Correction Methods for Neutron Imaging on the Basis of Monte-Carlo Simulations

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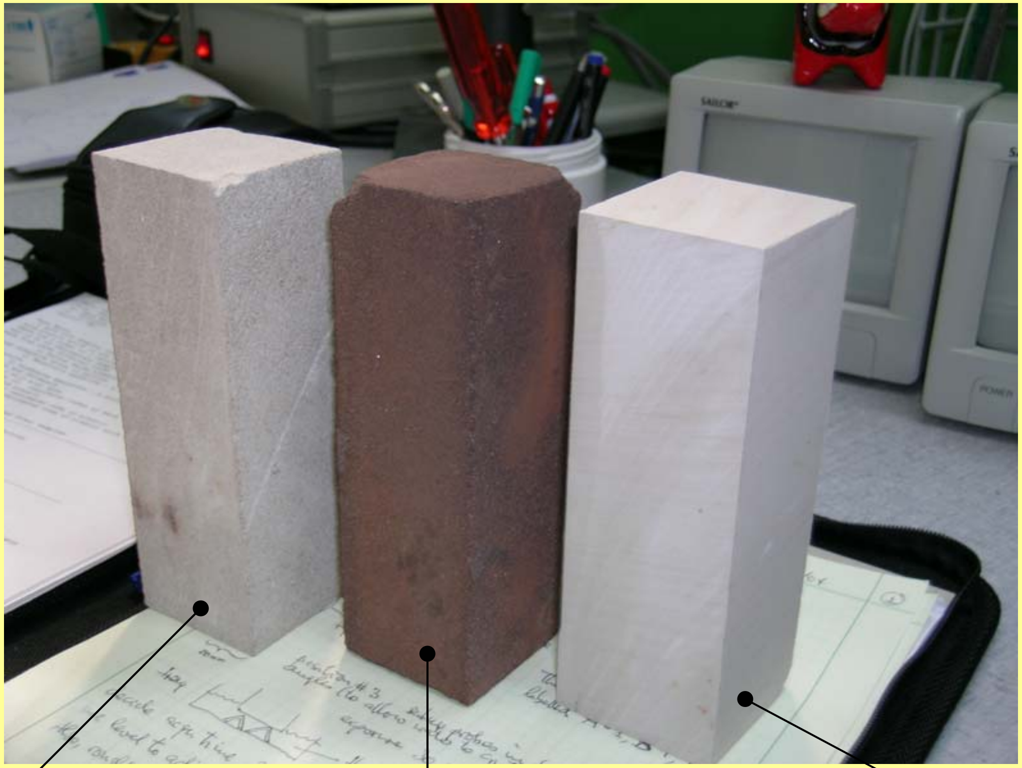
The content is part of the PhD thesis of R. Hassanein

Outline

- Introduction: the problem in quantification → scattering
- Setup of the transmission experiment
- Monte-Carlo model: The Point-Scattered Function approach
- Parameters and relevant data
- Correction tool: QNI
- Results of practical applications
- Outlook: further improvments

Water Distribution in Limestones

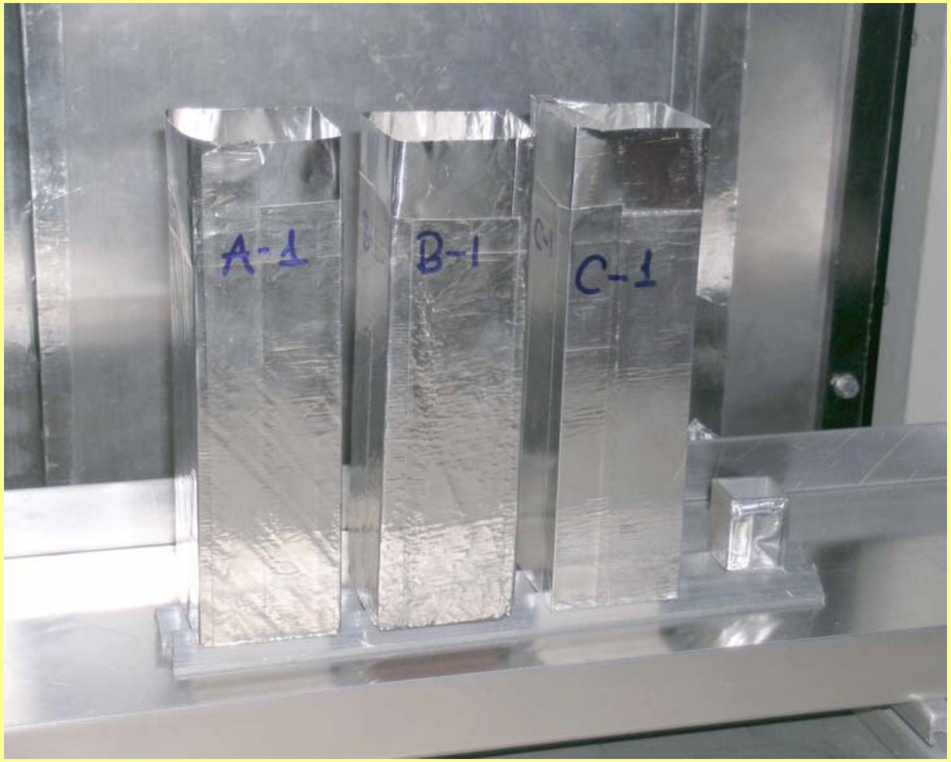


Porous **Salem Limestone** ('the' Indiana Limestone; a coarse-grained stone of calcite)

Mansfield Sandstone (a red stone with relatively coarse grains)

Hindustan Whetstone (a siltstone with angular, fine-grained quartz and feldspars)

Experimental Setup



Absorption of water in **upward direction**
(Prof. H.O. Meyer, Indiana University)

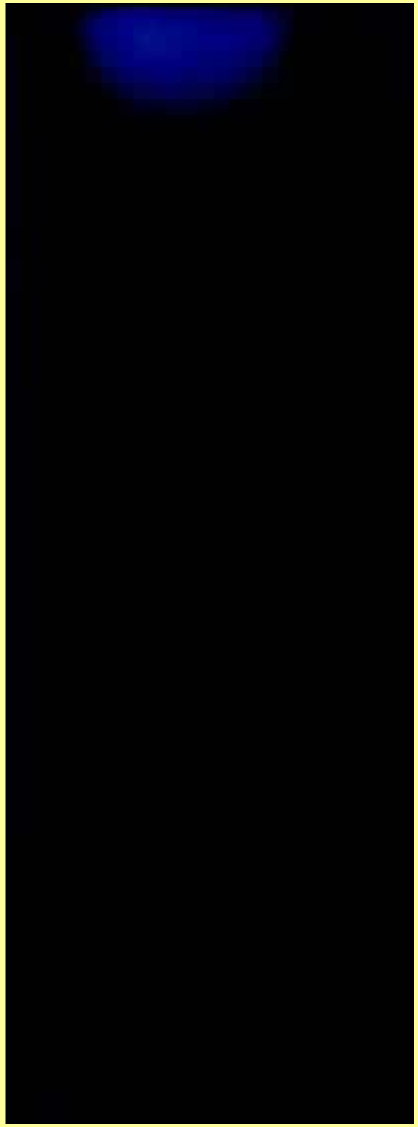
Aluminum cover to
prevent evaporation from surface

Absorption of water
in **downward direction**

sealing and surfaces
treated with silicon

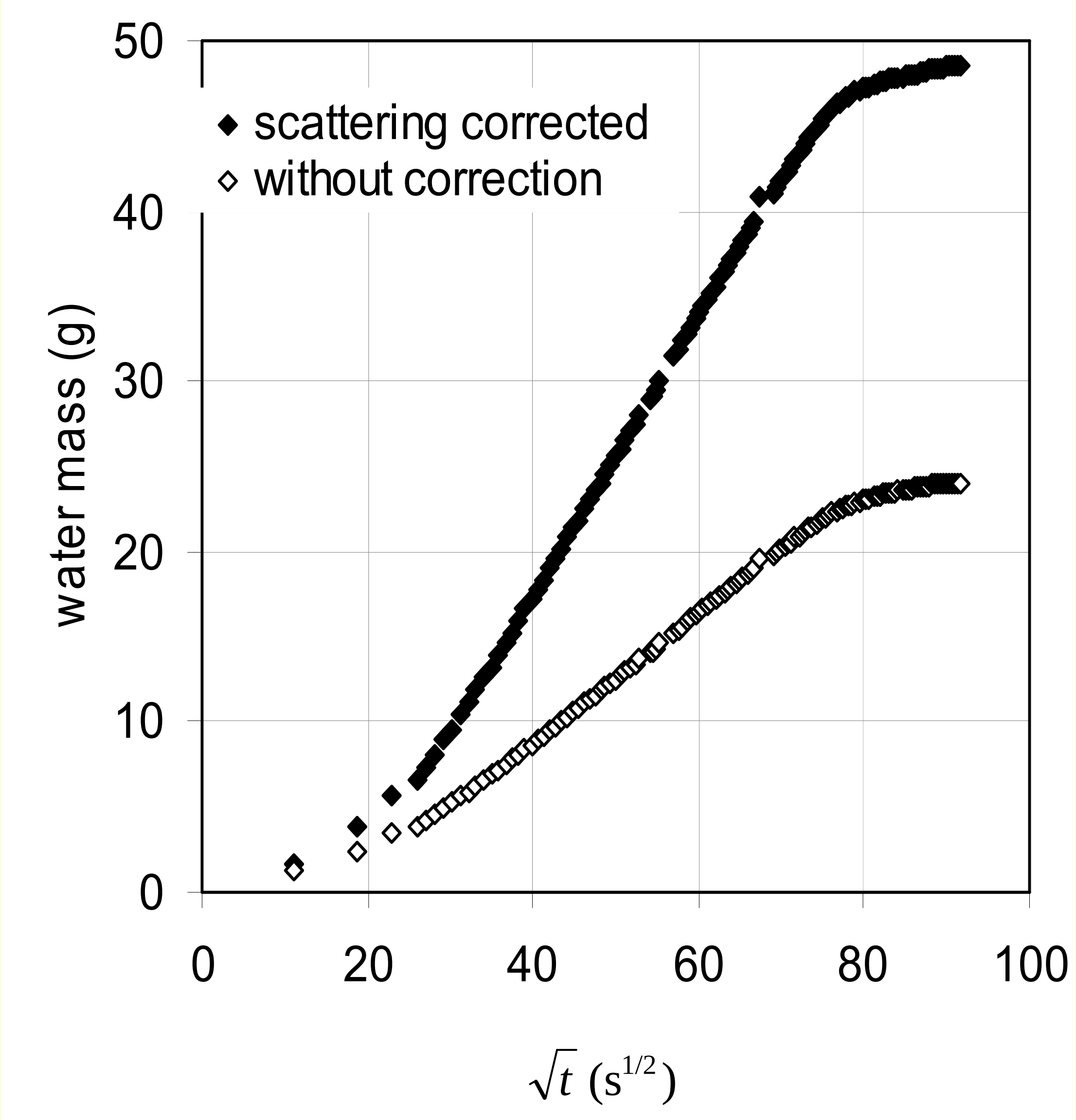
Water migration in sandstones radiography

downward flooding



upward soaking

Water migration in sandstones

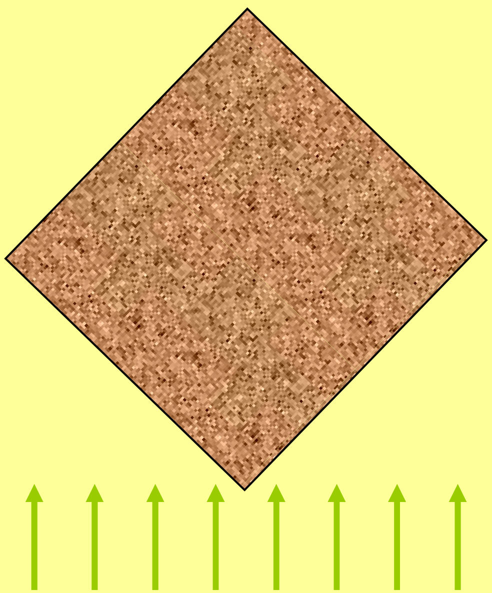


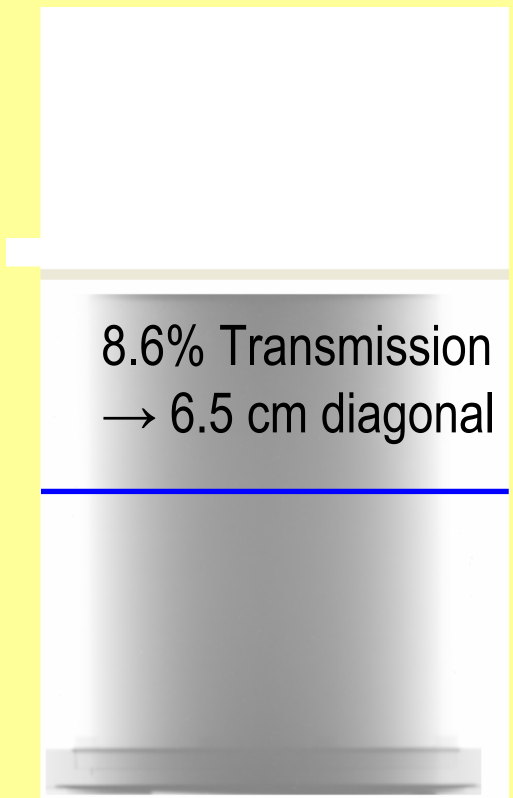
The error in the quantification can be up to 100%!

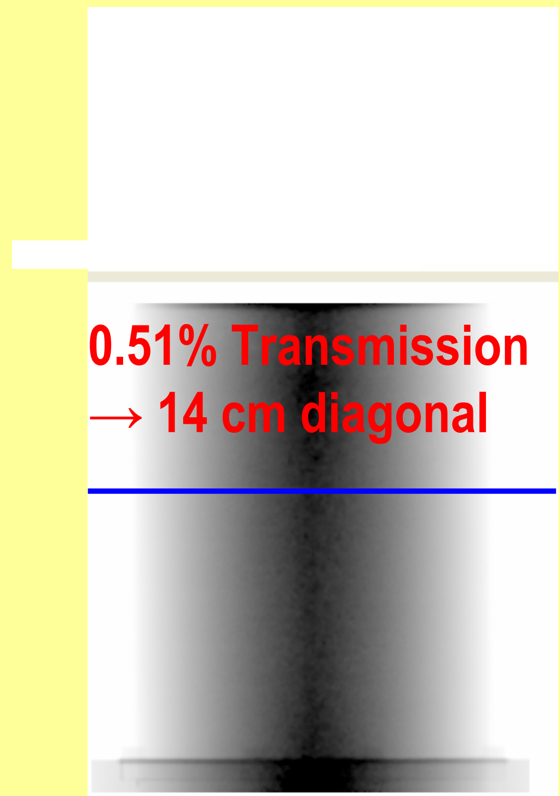
Water Content in Sand Columns -tomography-

45° view: before

after correction

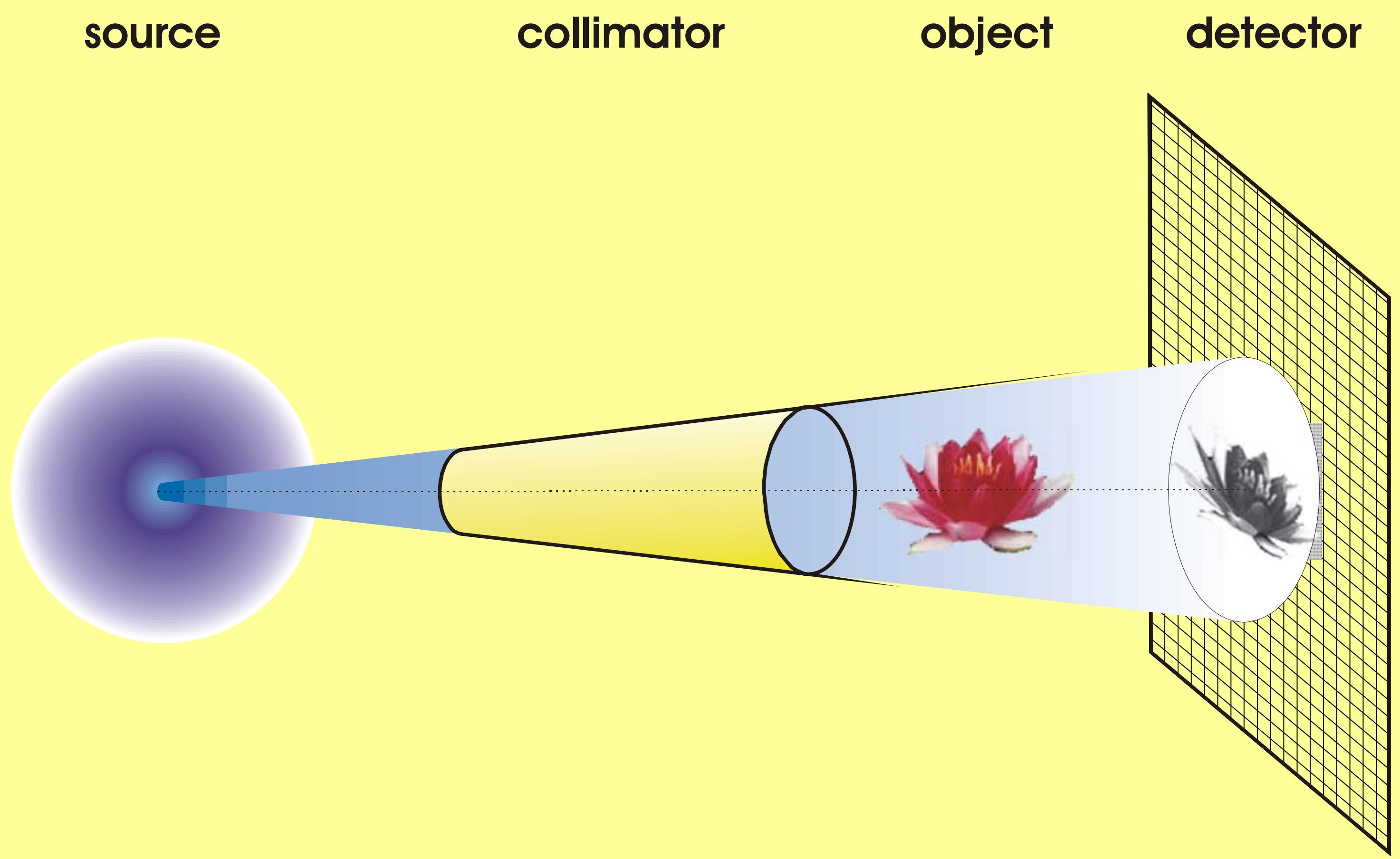


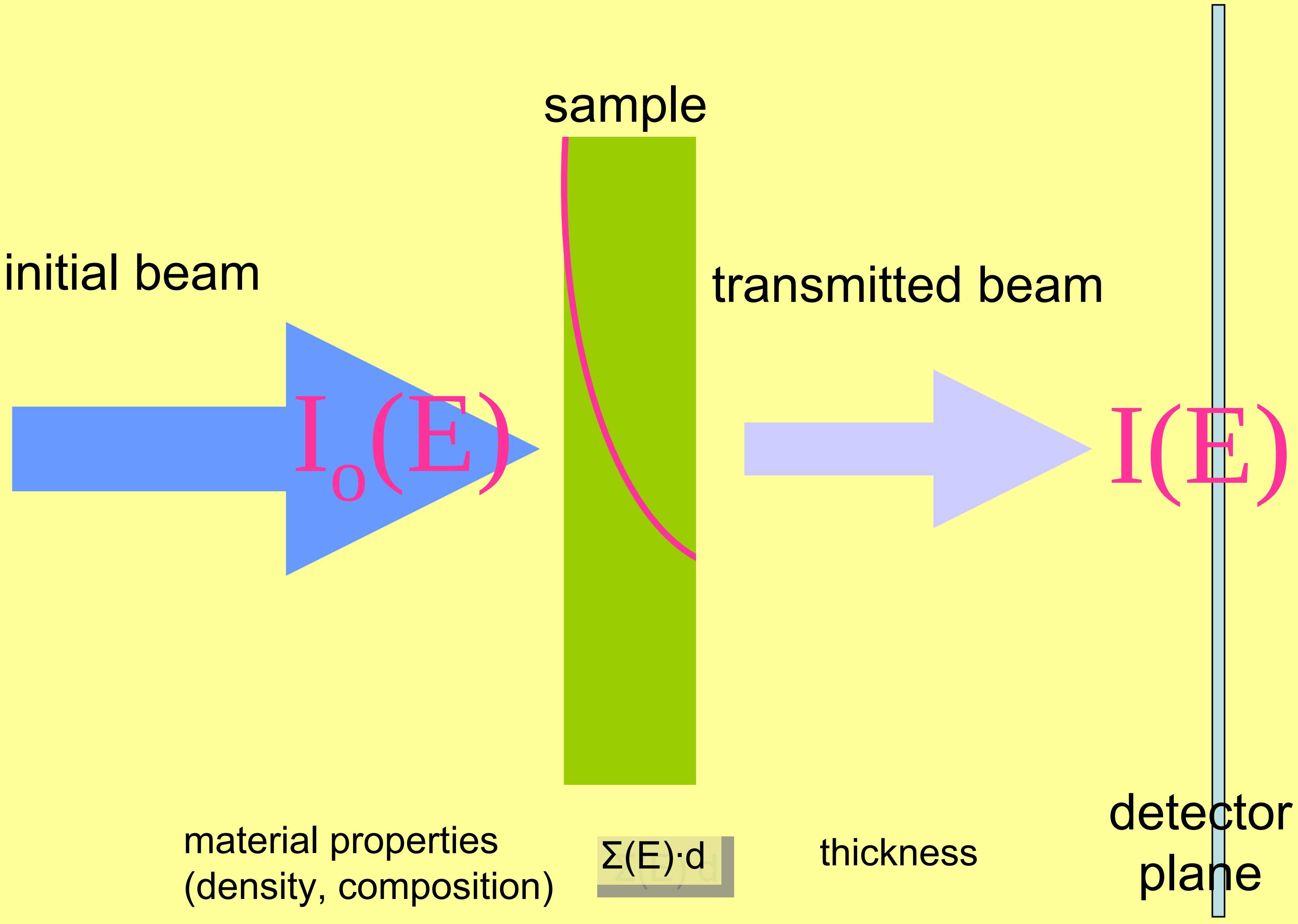




The principle

Simplified setup for radiographic studies




sample
initial beam
transmitted beam
$I_o(E)$
$I(E)$
material properties
(density, composition)
Σ(E)·d
thickness
detector
plane

Approach for quantification

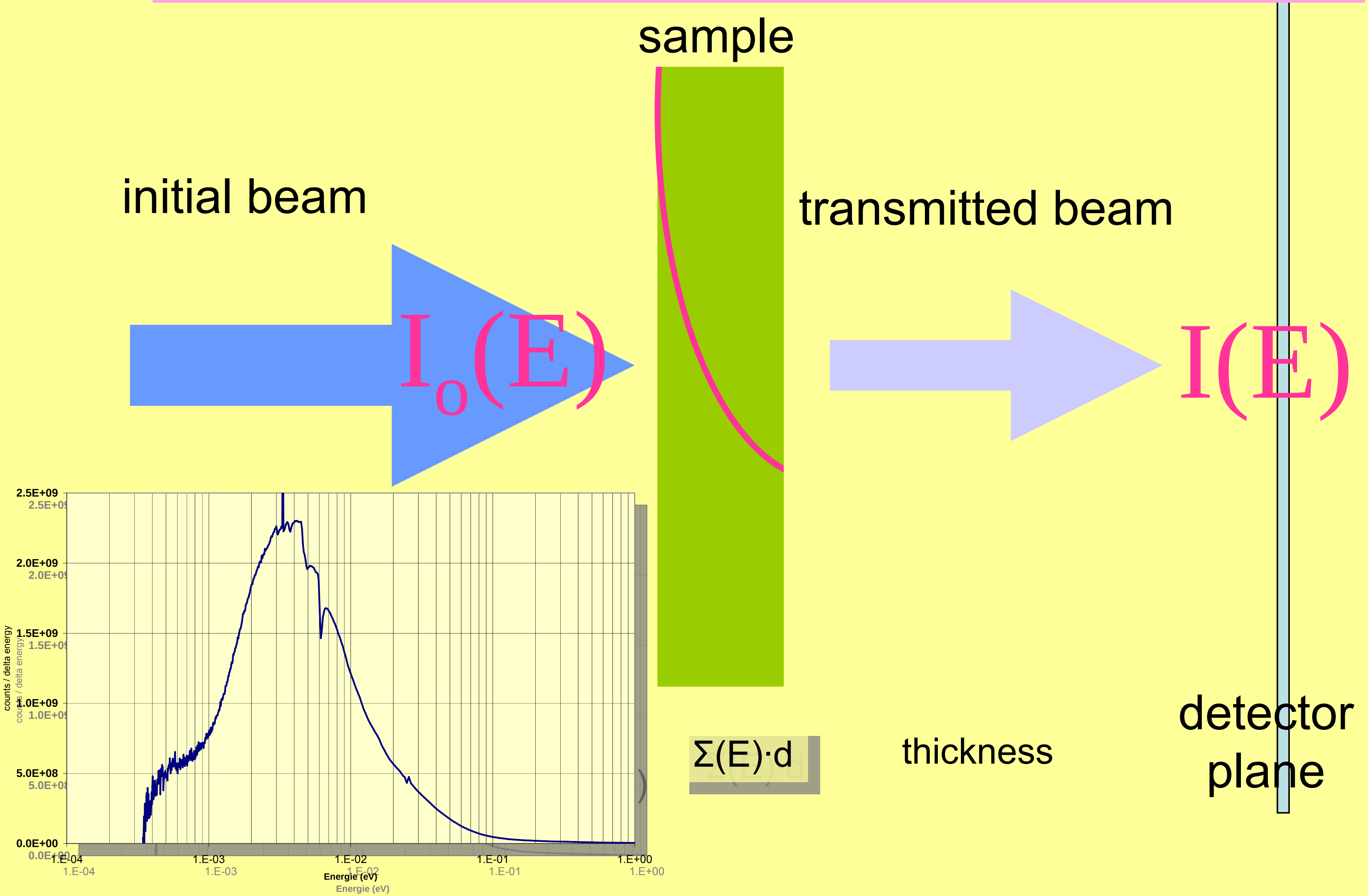
(also in use for tomography)

$$I(E') = I_0(E) \cdot e^{-\Sigma(E) \cdot d}$$

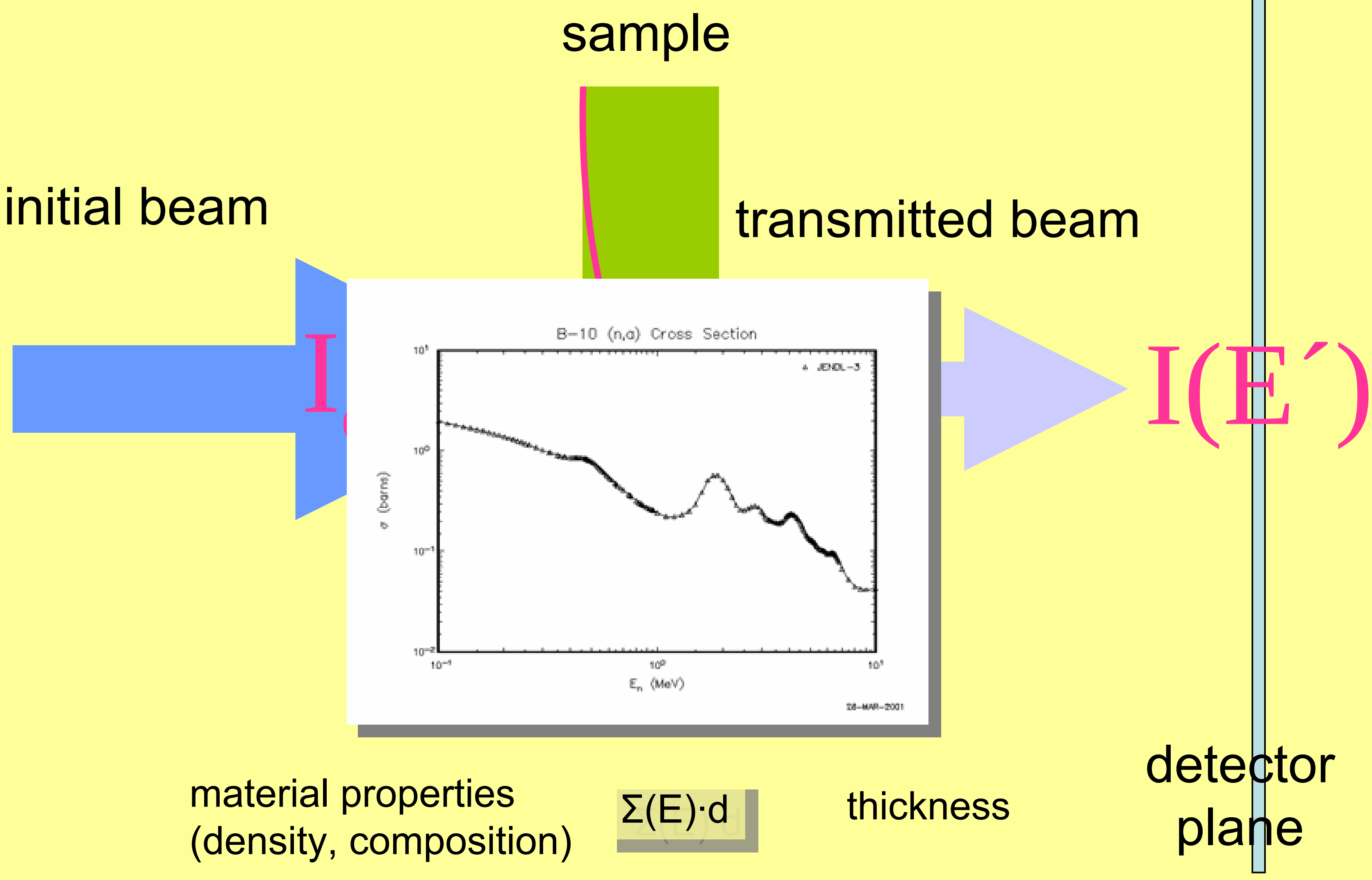
- Assumed, the intensities I_o and I are measured precisely:

- The *sample thickness d* can be obtained, if the material composition is known
- The *material properties Σ* can be obtained, if the sample thickness is known

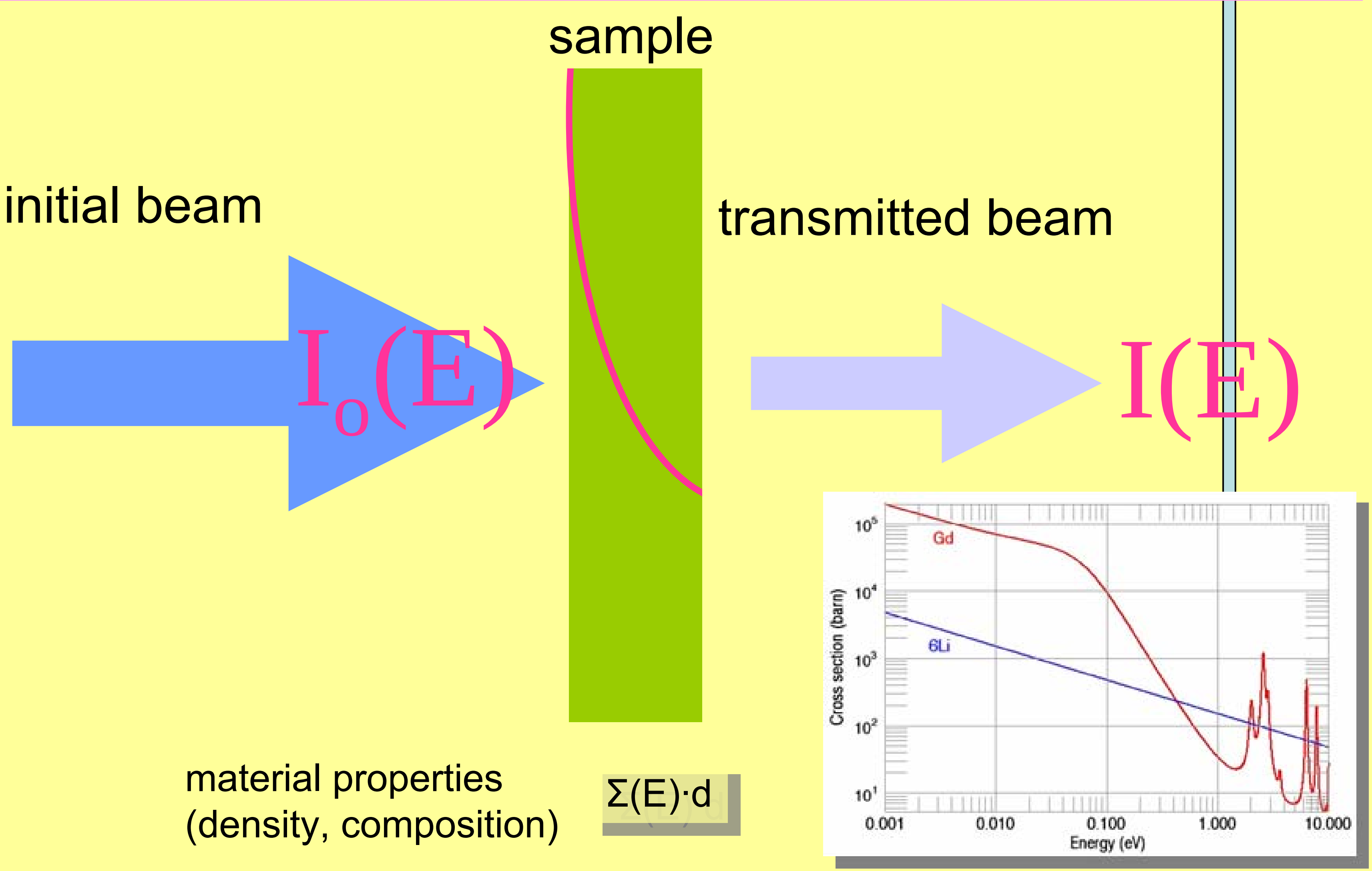
Problem 1: The initial beam has a spectral distribution (about a Maxwellian)



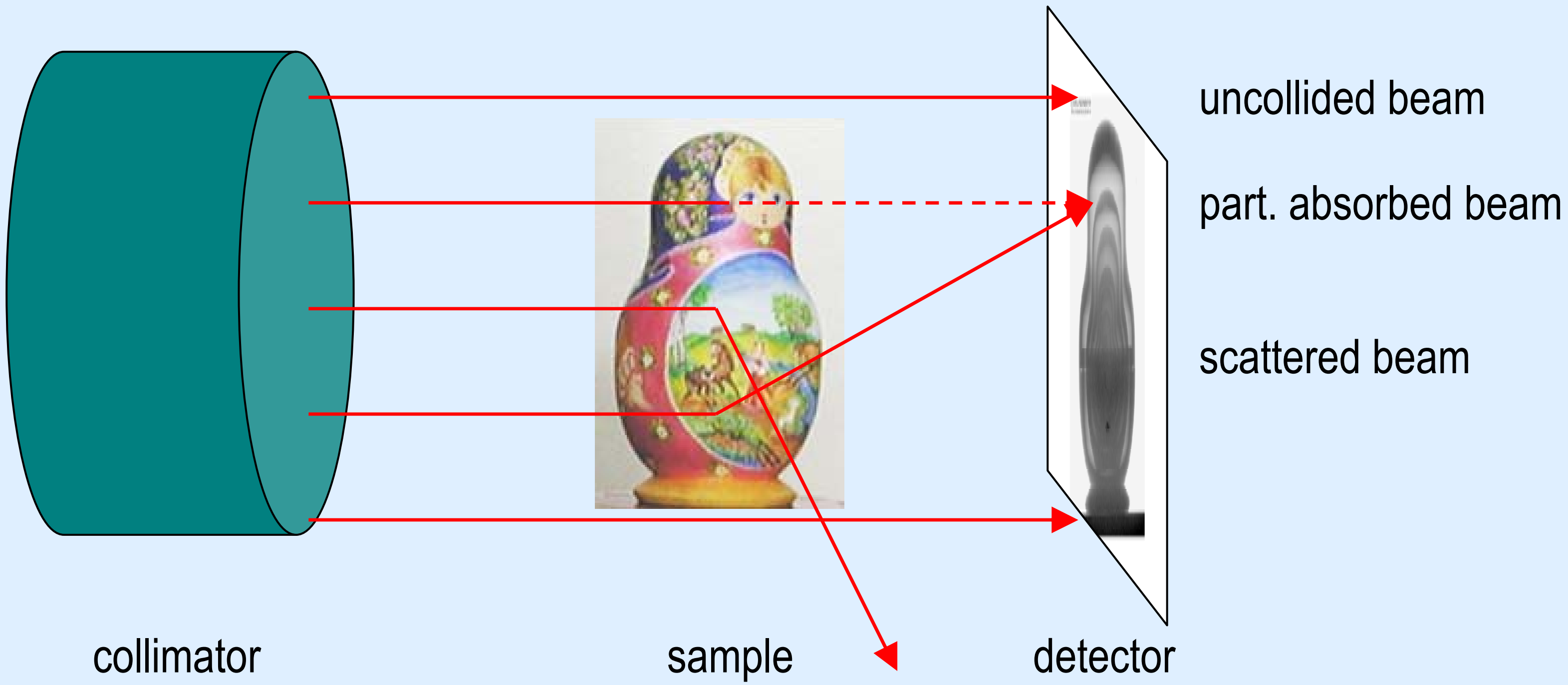
Problem 2: The sample cross-section Σ is energy dependent, modifying the transmitted spectrum



Problem 3: The detector has an energy dependent response, weighting the neutrons differently



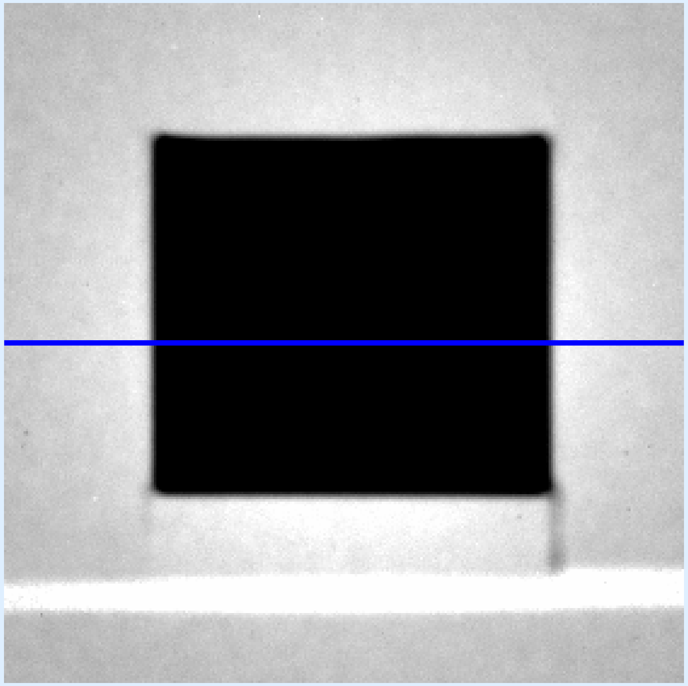
Problem 4: The transmitted beam is "contaminated" by diffuse scattered neutrons

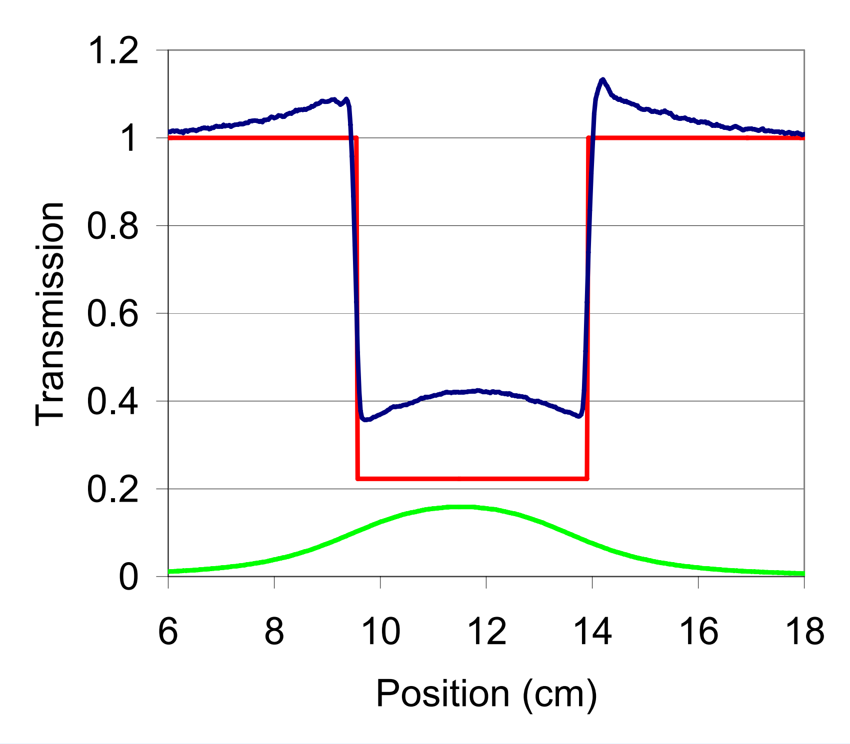


The scattering pretends a higher transmission value behind the sample, which is mistaken for less mass thickness.

Skyshine by the Sample Scattering

Radiograph of 5 mm water in 2 cm distance to the detector with a horizontal profile





Monte Carlo Approach

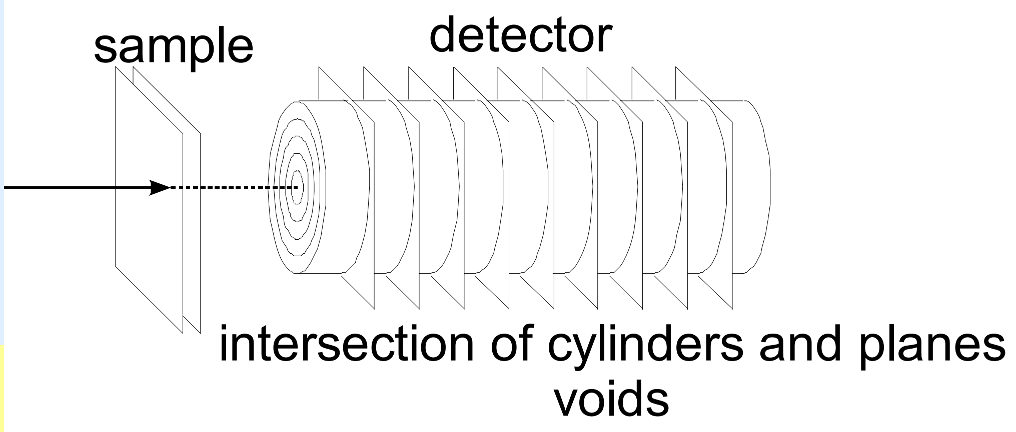
- MCNPX is able to simulate all details of the transmission process
- This enables to consider all effects of neutron interaction with sample and detector
- The processes are separable into the transmitted and scattered component, defining the Point Scattered Function (PScF)
- The cross-section data are within the embedded data libraries of the code (some need for modification was identified)
- The F1 tally was used mainly

Simulation of the Point Scattered Function

The PScF is simulated by the **Monte-Carlo software MCNPX**.

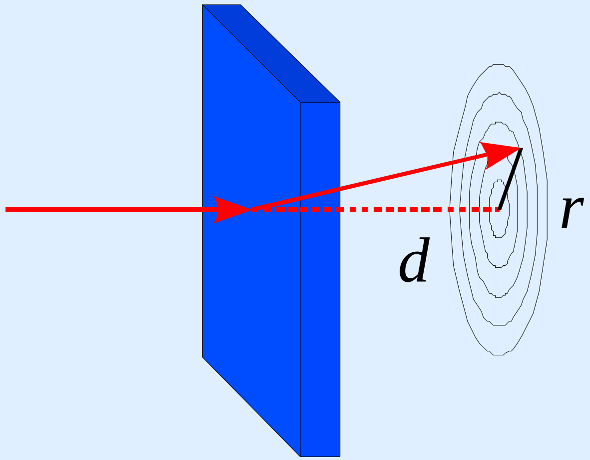
The main parameters are:

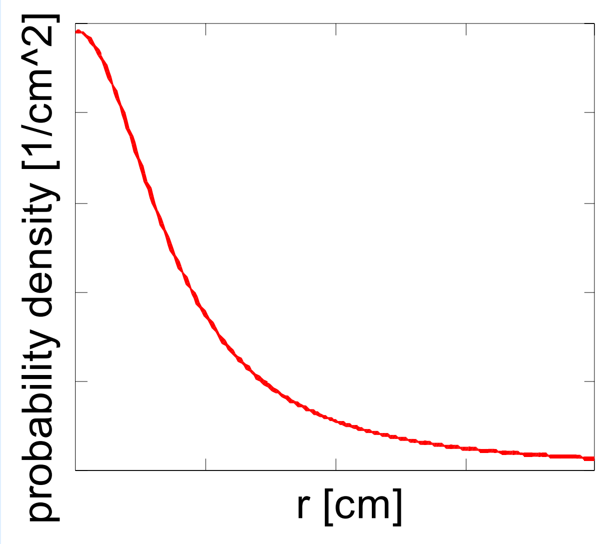
- sample composition
- sample thickness
- energy spectrum of the neutron source, beam geometry
- detector material and thickness (energy sensitivity)
- sample – detector distance



Correction of the Sample Scattering

Computation and subtraction of the sample scattering
The sample scattering is computed based on **"Point Scattered Functions" (PScF)**.





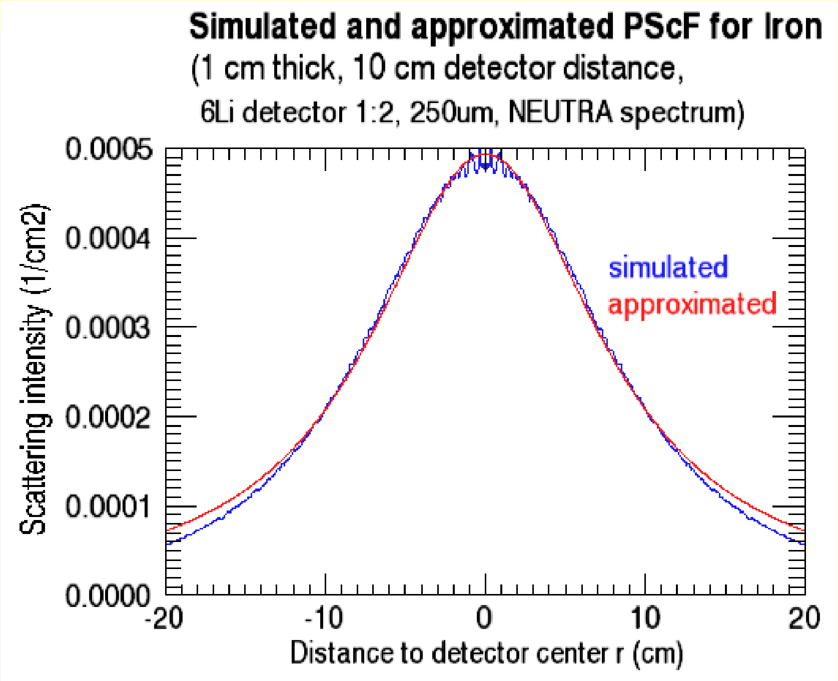
point source I_0 sample layer point scattered function

Approximation of the PScF

Since the simulated PScF are noisy and are obtained for discrete sample thicknesses, detector distances and pixel sizes, an **approximation is necessary for the arbitrary values of a real experiment**.

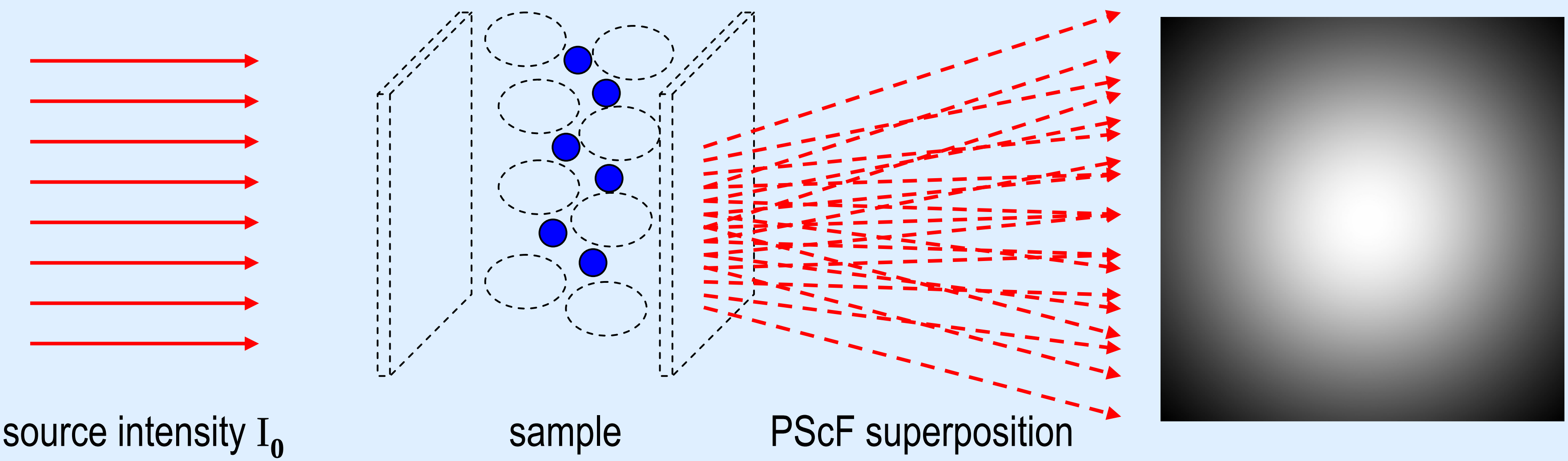
The approximation is based on isotropic scattering:

$$PScF_{Approximation}(r) = S_A \cdot \frac{d_A}{4\pi\left(d_A^2 + r^2\right)^{3/2}}$$



Computation of the Sample Scattering

The total sample scattering is the **superposition of the corresponding PScF**, where each point* of the sample can have its own PScF (corresponding to the detector distance, sample material and transmitted thickness).



* “point” = group of about 4×4 pixels (depending on the image size) because of the computation time ~ (group width)$^{-4}$

Iterative Algorithm

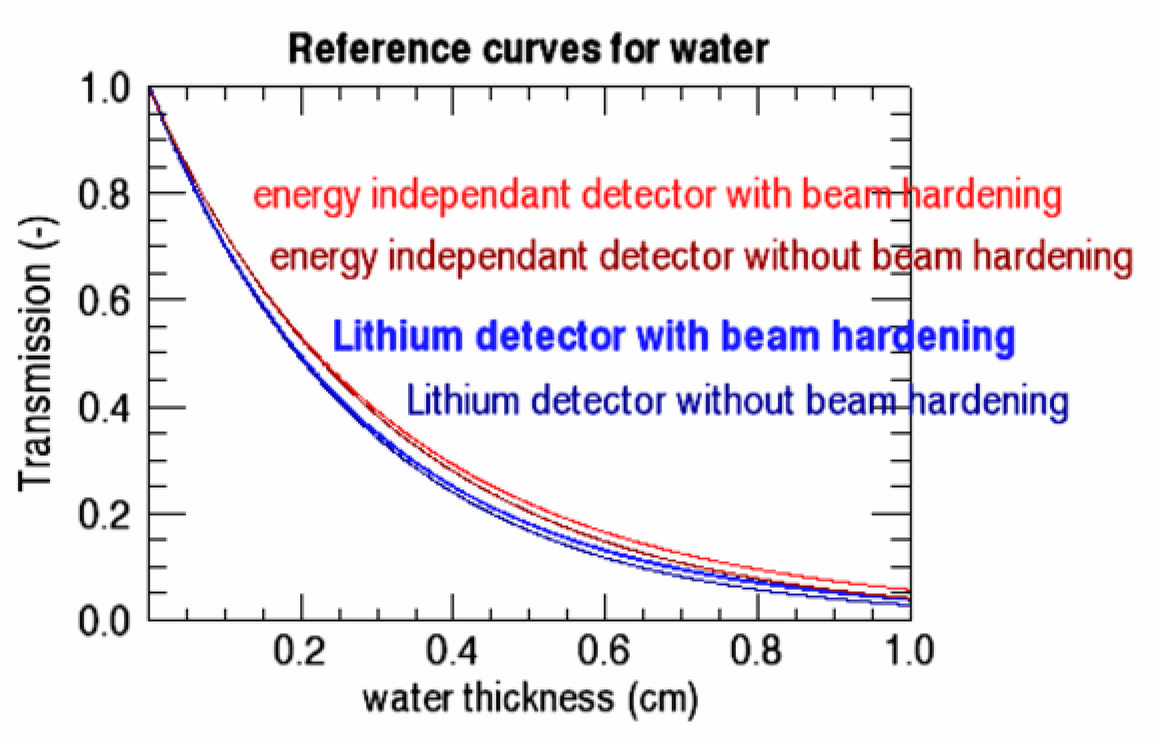
- **Corrected transmission image = radiography – sample scattering**

- With the corrected image, a more precise base for the choice of the PScF is available and the computation is repeated.
- After about 4 iterations the algorithm converges in the range of ±1 %.

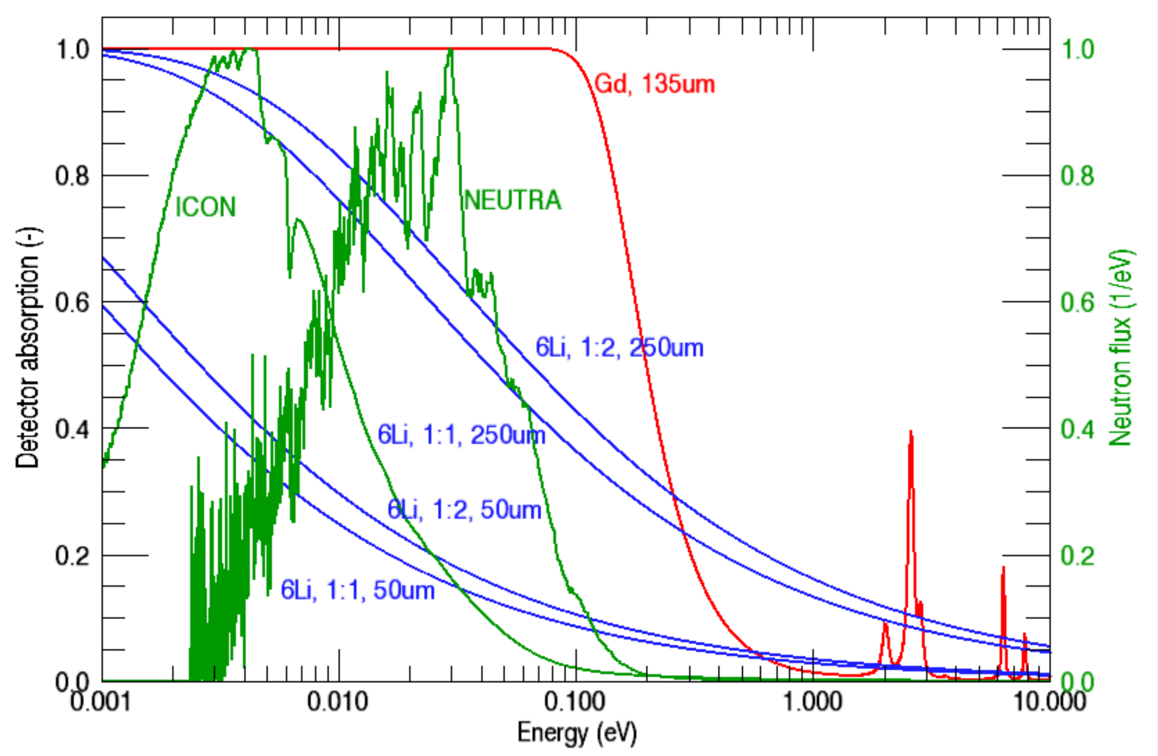
Correction of the Spectral Effects

The Monte-Carlo simulations of the PScF provide also **reference curves** for the correction of the

- beam hardening
- energy dependent detector sensitivity



Detector Absorption Rates



Detector absorption rate: $A(E) = 1 - \exp\left(-\Sigma_{\text{detector}}(E) \cdot t_{\text{detector}}\right)$

Effective Cross Section

Cross section of 2 mm water for the different detectors:

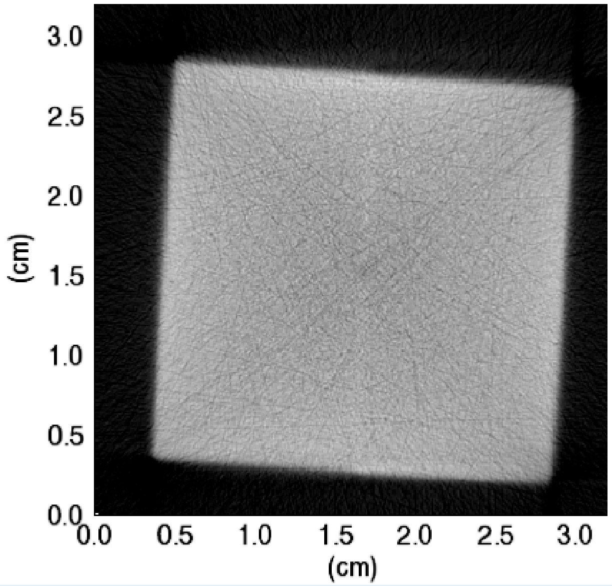
$$\Sigma_{\mathrm{eff},\,\mathrm{H_2O}} = \frac{-1}{t_{\mathrm{H_2O}}} \cdot \ln \frac{\int I(E) \cdot \exp\left(-\Sigma_{\mathrm{H_2O}}(E) \cdot t_{\mathrm{H_2O}}\right) \cdot A(E)\,\mathrm{d}E}{\int I(E) \cdot A(E)\,\mathrm{d}E}$$

detector	NEUTRA Σ_{eff} (1/cm)	ICON Σ_{eff} (1/cm)
Gd, 135 µm	3.29	4.11
^{6}Li, 1:2, 250 µm	3.40	4.20
^{6}Li, 1:1, 250 µm	3.42	4.27
^{6}Li, 1:2, 50 µm	3.51	4.62
^{6}Li, 1:1, 50 µm	3.52	4.65

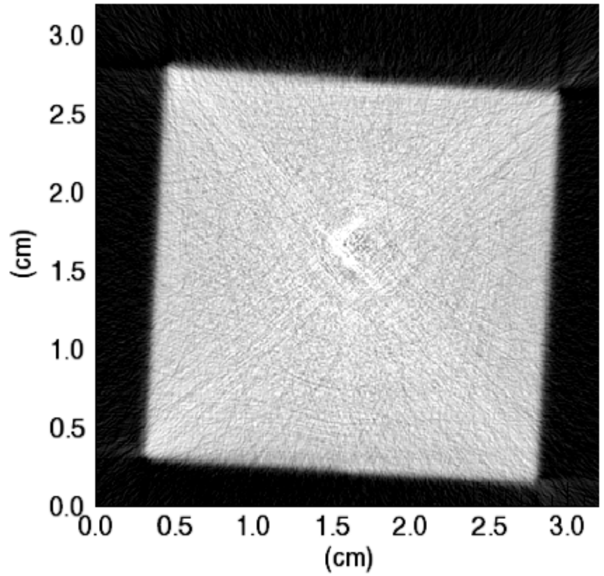
Correction of Tomograms

For tomograms **each projection is corrected** in a pre-processing step.
(The change of the sample geometry and detector distance in each projection must be considered)

horizontal slice of an iron cube (side length 2.5 cm)



uncorrected

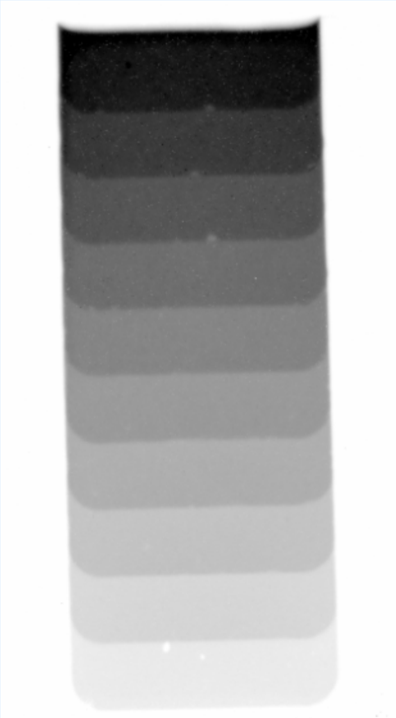


corrected

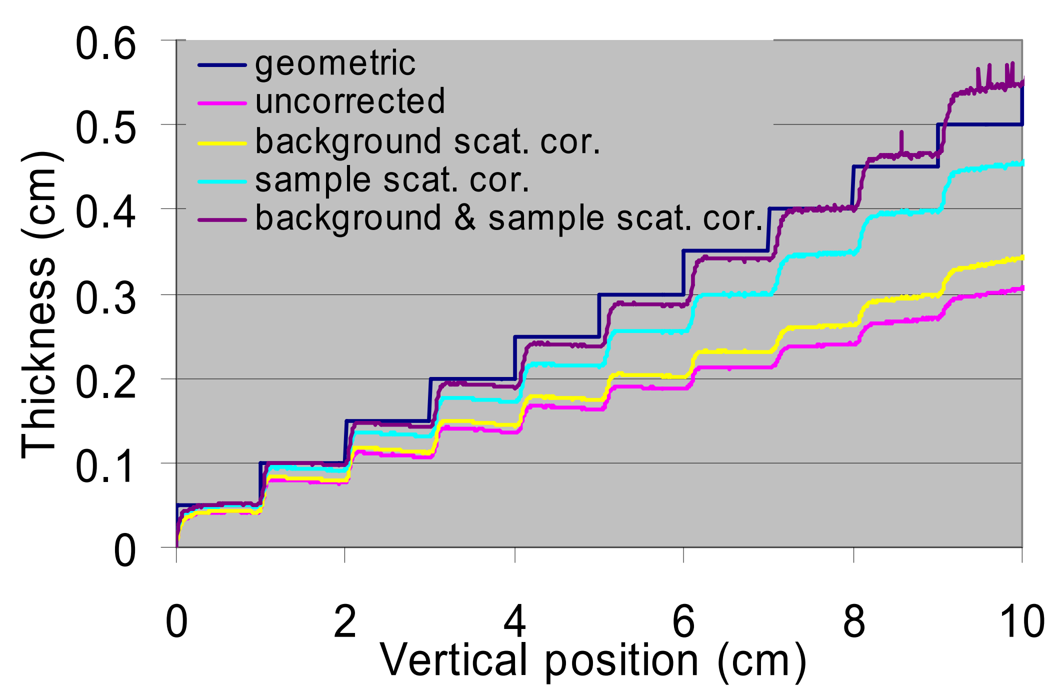
Application 1

Experiments at ANTARES, FRM-II Munich

Example water steps: size 4×10 cm, thickness 0.5–5.0 mm, detector distance 4 cm



corrected radiography

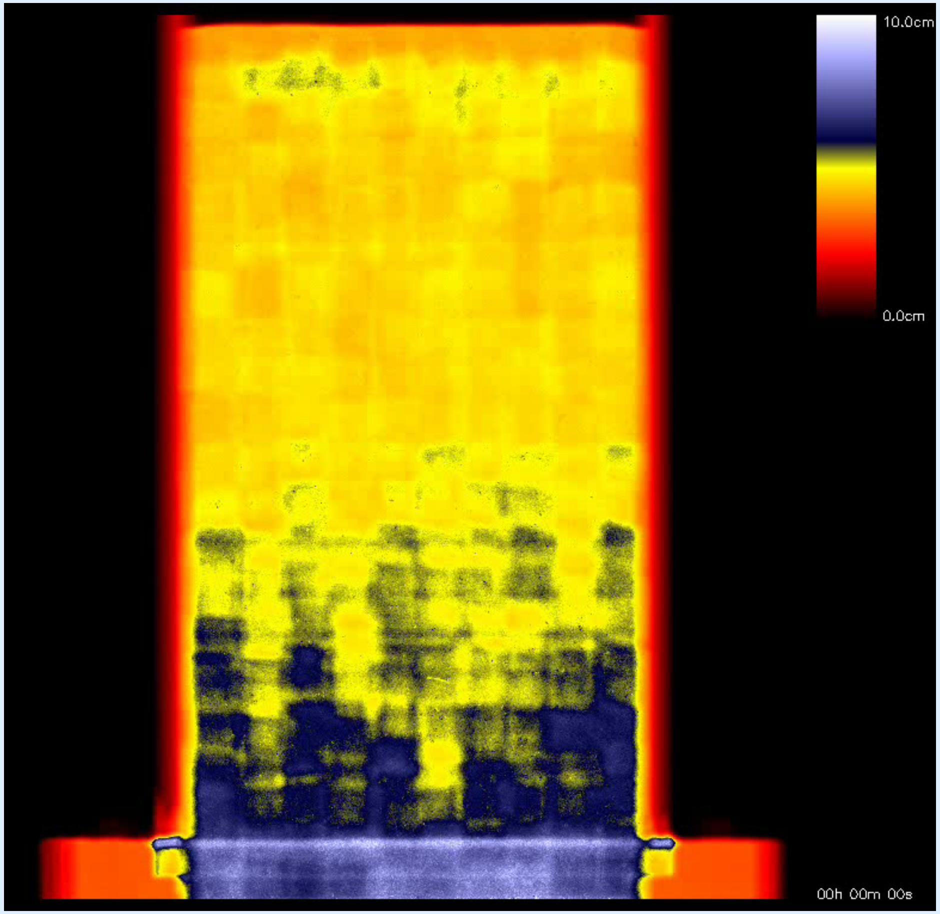


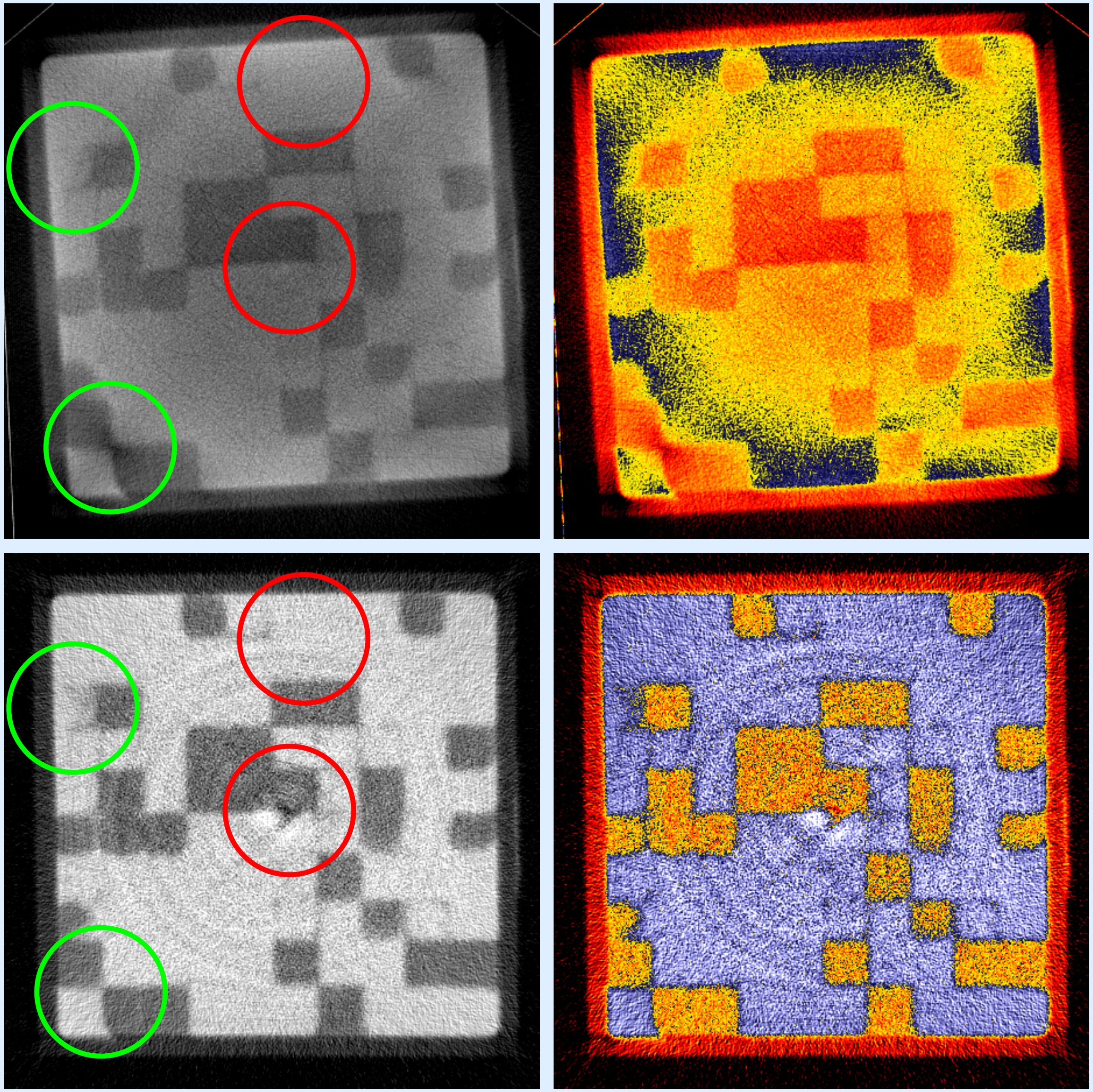
remaining error ≤ 5 %

Application 2

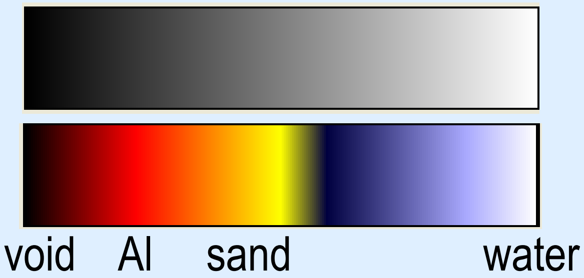
Imbibition and Drainage of Sand Columns with D_2O

(Experiment: I. Neuweiler, M. Vasin, P. Lehmann, Univ. Stuttgart & ETH Zurich)





uncorrected slice



corrected slice

− more noise

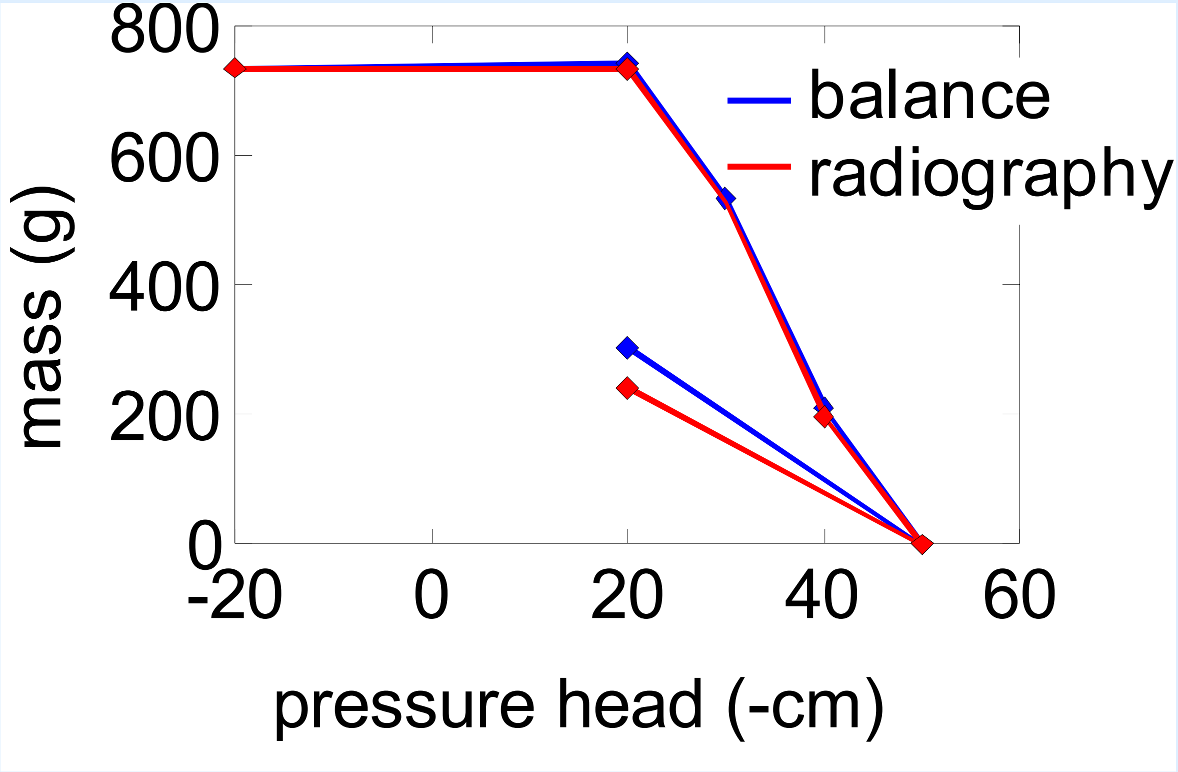
− more artefacts

+ less blurring

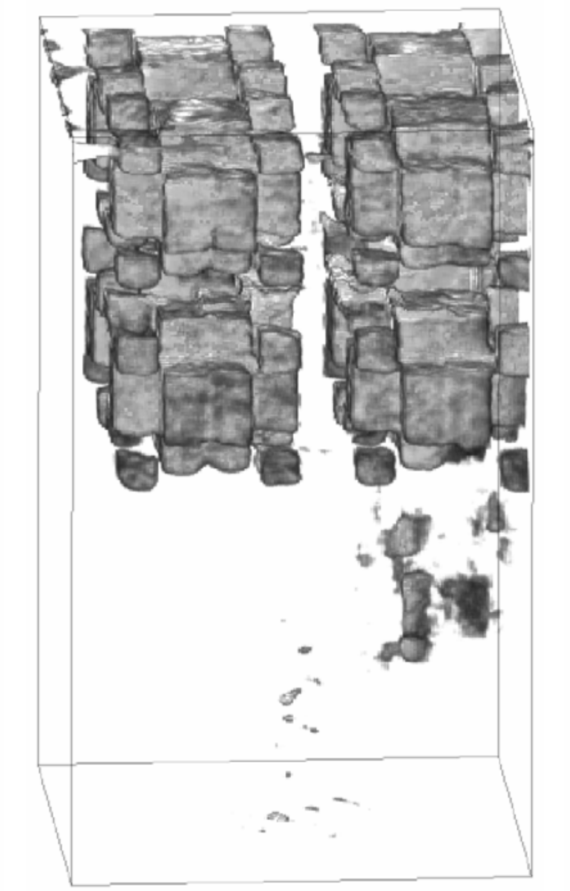
+ more details

+ correct attenuation values

Imbibition and Drainage of Sand Columns with D_2O



remaining error ≤ 5 %



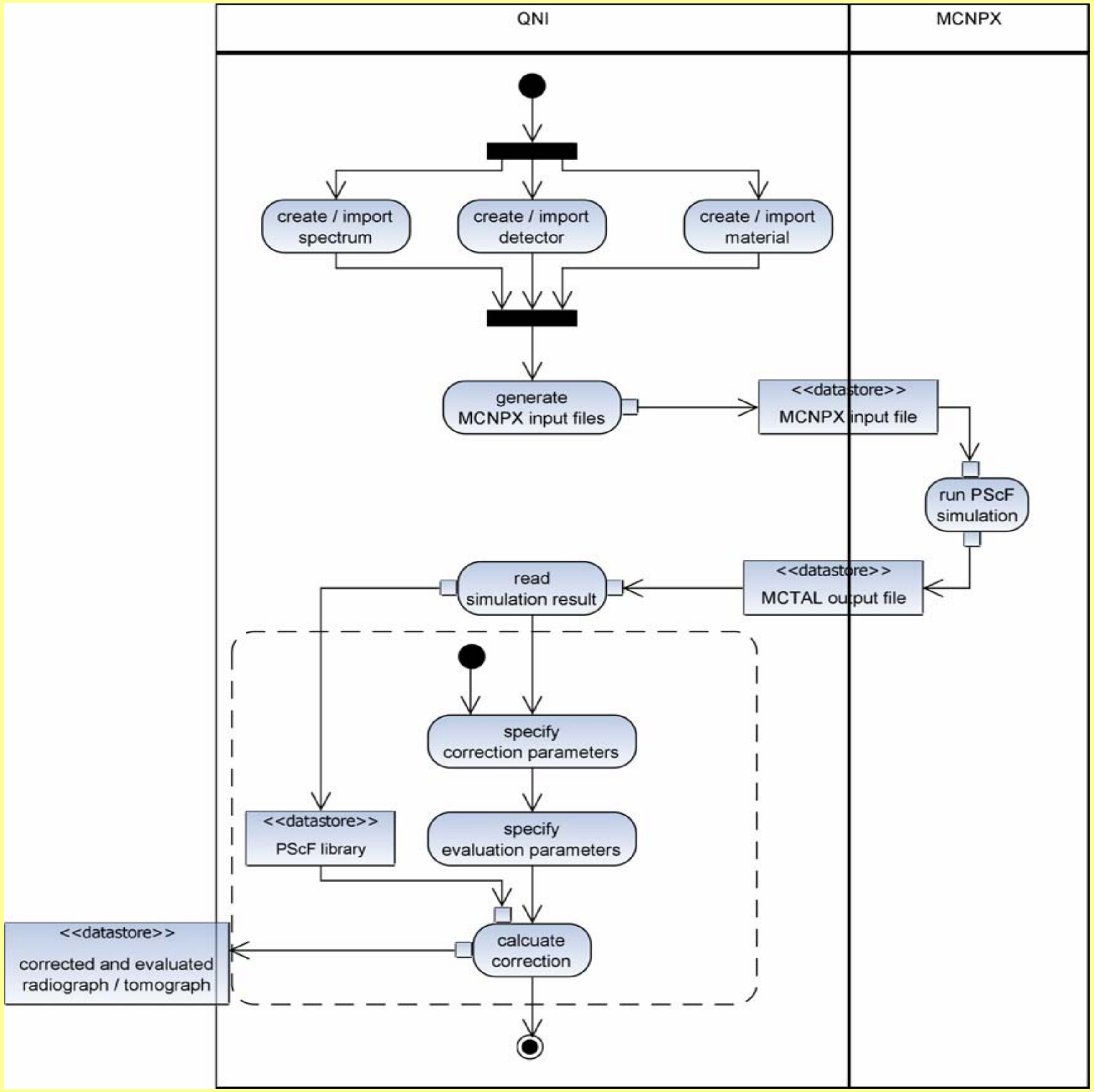
Conclusions

- Neutron radiography (NR) is suitable method for **quantitative**, non-destructive investigations with an accuracy of ~5 %, depending on the material combination.
- An **appropriate experimental setup** is decisive (facility, material, dimensions, detector system)
- The **properties of the NR facility** must be known (energy spectrum, detector)
- **Monte-Carlo simulations** are a valuable tool for the investigation of effects in NR (e.g. scattering, beam hardening, detector efficiency)
- A **"user friendly" implementation** of the correction algorithm allows to use the correction methods in the daily work and improve the results.

Outlook

- QNI – the correction tool written in IDL
- Improved experimental conditions
- Further approaches needs considerations (cold neutron imaging, energy selective studies)

QNI – the correction tool



Work-flow

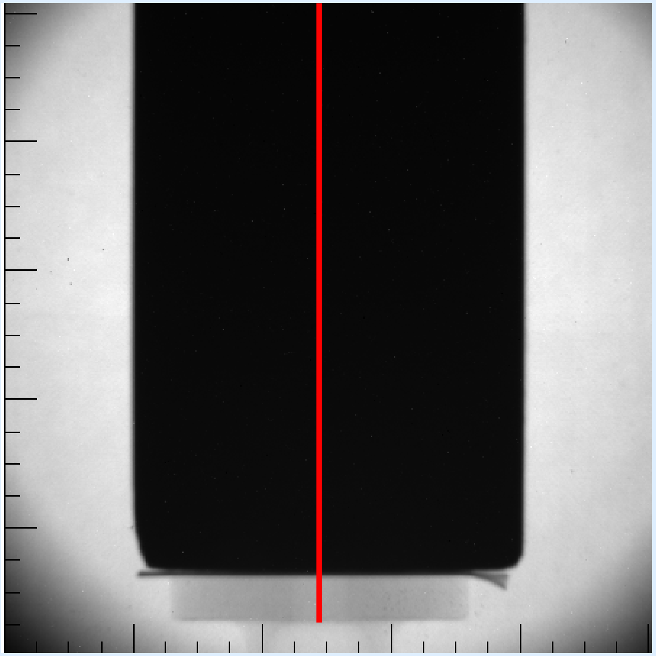
- Based on PhD work of **René Hassanein**
- Programmed in IDL
- Available for other users in October 2006

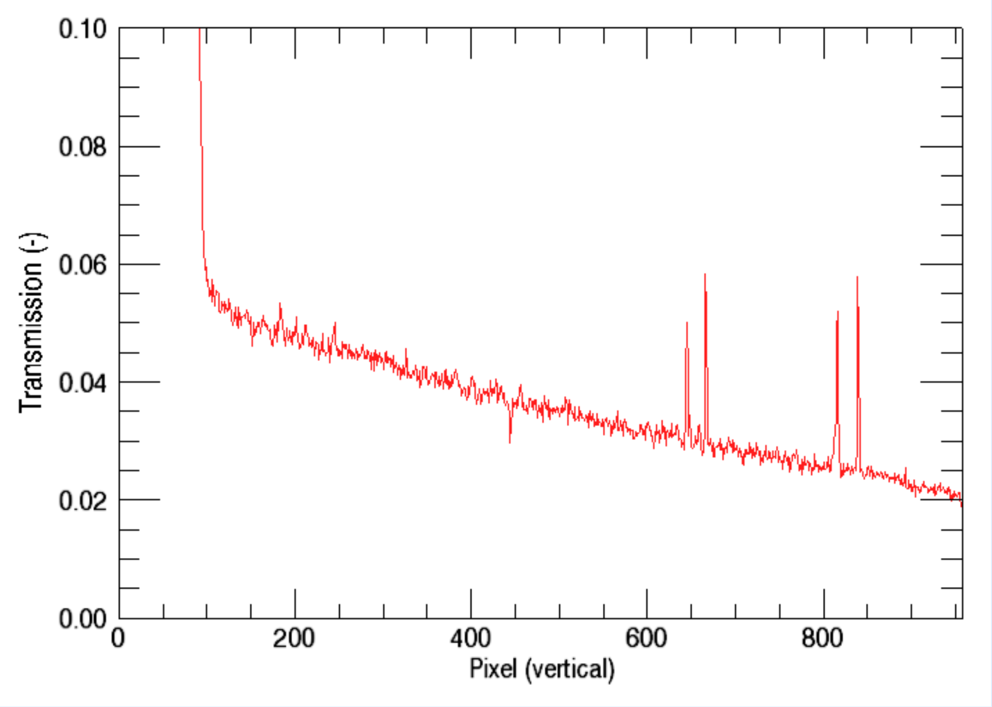
Avoiding Background Scattering: Beam Delimiters

Beam limitations in order to avoid scattering sources:

- aperture at the front position
- aperture at the collimator exit
- limitation of the field of view (figure)

Recording of the Background Scattering

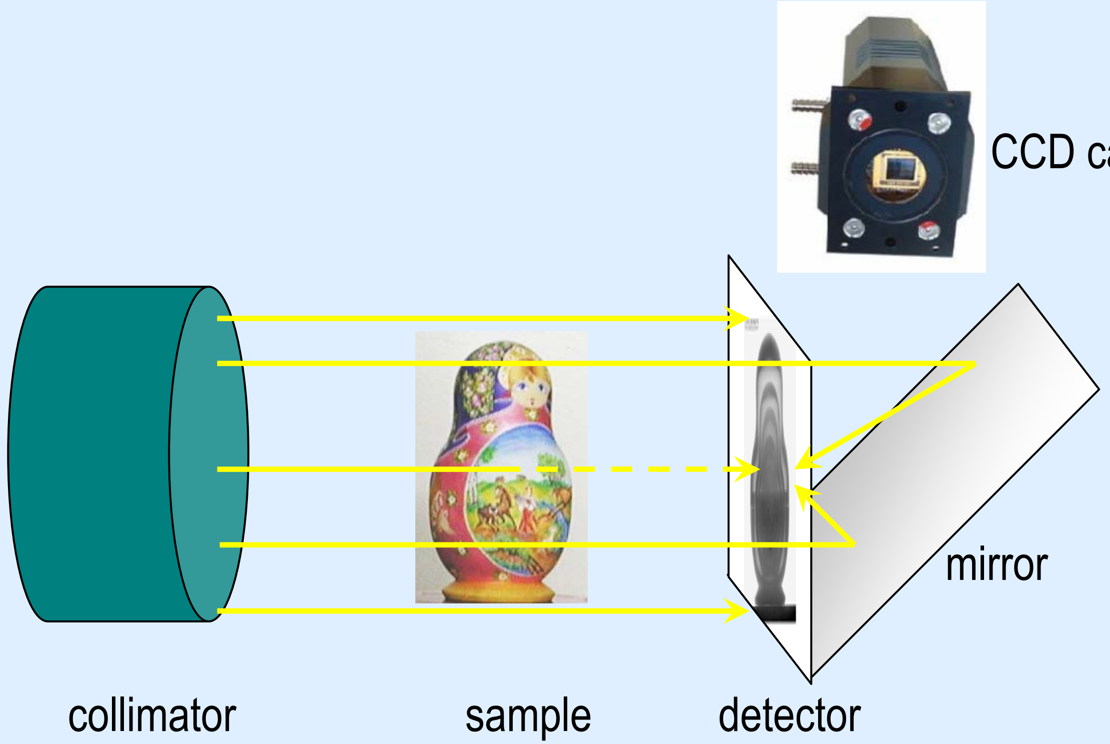




Measurement of the scattering behind a black body:

- not constant
- to be scaled

Distortion by Scattering at the Experimental Setup



Neutrons are scattered by the surrounding of the sample (e.g. camera box and shielding) and pretend again high transmission and **less mass thickness**.

Experiments at the Bragg edges of the materials
→Improvement of the data base in MCNPX