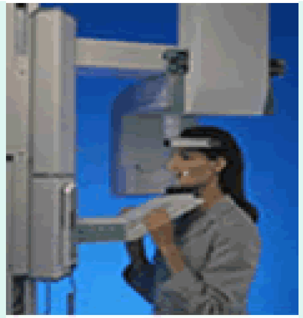
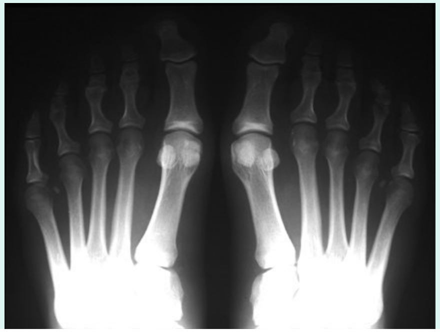
March 1, 2012
Prof. Judit Fidy

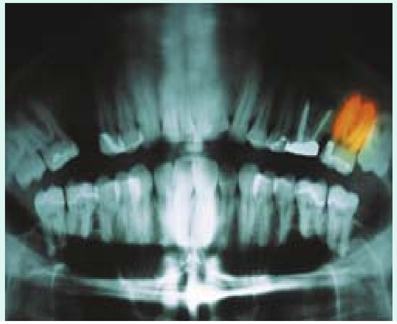
X - rays

Medical X-Ray



Dental X-Ray





The „Golden Years" of physics

1895: X-radiation – Röntgen
1896: radioactivity – Becquerel
1897: electron – J. J. Thomson
1898: Radium – Pierre and Mme Curie

Wilhelm Conrad Roentgen

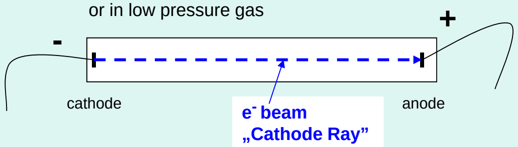
Discovery in November -> publication in December ->
***-> 1896 January:* Medical applications**
Hungary: Device for Medical diagnostics is constructed at the Technical University (Budapest) in 1896

Roentgen's X-ray picture of the hand of his wife, taken 23 January 1896.

Basic experimental device: Cathode Ray Tube – CRT

- discovery of X-rays
- discovery of the electron

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

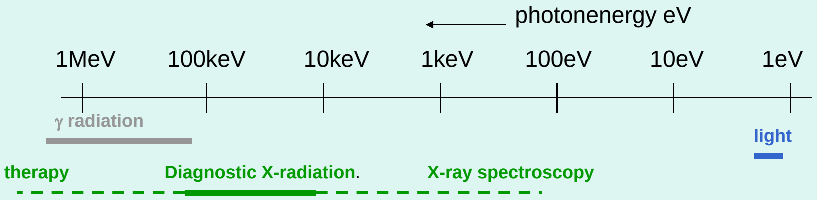


Electrons emitted by the cathode due to field emission, and accelerated by the positive potential of the anode.

Later: cathodes were heated by an electric circuit to emit more electrons

Roentgen's observations

- cathode ray generates radiation in the wall of the tube
- the radiation is similar to UV light – induces fluorescence
- but is of much higher penetration
- is not reflected and refracted like light



X-radiation: *electromagnetic radiation of high photonenergy as compared to light*

reminder

Electromagnetic radiations

Photon-concept in material interactions
The interacting partner of the photon is the electron
The photonenergy is generally expressed in eV units

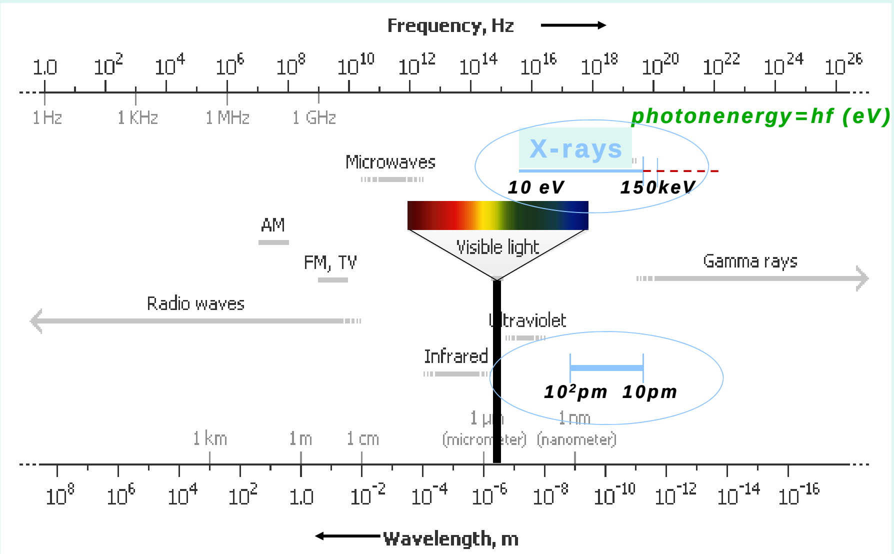
$$E_{photon} = hf$$

1 eV = 1.6 x 10^{-19} Joule

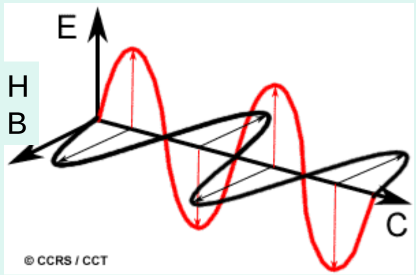
Light – X-rays electromagnetic waves

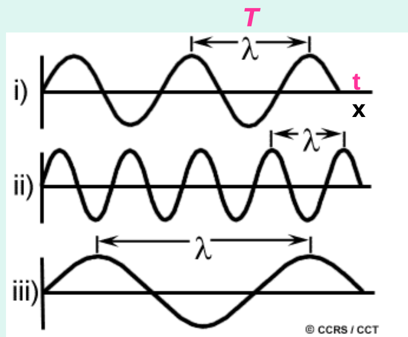
Log scale

$$10^{-9} m = 1\, nanometer$$



EM waves





c = λ / T , f = 1/T, c = f λ(m/s)

c = 299,792,458 m/s vacuum

$$c = \frac{E}{B}$$

reminder

Electromagnetic radiations

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Electromagnetic radiations

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Vis light ~ 1.5 - -3 eV

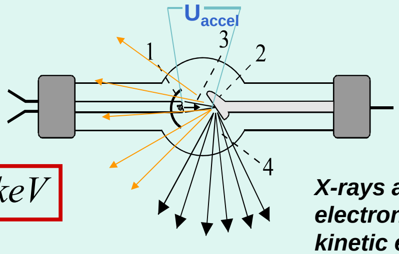
„ionizing" and „non-ionizing" radiations

Visible light :
photons when absorbed cause
electronic excitation

X-rays:
photons when absorbed cause
electronic ionization

X-ray Tube: X-ray source for Medical Diagnostics

a special case of the CRT



1. Heated cathode
2. Anode
3. Electron beam
4. X-radiation

$$20keV \le hf \le 150keV$$

X-rays are produced when electrons of high enough kinetic energy hit the anode of high atomic number

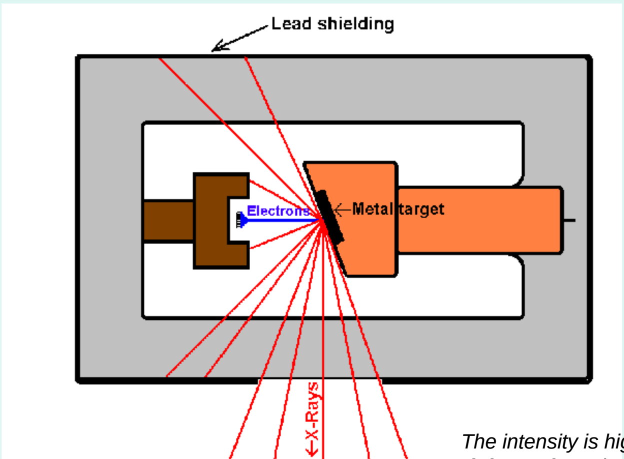
The efficiency of the X-ray production is very low.

$$\eta = \frac{P_{Xrays}}{P_{electric}} < 1\%$$

How they really look like → rotating anode → cooled housing

Most of the electric power is turned into heat!

Another schematics of the X-ray tube



*The intensity is highest at **right angle** to the e^- beam*

Steps of producing X-rays

construction of a source of charged particles

(e^-, H^+, D^+, light ions)

acceleration

on linear path → X-ray tube – medium speed

→ linear accelerator – high speed

(on circular path (cyclotron))

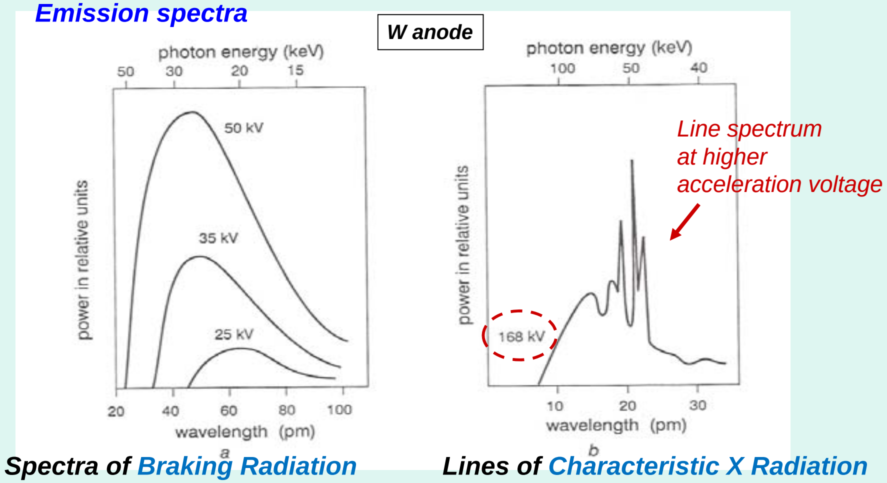
deceleration

usual target metal: ^{29}Cu, ^{42}Mo, ^{74}W, ^{78}Pt

The radiation emitted by the X-ray Tube

Emission spectra

W anode



Spectra of Braking Radiation (Bremsstrahlung) **Lines of Characteristic X Radiation**

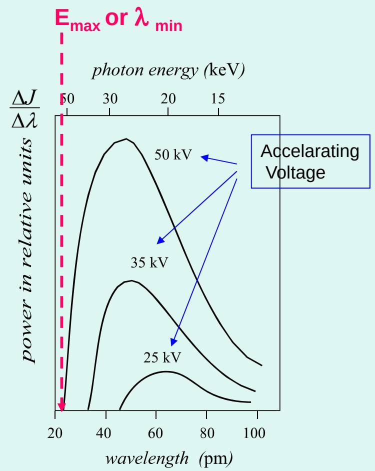
Two different mechanisms to produce X-rays

Braking Radiation - Bremsstrahlung

Spectral properties

Tungsten (W) anode,

Emission spectra taken at a variety of accelerating voltages →



1. *Photonenergies are continuously represented in the spectra below a photonenergy maximum.*
2. *The emitted power grows with the accelerating voltage*

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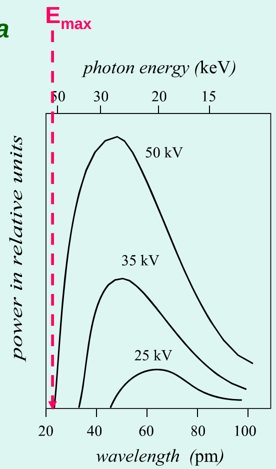
1. ***Photonenergies are continuously represented in the spectra below a photonenergy maximum.***

The photonenergy has an upper limit

The photonenergy is determined by the kinetic energy loss of one electron in one step of deceleration. Great varieties in the steps of deceleration -> continuous spectrum

$$q_e * U = \tfrac{1}{2} m_e v^2 = h * f_{\max}$$



Photonenergy maximum ⟷ total loss of kinetic energy in one step of deceleration

---

1. ***Photonenergies are continuously represented in the spectra below a photonenergy maximum.***

The photonenergy has an upper limit
The wavelength range is limited from below

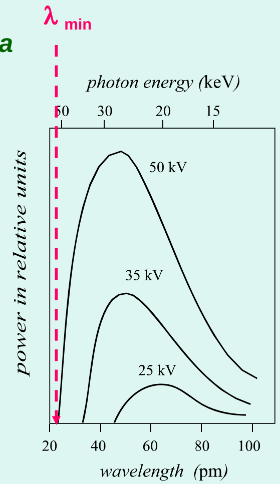
speed of light

$$hf_{\max} = h\frac{c}{\lambda_{\min}} = q_{electron} U_{accel}$$

Planck's constant

$$\lambda_{\min} = \frac{hc}{q_e}\frac{1}{U_a}$$

Duane-Hunt law



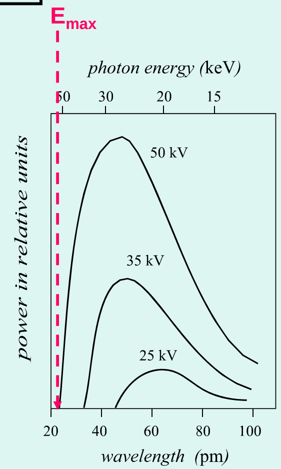
The power of Bremsstrahlung

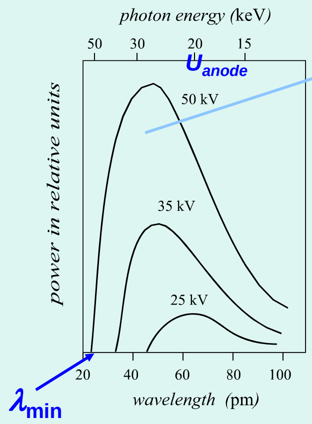
The total power of the radiation
- all photonenergies –
„area below the curve"

$$P = const_{Xray} \cdot U_{anode}^{2} \cdot Z_{anode} \cdot I_e$$

empirical constant

$$c \approx 1.1 \cdot 10^{-9} V^{-1}$$





$$P = const_{Xray} \cdot U_{anode}^{2} \cdot Z_{anode} \cdot I_e$$

How do U and I influence the Radiation?

$$P \approx U^2$$

$$P \approx I$$

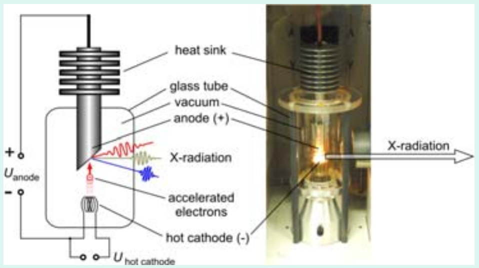
$$\lambda_{\min} \approx \frac{h \cdot c}{q_e} \cdot \frac{1}{U}$$

Warning: increasing the Voltage changes the spectrum towards higher photonenergies.

$$P \approx U^2$$

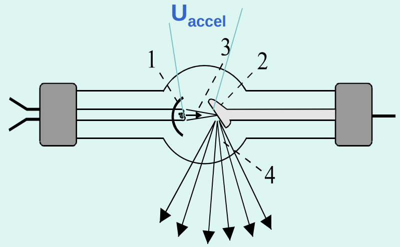
$$P \approx I$$

$$\lambda_{\min} \approx \frac{h \cdot c}{q_e} \cdot \frac{1}{U}$$



Places of adjusting the emitted power
~ intensity of radiation → contrast

The radiation yield of the X-ray Tube



$$efficiency\,(\eta) = \frac{useful\ output}{total\ input}$$

100 kV

$\sim 10^{-9}$

$Z_W = 74$

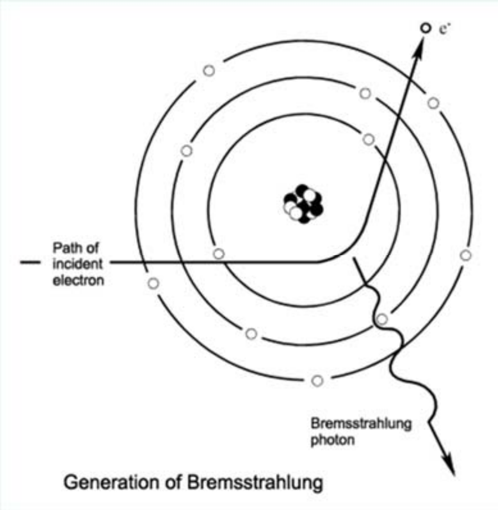
$$\eta = \frac{P_{radiation}}{P_{electric}} = \frac{const_{Xray} U^2 I Z}{U\ I} = c_{Xray} U\ Z$$

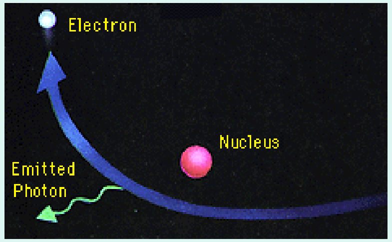
$$\eta \approx 0.008$$

The radiation yield is very low < 1%

Great heat loss!

The mechanism of producing Bremsstrahlung



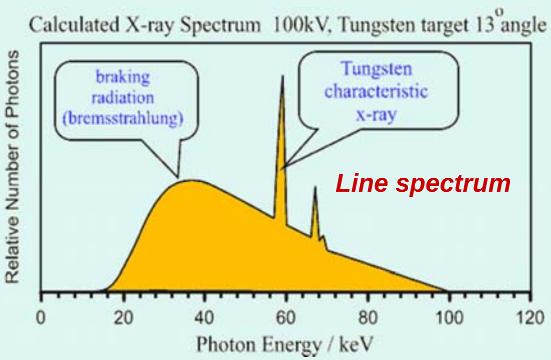


The spectrum and power of Bremsstrahlung is the basis of diagnostic applications of X rays

Characteristic X-radiation

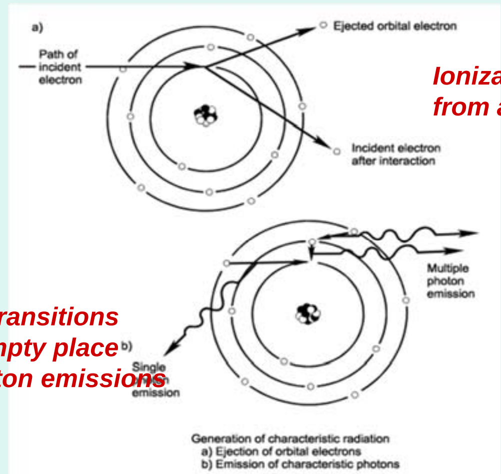
Spectral properties

„line" spectrum superimposed on the spectrum of Bremsstrahlung at higher accelerating Voltages



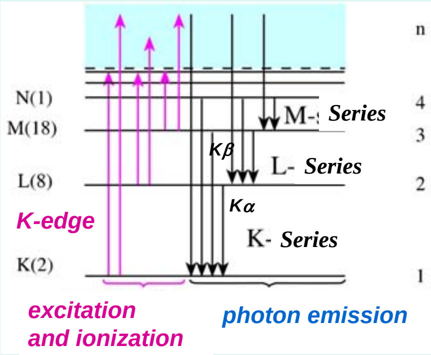
The mechanism of Characteristic X-radiation

Ionization of electron from an inner orbital



Electronic transitions to fill the empty place lead to photon emissions

Electronic orbitals of the ***Cu*** atom with 29 electrons



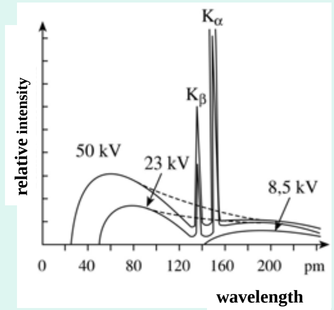
$\Delta E = hf \approx VIS\ photon$

$\Delta E = hf \approx 10^4 * VIS\ photon$

In the case of high Z (many electrons) the energy difference between inner orbitals is much larger than that of external orbitals

Characteristic lines in the X-ray emission spectrum of Cu

~ 8 keV



Ionization energies from the K level: „K-edge”

Al(13)	1.6 keV
Fe(26)	7.1 keV
Cu(29)	9.0 keV
Zn(30)	9.7 keV

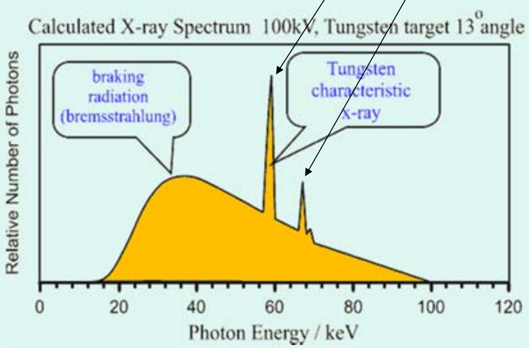
atomic number

The energy differences between inner shells grow with the number of electrons in the atom

The energy (wavelength) of the emission lines in the spectrum of characteristic X-radiation does not depend on the voltage, only on the electronic orbitals of the anode

Lines in the spectrum of Characteristic X-radiation

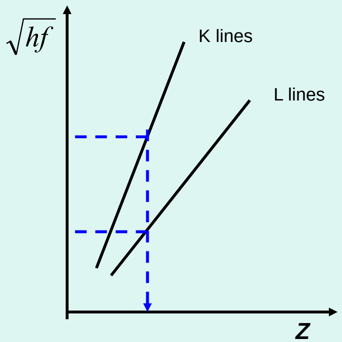
transitions terminating in the K shell give rise to the K-lines, those terminating in the L shell produce the L - lines, and so on.



Practical applications of Characteristic X-radiation

1. Chemical analysis

- from minute amounts
- sample plays the role of an anode

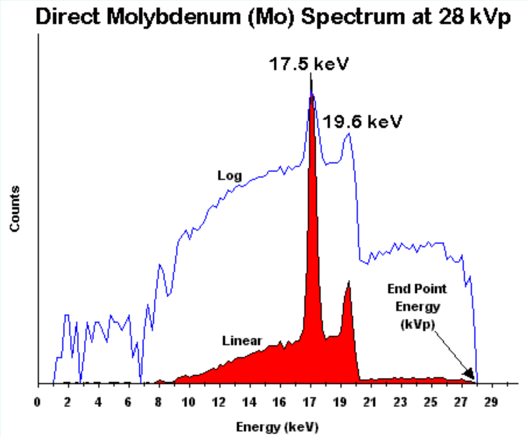


qualitative analysis:

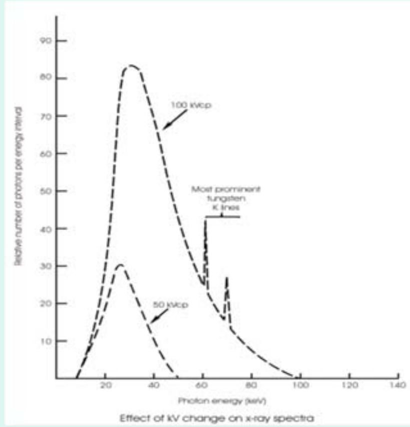
photon energies of spectral lines define the atomic number of the sample

Analysis in criminology

2. Characteristic X-ray emission of a Mo anode is used in Mammography



3. Characteristic lines do not contribute significantly to the total intensity of X radiation – in common diagnostic applications they are neglected.



Diagnostic applications of X-rays – braking radiation

The applications are based on the absorption phenomena

The exponential absorption law is valid for X-rays $J = J_0 e^{-\mu x} = J_0 e^{-\mu_m \rho x}$

Density

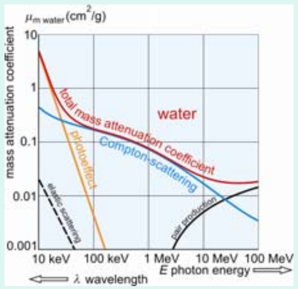
Absorption coefficient

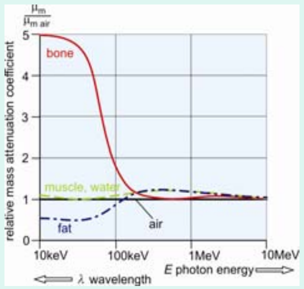
Mass-attenuation coefficient

Quality parameter

Material of absorber

Photonenergy of the radiation

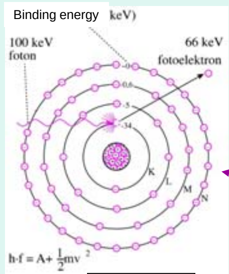




diagnostics ← → therapy

The applications are based on the absorption phenomena
Absorption of photon energies leads to ionization.

Ionization mechanisms (< 200 keV)



photoeffect

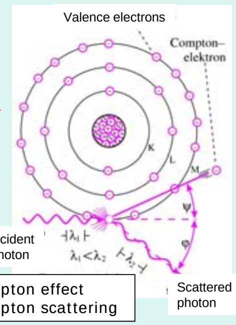
Absorption coefficient

Mass attenuation coefficient

$$J = J_o e^{-\mu x} = J_o e^{-\mu_m \rho x}$$

$$\mu = \mu_m \rho$$

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



Compton effect
Compton scattering

$$hf = A + \frac{1}{2}mv^2 + hf^*$$

Diagnostics is based on τ_m

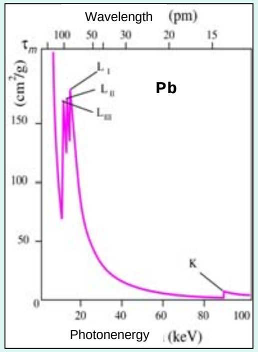
Dependence of the probability of X-ray absorption (τ_m) on the photonenergy (or λ)

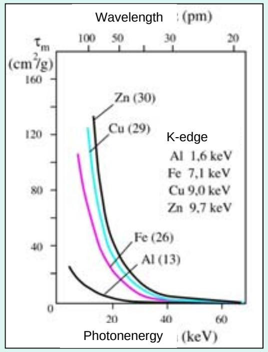
absorption spectra

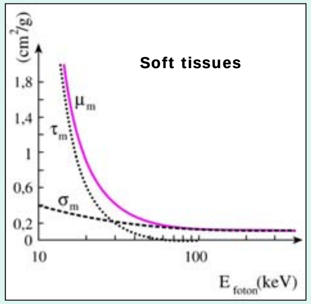
Mechanism of absoption	μ_m dependence on Z	μ_m dependence on E photon-energy
scattering	$\mu_m \sim Z^2$	$\mu_m \sim 1/E^2 \sim \lambda^2$
photoeffect	$\mu_m \sim Z^3$	$\mu_m \sim 1/E^3 \sim \lambda^3$
Compton scattering	Slight dependence	Slight decrease

Dominance in the effects

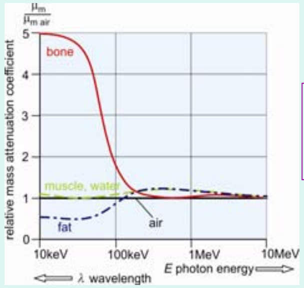
$$\mu_m(hf) \approx \tau_m(hf)$$







Aspects of X-ray -diagnostics – contrast enhancement

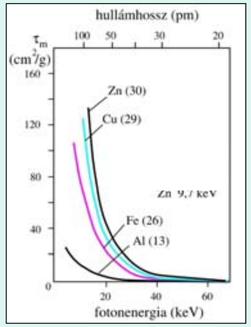


$$\tau_m = const * \lambda^3 Z^3$$

$$J = J_o e^{-\mu x} = J_o e^{-(\tau_m + \sigma_m) * \rho * x}$$

$$Z_{eff} = \sqrt[3]{\sum_{i=1}^{n} w_i Z_i^3}$$ | Molar ratio

medium	Z_{eff}	ρ (g/cm3)
air	7,3	$1{,}3 \cdot 10^{-3}$
water	7,7	1
Soft tissue	7,4	1
Bones	13,8	1,7-2



Contrast depends on

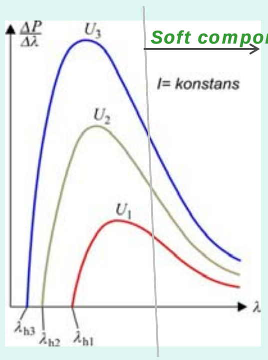
- ***Density-differences***
- ***-> negative contrast materials***
- ***Atomic number differences***
- ***-> pozitive contrast materials***

Example for using both positive and negative contrast materials

X-ray transmission image of the colon

„Windows" in visualization

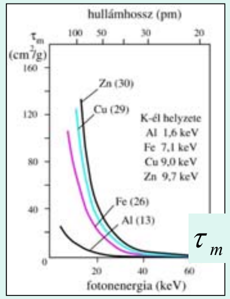
Aspects of X-ray -diagnostics – filtering for soft components



$$\tau_m \approx \lambda^3$$

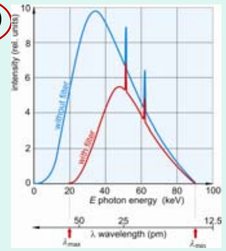
Enhanced absorption!

Filters :metals of medium Z to make use of the enhanced absortion for soft radiation components (long λ)



$$\tau_m \approx Z^3$$

Al(13)



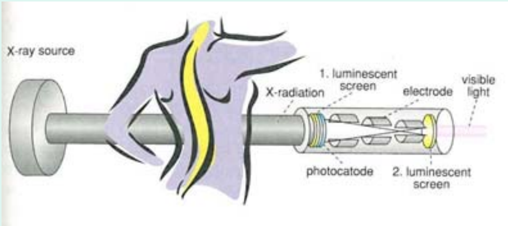
The emission spectra of Bremstrahlung is very broad in wavelength (or photonenergy).

Aspects of X-ray -diagnostics – decreasing radiation side-effects, digitalization

X-ray image amplifier

-transformation into optical image
-amplification → decreased X-ray dose
-loss of resolution

C-arm device with X-ray image amplifier



Laser scanner

Developing new luminescent materials

Aspects of X-ray -diagnostics – decreasing radiation side-effects, digitalization

Aspects of X-ray -diagnostics – significance of digitalization :DSA

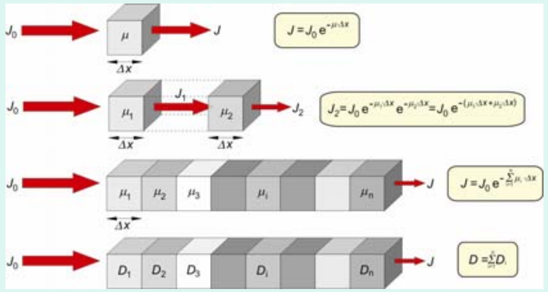
DSA: Digital Subtraction Angiography

Steps of measurement

1. *Transmission X-ray image → digitalization, data saved in computer*
2. *Injection of positive contrast material (patient is in fixed position)*
3. *Second X-ray image in the same position → digitalization, data saved in computer*
4. *Pixel-to-pixel subtraction → visualization of the difference*

Blood vessels of the abdomen visualized by iodine contrast

Aspects of X-ray -diagnostics – X-ray transmission leads to „summation" image



$$D = \lg \frac{J_0}{J}$$

Solution for depth resolution: **absorption is measured in cross sectional layers along with narrow beams of varying direction → each element is measured in many different combinations →**

X-ray- CT *(see also lab. practice)*

The lecture ended here

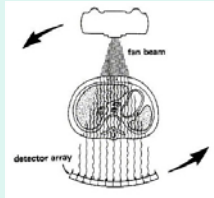
The additional slides may be useful for further studies

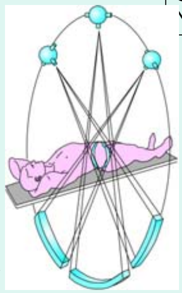
X-ray-CT

G.H.Hounsfield A.M.Cormack
Nobel price 1979

Data acquisition

-along with well defined narrow beams in one sectional plane





Radiation dose is high

~ 100 – 500 x normal

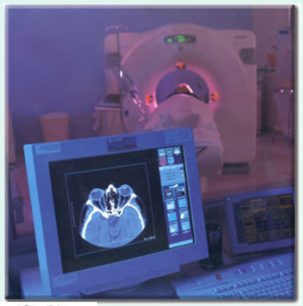
-all elements are measured at least along with two independent directions

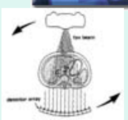
-evaluation: solving the summation equations = computation

→ μ_i of each element → pixels of visualization

X-ray-CT

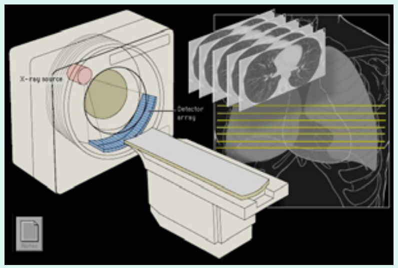
Sections perpendicular to the body axis are measured → μ-distributions





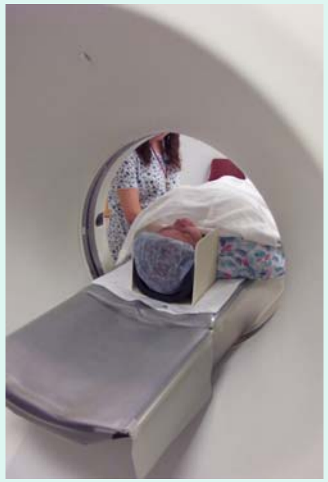
CAT-SCAN → 3D data set

Axial sections



X-ray-CT

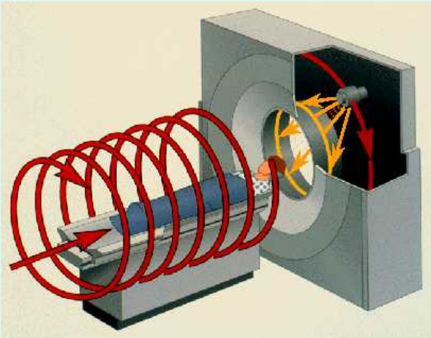
CAT-SCAN device



X-ray-CT

the latest development

SRIRAL-CT



X-ray-CT

Hounsfield-scale - windows

$$HU = \frac{\mu - \mu_{viz}}{\mu_{viz}} * 1000$$

Bones	100 -1000
Liver	65
Muscle	45
Kidney	30
Coagulated blood	80
Blood	55
Fat tissue	-65
Lungs	-500, -800

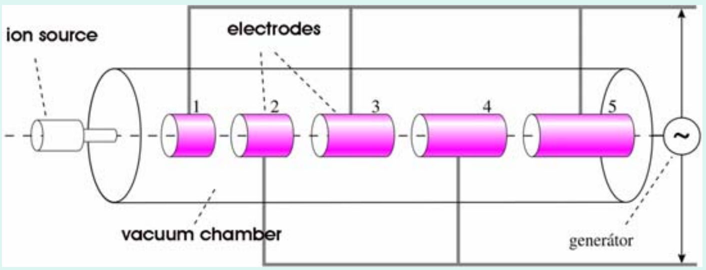
Defining windows for visualization eg. „soft tissue window”:

Selected region of HU is expanded over the full gray-scale of the display.

X-rays for therapy

$$hf_{\max} = \tfrac{1}{2} m_e v^2$$

High photonenergy can be achieved by producing electron beam of high kinetic energy -- out of the capacity of X-ray tubes



~1 MeV

Linear accelerator with cylindrical electrodes

The particles are accelerated when passing through the gaps.
By increasing the velocity the path length of the particles within one half period of the AC acceleration will be longer, as well as the length of electrodes.

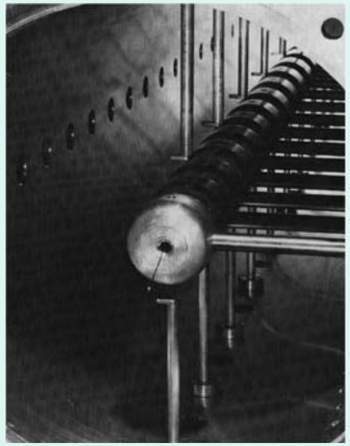
Particle accelerators

Linear Accelerator

electron
Proton
deuteron

Stanford ”2 miles” LINAC 20 GeV
upgraded to 50 GeV

for therapy ~ MeV)



Los Alamos proton LINAC 800 MeV

X-ray image of a car-driver

End of the lecture