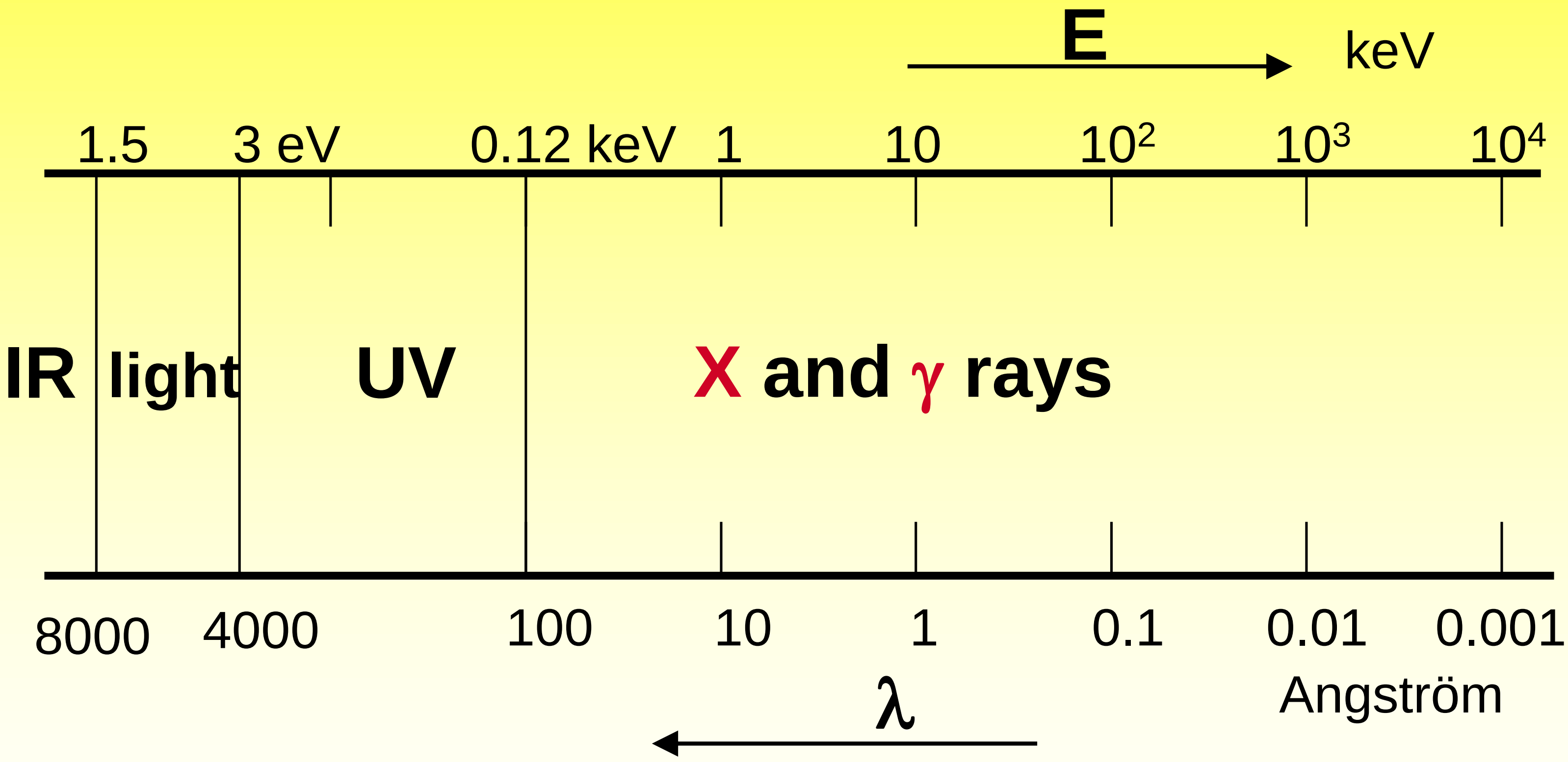
DIAGNOSTIC RADIOLOGY

Introduction

www.oghabian.net

Electromagnetic spectrum



E → keV

1.5 3 eV 0.12 keV 1 10 10^2 10^3 10^4

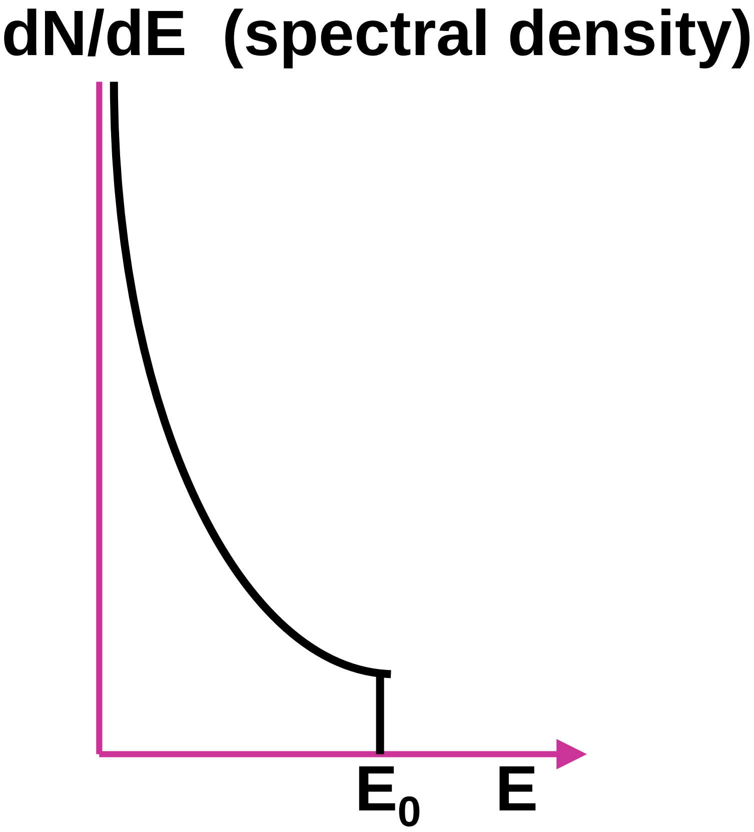
IR **light** **UV** **X and γ rays**

8000 4000 100 10 1 0.1 0.01 0.001

λ ← Angström

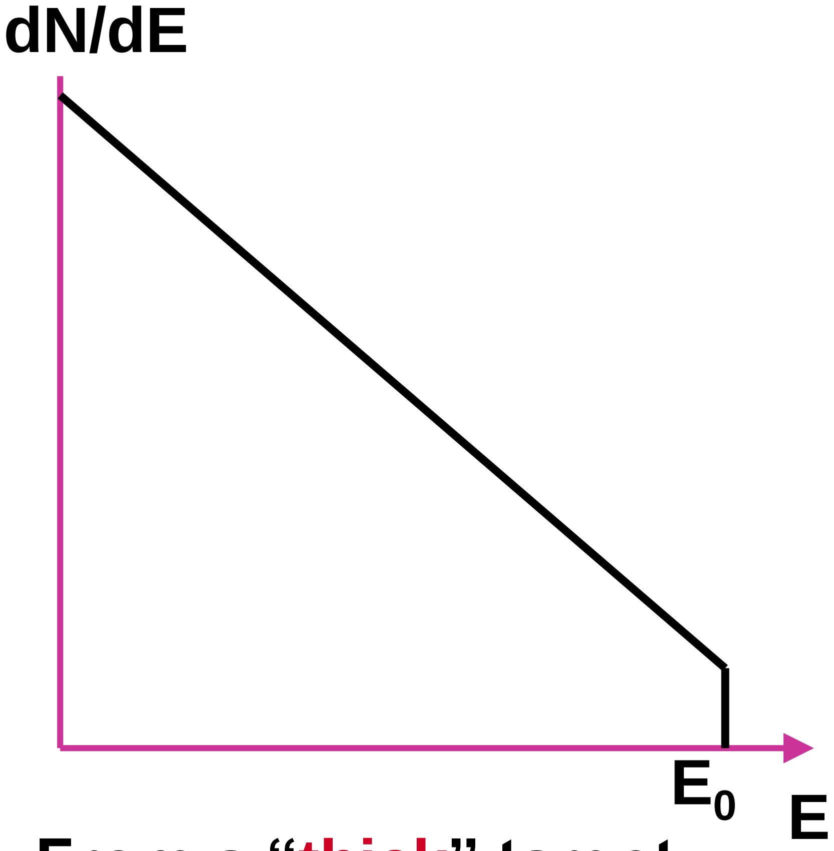
IR : infrared, UV = ultraviolet

Bremsstrahlung spectra



From a “thin” target

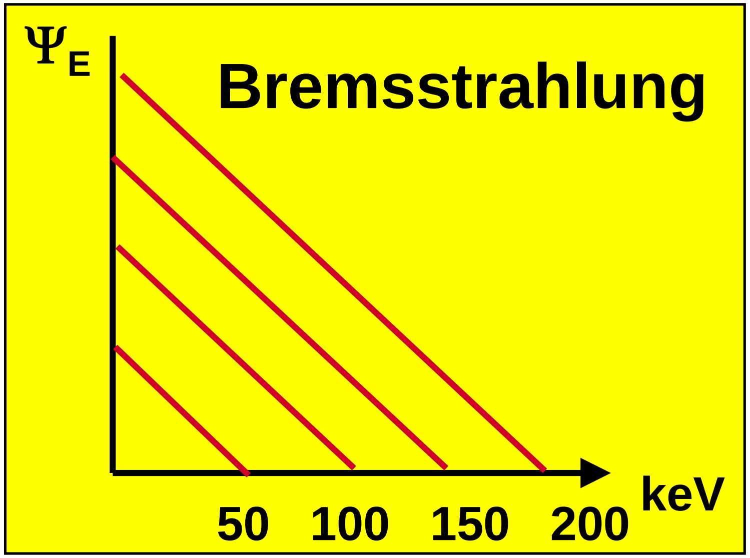
E_0= energy of electrons

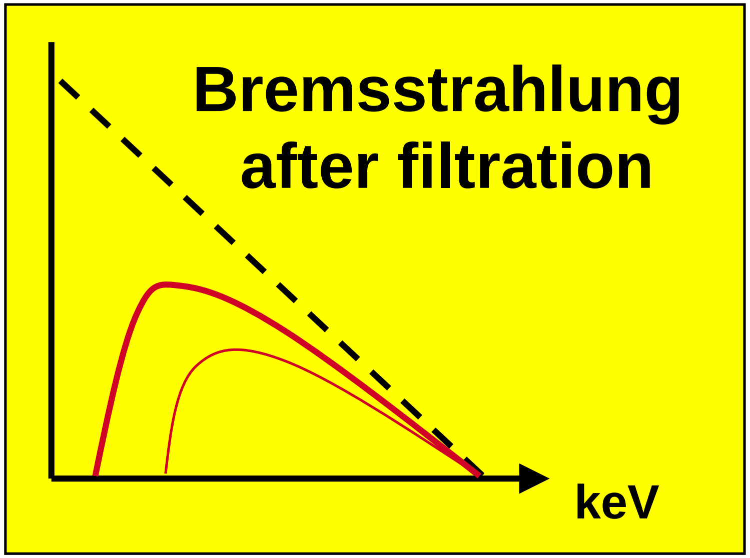


From a “thick” target
E = energy of emitted photons

X-ray spectrum energy

- Maximum energy of Bremsstrahlung photons
  - kinetic energy of incident electrons
- In X-ray spectrum of radiology installations:
  - Max (energy) = X-ray tube peak voltage





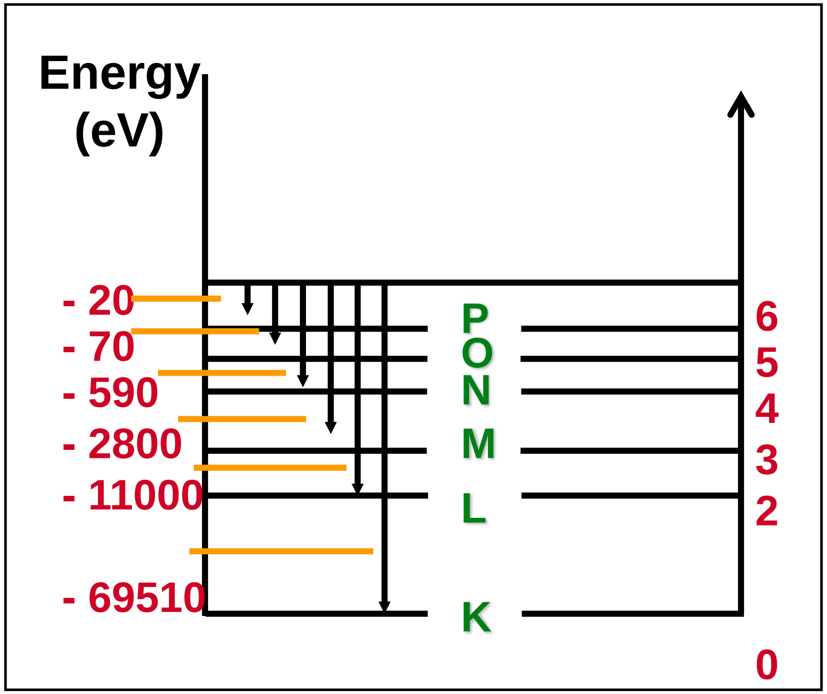
Ionization and associated energy transfers

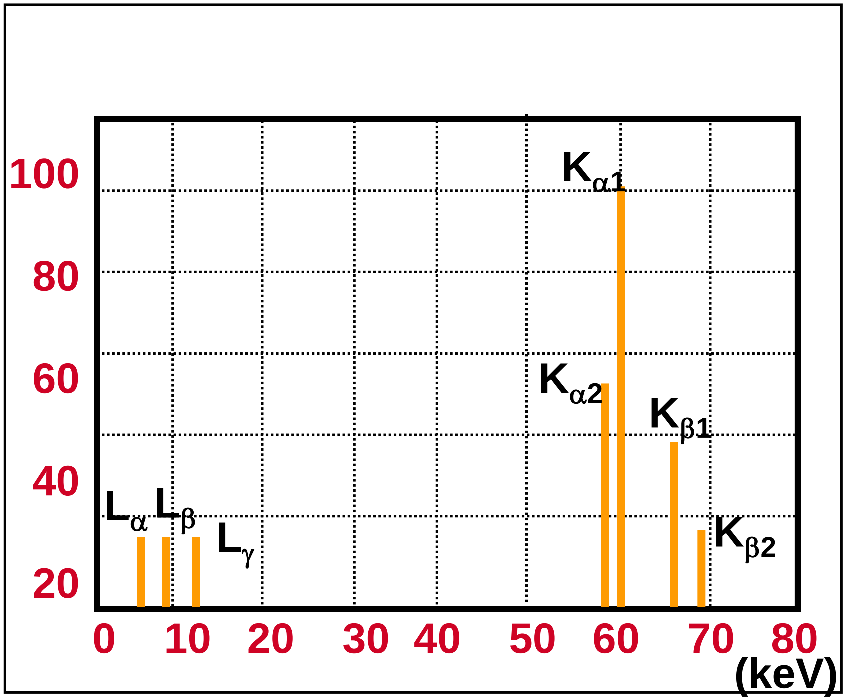
Example: electrons in water

- ionization energy : 16 eV (for a water molecule)
- other energy transfers associated to ionization
  - Excitation energy (each requires only a few eV)
  - thermal transfers (at even lower energy)

- W = 32 eV is the average loss per ionization
  - it is characteristic of the medium
  - independent of incident particle and of its energy

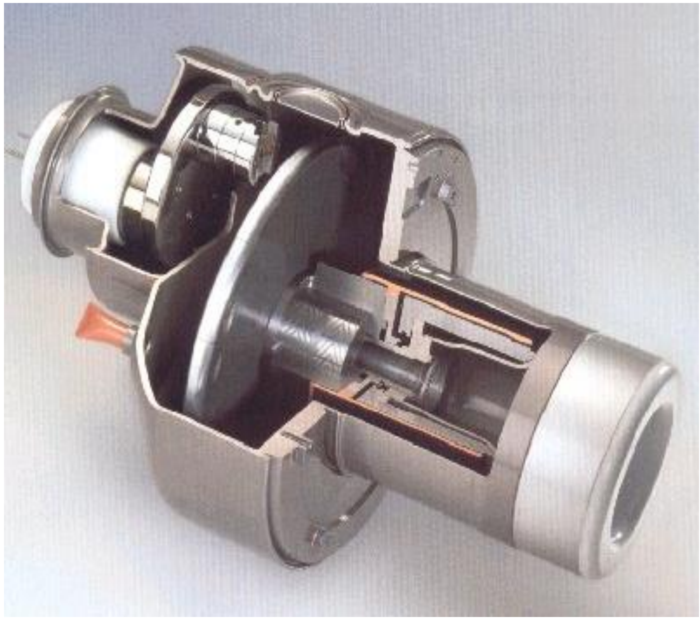
Spectral distribution of characteristic X-rays (II)





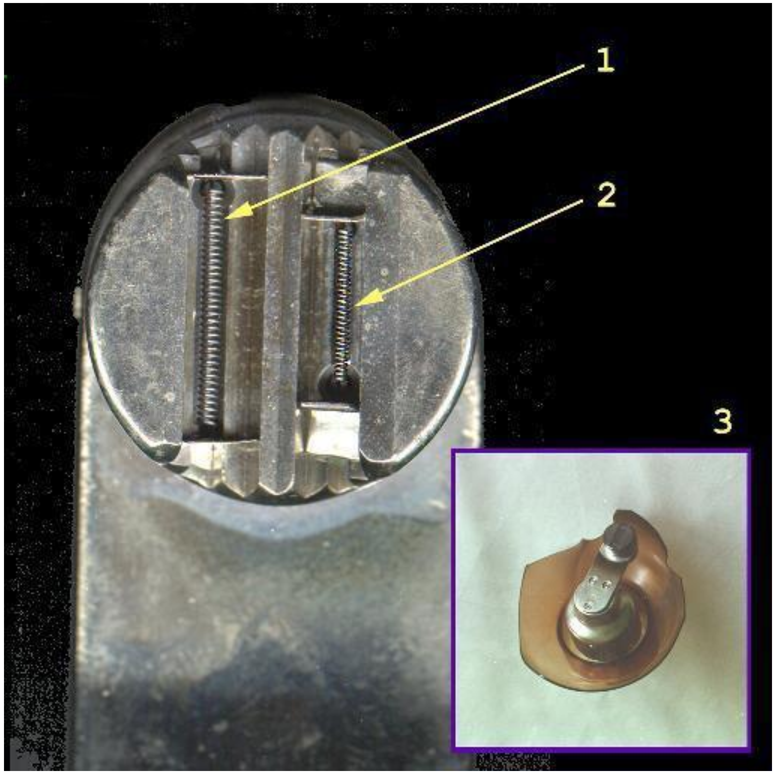
Basic elements of the x-ray assembly source

- Generator : power circuit supplying the required potential to the X-ray tube
- X-ray tube and collimator: device producing the X-ray beam



X-ray tube components

1: mark of focal spot



1: long tungsten filament

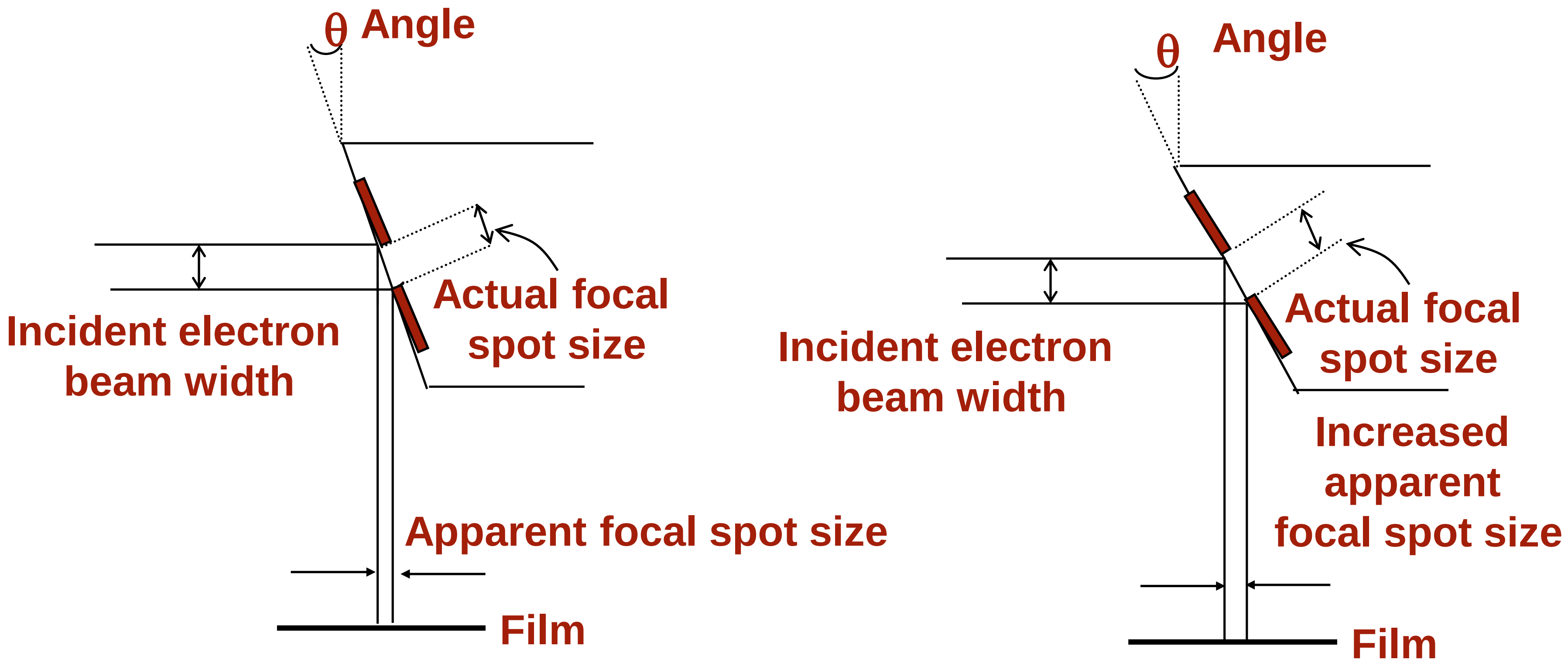
2 : short tungsten filament

3 : real size cathode

Anode angle (I)

- The Line-Focus principle
  - Anode target plate has a shape that is more rectangular or ellipsoidal than circular
    - the shape depends on :
      - **filament size and shape**
      - **focusing cup's and potential**
      - **distance between cathode and anode**
  - Image resolution requires a small focal spot
  - Heat dissipation requires a large spot
- This conflict is solved by slanting the target face

Anode angle (II)



THE SMALLER THE ANGLE THE BETTER THE RESOLUTION

Anode heel effect (I)

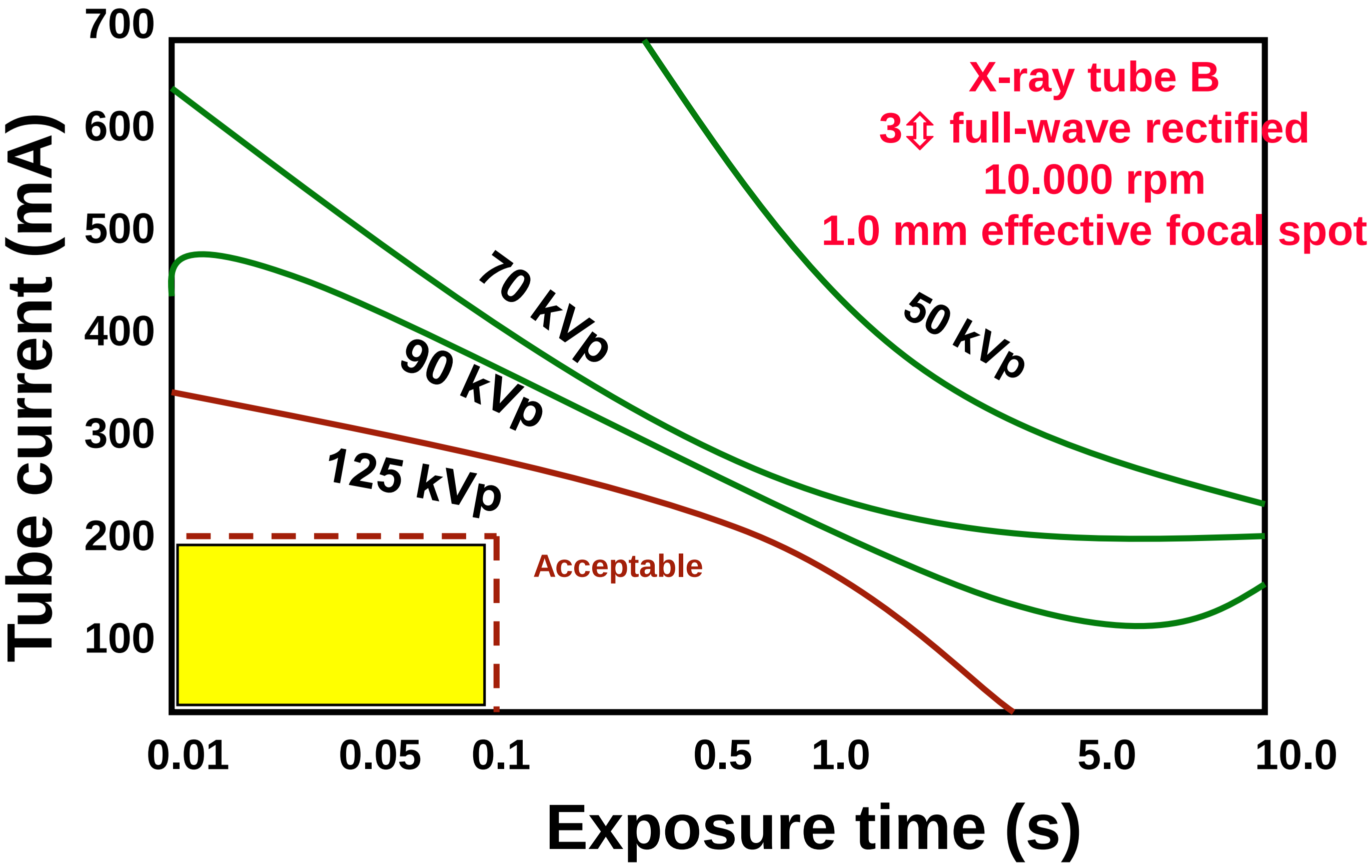
- Anode angle (from 7° to 20°) induces a variation of the X-ray output in the plane comprising the anode-cathode axis
- Absorption of photons by anode body is more in low emission angle
- The magnitude of influence of the heel effect on the image depends on factors such as :
  - **anode angle**
  - **size of film (FOV)**
  - **focus to film distance**
- Anode aging increases heel effect

Heat loading capacities

- A procedure generates an amount of heat depending on:
  - **kV used, tube current (mA), length of exposure**
  - **type of voltage waveform**
  - **number of exposures taken in rapid sequence**
- Heat Unit (HU) [joule] :

  unit of potential x unit of tube current x unit of time
- The heat generated by various types of X-ray circuits are:
  - 1 phase units : HU = kV x mA x s
  - 3 phase units, 6 pulse : HU = 1.35 kV x mA x s
  - 3 phase units, 12 pulse: HU = 1.41 kV x mA x s
  - ***J = HU x 0.71***

X-ray tube rating chart (IV)

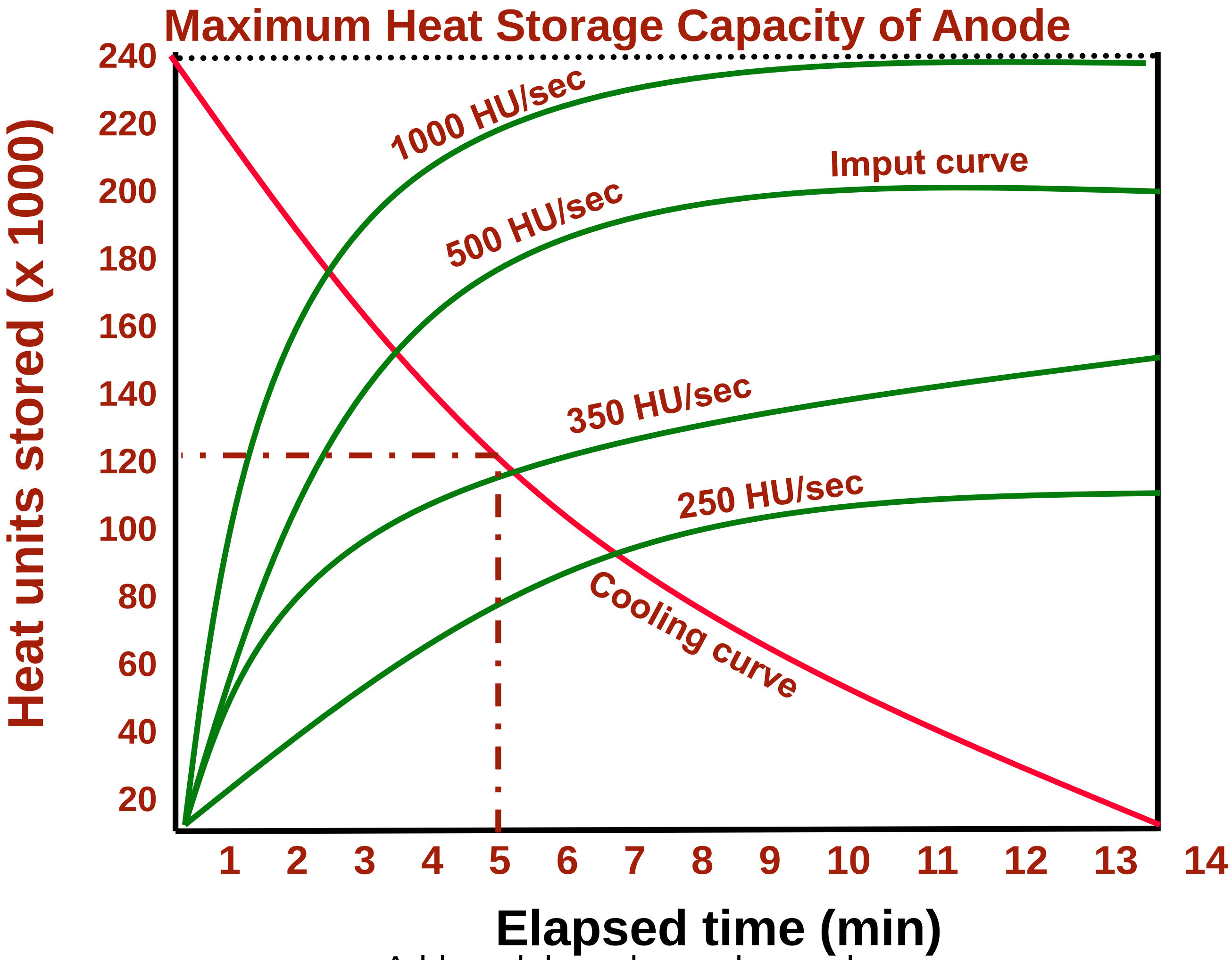


X-ray tube B
3⇳ full-wave rectified
10.000 rpm
1.0 mm effective focal spot

Anode cooling chart (I)

- Heat generated is stored in the anode, and dissipated through the cooling circuit
- A typical cooling chart has :
  - input curves (heat units stored as a function of time)
  - anode cooling curve
- The following graph shows that :
  - a procedure delivering 500 HU/s can go on indefinitely
  - if it is delivering 1000 HU/s it has to stop after 10 min
  - if the anode has stored 120.000 HU, it will take ≈ 5 min to cool down.

Anode cooling chart (II)



X-ray generator (II)

- Generator characteristics have a strong influence on the contrast and sharpness of the radiographic image
- The motion unsharpness can be greatly reduced by a generator allowing an exposure time as short as achievable

- Since the dose at the image plane can be expressed as :

$$D = k_0 \,.\, kVp^n \,.\, I \,.\, T$$

  - **kVp** : peak voltage (kV)
  - **I** : mean current (mA)
  - **T** : exposure time (ms)
  - **n** : ranging from about 3 at 150 kV to 5 at 50 kV

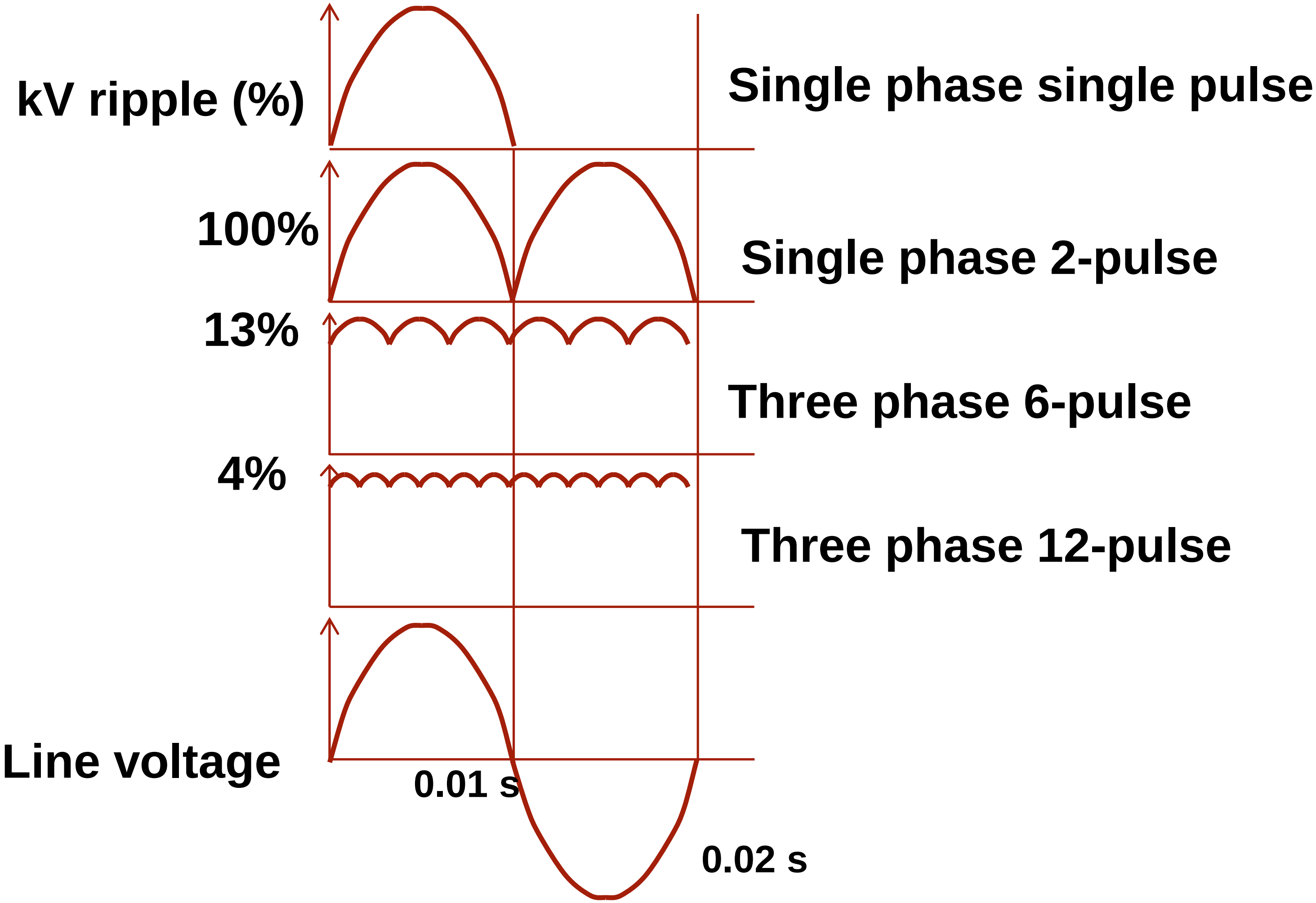
X-ray generator (III)

- Peak voltage value has an influence on the beam hardness
- It has to be related to medical question
  - **What is the anatomical structure to investigate ?**
  - **What is the contrast level needed ?**

- The ripple "r" of a generator has to be as low as possible

$$r = [(kV - kV_{min})/kV] \times 100\%$$

Tube potential wave form (II)



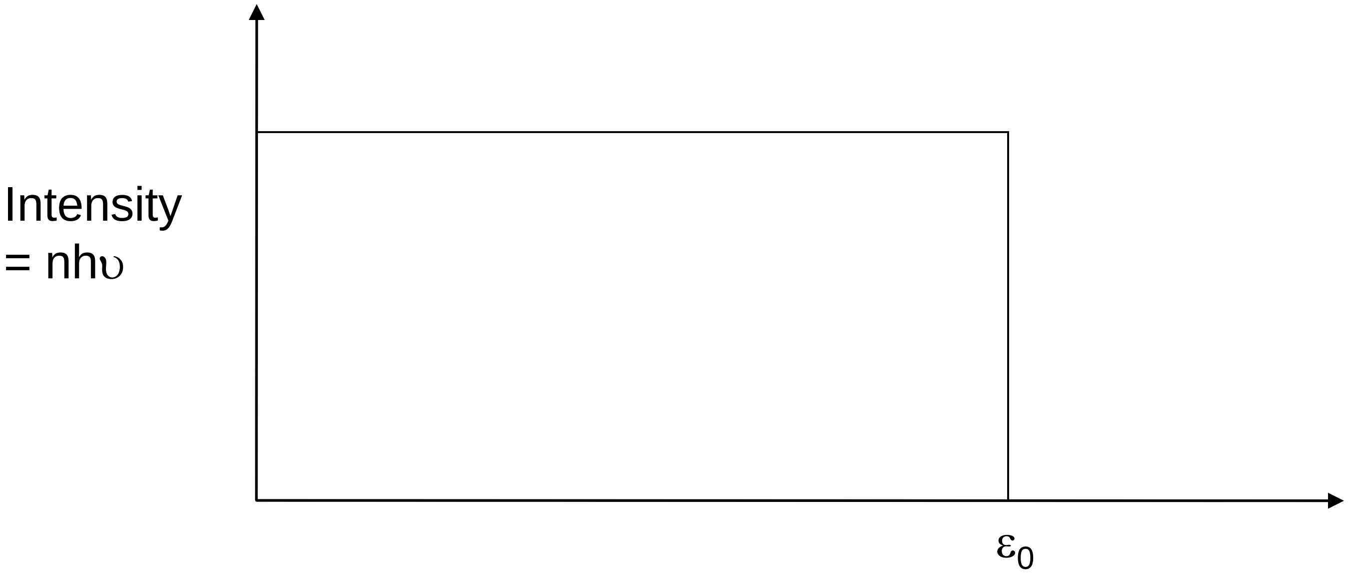
Radiation emitted by the x-ray tube

- Primary radiation : before interacting photons
- Scattered radiation : after at least one interaction
- Leakage radiation : not absorbed by the x-ray tube housing shielding
- Transmitted radiation : emerging after passage through matter ➔ Antiscatter grid

Thin Target X-ray Formation

Interestingly, this process creates a relatively uniform spectrum.

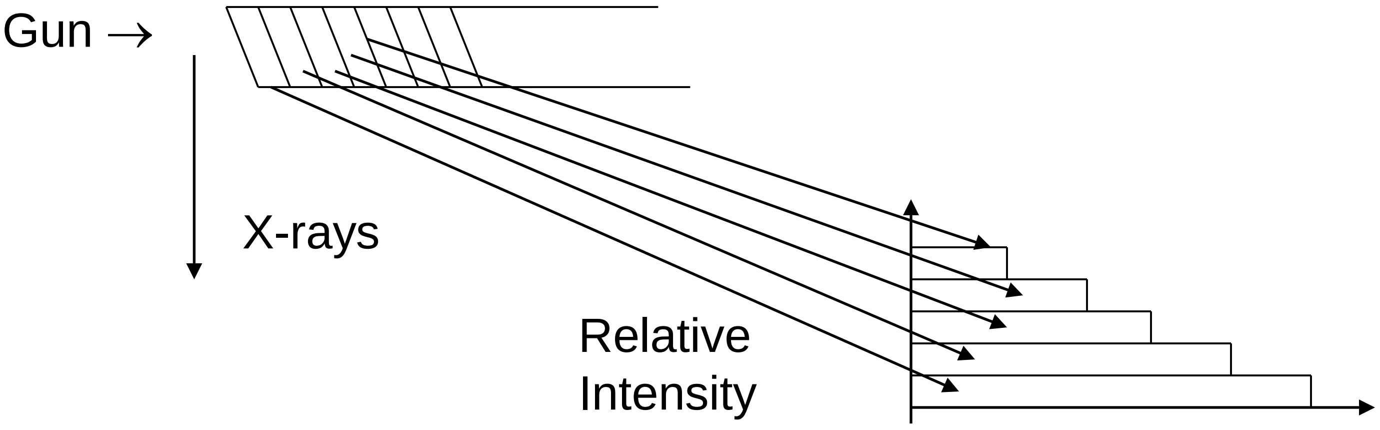
Maximum energy is created when an electron gives all of its energy, ε_0 , to one photon. Or, the electron can produce n photons, each with energy ε_0/n. Or it can produce a number of events in between. Power output is proportional to $\varepsilon_0{}^2$

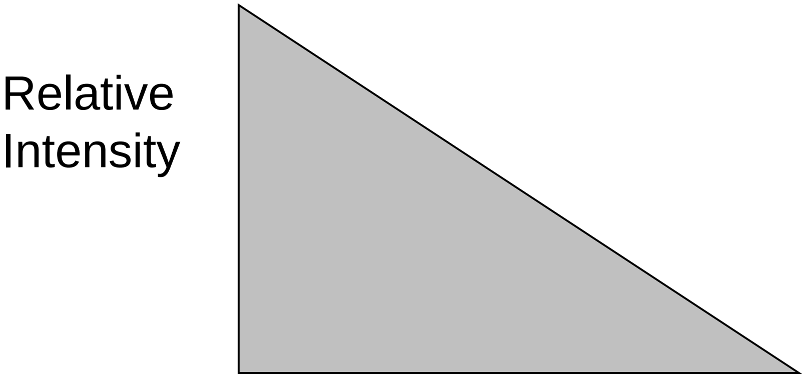


Photon energy spectrum

Thick Target X-ray Formation

We can model target as a series of thin targets. Electrons successively loses energy as they moves deeper into the target.





Each layer produces a flat energy spectrum with decreasing peak energy level.

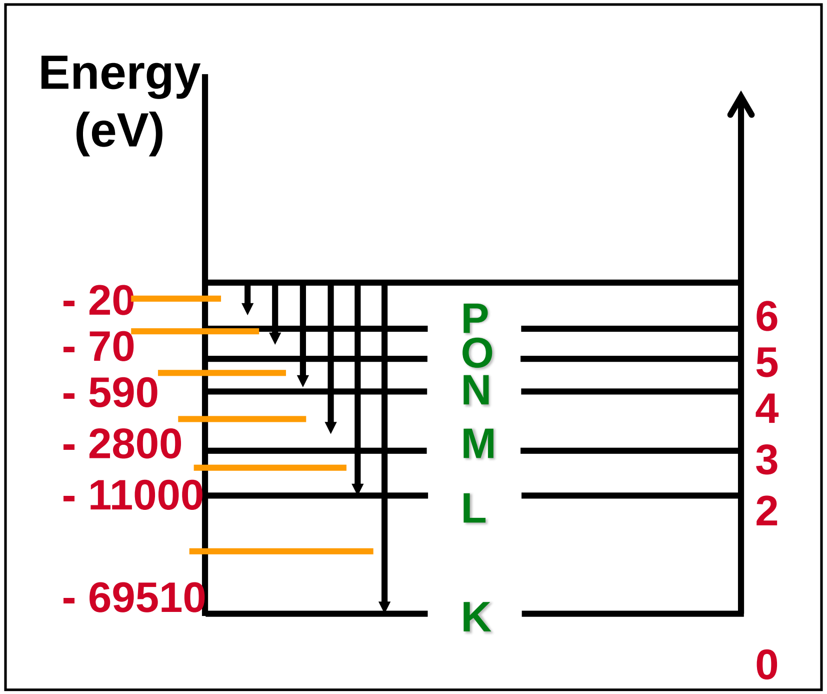
Stopping power

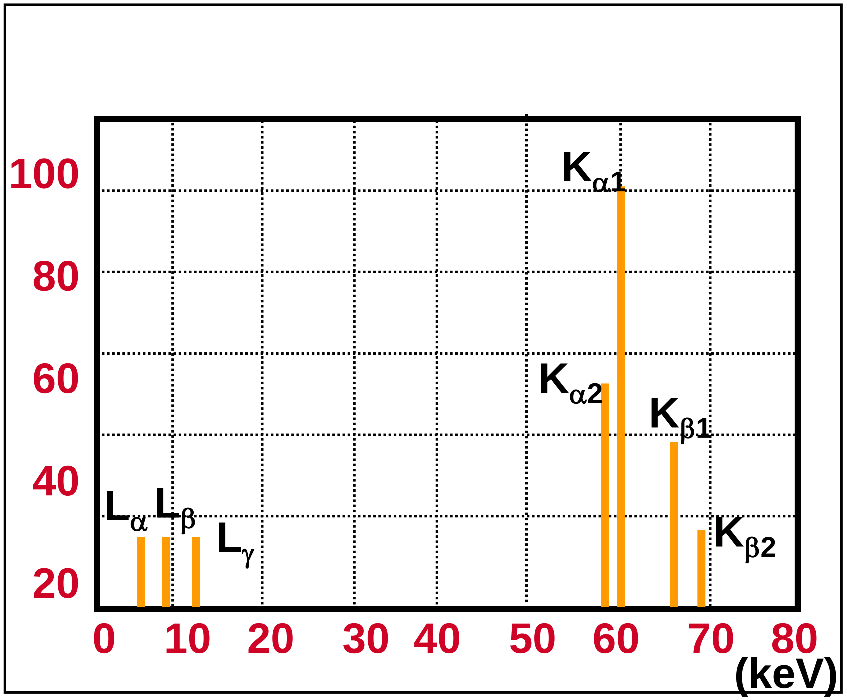
- Loss of energy along track through collisions
- The linear stopping power of the medium

$$\mathbf{S = \Delta E / \Delta x} \quad [\mathrm{MeV.cm^{-1}}]$$

  - ΔE: energy loss
  - Δx: element of track
- for distant collisions : the lower the electron energy, the higher the amount transferred
- most Bremsstrahlung photons are of low energy
- collisions (hence ionization) are the main source of energy loss
- except at high energies or in media of high Z

Spectral distribution of characteristic X-rays (II)





Thick Target X-ray Formation

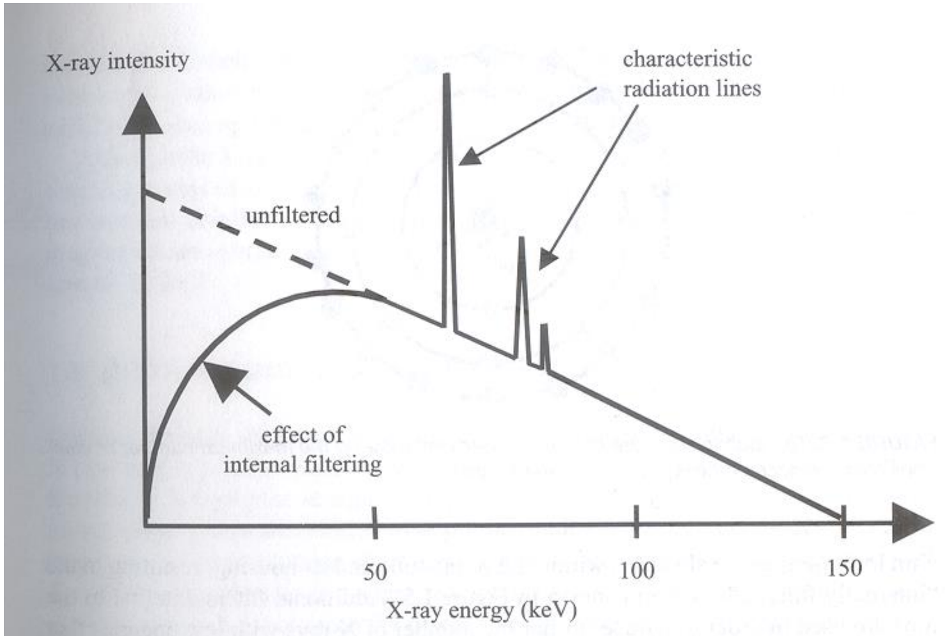


FIGURE 1.5. *A typical X-ray energy spectrum produced from a tube with a kV$_p$ value of 150 keV, using a tungsten anode. Low-energy X-rays (dashed line) are absorbed by the components of the X-ray tube itself. Characteristic radiation lines from the anode occur at approximately 60 and 70 keV.*

Andrew Webb, Introduction to Biomedical Imaging, 2003, Wiley-Interscience.

(

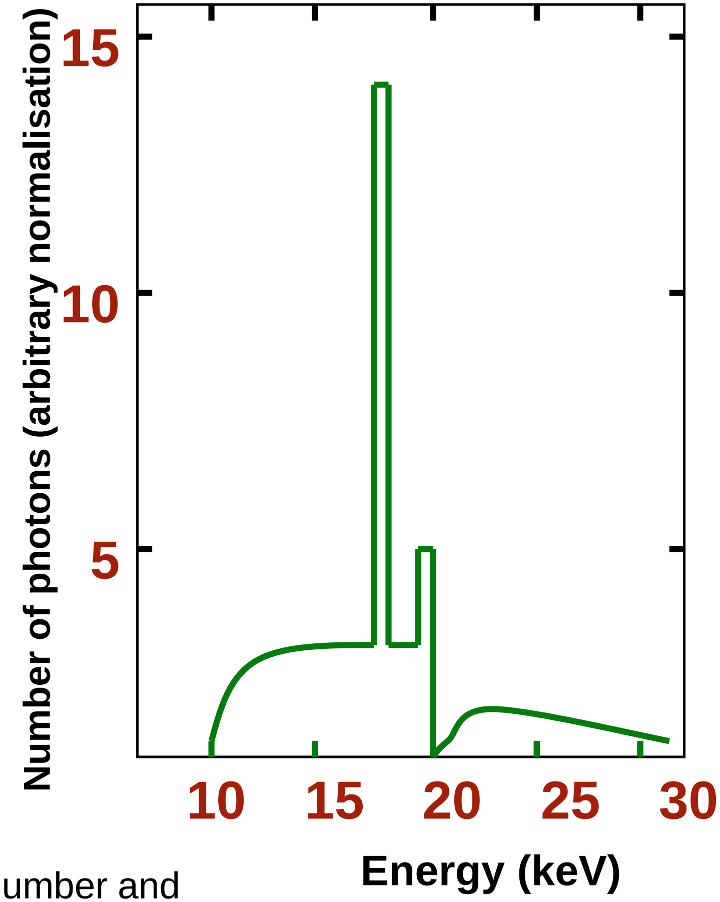
Lower energy photons are absorbed with aluminum to block radiation that will be absorbed by surface of body and won’t contribute to image.

The photoelectric effect will create significant spikes of energy when accelerated electrons collide with tightly bound electrons, usually in the K shell

Factors influencing the x-ray spectrum

- tube potential
  - kVp value
- wave shape of tube potential
- anode track material
  - W, Mo, Rh etc.
- X-ray beam filtration
  - inherent + additional

X-ray spectrum at 30 kV for an X-ray tube with a Mo target and a 0.03 mm Mo filter



Automatic exposure control

- Optimal choice of technical parameters in order to avoid repeated exposures (kV, mA)
- Radiation detector behind (or in front of) the film cassette (with due correction)
- Exposure is terminated when the required dose has been integrated
- Compensation for kVp at a given thickness
- Compensation for thickness at a given kVp

Interaction of radiation with matter
Radiation Contrast

Linear Energy Transfer

- Biological effectiveness of ionizing radiation

- Linear Energy Transfer (LET): amount of energy transferred to the medium per unit of track length of the particle

- Unit : e.g. [keV.μm^{-1}]

How do we describe attenuation of X-rays by body?

Assumptions:

1) Matter is composed of discrete particles (i.e. electrons, nucleus)
2) Distance between particles >> particle size
3) X-ray photons are small particles
   Interact with body in binomial process
   Pass through body with probability p
   Interact with body with probability 1-p (Absorption or scatter)

The number of interactions (removals=ΔN) α number of x-ray photons N and Δx.

$$N \rightarrow | \leftarrow \Delta x \rightarrow | \rightarrow N - \Delta N$$

$$N_{in} \rightarrow | \overset{}{\underset{\mu}{\leftarrow x \rightarrow}} | \rightarrow N_{out}$$

$$\Delta N = -\mu N \Delta x$$

$\mu = f(Z, \varepsilon)$ Attenuation a function of atomic number Z and energy ε

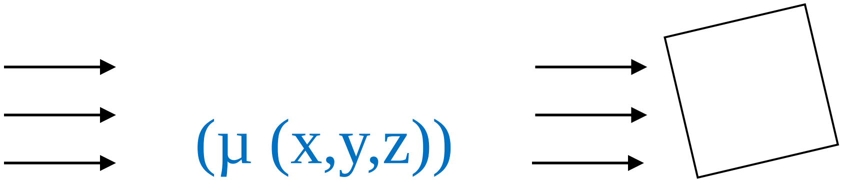
Solving the differential equation: $dN = -\mu N dx$

$$\int_{N_{in}}^{N_{out}} dN/N = -\mu \int_0^x dx \qquad \ln(N_{out}/N_{in}) = -\mu x$$

$$N_{out} = N_{in}\, e^{-\mu x}$$

If material attenuation varies in x, we can write attenuation as μ(x)

$$N_{out} = N_{in}\, e^{-\int \mu(x)\, dx}$$



If I_o photons/cm^2

(μ (x,y,z))

I_d (x,y)

Detector Plane

$$I_d\,(x,y) = I_0 \exp\left[\, -\int \mu(x,y,z)\, dz \right]$$

Assume: perfectly collimated beam (for now),
perfect detector
no loss of resolution

Actually recall that attenuation is also a function of energy ε, $\mu = \mu(x,y,z,\varepsilon)$

$$I_d(x,y) = \int I_0(\varepsilon) \exp[-\int \mu(x,y,z,\varepsilon)\, dz]\, d\varepsilon$$

Which Integrate over ε and depth.

For a single energy $I_0(\varepsilon) = I_0\, \delta(\varepsilon - \varepsilon_o) = I_0$

After analyzing a single energy, we can add the effects of other energies by superposition.

If homogeneous material, then $\mu(x,y,z,\varepsilon_0) = \mu_0$

$$I_d(x,y) = I_0\, e^{-\mu_0 \Delta z}$$

Attenuation of an heterogeneous beam

- Various energies ⇒ No more exponential attenuation
- Progressive elimination of photons through the matter
- Lower energies preferentially
- This effect is used in the design of filters
- ⇒ Beam hardening effect

Half Value Layer (HVL)

- HVL: thickness reducing beam intensity by 50%

- Definition holds strictly for monoenergetic beams
- Heterogeneous beam ⬇ hardening effect
- $I/I_0 = 1/2 = \exp(-\mu\ \mathrm{HVL})$ $\mathrm{HVL} = 0.693 / \mu$
- HVL depends on material and photon energy
- HVL characterizes *beam quality*
- ⬇ modification of beam quality through filtration
- ⬇ HVL (filtered beam) ≠ HVL (beam before filter)

(HVL) Half Value Layer :

- HVL اندازه گیری (معیار) غیر مستقیم انرژی فوتون یا کیفیت تشعشع می باشد.

- Homogeneity Coefficient:
- از آنجائیکه تشعشع بر مشترالانگ تک انرژی نیست ، مقدار تشعشع کاهش یافته در ضخامت های اولیه مثلاً اولین HVL سریعتر از لایه های دوم و سوم خواهد بود ولی تشعشع سخت تر می شود نسبت HVL اول به دوم ضریب یکنواختی نام دارد و پراکندگی انرژی تشعشع را نشان می دهد

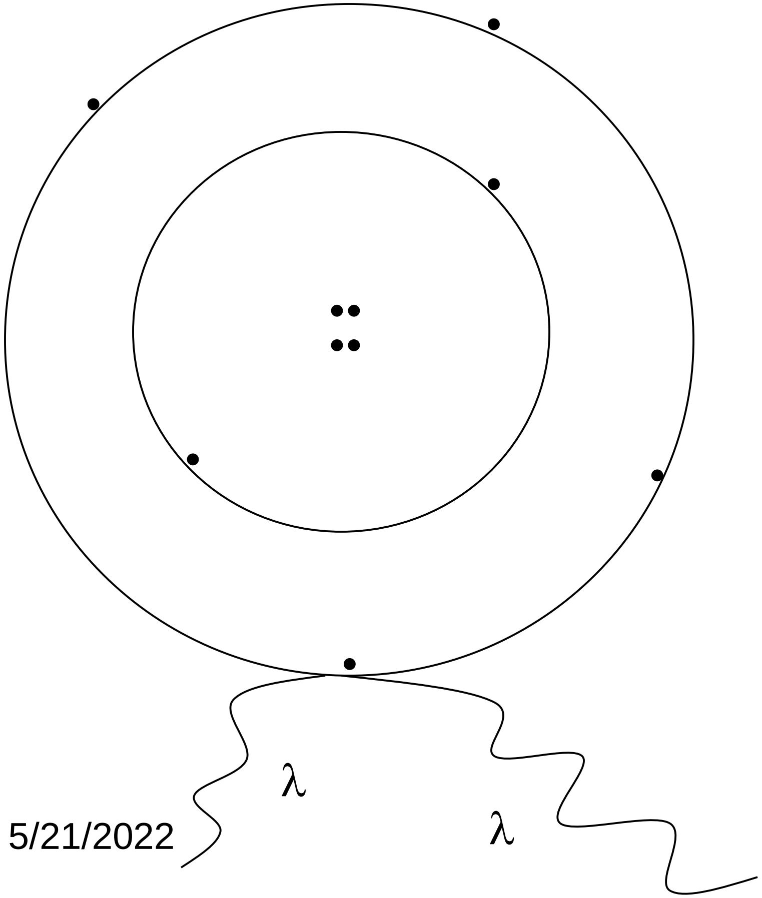
$$HC = HVL_1/HVL_2$$

X-ray interaction with matter

Coherent Scattering
Photoelectric Effect
Compton Scattering
Pair Production
Photodisintegration .

Physical Basis of Attenuation Coefficient

Coherent Scattering - Rayleigh



Coherent scattering varies
over diagnostic energy range as:

$$\mu/p \;\alpha\; 1/\varepsilon^{2}$$

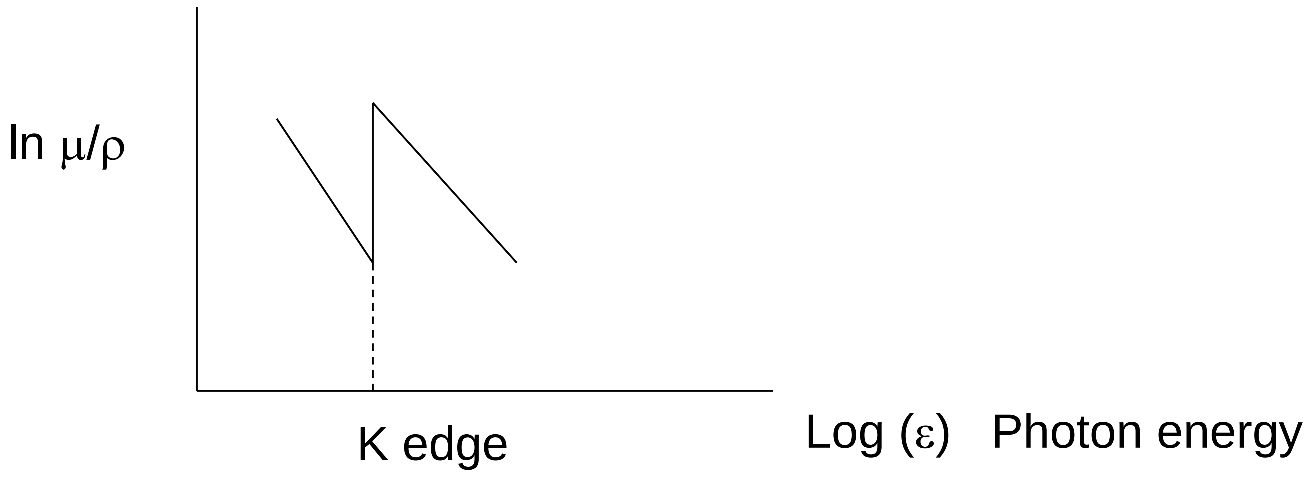
Photoelectric effect

- Incident photon with energy $h\nu$
- Absorption: ≈ all photon energy absorbed by a tightly bound orbital electron

  ↓ ejection of electron from the atom
- Kinetic energy of ejected electron : $E = h\nu - E_B$
- Condition : $h\nu > E_B$ (electron binding energy)
- Recoil of the residual atom
- Attenuation (or interaction): photoelectric absorption coefficient

$$\boxed{\frac{Z^3}{E^3} = \frac{Z^3}{(hf)^3}}$$

We can use K-edge to dramatically increase absorption in areas where material is injected, ingested, etc.



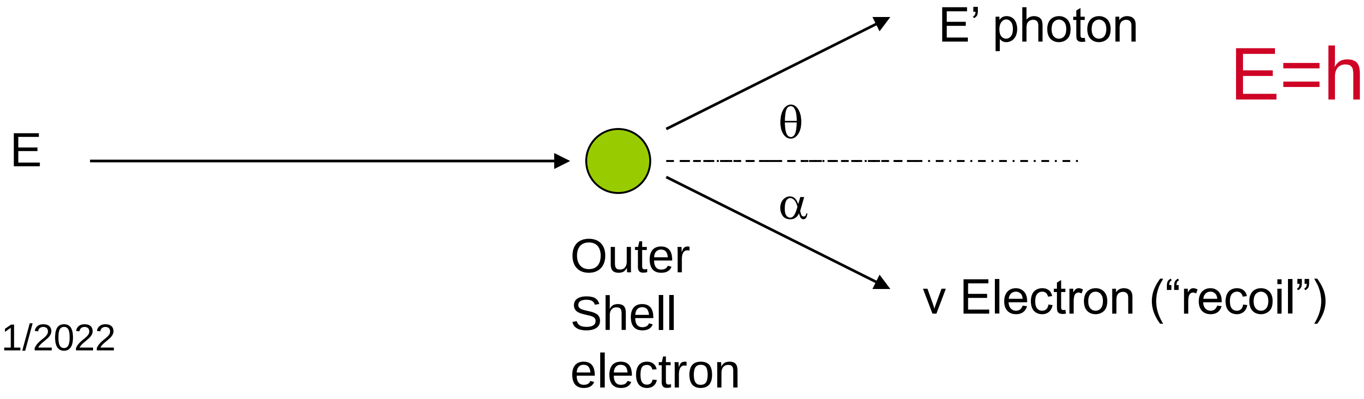
Compton scattering

- Interaction between photon and electron
- $h\nu = E_a + E_s$ (energy is conserved)
  - E_a: energy transferred to the atom
  - E_s: energy of the scattered photon
  - momentum is conserved in angular distributions

- Compton is practically independent of Z in diagnostic range
- The probability of interaction decreases as $h\nu$ increases
- Compton effect is proportional to the electron density in the medium

Compton Scatter

- Interaction of photons and electrons produce scattered photons of reduced energy.
- The probability of interaction decreases as hν increases
- Compton effect is proportional to the electron density in the medium



$$E = h\nu = E' + E_e$$

Satisfy Conservation of Energy:

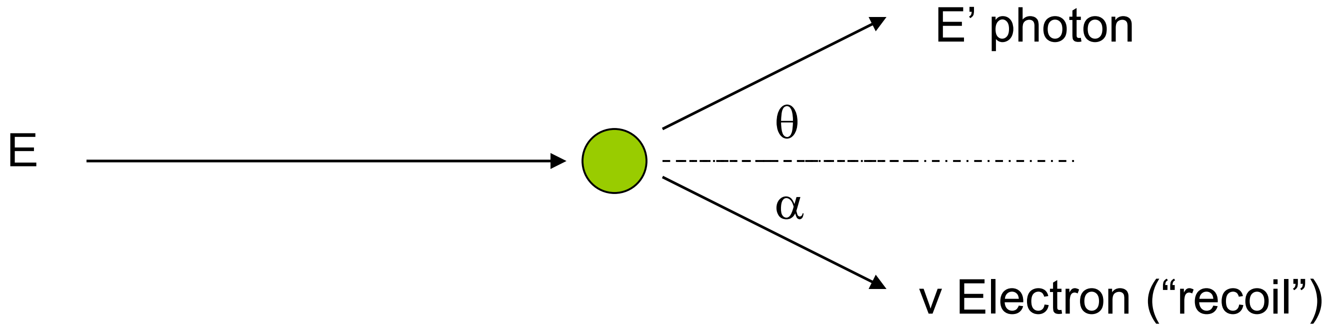
$$E = E' + (m - m_0)c^2$$ {(m-m$_o$)c^2= increase in electron energy}

$$m = m_0 / \sqrt{1-(v/c)^2}$$ (Mass of moving electron)

Conservation of Momentum in x and y direction:

$$\frac{E}{c} = \frac{E'}{c}\cos(\theta) + mv\cos(\alpha)$$

$$0 = \frac{E'}{c}\sin\theta - mv\sin\alpha$$



Energy of Compton or recoil electron ΔE:

$$\Delta E = E - E'$$

change in energy of photon

$$\Delta\lambda = \frac{hc}{E^{'}} - \frac{hc}{E}$$

change in wavelength of photon

h = 6.63 x 10^{-34} Jsec
eV = 1.62 x 10^{-19} J
m_o = 9.31 x 10^{-31} kg

$\Delta\lambda = h/\ m_oc\ (1 - \cos\theta) = 0.0241\ A^0\ (1 - \cos\theta)$

$\Delta\lambda$ at $\theta = \pi = 0.048$ Angstroms

Energy of Compton photon:

$$h\nu' = \frac{h\nu}{1 + (1 - \cos\theta)\dfrac{h\nu}{m_0 c^2}}$$

Rayleigh, Compton, Photoelectric are independent sources of attenuation

$$t = I/I_0 = e^{-\mu l} = \exp\left[-(\mu_c + \mu_R + \mu_p)l\right]$$

$$\mu(\varepsilon) \approx \rho N_g \{C_c(1/\varepsilon) + C_R (Z^2/ \varepsilon^{1.9}) + C_p (Z^{3.8}/ \varepsilon^{3.2})\}$$

Compton Rayleigh Photoelectric

Mass attenuation coefficient $(\mu/\rho) \propto$ electron mass density N_g

N_g = electrons/gram

ρN_g = electrons/cm^3

$N_g = N_A (Z/A) \approx N_A /2$ (all but H) A = atomic mass

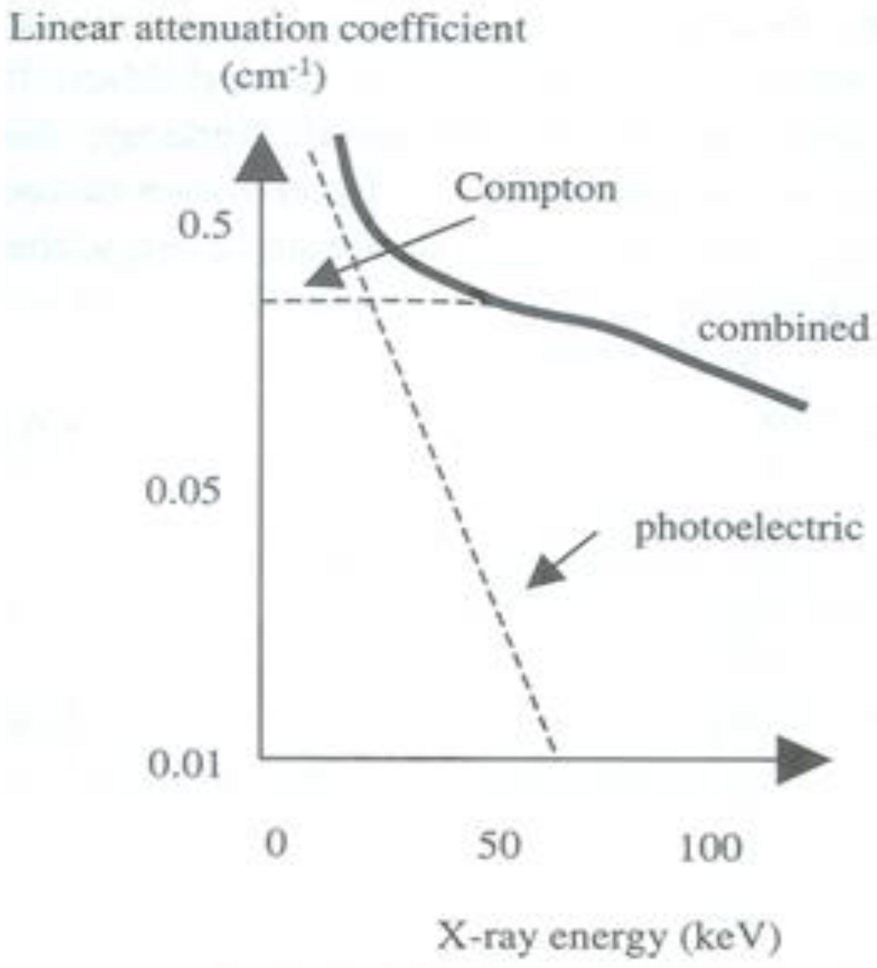
N_A =6.0 x 1023

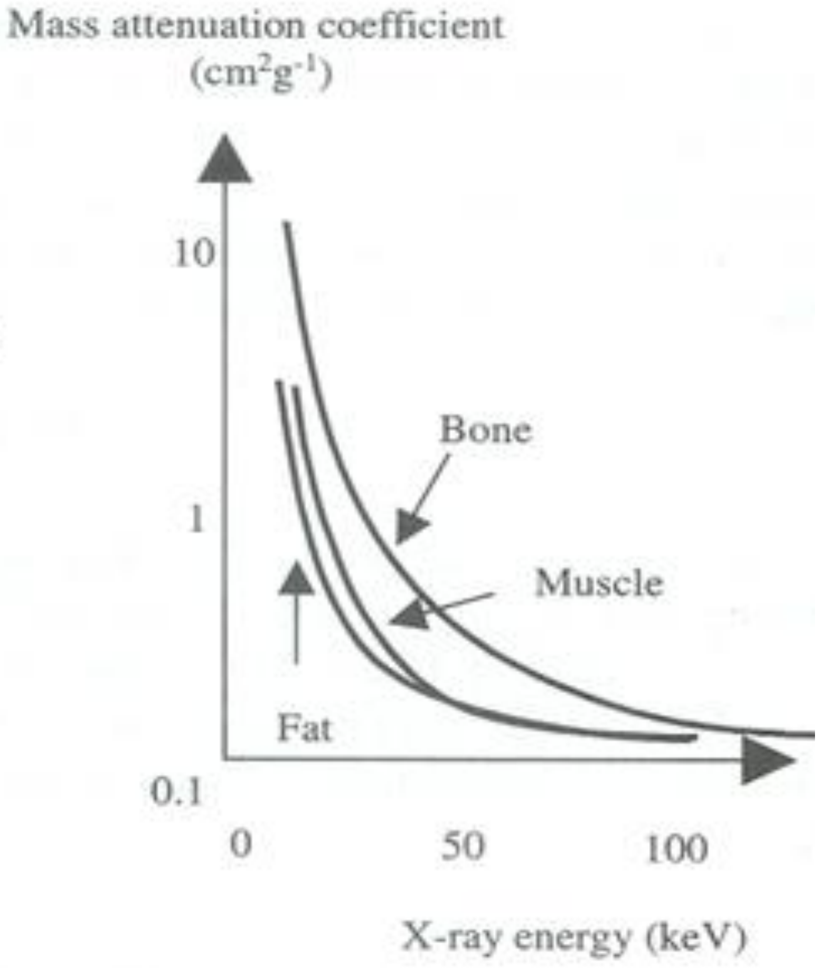
Unfortunately, almost all elements have

electron mass density ≈ 3 x 10 ^{23} electrons/gram

Hydrogen (exception) ≈ 6.0 x 10^{23} electrons/gram

Attenuation Mechanisms





Curve on left shows how photoelectric effects dominates at lower energies and how Compton effect dominates at higher energies.

Curve on right shows that mass attenuation coefficient varies little over 100 kev. Ideally, we would image at lower energies to create contrast.

Photoelectric vs. Compton Effect

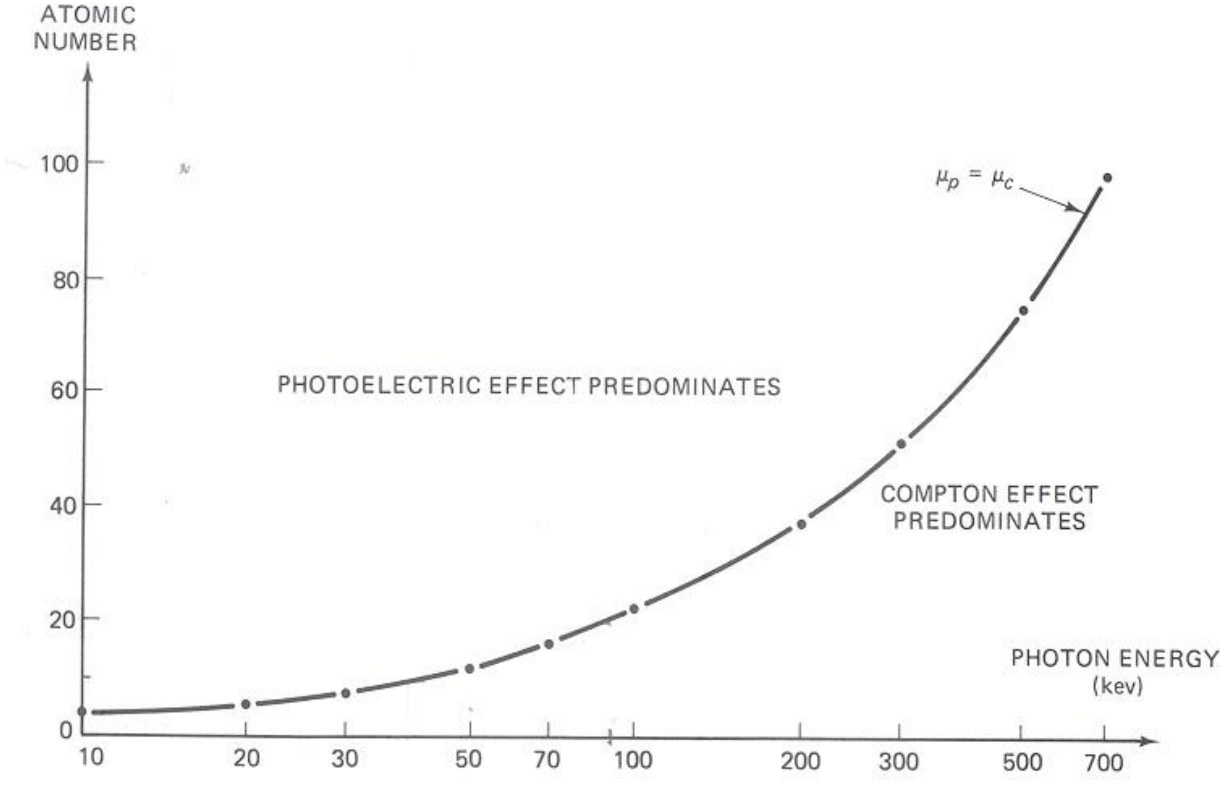


FIG. 3.6 Relative importance of the two major types of x-ray interaction. The line shows the values of Z and photon energy $h\nu$ for which the photoelectric and Compton effects are equal.

The curve above shows that the Compton effect dominates at higher energy values as a function of atomic number.

Ideally, we would like to use lower energies to use the higher contrast available with The photoelectric effect. Higher energies are needed however as the body gets thicker.

Scattered radiation

- Effect on mage quality
  - increasing of blurring
  - loss of contrast
- Effect on patient dose
  - increasing of superficial and depth dose

Possible reduction through :

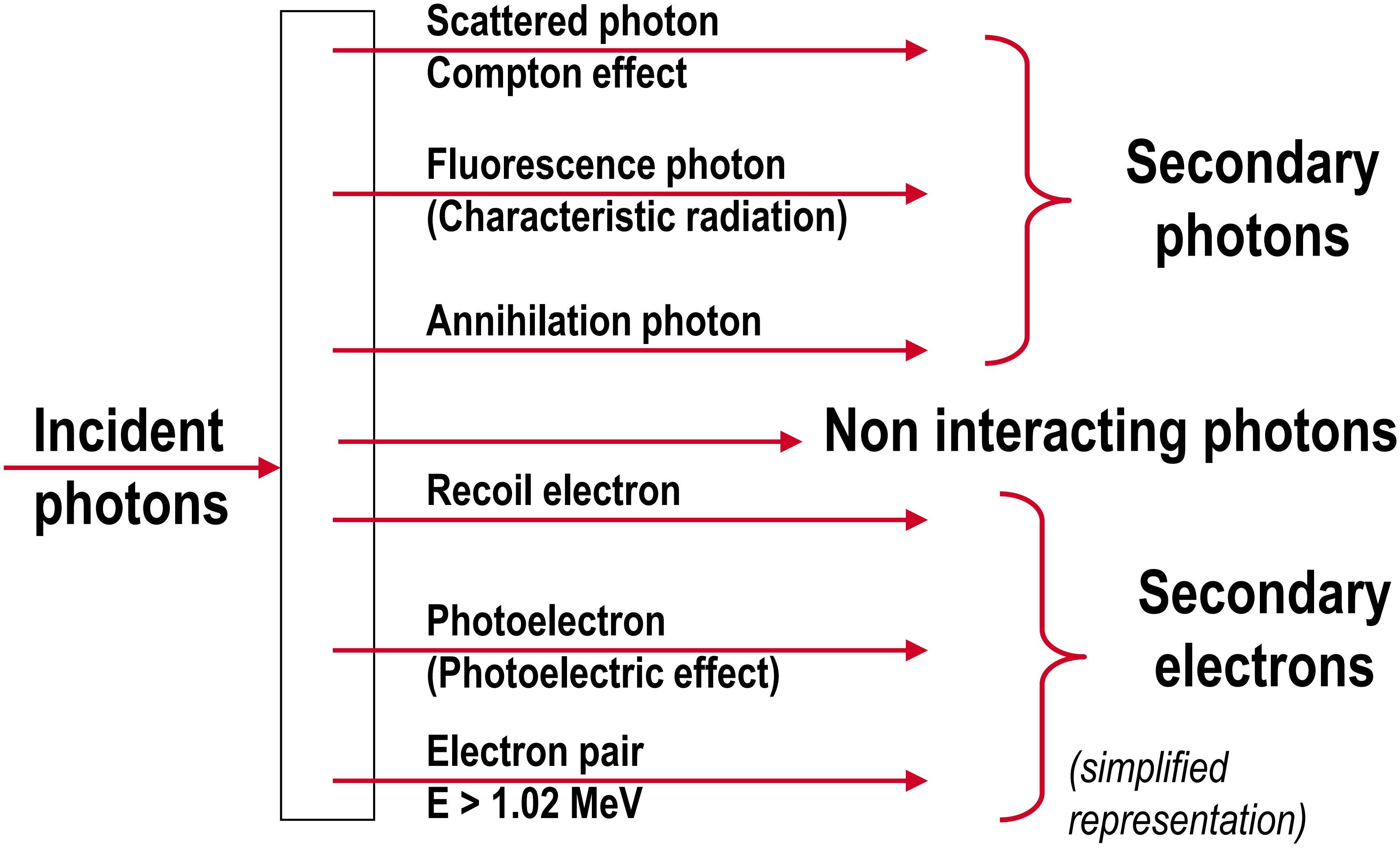
⇒ use of grid

⇒ limitation of the field to the useful portion

⇒ limitation of the irradiated volume (e.g.:breast compression in mammography)

⇒ Higher kVp

Photon interactions with matter



Incident photons

Scattered photon
Compton effect

Fluorescence photon
(Characteristic radiation)

Annihilation photon

Secondary photons

Non interacting photons

Recoil electron

Photoelectron
(Photoelectric effect)

Electron pair
E > 1.02 MeV

Secondary electrons

(simplified representation)

Radiation Exposure :

- – واحد قدیمـی آن Roentgen می باشد. یک رونتگن ، مقدار اشعه X یا گامائی است که تا ایجاد 2.58*10-4کولن بار در یک کیلوگرم هوا بکند.

- – برای تشعشع در زمان محدود مثل رادیوگرافی 1mR ایجاد دانسیته فتوگرافی (Photographic Density) حدود 1.0 می نماید.

Radiation Exposure:

- – در تصویربرداری پیوسته مثل فلورئوسکپی، اطلاعات به بیننده براساس زمان ثبت اطلاعات (Storage Time) مغز انسان (زمانی که اطلاعات ثبت شده باقی می ماند) دارد که حدود 100 Ms است.
- در فلورئوسکپی اطلاعات براساس Exposure Rate (mR/S) است.

$$50\ \mu \mathrm{Rs}^{-1}$$

- لذا برای مقدار معمول Exposure rate در فلوئورسکپی و براساس Storage Time مقدار اکسبوزر عبارت است:

$$50\times 0.1=5\ \mu \mathrm{R}$$

- – شدت تشعشع خروجی دستگاه X-ray همچنین بصورت (mR/ MAS) بیان می شود.