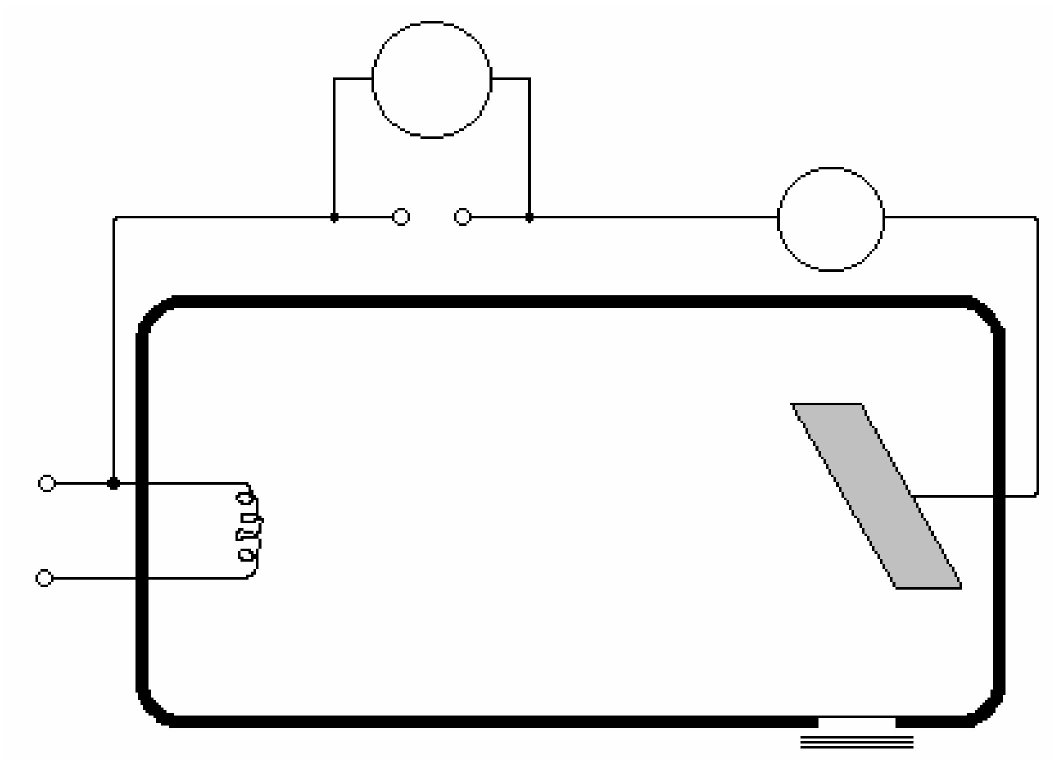
PRODUCTION OF X-RAYS

X-rays are electromagnetic radiation with frequencies greater than those of ultra-violet, i.e. > 3 x 10^{16} Hz (wavelength less than 10 nm). As with all types of EMR, X-rays are produced by the deceleration of charged particles. The charged particle used for the production of X-rays is virtually always the electron.

Fig 1: Schematic Diagram of an X-ray tube



In a diagnostic X-ray tube, a low voltage supply is passed through a tungsten filament causing heating and thus the thermionic emission of electrons. These electrons are then accelerated, through a vacuum, by a large potential difference (of the order of tens of kilovolts). They strike a target (usually made of tungsten) causing the production of heat and X-ray photons. The X-ray photons are emitted at all angles. By shielding the X-ray tube with lead, but leaving a small window, a diverging beam of X-ray photons is produced.

There are four processes that may take place when the fast-moving electrons hit the anode and interact with the target atoms;

(i) excitation of an outer orbital electron,

(ii) ionisation of an outer orbital electron,

(iii) ionisation followed by the emission of a characteristic X-ray,

(iv) bremsstrahlung ("braking radiation") production.

The first two of these processes lead to the production of heat. In an X-ray tube 95% to 99% of the energy from decelerating electrons goes to heat via excitation and ionisation of outer orbital electrons.

The third and fourth of these processes lead to the production of X-ray photons. Between 1% and 5% goes to X-ray energy, mostly Bremsstrahlung.

Figure 2

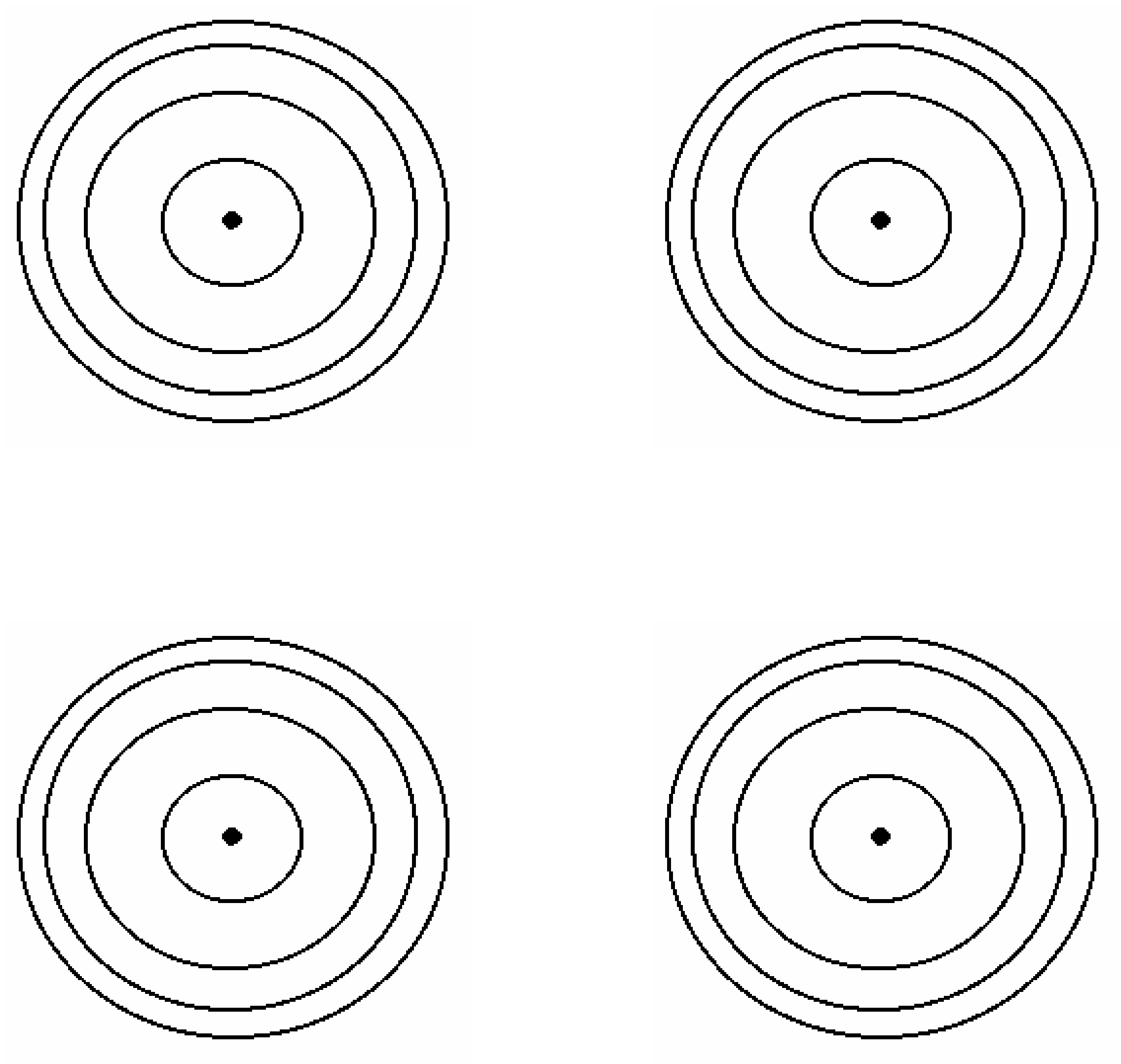
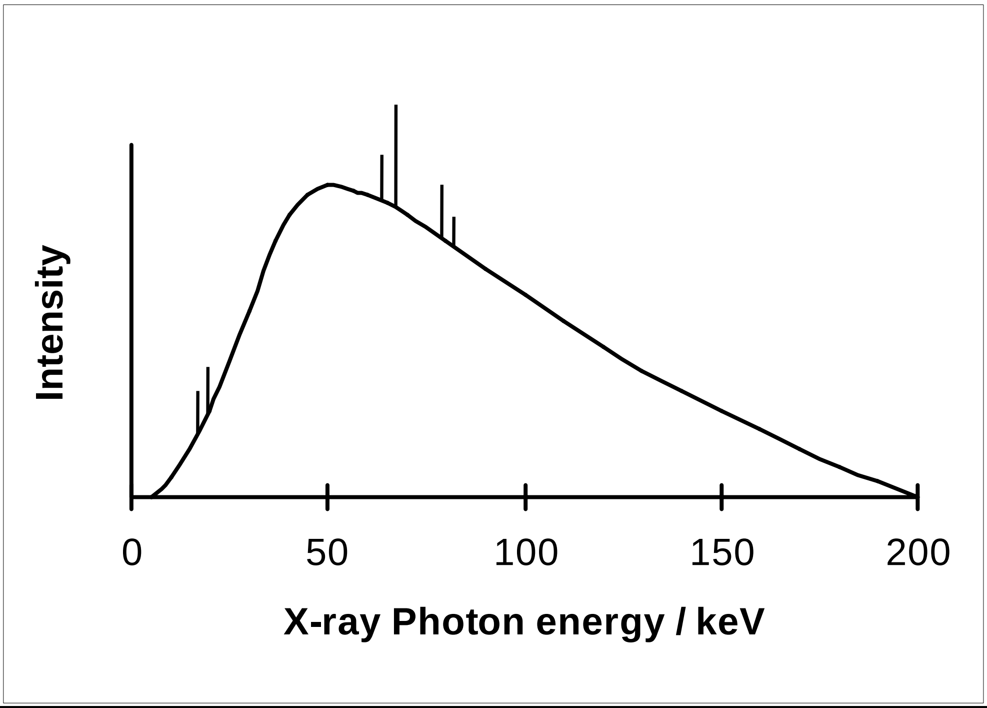


Fig 3 shows a typical X-ray spectrum.

Fig 3. Typical X-ray spectrum



The photon energy is normally quotes in keV (kilo-electron volts) rather than joules. The maximum energy gained by a charged particle of charge q coulombs accelerating across a voltage V volts is E_{max} = q.V. For electrons, q = 1.6 x 10^{-19} C, but is often given the symbol e.

Therefore, 1 keV = 1 x (1.6 x 10^{-19} C) x 1000 V = 1.6 x 10^{-16} J

The main curve of the graph represents the bremmstrahlung X-rays. The vertical lines superimposed on this curve represents the characteristic X-rays. The position on the x-axis of the characteristic X-ray lines depends purely on the target material.

[Fig 4. There is no figure four]

The maximum photon energy depends on the maximum potential difference across the tube, known as the kVp. If the tube voltage is 100 kVp, then the highest possible photon energy (produced by an electron being totally halted by the bremmstrahlung process) is 100 keV.

The shape of the bremmstrahlung curve can be explained thus: the theoretical number of bremmstrahlung X-ray photons produced of each energy is shown in figure 5. The intensity of the X-ray beam is proportional to the energy of the photons as well as the number of photons. By multiplying the number of photons of each energy with the energy a graph of the theoretical intensity of the X-ray beam produced has been plotted as figure 6.

Fig. 5 Number of photons produced at various energies

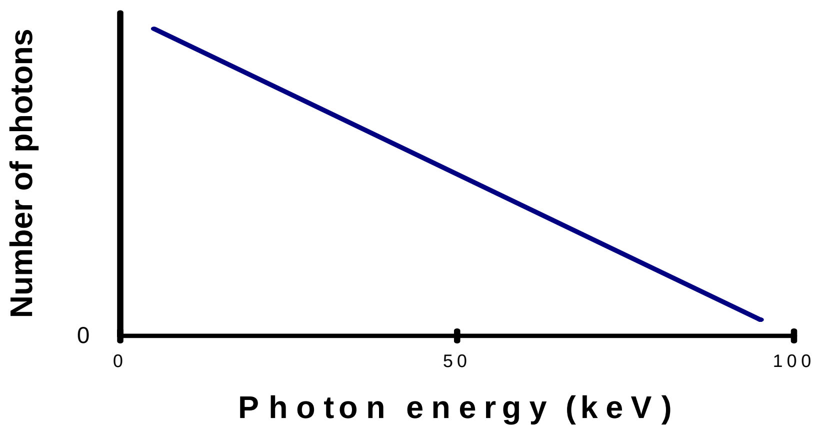
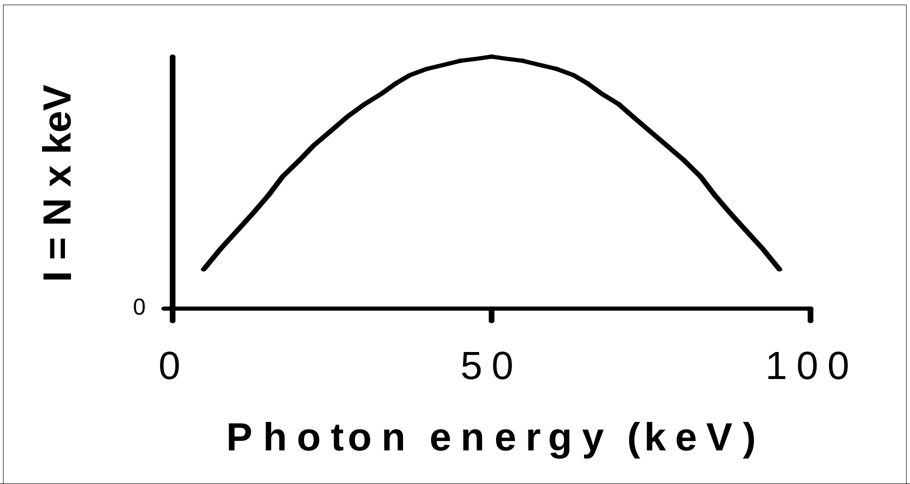


Fig. 6 Theoretical spectrum from target model



The model shown in figure 6 does not show the sharp cut off at lower energies shown in the "real" X-ray spectrum of figure 3. This cut off is caused by absorption of X-rays inside the target and the window of the X-ray tube. At diagnostic energies, the photoelectric effect is the dominant absorption process. The mass attenuation coefficient for the photoelectric effect is proportional to $1/E^3$, where E is the photon energy, and therefore low energy photons are attenuated more than high energy photons.

BEAM INTENSITY

Amount of energy, per unit time, through unit area of a plane at right angles to the direction of propagation ($J/s/m^2$).

Exposure rate (R/min or C/kg/min) ↘
dose rate (Gy/min) →All proportional to intensity
air kerma rate (Gy/min) ↗
etc.

BEAM QUALITY

The quality of an X-ray beam is a measure of its penetrating power.

Changing the quality of the beam will change the contrast between different types of tissue.

A highly penetrating beam is sometimes called a hard beam and a poorly penetrating beam is sometimes called a soft beam. Increasing the quality of the beam is sometimes called beam hardening.

Measuring quality

Beam quality can be described in various ways. The most commonly used parameter in diagnostic X-ray work is the **half-value thickness** (also known as HVT, half-value layer or HVL). This is usually the amount of aluminium needed to halve the intensity of an X-ray beam. A typical X-ray beam at 80 kVp might have an HVT of 3 mm aluminium.

An X-ray beam is usually **heterogeneous**. This means that it contains X-ray photons with lots of different energies (a spectrum of energies).

Homogeneous (monochromatic, monoenergetic) radiation beams contain photons which all have exactly the same energy.

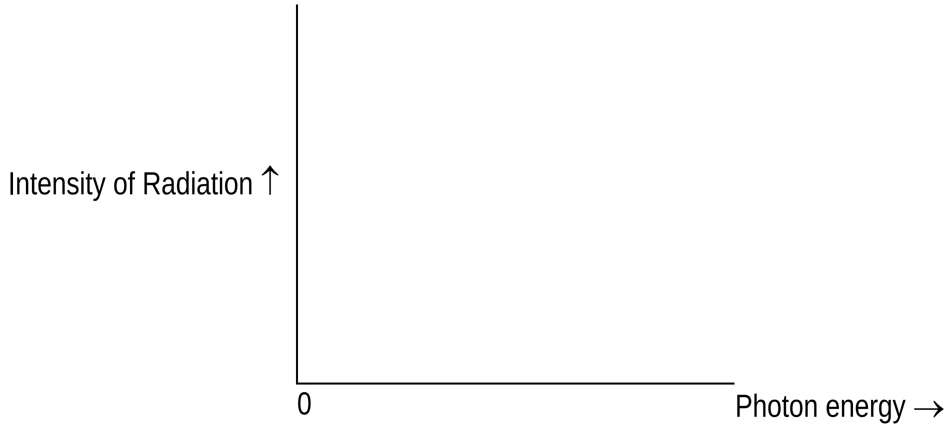
The radionuclide (radioactive chemical) technetium-99m (^{99m}Tc) emits homogeneous photons with an energy equivalent to 141 keV (i.e. all the photons have exactly 141 keV of energy). This beam will have an HVT of 17.8 mm aluminium. Therefore, an (heterogeneous) X-ray beam with an HVT of 17.8 mm Al can be said to have an **effective energy** of 141 keV, because it has the same HVT as a 141 keV homogeneous beam (it will, however, have a peak voltage, kVp, much greater than 141 kV).

As photon energy increases so penetrating power increases.

FACTORS AFFECTING BEAM INTENSITY AND QUALITY

Tube output depends upon;	tube voltage (kVp),	tube current (mA),
	target material,	H.T. waveform,
	filtration.	distance

(1) Tube Voltage - kVp

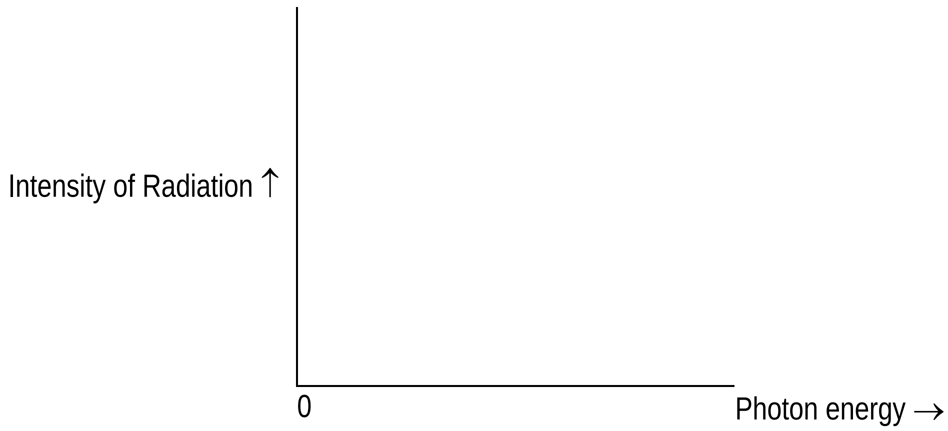


Intensity ∝ kV_P^2

(i.e. if kV is doubled, the intensity will be quadrupled.)

Quality increases with kV_p

(2) Tube Current - mA

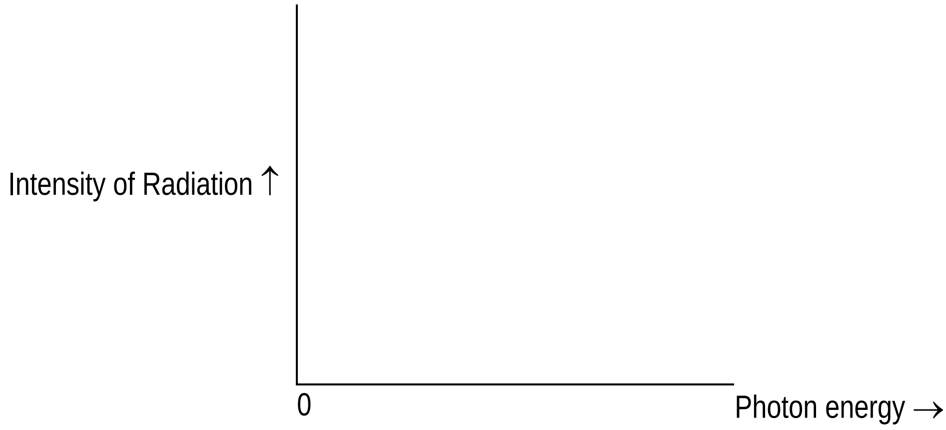


Intensity ∝ mA

(i.e. if mA is doubled, the intensity will be doubled.)

Quality independent of mA

(3) Target material - Z, the atomic number



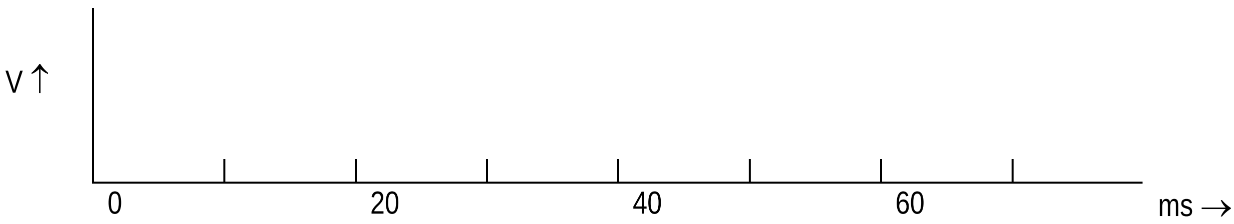
Intensity ∝ Z

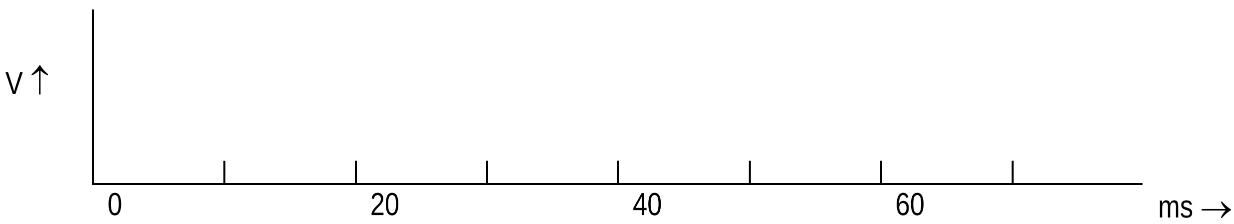
e.g. for tin, Z=51; for tungsten, Z=74.

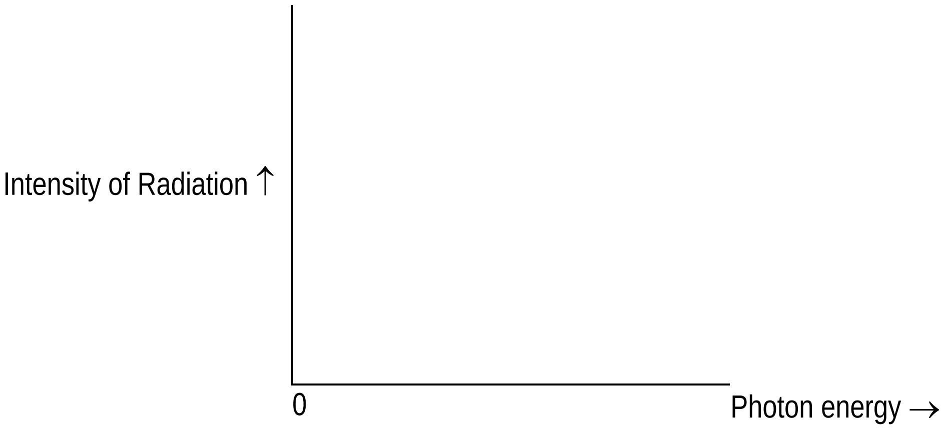
So for two X-ray sets with identical parameters, except that one has atin target and the other a tungsten target, the intensity produced bythe tungsten target tube will be 74/51 times greater.

Quality - Bremmstrahlung is unaffected, but characteristic radiation changes.

(4) H.V. Waveform



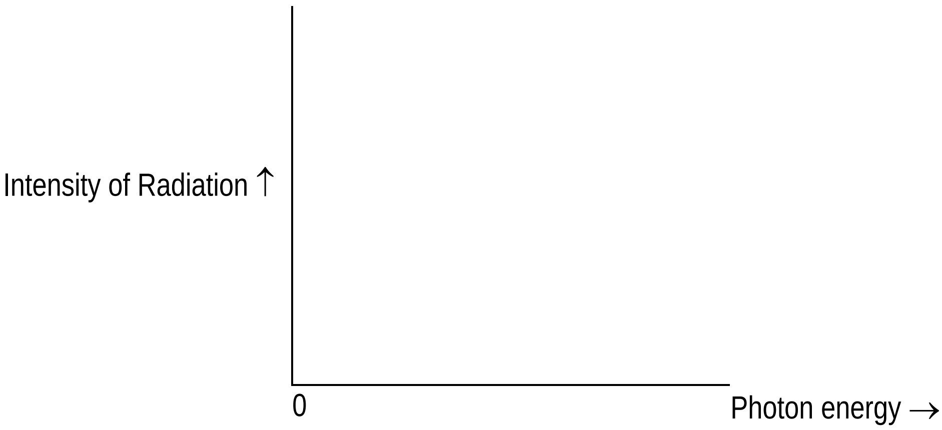




Intensity highest for constant potential as average kV is greatest.

Similarly, quality highest for constant potential.

(5) <u>Filtration</u>



Filtration reduces intensity

Filtration HARDENS the beam i.e. higher quality

(*Aside:* For monoenergetic beams, $I = I_0 \exp(-\mu.x)$ where x is the thickness of the filter, and μ is the linear attenuation coefficient. μ depends upon the photon energy, and the filter material, atomic number and electron density)

(6) Distance - THE INVERSE SQUARE LAW

The ISL states that the intensity of the radiation from a point source varies inversely as the square of the distance from thesource, providing there is no absorption or scattering by the medium.

Example 1

Q. If the exposure rate at 50 cm is 0.7 R/s, what is the exposure rate at 100 cm ?

A. Distance has increased by a factor of $^{100}/_{50} = 2$.

Therefore, by the inverse square law, the intensity is reduced by a factor $(^1/_2)^2 = 0.25$

i.e. exposure rate at 50 cm = 0.25 x 0.7 R/s = 0.175 R/s

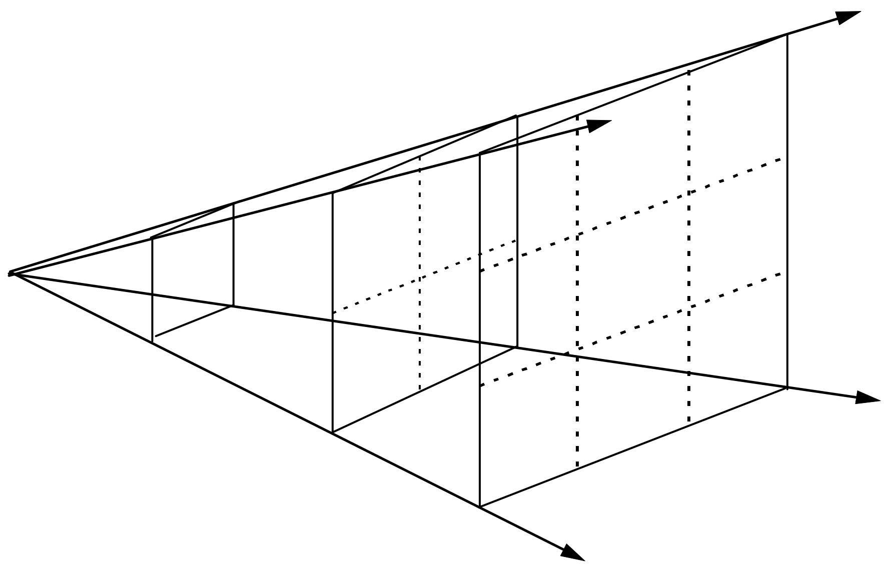
Example 2

Q. If the exposure rate at 70 cm is 0.45 R/s, what is the exposure rate at 80 cm ?

A. Distance has increased by a factor of $^{80}/_{70} = 1.14$.

Therefore, by the inverse square law, the intensity is reduced by a factor $^1/_{(1.14)}{}^2 = 0.769$

i.e. exposure rate at 70 cm = 0.769 x 0.45 R/s = 0.346 R/s



(7) Focal Spot Size

Most X-ray units have a choice of fine focus or broad focus. The size of the focal spot does not affect the intensity or quality of the beam.