BASIC PRODUCTION OF X-RAYS

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Basic X-Ray Production

- Background Physics
- Production of X-Rays
  - Bremsstrahlung
  - Characteristic
  - Auger e^-s
- Some more Physics
  - Transformers
- X-Ray Unit
  - Energy Requirements
  - Rectifiers

- If time permits, we will discuss diagnostic x-ray production in more detail!

Definitions

- Electrical Potential (Volt=J/C)→ Represents the work done to bring a unit of electric charge from infinity to a specified point in an electric field.

$$V = \frac{J}{C}$$

→ 1 joule of work must be done to take 1-coulomb of charge through a potential difference of 1 volt

- Units of Energy:Joule, eV

$$eV = 1.6*10^{-19} C * V = 1.6*10^{-19} C * \frac{J}{C} = 1.6*10^{-19} J$$

Constant: $$eV = 1.6*10^{-19} J$$

Some Basic Physics

- Ohm's Law

$$V = IR$$

- Units:

$$R = \mathrm{Resistance} = \Omega$$

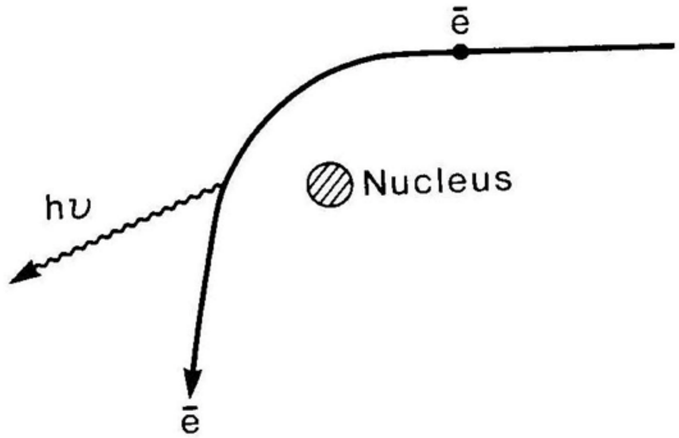
$$I = Current = \frac{Charge}{time} = \frac{C}{s} = Amp$$

BREMSTRALLUNG X-RAYS

"Pump the electron brakes"

Bremsstrahlung Radiation
“Braking Radiation”

- Occurs when e^- comes in close proximity to a large Electric Field caused by the + charge on the target nucleus
  - Electron passes in the vicinity of a nucleus all or part of the electron’s energy is dissociated from it and propagates in space as EM radiation

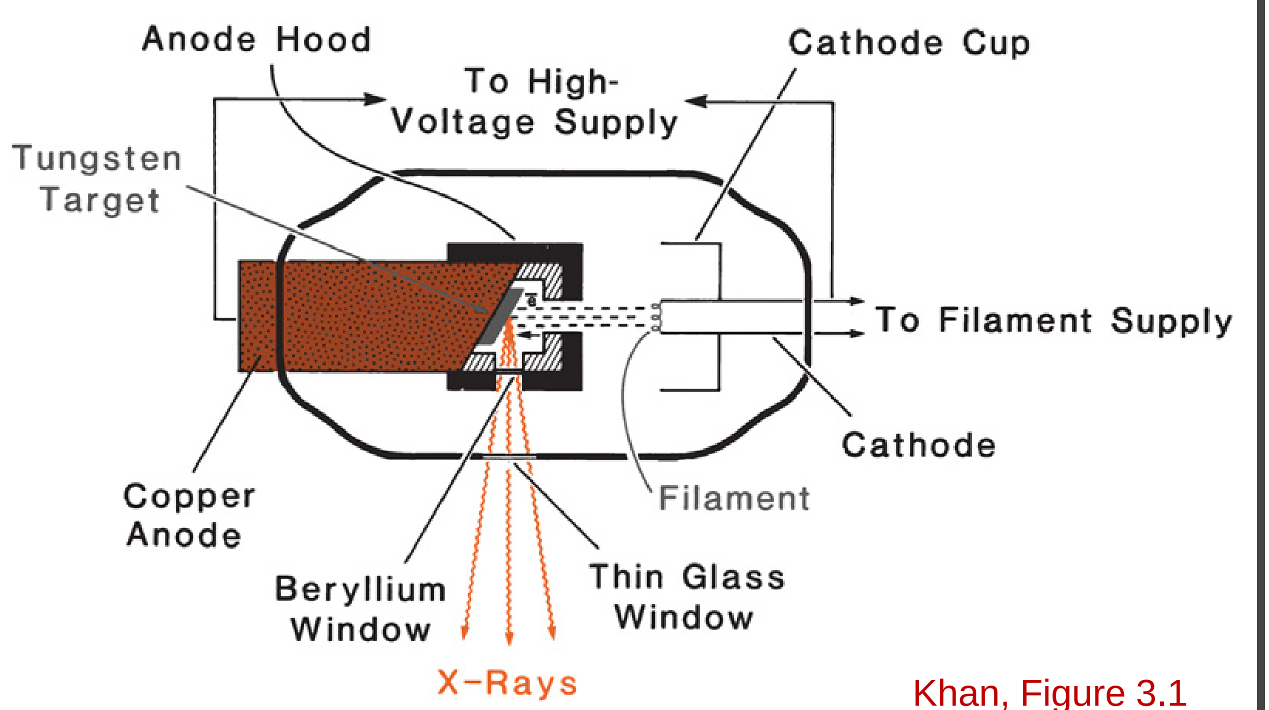


Bremsstrahlung Radiation
"Breaking Radiation"

- X-Rays are produced when the kinetic energy of an electron is converted to electromagnetic radiation.

- A large potential difference is applied between two electrodes in an evacuated envelope.
  - Cathode = **NEGATIVE** Electrode = e^- source
  - Anode = **POSITIVE** Electrode = Target

General Xray Tube Design



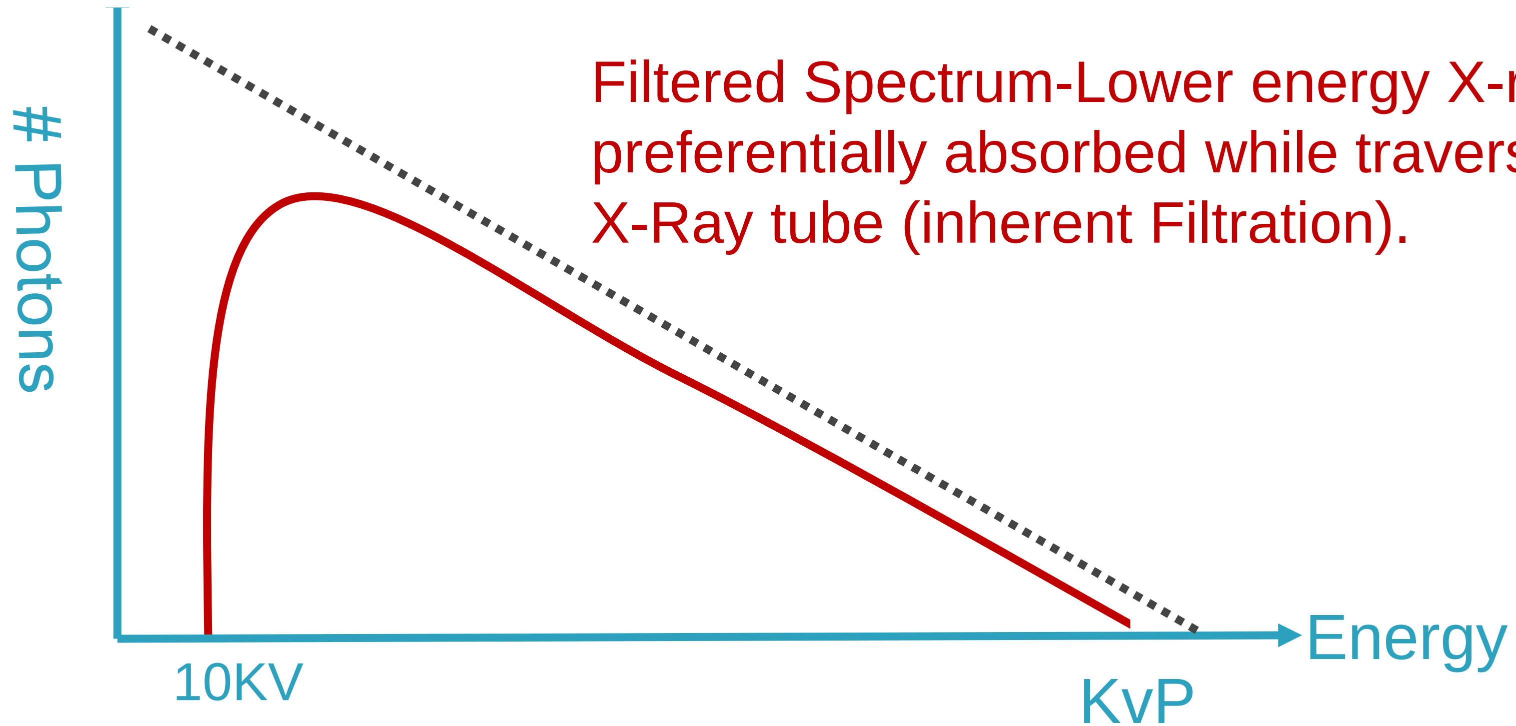
Khan, Figure 3.1

Bremsstrahlung Spectrum

Unfiltered spectrum has wedge shape:

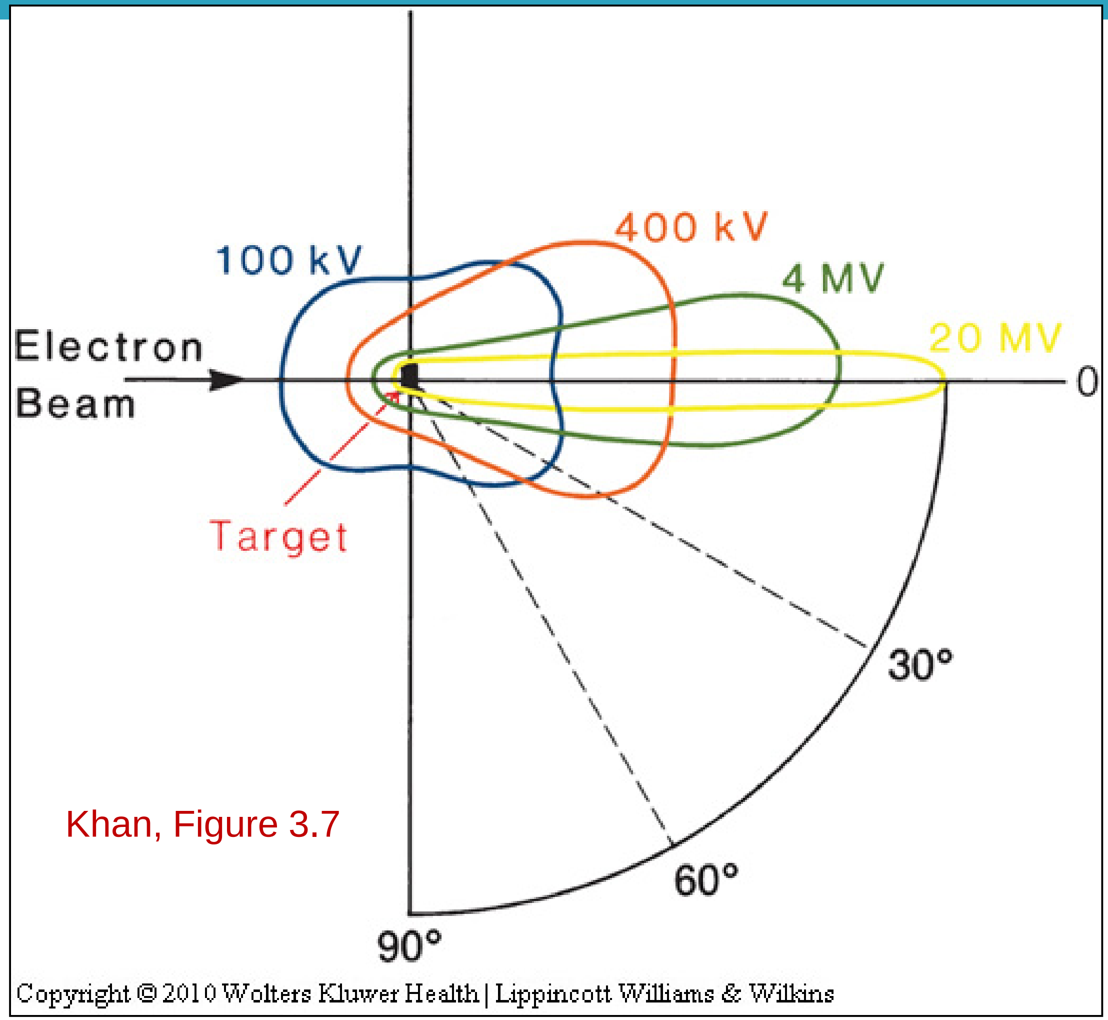
Many→ Low Energy Photon

Few→ High Energy Photons



Characteristics of Bremsstrahlung

- When the incident electron beam is <100KeV, the resulting photons are emitted equally in all directions.
- As the energy of the incident radiation is increased, the Bremsstrahlung radiation beam becomes more "forward peaked".



Khan, Figure 3.7

CHARACTERISTIC X-RAYS

Are produced differently from Brems. X-rays

Production of Characteristic X-Rays

- Electron-electron interactions can result in the ejection of an inner shell e-, leaving a vacancy in the electron orbit.
  - An outer shell electron will drop down to fill the vacancy.
  - A photon with an energy equal the difference in the binding energies of the involved electrons is released.
- Characteristic X-Rays can ONLY be produced when the energy of the electron exceeds the binding energies of the inner shell electrons in the target.

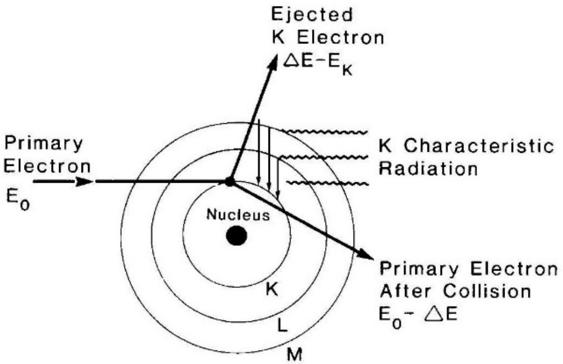
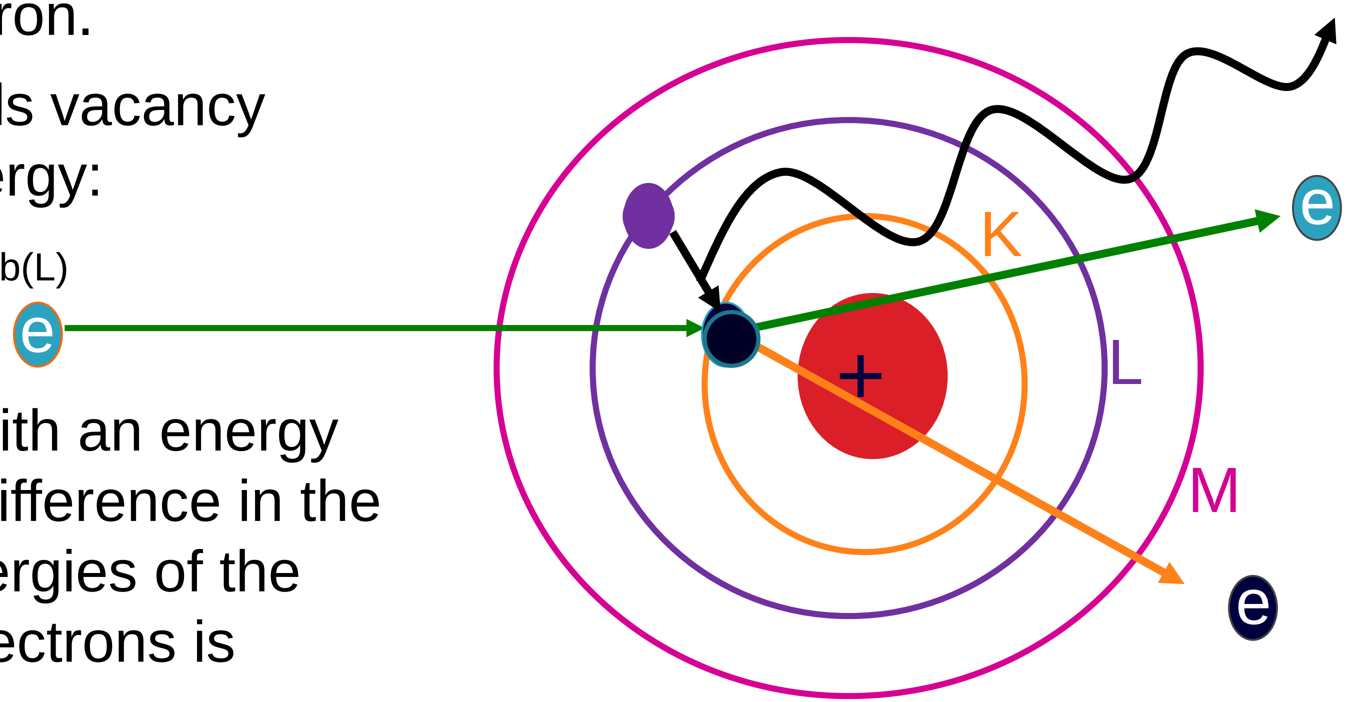


FIG. 3.8. Diagram to explain the production of characteristic radiation.

Characteristic X-Ray Production

1. Incident e^- ejects k shell electron.
2. L shell e^- fills vacancy excess energy: $E=E_{b(K)} – E_{b(L)}$



3. A photon with an energy equal the difference in the binding energies of the involved electrons is released.

Note: characteristic x-rays can also be produced following a photoelectric photon interaction (incident photon ejects electron rather than incident electron).

Characteristic X-Ray Nomenclature

- K,L,M designation refers to original vacancy location (orbital shells)
  - α,β, etc refers to where the e- that filled the vacancy ca
    - α → adjacent shell transition
    - β → nonadjacent shell transition

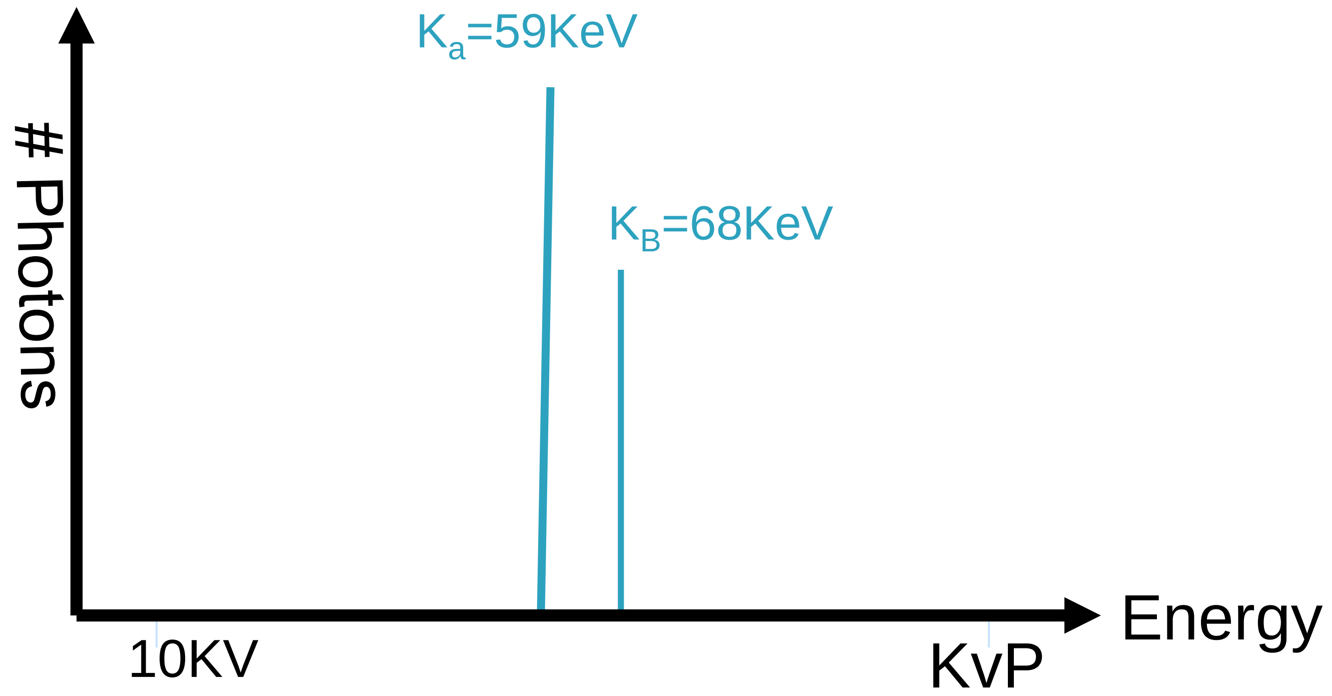
$K_\alpha = L \rightarrow K$

$K_\beta = M \rightarrow K$

- The binding energies associated with the different "electron shells" are specific for each element's atom
  - K_α for Tungsten will be different from K_α for Molybdenum
- For a given atom, electrons residing in shells closer to the nucleus have higher binding energies.

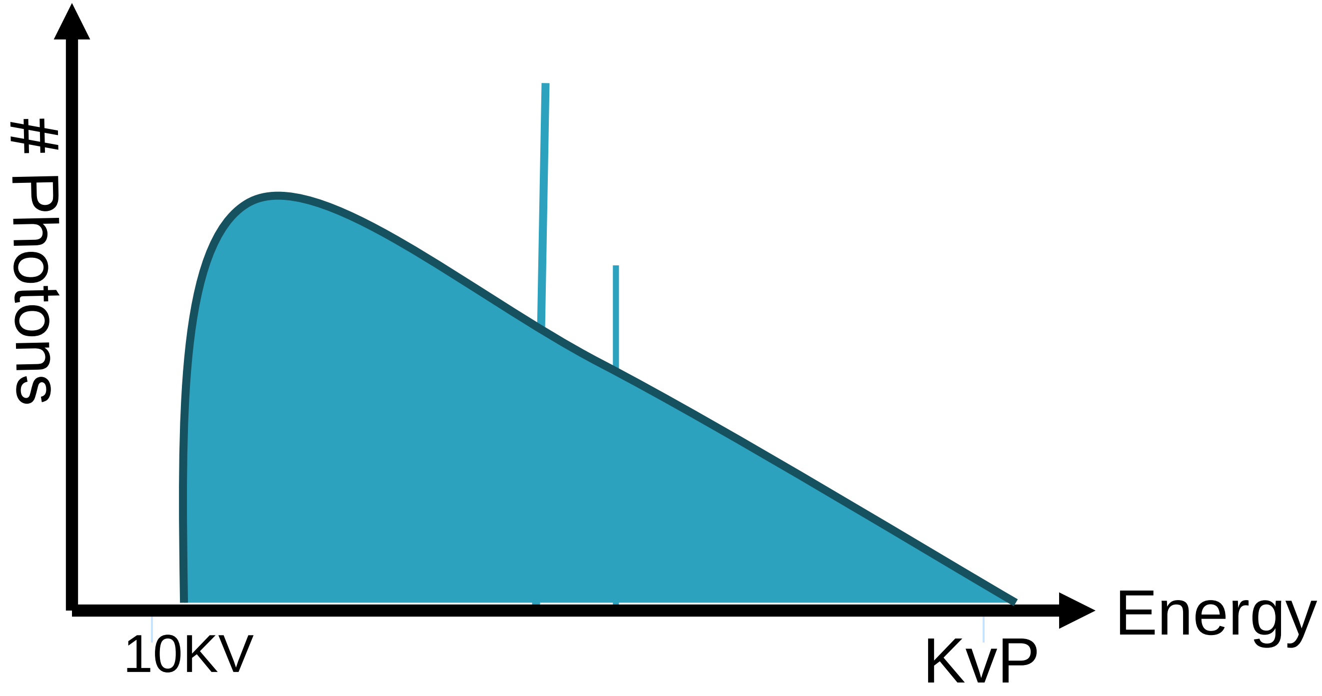
Characteristic X-Ray Spectrum: W

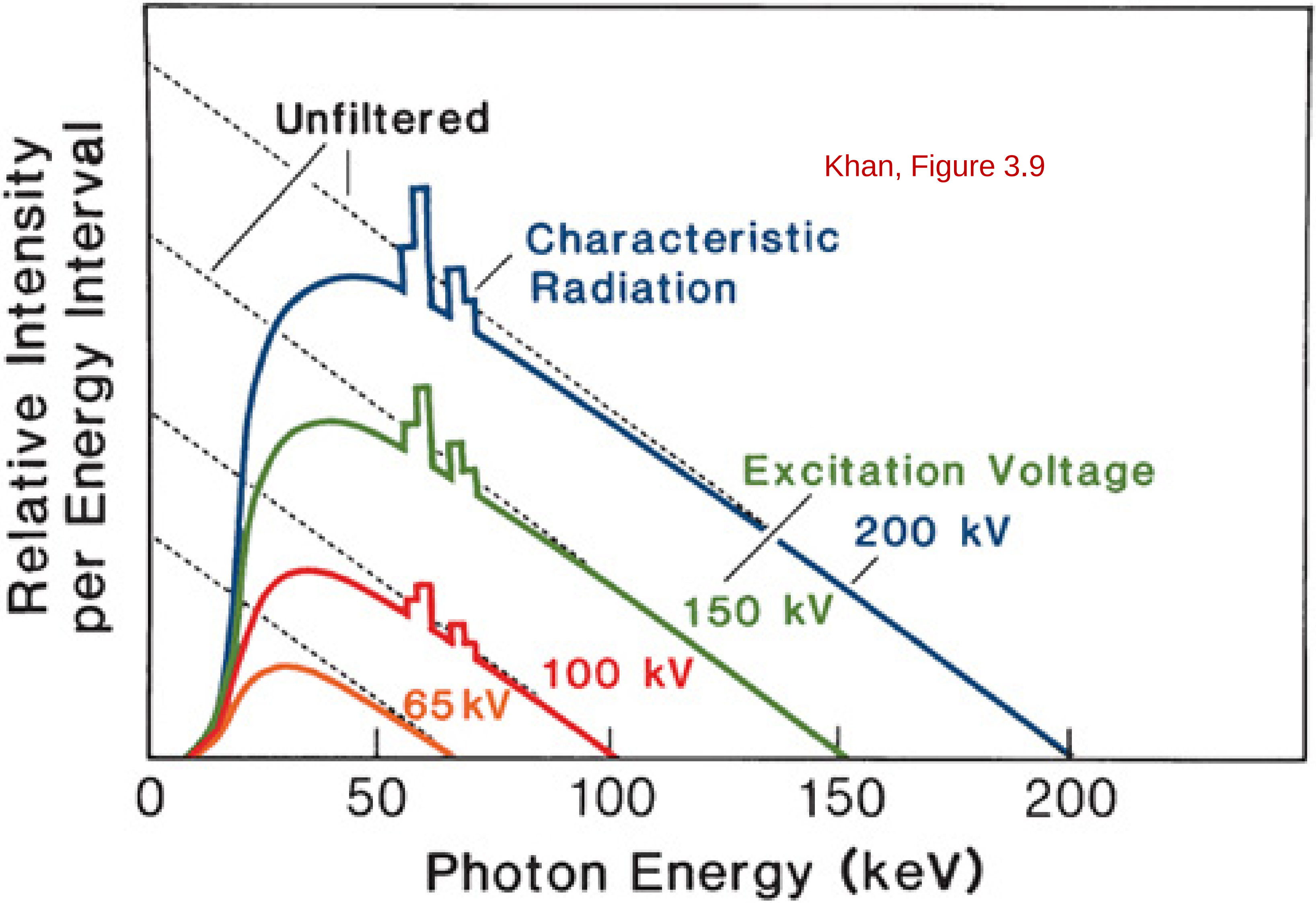
$Energy_{(Ka)} < Energy_{(KB)}$



“Complete” X-Ray Spectrum

- The true x-ray spectrum shows characteristic X-Rays with discrete energies) superimposed with the continuous distribution of energies for the bremsstrahlung photons.





Khan, Figure 3.9

Question

- The characteristic x-rays emitted from a tungsten target when100keV electrons are fired at it:

  A. Have a continuous spectrum up to 100kV.
  B. Are about equal in intensity to the bremsstrahlung.
  C. Have energies equal to differences in the binding energies.
  D. Do NOT contribute significantly to the imaging process.

Question

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  C. Have energies equal to differences in the binding energies.
  D. Do NOT contribute significantly to the imaging process.

- Correct Answer. C. Have energies equal to differences in the binding energies.

X-RAYS TUBE DESIGN:

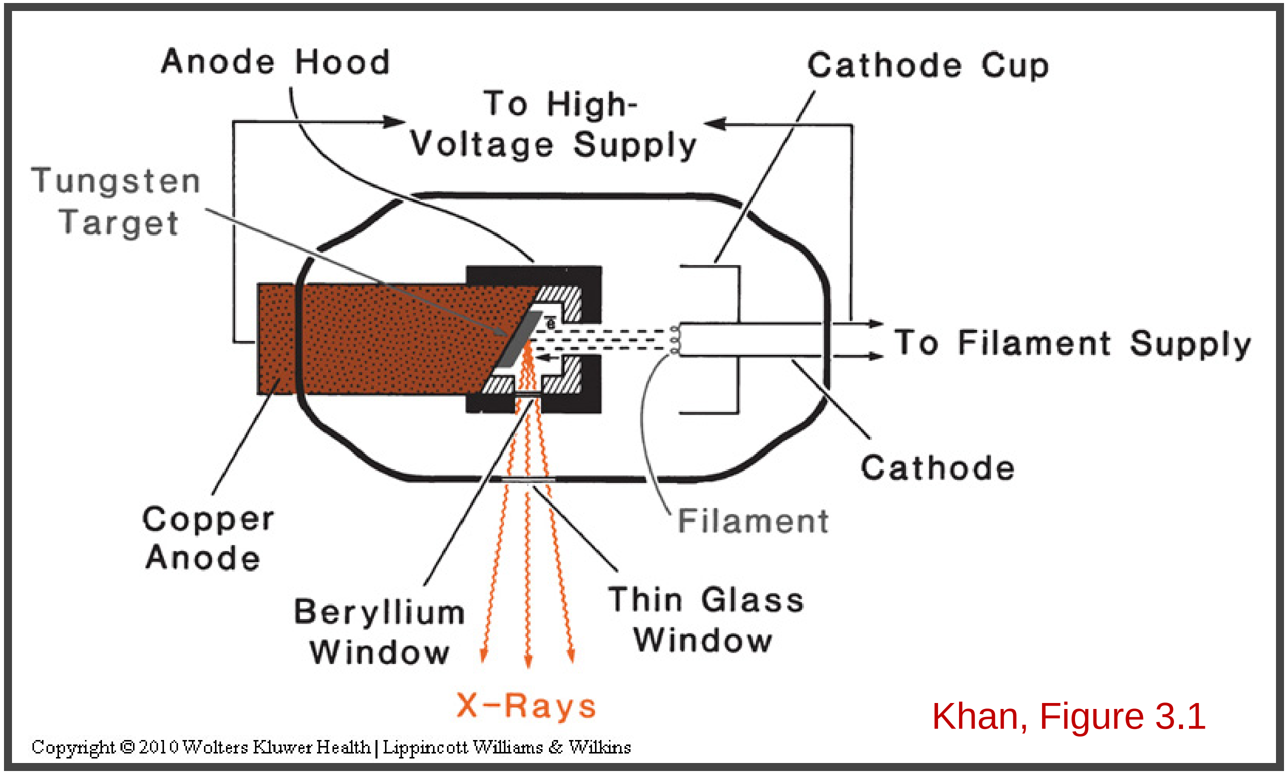
Back to Bremsstrahlung

Generic Xray Tube Design

- "Tubes" include shielded housing (envelope)
- "Windows" of material provide inherent filtration

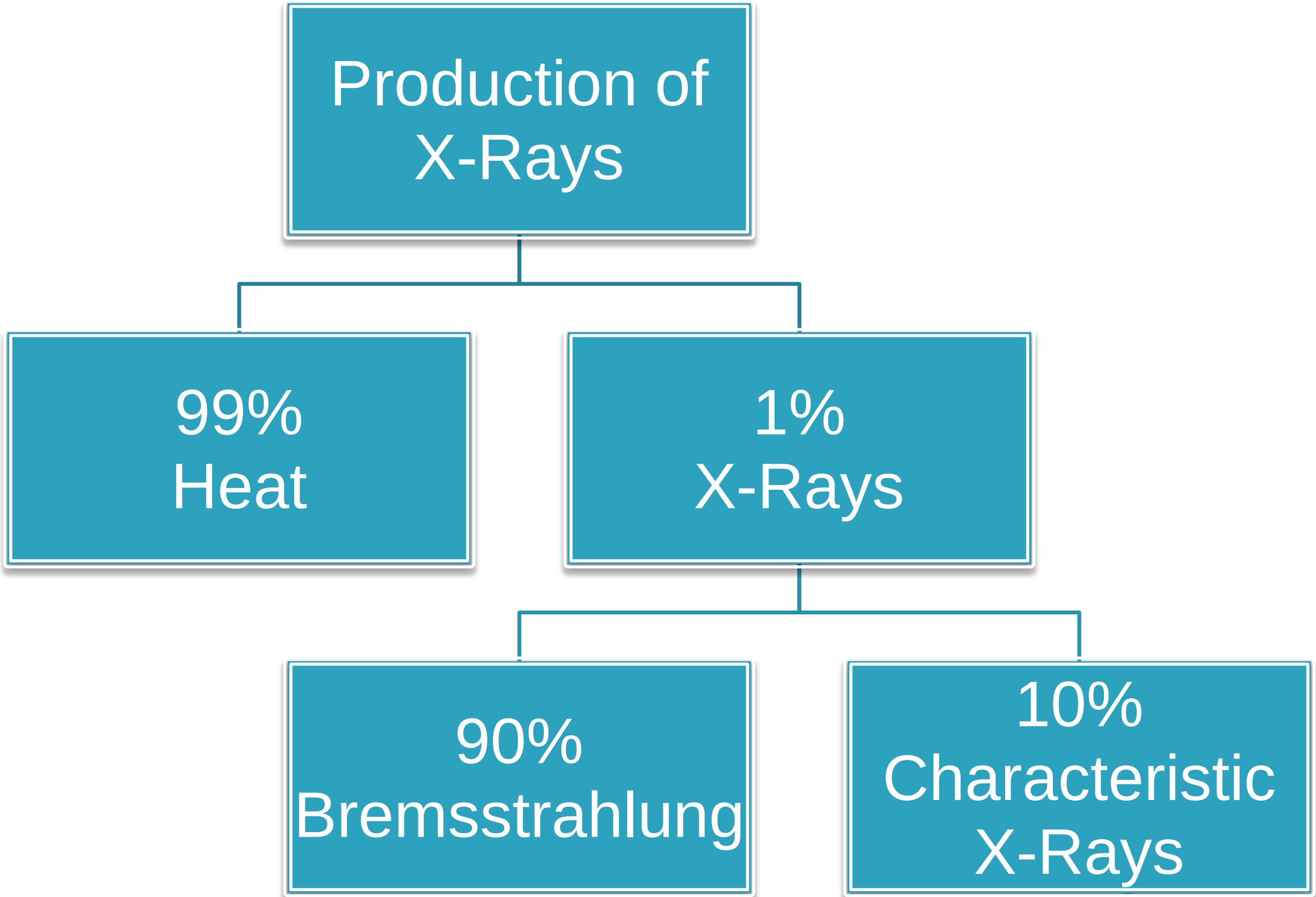
- A large potential difference is applied between two electrodes in an evacuated envelope.
  - Cathode = **NEGATIVE** Electrode = e^- source
  - Anode = **POSITIVE** Electrode = Target

General Xray Tube Design



Khan, Figure 3.1

Efficiency of X-Ray Production Diagnostic Type Energies (kV)



Efficiency of X-Ray Production

$$Efficiency = 9x10^{-9}\,ZV$$

$$Z = \text{atomic number of target}$$

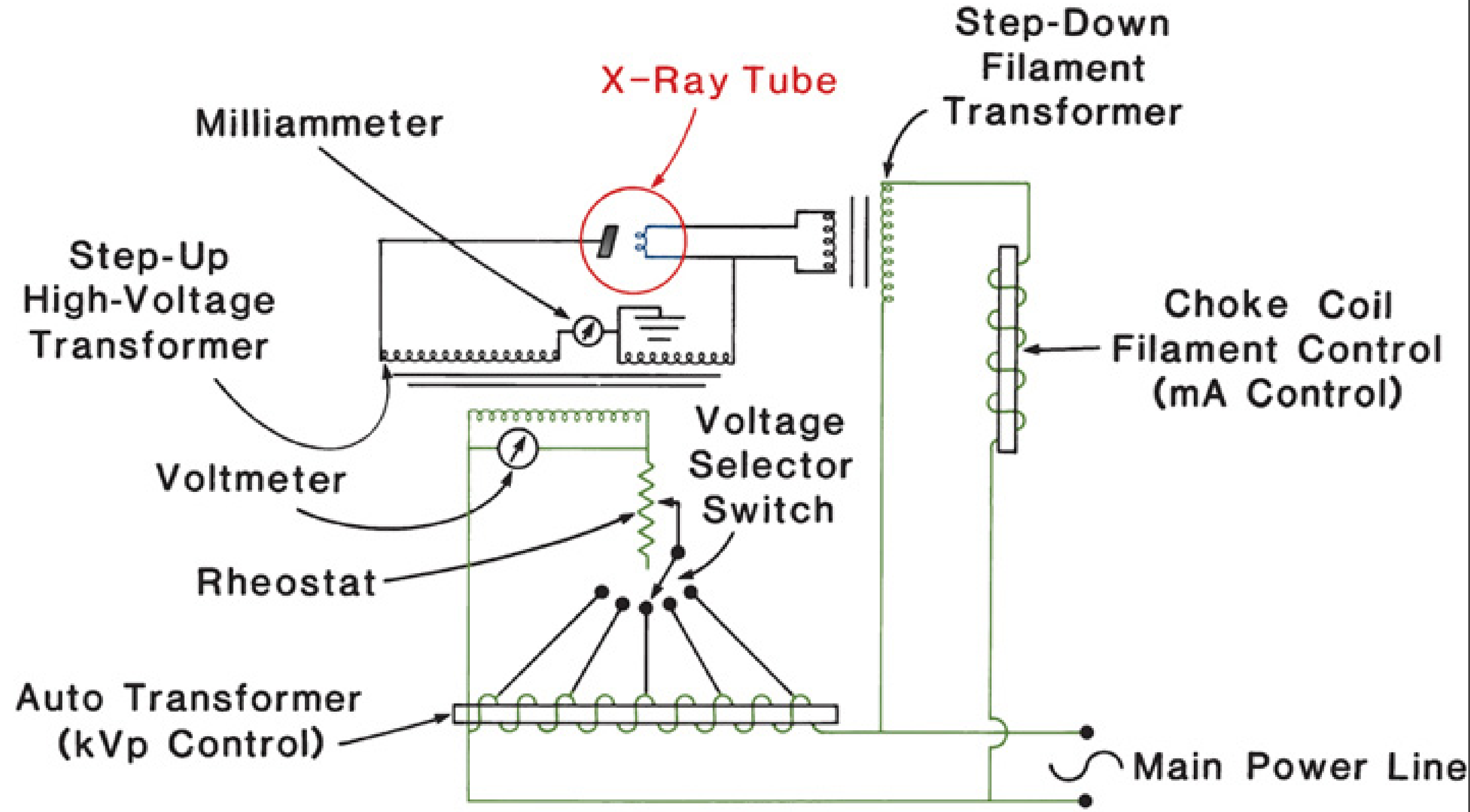
$$\text{V} = \text{Accelerating voltage in volts}$$

- The accuracy of this equation is limited to a few megavolts.

X-Ray Energy	% X-Rays Produced	% Heat Produced
100 KeV	0.7%	99.3%

- Efficiency improves considerably for high-energy x-rays.

Production of X-Rays: The “Big Picture”



Some Important Definitions

- **Quality:** Describes penetrability of X-ray beam, dependent on filtration. (Average Beam Energy).
- **Quality**: Number of photons in the Beam (Fluence).
- **Intensity y** (Energy Flux, Energy Fluence Rate): Energy weighted flux of photons within the spectrum.

Factors Effecting X-ray Emission

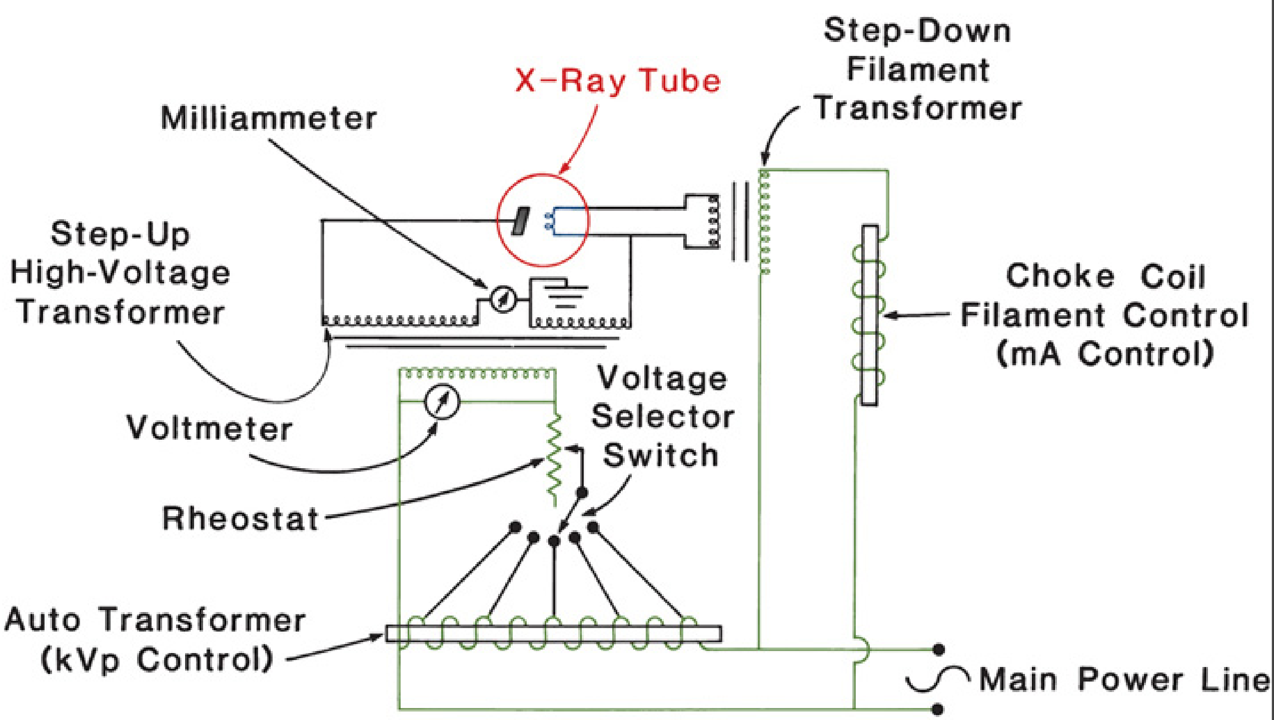
- **Target Material**
  - ⇧Z ⇧Quantity of Bremsstrahlung
  - ⇧Z ⇧Quality of Chacracteristic. X-Rays
- **kVp**
  - ⇧kVp ⇧Quality of Bremsstrahlung
- **mAs**
  - ⇧mAs ⇧Quantity of Brems/chac. X-rays
- **Generator Waveform:** Waveforms with lower Ripple will have higher average energy, thus having higher Quality/Quantity Bremsstrahlung.
- **Beam Filtration:** Selectively removes low energy photons, thus increasing the average energy thus having higher quality Bremsstrahlung photons.

Let’s backtrack and look at the x-ray tube in detail and consider:

“Where do the incident electrons come from?”

X-Ray Unit
Two Electrical Energy Requirements

1. Energy to “boil” electrons from filament (cathode): Provided by filament circuit → Low Voltage
2. Energy to accelerate the e-s toward target: Provided by tube circuit → High Voltage



Khan,
Figure 3.3

Energy Requirements

- A small potential difference applied to cathode by filament circuit, cathode heats up, electrons released via thermionic emission.
  - The higher the temperature, the more electrons released. The temp is increased by increasing filament mA.
  - Rate of e- emission det. by filament mA

- A Large potential difference is applied between anode and cathode
  - Maintains anode at higher potential (voltage difference) with respect to cathode.
  - Causes electrons released by cathode to be accelerated to anode, the potential difference is large enough that all e-s are accelerate to anode!!

How do we get both low and high voltage out of same AC input line?

Transformers

Transformer is an electrical device that increases, decreases, or isolates electrical current and voltage.

Transformers

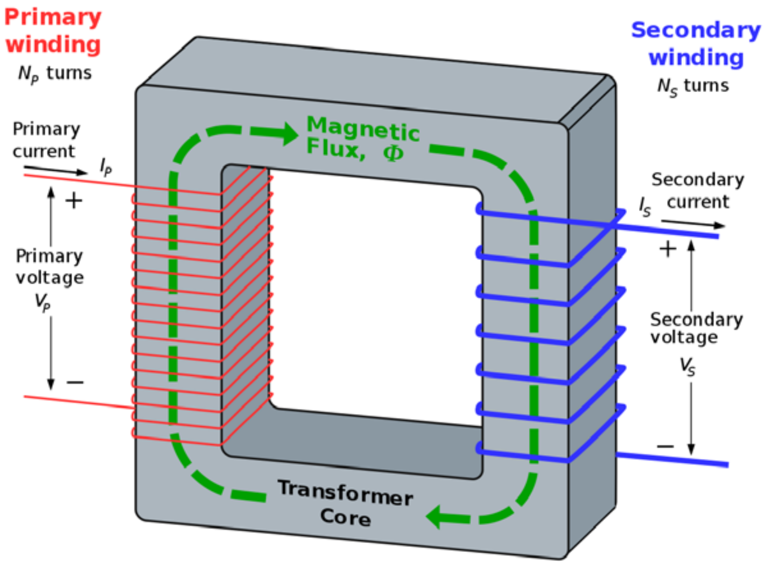
- When a primary voltage is applied to one coil, it sets up a secondary voltage in the second coil via **electromagnetic induction**.
  - When current flows through the primary coil, it creates a magnetic field within the ring, and this magnetic field induces the current in the second coil.
  - Current only flows through the 2^{nd} coil when the magnetic field is changing.
    - No current flows when the magnetic fields is in a steady state. AC line voltages are used because its voltage is continuously changing, so it provides a continuously changing magnetic field.

Start with AC line Voltage

Transformers

Isolation, Step UP, Step Down

- Transformer is an electrical device that increases, decreases, or isolates electrical current and voltage.



Consists of two wire coils wrapped around a closed core (Fe):

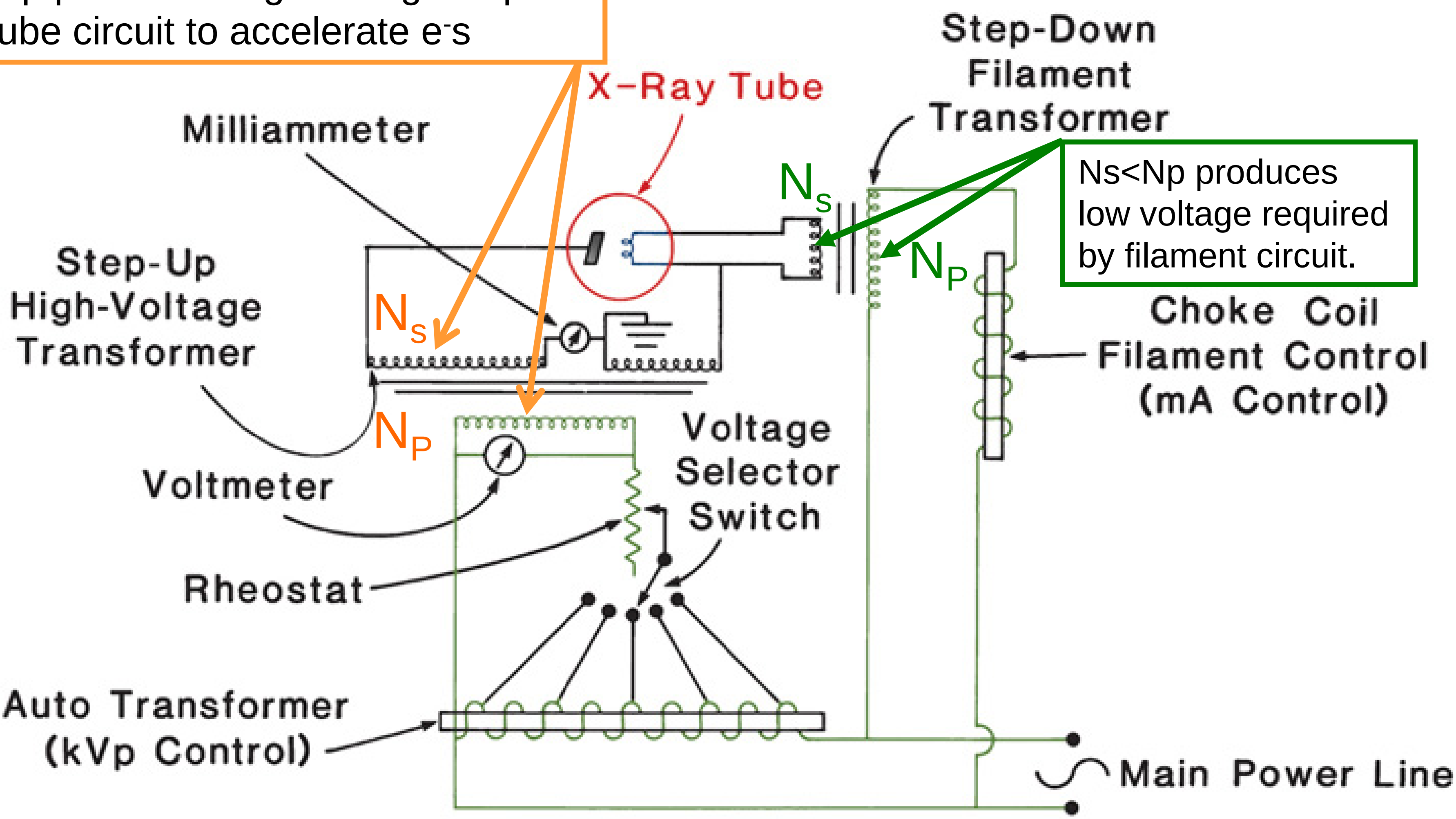
Law of Transformers:

$$\frac{N_p}{N_s} = \frac{V_p}{V_s}$$

Basic equation that relates the voltage to the number of windings on each side of the transformer.

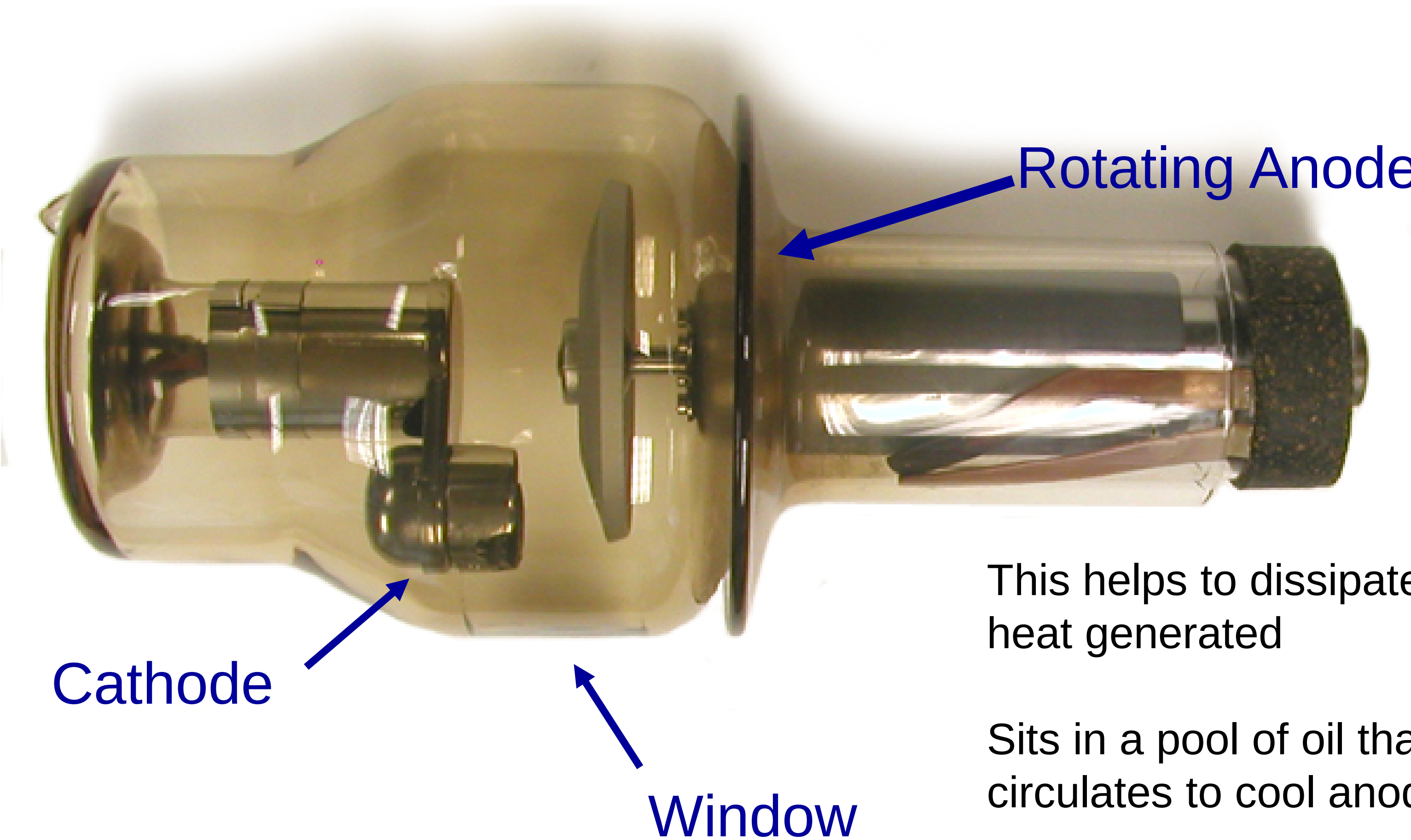
Energy Requirements

Ns>Np produces High voltage required by Tube circuit to accelerate e-s



Khan, Figure 3.3

Rotating Anode



This helps to dissipate the heat generated

Sits in a pool of oil that circulates to cool anode

The Efficiency is POOR
This Effects the X-ray unit Design

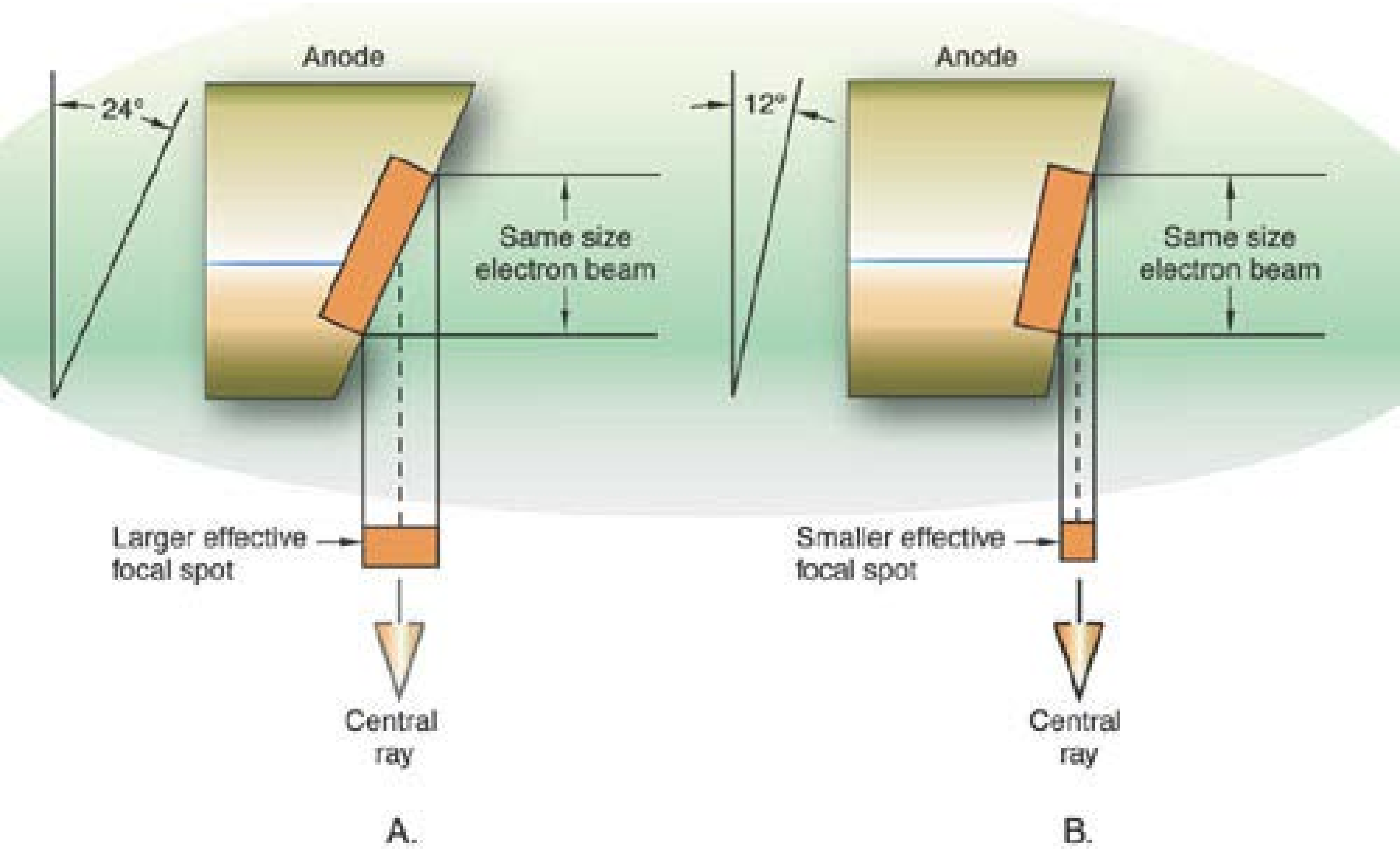
- For Good Image Quality: small focal spot
  - Focal spot is the area of the target intercepted by the electron beam (where the x-rays are emitted).

- But, we have a lot of heat, so we are limited.

Line Focus Principle

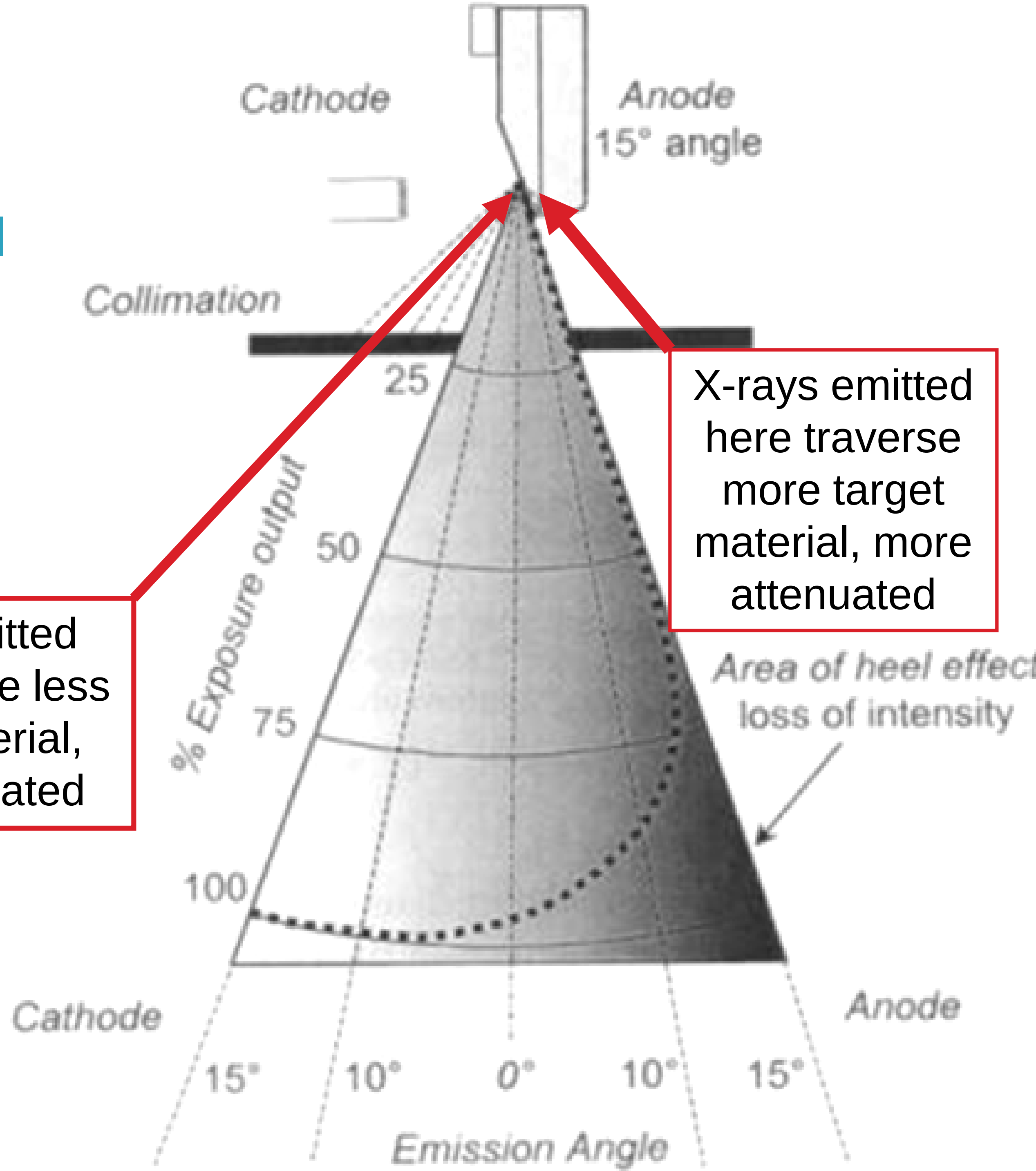
- If the target is angled, the focal spot projected on the patient is smaller (than the actual focal spot).
- We achieve both good image quality by making the projected focal spot small, and minimize heat loading by having a large "real" focal spot.

Line Focus Principle



Heel Effect

- Decrease in x-ray beam intensity from cathode to anode side of target.
- Heel effect is a consequence of angled anode!

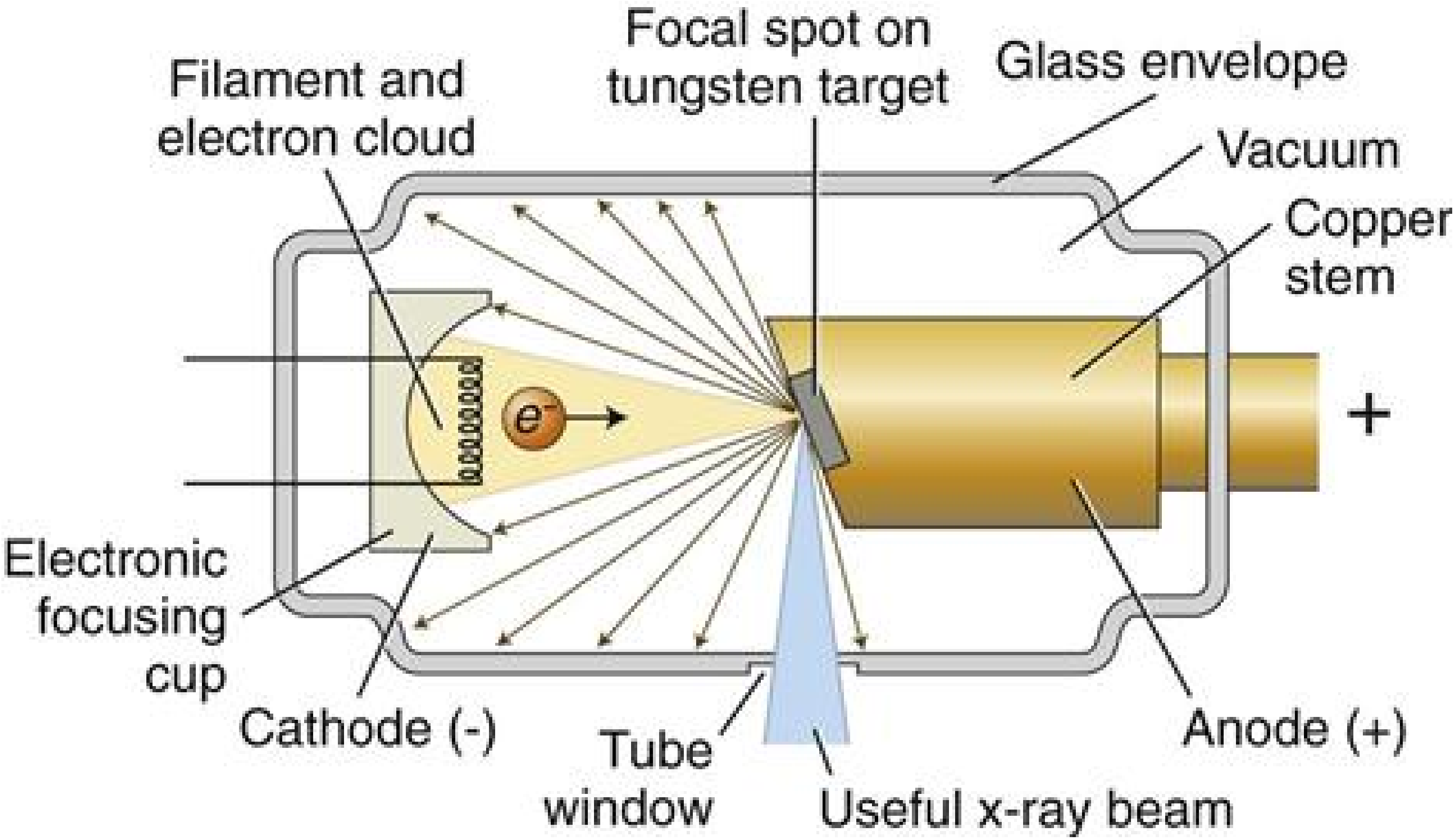


Dual Filament Tubes

- Some x-ray tubes contain 2 filaments:
  - Small focal spot size
  - Large focal spot size

- Choose best filament for particular technique:
  - Use small focal spot when imaging smaller anatomy (not limited by FOV, get best possible quality)
  - Use larger focal spot for larger anatomy (a small focal spot would limit the FOV, thus larger focal spot necessary despite poorer image quality)

X-ray Generation: The kV Story



References

- Physics of Radiation Therapy, Faiz M. Khan; 4th (2010): Chapter 3
- The Essential Physics of Medical Imaging, Jerrold T. Bushberg (1994): Chapter 4