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Diagnostic X- Rays, Generation and Applications

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Abstract

Due to the predominance of non-radiative collisions that produce heat (Bremsstrahlung Radiation), low cross-sections for X-ray emission, and self-absorption tube components, only around 1% of the energy provided to the X-ray tube is transformed into distinctive X-ray. The key to improving the design, operation, and cooling of industrial and medical X-ray systems is an understanding of this constraint. It is recommended to experiment with various framework models that use a magnetic field to collimate the ejected electrons within a focal point, improving the characteristic X-ray yield. A hypothetical model is proposed that focuses on the magnetic targeting of the electron beam within the X-ray tube shell, aiming to encourage further research into how such a magnetic field could enhance the gain of characteristic X-ray production while managing heat, by engineering modifications to the spatial orientation of X-ray tube components.

Keywords

Diagnostic X-rays;
X-ray generation;
X-ray tubes;
Bremsstrahlung Radiation;
Magnetic-Field-Assisted Electron Focusing.

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Introduction:

X-rays are a form of electromagnetic radiation with high energy and short wavelength, discovered by Wilhelm Conrad Roentgen in 1895. They possess the unique ability to penetrate various materials, depending on their density and thickness. X-rays are categorized into soft and hard X-rays based on their energy levels. Due to their penetrating power, they are widely used in medical diagnostics, industrial inspection, and scientific research. In medicine, X-rays are essential for imaging bones, detecting lung infections, and guiding surgical procedures. Industrial applications include examining welds, detecting structural flaws, and quality control. In research, X-ray crystallography is a key method for determining molecular structures. The production of X-rays typically involves accelerating electrons toward a metal target in an evacuated X-ray tube. Despite their benefits, exposure to X-rays must be controlled to avoid biological damage, as they are a form of ionizing radiation. Natural X-rays are electromagnetic radiations of wavelengths 10^{-12} – 10^{-10} meters as seen by figure 1.

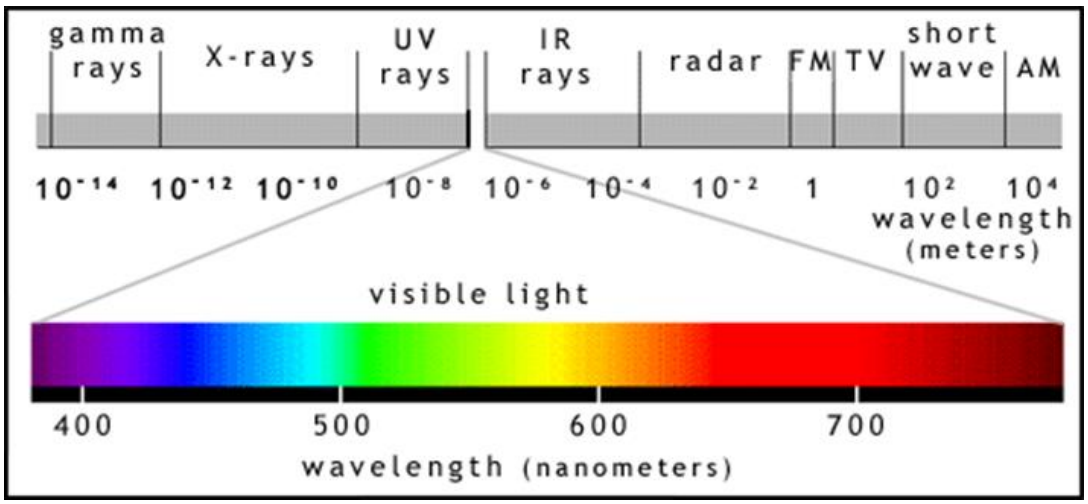


FIG: 1 The natural light spectrum.

X-rays are generated when high-energy electrons strike a metal target, causing the inner-shell electrons of the target atoms to be ejected. This creates an electron vacancy, which is then filled by an electron from outer-shells. The energy difference between the shells is released as an X-ray photon. X-rays originating in different terms such as Kα1, Kα2sub shells (2p3/2,2p1/2) of the L to K shell transitions, and Kβ (Kβ1 + Kβ2) from M to K transitions, and so forth (figure 2).

- $2p_{3/2} \rightarrow 1s$ ($K\alpha_1$)
- $2p_{1/2} \rightarrow 1s$ ($K\alpha_2$)
- $3p \rightarrow 1s$ (**Kβ1& Kβ2**)

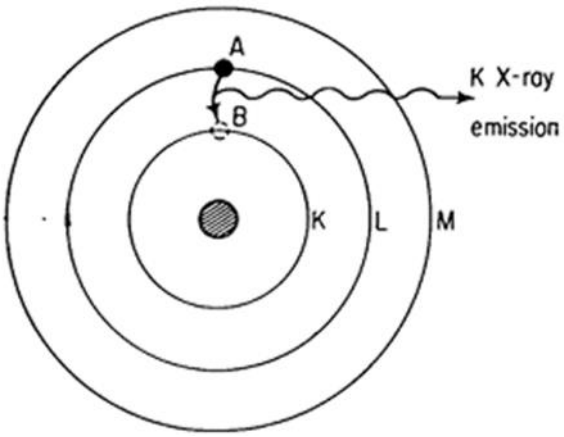


FIG: 2 Schematic diagram showing X-ray emission caused by L-shell electron (A) filling a K-shell vacancy (B), it emits a characteristic K $_x$-ray.

X-ray energy could be calculated as the transition energy E), by the following relationships (Eq.1-3):

$$\Delta E = E_{\text{initial}} - E_{\text{final}} = R_\infty hcZ^2\left(\frac{1}{n^2_{\text{initial}}} - \frac{1}{n^2_{\text{final}}}\right) \quad \text{.....Eq.1}$$

$$E_x^{\text{K}} = 13.6\left(\frac{1}{1^2} - \frac{1}{2^2}\right)Z^2\ \text{eV} \quad \text{.....Eq.2}$$

$$E_x^{\text{L}} = 13.6\left(\frac{1}{2^2} - \frac{1}{3^2}\right)Z^2\ \text{eV} \quad \text{.....Eq.3}$$

., where Z= the atomic number of solid metal target and **eV** is the electric potential in electron volt.

Mössbauer effect:

The topic of why gamma-ray resonance was conceivable in solids but not in gases was brought up by the observation of resonance in solid iridium by German physicist Rudolph L. Mossbauer in 1958. According to equation 4, Mössbauer postulated that in the case of atoms bound into a solid structural form, under specific conditions, a portion of the nuclear processes might occur practically without recoil. Table-1 is showing the best materials for X-rays generation.

$$E_{\text{R}} = \frac{E_\gamma^2}{2Mc^2} \quad \text{.....Eq.4}$$

., where E_R is the recoil energy of the metal, c is the velocity of light and M is the mass of nucleus.

Artificial X-ray production:

Artificial X-ray is produced using x-rays system that is composed by **x-ray machine** that contains the high voltage generator and the recycling cooling cycle for the tungsten anode and the **x-ray tube**.

Table 1: Binding energies and monoenergetic radiations resulting from exciting interactions for Tungsten W (Z=74), Molybdenum Mo (Z=42) and Rhodium Rh (Z=45).

Element	Binding energy, keV		Energies of characteristic X rays, keV			
	L-shell	K-shell	K_{a1}	K_{a2}	K_{b1}	K_{b2}
W	12.10/11.54/10.21	69.53	59.32	57.98	67.24	69.07
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

X-ray machine:

As seen by figure 3, it composed of the X-ray electric generator which supplies high-voltage electrical energy to the X-ray tube to accelerate electrons from the cathode to strike the anode target, **typically made of tungsten and the oil cooling cycle**. Heat is generated at the anode is transferred to the oil, which then circulates through a heat exchanger or radiator system to dissipate the heat efficiently. In advanced systems, fans or water-cooled heat exchangers assist in maintaining optimal temperature, ensuring reliable and safe operation of the X-ray tube under continuous or high-load imaging conditions.

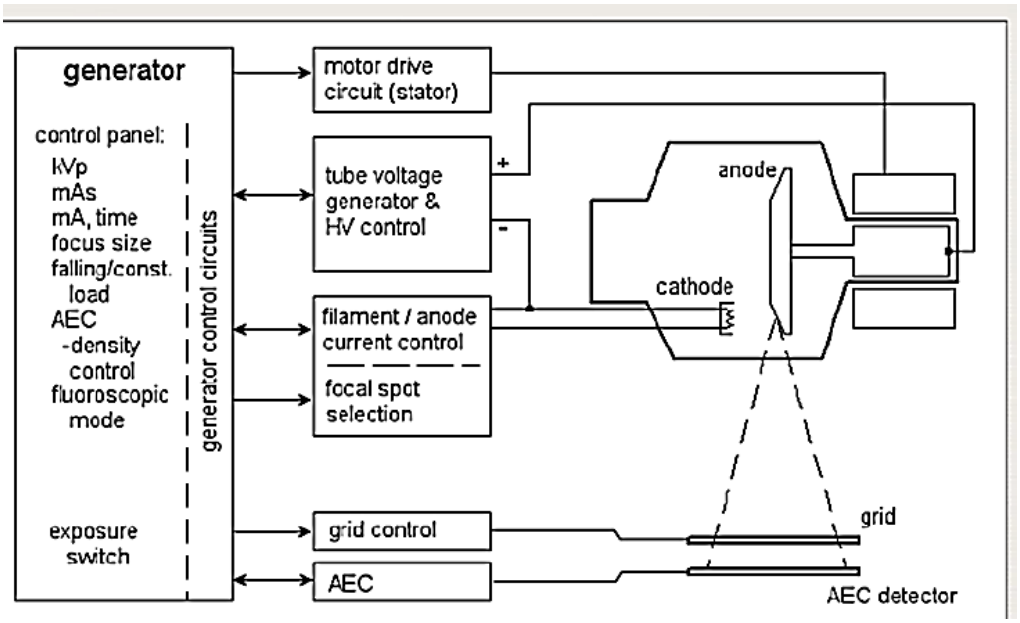


FIG: 3 Schematic diagram for a basic X-rays generator system.

X-ray tube structure:

1-The Main Components of an X-ray Tube are seen by the following (Figures 4 &5):

1. Cathode: Contains filament(s) (usually tungsten) which is heated up to emit electrons via thermionic emission and includes a focusing cup to direct the electron beam towards the anode.
2. Anode: Target material (commonly tungsten, molybdenum, or rhodium) where the accelerated electrons strike Table-2 illustrate the properties of Tungsten (W), Molybdenum (Mo) and Rhenium (Rh) that are compatible with being used as metal target in the manufacturing of x-ray tubes. Molybdenum (Mo) and Rhenium are fitted for x-ray mammography because of their moderate energy, meanwhile Tungsten (W) is used for general x-ray radiography. Produces X-rays via bremsstrahlung and characteristic radiation. Can be stationary or rotating to spread heat.
3. Glass or Metal Envelope: Houses the cathode and anode. Maintains a vacuum to prevent electron scattering. Protective Housing: Provides mechanical support, radiation shielding, and electrical insulation. Includes oil cooling or air-cooling system to dissipate heat.
4. Window (X-ray Exit Port): A thin section (often beryllium) that allows X-rays to exit with minimal absorption.
5. Filters (External or Built-in): Usually aluminum or copper. Remove low-energy X-rays to reduce patient dose (beam hardening).
6. High-Voltage Supply: Provides potential difference (typically 40–150 kV) between cathode and anode to accelerate electrons (for portable dental x-ray machines).

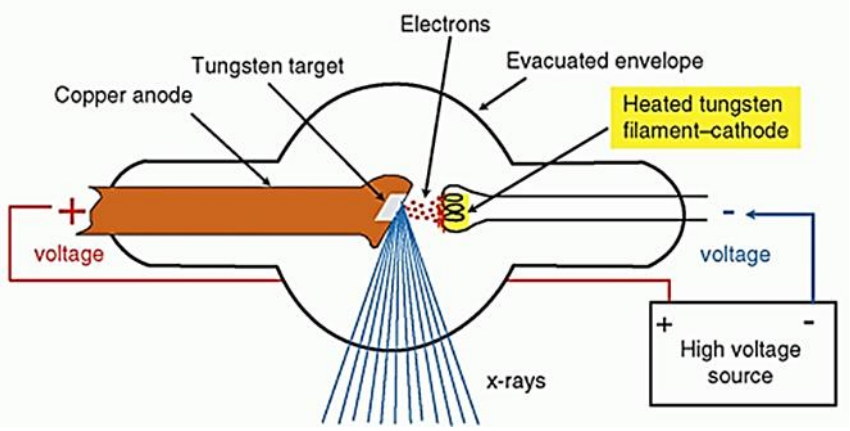


FIG: 4 The schematic diagram for x-ray tube operation.*

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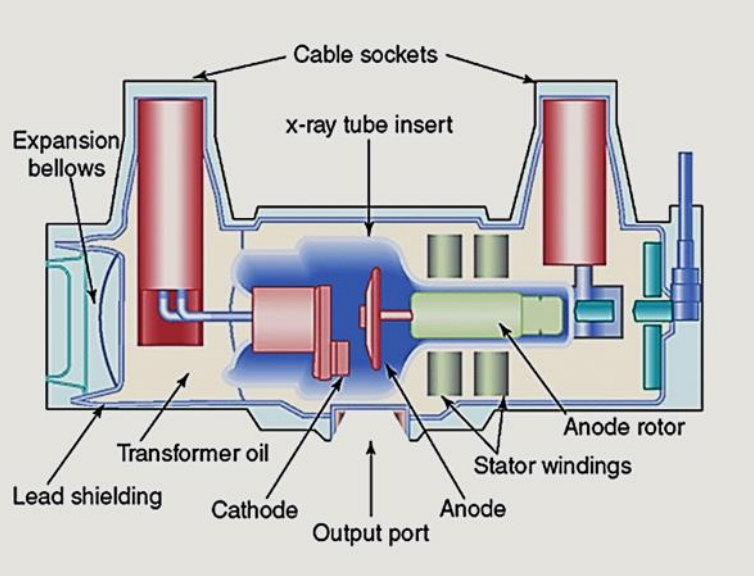


FIG: 5 A diagram of the major components of a modern x-ray tube and its housing assembly. *

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Table 2: Properties of W, Mo, and Rh Suitable for X-ray Tube Targets.

Property	Tungsten (W)	Molybdenum (Mo)	Rhodium (Rh)	Importance for X-ray Tube
Atomic number (Z)	74	42	45	Higher Z → More efficient Bremsstrahlung X-ray generation
Characteristic X-ray energy	Kα ≈ 59.3 keV Kβ ≈ 67.2 keV	Kα ≈ 17.5 keV Kβ ≈ 19.6 keV	Kα ≈ 20.2 keV Kβ ≈ 22.7 keV	Determines the energy range of emitted X-rays
Melting point	3422 °C	2623 °C	1964 °C	High MP resists heat from electron bombardment
Thermal conductivity	High (~170W/m·K)	Moderate (~138 W/m·K)	High (~150 W/m·K)	Efficient heat dissipation
Mechanical strength	Very strong	Moderate	Moderate	Withstands long operation under stress
Application	General-purpose X-rays	Mammography (soft X-rays)	Mammography, angiography	Tailored to energy needs

2-Mechanism of X-Ray Production:

Inside an X-ray tube, high-energy electrons are emitted from a heated filament cathode and accelerated toward a metallic target (usually tungsten) by a high operating voltage (typically 20-150 kV), the X-ray tube is enclosed in a metal housing filled with dielectric cooling oil, which serves two purposes, electrical insulation and thermal regulation (Figure 6 &7).

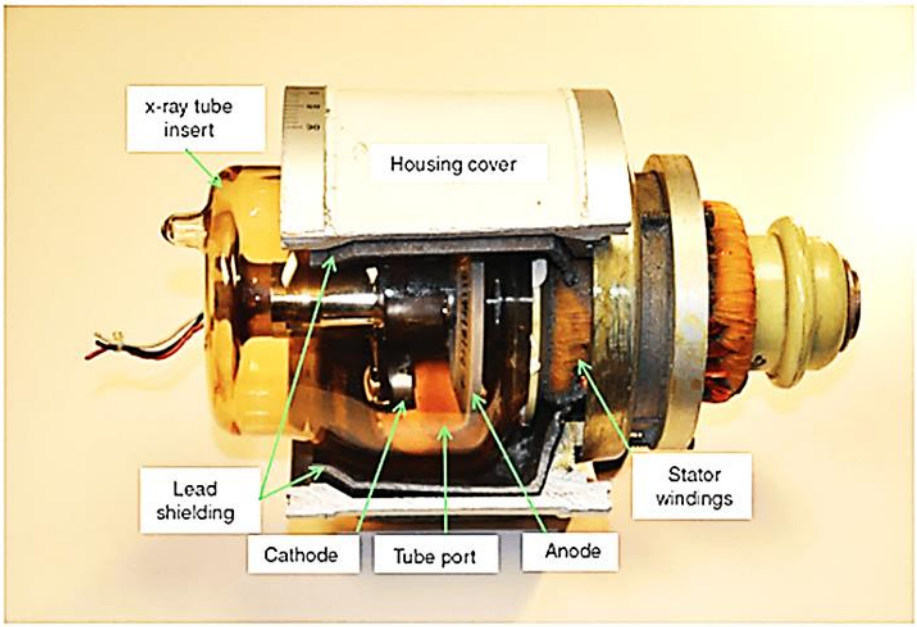


FIG: 6 The x-ray tube components including the x-ray tube glass envelope and partially cut-away tube protecting housing with a lead shielding of 2 mm thickness. *

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FIG: 7 The evacuated glass envelope of x-ray tube. *

*https://www.shutterstock.com/image-photo/vacuum-glass-ampoule-xray-tube-rotating-1609

Pathways for electron interactions with anode:

When the electrons strike the anode target atoms, they have different probable paths. This interaction of the accelerated electrons with anode produces X-rays primarily through bremsstrahlung and characteristic radiations. However, less than 1% of the electrical energy is converted into useful X-ray (characteristic x-ray), while over 99% becomes heat (Bremsstrahlung radiation), which can damage the tube components.

To manage this thermal load, a specialized cooling cycle is implemented throughout the system. the interactions with the atomic structure of the target anode are carried out by two major paths.

a) Bremsstrahlung Radiation ("Braking Radiation"):

Bremsstrahlung (from German *"bremsen" = to brake, "Strahlung" = radiation*) is a type of X-ray radiation generated when high-speed electrons are suddenly decelerated upon interacting with the nucleus of a target atom (usually in the anode of the X-ray tube) in figure 8.

b) Electrons are decelerated by the Coulomb field of the nuclei of the target atoms; this sudden deceleration results in the emission of X-ray photons. The energy of emitted photons varies, resulting in a continuous spectrum due to probable electrons paths as seen by figure 9. This is the dominant X-ray production mechanism in most x-ray tubes.

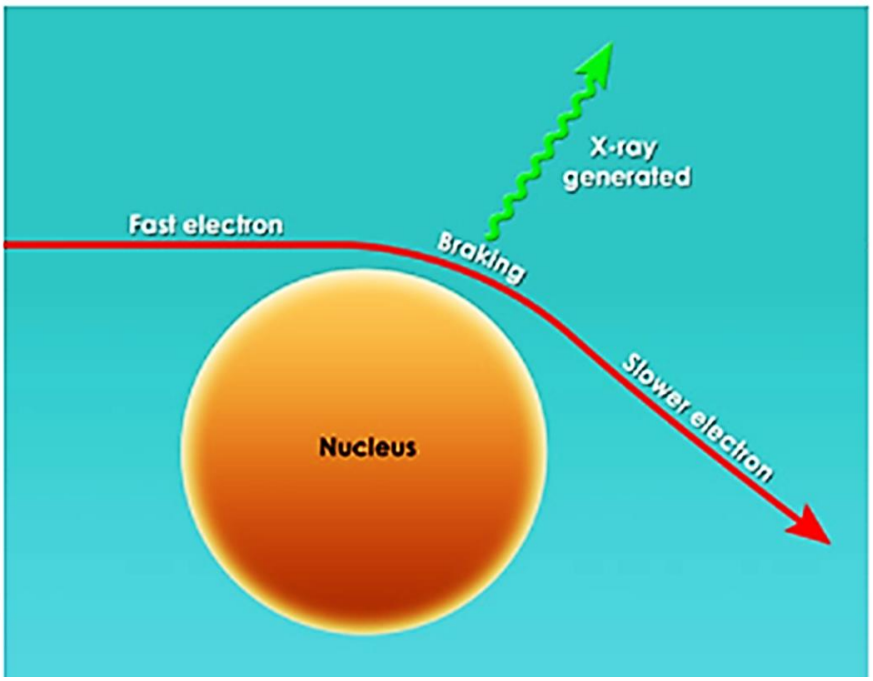


FIG: 8 Bremsstrahlung Radiation.

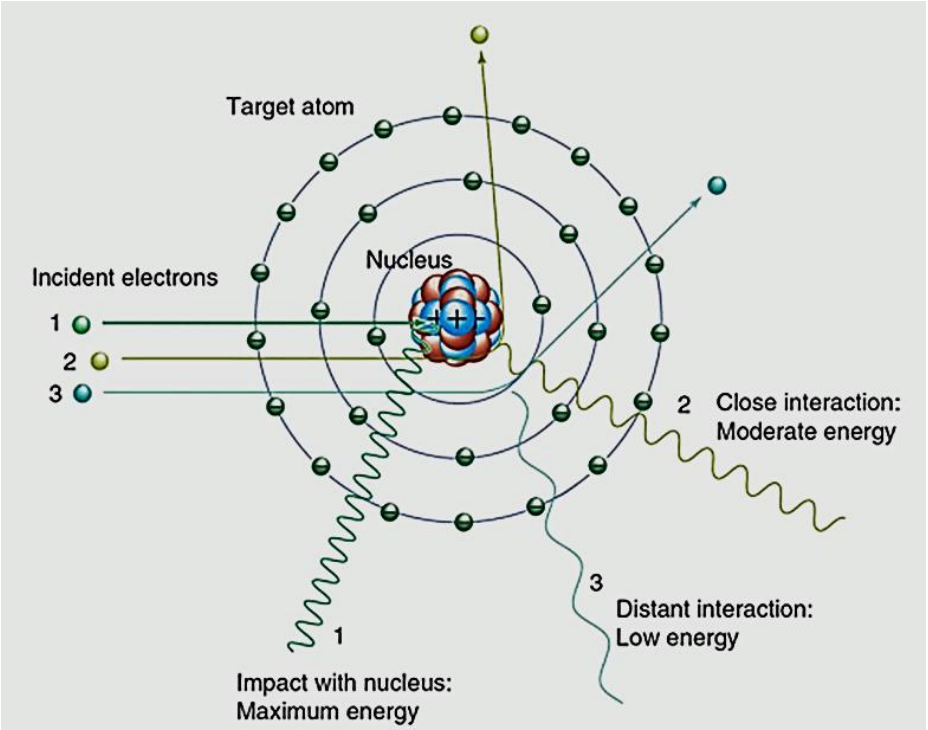


FIG: 9 Different electronic -nucleus interactions paths. *

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Probability of X-ray Generation:

Even with tungsten and high operating voltage (e.g., 100 kV), the efficiency (η) is only around 1% (Kα1, Kα2& $K_\beta 1$) as seen from equation 5, due to the high **cross-section** for Bremsstrahlung, hence characteristic X-ray emission is **much smaller** than that for the inelastic scattering that produces heat as seen by figure 10.

$$\eta \approx 9\times10^{-10}ZV \quad \text{..... Eq.5}$$

where:

η: efficiency
Z: atomic number of the target (e.g., 74 for tungsten).
V: tube voltage (in volts).

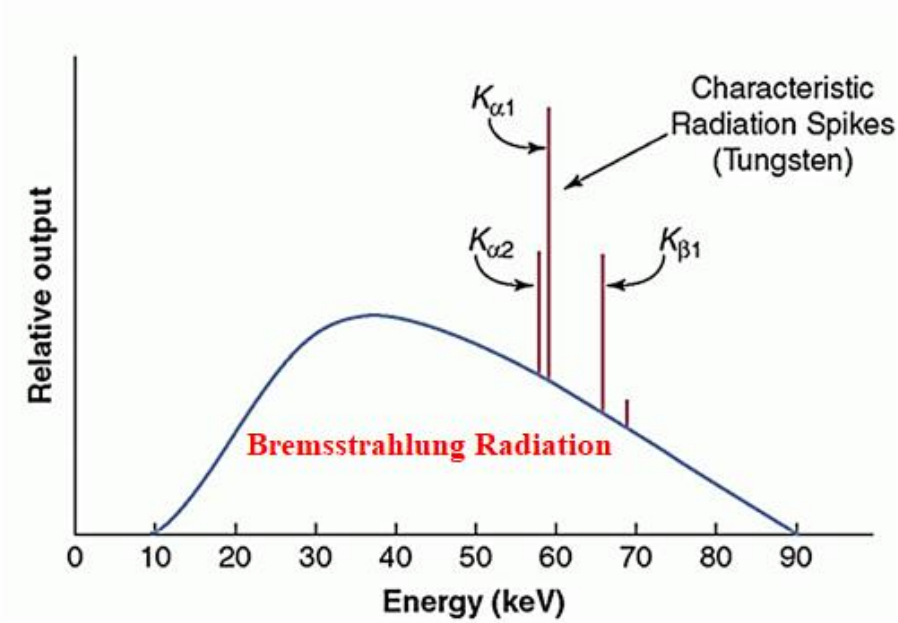


FIG: 10 The filtered spectrum of bremsstrahlung and characteristic radiation from a tungsten target with a potential difference of 90 kV, illustrates the specific characteristic radiation energies from *Kα* and *Kβ* transitions.

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Predominance of Heat-Producing Collisions:

Most collisions between the incoming electrons and the target atoms result in **excitation or ionization**, not X-ray production. These non-radiative processes cause **target atoms to vibrate**, producing **thermal energy (heat)**. Thus, the **net useful X-ray output** is even further reduced.

Heating of the anode:

This phenomenon is the major limitation of x-ray production the generation:

The excessive heat that could be calculated by equations 6 or 7.

Heat (J) = kVe x mAs 6

Heat (J) = w x kVp x mAs..... 7 ,
Where:

kVe = effective operating Kv, **w** = The waveform of the voltage through the x-ray tube. The more uniform the waveform the lower the heat production.

kVp = peak kV and **mAs** = current exposure time product

Energy Loss in Filtration and Target Self-Absorption:

Some of the produced X-rays are **absorbed within the target** itself and by the **tube's inherent filtrating material**, as well as the glass envelope or extra added filters as seen by table 3. Within the X-ray broad beam, a spectrum of distinctive X-ray energy (1%) is generated due to characteristic and bremsstrahlung radiation emission. By altering the X-ray tube's voltage or current settings or by adding

filters to absorb low energy X-rays, this spectrum can be controlled. As shown in figure 11, radiographers can use these Techniques to apply various X-ray beam spectra to various body sections.

As seen from figure 9 that the energy of K_α is less than K_β because of that more of accelerated electron's energy is exhausted to eject the K-shell electrons.

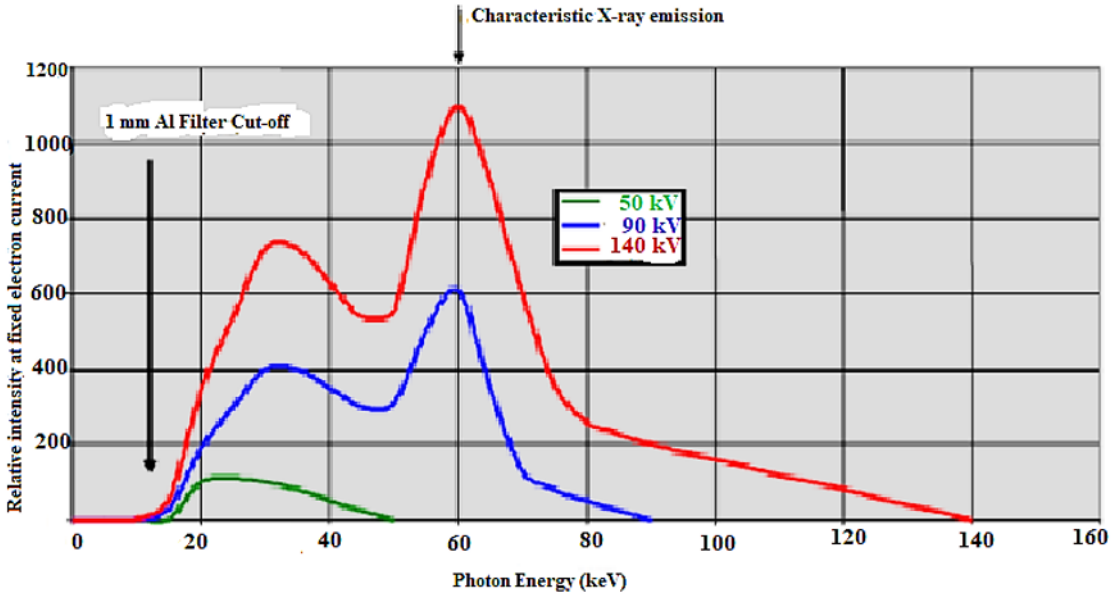


FIG: 11 X-ray emission from Wolfram anode X-ray tube. Observe that for a given tube voltage, the higher the energy of the photons, the less there are. And if the number of photons is to increase, then the tube voltage should increase.

Table 3: Common X-ray Filter Materials

Filter Material	Atomic Number (Z)	Main Use	Why Used
Aluminum (Al)	13	General radiography	Removes low-energy X-rays; cheap, effective
Copper (Cu)	29	Fluoroscopy, pediatrics, angiography	Stronger filtering than Al, used in higher-energy beams
Molybdenum (Mo)	42	Mammography (with Mo anode)	Matches K-edge to remove lower-energy X-rays and shape spectrum
Rhodium (Rh)	45	Mammography (with Rh anode)	Better penetration for dense breasts
Tin (Sn)	50	Dual-energy CT, angiography	Filters very soft X-rays, pre-hardens the beam
Lead (Pb)	82	Not for filtering diagnostic beams directly, but for shielding	Absorbs all scattered or unused X-rays
Titanium (Ti) *(rare)*	22	Used in some CT or special systems	Low Z, mild filtering

Thermal Management Implications:

Because ~99% of energy becomes heat:

- **Rotating anodes** are used to spread heat across a wider area.
- **Cooling systems** (oil, fans, or water) are essential to prevent overheating.
- **Tube current (mA)** and **exposure time (s)** must be carefully optimized to balance **X-ray yield and tube lifespan**.

Engineering modifications:

The goal is to **maximize the X-ray yield** while ensuring the tube remains undamaged. Use **high Z targets** (like tungsten, molybdenum):

- Optimize **tube voltage** and **current** for specific imaging tasks.
- Use **filtration** to remove low-energy, non-penetrating X-rays that increase patient dose without contributing to image quality.

Diagnostic x rays:

Figure 12 illustrates how diagnostic X-rays can be beneficial in identifying anomalies within the body. They are a non-invasive, painless method of diagnosing issues like cancers, tooth decay, broken bones, and foreign substances. A focused x-ray beam and a plate with sensitive photographic film are placed between the body part to be inspected in order to perform a diagnostic x-ray. There is no pain involved in this technique. The denser the material through which the x-rays travel, the more rays are absorbed. As seen in figure 13, tumors may absorb more x-rays than surrounding tissue, and bone absorbs more x-rays than muscle or fat.

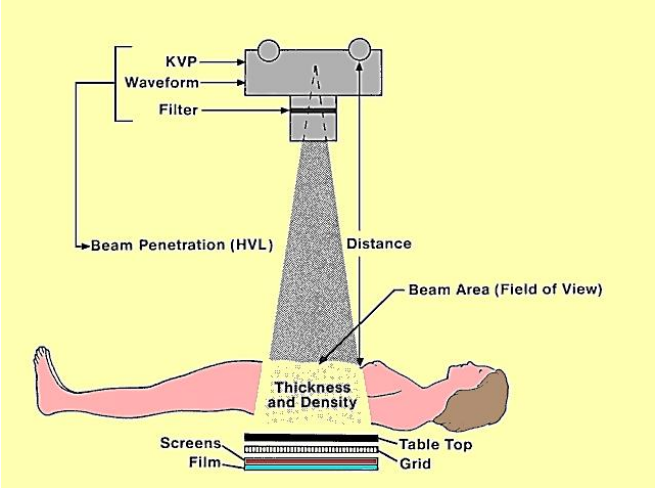


FIG: 12 X-ray patient exposure and protection

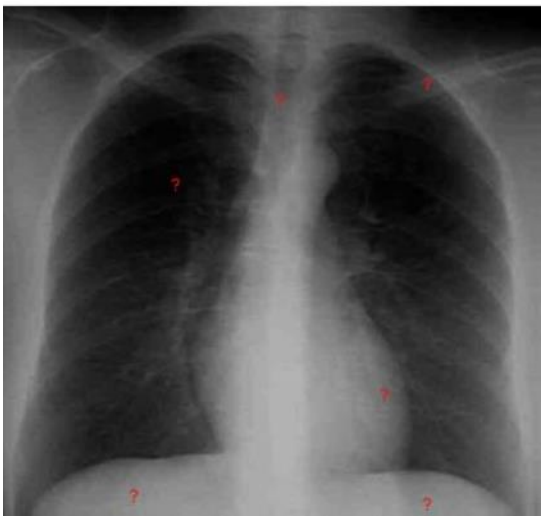


FIG: 13 Normal chest X-ray image.

With varying intensities, X-rays that travel through the body interact with silver molecules on the film's surface after striking the photographic plate. After processing the film plates (fig. 14) as a negative image, airspaces appear black, softer tissues appear as shades of gray, and dense objects like bones appear as white. After reviewing the images, a radiologist a medical professional qualified to interpret diagnostic x-rays reports back to the ordering physician. In a hospital, radiological center, clinic, doctor's or dentist's office, or at the patient's bedside using a portable dental x-ray equipment, plain film x-rays often only take a few minutes to complete (Figure 15).

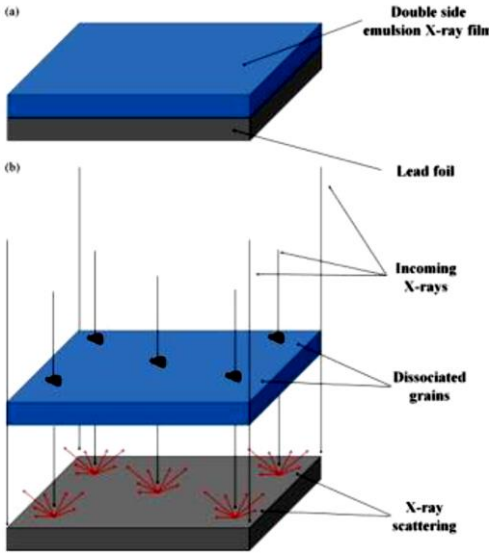


Fig.-14 Components of dental photographic film.



FIG: 15 portable dental x-ray machine.

Computed Tomography (CT) system:

As seen in figure 16, a Computed Tomography (CT) system, commonly known as a CT scanner or CAT scanner (Computed Axial Tomography), is a sophisticated medical imaging tool that creates comprehensive cross-sectional images (slices) of the body by combining computer processing and X-ray technology.

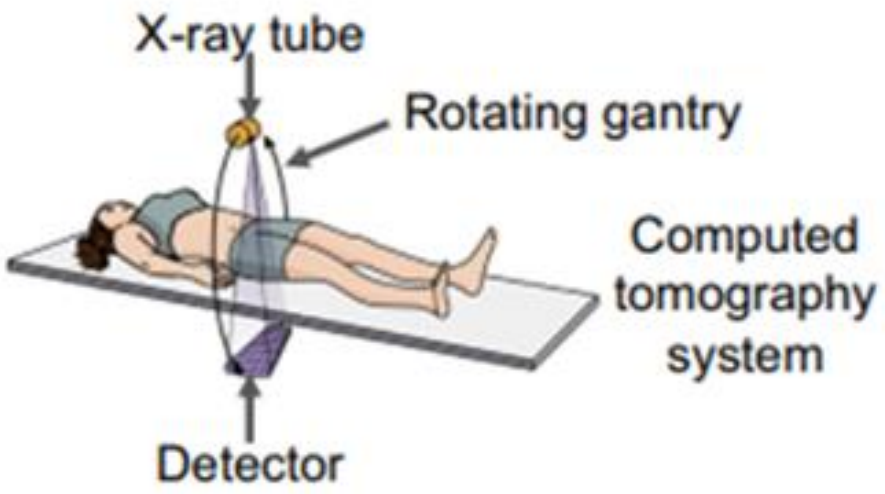


FIG: 16 Tomography Computed System.

Main Components of a CT System:

1. X-ray tube: This device creates a concentrated X-ray beam that enters the patient's body.
2. Gantry: The CT scanner's revolving, circular section that houses the detectors and X-ray tube.
3. Detector array: This device, which is located across from the X-ray source, picks up X-rays as they travel through the body and transforms them into electrical impulses.

The fourth is the Patient device (Couch), a motorized device that slides the patient across the gantry to scan various body parts.

5. Analog signals from detectors are converted into digital data by the Data Acquisition System (DAS).
6. Computer System use algorithms (such as filtered back projection and iterative reconstruction) to reconstruct raw data into cross-sectional images.
7. Display/Console: This enables technicians and radiologists to view and work with images.

How a CT System Works (Basic Process):

1. X-ray imaging is carried out using X-ray tube which emits a narrow beam of X-rays.
2. Body Scanning: As the tube rotates around the body, the X-rays pass through different tissues.
3. Detection: The detectors measure the intensity of transmitted X-rays (attenuated by body tissues).
4. Data Processing: The system collects data from many angles and reconstructs a 2D image slice.
5. 3D Imaging: Multiple 2D slices are stacked to form a 3D view of internal structures
6. Body Scanning: As the tube rotates around the body, the X-rays pass through different tissues.
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8. Data Processing: The system collects data from many angles and reconstructs a 2D image slice.

9. 3D Imaging: Multiple 2D slices are stacked to form a 3D view of internal structures.

Types of CT scans:

- Conventional CT: Step-by-step, slice-by-slice scan.
- Spiral/Helical CT: Continuous rotation and table movement create faster scans and better images.
- Multi-slice CT (MSCT): Has multiple rows of detectors (e.g., 64-slice, 128-slice), providing higher resolution.
- Dual-energy CT, is done by imaging with two X-ray energy levels to differentiate materials.

Applications of CT:

- Brain: Stroke, bleeding, tumors.
- Chest: Lungs, pulmonary embolism and heart.
- Abdomen/Pelvis: Kidney stones, liver disease and cancer staging.
- Orthopedic: Bone fractures, joint evaluation.
- Trauma: Fast imaging of internal injuries.

Radiation and Safety:

- CT involves ionizing radiation (higher dose than standard X-rays).
- Dose reduction technologies (e.g., filters, iterative reconstruction) are used.
- Appropriate justification and optimization are critical, especially in children and pregnant women.

Dental X-rays:

Dental X-rays capture images of the teeth, surrounding soft tissues, and bones, helping to identify disorders in the jaw, mouth, and teeth. X-ray images reveal cavities, hidden dental structures (like wisdom teeth), and bone loss that are invisible to the naked eye.

Dental X-rays can also be performed using a dental x-ray machine as a follow-up procedure following dental procedures (figure 17); it is crucial to wear a thyroid collar to protect the thyroid glands. The following types of dental X-rays are commonly used. The X-rays use low amounts of radiation:
Bitewing X-rays show the upper and lower back teeth in a single view.

Periapical X-rays show the entire tooth.
Occlusal X-rays show the roof or floor of the mouth and are used to identify extra teeth.
Panoramic X-rays show a broad view of the jaws, teeth, sinuses, nasal area, and temporomandibular (jaw) joints as seen by figure 18.
Digital X-rays can be sent to a computer to be recorded after upgraded by montage as seen by figure, and saved.



FIG: 17 Dental x ray machine and patient is wearing a lead collar.



FIG: 18 Panoramic x-ray radiography of the teeth of a 64-year-old male.

Table 4 illustrates the radiation dose reference levels for different X-rays imaging which range from very high to high levels, when the values are compared with the annual personal does record in table 5 on bases of ALARA principal values, therefore the administration x-ray image is to the final required decision.

Table 4: Current Dose Rate Limits for Common X-ray Procedures. *

Examination	Typical Adult (DRL) (Entrance Skin Dose)	Dose (mrem)
Chest X-ray (PA)	0.1 m Gy	10
Chest X-ray (LAT)	0.3 m Gy	30
Abdomen X-ray (AP)	4.0 m Gy	400
Lumber Spine (AP)	6.0 m Gy	600
Lumber Spine (LAT)	15 m Gy	1500
Skull (AP/LAT)	2-3 m Gy	200-300
Dental Panoramic X-ray	14-24 μ Gy (Effective dose)	1.4-2.4

***(ACR & ICRP recommendations – updated 2024), DRL: Dose Reference Levels.**

Note: Effective dose = how much *biological risk* there is (in μSv or mSv).

Table 5: Radiation Exposure - Annual Limit

	Member of the Public/ Non-NEW		Nuclear Energy Worker (NEW)	
	Annual (mSv)	Pregnant (mSv)	Annual (mSv)	Pregnant (mSv)
Whole Body	1	1	20	20 4 over 9 months
Extremities (hands & feet)	50	50	500	500
Lens of the Eye	15	15	150	150
Skin	50	50	500	500

Radiation Monitoring radiation and Safety:

The annual permissible dose for the radiation officer is 2000 m Rem., that is equal 10 m Rem./ day, hence it is necessary to verify the accumulated radiation dose weekly or monthly, if the accumulated dose exceeded the permissible limit recorded in table 5, the radiation officer, will need to be relocated away from the radiation source to remain within the permissible dose limit. They daily radiation doses are measured by Photographic film badges (Figure19) and TLD sensitive (pocket pen as seen by figure 20) devices:

When photographic film absorbs radiation, such as visible light, it becomes darker. The darker the film is when developed, the more radiation it absorbs. Workers that handle radiation wear film badges, which are routinely inspected to track radiation absorption levels. A typical radiation badge's inside is depicted in the diagram both closed and open. Tritium (H-3), sulfur 35 (S-35), and carbon 14 (C-14) are examples of weak beta emitters that do not affect TLDs. The two most prevalent forms of TLDs are calcium fluoride and lithium fluoride, which include one or more impurities that provide trap states for energetic electrons. LiF dosimeters can be enriched in lithium-6 to increase or decrease this effect. The former is used to record gamma exposure, while the latter is used for gamma and neutron exposure (indirectly, via the Li-6 (n, alpha) nuclear reaction).

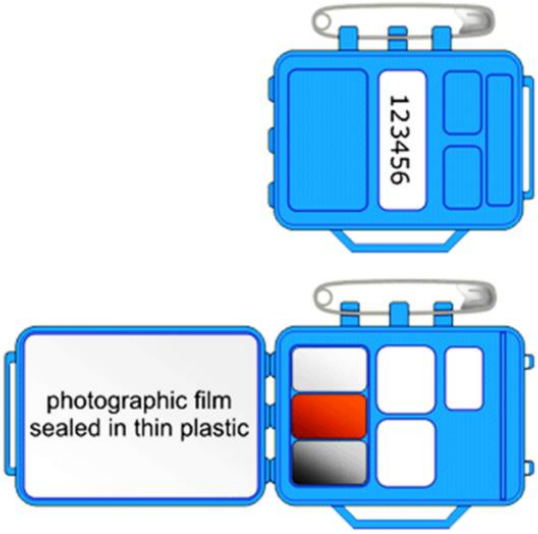


FIG: 19 The photographic Badge film.



FIG: 20 Self-reading dosimeters.

How to Ensure Safety?

- Use *pulsed* vs continuous fluoroscopy.
- Ensure that the collimation is tight around the region of interest.
- Avoid repeat images and improve positioning skill.
- Use high kVp / low mAs technique where appropriate.
- Apply shielding if necessary (especially thyroid, gonads).

Cone-Beam CT: 3-D Images, More Radiation:

Recently, some dentists have begun using cone-beam computed tomography CT). These machines produce three-dimensional images of the teeth and jaw bones. Cone-beam CT exposes patients to more radiation than a standard full-mouth series of X-rays or a panoramic X-ray. Therefore, cone-beam CT should be used only where it provides a clear advantage over standard X-rays.

- Regular inspections and licensing: State local health departments regularly check X-ray

machines to make sure they are accurate and safe.

- Lead shields: Before you get X-rays, you will be covered from the neck to the knees with a lead-lined
- Full-body apron: Sometimes you'll also have a separate neck protector, called a thyroid collar. The American Academy of Oral and Maxillofacial Radiology recommends the use of a thyroid collar on patients under age 30. Younger adults and children are at greater risk for radiation-induced thyroid cancer than older adults. These shields have been used for decades, and many states require them. Today, however, they offer more peace of mind than actual protection. That's because modern dental X-ray machines emit almost no scatter (stray) radiation.
- Limited use of X-rays: Dentists take X-rays only when they believe they are necessary for an accurate dental assessment or diagnosis.

Results and Discussion:

A wide range of X-rays and heat (Bremsstrahlung) are emitted when electron energies rise because there are more interactions through the anode's successive layers. The square power of the electron energy determines how much the interactions increase. Given that the bombarding electrons' kinetic energy is supplied by the X-ray tube potential (UA), the radiations' output energies are proportional to UA 2. Magnetic flux fields are thought to maximize X-ray output at the expense of thermal profiles by concentrating blasted electrons within focal point and guiding backscattered electrons.

According to the following ideas, the magnetic field pushes electrons toward the anode, increasing the percentage of electrons released from the cathode, and pushes reflected electrons from the anode back to the anode, resulting in an additional increase in the efficiency of the X-ray tube.

1-Cathode Focusing and Electron Beam Compression:

Electrons are intended to be emitted and focused toward a specific region of the anode by the cathode assembly. The electron cloud is compressed and directed toward the focal track spot by the electrostatic field created by the curved focusing cup. The concentration of the electron beam raises the electron density at the target, increasing the likelihood of inner-shell ionization in the anode material's atoms. A more concentrated and smaller electron beam results in the following (Figure 22):

- Improved spatial resolution.
- Reduced geometric unsharpness.
- Increased local electron flux.
- More efficient characteristic X-ray generation.

2. Angled Anode and Line-Focus Principle:

The tilted target makes use of the line-focus principle, which states that a comparatively large actual focal area dissipates heat while appearing to the detector as a smaller effective focal spot. Benefits consist of:

- Higher image resolution.
- Better heat distribution.
- Increased tube loading capacity.
- Maintenance of X-ray intensity without excessive target damage.

The effective focal spot size may be approximated as:

$$F_{eff} = F_{actual} \sin \theta$$ where:

- F_{eff} = effective focal spot size
- F_{actual} = actual electron impact area
- θ = anode angle

A lower anode angle enhances image detail while decreasing the effective focal point.

3. Characteristic X-ray Production:

When accelerated electrons expel inner-shell electrons from the target heavy atoms, characteristic X-ray radiation is created. Photons with distinct energy are released by subsequent electronic transitions. The typical X-ray yield is roughly correlated with:

$$Yc \propto I(V-V_K)^n$$ where:

- Yc = characteristic X-ray yield
- I = tube current
- V = tube voltage
- V_K = K-shell excitation threshold
- n ≈ 1–2 depending on target material

According to this connection, typical radiation rises when the accelerating voltage and electric current exceed the shell binding energy threshold.

4. Proposed Magnetic-Field Enhancement Concept:

The Lorentz force may change the paths of electrons if an external magnetic field is applied surrounding their path:

$F= q\ v\ B$ where: V= tube voltage and B= magnetic flux density (Tesla).

A properly oriented magnetic field could:

- Reduce electron beam divergence.
- Increase beam concentration at the focal spot.
- Increase local electron density.
- Potentially enhance characteristic X-ray production efficiency.

To encourage more research into the potential impact of such a magnetic field on the gain of characteristic X-ray production on the cost of heat, a theoretical model concerning magnetic focusing of the electron beam within the X-ray tube shell by engineering modifications of X-ray tube components through the geometrical spatial orientation within the tube shell bulb is proposed. According to the following equation, the hypothetical model postulates that the application of such a magnetic field may enhance electron-beam confinement towards the focusing target anode, increasing the likelihood of inner-shell interactions responsible for distinctive X-ray emission.

$$Y_c = CZI(V - V_K)ne^{\beta B}$$ where:

- Y_c= characteristic X-ray yield (or intensity)
- C= proportionality constant
- Z= atomic number of the target material
- I= tube current
- V= tube voltage
- V_K= threshold (K-shell ionization) voltage
- n= electron flux factor or electron density term
- B= magnetic flux density (Tesla)
- β= magnetic-field coupling coefficient

Under this assumption, the magnetic field contribution is represented by the factor ($e^{\beta B}$), where (β) describes the effectiveness of magnetic focusing. At present time, this relationship should be regarded as a conceptual model rather than a validated physical law. Its purpose is to provide a mathematical basis for future theoretical, computational, and experimental studies examining whether magnetic-field-assisted electron focusing can enhance characteristic X-ray yield. Verification of this hypothesis will require detailed electron-trajectory simulations, measurements of X-ray output under controlled magnetic-field conditions, and comparison with conventional X-ray tube designs if supported by future investigations, the concept may offer new opportunities for improving X-ray generation efficiency and optimizing diagnostic imaging systems. Consequently, the proposed model is presented as a research direction intended to encourage further exploration of magnetic-field effects in X-ray tube technology [24,25].

Several studies and papers tried external magnetic fields and reducing the excessive heat generated at the anode showing promising results [26-32].

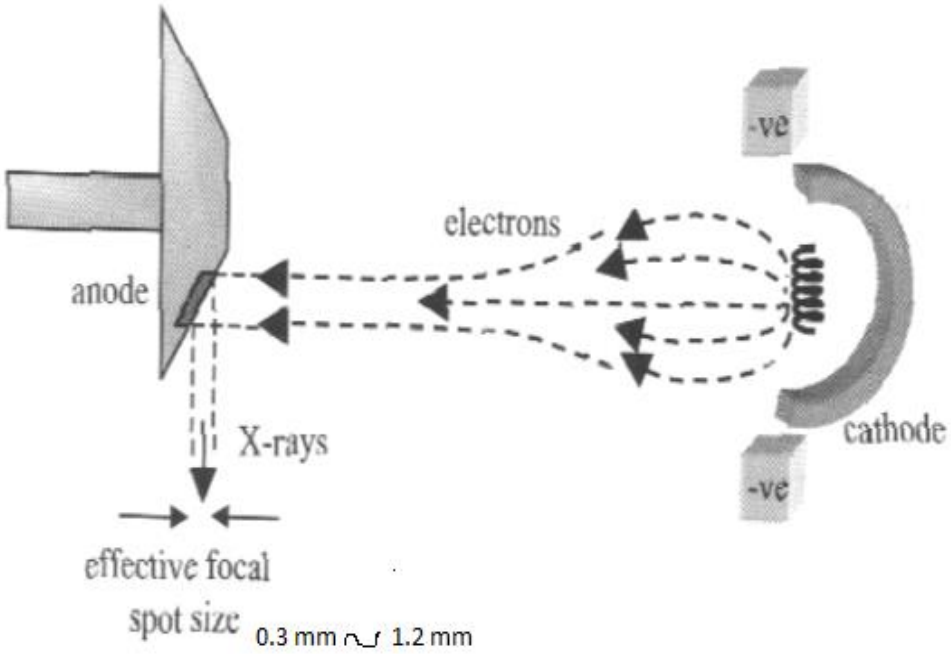


FIG: 22 X-ray tube showing curved cathode, filament and the rotating tungsten anode.

Conclusion:

Due to the predominance of non-radiative collisions that produce heat (Bremsstrahlung Radiation), low cross-sections for X-ray emission, and self-absorption tube components, only around 1% of the energy provided to the X-ray tube is transformed into distinctive X-ray. The key to improving the design, operation, and cooling of industrial and medical X-ray systems is an understanding of this constraint. It is recommended to experiment with various framework models that use a magnetic field to collimate the ejected electrons within a focal point, improving the characteristic X-ray yield.

A hypothetical model is proposed that focuses on the magnetic targeting of the electron beam within the X-ray tube shell, aiming to encourage further research into how such a magnetic field could enhance the gain of characteristic X-ray production while managing heat, by engineering modifications to the spatial orientation of X-ray tube components.

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