Measurement of X-ray machine spectra

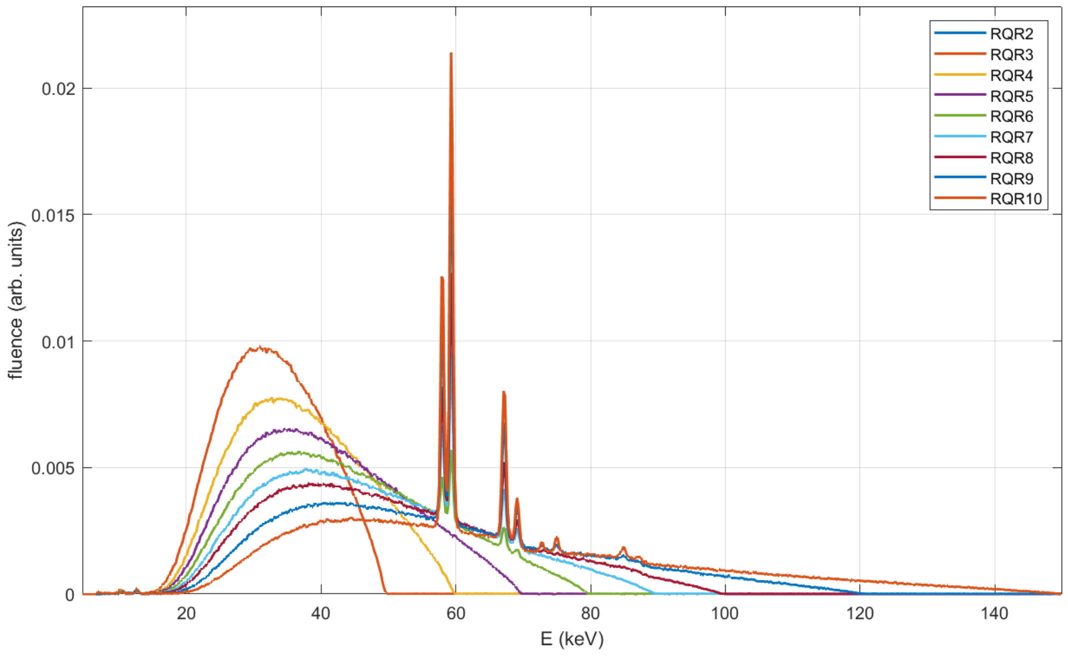
CCRI webinar, 31.5.2022

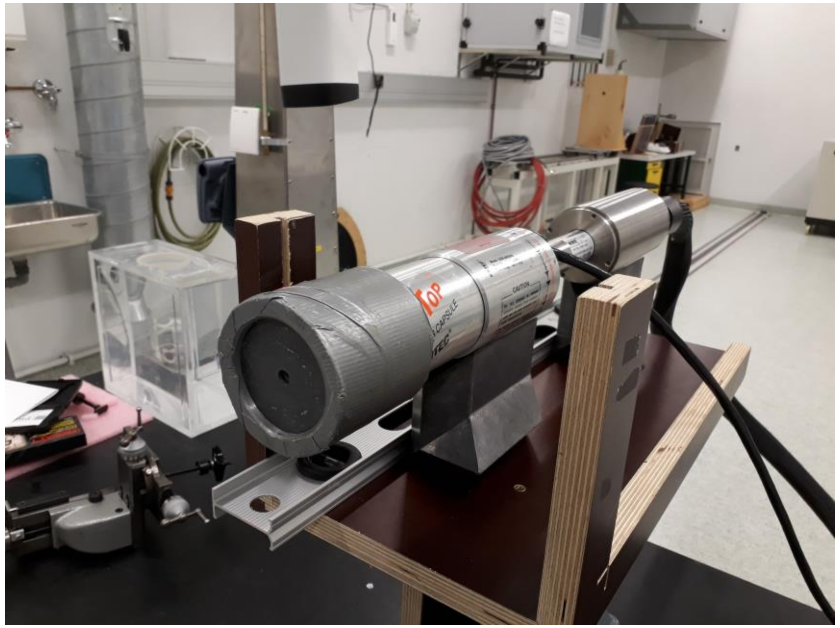
Joonas Tikkanen

Note: X-ray spectrometry can also refer to measurement of characteristic radiation in material analysis (for example X-ray fluorescence, XRF)

Introduction

- Photon fluence/flux spectrum: how many photons at each energy
  - Energy distribution of photons
- The fluence spectra from an X-ray machine can be measured, but not "directly"
  - Spectra measured with a spectrometer require further processing





Introduction

Applications

- Calibration of radiation protection dosimeters (operational quantities)

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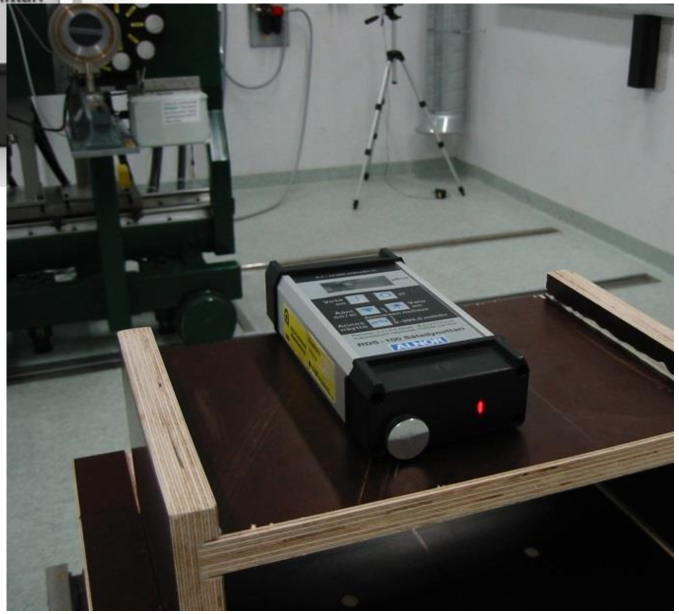
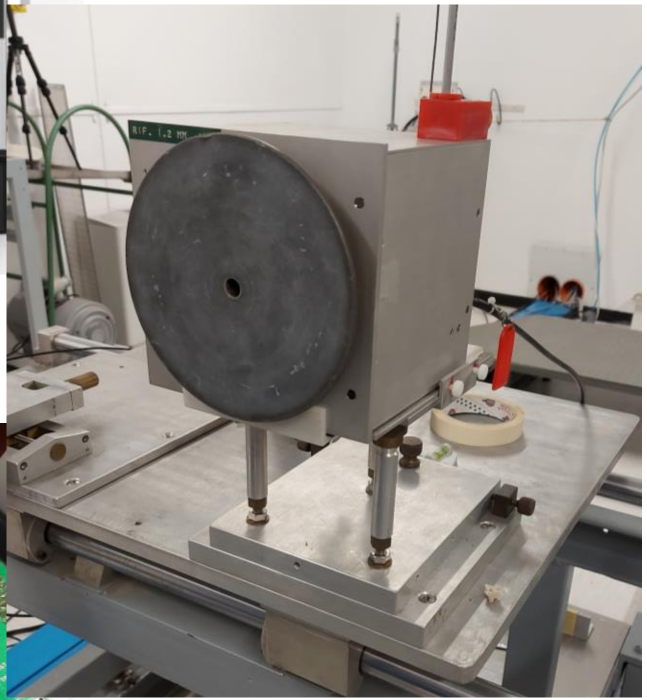
  - Dose equivalent from air-kerma by using a conversion coefficient (radiation-quality specific)
  - Low X-ray tube voltages: the coefficients need to be determined from experimental fluence spectra

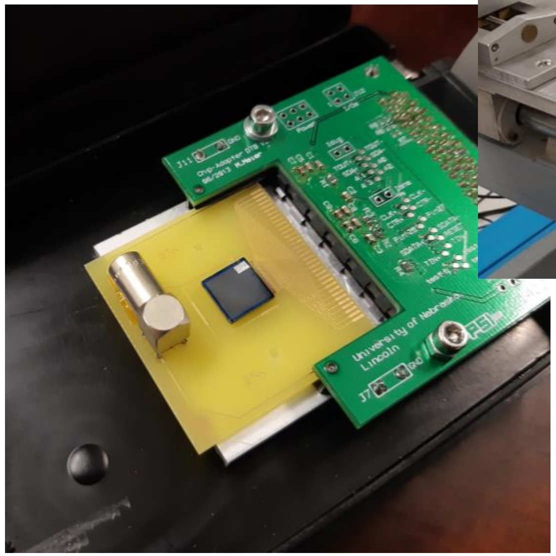


Introduction

Applications

- Calibration of radiation protection dosimeters (operational quantities)
  - Dose equivalent from air-kerma by using a conversion coefficient (radiation-quality specific)
  - Low X-ray tube voltages: the coefficients need to be determined from experimental fluence spectra
- Attenuation in air
  - Corrections for free-air-chambers
  - Correction to NTP conditions for low energies
- Detector development, research…





Introduction

Spectrometry: Most information about the radiation

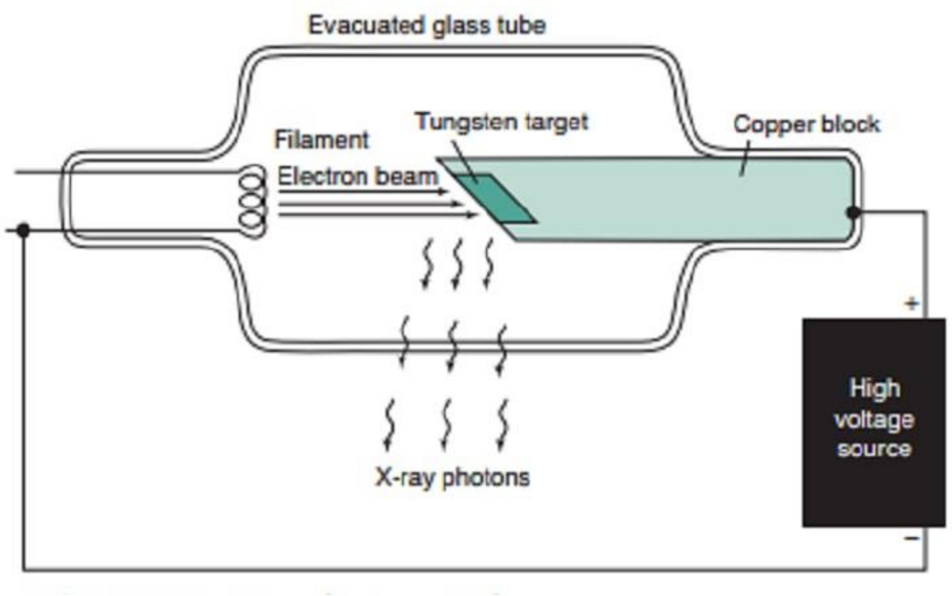
- What energies the photons hitting the chamber/detector have

Steps in determining fluence spectra

1. Measurement of uncorrected spectra
2. Monte Carlo modelling of the spectrometer
3. Response simulations
4. Unfolding procedure

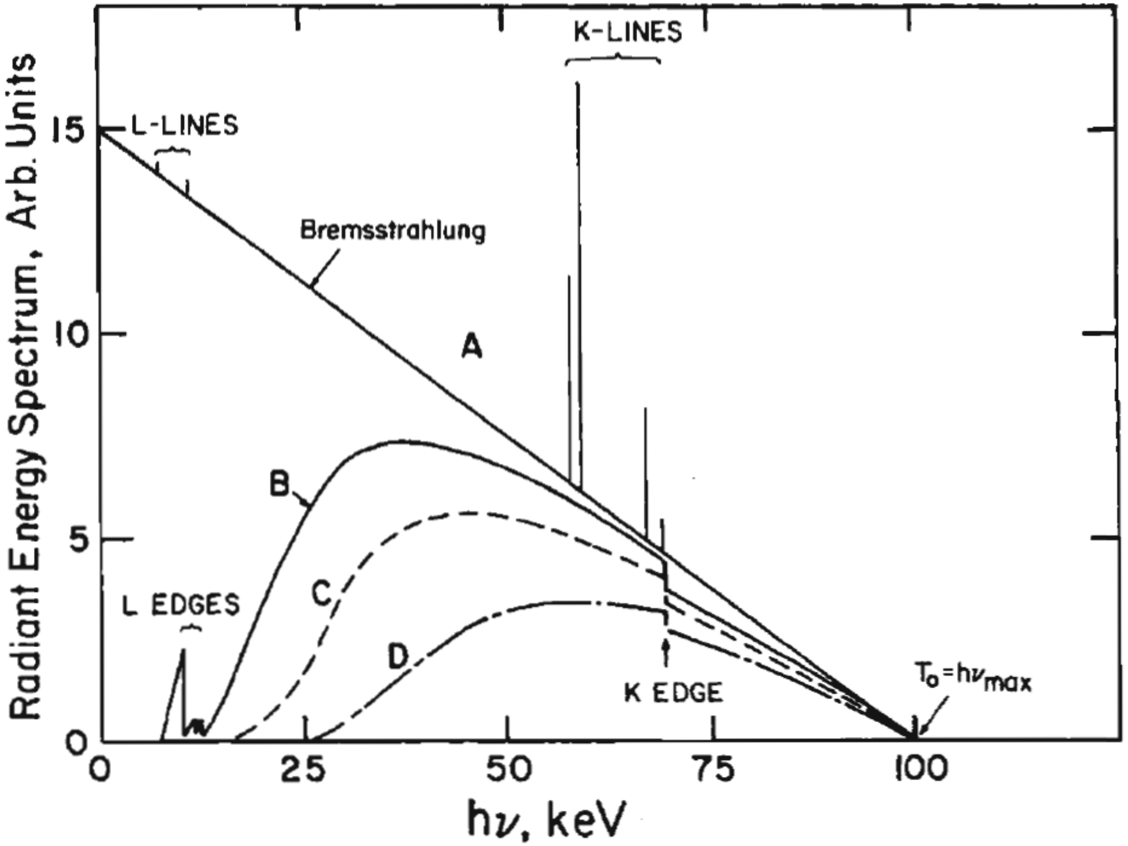
X-ray generation and spectrum

- Electrons accelerated in an electric field and collided with the anode
  - Electron kinetic energy $E_{kin} = Ve$, where V is the tube voltage and e electron charge
- Photon production through Bremsstrahlung, photon energies between 0 and E_{kin}
- Excitation of inner shell electrons in the anode
  - Characteristic X-rays
  - Only if E_{kin} is higher than the ionization energy of the shell
  - For tungsten, K-edge at approximately 70 keV
- Attenuation in the anode, tube window and filters

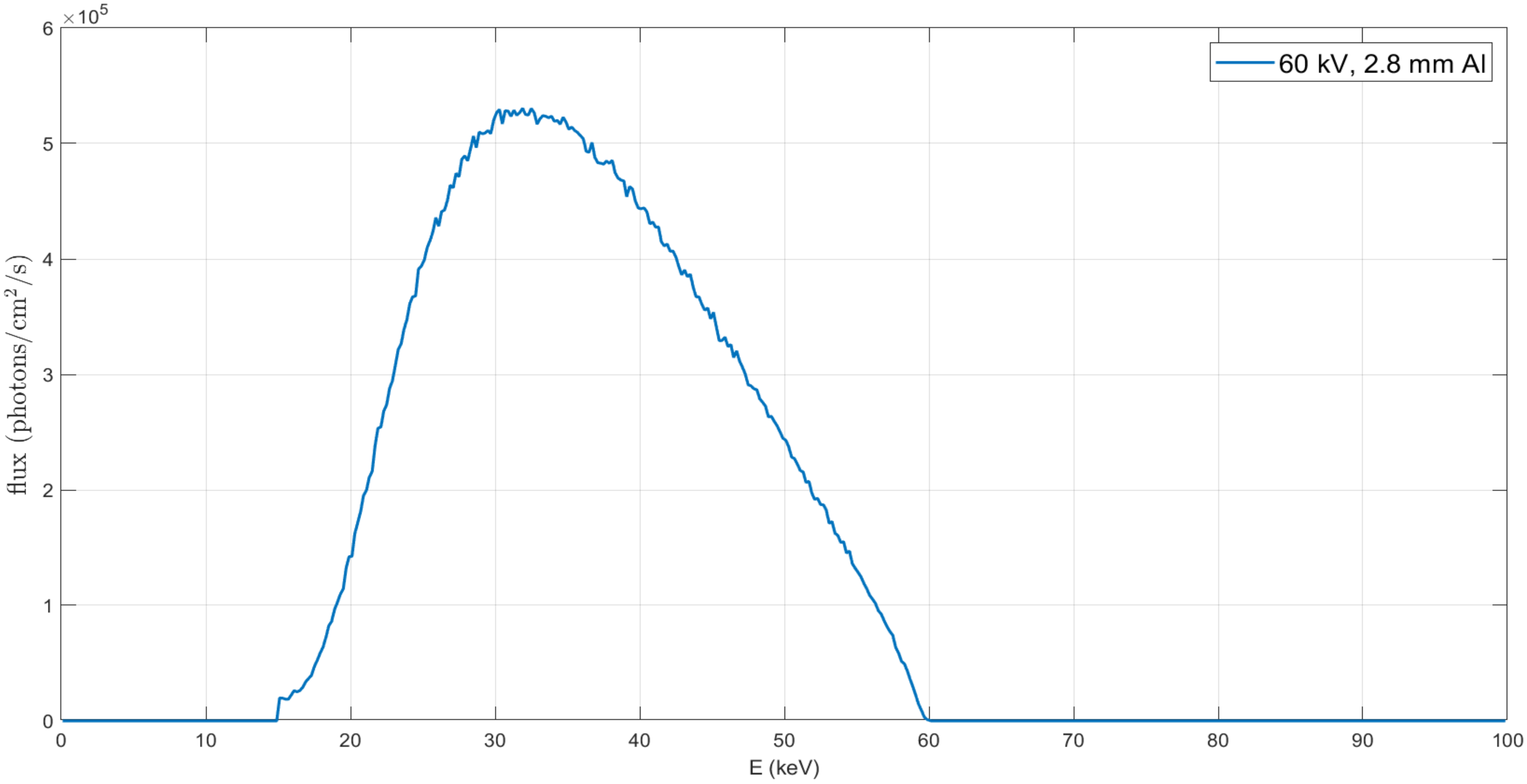


X-ray generation and spectrum

- A: Generated photons
- B: photon spectrum emitted from the anode
- C, D: Spectrum after attenuation in filters



F H Attix, Introduction to radiological physics and radiation dosimetry, 1986



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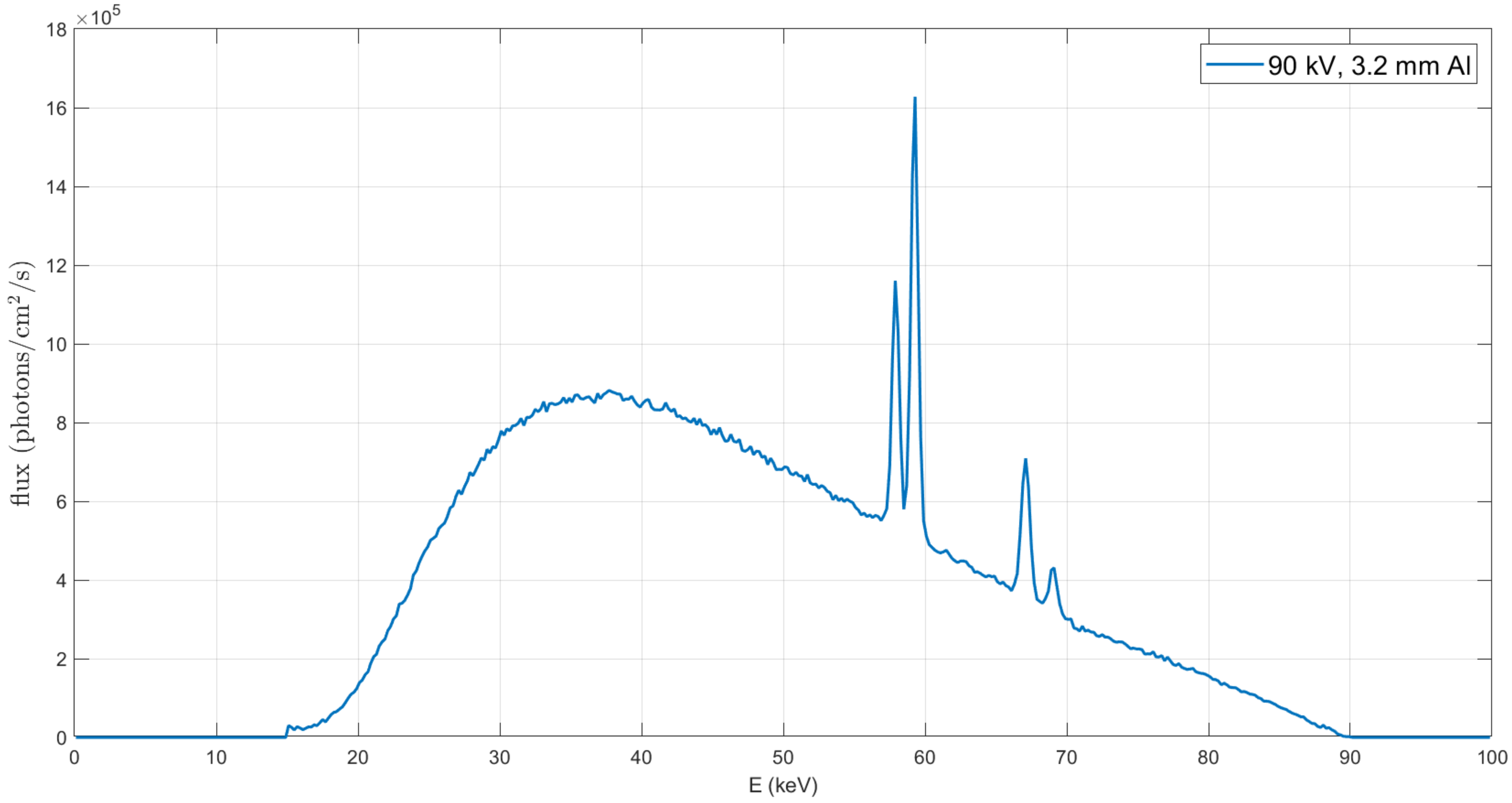
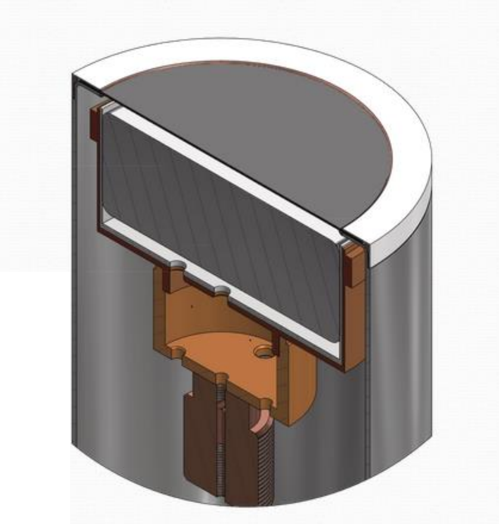


×10^5
18
16
14
12
10
8
6
4
2
0
flux (photons/cm^2/s)
0
10
20
30
40
50
60
70
80
90
100
E (keV)
90 kV, 3.2 mm Al

Semiconductor detector materials

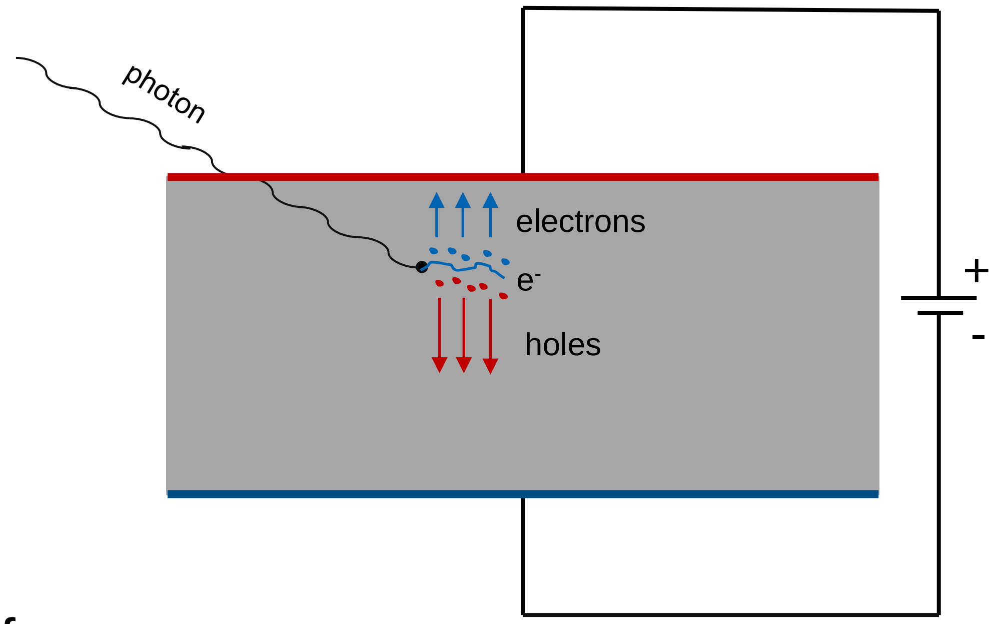
- Germanium
  - Good photon absorption
  - Best energy resolution
  - Large crystal sizes possible
  - Has to be cooled down
    - Liquid nitrogen (77 K) or electric cooling
- Cadmium Telluride (CdTe)
  - High Z material, very good photon absorption
  - Can be used in room temperatures
  - Good energy resolution
  - Problems with higher energies
  - Difficult material, available in relatively small sizes



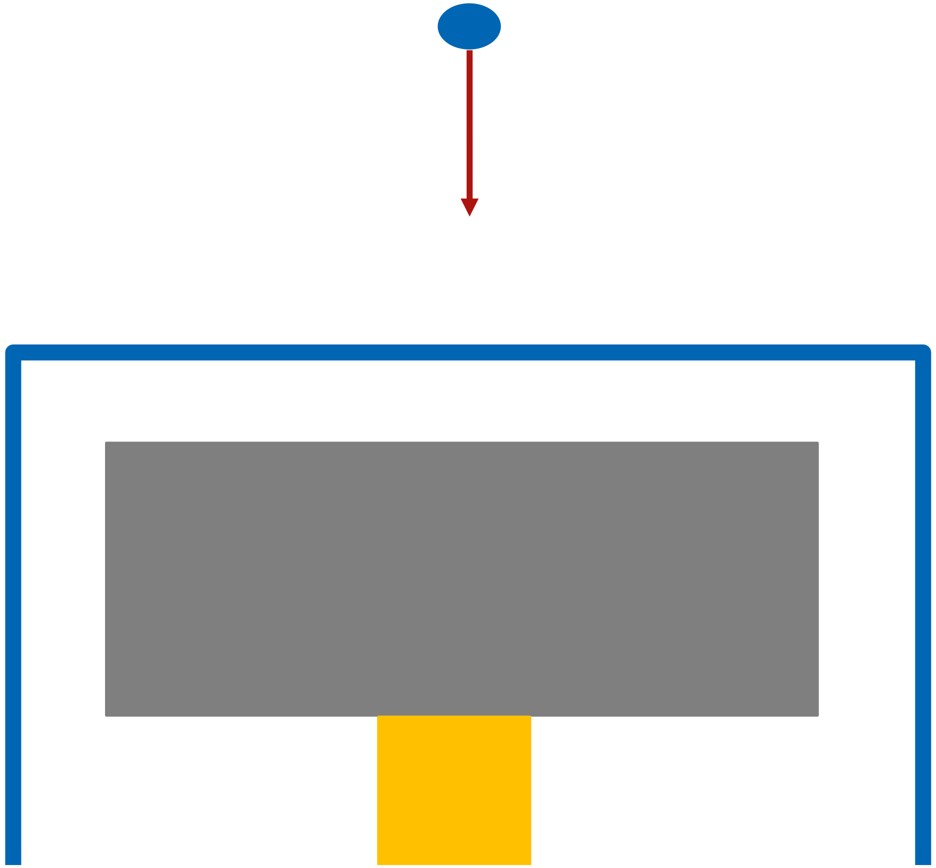
Semiconductor detectors and spectrometry

- Photon interaction inside a semiconductor
  - Secondary electron
  - Secondary electron excites more electrons from valence band to conduction band → electron-hole pairs
  - Electric field collects the charge → charge pulse
- Energy needed to create one electron-hole pair is independent of the photon energy (2.96 eV for Ge) → Charge is proportional to the energy imparted by the photon

- Photoelectric interaction: photon energy from the size of the charge pulse

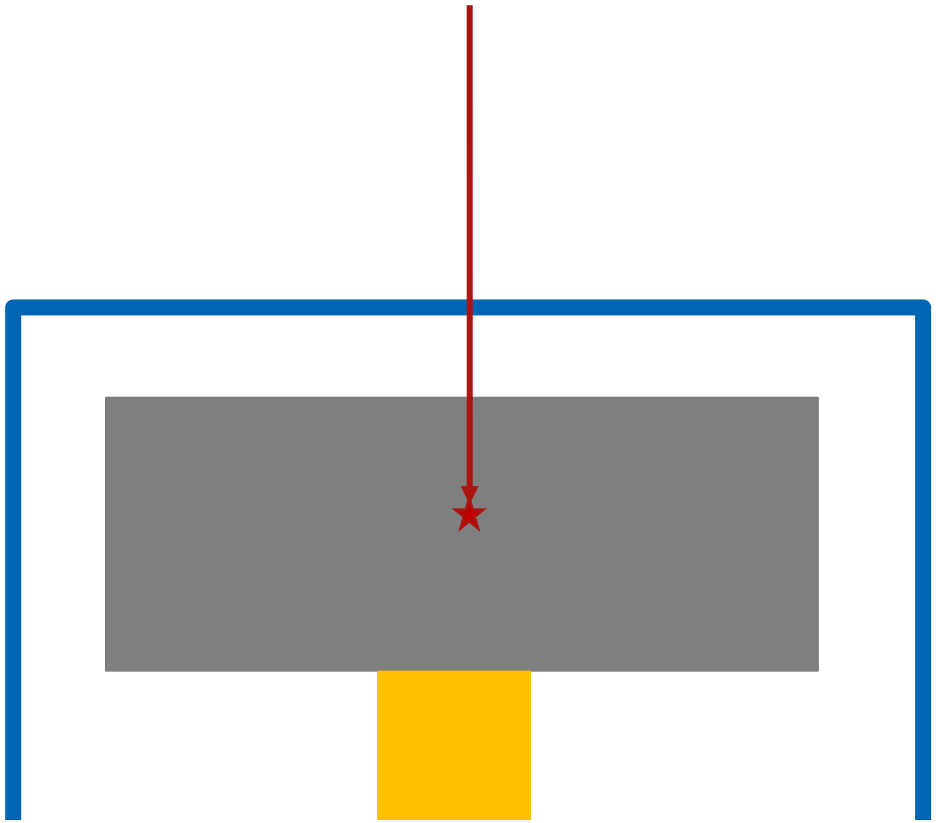


Formation of spectrum



- Monoenergetic photon source

Formation of spectrum



- Monoenergetic photon source
- Photoelectric absorption → photopeak

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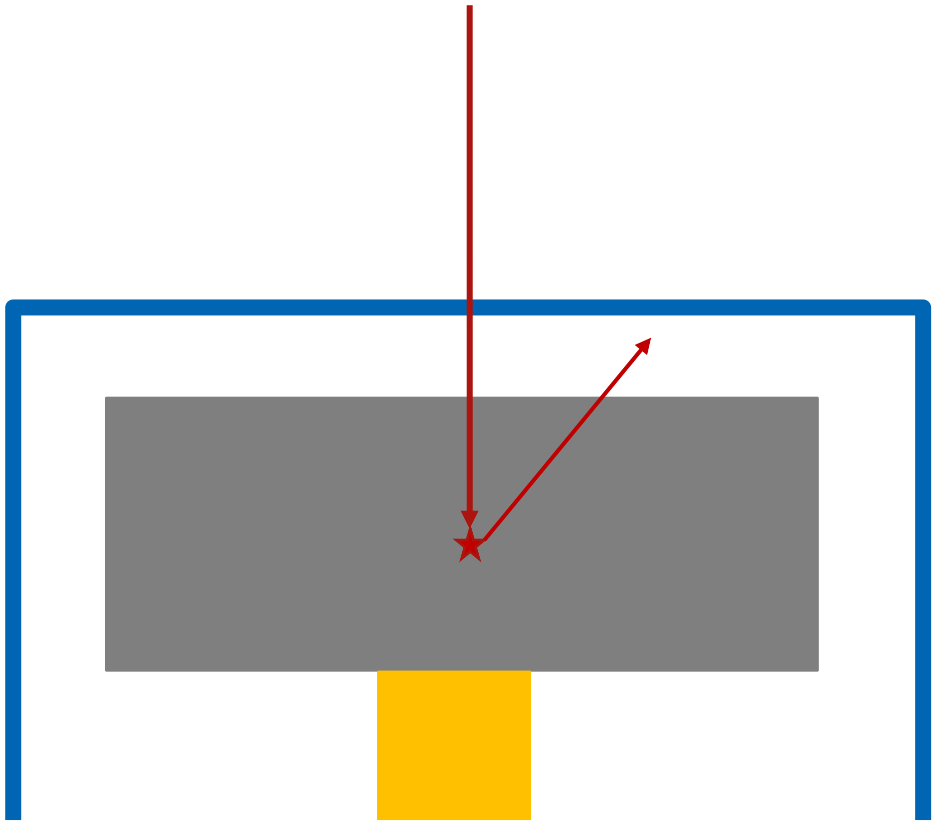

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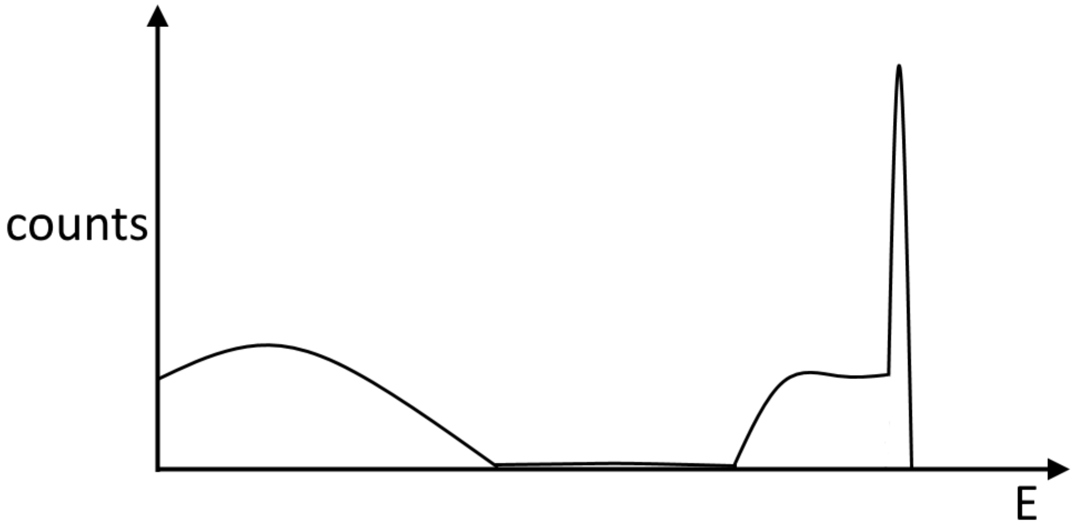
- Compton scattering → Compton continuum



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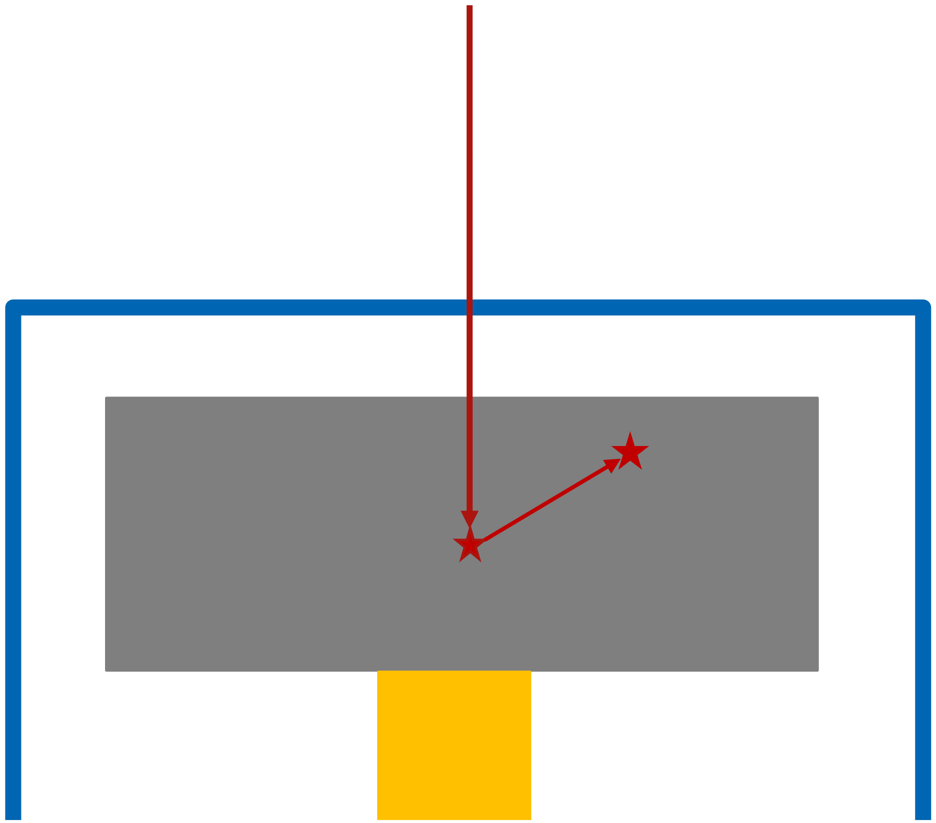
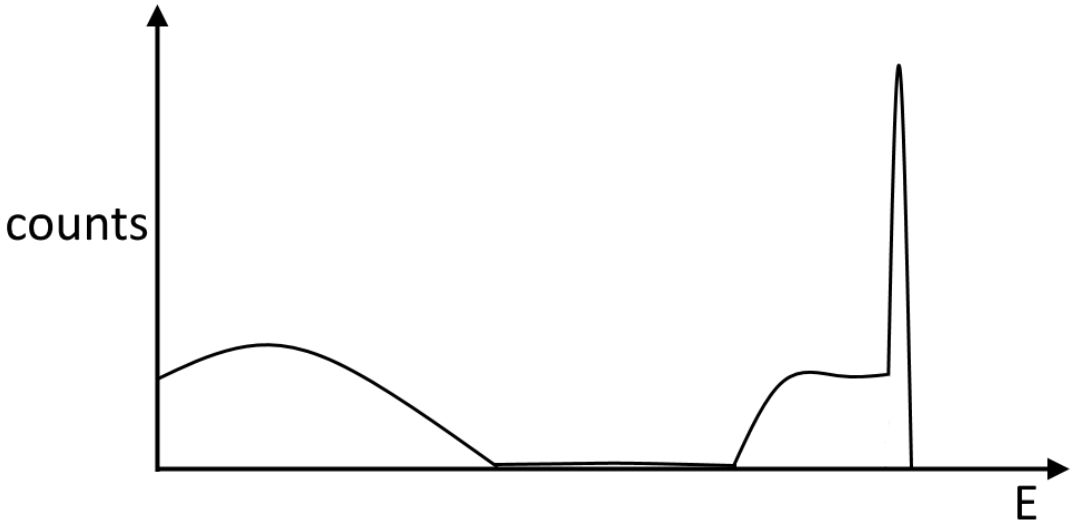


- Monoenergetic photon source
- Photoelectric absorption → photopeak
- Compton scattering → Compton continuum
  - Scatter and absorption → photopeak



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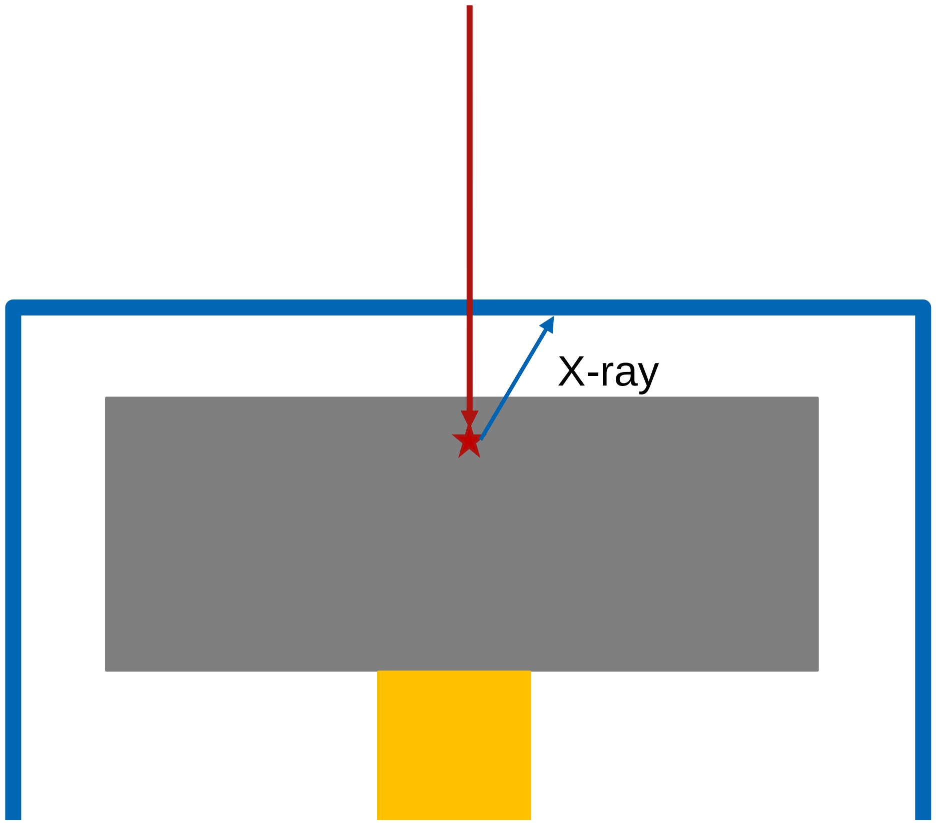

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- Photoelectric absorption → photopeak
- Compton scattering → Compton continuum
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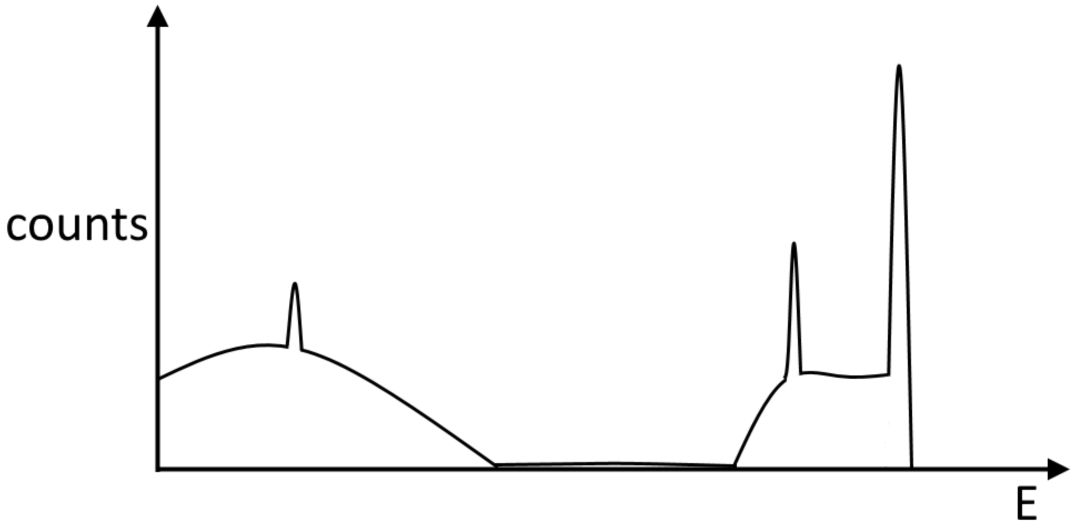
- X-ray escape peak



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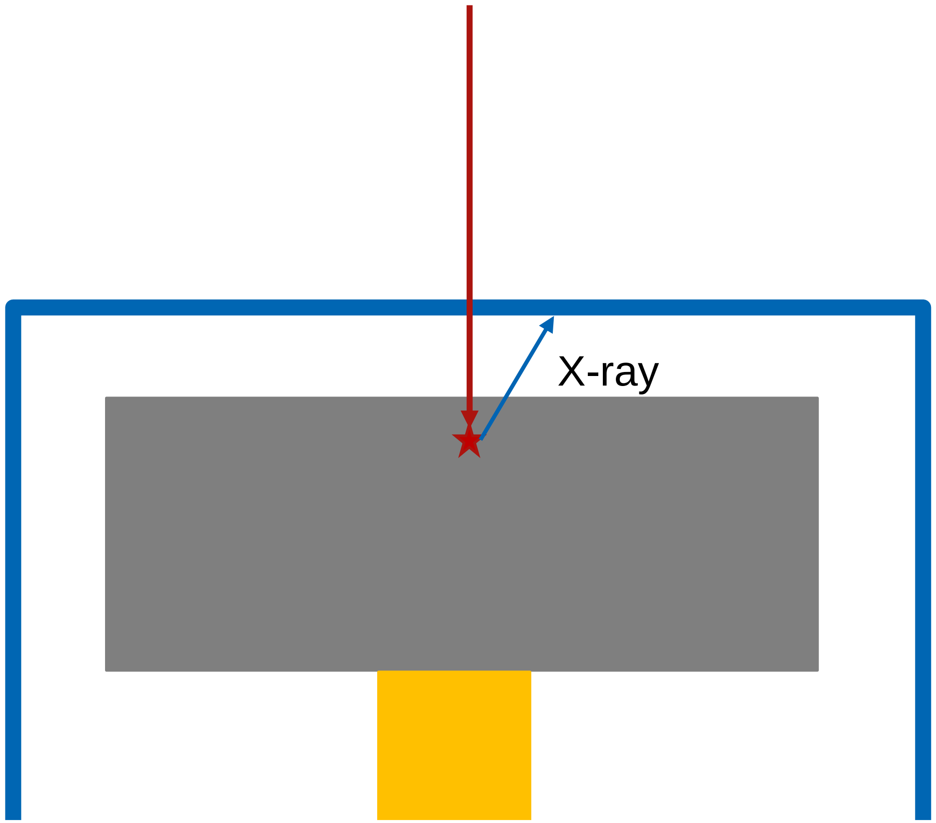

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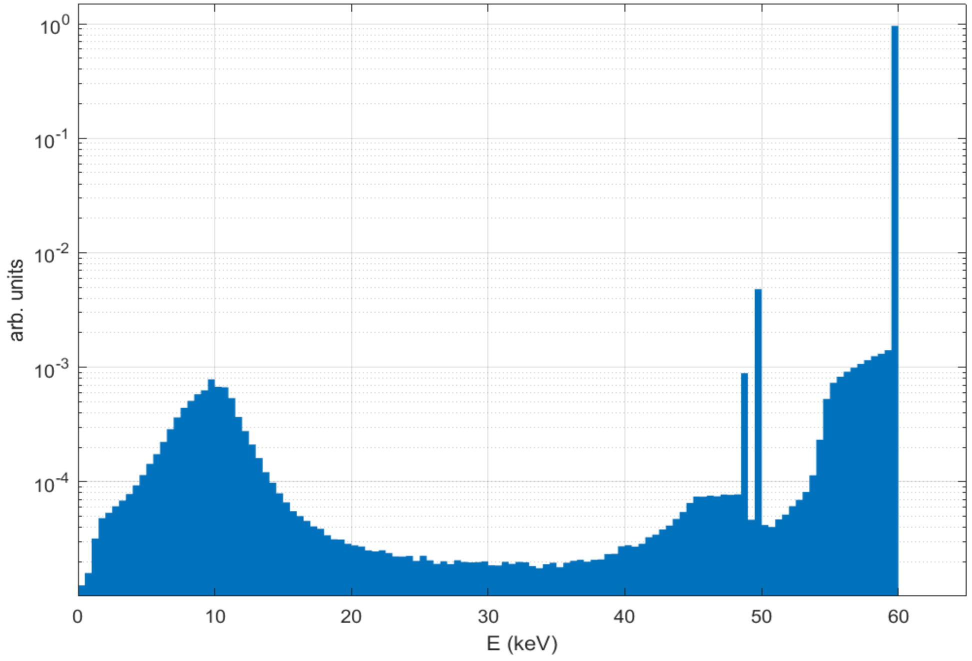
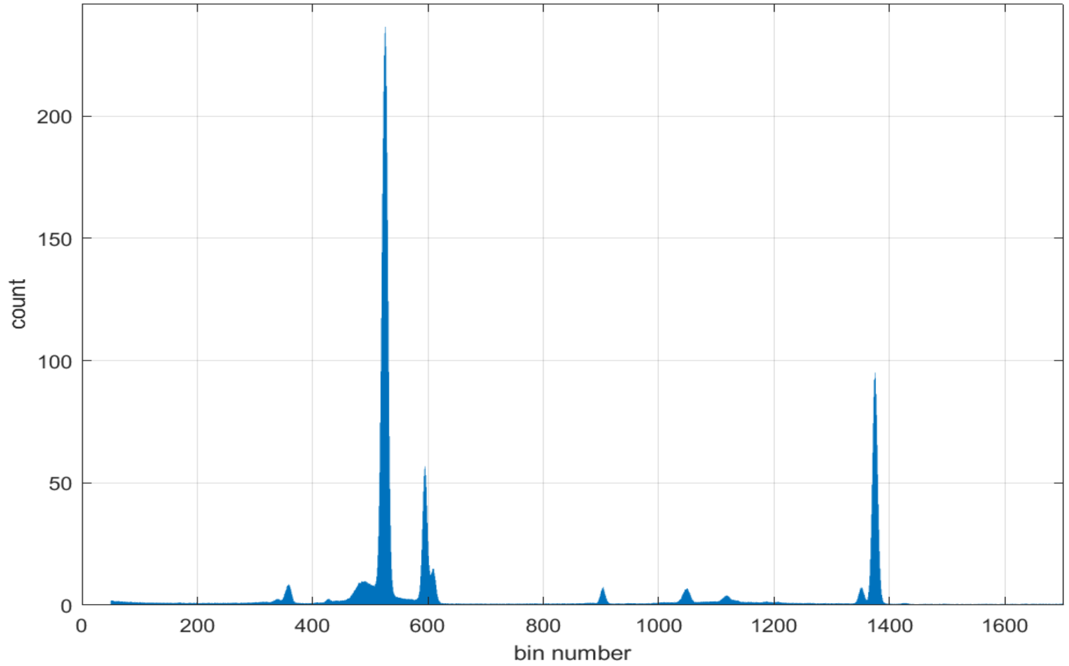


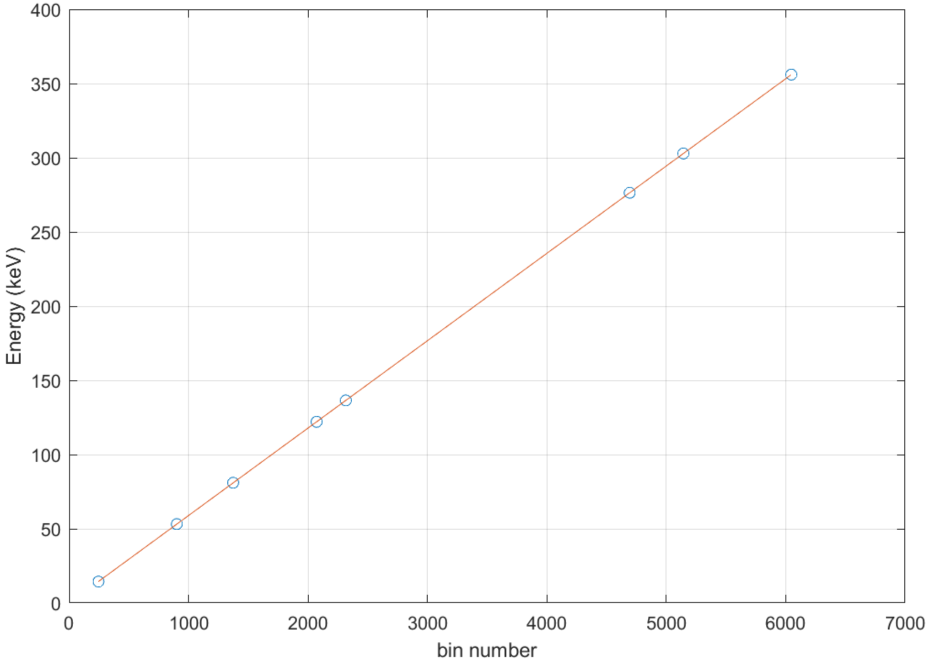
Steps in determining fluence spectra

1. Measurement of uncorrected spectra
2. Monte Carlo modelling of the spectrometer
3. Response simulations
4. Unfolding procedure

Energy calibration

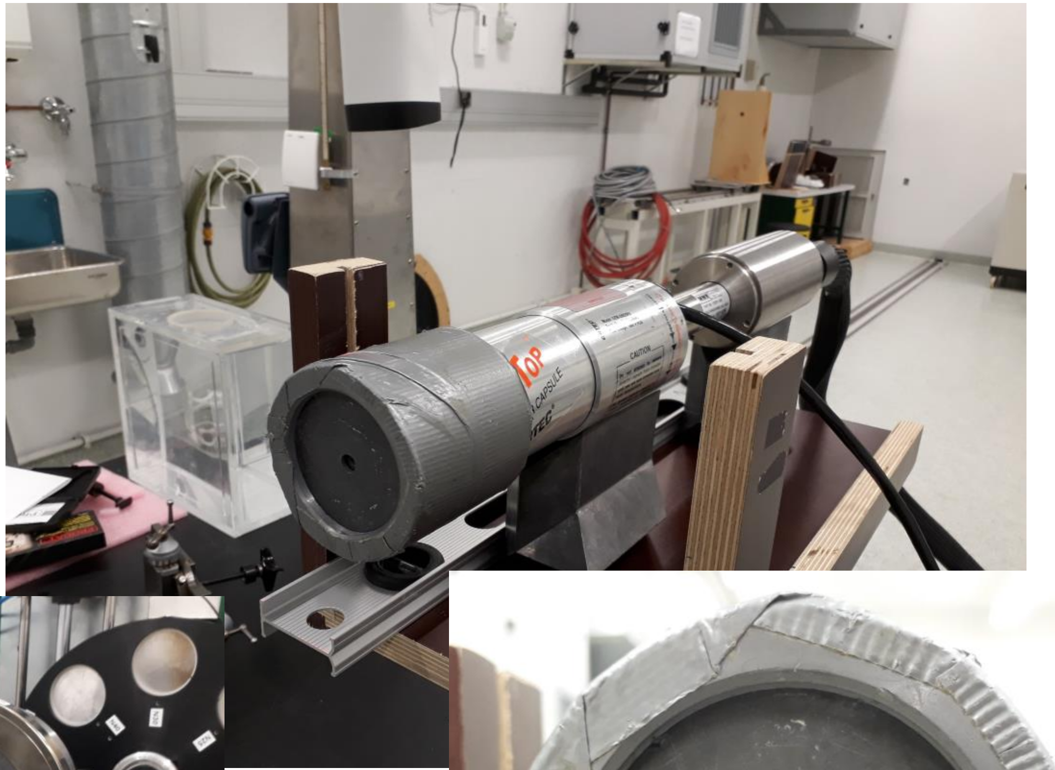
- Radionuclide sources: Photons with accurately known energies
- Bin number of spectrum calibrated into energy by determining the center bin of a peak
- Multiple peaks, multiple calibration points
  - Linear, or second order polynomial fit
  - Second order more precise, but calibration curve very close to linear

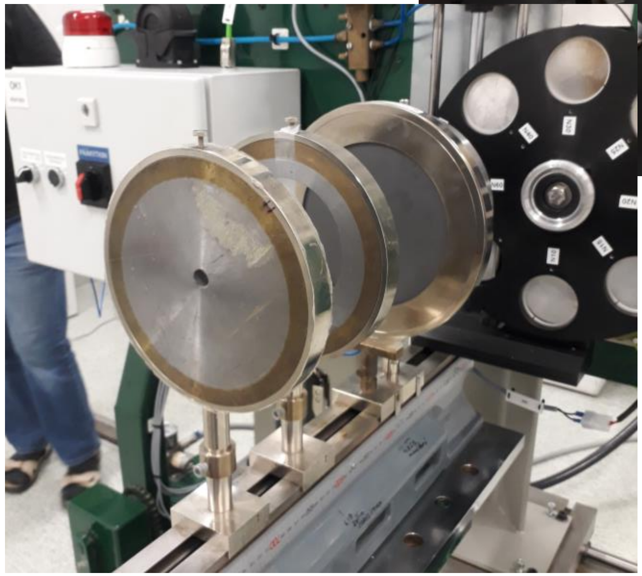




X-ray spectrum measurements

- High fluence → collimation





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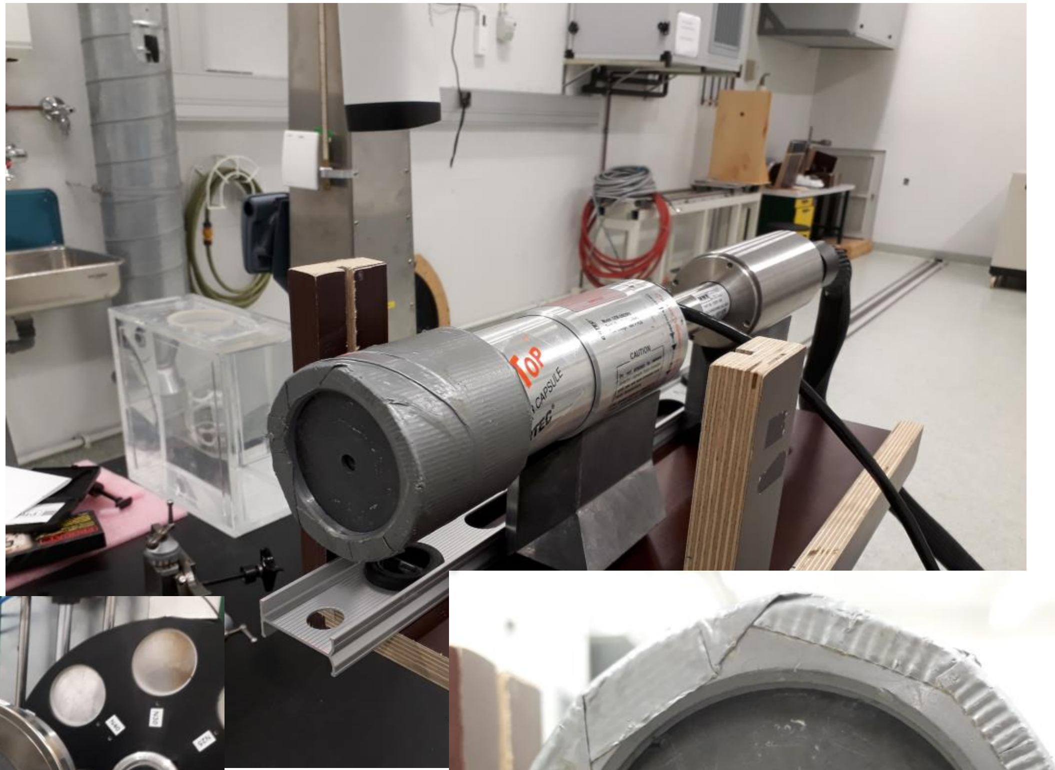
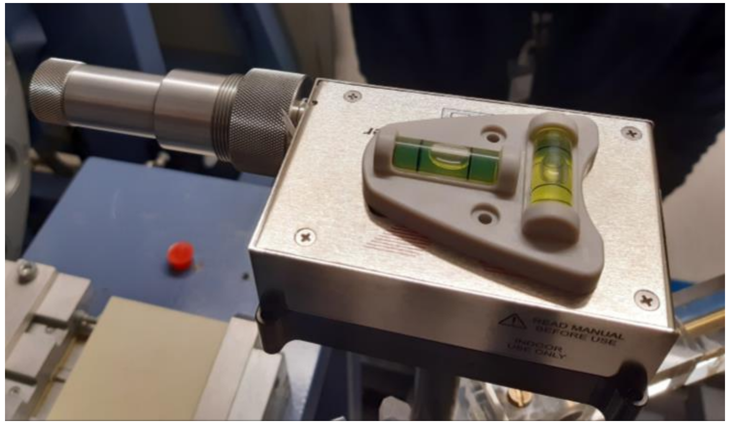
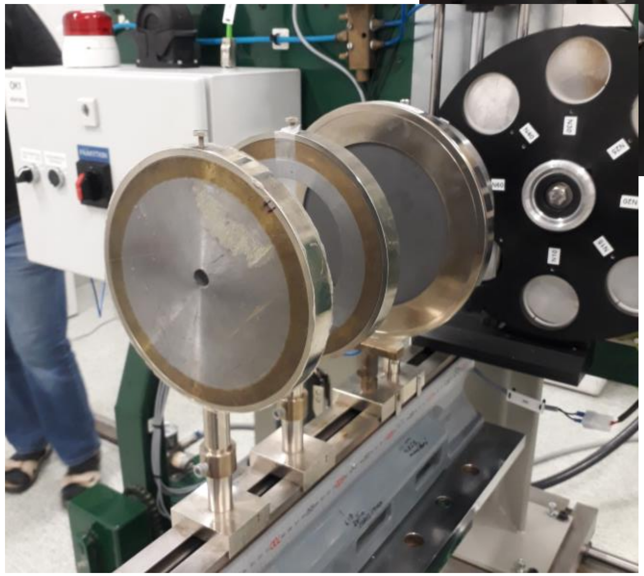
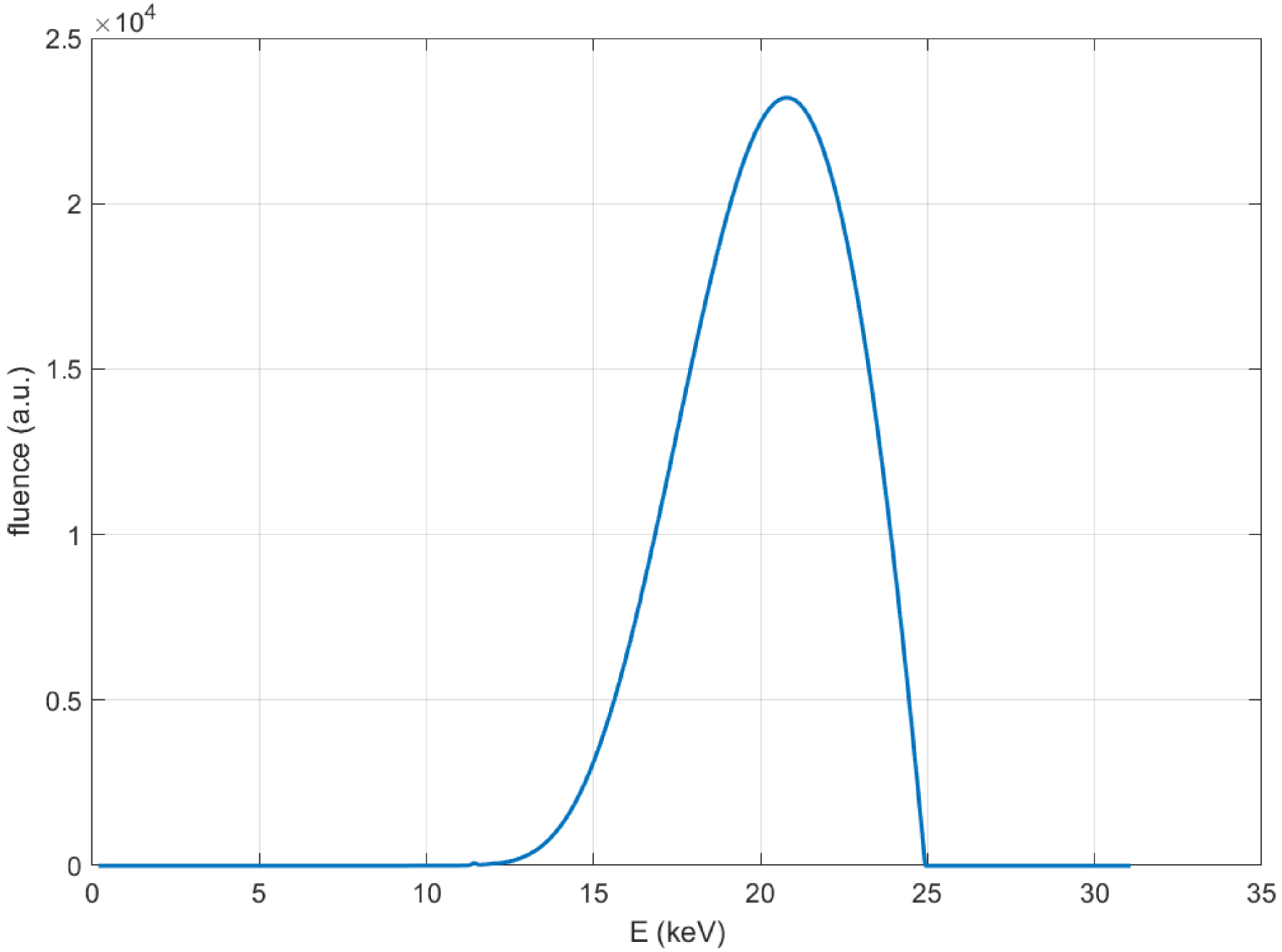


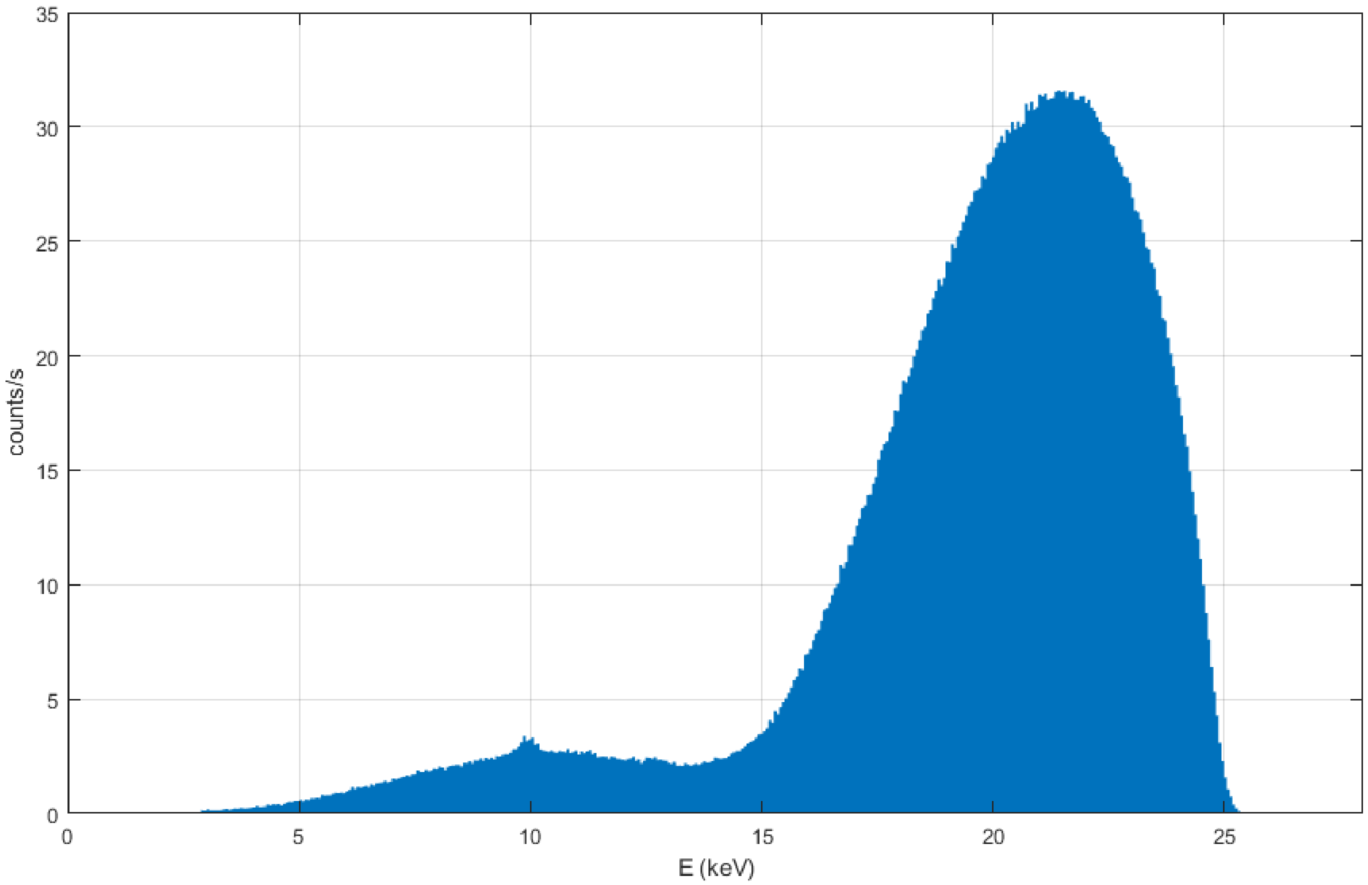




Fluence spectrum



Measured (uncorrected) spectrum



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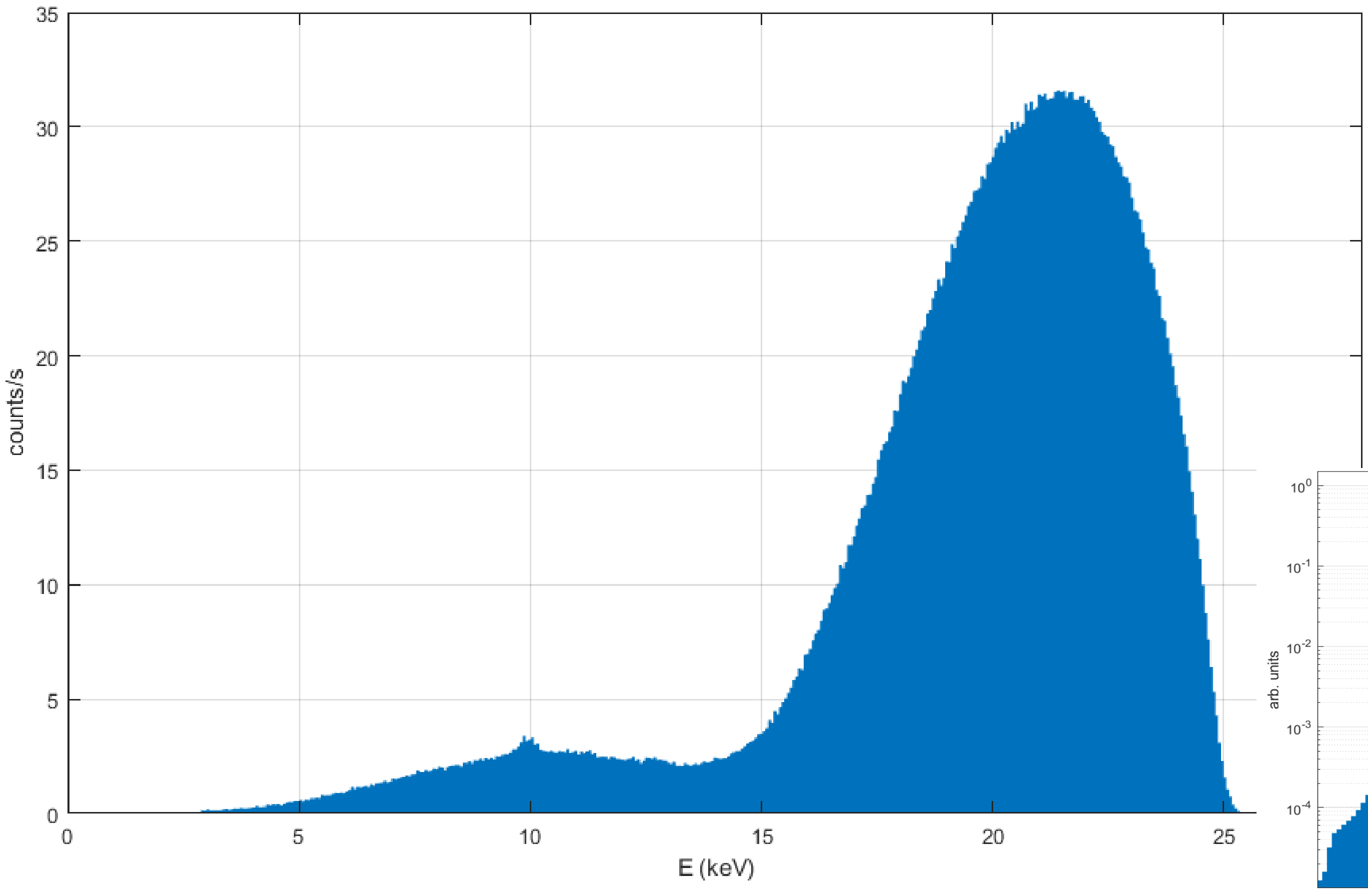

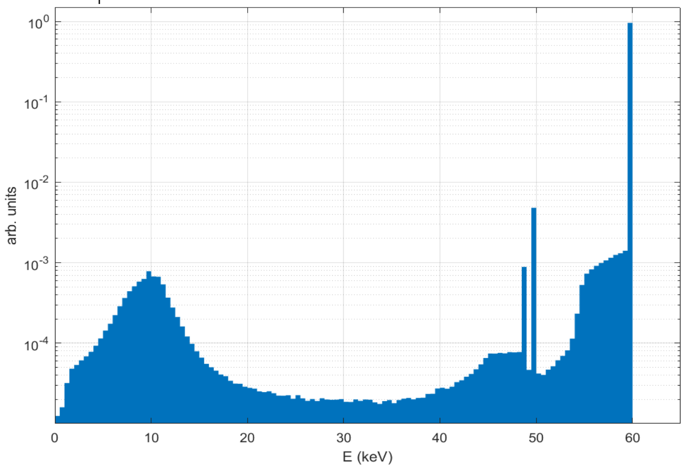

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Steps in determining fluence spectra

1. Measurement of uncorrected spectra
2. Monte Carlo modelling of the spectrometer
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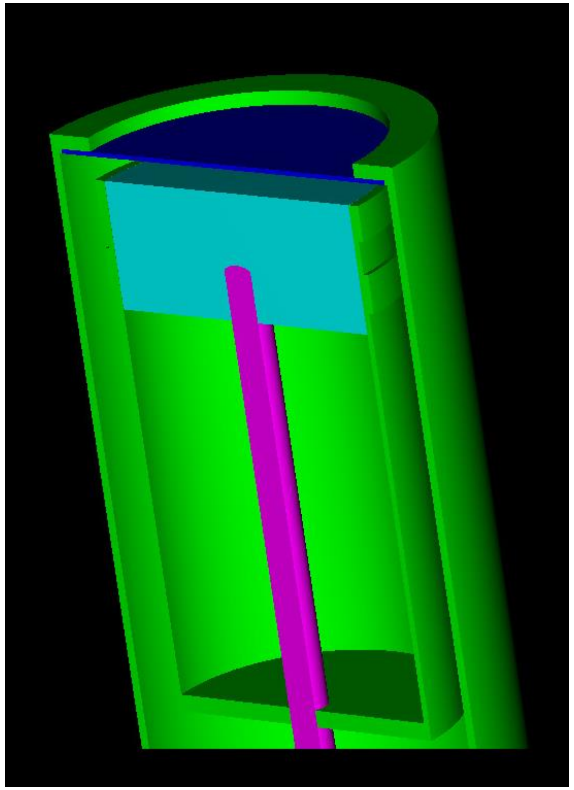
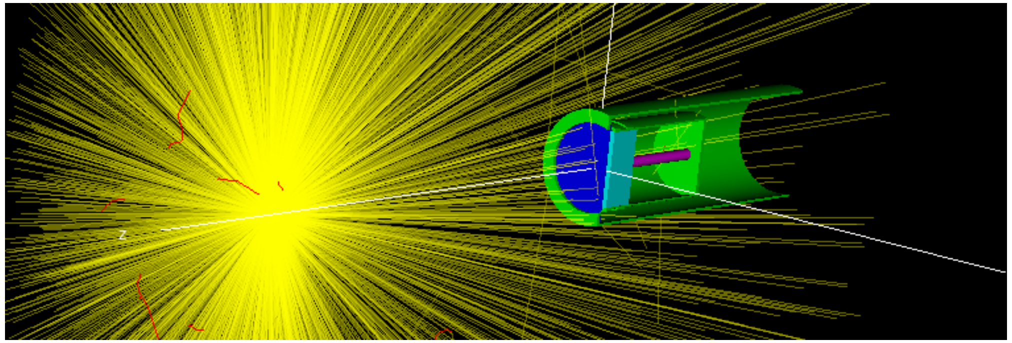
Monte Carlo modelling

- Accurate model of the spectrometer
  - Manufacturer data, X-ray images
  - The front of the detector most important
    - Window, electric contact, dead layer
- Validation of the model with radionuclide source spectrum measurements
  - Detection efficiency (how many of the emitted photons are detected in the photopeak), and spectrum shape comparison
  - Interest in low energies: Co-57, Am-241, Fe-55…
  - Simulation in the same geometry as the measurements





Monte Carlo modelling

- Penelope, EGSnrc (egs_phd, DOSRZ), Geant4, MCNP
- Simulations for validation of the model can be run easily on a laptop
- CdTe: radiation transport MC might not be sufficient for comparison to measured spectra

Steps in determining fluence spectra

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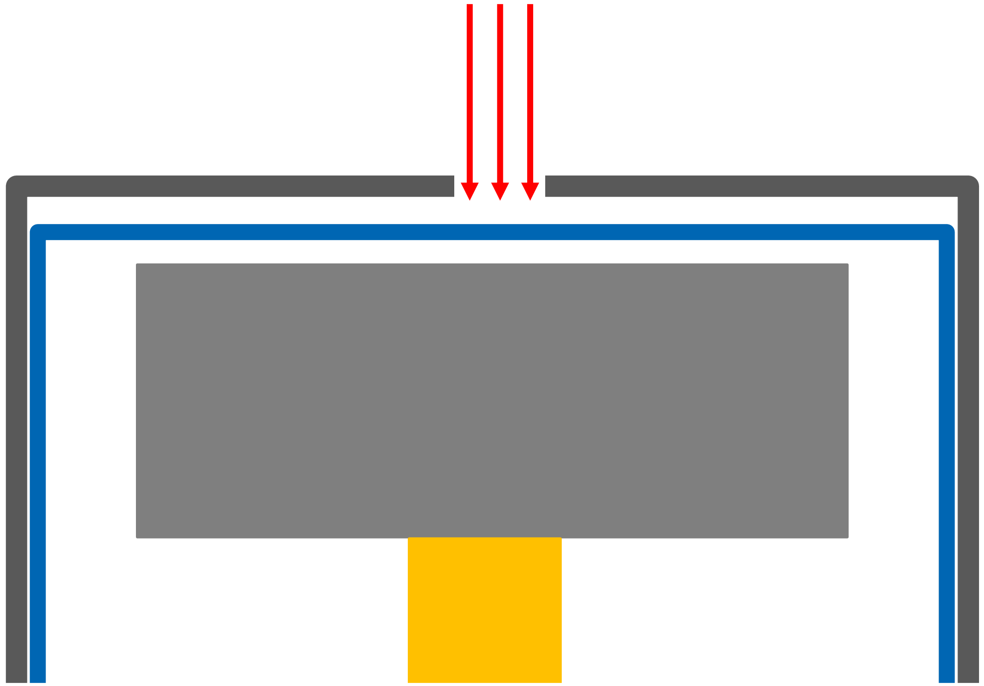
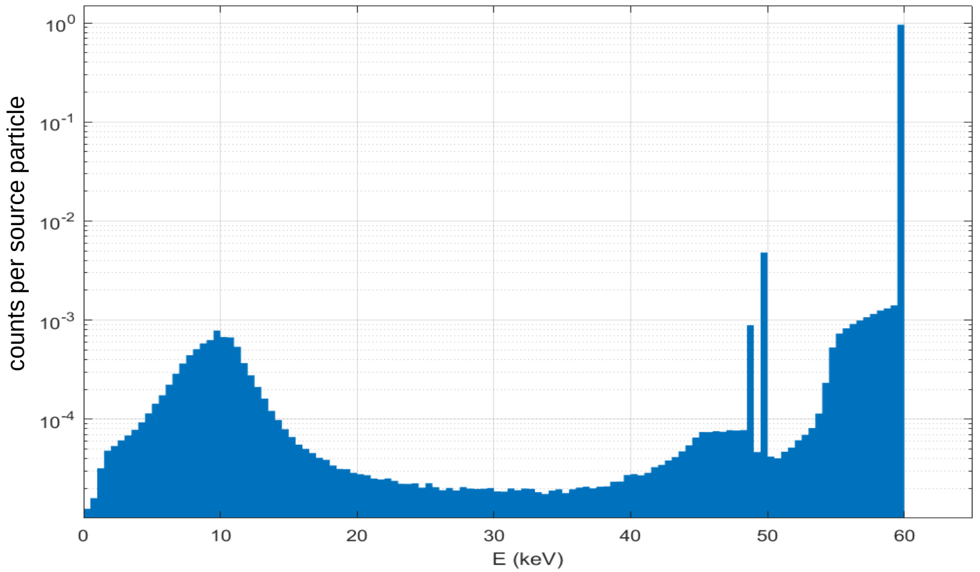
Detector response simulations

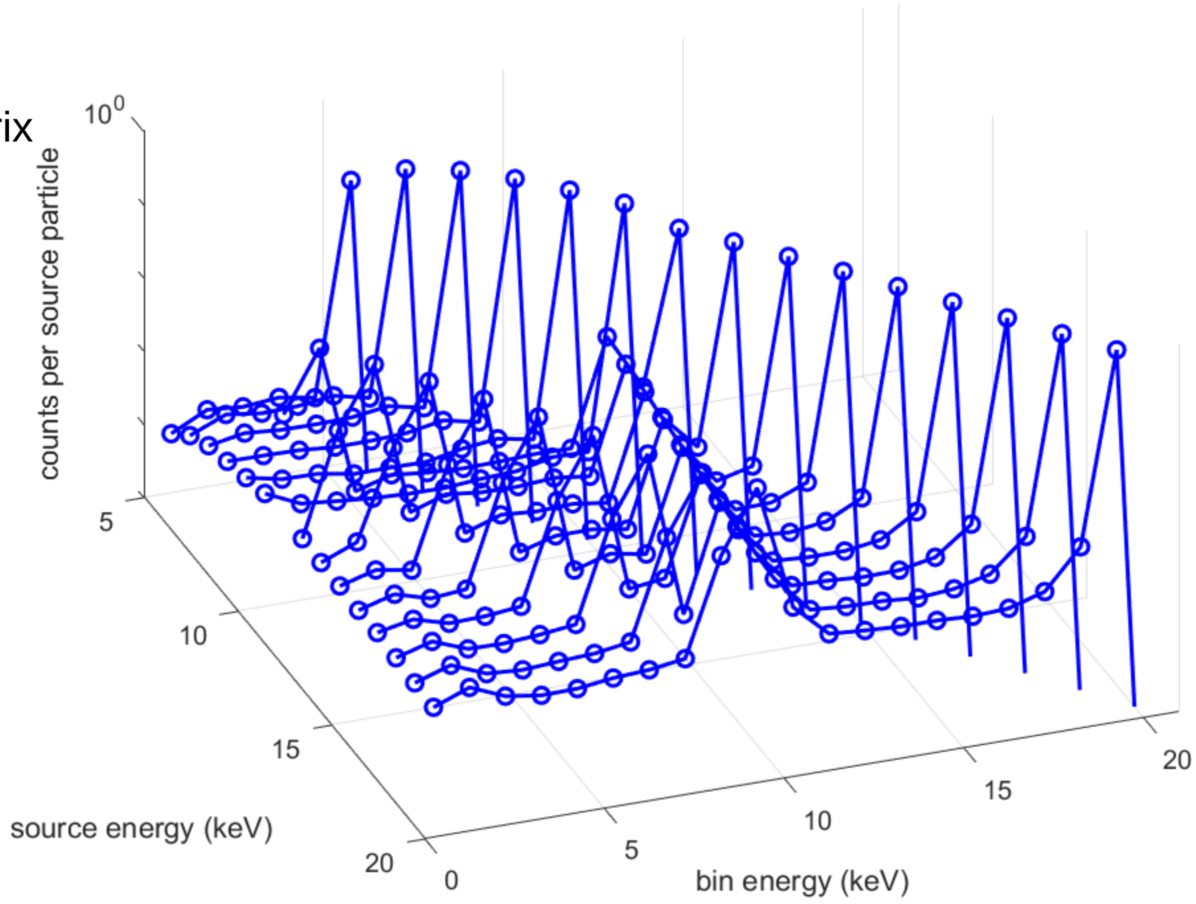
- Simulation of the detected spectrum shape in the whole energy range
- Mono-directional, mono-energetic (parallel beam) source
- Source energy from 0 to E_{max} in constant intervals
  - For example, 1 keV intervals: simulation with energies 0.5 keV, 1.5 keV, 2.5 keV… up to some maximum energy
  - Our calculations: 0.2 keV intervals
- Response of the detector for photons in the X-ray measurement geometry with energy of each bin of the measured spectrum





Detector response simulations

- Electron transport has an effect also at low energies
- Simulations run, and results collected automatically with a script
- Results can be gathered into a **response-matrix**
  - Spectrum form each simulation fills one column of the matrix
  - In order from smallest to largest source energy
  - Separate matrix for the simulation uncertainties
- Table-top computer works, laptop not preferable



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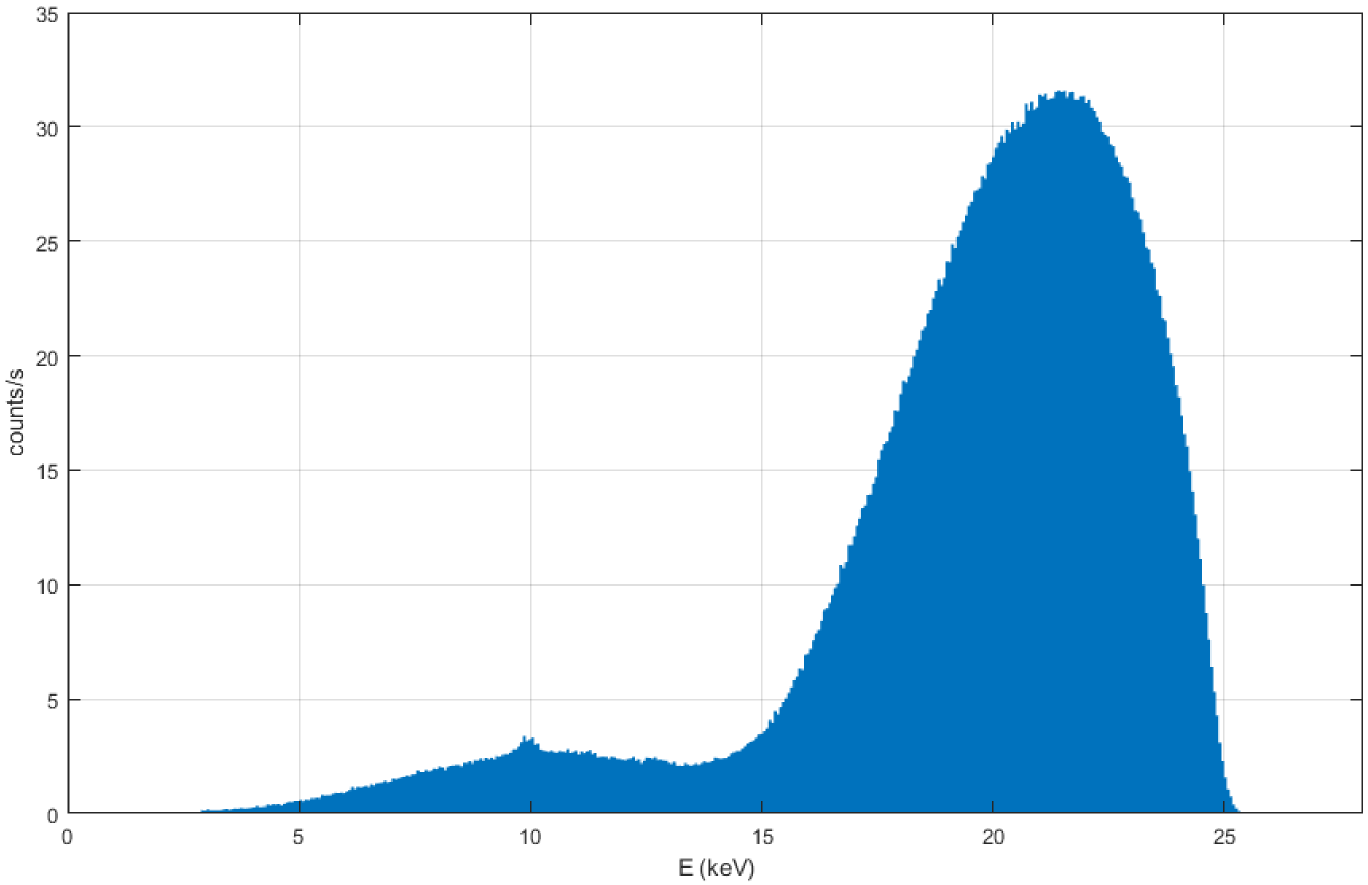

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Spectrum unfolding

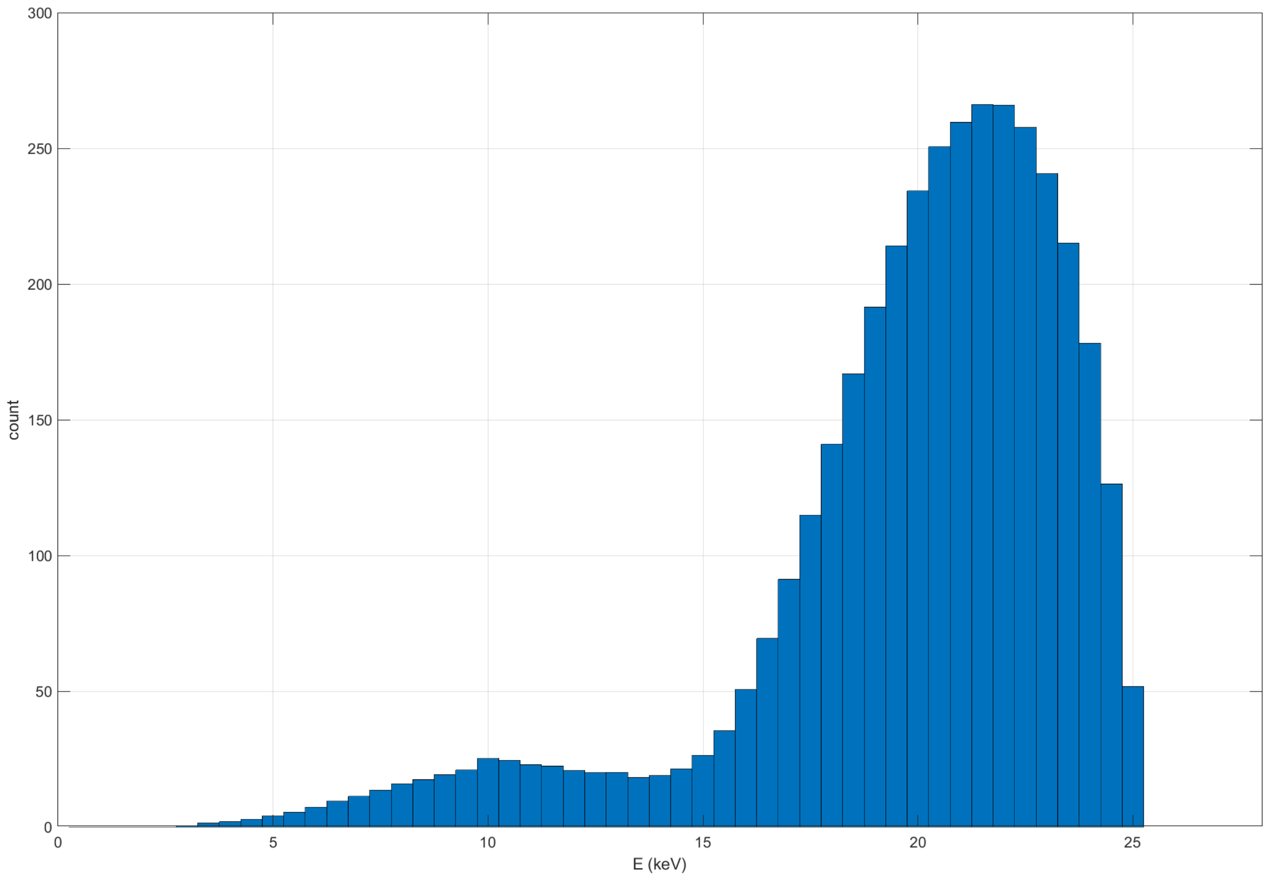
Method 1: inverse response-matrix method

- $s = \mathbf{M}\phi \;\Rightarrow\; \phi = \mathbf{M}^{-1}s$
- s is the measured spectrum, ϕ the fluence spectrum and **M** the response-matrix collected from the response simulations
- Software must be able to do the matrix inversion

Spectrum unfolding

Method 2: peeling method

- Highest bin: only full absorption events → Subtract “extra” pulses (Compton and X-ray escape) from lower bins



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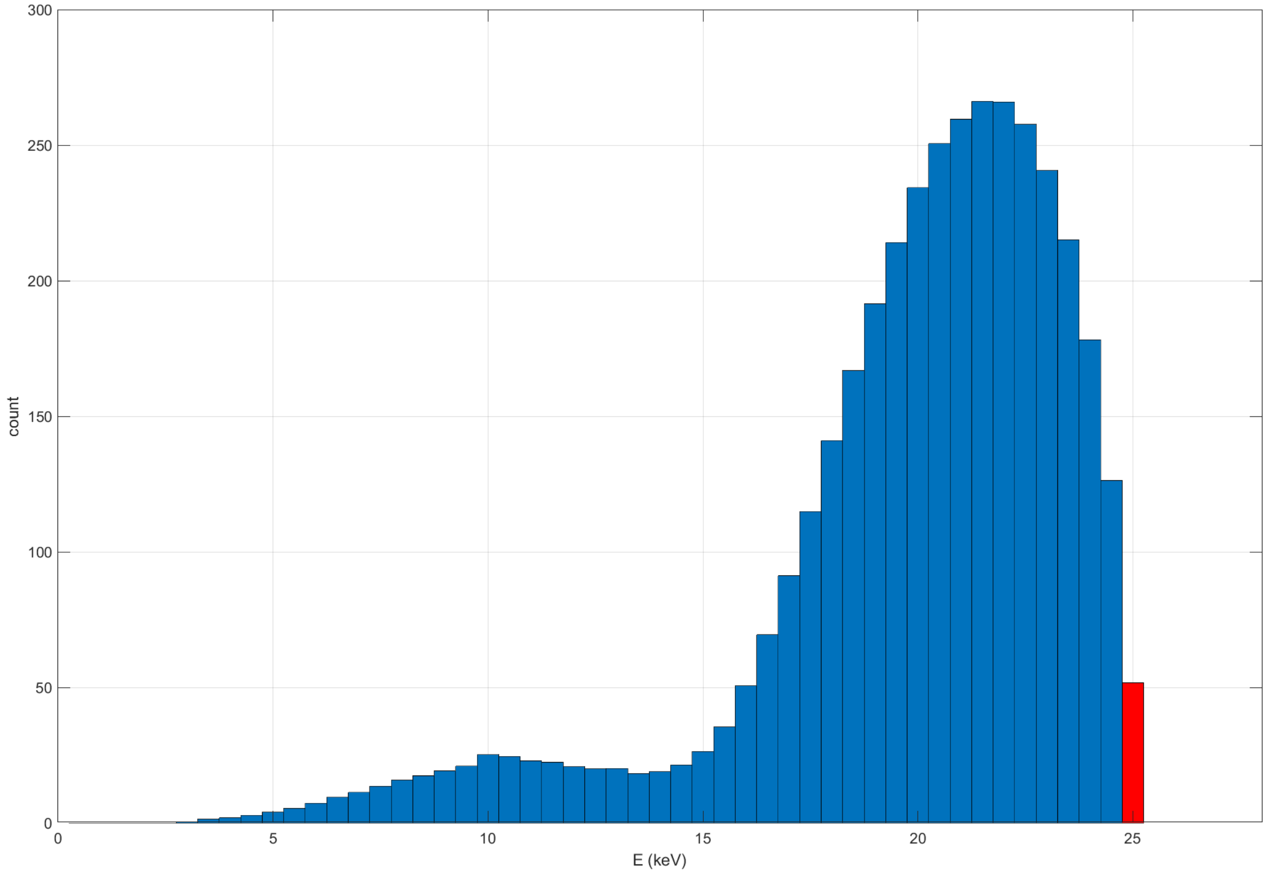

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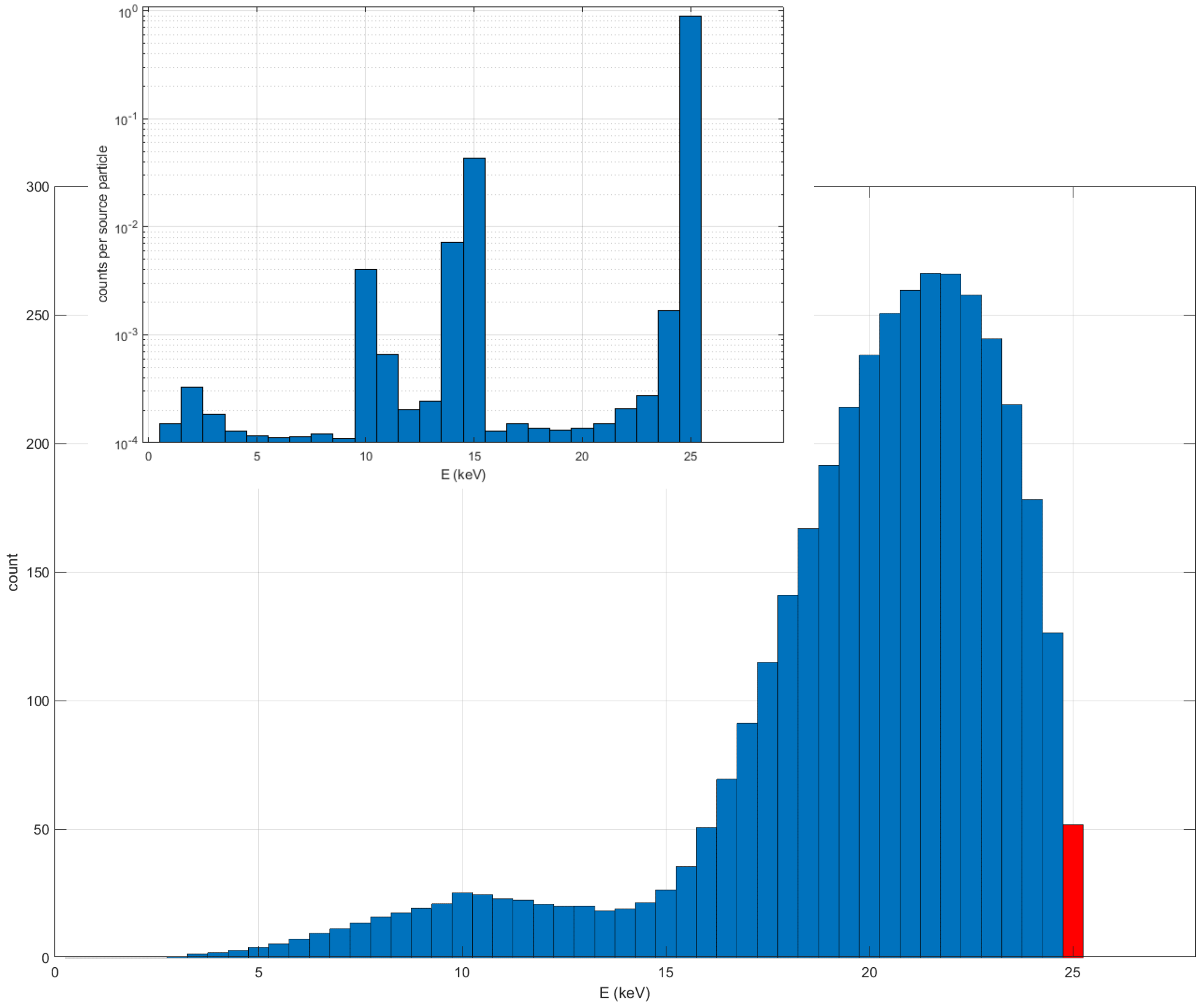

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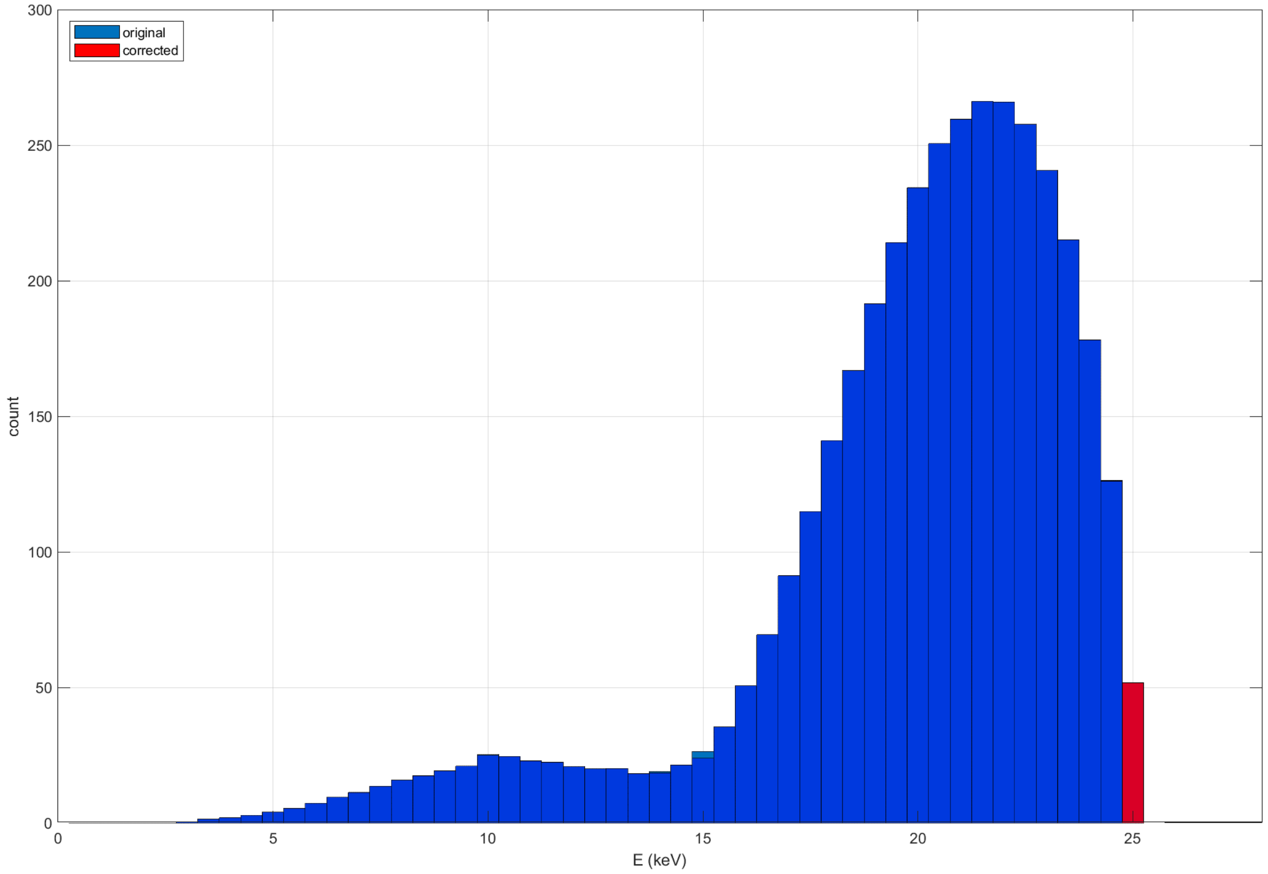

Spectrum unfolding

Method 2: peeling method

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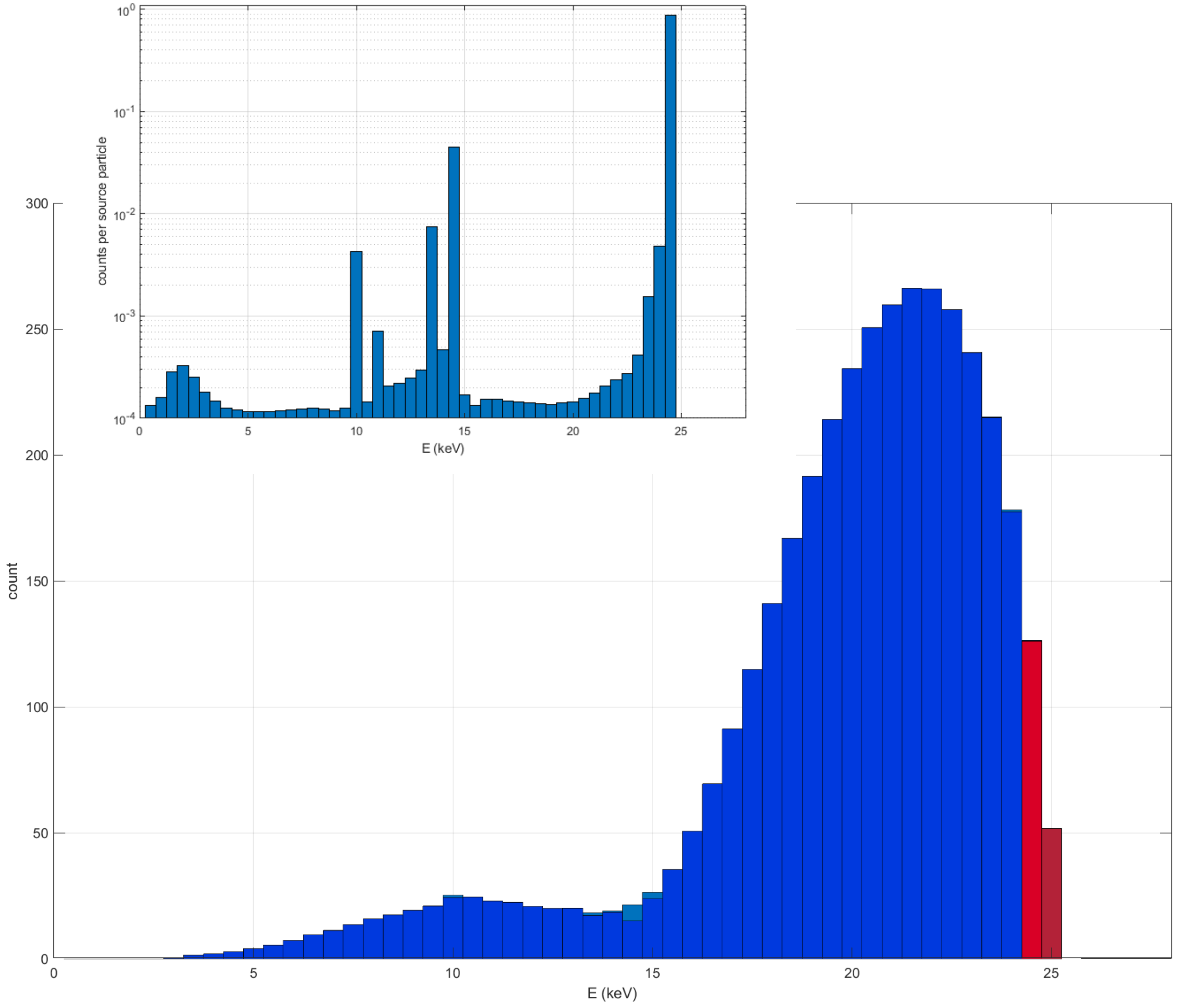
- Second highest bin: no Compton pulses after the first subtraction → Subtract extra pulses from lower bins



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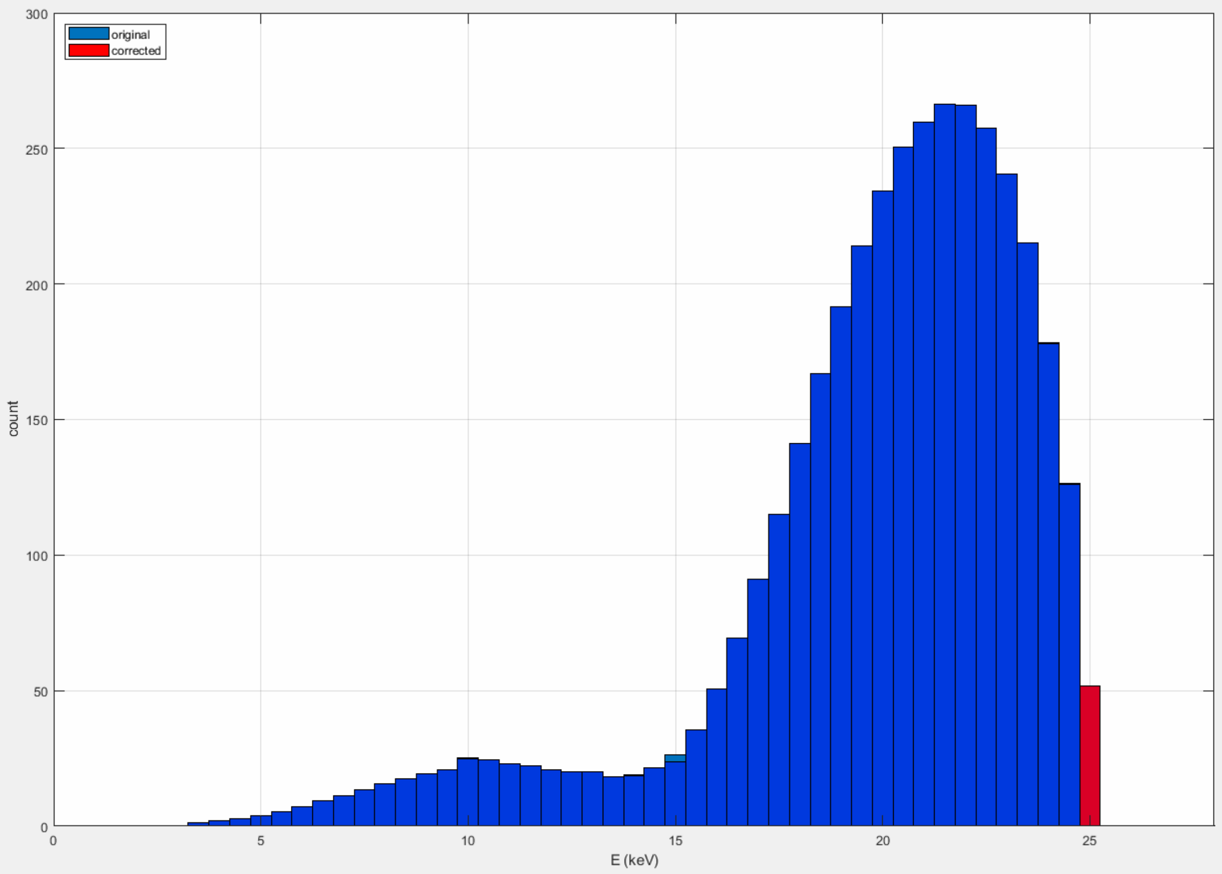
- Third highest bin…
- Continue through the whole spectrum
- Spectrum with full energy absorption events only (s_{corr})



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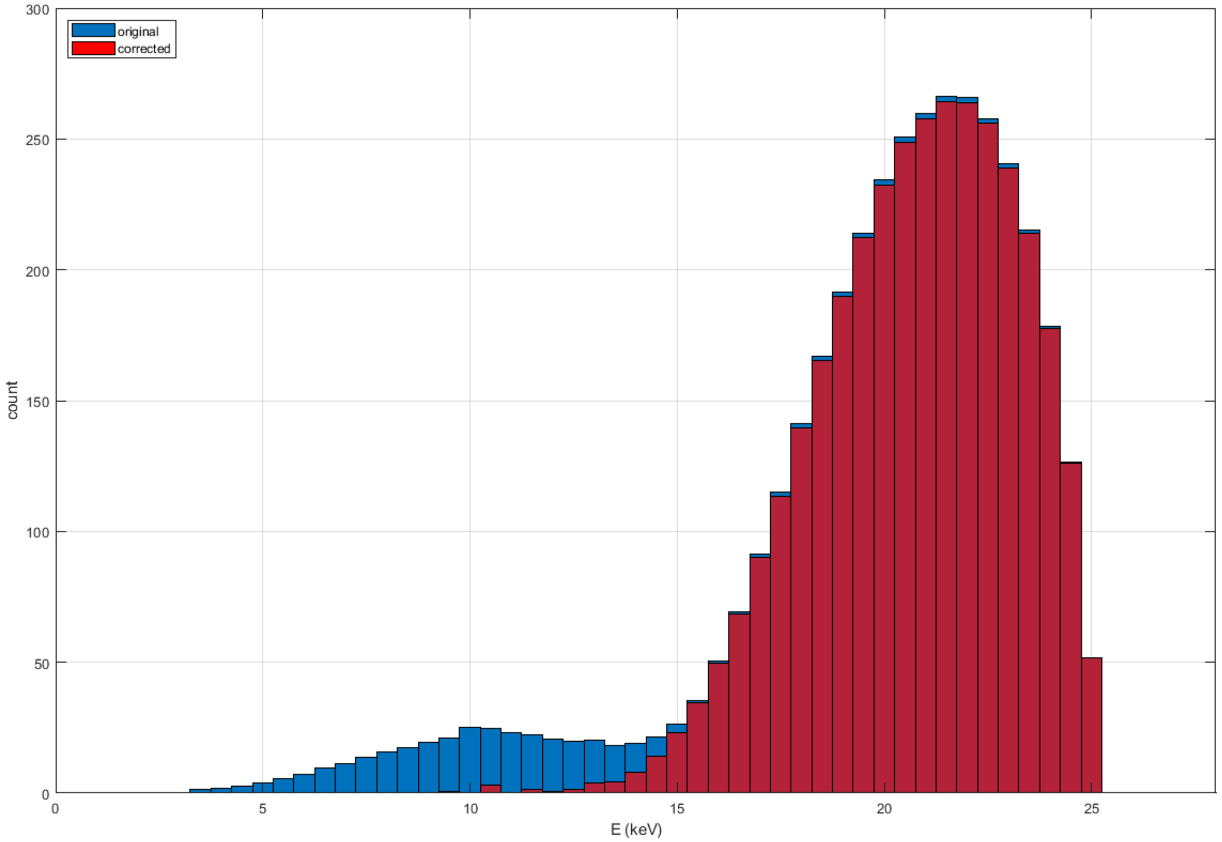
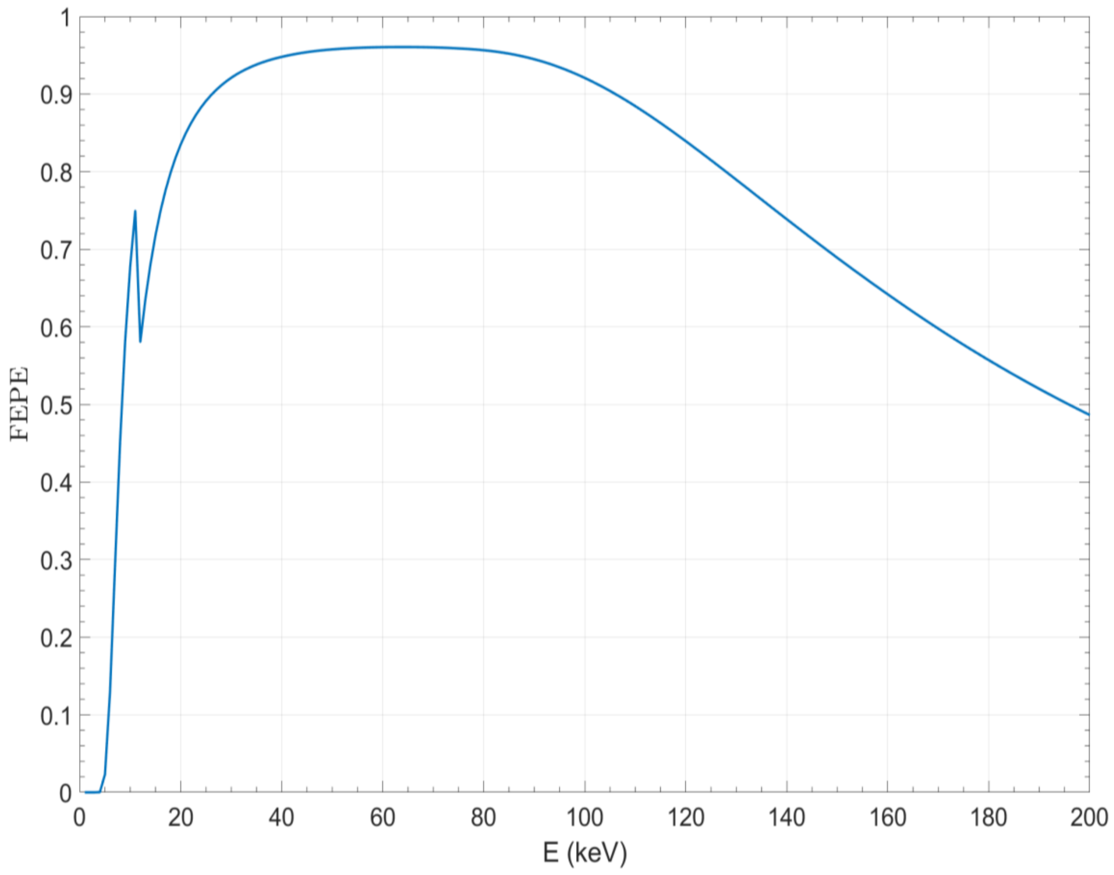


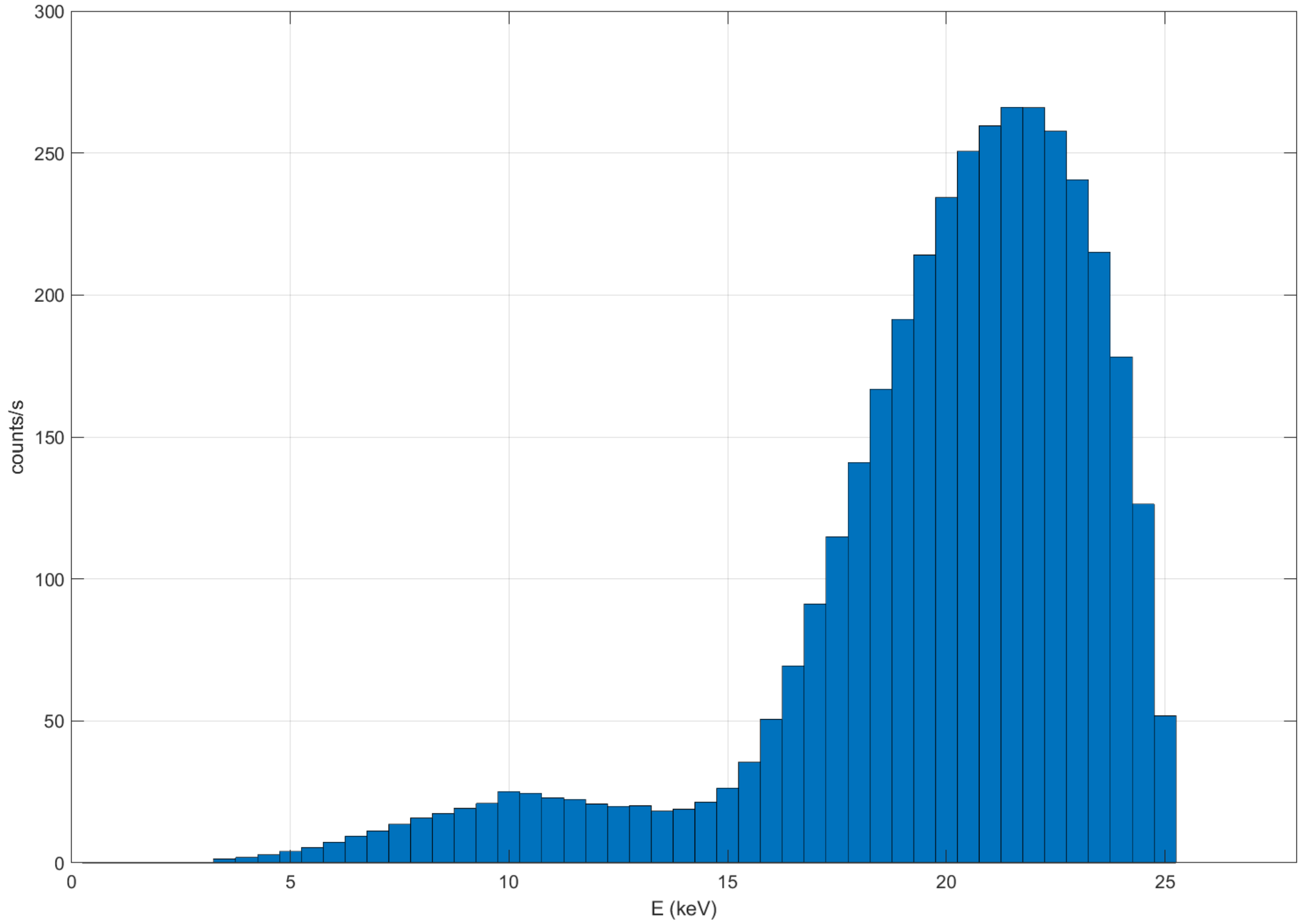
Spectrum unfolding

- Full-energy peak-efficiency (FEPE, ε): what portion of the photons are detected in the photopeak
- Fluence spectrum is obtained from the corrected spectrum with ε and the collimator hole area A:

$$\phi(E) = \frac{s_{corr}(E)}{A\varepsilon(E)}$$

- FEPE is defined for photons coming through the collimator hole, and hence is quite high





300
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counts/s
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10
15
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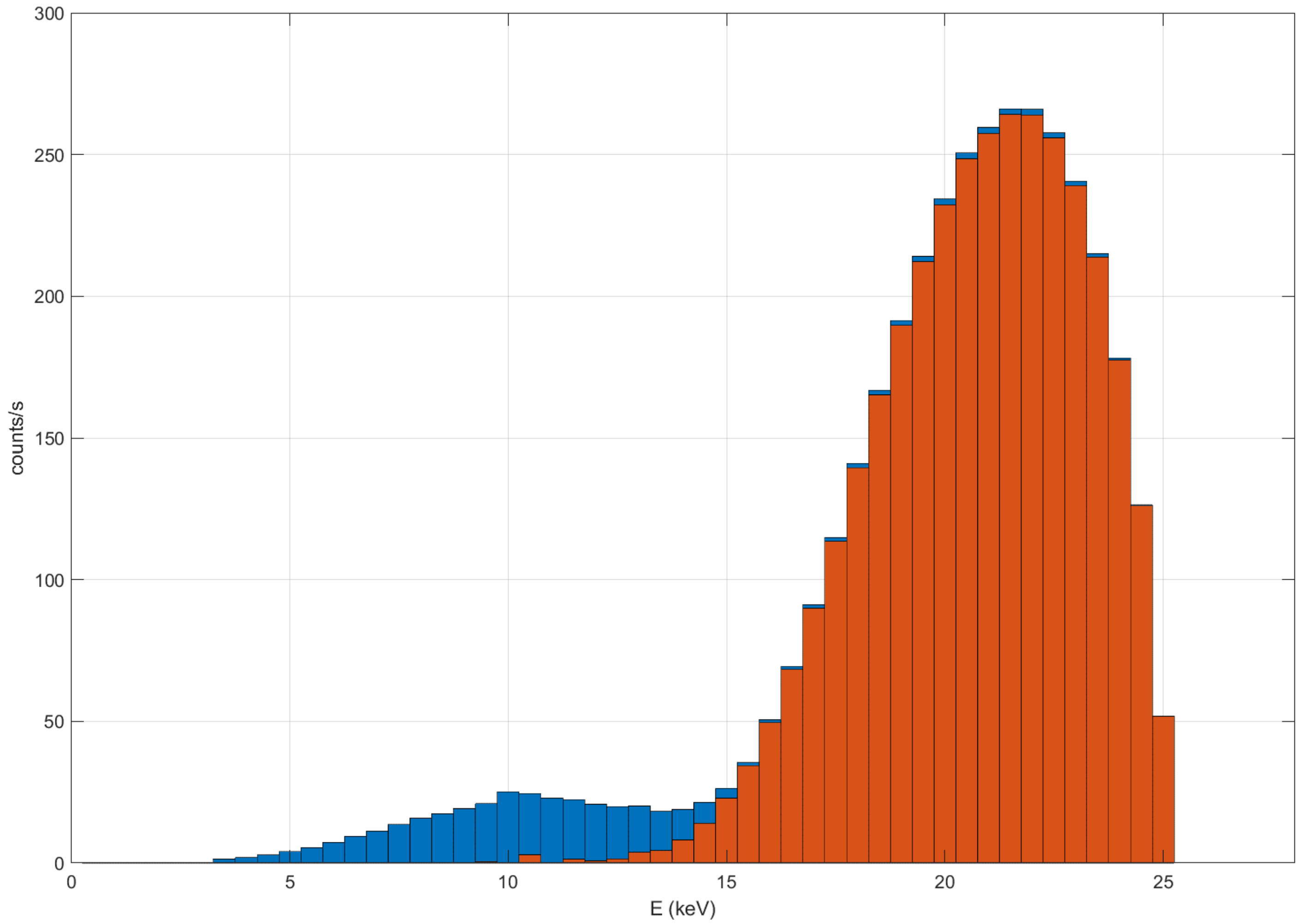
25
E (keV)



300
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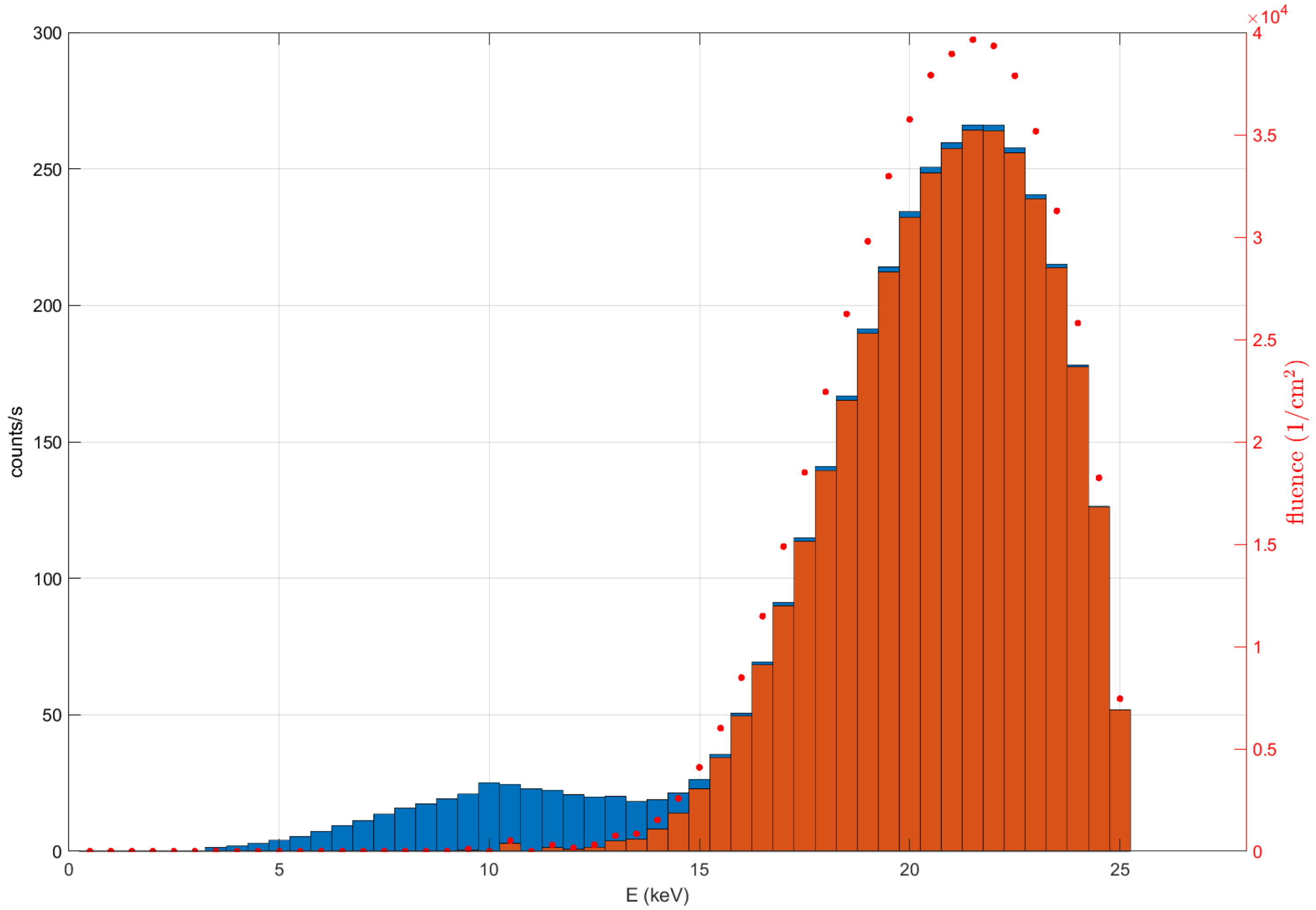

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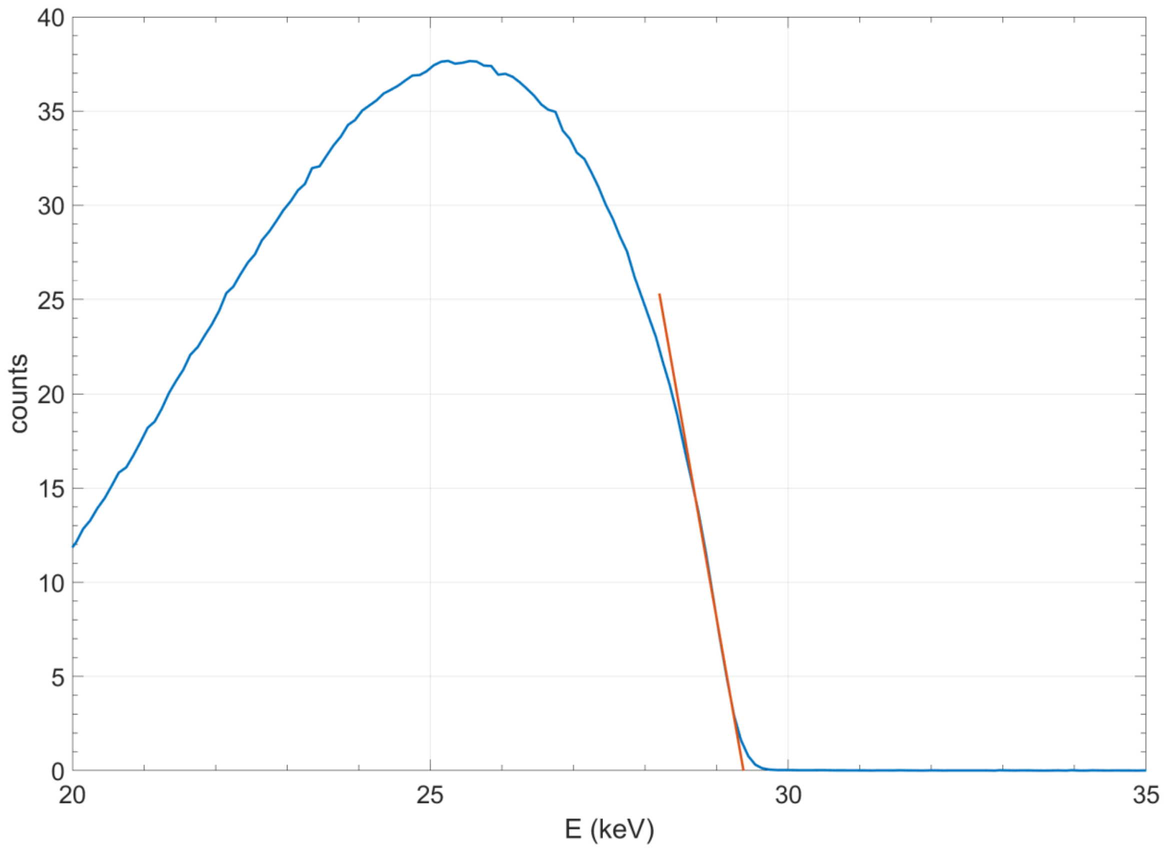
Applications

Tube voltage

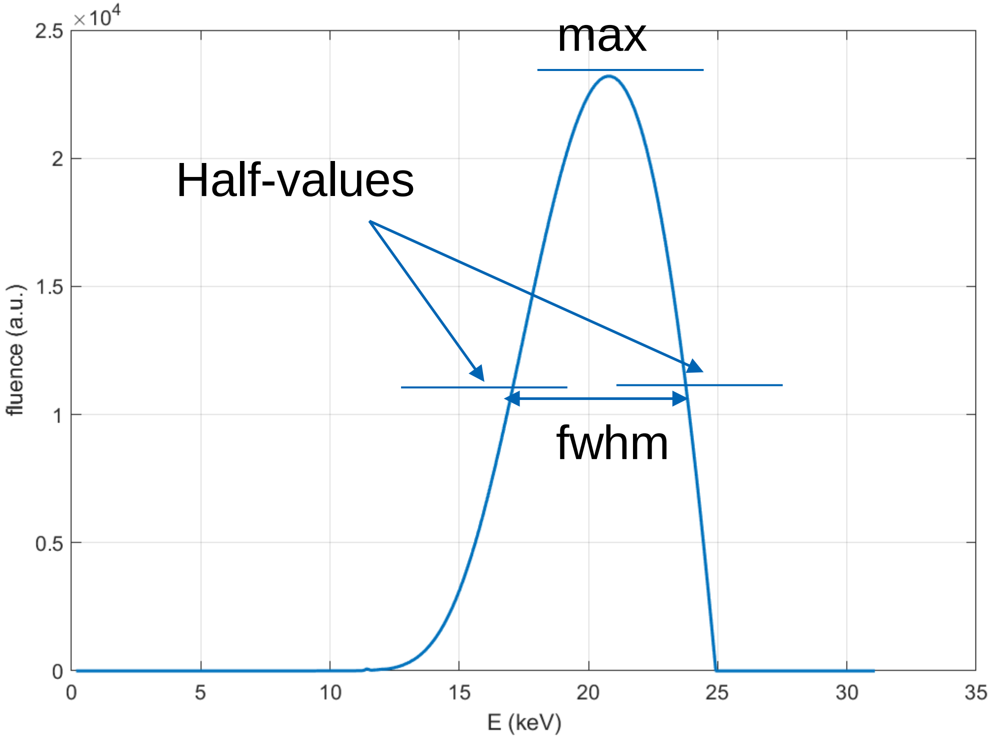
- Maximum energy of photons with tube voltage *V* is $E_{max} = E_{kin} = Ve$
- Tube voltage obtained from the edge of the spectrum $\left(V = \frac{E_{max}}{e}\right)$

- Not considered accurate enough for ISO 4037 at low voltages



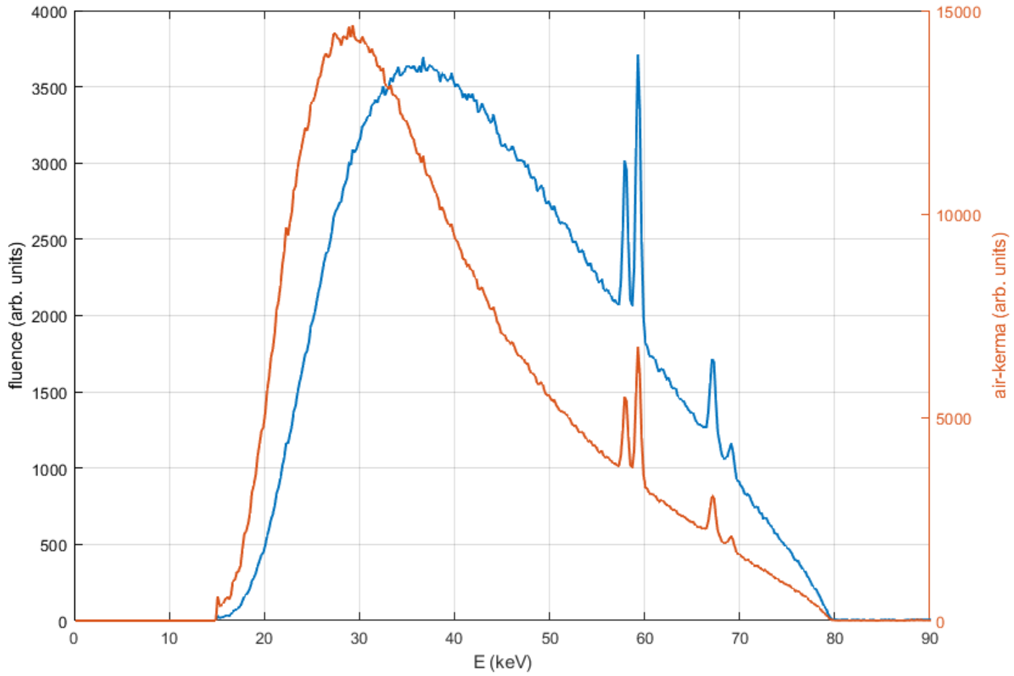
Mean energy and spectrum width

- $E_{mean} = \sum s_i E_i / \sum s_i$
  - Weighed mean, the weights are the counts in each channel
- Width
  - Find the half value of the maximum on rising and falling edge
  - The width (full-width at half maximum, FWHM) is the difference in energy between these points



Air-kerma

- Air-kerma used mainly for further calculations
- For monoenergetic photons $K_a = \phi E \mu_{en}(E)$
  - $\mu_{en}(E)$ is the mass-energy attenuation coefficient with photon energy *E*
  - Air-kerma calculated for each bin: air-kerma spectrum
- Spectrum: sum over the air kerma in each channel
  - $K_a = \int \phi E \mu_{en}(E) dE$
  - Or in practice: $K_a = \sum_i \phi_i E_i \mu_{en}(E_i)$



HVL

- HVL can be solved numerically with the air-kerma spectrum
- Give an initial guess for the HVL
- Attenuate the spectrum in each bin
- Calculate air-kerma for the attenuated spectrum and compare the air-kerma to the original
  - If the ratio is more than half, increase the guessed width
  - If less than half, decrease the width
- Continue until the ratio is close enough to 0.5

- HVLs from spectrometry are slightly smaller than from dosimetric measurements

Dose equivalent and conversion coefficients

- $H_p(10)$, $H_p(3)$, $H_p(0,07)$, $H^*(10)$…
- Monoenergetic photons: $H = K_a h_E$
  - h_E is the monoenergic conversion coefficient for energy E (given in ISO 4037-3)
- Calculate dose equivalent in each bin (H_i), and $H = \sum H_i$
- Conversion coefficient from air-kerma to dose-equivalent for a radiation quality: $h = \frac{H}{K_a}$

- Similar procedure works also for effective dose from ICRP116

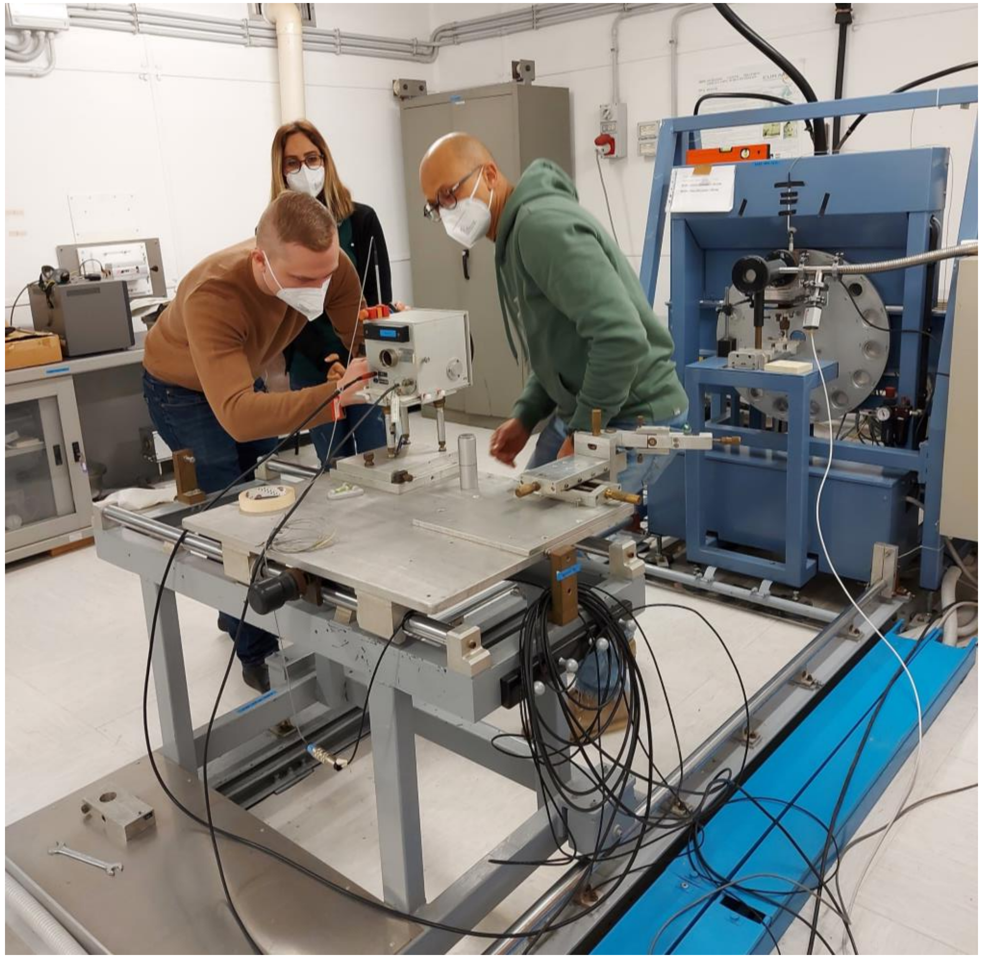
Conclusions

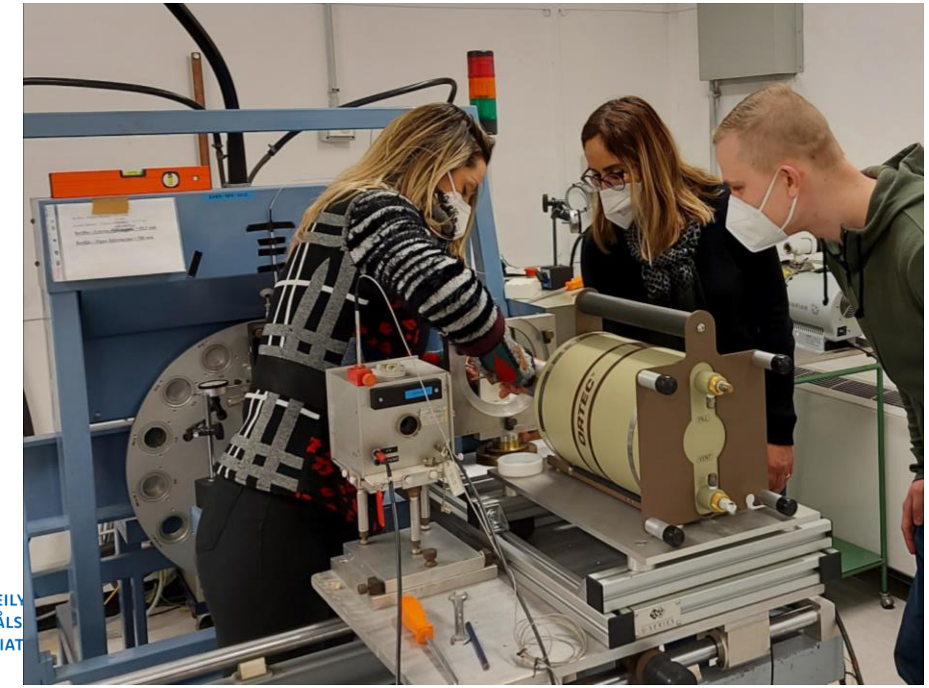
- Spectrometry answers question: what is coming out of the tube?
- Allows determination of multiple quantities for your spectra
  - Same methods can be applied to sealed radionuclide sources, or other sources with continuous spectrum
- Research, detector development…

- Establishing the method is not straightforward
  - Requires (learning) a wide range of skills: gamma-ray spectrometry, pulse processing, dosimetry, Monte Carlo, scripting…
    - Support from radioactivity/gamma lab helps a lot
  - Pulling all this off requires resources

Conclusions

- EURAMET Mentoring scheme award (MSA): Collaboration with ENEA on X-ray spectrometry
- Goal: Publish material (MC models, scripts, documentation) as open source
- Make spectrometry easier for others!





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Future

Could simulated spectra be used instead of measured ones?