X-Rays

Production and properties

Two lectures
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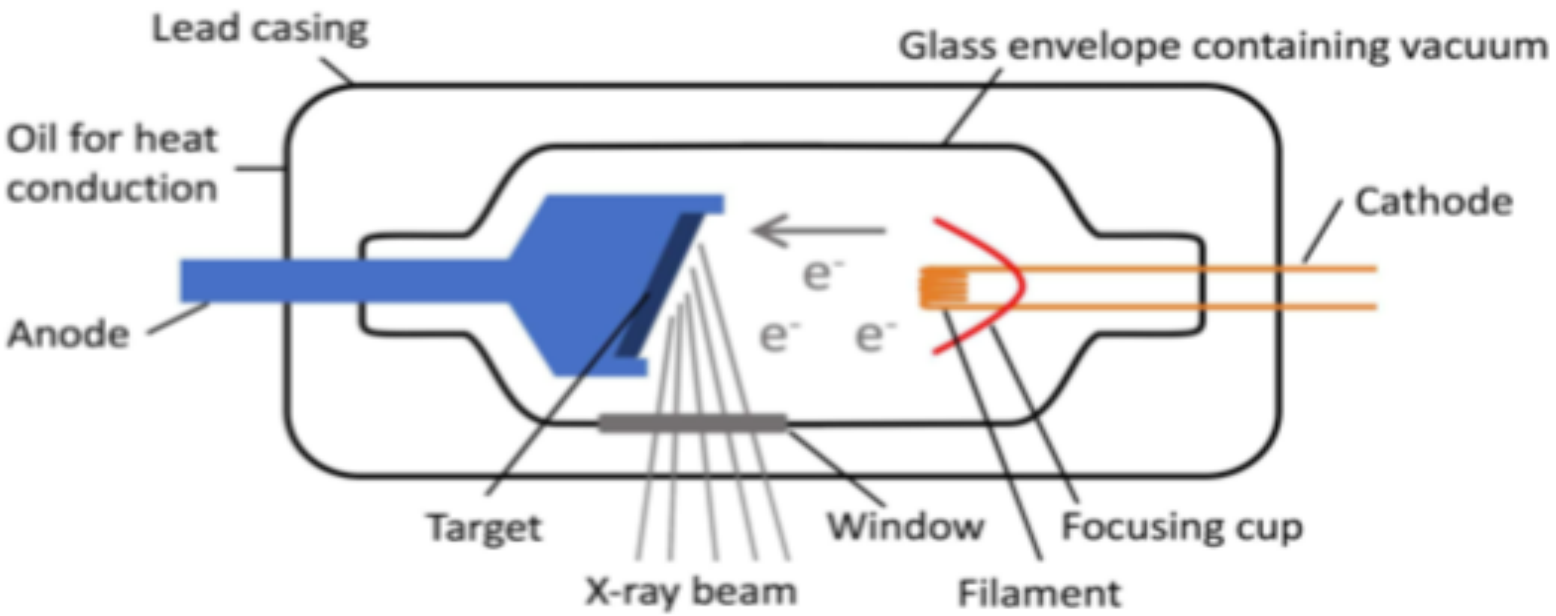
Production of X- rays



An x-ray tube

1. A current is passed through the tungsten filament and heats it up.
2. As it is heated up the increased energy enables electrons to be released from the filament through **thermionic emission**.
3. The electrons are attracted towards the positively charged anode and hit the tungsten target with a maximum energy determined by the tube potential (voltage).
4. As the electrons bombard the target they interact via Bremsstrahlung and characteristic interactions which result in the conversion of energy into heat (99%) and x-ray photons (1%).
5. The x-ray photons are released in a beam with a range of energies (**x-ray spectrum**) out of the window of the tube and form the basis for x-ray image formation.

X-Ray Tube components

1- Cathode

Filament

- Made of thin (0.2 mm) tungsten wire because tungsten:
    - has a high atomic number (A 184, Z 74)
    - is a good thermionic emitter (good at emitting electrons)
    - can be manufactured into a thin wire
    - has a very high melting temperature (3422°c)
- The size of the filament relates to the size of the focal spot. Some cathodes have two filaments for broad and fine focusing.

Focusing cup

- Made of molybdenum as:
    - high melting point
    - poor thermionic emitter so electrons aren't released to interfere with electron beam from filament
- Negatively charged to focus the electrons towards the anode and stop spatial spreading

2- Anode

- Target made of tungsten for same reasons as for filament
- Rhenium added to tungsten to prevent cracking of anode at high temperatures and usage
- Set into an anode disk of molybdenum with stem
- Positively charged to attract electrons
- Set at angle to direct x-ray photon beam down towards patient. Usual angle is 5º - 15º

3- Window

Window: made of beryllium with aluminium or copper to filter out the soft x-rays. Softer (lower energy) x-ray photons contribute to patient dose but not to the image production as they do not have enough energy to pass through the patient to the detector. Therefore, to reduce this redundant radiation dose to the patient these x-ray photons are removed.

4- **Glass envelope:** contains vacuum so that electrons do not collide with anything other than target.

5- **Insulating oil:** carries heat produced by the anode away via conduction.

6- **Filter:** Total filtration must be >2.5 mm aluminium equivalent (meaning that the material provides the same amount of filtration as a >2.5 mm thickness of aluminium) for a >110 kV generator

Producing an X-Ray beam

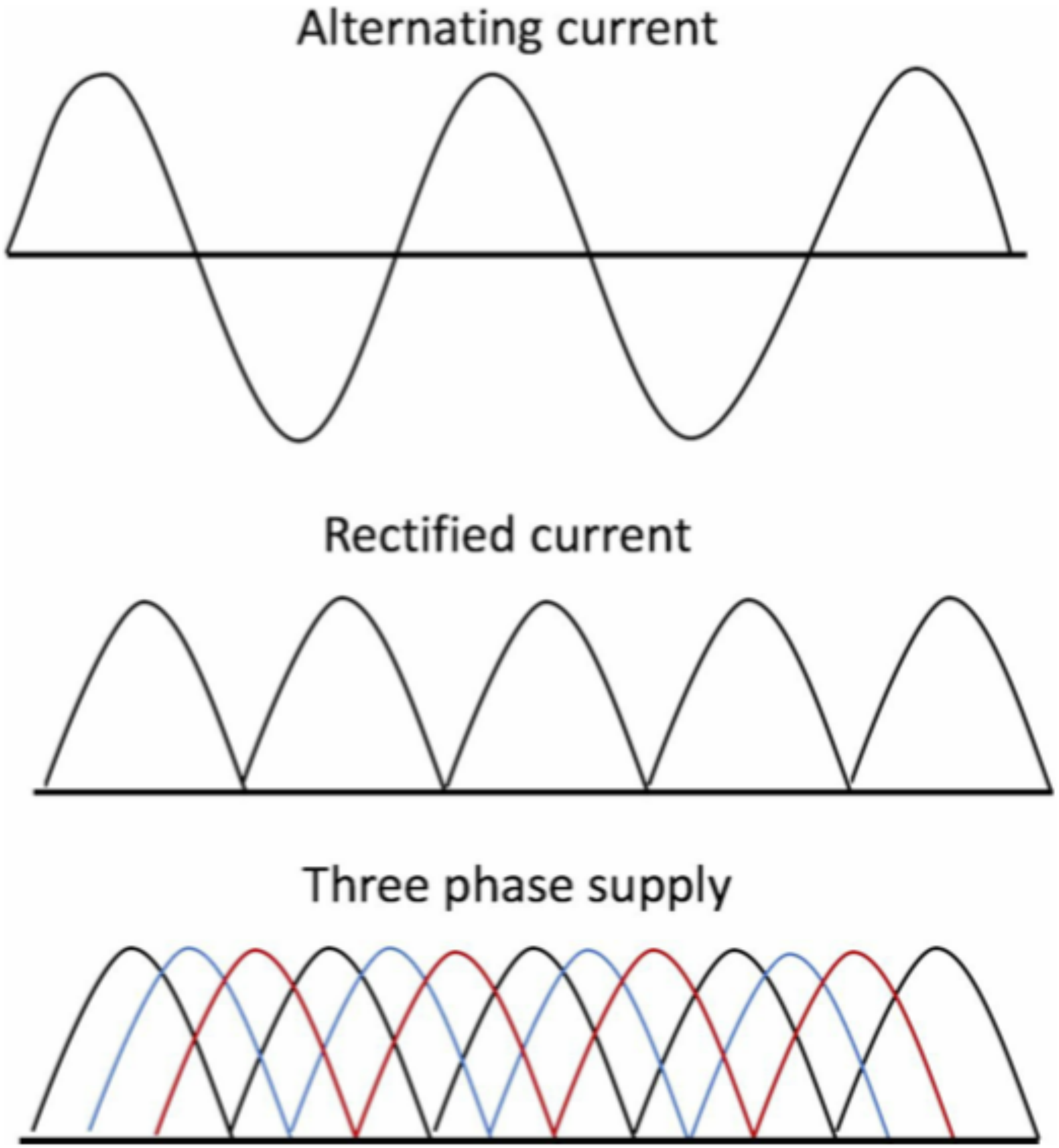
1- Electrons produced (Thermoionic emission)

A current is applied through the cathode filament, which heats up and releases electrons via thermionic emission. The electrons are accelerated towards the positive anode by a tube voltage applied across the tube. At the anode, 99% of energy from the electrons is converted into heat and only 1% is converted into x-ray photons.

Accelerating potential

It is the voltage applied across the tube to create the positive to negative gradient across the tube and accelerate the electrons across the anode.

. It is normally 50-150 kV for radiography, 25-40 kV for mammography and 40-110 kV for fluoroscopy. UK mains supply is 230 V and 50 Hz of alternating current. When the charge is negative the accelerating potential is reversed (the cathode becomes positive and the anode becomes negative). This means that the electrons are not accelerated towards the anode to produce an x-ray beam. Ideally you want a uniform output with a constant charge. This is done by rectification.



Accelerating and rectified potentials

Effect of rectification on spectrum

- Increased mean photon energy - *fewer photons of lower energy*
- Increased x-ray output - *stays closer to the maximum for longer*
- Shorter exposure - *as output higher, can run exposure for shorter time to get same output*
- Lower patient dose - *increased mean energy means fewer low energy photons that do not contribute to the final image*

- Filament current is applied across the tungsten cathode filament (10 A) and affects the **number** of electrons released.
- Tube current is applied across the x-ray tube from cathode to anode and affects the **energy and number** of electrons released.

X-rays production at the anode

The electrons hit the anode with a maximum kinetic energy of the kVp and interact with the anode by losing energy via:

- **Elastic interaction:** rare, only happens if kVp < 10 eV. Electrons interact but conserve all their energy
- **Ineleastic interaction:** causes excitation / ionisation in atoms and releases energy via electromagnetic (EM) radiation and thermal energy

Interactions

At the anode, electrons can interact with the atoms of the anode in several ways to produce x-ray photons.

1. Outer shell interaction: low energy EM released and quickly converted into heat energy
2. Inner shell interaction: produces **characteristic radiation**
3. Nucleus field interaction: aka **Bremsstahlung**

Characteristic radiation

1. A bombarding electron knocks a k-shell or l-shell electron out.

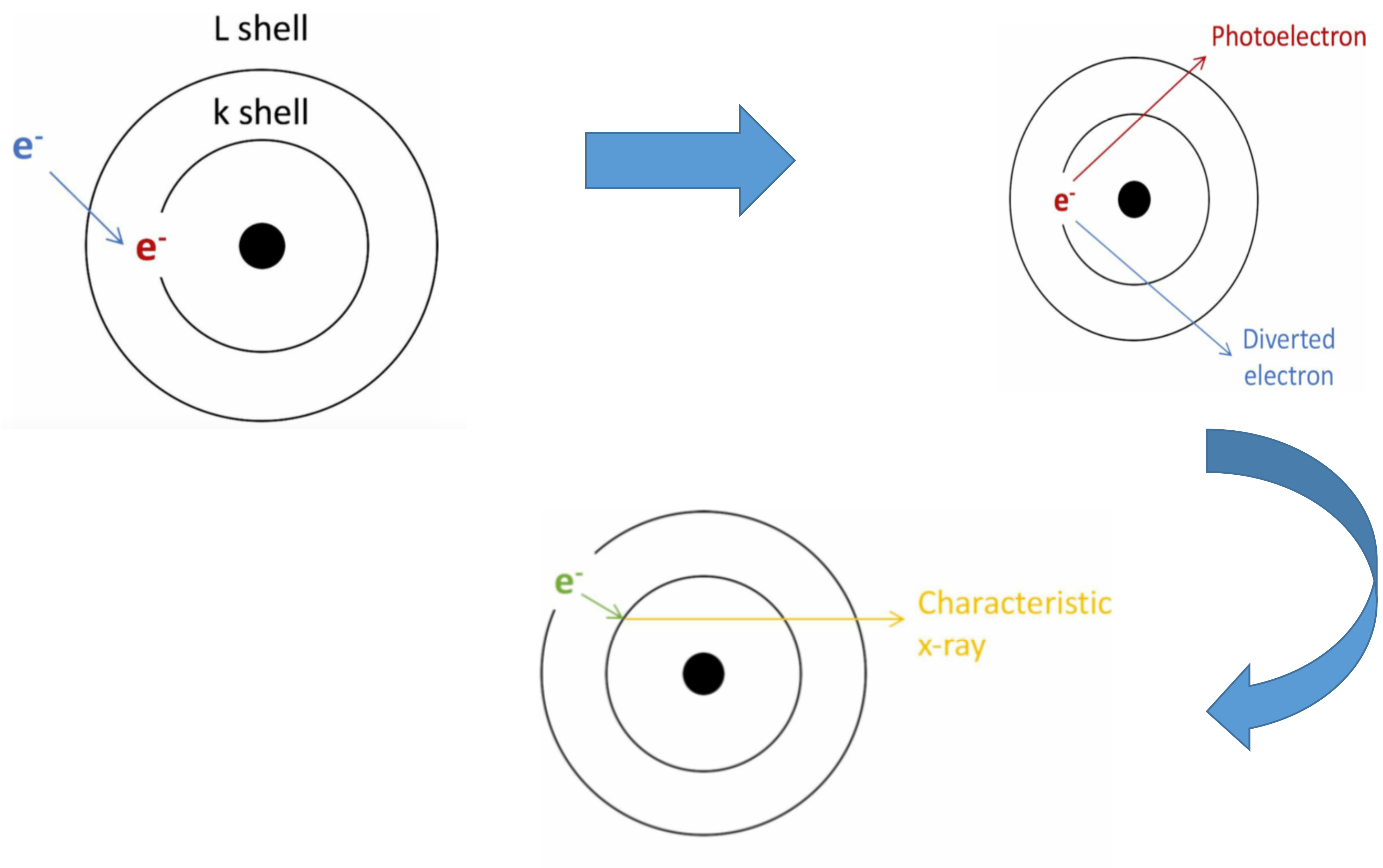
2. A higher shell electron moves into the empty space.
3. This movement to a lower energy state releases energy in the form of an x-ray photon.
4. The bombarding electron continues on its path but is diverted.

It is called "characteristic" as energy of emitted electrons is dependent upon the **anode material**, not on the tube **voltage**. Energy is released in characteristic values corresponding to the binding energies of different shells.

For tungsten:

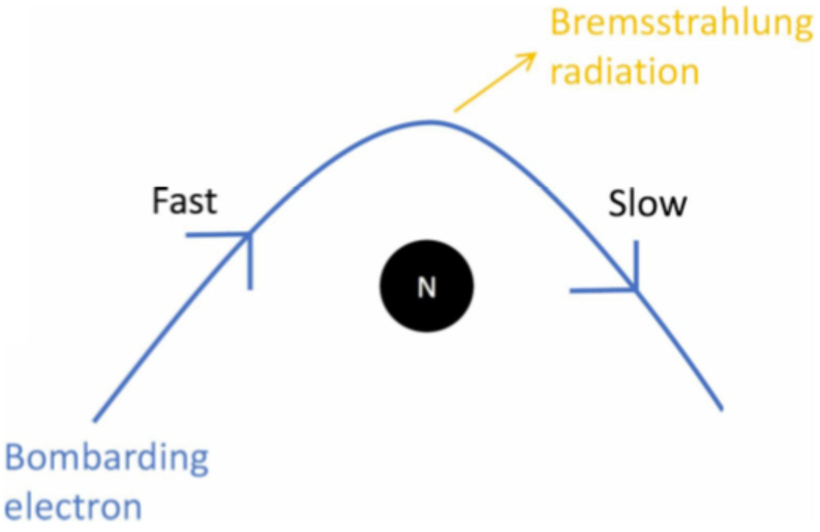
Ek - El (aka Kα) = 59.3 keV

Ek - Em (aka Kβ) = 67.6 keV


L shell
k shell
e-
e-
Photoelectron
e-
Diverted electron
e-
Characteristic x-ray

Bremsstrahlung

1. Bombarding electron approaches the nucleus.
2. Electron is diverted by the electric field of the nucleus.
3. The energy loss from this diversion is released as a photon (**Bremsstrahlung radiation**).

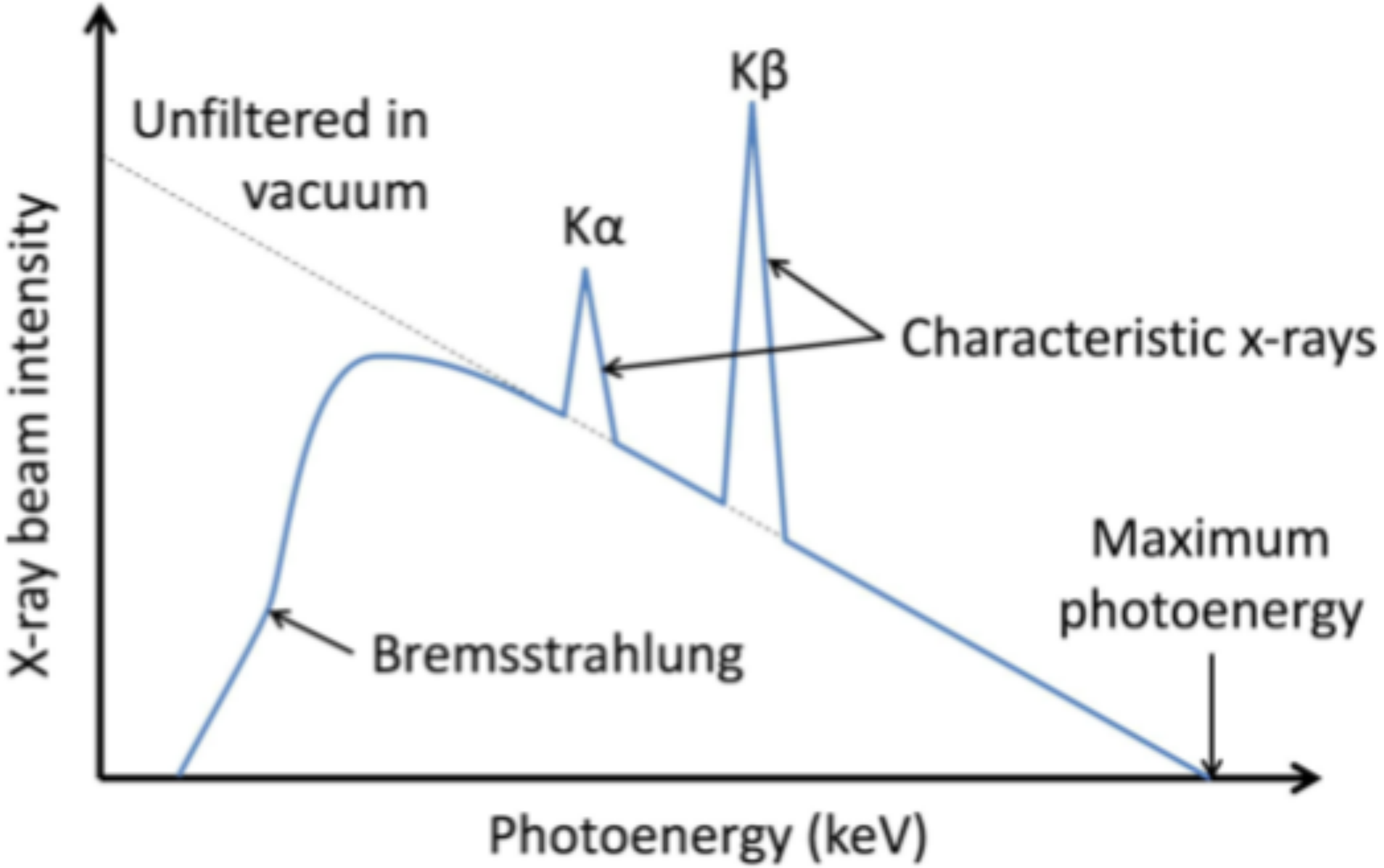


Bremsstrahlung causes a spectrum of photon energies to be released. 80% of x-rays are emitted via Bremsstrahlung. Rarely, the electron is stopped completely and gives up all its energy as a photon. More commonly, a series of interactions happen in which the electron loses energy through several steps.

Compare

Characteristic radiation	Bremasstrahlung
Only accounts for small percentage of x-ray photons produced	Accounts for 80% of photons in x-ray beam
Bombarding electron interacts with inner shell electron	Bombarding electron interacts with whole atom
Radiation released due to electron dropping down into lower energy state	Radiation released due to diversion of bombarding electron as a result of the atomic pull
Radiation released is of a specific energy	Radiation released is of a large range of energies
X-ray beam energy depends on element of target atoms not tube voltage	X-ray beam energy depends on tube voltage

X-Rays spectrum



The resulting spectrum of x-ray photon energies released is shown in the graph. At a specific photoenergy there are peaks where more x-rays are released. These are at the **characteristic radiation** energies and are different for different materials. The rest of the graph is mainly Bremsstrahlung, in which photons with a range of energies are produced. Bremsstrahlung accounts for the majority of x-ray photon production.

Beam quality: the ability of the beam to penetrate an object or the energy of the beam.

Beam quantity: the number of x-ray photons in the beam