Ionising Radiation Physics
X-ray Production

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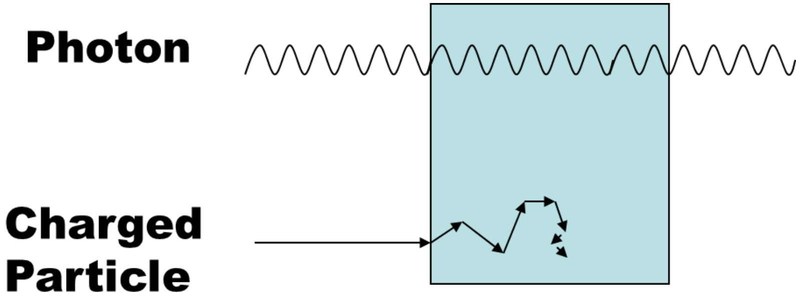
Review of Last Lecture



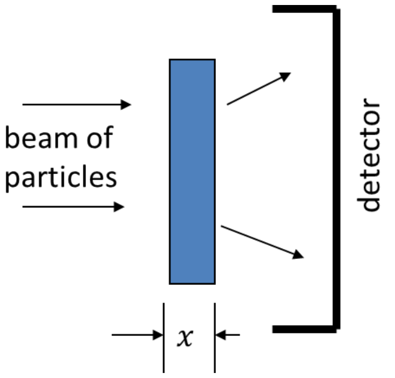
<u>Charged particles</u>

- many interactions per unit length
- small energy loss per interaction

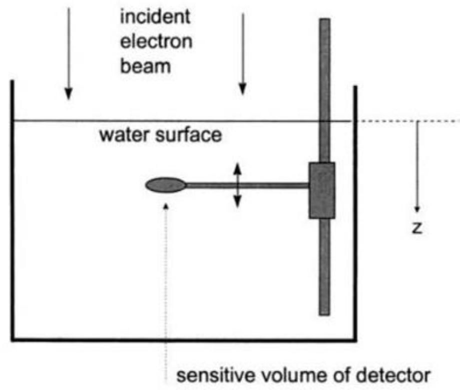
- Stopping power, ${}^{dE}/_{dx}$
  - Collisional – electrons emitted
  - Radiative – Bremsstrahlung photons emitted (or others)

- Range, r_0
  - Approximations
    - CSDA
    - Straight ahead approximation
    - Detour factor
  - Experimental measurements

Transmission



Depth dose



Review of Last Lecture

- Bethe formula

$$\frac{1}{\rho}\left(\frac{dT}{dx}\right)=\frac{4\pi r_0^2 m_0 c^2}{\beta^2}\frac{1}{u}\frac{Z}{A}z^2\left[\ln\left(\frac{2m_0c^2\beta^2\gamma^2}{I}\right)-\beta\right]$$

$$Stopping\ power \propto \frac{z^2}{v^2}$$

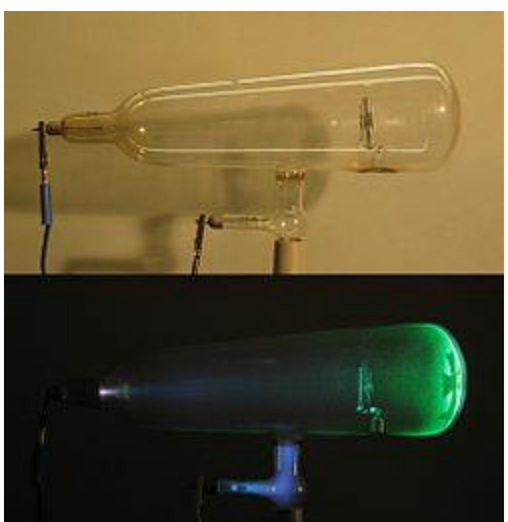
  – Restricted stopping power – under “Cut-off energy”

- Bremsstrahlung
  – Breaking radiation

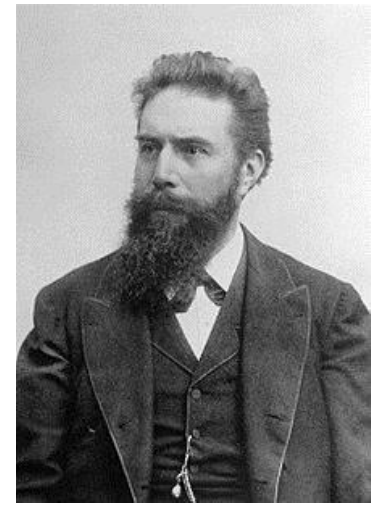
$$I \propto \frac{z^2 Z^2 e^4}{m^2}$$

Discovery of X-rays

- Found by accident after investigating “cathode rays” produced by a Crookes tube
- Certainly observed before him, but he quantified transmission through many materials and published



Wilhelm Roentgen

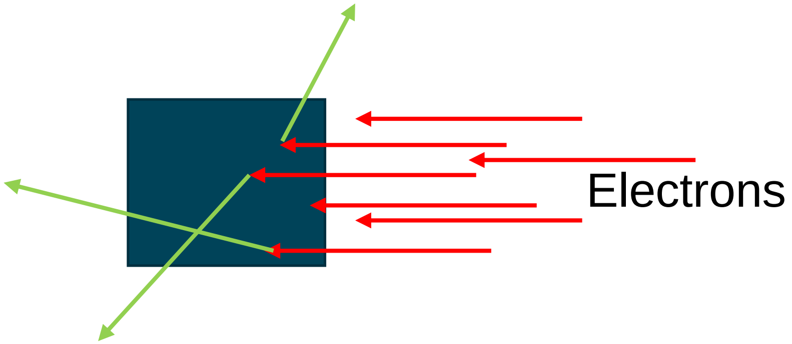


Nobel Prize in Physics
1901

“in recognition of the extraordinary services he has rendered by the discovery of the remarkable rays subsequently named after him”

Physics and Interactions

Physics

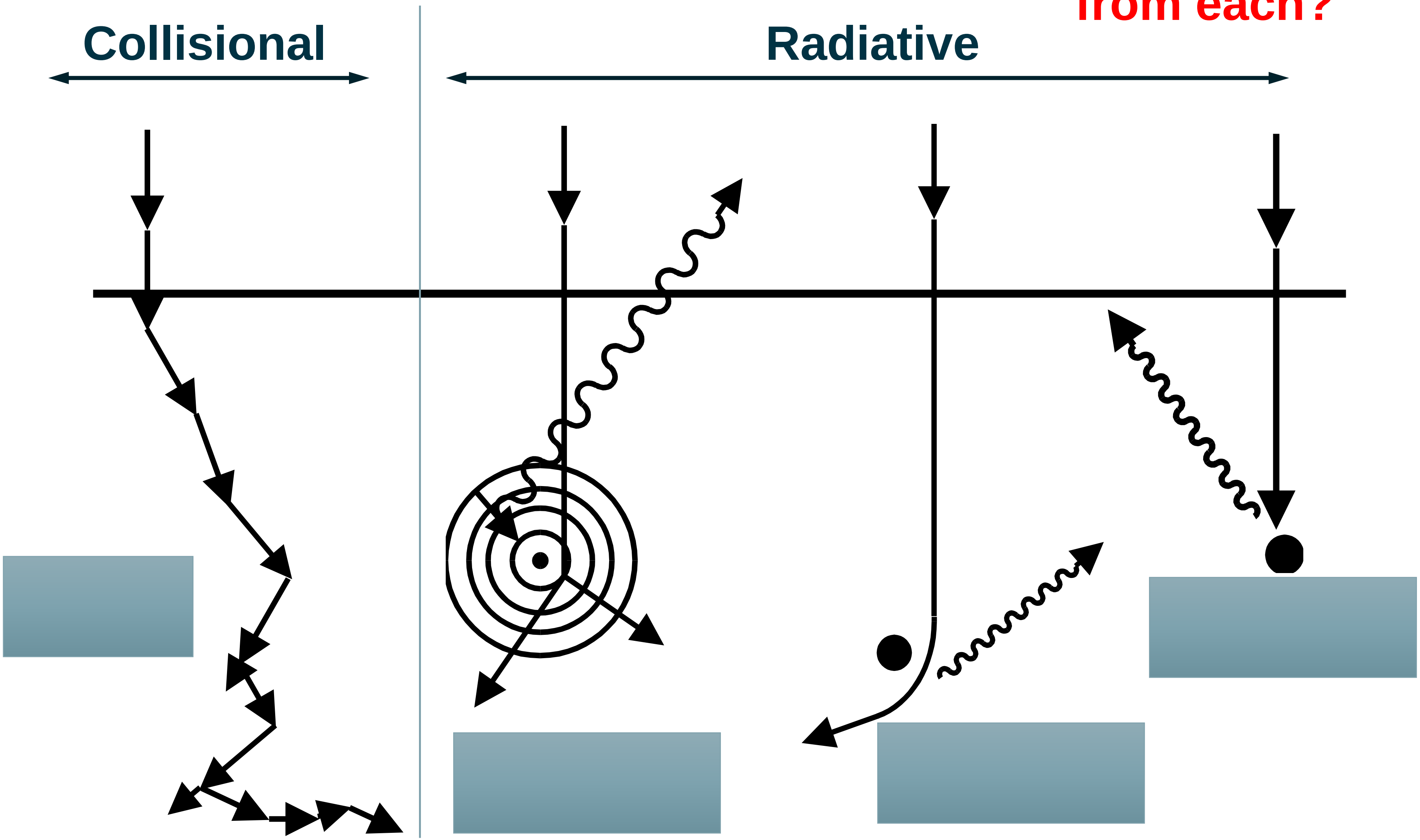


- High energy electrons
- Impact on metal target

- What is produced?
- How?

Electron Interactions with Matter

What results from each?



Collisional Loss

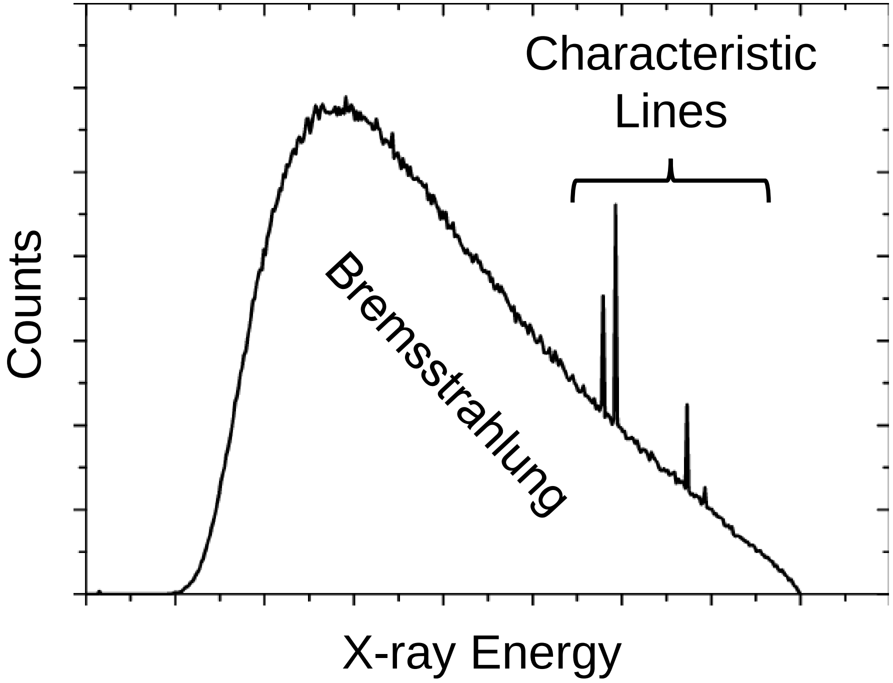
- Described in detail in last lecture
  - CSDA
  - Beth equation
  - Numerous collisions losing small % of energy each time

- In most cases leads to heat generated in target material
  - Coulombic recoil
  - Excitation followed by vibrational relaxation
  - Ionisation emitting extra electron

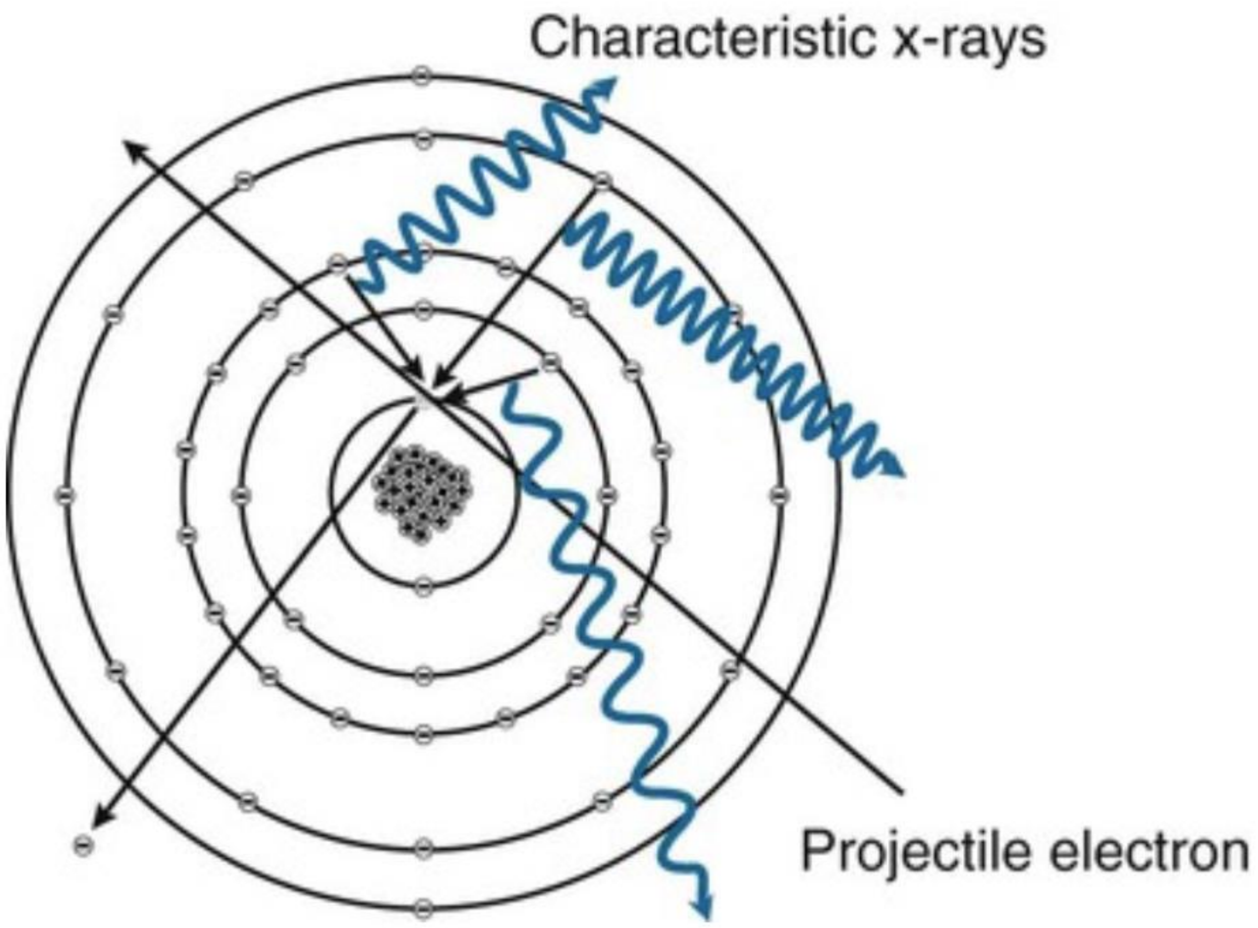
- Not the purpose of an X-ray tube

Radiative Loss

- Responsible for X-ray production
- X-ray spectrum
- Two features
  - Characteristic lines
  - Bremsstrahlung



Characteristic X-rays



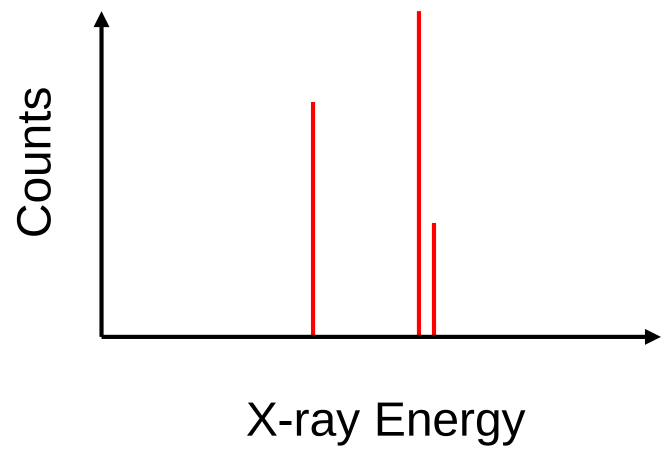
Characteristic X-rays

- Incoming electron interacts with inner shell atomic electron
  - Frees atomic electron (with additional KE)
  - Leaves excited ion behind

- Electron from higher orbital falls to lower hole

- Photon released characteristic to atom’s electron energy levels
  - $hv = BE_m – Be_k$

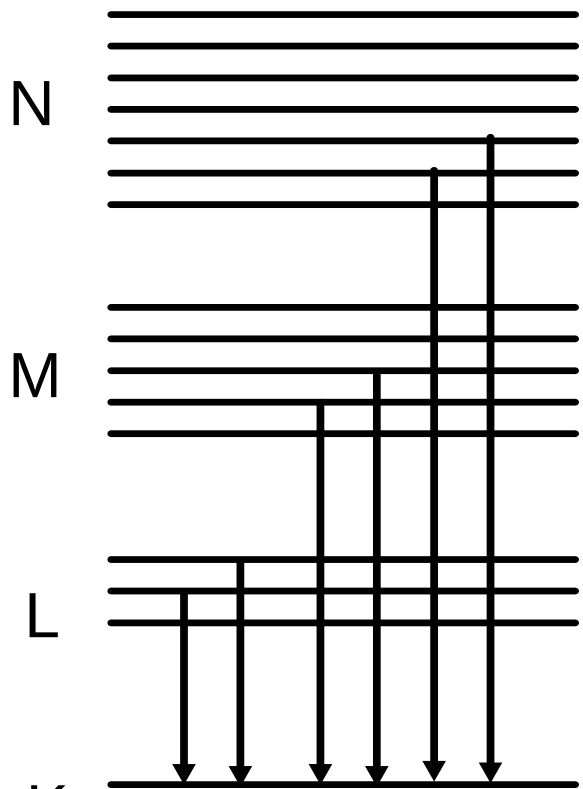
- Produces characteristic “lines” in the X-ray spectrum



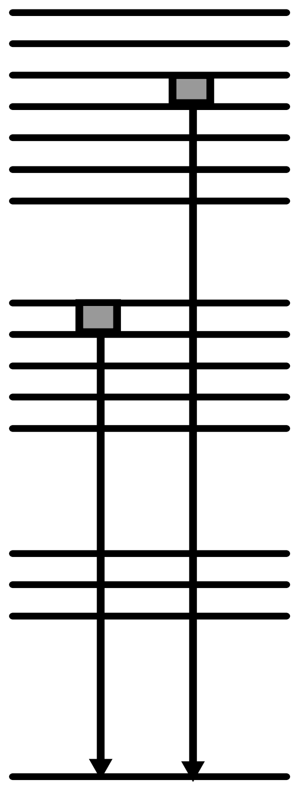
Why multiple lines?

Characteristic lines

- Each shell has multiple energy states
- Not all electron transitions are “allowed”



Normal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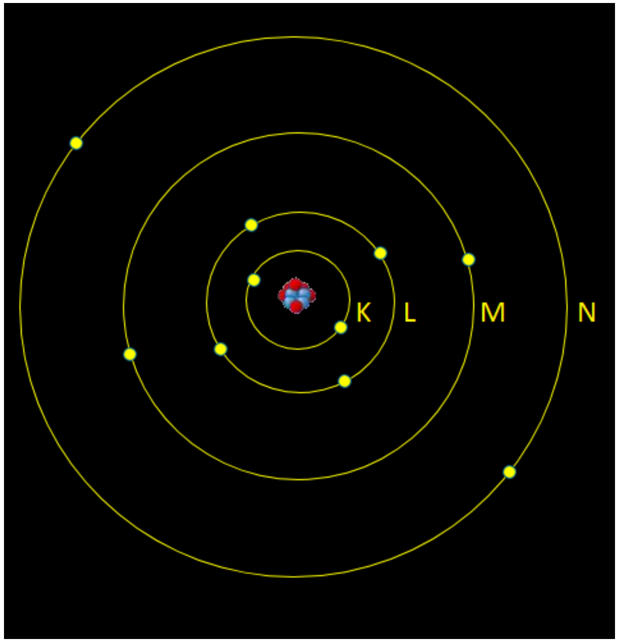


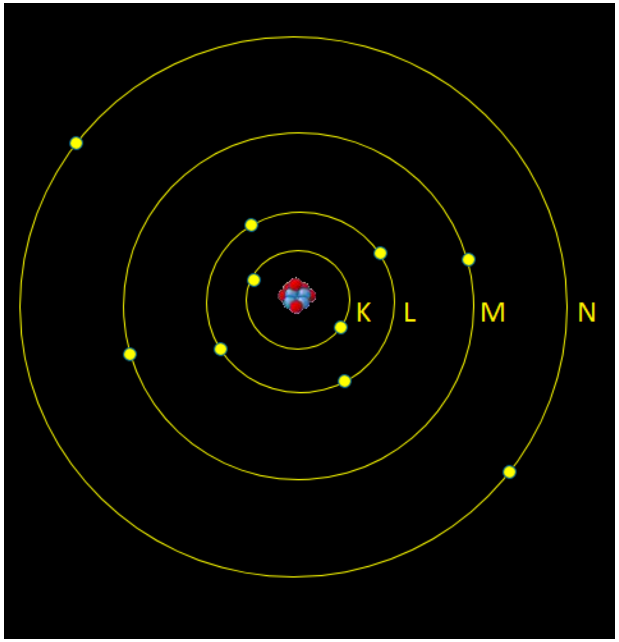
Common X-ray target electron energy levels

- Energy required to eject atomic electron from shell (keV)

Shell	Molybdenum (Z=42)	Tungsten (Z=74)
K	20.000	69.525
L_I	2.867	12.098
L_{II}	2.625	11.541
L_{III}	2.521	10.204
M_I	.505	2.820
M_{II}	.410	2.575
M_{III}	.392	2.281
M_{IV}	.230	1.871
M_V	.228	1.809

Example

- K electron ejected from tungsten. L_{III} electron moves into K orbit to fill the gap (K-L_{III} *transition*)
- Energy of x-ray is equal to the difference between the energy levels of the orbits
- i.e. 69.525 - 10.204 = 59.321 keV

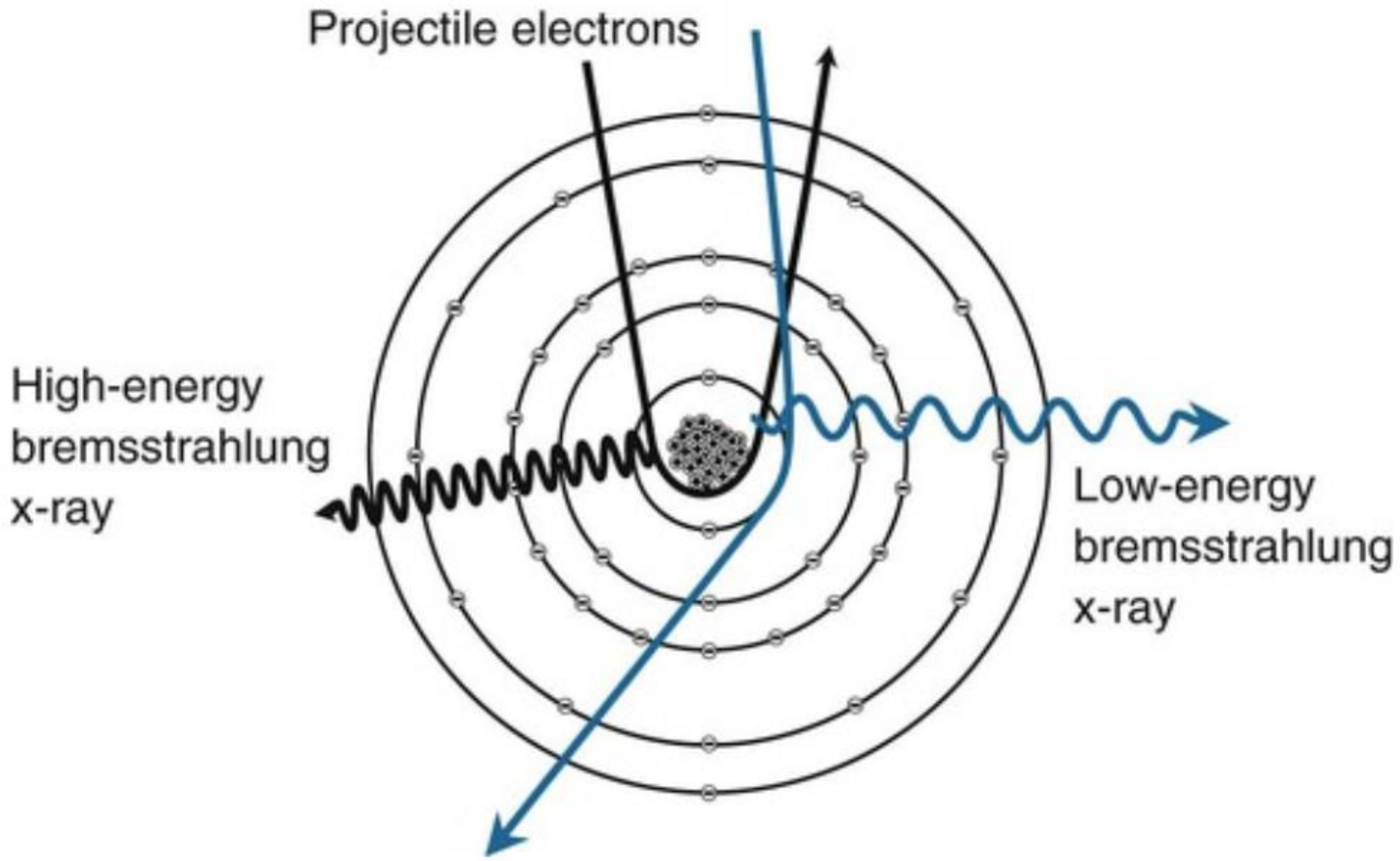


If incoming electron energy > electron binding energy characteristic lines will be present on spectrum

Characteristic Lines

K Lines of Tungsten			L Lines of Tungsten		
Transition	Energy (keV)	Relative number	Transition	Energy (keV)	Relative.. number..
$K\text{-}N_{II}$	69.081	7	$L_{I}\text{-}N_{III}$	11.674	10
$K\text{-}M_{III}$	67.244	21	$L_{II}\text{-}N_{IV}$	11.285	24
$K\text{-}M_{II}$	66.950	11	$L_{III}\text{-}N_{V}$	9.962	18
$K\text{-}L_{III}$	59.321	100	$L_{I}\text{-}M_{III}$	9.817	37
$K\text{-}L_{II}$	57.894	58	$L_{I}\text{-}M_{II}$	9.523	29
K Lines of Molybdenum			$L_{III}\text{-}M_{V}$	8.395	100
$K\text{-}M_{II}$	19.602	24	$L_{III}\text{-}M_{IV}$	8.333	11
$K\text{-}L_{III}$	17.479	100			
$K\text{-}L_{II}$	17.375	52			

Bremsstrahlung X-rays



Bremsstrahlung X-rays

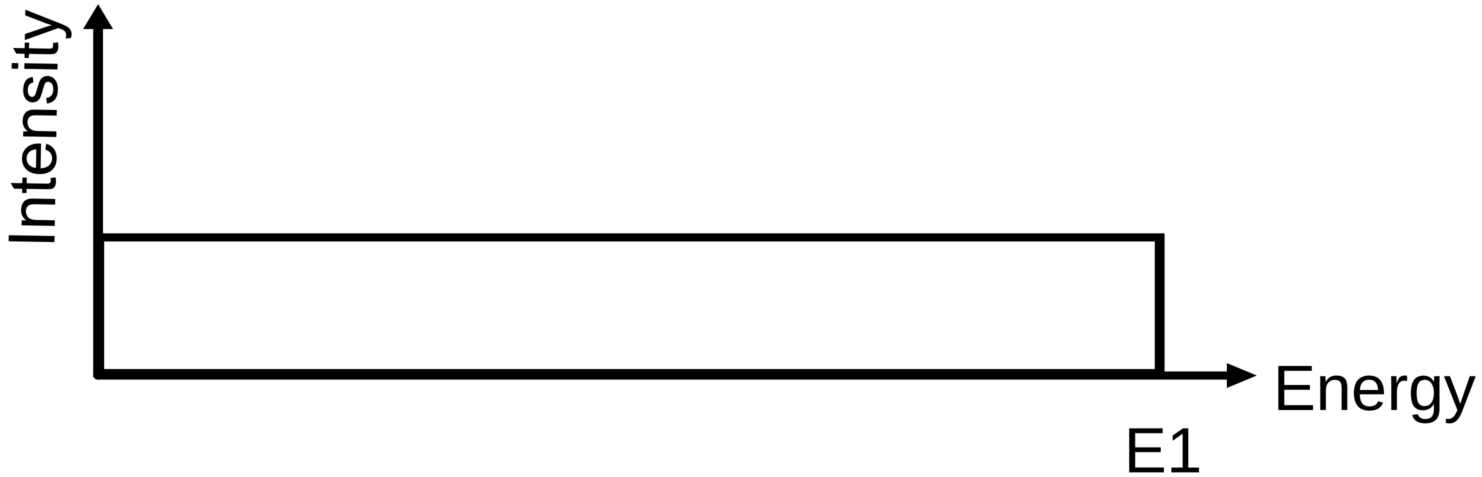
- When an incident charged particle is accelerated it emits photons with intensity:

$$I \propto \frac{Z^2}{m^2}$$

- Coulombic interaction with nucleus
  - Photons can radiate with any energy up to the kinetic energy of the incoming electron
  - Photons can radiate in any direction, but some are preferred

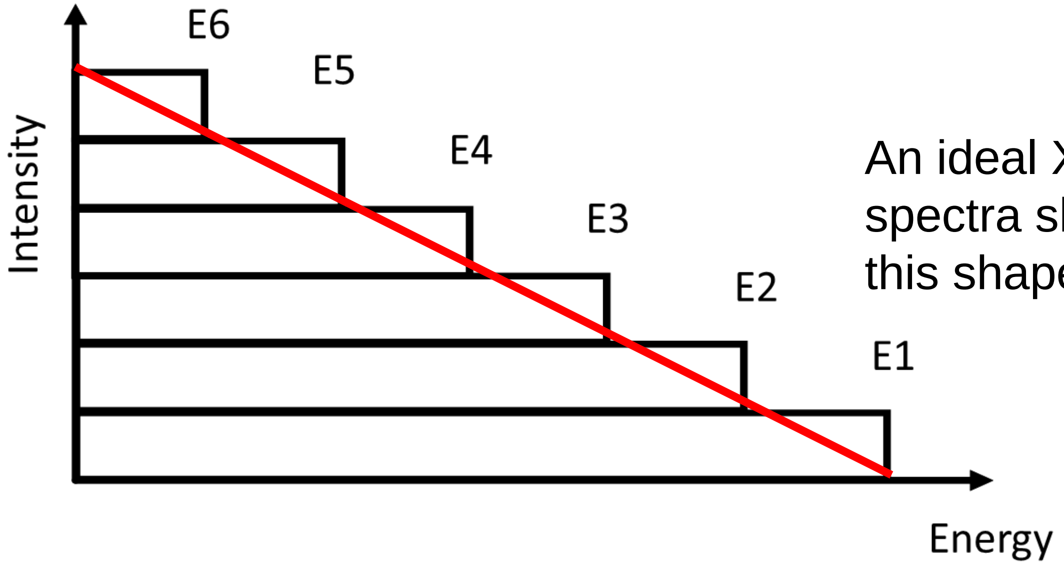
Thin target

- Assumption
  - Target is so thin that no electrons undergo more than one collision
- Consider an electron beam of kinetic energy E1 hitting target
  - All ‘degrees’ of bremsstrahlung interactions are equally likely



Thick target

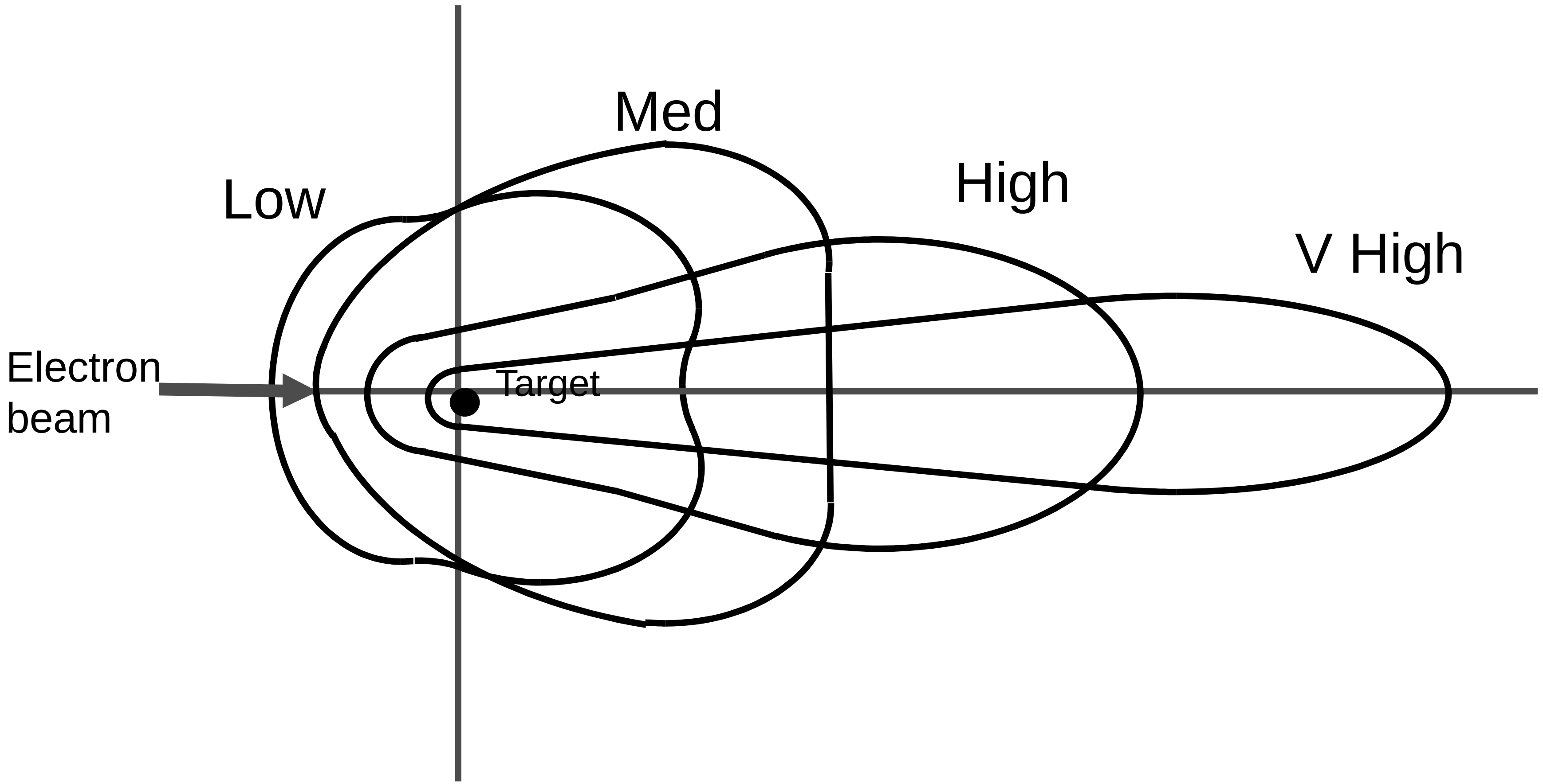
- Consider a thick target as being made of multiple thin targets



An ideal X-ray spectra should show this shape

- Electrons passing through each layer will have reduced energy
  - Producing new bremsstrahlung x-ray spectra at each layer with reduced max energy

Bremsstrahlung Angular Distribution



Ratio of radiative to collisional loss

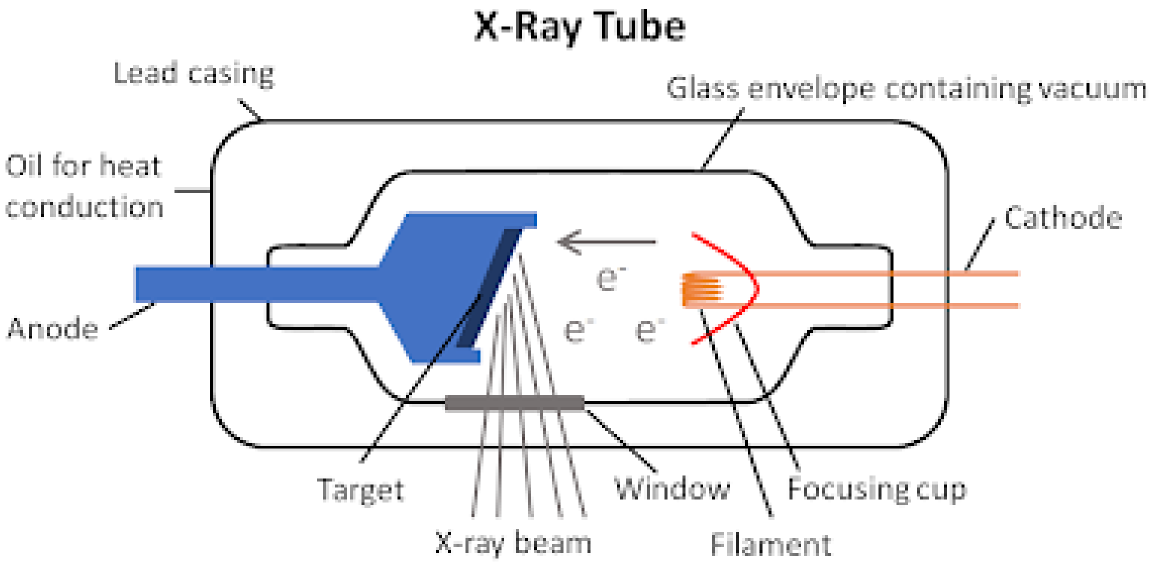
$$\frac{\left(dT/ds\right)_{rad}}{\left(dT/ds\right)_{col}} \approx Z\left(\frac{m_o}{M_o}\right)^2\left(\frac{T}{1400\, m_o c^2}\right)$$

- Probability of radiative to collisional loss increases directly with Z of target and energy, T of incident electron
- At low energies (i.e. diagnostic), ratio is very small
  - Around 1%
  - 99% of electron energy lost to heat!
- At high energies (therapy) more efficient

Anatomy of an X-ray Tube

X-ray tube components

- Glass envelope
- Cathode (source of electrons)
- Anode (target)
- Protective housing

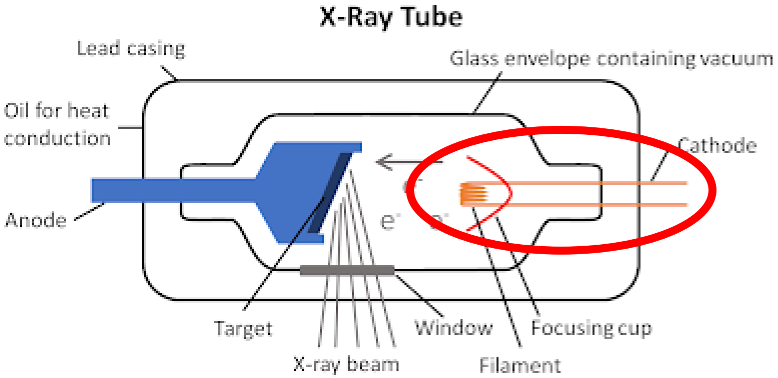


Glass Envelope

- Typically Pyrex, sometimes ceramic
  - Withstand tremendous heat
- Maintains vacuum
- Tube window
  - Area of envelop that is thinner
  - Contributes to inherent filtration

Cathode

- Negatively charged electrode
- Two primary parts
  - Filament
  - Focusing cup

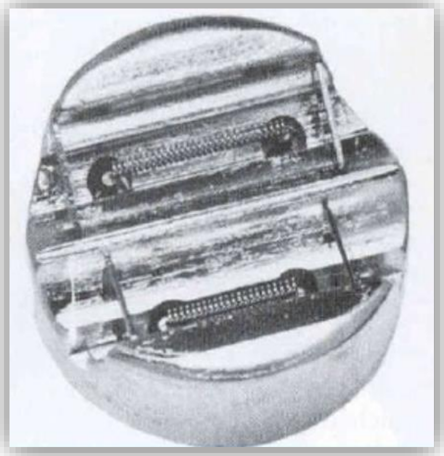


Filament

- Coil of metal wire
  - High melting point (temperatures above 2700°C)
  - High thermionic emission
  - Carry a high current to produce high temperature
  - Resist evaporation
  - Expansion / contraction causing cracking

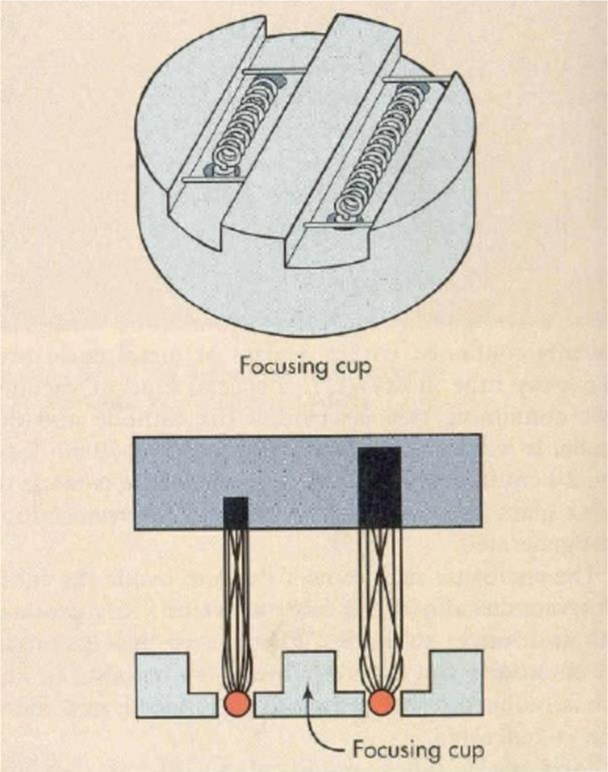
- Modern X-ray tube tend to have two filaments
  - Different focal spot sizes (see later)

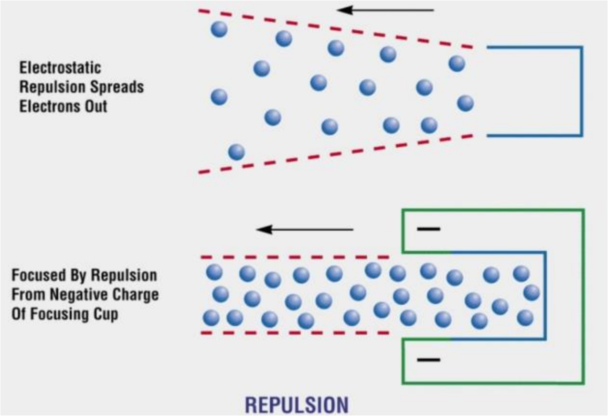
- Current flows to heat filament
  - Electrons ‘boiled off’ – thermionic emission
  - Cloud of electrons at filament (space charge)



Focusing Cup

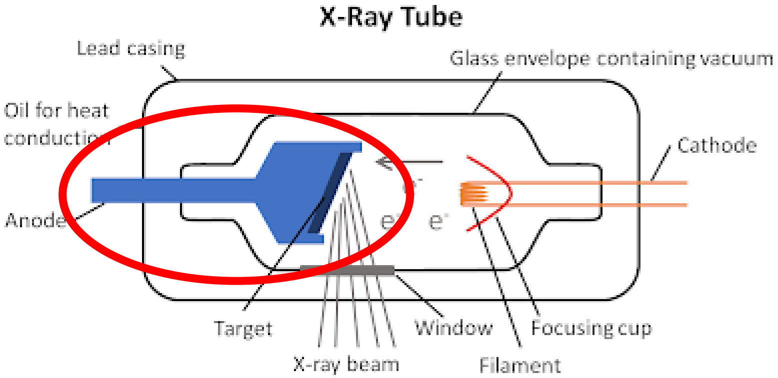
- Metallic shroud housing filaments
  - Typically made of nickel
- Electron cloud wants to spread out (electrostatic repulsion)
- Negatively charge to condense/focus electron cloud





Anode

- Positively charged electrode
- Primary functions
  - X-ray production
  - Heat management
- Two types
  - Stationary
  - Rotating



Anode Structure

- Electron interaction target producing X-rays

- Properties required
  – High Z for efficient bremsstrahlung production
  – High melting point – (99% heat at diagnostic energies)
  – High conductivity to transfer away heat produced
  – Small “apparent” source size

Anode Structure

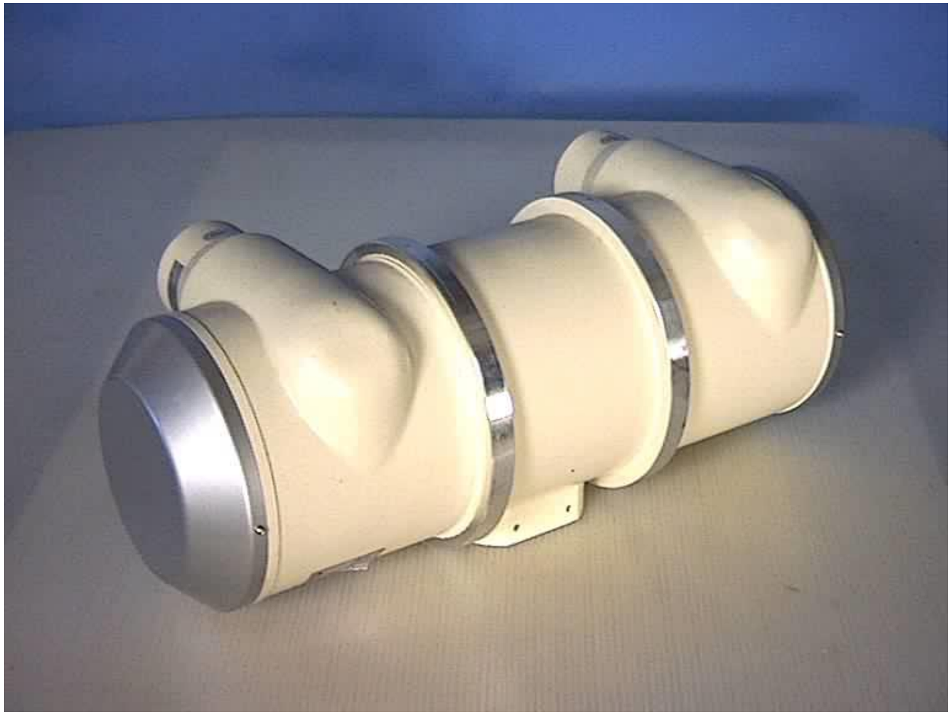
- Materials (diagnostic X-ray)
  - Tungsten (Z = 74, mpt = 3370°C, good thermal capacity)
    - Produces broad range of energies (mainly Bremsstrahlung)
    - General purpose imaging
  - Molybdenum (Z = 42, mpt = 2617°C)
    - Produces 2 low energy lines (mainly characteristic)
    - Used in mammography
  - Rhenium (Z = 75, mpt = 3185°C)
    - High creep resistance – less damage by heating

- Materials (specialist, non-medical)
  - silver, copper, gold, rhodium

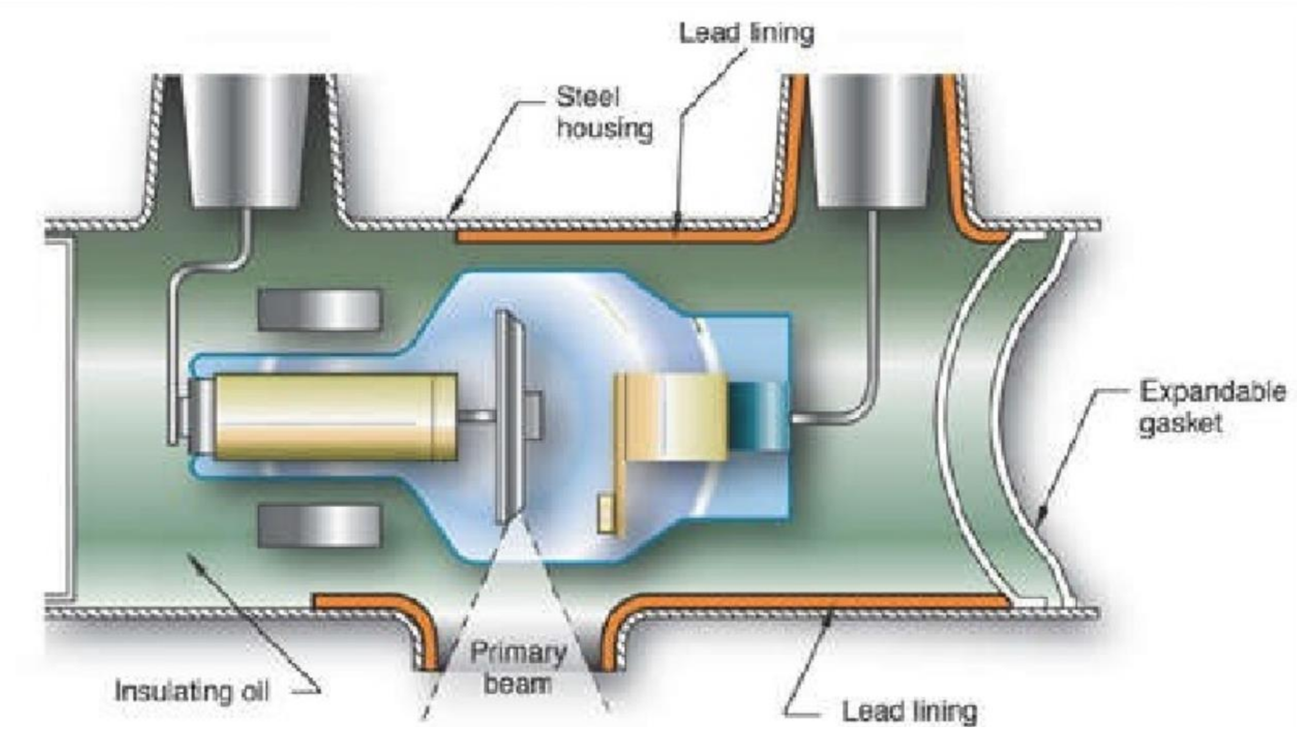
Protective Housing

- Made of “protective” steel
- Lined with 3mm lead
- Oil insulation between lead and glass tube

- Prevents leakage radiation
- Prevents electric shock
- Dissipates heat



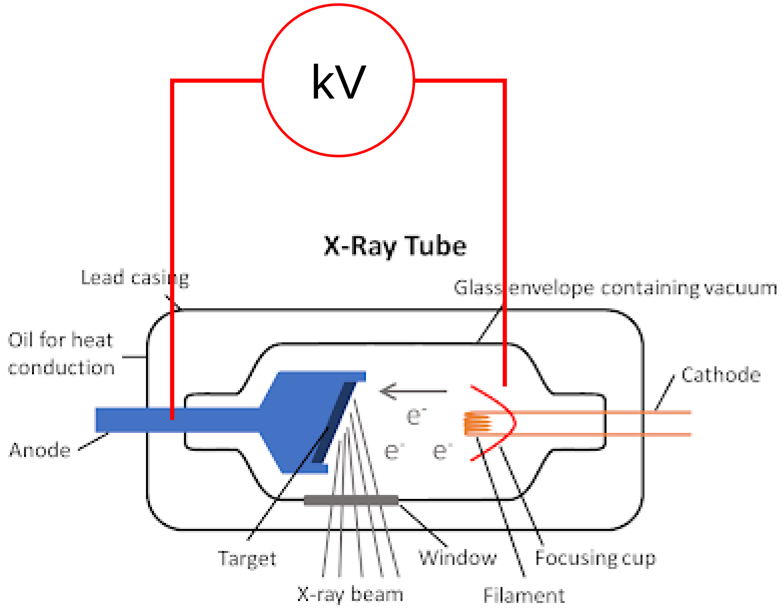
Protective Housing



X-ray Tube Operation

Voltage

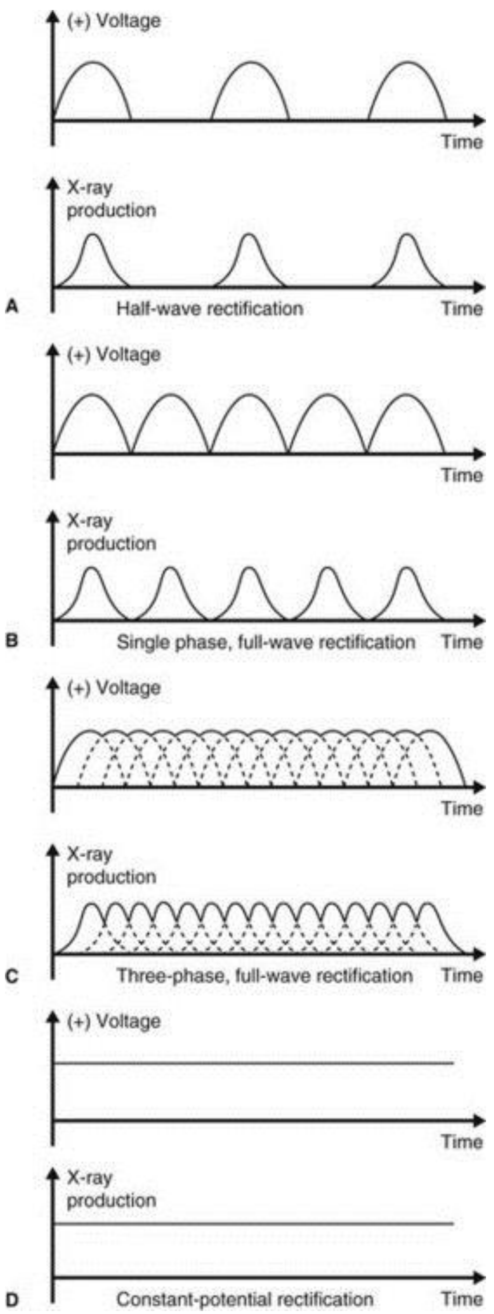
- High anode-cathode voltage applied
- Accelerate electrons
- Electrons impact on anode
- 10s-100s kV typical



kilovolts peak (kVp): maximum voltage applied across the tube, related to maximum energy carried by a thermionic electron across the tube, gives maximum possible X-ray energy

Voltage

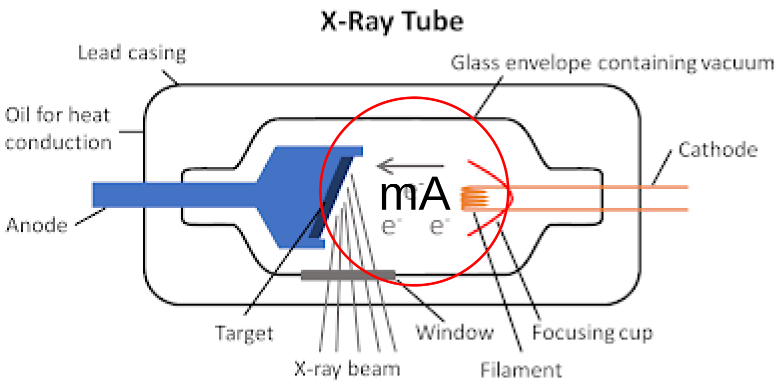
- Direct AC
  – Inefficient, tube damage
- HW rectification
  – Poor output, 50%
- FW rectification
  – Better but still most output below kVp
- 3 phase
  – Reduce variability to 15%
- Constant potential
  – Most common in modern generators



Current

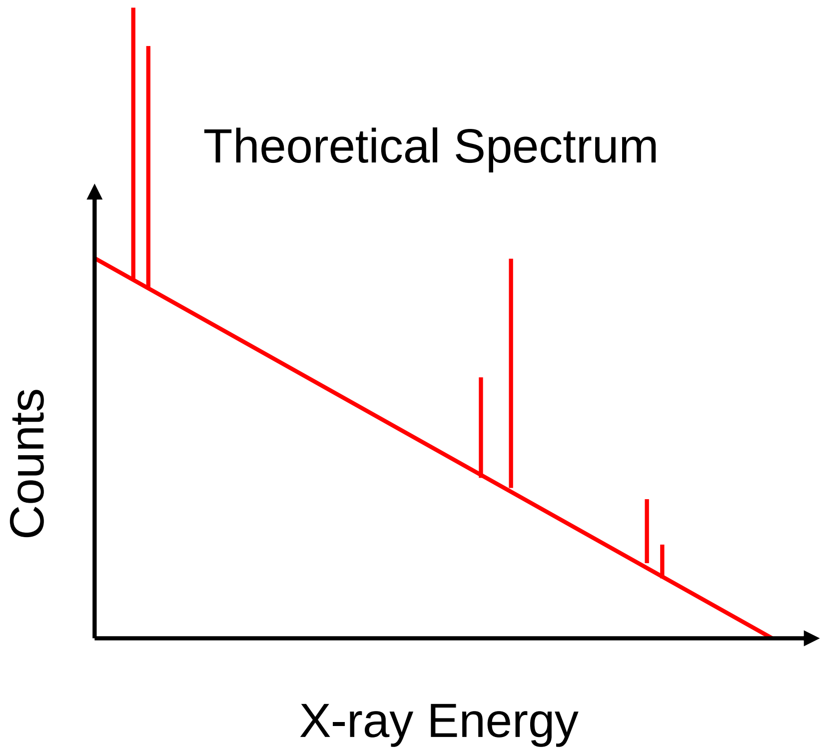
- Number of thermionic electrons passing between cathode and anode
- Can be adjusted
- Measured in milliamps (mA)
- Not the same as filament current (typically few amps)

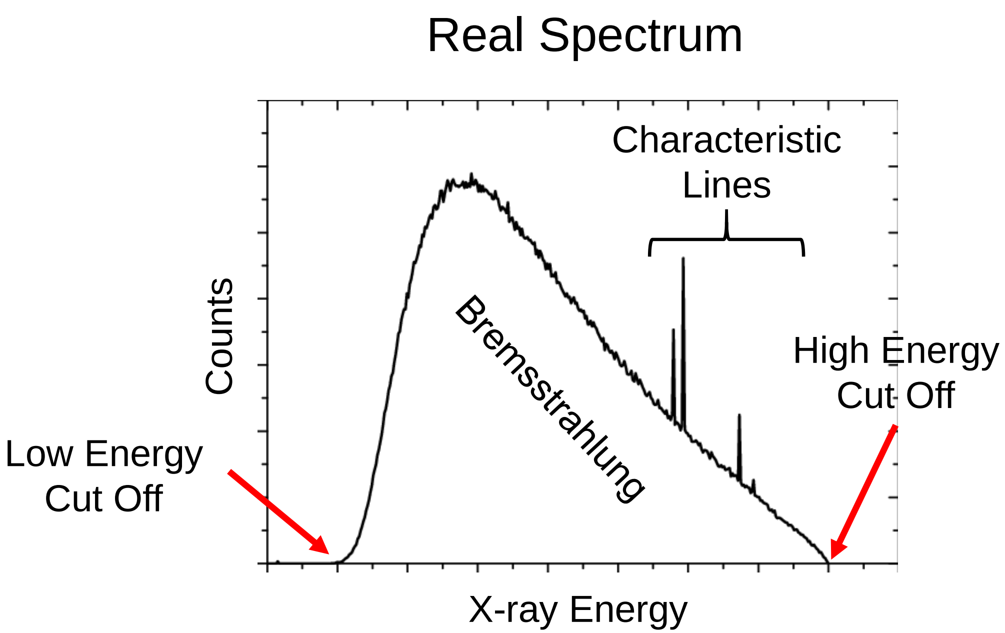
milliampere seconds (mAs): a measure of radiation produced over a set amount of time in an x-ray tube, related to number of thermionic electrons passing per unit time from the cathode to the anode.



Practical X-ray Spectrum

- Continuum emission (Bremsstrahlumg)
- Discrete emission (characteristic lines)





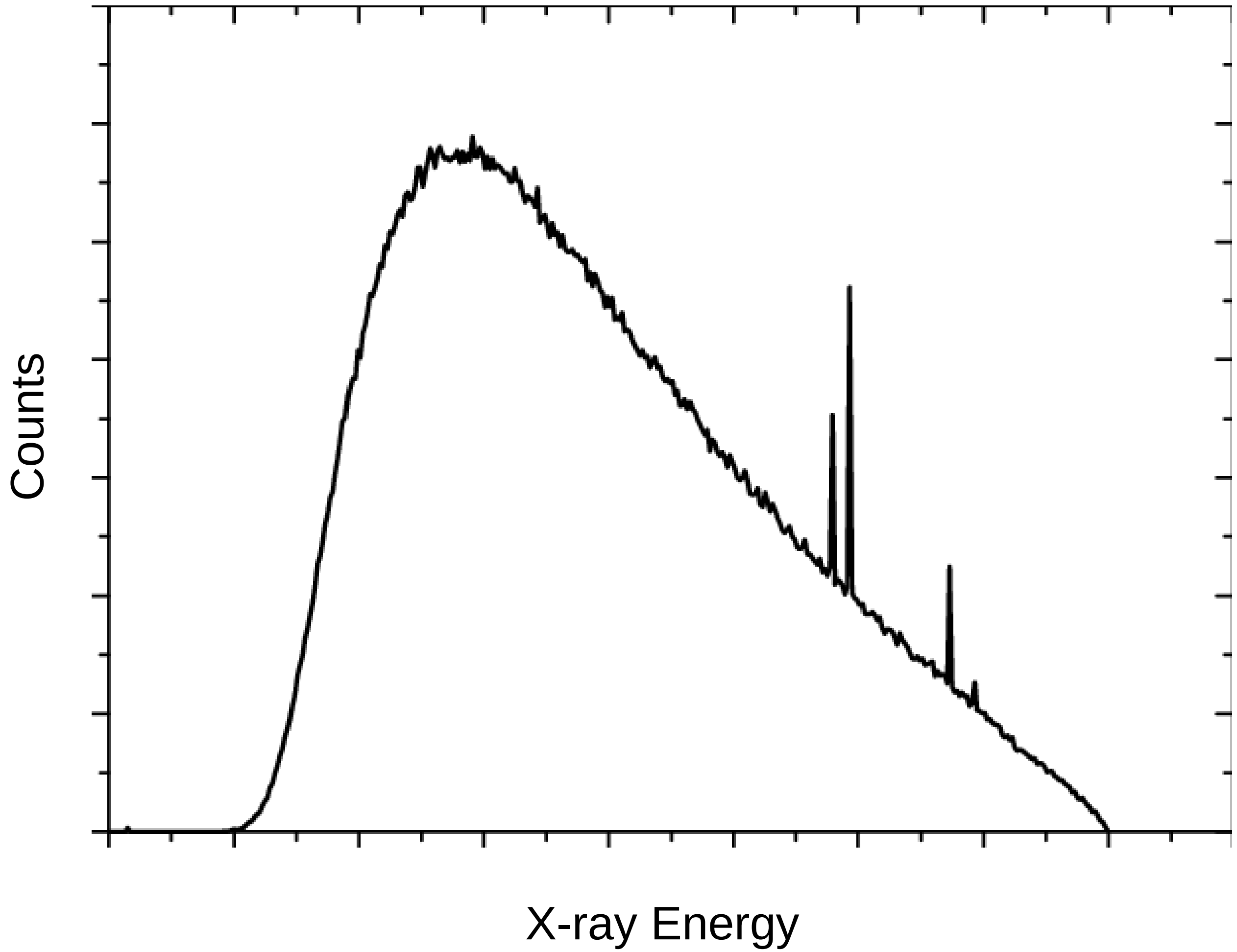
High Energy Cut Off

- Maximum electron energy depends on applied kV
- Electron can (occasionally) give up all energy to X-ray production
- Production of X-rays above high energy cut off not possible

Low Energy Cut Off

- Low energy X-ray easily attenuated
- Real X-ray tube has ‘filtration’
  - X-ray target
  - Glass envelope
  - Cooling oil
  - Protective enclosure window
- X-rays below low energy cut off cannot penetrate these layers

Diagnostic X-ray Spectrum



Quality vs Quantity

- Changing operating factors can change X-ray spectrum

- **Quantity**
  - Magnitude changes, shape remains unaltered

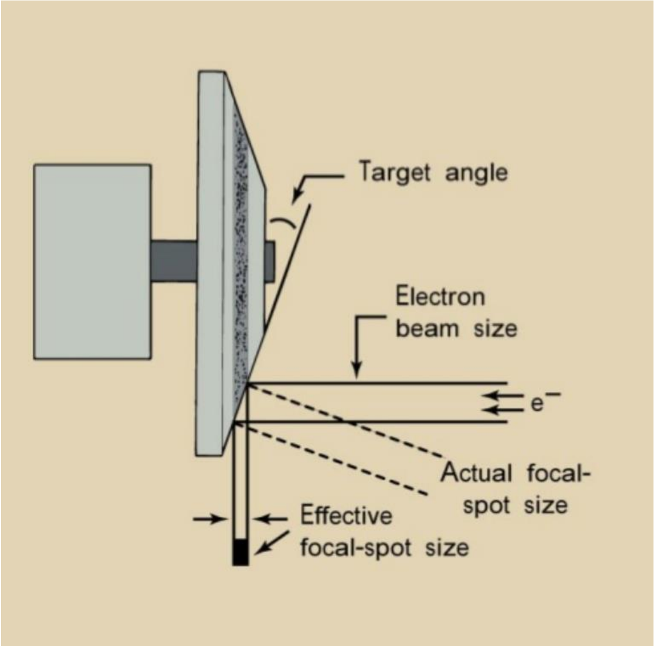
- **Quality**
  - Non-uniform change in intensities, shape changes

Factors Affecting Performance

Focal Spot Size

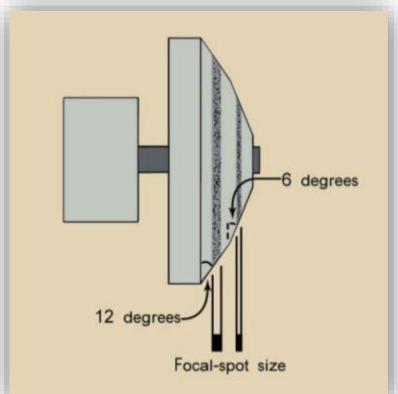
- Area on anode where X-ray are emitted

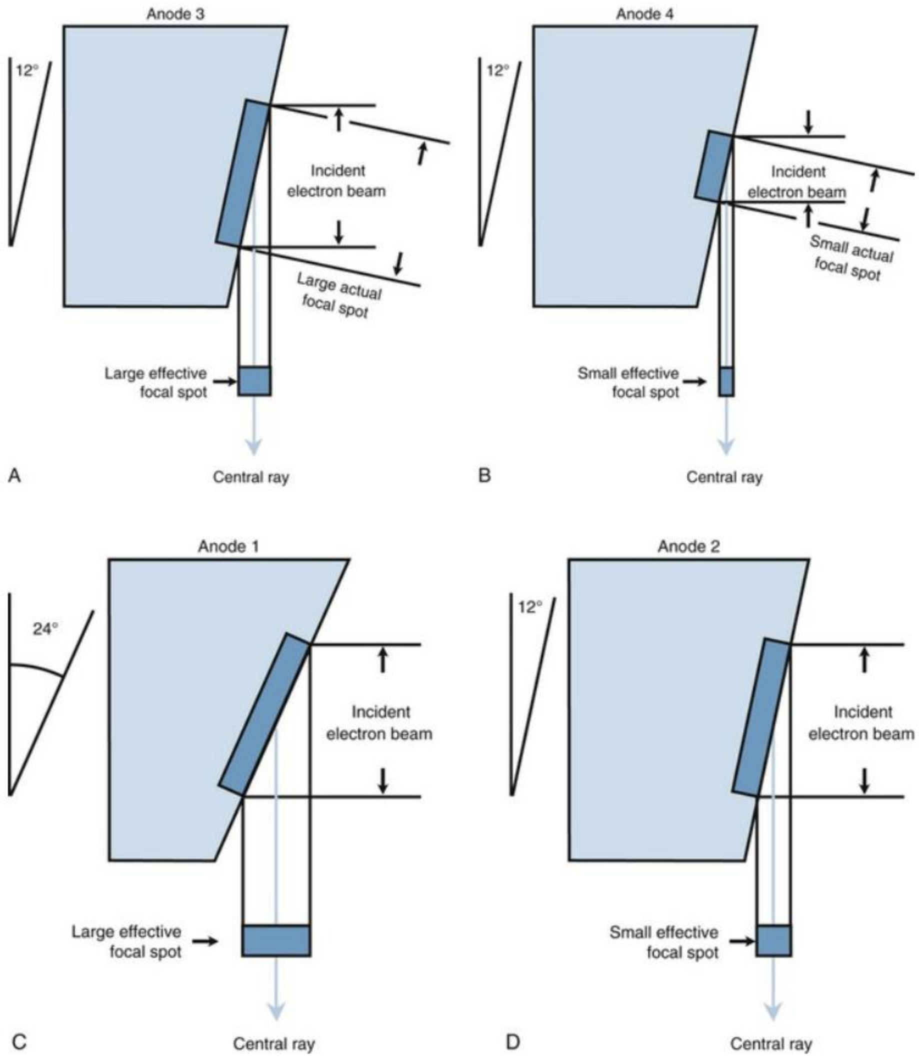
- Size controlled by:
  - X-ray target angle
  - Electron beam size



Focal Spot Size

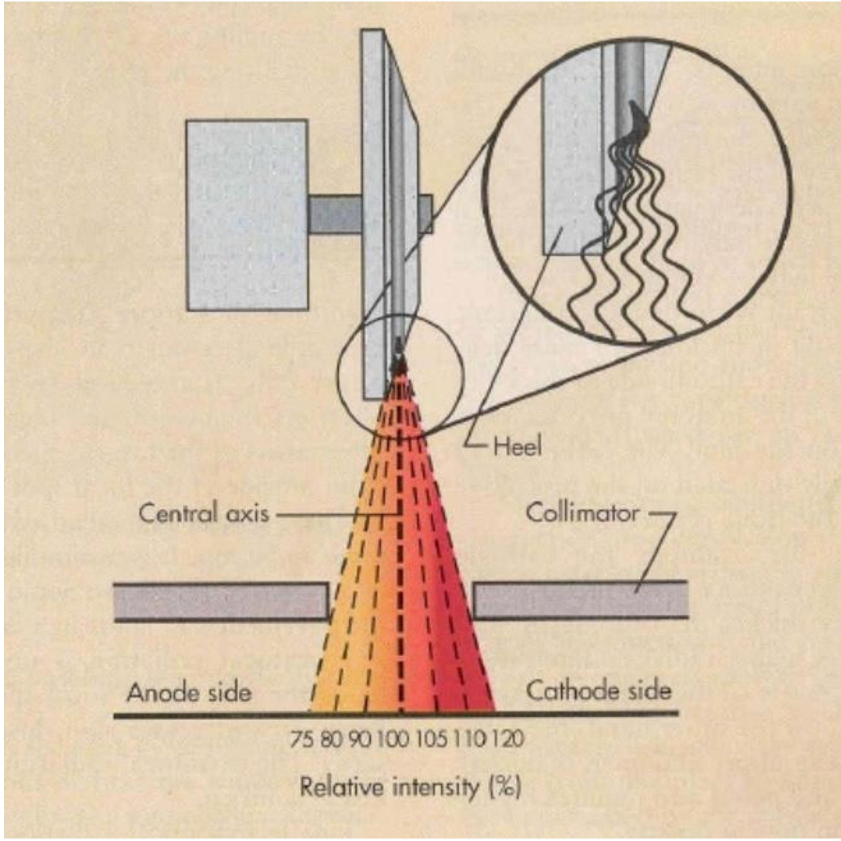
- Electron beam size
  - Choose large/small filament
- X-ray target angle
  - Line focus principle
  - Biangular target





Anode Heel Effect

- Greater attenuation on anode side
  - Travel through more of the target
- Non-uniform intensity and energy distribution
- Can be advantageous



Focal Spot Size

Small

- Better resolution images
- Useful for imaging smaller parts of the body
- Heat concentrated in smaller area
- Limit on X-ray flux available

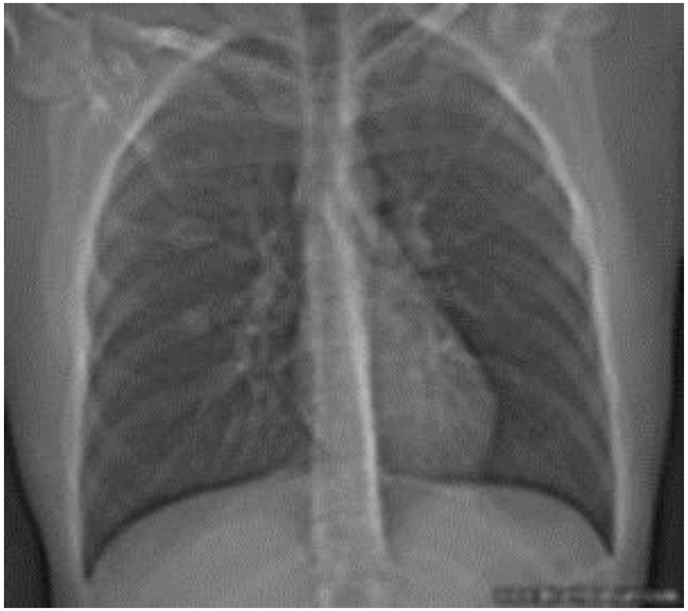
Large

- Lower resolution images
- Useful for imaging large structures
- Heat spread out
- Greater flux available – faster exposure

Focal Spot Size

Small

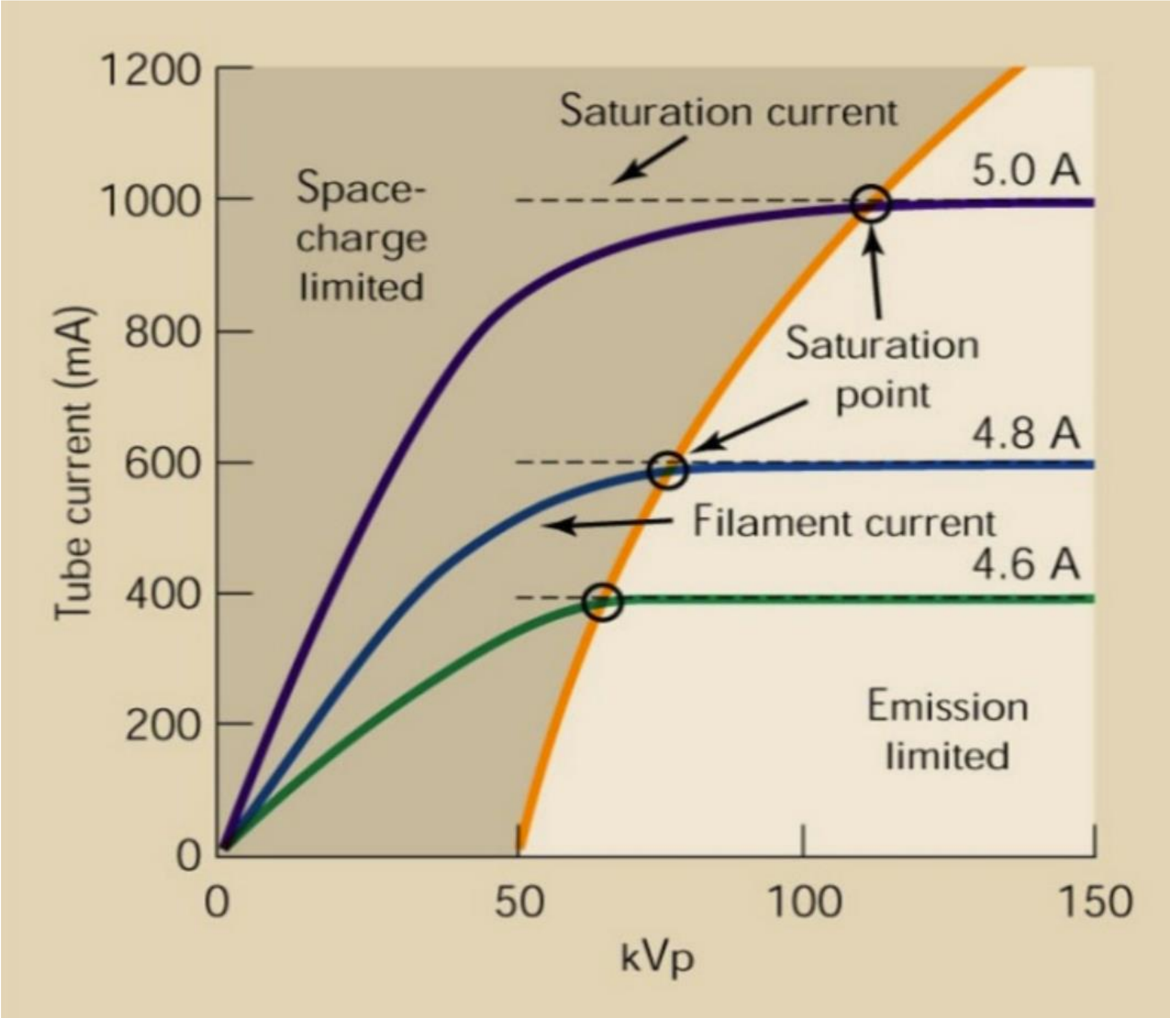
Large



Space Charge Effect

- Current flows to heat filament
  – Electrons ‘boiled off’ – thermionic emission
- Electrons remain at cathode momentarily
  – Cloud of electrons at filament (space charge)
- Space charge becomes more negative
  – Difficult for subsequent electrons to be emitted from filament
  – Negative charges of the cloud and the thermionic electrons repel

Space Charge Effect



Thermal Management

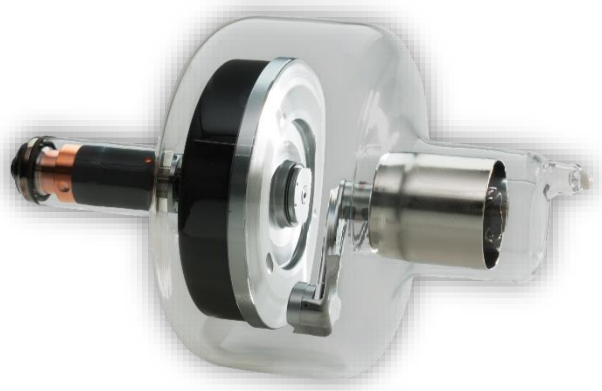
- Operating parameters
  - kV, mA → Power (P = IV)
- Anode design
  - Stationary or Rotating
- External cooling capacity
  - Passive, forced air, pumped coolant, active chilling/refrigeration

X-ray Production vs. Heating

Operating Voltage	Per Cent Energy in : HEAT	Per Cent Energy in : X RAYS
60 kV	99.5	0.1
200 kV	99	1
4 MV	60	40
20 MV	30	70

- For diagnostic X-rays, cooling the electron target will define the design of the X-ray tube

Anode Design



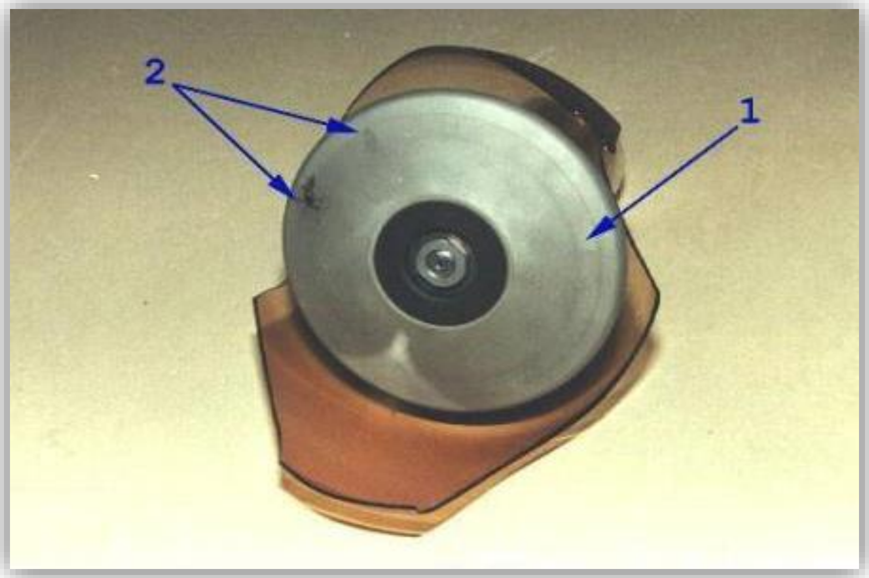
Stationary

- Concentrated electron impact
- Localised heating
- Low power applications only
  - Dental

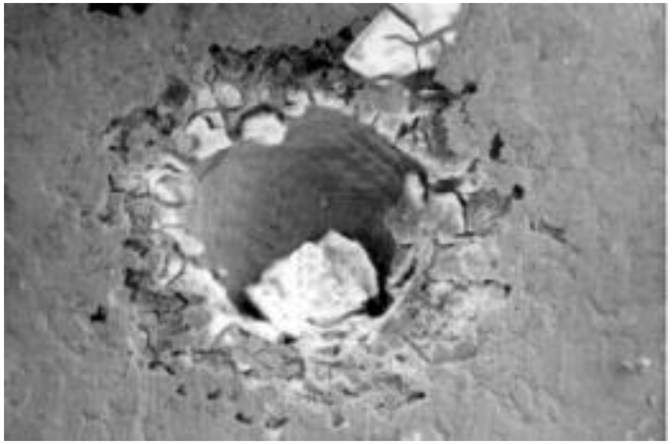
Rotating

- Electron impact spread over large area
- Energy delivered per unit area reduced
- High power applications
  - Diagnostic imaging

Thermal Anode Damage



1 : anode track
2 : anode pitting

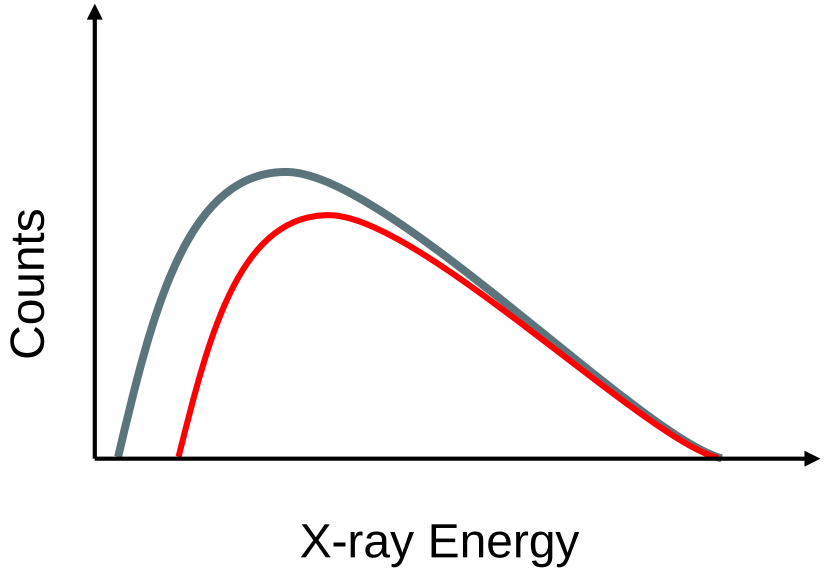


anode pitting

- Small regions of the anode surface overheat, reaching their melting point
- liquefied anode material will flow and 'creep' to a new location surrounding its original position

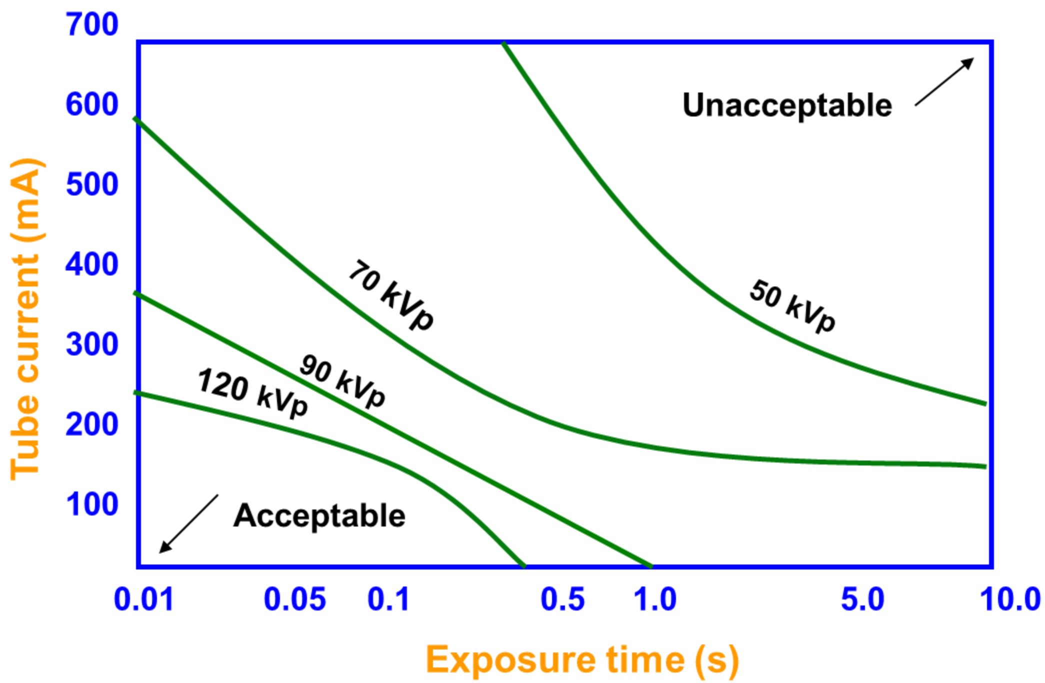
Thermal Anode Damage

- Result
  - Beam hardening
  - X-ray must pass through more material to escape target
  - Increased mean energy



Tube Rating

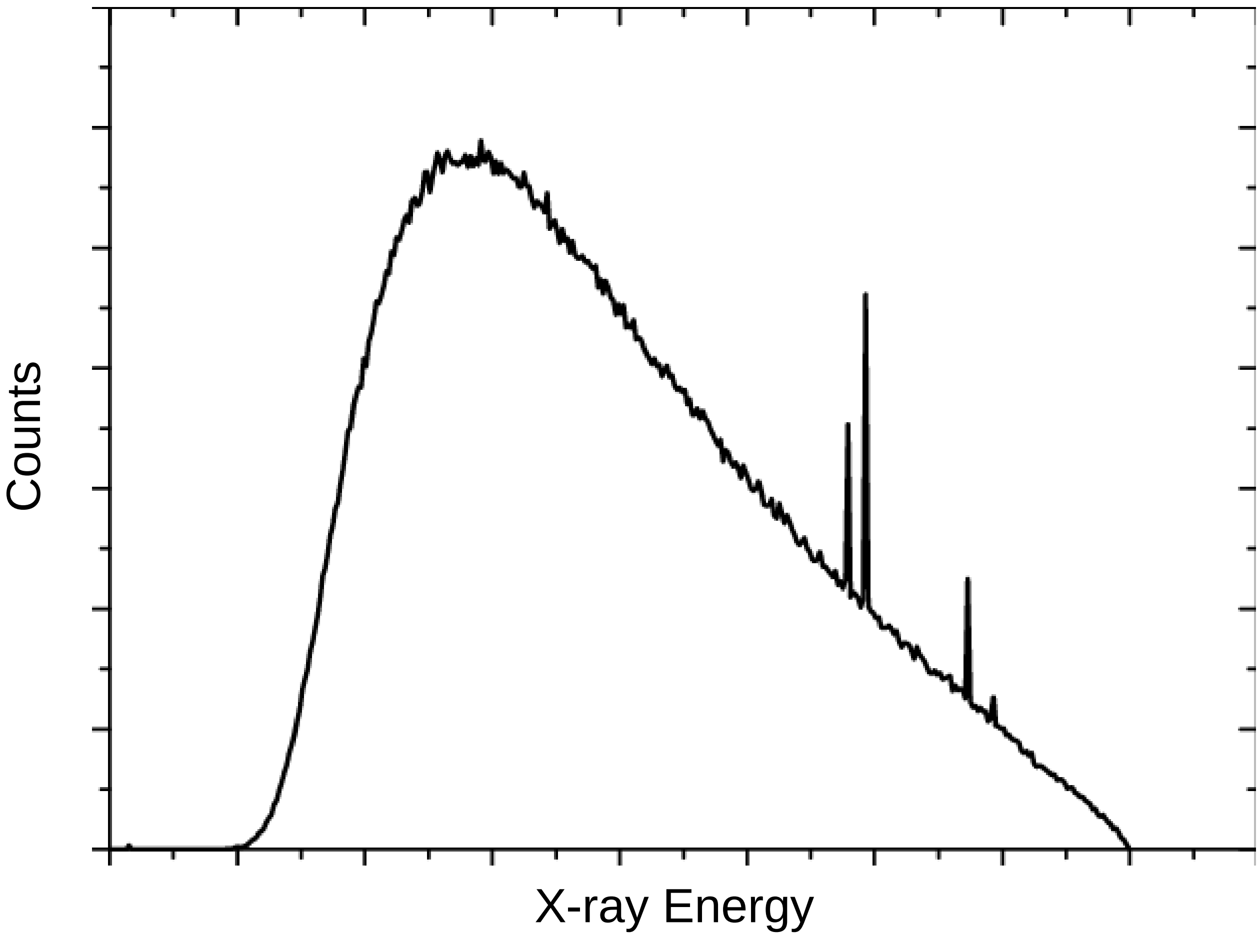
- Set limits on usage (kV, mA, exposure time)
- Manufacturer supplied information
- Prolong life of tube



Worked Examples

X-ray Spectrum

- Draw a spectrum for higher kVp



Operating parameters

- What is the effect of changing the following ‘parameters’?
  - Tube current (mA)
  - Applied voltage (kV)
  - Exposure time
  - Filtration

- Does each affect Quantity or Quality of the spectrum?

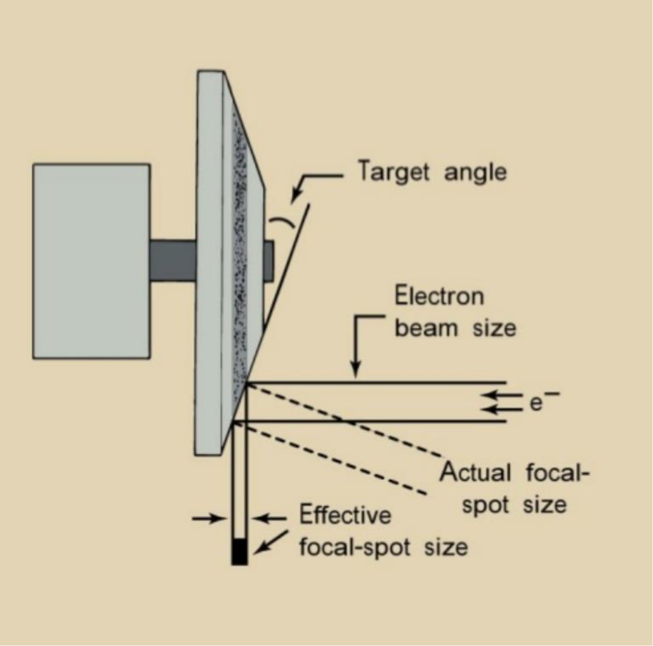
Operating parameters

Focal Spot 1

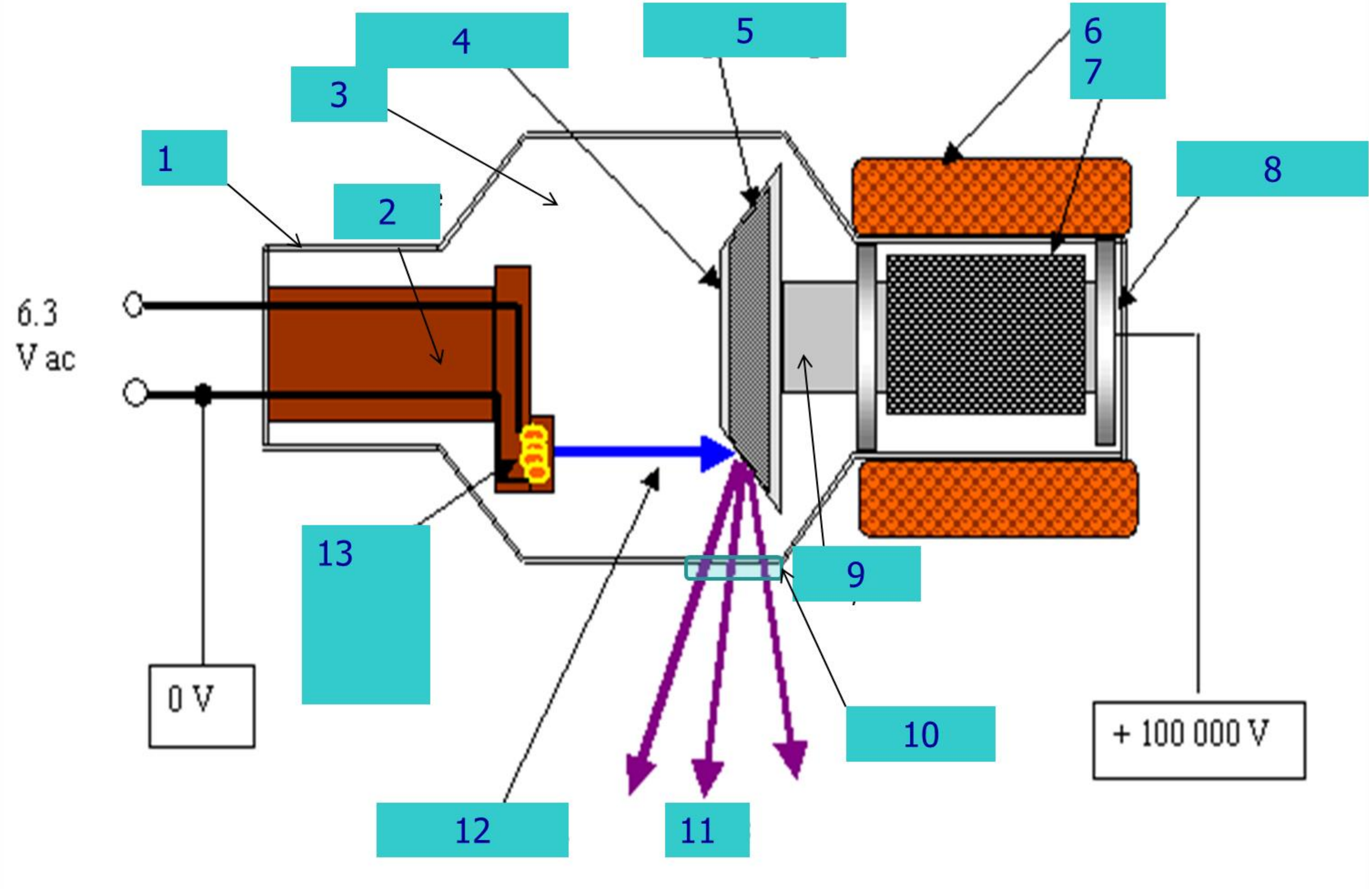
- Consider focal spot measuring 6 × 2 mm
- What is the **ratio of area for heat absorption** for a stationary target and a rotating target with mean radius of 40 mm?

Focal Spot 2

- Calculate the effective focal spot size for target angle:
  - 6°
  - 12°
- Assume electron beam height = 6 mm



Summary



X-RAY tube components & MATERIALS