X-ray Production, X-ray Tubes and Generators
Bushberg – Chapter 5

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a copy of this lecture may be found at:
http://courses.washington.edu/radxphys/PhysicsCourse.html

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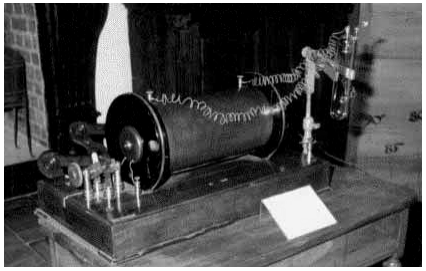
X-rays – the Basic Radiological Tool

November 8, 1895
Roentgen's experimental apparatus (Crookes tube) that led to the discovery of the new radiation. Roentgen demonstrated that the radiation was not due to charged particles, but due to an as yet unknown source, hence "x" radiation or "x-rays."



Known as "the radiograph of Bera Roentgen's hand" taken December 22, 1895

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Objectives – Chapter 5 Lecture

- How x-rays are *produced*, what *spectrum* results and how do radiographic *technique factors* and *target* atomic number (Z) affect the spectrum?
- What elements comprise an *x-ray tube* and how do they work together to generate x-rays?
- How are x-rays collimated and the exposure timed?
- What is an x-ray *generator*, how does it assist in the production of x-rays and how does its design affect the resulting output spectrum and patient dose?
- How does the x-ray tube heat loading and cooling affect the duration and number of radiographic exposures?

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Review – Interaction with Matter (Ch. 3)

- X-ray and γ-ray interactions
  - Rayleigh scatter
  - Compton scatter
  - Photoelectric absorption
  - Pair production
- Particle interactions
  - Excitation
  - Ionization
  - Radiative losses – Bremsstrahlung

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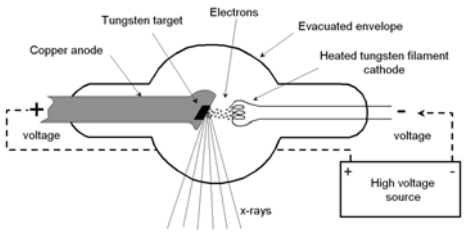
Basic X-ray Production

- Electron source – cathode
- Target – Anode
- Evacuated path for the e^-s to travel through – x-ray tube insert
- External energy source to accelerate the e^-s – generator



c.f.: Bushberg, et al., The Essential Physics of Medical Imaging, 2nd ed., p. 98.

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Basic X-ray Production

- Electron interactions with the anode (target) produce:
  - Heat – the kinetic energy (KE) of the electron deposits its energy in the form of heat
    - Collision-like interactions with atoms (KE incident e^- < BE orbital e^-)
    - Accounts for the majority of the interactions with the target (~99%)
  - <u>Only ~1% of the electron interactions result in x-rays production</u>
    - Bremsstrahlung – continuous energy spectrum
      - Coulomb interactions
    - Characteristic x-rays – discrete energies
      - Incident e^- collision with orbital e^- (KE incident e^- > BE orbital e^-)

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X-ray Production:
The Bremsstrahlung Process

c.f.: Bushberg, et al., The Essential Physics of Medical Imaging, 2nd ed., p. 98.

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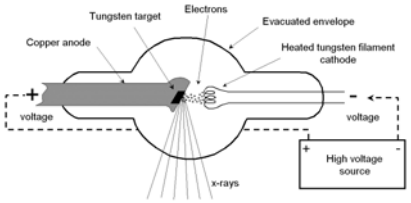
X-ray Production:
The Bremsstrahlung Process



- Cathode – source of e^-s; negatively charged electrode
- Anode – target for e^-s; positively charged electrode
- A large potential difference (kilovoltage potential – kVp) is applied across the two electrodes in an evacuated envelope (x-ray tube insert)

c.f.: Bushberg, et al., The Essential Physics of Medical Imaging, 2nd ed., p. 98.

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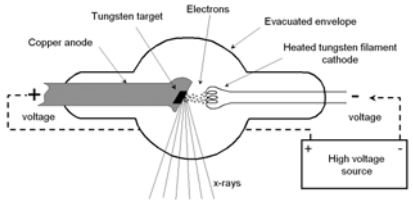
X-ray Production:
The Bremsstrahlung Process



- e^-s released from the cathode gain KE as they are accelerated towards the anode
  - Energy of the e^-s is expressed in keV
  - The KE of the e^- is proportional to kVp (e.g. energies of electrons accelerated by potential differences of 20 and 100 kVp are 20 and 100 keV, respectively)

c.f.: Bushberg, et al., The Essential Physics of Medical Imaging, 2nd ed., p. 98.

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X-ray Production:
The Bremsstrahlung Process

- Target nucleus positive charge ($Z \cdot p^+$) attracts incident e^- (Coulomb interaction)
- Deceleration of an incident e^- occurs in the proximity of the target atom nucleus
- Conservation of Energy (Law of Physics)
  - E lost by e^- gained by the EM photon (x-ray) generated
  - Coulomb force of attraction varies strongly with distance ($\propto 1/r^2$)
- X-rays that are produced by the conversion of the incident electron KE into EM radiation is known as *Bremsstrahlung* (German: "braking radiation")

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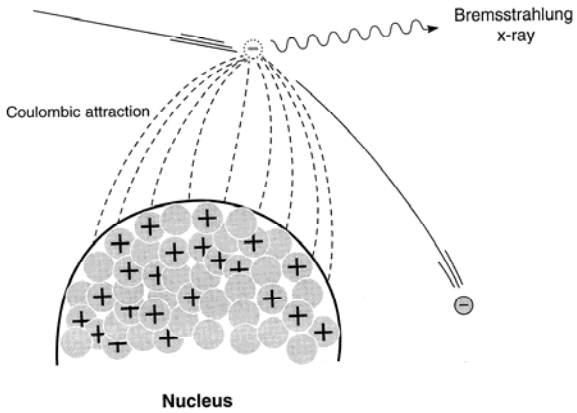
X-ray Production:
The Bremsstrahlung Process



c.f.: Bushberg, et al., The Essential Physics of Medical Imaging, 2nd ed., p. 35.

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X-ray Production:
The Bremsstrahlung Process

- Coulomb force of attraction varies strongly with distance ($\propto 1/r^2$)
- Impact parameter distance – the closest approach to the nucleus by the e^- – determines the amount of energy lost by the incident electron
  - ↓ distance – ↑ amount of E lost by incident e^- and ↑ photon E
  - Direct impact on the nucleus (rarest event) determines the maximum x-ray E (E_{max})

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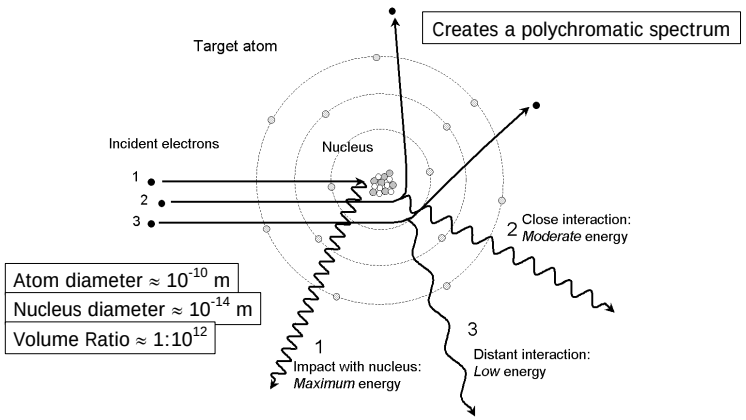
X-ray Production:
The Bremsstrahlung Process



c.f.: Bushberg, et al., The Essential Physics of Medical Imaging, 2nd ed., p. 99.

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X-ray Production:
The Bremsstrahlung Process

- The unfiltered energy spectrum is polychromatic
  - Contains a large number of very low E photons
  - The spectrum ↓ approximately linearly as photon E ↑ due to the higher probability of a large impact parameter distance
  - The peak voltage (kVp) applied across the electrodes of the x-ray tube determines the highest x-ray E (E_{max})
  - The lowest E of the unfiltered x-ray spectrum is not easily determined, due to severe attenuation of these photons by the material and thickness of the x-ray tube envelope
- All diagnostic x-ray equipment have filters
  - Preferentially remove low-energy x-rays (dose contribution)
  - Average x-ray energy is ~ 1/3 to 1/2 E_{max}

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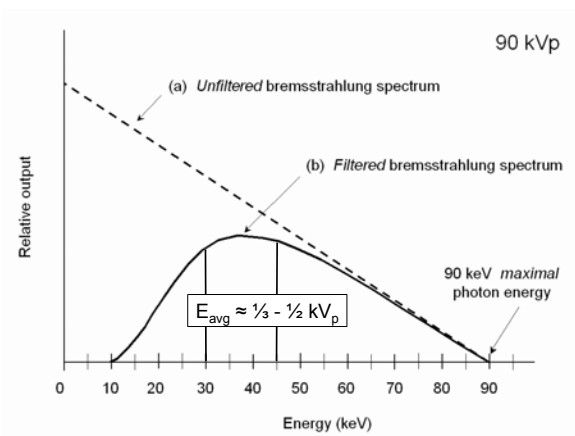
X-ray Production:
The Bremsstrahlung Process



c.f.: Bushberg, et al., The Essential Physics of Medical Imaging, 2nd ed., p. 99.

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X-ray Production:
The Bremsstrahlung Process

- X-ray production efficiency is influenced by the target atomic number (Z) and acceleration potential (kVp)
  - Efficiency is the ratio of the radiative energy loss to collisional energy loss

$$\text{X-ray efficiency} \approx E_{max} \cdot Z \cdot 10^{-6}$$

$$I(E_i) = k \cdot Z \cdot (E_{max} - E_i)$$

- Example:
  - Diagnostic – 100-keV electrons impinging on tungsten (Z = 74)
    - X-ray production ~ 0.7%
  - Therapeutic – 6-MeV electrons, tungsten target
    - X-ray production ~ 44%

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X-ray Production:
Characteristic X-ray Spectrum

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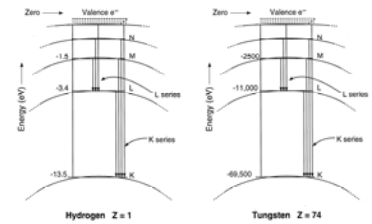
X-ray Production:
Characteristic X-ray Spectrum

- Recall: orbital e^- binding energy (BE) depend on Z
  - $BE_K \propto Z^2$
  - Additionally, $BE_K > BE_L > BE_M > ...$
- If e^-(KE) incident on the target exceeds the target atom e^-(BE), it's energetically possible for a collisional interaction to eject the bound electron and ionize the atom



c.f.: Bushberg, et al., The Essential Physics of Medical Imaging, 2nd ed., p. 22.

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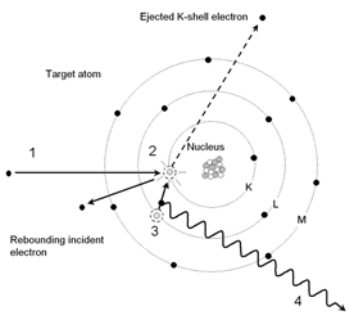
X-ray Production:
Characteristic X-ray Spectrum

- Unfilled inner shells are energetically unstable
- An outer shell e^- with lesser BE fills inner shell vacancy
- As e^- transitions to a lower E state, the excess E can be released as a characteristic x-ray photon with E equal to the difference between the BE of the e^- shells
- As BE are unique to a given element (Z), the emitted x-rays have discrete energies characteristic of that element



c.f.: Bushberg, et al., The Essential Physics of Medical Imaging, 2nd ed., p. 101.

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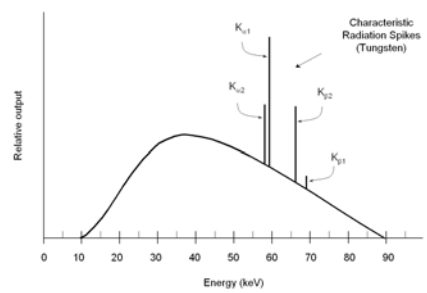
X-ray Production:
Characteristic X-ray Spectrum



- Characteristic x-rays are shown as discrete E lines superimposed on the continuous bremsstrahlung spectrum
- Example shown: The <u>filtered</u> energy spectrum, <u>90 kVp</u> potential difference (E_{avg} = 30-45 keV) and <u>tungsten</u> target.
  - A variety of E transitions occur from adjacent (α) and non-adjacent (β) e^- shells – K_β x-rays are more energetic than K_α x-rays

c.f.: Bushberg, et al., The Essential Physics of Medical Imaging, 2nd ed., p. 101.

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X-ray Production:
Characteristic X-ray Spectrum

TABLE 5-1. ELECTRON BINDING ENERGIES (keV) OF COMMON X-RAY TUBE TARGET MATERIALS

Electron Shell	Tungsten	Molybdenum	Rhodium
K	69.5	20.0	23.2
L	12.1/11.5/10.2	2.8/2.6/2.5	3.4/3.1/3.0
M	2.8–1.9	0.5–0.4	0.6–0.2

- The target materials used in x-ray tubes for diagnostic medical imaging include:
  - W (Z=74) – general radiography
  - Mo (Z=42) – mammography
  - Rh (Z=45) – mammography
- Within each shell (other than K) there are discrete E orbitals (ℓ = 0, 1, ... , n-1) resulting in a fine E splitting of the characteristic x-rays

c.f.: Bushberg, et al., The Essential Physics of Medical Imaging, 2nd ed., p. 100.

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X-ray Production:
Characteristic X-ray Spectrum

- Characteristic x-rays other than those generated through K-shell transitions are not important in Dx imaging
  - Other transitions – characteristic x-ray energies almost entirely attenuated by the x-ray tube window or added filtration
- K-shell characteristic x-rays *only* occur if the KE of the incident e^- is greater than the BE of the e^-s in the K-shell (e.g. kVp > 69.5 for W)
- As the E of the incident e^- increases above the threshold E for characteristic x-ray production, the % of characteristic x-rays ↑
  - Example: for W target: 5% @ 80 kVp vs. 10% @ 100 kVp

TABLE 5-2. K-SHELL CHARACTERISTIC X-RAY ENERGIES (keV) OF COMMON X-RAY TUBE TARGET MATERIALS[a]

Shell Transition	Tungsten	Molybdenum	Rhodium
$K_{\alpha 1}$	59.32	17.48	20.22
$K_{\alpha 2}$	57.98	17.37	20.07
$K_{\beta 1}$	67.24	19.61	22.72

[a]*Note:* Only prominent transitions are listed.

c.f.: Bushberg, et al., The Essential Physics of Medical Imaging, 2nd ed., p. 102.

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c.f.: Bushberg, et al., The Essential Physics of Medical Imaging, 2nd ed., p. 101.

Raphex 2000 General Question

- **G36**. The ratio of heat to x-rays (heat : x-rays) produced in a typical diagnostic target is:
  - A. 1 : 99
  - B. 10 : 90
  - C. 50 : 50
  - D. 90 : 10
  - E. 99 : 1

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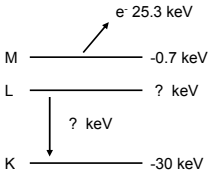
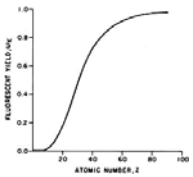
Raphex 2000 General Question

- **G37**. Consider an atom with the following binding energies: K-shell, 30 keV; M-shell, 0.7 keV. An electron with a kinetic energy of 25.3 keV is ejected from the M-shell as an Auger electron following L to K transition. The binding energy of the L-shell electron is _____ keV.
  - A. 1.4
  - B. 4.0
  - C. 4.7
  - D. 15.0
  - E. 29.3





- E = 25.3 + 0.7 = 26 keV where E is equal to the difference between the binding energies of the K- and L-shells.
- 26 keV = $BE_K - BE_L$ = 30 keV - BE_L; BE_L = 4 keV.

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Raphex 2002 General Question

- **G40.** Tungsten has the following binding energies: K = 69 keV, L = 12 keV, M = 2 keV. A 68 keV electron striking a tungsten target could cause emission of which of the following photons?
  - 1. 66 keV characteristic x-ray.
  - 2. 57 keV bremsstrahlung.
  - 3. 57 keV characteristic x-ray.
  - 4. 10 keV characteristic x-ray.

  - A. 1, 2, 3 and 4
  - B. 1, 3
  - C. 2, 4
  - D. 4 only

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X-rays – the Basic Radiological Tool

- Each part of the x-ray tube is essential to create the environment necessary to produce x-rays via
  - Bremsstrahlung
  - Characteristic x-rays
- The potential difference (kVp), tube current (mA), and exposure time (sec) are selectable parameters to determine the x-ray spectrum characteristics (quality and quantity of x-ray photons

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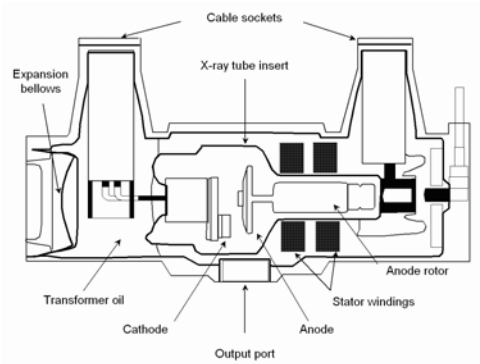
X-ray Tube



- Tube insert – cathode, anode, rotor assembly, support structures
- Tube housing – oil bath (heat conduction, electrical insulation), bellows (oil expansion), lead shielding (leakage radiation < 100 mR/hour @ 1 m when operated at max. settings)

c.f.: Bushberg, et al., The Essential Physics of Medical Imaging, 2nd ed., p. 103.

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X-ray Tube:
Cathode – Filament

- Cathode – e^- source
  - Helical tungsten wire filament
    - Traces of thorium – prolong filament life and increase electron emission efficiency
  - Filament is surrounded by a focusing cup
- Filament circuit: 10V, 7A
- Electrical resistance heats the filament and releases e^- via thermionic emission ("electron cloud")
  - Lights up – incandescence – light bulb
- Filament current adjustments controls tube current (rate of e^- flow from cathode to anode - mA)

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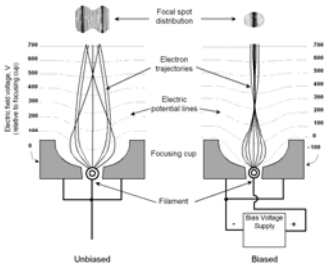
X-ray Tube:
Cathode – Focusing Cup

- Cathode block – shapes e^- distribution (unbiased)
  - Same circuit as filament
- Biased x-ray tubes – the circuit for the focusing cup is isolated from filament
  - Application of a negative bias V constrains e^- distribution further (typically -100 volts)
  - Tighter electrical field around the filament – reduces the spread of electrons
  - Smaller focal spot width



c.f.: Bushberg, et al., The Essential Physics of Medical Imaging, 2nd ed., pp. 104.
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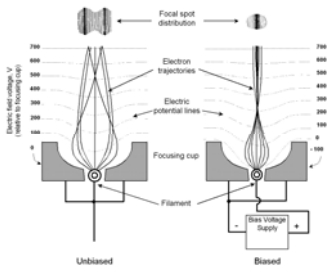
X-ray Tube:
Cathode – Focusing Cup

- Focusing cup slot width determines the focal spot (FS) width
- Filament length determines FS length
- Small and large FS filaments (power loading)
  - Typical Dx focal spot sizes – 0.6 mm and 1.2 mm



c.f.: Bushberg, et al., The Essential Physics of Medical Imaging, 2nd ed., pp. 104.
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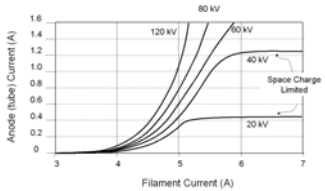
X-ray Tube:
Cathode – Space Charge Limitation

- Filament current (A)
  - Electrical resistance heats the filament (T ↑) increases thermionic emission rate
- If kVp = 0 applied, an e^- cloud forms around the filament (space charge cloud)



- If kVp applied → tube current forms b/c e^-s attracted to anode
  - For ≤ 40 kVp: space charge cloud shields the electric field → only some e^- are accelerated towards the anode: *space charge limited* (upper limit on tube current)
  - For > 40 kVp: space charge cloud effect overcome by applied kVp → tube current only limited by the emission of e^- from the filament: *emission-limited operation*
- Tube current (usually mA) about 5-10 times less than the filament current in the emission-limited range

c.f.: Bushberg, et al., The Essential Physics of Medical Imaging, 2nd ed., pp. 105.
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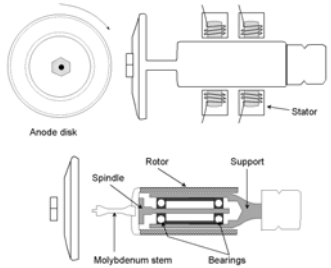
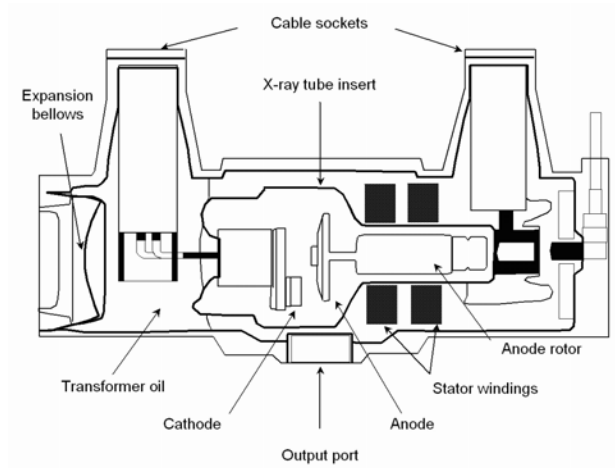
X-ray Tube:
Anode Configuration



- High melting point (heat production) & high atomic number (bremsstrahlung production)
  - Gen rad – tungsten (W, Z = 74) (10% rhenium)
  - Mammo – Molybdenum (Mo, Z = 42) and Rhodium (Rh, Z = 45)
- Fixed anode
  - W target embedded in Cu
  - Dental x-ray, portables, c-arms
- Rotating anode – better heat dissipation
- Induction motor – stator (series of electromagnets) and rotor
  - Rotor bearings are heat sensitive; Mo stem (poor heat conductor) isolates anode → anodes cools through radiative emission, heat transfers to oil bath of tube insert

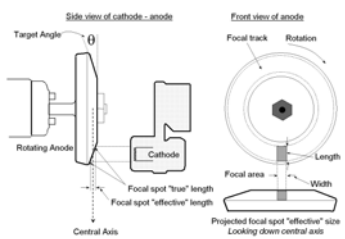
c.f.: Bushberg, et al., The Essential Physics of Medical Imaging, 2nd ed., p. 107. © UW and Renée Dickinson, MS 33

X-ray Tube



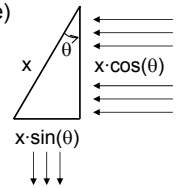
c.f.: Bushberg, et al., The Essential Physics of Medical Imaging, 2nd ed., p. 103. © UW and Renée Dickinson, MS 34

X-ray Tube:
Anode Configuration – Angle and Focal Size



- Anode angle (**θ**) range : 7° - 20°
- Actual focal spot (FS) – defined by filament length and focusing cup (width)
  - FS width not affected by anode angle, therefore effective FS width = actual FS width
  - Effective FS length < actual FS length
- Foreshortening of FS length (line focus principle)
  - Effective FS size = length and width of the FS projected along the central axis of the x-ray field

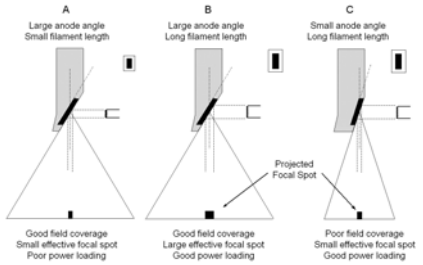
$$\text{Effective FS} = \text{Actual FS} \cdot \sin\theta$$

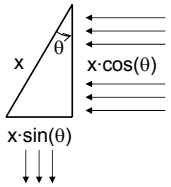


- Smaller FS → improved spatial resolution

c.f.: Bushberg, et al., The Essential Physics of Medical Imaging, 2nd ed., p. 108-109. © UW and Renée Dickinson, MS 35

X-ray Tube:
Anode Configuration – Angle and Focal Size



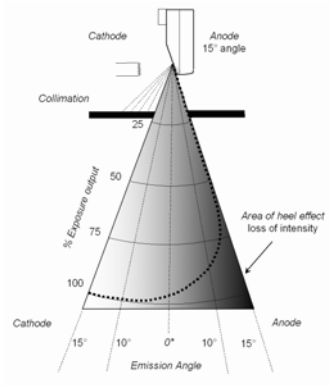


- 1. ↑ **θ** → ↑ apparent focal spot size (B and C)
- 2. ↑ **θ** → ↑ heat loading
- 3. ↑ **θ** → ↑ field coverage (compare B and C)
  - 7-9 degrees – small FOV clinical apps (fluoro II size and SID limitations)
  - 12-15 degrees – gen rad apps w/short FS-to-image distance (e.g. 40”)

c.f.: Bushberg, et al., The Essential Physics of Medical Imaging, 2nd ed., p. 108-109. © UW and Renée Dickinson, MS 36

X-ray Tube:
Anode Configuration – Heel Effect

- Reduction of x-ray beam intensity towards the anode side of the x-ray field
- Although x-rays generated isotropically at depth on interaction
  - Self-filtration by the anode
  - Anode bevel causes greater intensity on the cathode side of the x-ray field
- Use to advantage
  - PA chest exposure – orient chest to anode and abdomen to cathode
  - Mammo – orient nipple to anode and chest wall to cathode
- Less pronounced as SID ↑



c.f.: Bushberg, et al., The Essential Physics of Medical Imaging, 2nd ed., p. 112.

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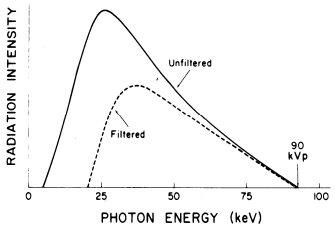
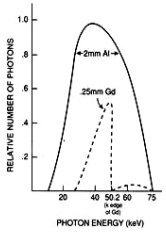
X-ray Tube:
Filtration



- Filtration: x-ray attenuation as beam passes through a layer of material
- Inherent filtration
  - Glass or metal insert at x-ray tube port (attenuate < 15 keV)
- Added filtration
  - Sheets of metal intentionally placed in the beam (in x-ray tube housing)
    - Common – Al, Cu, plastic, Mo, Rh
  - Absorb low-energy x-rays, reduce patient dose
  - ↑ beam quality
- Some filters reduce scatter: Gd
- HVL – half value layer (mm Al)
  - Indirect measure of effective energy of x-ray beam
  - US – CFR Title 21 compliance – minimum HVL



c.f.: Curry, et al., Christensen's Physics of Diagnostic Radiology, 4th ed., pp. 89, 91.

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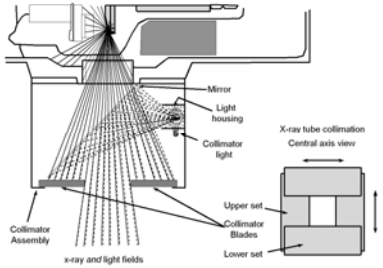
X-ray Tube:
Collimation



- Collimators adjust size and shape of x-ray beam
- Parallel-opposed lead shutters
- Light field mimics x-ray field (CFR Title 21 Regs)
- Reduces dose to patient; ALARA: as low as reasonably achievable
- Limited irradiated field → reduced scatter radiation to image receptor → improved image contrast
- Positive beam limitation (PBL) – auto beam collimation (CFR Title 21 Regs)

c.f.: Bushberg, et al., The Essential Physics of Medical Imaging, 2nd ed., p. 115.

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Raphex 2003 General Question

- **G35.** Two filaments are found in some x-ray tubes. The purpose is to:
  - A. Function as a spare in case one filament burns out.
  - B. Produce higher tube currents by using both filaments simultaneously.
  - C. Double the number of heat units that the target can accept.
  - D. Enable the smallest focal spot to be used, consistent with the kVp/mA setting.

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