Electromagnetic radiation (chapter 5)

- visible light and x-rays are two different segments of the electromagnetic spectrum
- particles: photons, energy E ← {~ eV for visible light; ~ keV for x-rays} ← quantum mechanics
- electromagnetic waves ($\underset{\sim}{\delta E}$, $\underset{\sim}{\delta B}$): wavelength λ or frequency, f
- speed of light, $c \approx 3.00 \times 10^{8}$ m/s

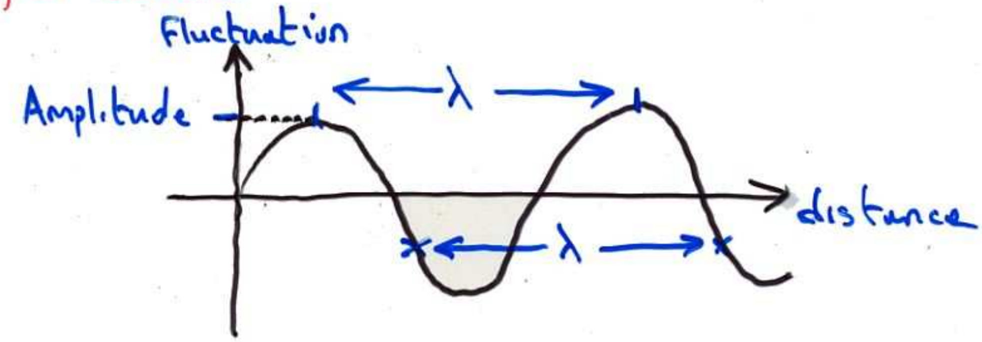
- For waves in general,

Frequency × wavelength = propagation speed

Frequency: # of "full waves" passing a point per second

wavelength: length of each "full wave"

propagation speed = distance travelled per second



∴ For light (i.e. electromagnetic rad$^{\underline{n}}$)

$$\boxed{\lambda f = c}$$

λ: m, f: Hz (← 1/s), c: m/s

$f = 2\,\text{Hz}$ ← $2\,s^{-1}$

$\lambda = 3\,\text{m}$

$c = 2\,s^{-1} \times 3\,\text{m} = 6\,\text{m}\,s^{-1}$

- photon energy, $E = hf$

h — Planck's constant: 4.2×10^{-15} eV.s or 6.6×10^{-34} J.s

- λ, f or E are interchangeable

- the <u>electromagnetic spectrum</u>

radio microwaves infrared visible (red … blue) ultraviolet x-ray gamma-ray

→ increasing E and f, decreasing λ

<u>e.g.</u> green light has $f \approx 6 \times 10^{14}$ Hz

$$\therefore \lambda = c/f = \frac{3 \times 10^{8}\ \mathrm{m/s}}{6 \times 10^{14}\ \mathrm{1/s}} = 5 \times 10^{-7}\ \mathrm{m} = 500\ \mathrm{nm}$$

nm = nanometre (10^{-9} m)

and $E = hf = 4.2 \times 10^{-15}\ \mathrm{eV.s} \times 6 \times 10^{14}\ \mathrm{Hz}$

$= 2.5\ \mathrm{eV}$

Intensity of radiation = energy per unit time falling on unit area

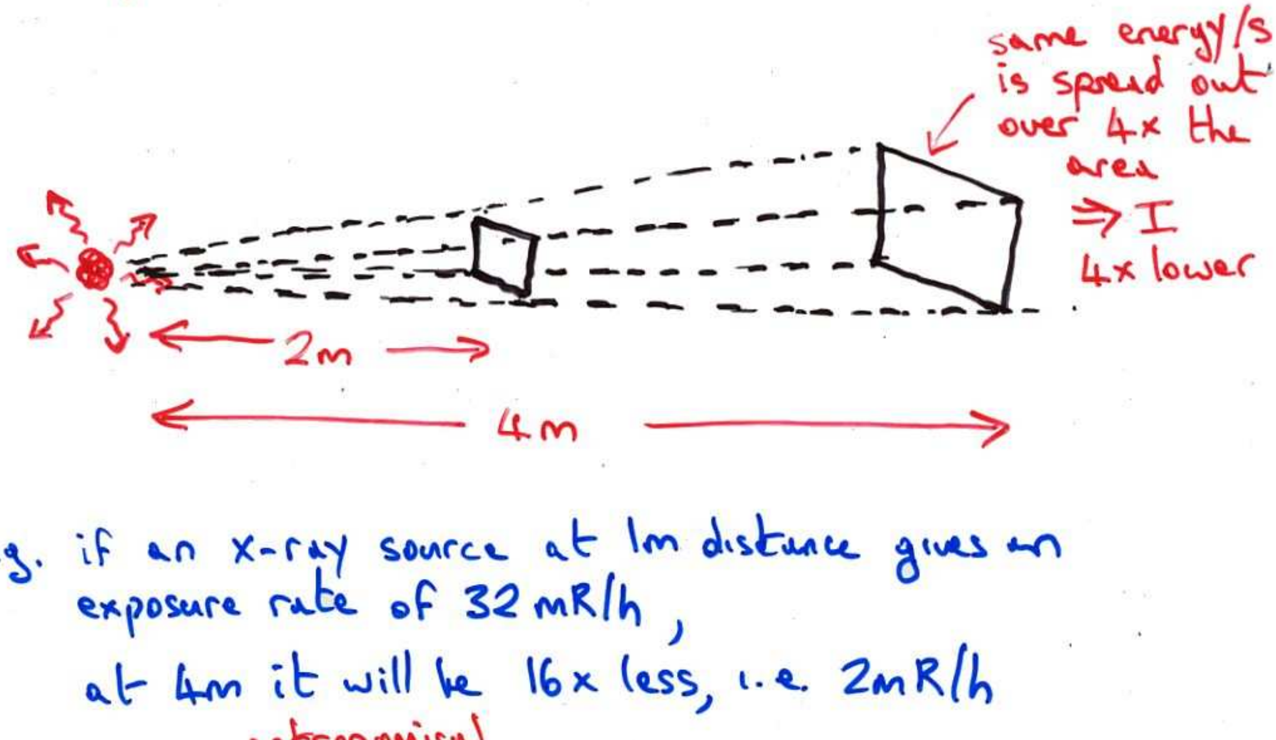
$J/s/m^2 = W/m^2$
or W/cm^2 etc

For x-rays, this is directly proportional to ionisations/second in a detector, so use milli-Roentgen/hr, mR/h as a measure.

- For a compact source,

$$I \propto 1/d^2$$ inverse-square law

intensity (I), distance (d)



e.g. if an x-ray source at 1m distance gives an exposure rate of 32 mR/h,

at 4m it will be 16x less, i.e. 2mR/h

e.g. sun at 1 A.U. (astronomical unit) = 1.5×10^{11} m has I comparable to 100 W light bulb at a few cm

The production of x-rays (chapter 11)

- electron strikes anode and slows down via interactions with nuclei and atomic electrons

initial electron kinetic energy → heat 99%

initial electron kinetic energy → x-rays 1%

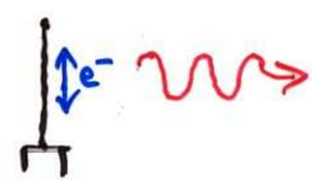
- x-rays → bremsstrahlung (80% of diagnostic x-rays)
- x-rays → characteristic x-rays (20%)

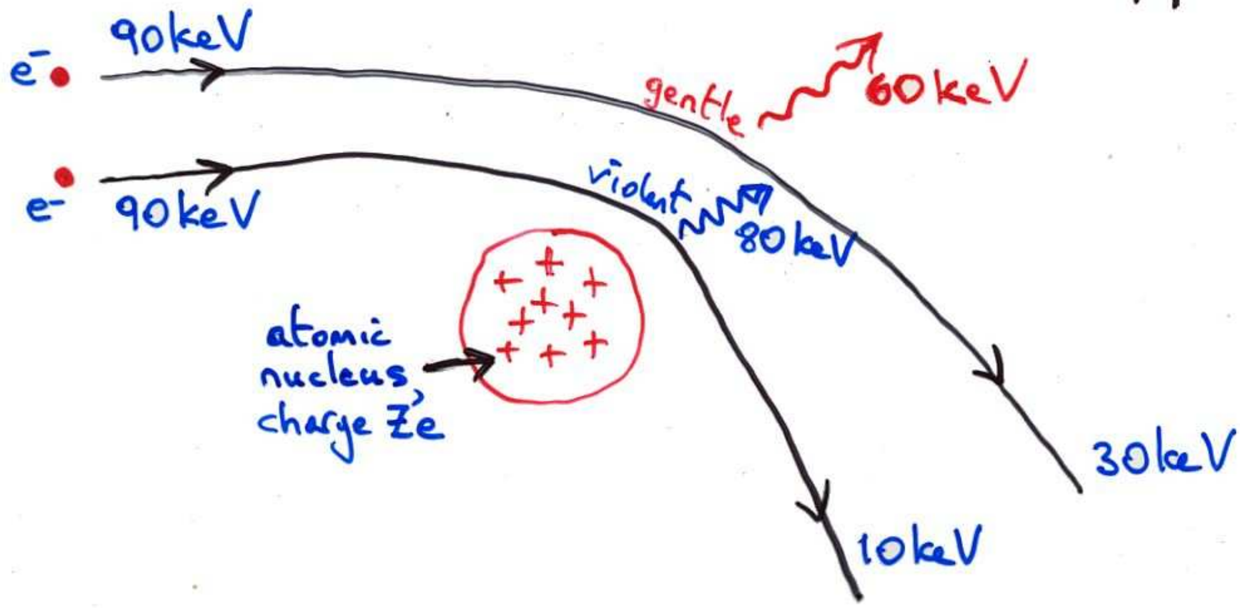
Bremsstrahlung, or "braking radiation" occurs when an energetic electron is deflected by the electric field near an atomic nucleus

accelerate an electron ⇒ radiation (photon emission)

(decelerate, deflect, ΔV)

eg/ radio transmitter





- energy of x-ray photon is determined by distance of e⁻ closest approach to the nucleus

  ⇒ continuous spectrum

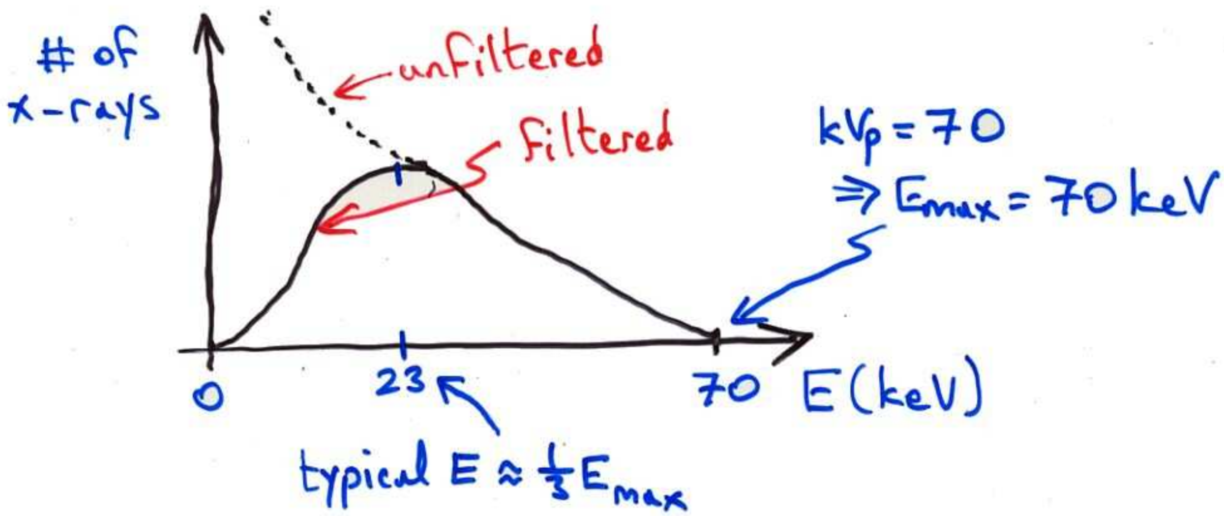
- many more weak deflections than strong deflections

  ⇒ more low-energy photons are produced than high-energy photons

- electron leaves the atom

  ⇒ max photon energy = energy of incident electron

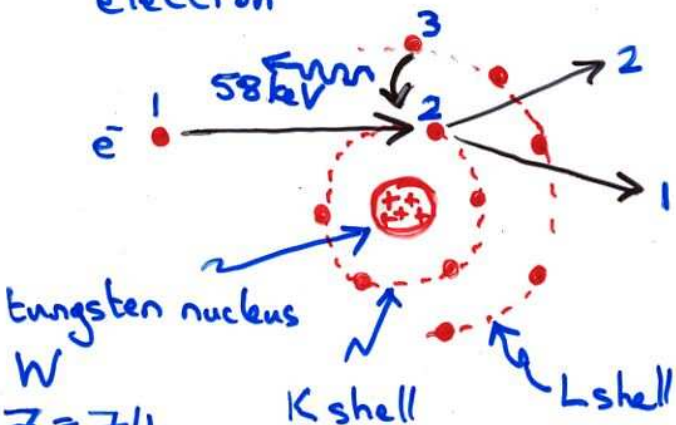
- electron will continue to interact with other nuclei it encounters ⇒ more low energy photons



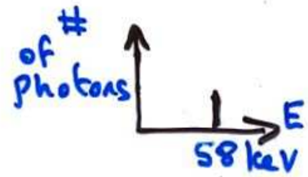
- low energy x-rays are less penetrating - filter out
  - won't pass through patient but would contribute to exposure to radiation

Characteristic x-rays

- produced by an electronic transition in an atom that fills an inner-shell vacancy induced by a projectile electron



W
Z = 74
↑ # of protons in nucleus "atomic number"



- photon produced by electron changing state ⇒ x-ray <u>line</u>
  - ⇒ definite energy, equal to energy difference between L & K shells (or M & K, etc)

e.g. W L→K 58 keV, M→K 67 keV (less often) } <u>K-characteristic</u> x-rays

[differs for different Z]

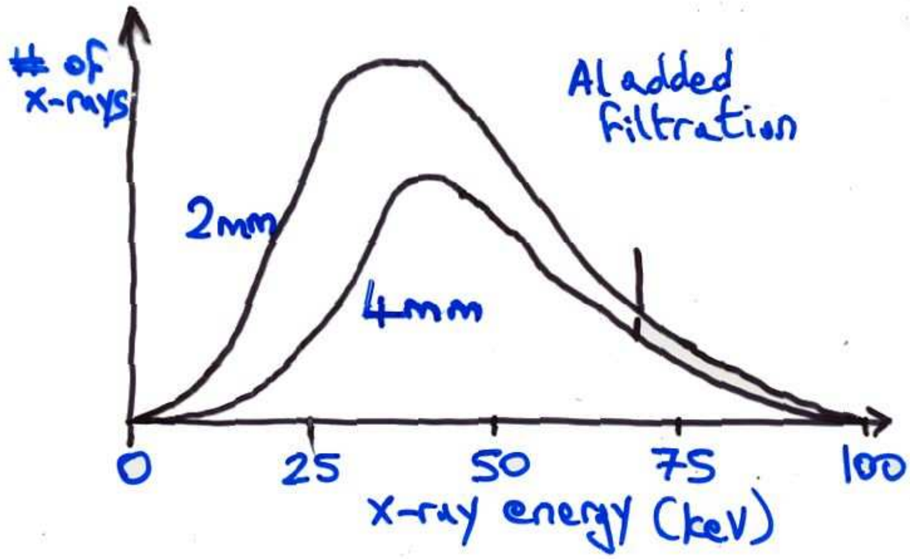
- original K-shell electron must be kicked out
  - takes 69.53 keV at least, so incoming e^- must have E > 70 keV
  - ⇒ K-characteristic x-rays occur at 70 kVp or higher [for tungsten anode]

- at 110–120 kVp, ~15% of beam is K-characteristic x-rays

- also L-characteristic x-rays, etc.
  - low energy

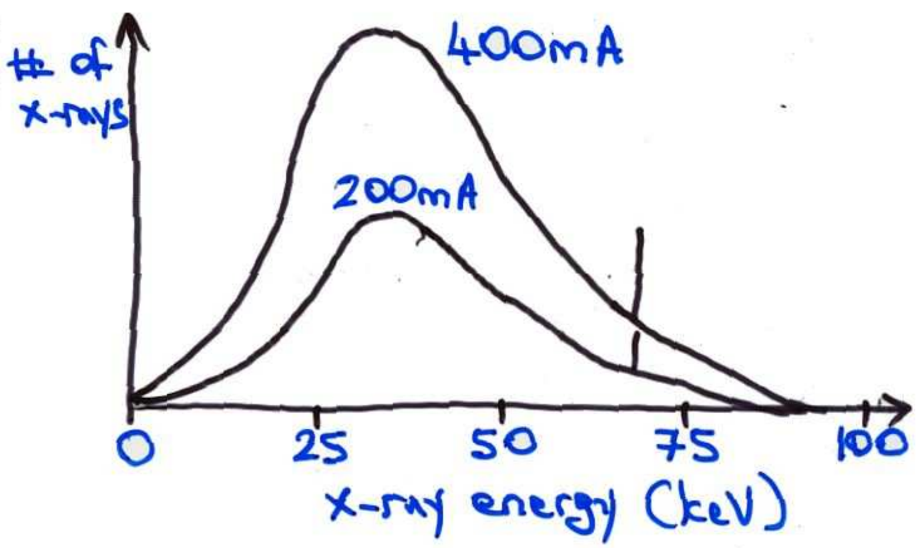
Filtration - thin sheets of Al or other metal attached to output port.

- preferentially blocks low E photons



mA - changes the quantity of X-rays but not the spectrum

- changes # of incident electrons, not their energy

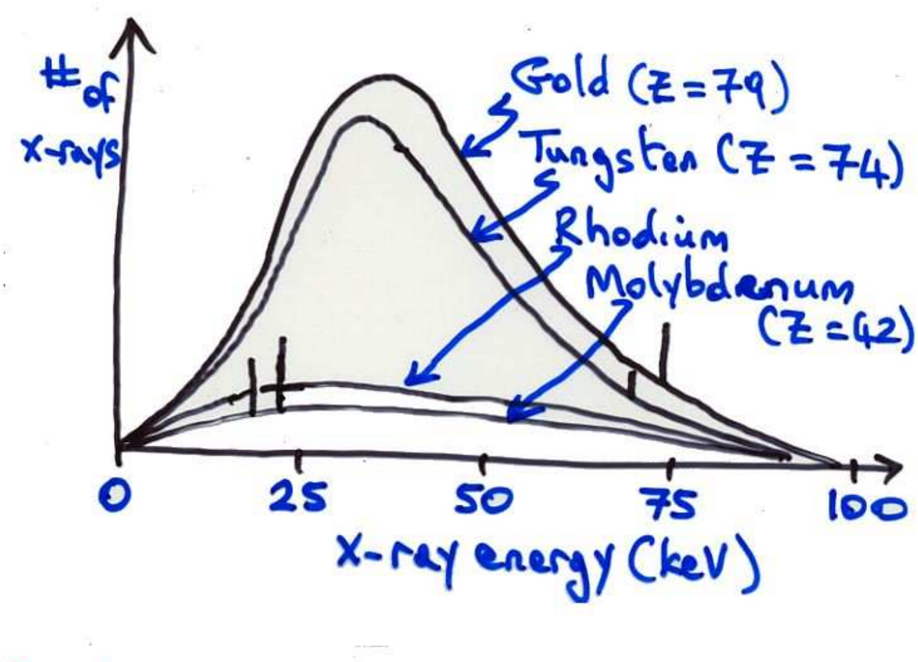


anode material

- determines amount of bremsstrahlung (increases for higher Z)

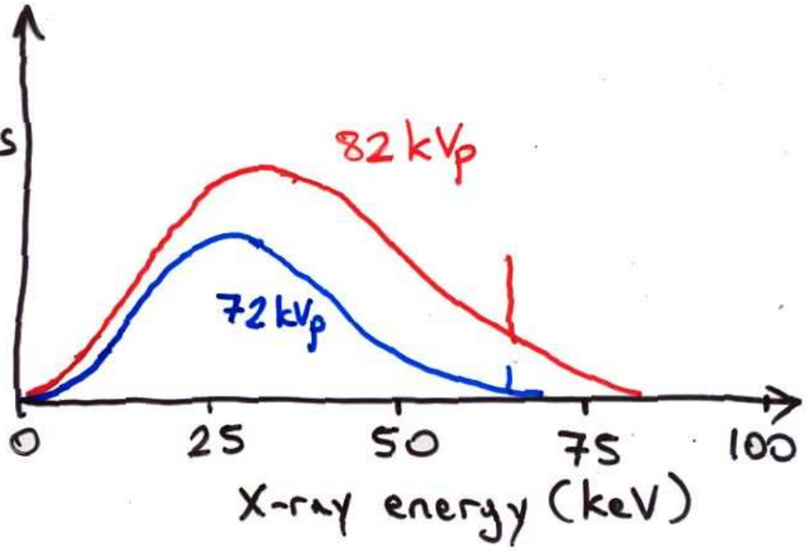
and the energies of the characteristic x-rays

- usually tungsten (Z=74)
- Molybdenum used for mammography as lower energy x-rays better for soft-tissue imaging



kVp – determines E_{max}, increases x-ray production for same mA

$E_{peak} \sim \frac{1}{3} E_{max}$ changes too

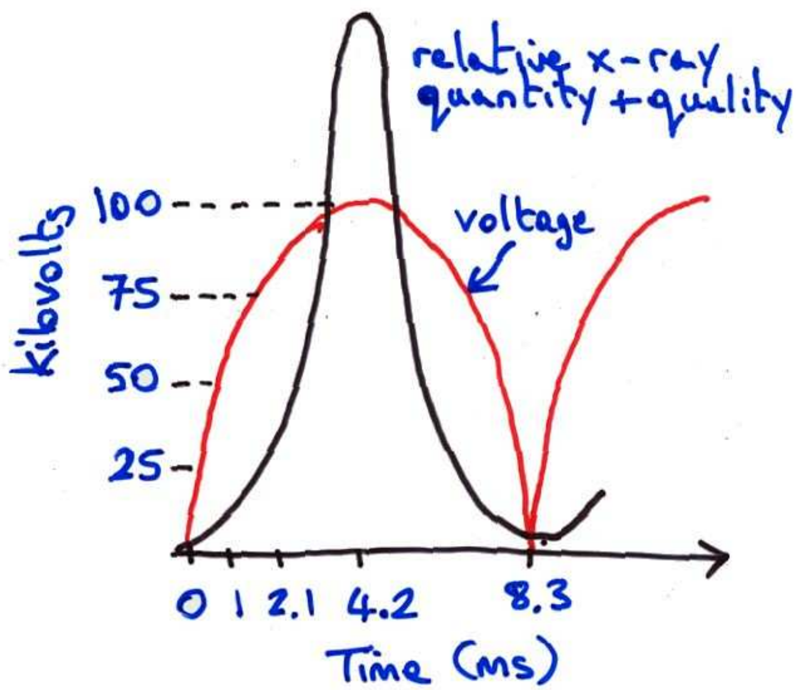


Time-dependence for single phase, fully-rectified

- strong function of voltage

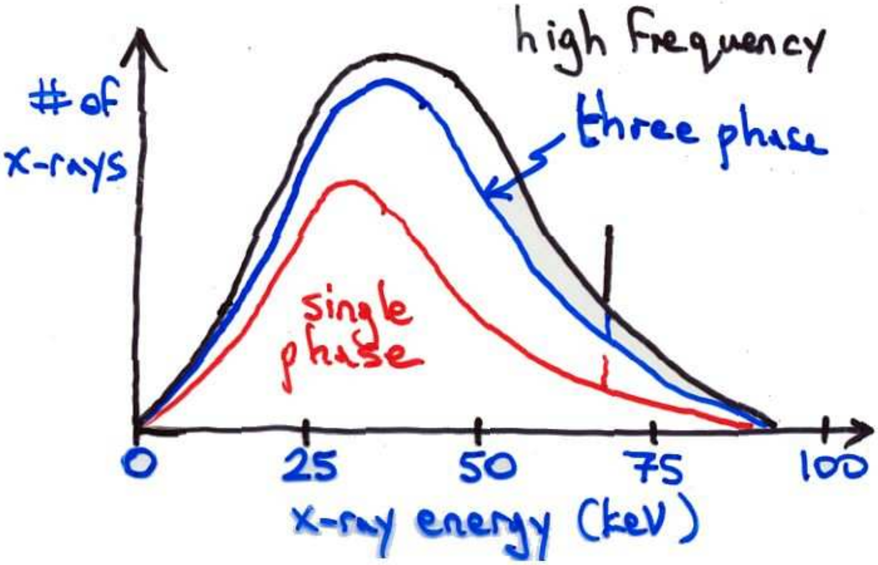
⇒ strongly peaked

⇒ quest for low ripple



circuit waveform

- low ripple is far more efficient

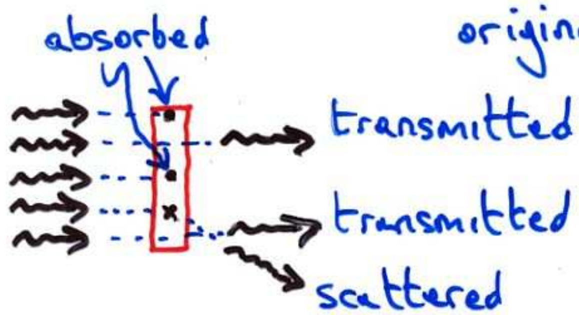


X-ray interactions

– determine imaging properties

x-rays may be absorbed, — gone!
or scattered, — change direction (& perhaps E)
or transmitted, — no change

absorbed + scattered → **attenuation** – reduction of original beam



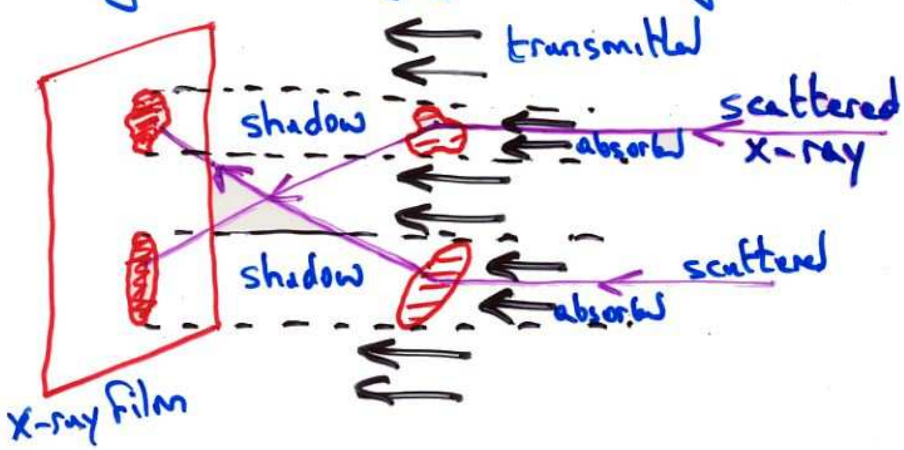
3 photons were attenuated

3 photons contribute to exit radiation

exit radiation – scattered + transmitted rad^n that leaves the patient

*typically ~99% of the rad^n incident on a patient is scattered or absorbed
~1% is transmitted

– scattering spoils imaging by reducing contrast



Attenuation

- determined by interaction of x-rays with electrons in patient (in principle also with nuclei)

- increased by increased tissue density, thickness and atomic number of material

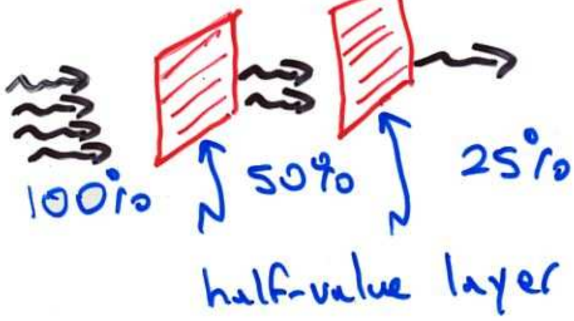
- reduced for higher energy x-rays (i.e. these have greater penetration) increasing kVp ⇒ decreased attenuation

material	ρ (g/cm³)	mean Z		
air	0.0013	7.6	N = 7, O = 8	radiolucent
lung	0.32	7.4	C = 6, N = 7, O = 8, H = 1	radiolucent
fat	0.91	6.3		
muscle	1.0	7.4		
bone	1.9	13.8	Ca = 20	
iodine	4.9	53		radiopaque
barium	3.5	56		radiopaque
lead	11.4	82		radiopaque

- air, iodine + barium often introduced to generate image contrast

The half-value layer is the amount of a certain material required to attenuate an x-ray beam by 1/2.

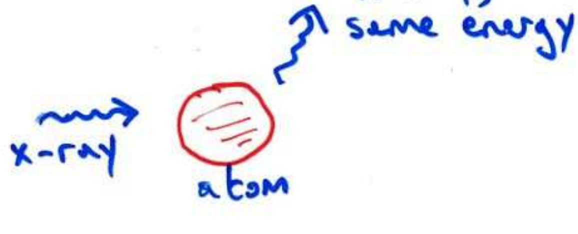
Note that 2 of these layers ⇒ 1/4 of the intensity



Types of x-ray interactions

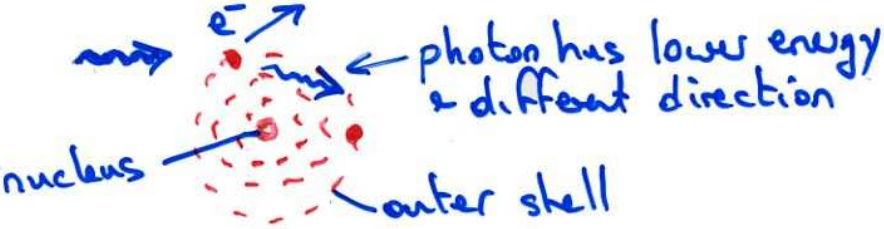
- ordered from low energy → high energy.

1. Coherent scattering or classical or Thomson scattering
   - x-ray interacts with an entire atom: absorbed; atom emits x-ray with same energy in a different direction.
   - important for x-ray energies below 10 keV, so not important
   - no ionisation



Compton scattering

- x-ray photon scatters off an outer-shell electron and kicks it out of the atom



- effect is almost independent of Z
  e.g. bone vs muscle
- decreases slowly with increasing energy
  - dominates photoelectric effect for $E \gtrsim 30$ keV

- scattered photon may well escape the patient
  - reduce image contrast
  - irradiate bystanders

Pair production

For $E > 1.02$ MeV, photon $\rightarrow e^+ + e^-$ when passing near an atomic nucleus

Photonuclear disintegration

$E \gtrsim 10$ MeV photons can kick out "pieces" of the atomic nucleus

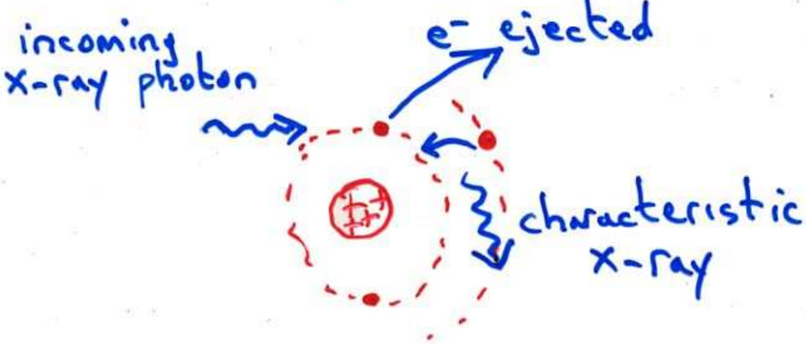
- Both processes irrelevant for diagnostic x-rays

Photoelectric effect

- x-ray photon is absorbed by an inner-shell electron, which is ejected from the atom
  - ↖ usually K-shell
  - "photoelectron"

- photoelectron is stopped by tissue within 1mm of ejection site

- characteristic X-ray emitted as inner-shell vacancy is filled
  - C, N, or O so very low energy and absorbed in the patient



- probability of this process increases with increasing Z
  - bone higher than tissue
- decreases with increasing (x-ray) energy

- this effect is what we exploit in x-ray imaging
  - incident x-ray photon is absorbed
  - photoelectron stopped within patient
  - characteristic X-ray photon also stopped