Radiation Safety Training Module: Diagnostic Radiology

Basic Concept of Diagnostic X-ray Equipment, X-ray Interaction and Personnel Monitoring

Radiological Safety Division
Atomic Energy Regulatory Board

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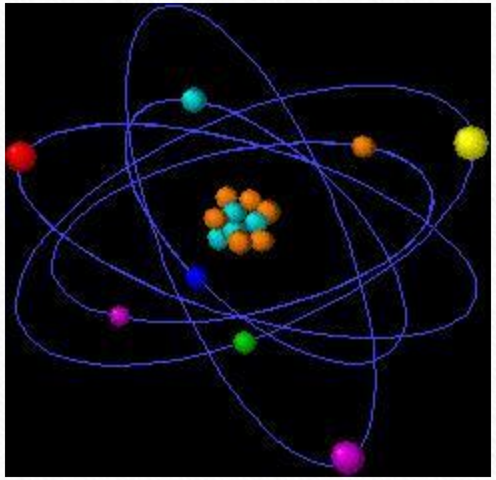
Expected questions to know after studying this lecture

- What is ionizing radiation?
- What is atomic number and mass number?
- Difference between X-rays & Gamma rays.
- How X-rays are produced?
- Properties of X-rays
- Basic components of X-ray equipment
- How X-rays interact with matter?
- Detection mechanism of X-rays

Atom Characteristics

- All matter is composed of atoms. The atom is the smallest division of an element in which the chemical identity of the element is maintained.
- The atom is composed of an extremely dense positively charged nucleus containing protons, neutrons and an extranucleus cloud of light negatively charged electrons.
- Atoms differ from one another in the constitution of their nuclei and in the number and arrangement of their electrons.



Atom Characteristic

- The **Atomic Number (Z)** of the atom is the number of protons in the nucleus.

- The **Mass Number (A)** of the atom is the total number of protons and neutrons in the nucleus.

Hydrogen	A = 1	Z = 1
Carbon	A = 12	Z = 6
Molybdenum	**A = 96**	**Z = 42**
Tungsten	**A = 183**	**Z = 74**
Uranium	A = 238	Z = 92

Radiation

Radiation: Radiation is the energy that travels through space or matter.

Ionizing and Non-ionising Radiation

- The radiation that we are exposed to can be ionizing or non-ionizing, depending on whether or not the radiation has enough energy to remove an electron from an atom with which it interacts.
- **Ionizing radiation:** is the type of radiation which causes the formation of ions (electrically- charged atoms or molecules) when interacting with matter. These ions can lead to biological damage in cells.
- X-rays, gamma rays, neutrons, cosmic rays are ionizing radiation. They contain enough energy per photon to eject electrons from the atoms with which they interact.
- **Non-ionising radiation:** is the type of radiation which does not have enough energy to eject electrons from the atoms with which they interact, hence can not cause ionisation
- Visible light, infrared waves, radiofrequency waves are non-ionizing radiation.

Radiation

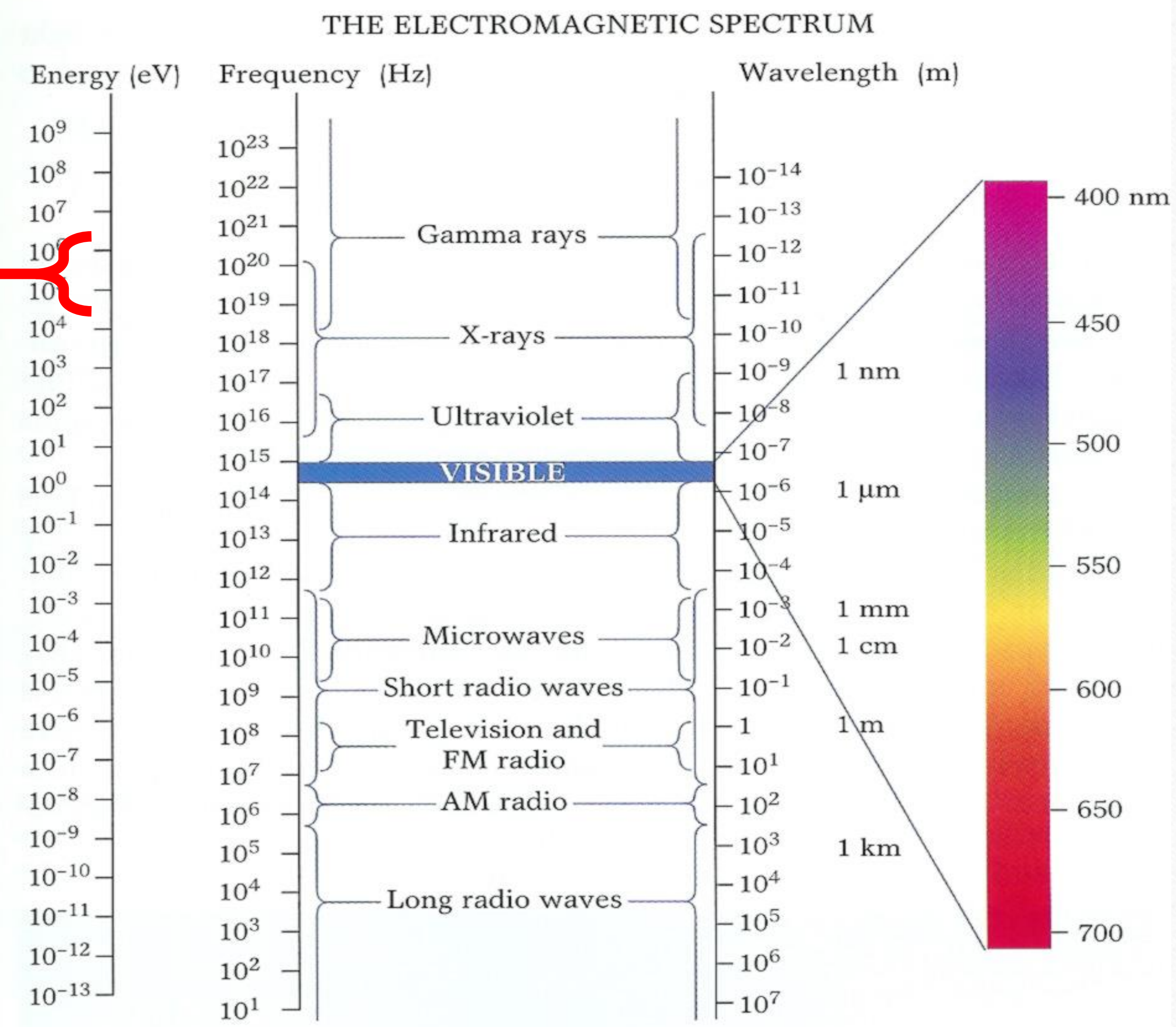
Electromagnetic Radiation: Electromagnetic radiation (EM) has no mass, is unaffected by either electrical or magnetic fields and has a constant speed in a given medium.

- Although EM radiation propagates through matter, it does not require matter for its propagation. Its maximum speed occurs $3X10^8$ m/sec in vacuum.

EM radiations used in diagnostic imaging include:

- **X-rays**, which are produce outside the nucleus and are used for radiological imaging purposes (radiography, mammography, computed tomography, Dental equipment etc.)
- **Gamma rays**, which are emitted from the nuclei of radioactive atoms (used to image the dtribution of radiopharmaceuticals in Nuclear Medicine as diagnostic procedure).

X-rays



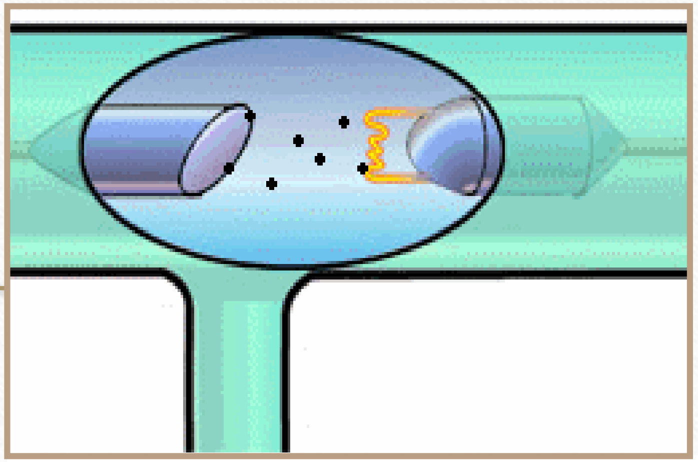
THE ELECTROMAGNETIC SPECTRUM
Energy (eV)
Frequency (Hz)
Wavelength (m)
Gamma rays
X-rays
Ultraviolet
VISIBLE
Infrared
Microwaves
Short radio waves
Television and FM radio
AM radio
Long radio waves
1 nm
1 μm
1 mm
1 cm
1 m
1 km
400 nm
450
500
550
600
650
700

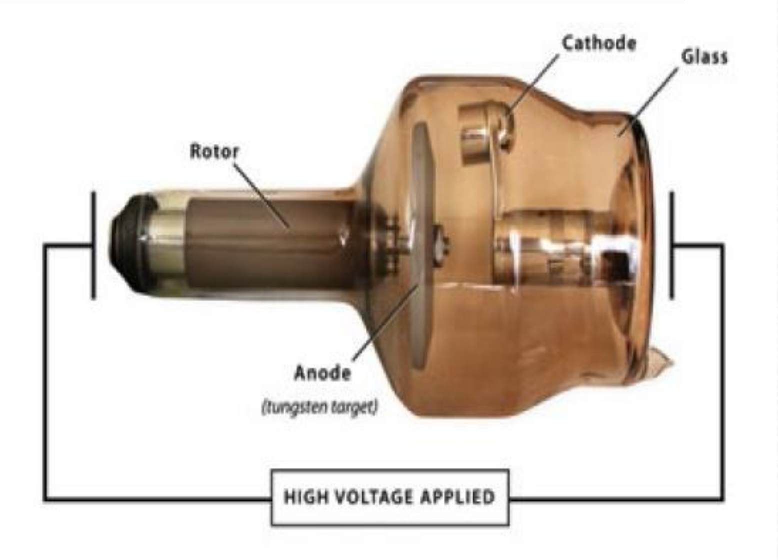
X-Rays and Gamma Rays

- X-rays and gamma rays are differed only **by their origin in the nucleus**.
- **Gamma rays** originate within the nucleus of the atom, whereas **X-rays** are generated outside the nucleus by the interaction of high speed electrons with the atom.
- Gamma rays emitted by a single radionuclide consist one or several discrete energies.
- X-rays consist of a broad spectrum of energies.
- X-rays and gamma rays are alike in their mode of interaction with matter, their biological effects and their photographic effects.

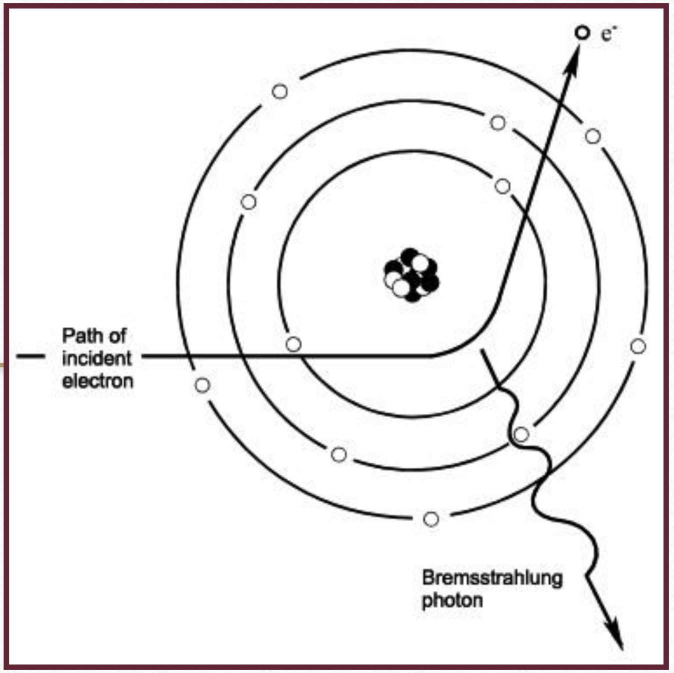
X-ray Production

- X-rays are produced when high energy electrons interact with matter and convert their kinetic energies into electromagnetic radiation.
- The production of an x-ray beam in a clinical imaging system is performed by the x-ray tube. Inside the x-ray tube, an electron beam is generated by liberating electrons from the filament via thermionic emission (heating of the filament).
- Electrons are accelerated towards the anode by applying potential difference between Anode and Cathode. As a result of interaction of electrons with target atoms, electrons transfer its kinetic energy into heat and x-ray photons.





X-ray Production…



X-rays are produced in two ways:

- Production of Bremsstrahlung Radiation
- Production of Characteristic Radiation

Production of Bremsstrahlung Radiation:

When an electron comes within the proximity of a positively charged nucleus of an atom in the target electrode, it decelerates resulting a significant loss of its kinetic energy in the form of x-ray photons. An x-ray photon with energy equal to the kinetic energy lost by the electron is produced (conversion of energy).

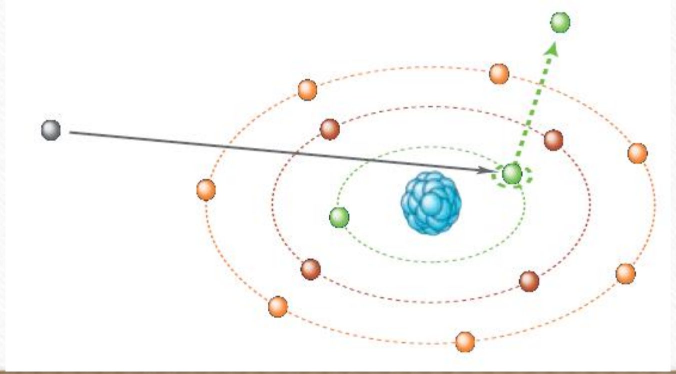
This radiation is termed as **bremsstrahlung**, a German word meaning “braking radiation” or radiation produced from the braking of projectile electrons.

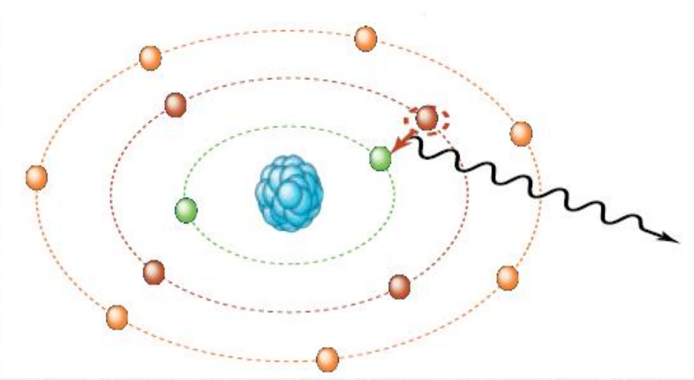
X-ray Production...

Production of Characteristic Radiation:

If energy of incident electron is more than binding energy of target atom, the incident electrons may eject electrons from the target atom creating vacancy in the shell. Electrons from higher shells then fill this vacancy, resulting in the emission of **characteristic X-rays**.

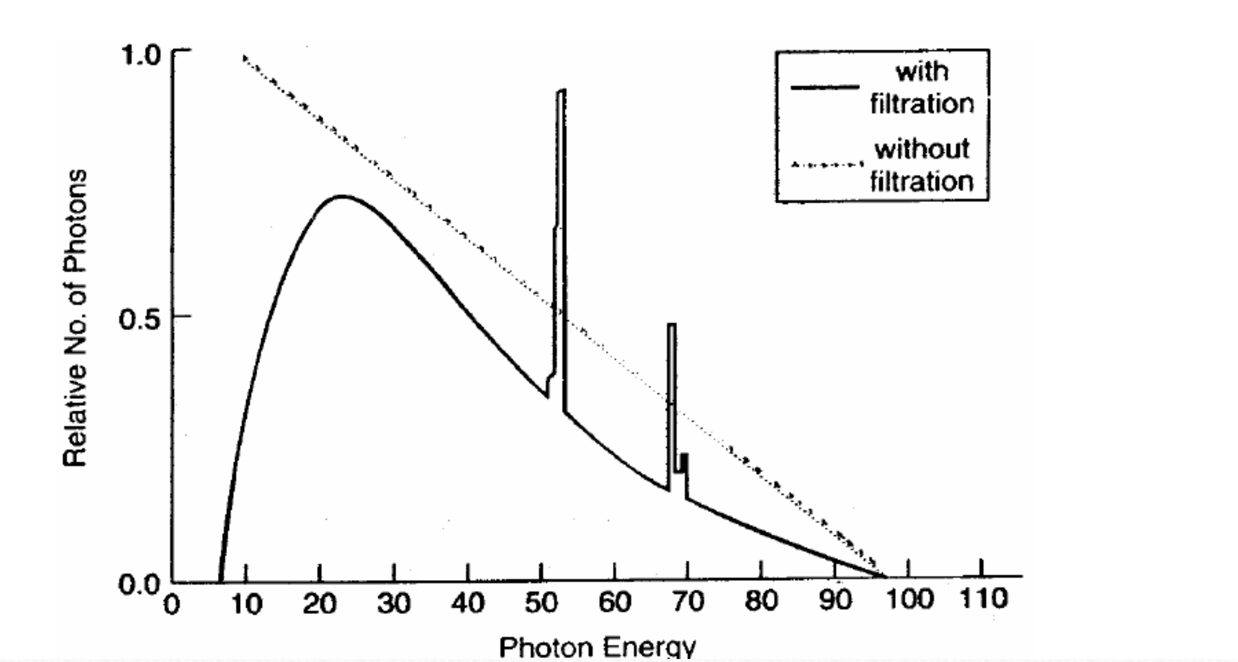
As a result of interaction between the electron and the target material, about 99% of the energy is converted into heat and about 1% is converted into X-ray energy.





X-ray Production…

- CONTINUOUS curve represents **Bremsstrahlung Radiation**
- DISCRETE line represents **Characteristic Radiation**



Properties of X-rays

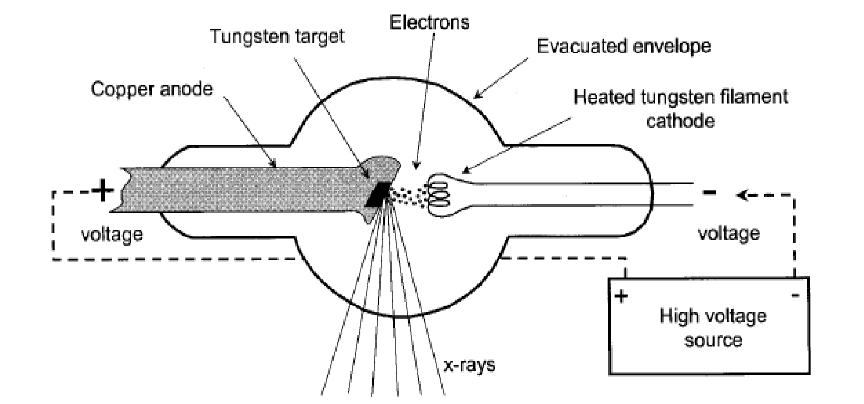
- X-rays are highly penetrating invisible rays.
- They are electrically neutral and can not be deflected by electric or magnetic fields.
- They are capable of ionizing the interacting medium.
- They produce biological and chemical changes in the interacting medium.
- They affect photographic film to produce an image which can be developed chemically.

Basic elements of an X- ray equipment

Basic elements of an X-ray equipment:

- X-ray Generator
- X-ray Tube - Cathode structure, Anode structure

  Focal Spot, Collimator, Tube Housing
- X-ray image receptor
- Couch



Basic elements of an X- ray equipment...

X-ray Generator

It is the power circuit supplying the required potential to the X-ray tube.

- It supplies the current to heat the filament of the cathode to emit electrons.
- It supplies the potential to accelerate electrons from cathode to anode.
- The generator also permits control of the x-ray output through the selection of voltage, current and exposure time.

Basic elements of an X- ray source assembly...

X-ray Tube :

- The X-ray tube provides an environment for X-ray production via bremsstrahlung and characteristic mechanism.

X-ray Tube Components:

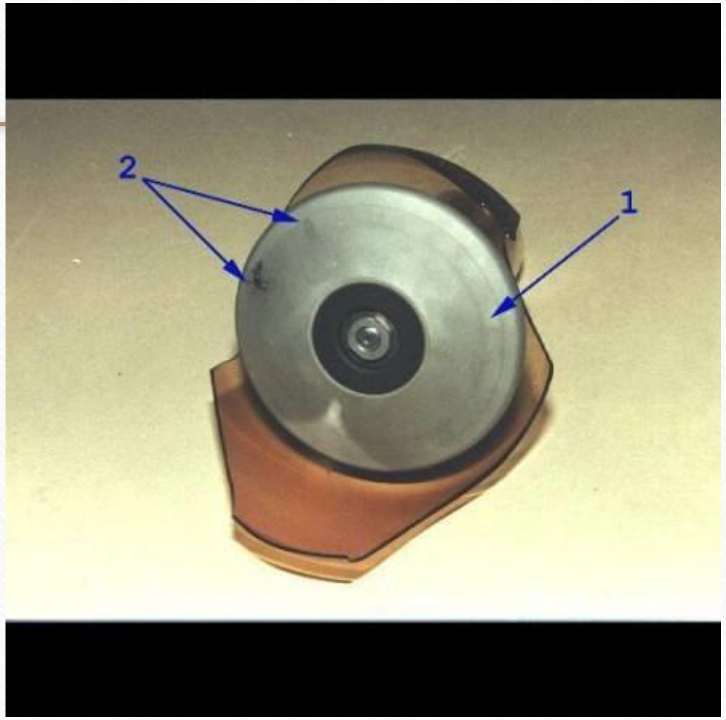
- **Cathode**: It contains filament which is the source of the electron beam directed towards the anode.
- **Anode**: It emits X-rays on impacted by electrons.
- **Metal tube housing:** It provides surrounding to glass X-ray tube.
- **Shielding material:** It provides protection against x-rays produced in the direction other than primary beam.

Basic elements of an X- ray equipment...

X-ray Tube Components

Anode

- The anode is made usually a massive piece of copper into the end of which small target (10% Rhenium, 90% Tungsten) is placed
- **Tungsten:-** High Melting point (3410 ^{o}C)
- **Rhenium:-**Used in small quantity (5-10%) to prevents crazing of the anode surface (Melting point 3182 ^{o}C).



1 : anode track
2 : anode track

Basic elements of an X- ray equipment...

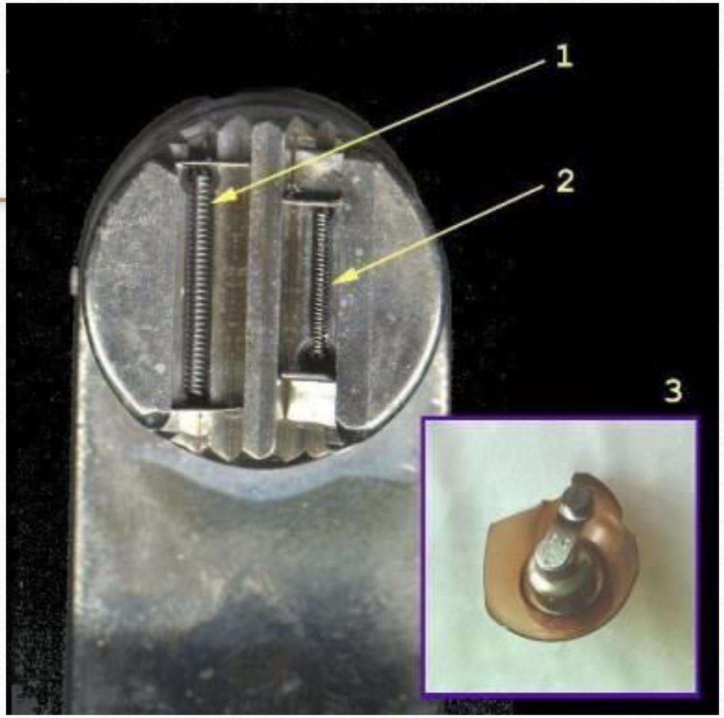
X-ray Tube Components

Cathode

Cathode is a negatively charged electrode, which contains filament for source of electrons.

Filament is made of tungsten (W) due to following properties:

- High melting point (3410 ^{o}C),
- High corrosion resistance,
- High temperature resistance,
- Inactive to react with inert gases.



1: long tungsten filament
2 : short tungsten filament
3 : real size cathode

Basic elements of an X- ray equipment...

X-ray Tube Components

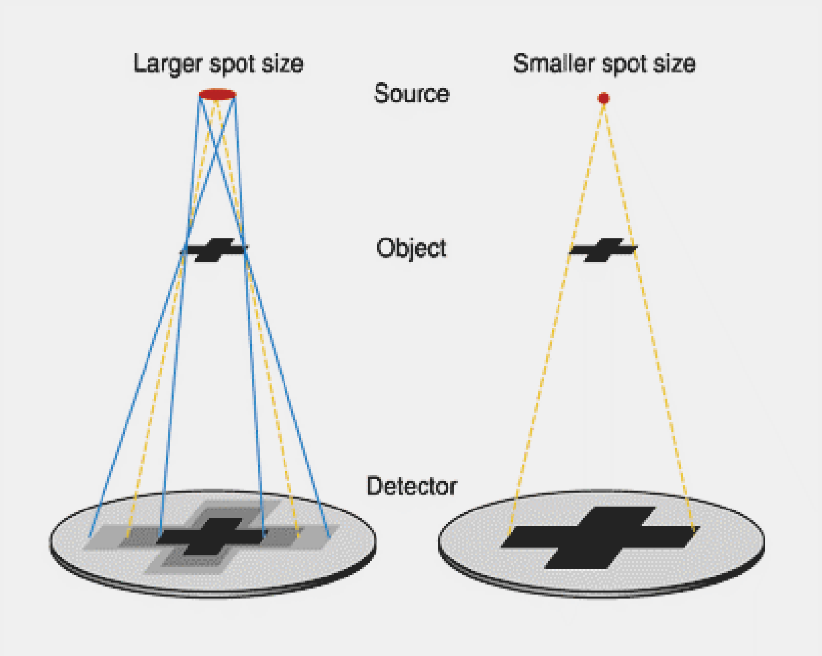
1: mark of focal spot

Focal Spot size is defined in two ways:

The **actual focal spot size** is the area on the anode that is struck by electrons and it is primarily determined by the length of cathode filament and the width of the focusing cup slot.

The **effective focal spot size** is the length and width of the focal spot as projected down in the X-ray field.

- Small focal spot size → reduced tube output (longer exposure time)
- Large focal spot → allows high output (shorter exposure time)



Basic elements of an X- ray equipment...

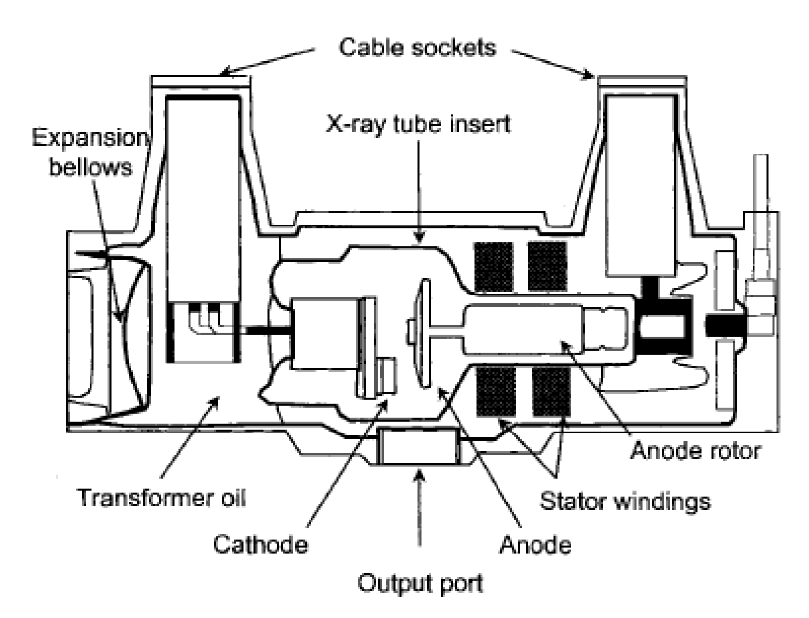
X-ray Tube Components

X-ray Tube Insert

- The x-ray tube insert contains the cathode, anode, rotor assembly and support structures sealed in glass or metal enclosure under a high vacuum.
- The high vacuum prevents electrons from colliding with gas molecules.

X-ray Tube Housing

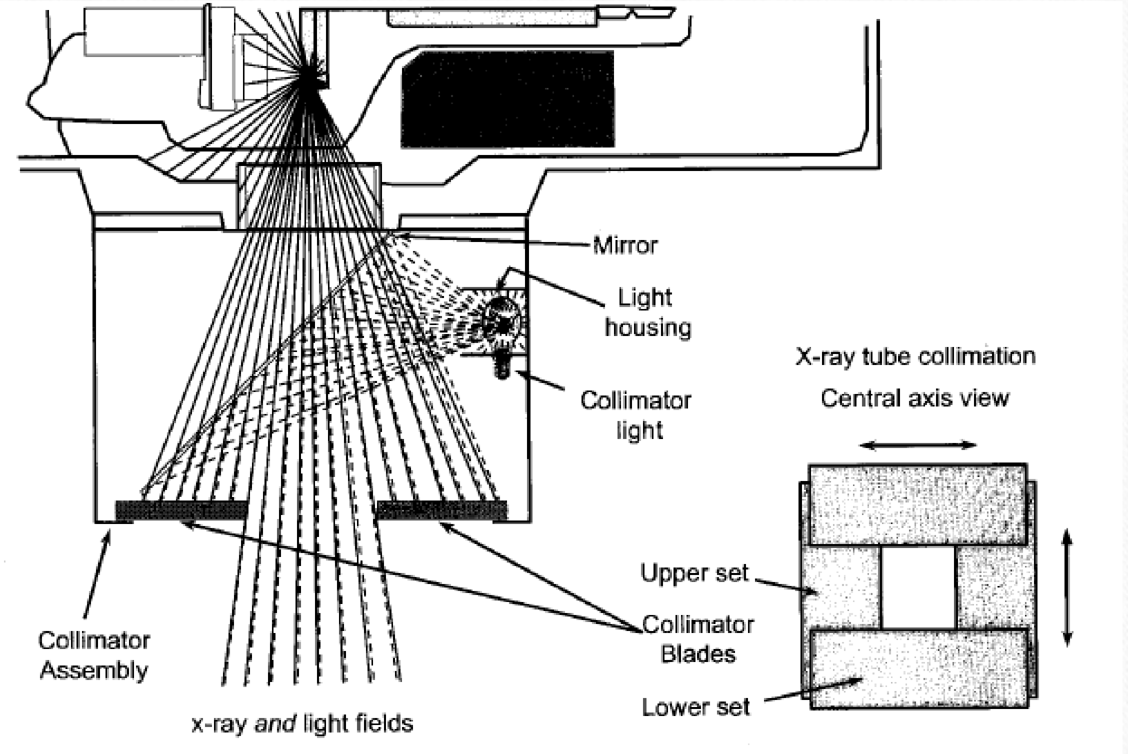
- The x-ray tube housing supports, insulates and protects the x-ray tube insert from the environment.
- The x-ray tube insert is bathed in a special oil, contained within the housing, that provides heat conduction and electrical insulation.
- A typical x-ray tube housing contains a bellows to allow for oil expansion as it absorbs heat during operation.



Basic elements of an X- ray equipment...
X-ray Tube Components

Collimators-

- Collimators adjust the size and shape of the X-ray field emerging from the tube port.
- The typical collimator assembly is attached to the tube housing at the tube port with a swivel joint. Adjustable parallel –opposed lead shutters define the x-ray field.
- In the collimator housing, a beam of light reflected by a mirror mimics the X-ray beam.



Basic elements of an X- ray equipment...

X-ray image receptors used in the x-ray equipment are as follows:

- X-ray film/Screen
- Computed Radiography cassette (CR)
- Digital detectors (DR)

The details about functioning of these detectors is covered in the another presentation on “Medical X-ray Imaging Techniques”

Couch: Couch is used as patient Support assembly during imaging. This is generally made up of carbon fiber. The X-ray attenuation of the couch shall be less than 1 mm of Al equivalence.

Typical X-ray equipment

FACTORS AFFECTING X RAY SPECTRUM

The output of an x-ray tube is described by the term quality, quantity, and exposure.

- **Quality** describes the penetrability of the X-ray beam, with higher energy x-ray photons having a larger HVL and higher quality.
- **Quantity** describes the number of photons comprising the beam.
- **Exposure** is a dosimetric quantity for ionizing radiation based on the ability of the radiation to produce ionization in air.

FACTORS AFFECTING X RAY SPECTRUM…..

X-ray Quality

- TUBE POTENTIAL
- FILTRATION
- WAVE FORM

X-ray Quantity

- TUBE CURRENT (mA)
- EXPOSURE TIME (s)
- TUBE POTENTIAL (kVp)
- WAVEFORM
- DISTANCE (FSD)
- FILTRATION

- The **Exposure (X)** is the total charge (dQ) of the ions produced in air when all the electrons liberated by photons per unit mass (dm) of air are completely stopped in air.

$$X = dQ/dm$$

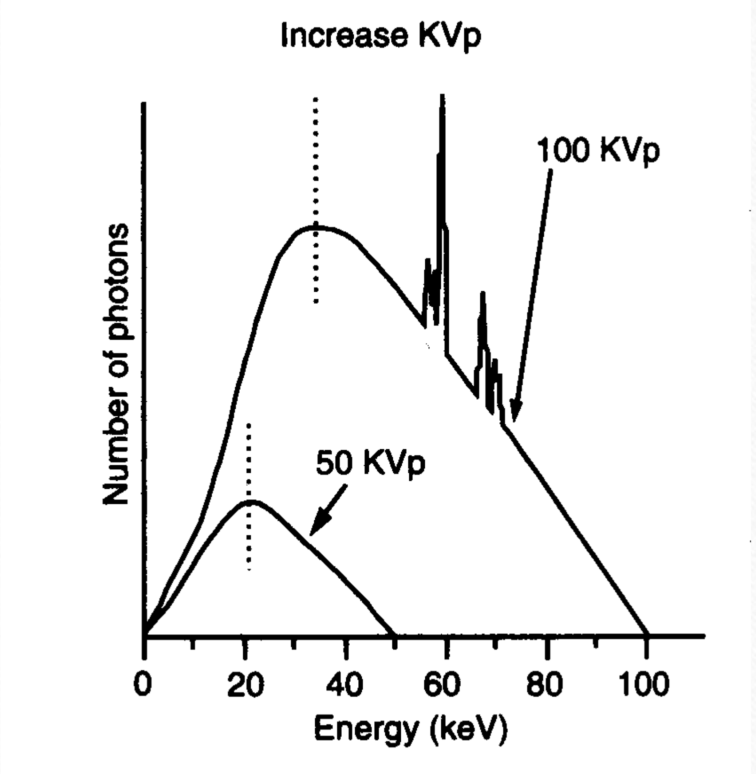
- The SI unit of exposure is Coulomb/kg [C kg-1] and former special unit was Roentgen [R] whereas **1 R = 2.58 x 10^{-4} C kg^{-1}**

FACTORS AFFECTING X RAY SPECTRUM…Tube Potential

Change in QUANTITY &

Change in QUALITY

- **Spectrum shifts to higher Energy**
- **Characteristic lines appear**

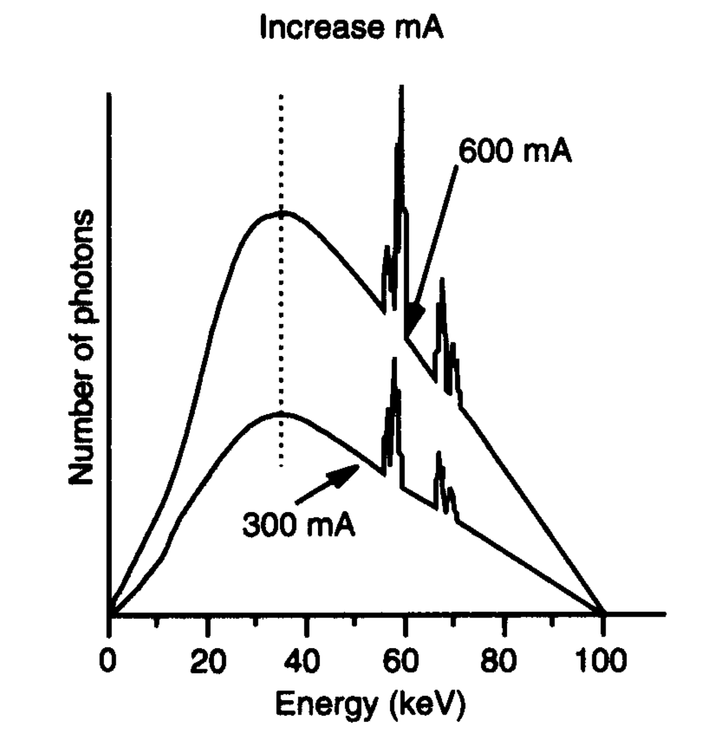


FACTORS AFFECTING X RAY SPECTRUM… Tube Current

Change of QUANTITY

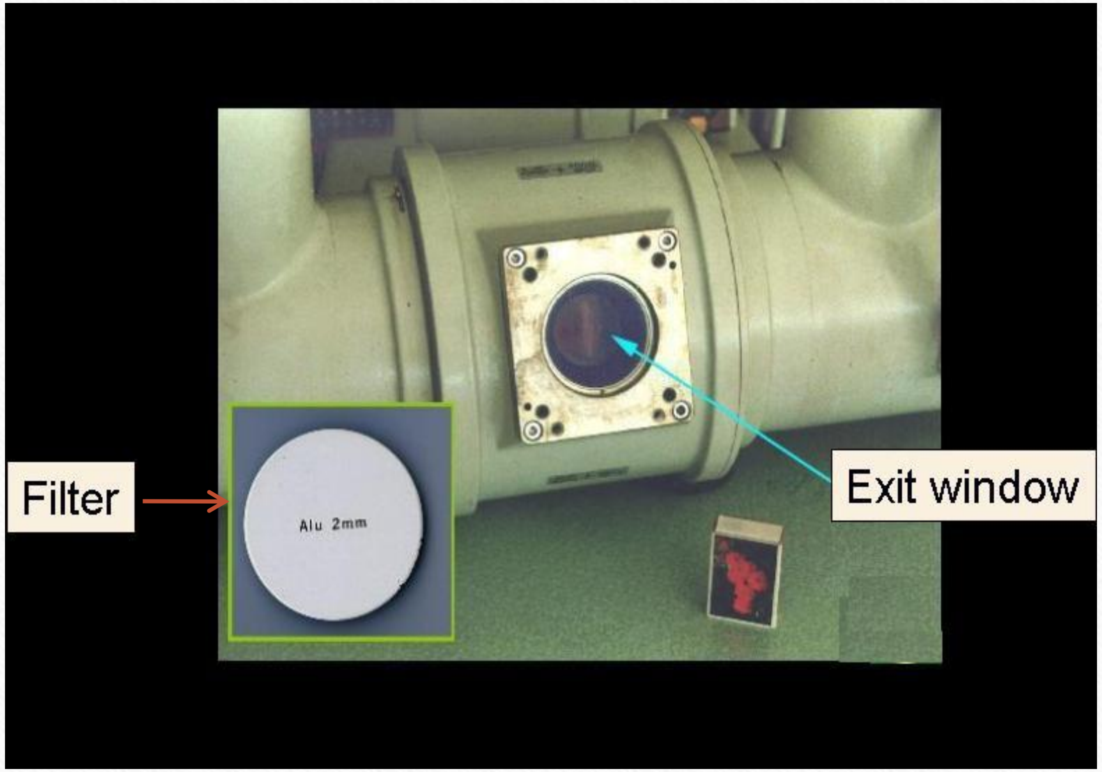
No change of quality

Effective kV not changed



FACTORS AFFECTING X RAY SPECTRUM…Tube filtration

- Filters are X-rays absorbers placed between X-ray source and object.
- Filters preferably absorb the lower energy photons or absorb parts of spectrum.



FACTORS AFFECTING X RAY SPECTRUM…Tube filtration

Inherent filtration (always present)

- Reduced entrance (skin) dose to the patient (cut off the low energy X-rays which do not contribute to the image)

Additional filtration (removable filter)

- Further reduction of patient skin and superficial tissue dose without loss of image quality.

Total filtration = Inherent + Added

- **Tolerances:**

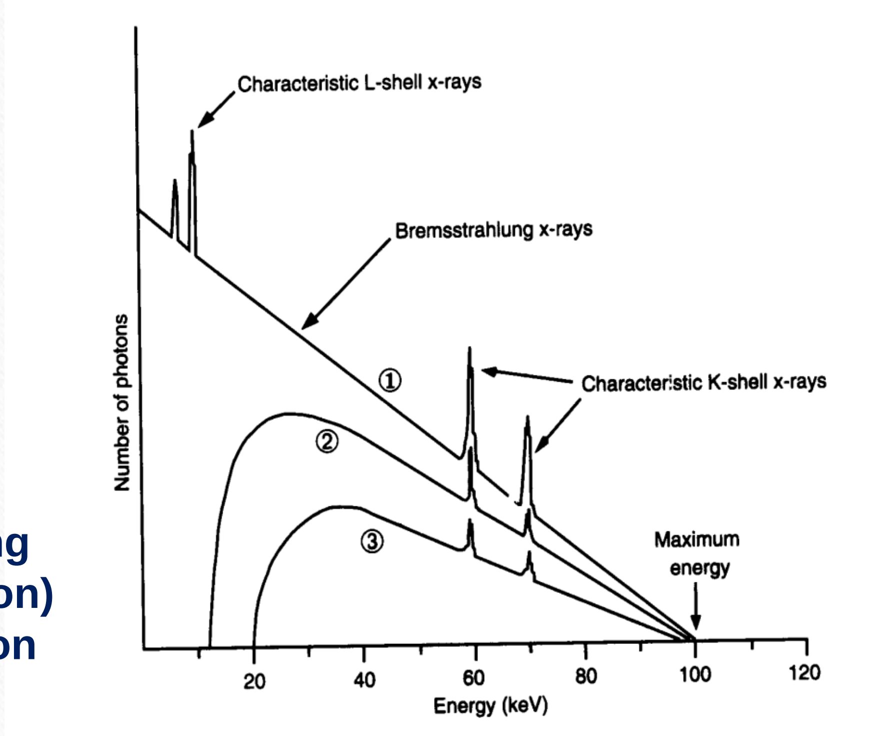
Maximum rated tube potential	Minimum total filtration (mm Al)
Less than 70	1.5
70 to and including 100	2.0
Above 100	2.5

FACTORS AFFECTING X RAY SPECTRUM…Tube filtration

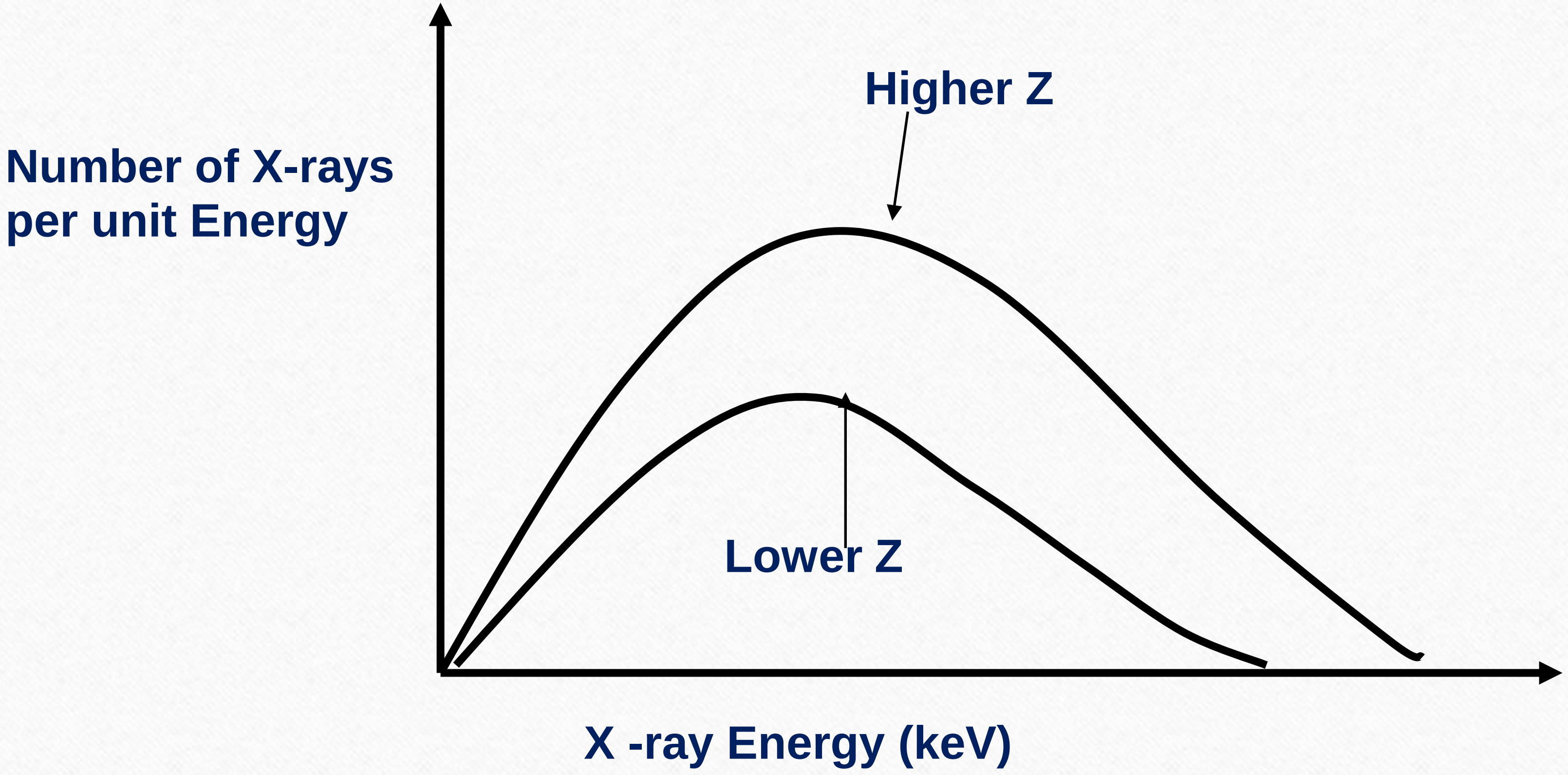
Change in QUANTITY & Change in QUALITY

- **Spectrum shifts to higher energy**

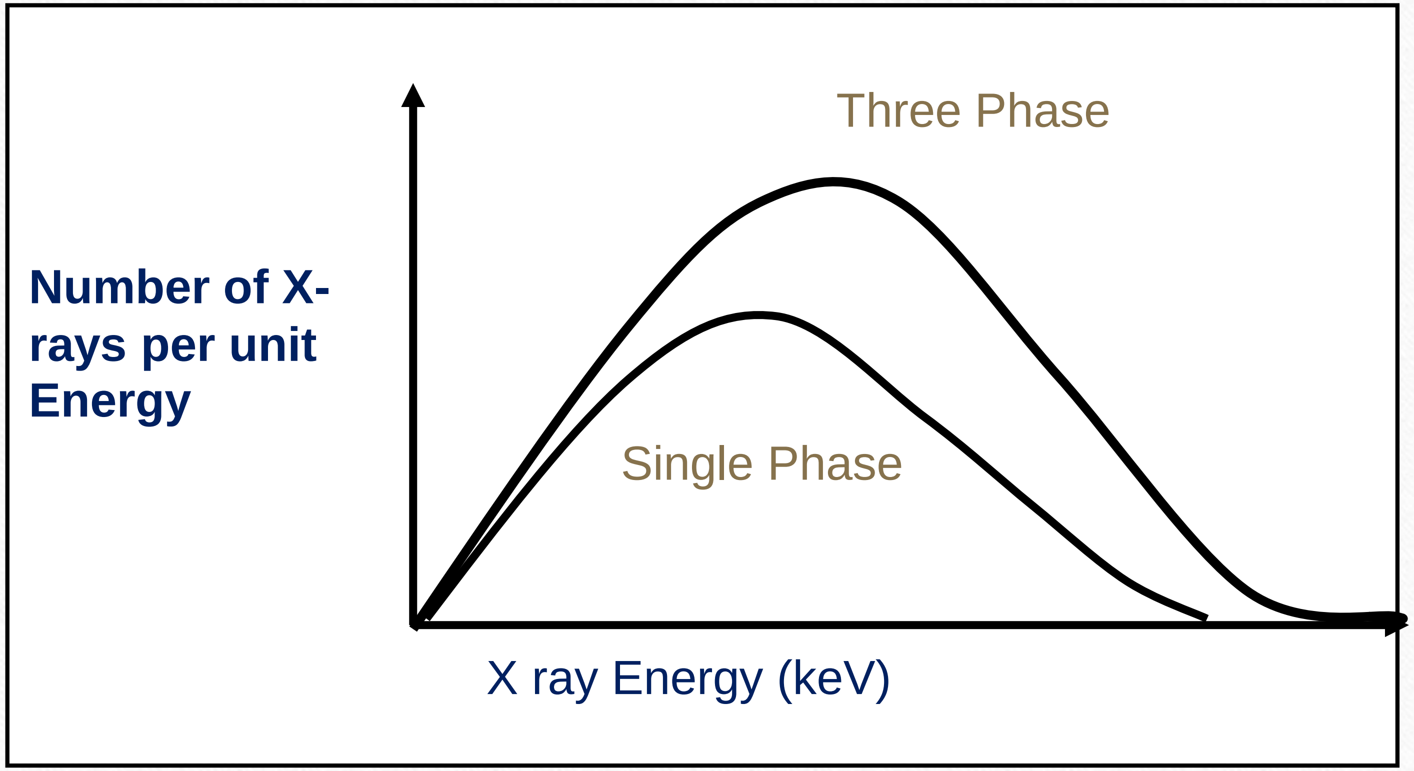
1- Spectrum out of anode
2- After window tube housing
(INHERENT filtration)
3- After ADDITIONAL filtration



FACTORS AFFECTING X RAY SPECTRUM…Target Z



FACTORS AFFECTING X RAY SPECTRUM…Waveform (i.e. Type of power supply)



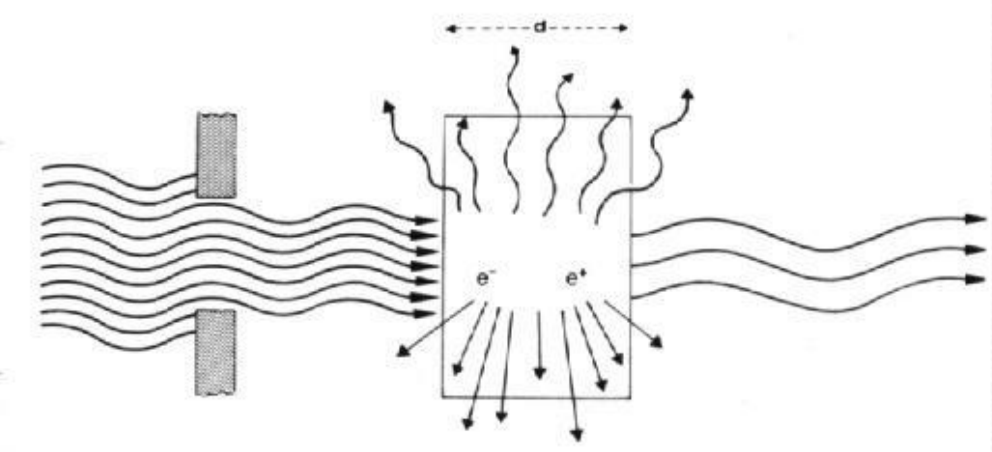
Interaction of X-rays with matter

When traversing matter, photons will penetrate, scatter or absorbed. There are three major types of interactions of X and gamma rays photons with matter:

- Photoelectric Effect
- Compton Scattering
- Pair Production

The absorption is characterized by Photoelectric Effect and Pair Production.

The scatter is characterized by Compton Scattering.



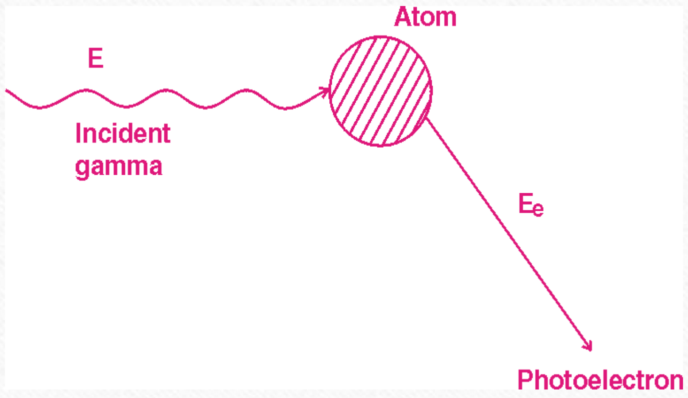
Interaction of X-rays with matter

Photoelectric Effect

- In the photoelectric effect, all of the incident photon energy is transferred to an electron, which is ejected from the atom. The kinetic energy of the ejected photoelectron (E_e) is equal to the incident photon energy (E_o) minus the binding energy of the orbital electron (E_b).

$$\mathbf{E_e = E_e - E_b}$$

- In order for the photoelectric absorption to occur, the incident photon energy must be greater than or equal to the binding energy of the electron that is ejected.



Photoelectric Absorption : Full energy deposition of the X-rays.

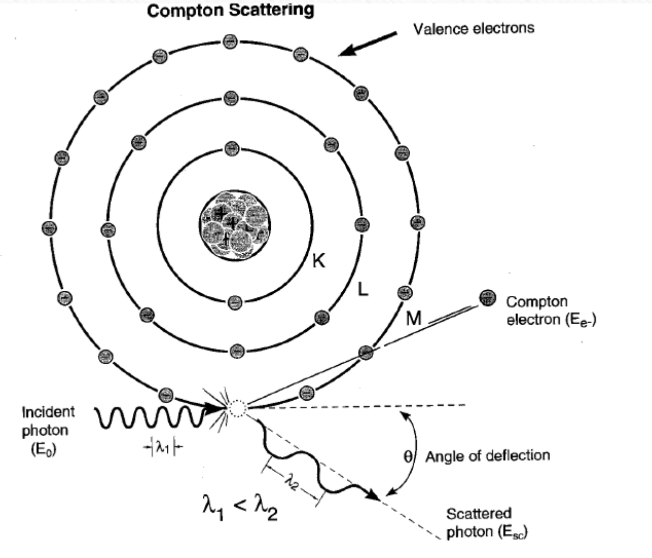
Interaction of X-rays with matter...

Compton Scattering

- Compton scattering is the predominant interaction of X-ray and gamma ray photons in the diagnostic energy range with soft tissues.
- This interaction is most likely to occur between photons and outer (valence) shell electrons. The electron is ejected from the atom and the photon is scattered with some reduction in energy.
- Thus the energy of the incident photon (E_0) is equal to the sum of the energy of scattered photon (E_{sc}) and the kinetic energy of the ejected electron (E_e) i.e.

$$\mathbf{E_0 = E_{sc} + E_e}$$

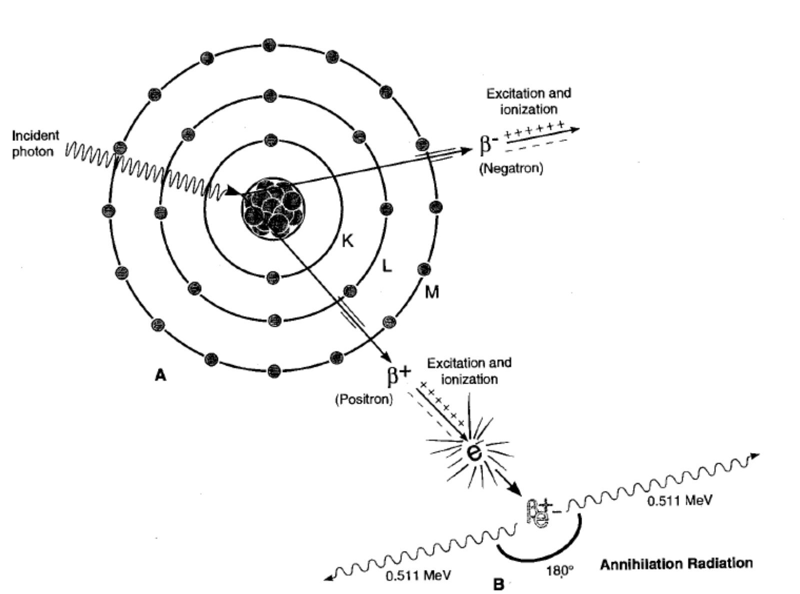
- The ejected electron will lose its kinetic energy via excitation and ionization of atoms in the surrounding material.



Interaction of X-rays with matter...

Pair Production

- Pair Production can only occur when the energies of X-ray and gamma rays exceed 1.02 MeV.
- In Pair-Production, an X -or gamma ray interacts with the electric field of the nucleus of the atom. The photon energy is transformed into an electron- positron pair.
- Photon energy in excess of this threshold is imparted to the electron and positron as kinetic energy. The electron and positron lose their kinetic energies via excitation and ionization. When the positron comes to rest, it interacts with a negatively charged electron, resulting in the formation of two oppositely directed 0.511 MeV annihilation photons



Radiation Detection and Measurement

Radiation Monitoring is carried out:

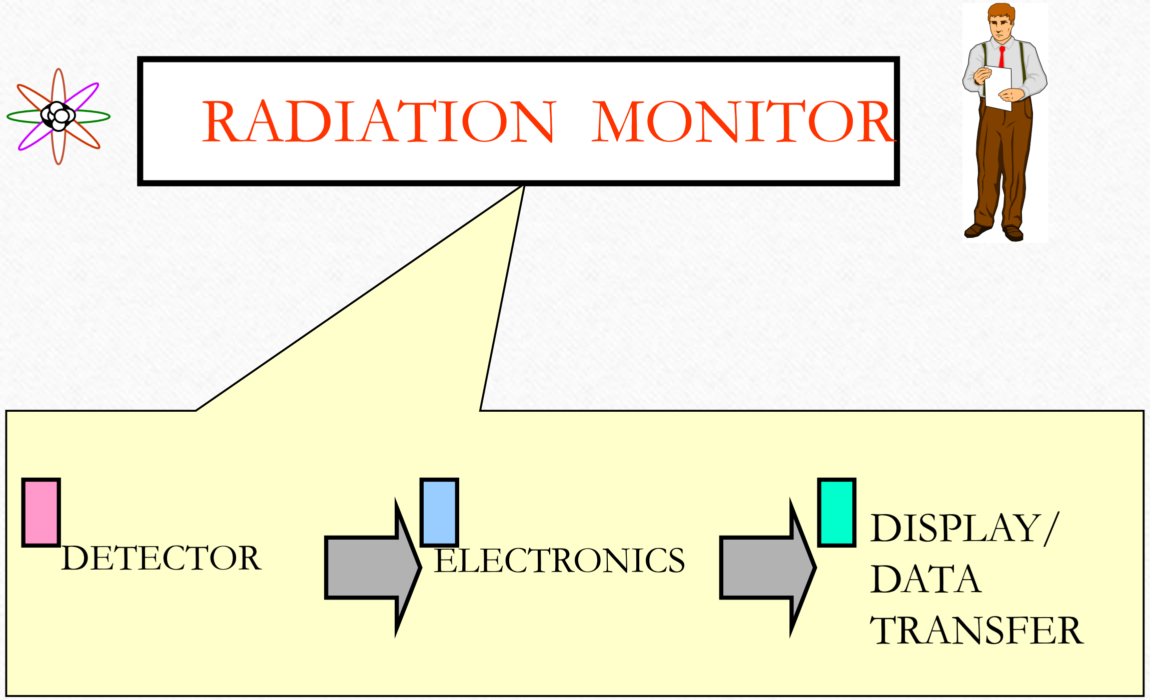
- To assess workplace conditions and individual exposure;
- To ensure acceptably safe and satisfactory radiological conditions of workplace and
- To keep records of monitoring over a long period of time for good practice.

Properties of Area Monitoring Instrument :

- A low battery visual indication
- Automatic zeroing, automatic ranging
- An analog or digital display
- Remote operation and display of readings

In Diagnostic Radiology, Mainly Ionization Chamber and Semiconductor based Survey Meters are used for radiation survey purpose.

Radiation Detection and Measurement...



Radiation Monitoring Instruments

Area Monitoring

Ionization based Survey Meter

Semiconductor based Survey Meter

Personal Monitoring

Thermo luminescent Dosimeter (TLD)

Direct Reading Dosimeter (DRD)

Radiation Detection and Measurement...

Personnel Monitoring:

In India, Thermo luminescence Dosimeter (TLD) are used for personnel monitoring purposes. Calcium Sulphate doped with Dysprosium ($CaSO_4$: Dy) is used as TL Phosphor for personnel monitoring applications.

Basic Principle:

Upon incidence of ionizing radiation, electrons and holes are produced and trapped immediately at the respective trapping centers. On heating, these trapped electrons/holes will be released from their respective sites and are free to move in the crystal. Recombination of these electrons and holes results in photon (of Energy ~ 3-4eV) emission of visible region.

<u>Energy released is proportional to absorbed radiation dose recorded by TLD.</u>

In summary,

- Radiation moves electrons into “traps”
- Heating moves them out
- Energy released is proportional to absorbed radiation

Radiation Detection and Measurement. .. Personnel Monitoring...

Direct Reading Personnel Monitor: It is used to provide a direct readout of dose at any time. These dosimeters are helpful for tracking of dose in day-to-day activities.

Operation: X/γ radiation falling on semiconductor diode detectors will give an electrical pulse. Pulse rate from the detector is proportional to the intensity of the radiation falling on it. These pulses are counted and after multiplication with a suitable factor displayed on a digital display.

Specifications:

Detector	PN junction silicon semiconductor
Radiation detected	X / γ radiation (> 40 keV)
Dose range	1 μSv to 99999 μSv
Power	Coin type Lithium Battery

Summary/ Learning Outcomes

- To understand the atom characteristics and electromagnetic radiation.
- To understand the principles of the X-ray production.
- To understand Bremsstrahlung and characteristic radiation.
- To understand that several factors (kV, filtration, current, waveform, target material) influence quality and/or quantity of the X-ray beam.
- To understand the concepts of interaction of X-rays with matter, radiation detection and measurement aspects of x-ray radiation.

This presentation will be helpful for the medical professionals associated with use of diagnostic X-ray equipment for understanding diagnostic x-ray equipment, interaction properties of X-rays with medium and radiation monitoring.

Expected Questions

Q.1 What is atomic number of an atom?

Ans. The Atomic Number (Z) of the atom is the number of protons in the nucleus as well as the number of electrons outside the nucleus.

Q.2 What is mass number of an atom?

Ans. The Mass Number (A) of the atom is the total number of protons and neutrons in the nucleus.

Q.3 What is atomic number and mass number of Tungsten?

Ans. Atomic Number (Z) = 74 Mass Number (M) = 183

Q.4 What is radiation?

Ans. Radiation is the energy that travels through space or matter.

Q.5 Give two examples of ionizing and non-ionising radiation?

Ans. Ionising radiation- Gamma rays and X-rays

Non-ionising radiation- Visible light and Infra-red waves.

Expected Questions

Q.6 How X-rays are produced?

Ans. X-rays are produced when highly energetic electrons interact with matter and convert their kinetic energy into electromagnetic radiation.

X-ray are produced in two ways:

- Production of Bremsstrahlung Radiation
- Production of Characteristic Radiation

Q.7 Why Tungsten is used as target material of X-ray production?

Ans. Tungsten is used as target material for X-ray production because of its high atomic number (Z=74) and high melting point (3410°C).

Q.8 Pl. explain three properties of X-rays?

Ans. 1. X-rays are highly penetrating invisible rays.

2. They are electrically neutral and can not be deflected by electric or magnetic fields.

3. They affect photographic film, producing a latent image which can be developed chemically.

Expected Questions

Q.9 How tube potential affect X-ray Production?

Ans.Tube potential (kVp) determines the maximum energy in the bremsstrahlung spectrum and affects the quality of the output spectrum.

Q.10 How x-rays interact with human tissue during imaging?

Ans. Photoelectric absorption is the primary mode of interaction of diagnostic X-rays with screen phosphors, radiographic contrast materials and bone. Compton scattering predominates at most diagnostic photon energies in materials of lower atomic number such as tissue and air.

Q.11 Why radiation monitoring is carried out in radiation facility?

Ans. To assess workplace conditions and individual exposure.

To ensure acceptably safe and satisfactory radiological conditions of workplace.

To keep records of monitoring over a long period of time for good practice.

Q.12 Which Thermo luminescence Phosphor is used in personnel monitoring in India?

Ans. In India, Calcium Sulphate doped with Dysposium ($CaSO_4$: Dy) is used as TL Phosphor for personnel monitoring applications.

References and sources for additional information

- The Essential Physics of Medical Imaging (J. T. Bushberg, J.A. Seibert, E.M. Leidholdt, J M Boone)
- The Physics of Radiology (H.E. Johns, J.R. Cunnighnam)
- Introduction to Health Physics (H. Cember)
- Radiation Detection and Measurement (G. Knoll)
- IAEA Presentations on Diagnostic Radiology

List of presentations in the training Module

Basics of Diagnostic X-ray Equipment
Biological effects of Radiations
Medical X-ray imaging techniques
Planning of Diagnostic X-ray facilities
Quality Assurance of X-ray equipment
Quality Assurance of Computed Tomography equipment
Radiation Protection in Diagnostic Radiology Practice
Causes, prevention and investigation of excessive exposures in diagnostic radiology
Regulatory Requirements for Diagnostic Radiology Practice

THANK YOU