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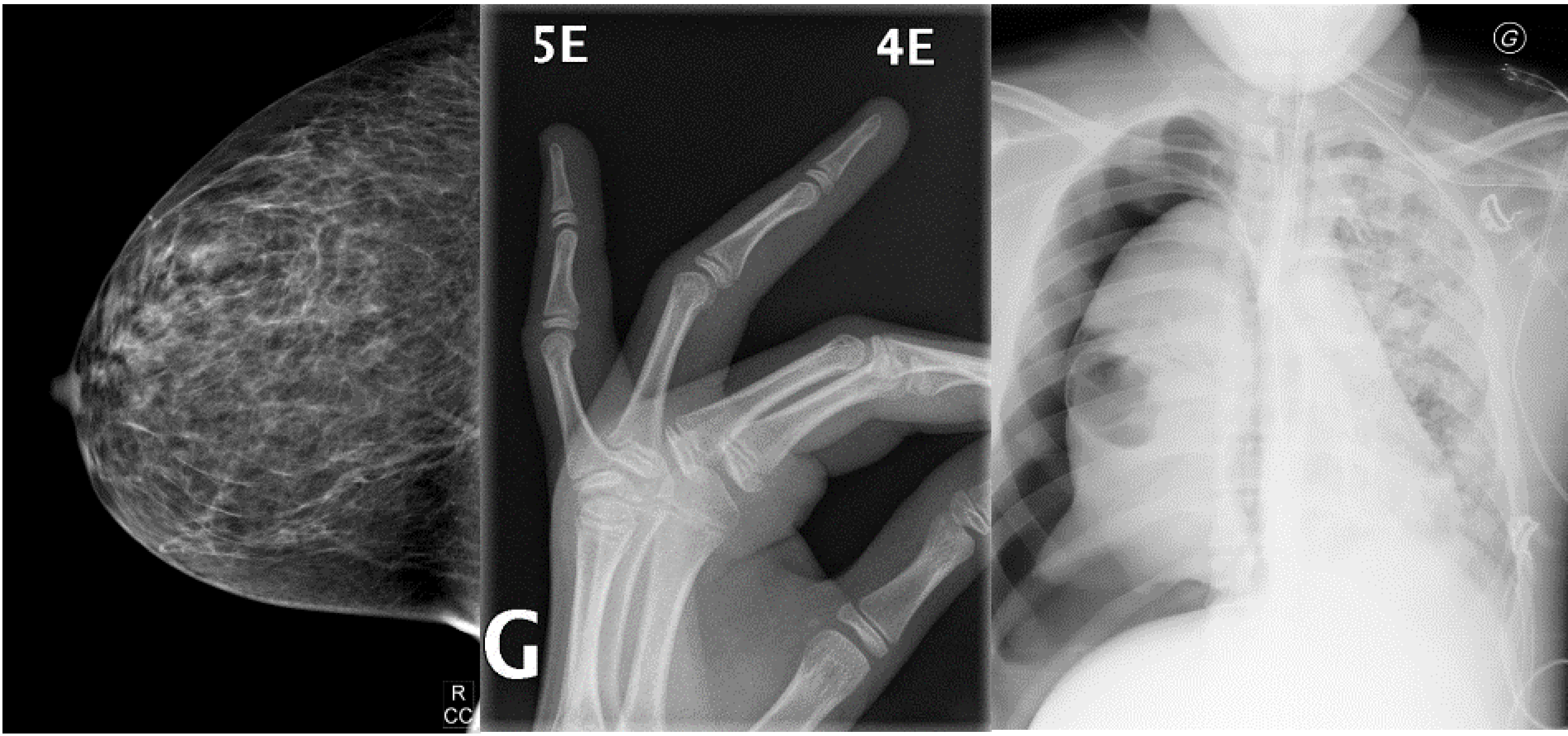
UNIL - CHUV

1. Radiography

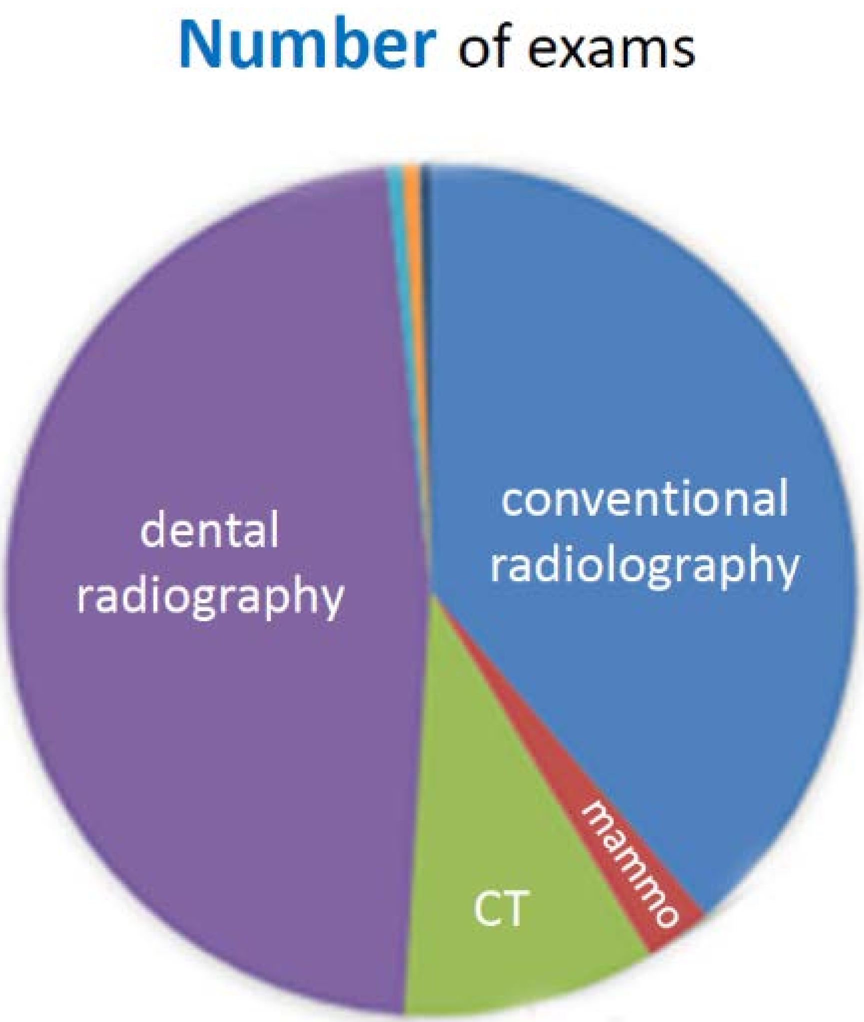
Learning objectives

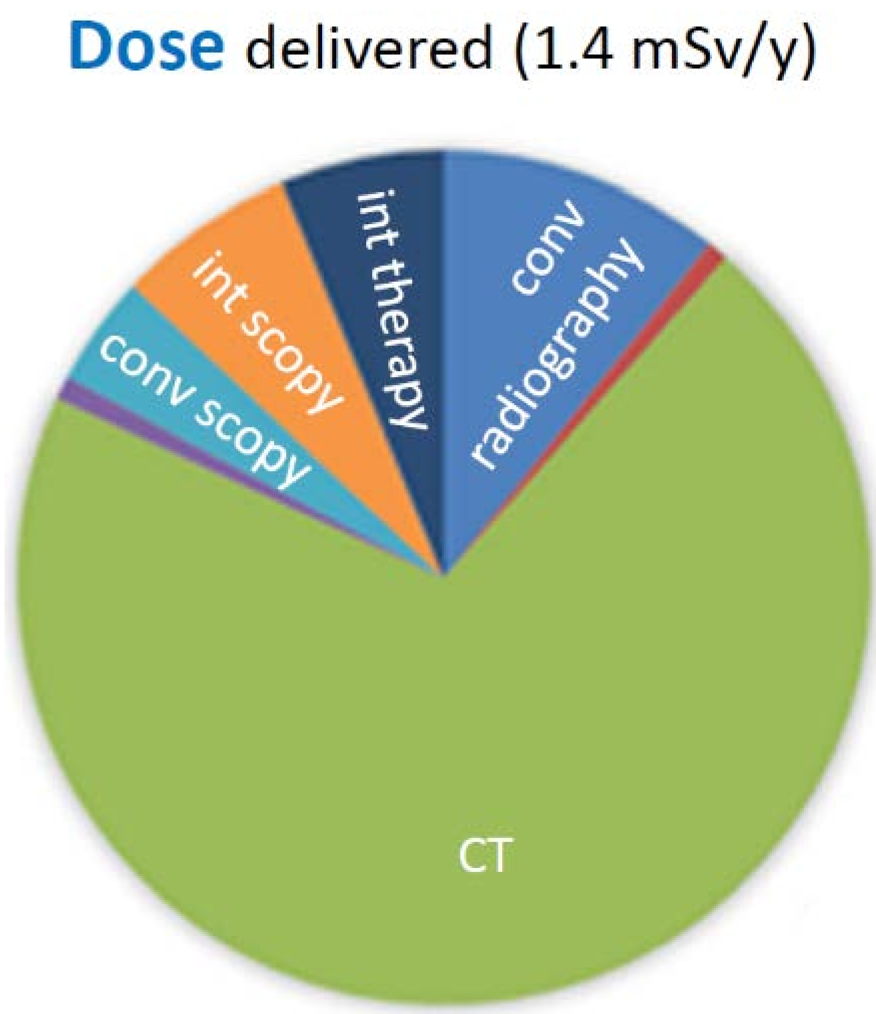
- Describe the **main parts** of an **x-ray device** from a physical point of view
- Describe and explain the **x-ray spectra** at different stages of the radiographic procedure
- Briefly describe the main **image receptors** used in diagnostic radiography

Radiography:
projection of the anatomy on a plane



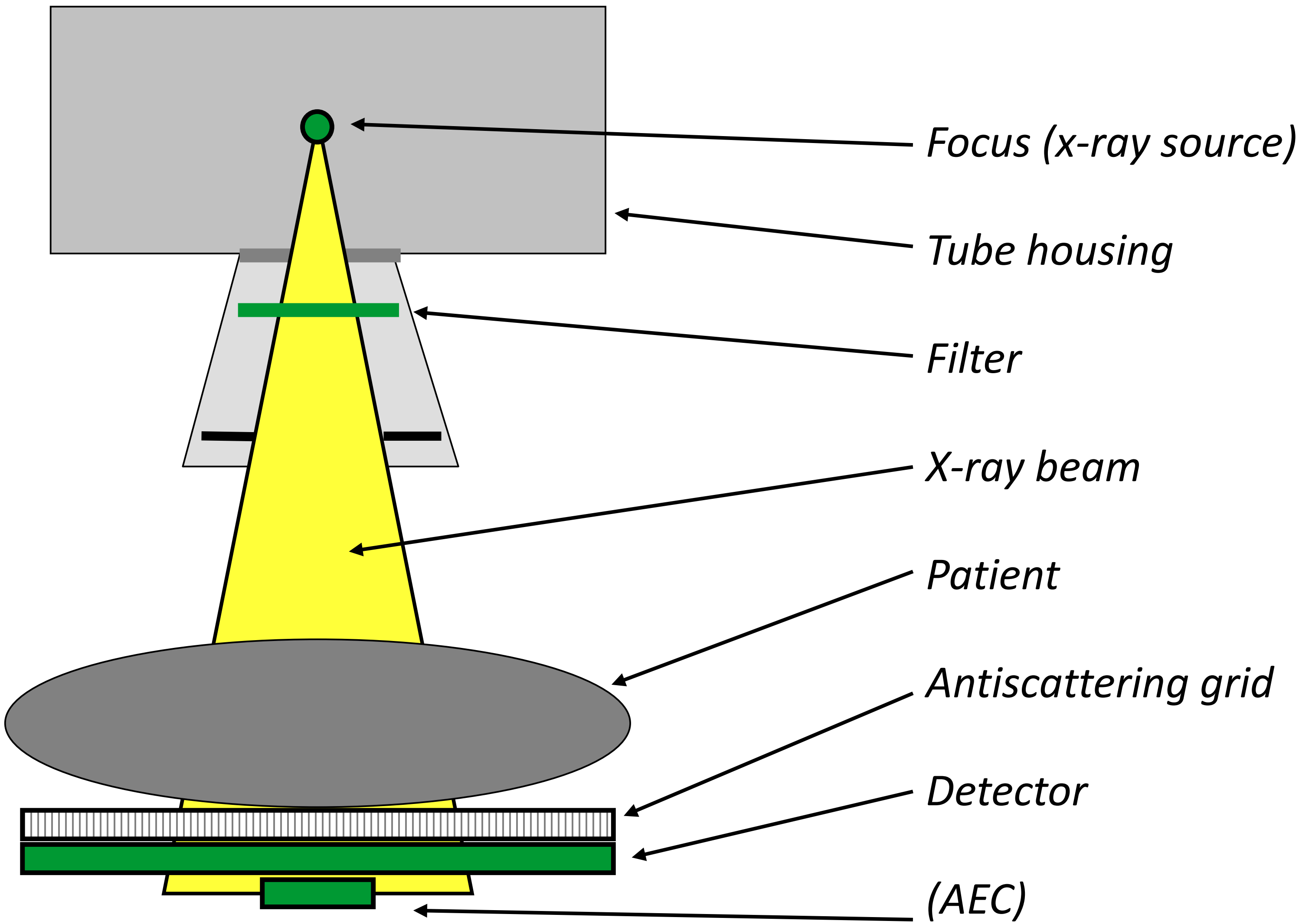
Dose delivered to **patients** in Switzerland

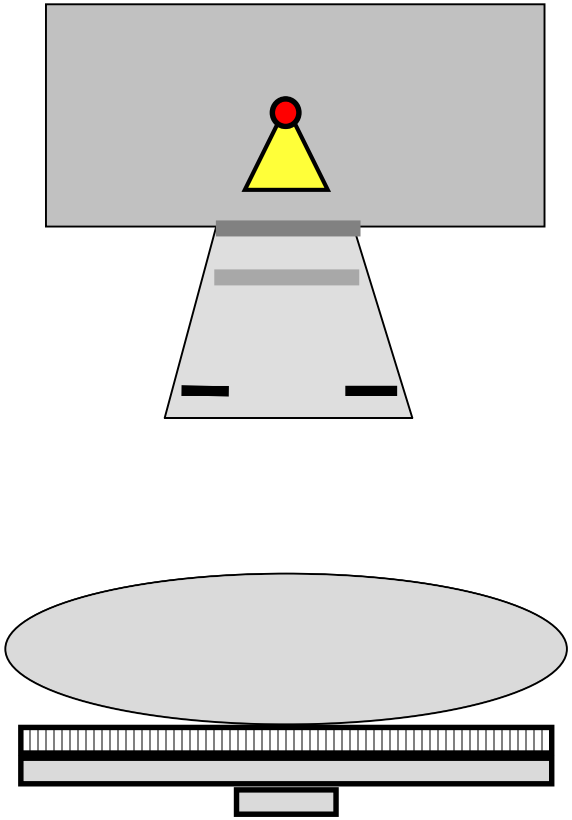




Swiss study 2013

Schematic of the radiological procedure





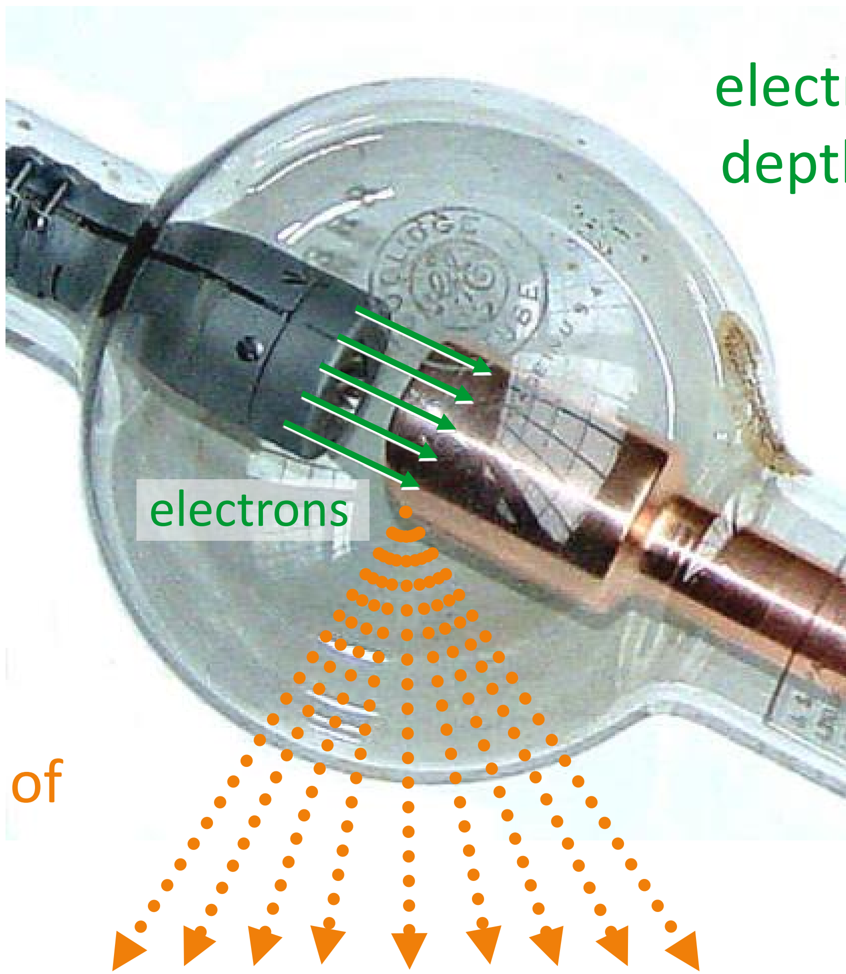
Radiography

1.1 X-ray production

X-ray production

cathode
-

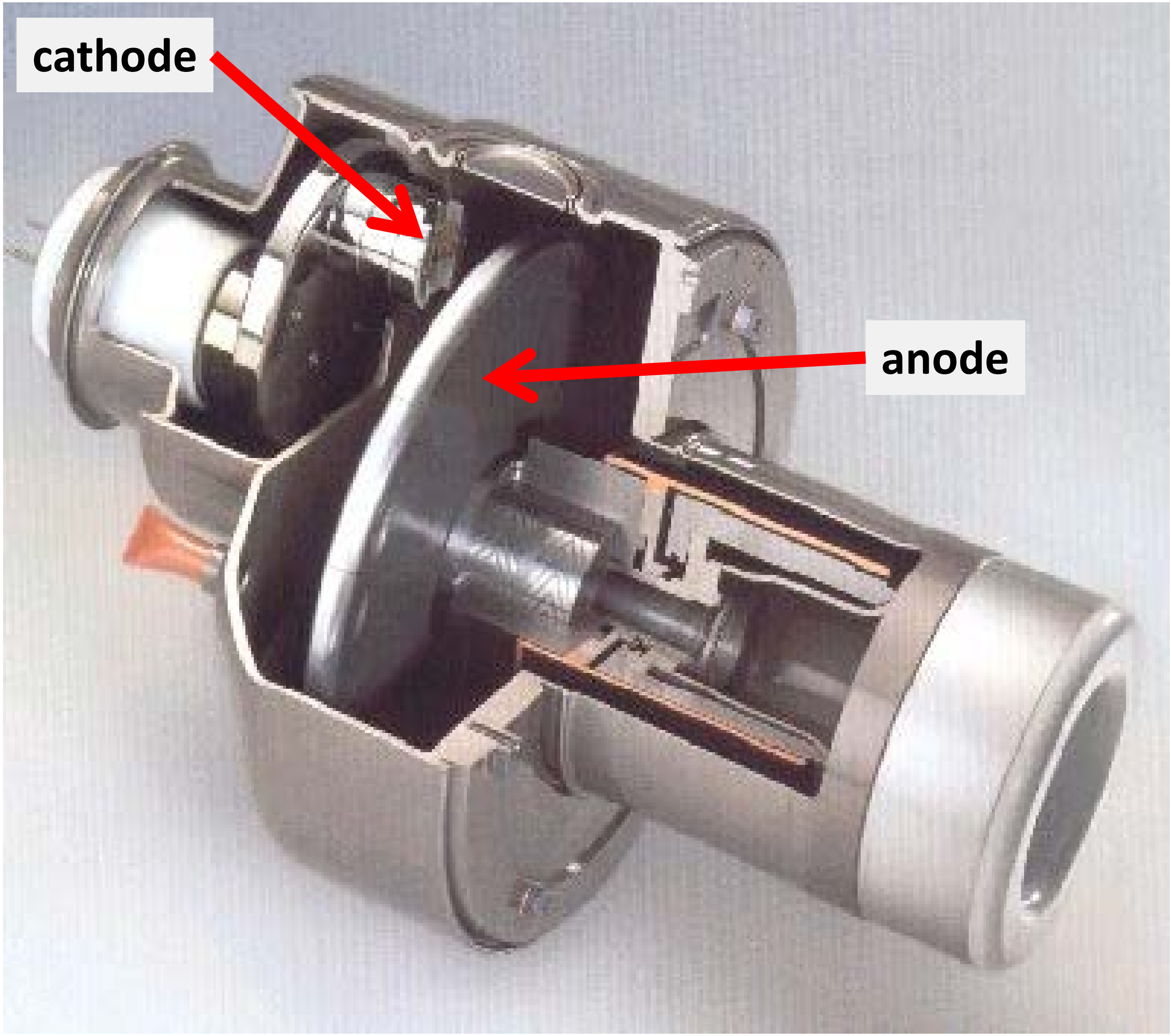
electrons penetration depth into the anode
some µm



anode
high Z
+

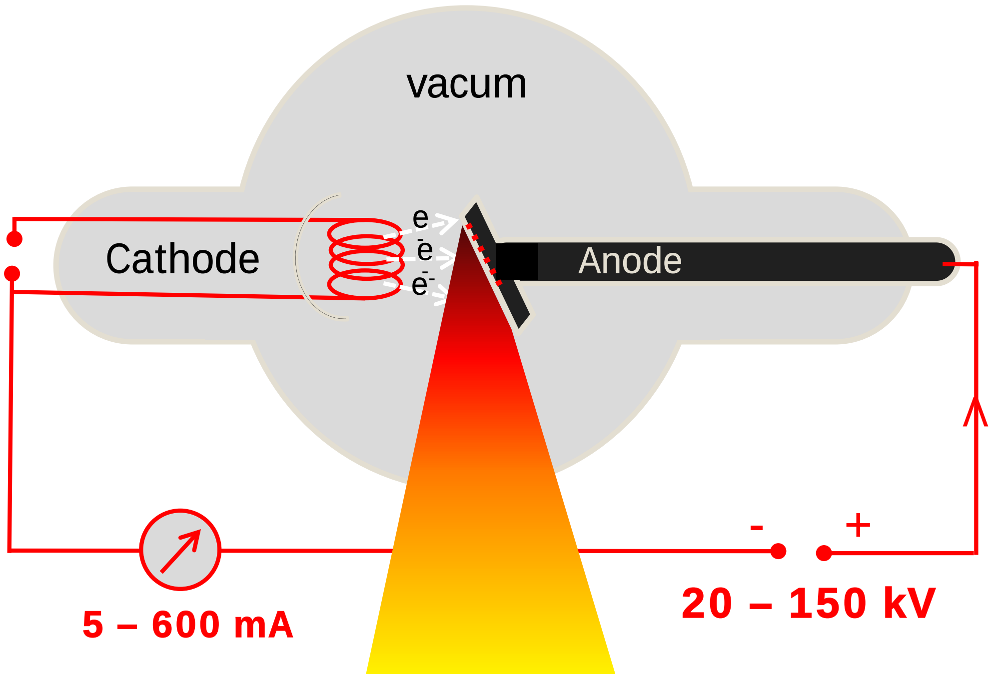
emission of
x-rays

Yield : **1% x-rays / 99% heat**


cathode
anode

X Ray tubes are maintained in vacuum

The X-ray tube



How does it work?

1. Thermo-**emission** of the electrons by a **filament**
2. **Acceleration** of the electrons by **high voltage**
3. **Absorption** of the electrons in a (tungsten) anode
4. **Production** of **x-rays** (yield 1%)

- 1 volt gives 1 eV to an electron

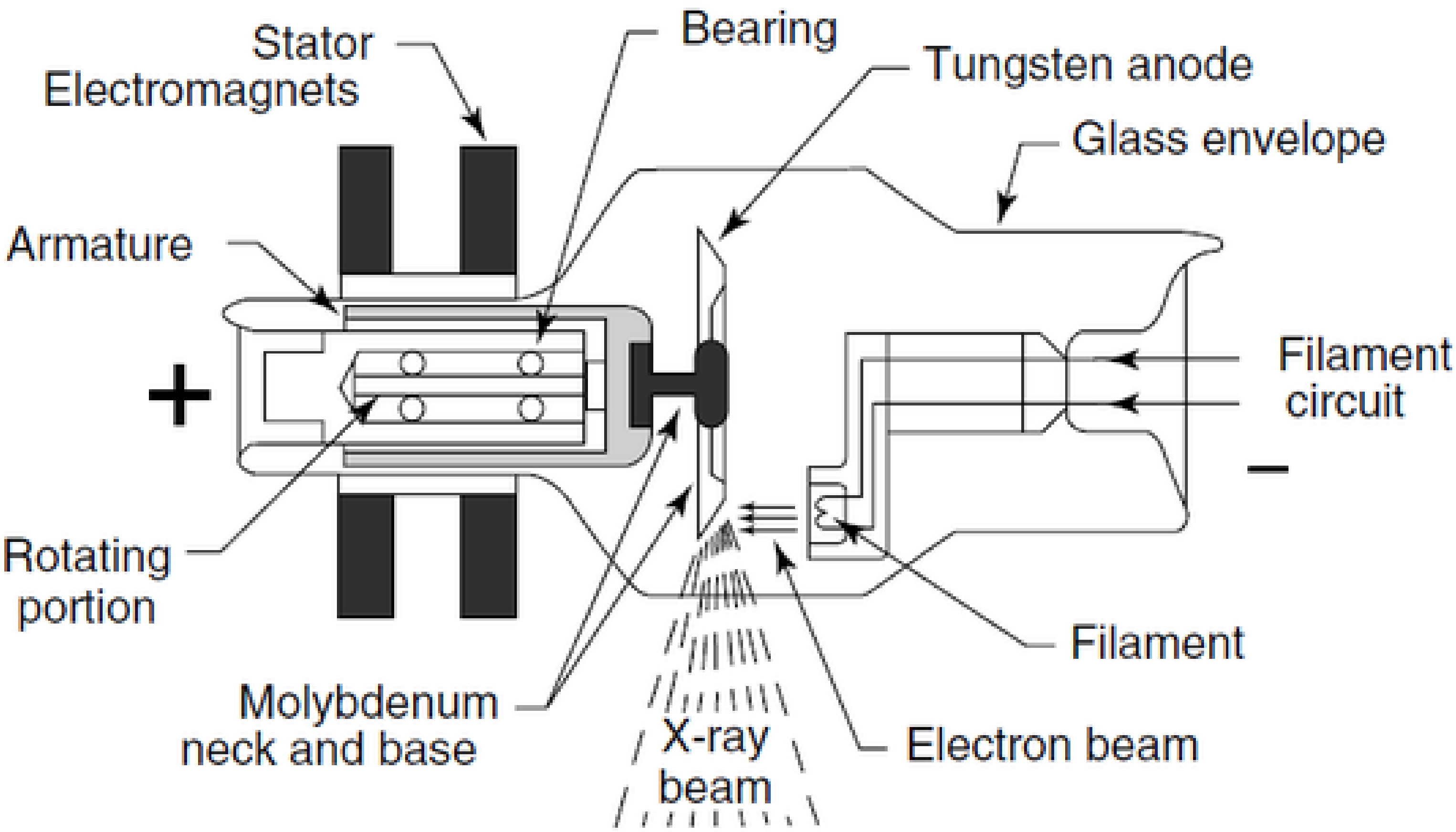
- **99 %** of the energy is lost **in heat**: rotating anode

Exercise

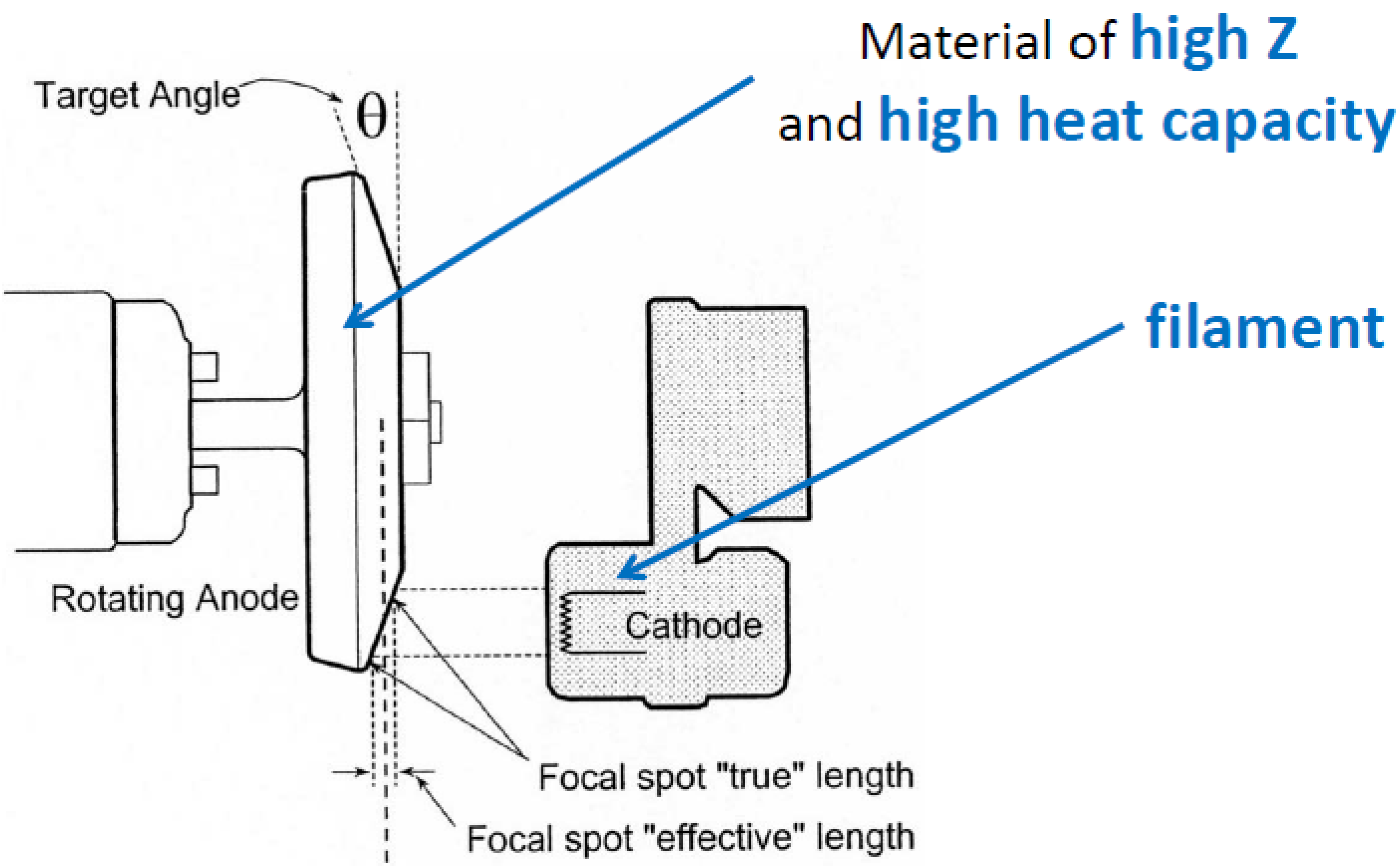
How many electrons flow from the cathode to the anode **each second** in an x-ray tube with a tube current of **50 mA**?

1. appr. $3x10^{9}$
2. appr. $3x10^{11}$
3. appr. $3x10^{13}$
4. appr. $3x10^{15}$
5. appr. $3x10^{17}$
6. appr. $3x10^{19}$

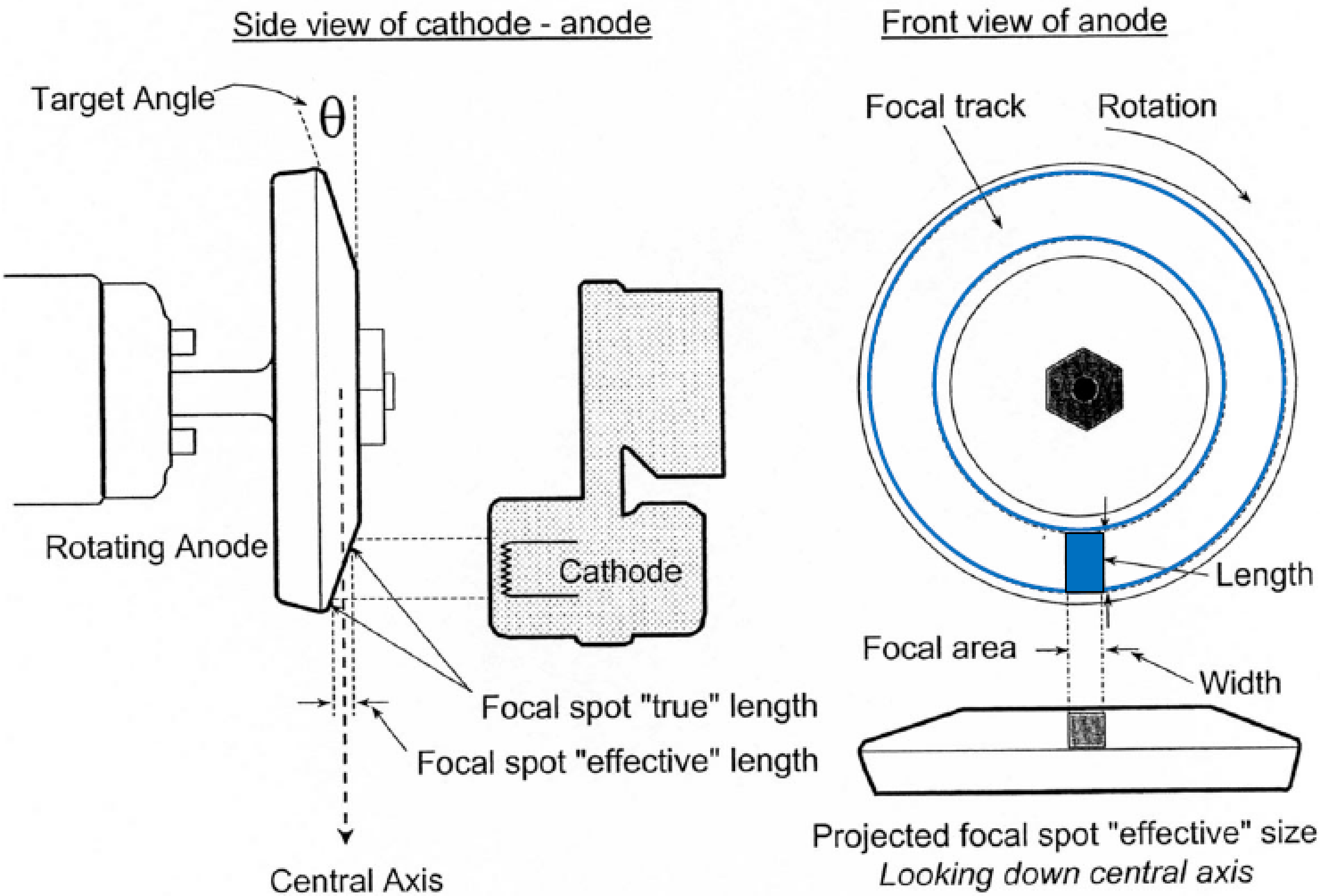
The X-ray tube



From Hendee, W.R. and Ritenour, E.R. (2002) Medical Imaging Physics, 4th Ed., John Wiley & Sons, New York



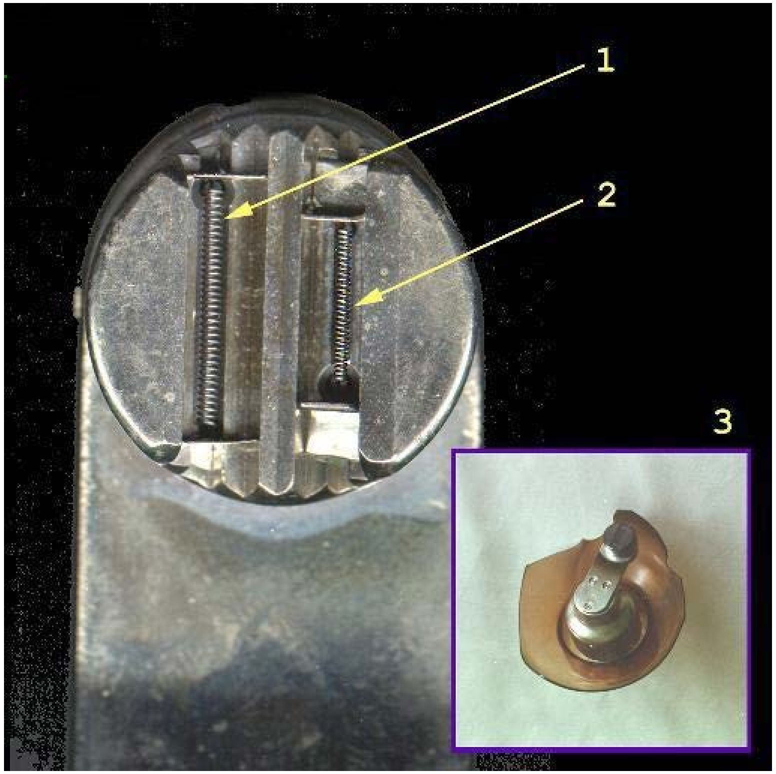
Thermal focal spot and **optical** focal spot **sizes** differ because of **the target angle θ**



Rotating the anode

increases the size of the **thermal focal spot**

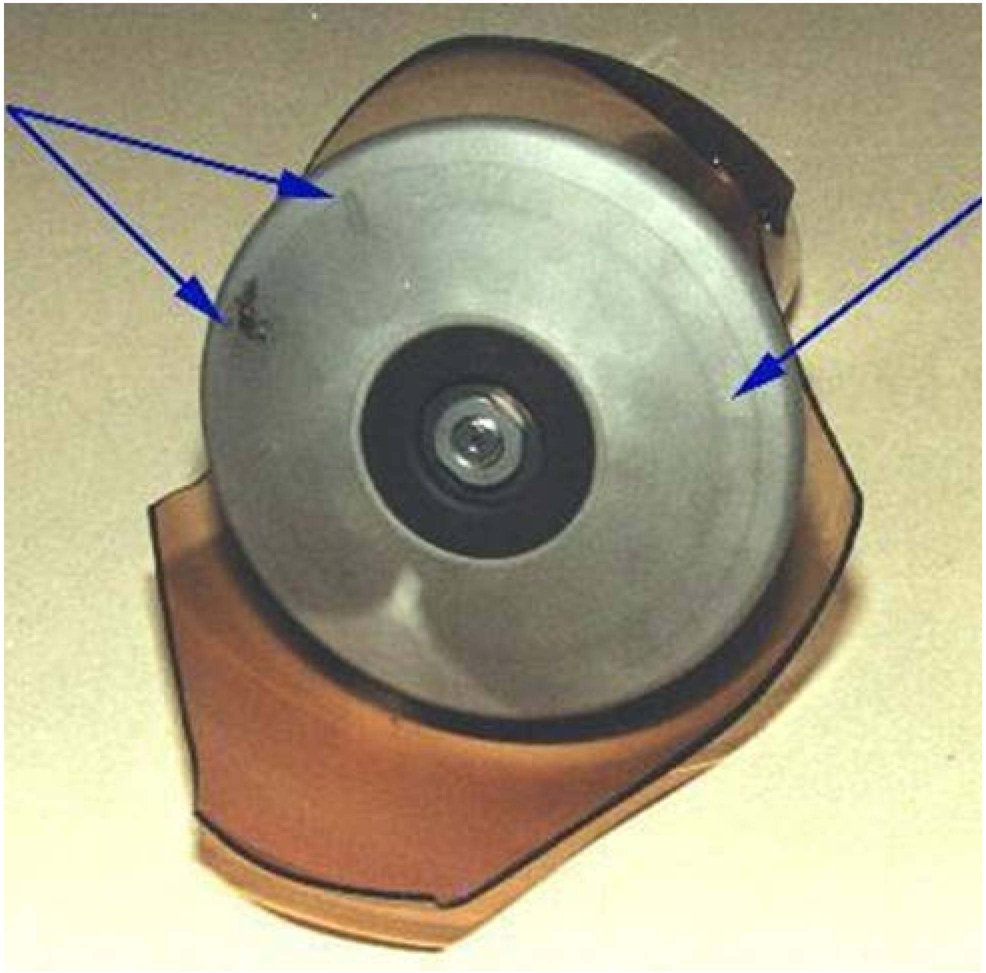
Examples of a cathode



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

Example of an anode

anode pits caused by electron beam being stationery on the anode

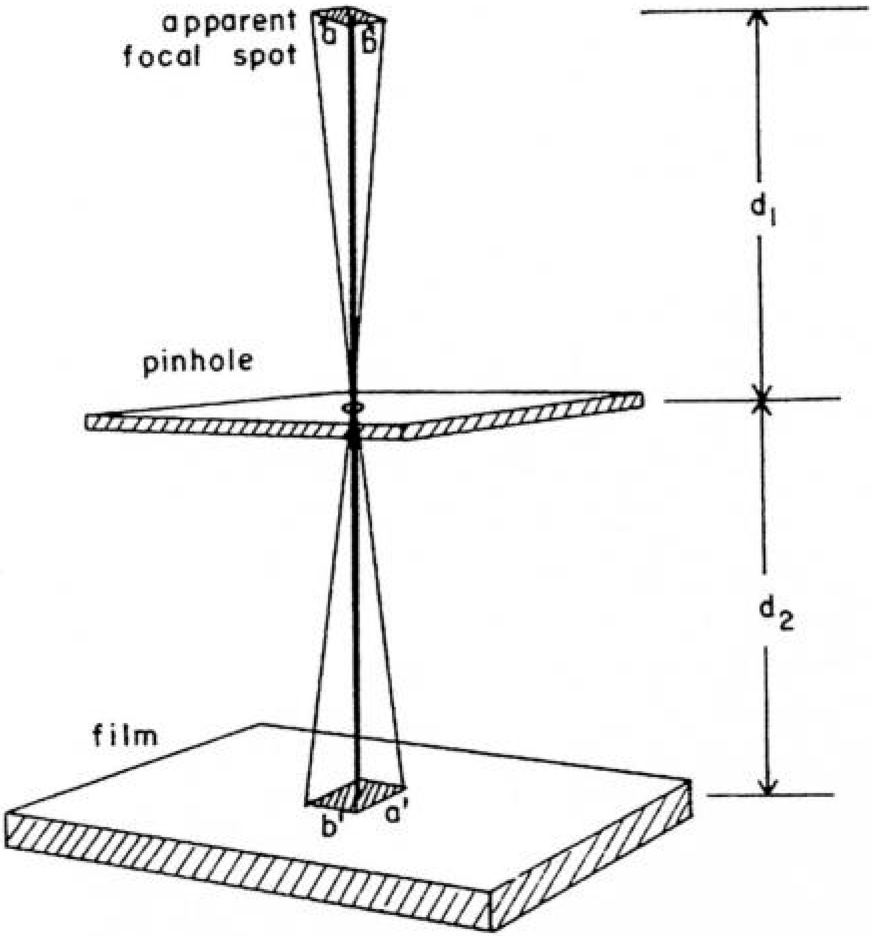


anode track

Measuring the **optical focal spot**

The apparent size of the focal spot *(optical focal spot)* can be estimated by a **pinhole** system

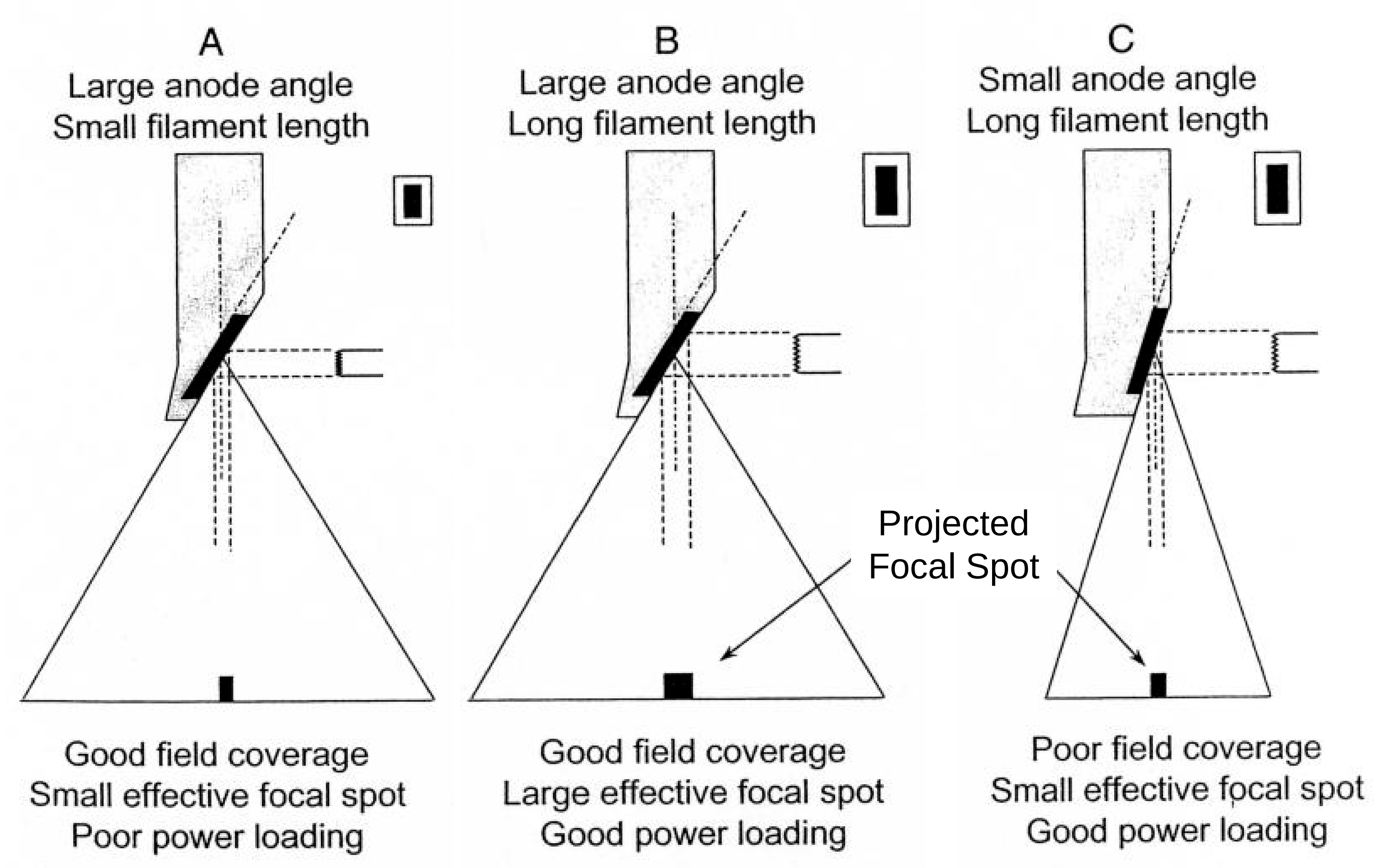
$$a' = a\left(\frac{d_2}{d_1}\right)$$



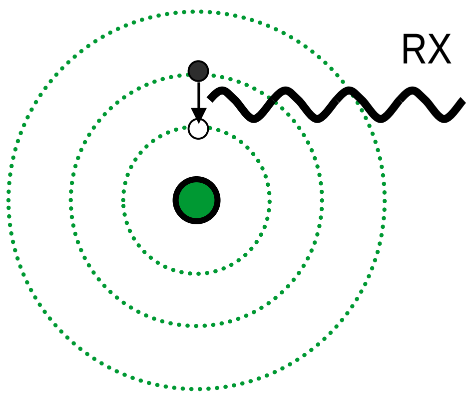
With pin-hole of diameter of about **0.1 mm**, do we need to pay attention to **diffraction**?

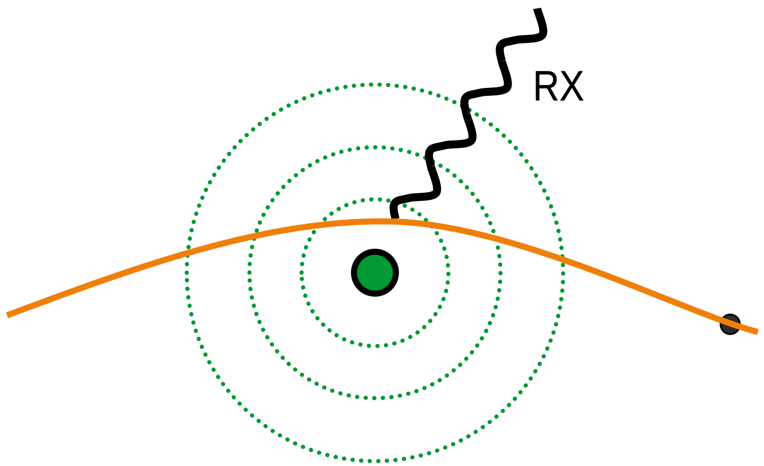
1. yes
2. no
3. I don't know

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



X-ray production





- **Characteristic ray**
  - 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
  - Important for high Z material
  - Continuous spectrum

Electrons slow down by **collision** and by **bremsstrahlung**

bremsstrahlung stopping power

kinetic energy of the electron (MeV)

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

atomic number of matter

collision stopping power

stopping power: *slowing down force from matter on the electrons*

Exercise

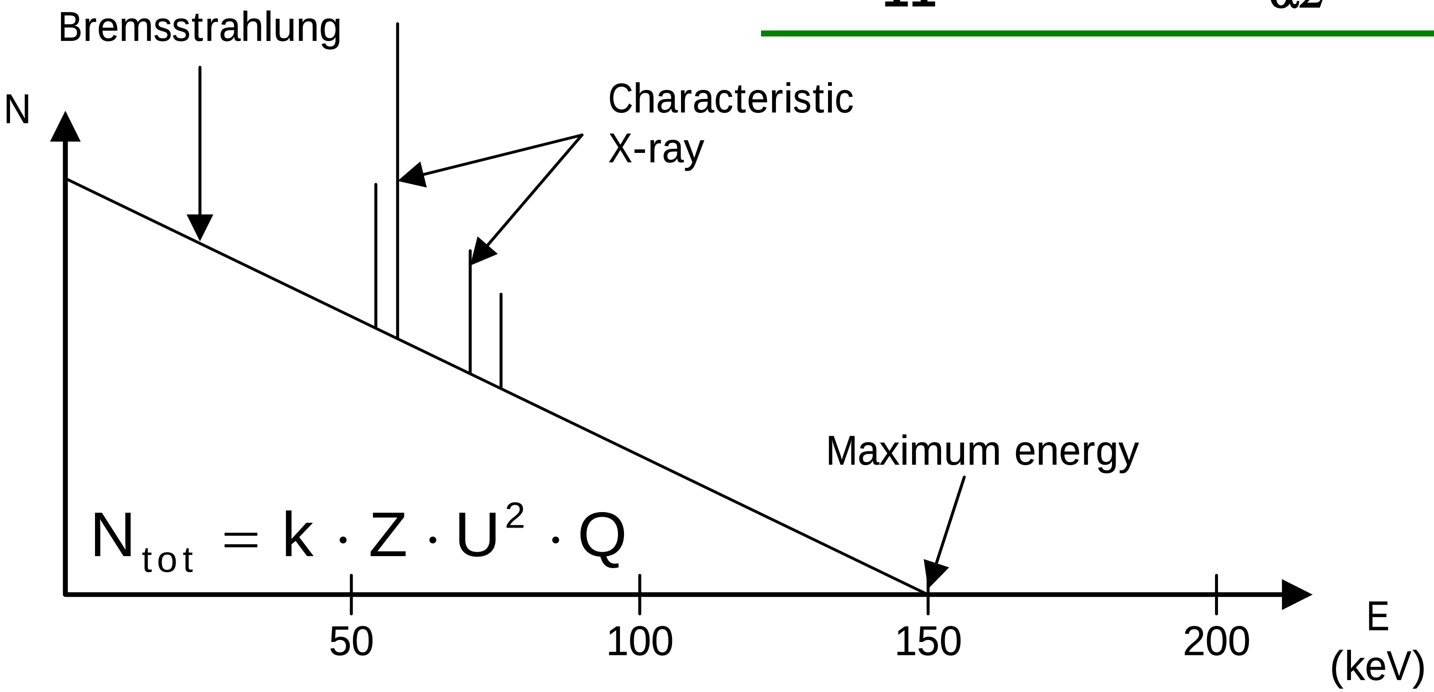
What **proportion of the energy** of an electron of **100 keV** kinetic energy is lost by bremsstrahlung in a tungsten *(Z=74)* anode?

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

X-ray production

- In tungsten (W)

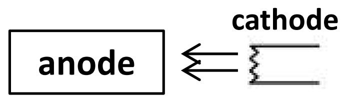
Transition		Energy
N - K	$K_{\beta 2}$	69.07 keV
M - K	$K_{\beta 1}$	67.24 keV
L_{111} - K	$K_{\alpha 1}$	59.32 keV
L_{11} - K	$K_{\alpha 2}$	57.98 keV

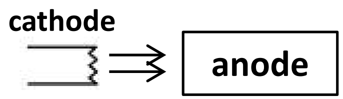


What does the color "**white**" mean on a classical radiograph?

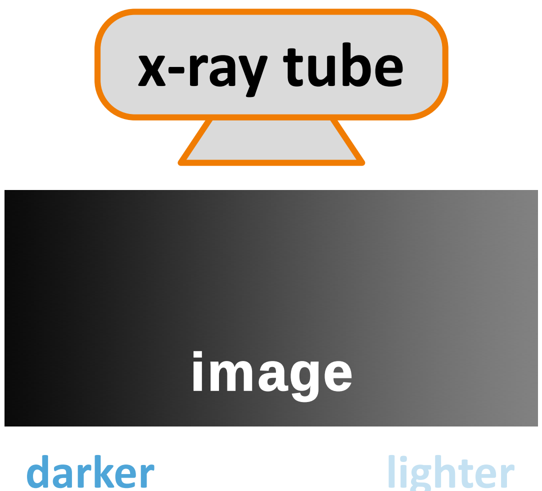
1. only a few photons arrived on the detector
2. many photons arrived on the detector
3. no idea

Where is the anode in this installation (compared to the cathode)?

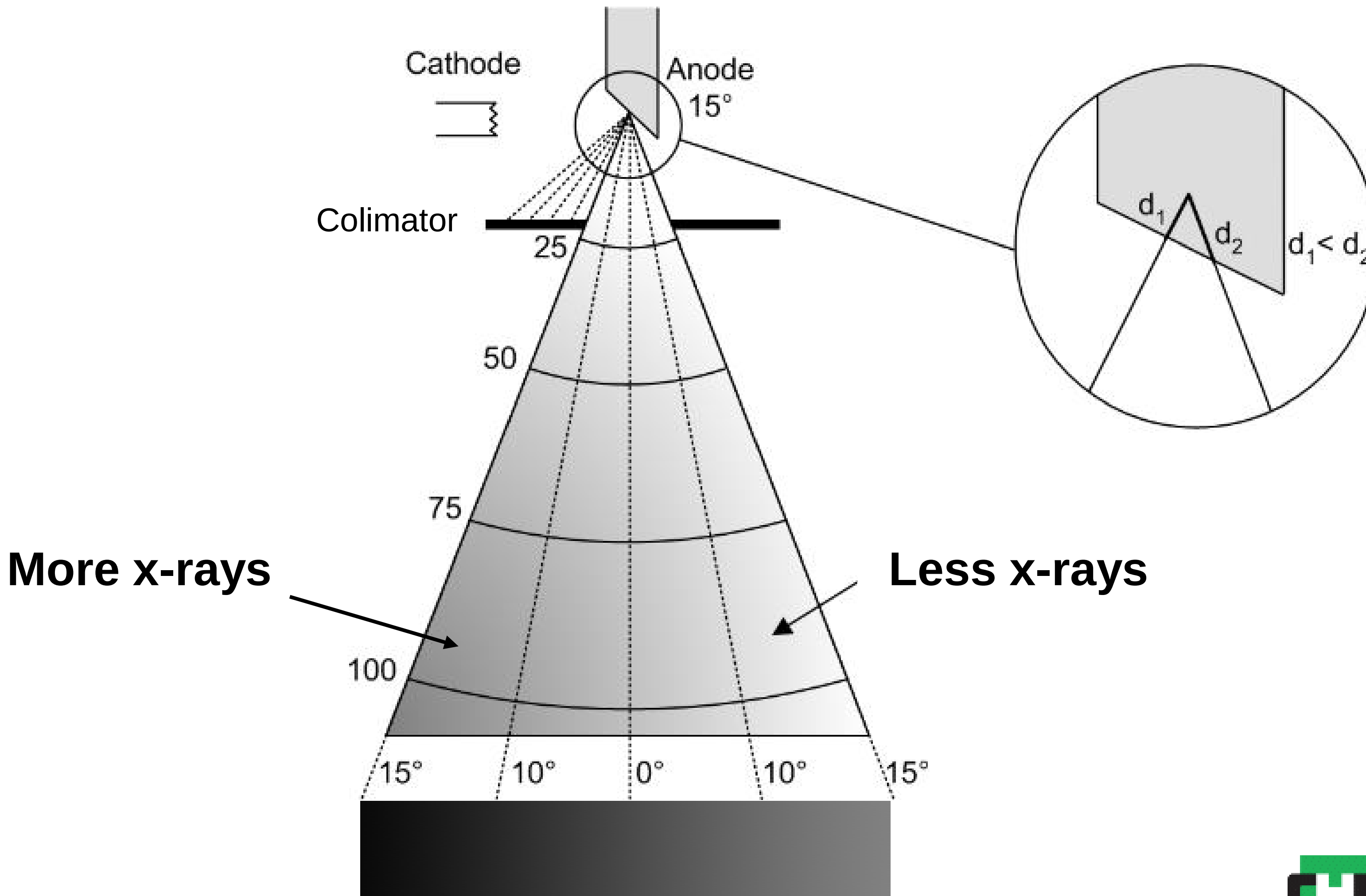
1. Left 

2. Right 

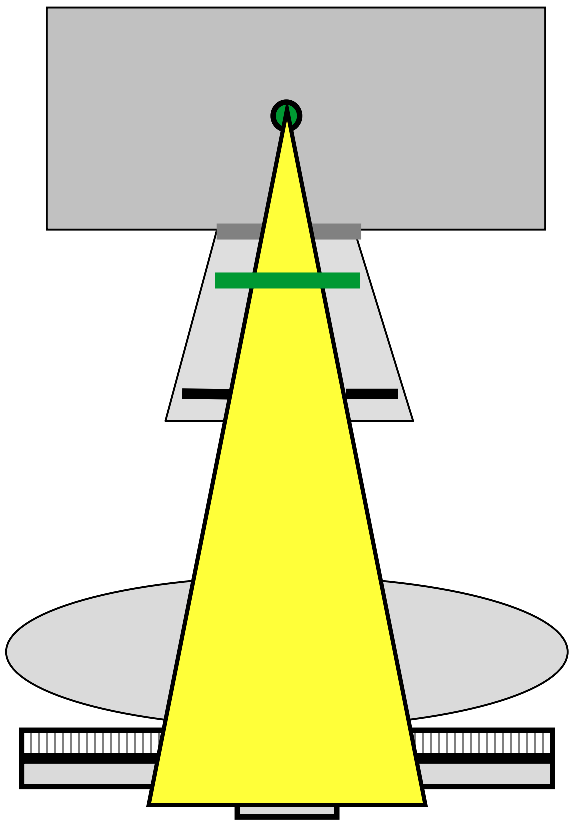
3. No idea



Heel effect



Cathode
Anode
15°
Colimator
25
50
75
100
d1
d2
d1< d2
More x-rays
Less x-rays
15°
10°
0°
10°
15°

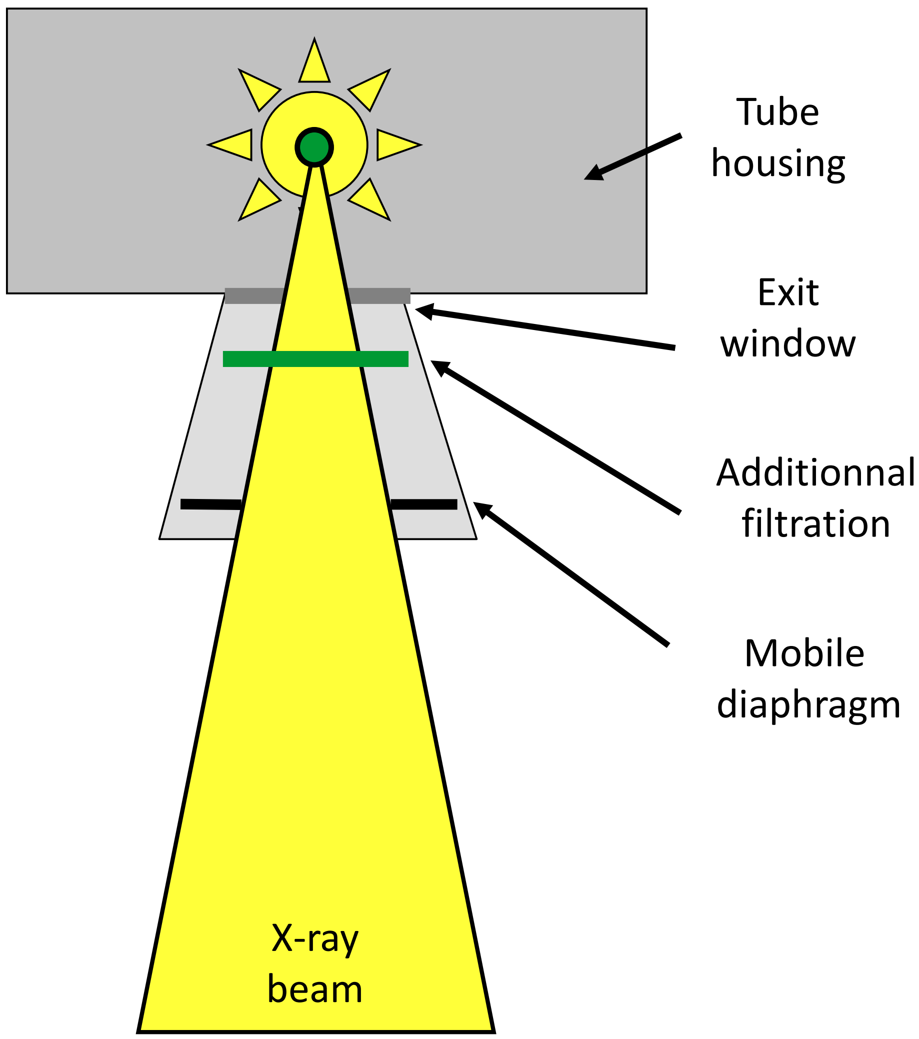


Radiography

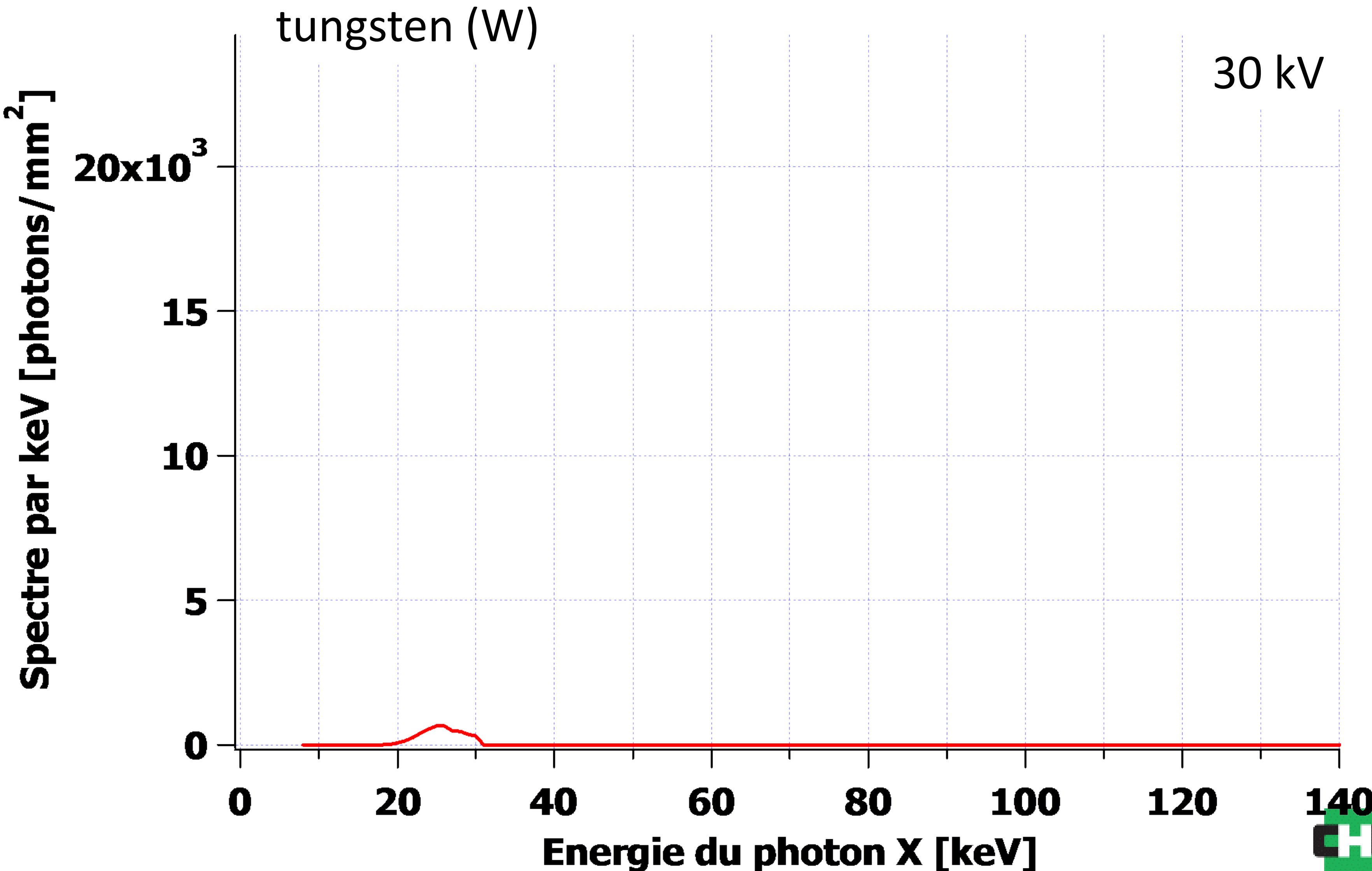
1.2 X-ray beam

X-ray beam

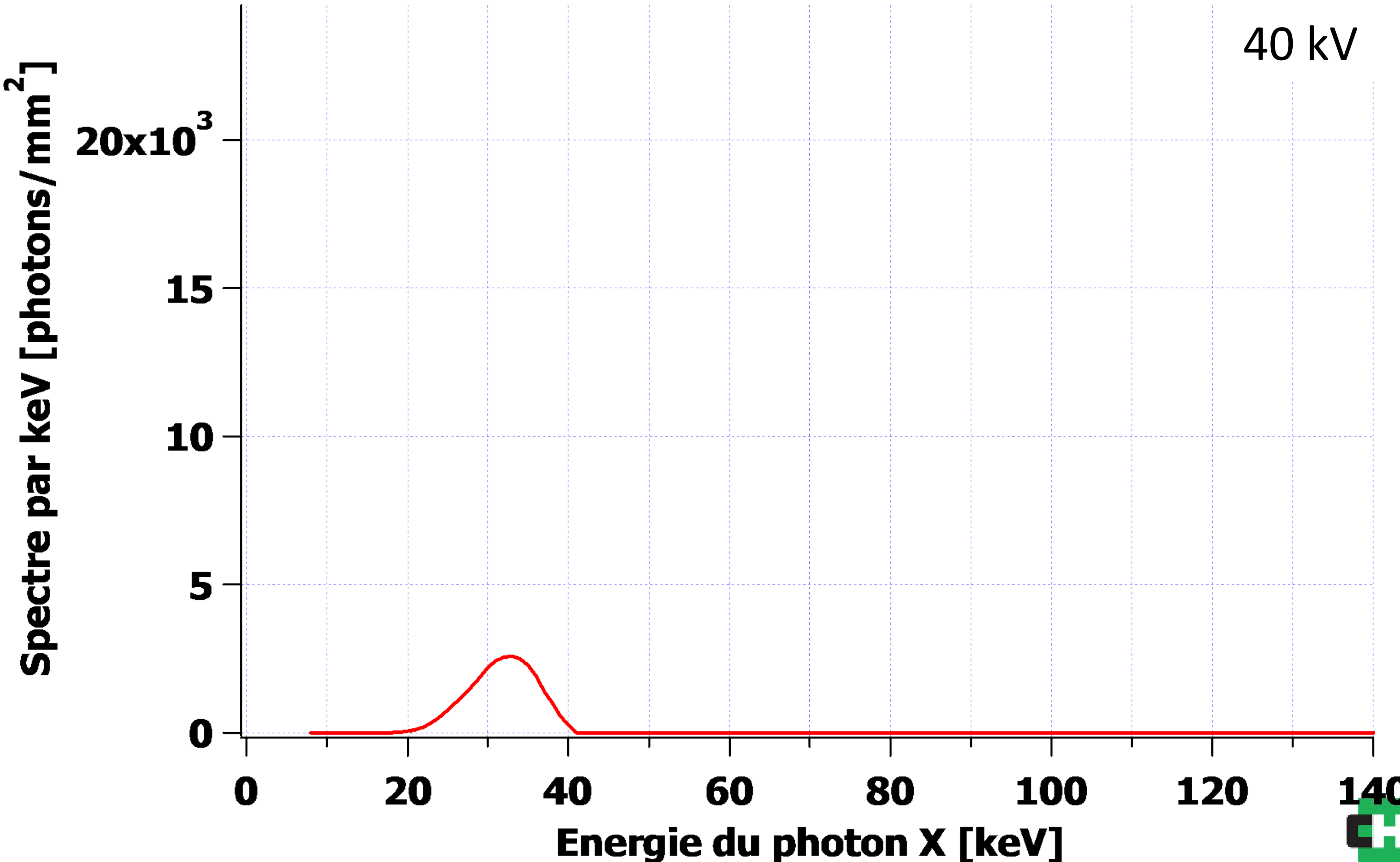
- **Emission** in whole directions
- **Absorption** in the tube housing
- Beam **filtration**
  - Preferential absorption of low-energy x-rays



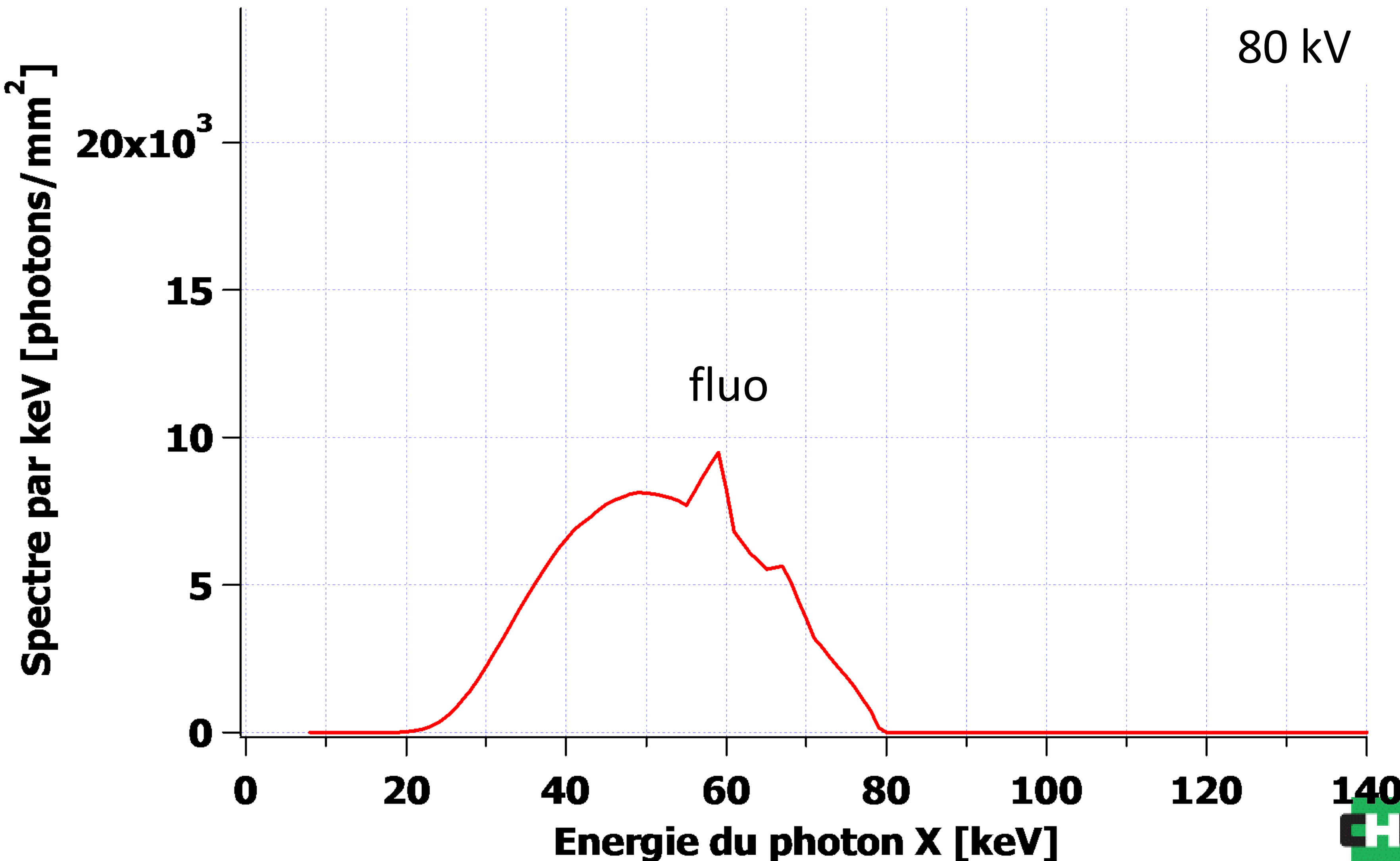
X-ray spectrum



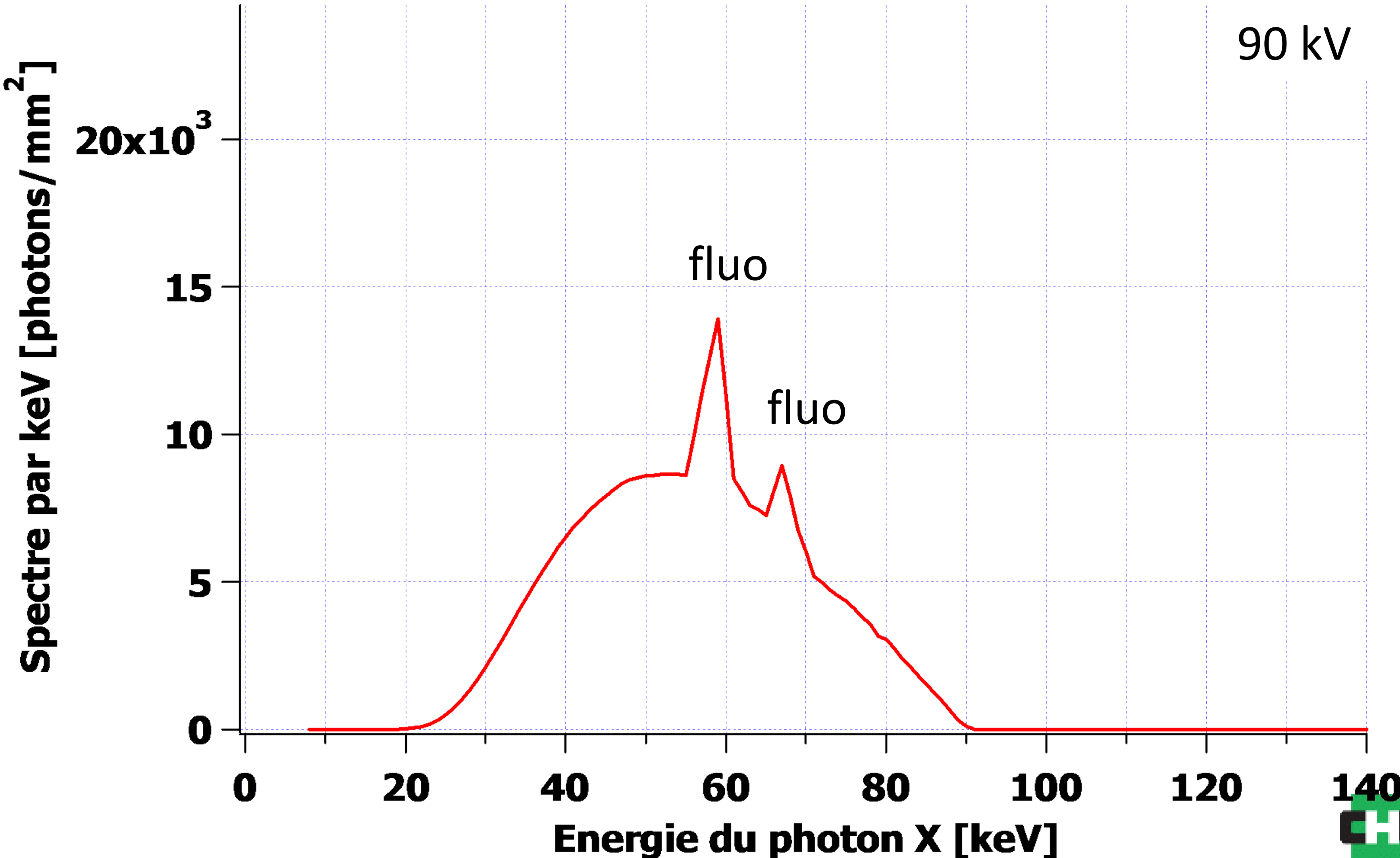
X-ray spectrum



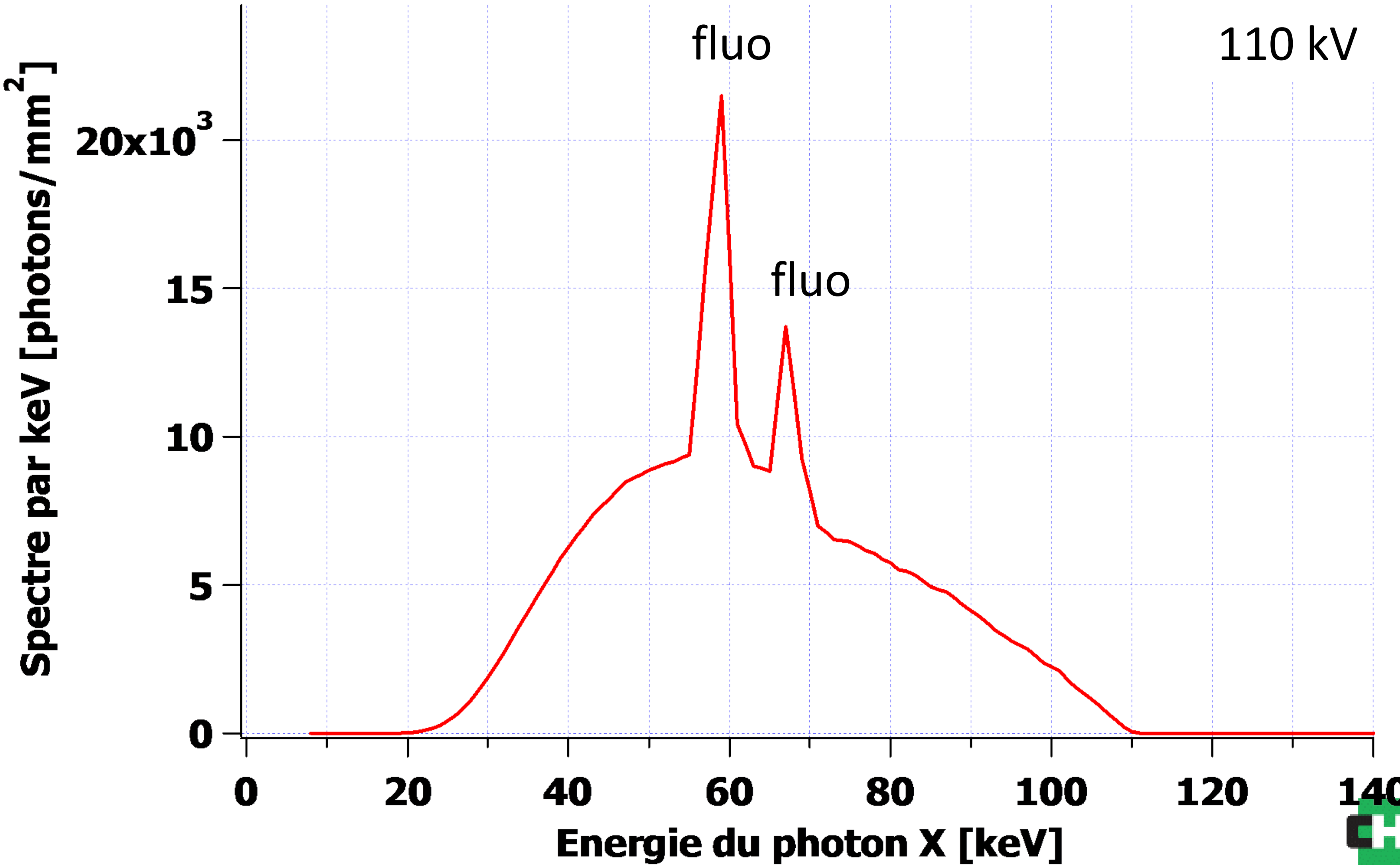
X-ray spectrum



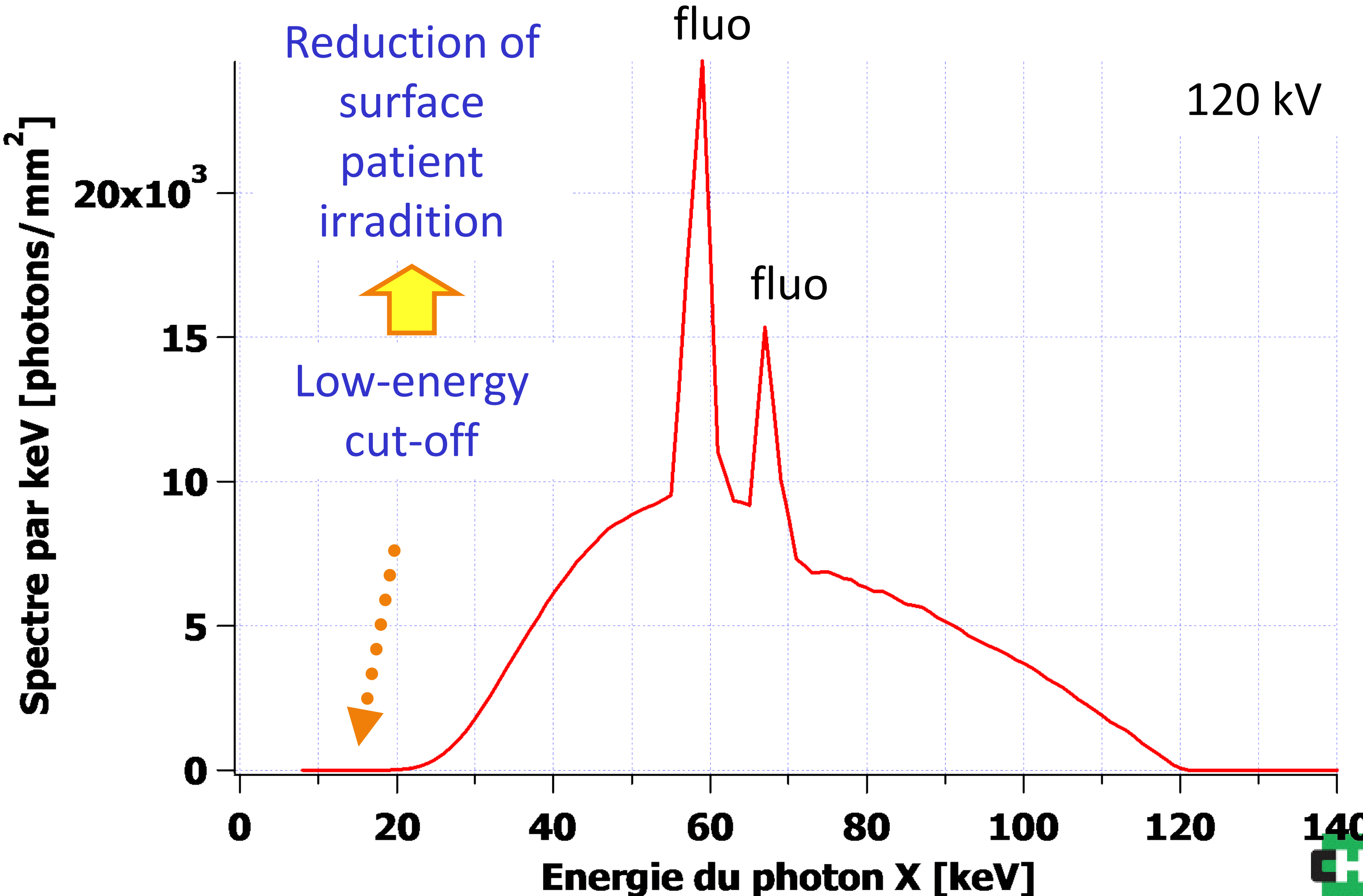
X-ray spectrum



X-ray spectrum



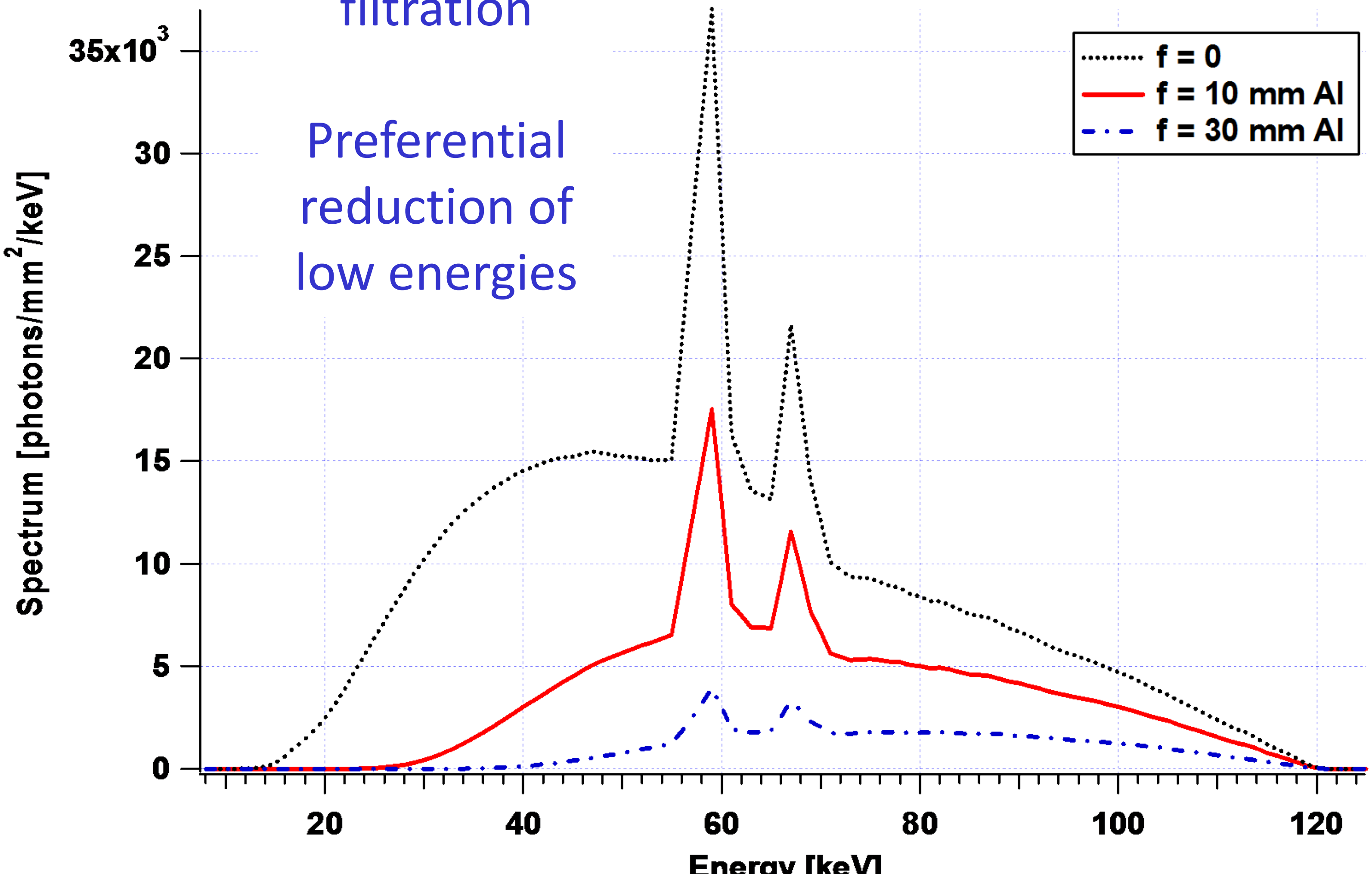
X-ray spectrum



X-ray spectrum: filtration

Increased filtration

Preferential reduction of low energies



Photon **attenuation** and **half-value layer**

linear attenuation coefficient

Number of mono-energetic photons crossing distance x without attenuation

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

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*

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

Exercise

We measure HVL = 3mm Al

What is the effective energy?

1. 25 keV
2. 35 keV
3. 45 keV
4. 55 keV
5. 65 keV
6. 75 keV
7. 85 keV

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

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

Photon **attenuation** and **half-value layer**

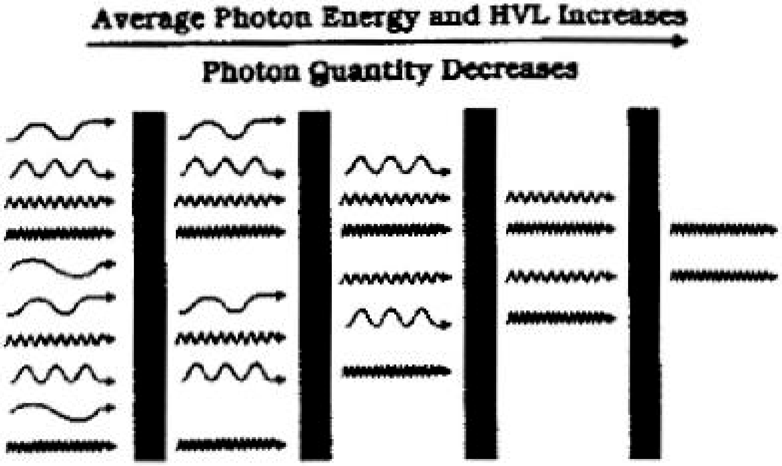
Effective energy

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

Beam hardening

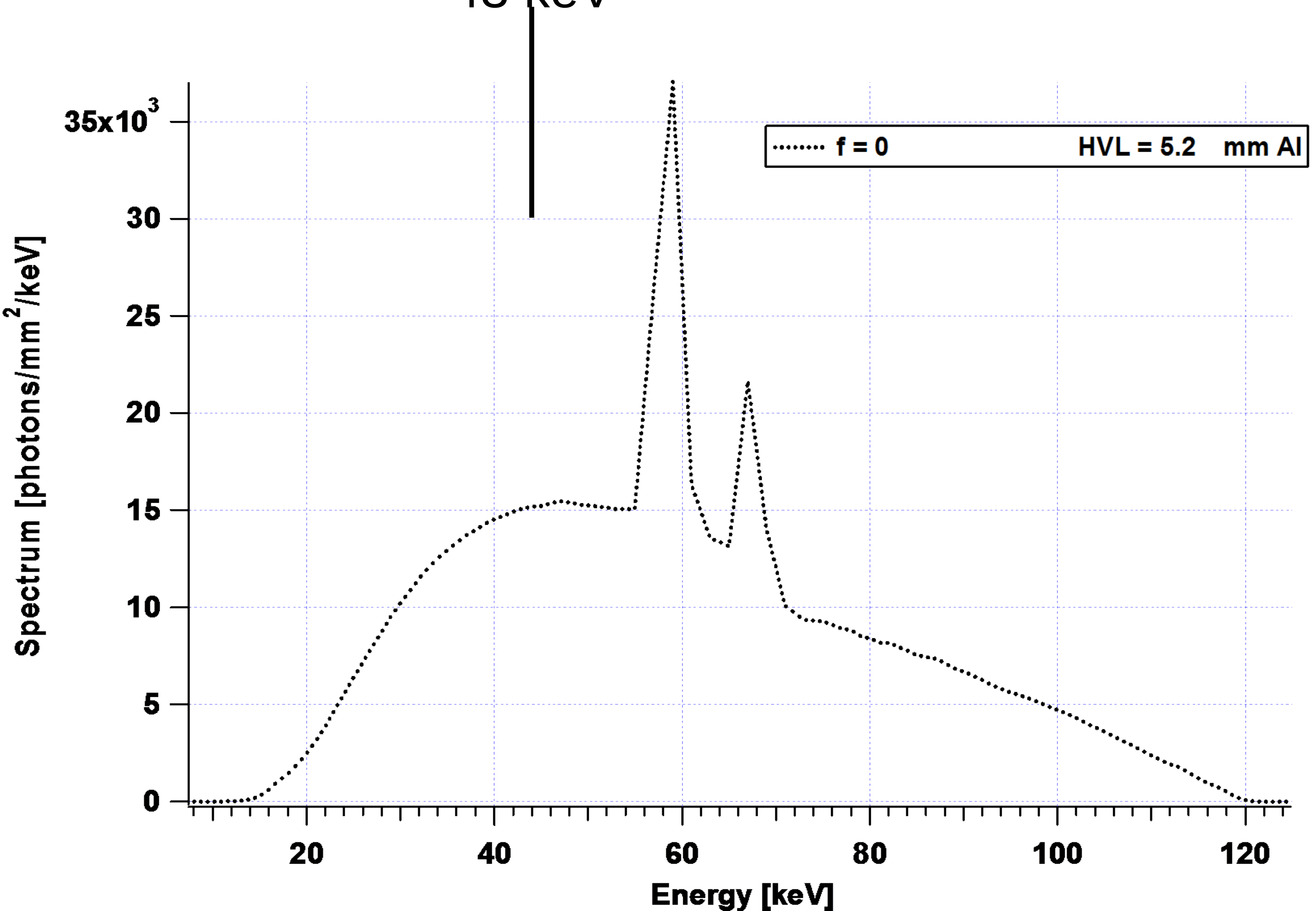
$$H = \frac{1^{st}\,\mathrm{HVL}}{2^{nd}\,\mathrm{HVL}}$$

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

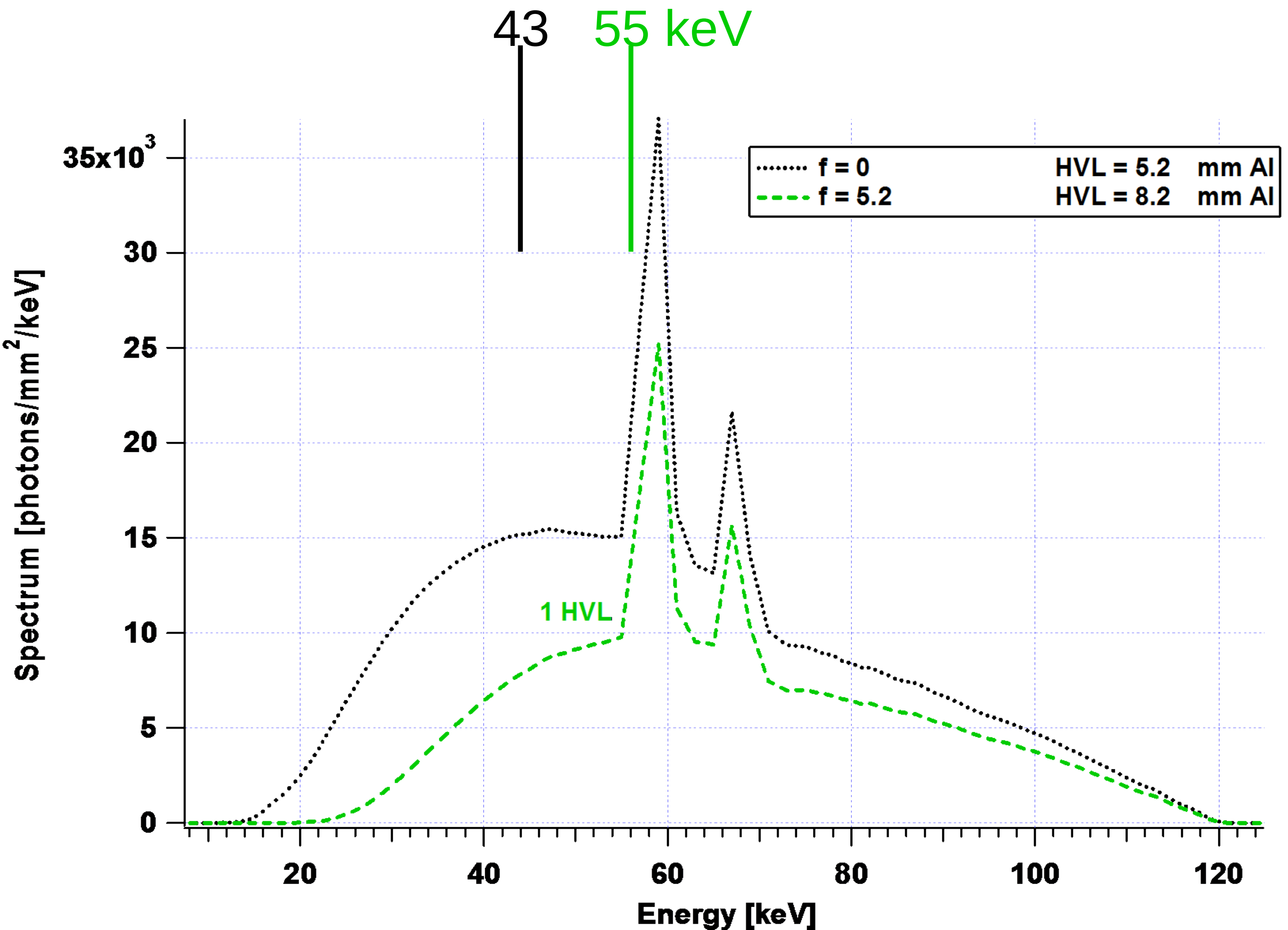


X-ray spectrum: HVL

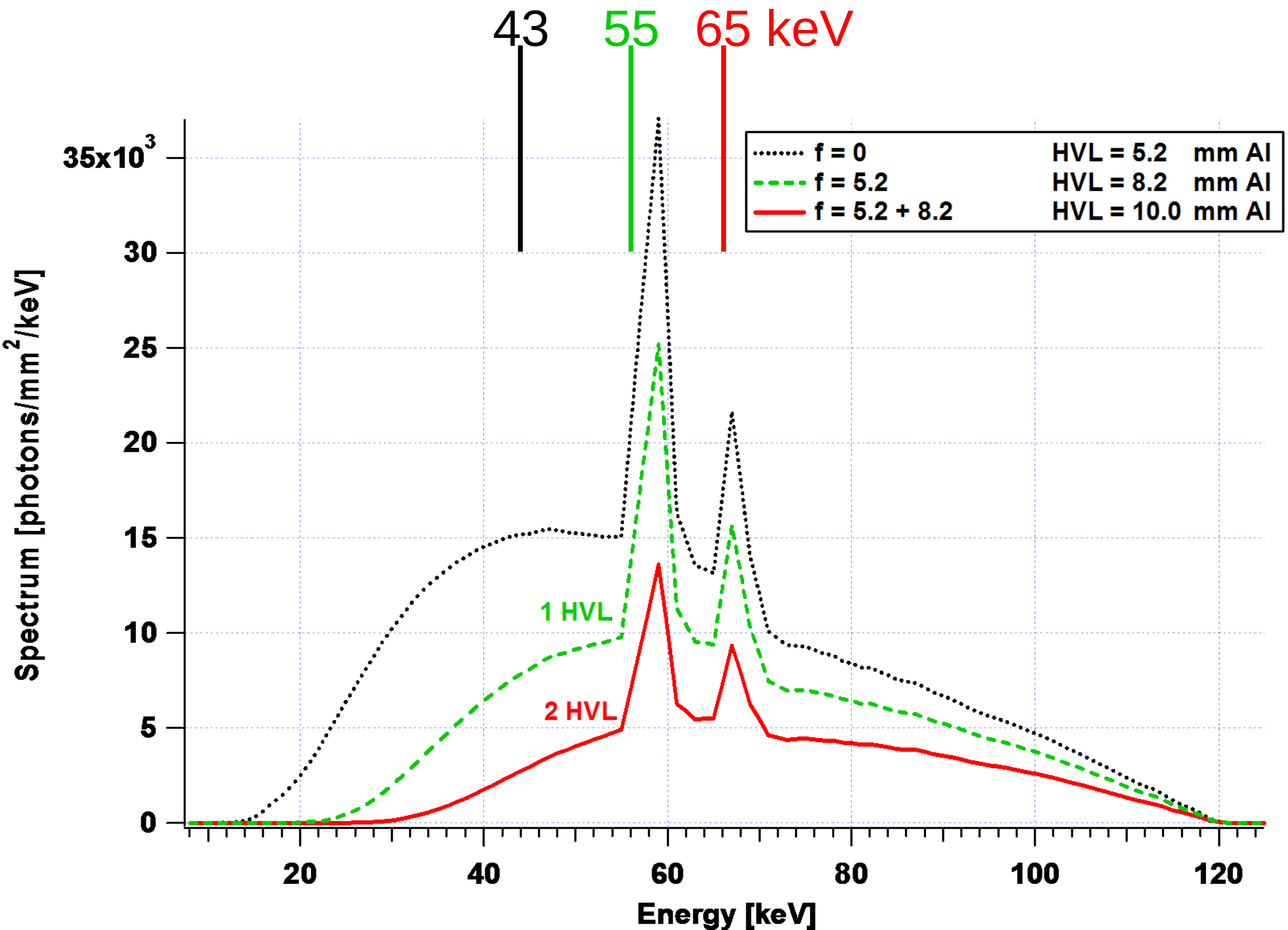
43 keV



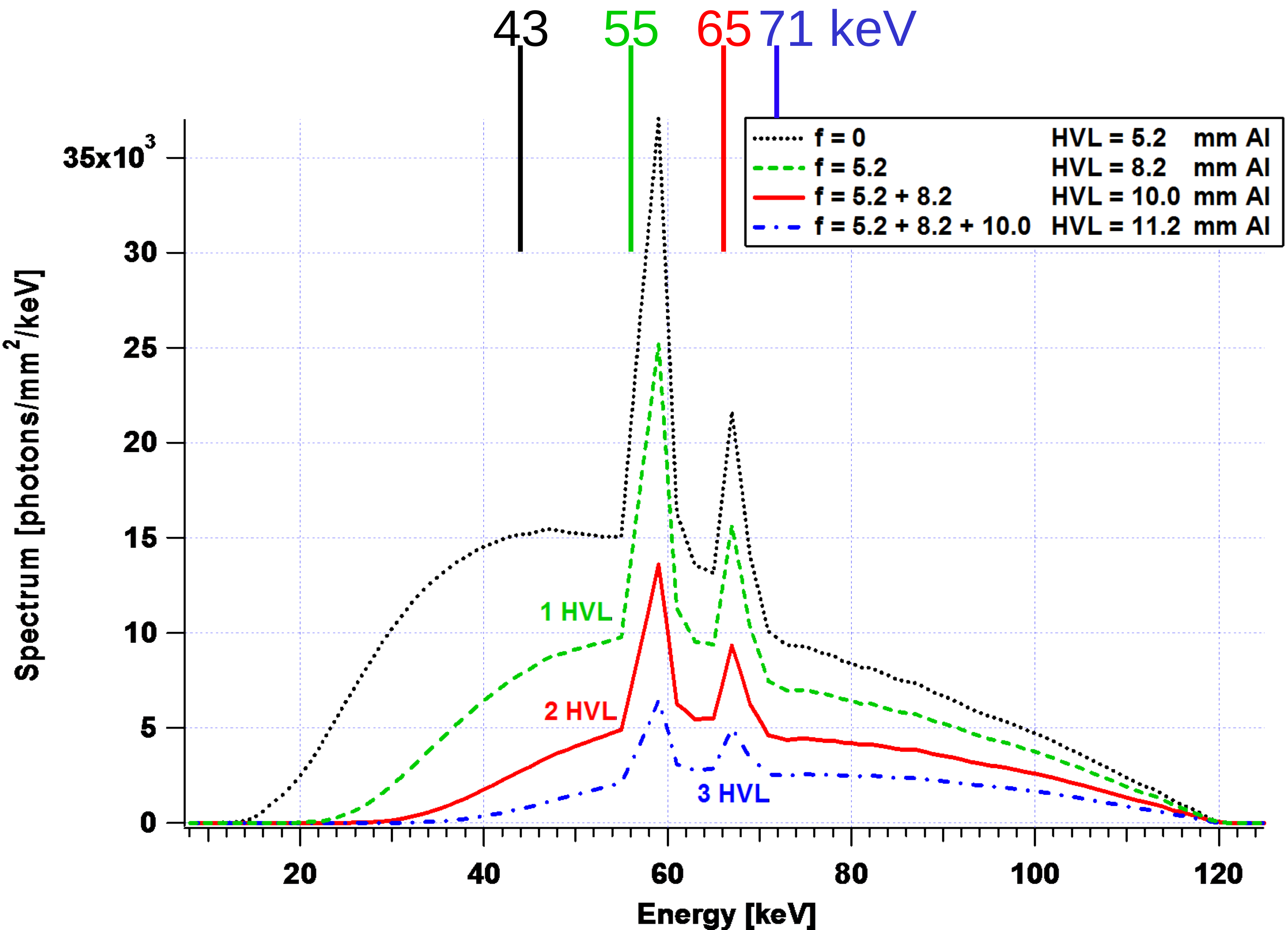
X-ray spectrum: HVL



X-ray spectrum: HVL



X-ray spectrum: HVL



Effects of **kVp** and **mAs**

kVp

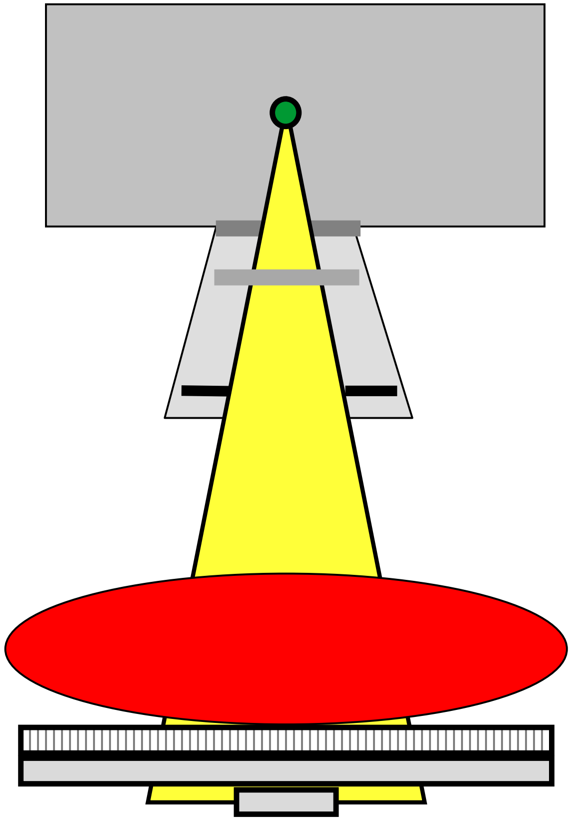
Beam **quality** defined by

voltage [kVp]
ripple
beam filter

mAs

X-ray **quantity** defined by

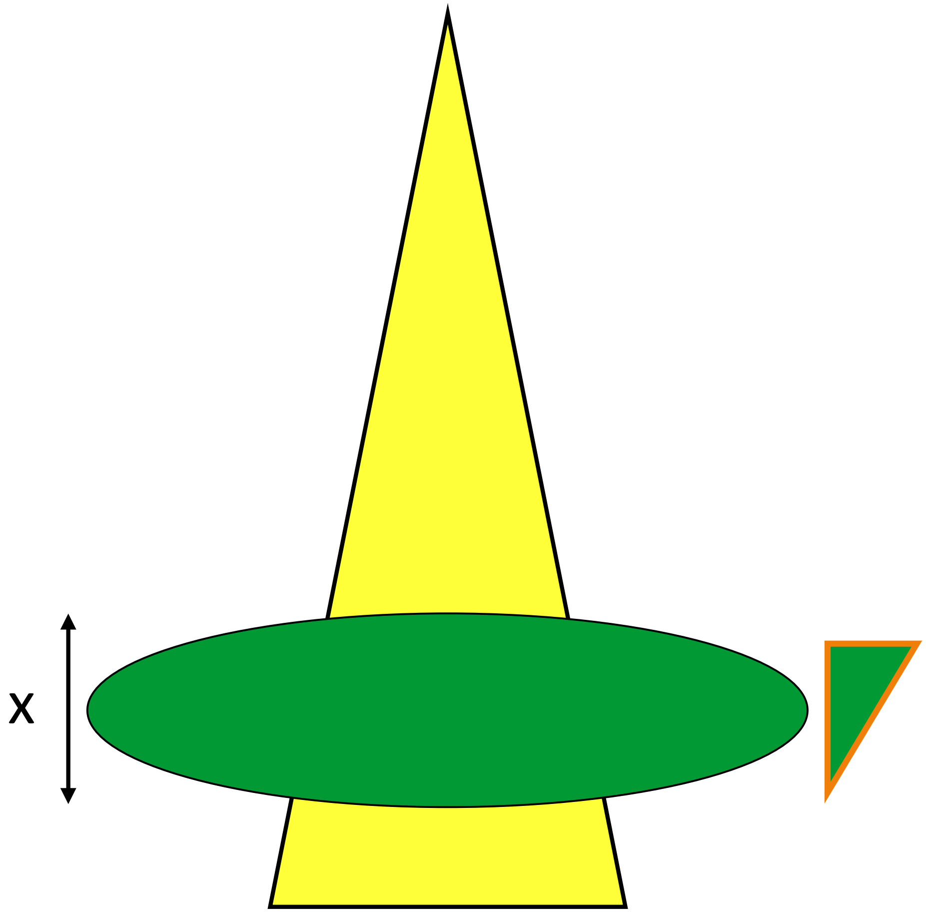
current [mA]
time [s]



Radiography

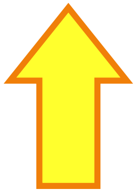
1.3 Interaction with the patient

Interaction with the patient



Radiography:
Transmission experiment

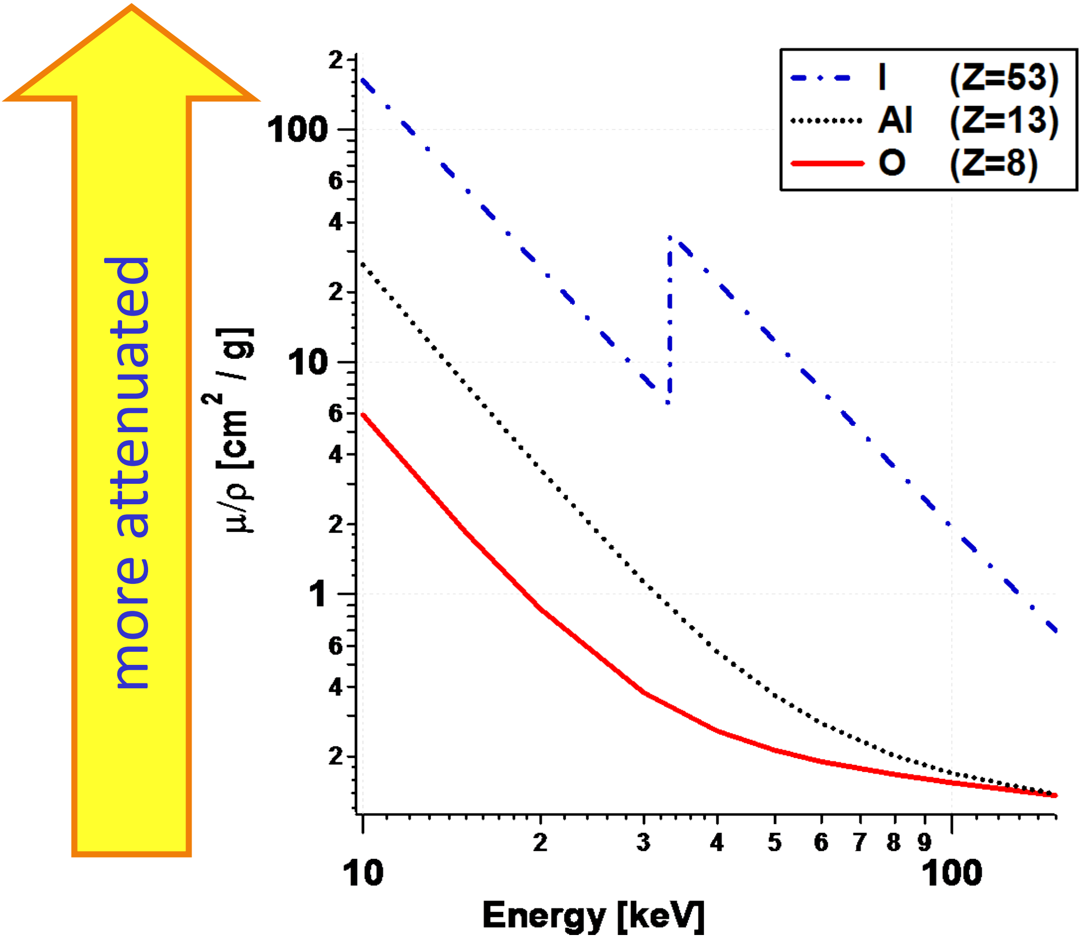
depends on
attenuation coefficient μ



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

exponential attenuation

Interaction with the patient



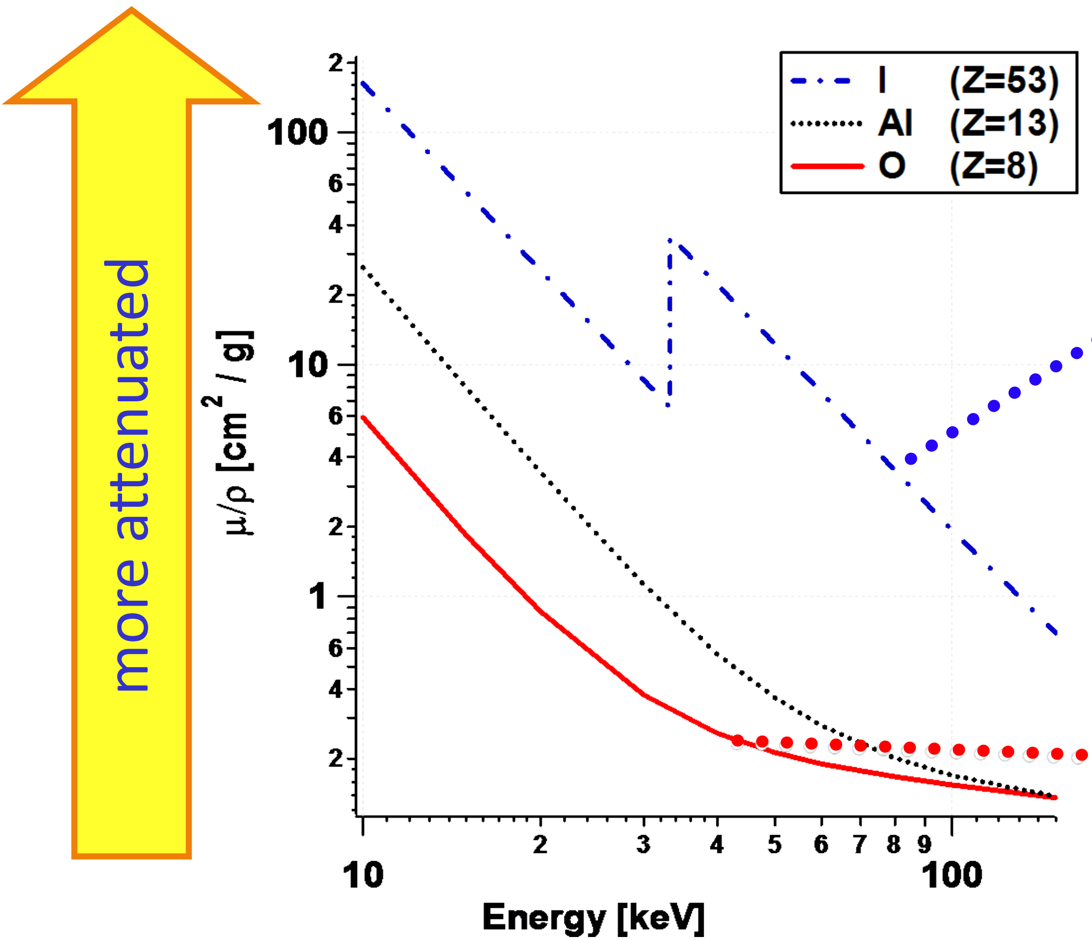
Radiography:
Transmission experiment

depends on
attenuation coefficient μ

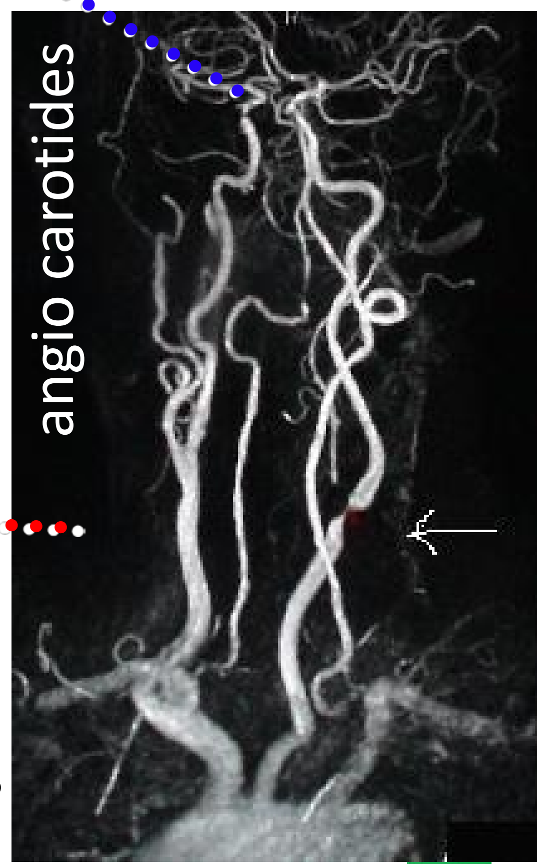
$$I(x) = I_0 \cdot e^{-\mu x}$$

exponential attenuation

Interaction with the patient



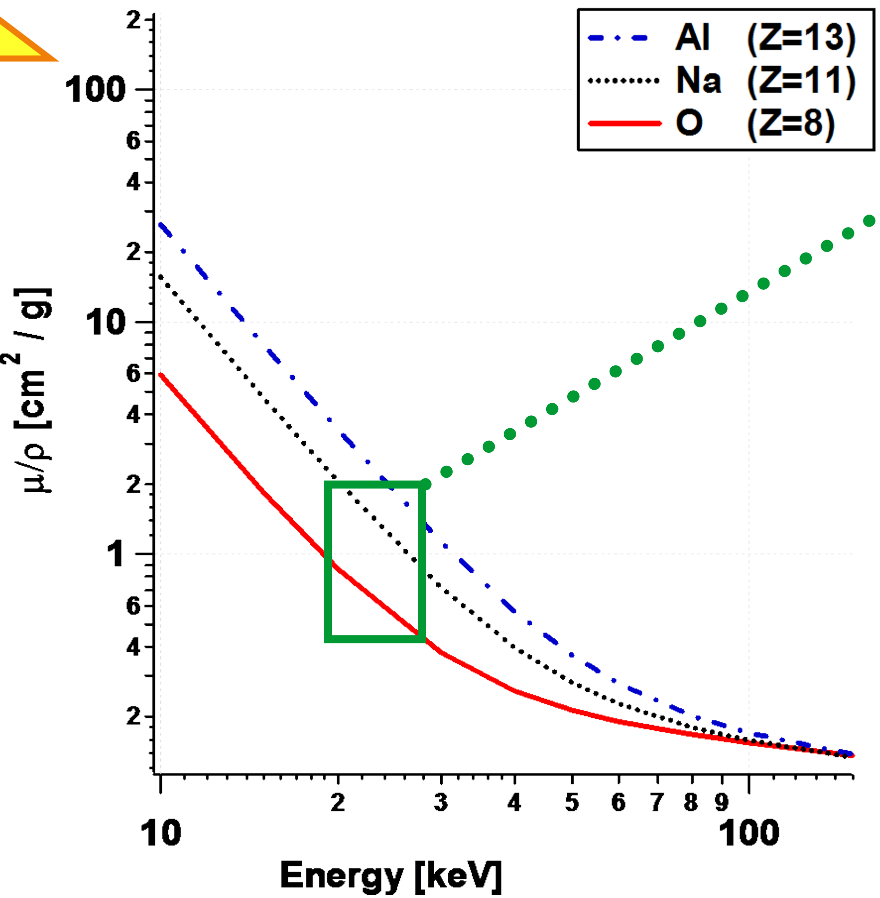
Contrast product
high Z material, much more attenuated than tissues



stenosis

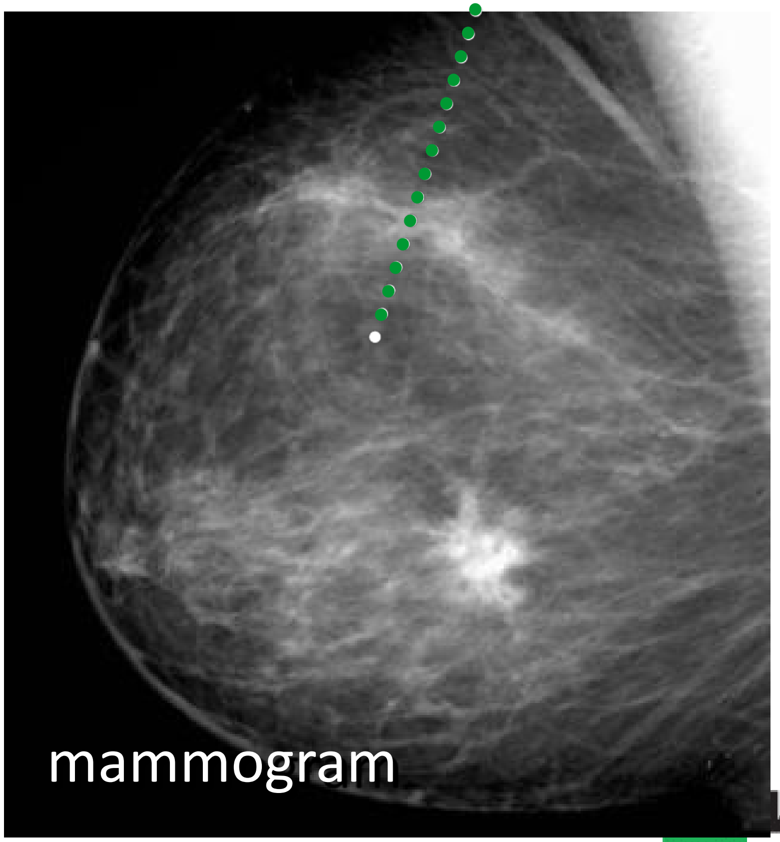
Interaction with the patient

more attenuated

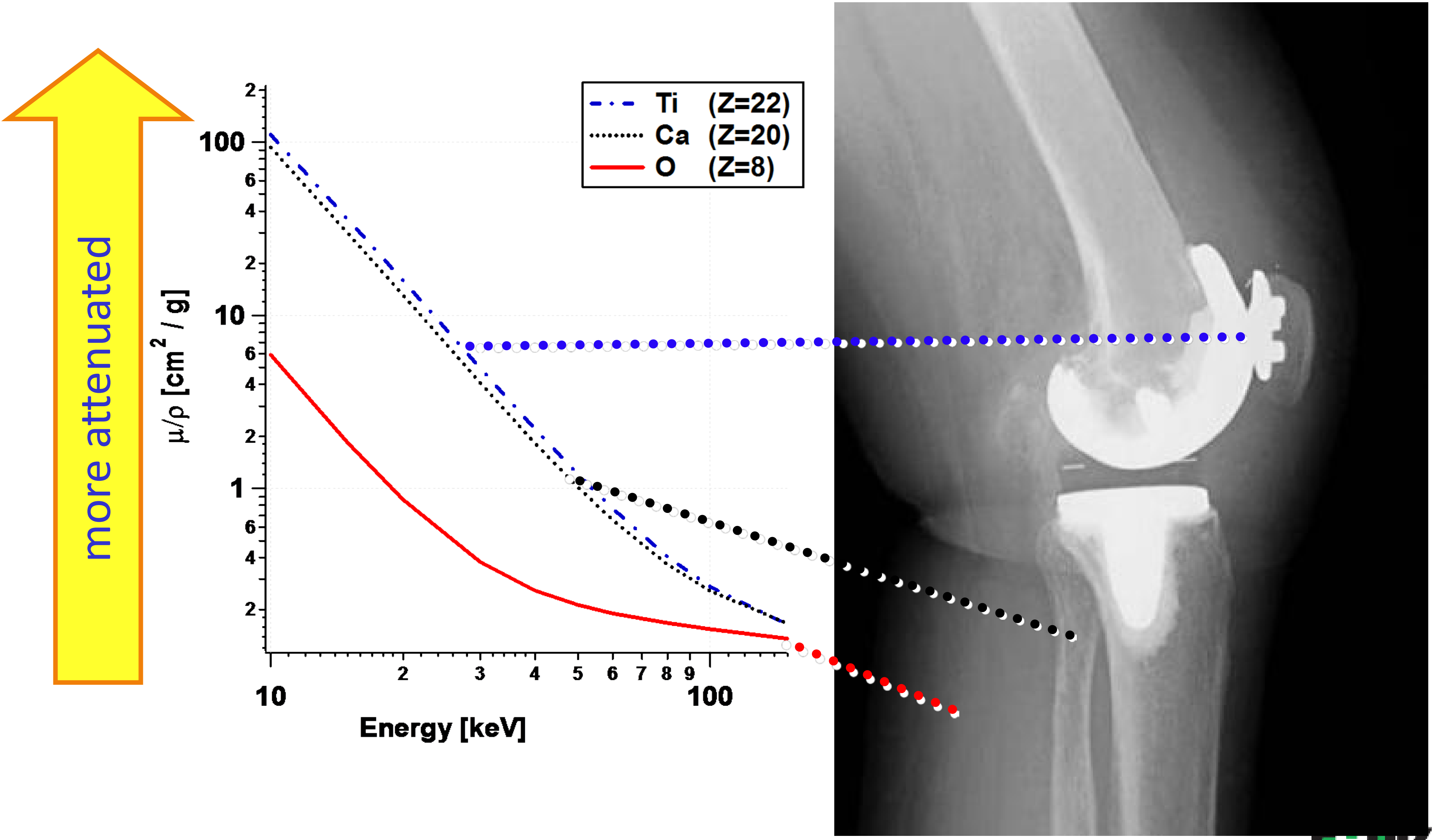


soft tissues

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

Dose-contrast relationship

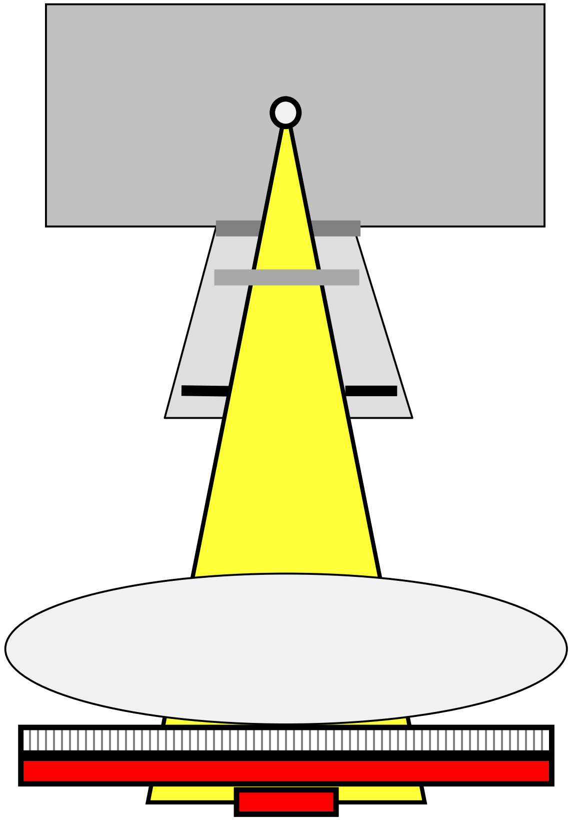
The absorbed dose is directly correlated to the attenuation

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

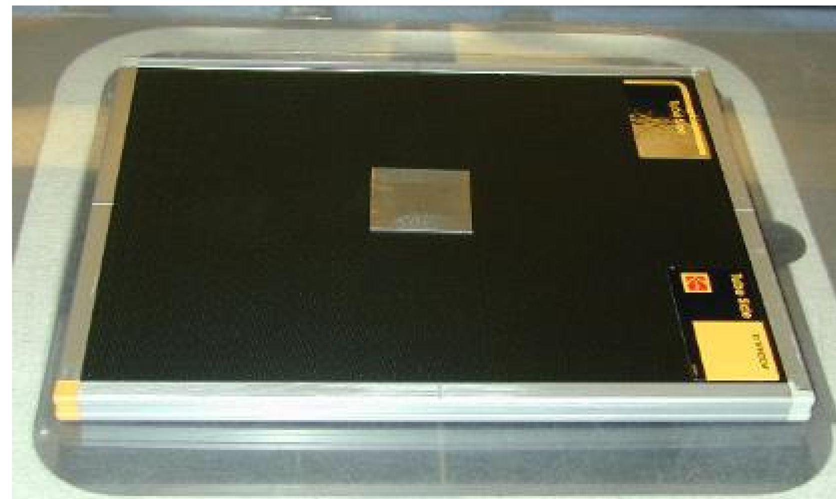


Radiography

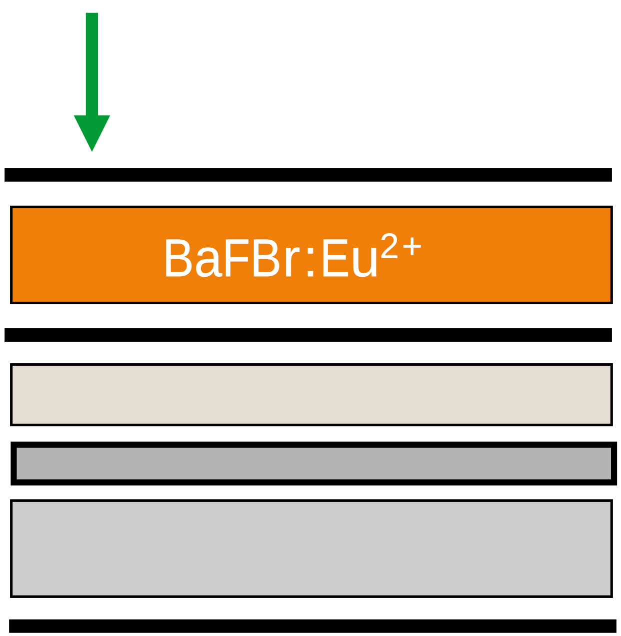
1.4 Detection system

CR computed radiography

- Latent image
  - within the phosphore
- Delayed reading
  - by laser
  - digital image



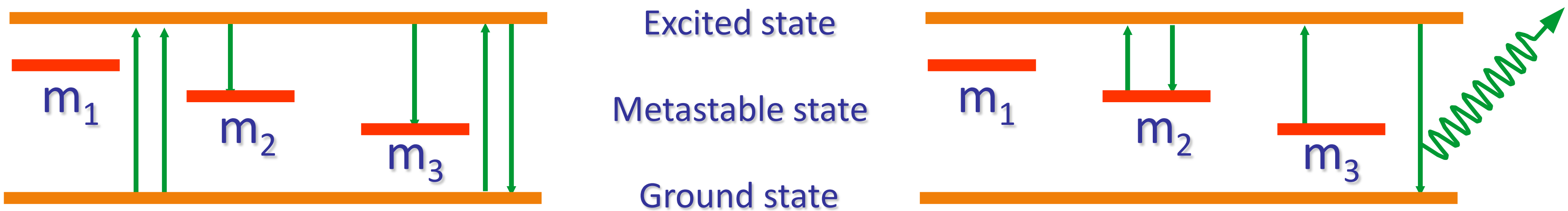
X-ray



CR computed radiography

during irradiation

during reading



Electrons excitation

metastable state

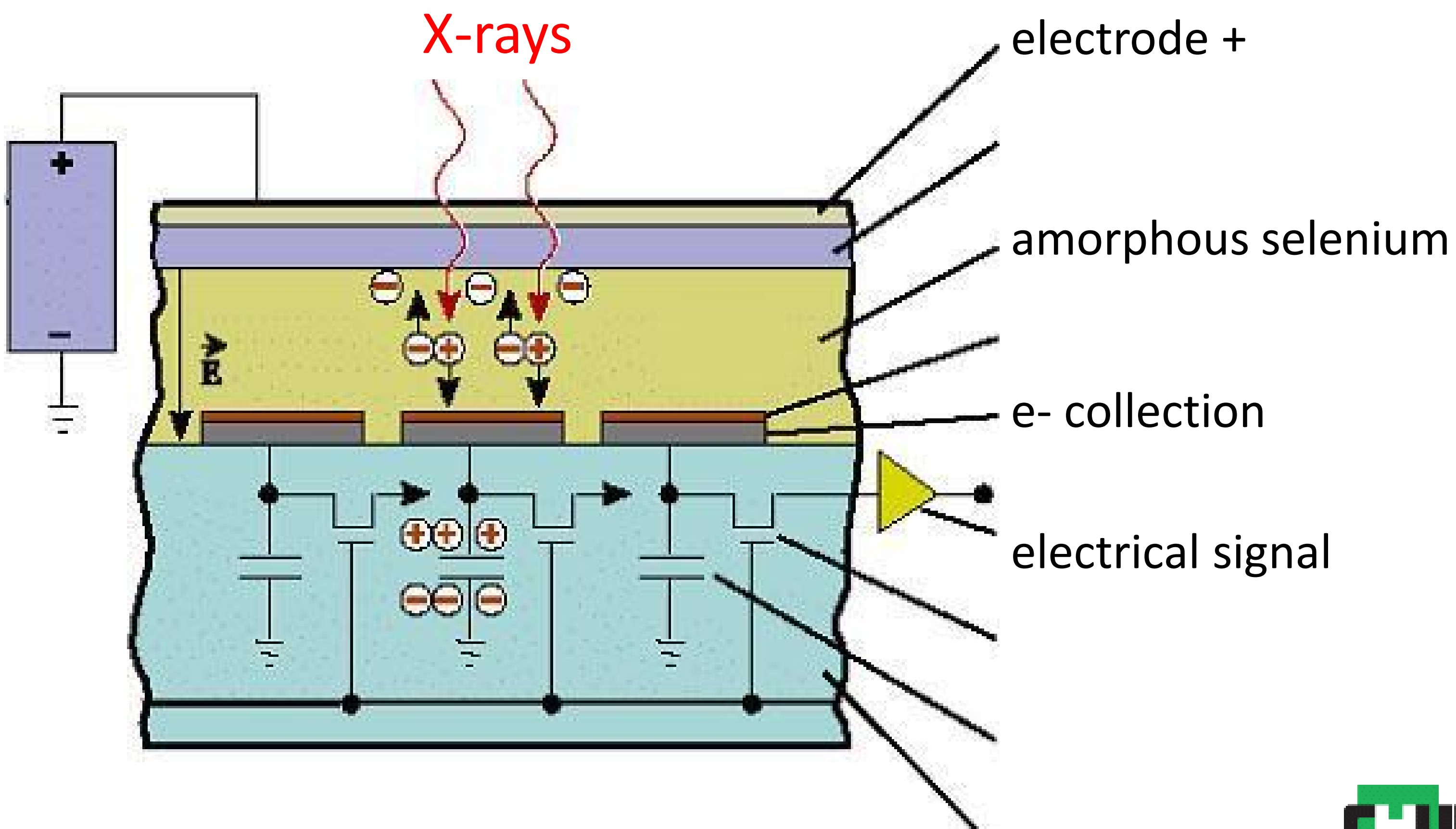
Laser excitation

Electron de-excitation to ground state

Light emission

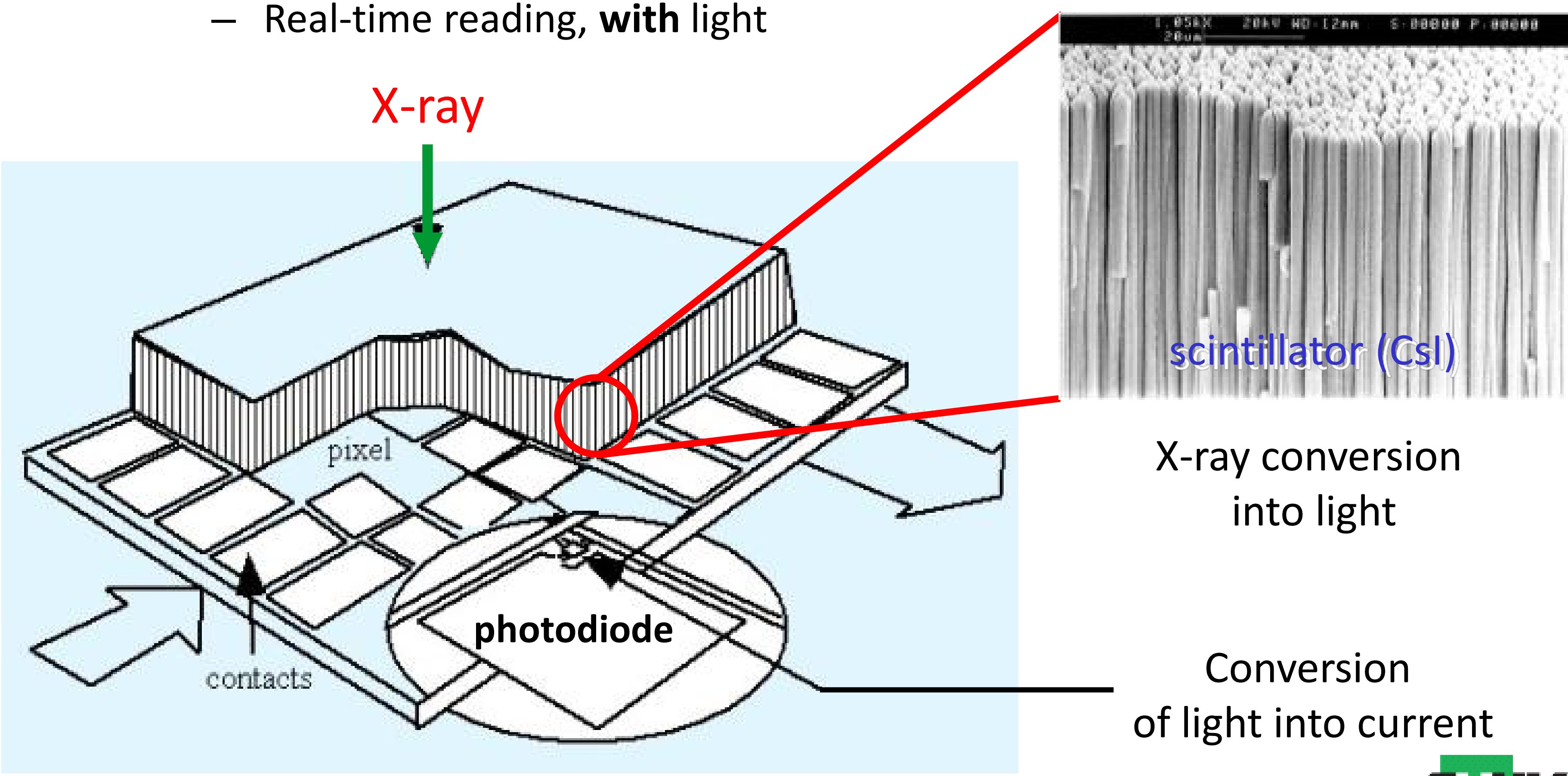
DR digital radiography

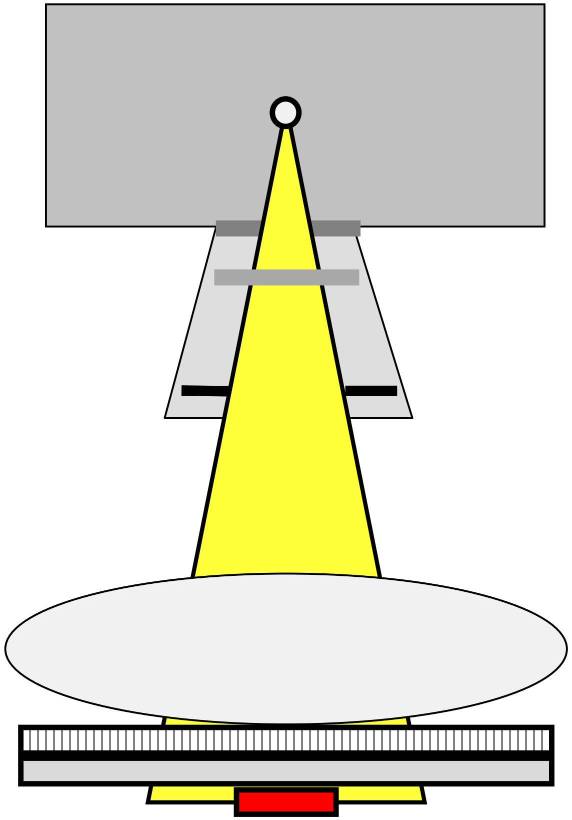
- **Direct** conversion of the x-ray into charge
  - Real time reading **without light**



DR digital radiography

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





Radiography

1.5 Dosimetry

What is the kerma?

1. The energy transferred by the photons to the electrons per unit of mass
2. A quantity that characterize the amount of radiation at a given point
3. The energy deposited in matter

X-ray beam : air kerma

ok between 75 and 125 keV

Charge (mAs)

$$K_{air} = C \cdot \left[\frac{U(kV)}{100}\right]^2 \cdot Q \cdot \frac{1}{r^2} \cdot \frac{3}{F(mmAl)}$$

radiological constant of air kerma

Distance to focus

Filtration

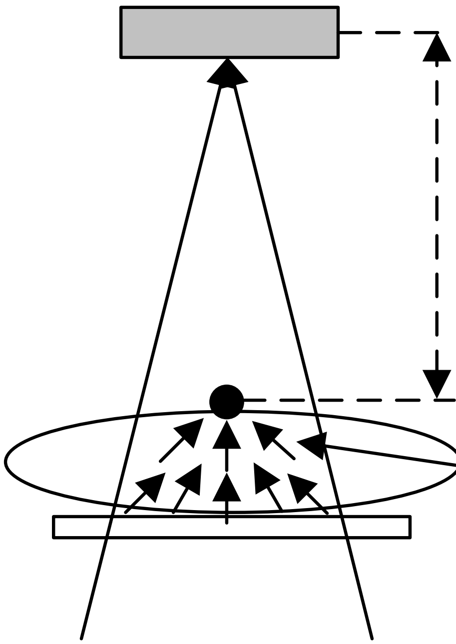
air kerma at 100 kV for 1 mAs at 1 m
Generic value : 0.1 mGy m^2/mAs

Accuracy : factor 2

CHUV

Dose calculation

- Entrance dose



$$ED[mGy] = C\left[\frac{mGy \cdot m^2}{mAs}\right] \cdot \left(\frac{U[kV]}{100\ kV}\right)^2 \cdot Q[mAs] \cdot \frac{1}{d_{FP}^2[m]} \cdot \frac{3mm}{F[mmAl]} \cdot BSF \cdot F_{KD}$$

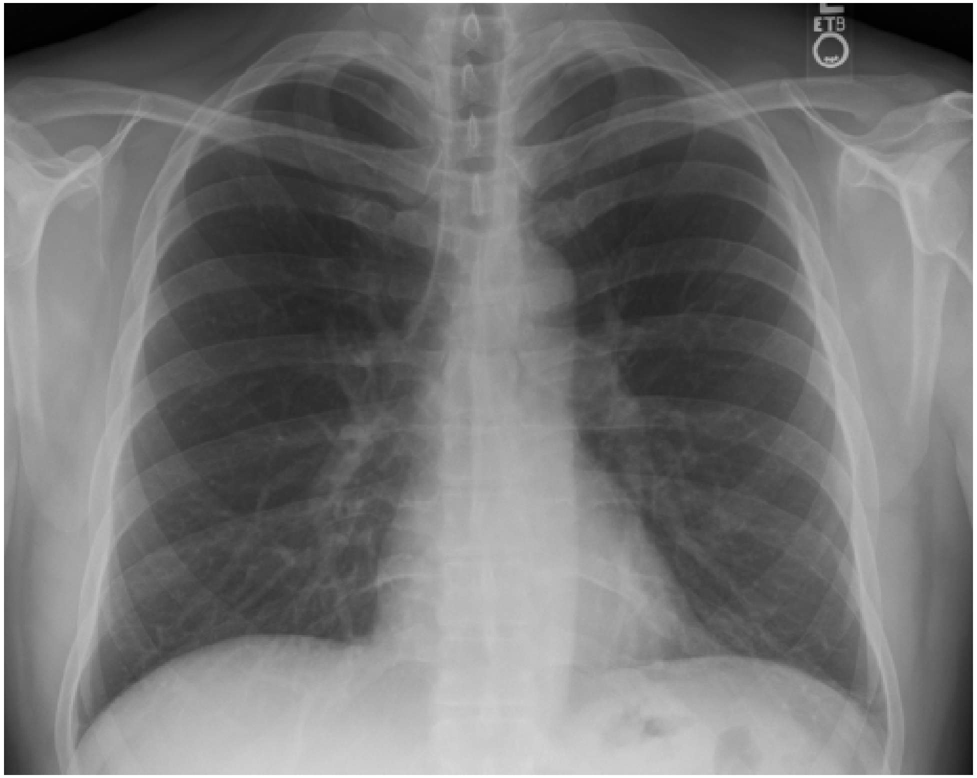
0.1

1.35 **backscatter factor**

kerma-dose conv factor (=1)

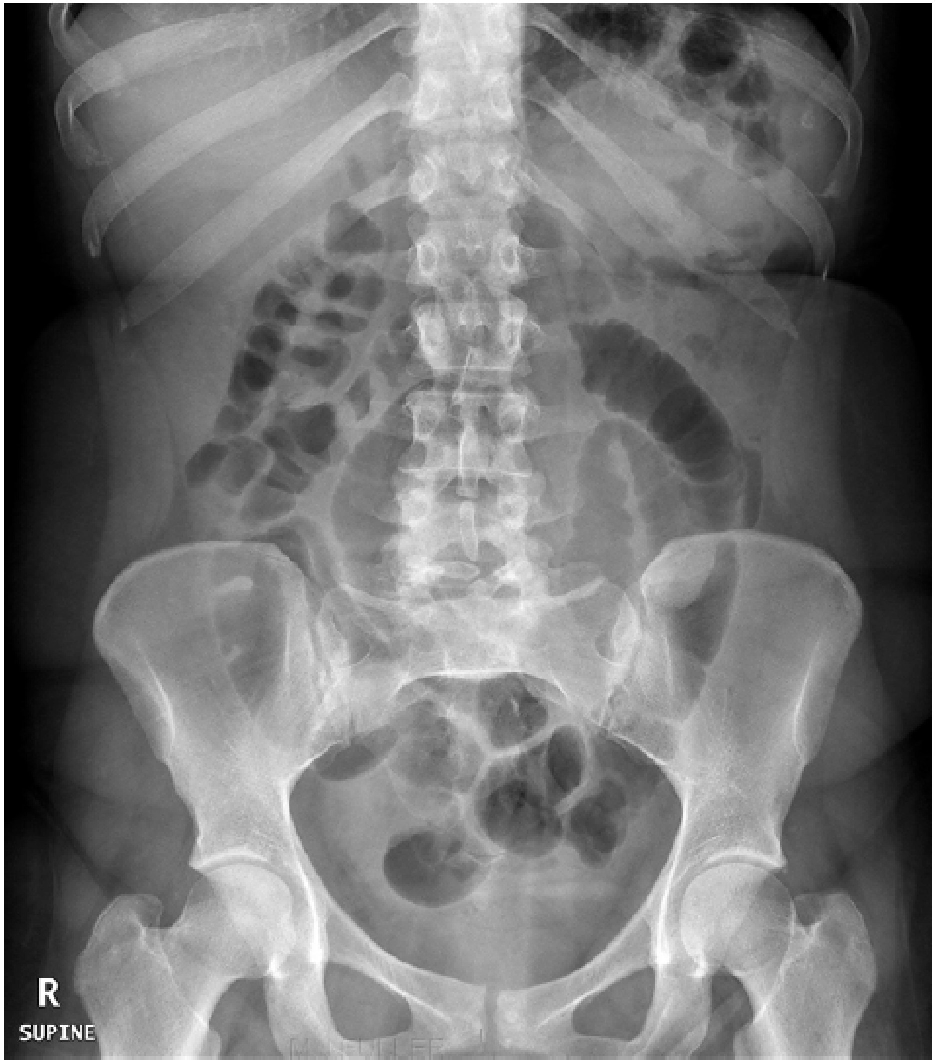
Chest radiography
Exercise

What is the
dose to the skin?
(120 kV / 0.5 mAs / 1.8 m)



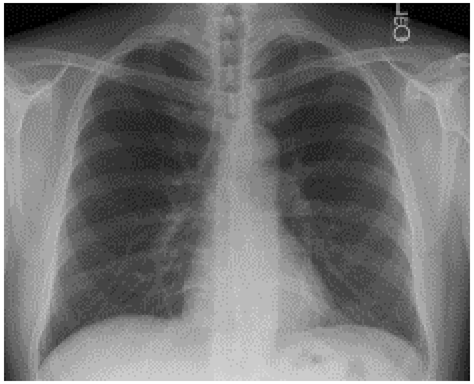
Abdomen radiography
Exercise

What is the
dose to the skin?
(80 kV / 80 mAs / 1 m)



skin dose
0.03 mGy

thickness
~18 cm
(density 0.3)



skin dose
6.9 mGy

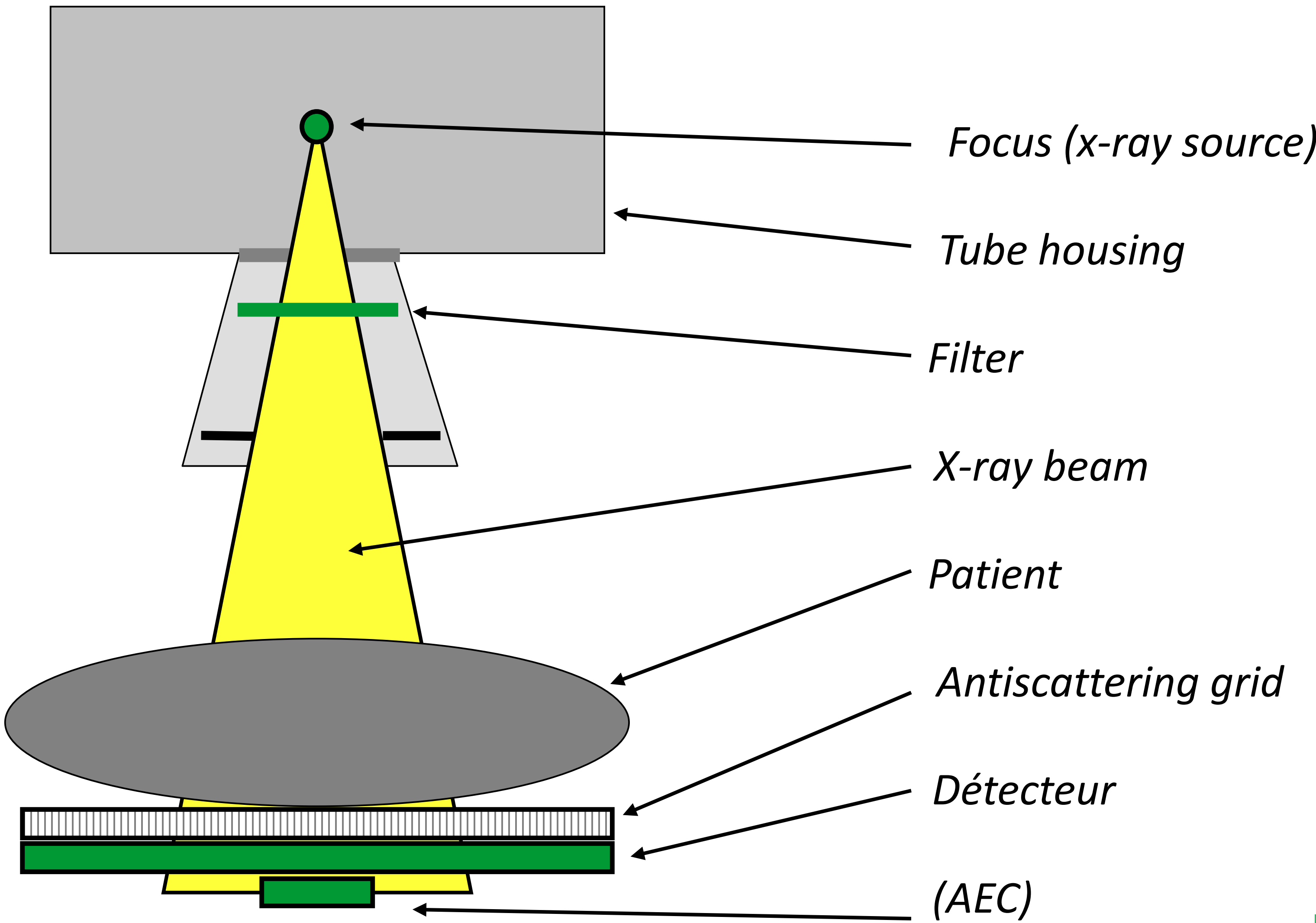
thickness
~18 cm
(density 1)

In both cases, we have **2 µGy** to the **detector**

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

Summary



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