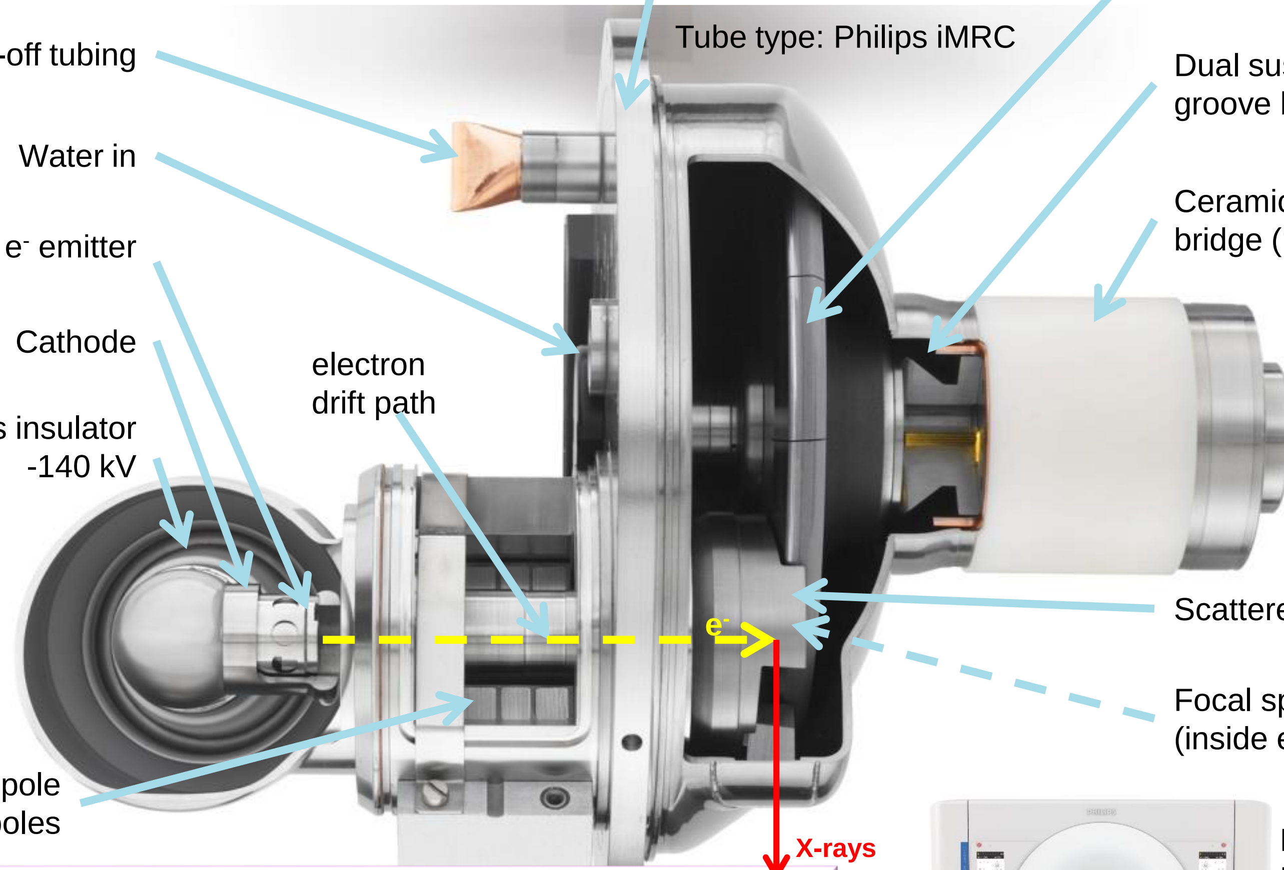


Scattered Electron Collector collects ~40% of the primary electron energy



Philips iMRC tube (Brilliance iCT and IQon)

Full Featured CT Tube & Highest FS Power

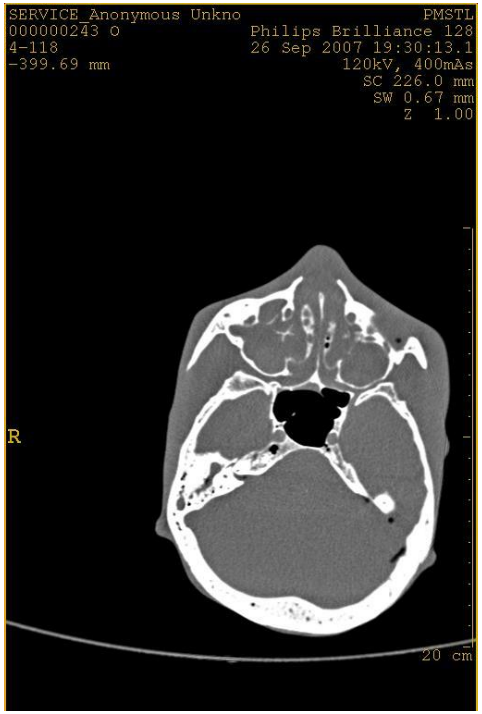


→ Pitfall: Initial costs

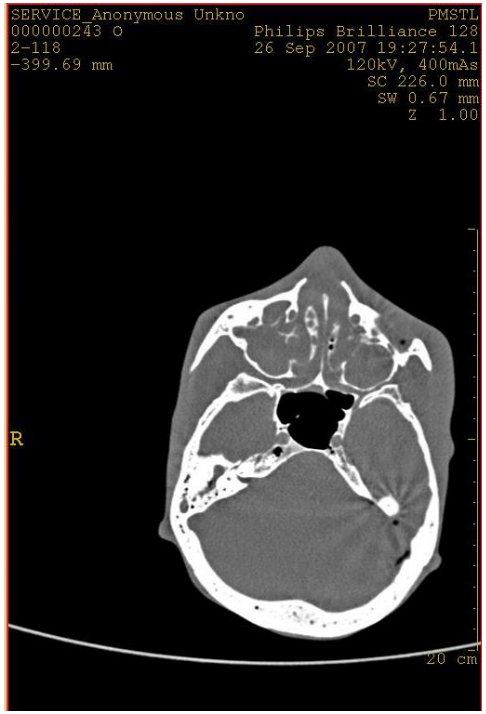
Philips Spectral Detection CT system IQon

Artifact Reduction by z/x FS Deflection

z-DFS

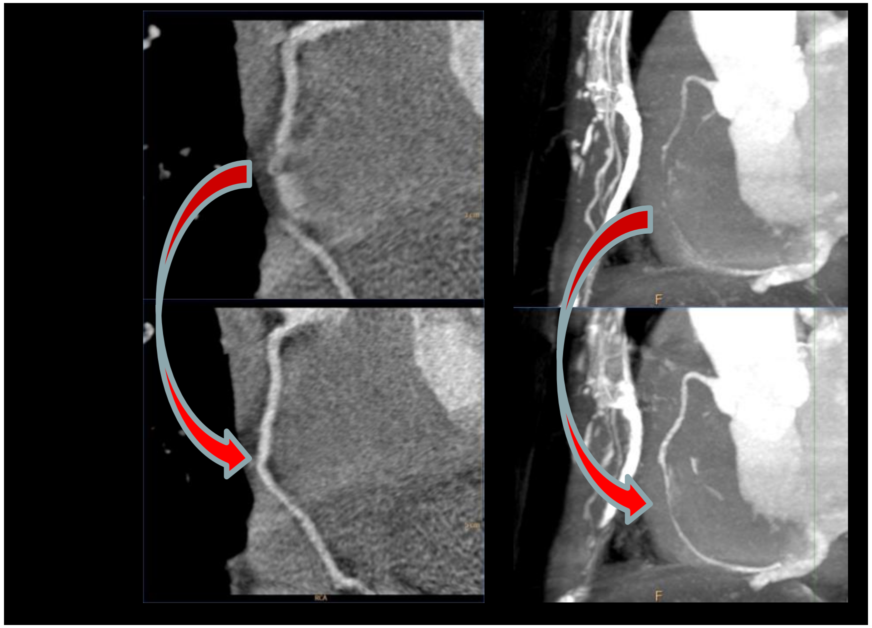


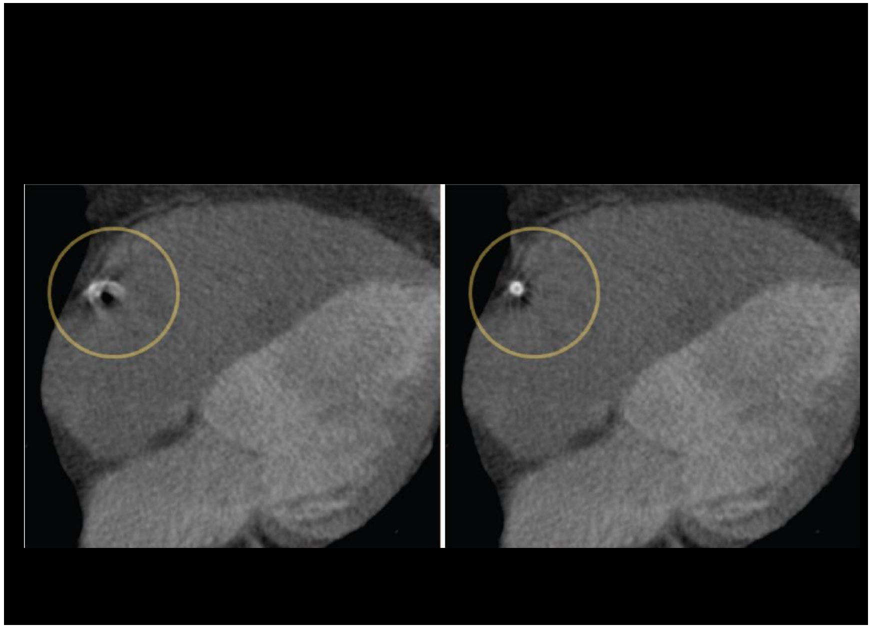
no z-DFS



→ Pitfall: Aliasing in CT

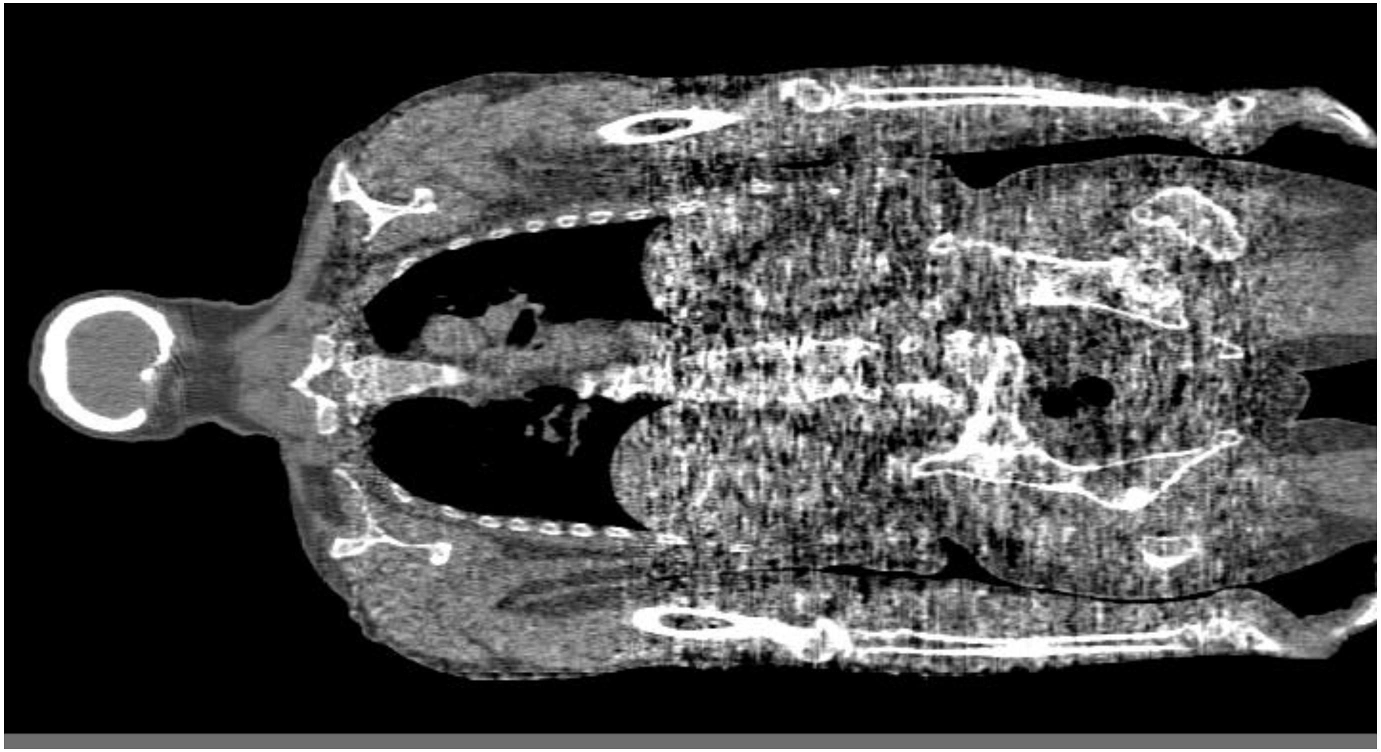
Lack of Power, Gantry Speed





→ Pitfall: Motion artifacts

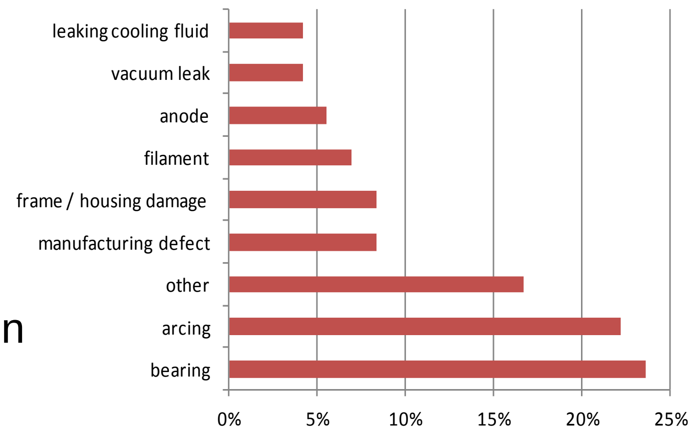
Lack of Power → Image Noise



→ Pitfall: No photons in some channels

Failure Modes
(CT tubes average)

- Arcing
- Low X-output / hard beam
- Vibration / noise / rotor frozen
- Electron emitter
- Implosion
- Run-away arcing
- Field emission
- Heat exchanger error
- Anode broken
- Stator burn-out
- Mechanical damage
- other



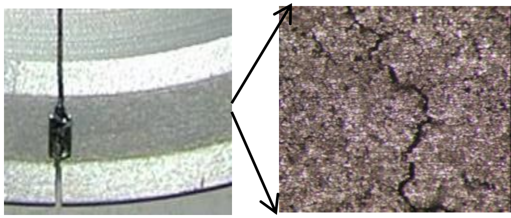
Tube Performance Characteristics and Comparison

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*

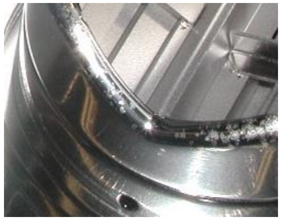
Tube life time statistics of GE CT tubes in 13 CT systems in the Sloan Kettering Center, NYC

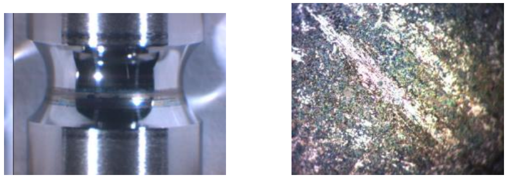

Anode crack (left), eroded focal spot track


Broken filament


Heat exchanger un-plugged → compressed


Glass coated→arcing


Arcing, craters


Worn-out ball raceway and ball

Pitfall: Early failures / short tube life

Quality Manufacturing

- Poor factory yield often translates to reliability issues

Cramped dusty workshop ca. 1920

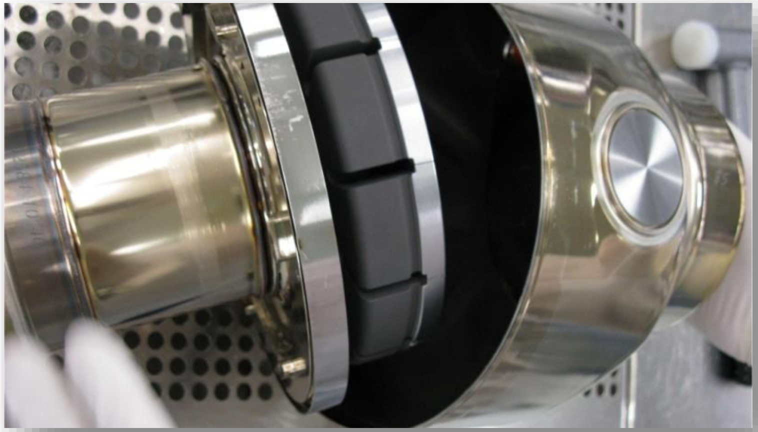
Automated production, quality boards 2016

Clean room, high skills 2016

→ Pitfall: Quality issues

Environmental Protection

- Recycling is a must
- Same or better performance vs. new material
- Cost saving
- Saving natural resources, sustainability
- Saving energy
- Select a quality supplier with recycling capability for sub-components of tubes



Pitfall: Environmental hazards (lead, Be...)

What can We do Better?

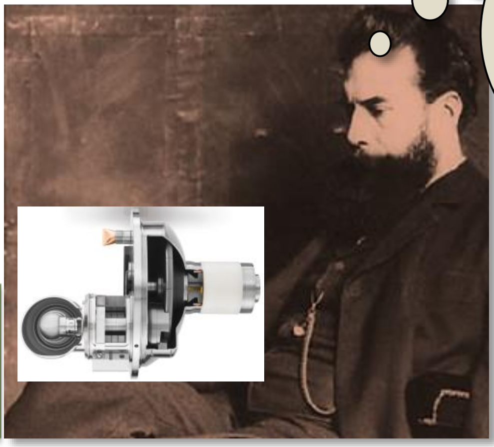
Investment / Maintenance / Environment

- Ignore Heat Units. Use new IEC metric
- Single tube or multiple tubes (costs)?
- Go with long-life supplier (up-time)
- Tube-included service contracts
- Ask about life time & degree of recycling

Clinical

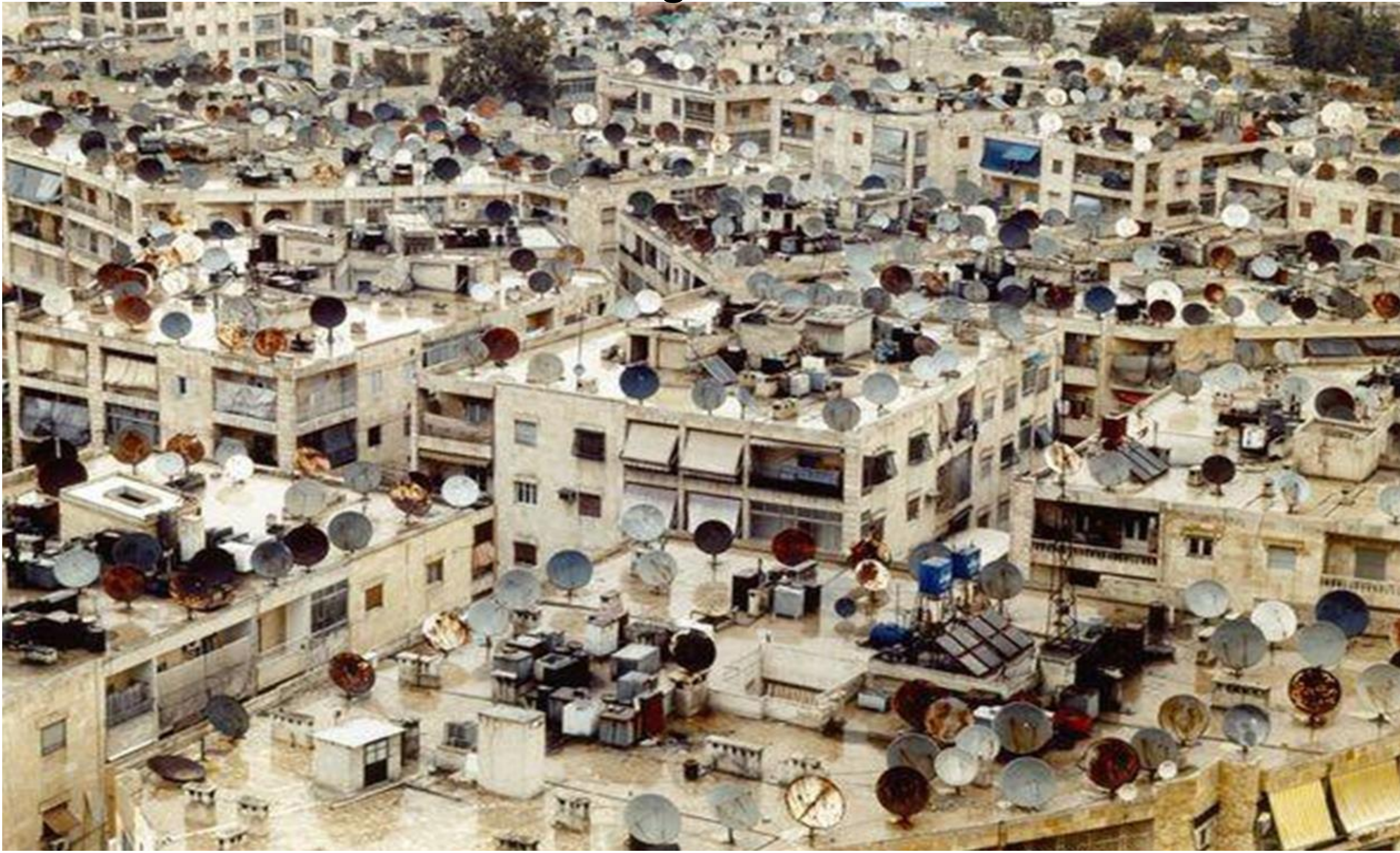
- No cold-start with high power / voltage
- Minimize time in prep mode
- Observe warning signals

→Select a quality supplier, drive right



2016:
Amazing
technology

Thank You for Listening



Abstract ID: 31410 for AAPM 2016

- Rolf.Behling@philips.com
- **Pitfalls: Reliability and performance of diagnostic X-sources**
-
- Purpose: Performance and reliability of medical X-ray tubes for imaging are crucial from an ethical, clinical and economic perspective. This lecture will deliver insight into the aspects to consider during the decision making process to invest in X-ray imaging equipment. Outdated metric still hampers realistic product comparison. It is time to change this and to comply with latest standards, which consider current technology. Failure modes and ways to avoid down-time of the equipment shall be discussed. In view of the increasing number of interventional procedures and the hazards associated with ionizing radiation, toxic contrast agents, and the combination thereof, the aspect of system reliability is of paramount importance.
-
- **Methods**: A comprehensive picture of trends for different modalities (CT, angiography, general radiology) has been drawn and led to the development of novel X-ray tube technology.
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- **Results**: Recent X-ray tubes feature enhanced reliability and unprecedented performance. Relevant metrics for product comparison still have to be implemented in practice.
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- **Conclusion**: The speed of scientific and industrial development of new diagnostic and therapeutic X-ray sources remains tremendous. Still, users suffer from gaps between desire and reality in day-to-day diagnostic routine. X-ray sources are still limiting cutting-edge medical procedures. Side-effects of wear and tear, limitations of the clinical work flow, costs, the characteristics of the X-ray spectrum and others topics need to be further addressed. New applications and modalities, like detection-based color-resolved X-ray and phase-contrast / dark-field imaging will impact the course of new developments of X-ray sources.

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