

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

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a copy of this lecture may be found at:

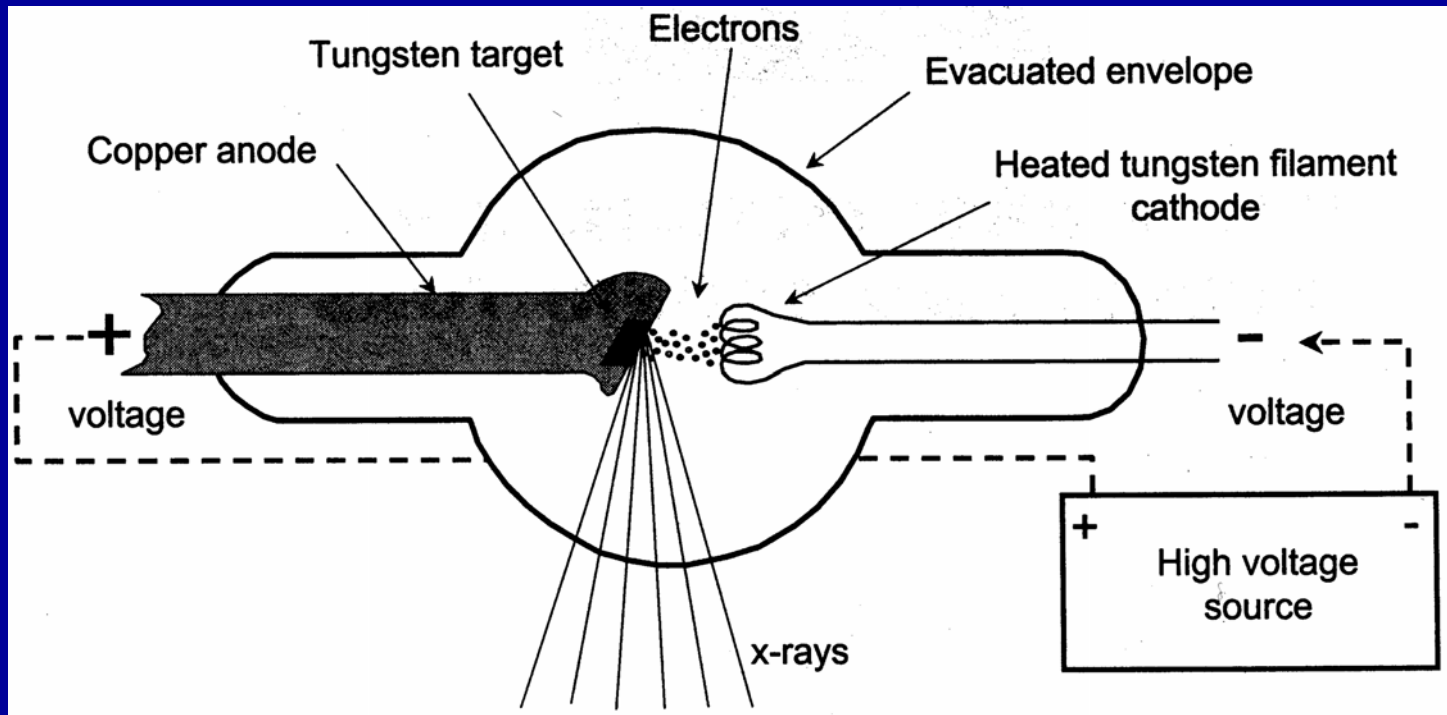
<http://courses.washington.edu/radphys/PhysicsCourse04-05.html>

Outline

- ❖ Production of X-rays
- ❖ X-ray Tubes
- ❖ X-ray Tube Insert, Housing, Filtration and Collimation
- ❖ X-ray Generator Function and Components
- ❖ X-ray Generator Circuit Designs
- ❖ Timing the X-ray Exposure in Radiography
- ❖ Factors Affecting X-ray Emission
- ❖ Power ratings and Heat Loading
- ❖ X-ray Exposure Rating Charts

Production of X-rays

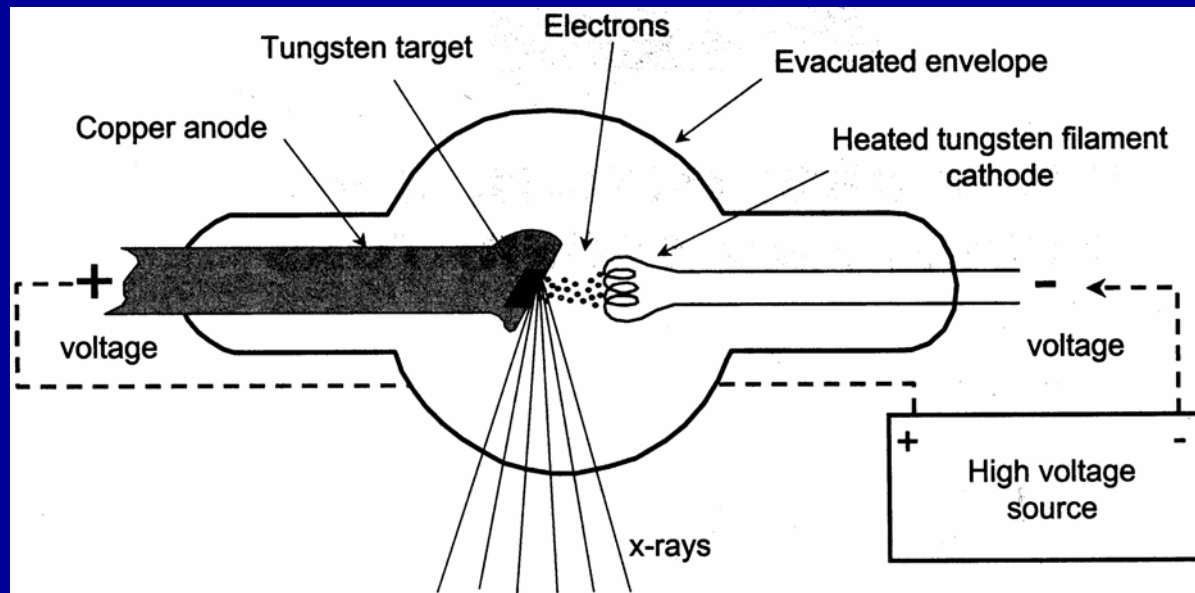
- ❖ X-rays are produced by the conversion of electron kinetic energy (KE) into electromagnetic radiation (EM)



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

The Bremsstrahlung Process (1)

- ❖ A large potential difference is applied across the two electrodes in an evacuated (usually glass) envelope
 - ❖ Negatively charged cathode is the source of electrons (e^-)
 - ❖ Positively charged anode is the target of electrons
- ❖ Electrons released from the cathode are accelerated towards the anode by the electrical potential difference and attain kinetic energy



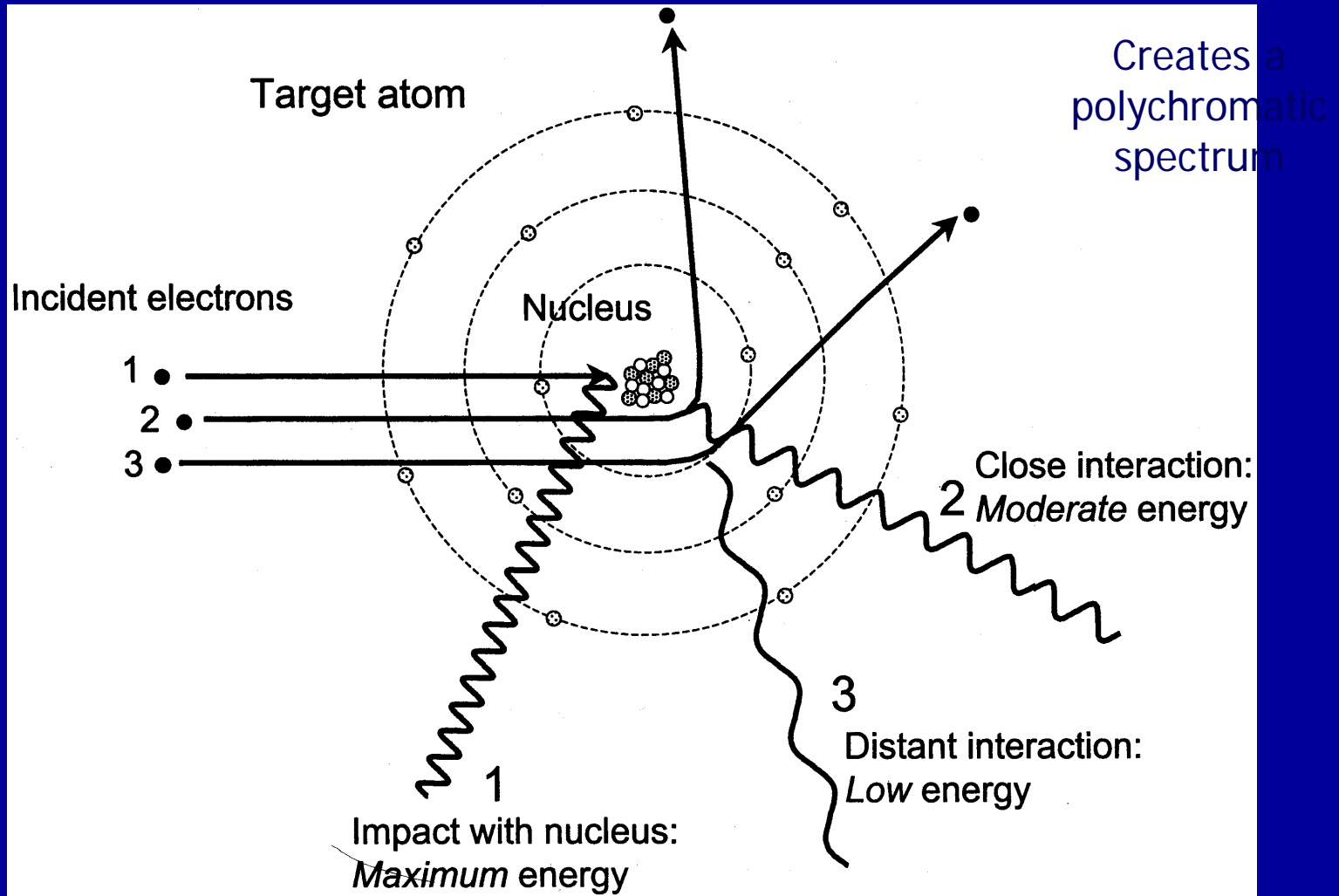
The Bremsstrahlung Process (2)

- ❖ About 99% of the KE is converted to heat via collision-like interactions
- ❖ About 0.5%-1% of the KE is converted into x-rays via strong Coulomb interactions (Bremsstrahlung)
- ❖ Occasionally (0.5% of the time), an e^- comes within the proximity of a positively charged nucleus in the target electrode
- ❖ Coulombic forces attract and decelerate the e^- , causing a significant loss of kinetic energy and a change in the electron's trajectory
- ❖ An x-ray photon with energy equal to the kinetic energy lost by the electron is produced (conservation of energy)

The Bremsstrahlung Process (3)

- ❖ This radiation is termed *bremsstrahlung*, a German word meaning “braking radiation”
 - ❖ The impact parameter distance, the closest approach to the nucleus by the e^- determines the amount of KE loss
 - ❖ The Coulomb force of attraction varies strongly with distance ($\propto 1/r^2$); as the distance \downarrow , deceleration and KE loss \uparrow
 - ❖ A direct impact of an electron with the target nucleus (the rarest event) results in loss of all of the electron’s kinetic energy and produces the highest energy x-ray

The Bremsstrahlung Process (4)

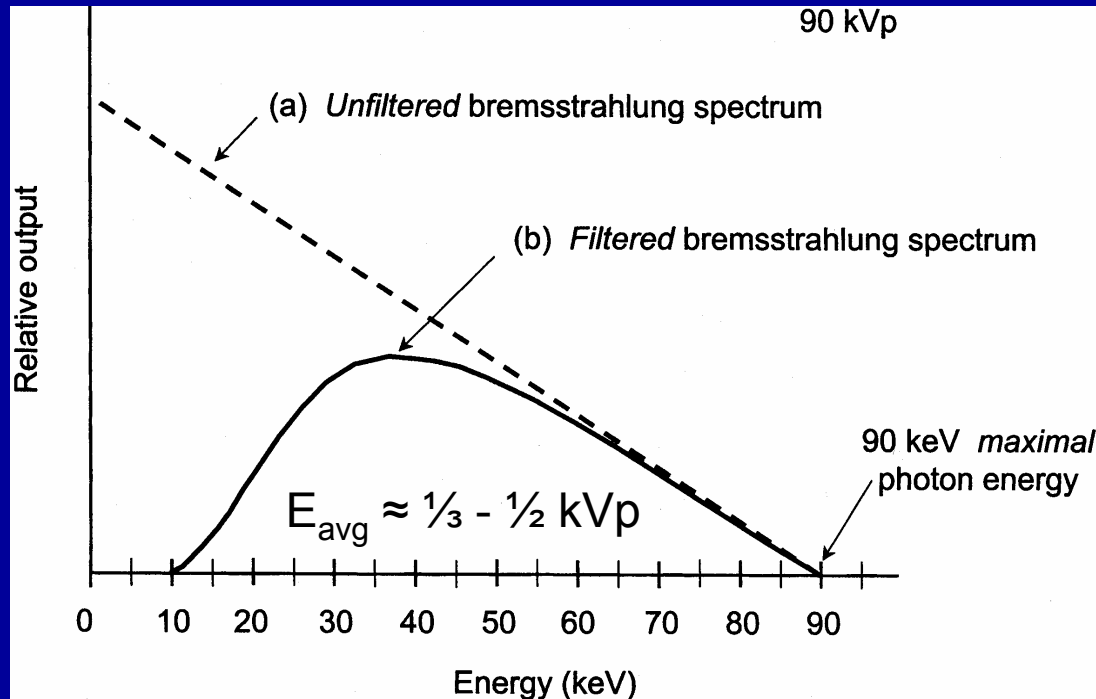


Bushberg, et al., The Essential Physics of Medical Imaging, 2nd ed., p. 99.

The Bremsstrahlung Process (5)

- ❖ The probability of an electron's directly impacting a nucleus is extremely low; atom mainly empty space and nuclear cross-section small
 - ❖ Low x-ray energies are generated in greater abundance
 - ❖ The number of higher-energy x-rays decreases approximately linearly with energy up to the maximum energy of the incident electrons

The Bremsstrahlung Process (5)



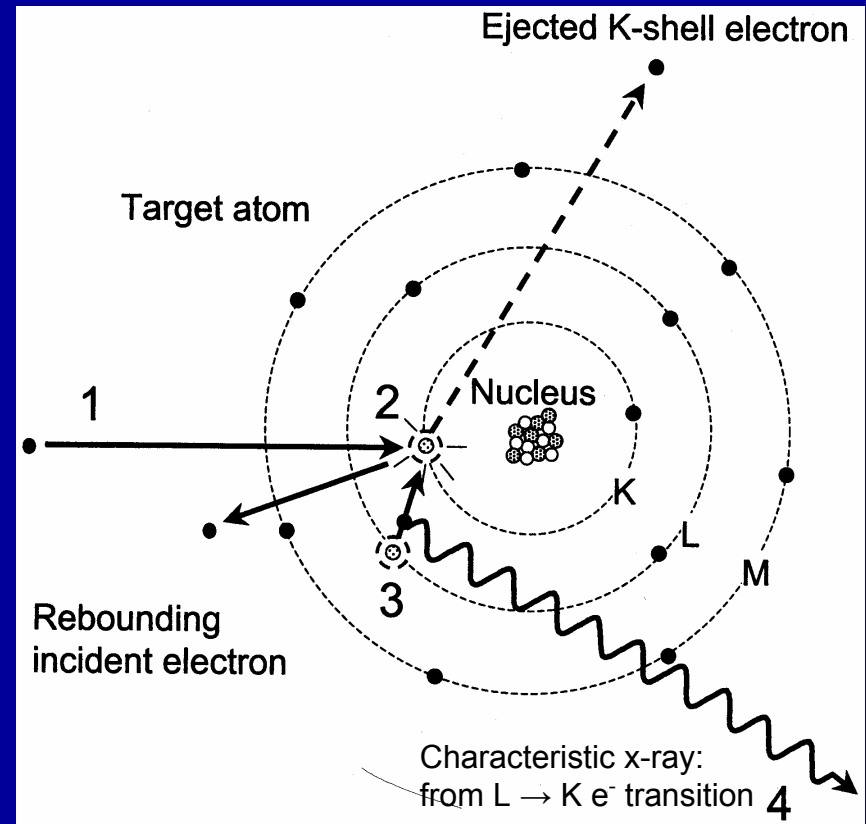
- ❖ A bremsstrahlung spectrum depicts the distribution of x-ray photons as a function of energy
 - ❖ The unfiltered b. spectrum shows a ramp-shaped relationship between the number and the energy of the x-rays produced, with the highest x-ray energy determined by the peak voltage (kVp) applied across the x-ray tube

The Bremsstrahlung Process (6)

- ❖ Filtration refers to the removal of x-rays as the beam passes through a layer of material
- ❖ A typical filtered b. spectrum shows that the lower-energy x-rays are preferentially absorbed, and the average x-ray energy is typically about one third to one half of the highest x-ray energy in the spectrum
- ❖ X-ray production efficiency (intensity) is influenced by the target atomic number and kinetic energy of the incident electrons (which is determined by the accelerating potential difference)

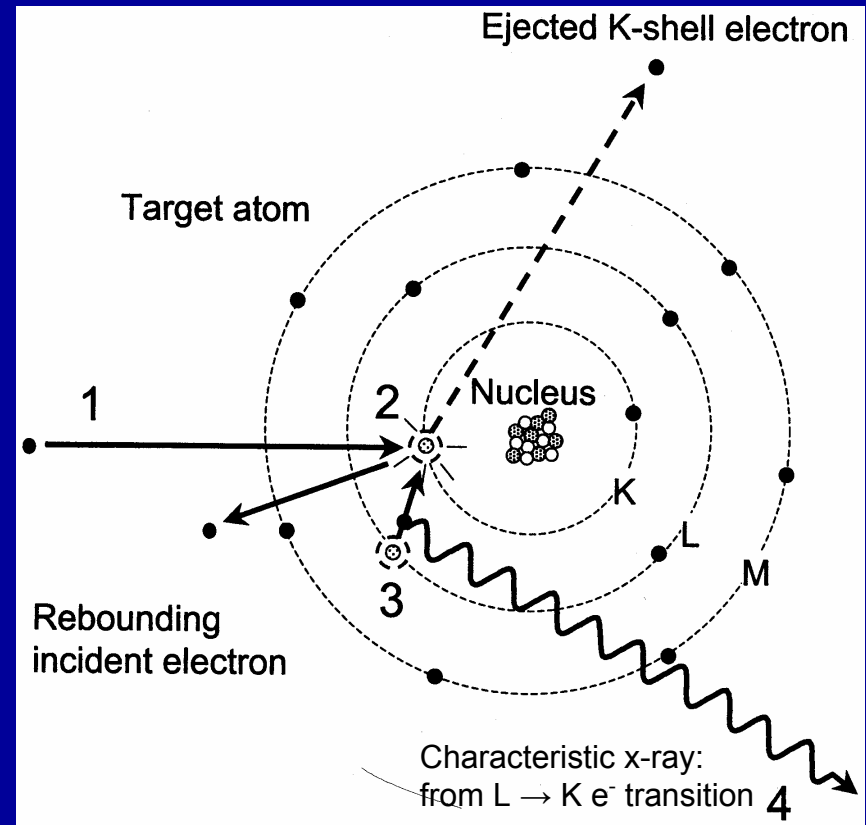
Characteristic X-ray Spectrum (1)

- ❖ Each electron in the target atom has a binding energy (BE) that depends on the shell in which it resides
- ❖ K shell – highest BE, L shell next highest BE and so on
- ❖ When the energy of an electron incident on the target exceeds the binding energy of an electron of a target atom, it is energetically possible for a collisional interaction to eject the electron and ionize the atom



Characteristic X-ray Spectrum (2)

- ❖ The unfilled shell is energetically unstable, and an outer shell electron with less binding energy will fill the vacancy
- ❖ As this electron transitions to a lower energy state, the excess energy can be released as a characteristic x-ray photon with an energy equal to the difference between the binding energies of the electron shells
- ❖ Binding energies are unique to a given element and so the emitted x-rays have discrete energies that are characteristic of that element



Characteristic X-ray Spectrum (3)

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

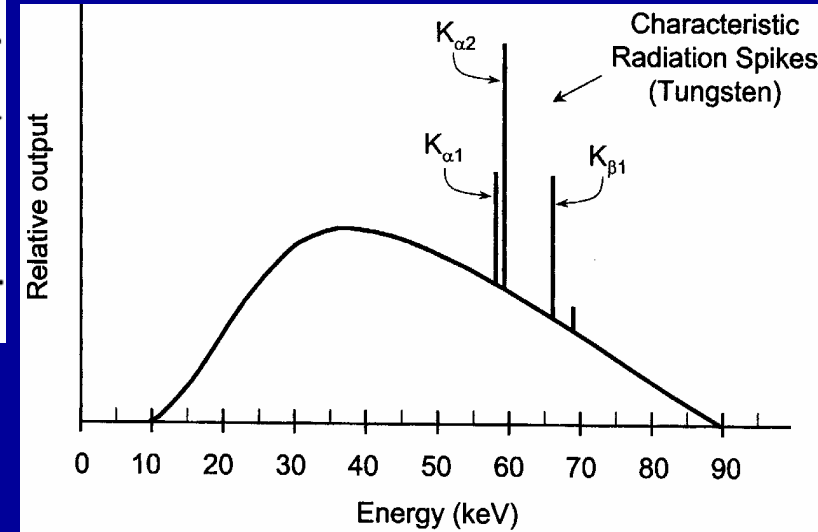
- ❖ The target materials used in x-ray tubes for diagnostic medical imaging include W ($Z=74$), Mo ($Z=42$) and Rh ($Z=45$): $BE \propto Z^2$
- ❖ As the E of the incident e^- increases above the threshold E for characteristic x-ray production, the % of char. x-rays increases (5% at 80 kVp versus 10% at 100 kVp)
- ❖ A variety of energy transitions occur from adjacent (α) and non-adjacent (β) e^- orbitals (shells) in the atom giving rise to discrete energy peaks superimposed on the continuous bremsstrahlung spectrum

Characteristic X-ray Spectrum (4)

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

^aNote: Only prominent transitions are listed.



- ❖ Within each shell (other than the K shell), there are discrete energy subshells, which result in the fine energy splitting of the characteristic x-rays
- ❖ Characteristic x-rays other than those generated by K-shell transitions are unimportant in diagnostic imaging because they are almost entirely attenuated by the x-ray tube window or added filtration

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

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
 - ❖ C. 4.7
 - ❖ D. 15
 - ❖ E. 29.3

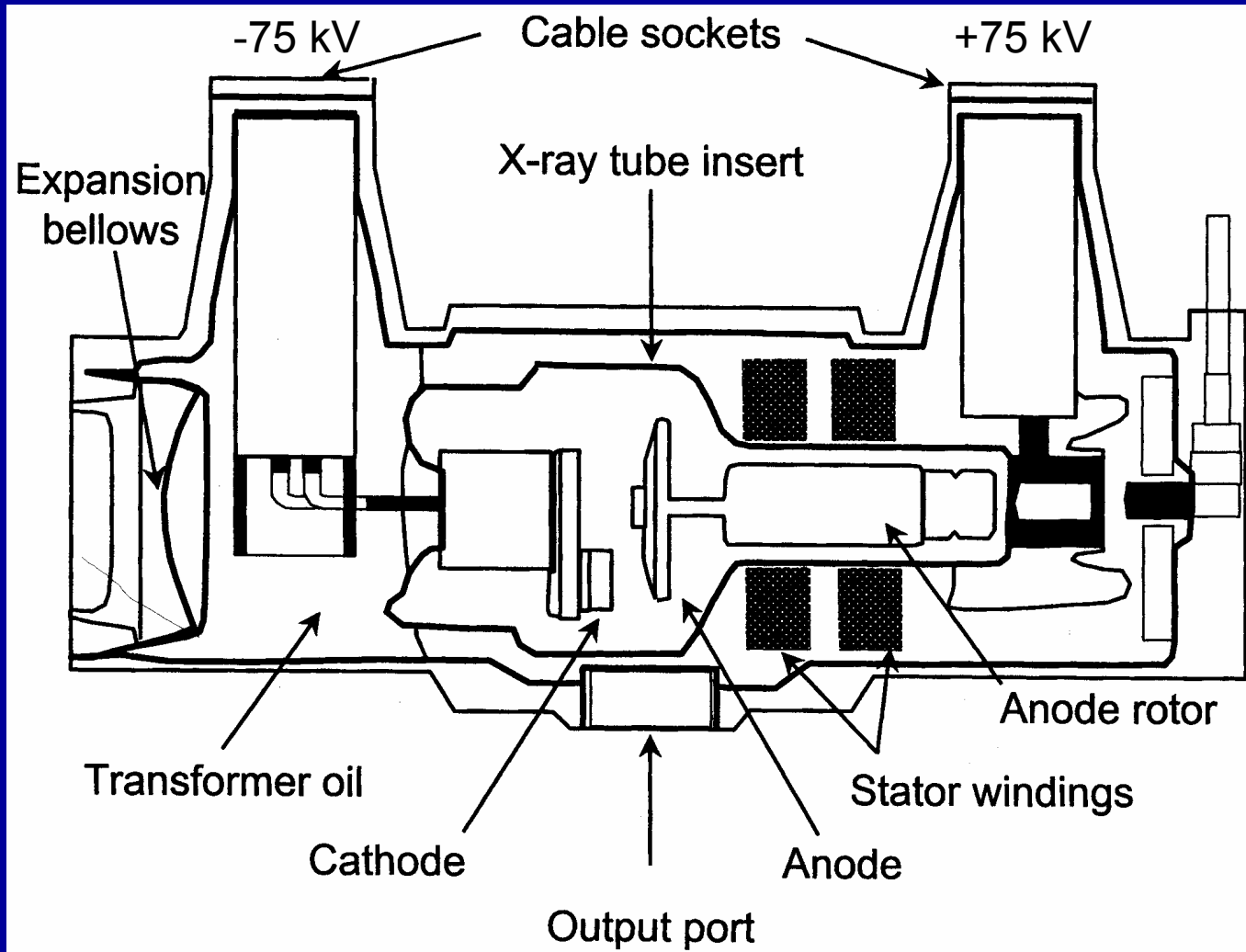
- ❖ **B.** $E = 25.3 + 0.7 = 26$ keV where E is equal to the difference between the binding energies of the K- and L-shells.
- ❖ $26 \text{ keV} = BE_K - BE_L = 30 \text{ keV} - BE_L$; $BE_L = 4$ keV.

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

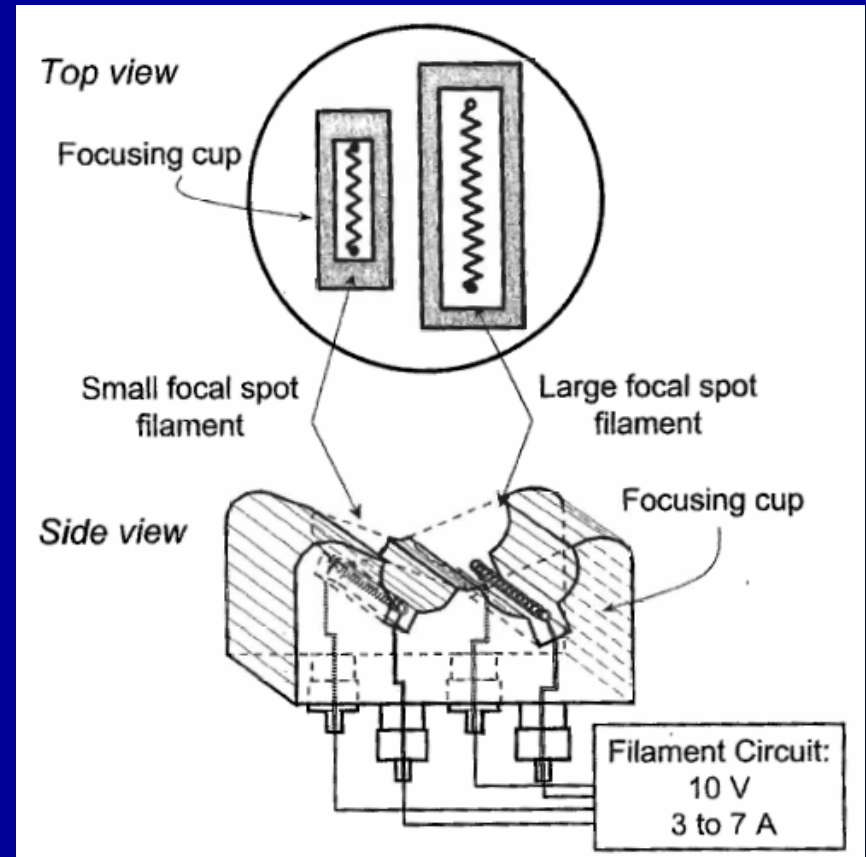
X-ray Tubes



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

X-ray Tube Cathode

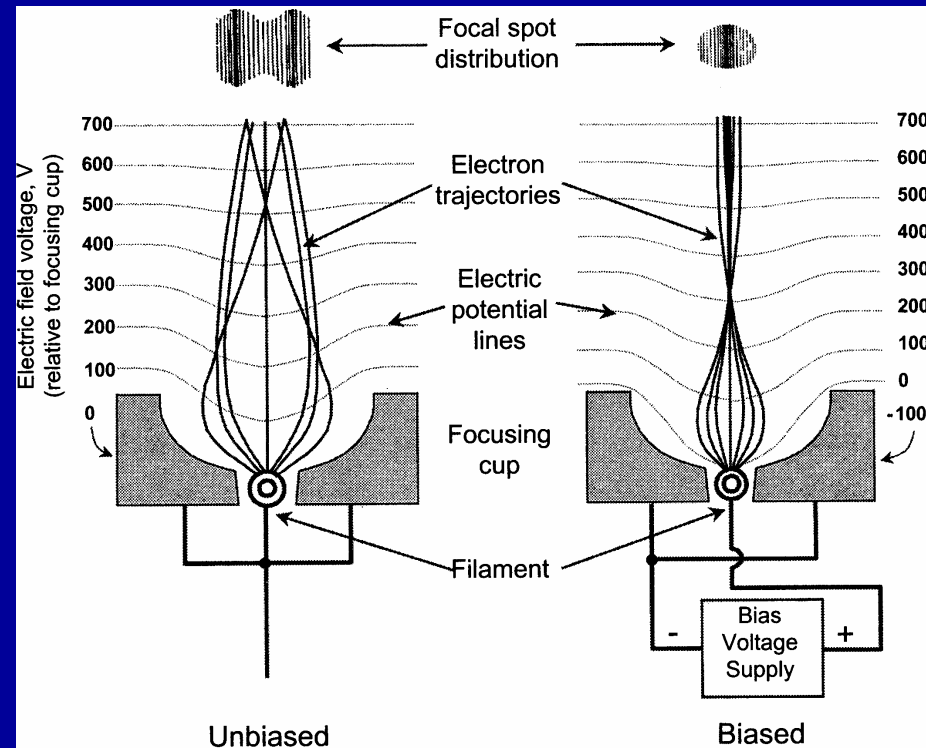
- ❖ Source of electrons is cathode, which is a helical filament of tungsten wire surrounded by a focusing cup
- ❖ Filament circuit - (10V, 7A)
- ❖ Electrical resistance heats the filament and releases electrons via *thermionic emission*
- ❖ Adjustment of the filament current controls the tube current (rate of e^- flow from cathode to anode)



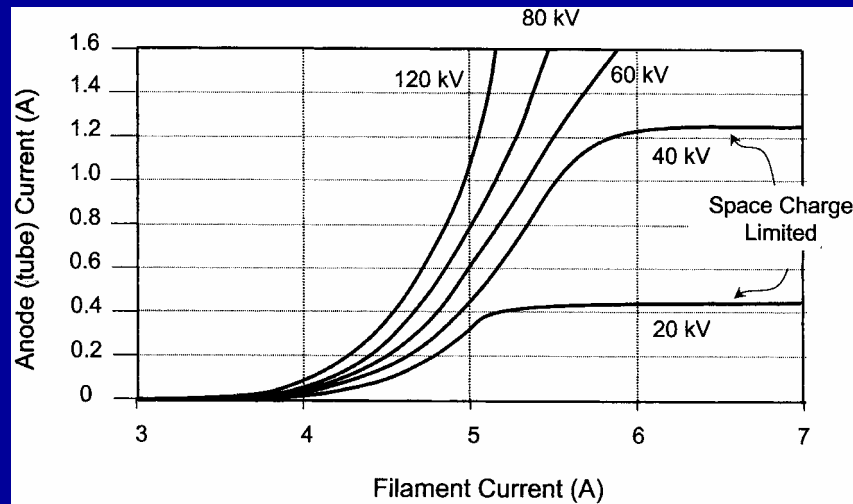
Bushberg, et al., The Essential Physics of Medical Imaging, 2nd ed., pp. 104-105.

X-ray Tube Cathode

- ❖ Focusing cup (cathode block)
 - ❖ Shapes the electron distribution when it is at the same voltage as the filament (unbiased)
 - ❖ Isolation of the focusing cup from the filament and application of a negative bias voltage reduced the electron distribution further (biased)
 - ❖ Width of the focusing cup slot determines the focal spot width
 - ❖ Filament length determines the focal spot length
 - ❖ Small and large focal spot filaments



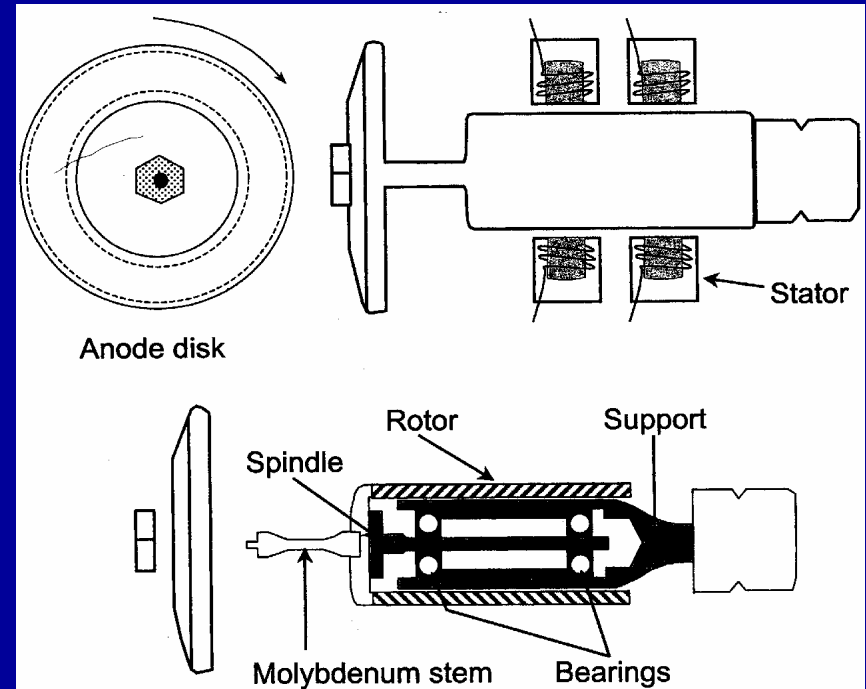
Space Charge Cloud



- ❖ The filament current determines the filament temperature and thus the rate of thermionic emission
- ❖ When no voltage is applied b/w the cathode and anode, an electron cloud, also called a space charge cloud, builds around the filament
- ❖ This space charge cloud shields the electric field for tube voltages of 40 kVp and lower, only some electrons are accelerated towards the anode (space charge limited)
- ❖ Above 40 kVp, the space charge cloud effect is overcome by the voltage applied and tube current is limited only by the emission of electrons from the filament (emission-limited operation)
- ❖ Tube current is 5 to 10 times less than the filament current in the emission-limited range

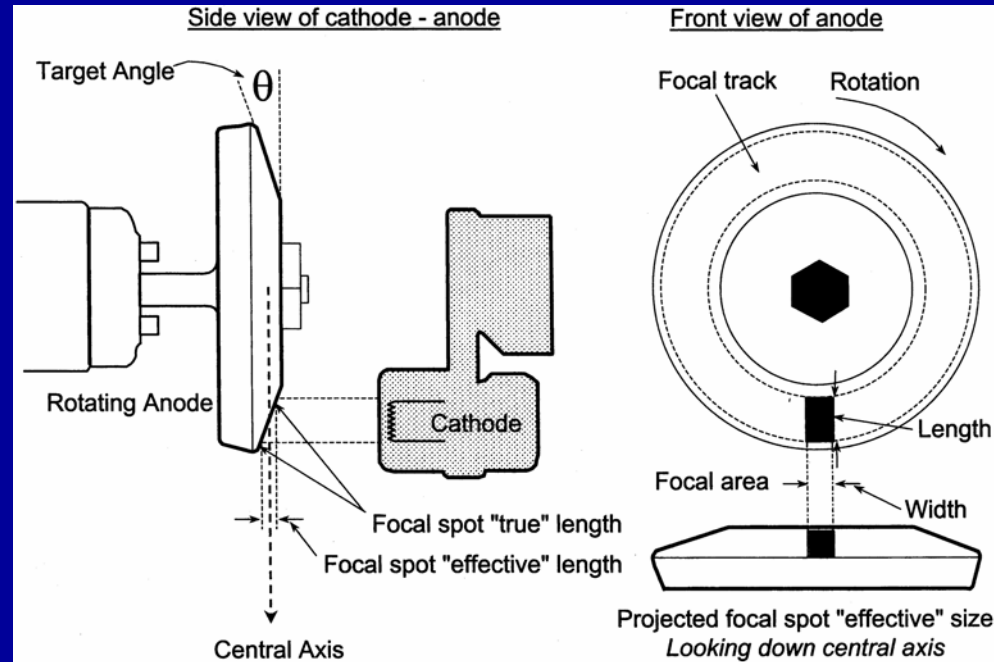
X-ray Tube Anode Configuration

- ❖ Tungsten anode disk
 - ❖ Mo and Rh for mammography
- ❖ Stator and rotor make up the induction motor
- ❖ Rotation speeds
 - ❖ Low: 3,000 – 3,600 rpm
 - ❖ High: 9,000 – 10,000 rpm
- ❖ Molybdenum stem is a poor heat conductor and connects the rotor to the anode to reduce heat transfer to the rotor bearings
- ❖ Anode cooled through radiative transmission
- ❖ Focal track area (spreads heat out over larger area than stationary anode configuration)

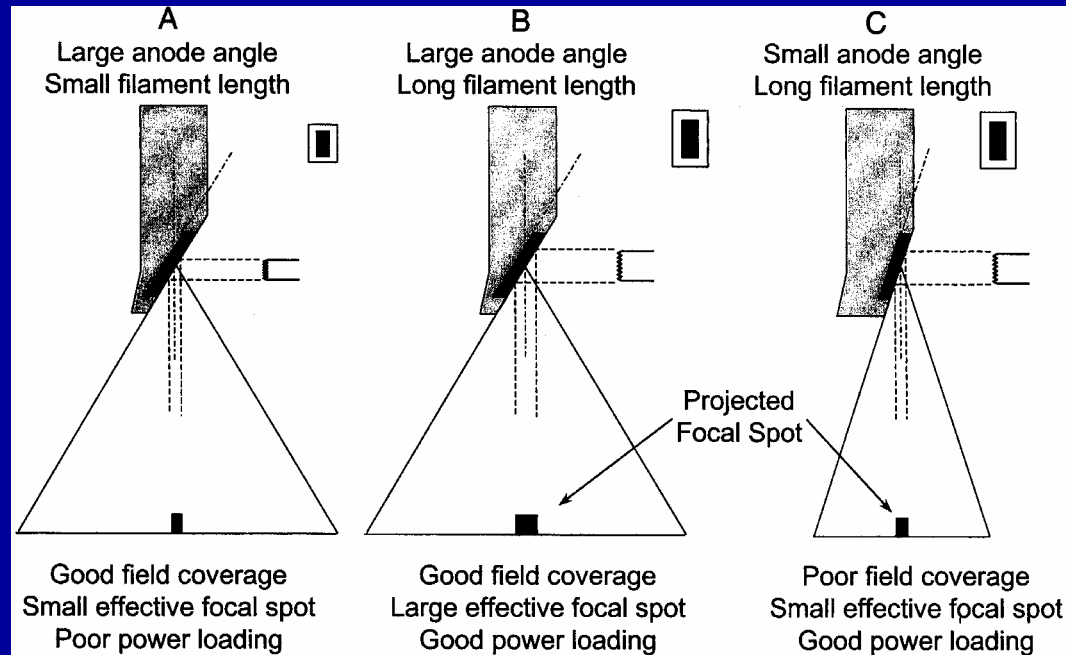


Anode Angle and Focal Spot Size

- ❖ The anode angle is defined as the angle of the target surface with respect to the central ray in the x-ray field
- ❖ Anode angle range: $7^\circ - 20^\circ$
- ❖ Line focus principle (foreshortening of the focal spot length)
 - ❖ The effective focal spot size is the length and width of the focal spot projected down the central ray in the x-ray field
 - ❖ Effective focal length = actual focal length $\cdot \sin(\theta)$



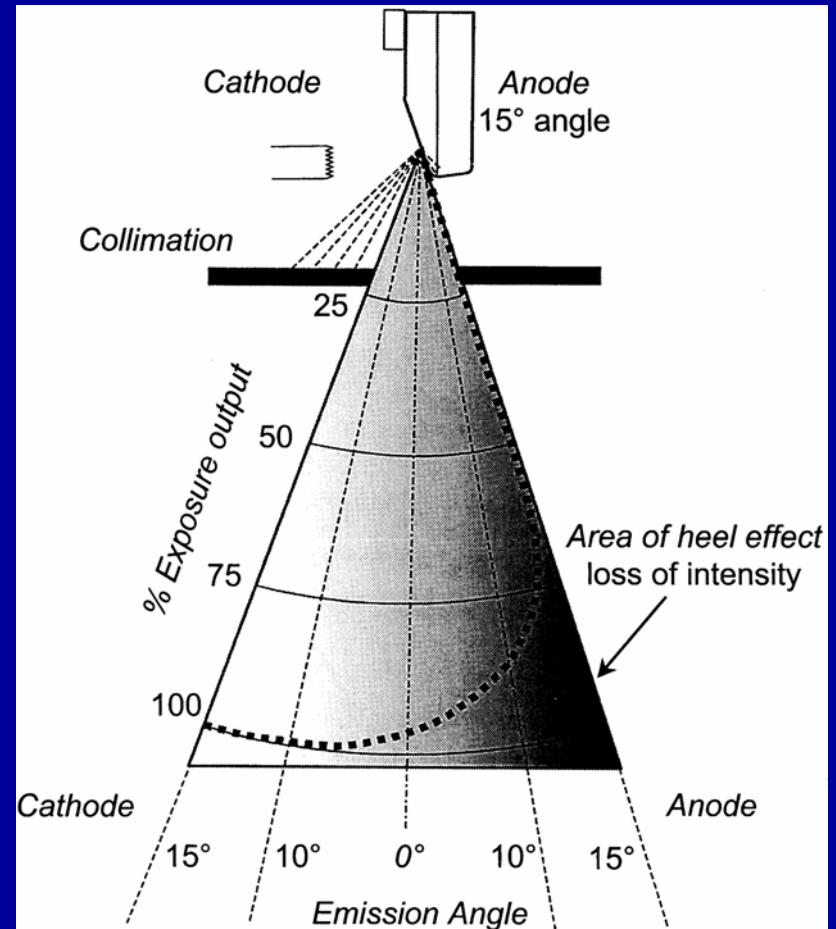
Anode Angle and Focal Spot Size



- ❖ Three major tradeoffs to consider for the choice of anode angle
- ❖ Field coverage and effective focal spot length vary with the anode angle
 - ❖ A smaller anode angle provides a smaller effective focal spot for the same actual focal area
 - ❖ However, a small anode angle limits the size of the usable x-ray field owing to cutoff of the beam
 - ❖ Field coverage is less for short focus-to-detector distances

Heel Effect

- ❖ Reduction of x-ray beam intensity towards the anode side of the x-ray field
- ❖ Although x-rays generated isotropically
 - ❖ Self-filtration by the anode
 - ❖ More attenuation and diminished intensity on the anode side of the x-ray field
- ❖ Can use to advantage, e.g.,
 - ❖ Cathode over thicker parts
 - ❖ Anode over thinner parts
- ❖ Less pronounced as source-to-image distance (SID) increases, because the image receptor subtends a smaller beam angle

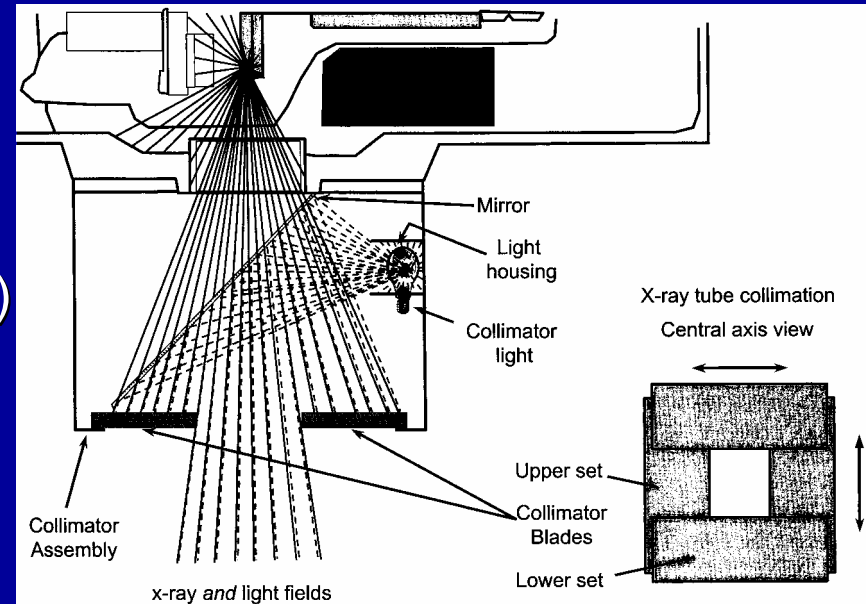


Bushberg, et al., The Essential Physics of Medical Imaging, 2nd ed., p. 112.

X-ray Filtration and Collimators

- ❖ Filtration is the removal of x-rays as the beam passes through a layer of material
- ❖ Inherent (glass or metal insert at x-ray tube port) and added filtration (sheets of metal intentionally placed in the beam)
- ❖ Added filters absorb low-energy x-rays and reduce patient dose
- ❖ HVL – half value layer (mm Al)

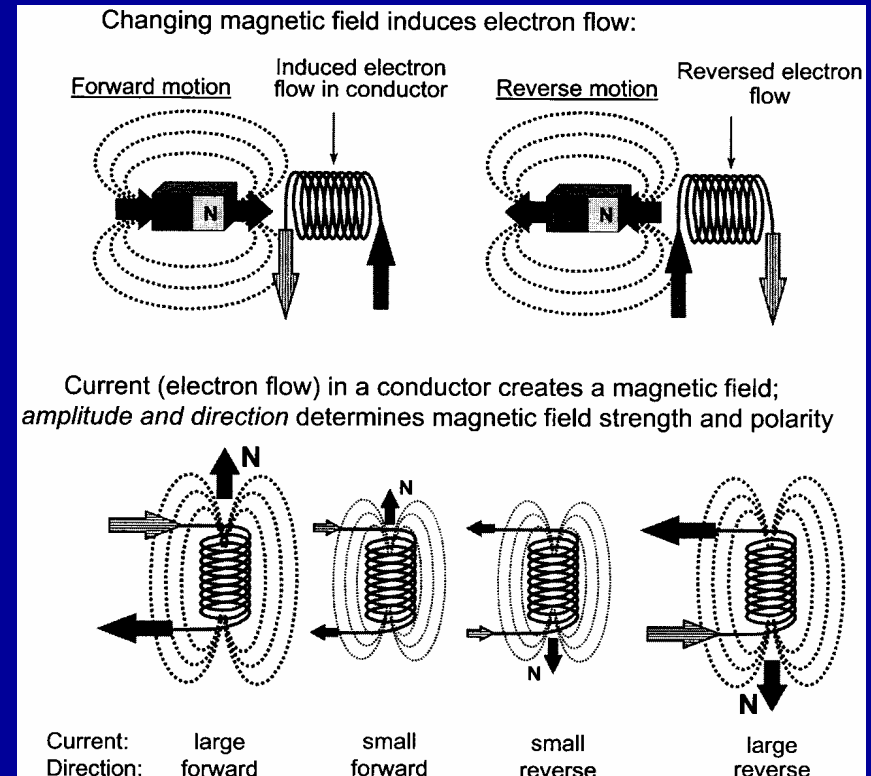
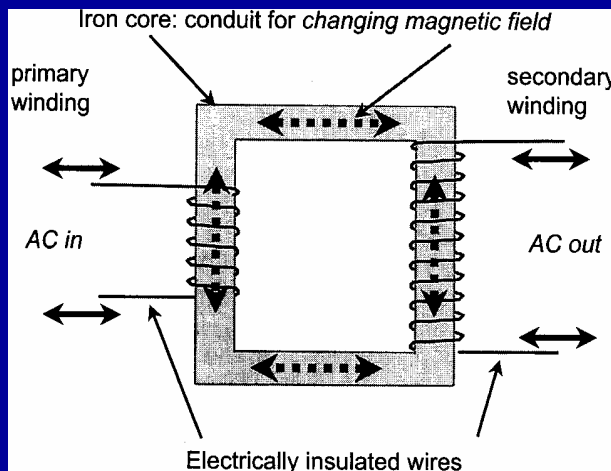
- ❖ Collimators adjust size and shape of x-ray beam
- ❖ Parallel-opposed lead shutters
- ❖ Light field mimics x-ray field
- ❖ Reduces dose to patient (ALARA)
- ❖ Reduced scatter radiation to image receptor
- ❖ Positive beam limitation (PBL) – automatic beam collimation



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

X-ray Generator Function and Components

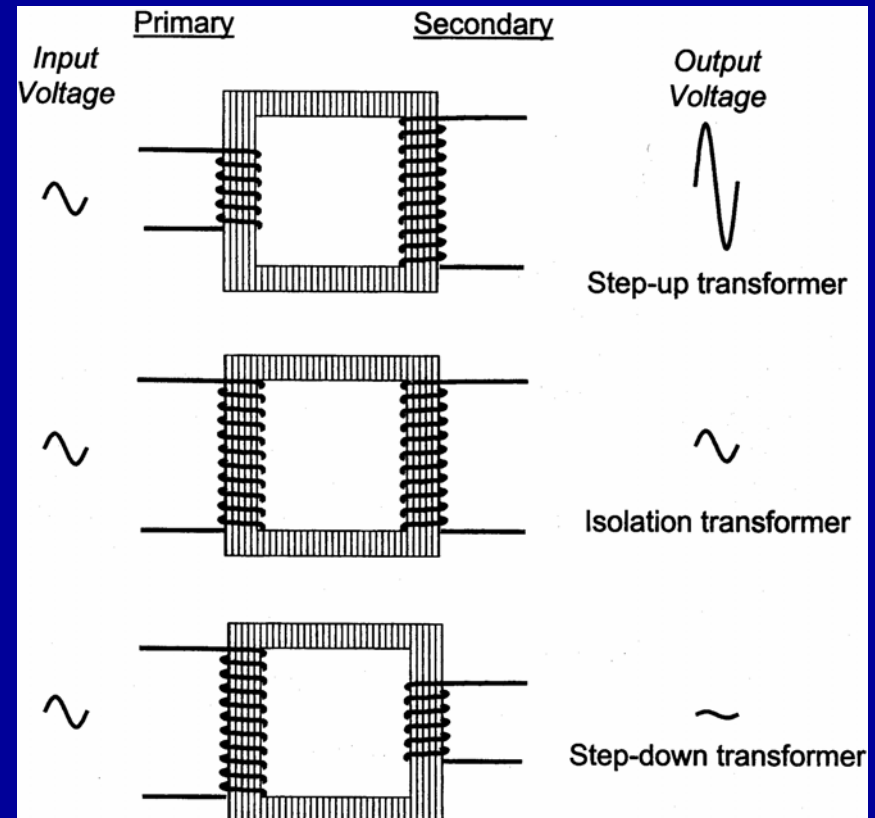
- ❖ The principal function of the x-ray generator is to provide current at a high voltage to the x-ray tube
- ❖ Transformers are the principal components of the x-ray generators; they convert low voltage into high voltage through a process called electromagnetic induction



Bushberg, et al., The Essential Physics of Medical Imaging, 2nd ed., p. 117.

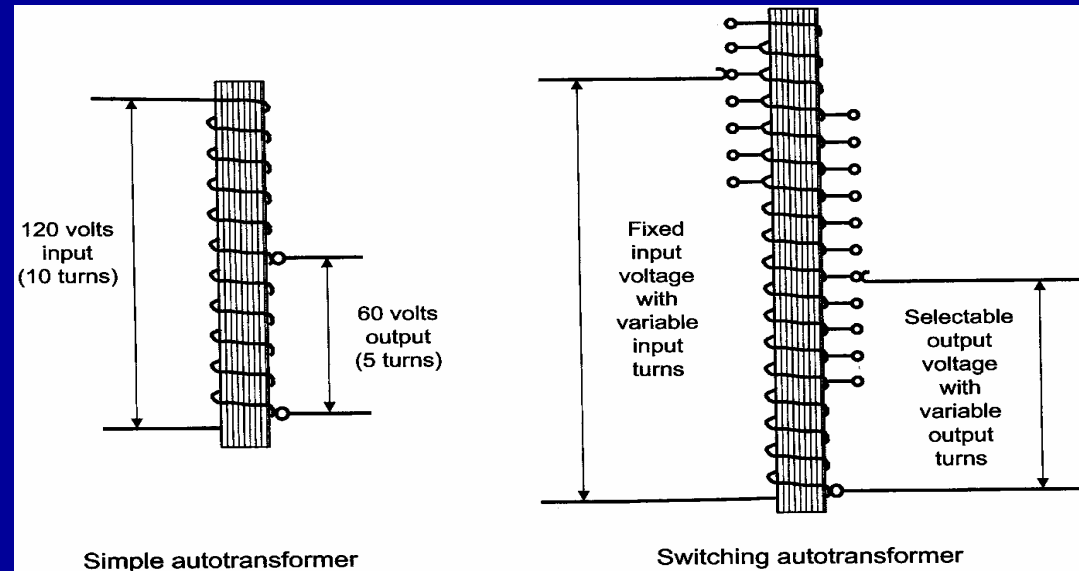
Transformer Relationships

- ❖ Mutual induction
- ❖ Law of Transformers:
 - ❖ $V_p/V_s = N_p/N_s$
- ❖ Step-up transformer:
 - ❖ $N_s > N_p$
- ❖ Isolation transformer:
 - ❖ $N_s = N_p$
- ❖ Step-down transformer:
 - ❖ $N_s < N_p$
- ❖ Power output ($I_s V_s$) = Power input ($I_p V_p$)
 - ❖ $V_p I_p = V_s I_s$



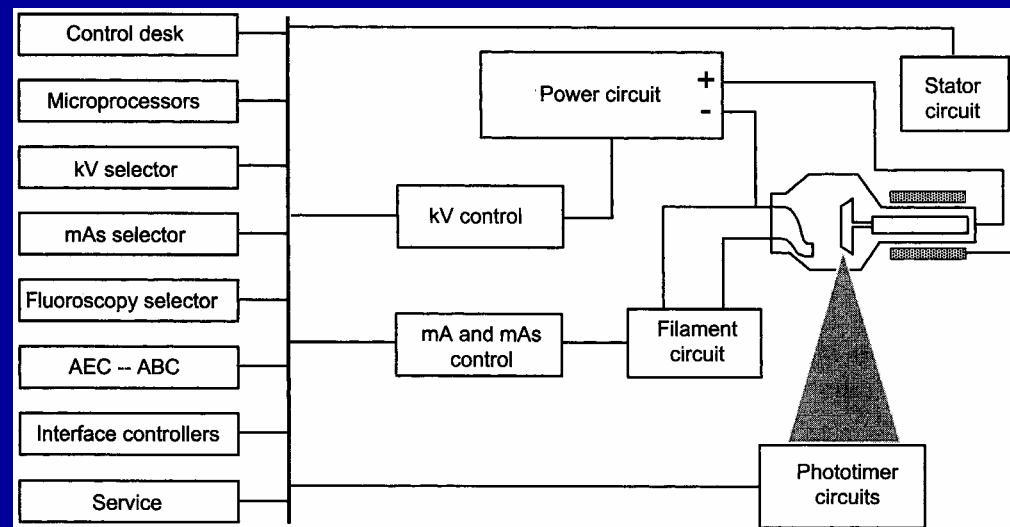
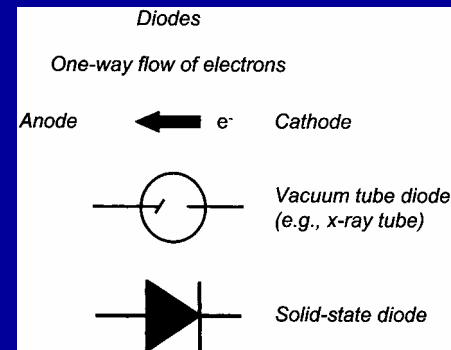
Autotransformer

- ❖ Autotransformer
 - ❖ It is an iron core wrapped with a single wire
 - ❖ Self induction
 - ❖ Conducting taps allow the input to output turns to vary, resulting in small incremental change between input and output voltages
 - ❖ A switching autotransformer allows a greater range of input to output values



X-ray Generator Components and Diodes

- ❖ Diodes – either vacuum tube or solid-state device: e^- flow in only a single direction (cathode to anode only)
- ❖ High-Voltage power circuit
 - ❖ Low input voltage
 - ❖ High output voltage
 - ❖ Autotransformer allows kVp selection
- ❖ Filament circuit
 - ❖ mA sets the tube current
 - ❖ sec sets the exposure duration
 - ❖ manual exposure or phototimed



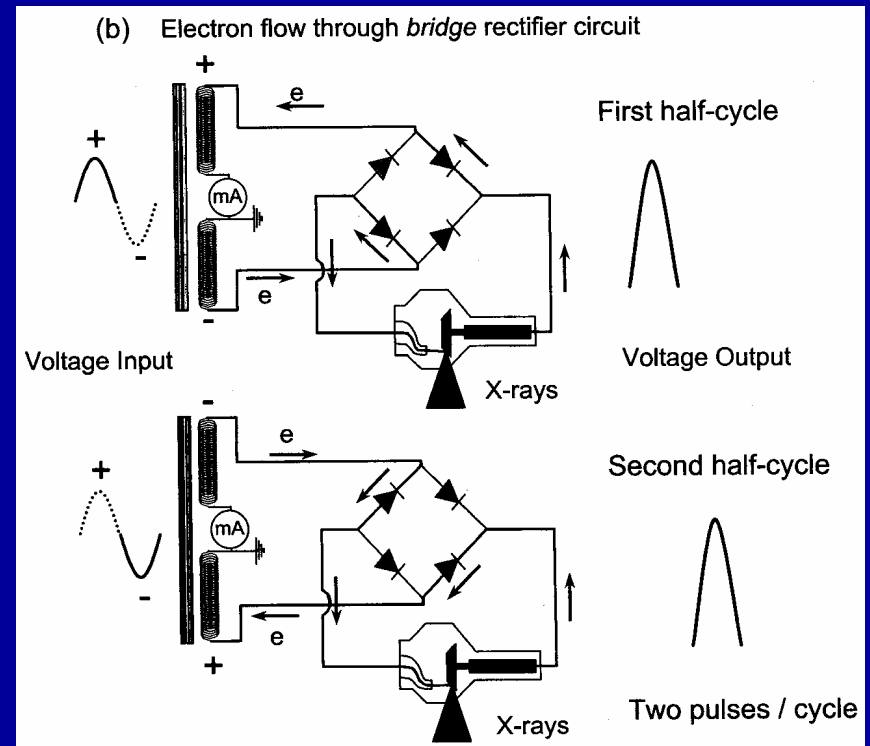
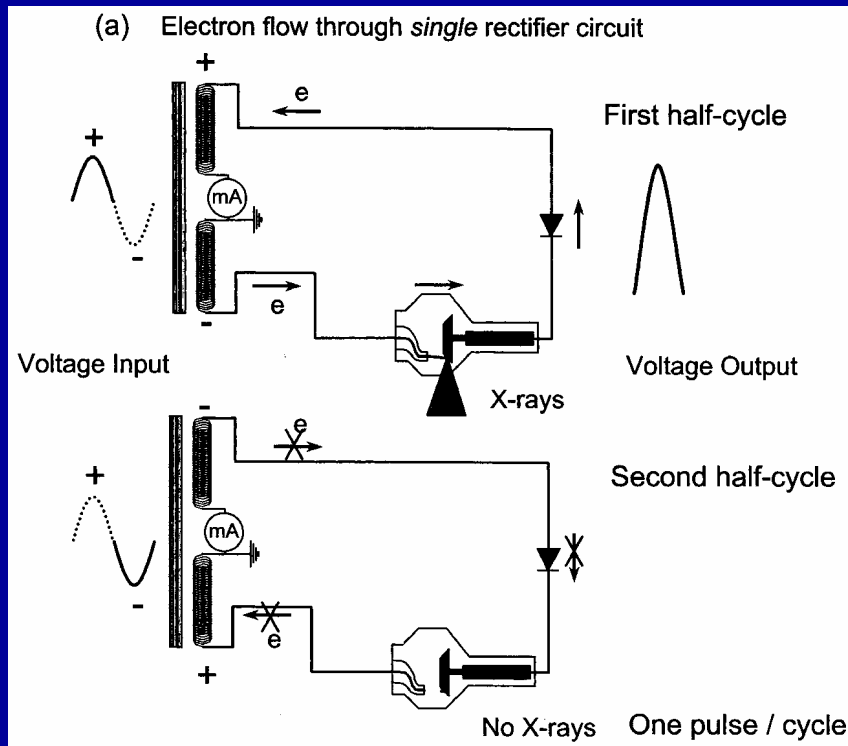
Bushberg, et al., The Essential Physics of Medical Imaging, 2nd ed., p. 123.

Operator Console

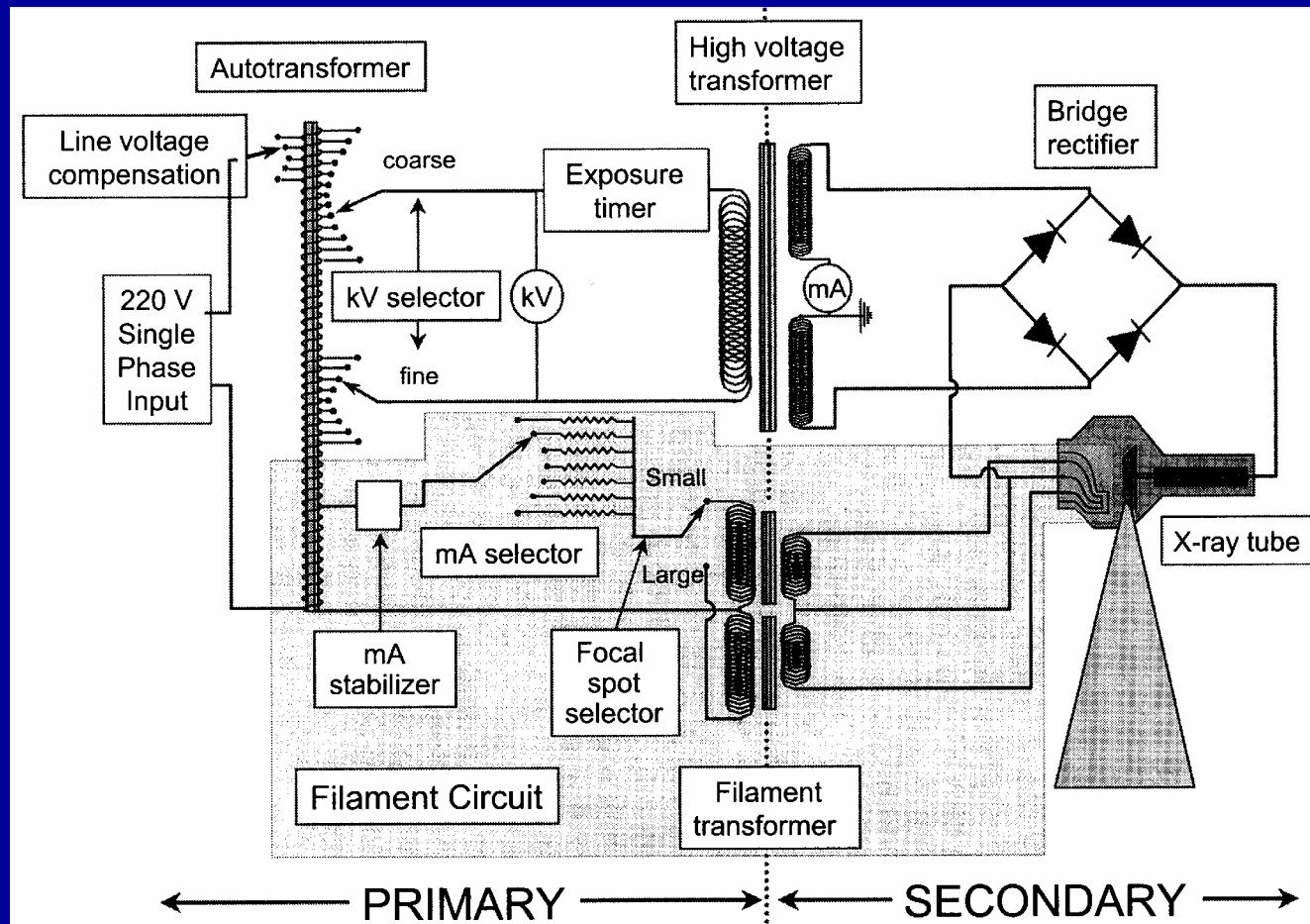
- ❖ The operator selects the peak kilovoltage (kVp), the tube current (mA), the exposure time and the focal spot size
- ❖ The kVp determines the x-ray beam quality (penetrability), which plays a role in subject contrast
- ❖ The x-ray tube current (mA) determines the x-ray flux (photons per square cm) emitted by the x-ray tube at a given kVp
- ❖ $mAs = mA \times \text{sec (exposure time)}$
- ❖ Low mA selections allow small focal spot size to be used, and higher mA settings require the use of large focal spot size due to anode heating concerns

Generator Circuit Designs

Single-phase (Half-wave & Full-wave) Rectifier Circuit



Complete Single-Phase Two-Pulse Rectifier Circuit



Bushberg, et al., The Essential Physics of Medical Imaging, 2nd ed., p. 126.

Different Types of Generators

- ❖ Single-phase
 - ❖ Uses single-phase input line voltage source (e.g., 220 V at 50 mA)
- ❖ Three-phase
 - ❖ Uses three voltage sources, (0, 120 and 240 deg)
- ❖ Constant-Potential
 - ❖ Provides nearly constant voltage to the x-ray tube
- ❖ High-Frequency Inverter
 - ❖ State-of-the-art choice
 - ❖ High-frequency alternating waveform is used for efficient transformation of low to high voltage

Voltage Ripple and Root-Mean-Square Voltage

- ❖ % voltage ripple =
$$\frac{(V_{\max} - V_{\min})}{V_{\max}} \cdot 100\%$$
- ❖ Root-mean-square voltage: (V_{rms})
 - ❖ The constant voltage that would deliver the same power as the time-varying voltage waveform
- ❖ As %VR ↓, the V_{rms} ↑



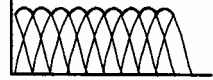



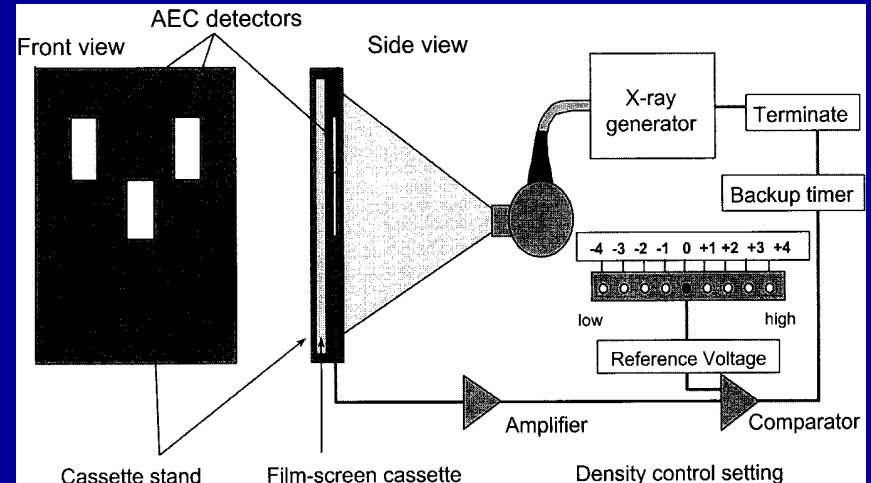
Generator type	Typical voltage waveform	kV ripple
Single-phase 1-pulse (self rectified)		100%
Single-phase 2-pulse (full wave rectified)		100%
3-phase 6-pulse		13% - 25%
3-phase 12-pulse		3% - 10%
Medium-high frequency inverter		4% - 15%
Constant Potential		<2%

TABLE 5-4. ROOT-MEAN-SQUARE VOLTAGE (V_{rms}) AS A FRACTION OF PEAK VOLTAGE (V_{peak})

Generator Type	V_{rms} as a fraction of V_{peak}
Single-phase	0.71
Three-phase six-pulse	0.95
Three-phase 12-pulse	0.99
High-frequency	0.95-0.99
Constant-potential	1.00

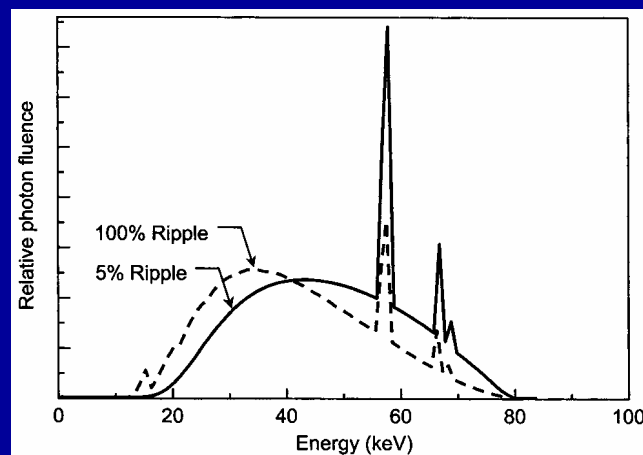
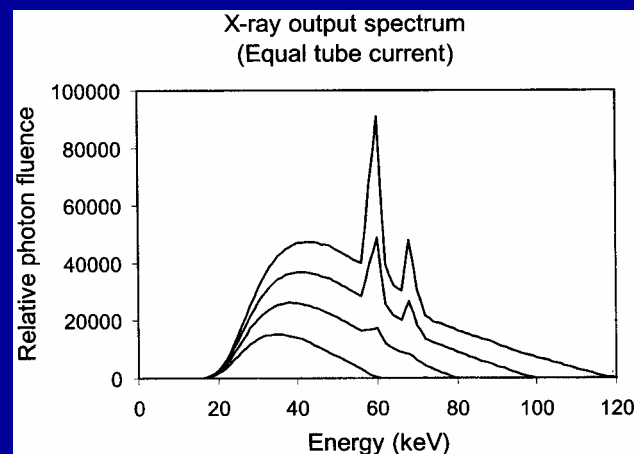
Phototimers

- ❖ Although a tech can manually time the x-ray exposure (set filament mA and exposure time or the mAs), phototimers help provide a consistent exposure to the image receptor
- ❖ Ionization chambers produce a current that induces a voltage difference in an electronic circuit
- ❖ Tech chooses kVp; the x-ray tube current terminated when this voltage equals a reference voltage
- ❖ Phototimers are set for only a limited number of anatomical views, thus +/- settings



Factors Affecting X-ray Emission

- ❖ Quantity = number of x-rays in beam
 - ❖ $\propto Z_{\text{target}} \cdot (\text{kVp})^2 \cdot \text{mAs}$
- ❖ Quality = penetrability of x-ray beam and depends on:
 - ❖ kVp
 - ❖ generator waveform
 - ❖ tube filtration
- ❖ Exposure depends on both quantity and quality
 - ❖ Equal transmitted exposure:
 - ❖ $(\text{kVp}_1)^5 \cdot \text{mAs}_1 = (\text{kVp}_2)^5 \cdot \text{mAs}_2$



Raphex 2000 General Question

- ❖ **G41.** All of the following affect the shape of the x-ray spectrum except:
 - ❖ A. The added filtration.
 - ❖ B. The type of rectification used in the x-ray circuit.
 - ❖ C. The speed of rotation of the anode.
 - ❖ D. The energy of the electrons hitting the target.
 - ❖ E. The composition of the x-ray target.

Raphex 2003 General Question

- ❖ **G41.** The quality of an x-ray beam cannot be characterized only in terms of the kVp, because beams with the same kVp may have different _____ .
 - ❖ A. Filtration
 - ❖ B. Half-value layers
 - ❖ C. Maximum wavelengths
 - ❖ D. Target materials
 - ❖ E. All of the above

Generator Power Ratings and X-ray Tube Focal Spots

- ❖ Power (kW) = 100 kVp · A_{\max}
(for a 0.1 second exposure)
- ❖ A_{\max} limited by the focal spot: ↑ focal spot → ↑ power rating
- ❖ Generally range between 10 kW to 150 kW
- ❖ Typical focal spots
 - ❖ Radiography: 0.6 and 1.2 mm
 - ❖ Mammography: 0.1-0.4 mm

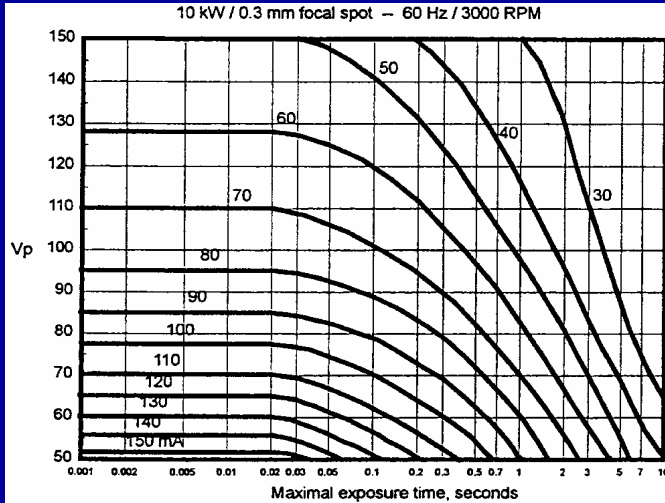
TABLE 5-6. X-RAY TUBE FOCAL SPOT SIZE AND TYPICAL POWER RATING

Nominal X-ray Tube Focal Spot Size (mm)	Typical Power Rating (kW)
1.2–1.5	80–125
0.8–1.0	50–80
0.5–0.8	40–60
0.3–0.5	10–30
0.1–0.3	1–10
<0.1 (micro-focus tube)	<1

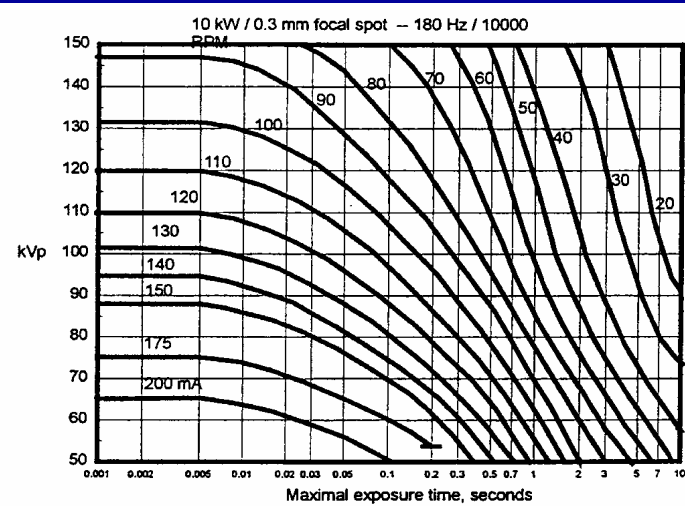
X-ray Tube Heat Loading

- ❖ Heat Unit (HU)
 - ❖ $HU = kVp \cdot mA \cdot sec \cdot factor$
 - ❖ $HU = kVp \cdot mAs \cdot factor$
 - ❖ factor = 1.00 for single-phase generator
 - ❖ factor = 1.40 for constant potential generator
 - ❖ factor = 1.35 for three-phase and high-frequency generators
- ❖ Energy (J) = $V_{rms} \cdot mA \cdot sec$
 - ❖ $V_{rms} = 0.71$ (1phase), 0.95-0.99 (3phase & HF) and 1.0 (CP)
- ❖ Heat input (HU) ≈ 1.4 Heat input (J)

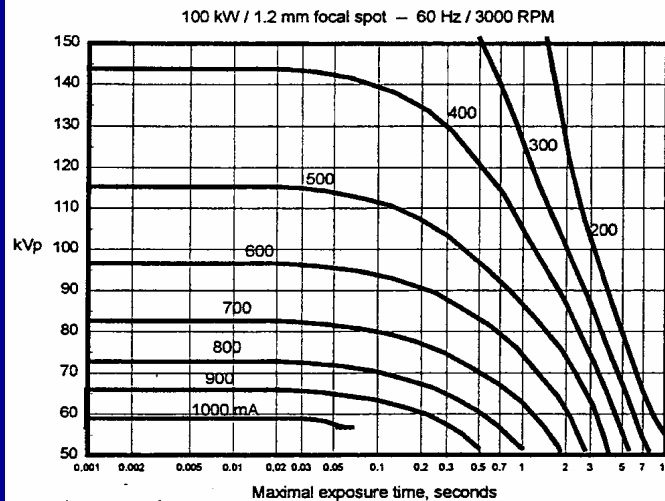
Single-exposure Rating Chart



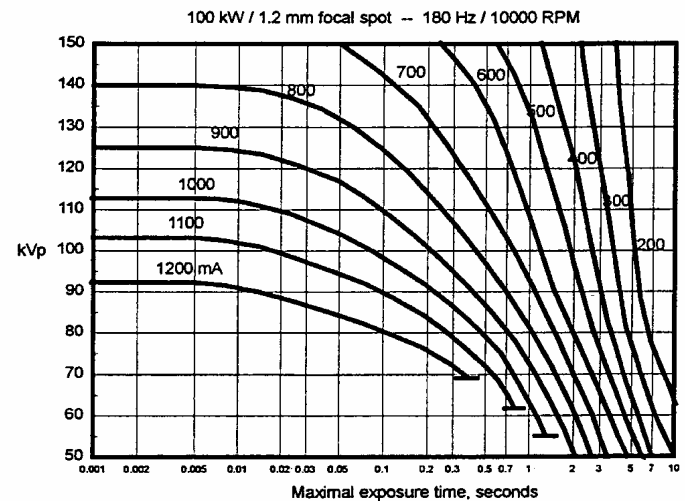
a



b

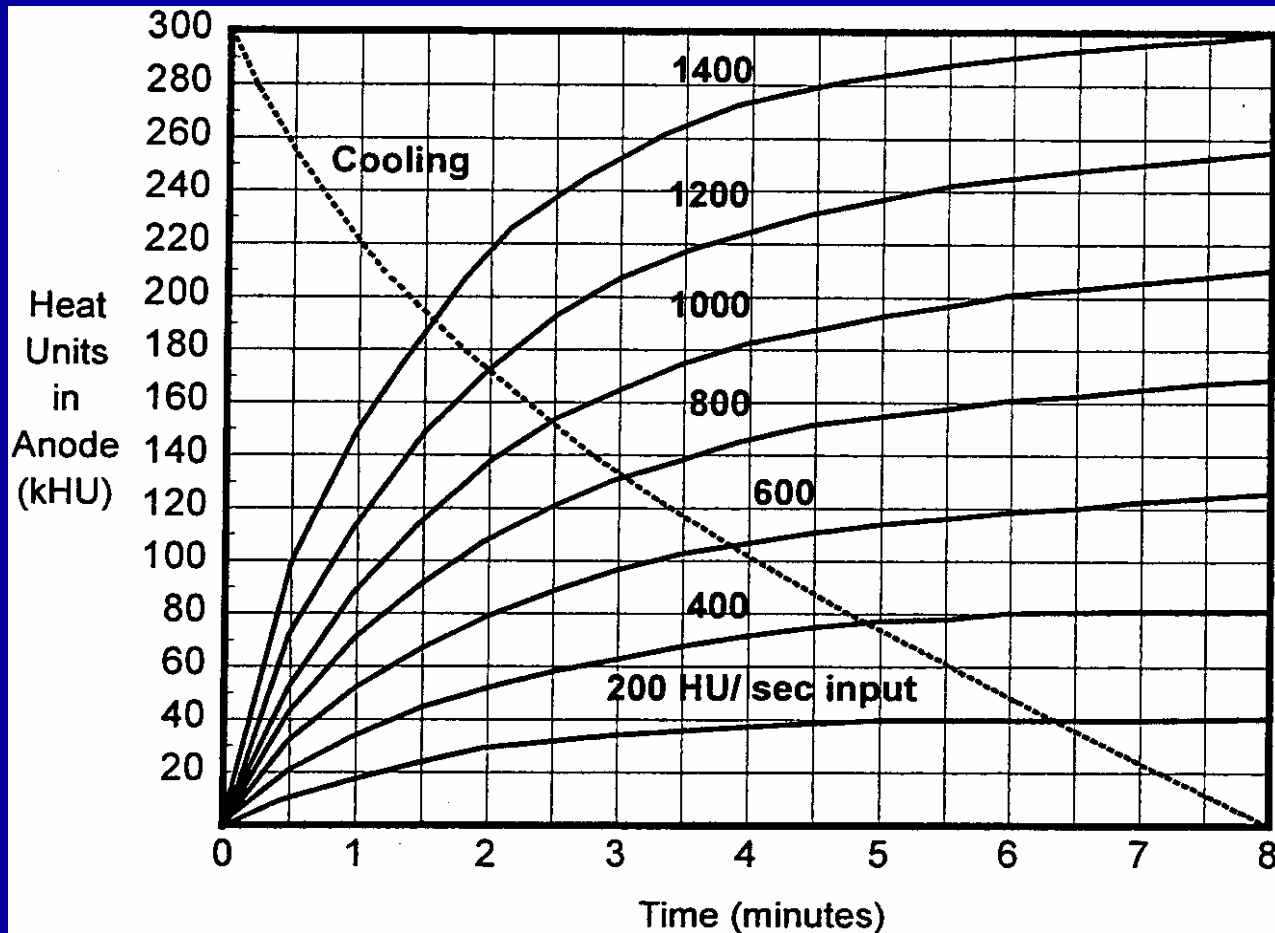


c



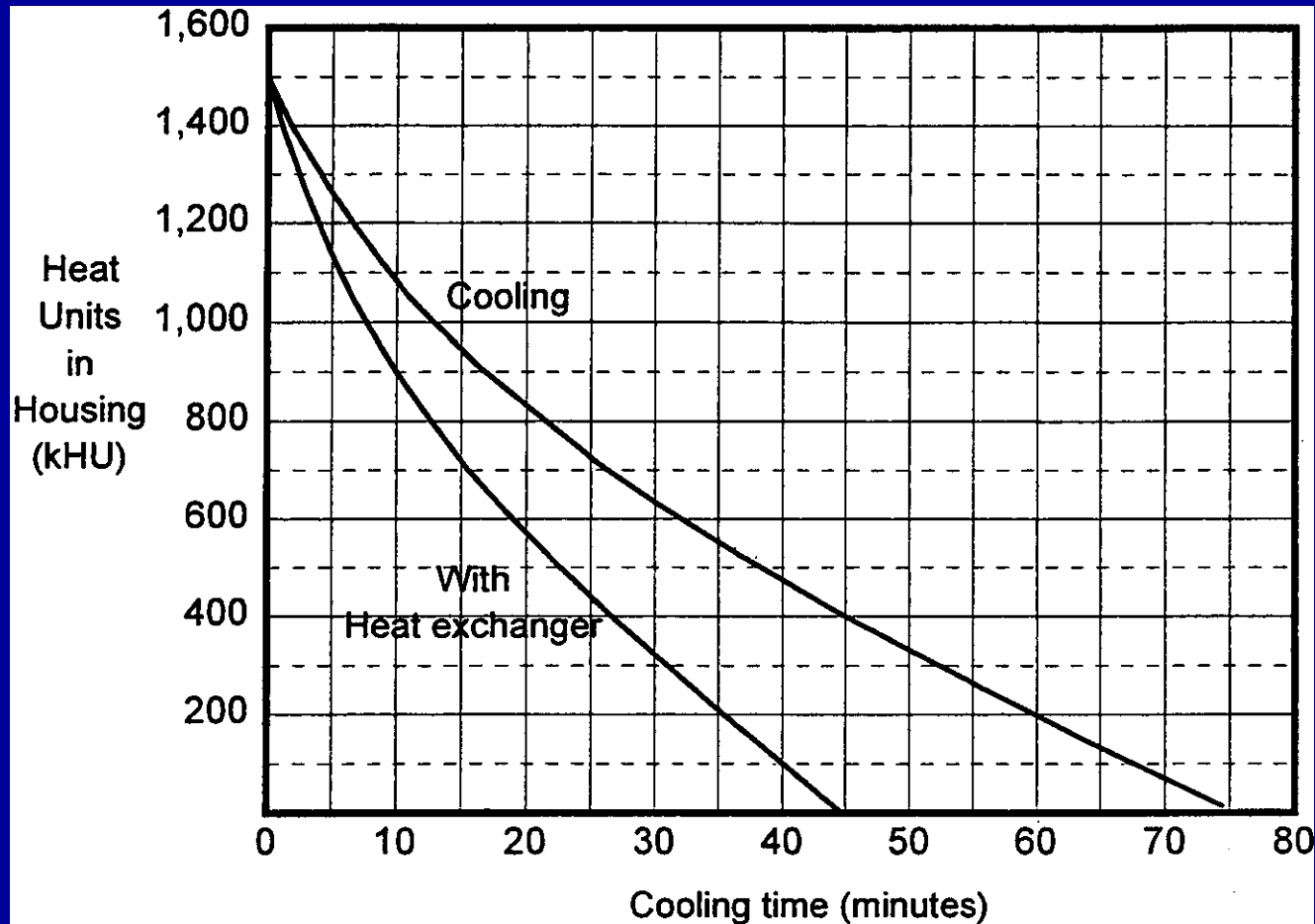
d

Anode Heat Input and Cooling Chart



Bushberg, et al., The Essential Physics of Medical Imaging, 2nd ed., p. 142.

Housing Cooling Chart



Bushberg, et al., The Essential Physics of Medical Imaging, 2nd ed., p. 144.

Raphex 2000 Diagnostic Question

- ❖ **D5.** A CT scanner is operated at 125 kVp and 170 mA. Scans are 3 seconds in duration. If the anode heat storage capacity of the x-ray tube is 1.5 MJ, how many consecutive CT slices can be taken without overheating the tube?
 - ❖ A. 10
 - ❖ B. 20
 - ❖ C. 30
 - ❖ D. 40
 - ❖ E. 50
- ❖ 1 slice = $125 \text{ kVp} \cdot 170 \text{ mA} \cdot 3 \text{ sec} = 63,750 \text{ J} = 63.75 \text{ kJ}$
- ❖ $1.5 \text{ MJ} = 1500 \text{ kJ}; 1500 \text{ kJ}/63.75 \text{ kJ} = 23.5 \text{ slices}$

Raphex 2002 General Question

- ❖ **G39.** In an x-ray machine with a tungsten target, increasing the kVp from 100 to 150 will increase all of the following except:
 - ❖ A. The total number of x-rays emitted.
 - ❖ B. The maximum energy of the x-rays.
 - ❖ C. The average energy of the spectrum.
 - ❖ D. The energy of the characteristic x-rays.
 - ❖ E. The heat units generated (for the same mAs).