Lecture 2

X - ray Production

The production of X rays involves the bombardment of a thick target with energetic electrons. These electrons undergo a complex sequence of collisions and scattering processes during the slowing down process, which results in the production of bremsstrahlung and characteristic radiation.

5.2.1. Bremsstrahlung

Energetic electrons are mostly slowed down in matter by collisions and excitation interactions. If an electron comes close to an atomic nucleus, the attractive Coulomb forces cause a change of the electron’s trajectory. An accelerated electron, or an electron changing its direction, emits electromagnetic radiation, given the name bremsstrahlung (braking radiation), and this energy of the emitted photon is subtracted from the kinetic energy of the electron. The energy of the bremsstrahlung photon depends on the attractive Coulomb forces and hence on the distance of the electron from the nucleus.

Using classical theory to consider the electron bombardment of a thin target yields a constant energy fluence from zero up to the initial electron kinetic energy (Fig. 5.1(a)). A thick target can be thought of as a sandwich of many thin target layers, each producing a rectangular distribution of energy fluence. As the electron is slowed down in each layer, the maximum energy in the distribution becomes less, until the electron comes to rest. The superposition of all these rectangular distributions forms a triangular energy fluence distribution for a thick target, the 'ideal' spectrum (Fig. 5.1(b)). Indeed, this model is a simplification, as quantum mechanical theory shows that the distribution for a thin layer is not rectangular and a stepwise reduction of the electron energy from layer to layer does not conform to the slowing down characteristics of electrons.

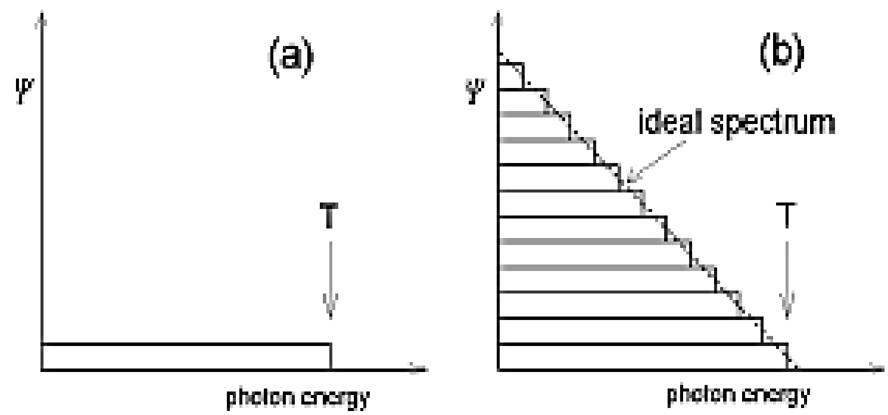

FIG. 5.1. (a) Rectangular distribution of the X ray energy fluence Ψ for a thin target bombarded with electrons of kinetic energy T. (b) For a stack of thin targets, each target layer contributes a rectangular fluence distribution, assuming a uniform electron energy decrease from layer to layer. The superposition forms a triangular ideal spectrum.

The triangular spectrum does not include any attenuation effects. Following the concept of the model, an increase in electron energy increases the number of thin layers each radiating X rays. The triangular area grows proportionally to the square of the electron energy. Considering that the total energy fluence is proportional to the triangular area, and as the X ray tube voltage U_A defines the kinetic energy of the electrons bombarding the anode, the radiation output of an X ray tube is proportional to U_A^2. This relationship only holds if spectral changes due to attenuation and emission of characteristic radiation are ignored. However, this is a reasonable rule of thumb.

5.2.2. Characteristic radiation

A fast electron colliding with an electron of an atomic shell could knock out the electron, provided its kinetic energy exceeds the binding energy of the electron in that shell. The binding energy is highest in the most inner K shell and decreasing for the outer shells (L, M, etc.). The scattered primary electron carries away the difference of kinetic energy and binding energy. The vacancy in the shell is then filled with an electron from an outer shell, accompanied by the emission of an X ray photon with an energy equivalent to the difference in binding energies of the shells involved. For each element, binding energies, and the monoenergetic radiation resulting from such interactions, are unique and characteristic for that element.

K radiation denotes characteristic radiation for electron transitions to the K shell, and likewise, L radiation for transitions to the L shell. The origin of the electron filling the vacancy is indicated by suffixes (α, β, γ, etc.), where α stands for a transition from the adjacent outer shell, β from the next outer shell, etc. K_α radiation results from L to K shell transitions; K_β radiation from M to K shell transitions, etc. Energies are further split owing to the energy levels in a shell, indicated with a numerical suffix. Further, each vacancy in an outer shell following from such a transition gives rise to the emission of corresponding characteristic radiation causing a cascade of photons.

Table 5.1 gives the binding energies and the K radiation energies for the common anode materials used in diagnostic radiology.

Instead of characteristic radiation, the energy available could be transferred to an electron that is ejected from the shell (Auger electron). The probability of Auger electron production decreases with atomic number.

TABLE 5.1. BINDING ENERGIES AND K RADIATION ENERGIES OF COMMON ANODE MATERIALS

Element[a]	Binding energy (keV)		Energies of characteristic X rays (keV)			
	L shell	K shell	$K_{\alpha 1}$	$K_{\alpha 2}$	$K_{\beta 1}$	$K_{\beta 2}$
Mo	2.87/2.63/2.52	20.00	17.48	17.37	19.61	19.97
Rh	3.41/3.15/3.00	23.22	20.22	20.07	22.72	23.17
W	12.10/11.54/10.21	69.53	59.32	57.98	67.24	69.07

[a] Mo: molybdenum; Rh: rhodium; W: tungsten.

5.2.3. X ray spectrum

The electrons are slowed down and stopped in the target, within a range of a few tens of micrometres, depending on the tube voltage. As a result, X rays are not generated at the surface but within the target, resulting in an attenuation of the X ray beam. This self-filtration appears most prominent at the low energy end of the spectrum (Fig. 5.2). Additionally, characteristic radiation shows up if the kinetic electron energy exceeds the binding energies. L radiation is totally absorbed by a typical filtration of 2.5 mm Al (aluminium equivalent, see Section 5.6.2). The K edge in the photon attenuation of tungsten can be noticed as a drop of the continuum at the binding energy of 69.5 keV. For tungsten targets, the fraction of K radiation contributing to the total energy fluence is less than 10% for a 150 kV tube voltage.

As shown in Section 2.4.4, the radiative mass stopping power of electrons is proportional to Z^2, where Z is the atomic number of the absorber. Integration of the radiative mass stopping power along the electron path gives the total X ray energy fluence, Ψ, as $\Psi \sim ZIU^2$, where I denotes electron current and U the tube voltage. If a high bremsstrahlung yield is required, metals with high Z are preferable. Tungsten (Z = 74) is commonly chosen, as it also withstands high temperatures (2757°C at 1.3×10^{-2} Pa vapour pressure). The efficiency for the conversion of electrical power to bremsstrahlung radiation is proportional to UZ. At 100 kV, the efficiency is as low as ~0.8%. This is the cause of most of the technical problems in the design of X ray tubes, as practically all electrical power applied in the acceleration of electrons is converted to heat.

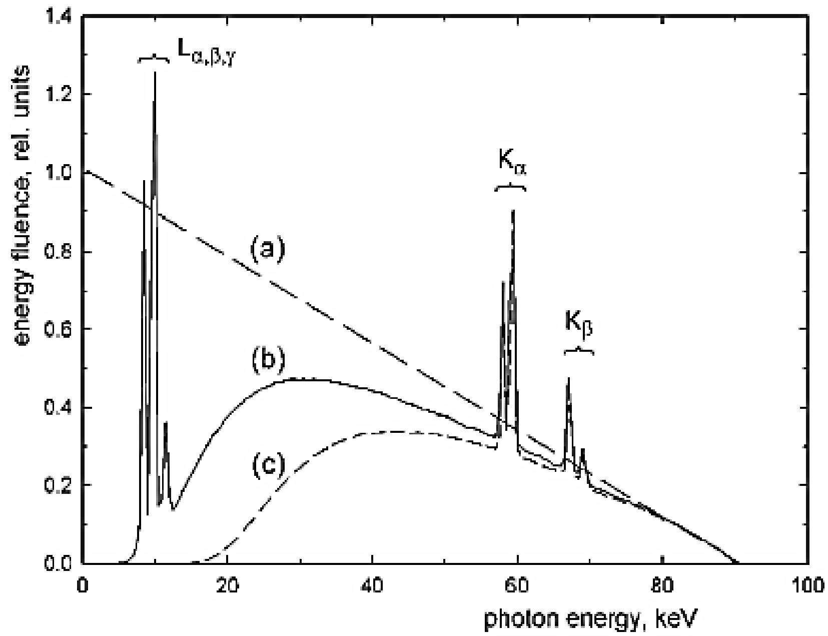

FIG. 5.2. (a) Ideal bremsstrahlung spectrum for a tungsten anode (tube voltage 90 kV), (b) an actual spectrum at the beam exit port, including characteristic X rays (anode angle 20°, inherent filtration 1 mm Be) and (c) the spectrum filtered with an equivalent of 2.5 mm Al.

The ideal spectrum appears triangular, with the energy fluence taken as the quantity describing the spectral intensity. The photon fluence is a more practical quantity for calculations using spectral data and is, therefore, used in the following sections. More refined models for the generation of X ray spectra have been