Physics of medical imaging

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LIBERTÉ ET PATRIE

Contents of the lecture today

1. Introduction
    1. History of x-ray imaging
    2. Principles of x-ray imaging
2. Radiography
    1. Chain of image formation
    2. X-ray production
    3. X-ray beam
    4. Interaction with patient
    5. Detector systems

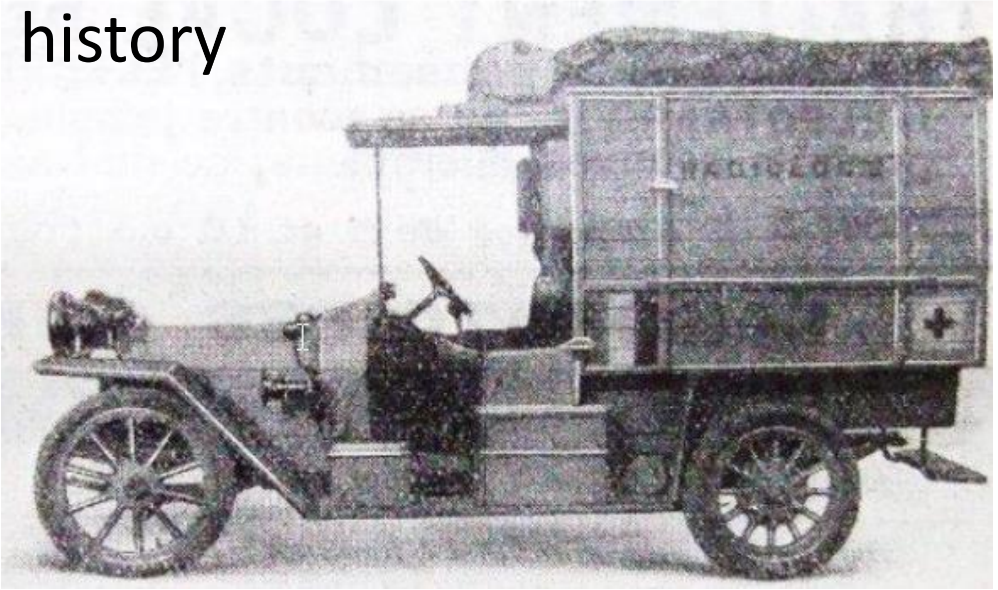
History of x-ray imaging

1895: **Discovery** of x-rays by Wilhelm Röntgen

1897: Antoine Béclère installs the first **radiology center** in France

1901: Röntgen receives **1st Nobel price** in history

1914: Radiographs become part of military medicine: Marie Curie drives truck «Les petites Curies» with **portable x-ray equipment** near the battlefields of France



History of x-ray imaging

X-ray: **Medical catchphrase**

«x-ray» golf balls for straight and longer flight

«x-ray whiskey» for «x-ray prophylactics»

1930s to 1960s: shoe stores used **shoe-fitting fluoroscopic boxes**

1940s: **long-term risk of radiation exposure** begins to be quantified

Today:

radiation exposure linked to several adverse effects

Dose in radiology

Deposit of energy [J]

Mass element

Physical quantity

Absorbed Dose: Energy per unit mass (J/kg)

D (gray : Gy)

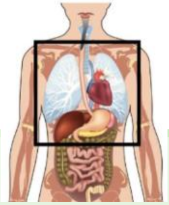
In radiology: energy absorbed by human tissue

W_R

Equivalent Dose: $H_T = D \times w_R$

H_T (sievert : Sv)

Addresses the impact that the type of radiation has on that tissue



W_T

Effective Dose: $E = \Sigma H_T w_T$

E (sievert : Sv)

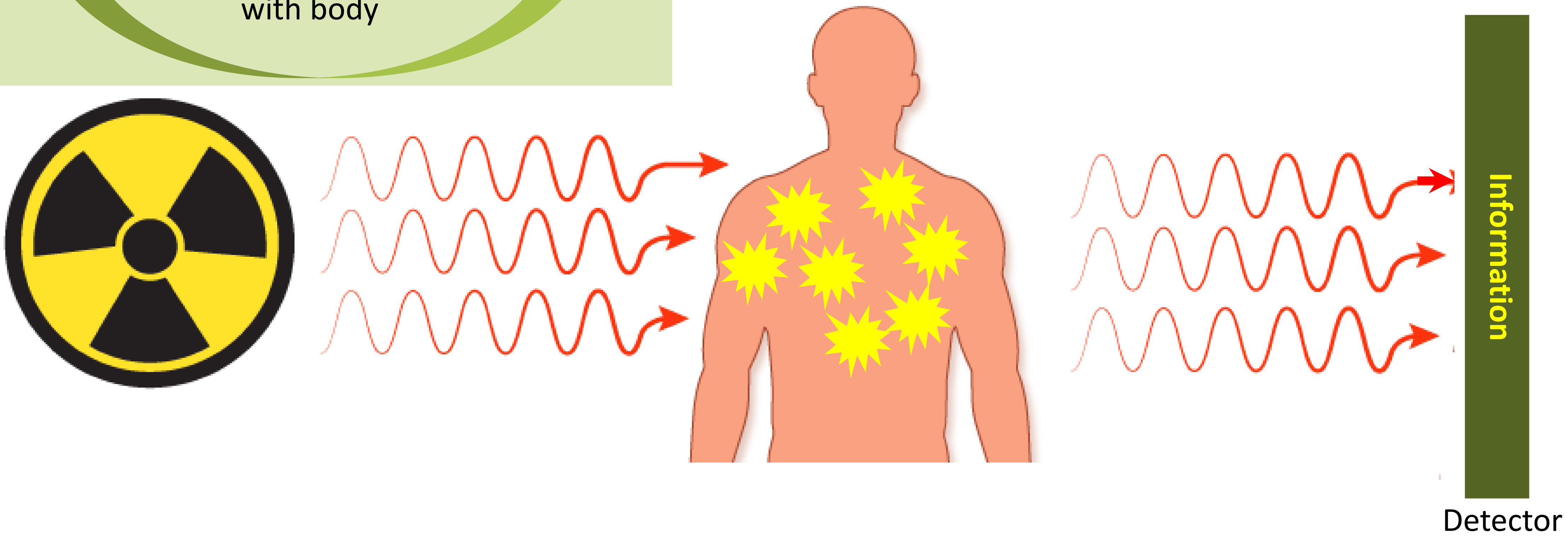
Takes into account the radiosensitivity of organs

Principles of x-ray imaging:

Energy → Human Body → Image

Must penetrate body to produce image

Interaction required with body



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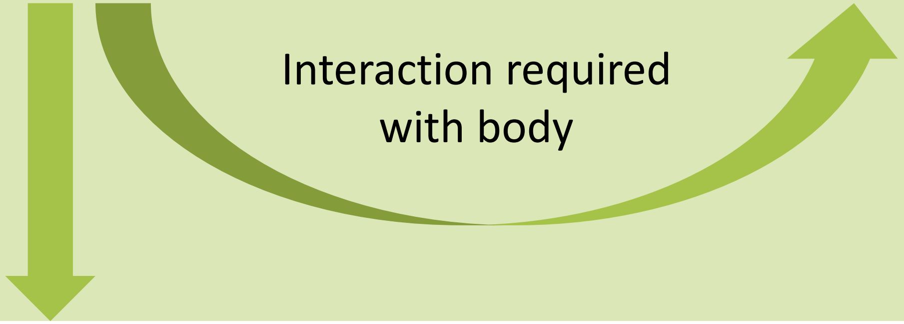
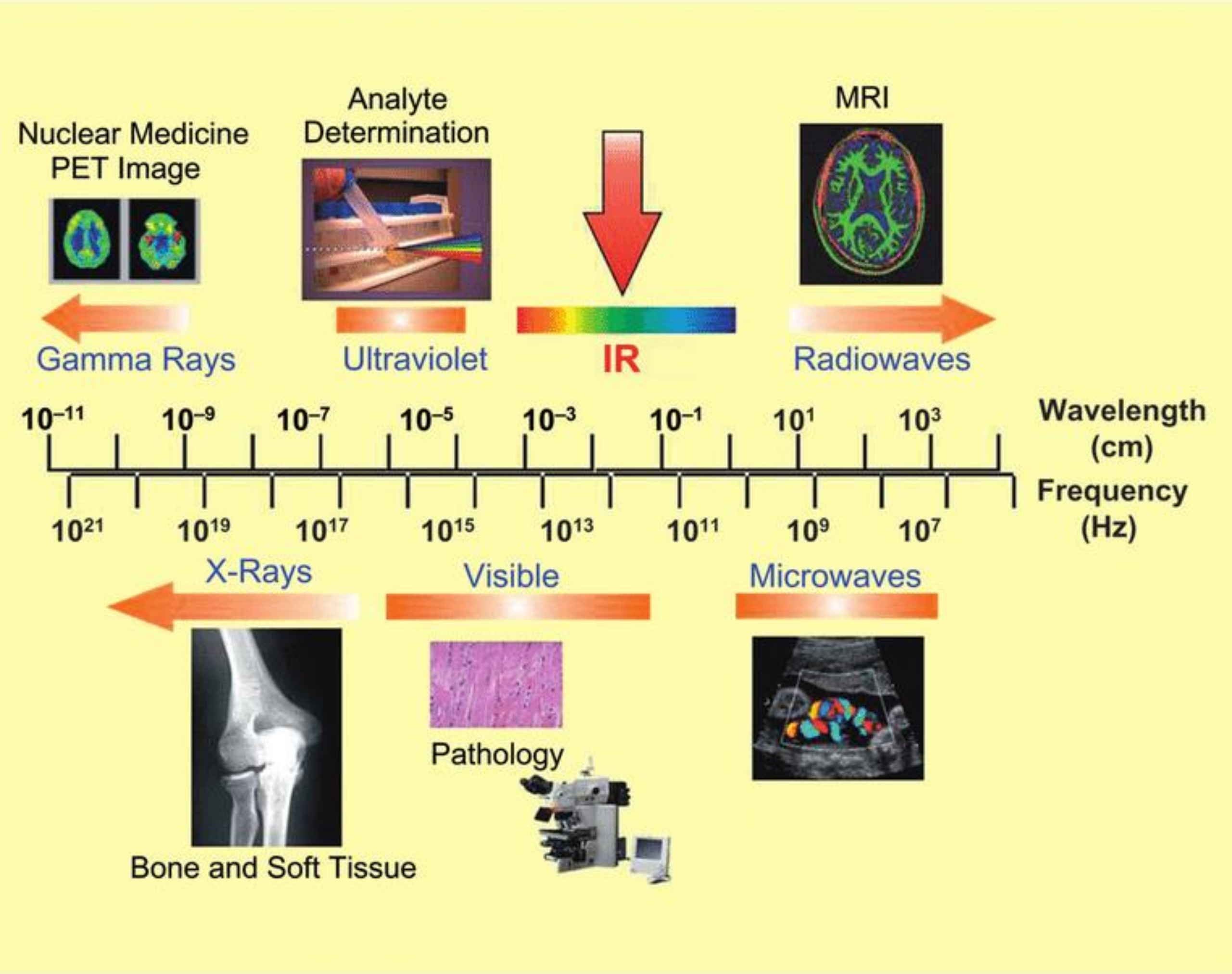


Medical Imaging in diagnostic radiology:
Electromagnetic spectrum outside visible light

X-rays (Radiography, CT, …)
Radiofrequency (MRI)
Gamma rays (nuclear medicine)



Principles of x-ray imaging:

Energy → Human Body → Image

Radiowaves : MRI (1mm – 10km)

Microwaves : Microwave Imaging (1mm – 1m)

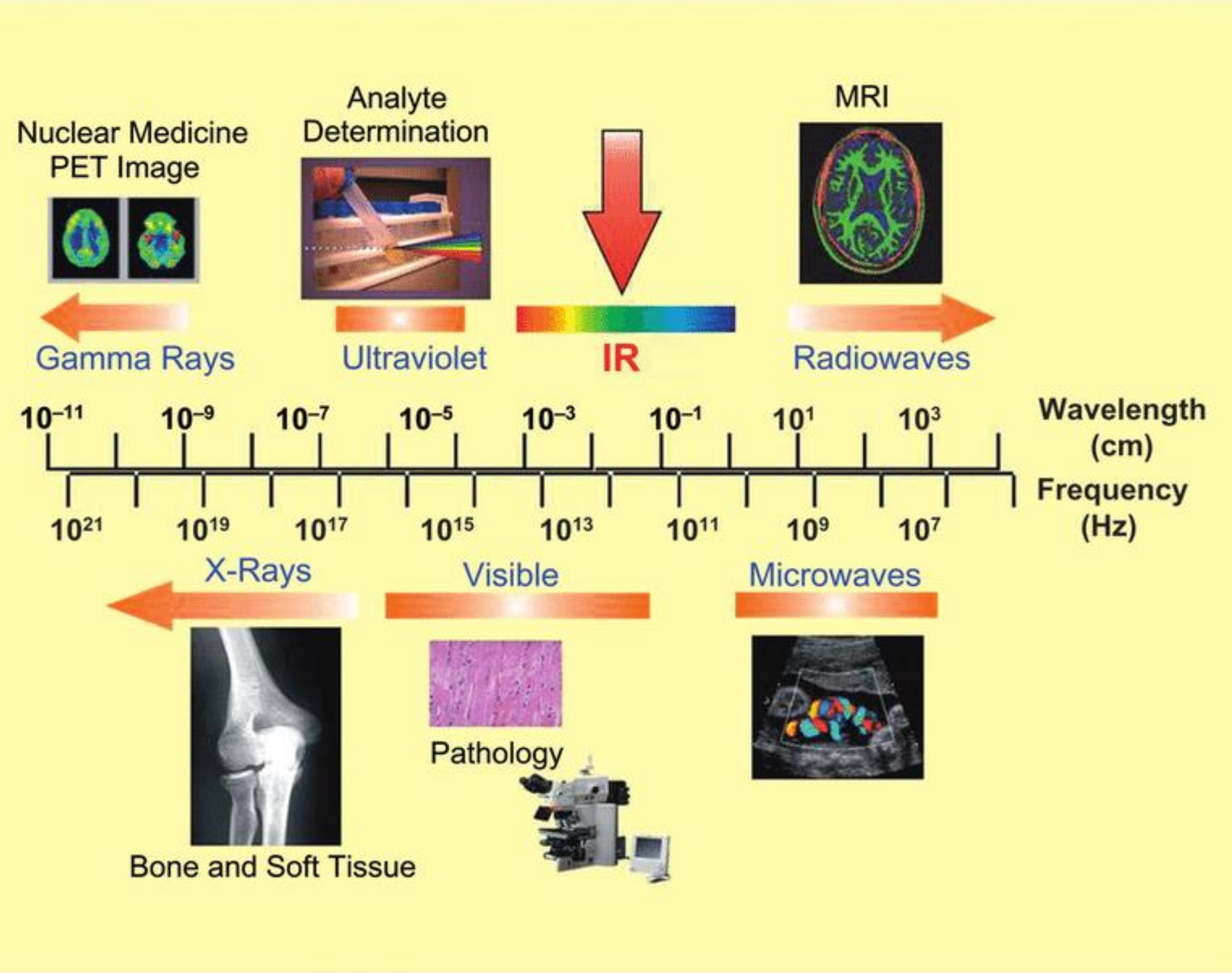
Infrared : Thermography (750nm – 1mm)

Visible Light : Optical (400nm – 750nm)

Ultraviolet : Fluorescence (10nm – 400 nm)

X-ray : Radiography / CT (0.01nm – 10nm)

Gamma Rays : PET /SPECT (< 0.01nm)



Principles of x-ray imaging:

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Ultraviolet : Fluorescence (10nm – 400 nm)

X-ray : Radiography / CT (0.01nm – 10nm)

Gamma Rays : PET /SPECT (< 0.01nm)

- **Anatomical** imaging technique (Radiology)
  - Projection
    - Radiography, fluoroscopy, mammography
  - Volume or 3D (even 4D) – (**Anatomical and functional**)
    - Ionizing radiations (CT)
    - Non-ionizing radiations (MRI)
- **Functional** and **molecular** imaging (Nuclear medicine)
  - Projection (scintigraphy)
  - Volume (SPECT, PET)

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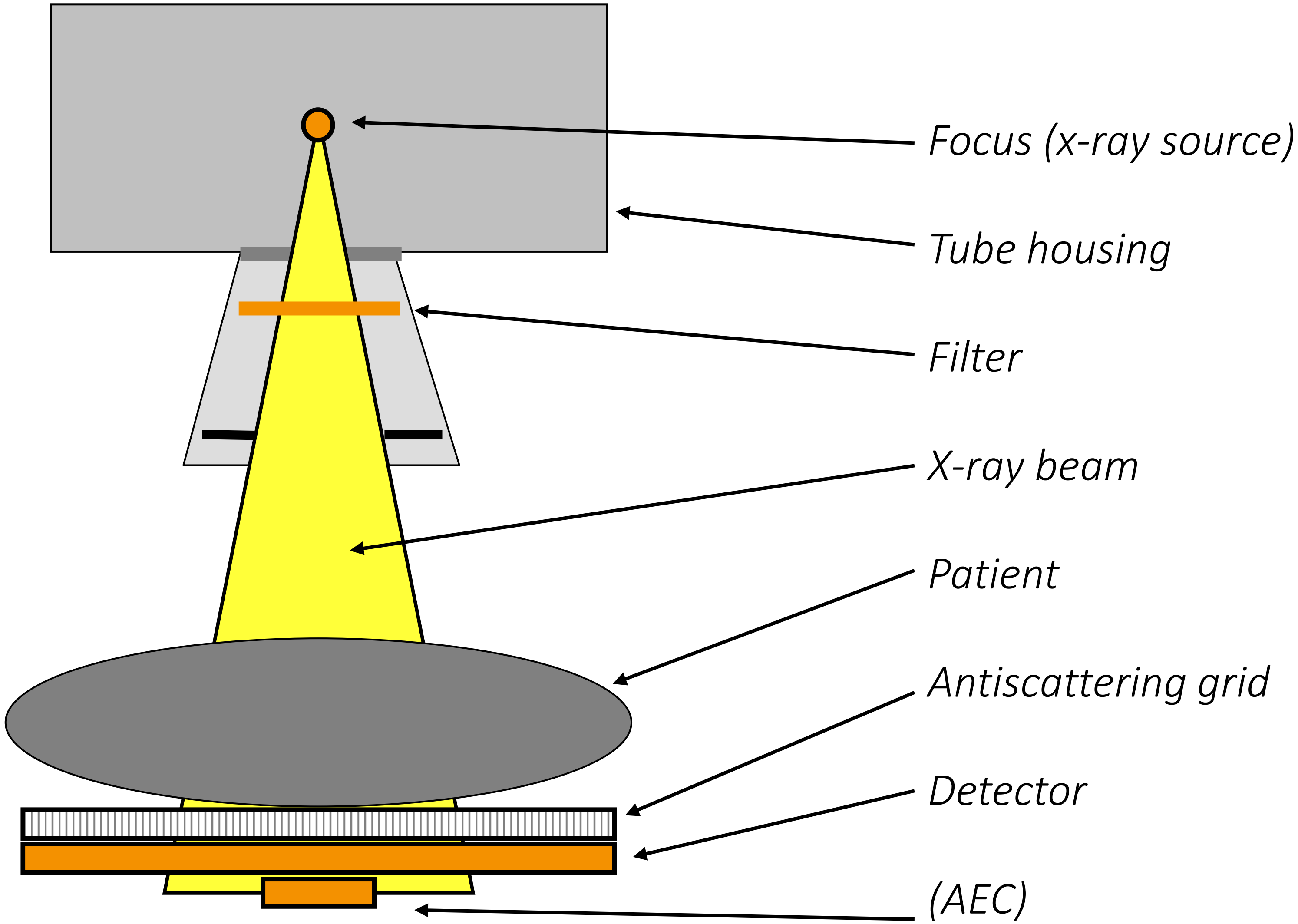
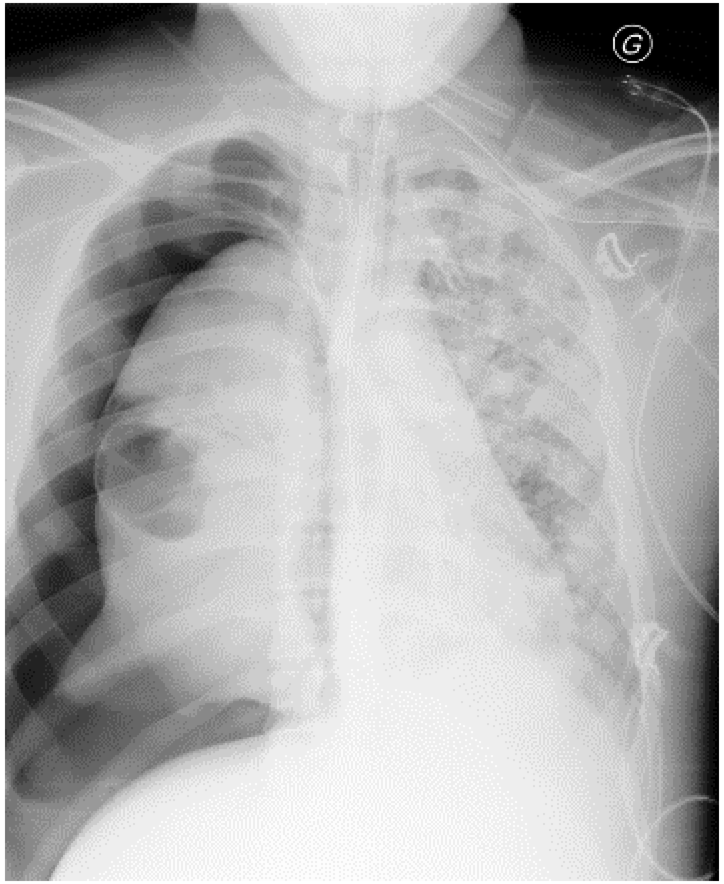
Schematic of the radiological procedure



Radiography:
projection of the anatomy on a plane



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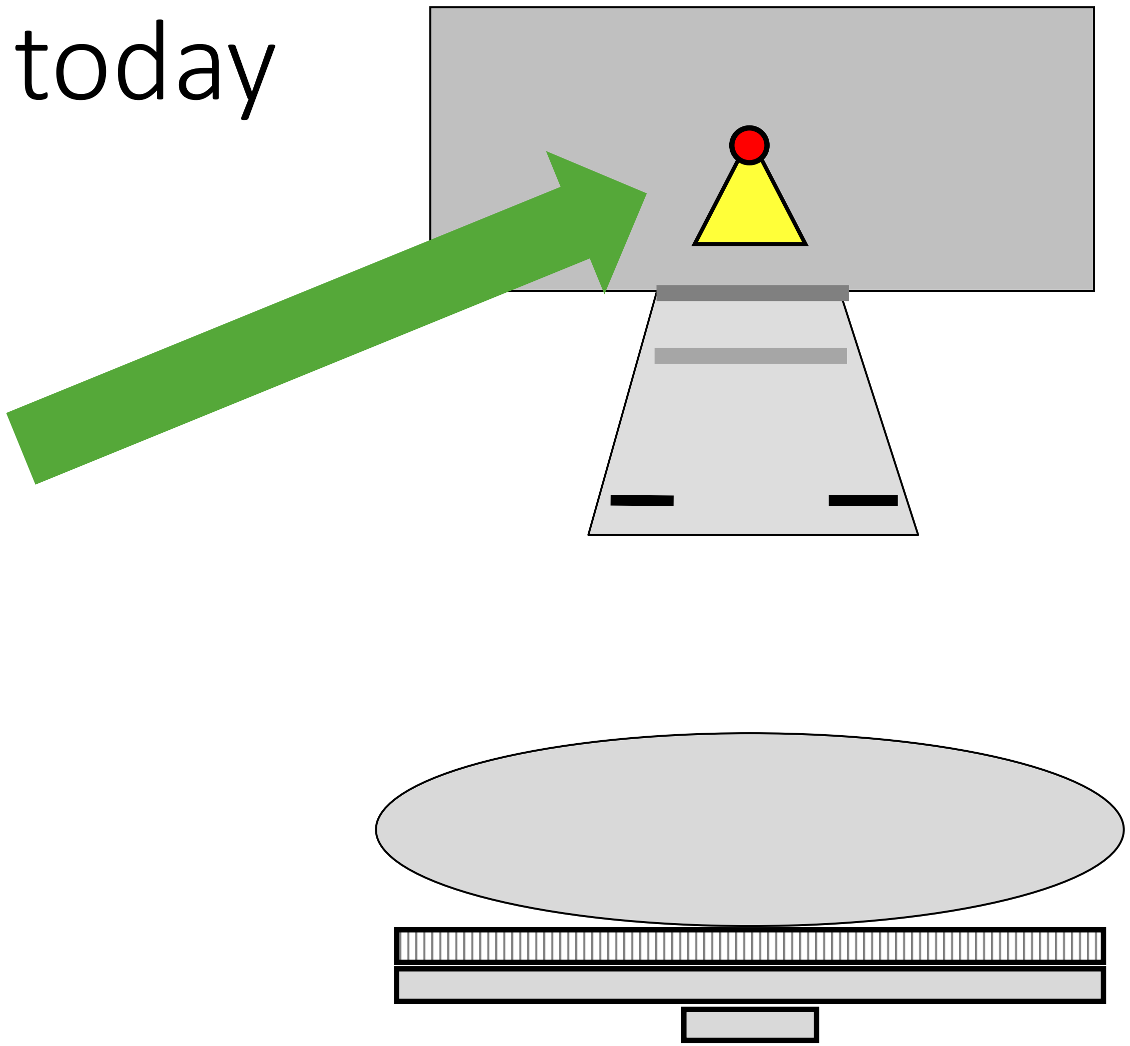


The X-ray tube

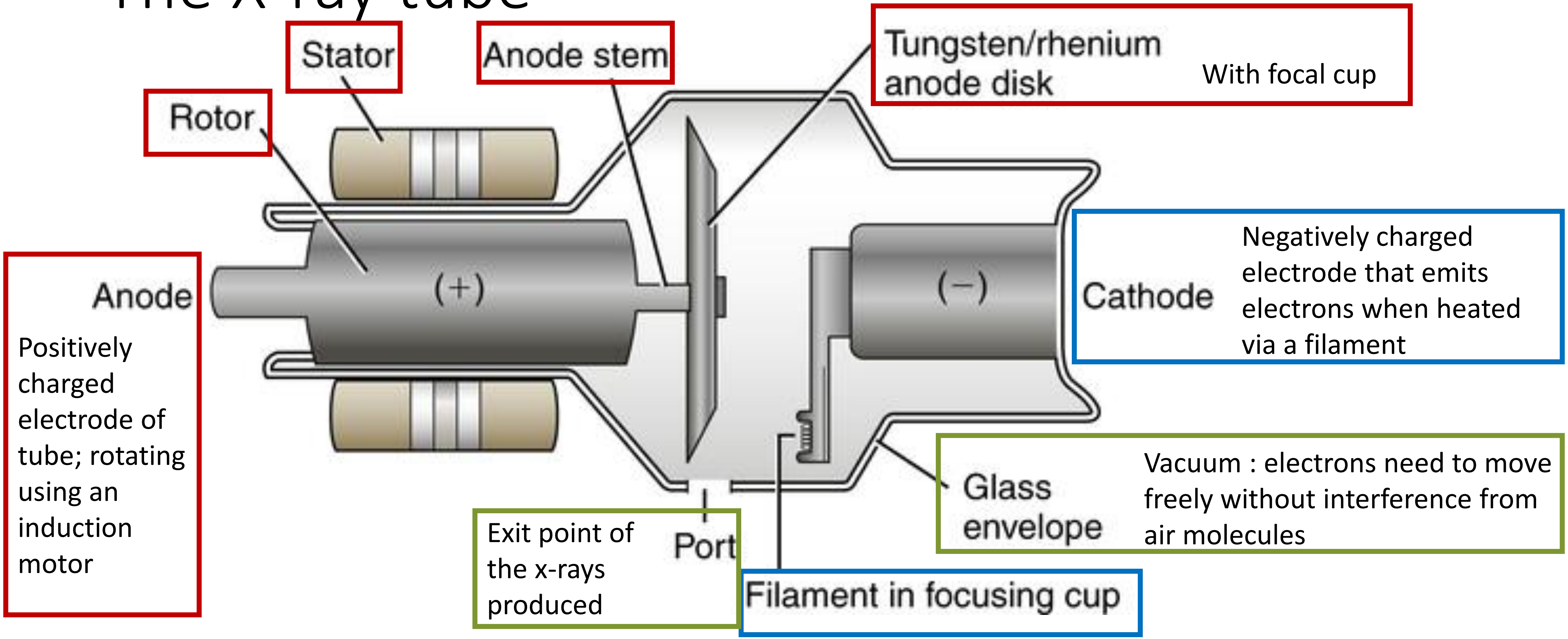


Diagramme de X-ray Tube | Quizlet

The X-ray tube

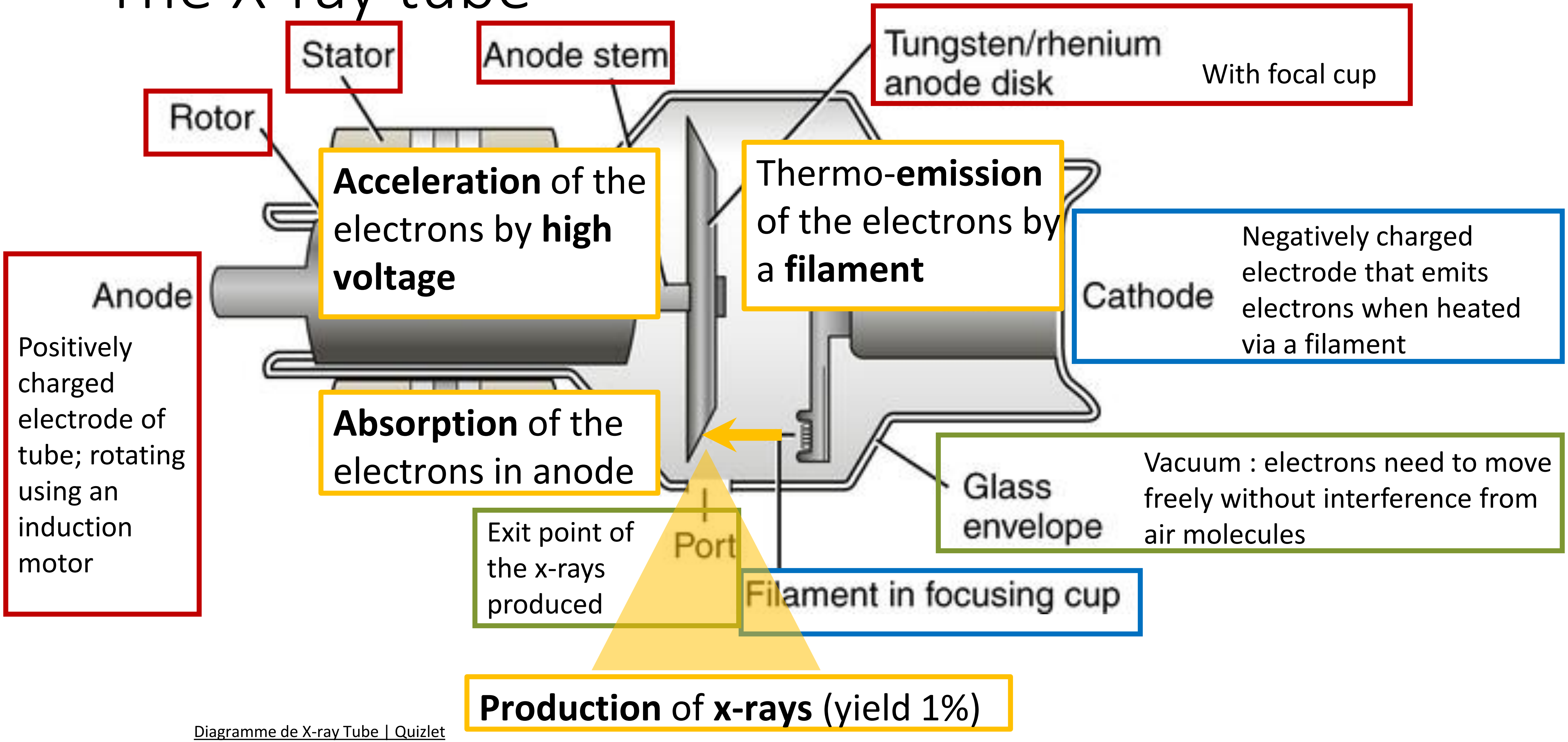
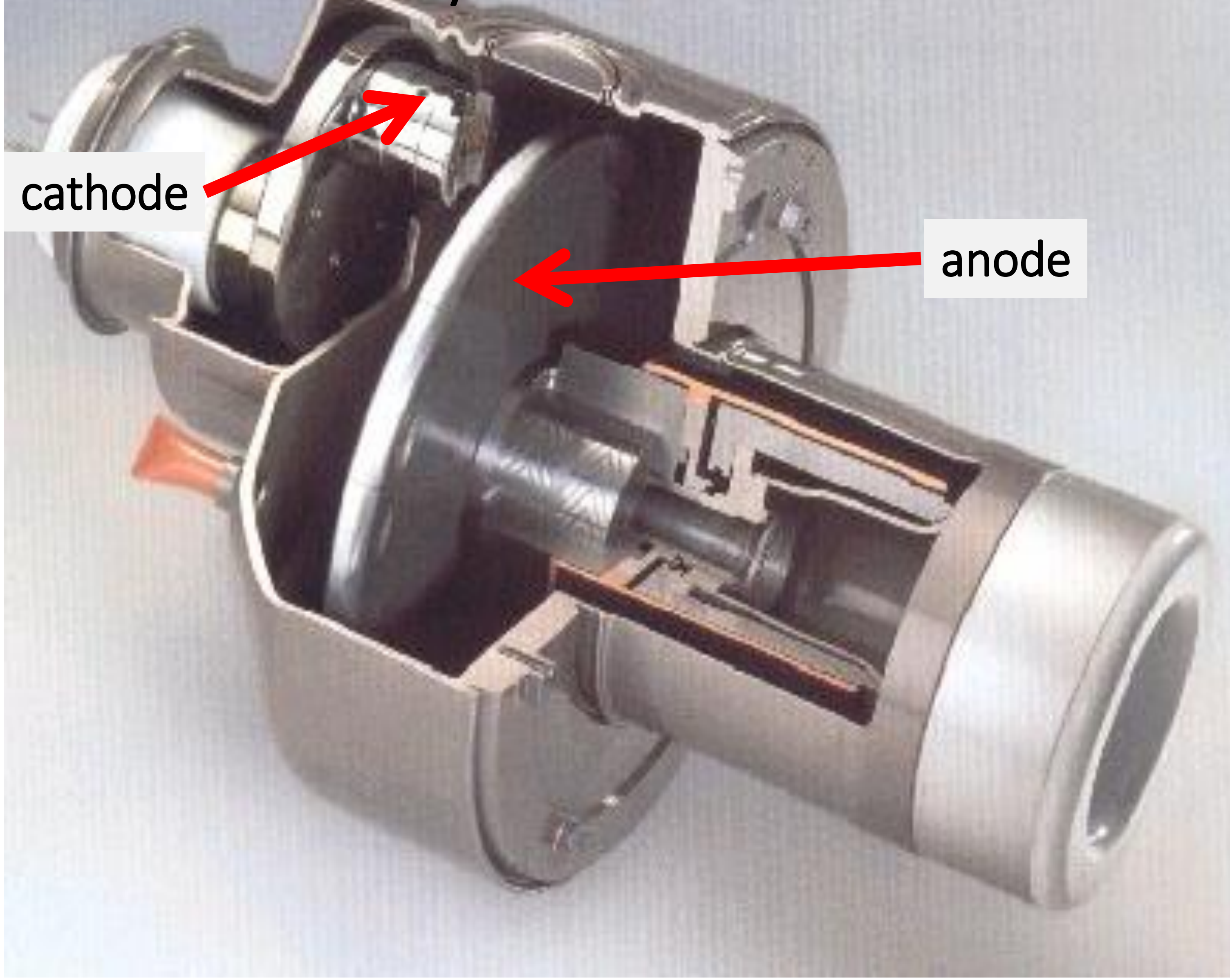


Diagramme de X-ray Tube | Quizlet

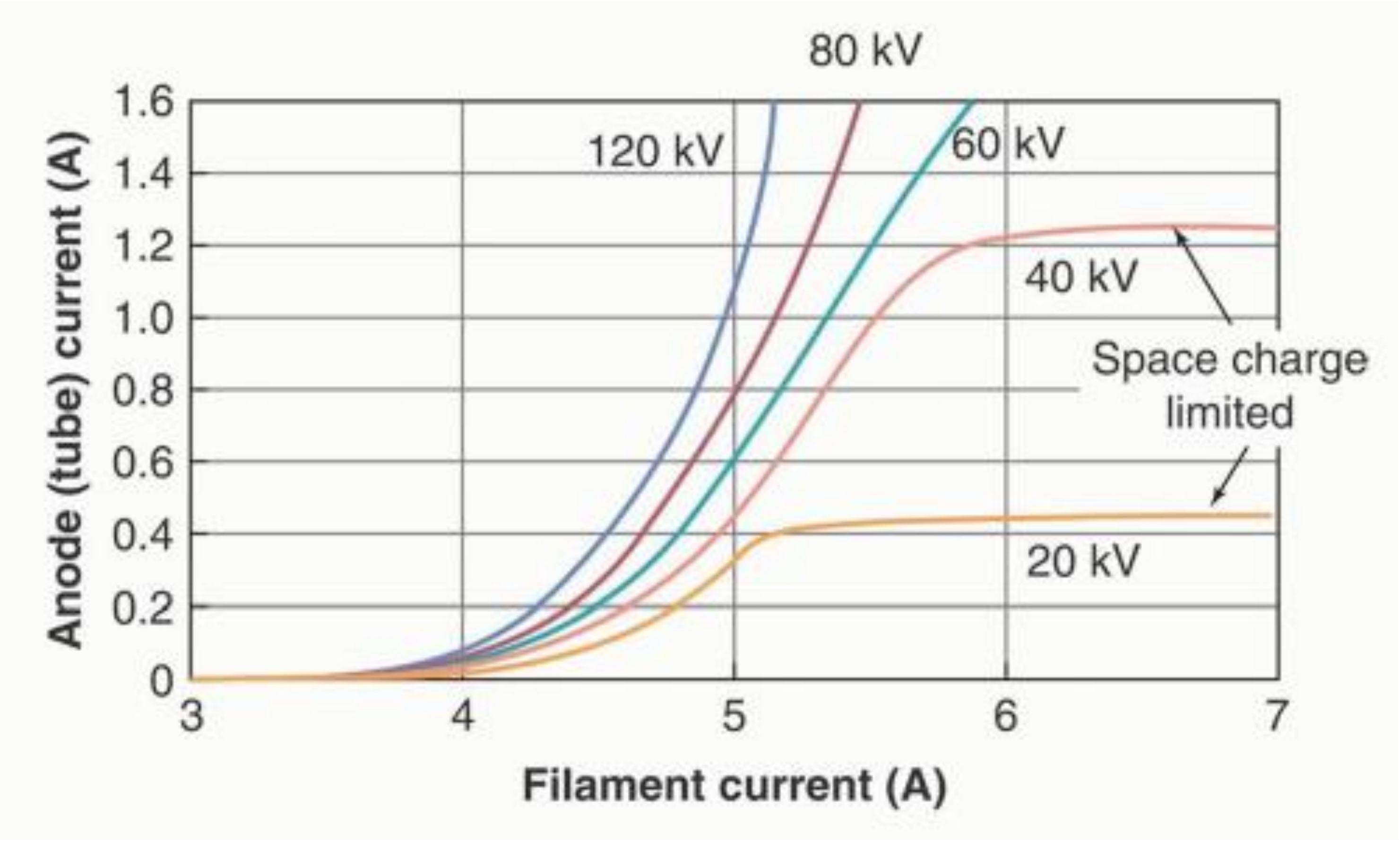
The X-ray tube



The X-ray tube
Example of a cathode

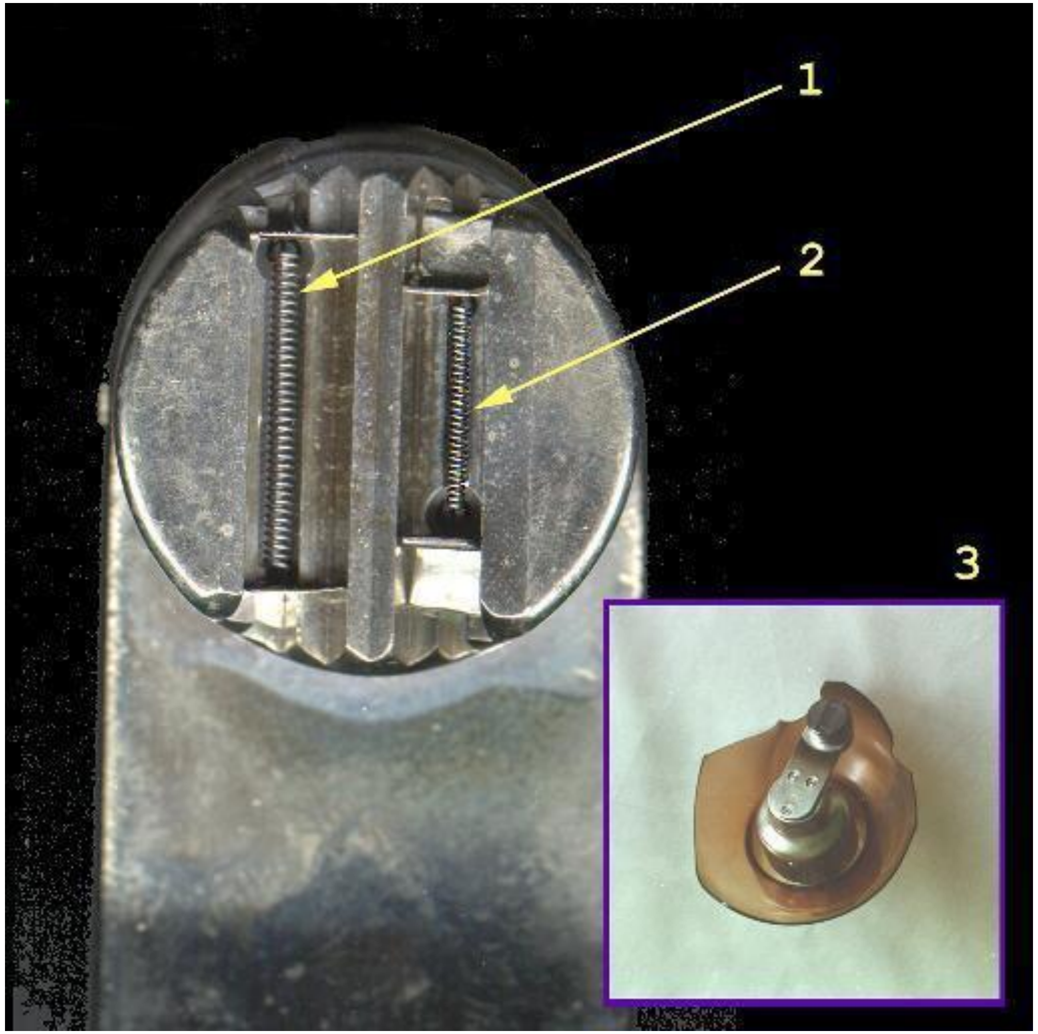
Made of (0.2 mm) tungsten :
- ✓ High atomic number
- ✓ Good thermoionic emitter
- ✓ High melting point
- ✓ Possible in thin wire

- Generate **thermal electrons**
  - Filament current: 10V, ~7A
  - Tube current: ~1500 mA



The X-ray tube
Example of a cathode

- Generate **thermal electrons**
  - Filament current: 10V, ~7A
  - Tube current: ~1500 mA
- Determines **actual focal spot size**
  - Small/large filament
  - Focusing cup : negatively charged
    - To focus and direct the electrons



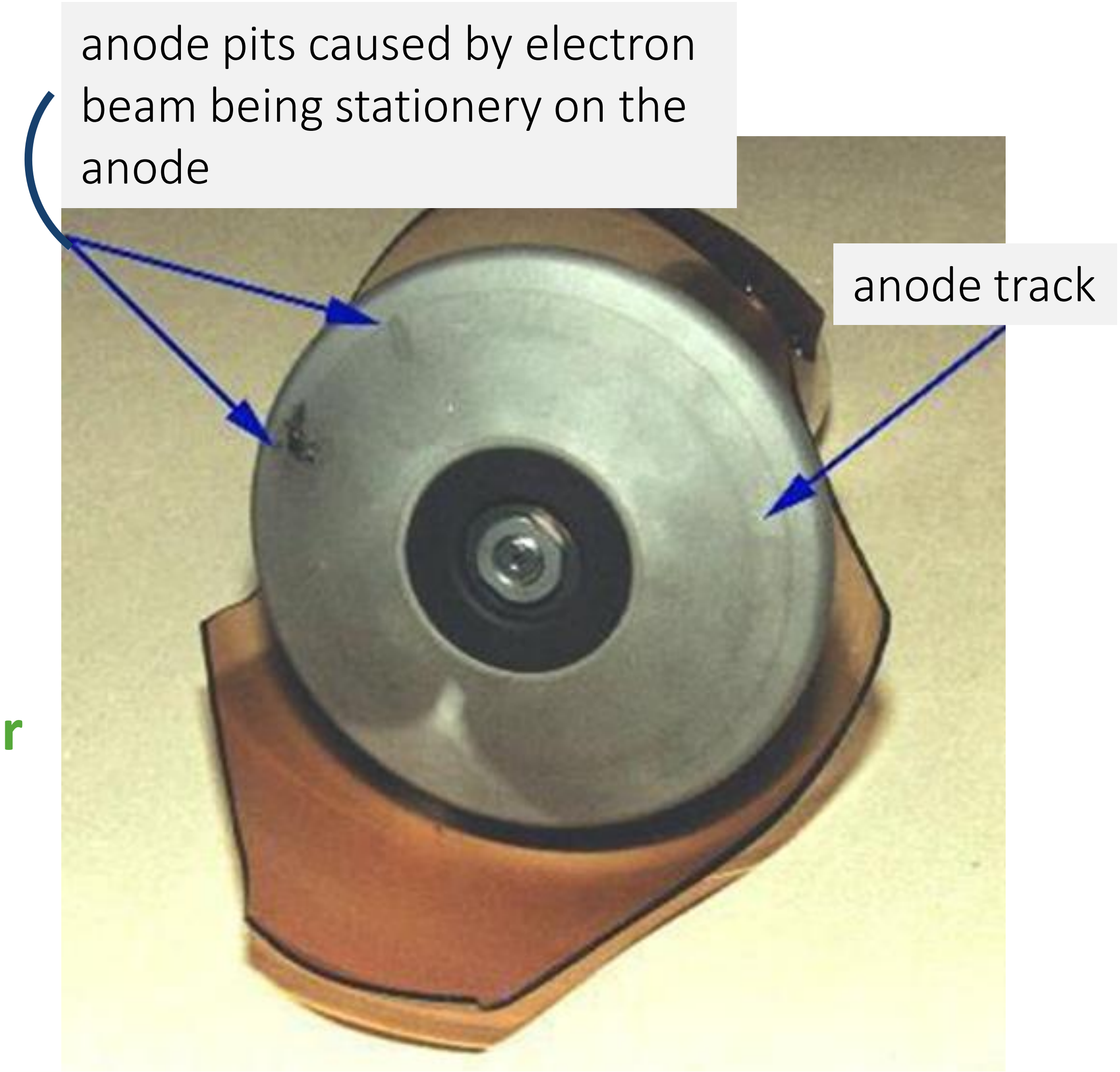
1: long tungsten filament
2 : short tungsten filament
3 : real size cathode

The X-ray tube
Example of an anode

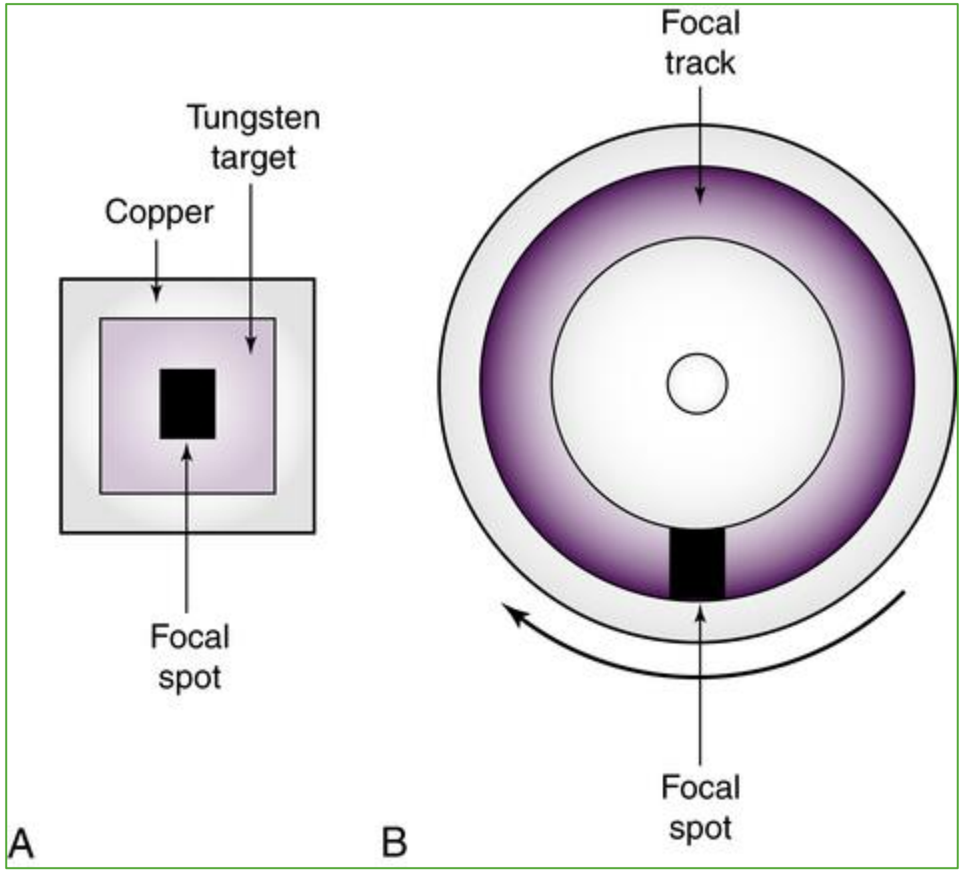
- Metal target with **positive potential**
  - Tungsten + copper → x-ray generation
  - Mostly by heat: more than 90%

- Tungsten: Z = 74
  - **High melting point, high atomic number**

- Molybdenum (42), Rhodium (45):
  characteristic x-rays for Mammographie



The X-ray tube
Anode configurations: Stationary and Rotating



Stationary Anode:

- Limit of tube current and x-ray output.
- Risk of damage due to excessive temperature

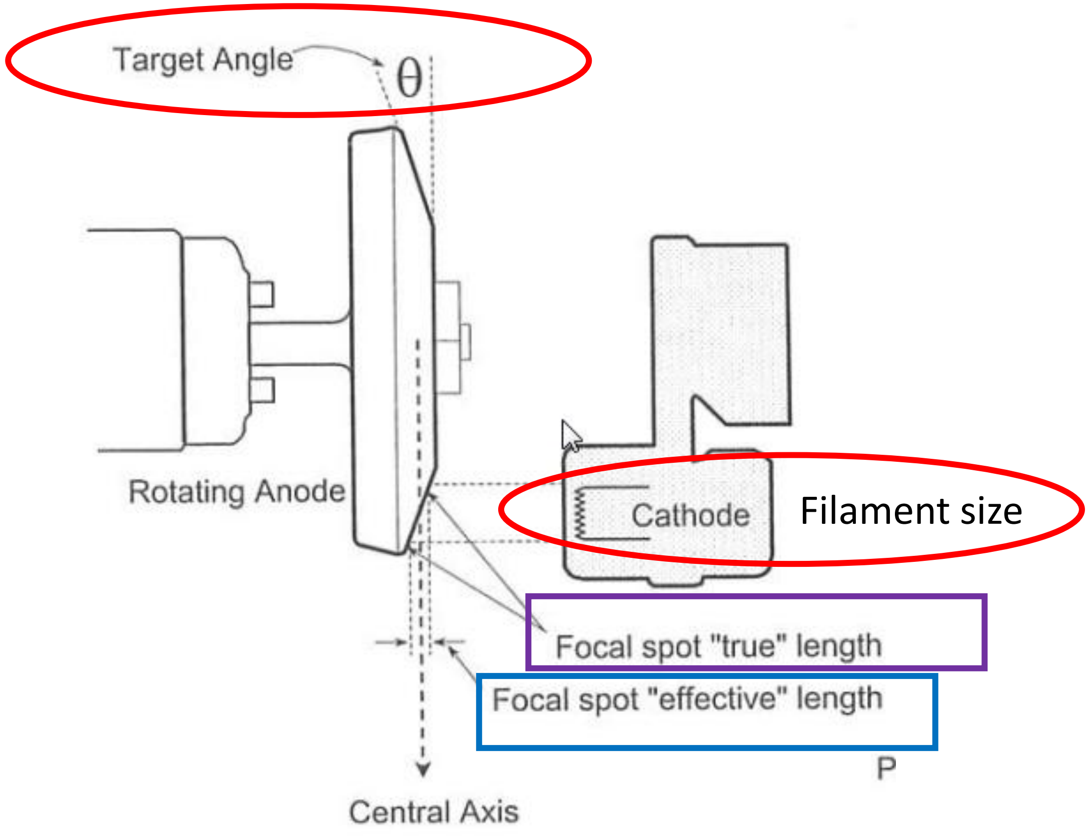
Rotating Anode:

- Used for most diagnostic x-ray applications
- Increases the size of thermal focal spot
- Inclination of the anode angle (7-20°), most common 12-15°.
- Rotor: ~3000-10000 rpm

Thermal (true) and optical (effective) focal spot

Focal spot = specific area on the anode where high-energy electrons from the cathode impact and produce X-rays

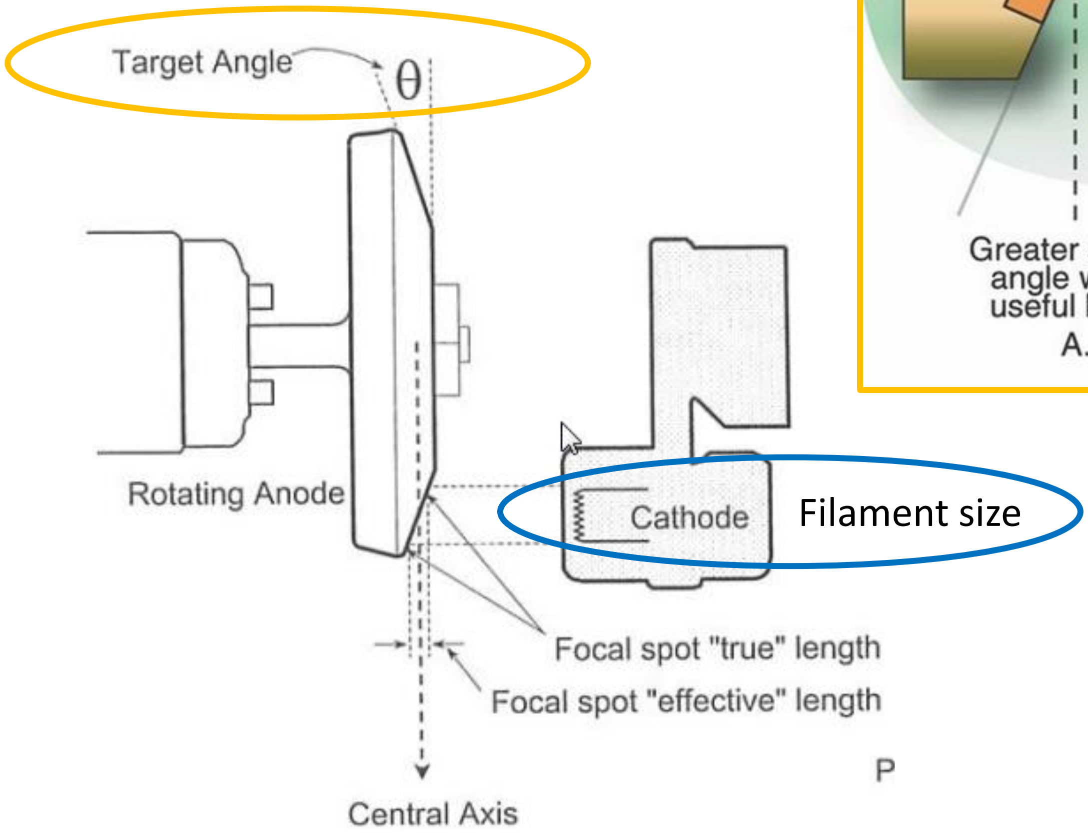
Size and shape of focal spot affect the quality and resolution of X-ray images

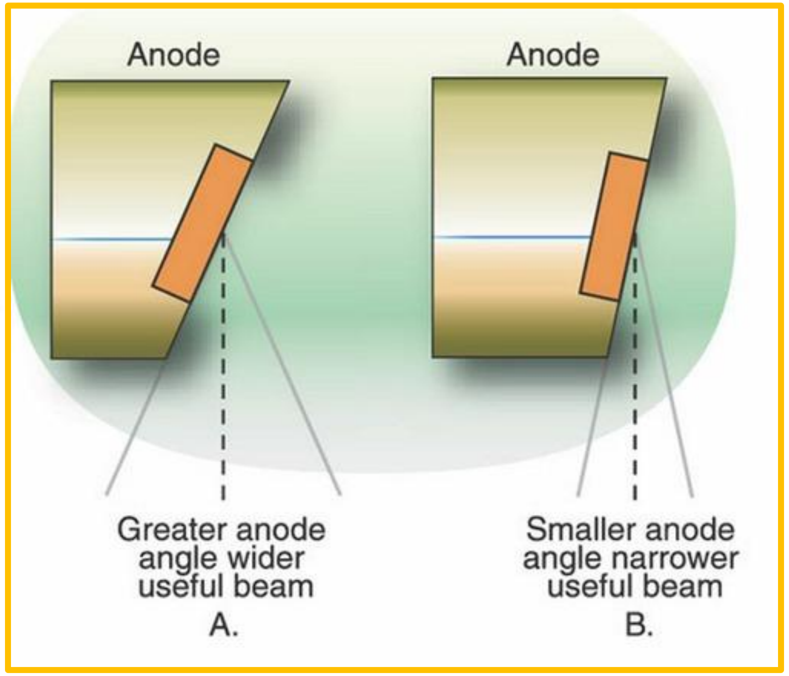


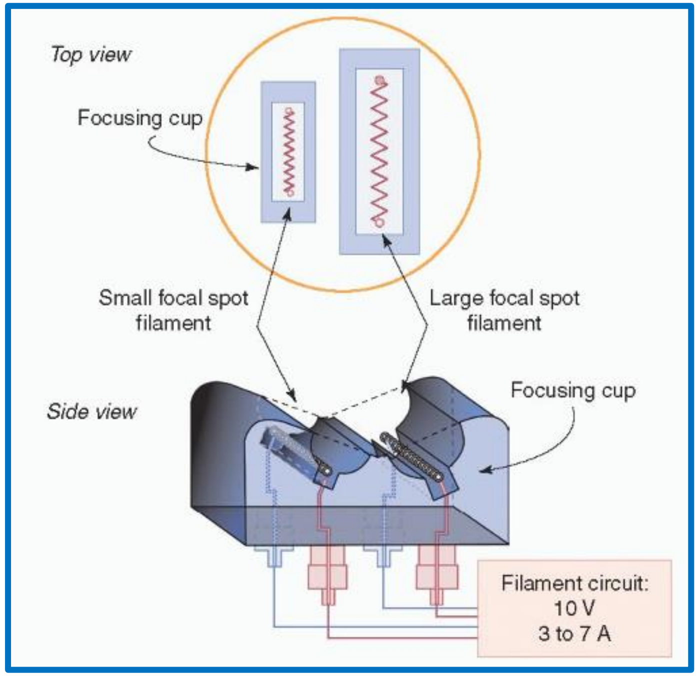
True (thermal / actual) focal spot length = determined by length of the cathode filament and width of the focusing cup slot and size of the electron target on the anode.

Effective focal spot length = Actual focal spot length x sinθ

Thermal (true) and optical (effective) focal spot





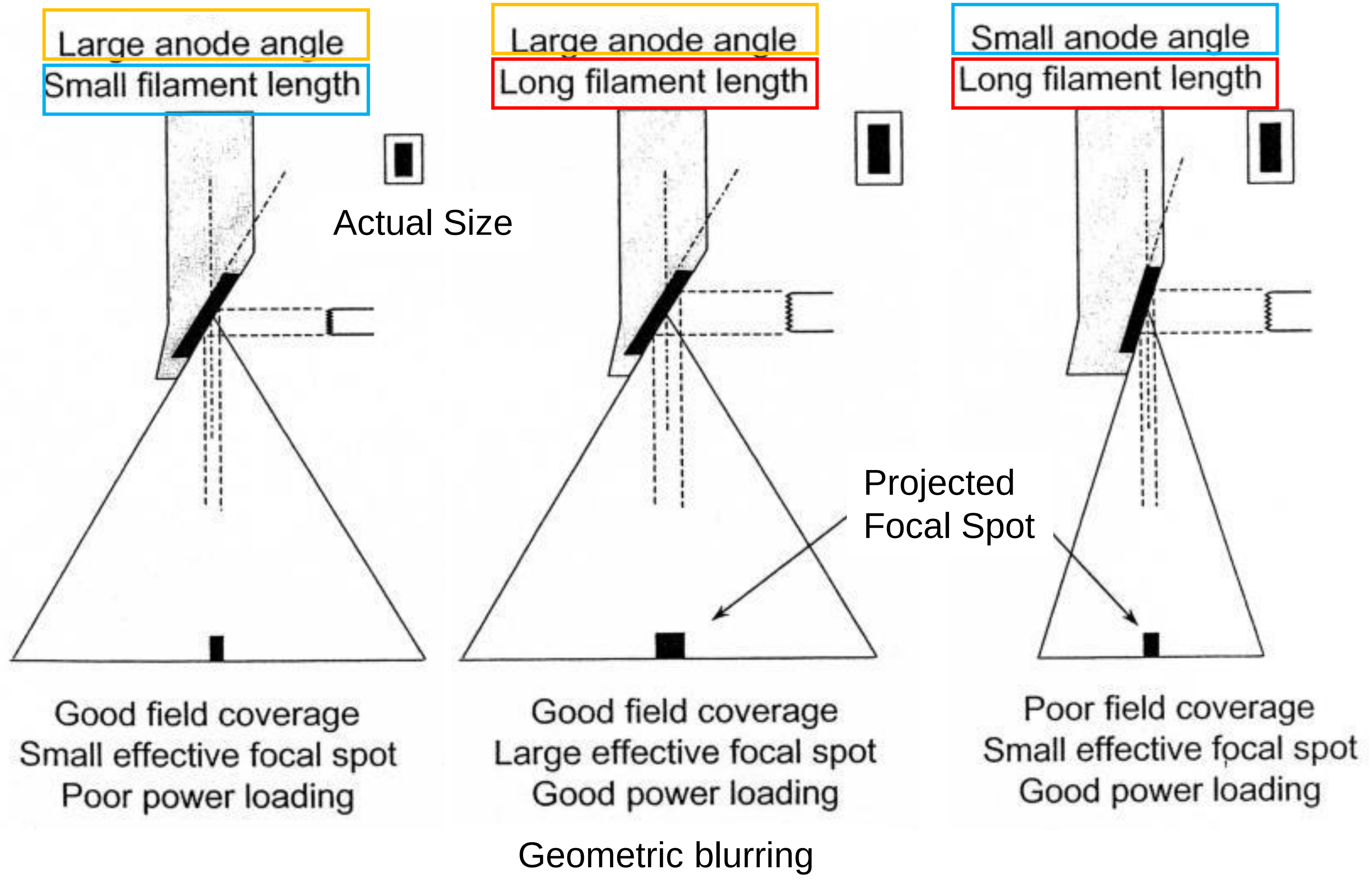


Field of view, focal spot size and heat capacity trade off

Physics: X-Ray Production 4 Cartes | Quizlet

Field of view, focal spot size and heat capacity trade off

- Optimal anode angle depends on clinical imaging application
- Small anode angle 7-9°: small field of view devices
- Larger anode angles 12-15°: general radiographic imaging

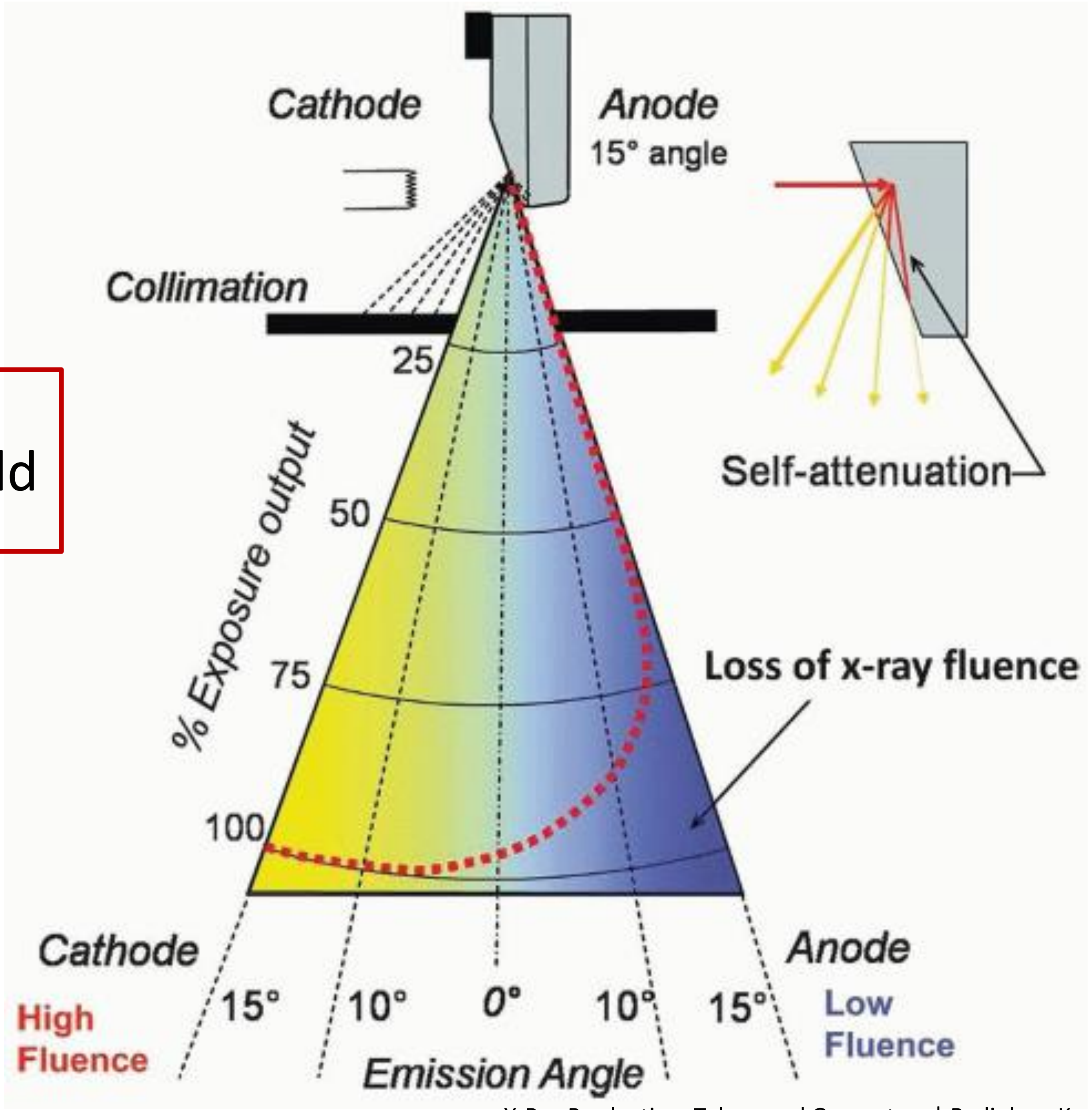


Heel Effect

Reduction of x-ray intensity toward anode side of the field

greater attenuation by the anode at anode side

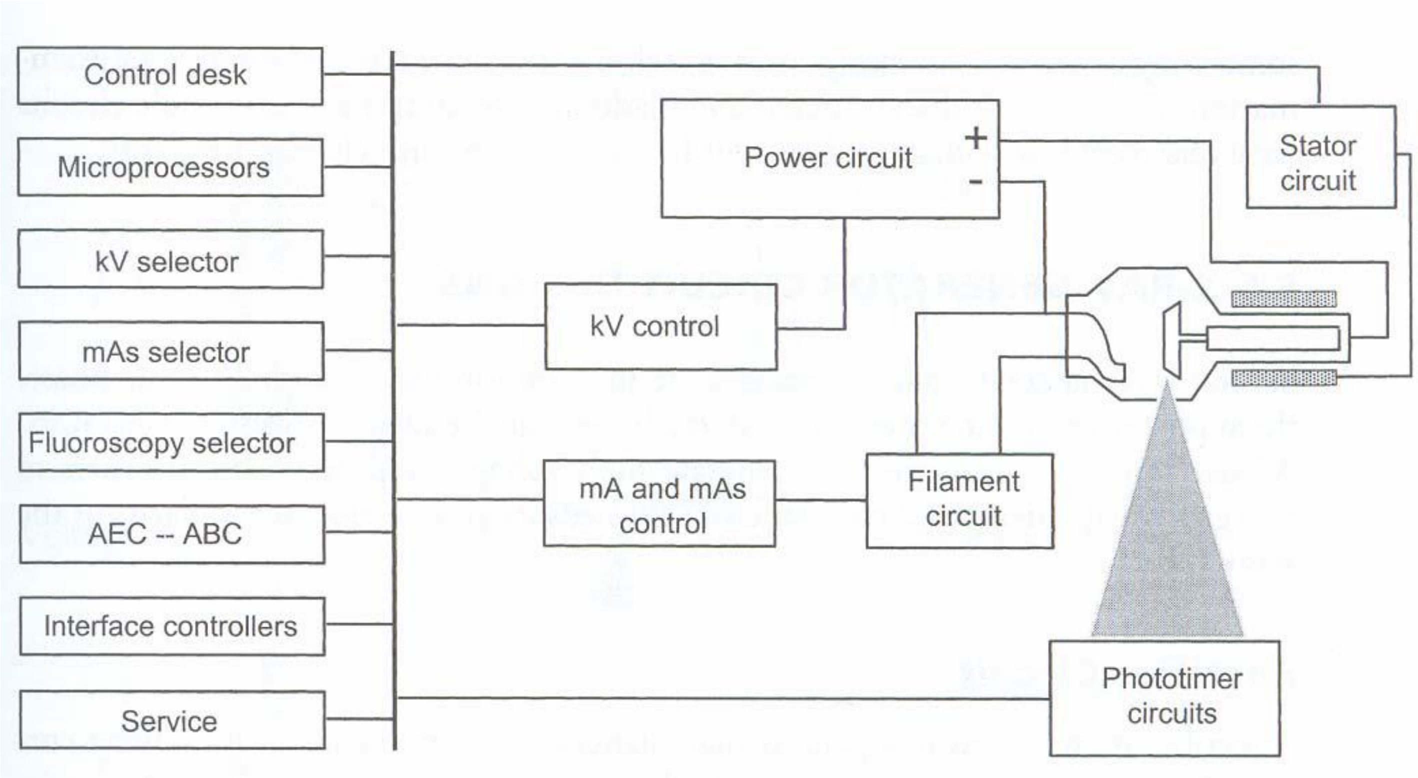
- ➢ orientation of patient: x-ray tube cathode over thicker body parts
- ➢ Filter to compensate



X-Ray Production, Tubes, and Generators | Radiology Key

X-ray Generators: modular schematic view

- Provide current at a high voltage to an x-ray tube
- Transformers: convert **low voltage to high voltage** (electromagnetic induction)
- i.e. **100 V → 100 kV**



Tube parameters

- mA : flux of electrons from filament to anode
- Exposure time [ms]

<u>Charge</u> :
Quantity of x-rays

- kV : acceleration of electrons
- Filtration : inherent and additional

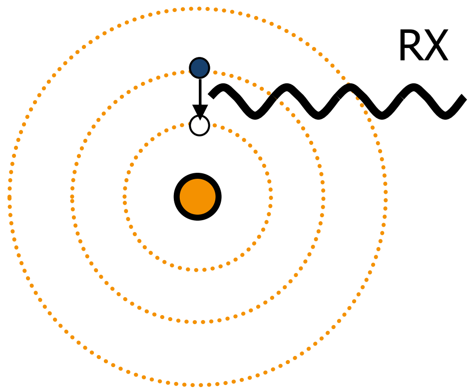
<u>Effective energy :</u>
Quality of x-rays

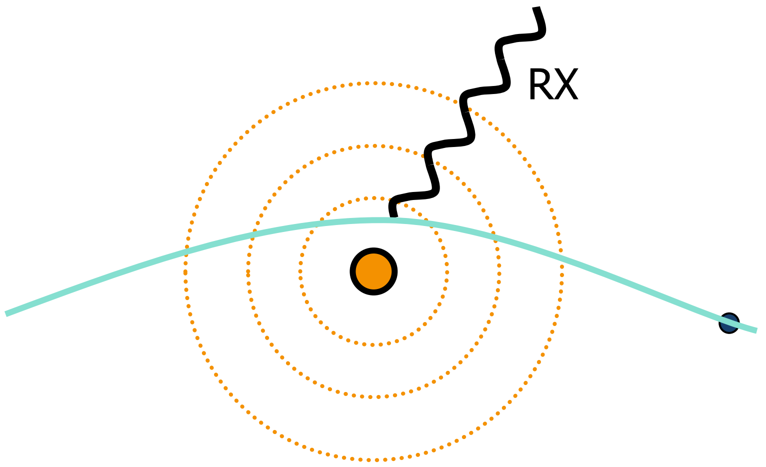
Exercise

How many electrons flow from the cathode to the anode each second in an x-ray tube with a tube current of 50 mA?

1. appr. 3×10^{9}
2. appr. 3×10^{11}
3. appr. 3×10^{13}
4. appr. 3×10^{15}
5. appr. 3×10^{17}
6. appr. 3×10^{19}

X-ray production: Physics !





- **Characteristic x-rays**
  - Ejection of an electron out of an inner shell
  - Filling by an external electron
  - Emission of a **fluorescence** photons
    - characteristic

- **Bremsstrahlung**
  - Deviation of the electron
  - Radiative energy loss
    - Photon emission (1%)
    - Emission of non-ionizing radiation (99%)
  - Important for high Z material
  - Continuous spectrum

X-ray production: Stopping power

Measure of how much energy a charged particle loses as it passes through a material

$$\frac{S_{rad}}{S_{col}} \cong \frac{TZ}{700}$$

- S_{rad}: bremsstrahlung stopping power
- S_{col}: collision stopping power
- T: kinetic energy of the electron (MeV)
- Z: atomic number of matter

Depends on:

- Particle energy T : the higher T the more radiative loss, the lower T the more collisional stopping
- Atomic number Z : The higher Z the more radiative loss

Exercise

What proportion of the energy of an electron of 100 keV kinetic energy is lost by bremsstrahlung in a tungsten *(Z=74)* anode?

1. appr. 0.01 %
2. appr. 0.1 %
3. appr. 1 %
4. appr. 10 %
5. appr. 30 %
6. appr. 50 %
7. appr. 99 %

What does the color "white" mean on a classical radiograph?

1. only a few photons arrived on the detector
2. many photons arrived on the detector
3. no idea

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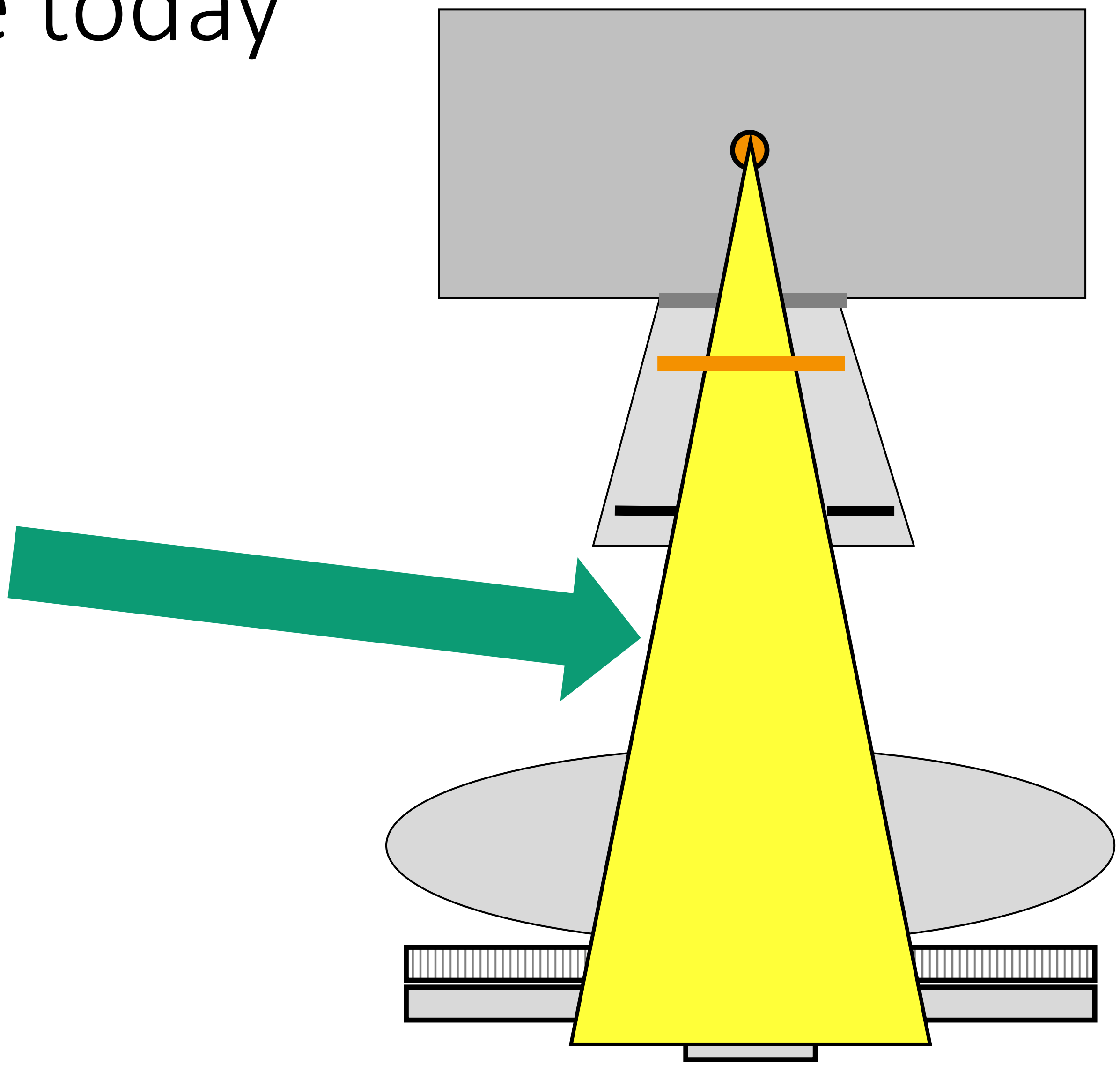
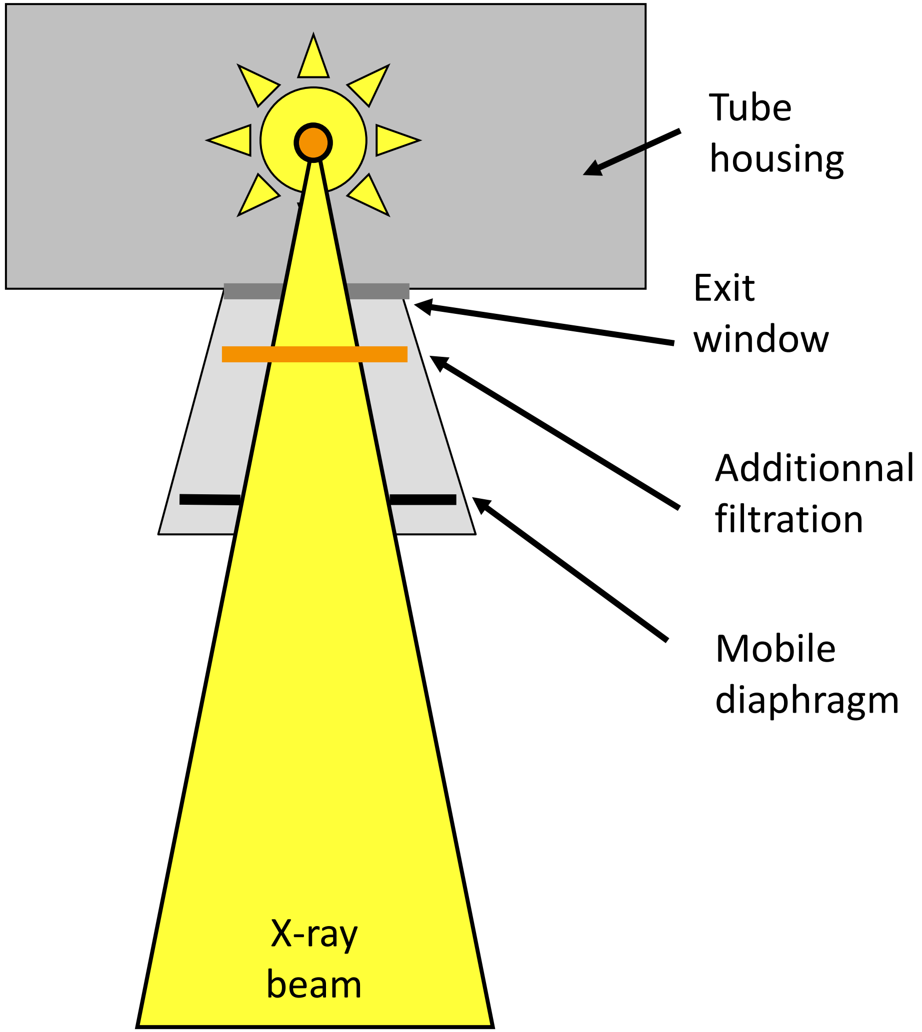
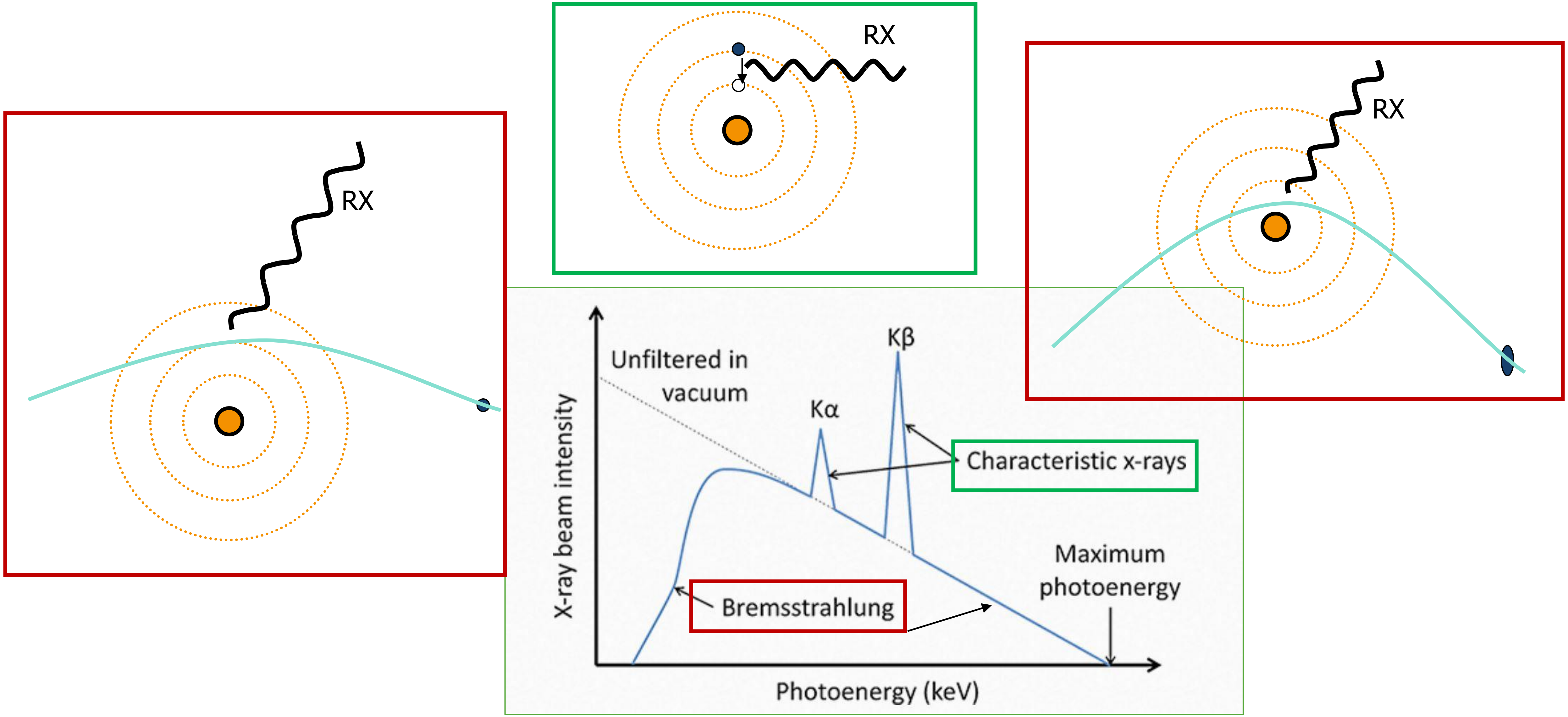


X-ray beam

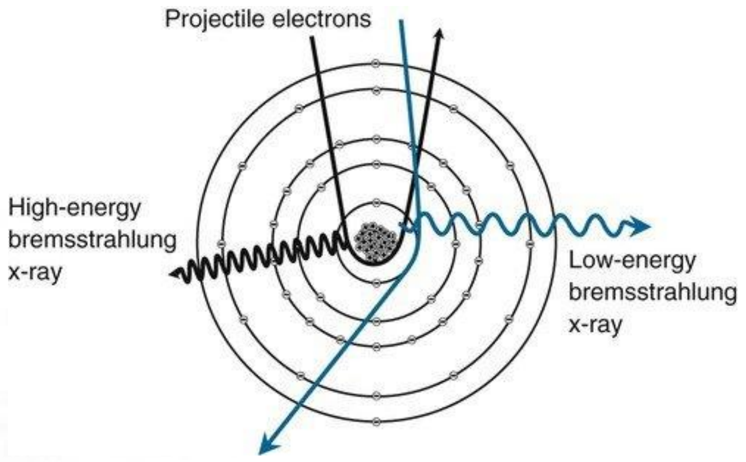
- **Emission** in whole directions
- **Absorption** in the tube housing
- Beam **filtration**
    - Preferential absorption of low-energy x-rays

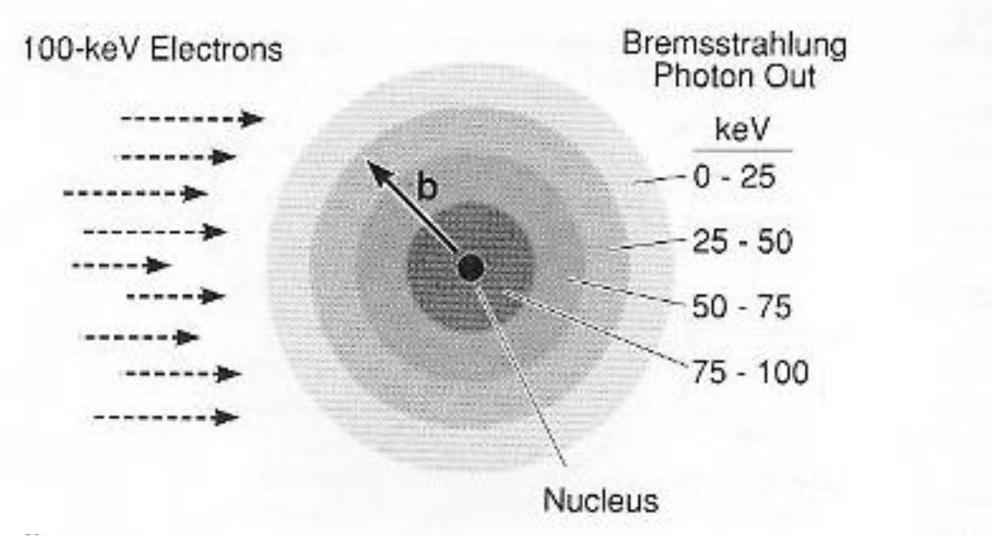


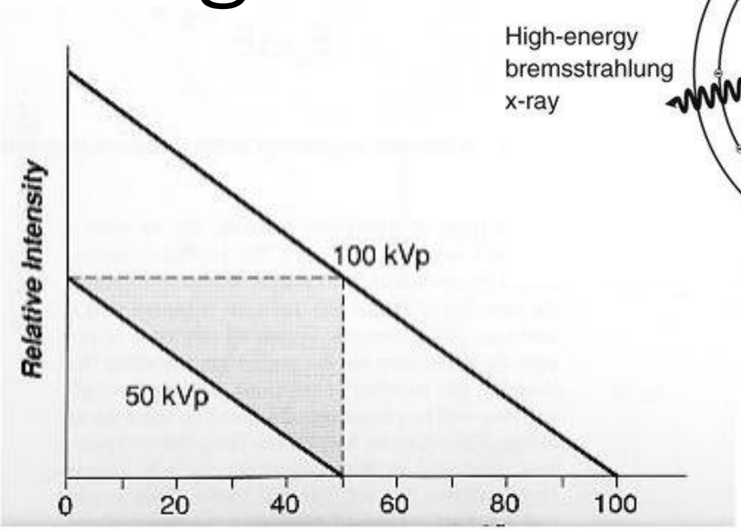
X-ray production: Spectrum

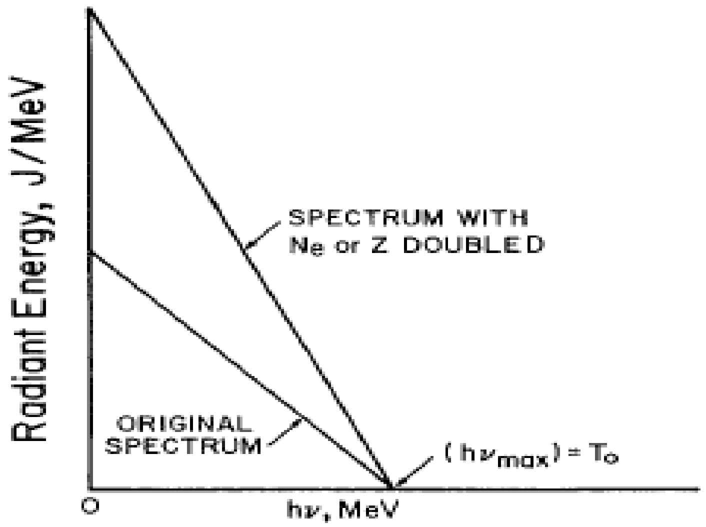


Spectrum of Bremsstrahlung







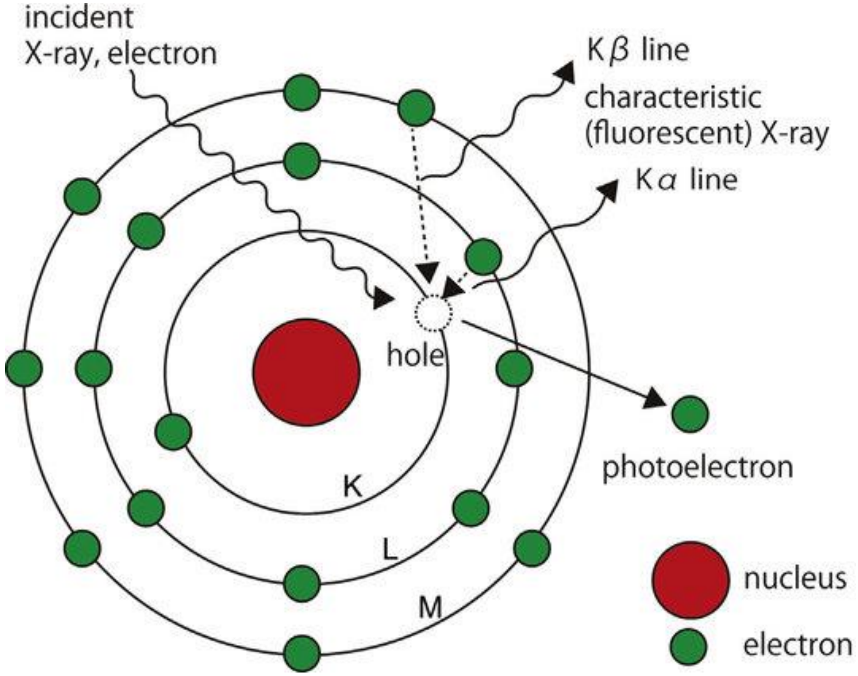


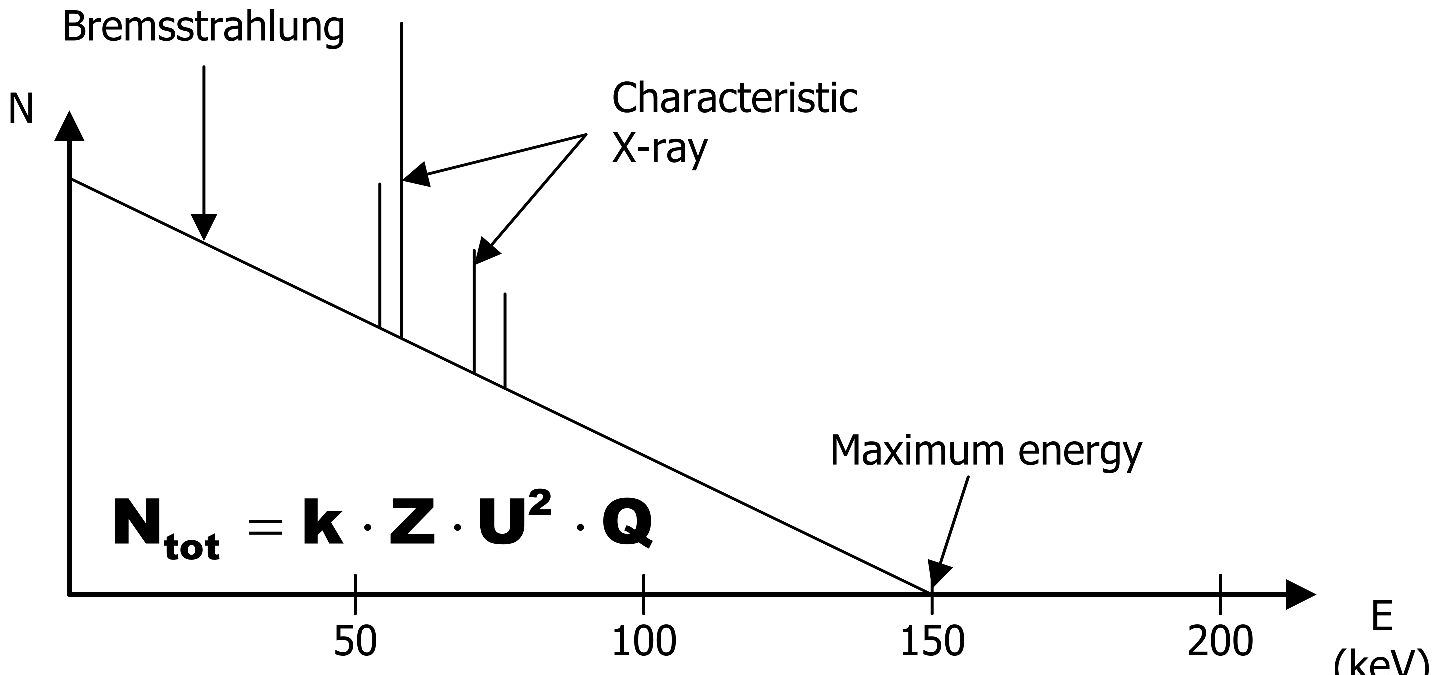
- Intensity increases with square of the voltage
- Intensity increases with the Z of the anode material

Spectrum of characteristic x-rays

- Characteristic radiation in Tungsten:

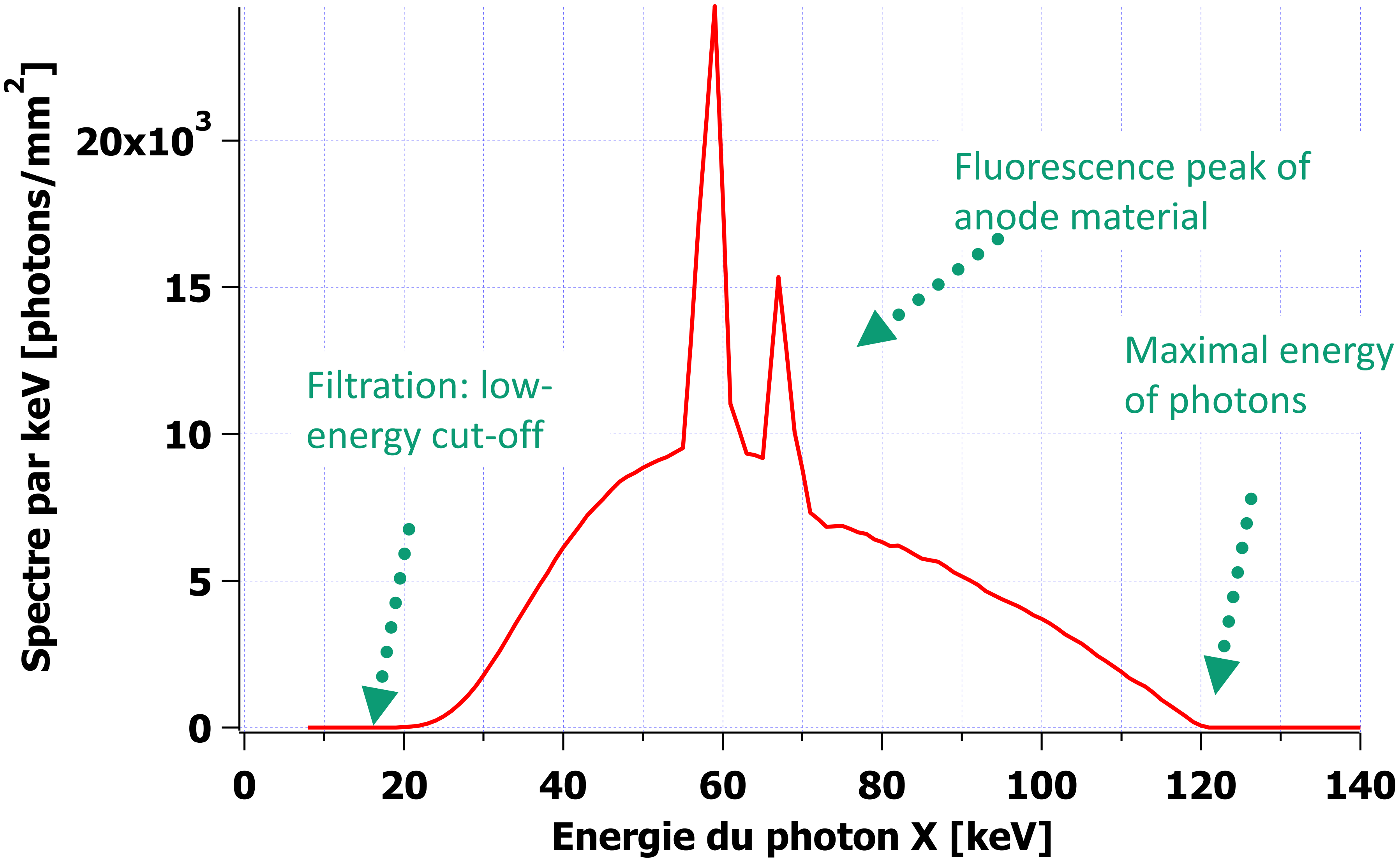
Transition		Energy
N - K	$K_{\beta 2}$	69.07 keV
M - K	$K_{\beta 1}$	67.24 keV
L_{111} - K	$K_{\alpha 1}$	59.32 keV
L_{11} - K	$K_{\alpha 2}$	57.98 keV





$$N_{tot} = k \cdot Z \cdot U^2 \cdot Q$$

X-ray spectrum at the tube exit



Characterization of the spectrum: Photon attenuation and half-value layer

- Attenuation : removal of photons from a beam by **absorption** and **scattering**
- **Linear attenuation coefficient** decreases with increasing energy (except at absoption edges).

- HVL : thickness of material required to recieve the intensity of an x-ray beam to **one half of its initial value**
- HVL : indirect measure of the photon energies of a beam → **beam quality** (under narrow-beam geometry, i.e. without scatter)

Photon attenuation and half-value layer

Number of mono-energetic photons crossing distance x without attenuation

linear attenuation coefficient

$$N(x) = N_0 e^{-\mu x}$$

half-value layer
thickness x that attenuates
50 % of the impinging photons

$$HVL = \frac{\ln 2}{\mu}$$

If we have spectrum, the measurement of HVL helps to define an *effective energy*

$$\mu_{eff} = \mu(E_{eff}) = \frac{\ln 2}{HVL}$$

Beam quality: effective energy

The effective energy of an x-ray spectrum is the energy of a mono-energetic beam of photons that has the same penetrating ability (HVL) as the spectrum of photon.

Energy [keV]	μ/ρ [cm^2/g]	μ [cm^{-1}]	HVL = ln 2 / μ [cm]
10	26.2	70.7	0.00980
15	7.96	21.5	0.0322
20	3.44	9.29	0.0746
30	1.13	3.05	0.227
40	0.568	1.53	0.452
50	0.368	0.994	0.698
60	0.278	0.751	0.923
80	0.202	0.545	1.27
100	0.17	0.459	1.51

Table of NIST : μ(Al) as a function of energy Al (ρ = 2.7 g/cm^3)

$$\mu_{moyen} = \mu(E_{eff}) = \frac{\ln 2}{HVL}$$

Example:
What is the effective energy of an x-ray beam with 80 kV and the HVL = 3 mm Al ?

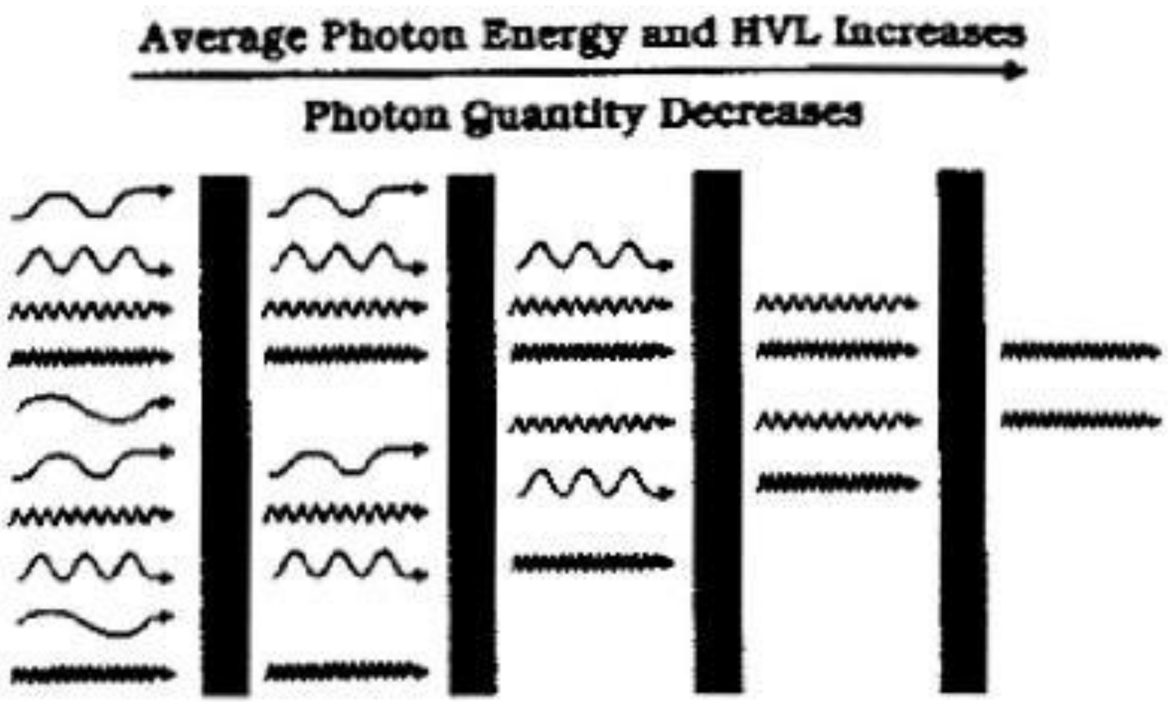
$E_{eff} \sim 35$ keV

Photon attenuation and half-value layer

Beamhardening

$$H = \frac{1^{st}\,HVL}{2^{nd}\,HVL}$$

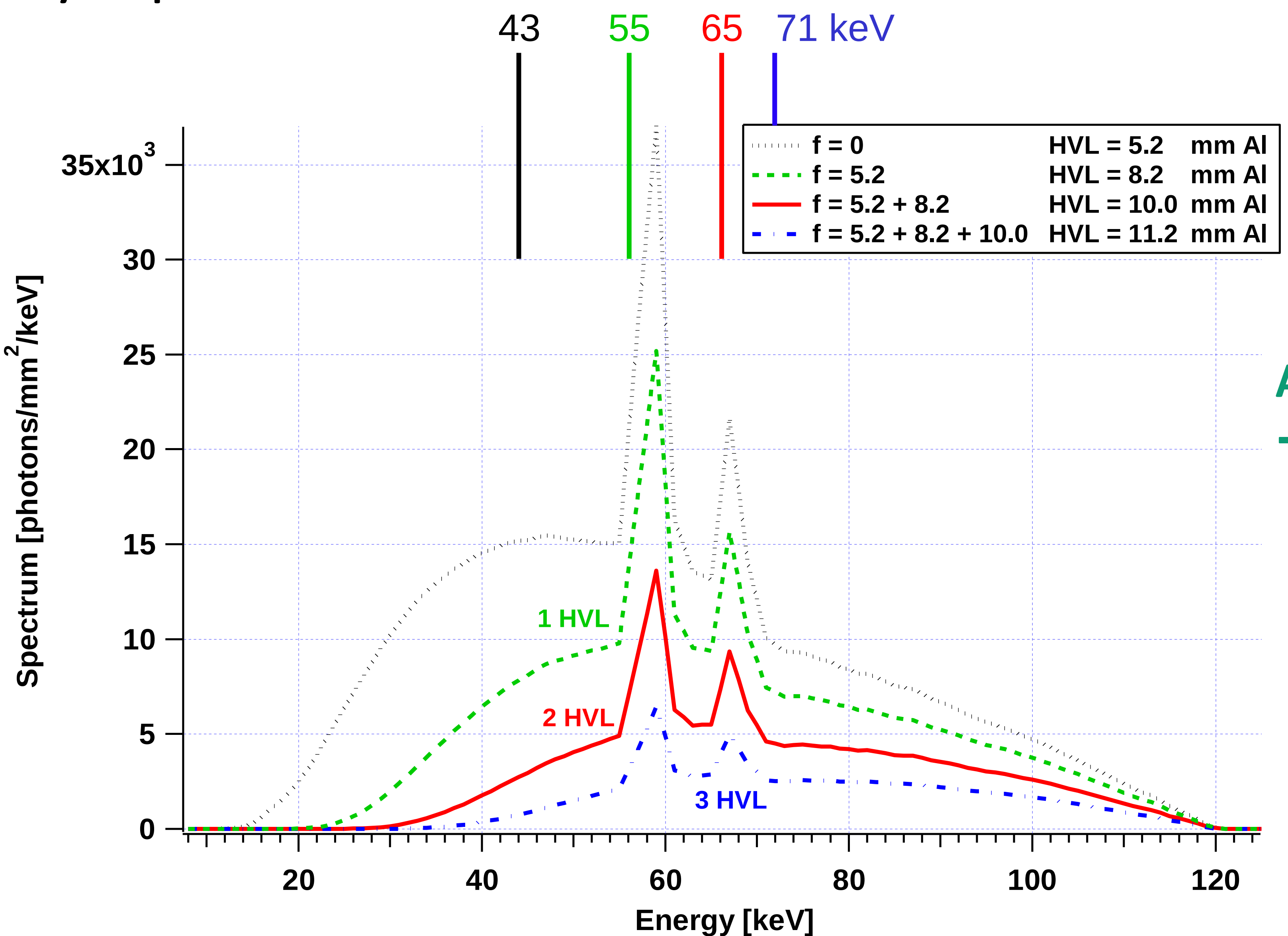
H = 1 for monoenergetic beams
H < 1 when beam hardening occurs



Why do we say that a polyenergetic beam is hardened when it is filtered?

1. The spectrum is hard to compute
2. The spectrum contains more high energies
3. The spectrum contains more low energies

X-ray spectrum: HVL



Additional filtration
→ Beamhardening

Filtration in practice

- Limit dose that does **not contribute to image contrast**
- Inherent filtration: **equivalent to 2.5 mm Al placed** at the anode outlet
- Additional filtration: in **copper** and/or in **aluminium**
- **Total filtration: inherent + additional**
  - Greater than 2.5 mm Al if the tube produces > 110 kV
  - Controlled by HVL

To remember: review of x-ray production

Beam Quality

Energetic spectrum

defined by

- Voltage [kV]

peak voltage [kVp]: determines maximum energy of Bremsstrahlung

- Beamfilter

reduces photon number; shifts average energy to higher value

Measured with: Half Value Layer

X-ray quantity

Number of photons - Intensity

defined by

- Current [mA]

Current from cathode to anode

Exposure ∝ mA: quantity control

- Time [s]

Current x time = [mAs]

Measured with: Air Kerma

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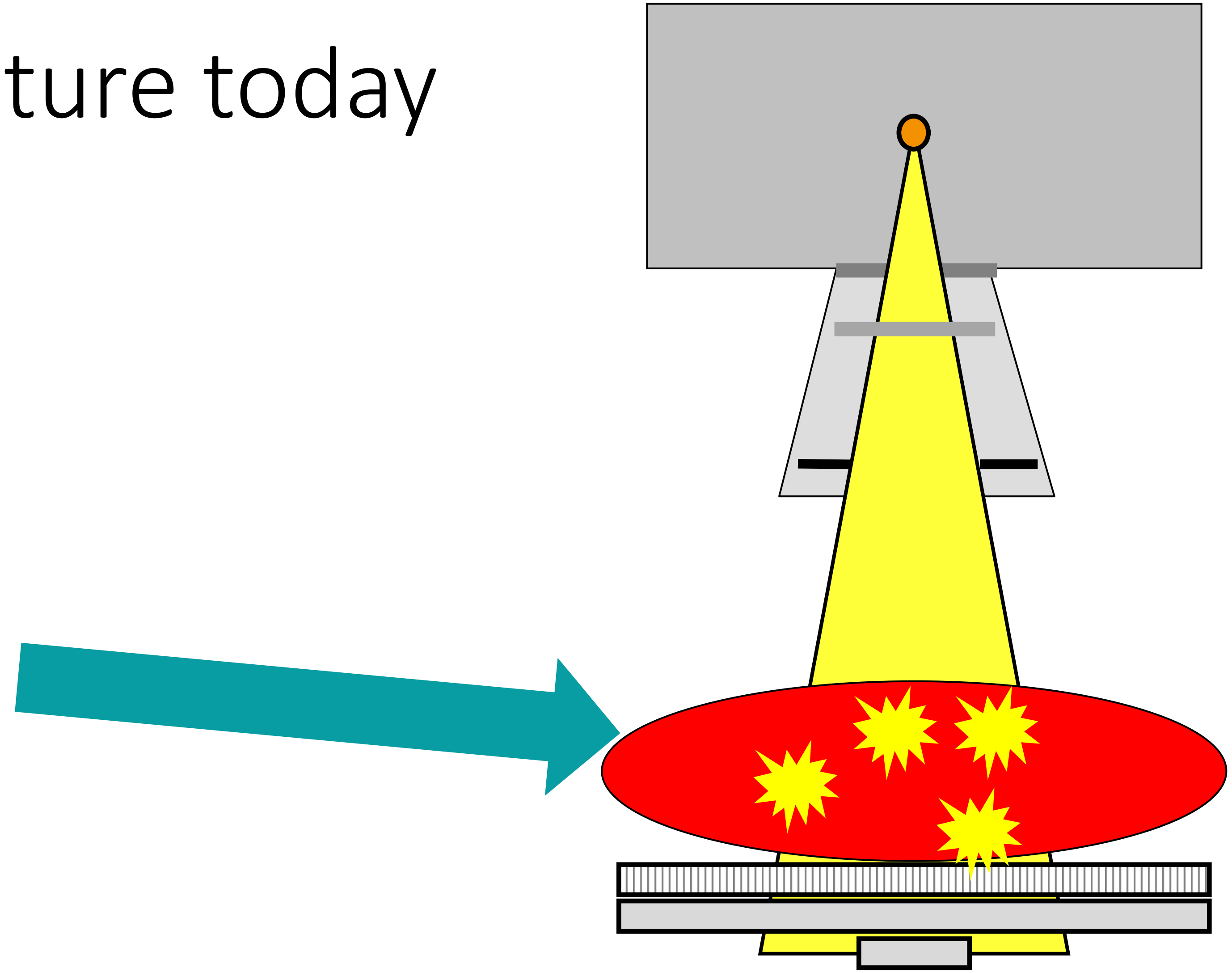


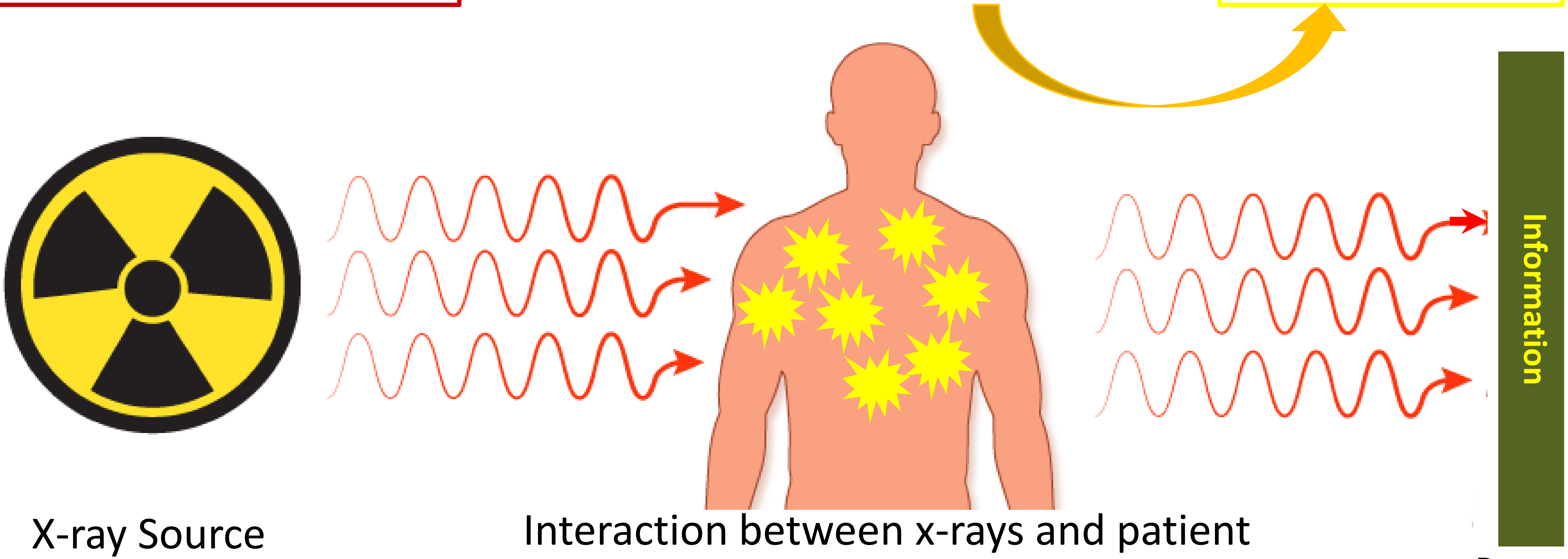
Radiography : a transmission experiment

Attenuation caused by absorption and scattering of the primary photons

$$I(x) = I_0 \cdot e^{-\mu x}$$

exponential attenuation

depends on **attenuation coefficient μ**

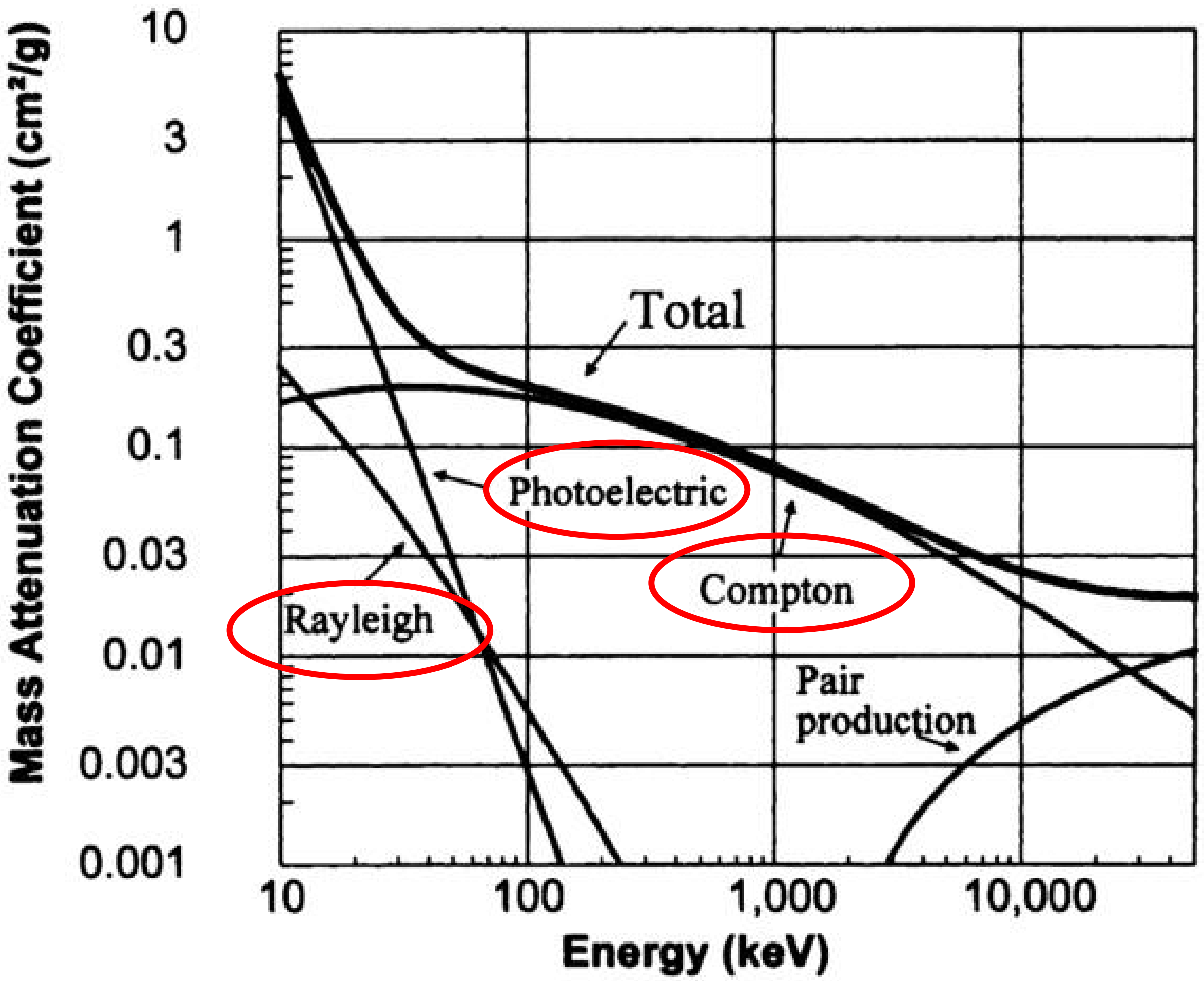


X-ray Source

Interaction between x-rays and patient

Detector

Interaction of radiation with matter



Photoelectric effect at **low photon energies** (<26 keV) with a probability dependant on photon energy and the atomic number of absorber

Compton scattering dominates at **higher energies with low Z materials**.

Rayleigh scattering: **low probability** in medical imaging (10% of interactions in mammography, 5% in chest radiography).

Pair production: beyond the range of diagnostic and nuclear radiology.

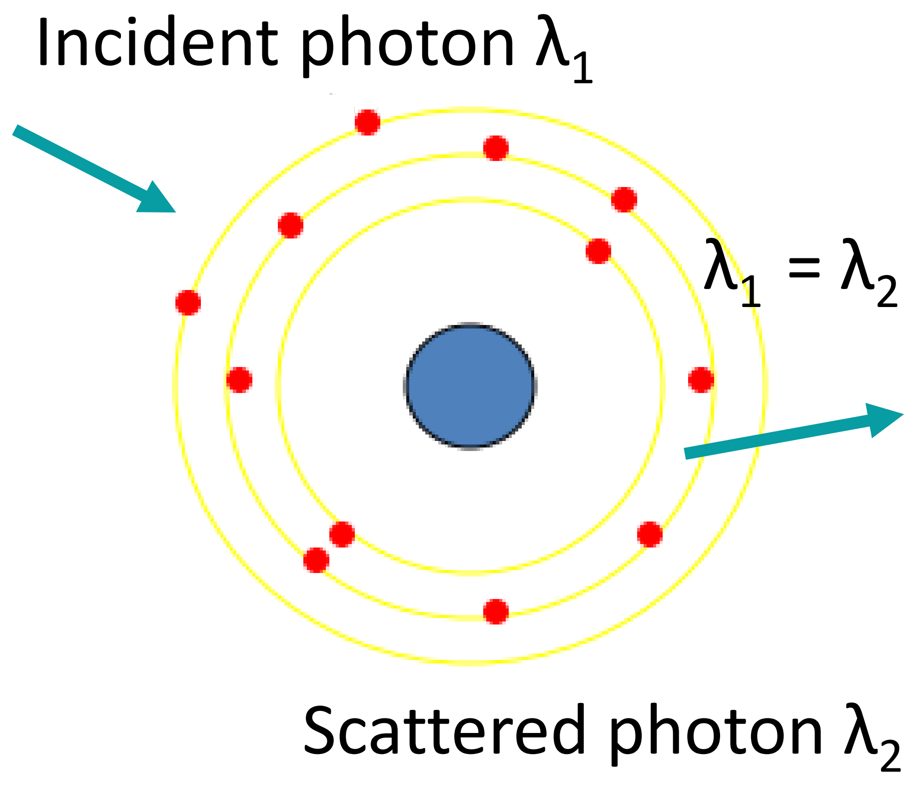
Linear attenuation coefficient

The total linear attenuation coefficient of a tissue is the **sum of the individual linear attenuation** coefficients for each type of interactions:

$$\mu = \mu_{\text{Rayleigh scatter}} + \mu_{\text{photoelectric effect}} + \mu_{\text{Compton scatter}} + \mu_{\text{pair production}}$$

Rayleigh scattering - coherent scattering

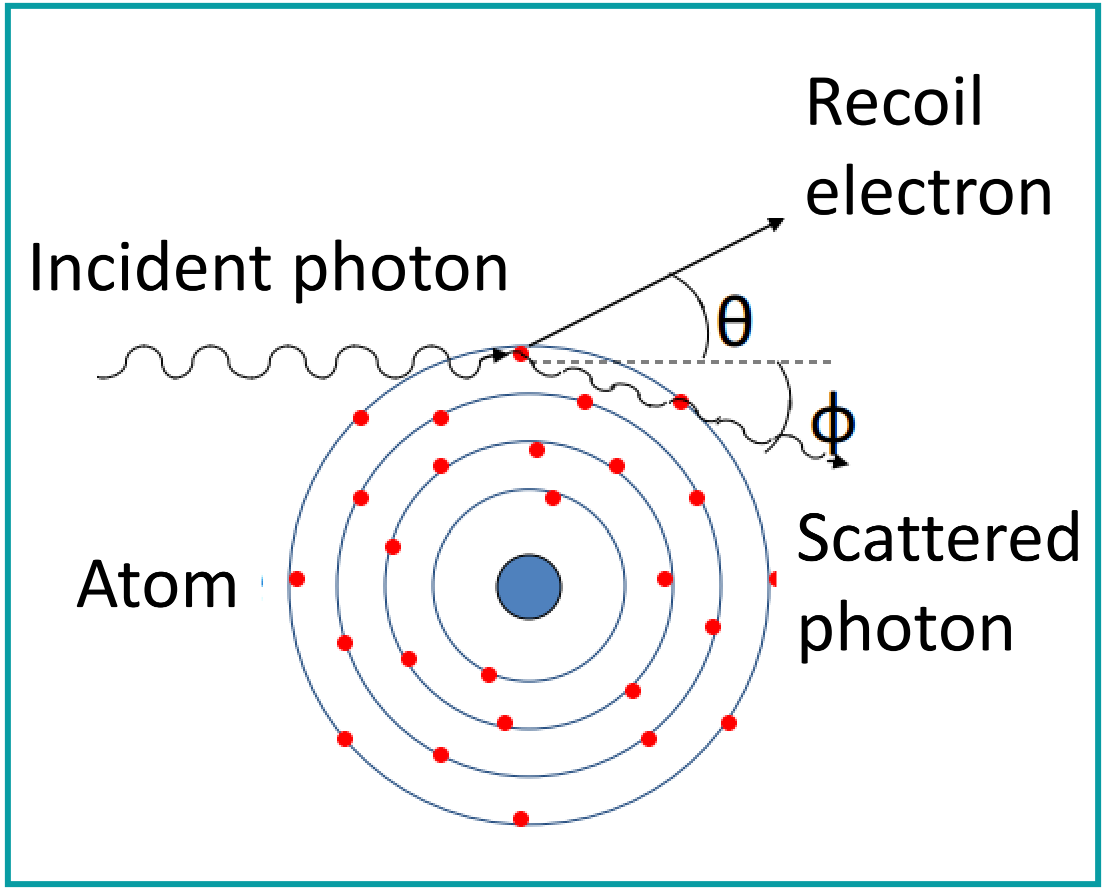
- Incident photon interacts with and excites the **total atom**
- Interaction at **low energies** (15-30 keV)
- Electric field of incident photon's electromagnetic wave expends energy → **electrons in atom oscillate** in phase
- Atom's electron cloud radiates this energy: **emitting a photon**
- Emitted photon: **same energy** than incident photon, but **slightly different direction**



In Medical imaging:
5% of interactions above 70 keV
10% of interactions at 30 keV

Compton scattering – inelastic scattering

- **Predominant interaction** in diagnostic energy range with soft tissue
- Interaction most likely between **photons and outer («valence»)-shell electrons**
- Electron ejected from shell → **ionisation**
- Scattered photon emitted with reduced energy

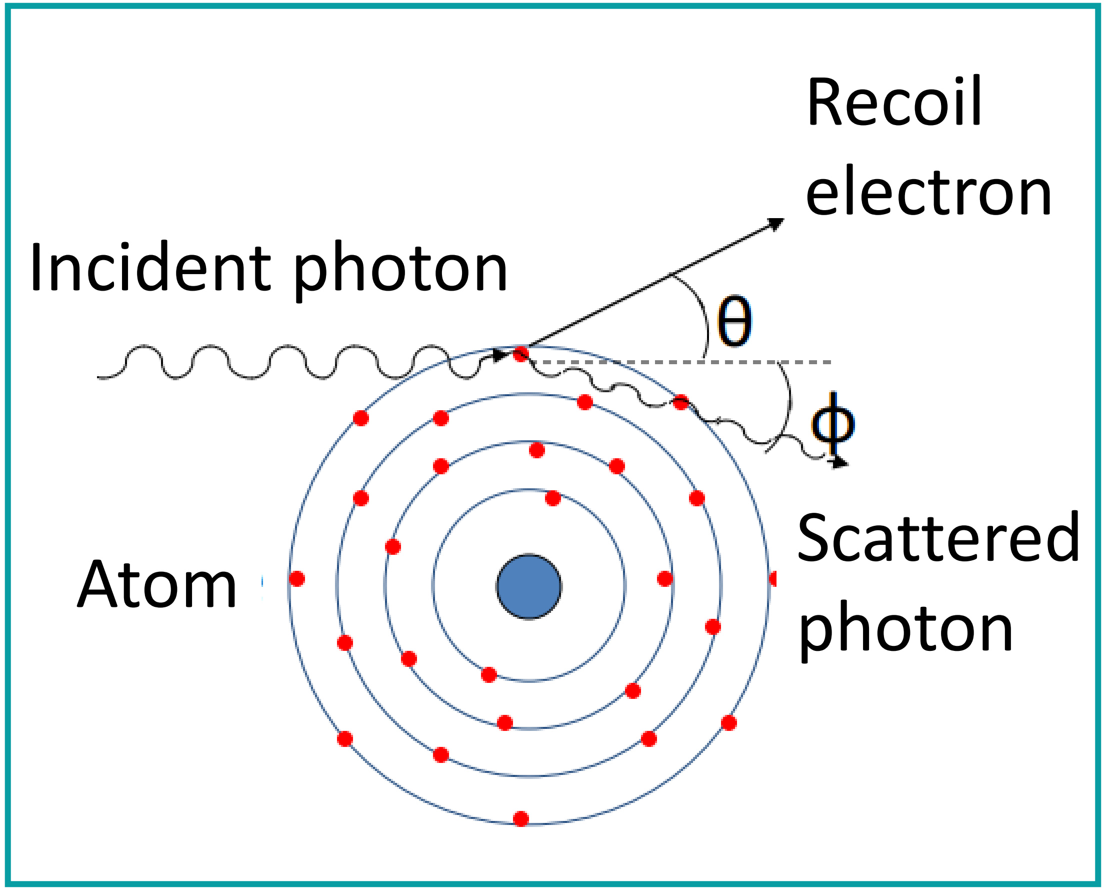


$$E_0 = E_{sc} + E_{e-}\ (E_{binding}\ \text{negligible})$$

Compton scattering in medical imaging

Compton scattering at lower x-ray energies (15-150 keV):

- **Majority of** incident photon **energy transferred to scattered photon**
- **Probability** of Compton interaction **increases with increase** of incident photon **energy**
- Probability depends on **electron density**

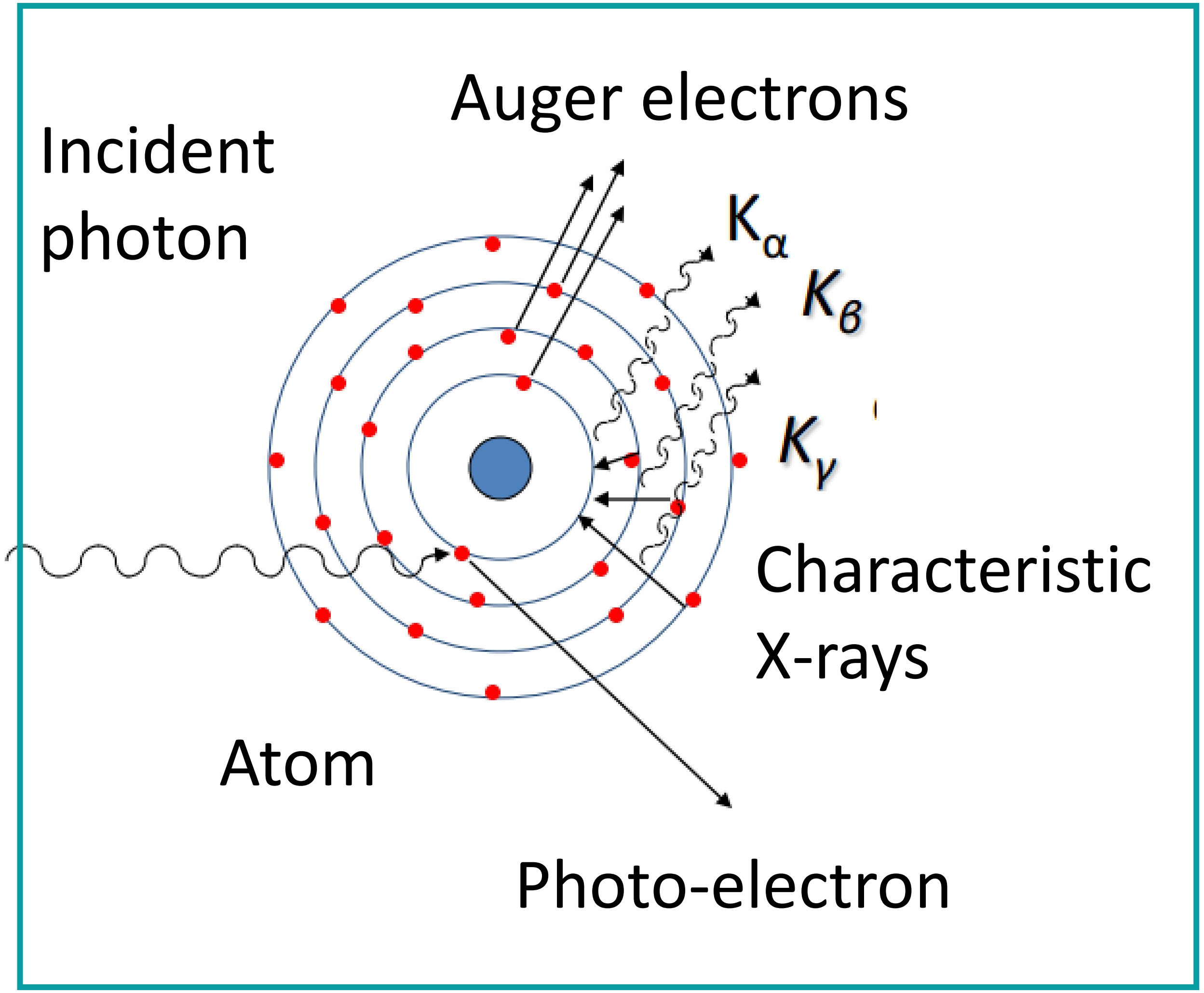


Photoelectric Effect

- **All** of incident photon energy **transferred** to an electron

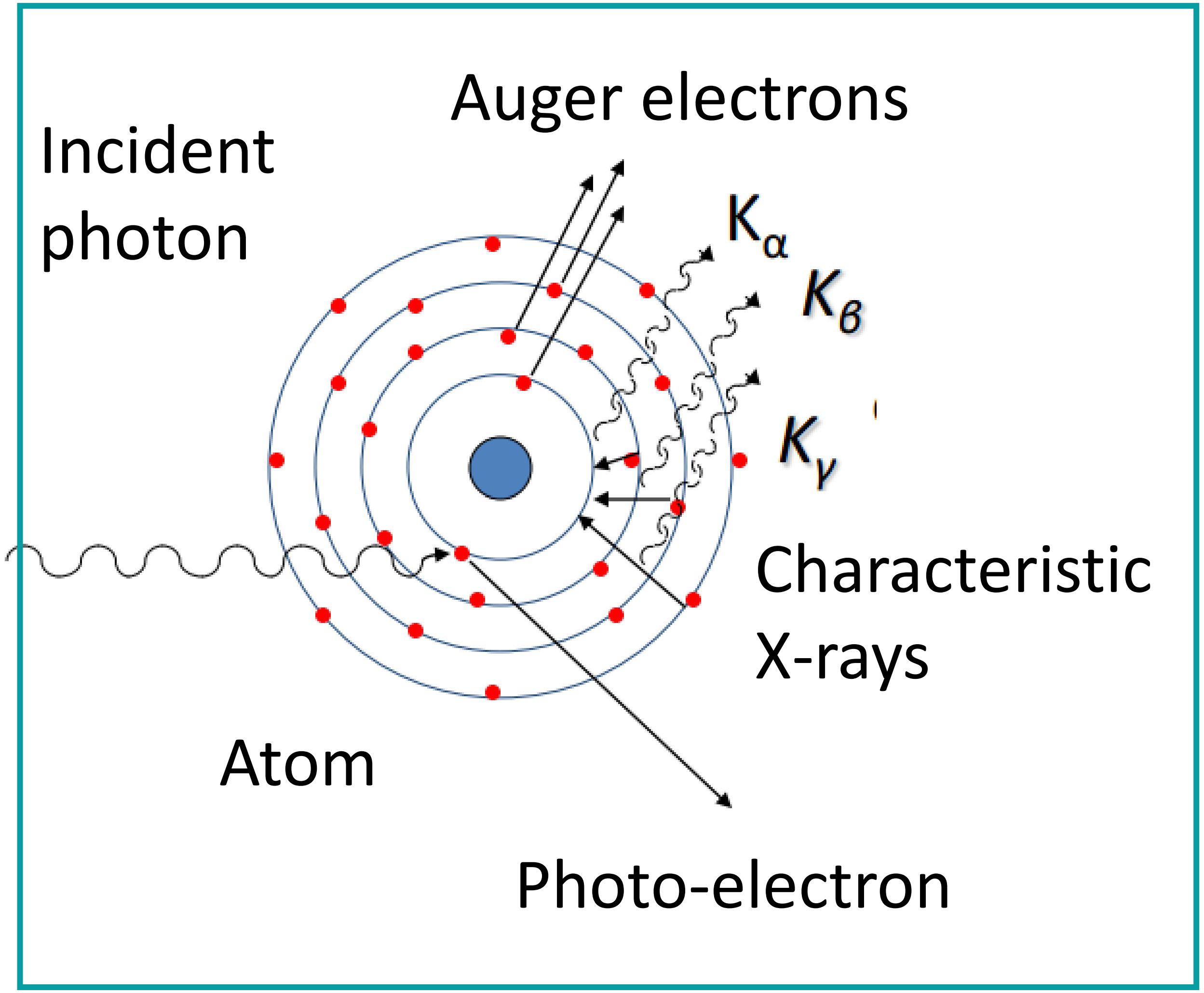
$$E_{pe} = E_0 - E_b$$

- **Ionisation** with **inner shell vacancy**
- Vacancy filled → **electron cascade** from outer to inner shells occurs
- Difference of binding energies: released as either **Auger electrons** or characteristic x-rays (less probable in medical imaging range).
- Probability proportional to Z^3/E^3

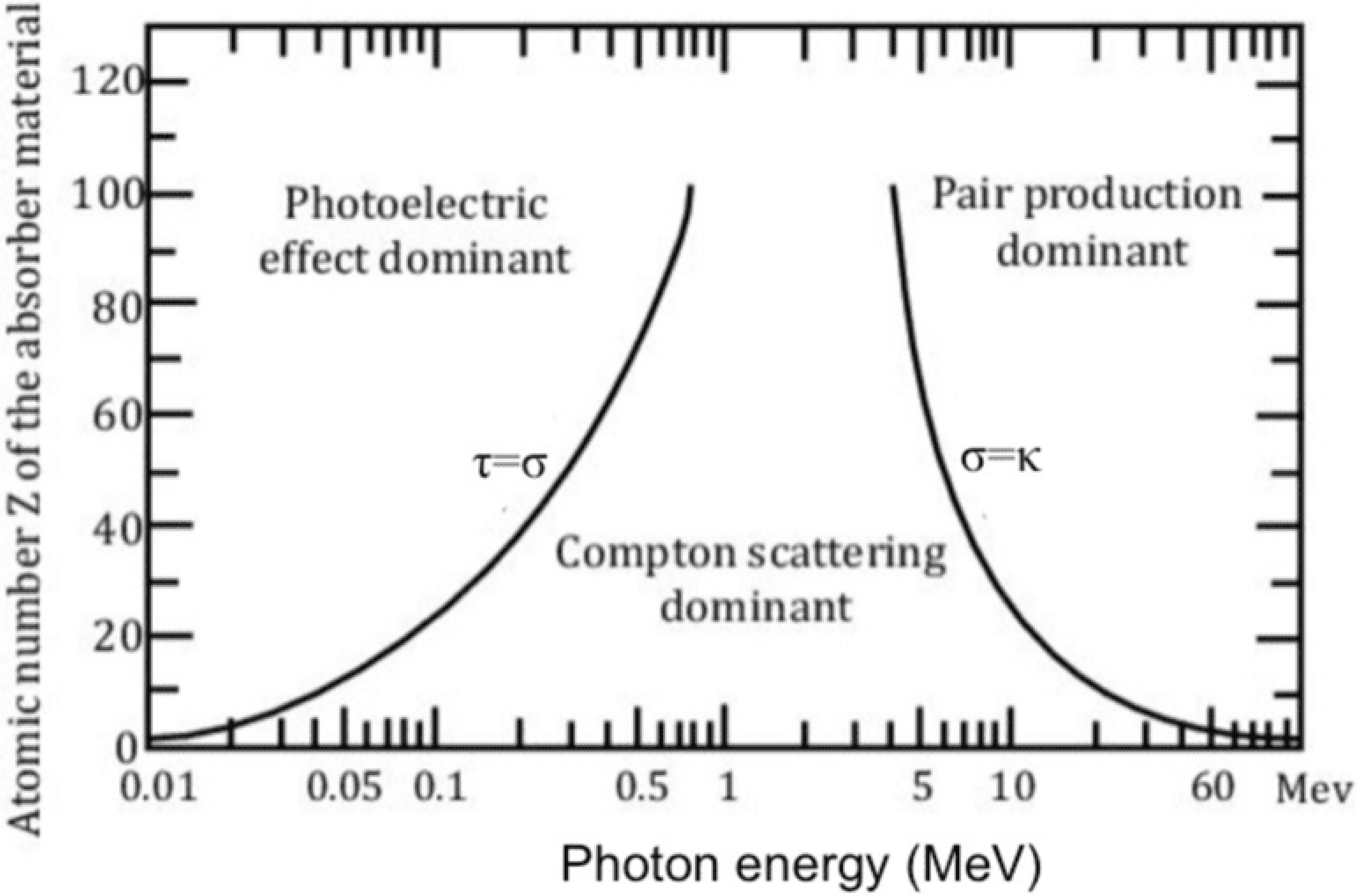


Photoelectric Effect in medical imaging

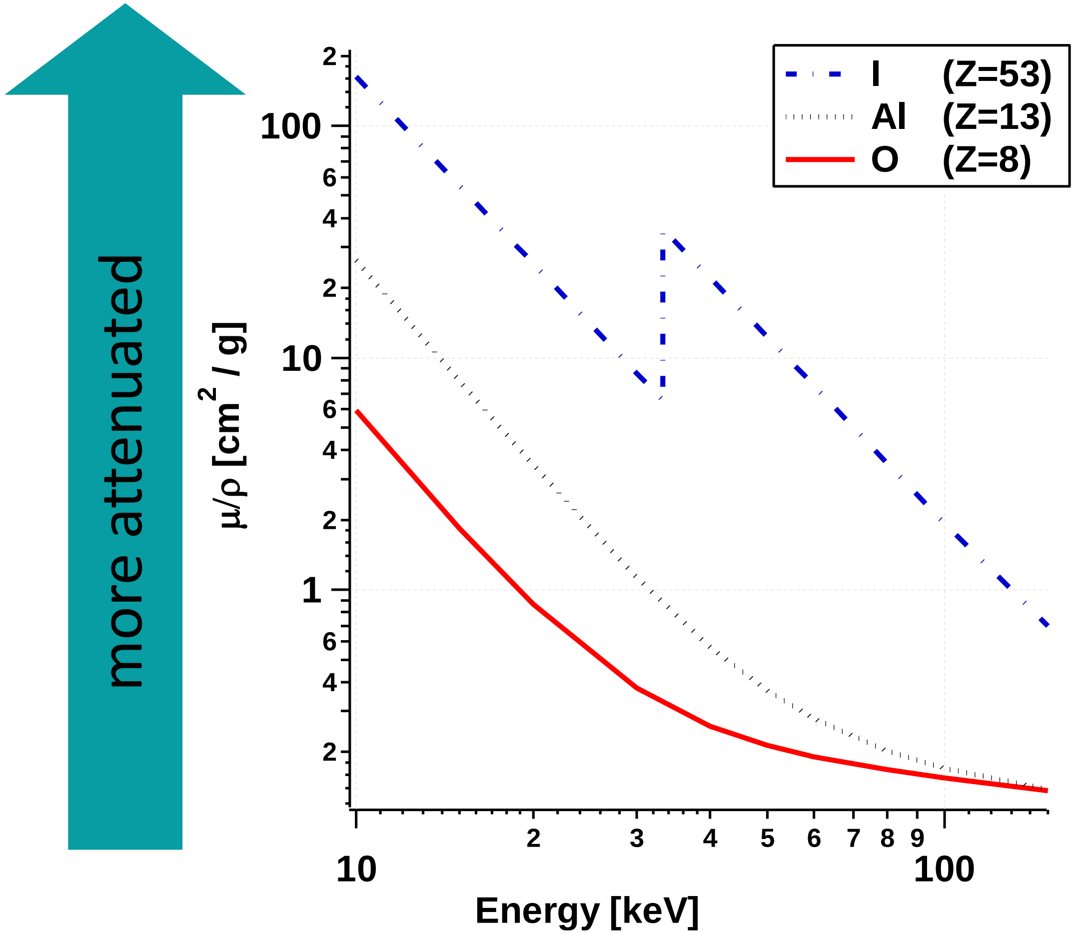
- Benefit: **no scattered photons**
- **Probability** of photoelectric effect **decreases with increasing photon energy** except at **absorption edges**
- Photoelectric effect **predominates** when lower photon energies interact with **high Z materials**
- Photoelectric absorption: **primary mode of interaction** of diagnostic x-rays with image receptors, radiographic contrast materials, and radiation shielding, **of all higher atomic numbers** than soft tissue



Interactions as a function of atomic number Z

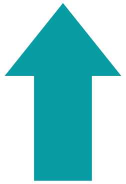


Interaction with the patient



Radiography:
Transmission experiment

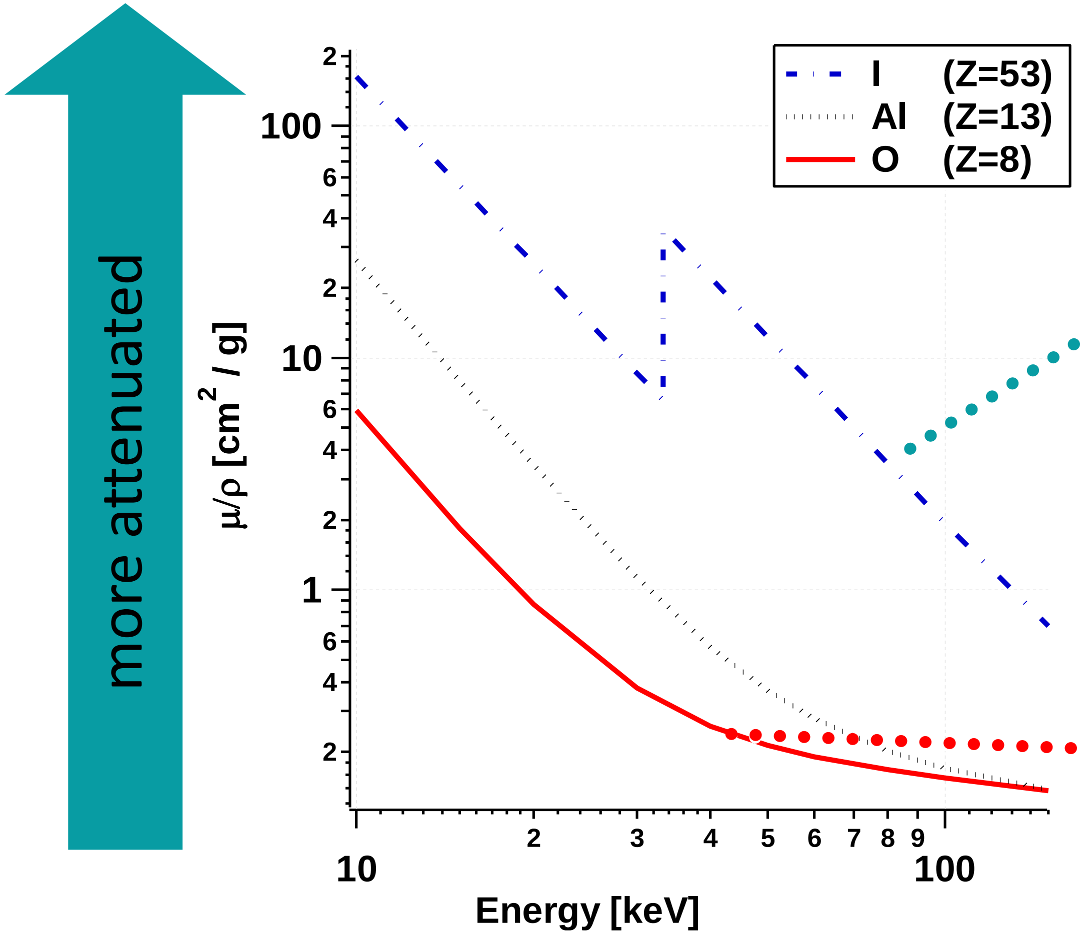
depends on
attenuation coefficient μ



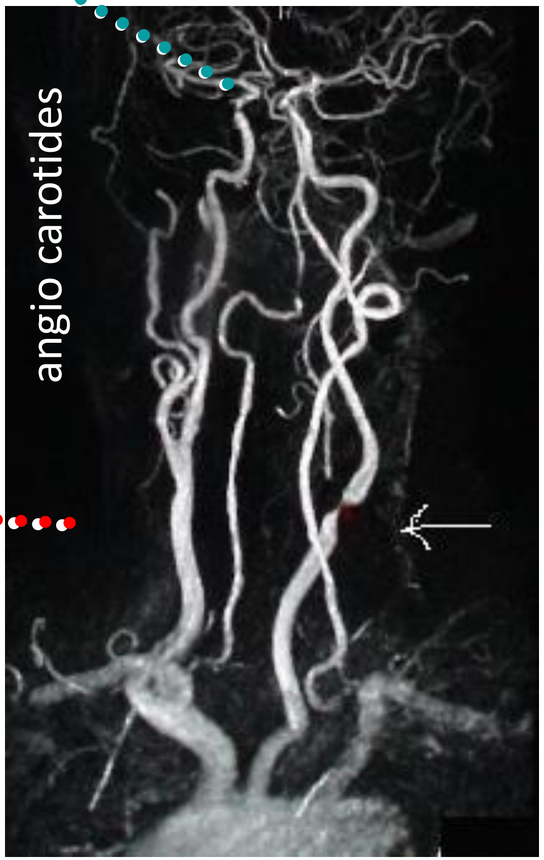
$$I(x) = I_0 \cdot e^{-\mu x}$$

exponential attenuation

Interaction with the patient



Contrast product
high Z material, much more attenuated than tissues

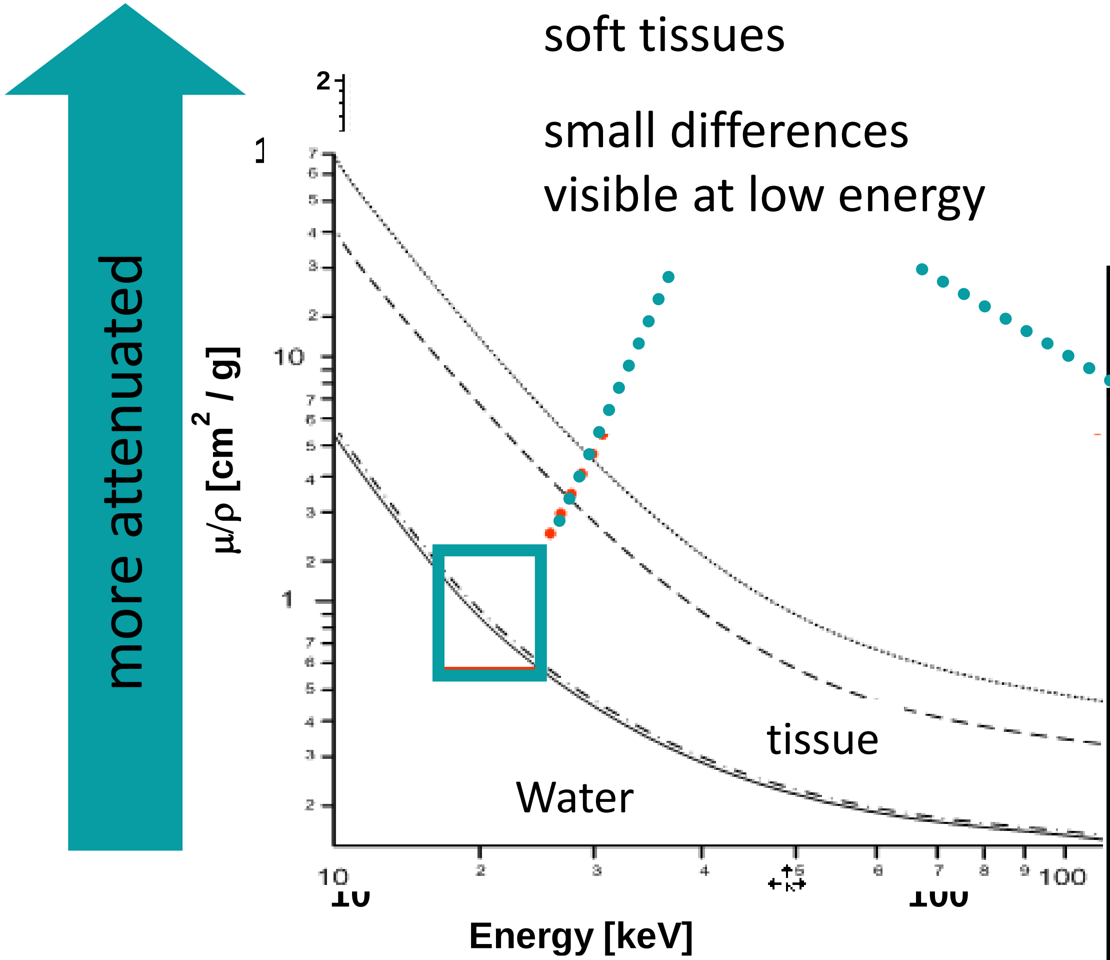


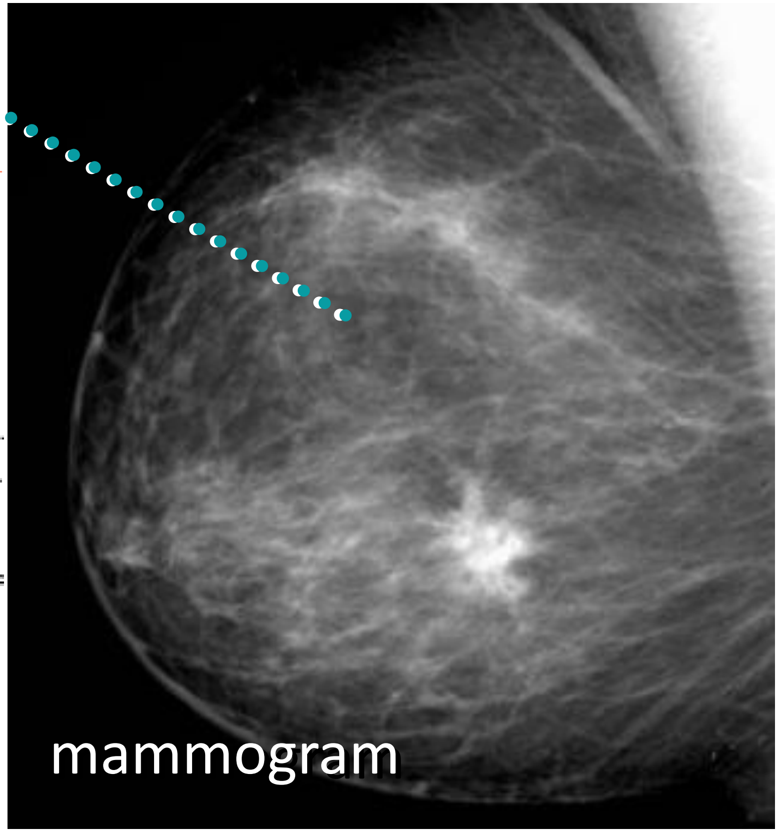
stenosis

Interaction with the patient

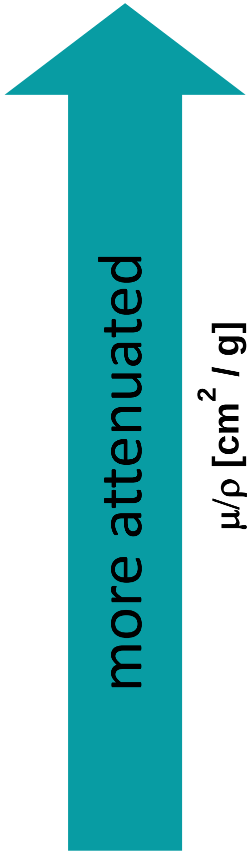
soft tissues

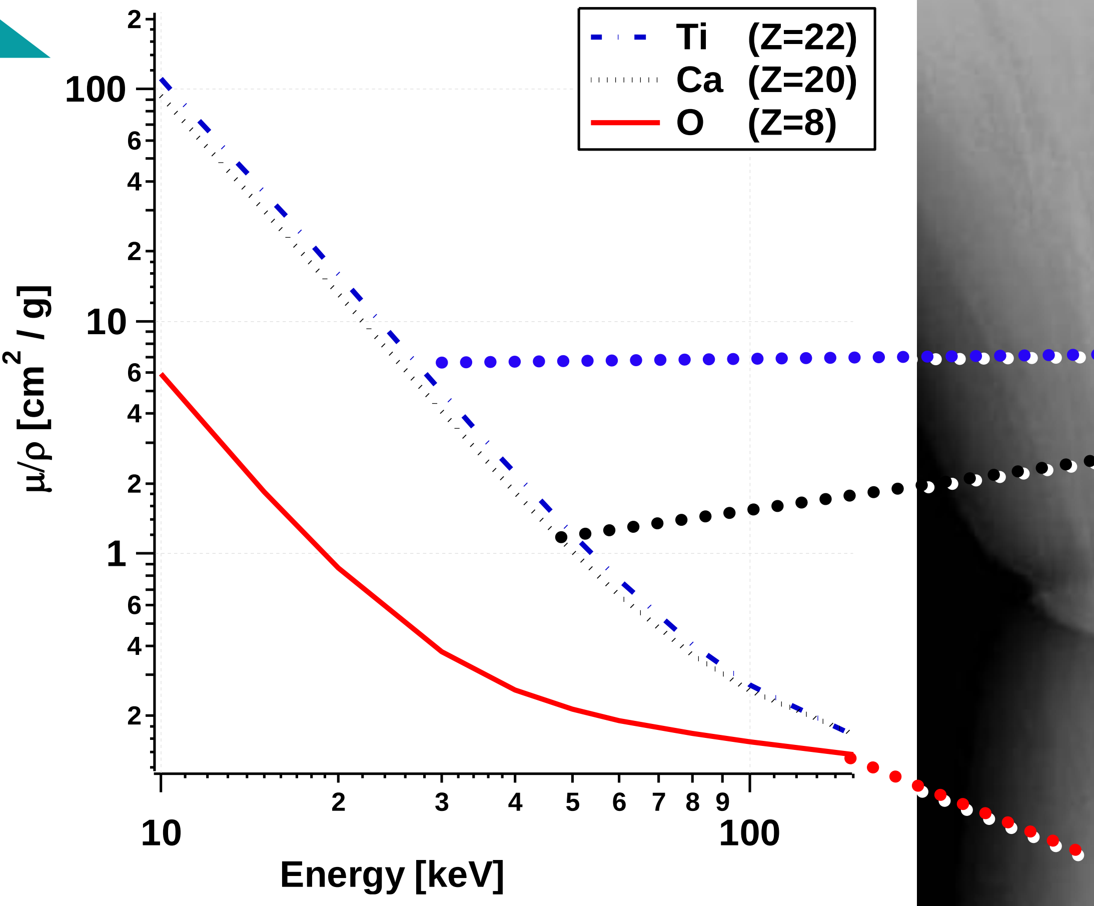
small differences
visible at low energy

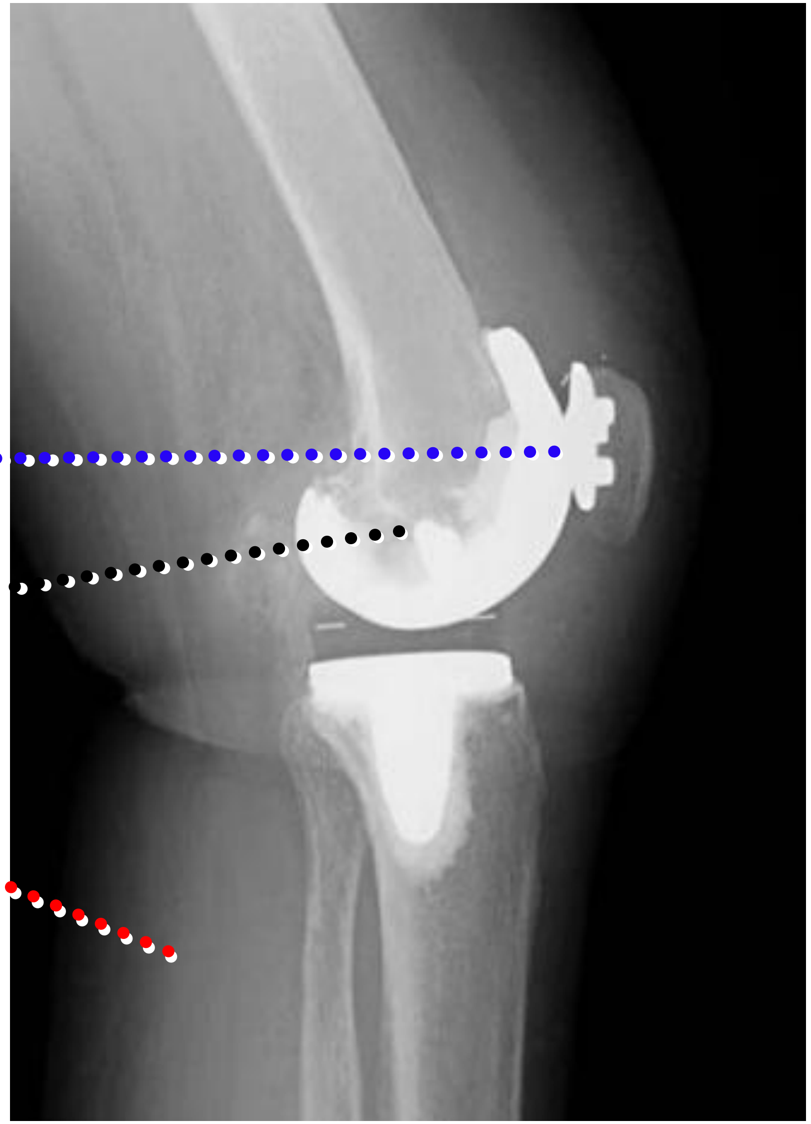




Interaction with the patient





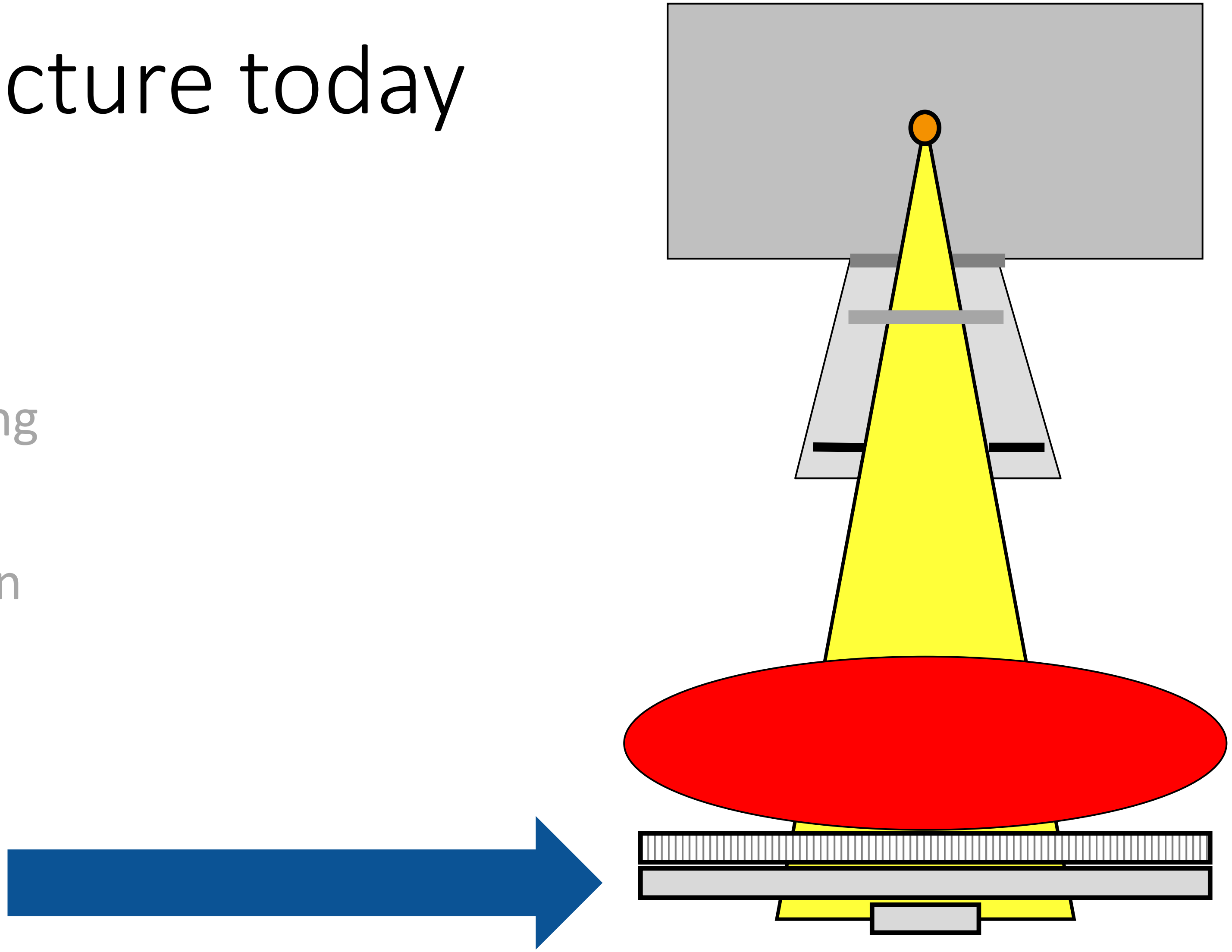


What voltage of x-ray beam would deposit the highest dose to the patient, for a given amount of photons on the detector?

1. high kV beam
2. low kV beam
3. no idea

Contents of the lecture today

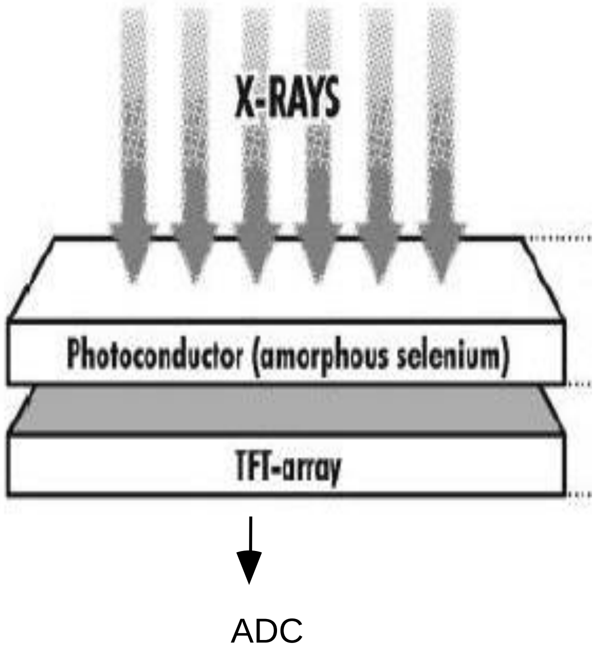
1. Introduction
    1. History of x-ray imaging
    2. Principles of x-ray imaging
2. **Radiography**
    1. Chain of image formation
    2. X-ray production
    3. X-ray beam
    4. Interaction with patient
    5. **Detection systems**

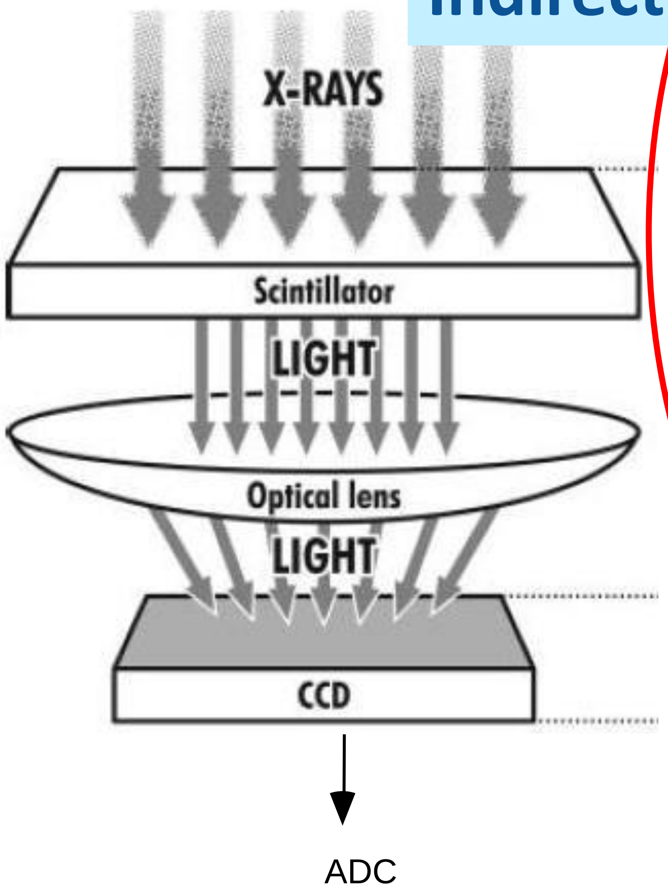


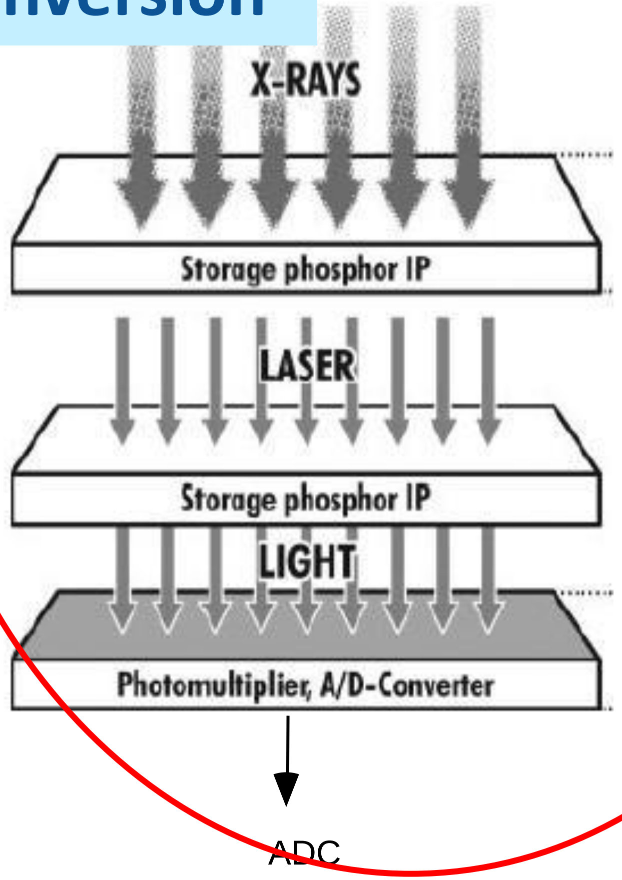
Detection Systems – Overview

Digital radiography | **Computed Radiography**

Direct conversion | **Indirect conversion**



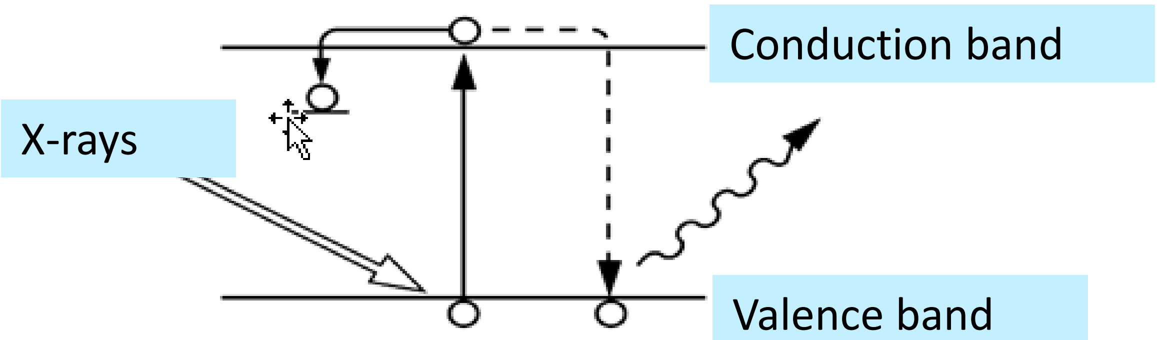




Computed radiography (CR) – 2 phases

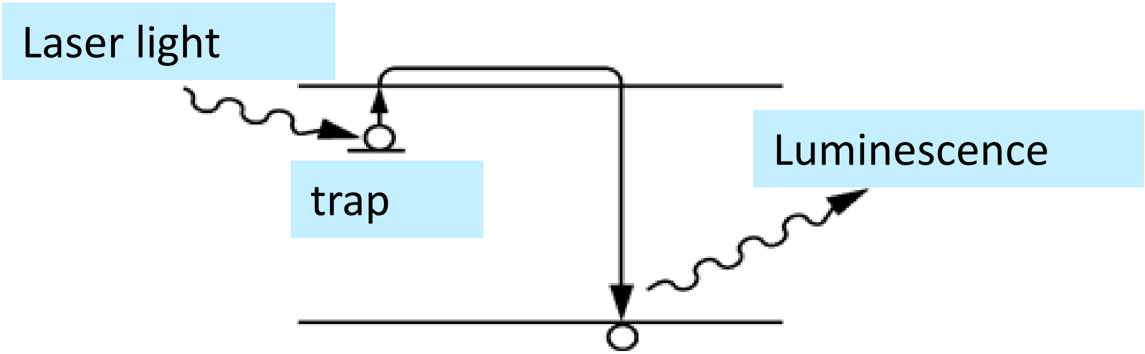
Exposure:

Excitation of electrons which will be «trapped» in a metastable state



Reading:

Excitation by laser light to «tear off» the electrons which return to a stable state by emitting light photons



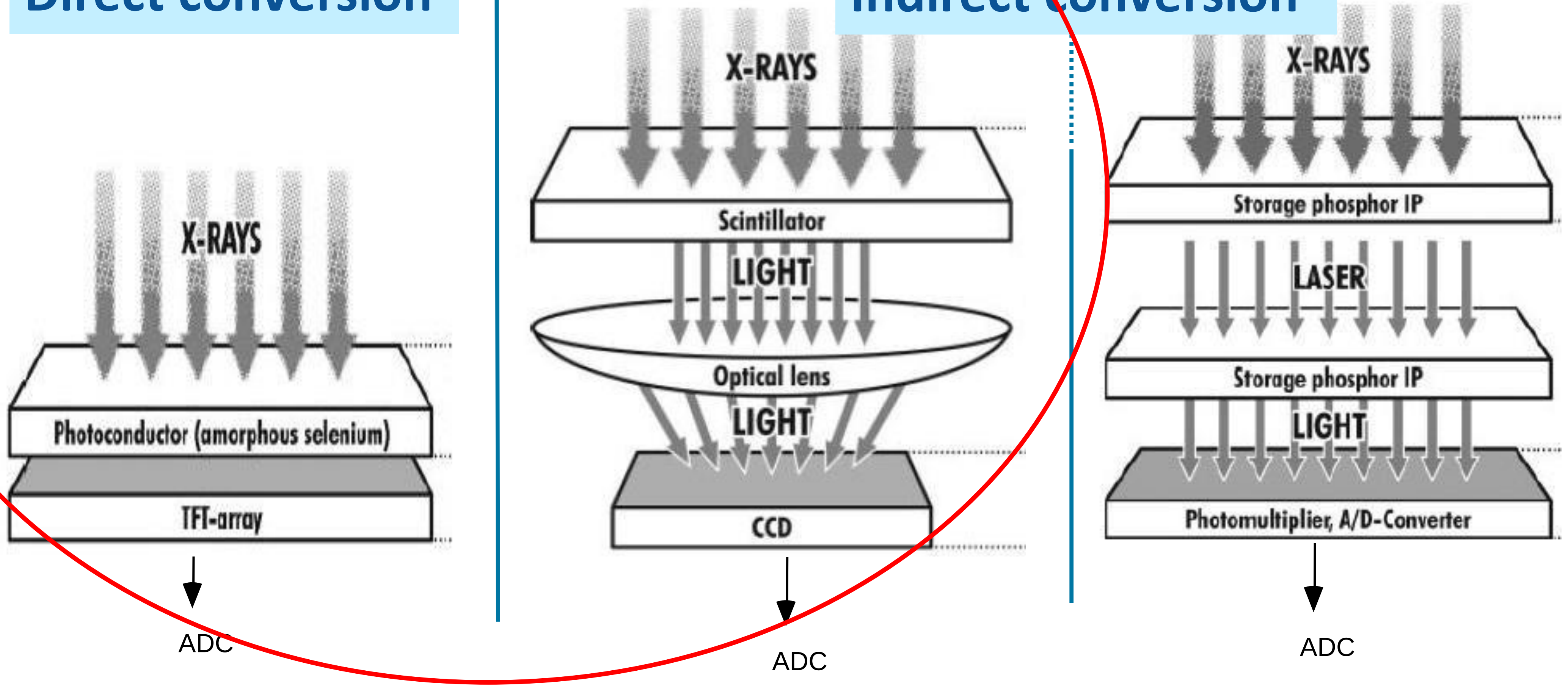
Detection Systems – Overview

Digital radiography

Computed Radiography

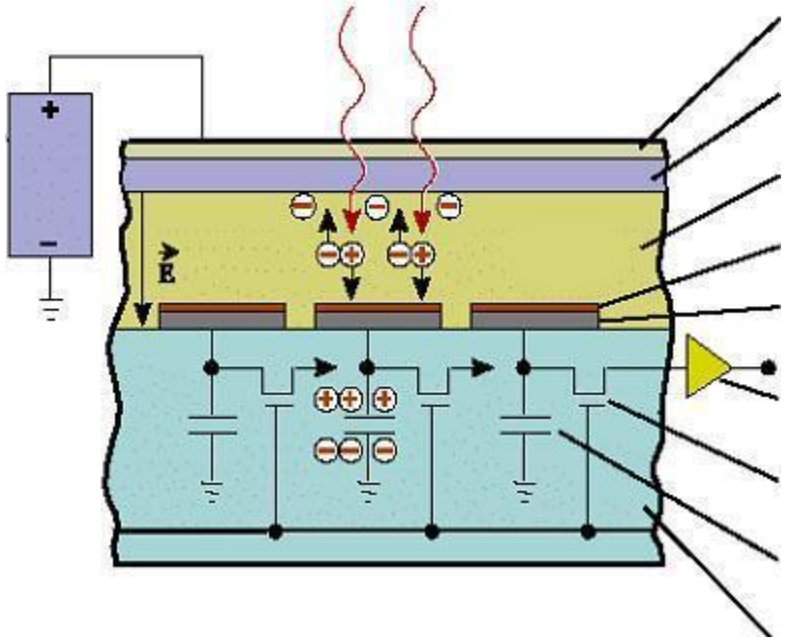
Direct conversion

Indirect conversion

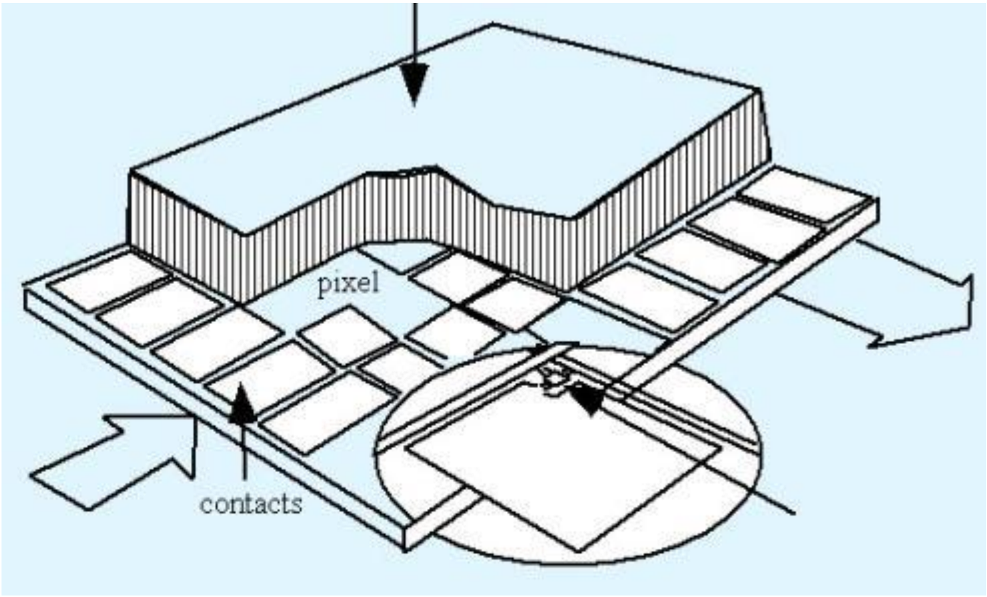


Digital radiography (DR) – realtime readout

Direct conversion



Indirect conversion



Digital radiography (DR)

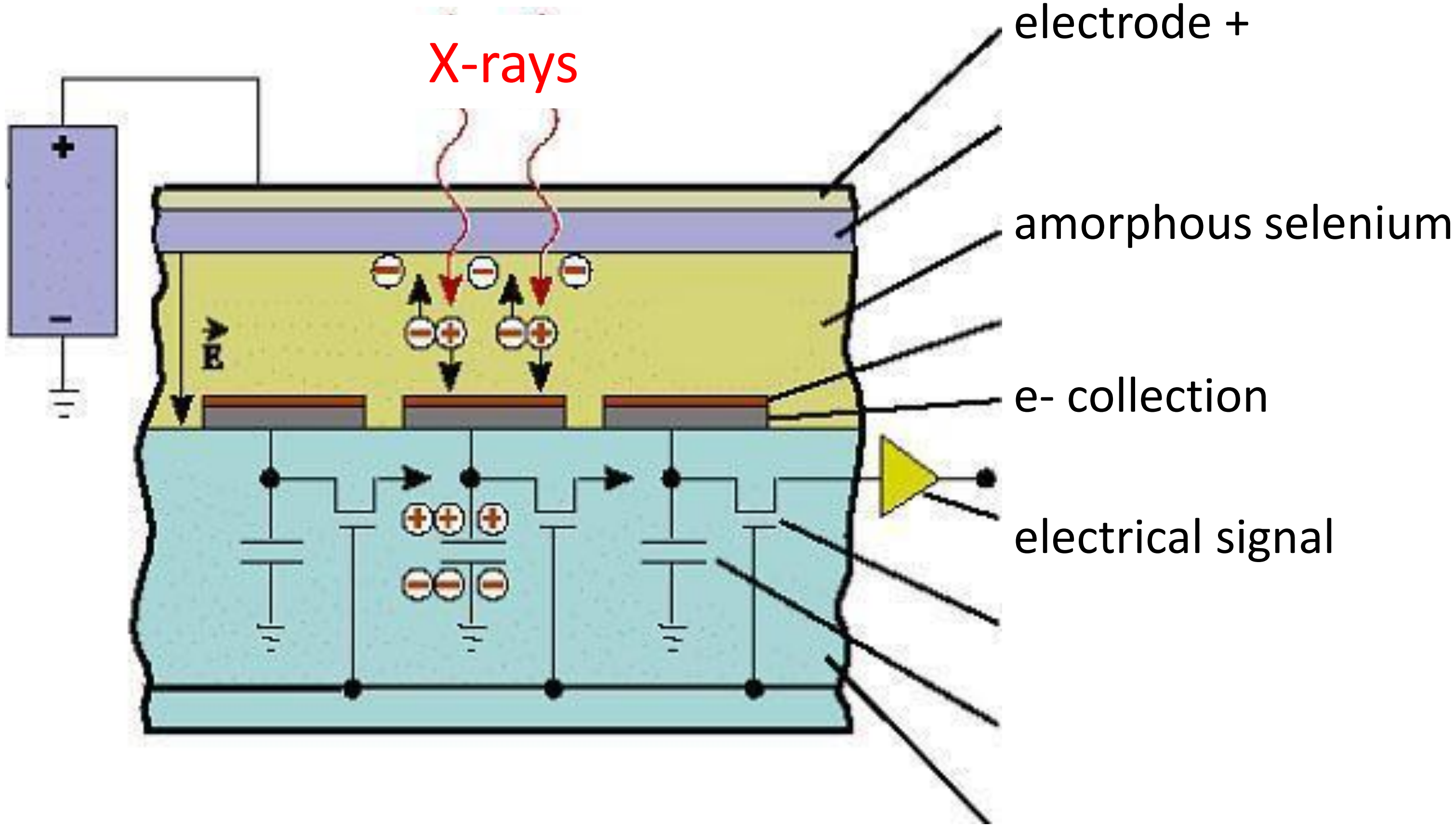
- **Direct** conversion of the x-ray into charge
  - Real time reading **without light**

Semiconductor material

→ Electron-hole pairs in proportion to incident x-rays

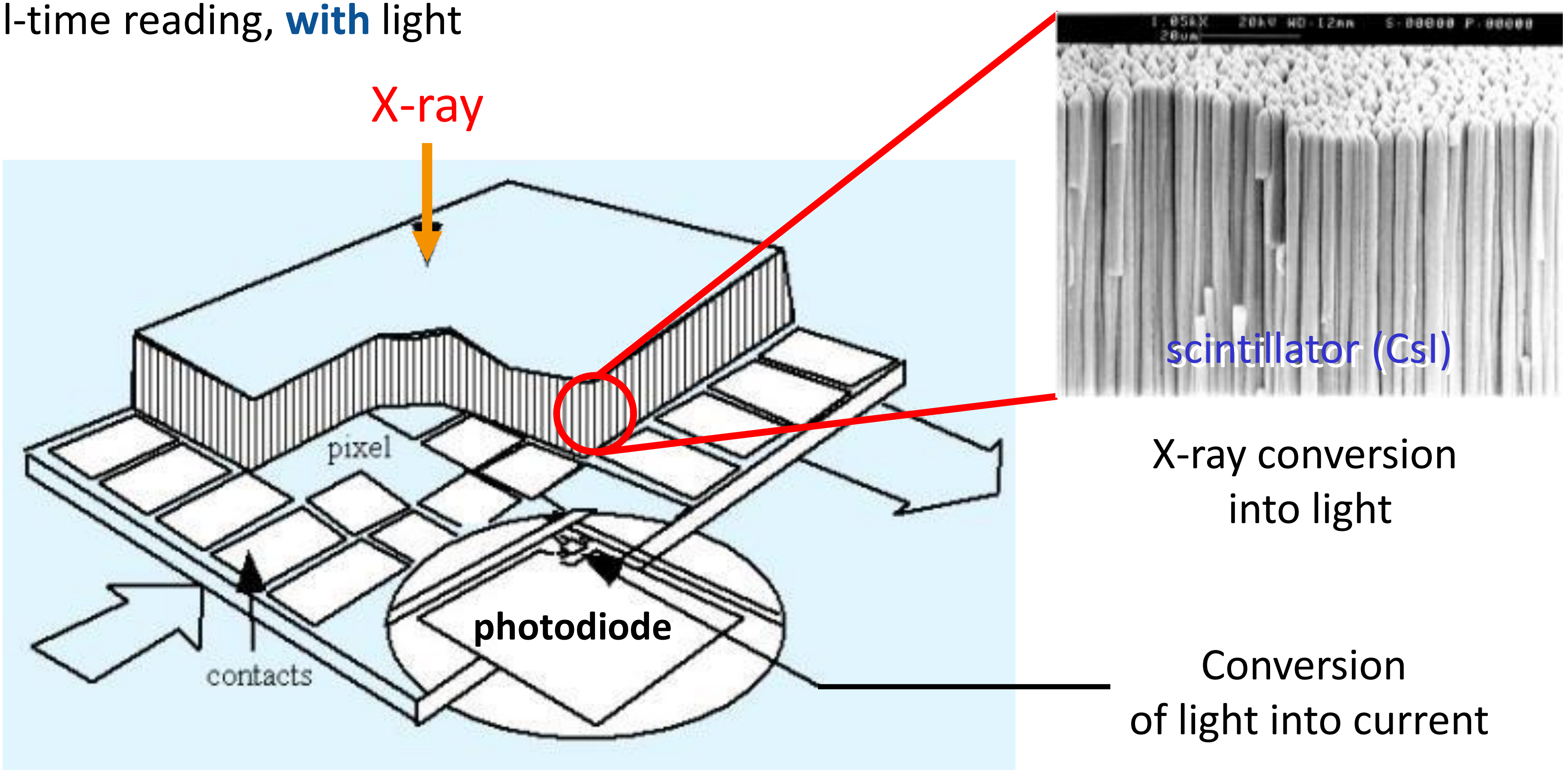
→ Absorbed x-ray energy directly converted into charge in the detector

→ High spatial resolution



Digital radiography (DR)

- **Indirect** conversion of the x-rays into charge
  - Real-time reading, **with** light



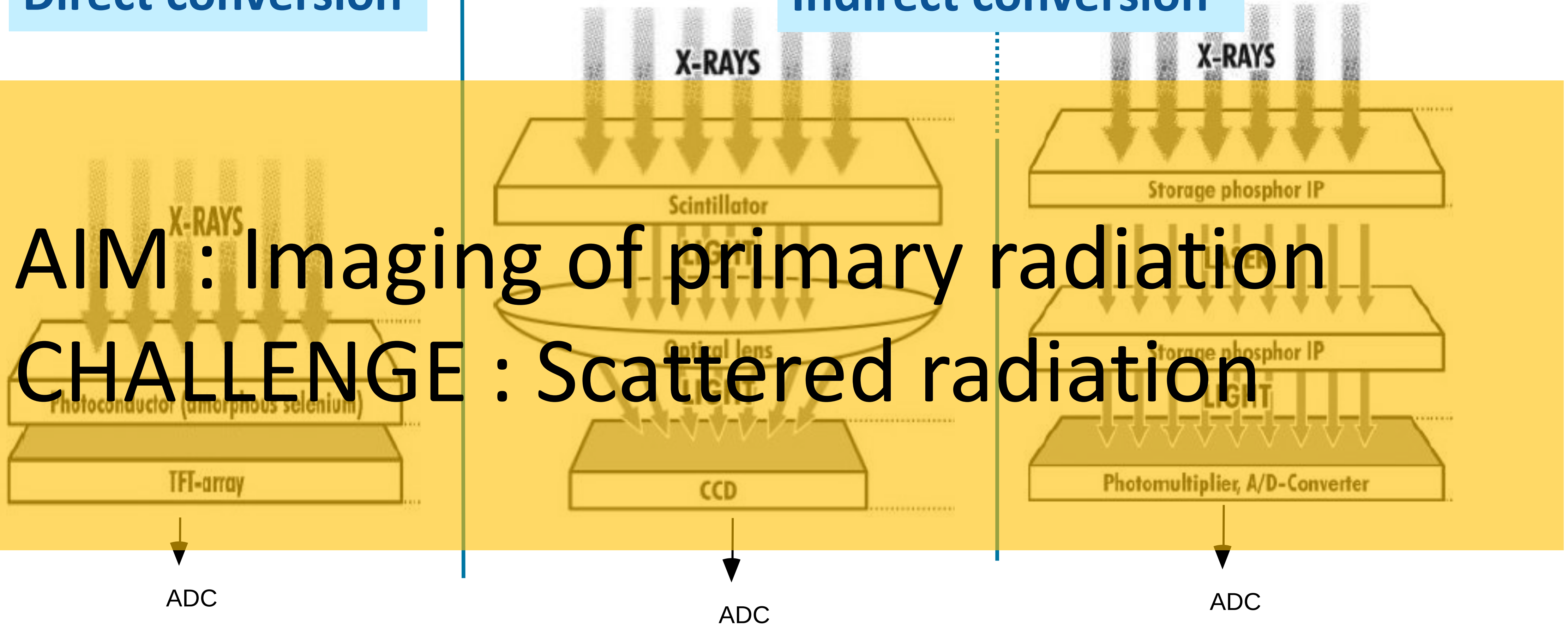
Detection Systems – Overview

Digital radiography

Computed Radiography

Direct conversion

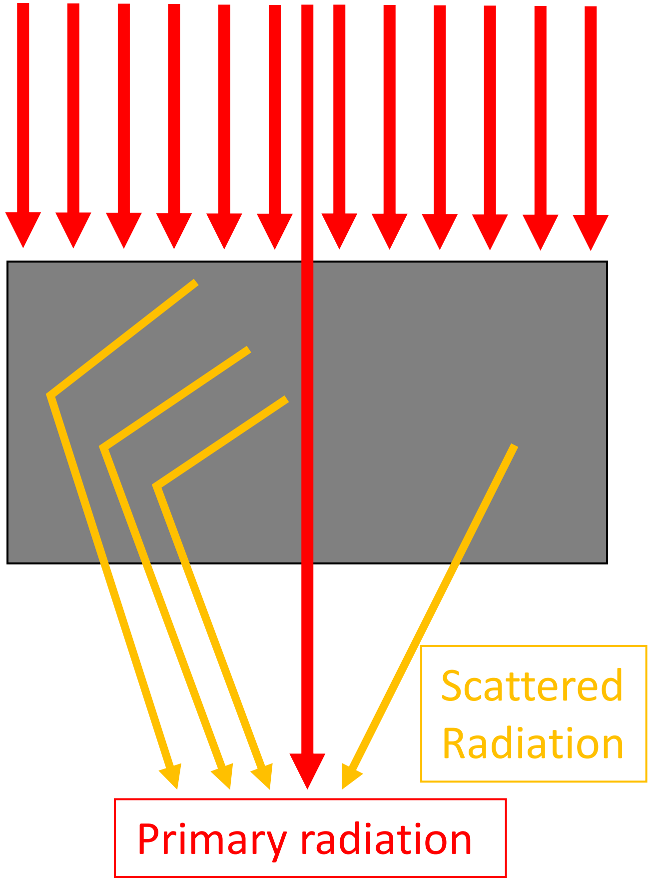
Indirect conversion



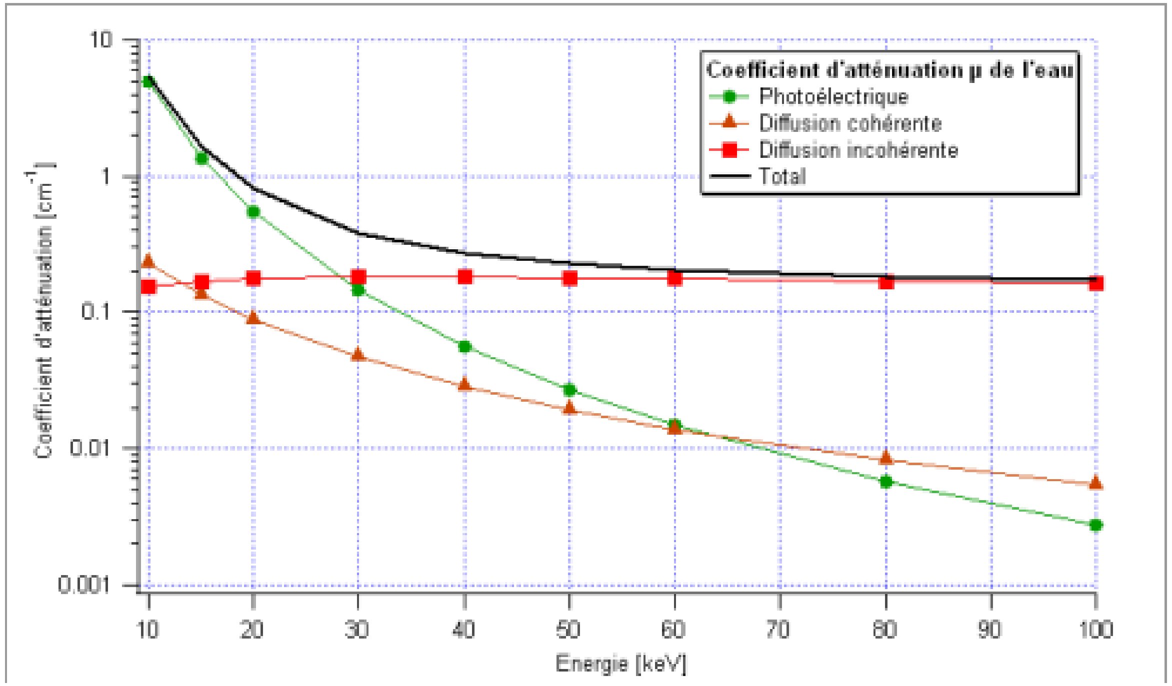
AIM : Imaging of primary radiation

CHALLENGE : Scattered radiation

Primary vs. Scattered radiation



When an **X-ray beam** passes through a patient, radiation is **completely stopped** (Photoelectric effect) or **partially attenuated** by the different densities crossed (Compton, Rayleigh), it is the **scattered radiation**.



Scattered radiation

- The relative contribution of the **scattered radiation** in the beam is ofter expressed by the fraction of scattered radiation, the S / (S + P) ratio which **increases** with:
  - the **thickness** of the patient
  - the **surface** of the **irradiation field** at the entrance to the patient

- The scattered radiation **propagates** in **all directions** in space

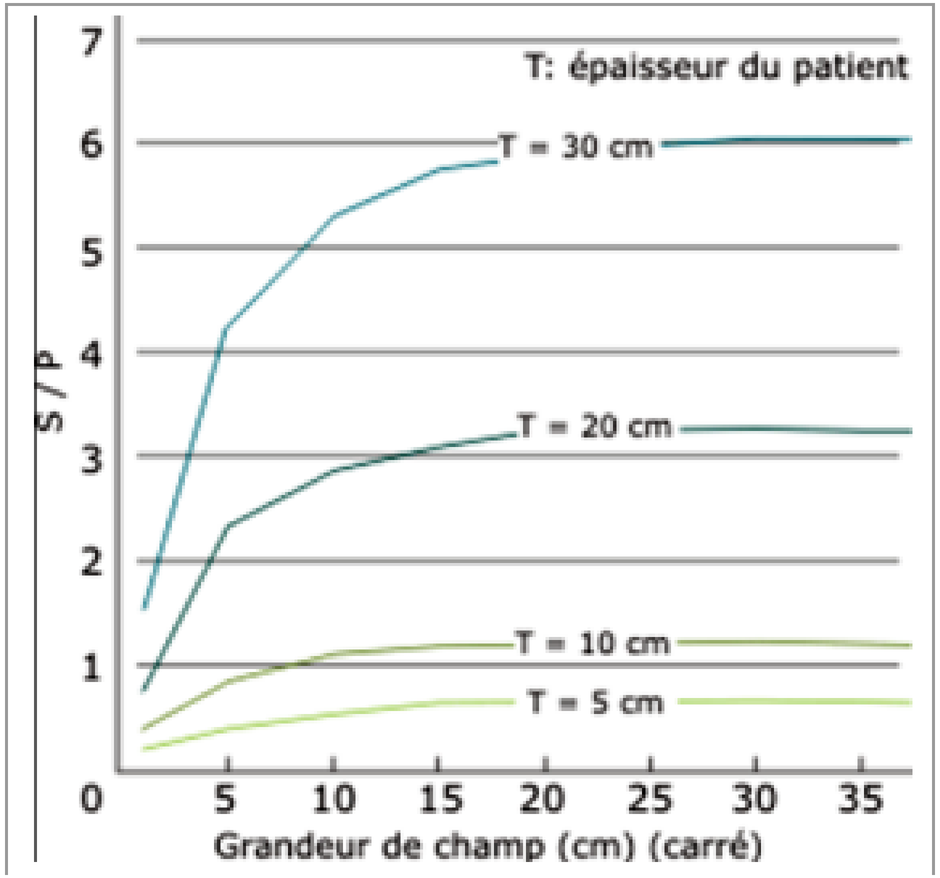
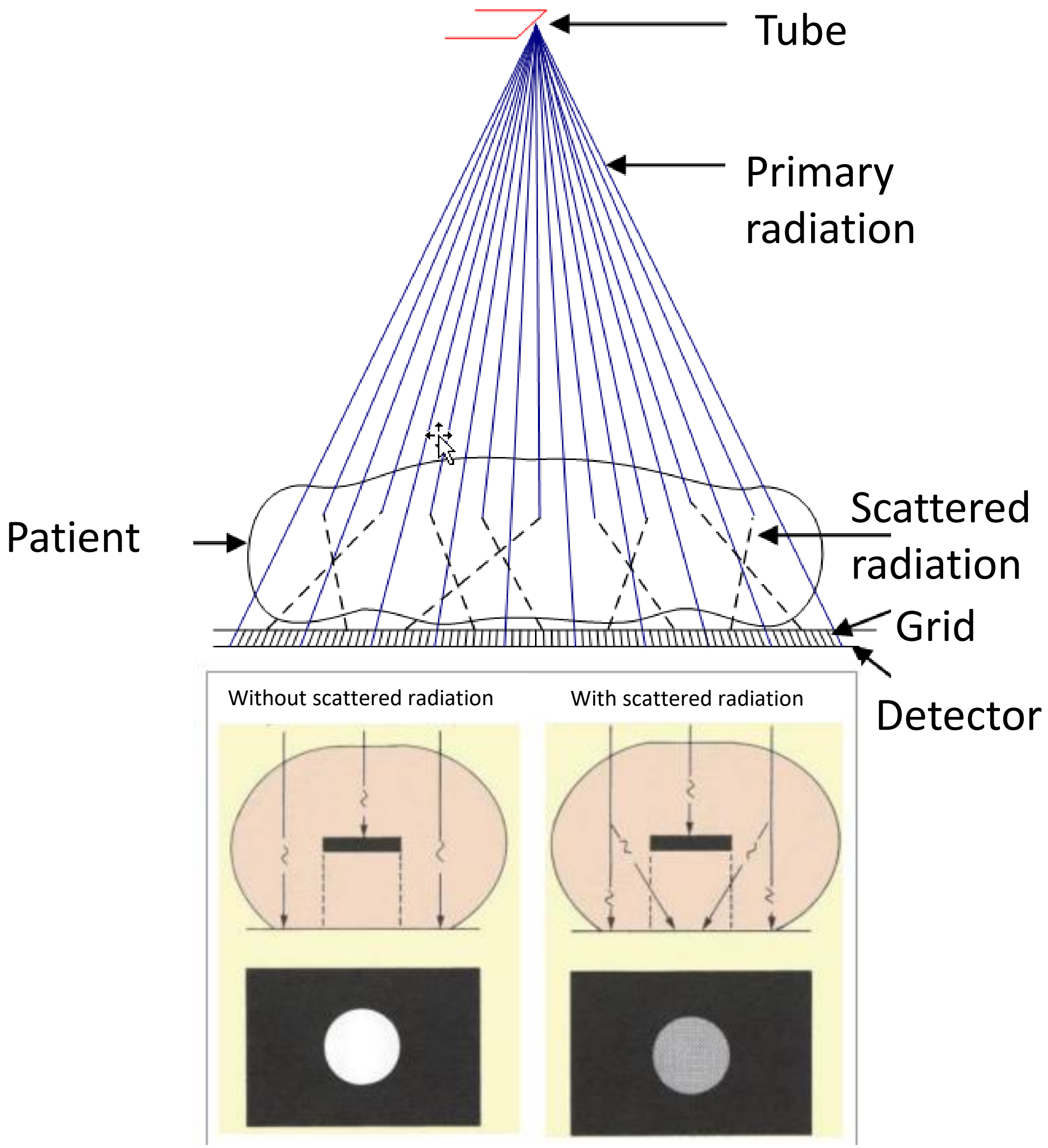
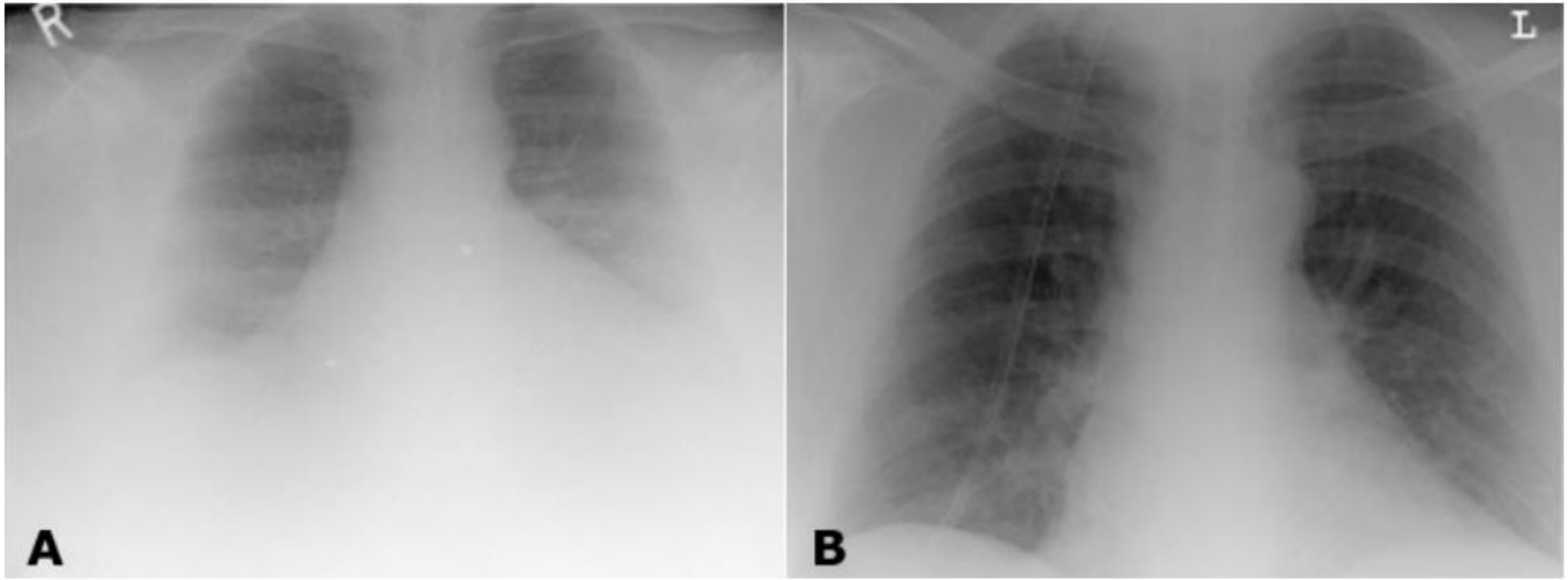


Image quality and scattered radiation

- Secondary photons !
- **Scattered photons** contribute to a (false) **signal** in the detector
- Scattered photons do **not provide useful information**
- Contrast **decreases** with a factor equal to $$\frac{1}{1+\frac{S}{P}}$$
- Solution : Use **anti-scatter grid**



Effect of anti-scatter grid

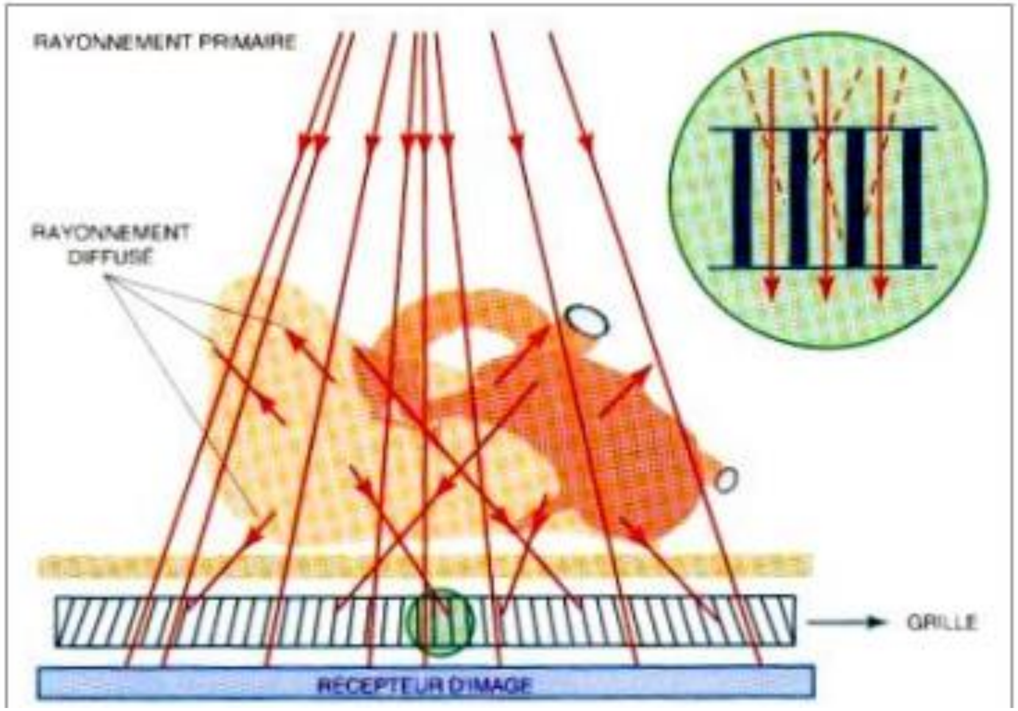


Without grid

With grid

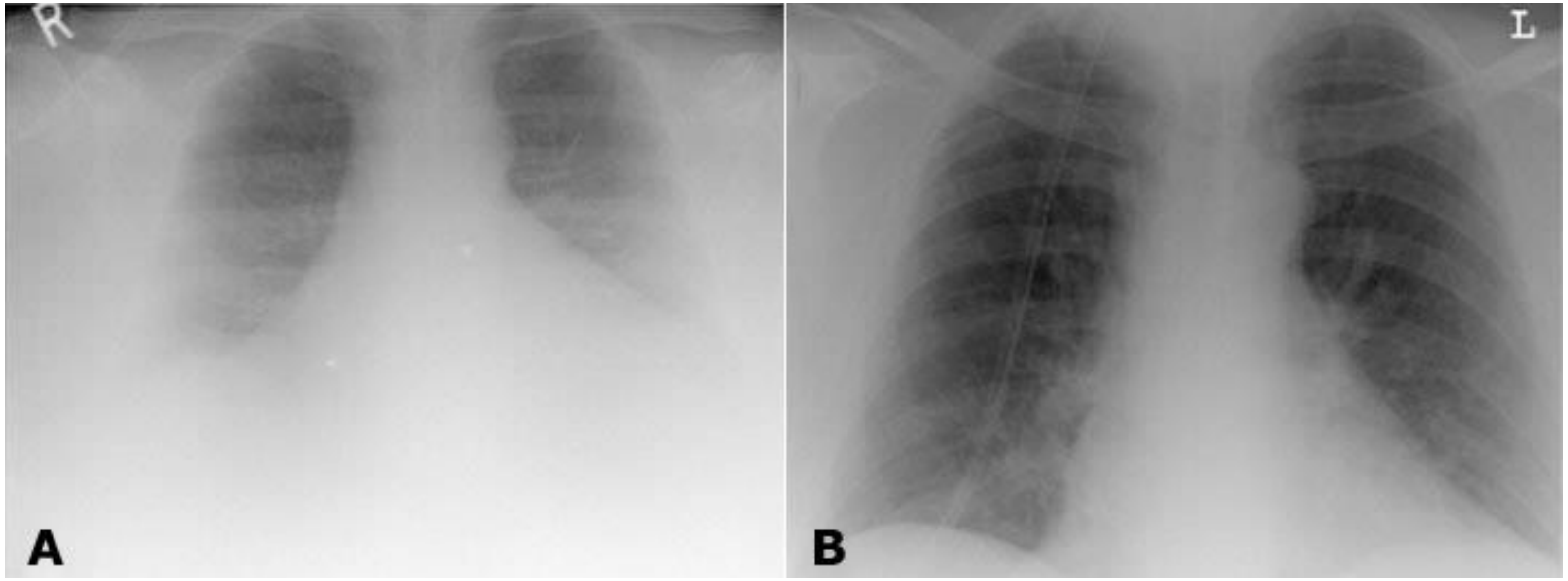
Anti-scatter grid

- **Anti-scatter grid**, placed in front of the detector, **rejects** the **scattered** radiation before it reaches the detector.
- Conventional grids are made of **thin parallel lead strips**
  - Allows the **primary radiation** parallel to the lamellae to **pass** between the lamellae.
  - The **scattered radiation**, whose direction of propagation is mostly not parallel to the lamellae, is **largely stopped** by the lamellae.

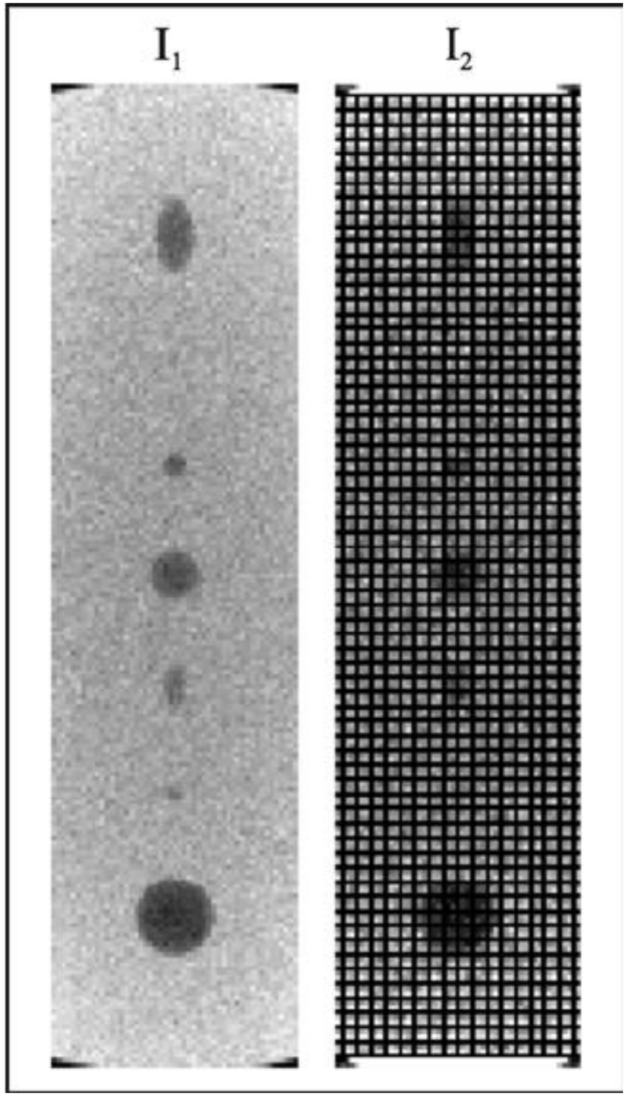


Anti-scatter grid (Limitation)

- To avoid that the **anti-scatter grid** be **visible** on images, the grid **oscillates during exposure**



without grid **with grid**



Dose-contrast relationship

The absorbed dose is directly correlated to the attenuation

Low energy

- More dose to the patient
  - because the beam is much attenuated
- Better differentiation of tissues
  - because photoelectric effect is favored

High energy

- Less dose to the patient
  - because crossing the patient is easier
- Less absorption difference between tissues

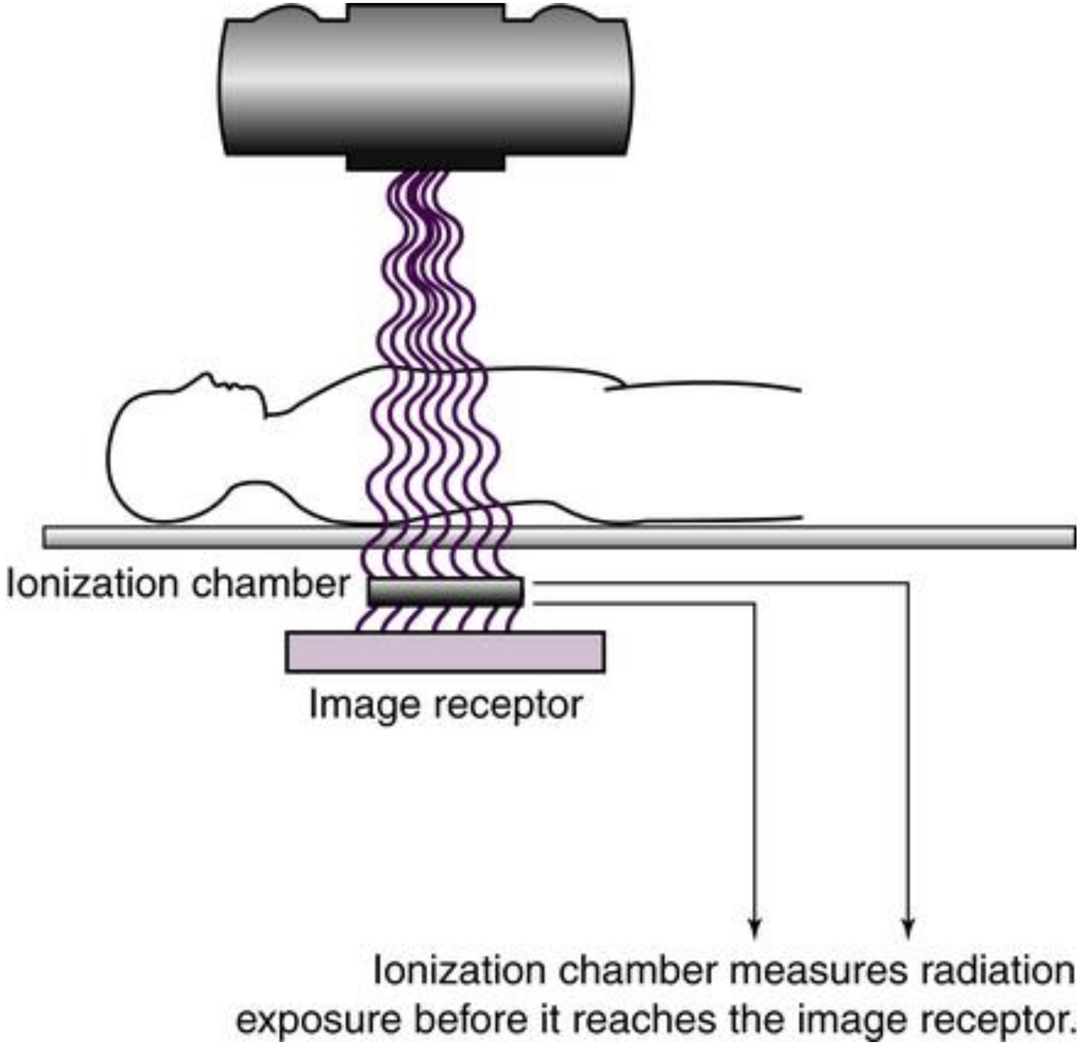
Automatic exposure control (AEC)

Optimal choice of technical parameters

- ✓kV, mA
- ✓to **optimize patient dose** and **image quality**

Radiation detector behind (or in front of) the image detector

Exposure is terminated when the required dose has been integrated



Exposure Technique Selection | Radiology Key

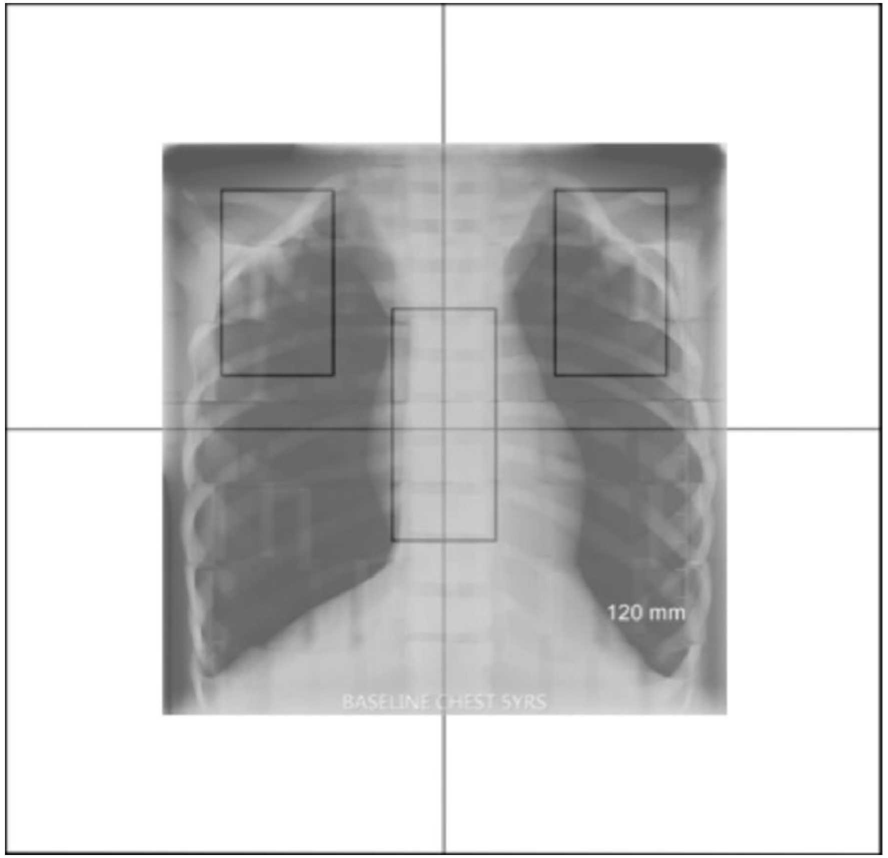
Automatic exposure control (AEC)

- In **Automatic Exposure Control** (AEC) mode, the current and the exposure time are chosen **automatically** by the system.
- X-ray installations are equipped with a **detector dose measurement** system (**cell**) to **stop irradiation** as soon as a sufficient dose has reached the detector.
- The choice of the **position of the cell** is therefore **critical** for the dose delivered to the patient.

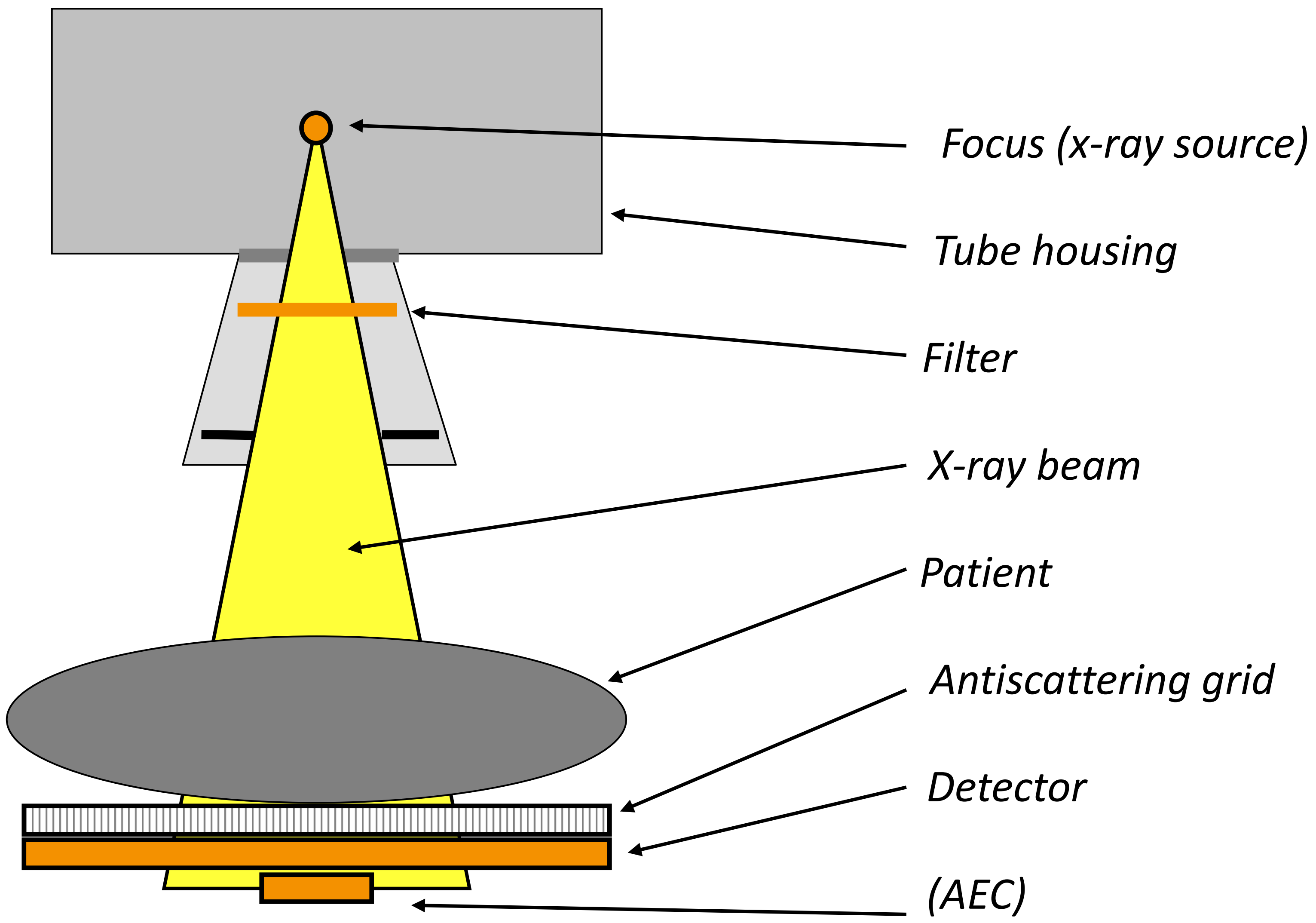
Automatic exposure control (AEC)

- Most installations are equipped with 3 cells: **one central and two lateral**.

If a cell covers an area of very absorbent tissue (bone tissue for example), it will receive little radiation and will prolong the exposure time (high dose). The situation is reversed if the cell is behind a more radio-transparent tissue.



Summary


Focus (x-ray source)
Tube housing
Filter
X-ray beam
Patient
Antiscattering grid
Detector
(AEC)