ETH zürich University of Zurich UZH

Biomedical Imaging

X-Ray Imaging (I)

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Lecture notes

Handouts + Exercises

https://moodle-app2.let.ethz.ch/course/view.php?id=11546

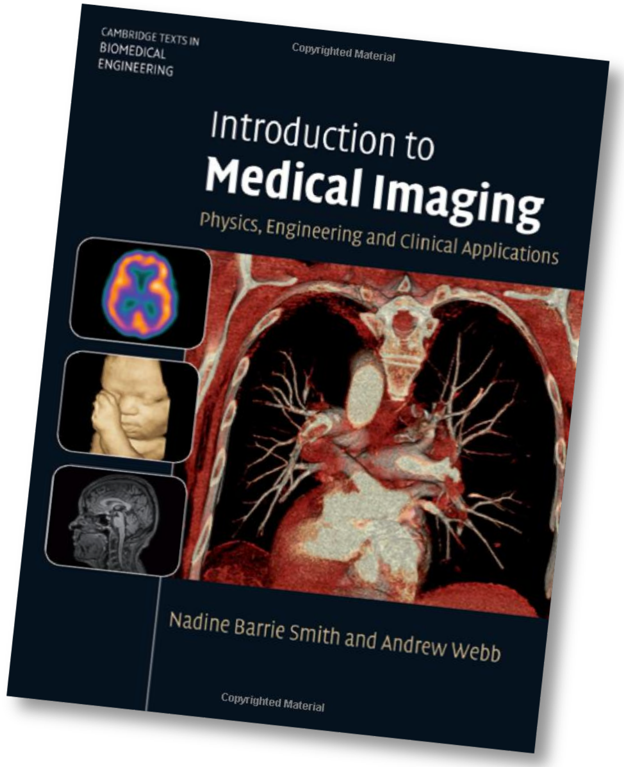
Book

Introduction to Medical Imaging

Cambridge University Press

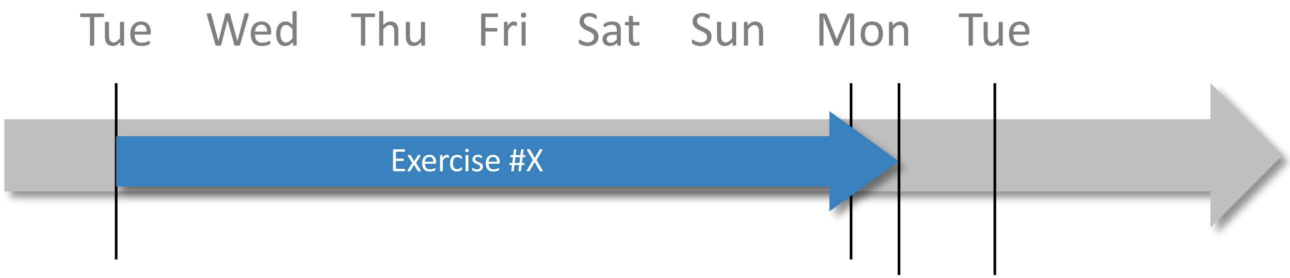
Nadine Barrie Smith, Andrew Webb

www.library.ethz.ch → online access



Exercises

- Matlab based (in groups of two); problem solving



13-15 HG E7 Lecture

15-16 HG E7 **Exercise (preparation)**

13-15 HG E19 **Computer room**

15-16 HG E7 **Exercise (solution, discussion)**

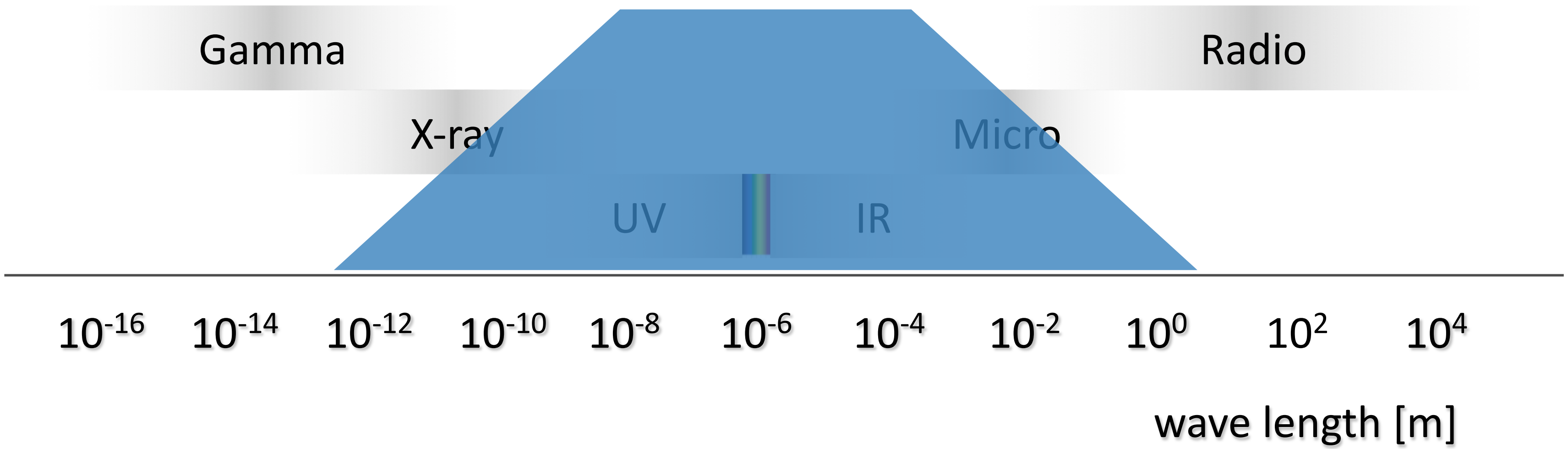
Mon <23:59 **Submit Solution in Moodle**

Today's Learning Objectives

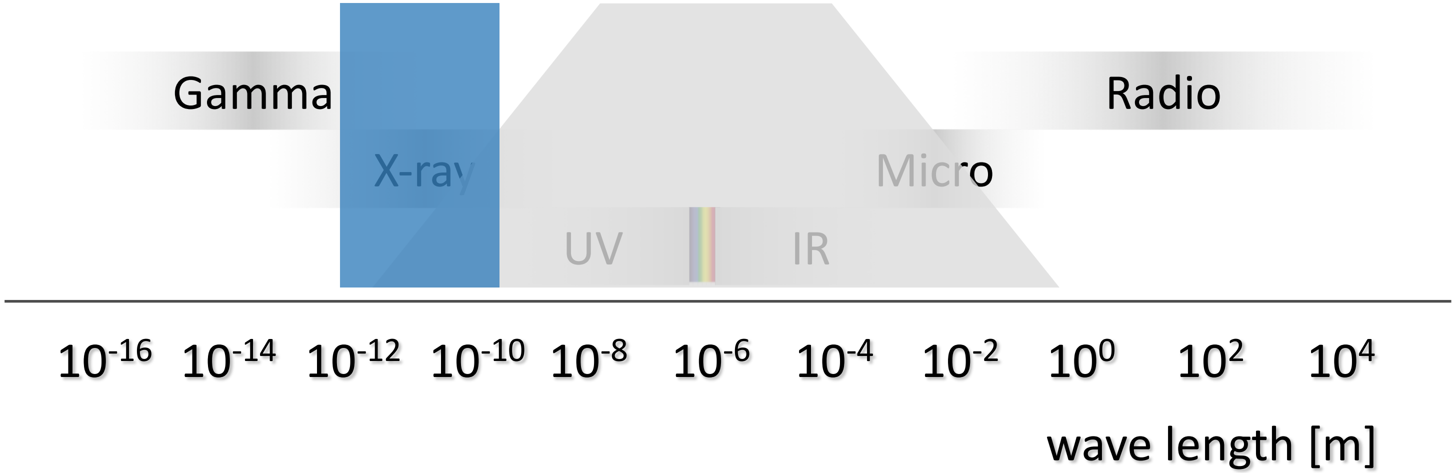
- **Describe mechanisms of X-ray generation and X-ray spectrum**
- **Relate interaction of X-rays in tissue to tissue properties**
- **Illustrate basic instrumentation for planar radiography**
- **Derive relation between modular transfer and spatial resolution**
- **Implement basic X-ray projection setup** (Exercise)

Medical imaging

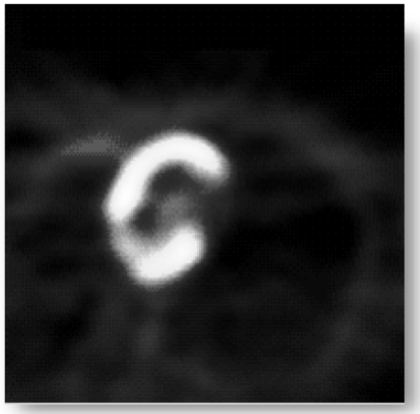
Electromagnetic spectrum and attenuation in the body



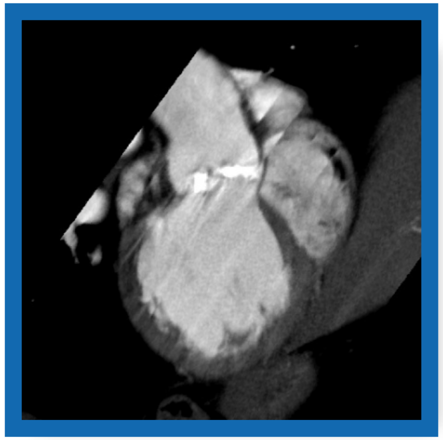
Medical imaging



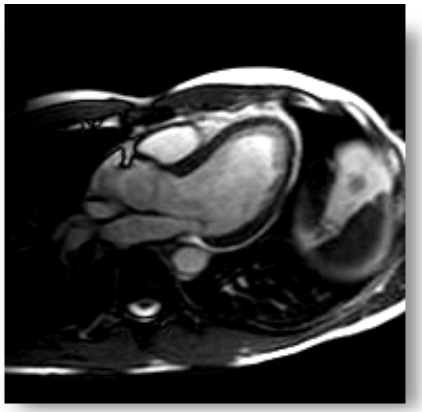
PET



X-ray, CT

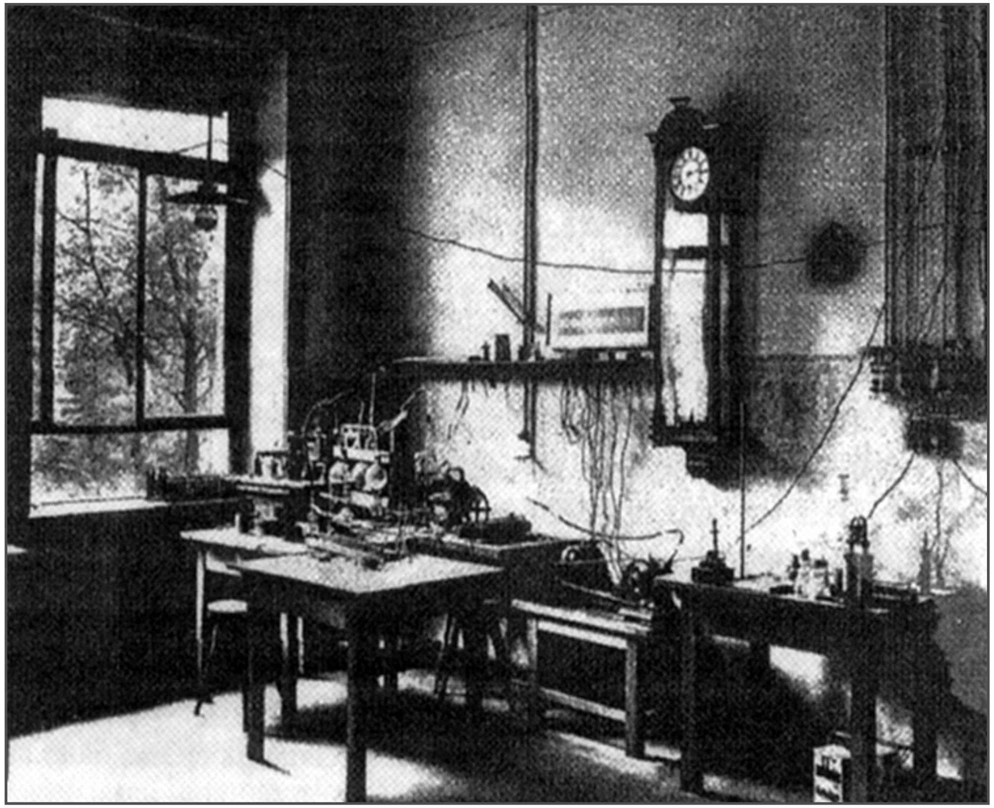


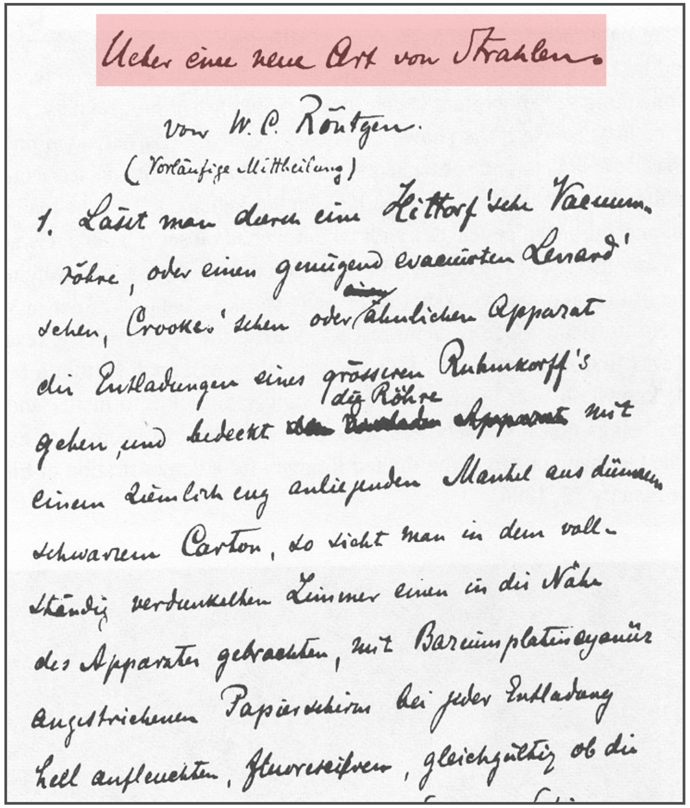
MRI



Wilhelm Conrad Röntgen, 1845-1923

Wilhelm Conrad Röntgen, 1845-1923





Ueber eine neue Art von Strahlen.

von W. C. Röntgen.

(Vorläufige Mittheilung)

1. Lässt man durch eine Hittorf'sche Vacuum-
röhre, oder einen genügend evacuirten Lenard'
schen, Crookes'schen oder einen ähnlichen Apparat
die Entladungen eines grösseren Ruhmkorff's
gehen, und bedeckt ~~den Entladungs Apparat~~ die Röhre mit
einem ziemlich eng anliegenden Mantel aus dünnem,
schwarzem Carton, so sieht man in dem voll-
ständig verdunkelten Zimmer einen in die Nähe
des Apparates gebrachten, mit Bariumplatincyanür
angestrichenen Papierschirm bei jeder Entladung
hell aufleuchten, fluoresciren, gleichgültig ob die

X-ray image (1895)

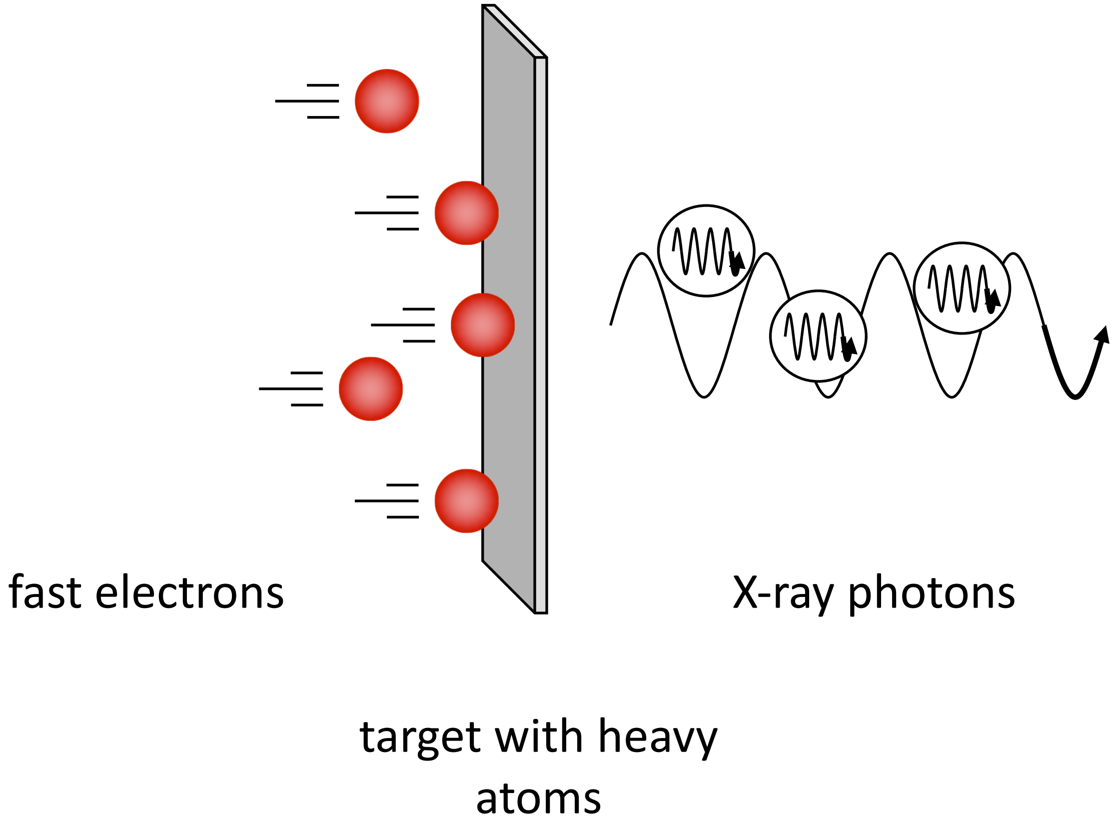
Original x-ray image made by W.C. Röntgen (hand of his wife)

X-rays in medical imaging

- Radiography
  - Thorax, bones etc.
- Computed Tomography (CT)
  - Bones and soft tissue
  - Angiography
- Angiography
  - Using contrast agent
  - Digital subtraction angiography (DSA)
- Fluoroscopy
  - Guidance of interventional procedures

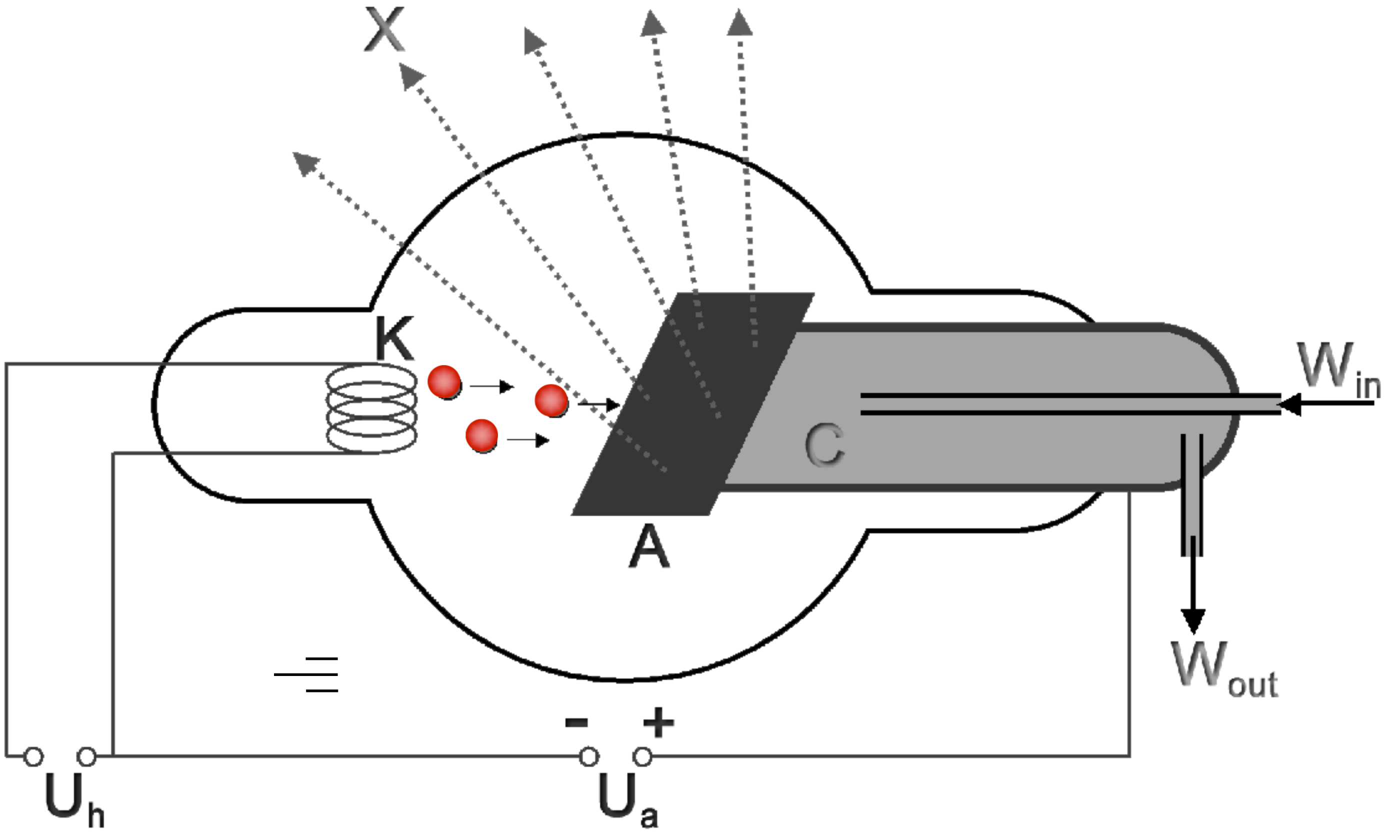
Generation of X-rays

Generation



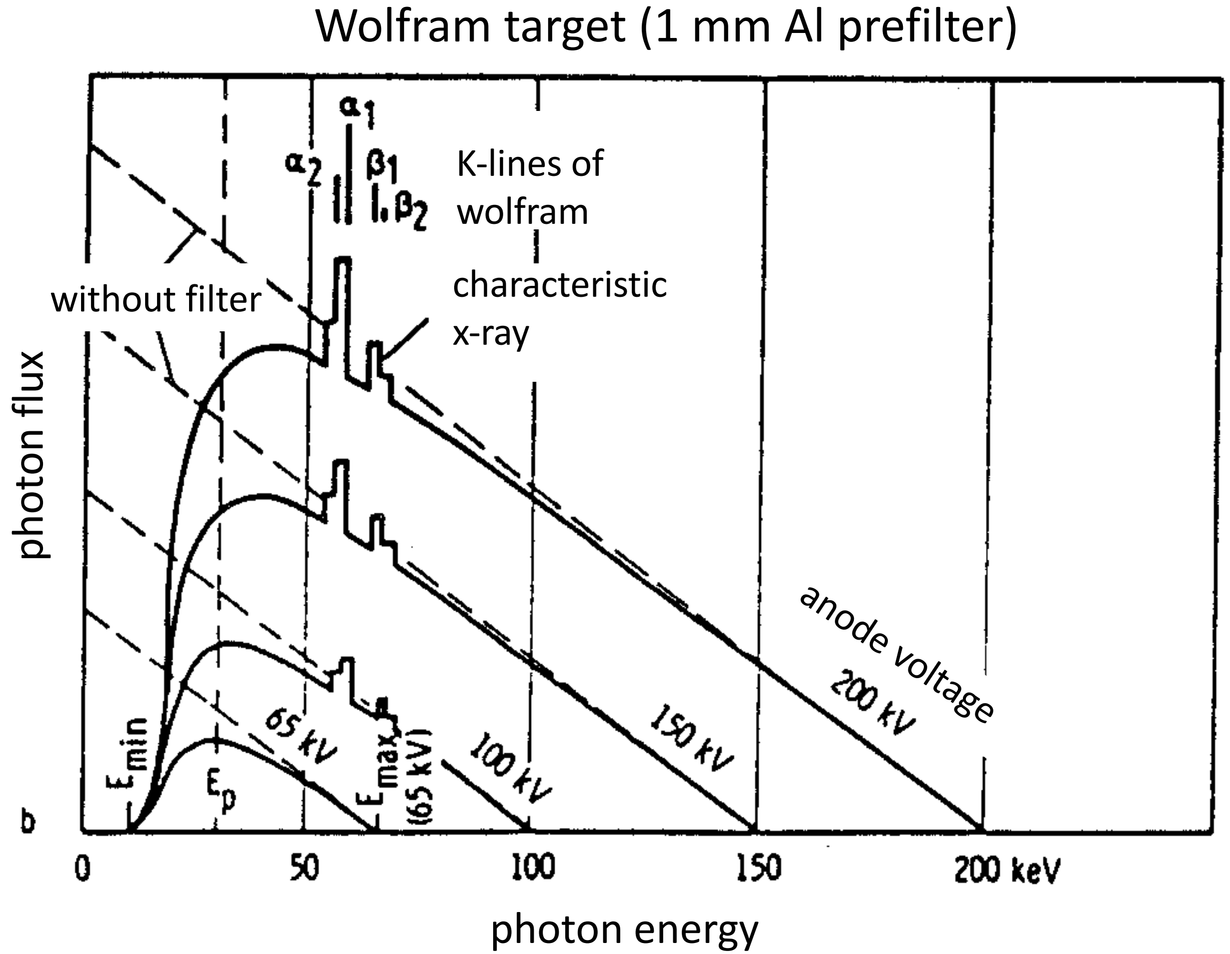
Electrons interact with inner e^- shells of target (X-rays are not radioactive!)

Generation – X-ray tube



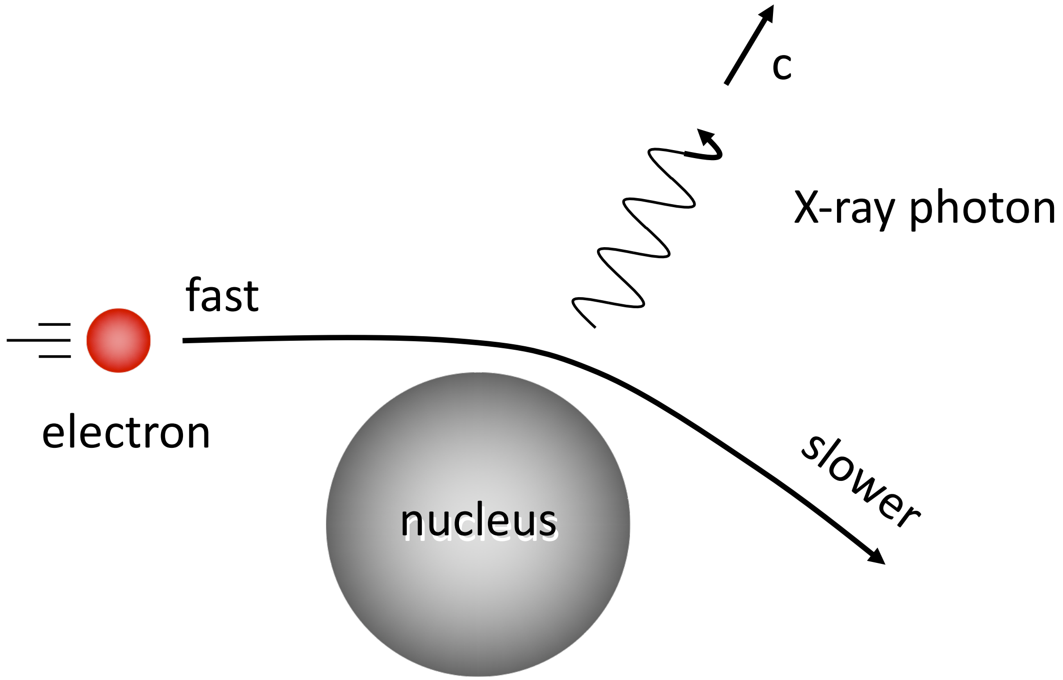
Acceleration of electron in vacuum tube (U_A = 30-200 kV, I_A = 50-100 mA)

Generation – Spectrum



- Bremsstrahlung ➔ continuous spectrum
- Characteristic radiation ➔ peaks/lines

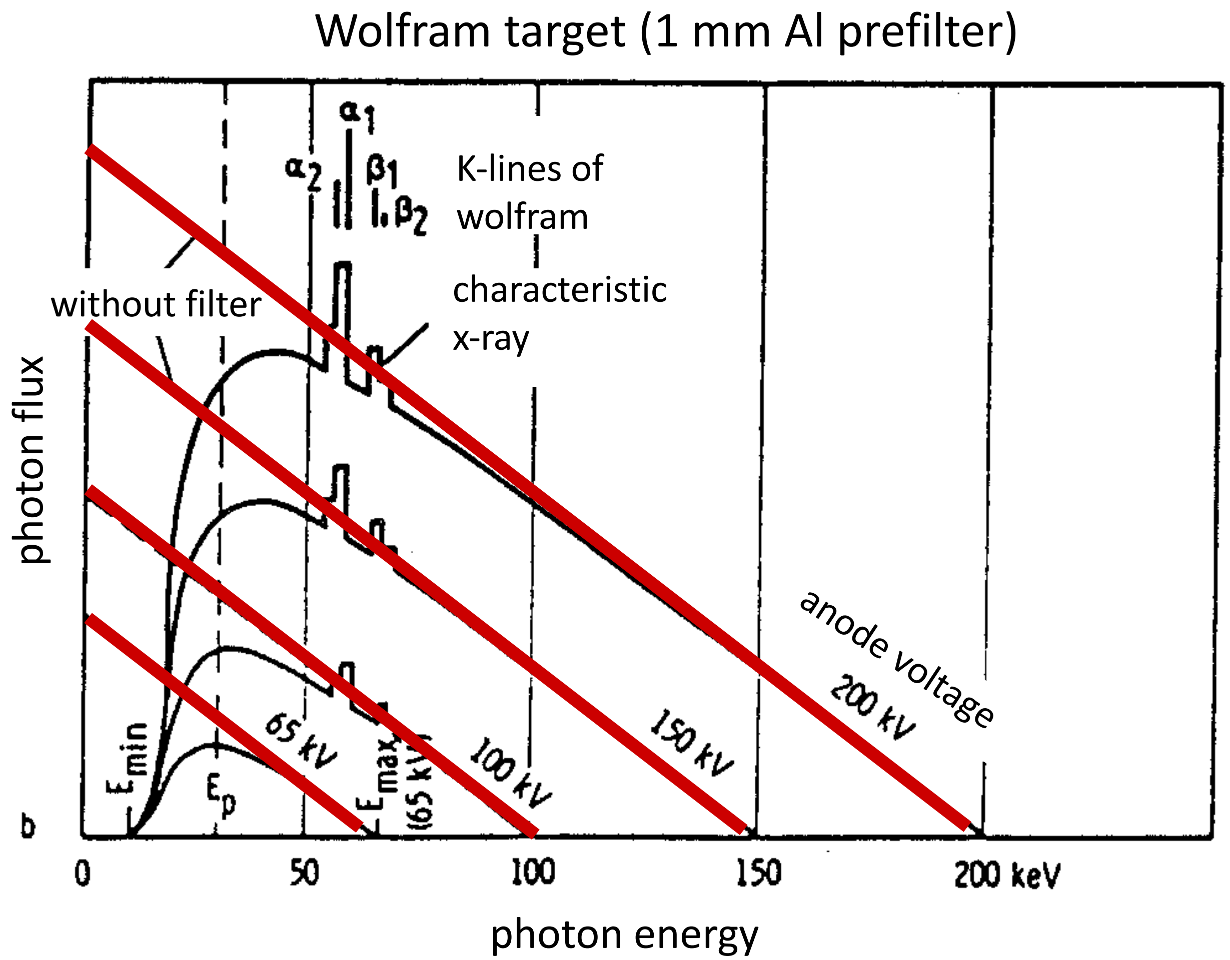
Generation – Bremsstrahlung



Fast-moving electron decelerates when it swings around a heavy nucleus:

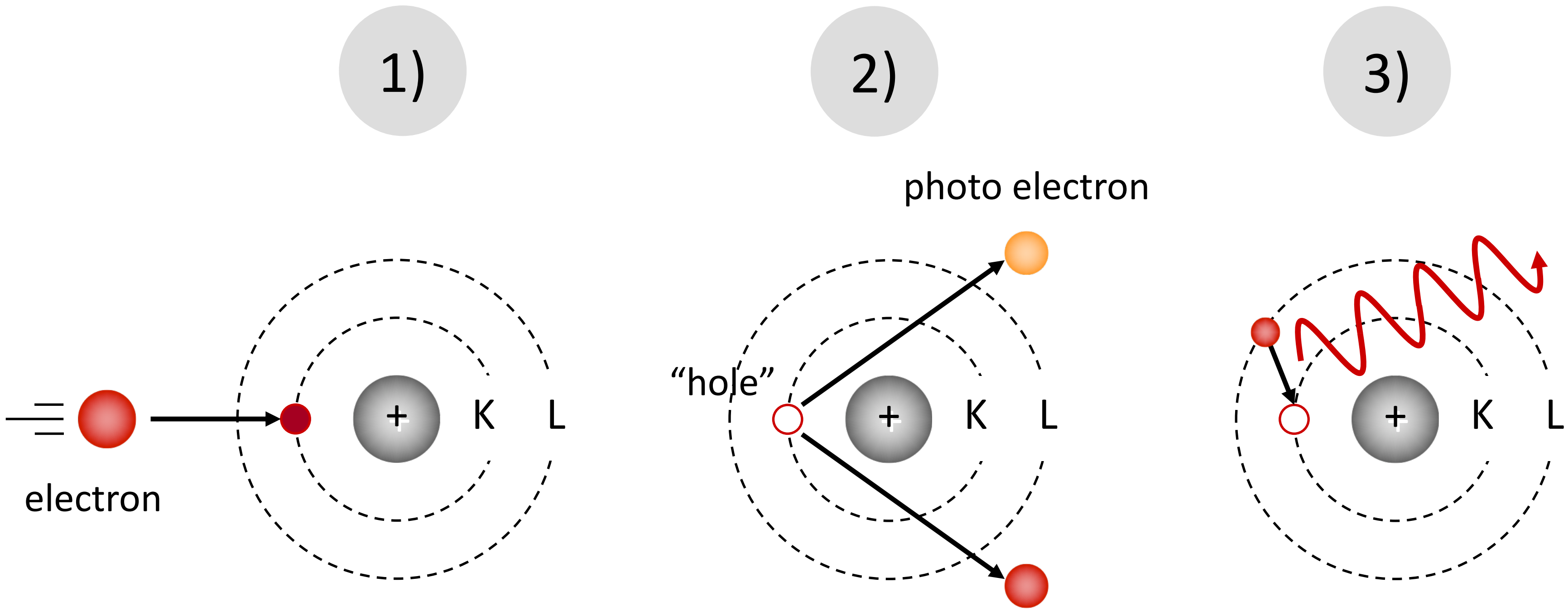
- electron interacts with electrons in outer shells
- energy depends on distance at which electron passes nuclei
- spectrum continuous 0 -> E_{max}
- interaction depends on Z value and E of electrons

Generation – Bremsstrahlung



- Bremsstrahlung ➔ continuous spectrum
- Characteristic radiation ➔ peaks/lines

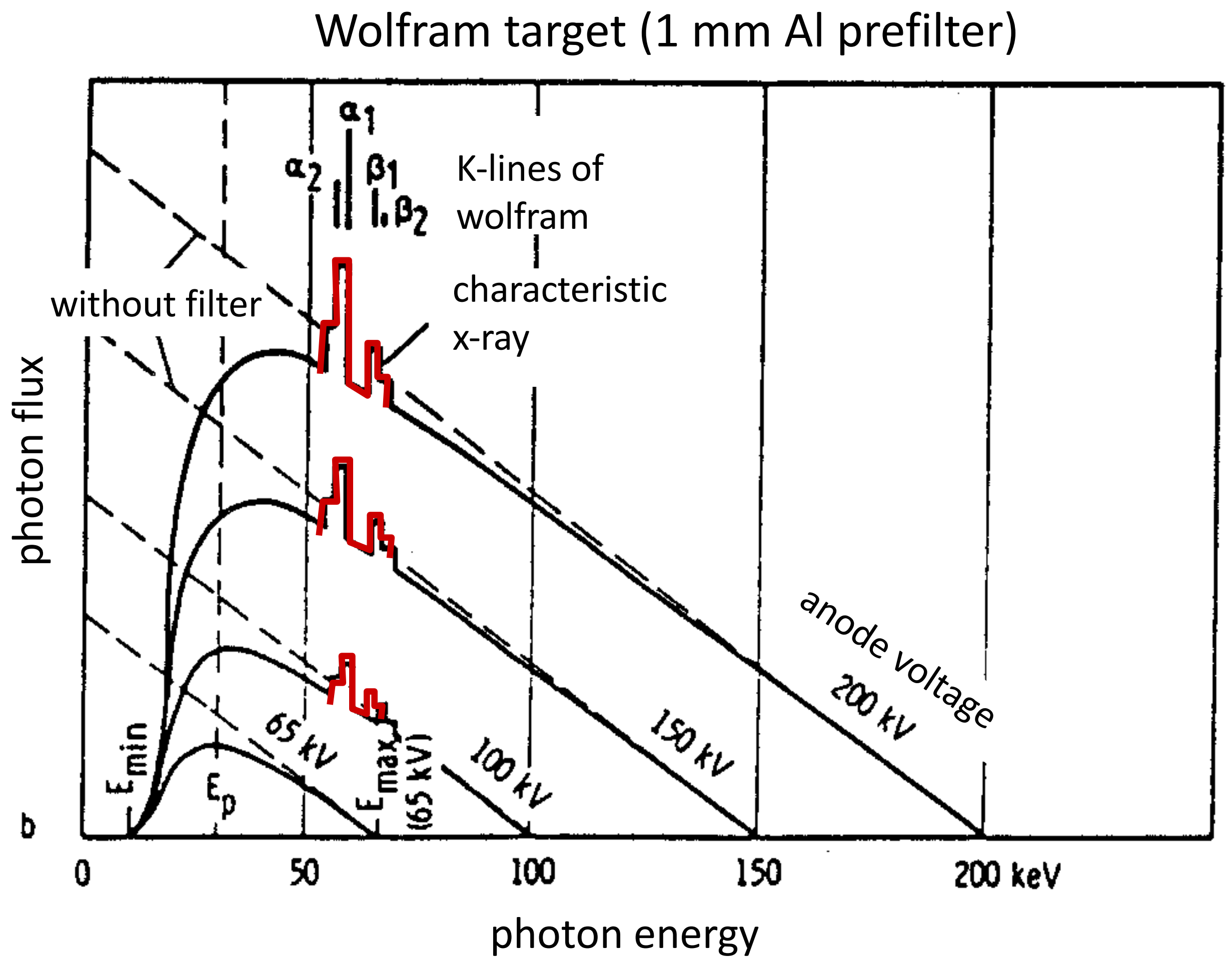
Generation – Characteristic radiation



Fast-moving electron interacts tightly with bound electrons in target:

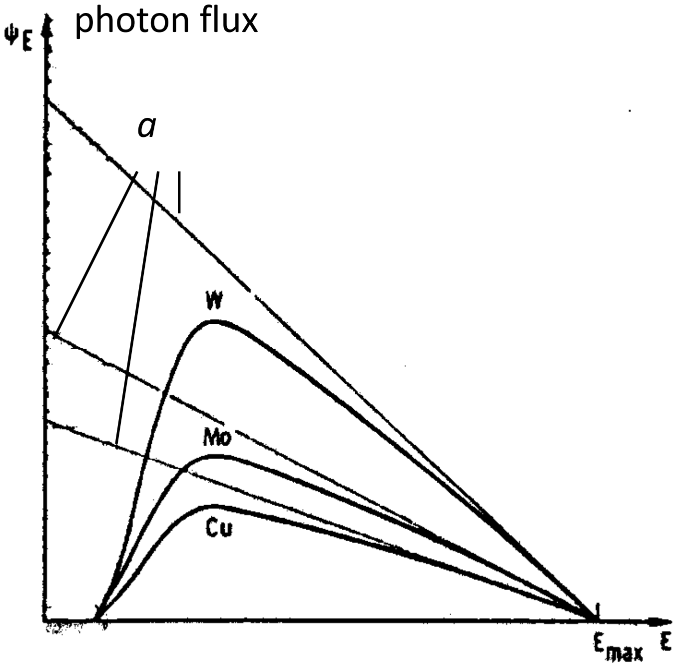
- K-shell electron is ejected
- Electron energy $E_{electron} > E_{binding, K}$
- Discrete energy of emitted radiation $E = E_{binding,K} - E_{binding,L}$

Generation – Characteristic radiation



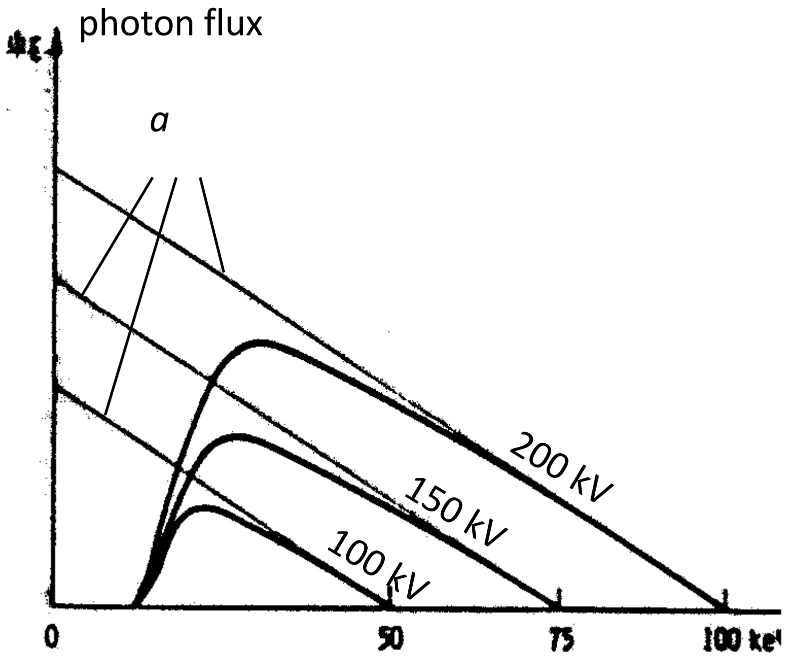
- Bremsstrahlung → continuous spectrum
- Characteristic radiation → peaks/lines

Generation – Materials and Electron energy



Energy spectrum (bremsstrahlung, photon flux as function of energy) in case of various target materials with pre-filter):

tungsten	Z = 74
molybdenum	Z = 42
copper	Z = 29



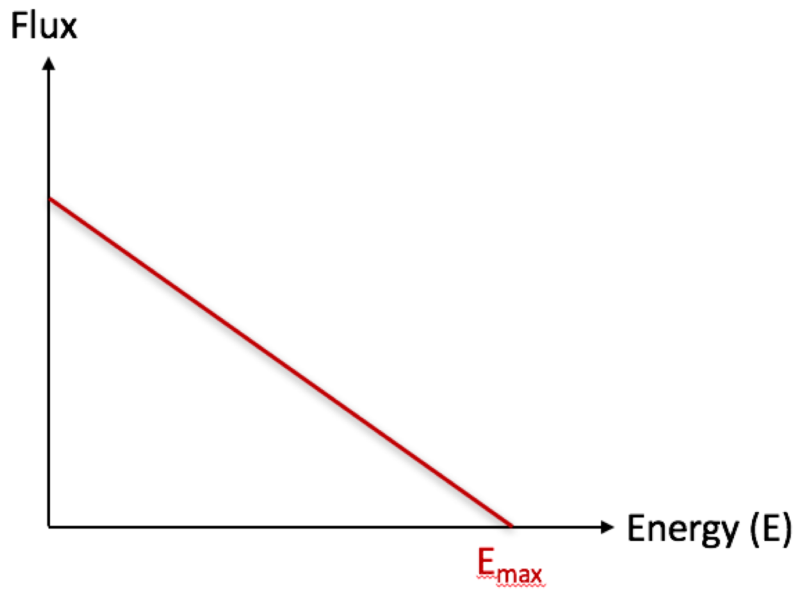
Energy spectrum (bremsstrahlung, photon flux as function of electron energy) for various accelerating fields:

a: Theoretical curve without prefilter and self-absorption

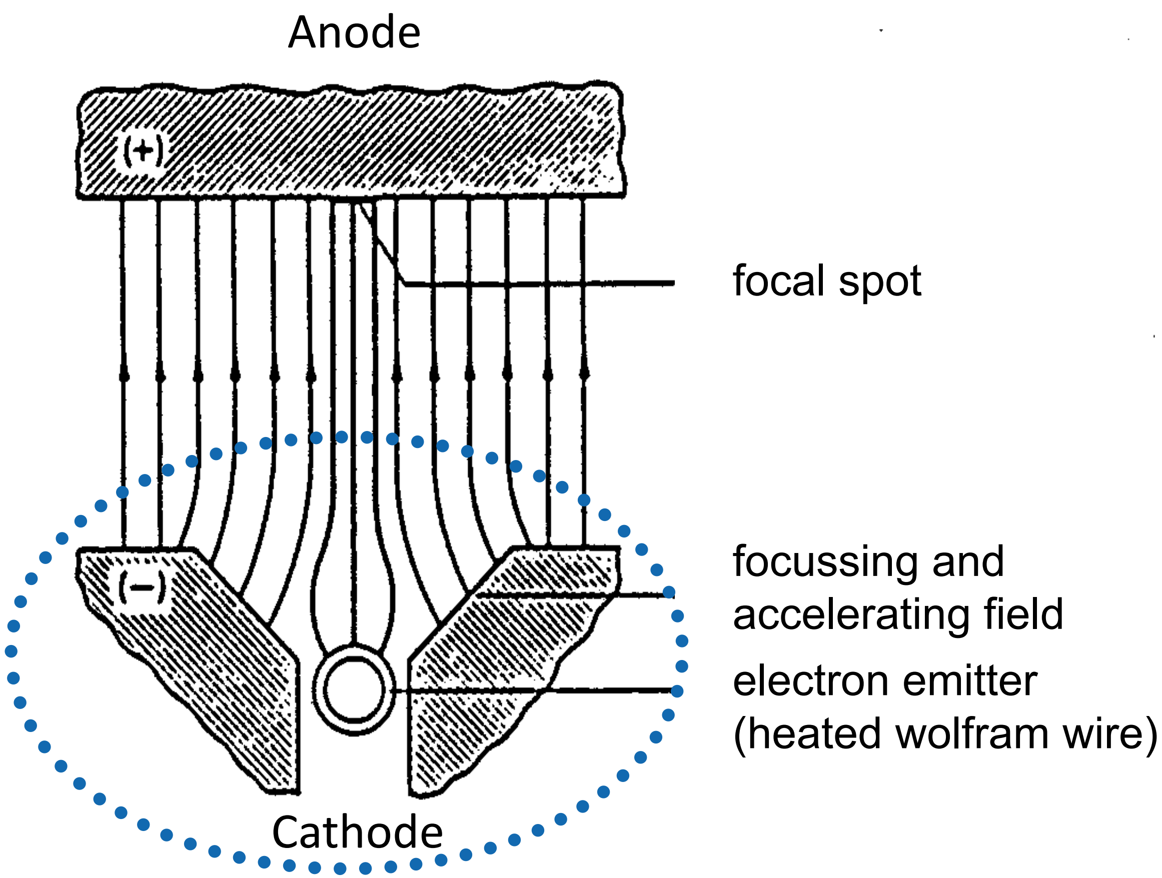
Clicker Activity (5 min)

Imagine the anode material is changed from a thick to a very thin structure (consisting of a single atomic layer) - how would the spectrum shown change?

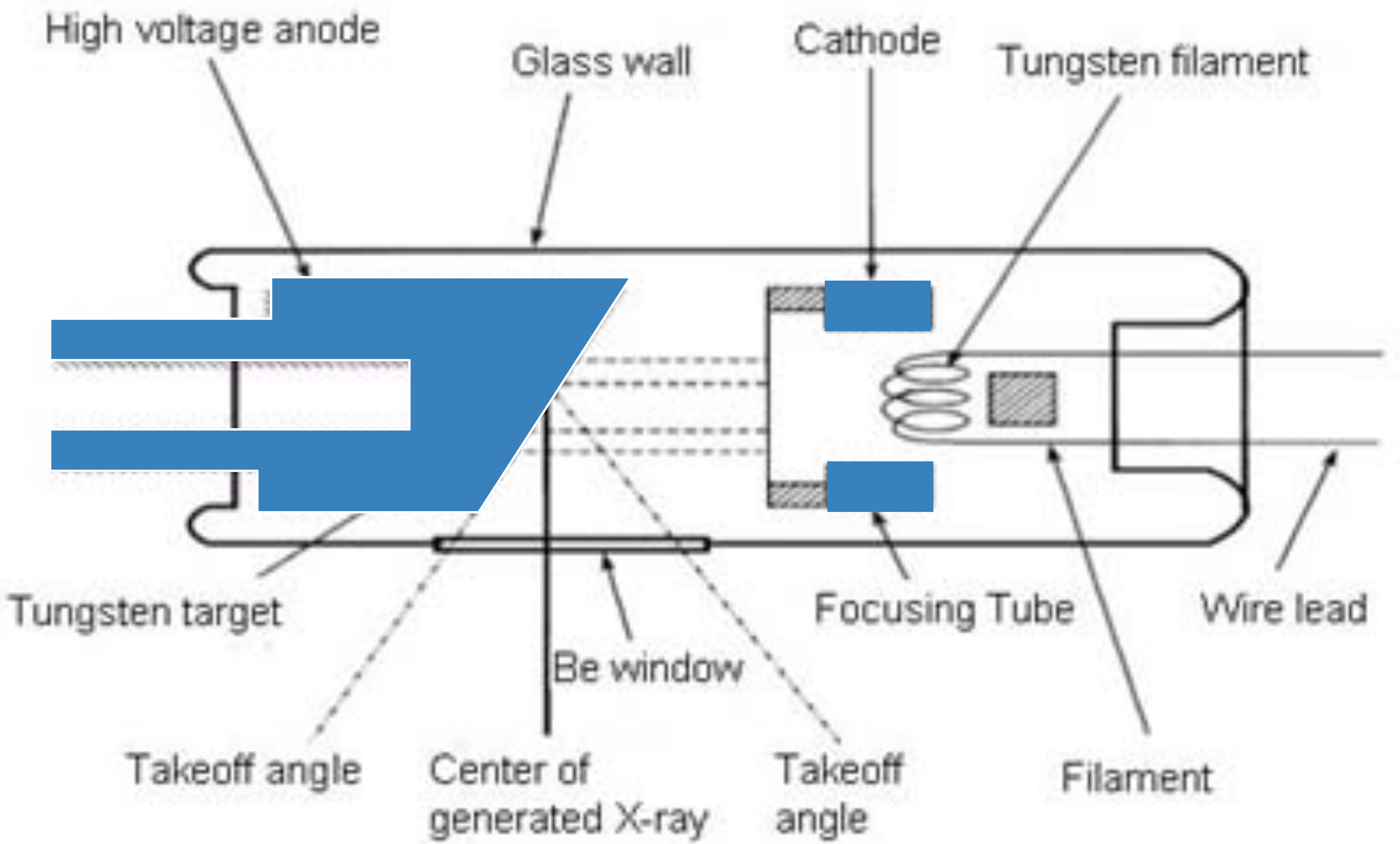
- Slope of spectrum gets steeper
- E_{max} is shifted to the right
- Spectrum disappears completely
- Constant flux up to E_{max} is seen.



Generation – Focal Spot



Generation – X-ray tube



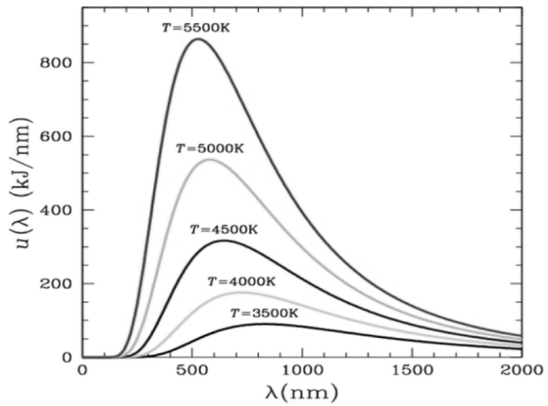
Generation – Heat production

Power absorption: $$\alpha = \frac{\text{absorbed power}}{\text{incident power}}$$ black body: $\alpha = 1$

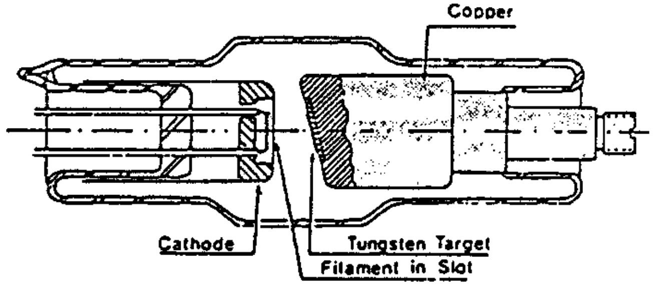
Stefan-Boltzman law: $$W = \sigma\left(T^4 - T_{\text{environent}}^4\right)$$ σ = 5.7 · 10-12 Wcm-2K-4

Wien's displacement law: $$\lambda_{\text{peak}} = \frac{b}{T}$$

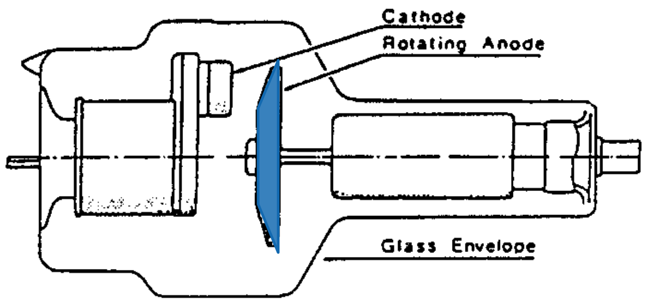
b = 2.9 · 10–3 mK



X-ray tube – Stationary and rotating anode

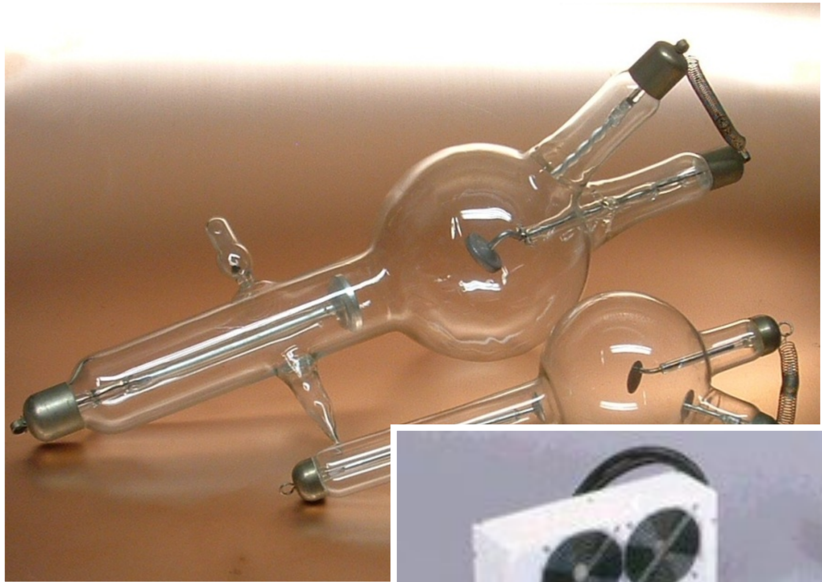


Stationary Anode Tube



Rotating Anode Tube

X-ray tube – History



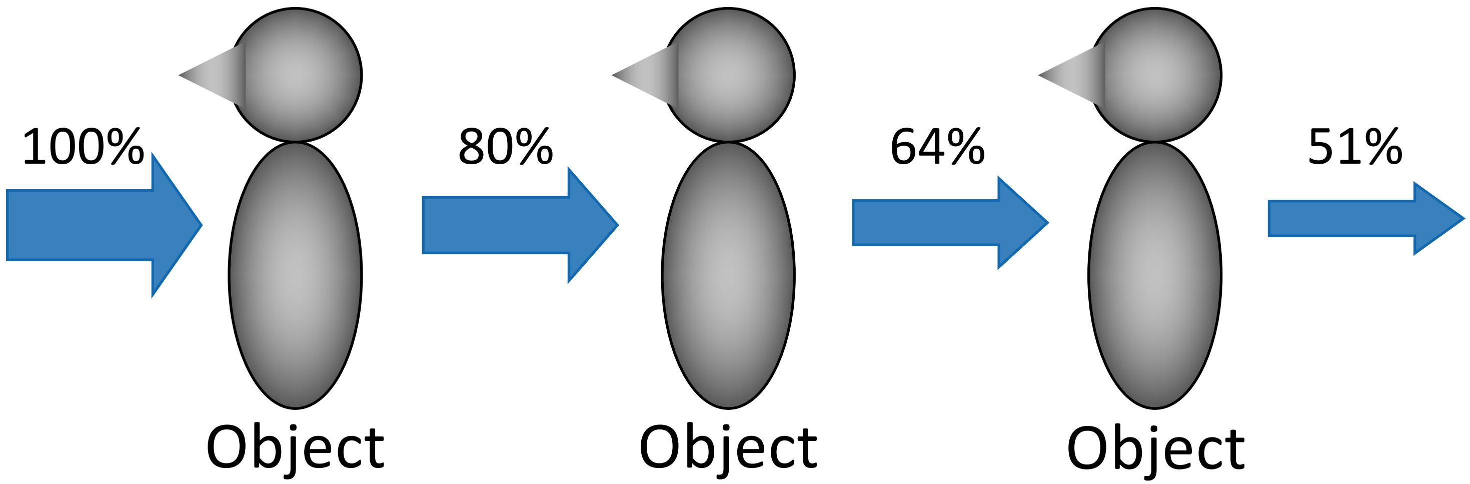
Attenuation of X-rays

Terminology

- Transmission
  - Photons passing through the body
- Absorption
  - Partial or total absorption of photon energy
- Scatter
  - Photons diverted in a new direction
- Attenuation
  - Absorption + scatter

Attenuation

Attenuation in body with transmission of 80%:



1) Photo effect
2) Compton effect
3) Interaction with bound electrons

Attenuation – Photo effect

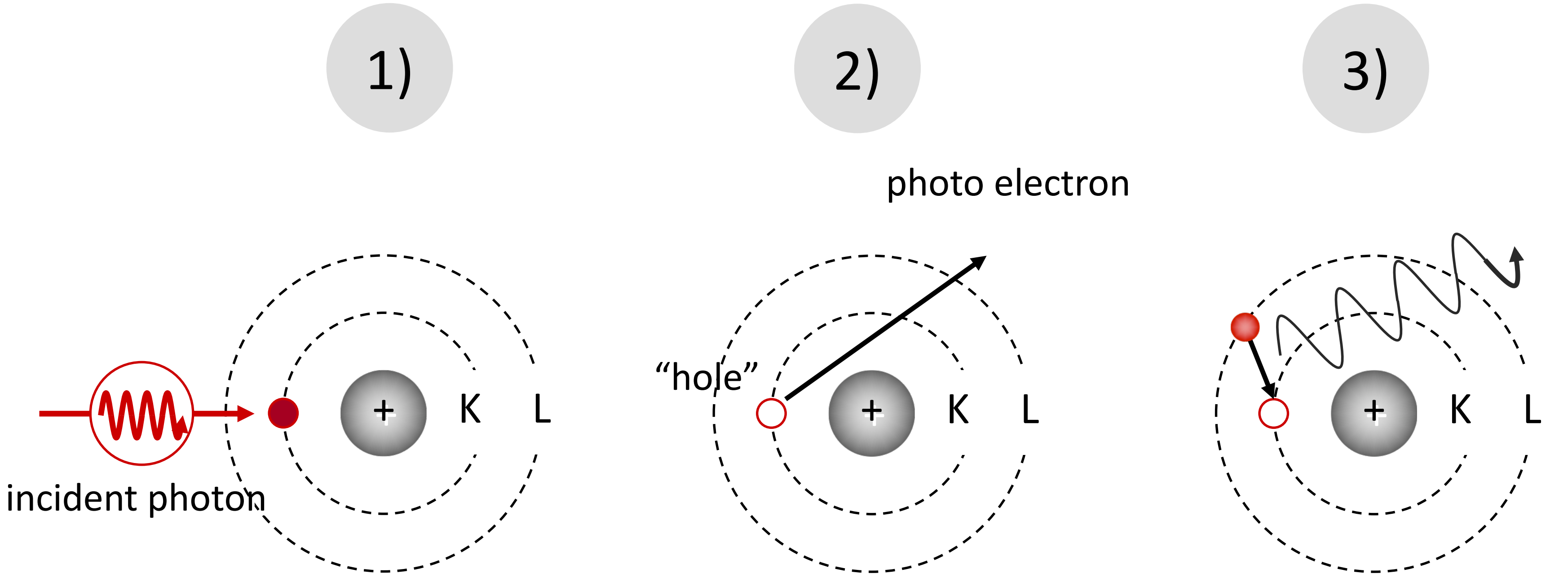
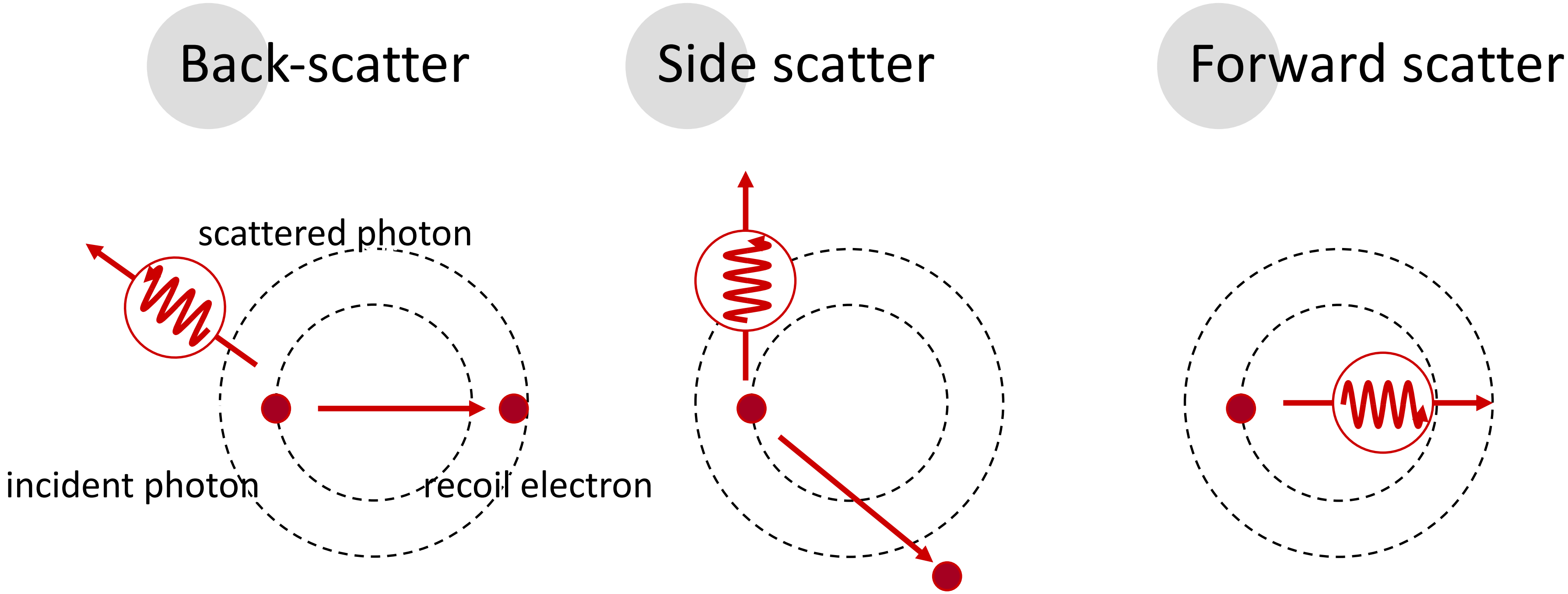


Photo effect leads to total absorption of photon:

- Generation of characteristic x-ray radiation with low energy
- Photo electrons cause biological "damage" ➔ "ionizing radiation"
- Probability ~ $\rho \cdot Z^3/E^3$

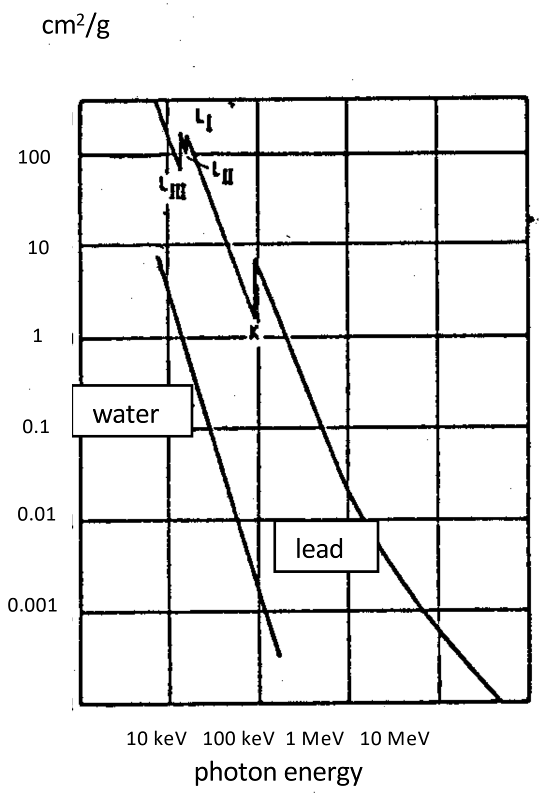
Attenuation – Compton effect



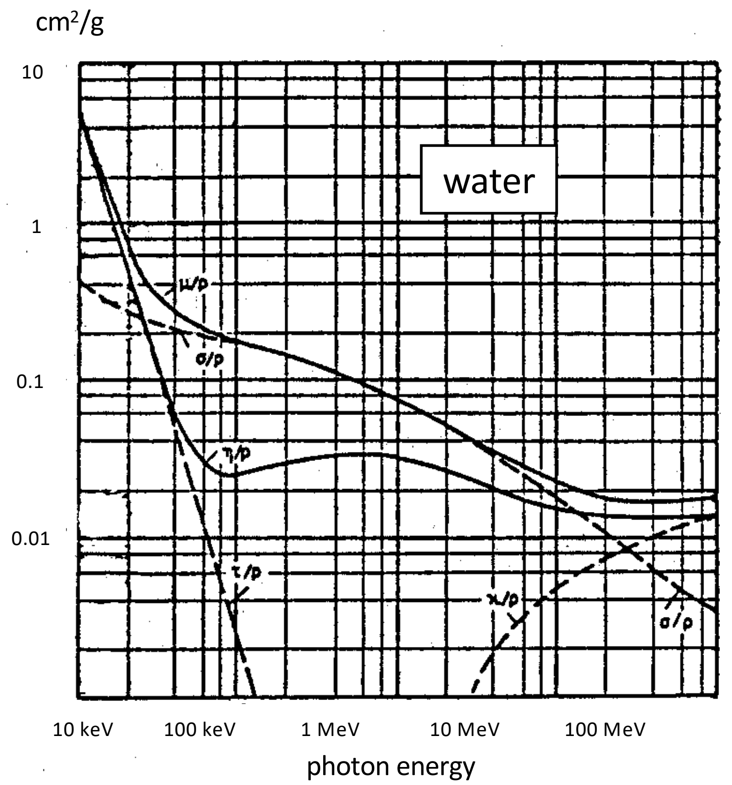
Compton effect leads to photon "bouncing":

- Photon loses (part of) its energy to kinetic energy of electron
- Detection of photon changes
- Recoil electron responsible for "biological" damage
- Probability ~ ρ/E

Attenuation – Mass absorption coefficient (μ')



a



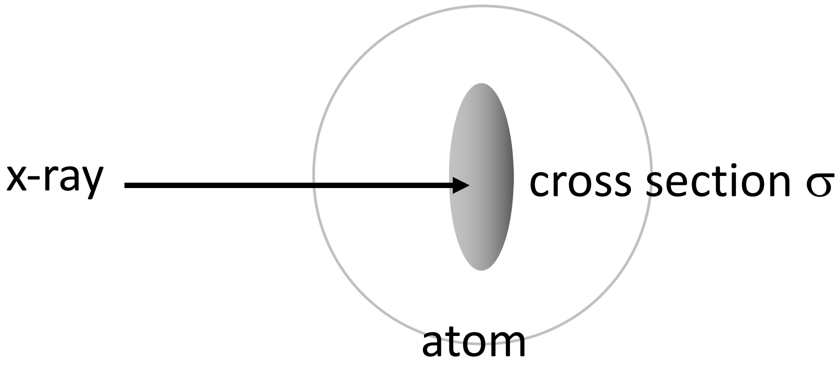
b

a Photoeffect

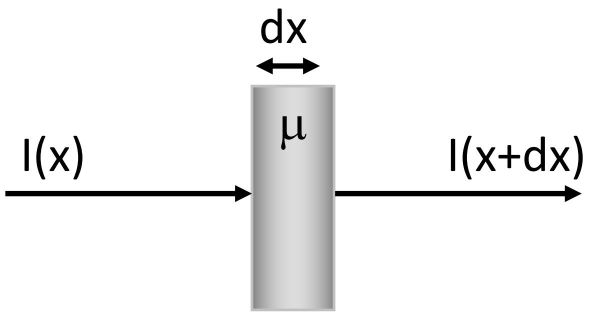
b Photoeffect (τ/ρ), Comptoneffect (σ/ρ), pair production (κ/ρ)

Attenuation coefficient

Mass attenuation coefficient μ' [cm^2/g]

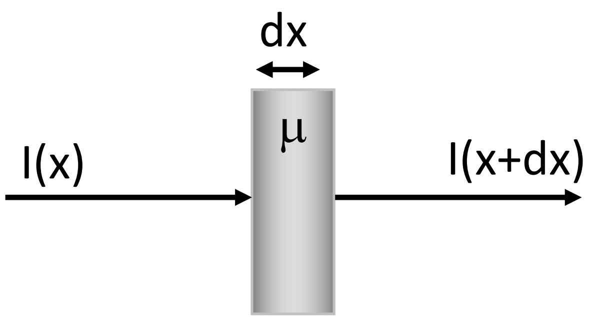


Linear attenuation coefficient $\mu = \mu' \cdot \rho$ [cm^{-1}]



Attenuation coefficient

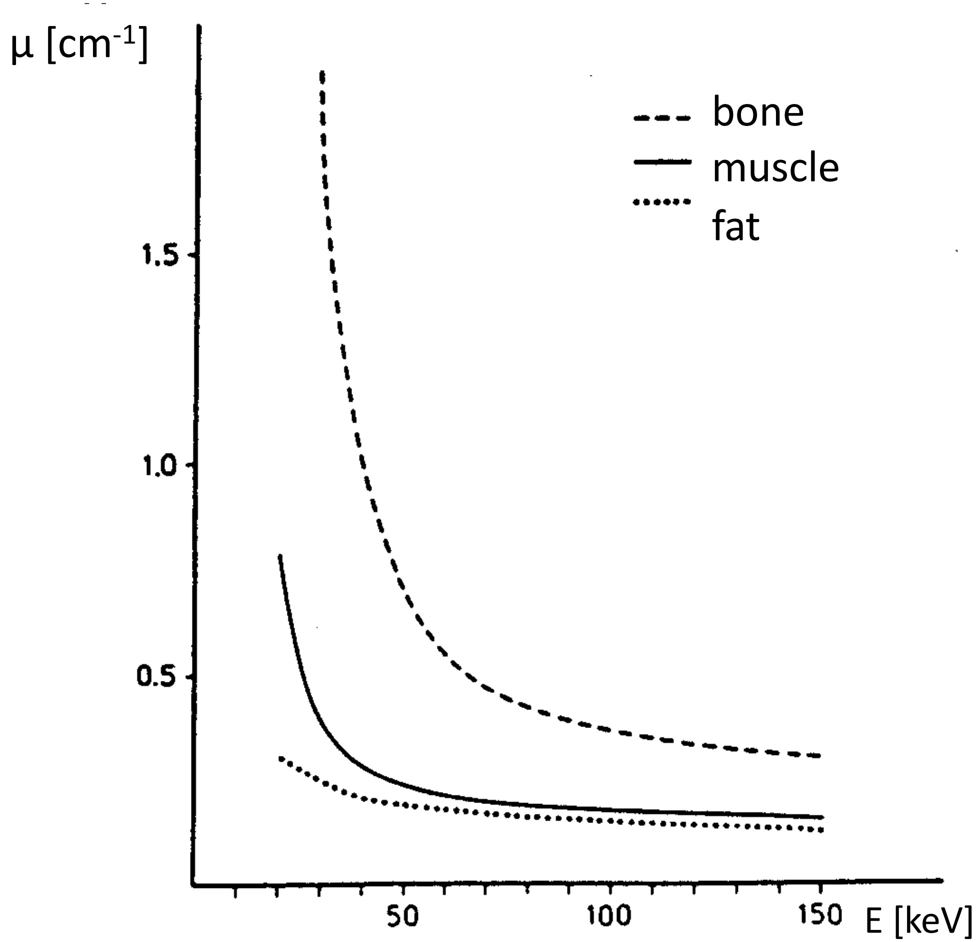
Linear attenuation coefficient μ



Beer-Lambert's law

$$I = \int_0^{E_{max}} I_0(E)\, e^{-\int_{-\infty}^{\infty} \mu(E,x)\,dx}\, dE$$

Attenuation – Linear attenuation coefficients (μ'·ρ)



Attenuation – Summary

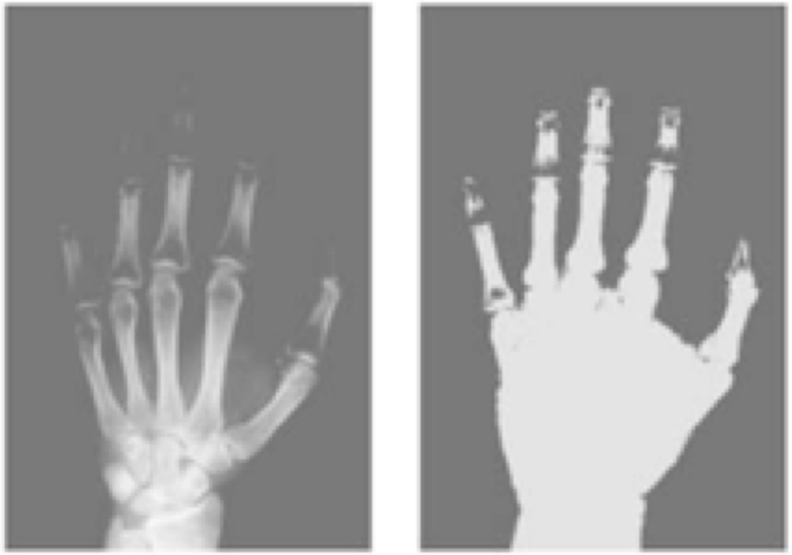
- Photo effect τ
  - X-ray photon disappears
  - Photo electron recoils
  - Effective in contrast agent, lead, bone
- Compton effect σ
  - Interaction with free electrons
  - Scatter
  - Water, air, soft tissue, bone
- (Pair production κ)
  - Electron-positron pair requires E > 1 MeV
  - Not relevant in medical imaging

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

Clicker Activity (5 min)

Assign energy values to the two projection images and explain the reasons for the differences in image contrast and signal intensity

- left/right: same energy but different display window/level settings
- left: high energy, right: low energy
- left: low energy, right: high energy



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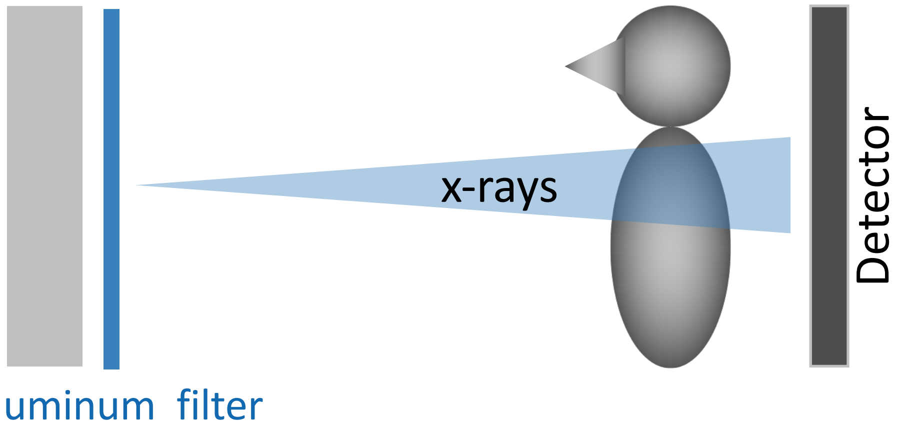
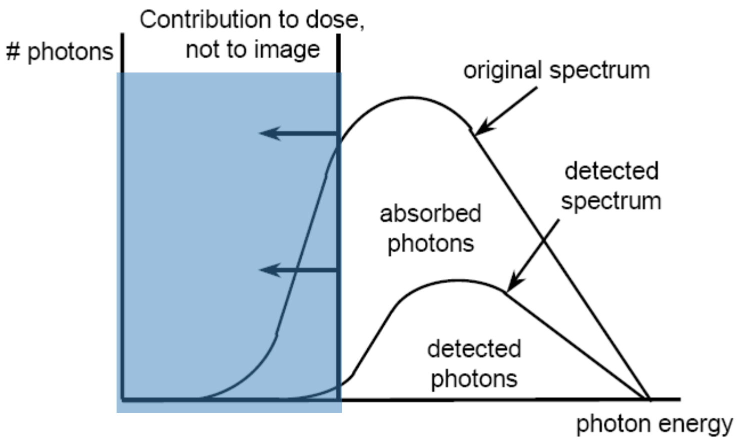
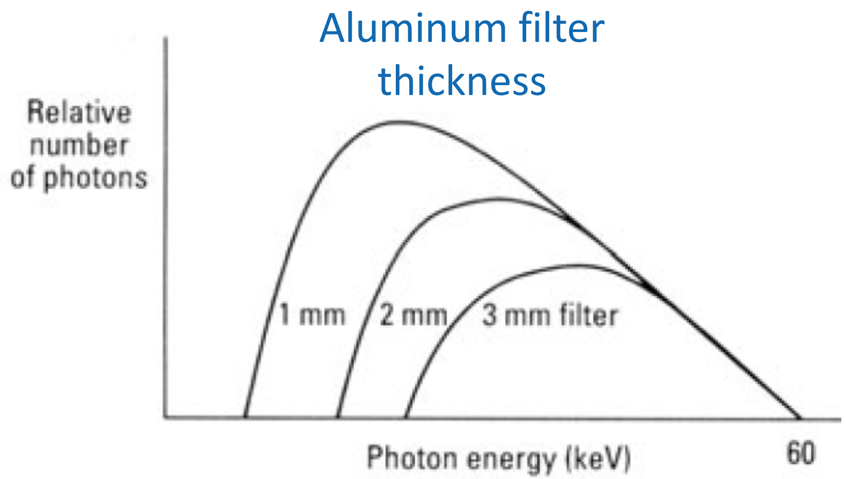
Projection imaging

Projection imaging – Pre-filtering







Chapter 1.3

Resolution of imaging procedures

- Spatial resolution
  - Blurring of object points when projected into image

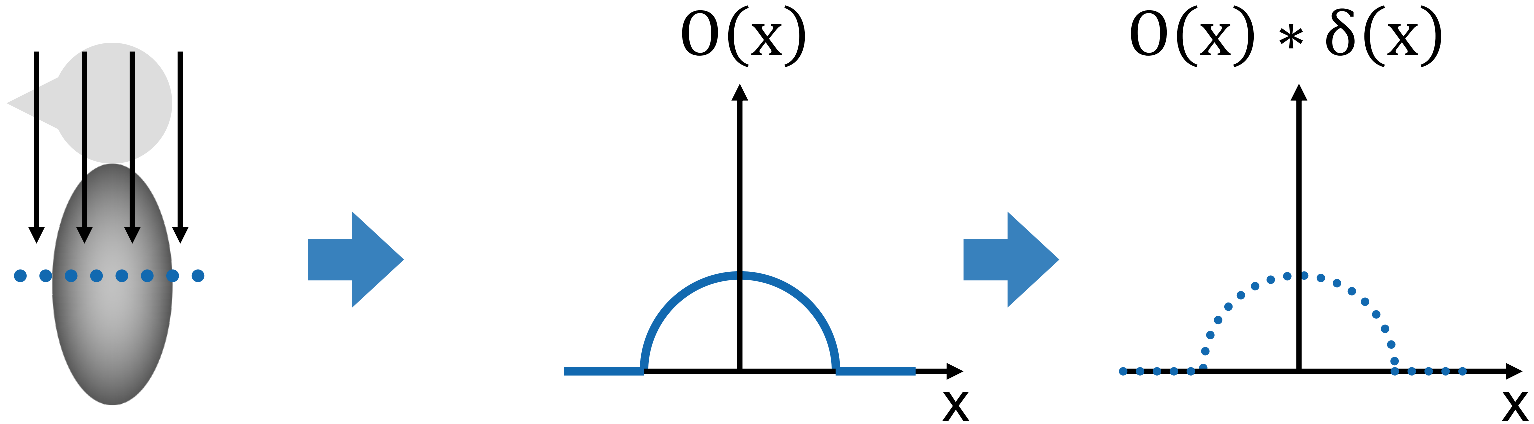
- Contrast
  - Difference in linear attenuation coefficients between tissues

- Temporal resolution
  - Sample rate of temporal recording

Resolution – Spatial resolution

Object representation

$$O(x) = \int_{-\infty}^{+\infty} O(X)\delta(x - X)\,dX$$



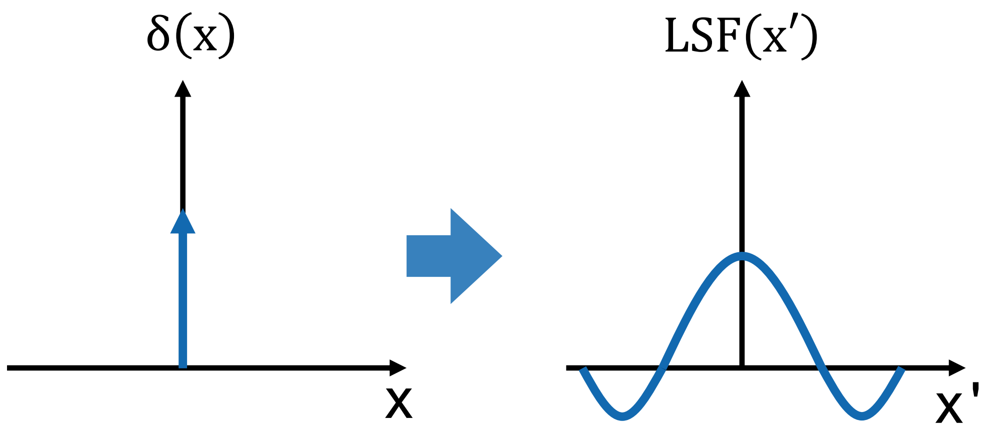
Resolution – Spatial resolution

Mapping object space onto image space

Object space **Image space**

$$\int_{-\infty}^{+\infty} \mathrm{O(X)}\delta(\mathrm{x}-\mathrm{X})\,\mathrm{dX} \rightarrow \int_{-\infty}^{+\infty} \mathrm{O(X)LSF}(\mathrm{x}'-\mathrm{X})\,\mathrm{dX}$$

Object space **Image space**

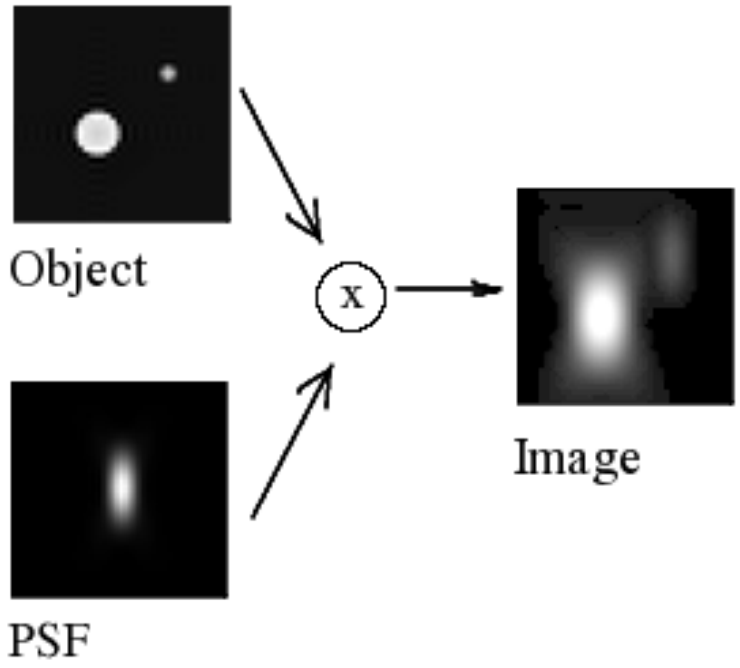


"Line Spread Function"
(LSF)

Resolution – Spatial resolution

Mapping object space onto image space (1D $\rightarrow$ 2D)

1D: LSF $\rightarrow$ **2D**: PSF



PSF: Point Spread Function

Resolution – Spatial resolution

Fourier series representation of object

$$O(x) = \int_{-\infty}^{+\infty} \left(a(k)\sin(kx) + b(k)\cos(kx)\right)dk$$

Wave number (see:. spatial frequency = k-space in MRI): $k = \frac{2\pi}{\lambda}$

Mapping Fourier representation of object onto image:

$$J_k(x) = a(k)\int_{-\infty}^{+\infty} \delta(x - X)\sin(kX)dX \rightarrow J_k^{'}(x') = a(k)\int_{-\infty}^{+\infty} L(x' - X)\sin(kX)dX$$

Resolution – Spatial resolution

Mapping Fourier representation of object onto image:

$$J_k(x) = a(k)\int_{-\infty}^{+\infty}\delta(x-X)\sin(kX)\,dX \rightarrow J_k'(x') = a(k)\int_{-\infty}^{+\infty}L(x'-X)\sin(kX)\,dX$$

Object space

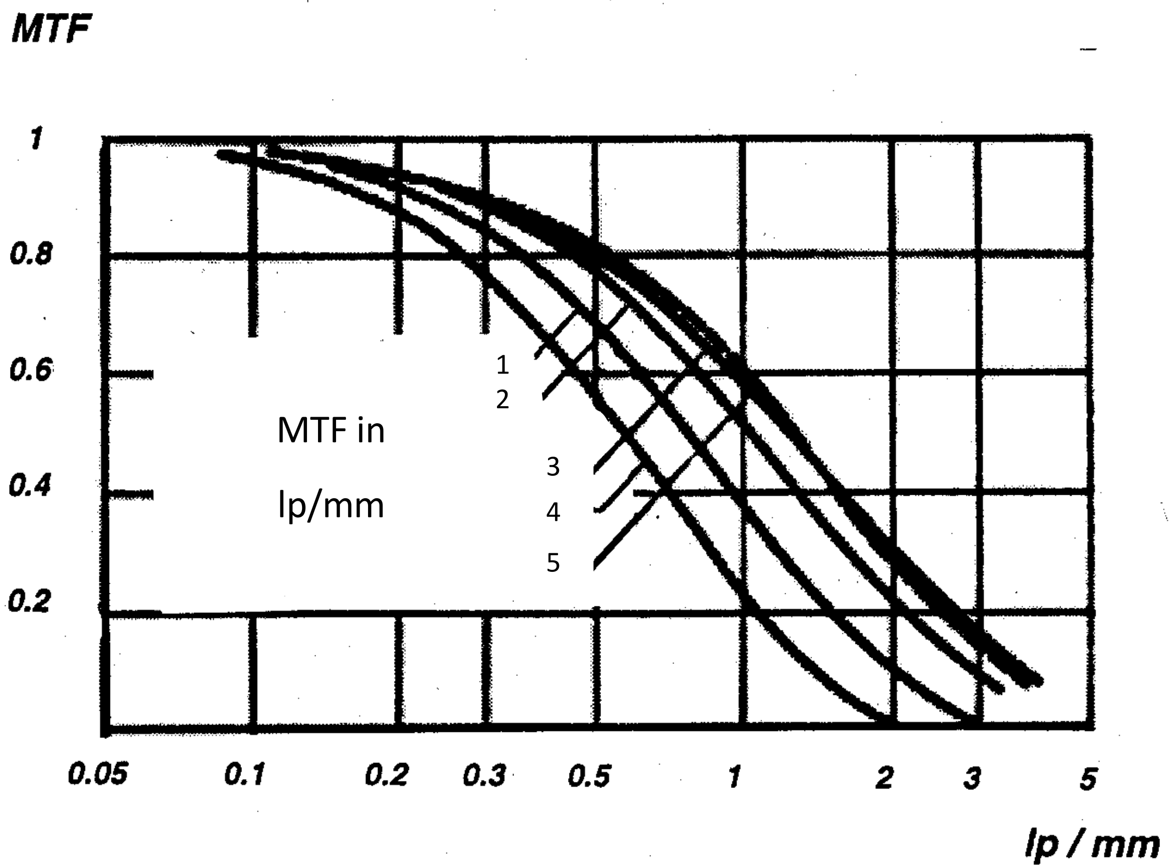
Image space

$$J_k'(x') = a(k)\eta(k)\sin(kx'-\varphi)$$

"MTF: Modulation Transfer Function"

$$\mathrm{FT(image)} = \mathrm{MTF}\cdot\mathrm{FT(object)}$$

Resolution – Modular Transfer Functions (MTF)



1: 25 cm image intensifyer, CsJ screen

2: 25 cm image intensifyer, 15 cm setting

3: 17 cm image intensifyer, CsJ screen

4: 17 cm image intensifyer, ZnS or CdS screen

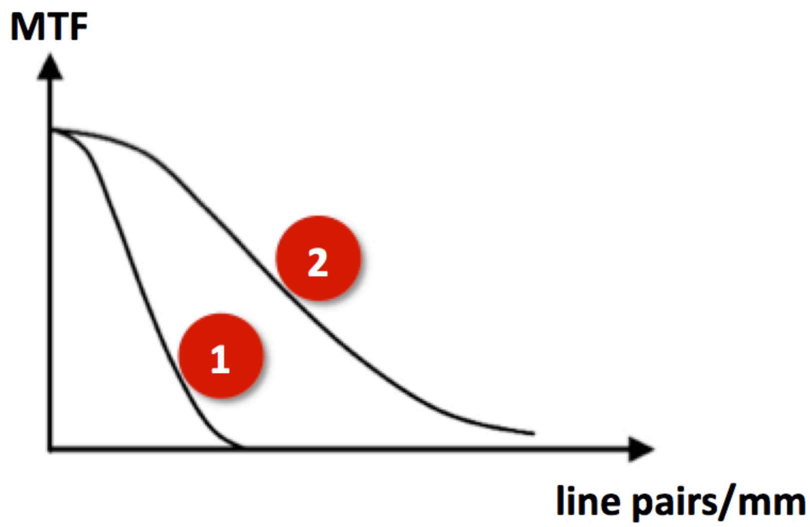
5: Film- intensifying screen combination

lp/mm: line pairs per mm

Clicker Activity (5 min)

Compare the Modular Transfer Function (MTF) of two different imaging systems

- The imaging system with MTF #1 yields best resolution
- The imaging system with MTF #2 yields best resolution
- Resolution of #1 and #2 is identical



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“The most important slides”