X-rays

Introduction

X-rays are photons of electromagnetic radiation. X-rays are basically the same as visible light rays in that both are forms of electromagnetic waves. X-rays have a shorter wavelength, a higher frequency and energy than visible light.

To generate X-rays, three items are requiered:

1. Production of electrons
2. Acceleration of the electrons to high velocity
3. Interaction with a target material

1- Production of electrons

Production of electrons takes place in the X-ray tube. The tube contains an electrode pair: a cathode and an anode (Figure 1). The cathode is a helical filament made of tungsten wire. Due to electrical resistance the filament heats up when a current (filament current) passes through the cathode. Transfer of the heat energy to the electrons of the filament results in emission of electrons from the filament. The rate of electron emission depends on the temperature, which is determined by the filament current.

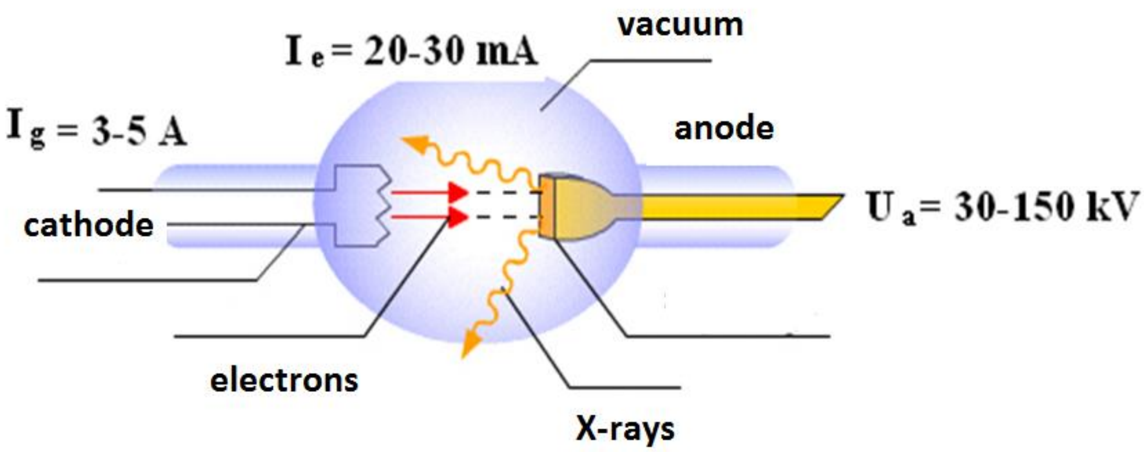

Figure 1: Scheme of X-ray tube.

2- Acceleration of the electrons

The X-ray tube contains a highly positively charged anode. Because of tube being positive at the anode sided and negative at the cathode side, an electrical potential difference (voltage U) is generated across the X-ray tube. This voltage, which ranges from 20 to 150 kV, is independent of the filament voltage and current that produces the electrons. The high voltage provides electric field and attractive electric force that accelerates the electrons toward the anode. Travel of the electrons from the cathode toward the anode forms the current of the X-ray tube which is mesured in milliamperes (mA). Furthermore, acceleration increases the velocity of electrons and their kinetic energy.

3- Interaction with a target material

The accelerated electrons make interactions on a very small area, known as the focal spot, of the target material, which also occupies a small area on the surface of the anode. Small focal spots provide better image resolution but relatively lower amounts of radiation than large focal spots. The dimensions of the focal spot, which usually range from 0.1 to 2 mm, are determined by the dimensions of the electron beam.

Tungsten is the most widely used target material. It has a high melting point and a high atomic number. High melting point allows more heat tolerance without damage to the anode surface. High atomic number increases the efficiency of X-ray emission. Other important target materials used in X-ray tubes are molybdenum and rhodium.

The accelerated electrons interact with the target and produce either Bremsstrahlung or characteristic X-rays.

Radiation from an accelerated charge: Bremsstrahlung

In inelastic interactions of the fast electrons with atomic nuclei as they pass through the matter, the electron path is deflected and energy is transferred to a photon, which is emitted. The emitted photon is known as Bremsstrahlung, which means „broke radiation“, in German. The energy of emitted photon can take any value from zero up to the energy of the initial electron, producing a continuous spectrum. Bremsstrahlung photons are the major component of the X ray apectrum emitted by X ray tubes. The energy of the emitted photon is substracted from the kinetic energy of the electron. The energy of the Bremsstrahlung photon depends on: the attractive Coulomb force (which is proportional to the anode voltage) and hence on the distance of the electron from the nucleus (Figure 2).

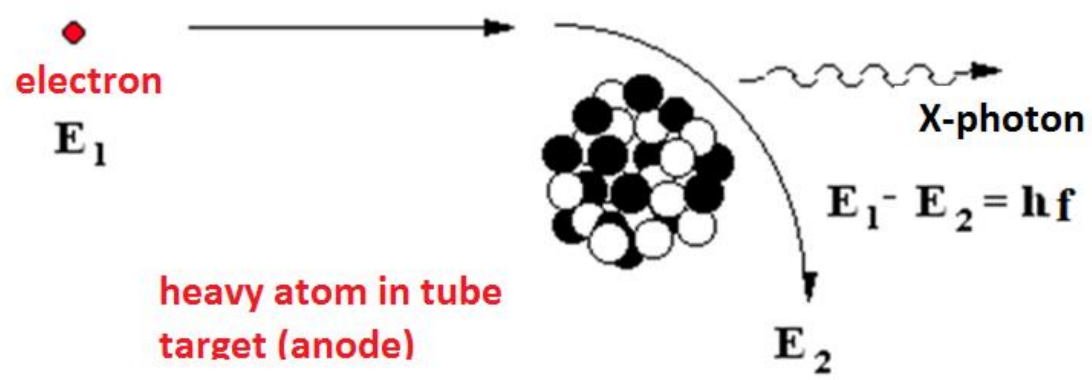

Figure 2: Bremsstrahlung radiation.

Photons with the highest energy in X-ray spectrum (Figure 3) have minimal wave length and maximal frequency which are determined from equations:

$Kinetic\ energy = Work\ in\ electric\ field = eU_a$

$eU_a = hf_{max} = h\lambda_{min}$

where e is elementary charge (the charge of proton or electron), U_a is the anode voltage.

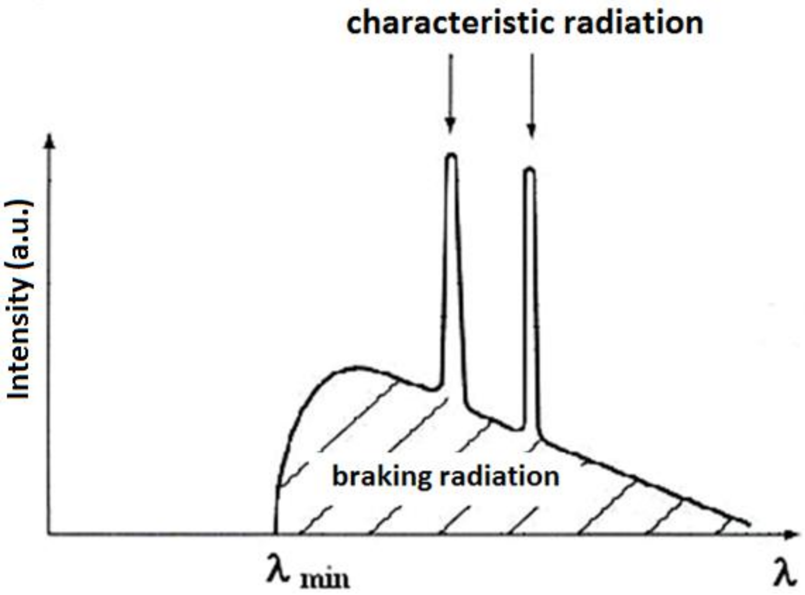

Figure 3: X-ray spectrum.

Characteristic radiation

For each element binding energies and the monoenergetic radiation resulting from such interactions are unique and characteristic for that element. The accelerated electrons may interact with the target atom by ejecting electrons from the inner shells (K-shell) out of their atoms. The atoms become ionized with unfilled inner shells. Electrons from higher energy shells immediatelly move to occupy the vacancies in the lower energy shells. The difference in the electron's energy or the binding energies of the two shells is released in the form of X-ray photons. The binding energy for Tungsten reduces from -69.5 to -1.9 keV. The minus sign is only to indicate that energy is required to remove the electron from its shell. The electron,s energy increases from -69.5 to -1.9 keV. Because the emitted photons have discrete values of energy represeting the energy difference between the levels, which, is turn, is determined by the electron configuration of the atom, the emitted photons are characterisic of each element type of the target material. The most common characteristic X-rays in the diagnostic energy range are due to X-shell vacancies, which are filled by electrons from the L, M and N shells.

The percentage of characteristic X-rays relative to the Bremsstrahlung X-rays depends on the acceleration potentials. At the anode voltage of 80 kV, approximately 10% of the total output is characteristic radiation. At the anode voltage of 100 kV, approximately 20% of the total output radiation.

Literature:

1. Prof. Perry Sprawls Lectures, Emory University
2. A. Mohamed: *Physics for Medical Students*, Wheatmark, Arizona, USA (2008)