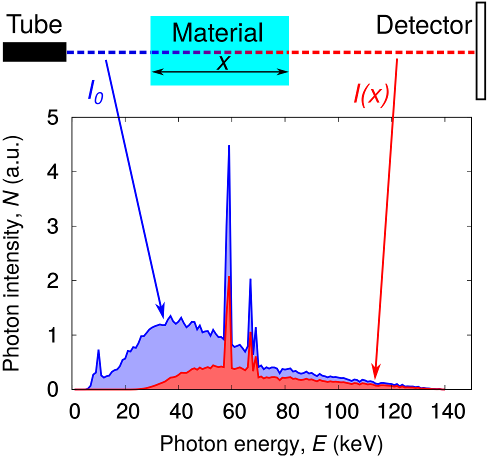
FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

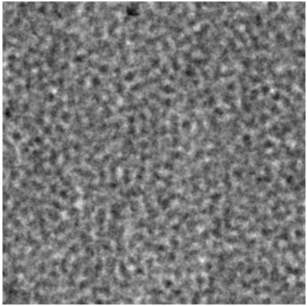
Institute for Multiscale Simulation MSS

X-ray radiography of granular systems – particle densities and dynamics

PhD defense
Manuel Baur

Funded by the German Federal Ministry for Economic Affairs and Energy, grant no. 50WM 1653





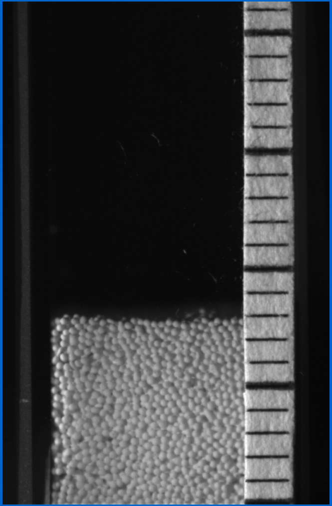
Granular flows

rough structure - replace text by images:

1. Motivate physical system of granular flow (nice challenge to study)
2. Motivate technique of radiography

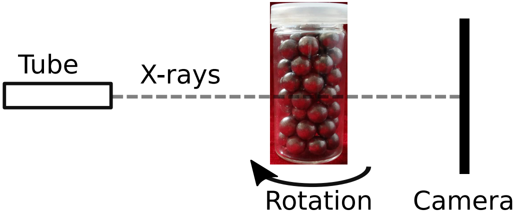
- Granular flows - fluidized bed reactors
- optically opaque
- X-ray reveal the inside
- Tomography: full 3D information - but slow (no dynamics)
- Radiography: single projections - knowledge on imaging physics
- Here two techniques to quantify: densities & dynamics

Particulate flows are **opaque**

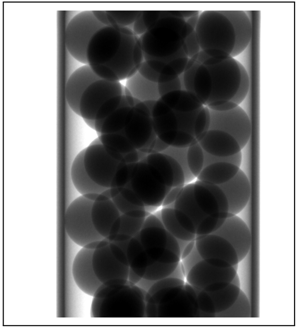


Master thesis Welm Pätzold

X-ray radiography



Radiogram



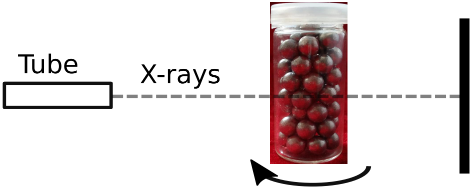
2D projections of 3D object

Short acquisition time

X-ray radiography

Tube

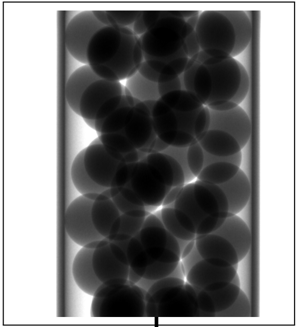
X-rays



Rotation

Camera

Radiogram

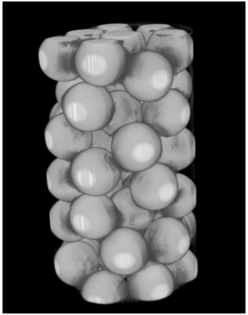


2D projections of 3D object

Short acquisition time

Reconstruction from
800 projections

Tomogram

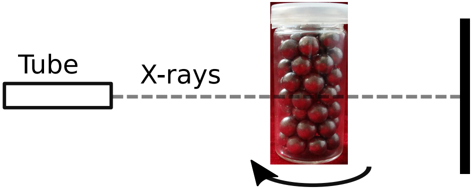


Full 3D information

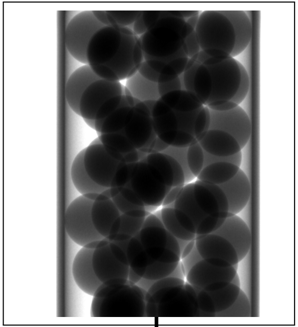
Long acquisition time

$\rightarrow$ static objects

X-ray radiography

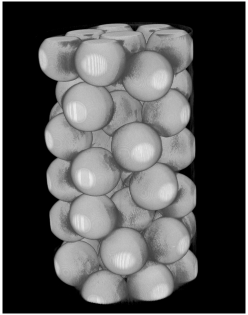


Radiogram



2D projections of 3D object
Short acquisition time

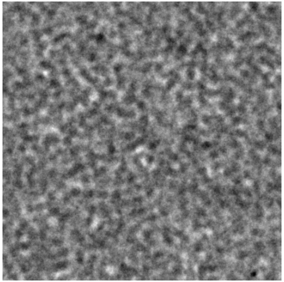
Tomogram



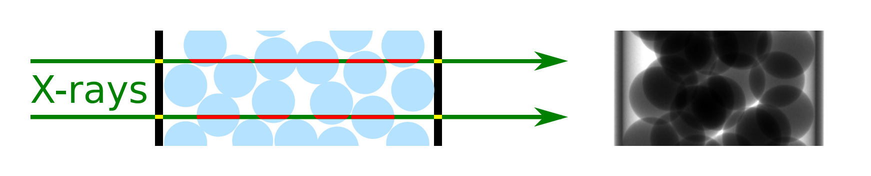
Reconstruction from
800 projections

Full 3D information
Long acquisition time
→ static objects

Dynamic system



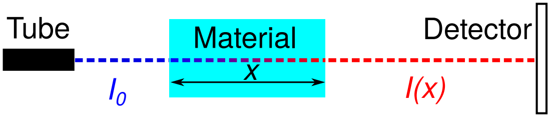
Measuring the volume fraction of **dynamic** granular systems



Correction of beam hardening in X-ray radiograms

In collaboration with Norman Uhlmann, Fraunhofer EZRT

Attenuation of X-rays

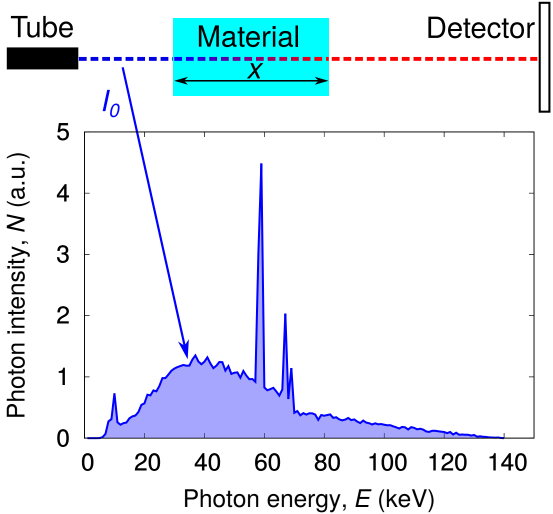


Beer-Lambert's law

$$I(x) = I_0 \exp(-\mu x)$$

Thickness: $x = -\frac{1}{\mu} \ln \frac{I(x)}{I_0}$

Attenuation of X-rays

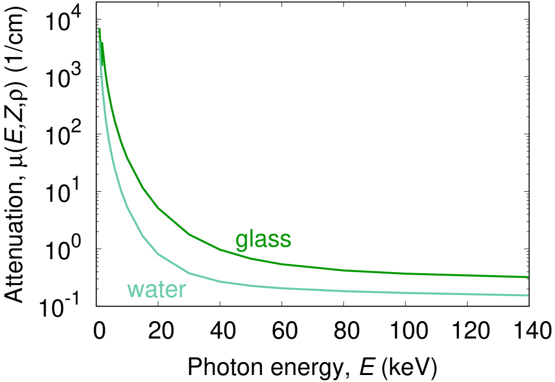


Beer-Lambert's law

$$I(x) = I_0 \exp(-\mu(E, Z, \rho)\, x)$$

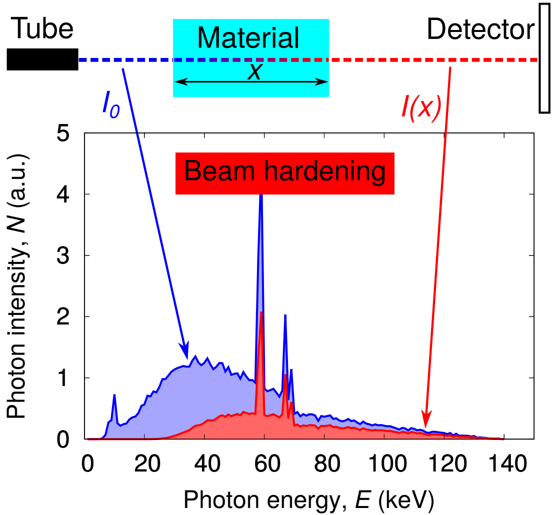
$$\mu \neq \text{const}$$

Thickness: $x = ?$



`https://www.nist.gov/pml/x-ray-mass-attenuation-coefficients`

Attenuation of X-rays

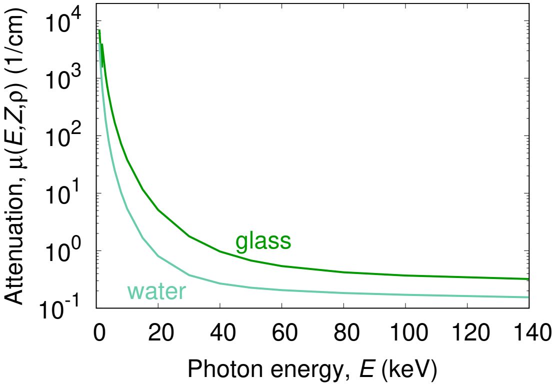


Beer-Lambert's law

$$I(x) = I_0 \exp(-\mu(E, Z, \rho)\, x)$$

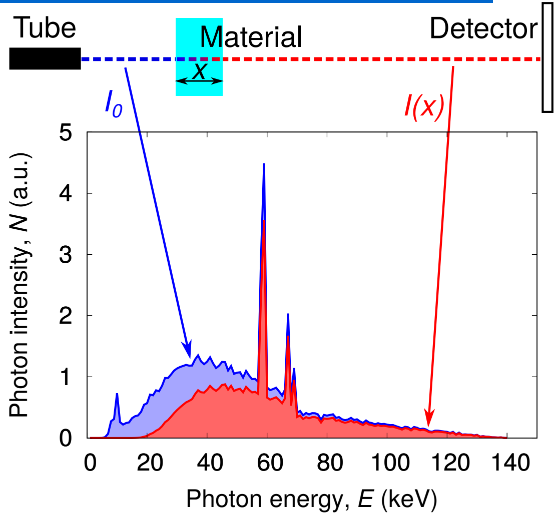
$$\mu \neq \text{const}$$

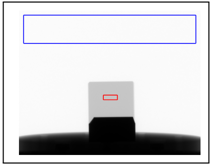
Thickness: $x = ?$



https://www.nist.gov/pml/x-ray-mass-attenuation-coefficients

The effective attenuation, μ_{eff}

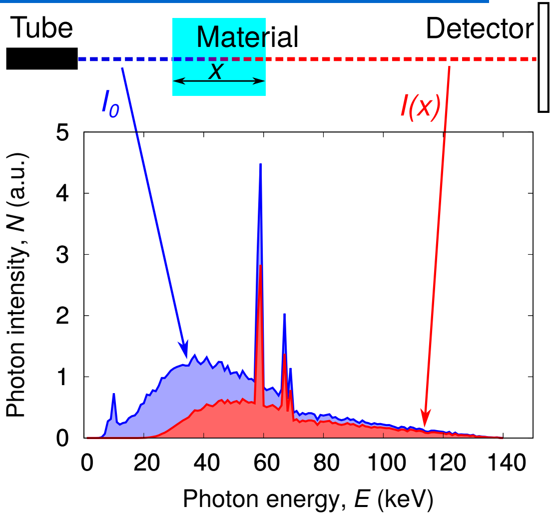


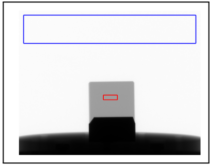


effective attenuation:

$$I(x) = I_0 \exp(-\mu_{\text{eff}}(x)\, x)$$

The effective attenuation, μ_{eff}

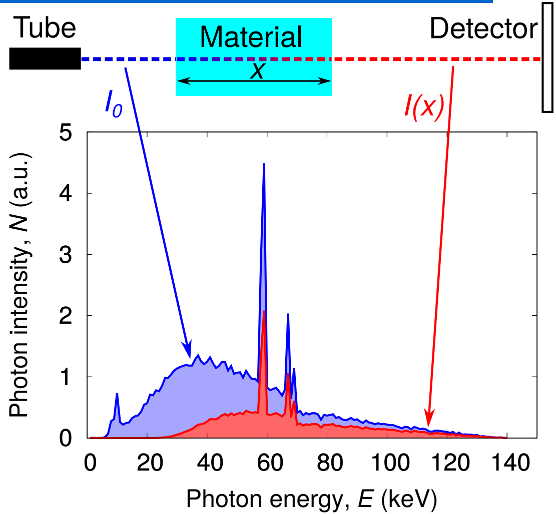


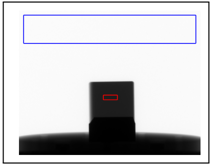


effective attenuation:

$$I(x) = I_0 \exp(-\mu_{\text{eff}}(x)\, x)$$

The effective attenuation, μ_{eff}

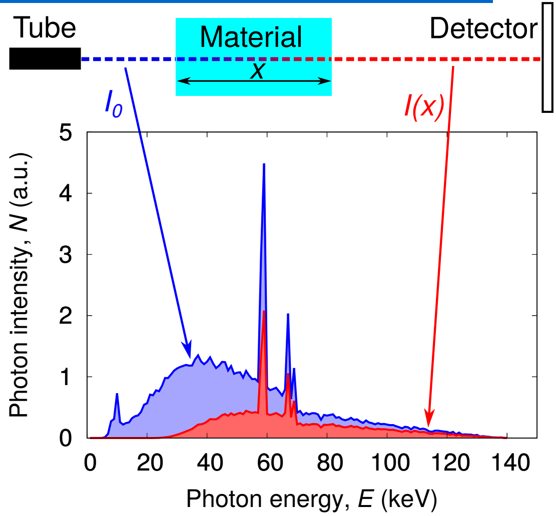


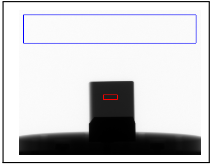


effective attenuation:

$$I(x) = I_0 \exp(-\mu_{\text{eff}}(x)\, x)$$

The effective attenuation, μ_{eff}

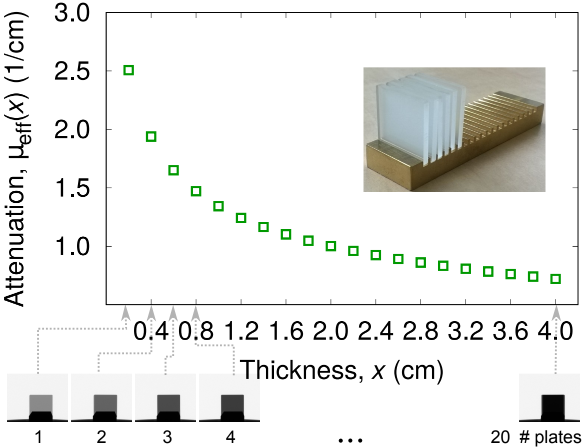




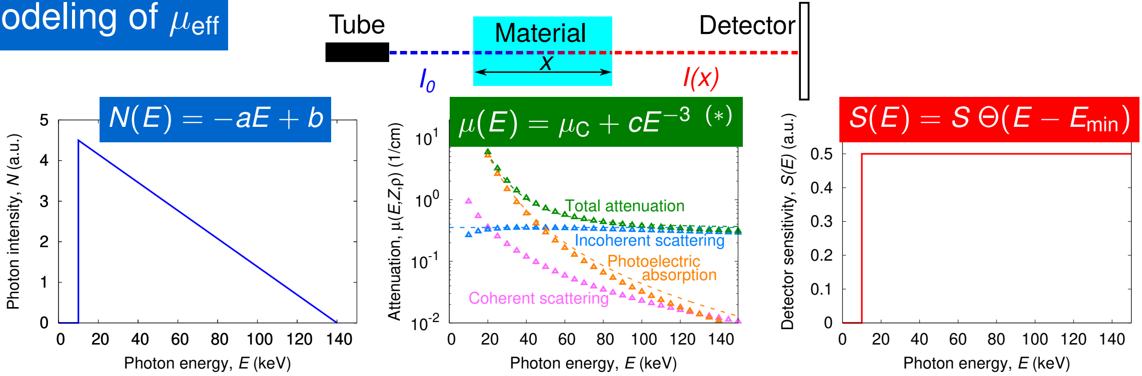
effective attenuation:

$$I(x) = I_0 \exp(-\mu_{\text{eff}}(x)\, x)$$

$$\mu_{\text{eff}}(x) = -\frac{1}{x}\frac{I(x)}{I_0}$$



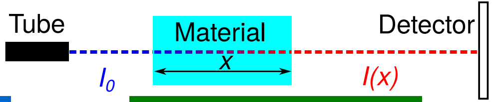
Modeling of μ_{eff}

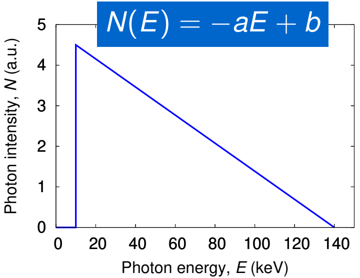


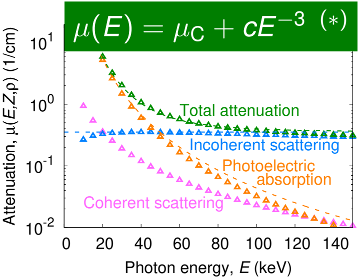
$$I(x) \propto \int N(E) \exp\{-\mu(E, Z, \rho)x\} S(E)\, \mathrm{d}E$$

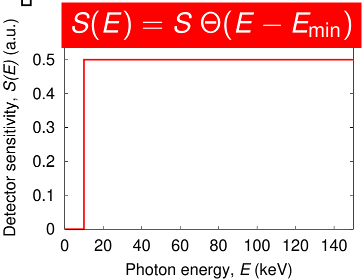
(∗) XCOM supplied by NIST

Modeling of μ_{eff}

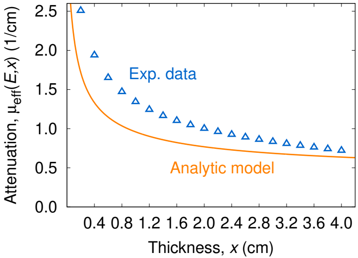






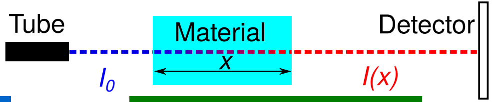


$$I(x) \propto \int N(E) \exp\{-\mu(E, Z, \rho)x\} S(E)\, \mathrm{d}E$$

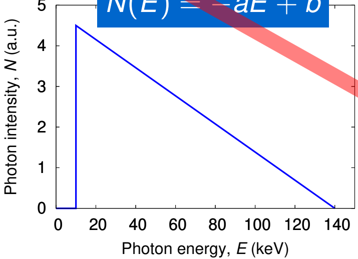


(∗) XCOM supplied by NIST

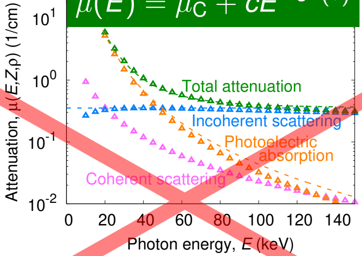
Modeling of μ_{eff}



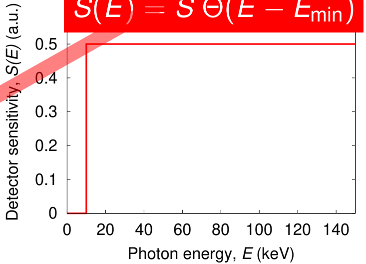
$N(E) = -aE + b$



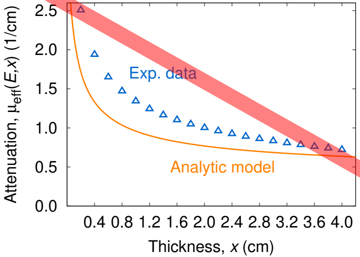
$\mu(E) = \mu_C + cE^{-3} \quad (*)$



$S(E) = S\,\Theta(E - E_{\min})$

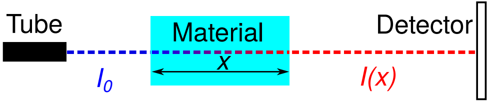


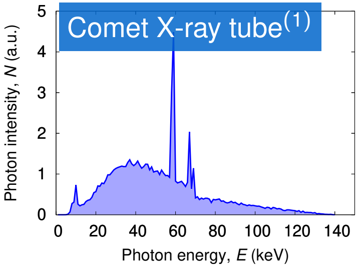
$$I(x) \propto \int N(E) \exp\{-\mu(E, Z, \rho)x\} S(E)\, \mathrm{d}E$$

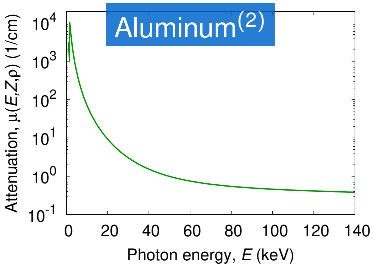


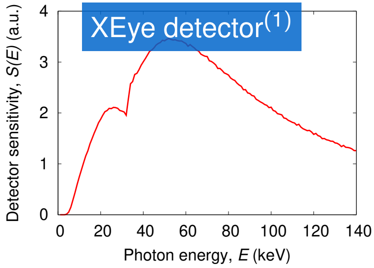
$(*)$ XCOM supplied by NIST

Numerical approx. of μ_{eff}







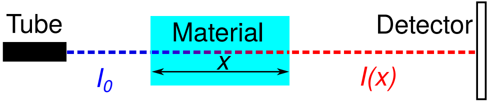


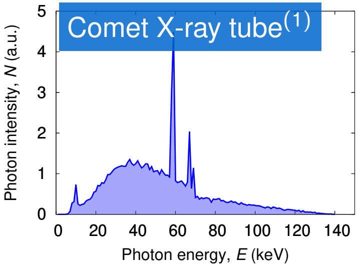
$$I(x) \propto \int N(E) \exp\{-\mu(E, Z, \rho)x\} S(E) \, \mathrm{d}E$$

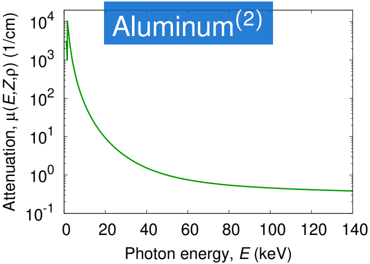
(1) Supplied by Norman Uhlmann, Fraunhofer EZRT

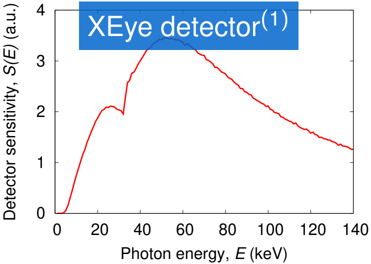
(2) XCOM supplied by NIST

Numerical approx. of μ_{eff}

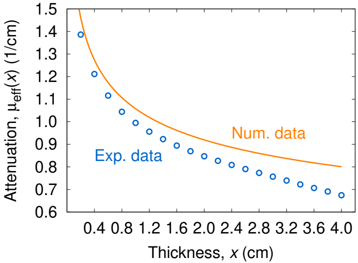








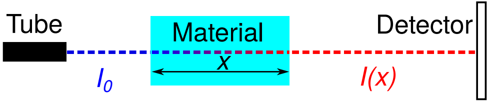
$$I(x) \propto \int N(E)\, \exp\{-\mu(E, Z, \rho)x\}\, S(E)\, \mathrm{d}E$$

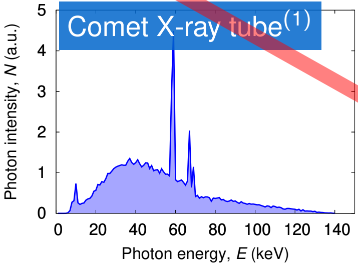


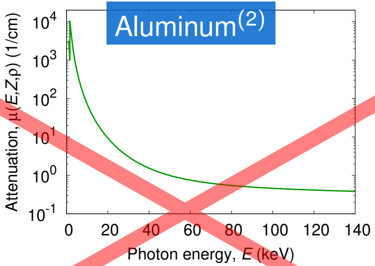
(1) Supplied by Norman Uhlmann, Fraunhofer EZRT

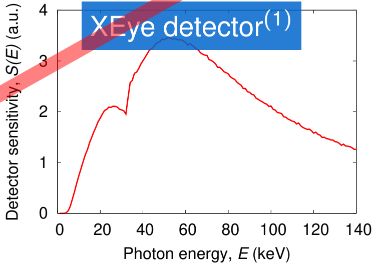
(2) XCOM supplied by NIST

Numerical approx. of μ_{eff}

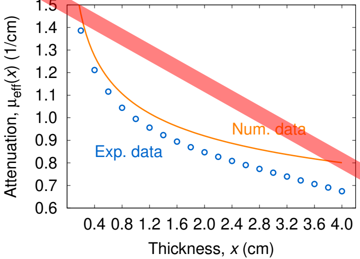








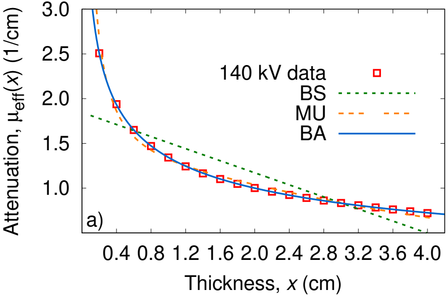
$$I(x) \propto \int N(E) \exp\{-\mu(E, Z, \rho)x\} S(E)\, \mathrm{d}E$$



(1) Supplied by Norman Uhlmann, Fraunhofer EZRT

(2) XCOM supplied by NIST

Heuristic model functions for μ_{eff}



$$\mu_{\text{eff}}(x) = \mu_0 - \lambda x$$

Bjärngard & Shackford (1994)

$$\mu_{\text{eff}}(x) = \frac{\mu_0}{1+\lambda x}$$

$$\mu_{\text{eff}}(x) = \frac{\mu_0}{(1+\lambda x)^\beta}$$

Yu *et al.* (1997)

$$\mu_{\text{eff}}(x) = \mu(E_{\text{max}}) + \frac{2\mu_1}{x\sqrt{-\lambda_1^2+4\lambda_2}} \times \left[\arctan\left(\frac{\lambda_1+2\lambda_2 x}{\sqrt{-\lambda_1^2+4\lambda_2}}\right) - \arctan\left(\frac{\lambda_1}{\sqrt{-\lambda_1^2+4\lambda_2}}\right)\right]$$

Kleinschmidt (1999)

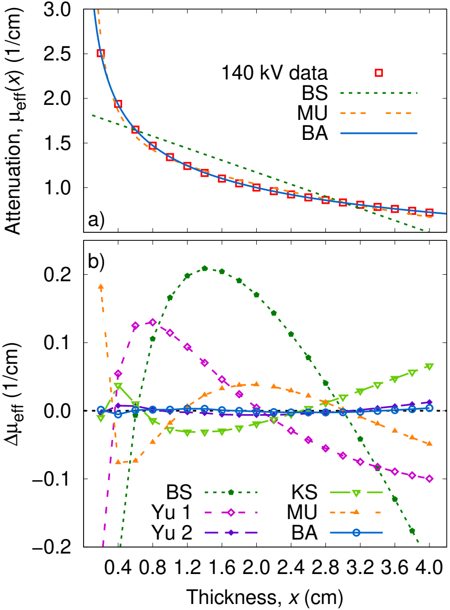
$$\mu_{\text{eff}}(x) = -\frac{1}{x}\ln\left[A + B\exp(-x/C)\right]$$

Mudde *et al.* (2008)

$$\boldsymbol{\mu_{\text{eff}}(x) = a + \frac{b}{x^\alpha}}$$

Baur *et al.* (2019)
(this work)

Heuristic model functions for μ_{eff}



$$\mu_{\text{eff}}(x) = \mu_0 - \lambda x$$

Bjärngard & Shackford (1994)

$$\mu_{\text{eff}}(x) = \frac{\mu_0}{1+\lambda x}$$

$$\mu_{\text{eff}}(x) = \frac{\mu_0}{(1+\lambda x)^\beta}$$

Yu *et al.* (1997)

$$\mu_{\text{eff}}(x) = \mu(E_{\text{max}}) + \frac{2\mu_1}{x\sqrt{-\lambda_1^2+4\lambda_2}} \times \left[\arctan\left(\frac{\lambda_1+2\lambda_2 x}{\sqrt{-\lambda_1^2+4\lambda_2}}\right) - \arctan\left(\frac{\lambda_1}{\sqrt{-\lambda_1^2+4\lambda_2}}\right)\right]$$

Kleinschmidt (1999)

$$\mu_{\text{eff}}(x) = -\frac{1}{x}\ln\left[A + B\exp(-x/C)\right]$$

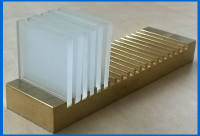
Mudde *et al.* (2008)

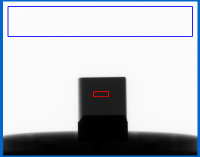
$$\boldsymbol{\mu_{\text{eff}}(x) = a + \frac{b}{x^\alpha}}$$

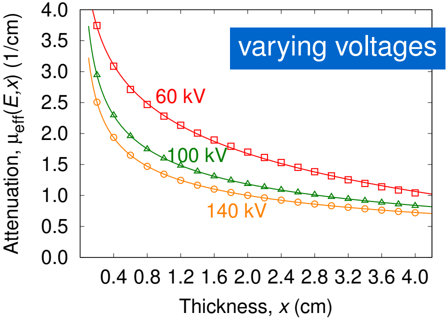
Baur *et al.* (2019)

(this work)

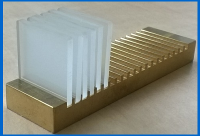
Universality of $\mu_{\text{eff}}(x) = a + \frac{b}{x^{\alpha}}$

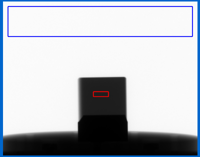


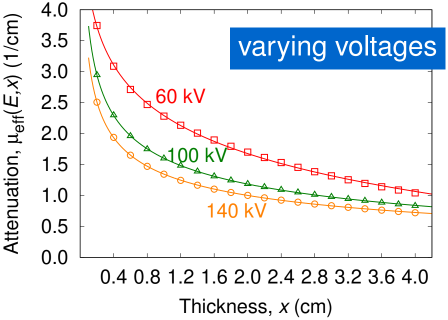


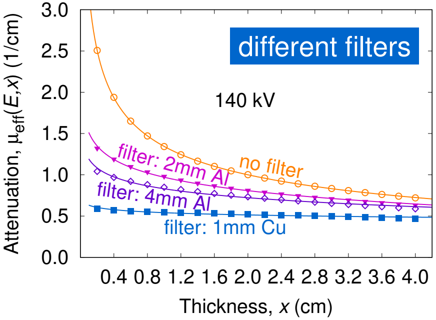


Universality of $\mu_{\text{eff}}(x) = a + \frac{b}{x^{\alpha}}$

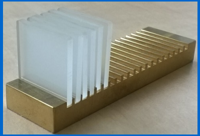


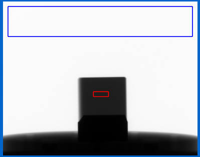


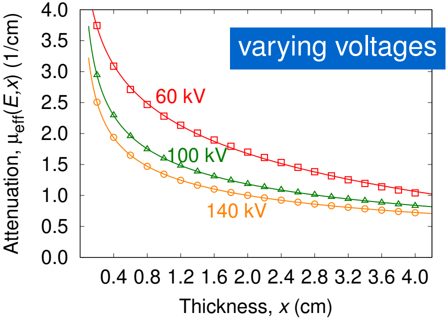


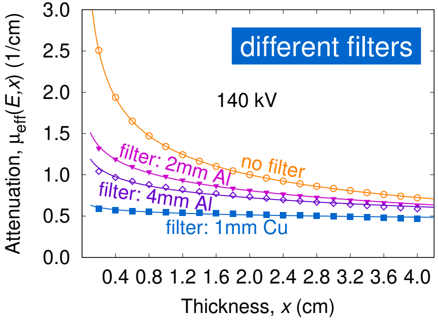


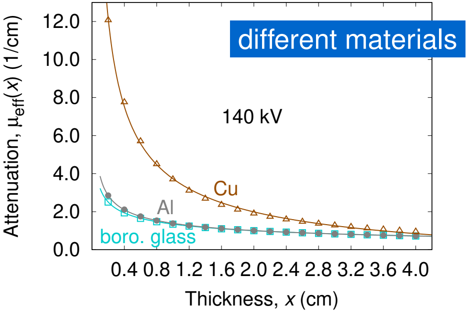
Universality of $\mu_{\text{eff}}(x) = a + \frac{b}{x^{\alpha}}$



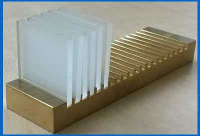


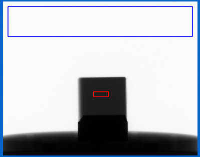


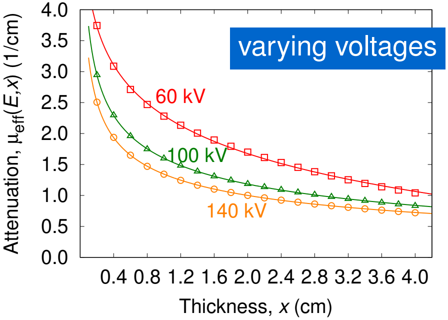


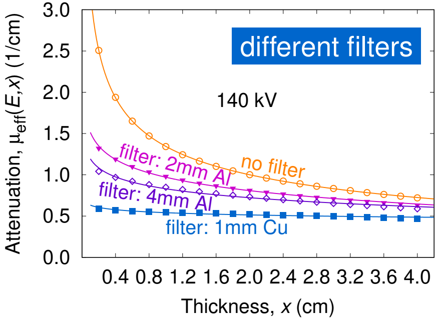


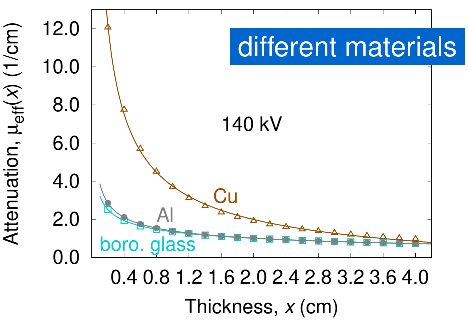
Universality of $\mu_{\mathrm{eff}}(x) = a + \frac{b}{x^{\alpha}}$

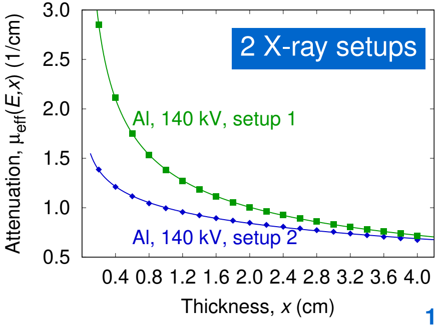












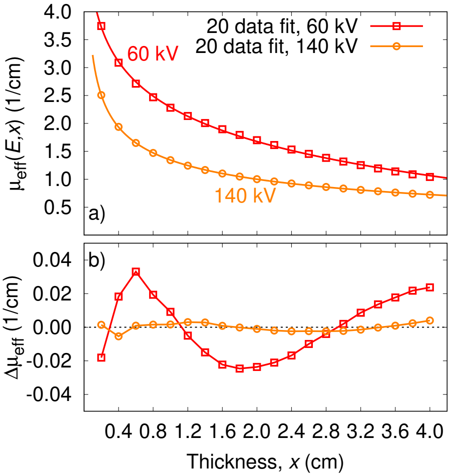
Determining the material thickness x

Generalized Beer-Lambert

$$I(x) = I_0 \exp(-\mu_{\text{eff}}(x)\, x)$$

Model function

$$\mu_{\text{eff}}(x) = a + \frac{b}{x^\alpha}$$



Determining the material thickness x

Generalized Beer-Lambert

$$I(x) = I_0 \exp(-\mu_{\text{eff}}(x)\, x)$$

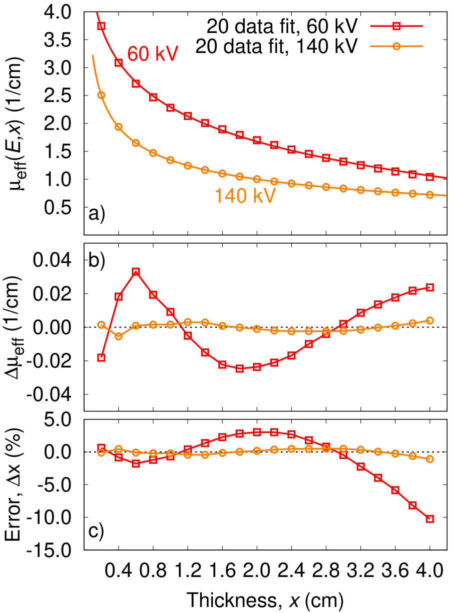
Model function

$$\mu_{\text{eff}}(x) = a + \frac{b}{x^\alpha}$$

Solve

$$ax + bx^{1-\alpha} + \ln\left(\frac{I(x)}{I_0}\right) = 0$$

e.g. Newton's method or look-up table



Determining the material thickness x

Generalized Beer-Lambert

$$I(x) = I_0 \exp(-\mu_{\text{eff}}(x)\, x)$$

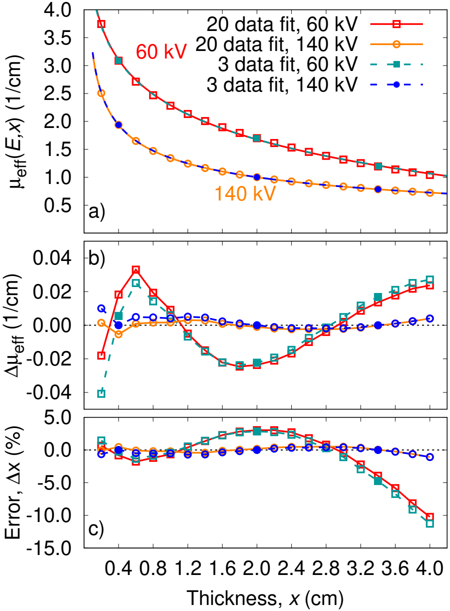
Model function

$$\mu_{\text{eff}}(x) = a + \frac{b}{x^{\alpha}}$$

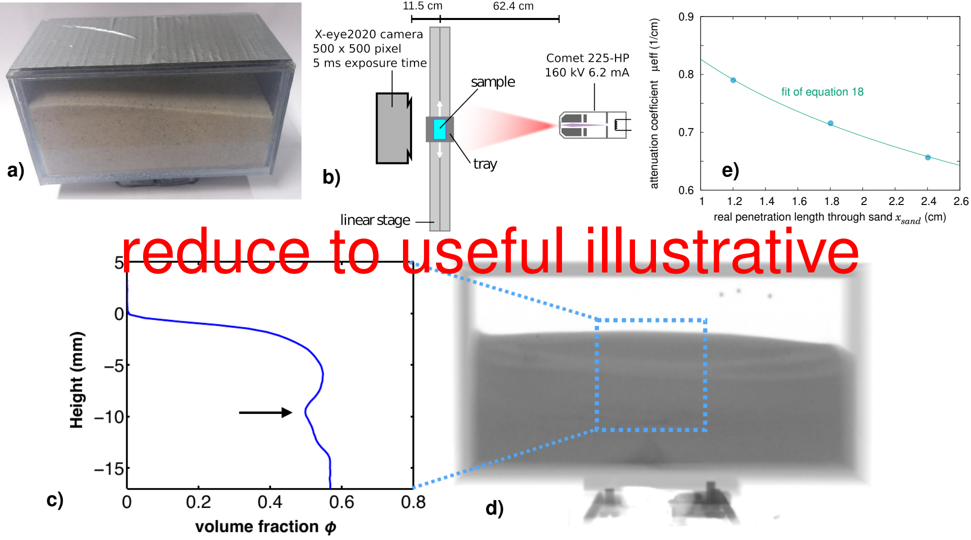
Solve

$$ax + bx^{1-\alpha} + \ln\left(\frac{I(x)}{I_0}\right) = 0$$

e.g. Newton's method or look-up table



Applications



reduce to useful illustrative

Kollmer *et al* 2020