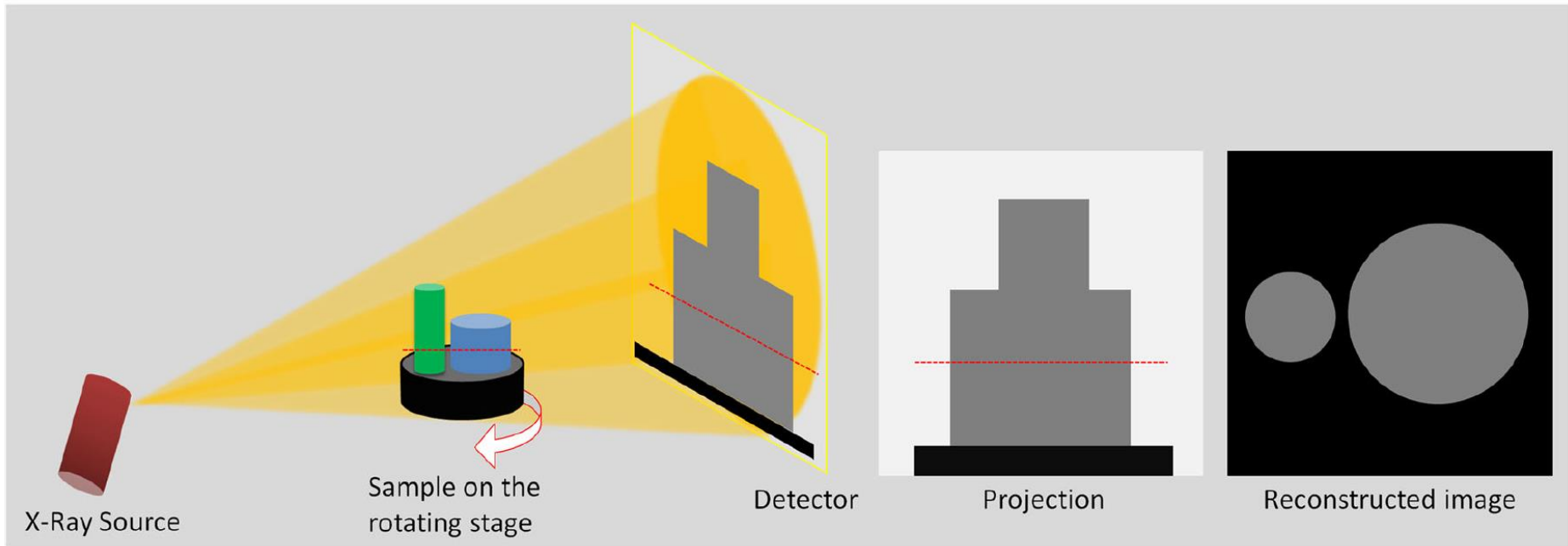


Spectral X-ray tomography for 3D mineral analysis

A new approach to achieve chemical data from a
3-dimensional CT scan

Jonathan Sittner, Jose R. A. Godinho, Axel D. Renno, Veerle Cnudde,
Marijn Boone, Thomas De Schryver, Antti Roine, Jussi Liipo

Principle of tomography

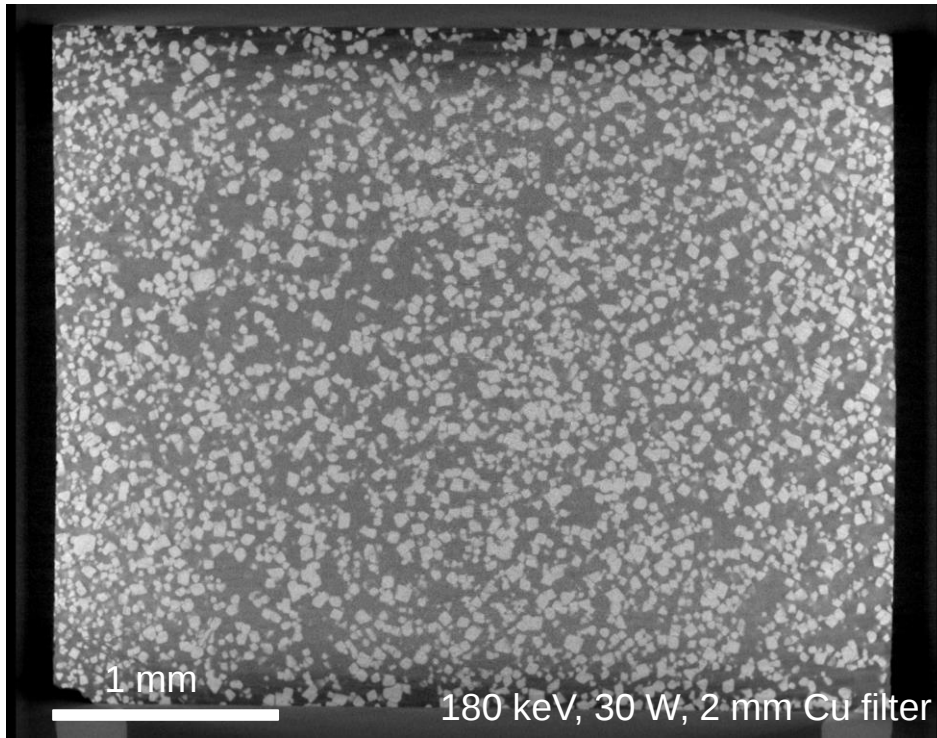


Cengiz et al., 2018

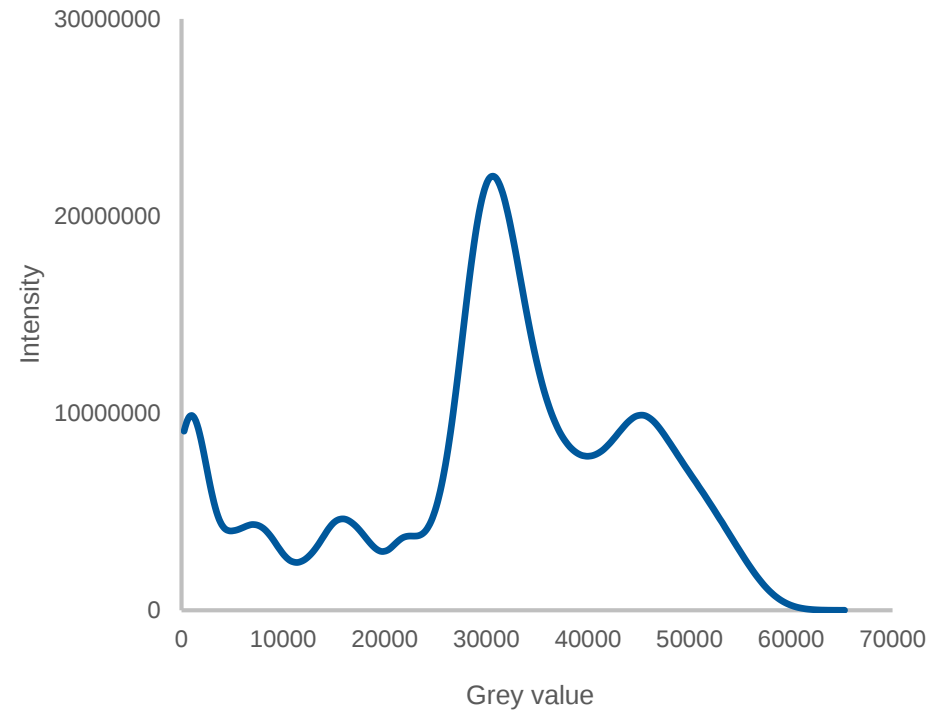
Principle of tomography

- In X-ray computed tomography (CT) the sample is in between the X-ray source and the detector
- Many X-ray absorption images (radiographs) from different rotation angles of the sample are recorded during one scan
- By using different algorithms, the 3D image can be reconstructed

Grey scale and threshold



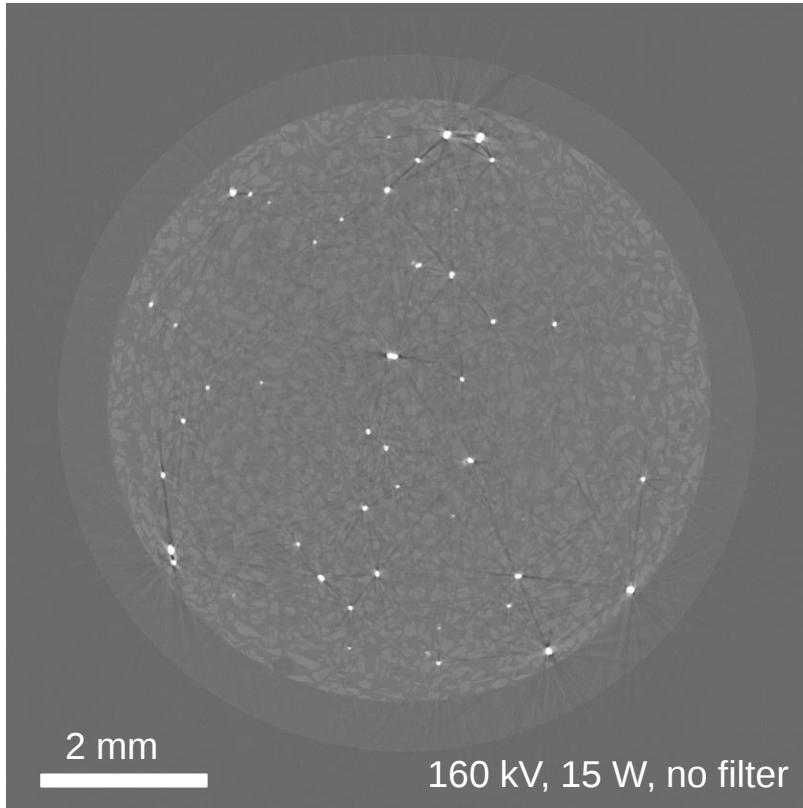
Chromite ore, Kemi mine, Finland



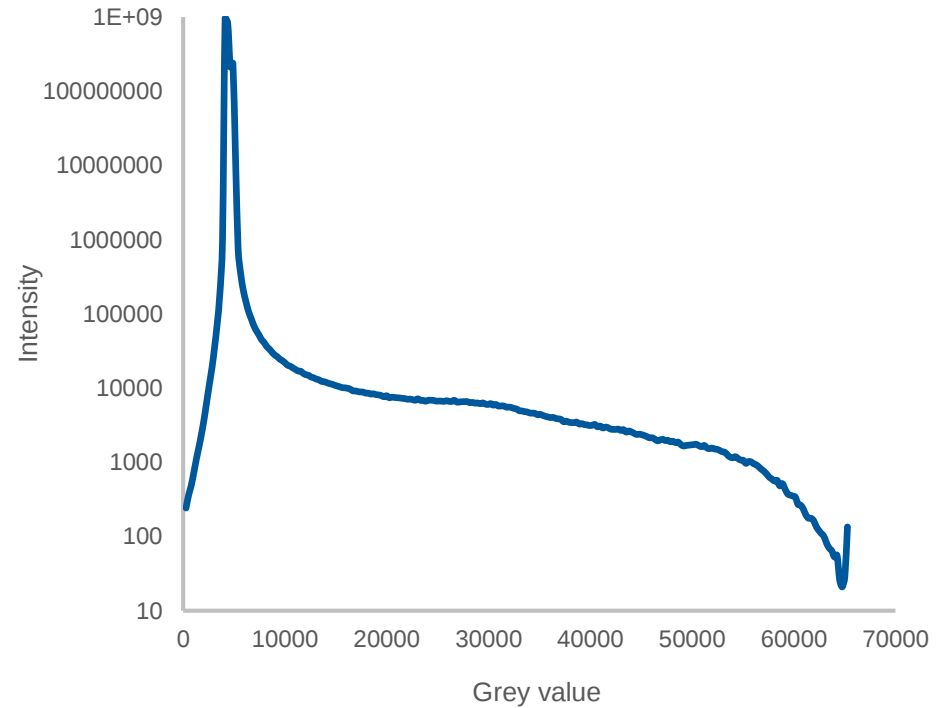
Grey scale and threshold

- Particle classification in computed tomography (CT) often exploits the greyscale histogram
- It shows different greyscales and their intensity of the sample
- The histogram can be used to select and classify particles based on different peaks but without any chemical information

Grey scale and threshold



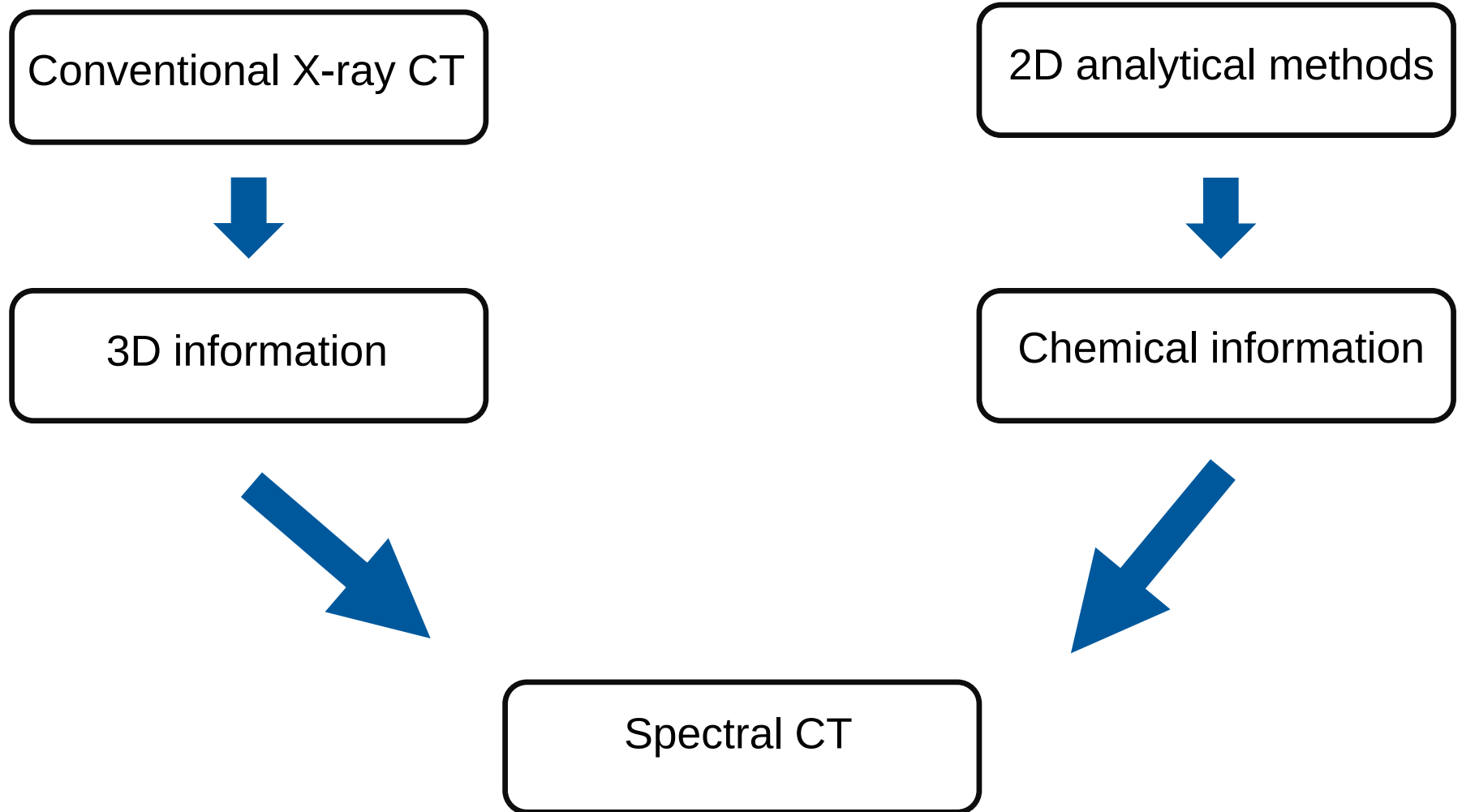
Quartz, gold, lead, tungsten mixture



Grey scale and threshold

- But in some samples it is not possible to see individual peaks for different phases in the greyscale histogram
- This makes a particle classification impossible

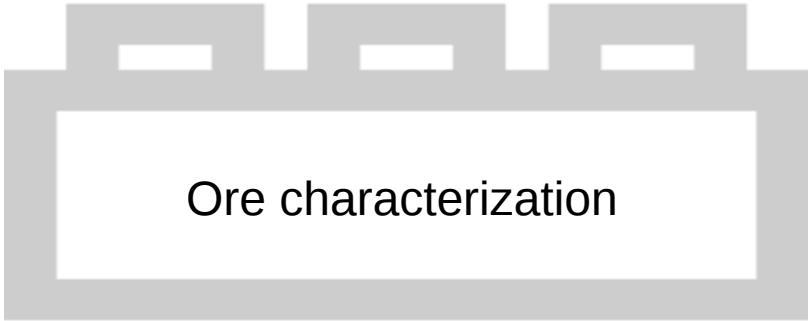
Idea of Spectral CT



Idea of Spectral CT

- The idea of spectral CT is to combine advantages of conventional CT and the chemical information you get from 2D analytical methods
- With the 3D information of CT and the chemical information of 2D methods

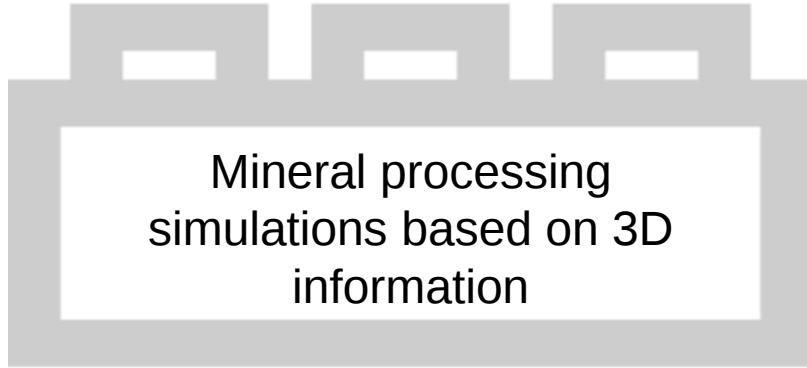
Idea of Spectral CT



Ore characterization

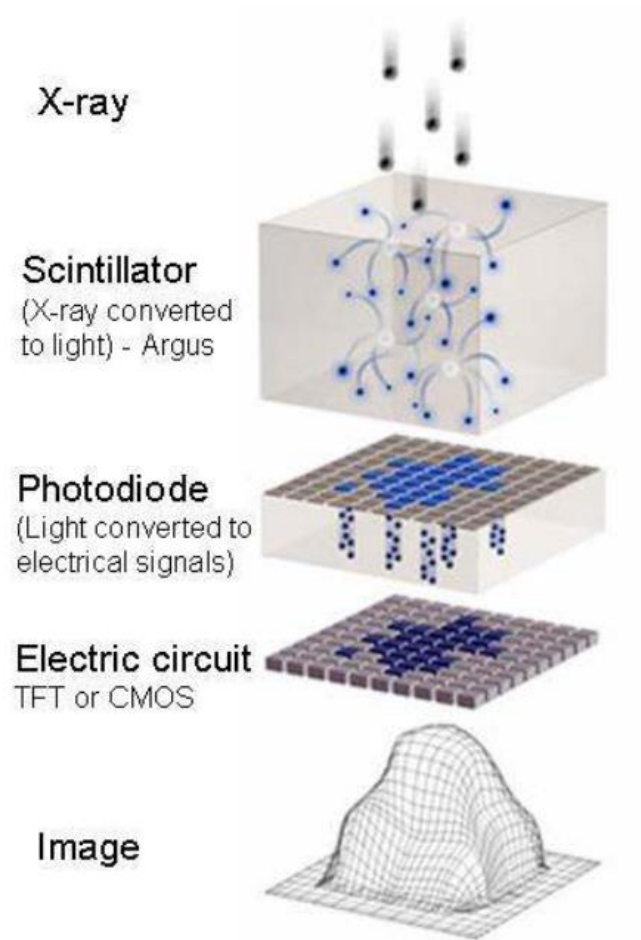


3D particle classification

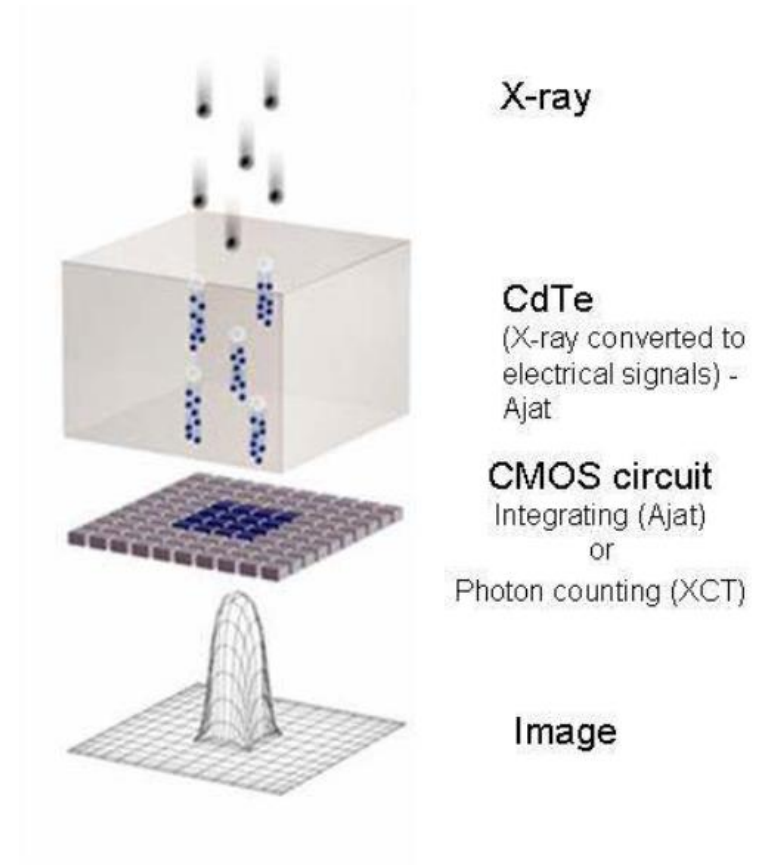


Mineral processing
simulations based on 3D
information

Indirect detection

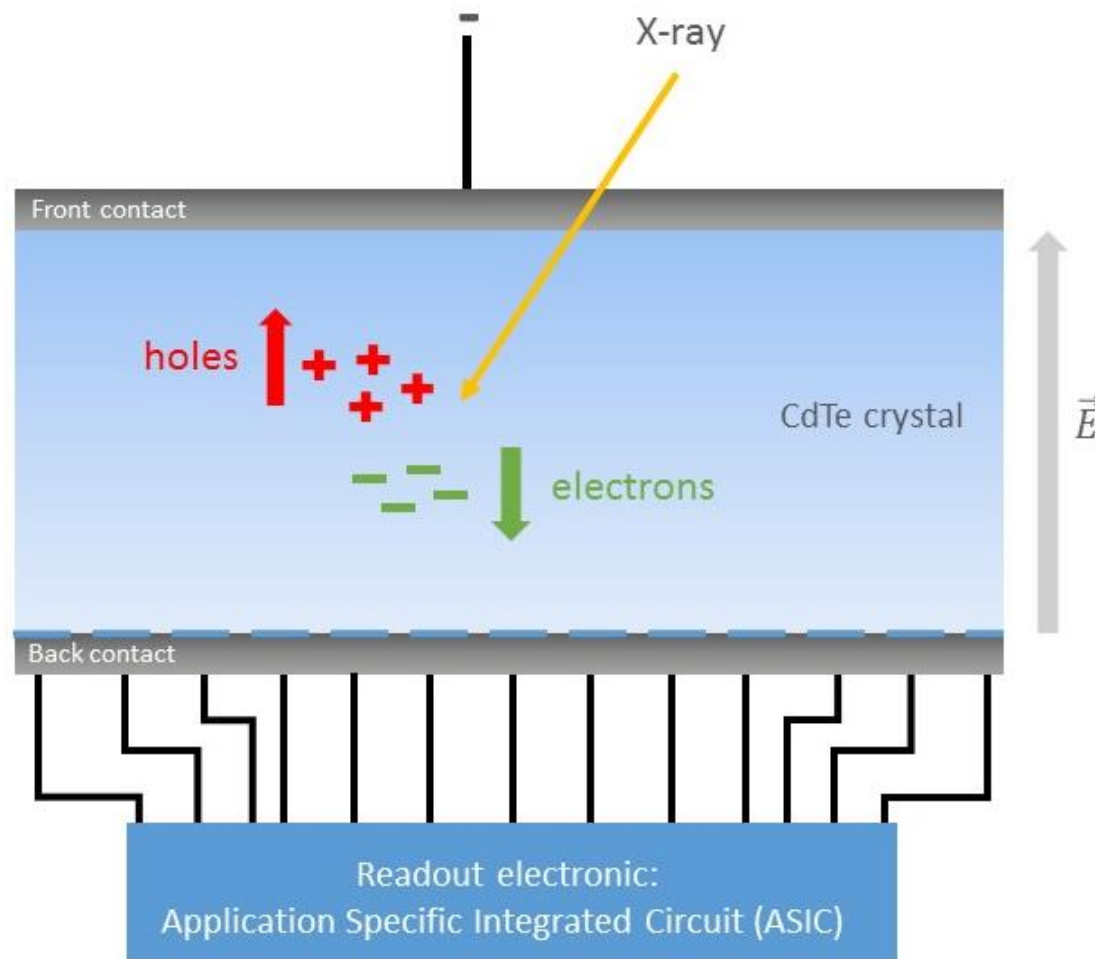


Direct detection



Schumacher et al., 2016

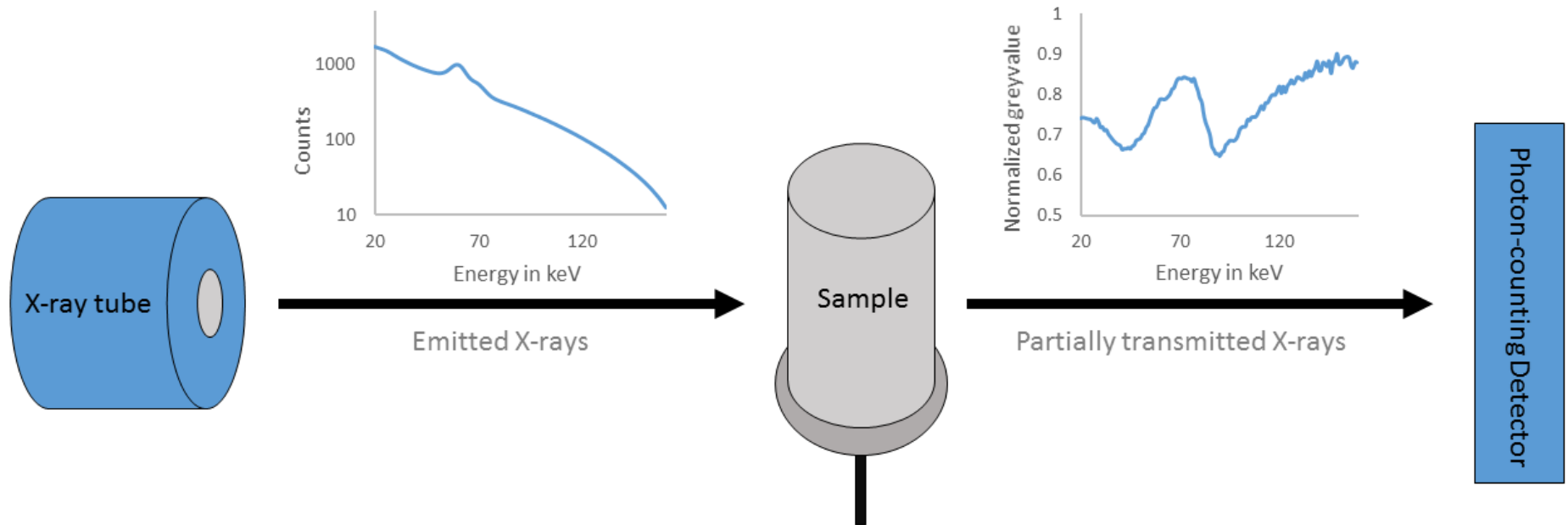
Principle of direct detection



Principle of direct detection

- Spectral CT uses a photon-counting semiconductor detector
- If an X-ray photon hits the detector it generates electron-hole-pairs in the semiconductor
- The applied voltage causes a separation of these charge carriers to the contacts
- The readout electronics further process and amplify the signal
- The detected signal is proportional to the energy of the incident X-ray photon

Principle of spectral CT

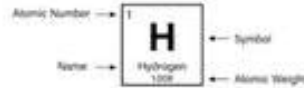


Principle of spectral CT

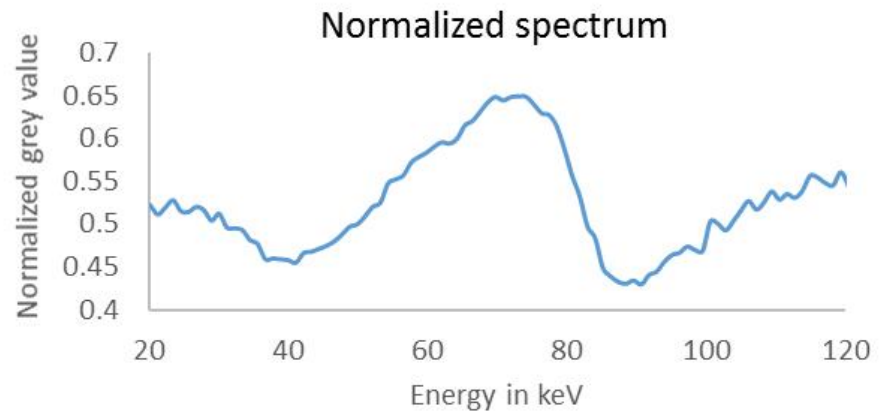
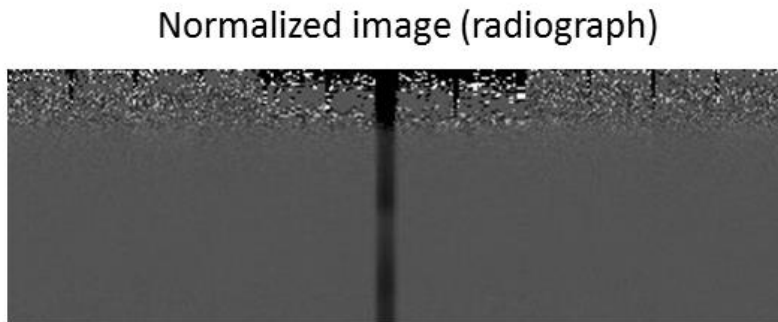
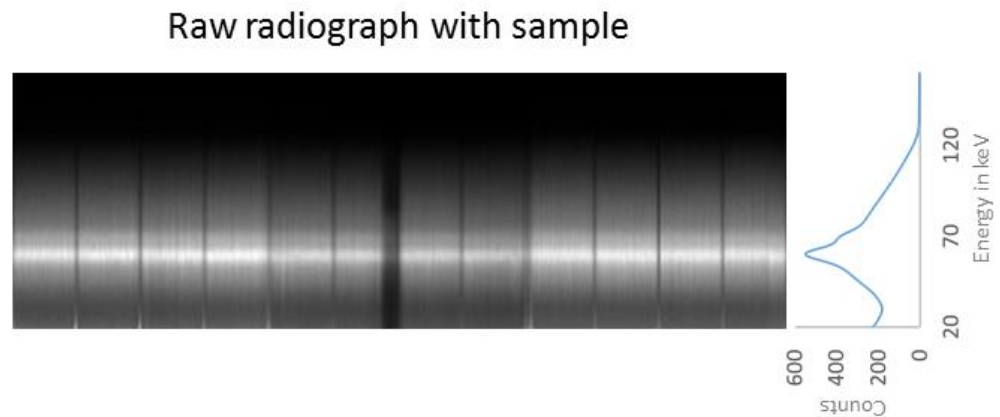
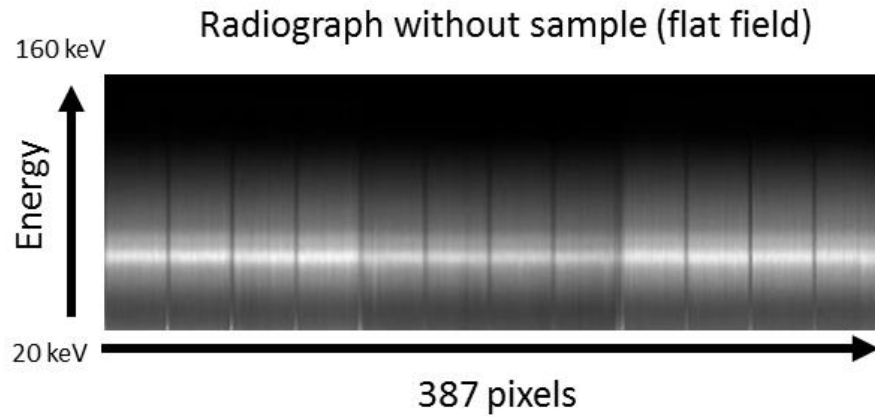
- Spectral CT uses the X-ray absorption spectrum of the sample
- It shows rapid changes in form of absorption edges (K-edges), which are element specific due to electronic transitions (Knoll, 1999)
- Based on the position of the absorption edge (K-edges), the element can be determined
- With a spectral range from 20 to 160 keV, elements from silver up to actinides can be analyzed by using the K-edge position

Principle of spectral CT – list of elements

1 H Hydrogen 1.008																	2 He Helium 4.002602								
3 Li Lithium 6.94	4 Be Beryllium 9.012182															5 B Boron 10.81	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.99840323	10 Ne Neon 20.1797				
11 Na Sodium 22.98976928	12 Mg Magnesium 24.304															13 Al Aluminum 26.9815385	14 Si Silicon 28.085	15 P Phosphorus 30.973761998	16 S Sulfur 32.06	17 Cl Chlorine 35.45	18 Ar Argon 39.948				
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955912	22 Ti Titanium 47.88	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938044	26 Fe Iron 55.845	27 Co Cobalt 58.933194	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.63	33 As Arsenic 74.921595	34 Se Selenium 78.9718	35 Br Bromine 79.904	36 Kr Krypton 83.798								
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90584	40 Zr Zirconium 91.224	41 Nb Niobium 92.90637	42 Mo Molybdenum 95.94	43 Tc Technetium 98	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.757	52 Te Tellurium 127.60	53 I Iodine 126.90547	54 Xe Xenon 131.29								
55 Cs Cesium 132.90545196	56 Ba Barium 137.327	57 - 71 Lanthanoids	72 Hf Hafnium 178.49	73 Ta Tantalum 180.94788	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.222	78 Pt Platinum 195.084	79 Au Gold 196.966569	80 Hg Mercury 200.59	81 Tl Thallium 204.38	82 Pb Lead 207.2	83 Bi Bismuth 208.98040	84 Po Polonium 209	85 At Astatine 210	86 Rn Radon 222								
87 Fr Francium 223	88 Ra Radium 226	89 - 103 Actinoids	104 Rf Rutherfordium 261	105 Db Dubnium 262	106 Sg Seaborgium 266	107 Bh Bohrium 264	108 Hs Hassium 277	109 Mt Meitnerium 268	110 Ds Darmstadtium 271	111 Rg Roentgenium 272	112 Cn Copernicium 285	113 Nh Nihonium 284	114 Fl Flerovium 289	115 Mc Moscovium 288	116 Lv Livermorium 293	117 Ts Tennessine 294	118 Og Oganesson 294								
57 La Lanthanum 138.90547	58 Ce Cerium 140.12	59 Pr Praseodymium 140.90766	60 Nd Neodymium 144.242	61 Pm Promethium 145	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92535	66 Dy Dysprosium 162.50015	67 Ho Holmium 164.93032	68 Er Erbium 167.259	69 Tm Thulium 168.93032	70 Yb Ytterbium 173.045	71 Lu Lutetium 174.967											
89 Ac Actinium 227	90 Th Thorium 232.0377	91 Pa Protactinium 231.03688	92 U Uranium 238.02891	93 Np Neptunium 237	94 Pu Plutonium 244	95 Am Americium 243	96 Cm Curium 247	97 Bk Berkelium 247	98 Cf Californium 251	99 Es Einsteinium 252	100 Fm Fermium 257	101 Md Mendelevium 258	102 No Nobelium 259	103 Lr Lawrencium 260											



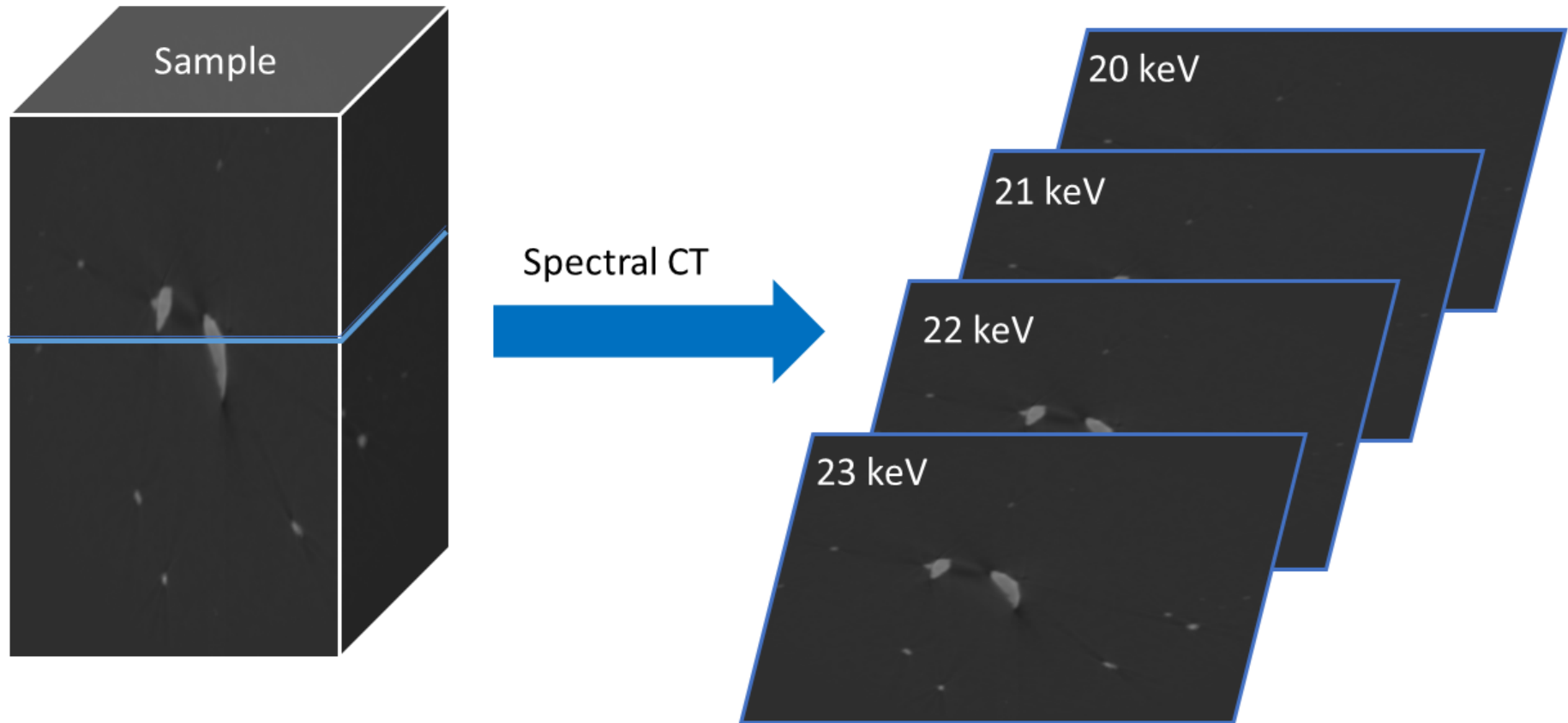
Principle of spectral CT



Principle of spectral CT

- The raw signal of the detector shows a local information at the x-direction
- The y-direction of the image (radiograph) represents the energy, from 20 to 160 keV
- The bright horizontal band in the radiographs is the tungsten K- α fluorescence caused by the X-ray tube
- The numerous dark vertical lines are caused by the readout electronics of the detector
- By normalization of the flat field and the radiograph with the sample, artifacts can be removed
- The spectrum can be extracted from the normalized image

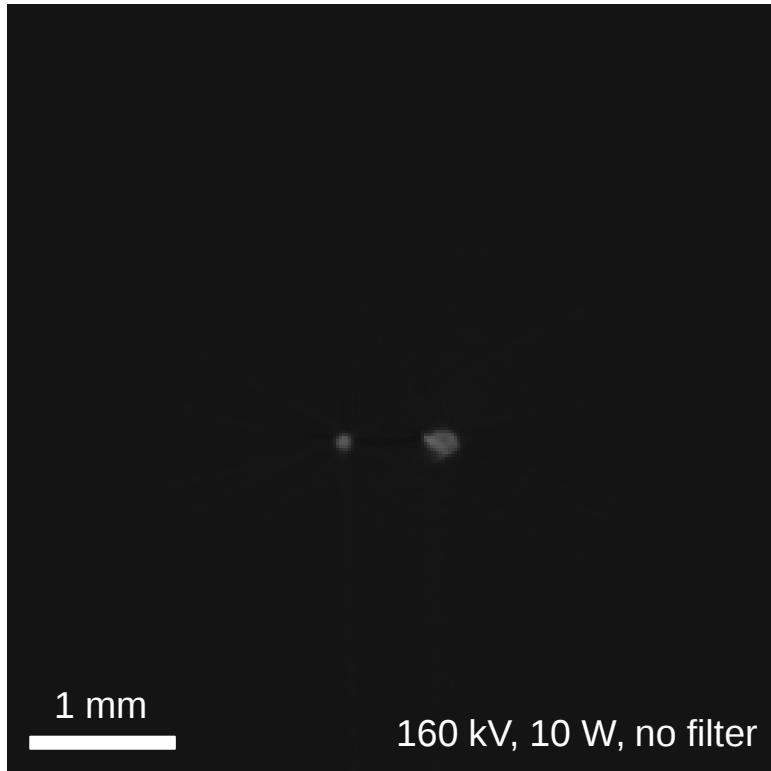
Principle of spectral CT



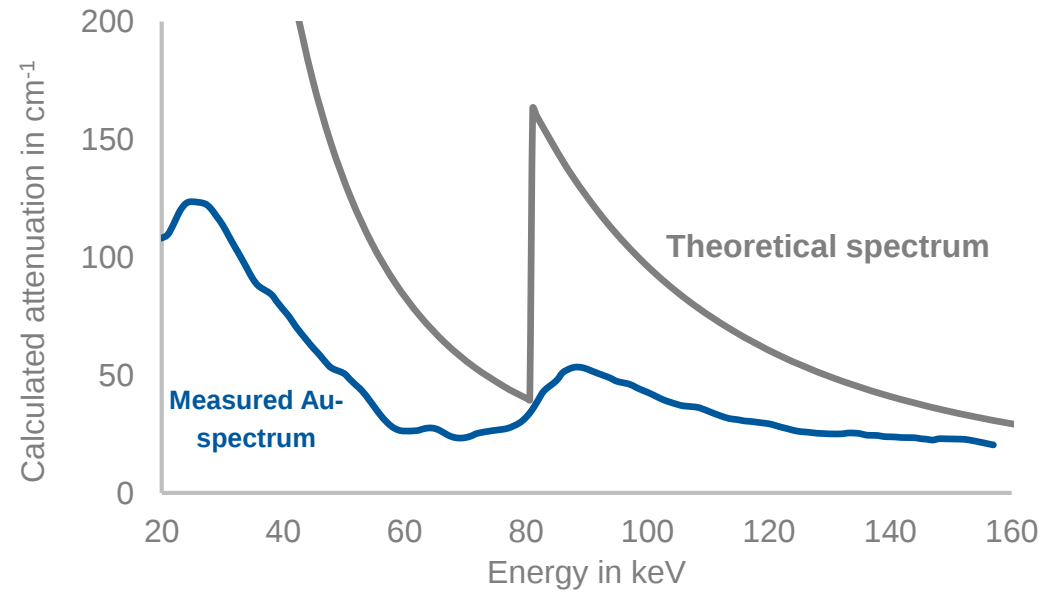
Principle of spectral CT

- One radiograph represents only one rotation angle
- For a full scan, many radiographs from different angles are required
- The result is a stack of images for a 2D plane of the sample, each representing one energy (20 to 160 keV)

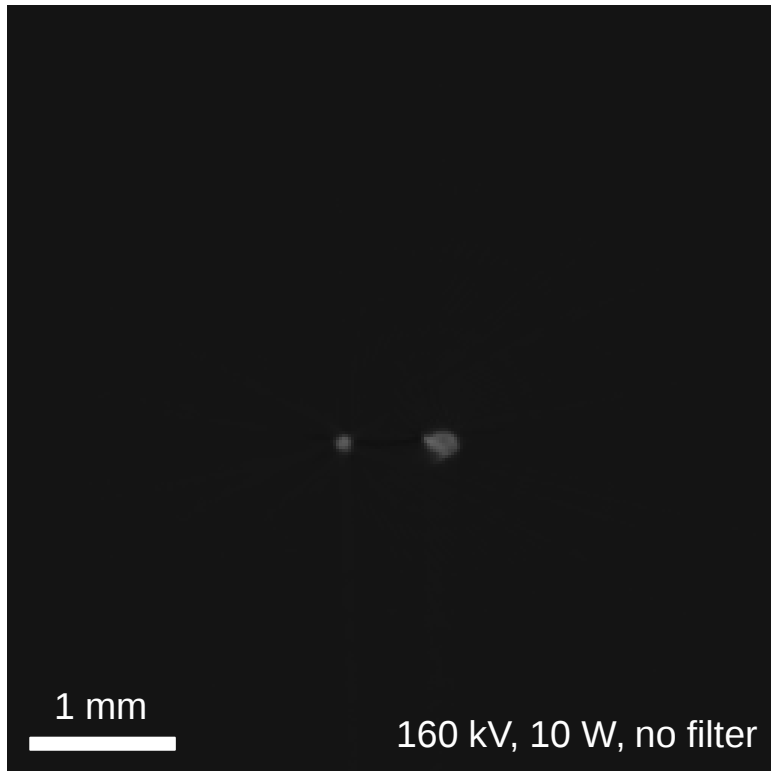
K-edge of gold



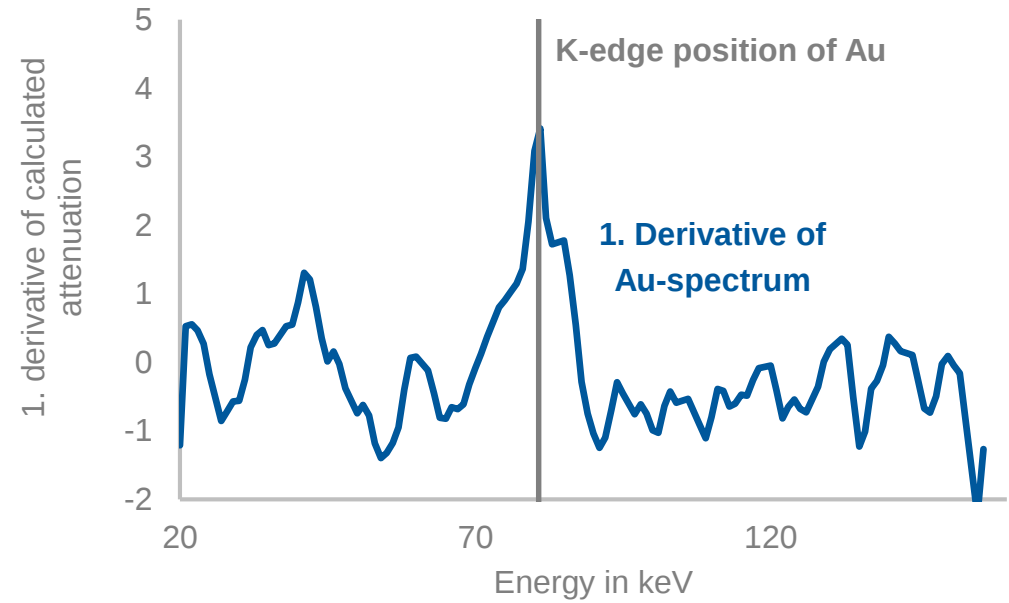
Gold particles



K-edge of gold



Gold particles



K-edge of gold

- The spectrum of a gold particle shows the K-edge
- Compared with the theoretical spectrum, there are some differences
- The first derivative shows the exact position of the peak better, to compare it with the theoretical value
- The K-edge position matches with the theoretical position

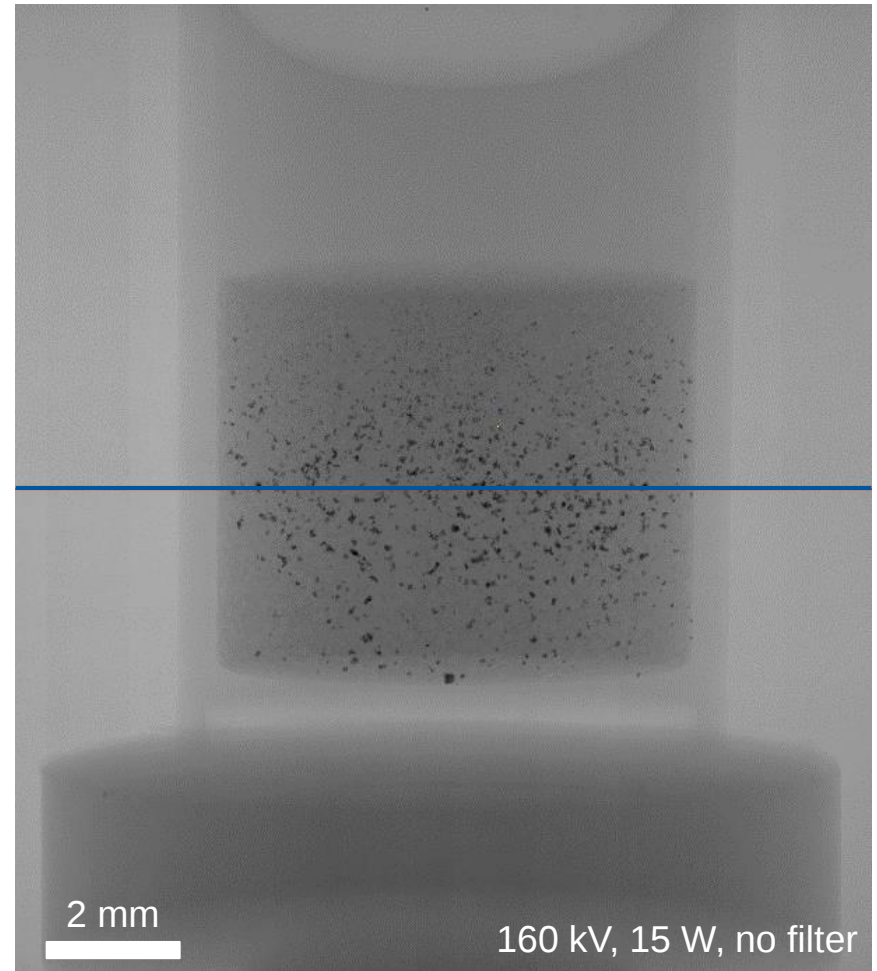
Particle classification



Preparation of a quartz-gold-lead-tungsten mixture



X-ray CT

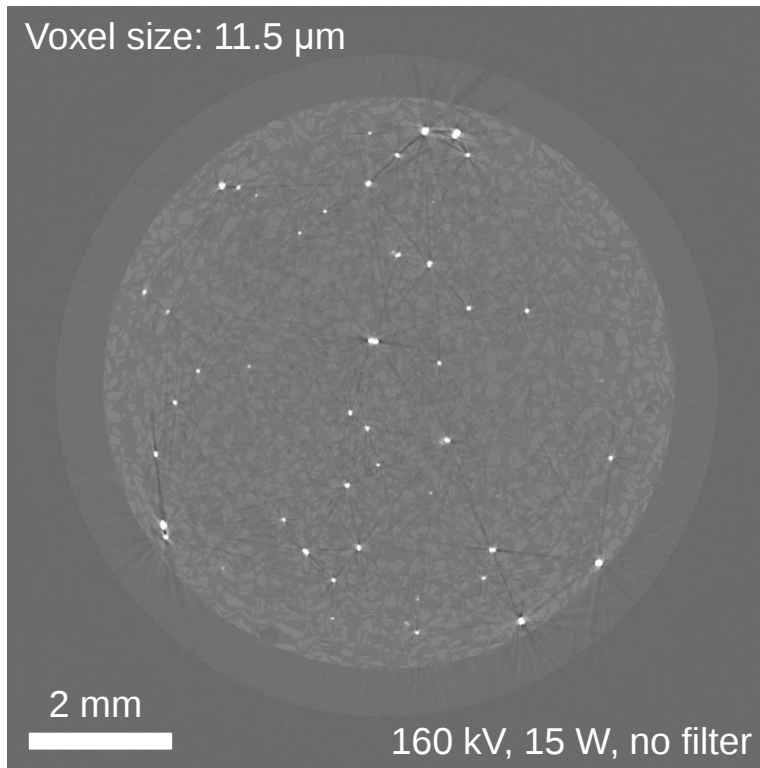


Quartz, gold, lead, tungsten mixture embedded in epoxy resin

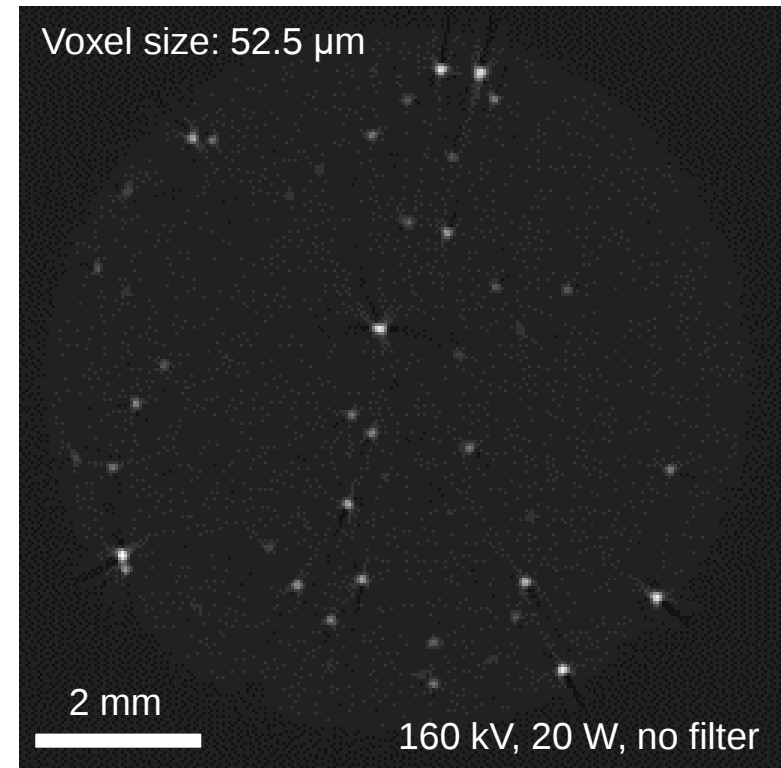
Preparation of a quartz-gold-lead-tungsten mixture

- To test the particle classification using spectral CT, a sample with gold, lead and tungsten was prepared
- Quartz was used as a matrix material, as it shows no absorption edge in the spectral range of interest

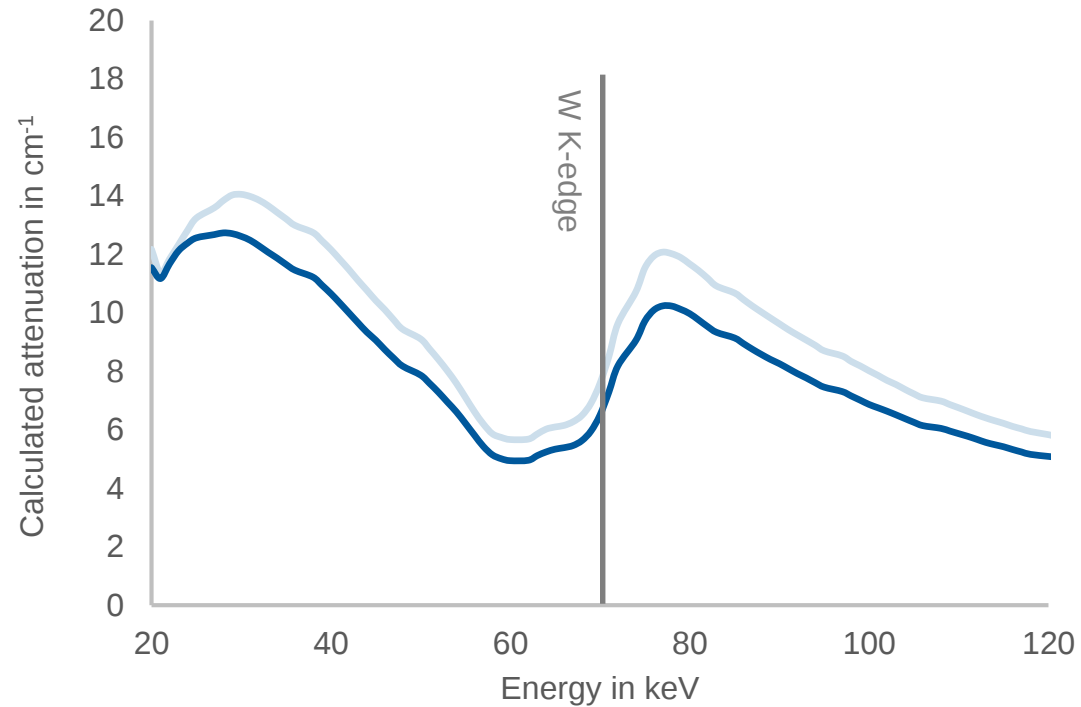
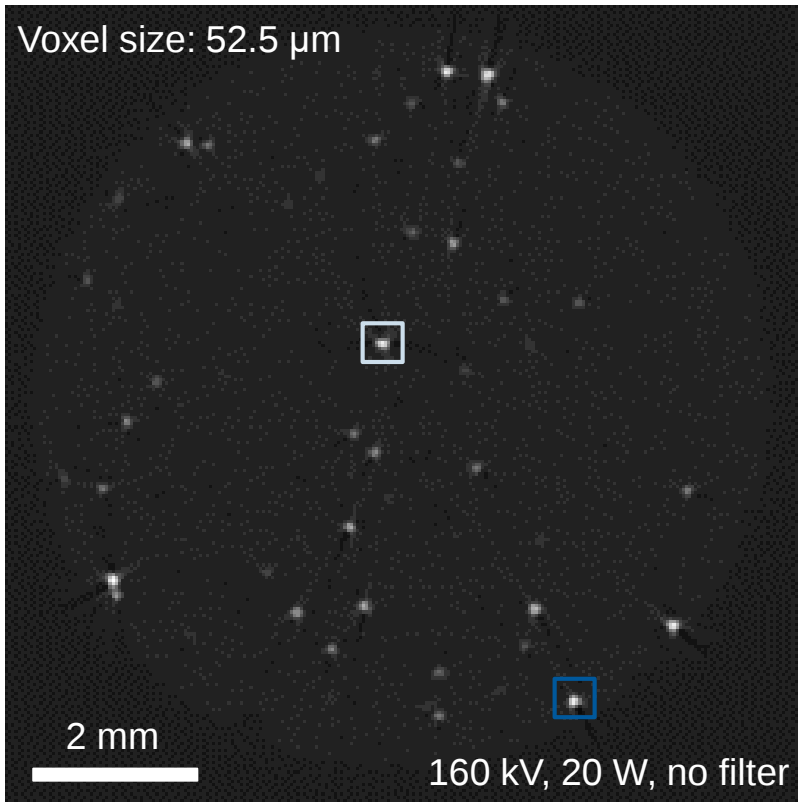
Conventional CT and spectral CT



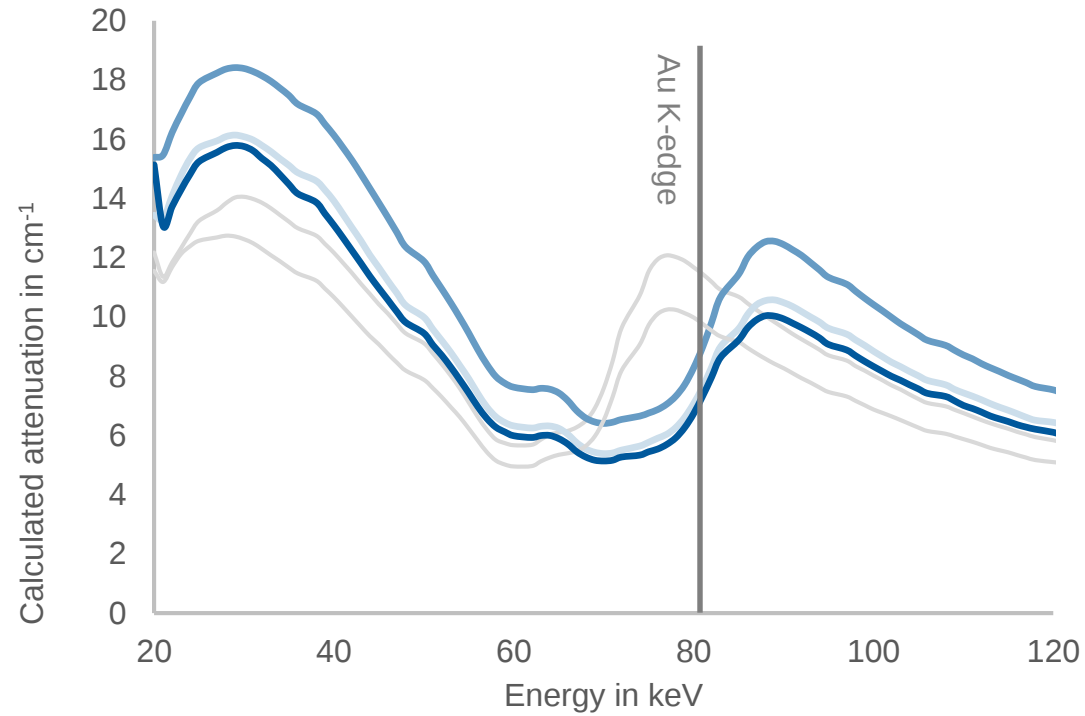
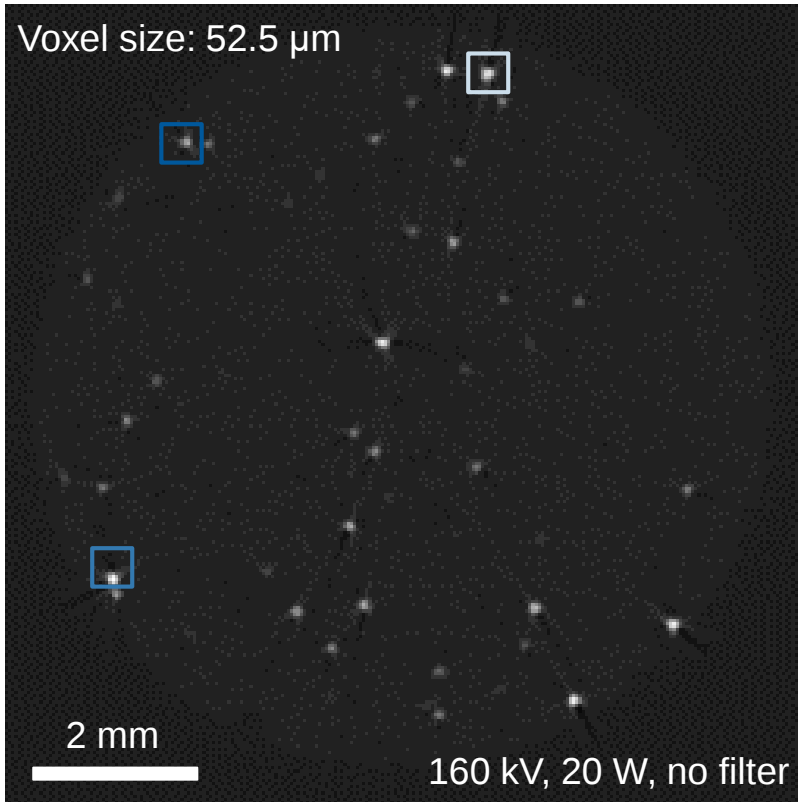
Spectral CT



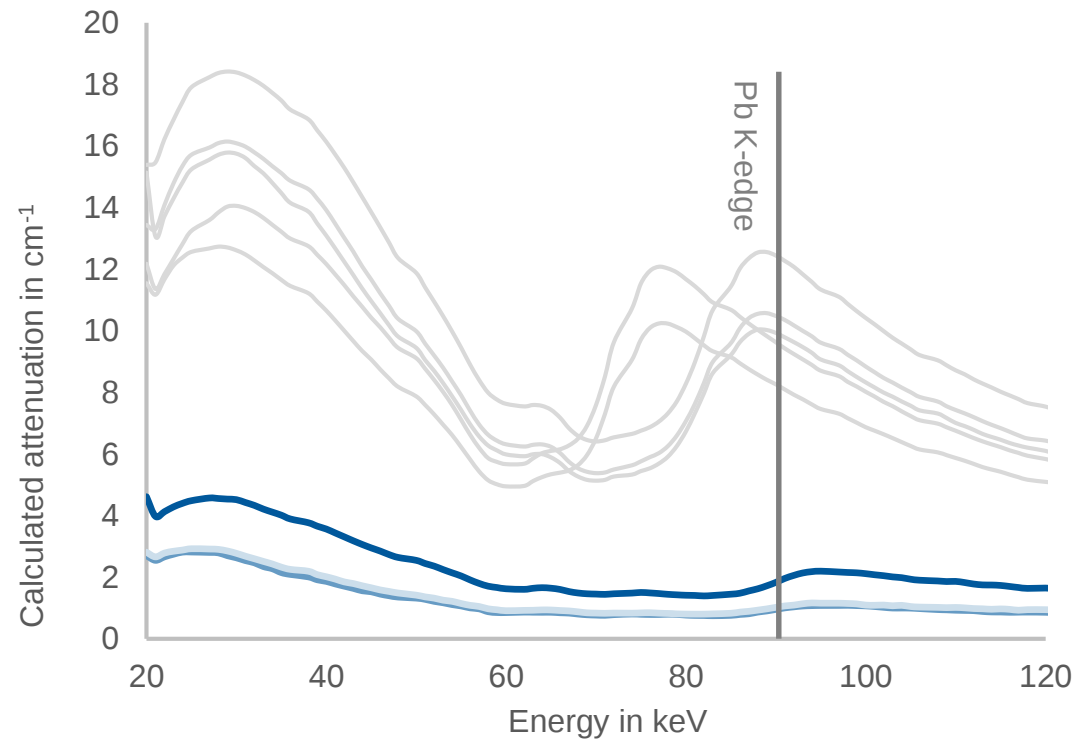
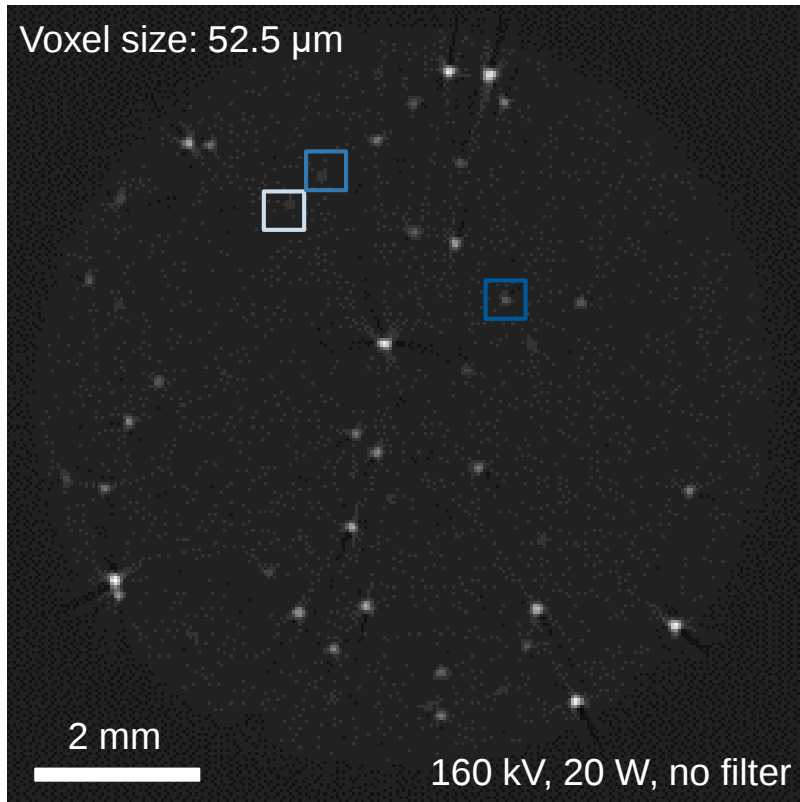
Particle classification – tungsten



Particle classification – gold

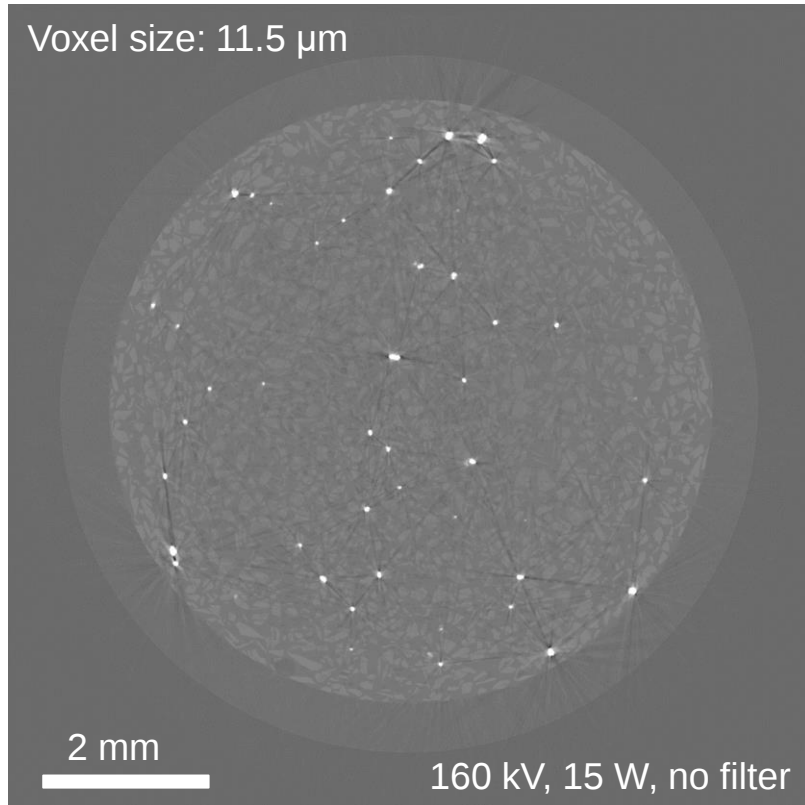


Particle classification – lead

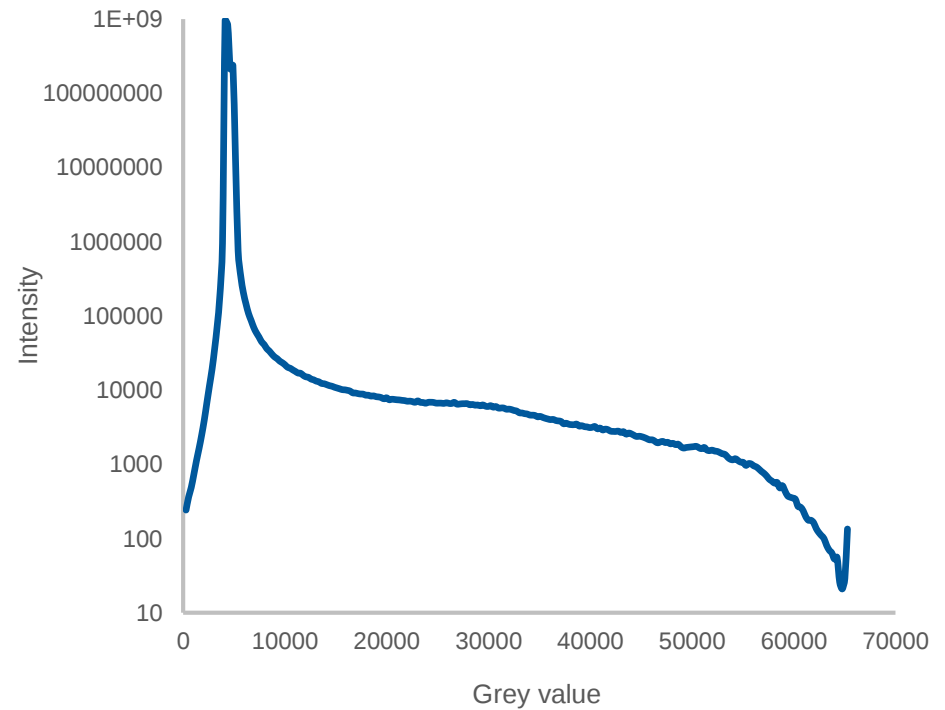


Based on the position of the K-edges in the spectrum, gold, lead and tungsten can be distinguished

Particle classification – conventional CT



Quartz, gold, lead, tungsten mixture

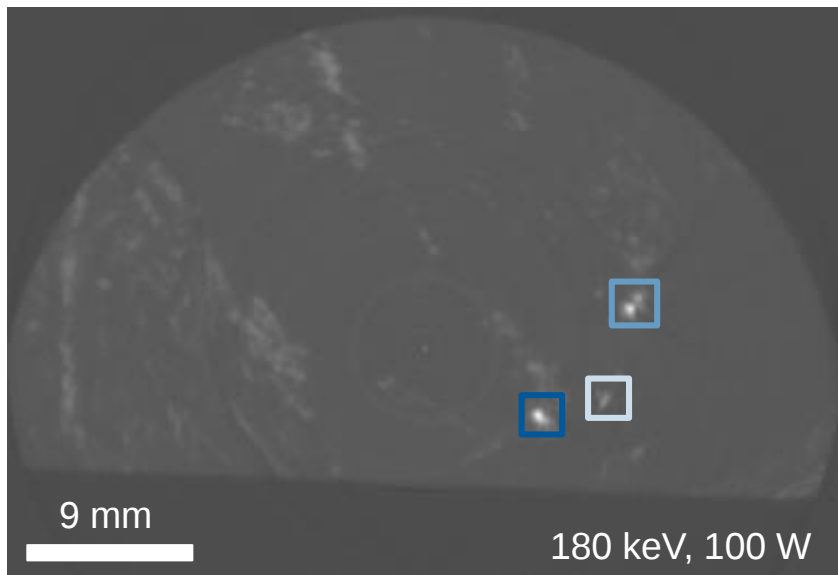


It is not possible to distinguish between the particles by using conventional CT with the same sample

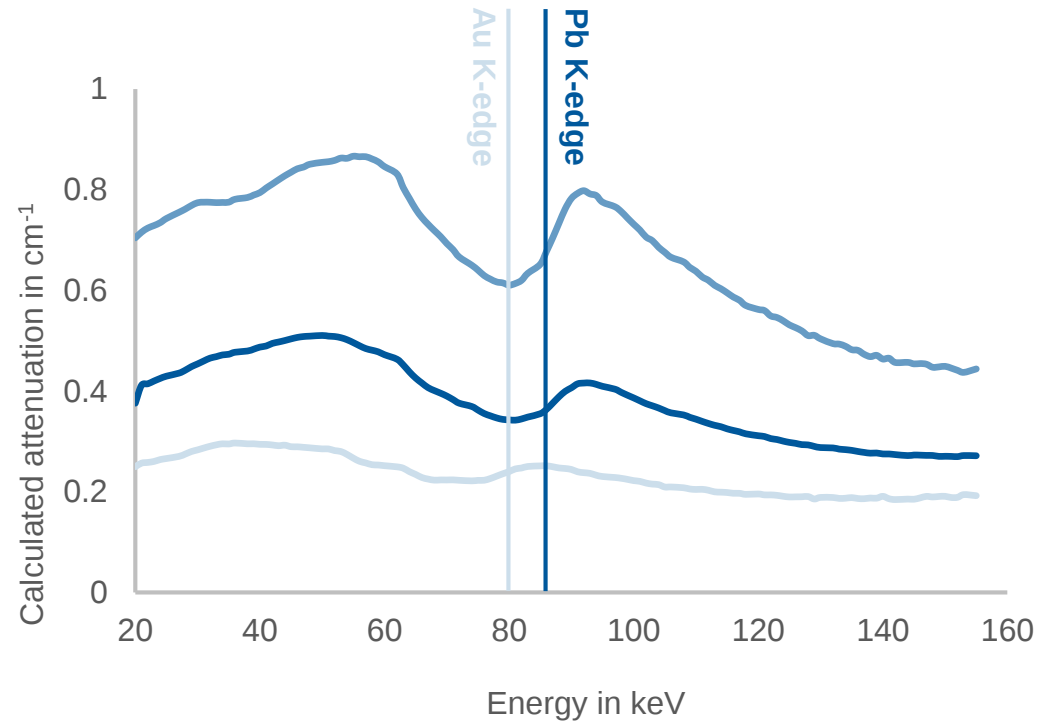
Particle classification

- All particles can be differentiated based on the position of the K-edge even though their greyscale pattern appears the same in the image
- With the greyscale histogram from a conventional CT it is not possible to differentiate the particles
- With spectral CT it is possible to obtain chemical information from a CT scan without using additional analytical methods

Particle classification – rock sample



Quartz vein with different sulfide minerals and native gold, Massawa Gold Deposit, Senegal



Particle classification – rock sample

- This gold ore from the Massawa deposit in Senegal contains different sulfide minerals and native gold
- With spectral CT we are able to differentiate between particles containing gold and lead
- The theoretical position of the K-edges matches with the measured spectra and allows a discrimination of both elements

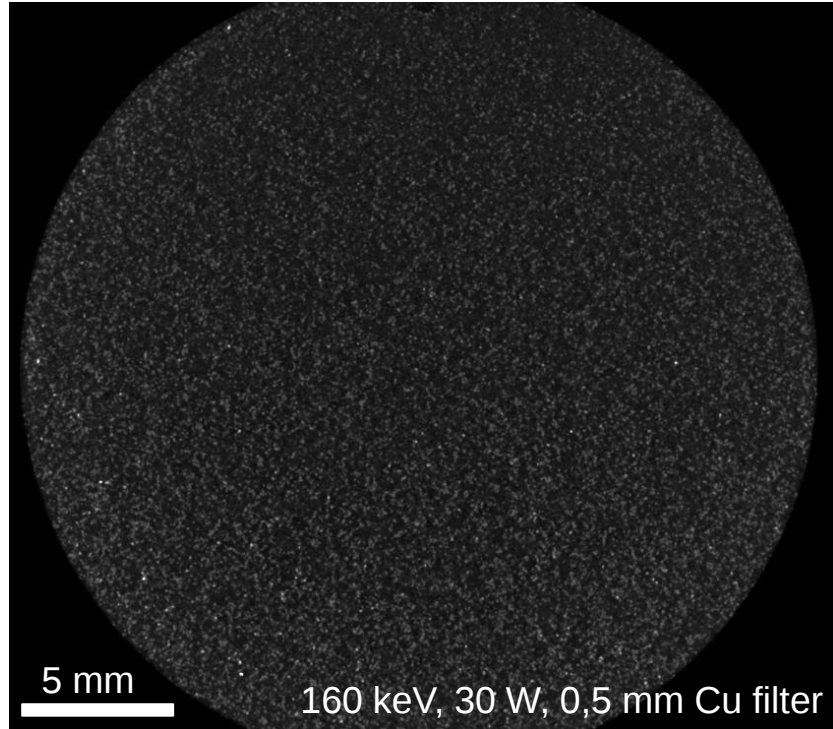
3D Particle Information



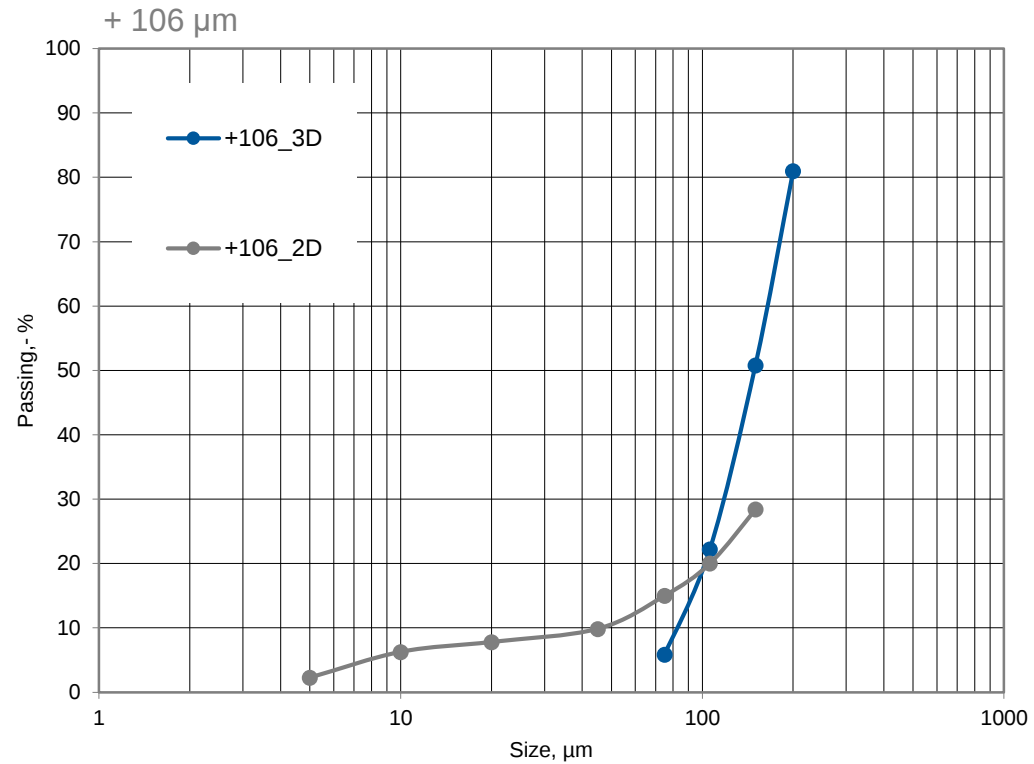
2D vs 3D particle information

- Usually simulations use 2D information of the particles measured in a sample
- CT provides the 3D information of the particles and can scan a larger volume, which is more representative
- Here we compare the 2D and 3D particle information in different size fractions of a gold floatation concentrate

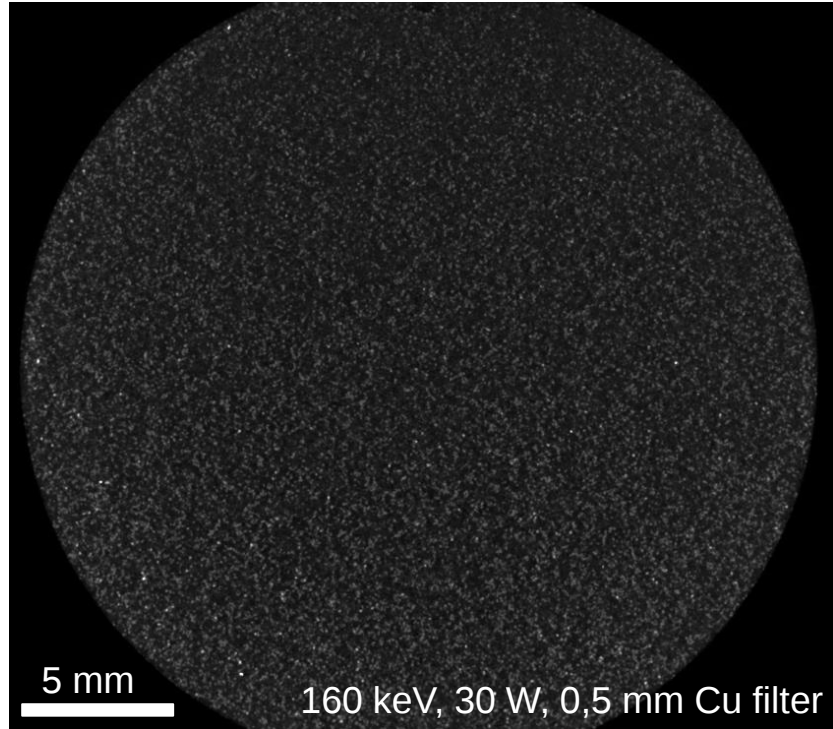
2D vs 3D particle information



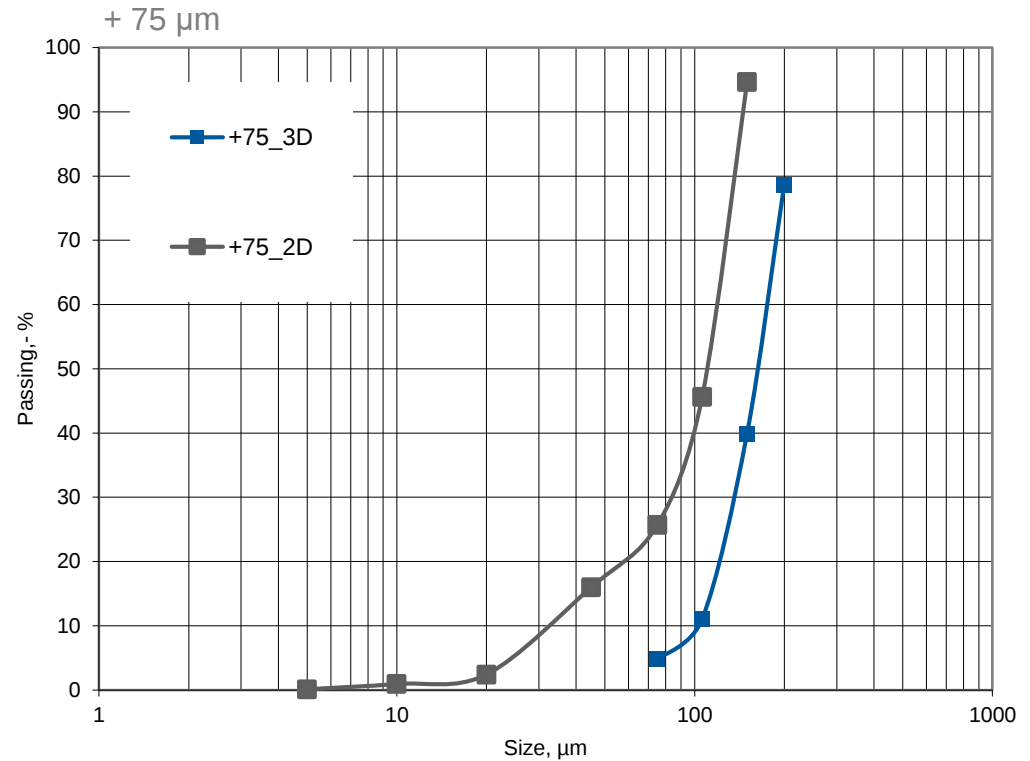
Gold flotation concentrate, Jokisivu Mine, Finland



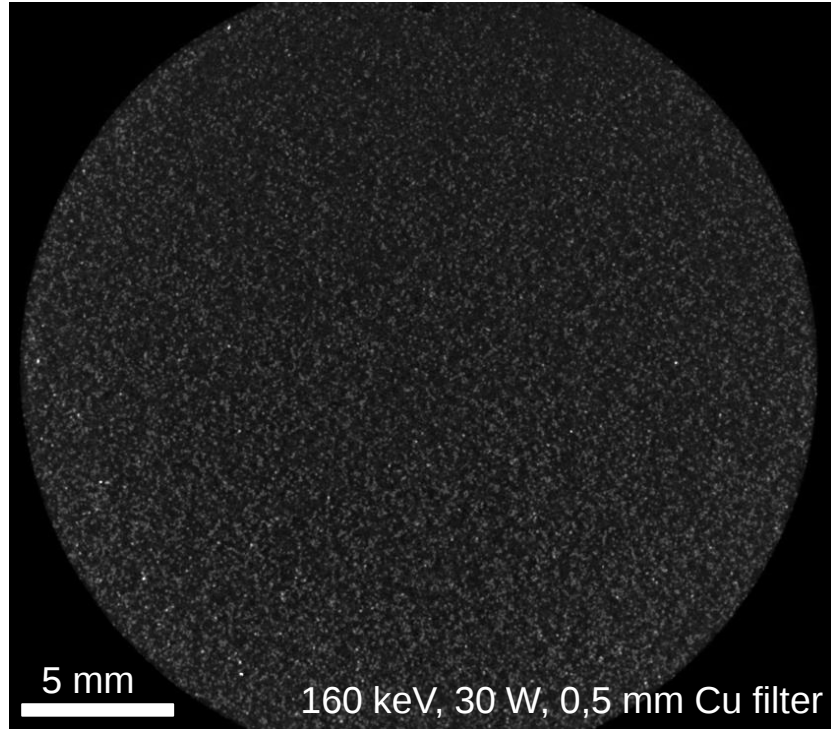
2D vs 3D particle information



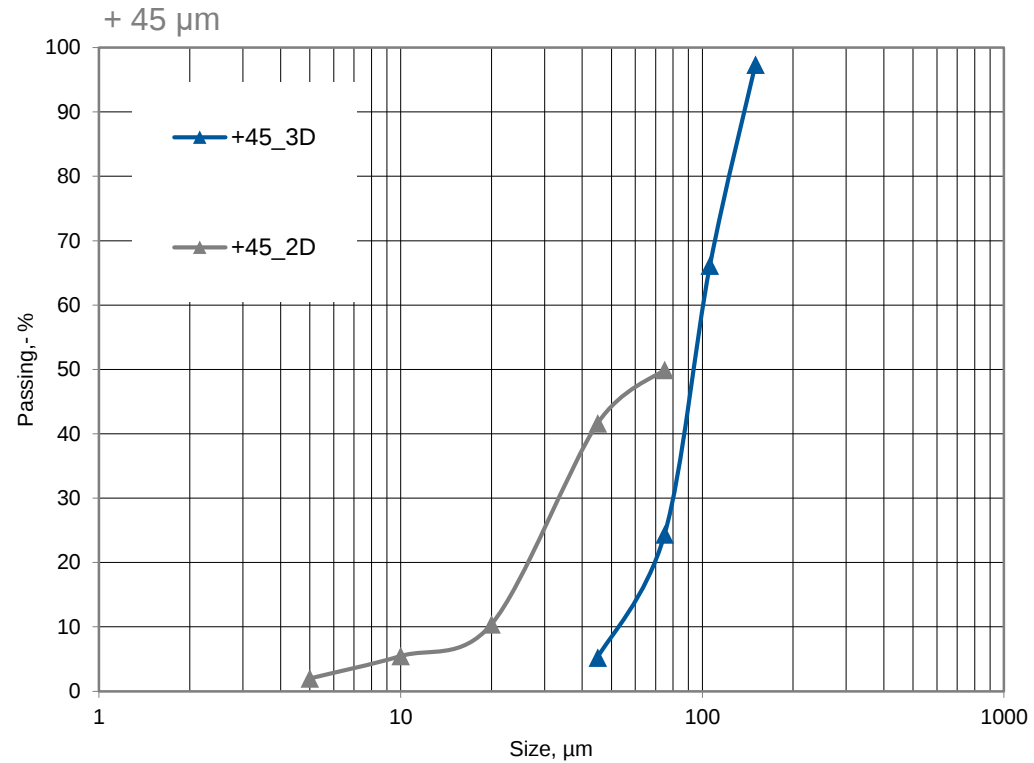
Gold flotation concentrate, Jokisivu Mine, Finland



2D vs 3D particle information



Gold flotation concentrate, Jokisivu Mine, Finland



2D vs 3D particle information

- A lot of simulation in minerals processing use 2D particle information
- With CT scans the particle information are available in 3D
- The comparison between 2D and 3D shows that the maximum particle size is larger in the 3D data and their shape is comparable
- With the 3D data the simulations are more reliable according to the specific sample

Summary

- Spectral CT combines conventional CT with a photon-counting detector
- Based on the X-ray absorption spectrum different absorption edges (K-edges) and therefore elements can be distinguished
- With the additional 3D particle information, simulations can be optimized

Thank you for your attention!



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a body of the European Union

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⁴ TESCAN XRE, Bollebergen 2B box 1, 9052 Ghent, Belgium

⁵ Outotec, Rauhalanpuisto 9, 02230 Espoo, Finland



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G. F. Knoll 1999. Radiation Detection and Measurement (New York: Wiley)