FUNDAMENTALS OF X-RAY PRODUCTION



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X-ray tube:

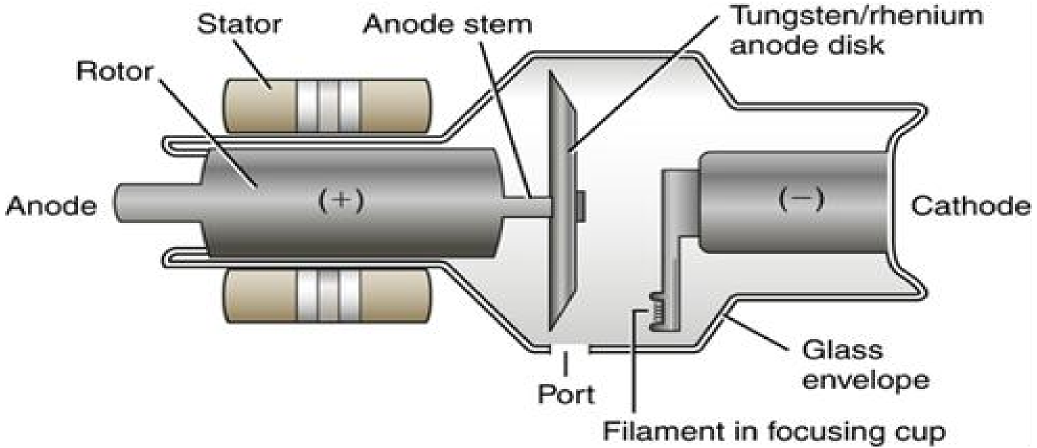
X-ray tube, also called Roentgen tube, is a vacuum tube that converts electrical input power into X-rays .**evacuated electron tube that produces X rays by accelerating electrons to a high velocity with a high-voltage field and causing them to collide with a target, the anode plate.**

An **X-ray tube** .

The availability of this controllable source of X-rays created the field of radiography, the imaging of partly opaque objects with **penetrating radiation**. In contrast to other sources of ionizing radiation, X-rays are only produced as long as the X-ray tube is energized.

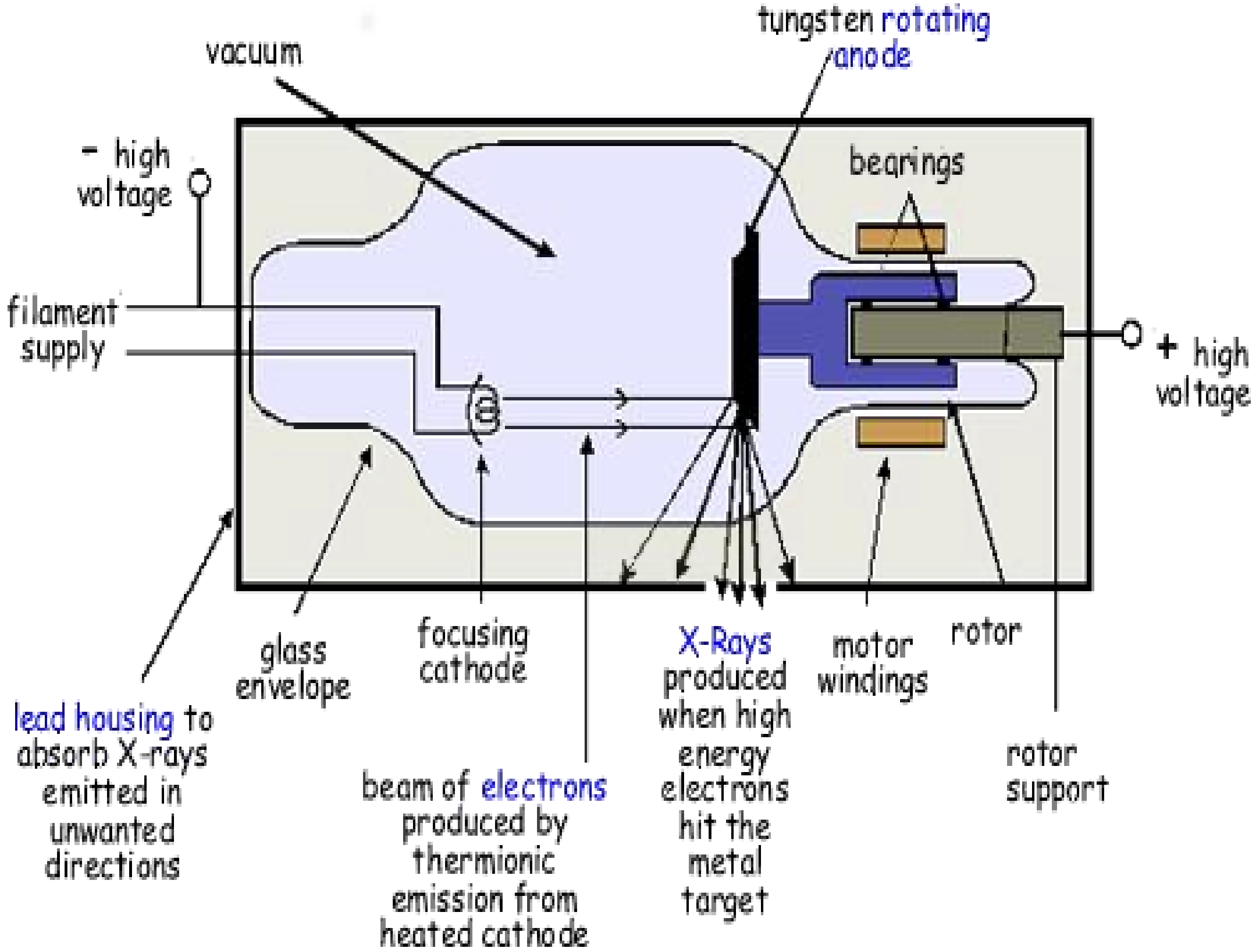
X-ray tubes are also used in **CT scanners**, **airport luggage scanners**, **X-ray crystallography**, **material and structure analysis**, and **for industrial inspection**.

Increasing demand for high-performance **Computed tomography (CT) scanning** and **angiography systems has driven development of very high performance medical X-ray tubes.**



A modern dental x-ray tube.

The heated cathode is on the left. Centre is the anode which is made from tungsten and embedded in the copper sleeve



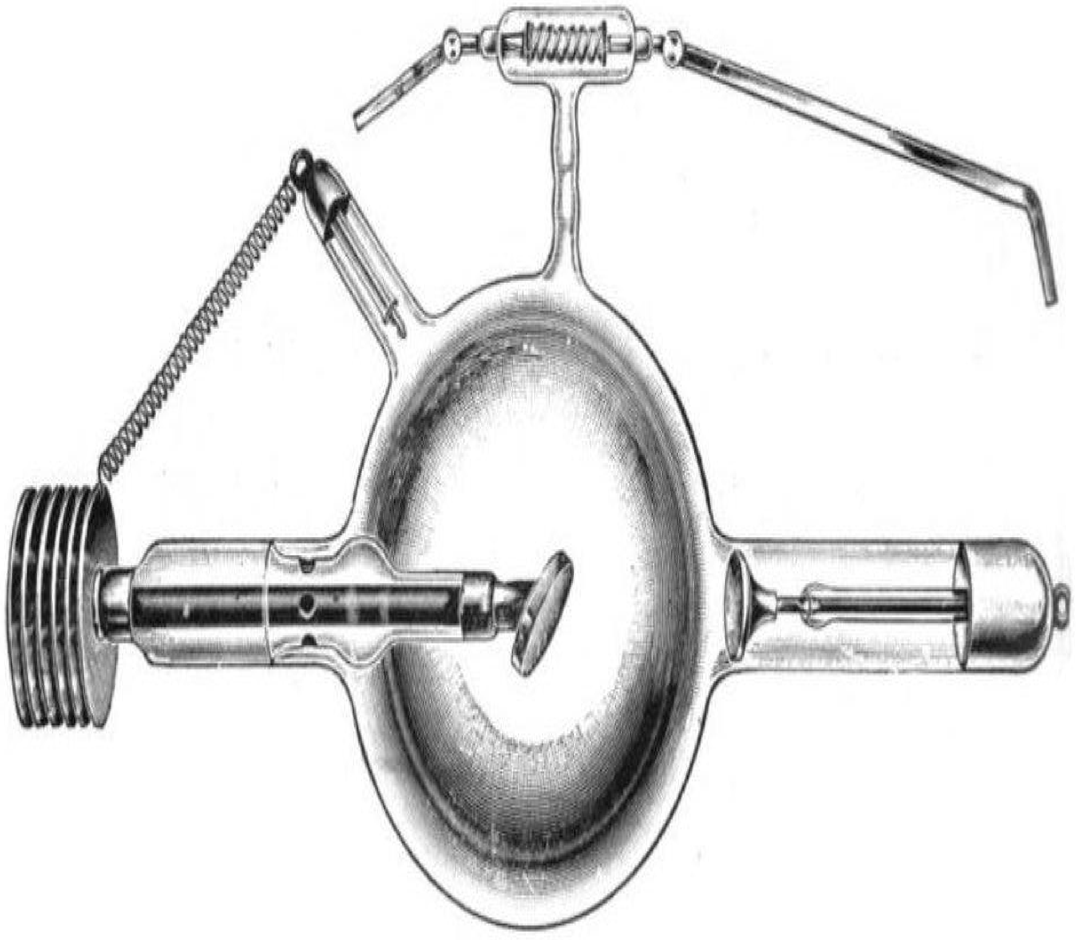
Types of X-ray tubes:

A- Crookes tube (cold cathode tube)

Crookes tubes generated the electrons needed to create X-rays by **ionization** of the **residual air in the tube**, instead of a **heated filament**, so they were partially but not **completely evacuated**.

They consi**10^{-6} to 5×10^{-8} atmospheric pressure of air (0.1 to 0.005 Pasted of a glass bulb with around**).

They had an **aluminum cathode plate** at **one end of the tube**, and a **platinum anode target** at the other end. The anode surface was angled so that the X-rays would radiate through the side of the tube. The cathode was concave so that the electrons were focused on a small (~1 mm) spot on the anode, approximating a point source of X-rays, which resulted in sharper images. The tube had a third electrode, an anticathode connected to the anode. It improved the X-ray output, but the method by which it achieved this is not understood. A more common arrangement used a **copper plate anticathode (similar in construction to the cathode)** in line with the anode such that the anode was between the cathode and the anticathode



Crookes X-ray tube from early 1900s. The cathode is on the right, the anode is in the center with attached heat sink at left. The electrode at the 10 o'clock position is the anticathode.
The device at top is a 'softener' used to regulate the gas pressure

Coolidge tube (hot cathode tube):

In the Coolidge tube, the electrons are produced by **thermionic effect** from a **tungsten filament heated by an electric current**.

The filament is the cathode of the tube. The high voltage potential is between the **cathode** and the **anode**, the electrons are thus **accelerated**, and then **hit the anode**.

There are two designs: End-window tubes and **Side-window tubes**.

End window tubes usually have **"transmission target"** which is thin enough to allow X-rays to pass through the target (X-rays are emitted in the same direction as the electrons are moving.)

In one common type of **end-window tube**, the filament is **around the anode** ("annular" or ring-shaped), the electrons have a curved path (half of a toroid).

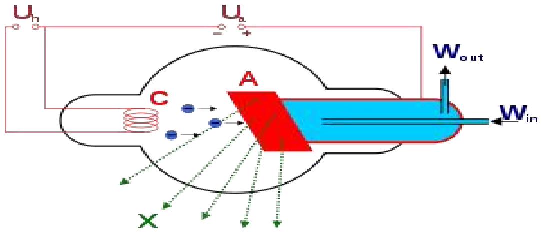
What is special about side-window tubes is an **electrostatic lens** is used to focus the beam onto a very small spot on the anode.

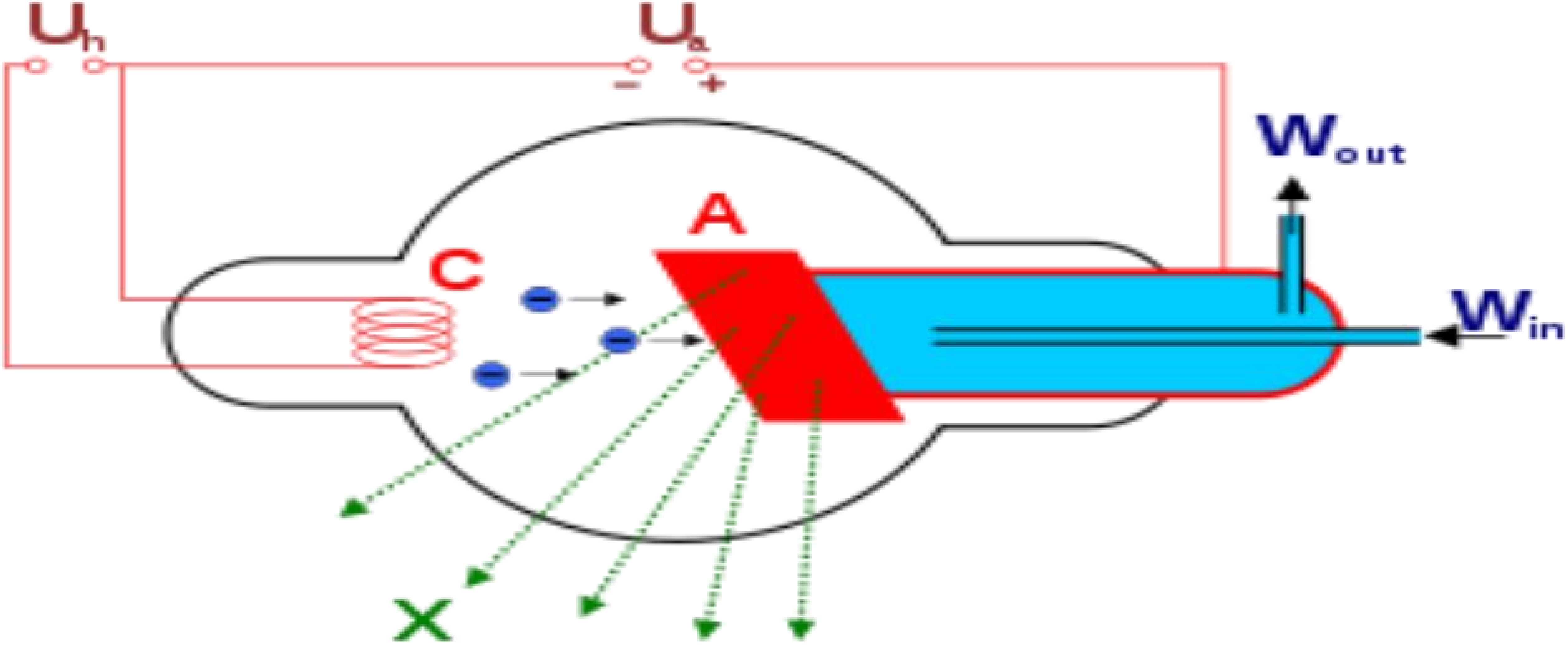
The anode is specially designed to dissipate the heat and wear resulting from this intense focused barrage of electrons.

The anode is precisely **angled at 1-20 degrees off perpendicular to the electron current so as to allow the escape of some of the X-ray photons which are emitted perpendicular to the direction of the electron current**.

The anode is usually made out of tungsten or molybdenum.

The tube has a window designed for escape of the generated X-ray photons





- A: anode (+)
- Coolidge side-window tube (scheme)
- C: filament/cathode (-)
- W_{in} and W_{out}: water inlet and outlet of the cooling device

Rotating anode tube:

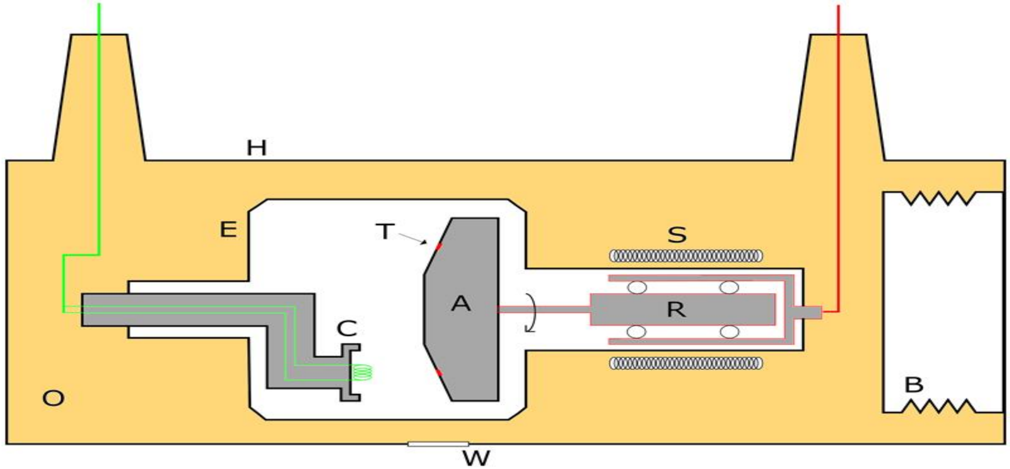
A considerable amount of heat is generated in the focal spot (the area where the beam of electrons coming from the cathode strike to) of a stationary anode. Rather, a rotating anode lets the electron beam sweep a larger area of the anode, thus redeeming the advantage of a higher intensity of emitted radiation, along with reduced damage to anode compared to its stationary state.

The focal spot temperature can reach 2,500 °C (4,530 °F) during an exposure, and the anode assembly can reach 1,000 °C (1,830 °F) **following a series of large exposures**.

Typical anodes are a tungsten-rhenium target on a molybdenum core, backed with graphite. The rhenium makes the **tungsten more ductile** and **resistant to wear from the impact of the electron beams**. **The molybdenum conducts heat from the target**. **The graphite provides** thermal storage for the anode, and minimizes the rotating mass of the anode

Simplified rotating anode tube schematic

A: Anode
C: cathode
T: Anode target
W: X-ray window

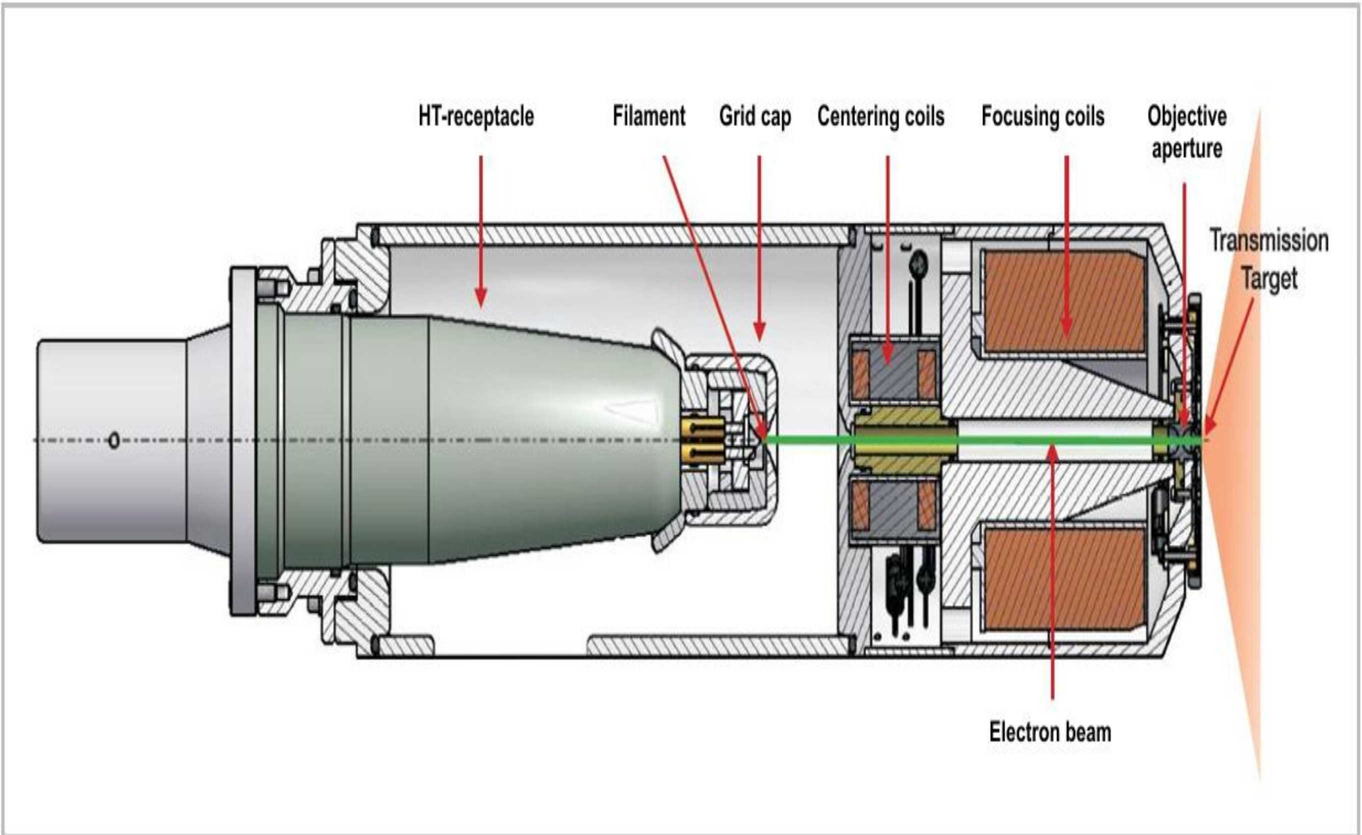


Microfocus X

Reflection Tube

Some X-ray exami **ng** and **3-D microtomography**) need very **high-res** tubes that can generate very small **focal spot sizes, typically below 50 µm in diameter**. These tubes are called **microfocus X-ray tubes.**

There are **two basic types of microfocus X-ray tubes**:
solid-anode tubes and
metal-jet-anode tubes.



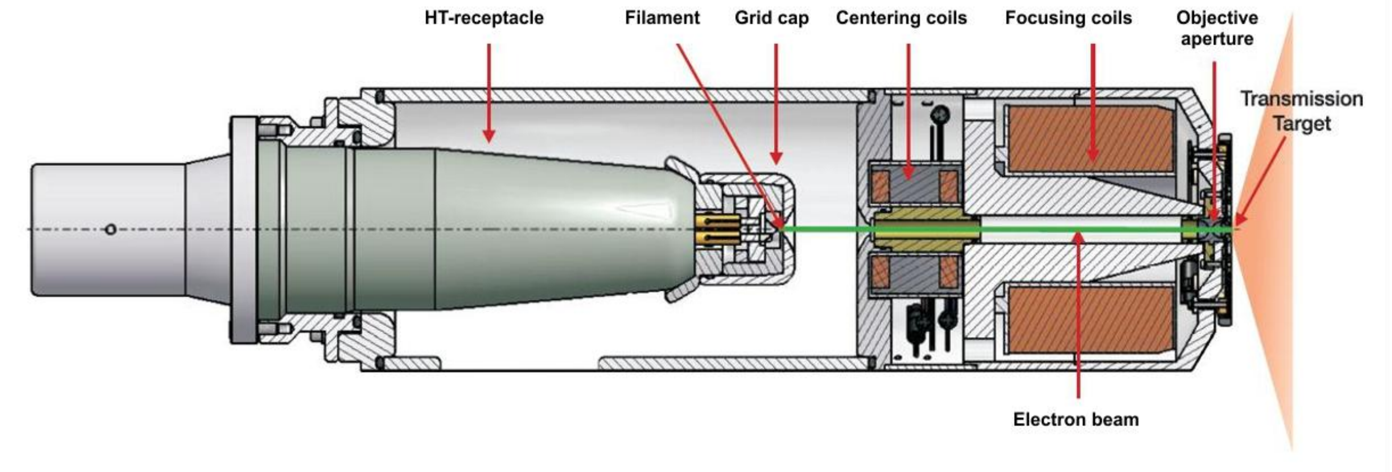
Cross section of transmission tube

Solid-anode microfocus X-ray tubes are in principle very similar to the **Coolidge tube**, but with the important **distinction that care has been taken to be able to focus the electron beam into a very small spot on the anode.**

Many microfocus X-ray sources operate with focus spots in the **range 5-20 µm**, but in the extreme cases spots **smaller than 1 µm may be produced**.

The major drawback of solid-anode microfocus X-ray tubes is the very low power they operate at. In order to avoid melting of the anode the electron-beam power density must be below a maximum value.

This value is somewhere in the **range 0.4-0.8 W/µm depending on the anode material**.This means that a solid-anode microfocus source with **a 10 µm electron-beam focus can operate at a power in the range 4-8 W.**



Cross section of transmission tube

In **metal-jet-anode microfocus X-ray tubes** the solid metal anode is replaced with a jet of liquid metal, which acts as the electron-beam target.

The advantage of the metal-jet anode is that the maximum electron-beam power density is significantly increased.

Values in the range 3-6 W/µm have been reported for different anode materials (**gallium and tin**)

In the case with a 10 µm electron-beam focus a metal-jet-anode microfocus X-ray source may operate at 30-60 W.

The major benefit of the increased power density level for the metal-jet X-ray tube is the possibility to operate with a smaller focal spot, say 5 µm, to increase image resolution and at the same time acquire the image faster, since the **power is higher (15-30 W)** than for solid-anode **tubes with 10 µm focal spots**

The Production of X Rays:

The Production of X Rays involves the **bombardment of a thick target** with **energetic electrons**

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**

A Simplified treatment of this process, based on **classical theory**, is **provided in this section**

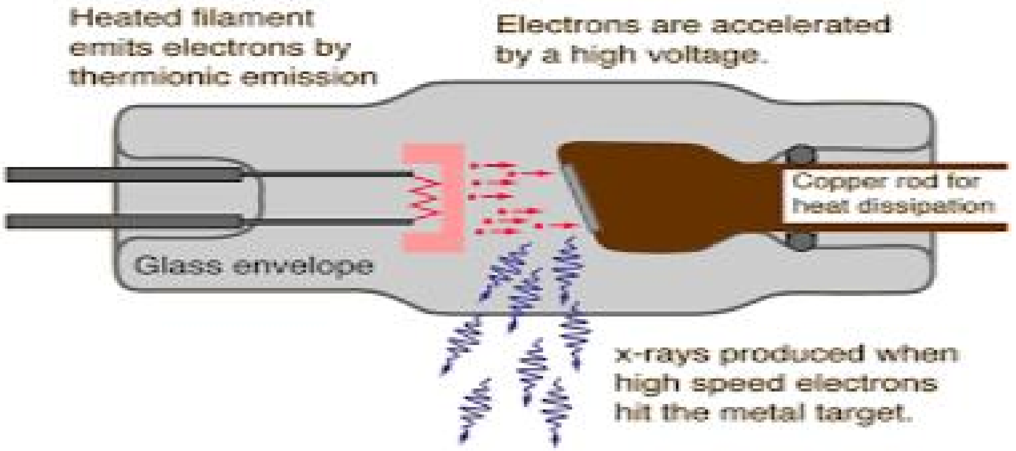
Energetic Electrons are mostly **slowed down in matter by**: **Collisions** and **Excitation interactions**

If an **electron comes** close to an **atomic Nucleus** the attractive **Coulomb forces** causes a change of the **electron's trajectory** .

An accelerated electron or an electron changing its direction **emits electromagnetic radiation** and **given the name Bremsstrahlung (braking radiation).**

The 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**



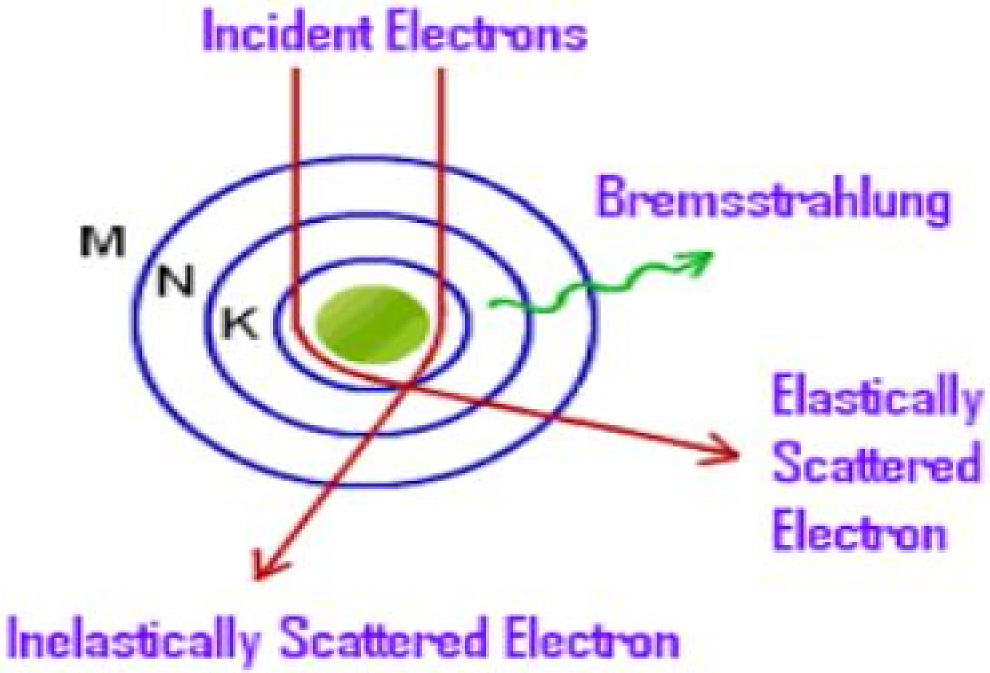
A thick target can be thought of as a sandwich of many thin target layers each producing a rectangular distribution of energy fluence

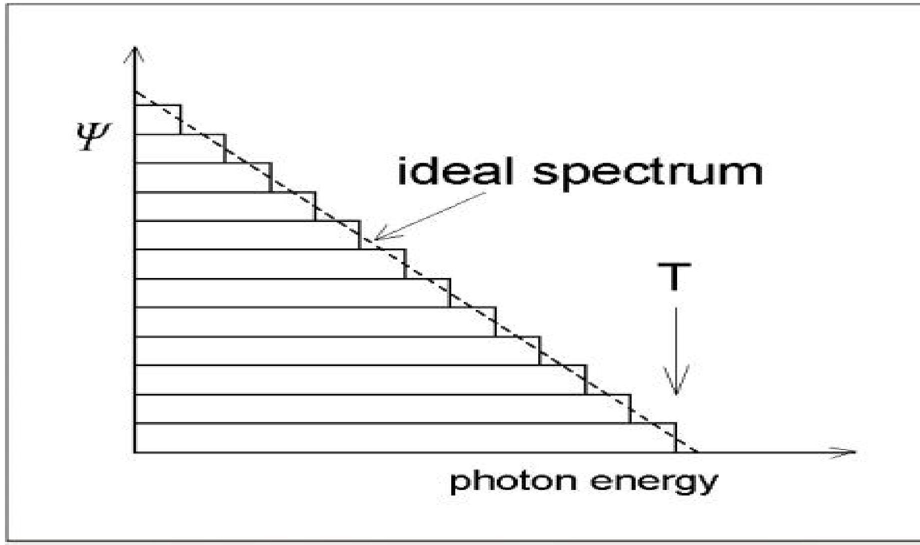
The superposition of all these rectangular distributions forms a triangular energy fluence distribution for a thick target, the **Ideal Spectrum**

According to this model An increase in electron energy increases the number of thin layers each radiating X rays.

The triangular area grows proportional to the square of the electron energy .

Therefore, the **Radiation Output of an XRT** is proportional to **U2 U**: tube voltage relationship holds if spectral changes due to attenuation and emission of **characteristic radiation** are **ignored**





The ideal spectrum does not include any attenuation effects

Characteristic radiation:

Is a type of **energy emission relevant for X-ray production** .A **Fast Electron** colliding with an **electron of an atomic shell** could **knock out** the electron once **its KE exceeds** the **binding energy of the electron in that shell .**

The binding energy is Highest in the most inner K-shell and **decreases for the outer shells (L, M, ..) .**

The Scattered primary electron **carries away the difference of kinetic energy** and **binding energy.**

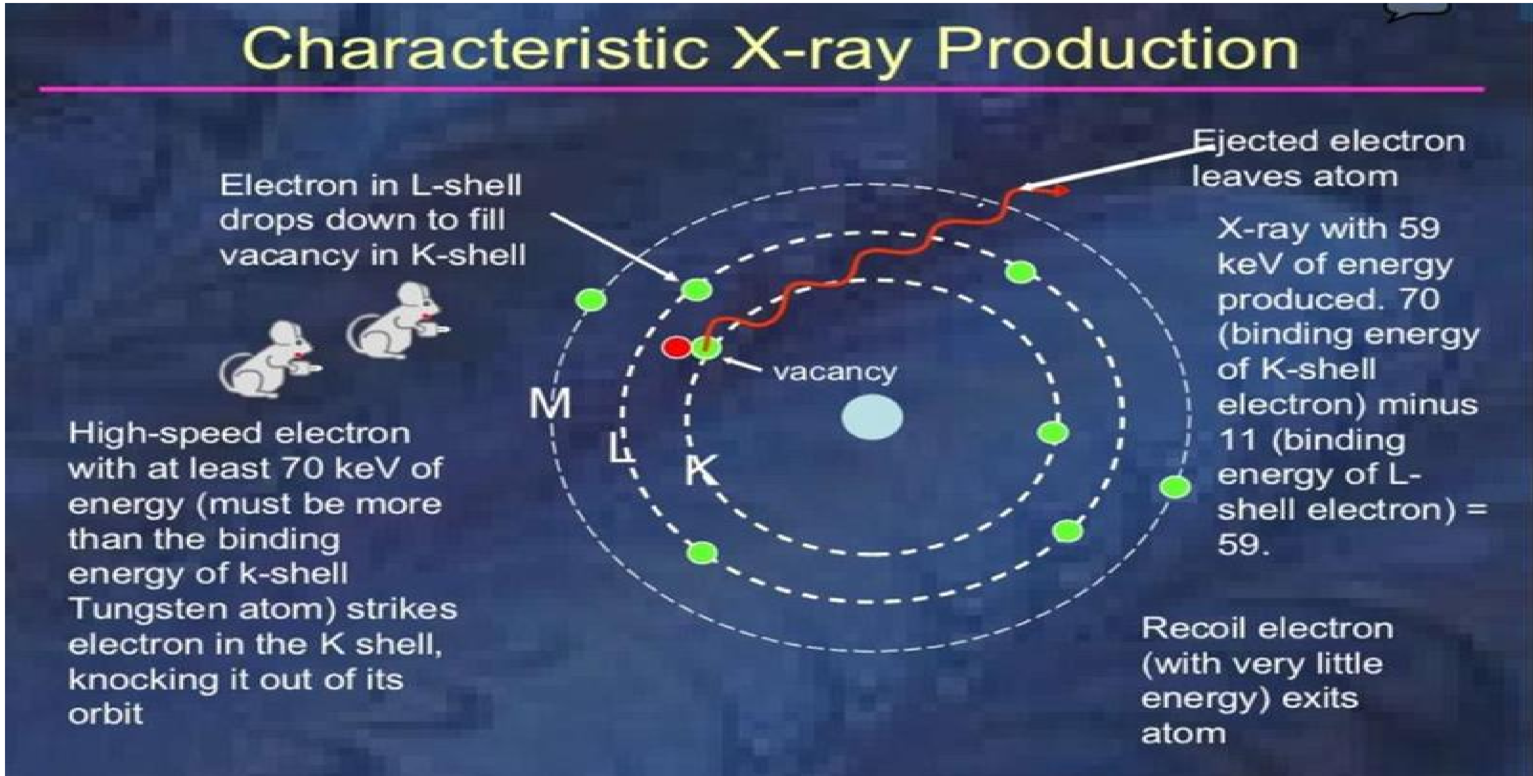
The vacancy in the shell is then filled with an electron from an outer shell accompanied by **the emission of an X Ray Photon with an energy equivalent to the Difference in binding energies of the shells involved.**

For example, in a tungsten target electron transitions from the L-shell to the K-shell produce x-rays photons of 57.98 and 59.32 keV. The two energy levels are as a result of the Pauli exclusion principle which states that no two particles of half-integer spin (such as electrons) in an atom can occupy exactly the same energy state at the same time; therefore the K-shell represents two different energy states, the L-shell eight states and so on.

When an electron falls (cascades) from the L-shell to the K-shell, the x-ray emitted is called a K-alpha x-ray. Similarly, when an electron falls from the M-shell to the K-shell, the x-ray emitted is called a K-beta x-ray. However, it is possible to have M-L transitions and so on but their likelihood is so low they can be safely ignored.

Each element differs in nuclear binding energies, and characteristic radiation depends on the binding energy of particular element.

Characteristic radiation never exists in isolation and the line spectra is usually superimposed on the continuous spectra of bremsstrahlung radiation.



Characteristic X-ray Production

Electron in L-shell drops down to fill vacancy in K-shell

High-speed electron with at least 70 keV of energy (must be more than the binding energy of k-shell Tungsten atom) strikes electron in the K shell, knocking it out of its orbit

Ejected electron leaves atom

X-ray with 59 keV of energy produced. 70 (binding energy of K-shell electron) minus 11 (binding energy of L-shell electron) = 59.

Recoil electron (with very little energy) exits atom

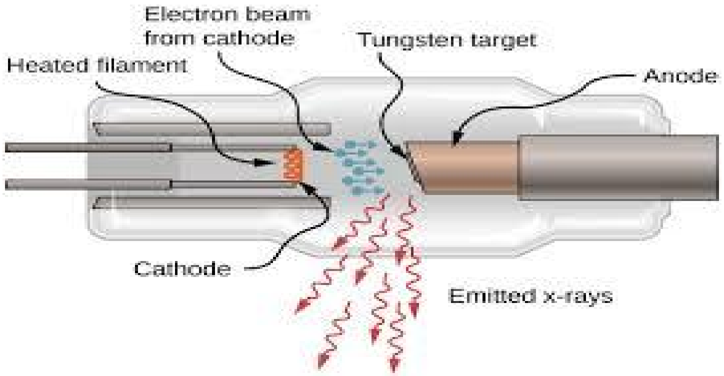
Why tungsten is the material of choice for Target?

Tungsten is the material of choice for the target on x-ray tube for general radiography is for 3 main reasons:

1. Atomoc number – tungsten’s high atomic number, 74, results in high-efficiency x-ray production and in high-energy x-rays.

2. Thermal Conductivity – Tungsten has a thermal conductivity nearly equal to that of copper. It is therefore an efficient metal for dissipating the heat produced.

3. High Melting Point – Any material, if heated sufficiently, will melt and become liquid. Tungsten has a high melting point (3400° C compared with 1100° C for copper) and therefore can stand up under high tube current with out pitting or bubbling.



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