SPECTRAL X-RAY IMAGING WITH SINGLE PHOTON PROCESSING DETECTORS

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OUTLINE

- Experimental setup
  - Simulation
  - Measurement
- Image contrast
  - Simulation of 10% contrast
  - Measurement of 1.0 mm and 1.1 mm of Al
- Material separation
  - Simulation and measurement of Pd and Ag
- Material identification
- Conclusions

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ACKNOWLEDGEMENTS

- Timepix is a device in the MEDPIX2-family developed within the MEDIPIX collaboration

- The Pixelman software and the FITPIX interface is developed by the Institute of Experimental and Applied Physics in Prague

- The CdTe detector is based on ACRORAD material and is processed and bonded in Freiburg.

EXPERIMENTAL SETUP

- Simulations using MCNP5
  - A pixellated detector with 32 x 32 pixels (110x110 um pixel size)
  - An average of 10000 photons/pixel

- "Ideal" conditions
  - Photon counting – every photon has the same weight
  - Discrete energies – same photon flux at each energy
  - Ideal detector – all photons are detected and contribute to the image, no charge loss or charge sharing

EXPERIMENTAL SETUP

- **Nanofocus X-ray tube**
  - Fluorescence spectrum

Material	K-alpha
Zr	15,770
Ag	22,163
Pr	36,026
Gd	42,996
Er	49,128
W	57,982

- **TIMEPIX readout chip with CdTe sensor**
  - 110x110 um pixel size
  - An average of 10000 photons/pixel

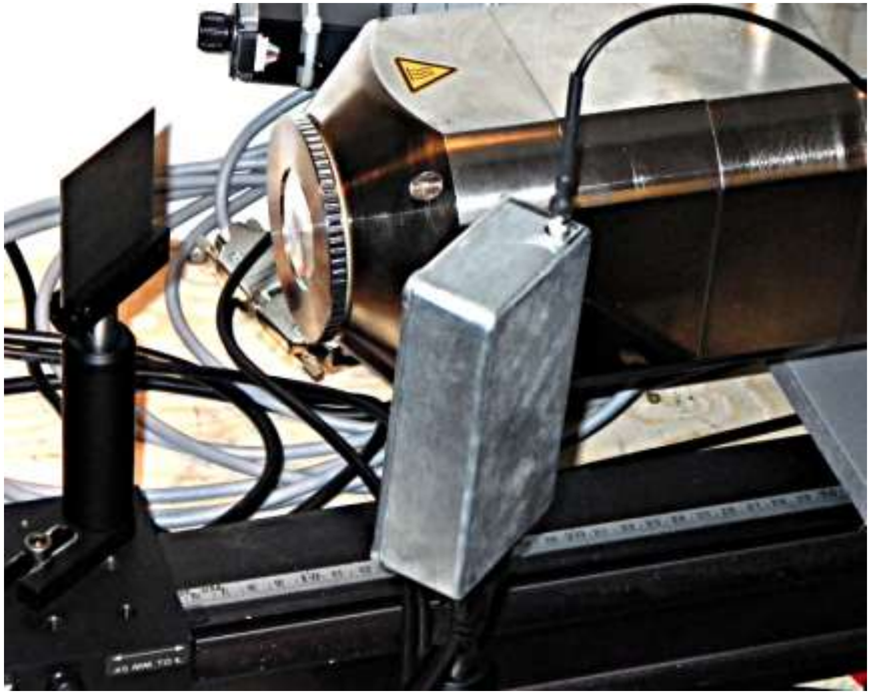


IMAGE CONTRAST

CONTRAST TO NOISE RATIO

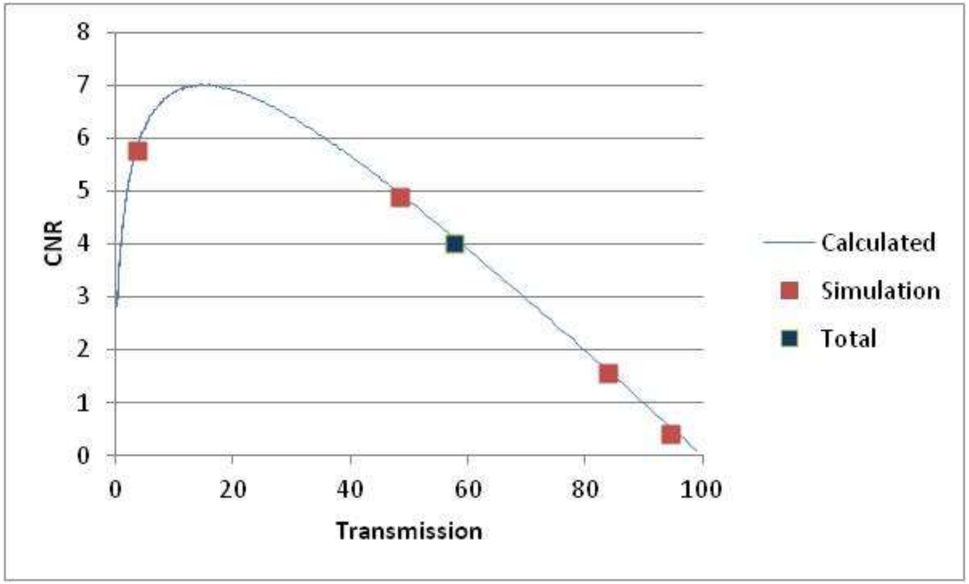
In this experiment the following definition has been used

$$CNR = \sqrt{\frac{2\left(S_{img} - S_{bg}\right)^2}{\left(\sigma_{img}{}^2 + \sigma_{bg}{}^2\right)}} \qquad (1)$$

SIMULATION OF CNR

The CNR has been calculated as a function of X-ray absorption

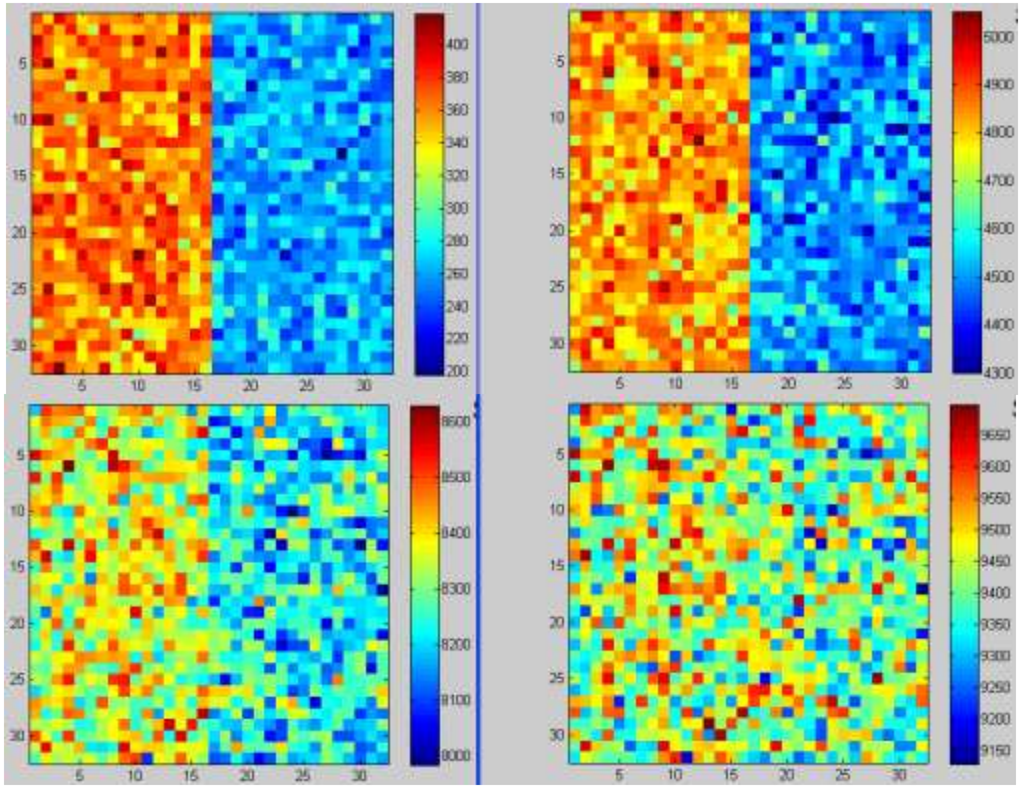
- For a homogenous material with a thickness difference of 10%
- Using four different photon energies and 10000 photons/pixel.



SIMULATION OF CNR

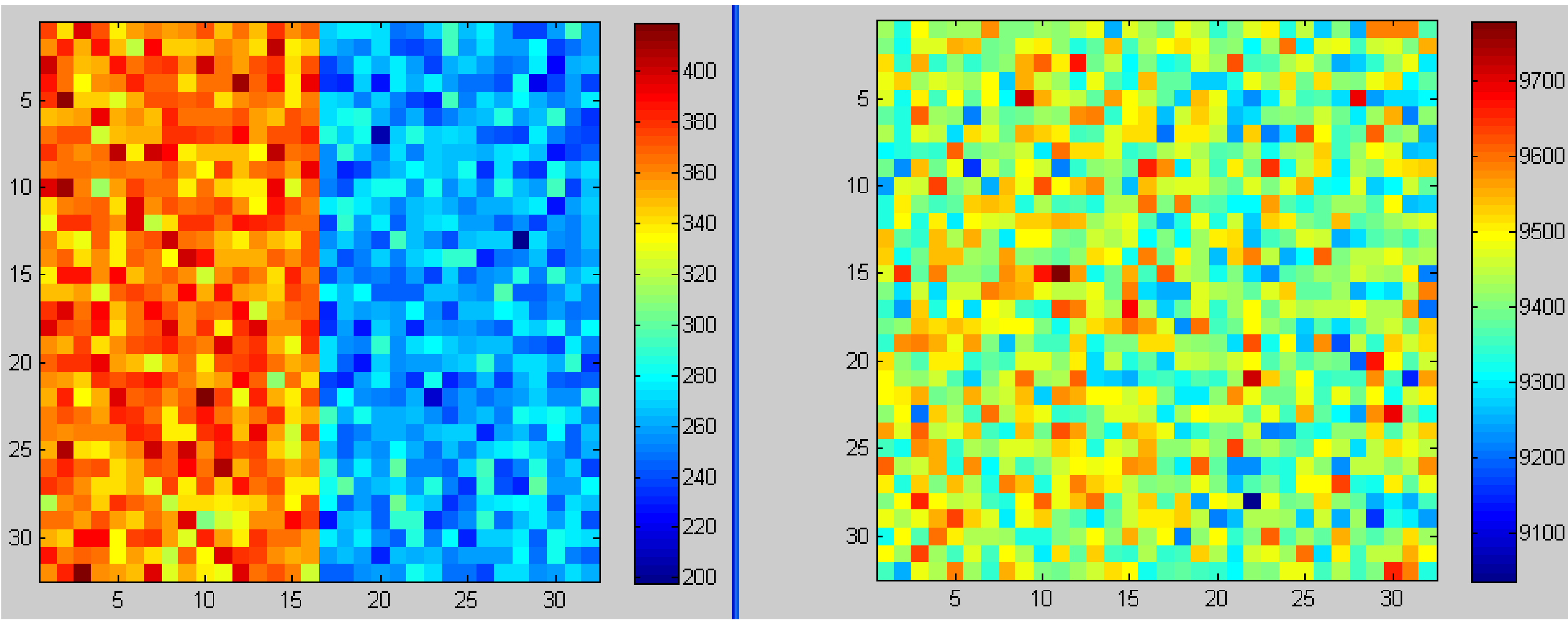
Four images taken at different photon energies corresponding to the red dots in the previous curve

- Upper left: 3.6 %
- Upper right: 48 %
- Lower left: 84 %
- Lower right: 94%



SIMULATION - IMAGE SUBTRACTION

E1: Transmission: 3.6 %, CNR: 5.78 E2:Transmission: 94%, CNR: 0.4



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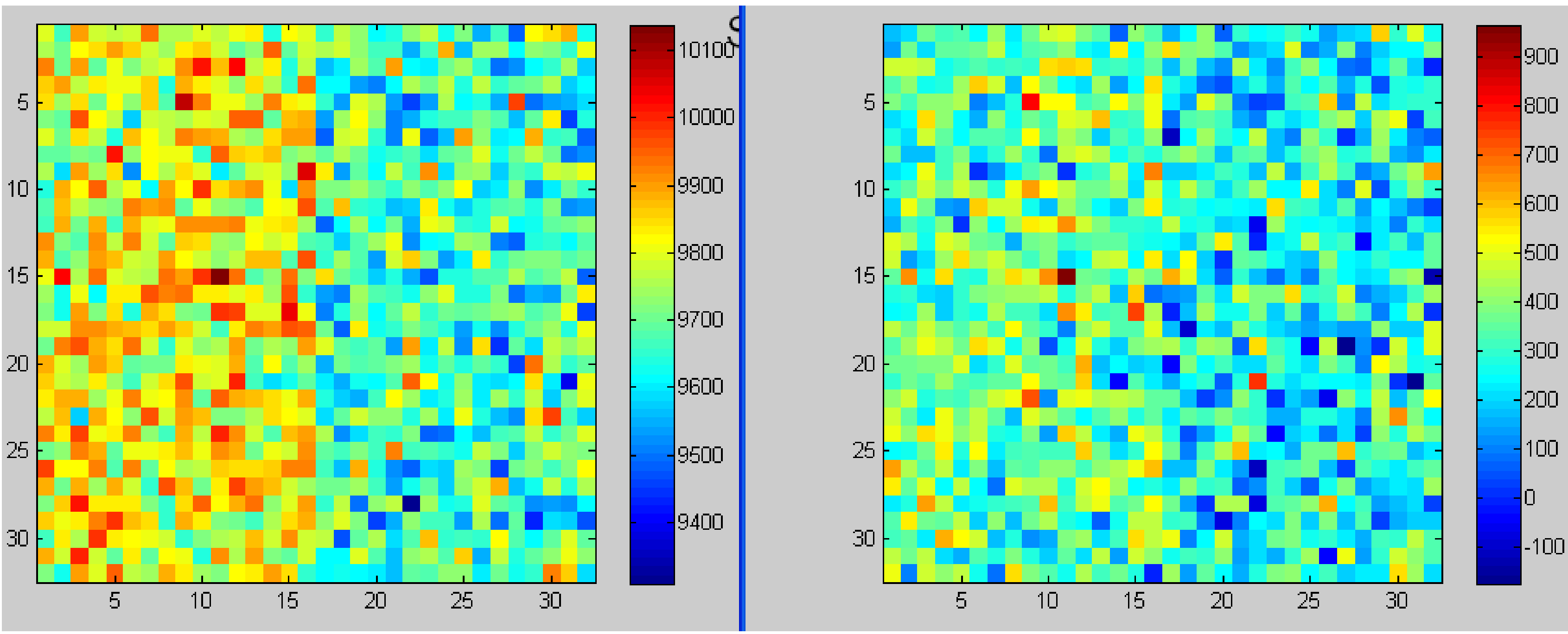
CNR: IMAGE SUBTRACTION

(E1+E2): CNR: 1.43

(E1+E2)-E2: CNR: 0.72



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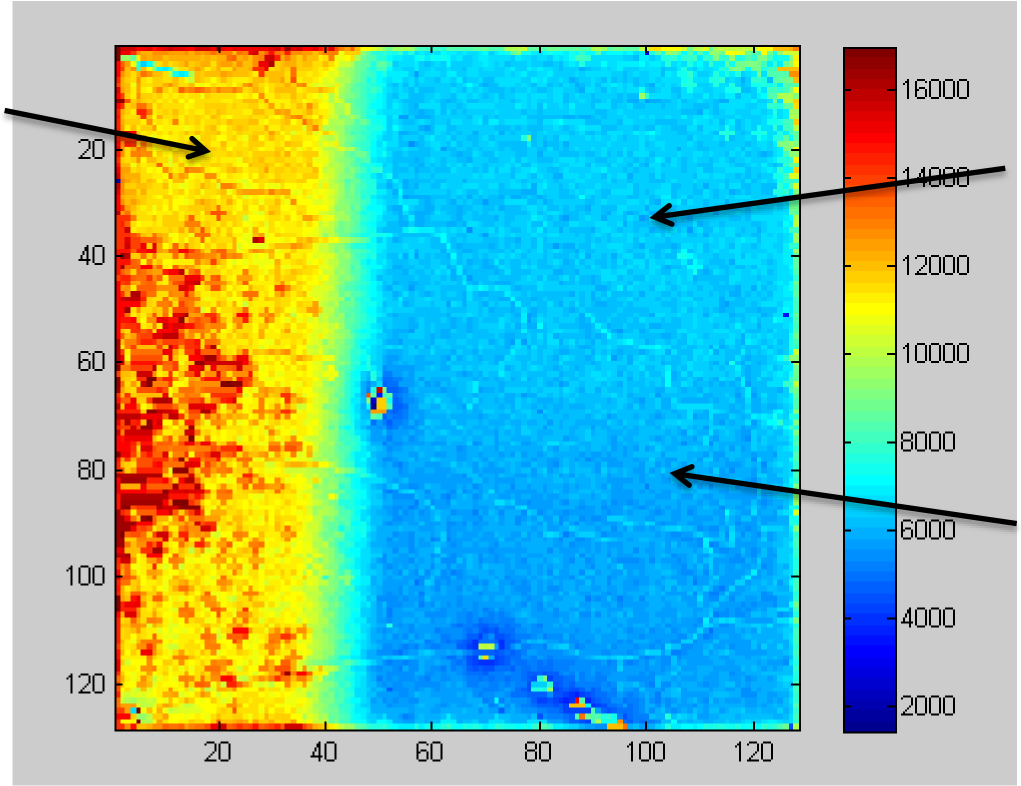
MEASURED CNR

- 1 mm thick Al + 0.1 mm Al on half of the image

Transmission in 1 mm Al				
Material	K-alpha	% transmission		CNR
		calculated	measured	
Zr	15,770	16	24	5,03
Ag	22,163	50	55	3,7
Pr	36,026	82	83	1,37
Gd	42,996	88	85	1,45
Er	49,128	90	89	0,73
W	57,982	92	94	0,15

MEASURED CNR



MEASURED CNR

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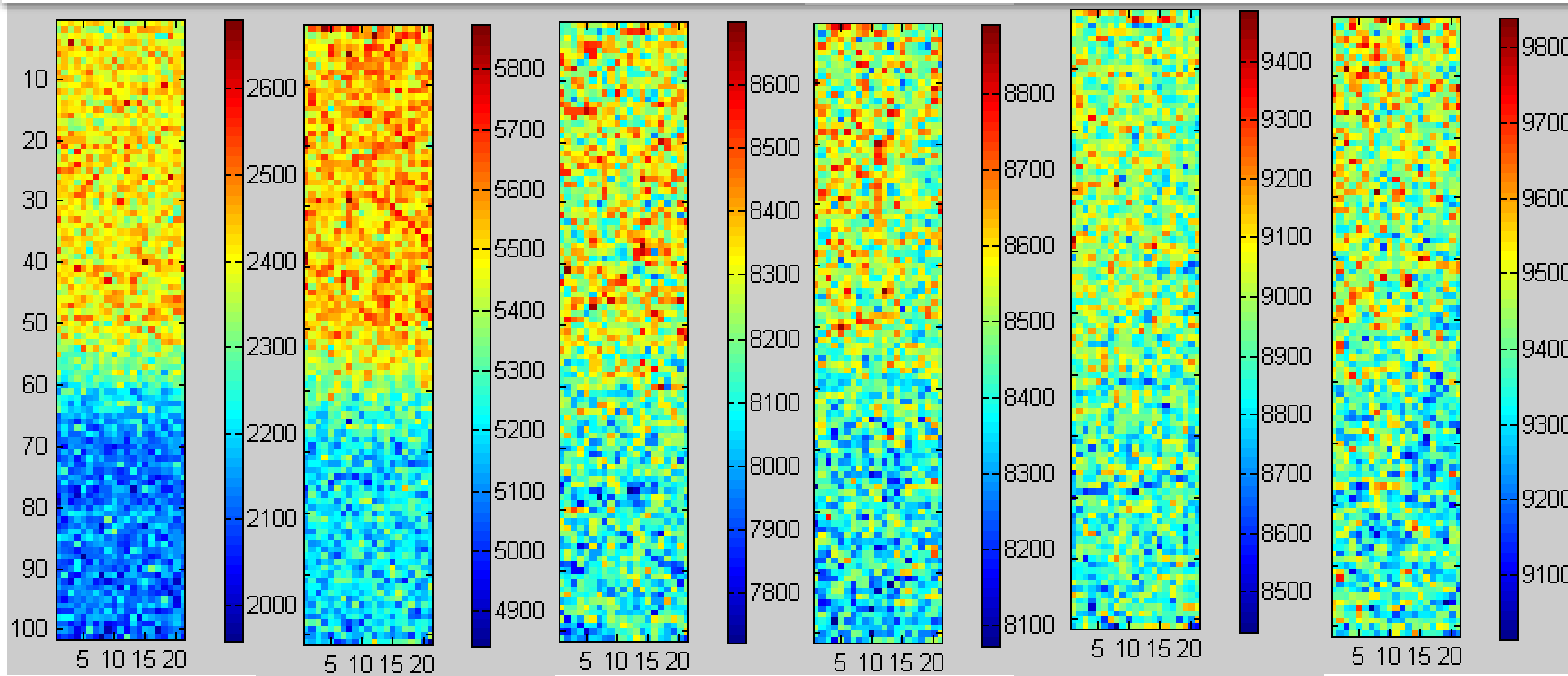

Zr Ag Pr Gd Er W

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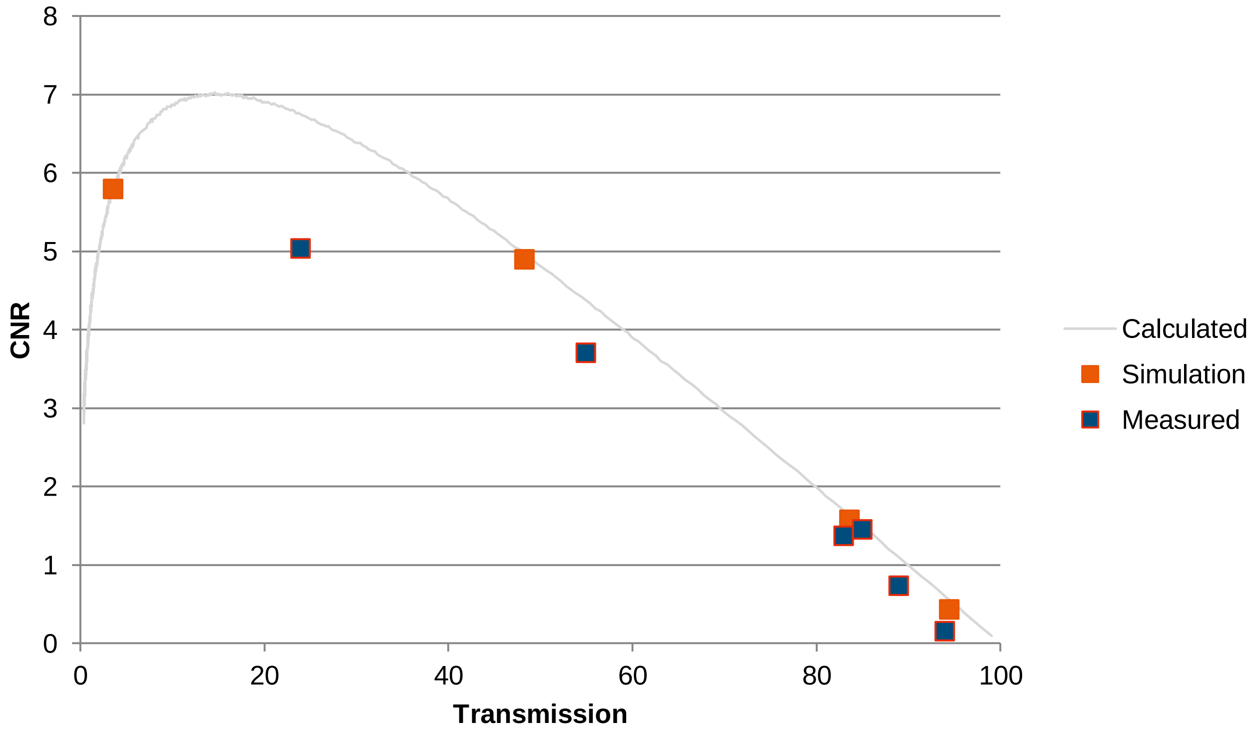

MATERIAL SEPARATION

- Eliminate one material from the image

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IMAGE SUBTRACTION - TWO MATERIALS

The basic equation:

$$\emptyset_{e1} = \emptyset_{0e1} e^{-\alpha_{e1} t}$$

or

$$\alpha_{e1} t = -ln\left(\frac{\emptyset_{e1}}{\emptyset_{0e1}}\right)$$

If α does not change or the difference is known a material can be eliminated by subtracting the logarithms of the response at two energies

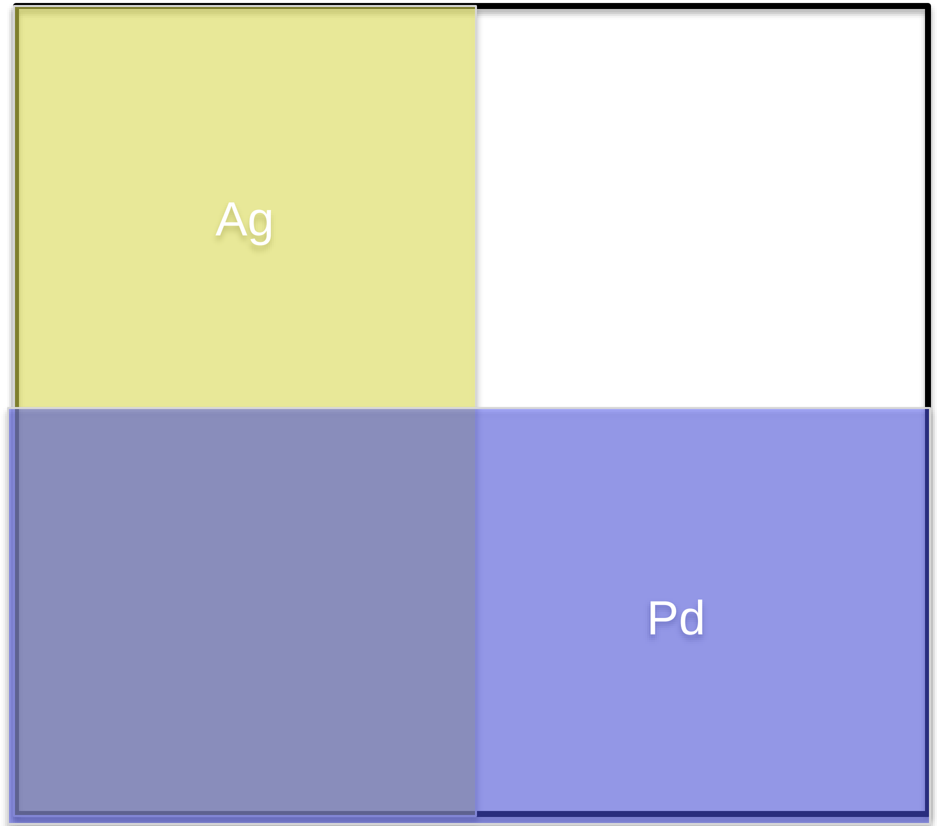
$$\ln\left(\frac{\emptyset_{e1}}{\emptyset_{0e1}}\right) = \ln\left(\frac{\emptyset_{e2}}{\emptyset_{0e2}}\right) * \frac{\alpha_{e1}}{\alpha_{e2}}$$

- Example Pd and Ag imaged at 24, 25 and 26 keV

SIM - PALLADIUM AND SILVER

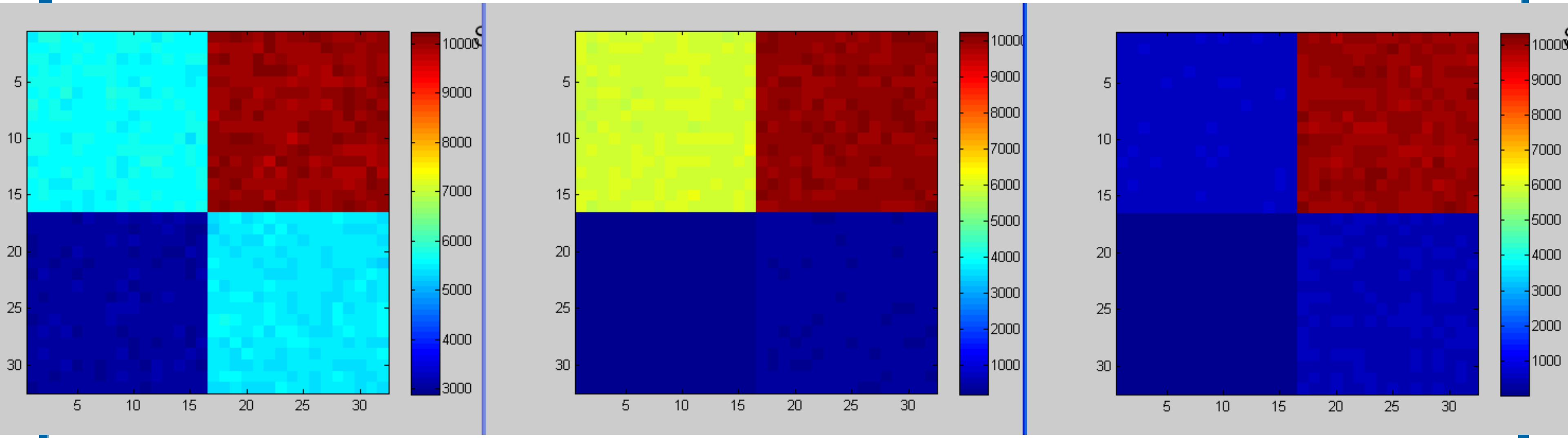
K-edges

- Pd = 24.365
- Ag = 25.531
- Thickness = 50 um



SIM - PRIMARY IMAGES

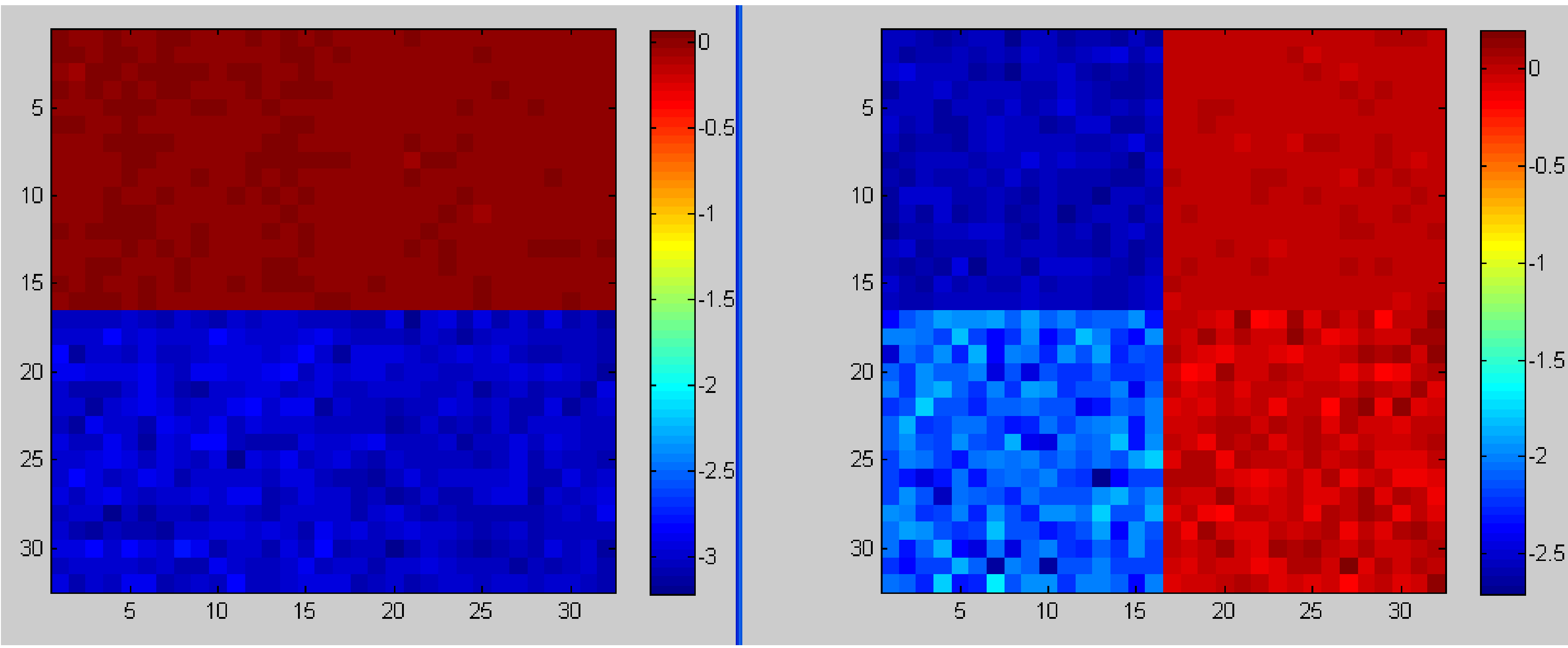
24 keV 25 keV 26 keV



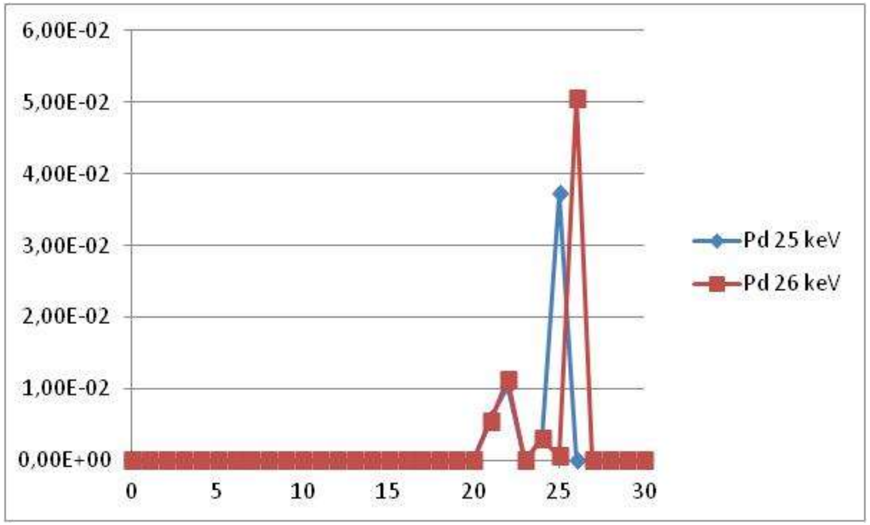
SIM - AFTER SUBTRACTION

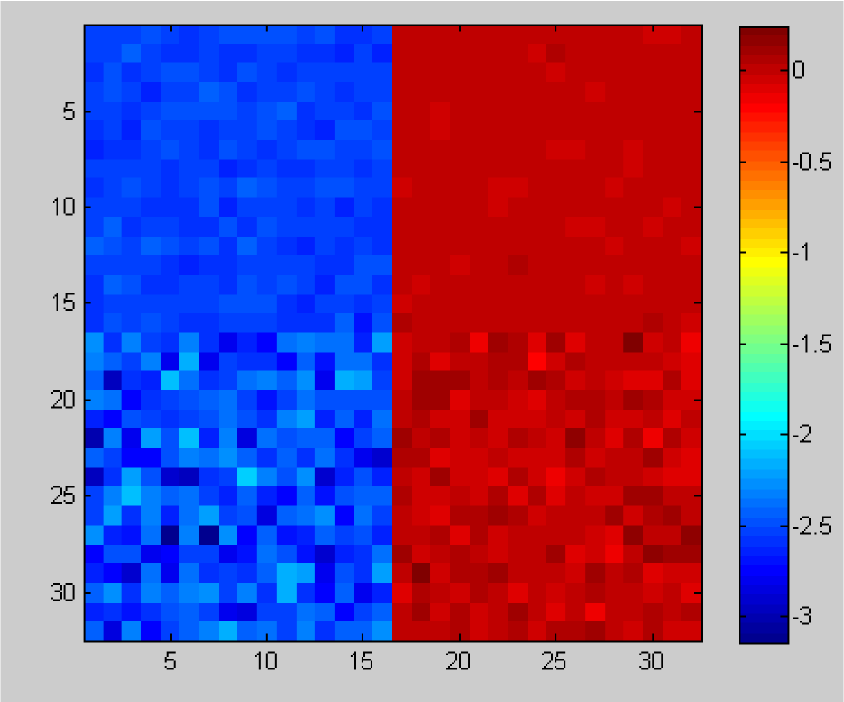
25 keV – 24 keV

26 keV – 25 keV

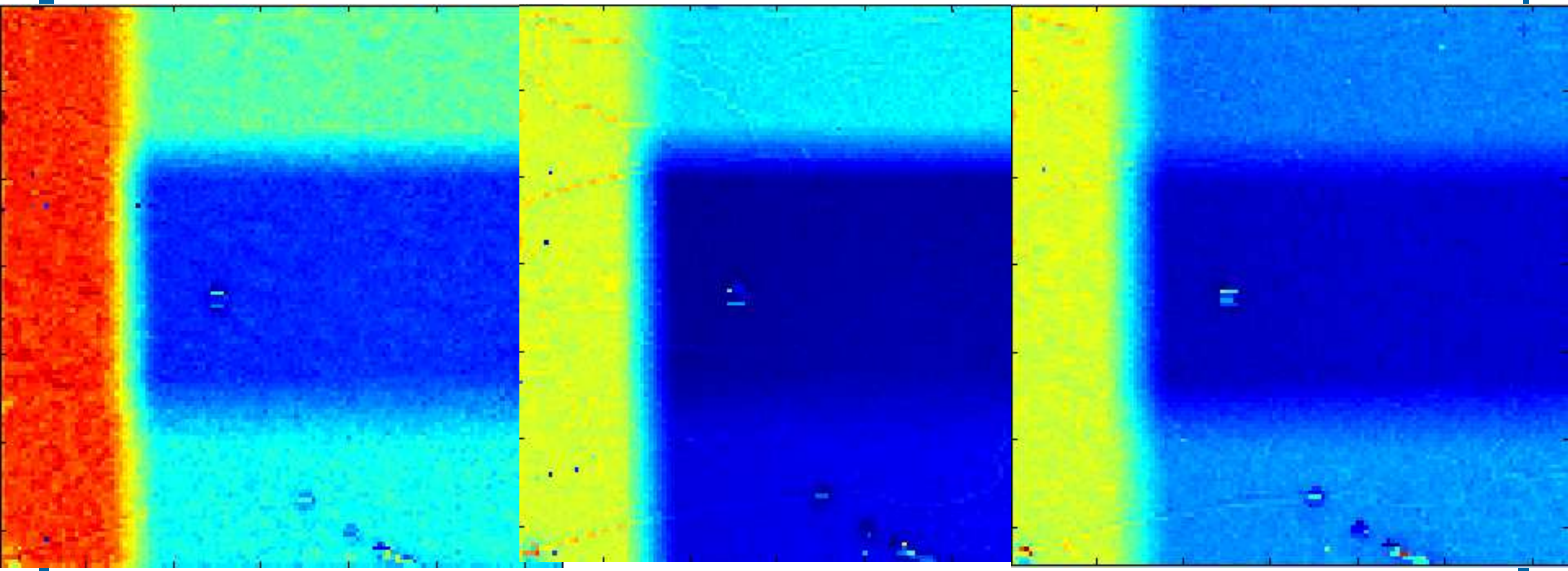


SIM - CORRECTED FOR FLUORESCENCE



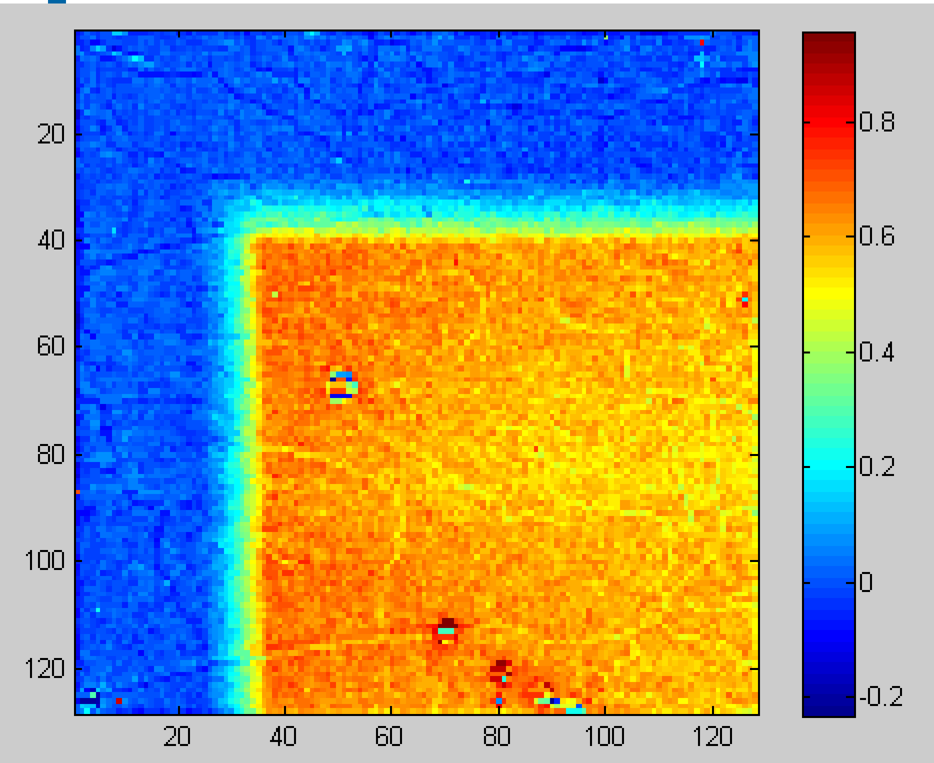


EXP - IMAGES AT THREE ENERGIES

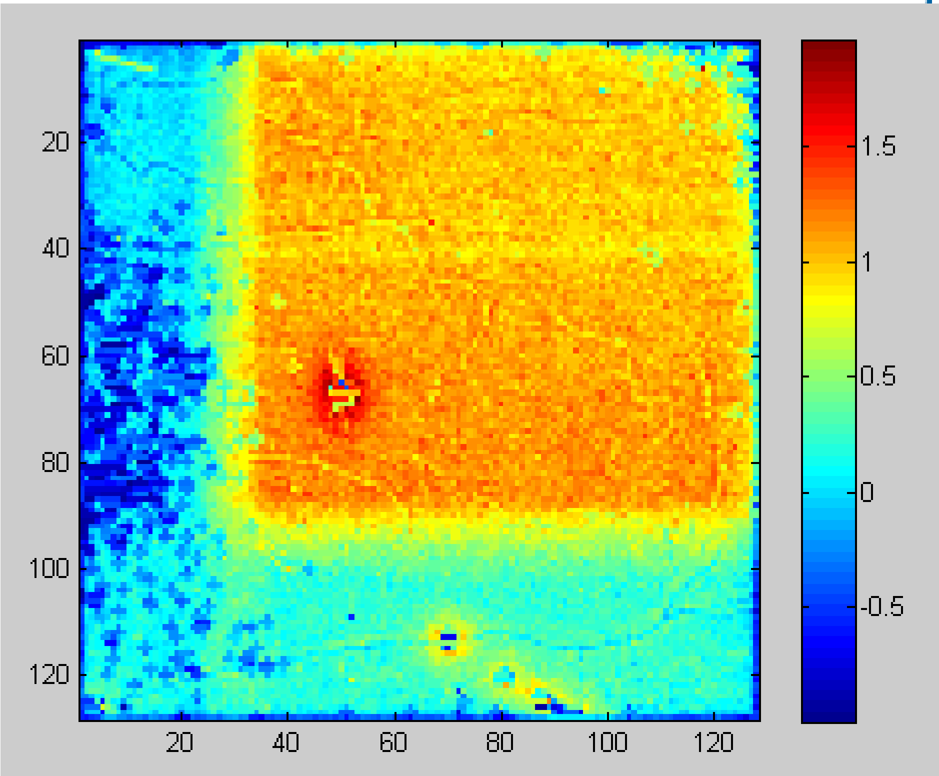


22,16 keV   25,27 keV   36,03 keV

EXP - MATERIAL SEPARATION



Pd (25.3 – 22.2 keV)



Ag (36.0 – 25.3 keV)

MATERIAL SEPARATION

- Calculate the thickness in a layered structure

MATERIAL SEPARATION

X-ray attenuation in two layers of different material:

$$\emptyset_{e1} = \emptyset_{0e1} e^{-(\alpha_{1e1} t_1 + \alpha_{2e1} t_2)} \qquad (2)$$

The thickness is then given by:

$$t_1 = \frac{\dfrac{-ln\left(\dfrac{\emptyset_{e1}}{\emptyset_{0e1}}\right)}{\alpha_{1e1}} + \dfrac{\alpha_{2e1}}{\alpha_{2e2}\alpha_{1e1}} ln\left(\dfrac{\emptyset_{e2}}{\emptyset_{0e2}}\right)}{1 - \dfrac{\alpha_{2e1}\alpha_{1e2}}{\alpha_{2e2}\alpha_{1e1}}} \qquad (4)$$

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MATERIAL SEPARATION

X-ray attenuation in two layers of different material:

$$\emptyset_{e1} = \emptyset_{0e1} e^{-(\alpha_{1e1} t_1 + \alpha_{2e1} t_2)} \qquad (2)$$

Valid only if m1 does not change the spectrum

The thickness is then given by:

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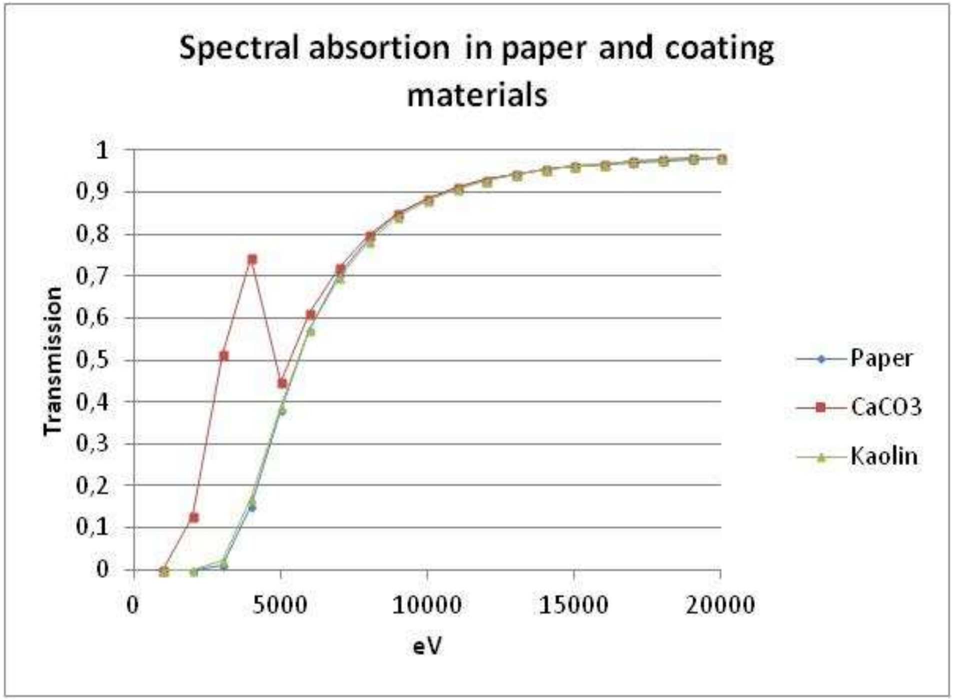
→ 0 if α varies in a similar way for both materials

TEST CASE: PAPER AND COATING

Coated paper

- Cellulose ($C_6H_{10}O_5$)
  - 300 um whole area
- Kaolin ($Al_2Si_2O_5(OH)_4$)
  - 20 um left part
- Calcium carbonate ($CaCO_3$)
  - 20 um right part

- Images taken at
  - 3 keV
  - 5 keV



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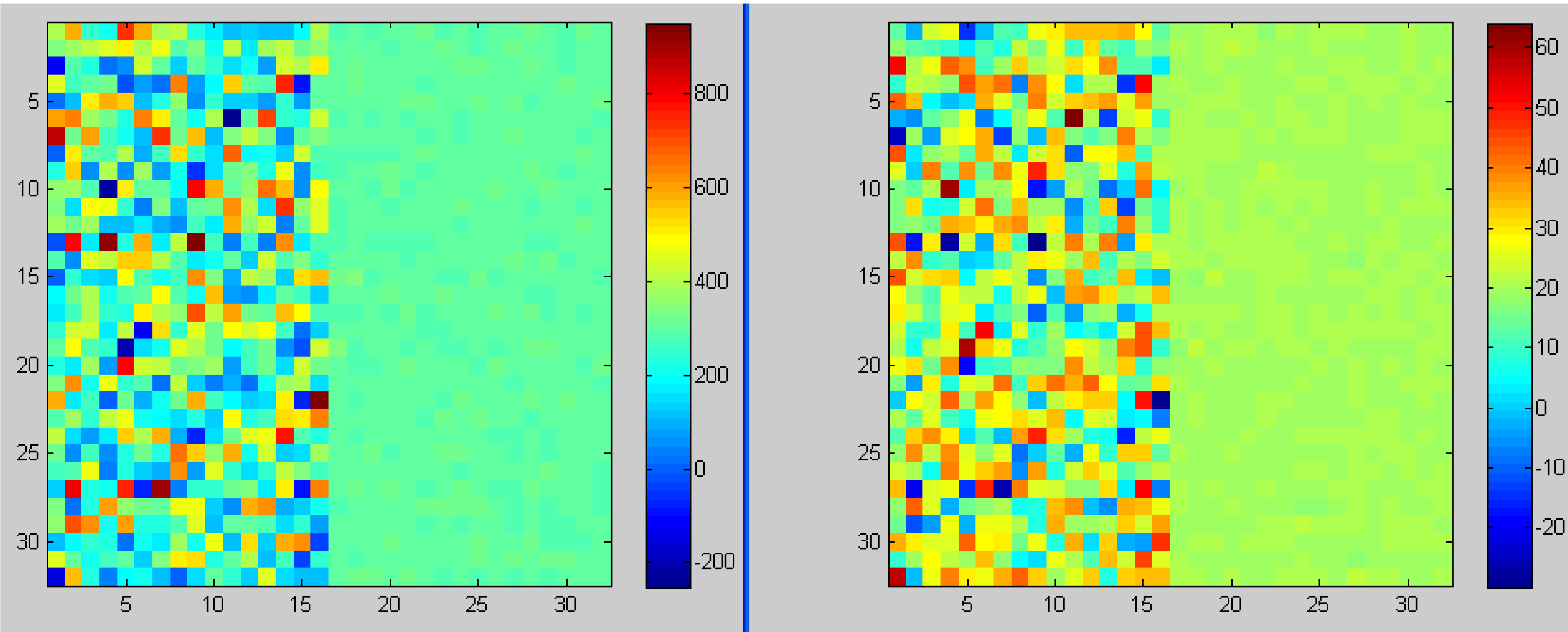
MATERIAL SEPARATION

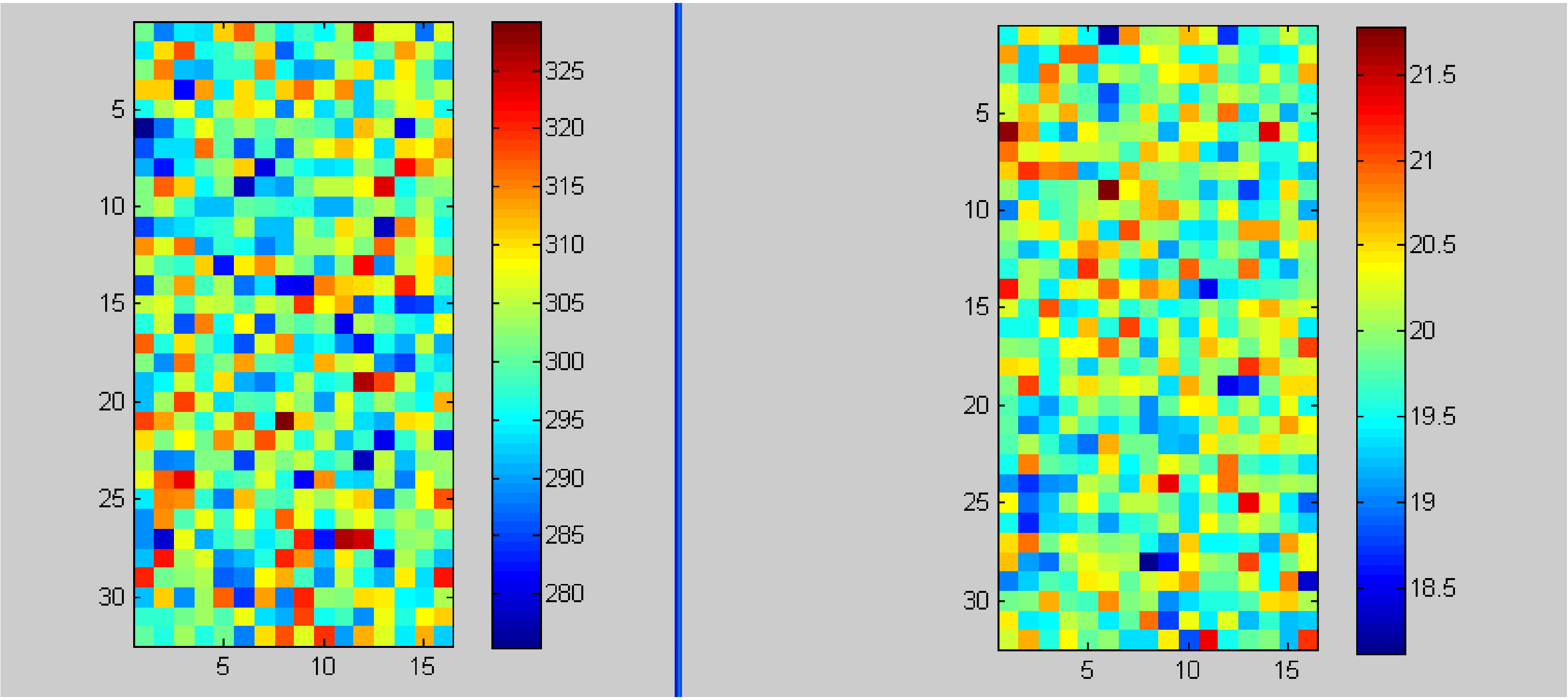
Thickness resolution for a two layer structure

- 300 um + 20 um – right part has K-edge in the spectrum

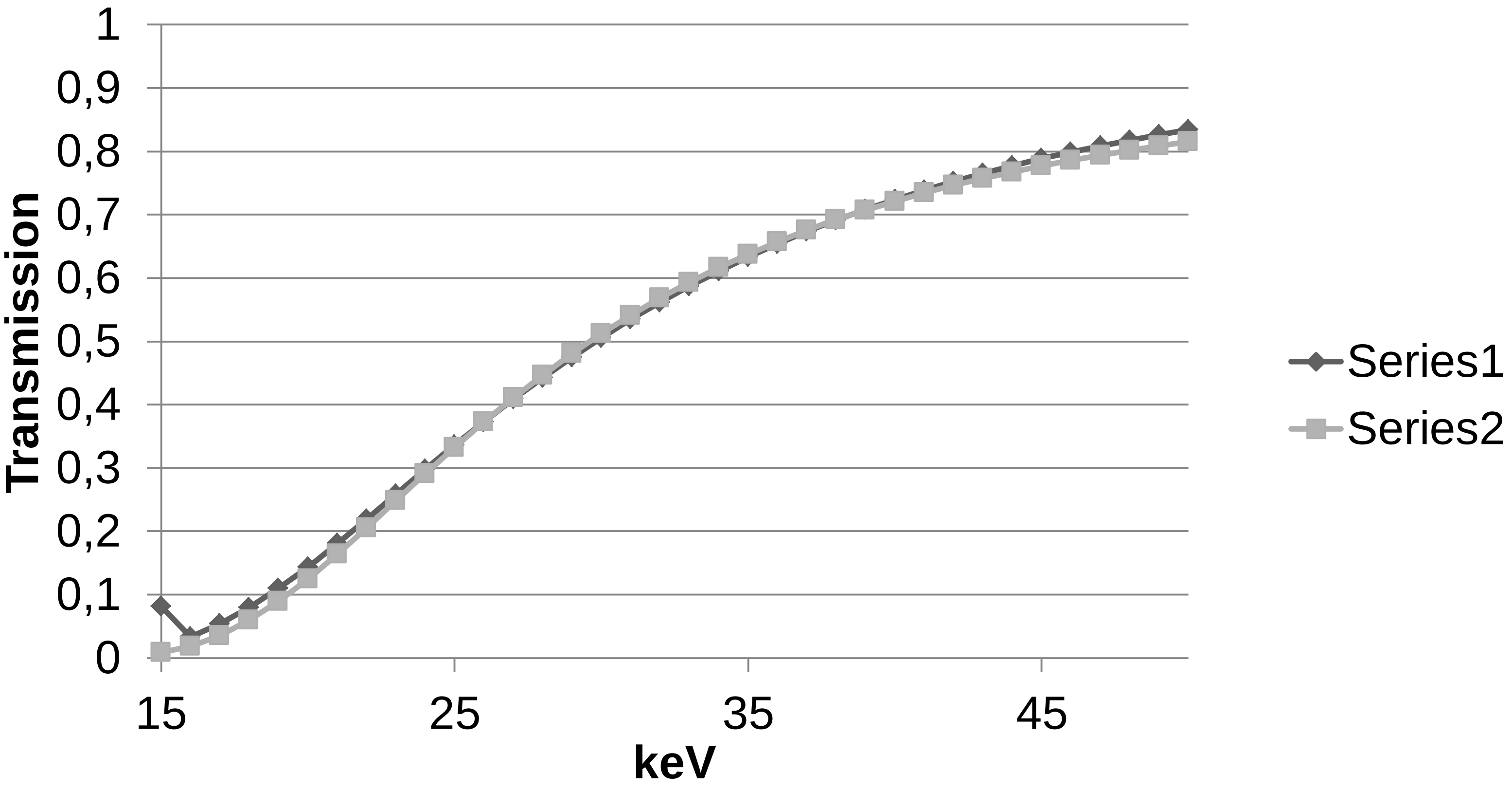


MATERIAL SEPARATION

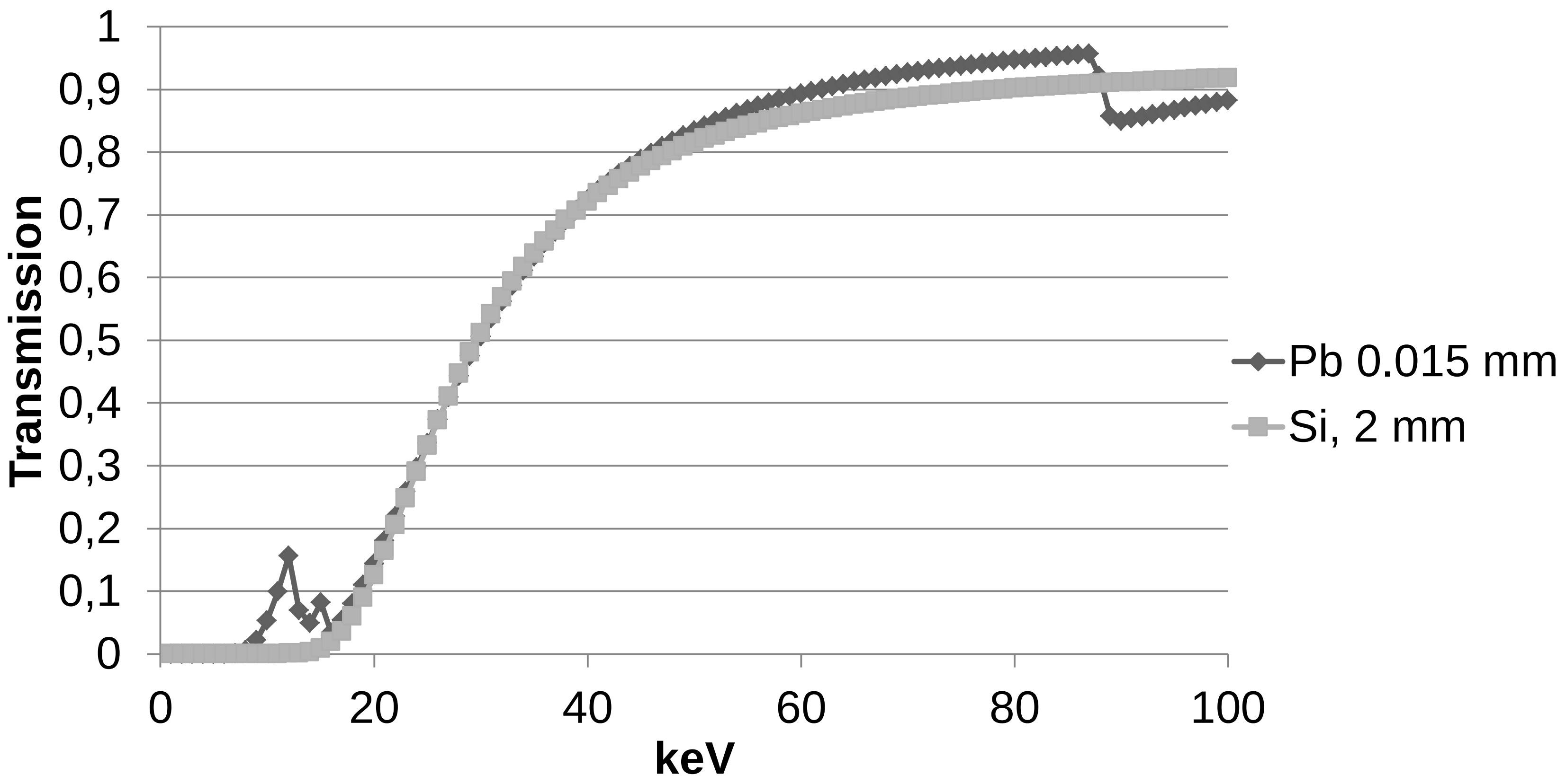
Right part at larger scale



WHICH TWO MATERIALS?



THE SOLUTION: SILICON AND LEAD



MATERIAL IDENTIFICATION

MATERIAL IDENTIFICATION

Basic equations:

$$\emptyset_{e1} = \emptyset_{0e1} e^{-\alpha_{e1} t}$$

or

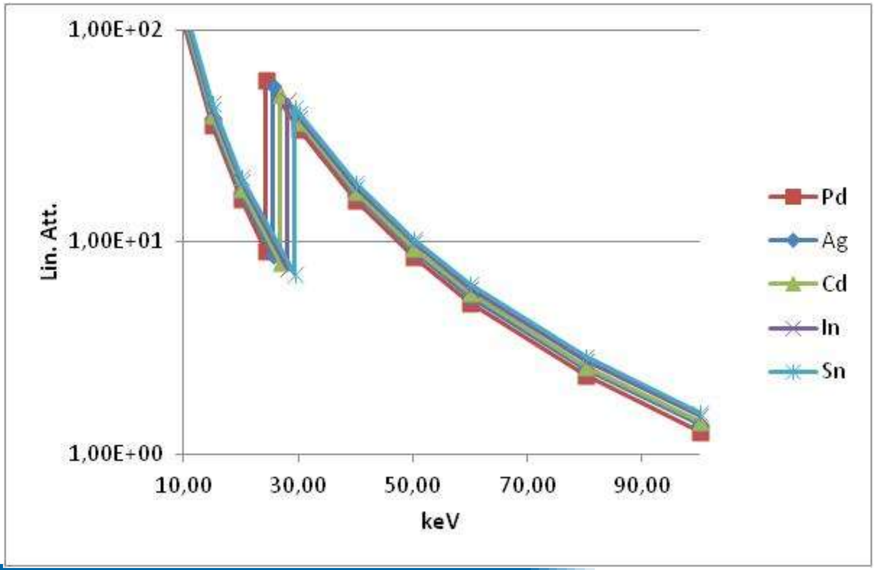
$$\alpha_{e1} t = -ln\left(\frac{\emptyset_{e1}}{\emptyset_{0e1}}\right)$$

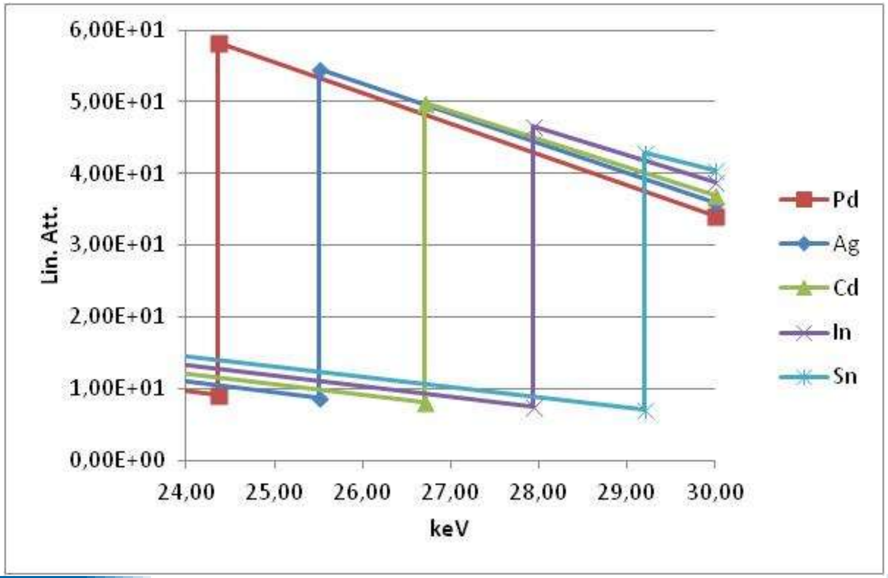
If the ratio between the linear attenuation coefficients is unique then the material can be identified

$$\frac{\alpha_{e1}}{\alpha_{e2}} = ln\left(\frac{\emptyset_{e1}}{\emptyset_{0e1}}\right) \Big/ ln\left(\frac{\emptyset_{e2}}{\emptyset_{0e2}}\right)$$

ATTENUATION IN FIVE MATERIALS

Attenuation curves have similar shapes except around the absorption edges.





CONCLUSIONS

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CONCLUSIONS

- Small contrast variations are best imaged at high absorption in the object
  - Getting rid of high energy photons improves the contrast
  - Image subtraction adds to the noise
- Two materials can be separated by comparing images at two different energies
  - The ratio between the attenuation coefficients fort the two materials must differ substantially (absorption edge of one material)
- A material can be uniquely identified by the ratio between the linear attenuation coefficients at two energies
  - Unique ratio if there is an absorption edge in the spectrum
- Even if a monoenergetic beam is used energy resolution at the detector is needed to eliminate the response from fluorescence