

X-ray



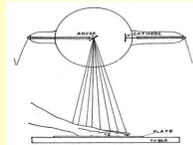
production and properties



Glass tube with two electrodes in vacuum or in low pressure gas

Experiments and observations of Wilhelm Conrad Roentgen

- cathode ray generates radiation in the wall of the tube
- the radiation induces fluorescence in barium platinocyanide
- it has much higher penetration than UV



This unknown radiation has high penetration distance

Roentgen's X-ray picture of the hand of his wife, taken December 22, 1895.



Age of Wilhelm Conrad Roentgen *1895 – the year*

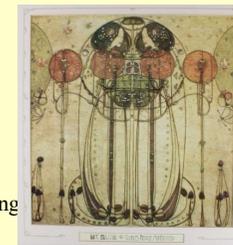
Roentgen discovers X-ray

On November 27, 1895, in Paris, Alfred Bernhard Nobel signed his will.

The cinématographe (Auguste and Louis Lumière) was patented on 13 February 1895

U.S. patent for an automobile by George B. Selden

Jungle Book was written by Rudyard Kipling

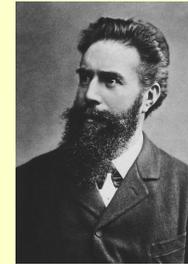
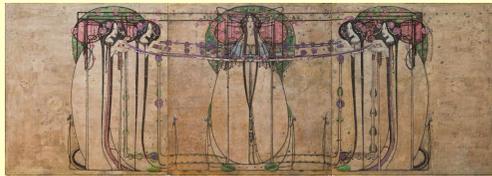


Discoveries of „Golden Years” in physics

1896: Becquerel – radioactivity

1897: Thomson – electron

1898: Pierre és Marie Curie – polonium and radium



X-ray

Discovery – November 1895

Publication – December 1895

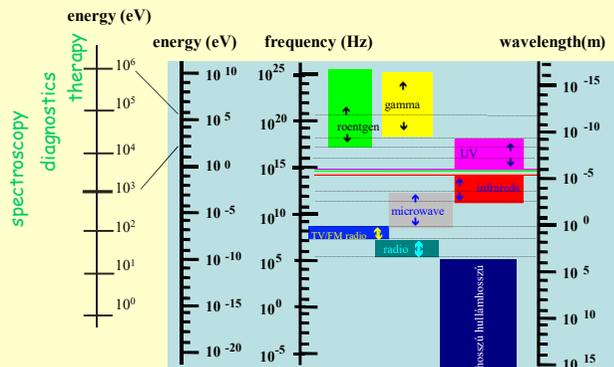
Medical application – January 1896

Wilhelm Conrad Roentgen

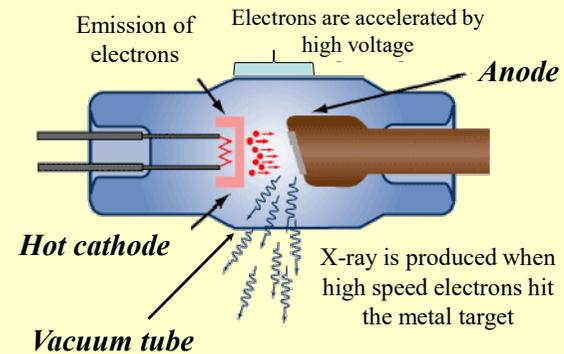
Nobel Prize in Physics 1901
in recognition the discovery of the remarkable rays subsequently named after him

X-ray

Elektromagnetic radiation

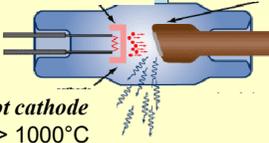


X-ray tube



Steps of producing X-ray

Emission of electrons



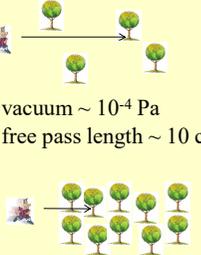
Hot cathode
 $T > 1000^\circ\text{C}$

Current density $\sim T^2$

$$I_{anod} = \frac{Q}{t} = \frac{n * e}{t}$$

$P_{electric} = UI$

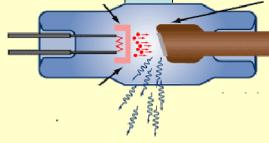
vacuum $\sim 10^{-4}$ Pa
 free pass length ~ 10 cm



In the air, under atmospheric pressure
 free pass length ~ 70 nm

Steps of producing X-ray

Acceleration of electrons



Pl. $U = 60$ kV
 $m_e = 9,1 \cdot 10^{-31}$ kg
 $e = 1,6 \cdot 10^{-19}$ C

Work of electric field

$$eU = \frac{1}{2} m_e v^2$$

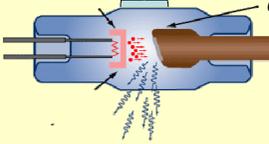
$$W = \Sigma F \Delta s = Q \Sigma E \Delta s$$

$$W = QU$$

$$W = \frac{1}{2} m_e v^2$$

$v = \sqrt{\frac{2eU}{m_e}} = 1,5 * 10^8 [\frac{m}{s}]$

Steps of producing X-ray



anode

Anode **material**: - high atomic number (e.g. ^{29}Cu , ^{42}Mo , ^{74}W)
 - high melting poin

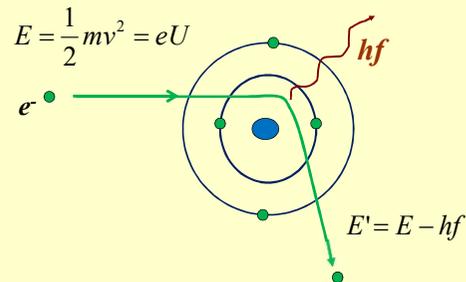
Anode **position**: - standing – lower possible power (few W/ mm²)
 It is enough in dentistry
 - rotating – heat distribution is better, higher possible power (10000 W/ mm²)

Steps of X-ray production

- Generation of charged particles
 $e, H^+, \text{light ions}$
- Acceleration
 $X\text{-ray tube, accelerators}$
- Deceleration
 $^{29}\text{Cu}, ^{42}\text{Mo}, ^{74}\text{W}, ^{78}\text{Pt}$

Mechanism of X-ray production

1. Bremsstrahlung or "braking radiation"



The electron is deflected from its original path and decelerated.

The electron's kinetic energy is reduced

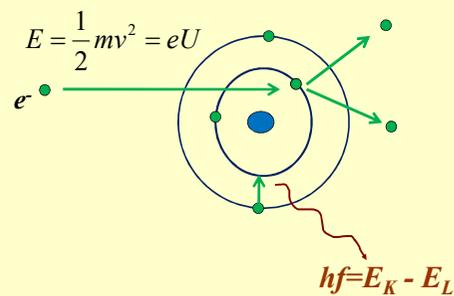
The energy lost by the electron takes the form of a Bremsstrahlung photon.

The photon energy depends on

- the kinetic energy of incoming electron
- distance of closest approach to the nucleus
- atomic number of target material

Highest photon energy is equal to the kinetic energy of incoming electron.

2. Characteristic radiation

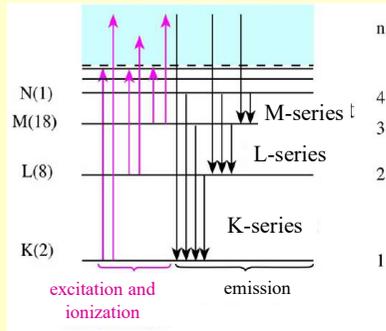


If the incident electron energy is high enough, it may interact with an (inner) orbital electron, ejecting it from its orbit (excitation/ionization).

The vacancy is occupied by an electron from a higher orbit

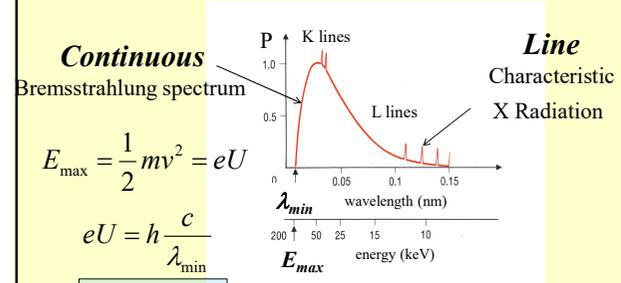
The discrete excess energy is emitted as a characteristic photon

Possible energy transitions of the Cu-atom with 29 electrons



Photon energies varies with the energy differences between neighbouring electronic states.

Spectral properties of X-ray

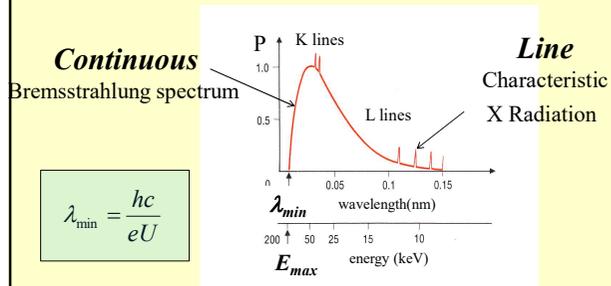


$$E_{\max} = \frac{1}{2}mv^2 = eU$$

$$eU = h \frac{c}{\lambda_{\min}}$$

$$\lambda_{\min} = \frac{hc}{eU}$$

Spectral properties of X-ray



$$\lambda_{\min} = \frac{hc}{eU}$$

Duane-Hunt law

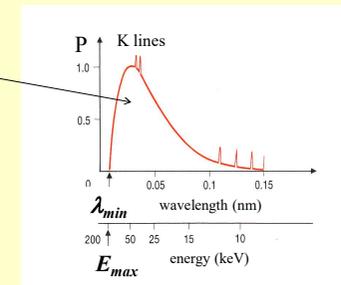
Power and efficiency of X-ray tube

$$P = cIU^2Z$$

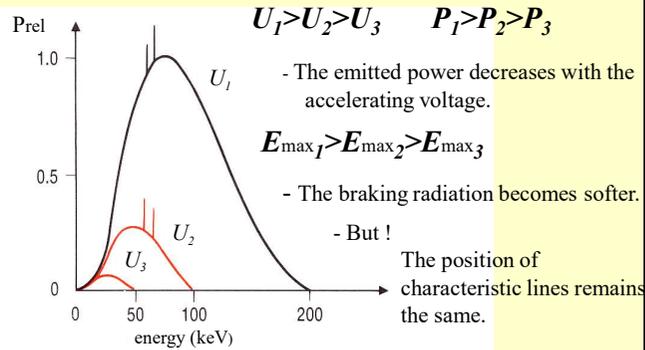
$$c = 1.1 \times 10^{-9} [1/V]$$

$$\eta = \frac{P_{\text{X-ray}}}{P_{\text{input}}} = cUZ$$

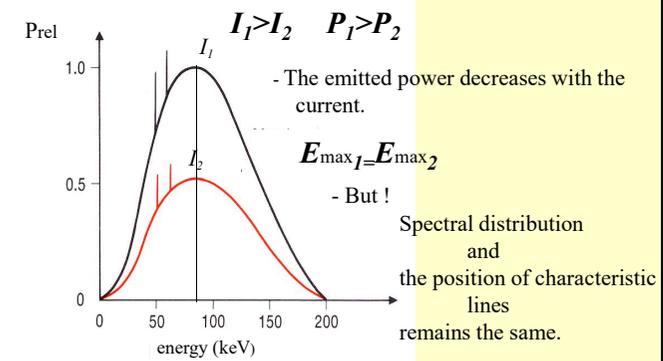
$$\eta < 1\%$$



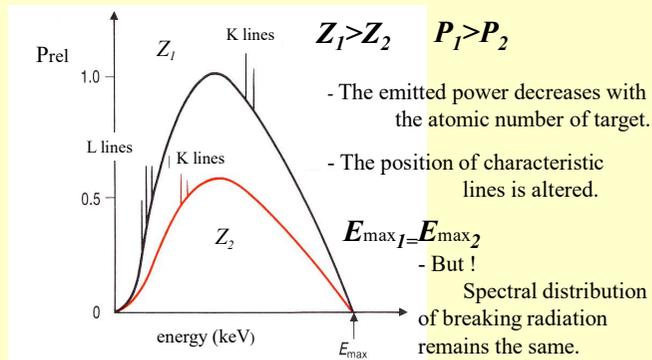
Decrease of accelerating voltage :



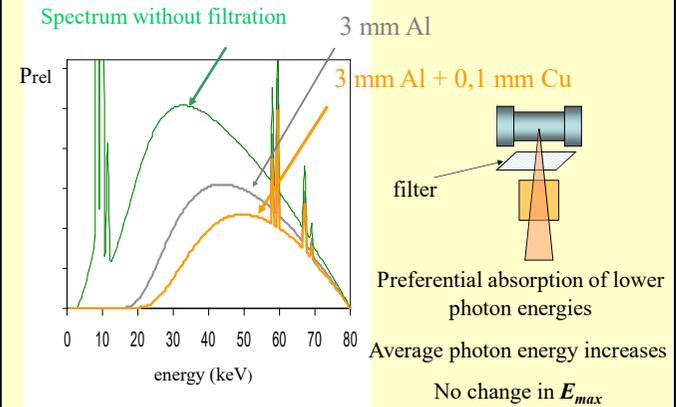
Decrease of current:



Effect of target (anode) material



Application of radiation filters



Application of radiation filters

Modification of the properties (spectrum, special distribution) of radiation

Inherent filter elements. e.g., anode material, wall of the tube, diaphragm etc.
External filters, typically Al or Cu plates.

Disadvantage: reduces the intensity
increases the exposition time

Advantage: reduces – approximately 80% – the exposure of the patient

Typical conditions for diagnostic X-ray production

Accelerating voltage: 25 – 200 kV

Current: 1 – 1000 mA

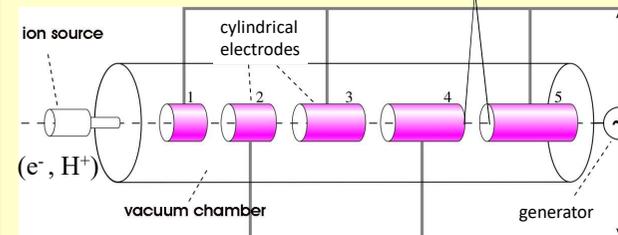
Anode material: W, in mammography Mo

Special conditions

Particle accelerators

Linear Accelerator

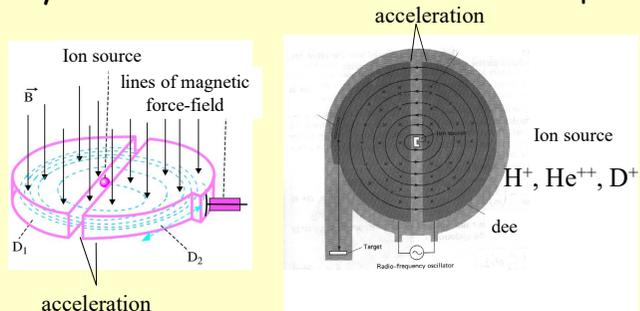
The particles are accelerated when passing through the gaps.



Linear accelerator (LINAC) is used in **Radiotherapy**



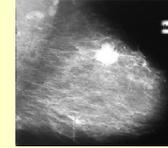
Cyklotron – acceleration on a circular path



Magnetic field (Lorenz-force) → circular path
 Electric field → acceleration; increased radius of circle

Medical applications of X-rays

X-ray diagnostics



Radiotherapy



Fertilization



Interaction of X-ray with matter

Law of radiation attenuation

$$J = J_0 e^{-\mu x}$$

μ (linear attenuation (absorption) coefficient) depends on
 photon energy
 quality (atomic number) of absorber
 density of absorber

$$\mu_m = \frac{\mu}{\rho}$$

BUT! Ratio of μ and the density is constant

μ_m [cm²/g] : mass attenuation coefficient

**Varies with – the photon energy
 – atomic number of absorber**

Law of radiation attenuation

$$J = J_0 e^{-\mu_m x_m}$$

x_m [g/cm²] : surface density

$$x_m = \rho x$$

$$\mu = \frac{0.693}{D}$$

and

$$D_m = \rho D$$

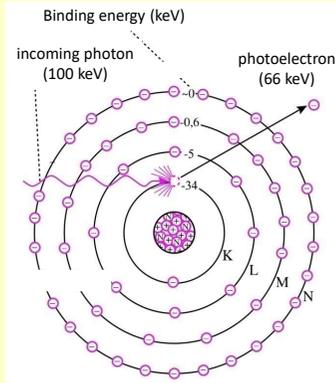
$$\mu_m = \frac{0.693}{D_m}$$

Mechanism of interaction (1)

Photoeffect

energy ballance:

$$hf = E_{\text{binding}} + \frac{1}{2} m_e v^2$$

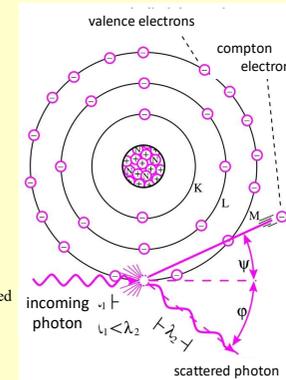


Mechanism of interaction (2)

Compton scatter

energy ballance:

$$hf = E_{\text{binding}} + \frac{1}{2} m_e v^2 + hf'_{\text{scattered}}$$



Mechanism of interaction (3)

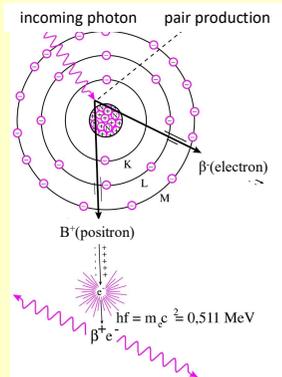
Pair production

energy ballance:

$$hf = 2m_e c^2 + 2 \frac{1}{2} m_e v^2$$

$$hf \geq 2m_e c^2$$

$$hf \geq 1.02 \text{ MeV}$$



Probability of interaction (absolute and relative) depends on

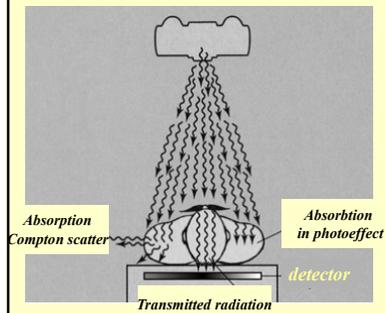
- the photon energy
- atomic number of absorber

$$\mu = \tau + \sigma + \kappa$$

photoeffect
Compton scatter
Pair production

$$\mu_m = \tau_m + \sigma_m + \kappa_m$$

Basic principle of X-ray diagnostic is the absorption of radiation



Possible interactions:

Compton scatter

photoeffect

no interaction

Checklist

Structure of X-ray tube

Parameters of X-ray tube

Mechanism of generation of Bremsstrahlung and characterization of its spectrum

Interpretation of λ_{\min}

Mechanism of generation of characteristic radiation and characterization of its spectrum

Parameters influencing the spectra of X-ray

Benefits of the application of outer filters

Damjanovich, Fidy, Szöllösi: Medical Biophysics

II. 3.1

3.1.1

3.1.2

3.1.3

3.1.4

3.1.5

3.1.6