PAUL SCHERRER INSTITUT PSI

IAEA International Atomic Energy Agency

CCMX Competence Centre for Materials Science and Technology

Wir schaffen Wissen – heute für morgen

Paul Scherrer Institut

Peter Vontobel

Quantification in Neutron Imaging

OUTLINE

1. Introduction
2. Definition of quantification in NI
3. Spatial resolution, sample morphology, defect size, beam divergence, magnification, …
4. Influence of energy spectrum: white beam - versus mono energetic neutron attenuation
5. Effects due to sample scattering
6. Assessing the importance of disturbing effects
7. QNI software

Quantification in neutron imaging NI

- **Neutron Imaging**: Neutron intensity measurements with a 2D (area) detector.

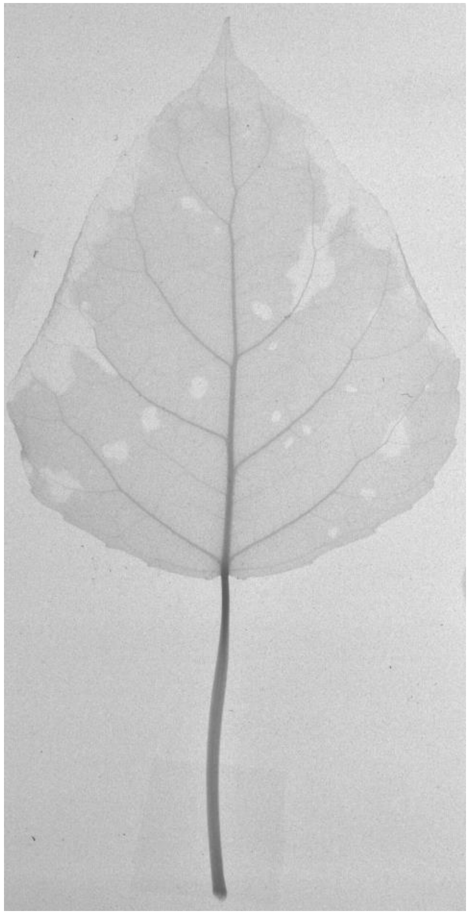
- **Quantification**: Any method used to convert raw image data (grey levels, photon stimulated luminescence, …) into a physical quantity i.e. : length (thickness), area, volume, transmission, attenuation coefficient, phase shift value, dark-field signal, material content, …

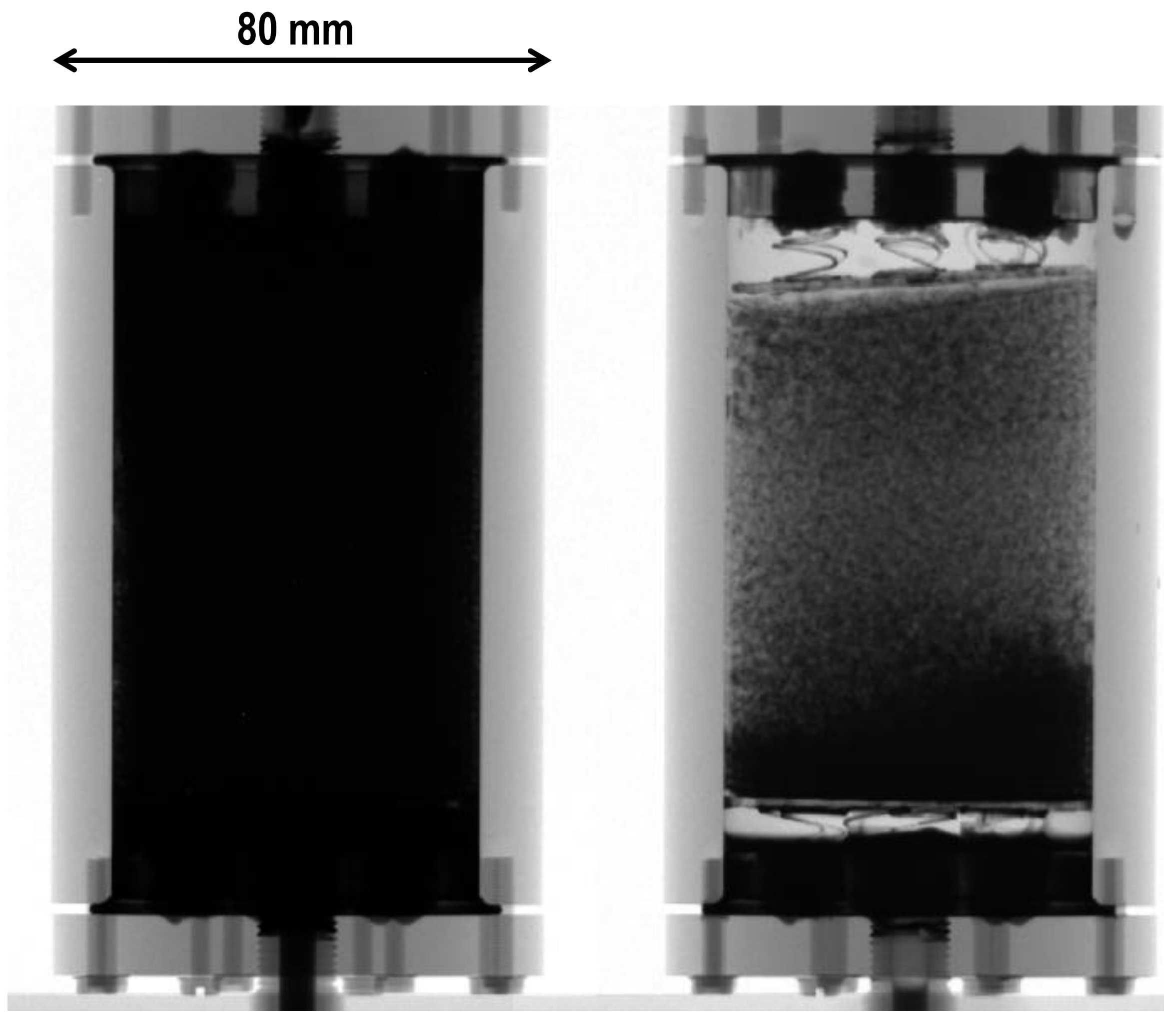
- **Image Correction**: Any method used to remove disturbing effects from the raw images i.e. denoising, offset correction (e.g. dark-current), flat-field correction, intensity normalization, …

- **Neutron radiation**: Can be described as particles with the Boltzmann neutron transport equation for the phase space distribution function $\Phi(\mathbf{r},\mathbf{k},t)$ and/or neutron wave propagation using the Schrödinger equation for neutron wave function ψ.

- **Exponential law of radiation attenuation**: Beer-Lambert law. Can be derived from the Boltzmann neutron transport equation for $\Phi(\mathbf{r},\mathbf{k},t)$. It applies only with restrictions discussed in the introductory lecture by M. Morgano.

High and low transmission & contrast





Weak contrast

No penetration

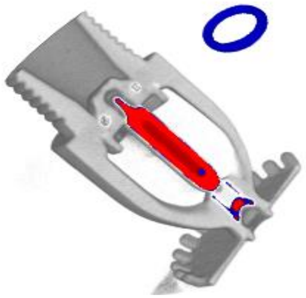
Information from neutron transmission tomography

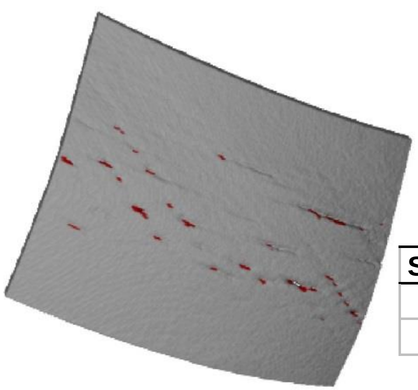
3D Volume data set with (arbitrarily scaled) linear attenuation value $\Sigma(x,y,z)$ distribution

Qualitative information: sample morphology as seen by neutrons, material discrimination, defects, PICTURES

Quantitative information i.e. NUMBERS

- Geometrical information e.g. object size [cm^3], wall thickness [cm], …
- Atom/Molecule densities [cm^{-3}], fluid concentrations, …



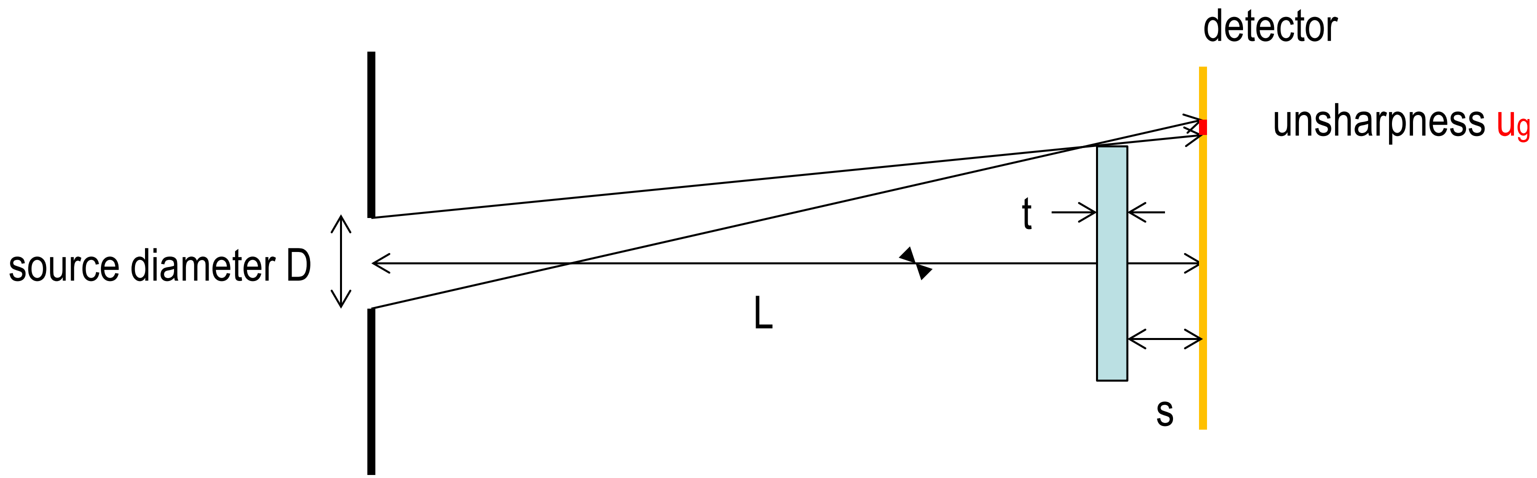


Slice	x [mm]	y [mm]	z [mm]	bot (x)	bot (y)	bot (z)	top (x)	top (y)	top (z)	thickness
67	7.33	2.44	8.91	7	1.85	8.84	7.52	2.38	8.84	0.20 - 0.60
69	7.33	2.71	9.17	7	1.85	9.11	7.66	2.64	9.11	0.20 - 0.60

Geometrical information: Location and size of fissures in rubber bellow with VGStudio Max ® measurement tool.

Geometrical unsharpness inherent to divergent beam

$$u_g = \frac{s}{L/D}$$



Flux intensity at detector

$$\Phi = S_f \frac{1}{(\frac{L}{D})^2}$$

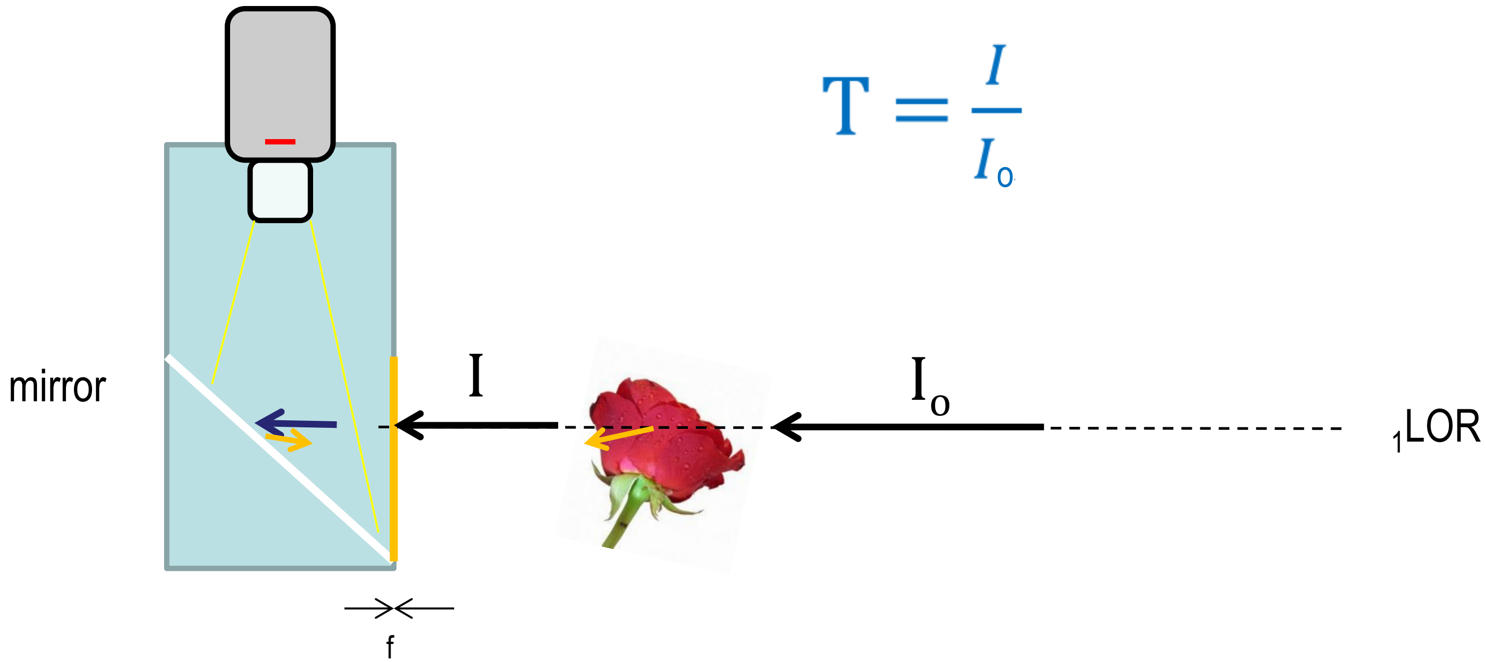
$s \ll L$

$L \gg D$

In general: u_g = function(t)

Transmission measured with area detector

camera area detector



$$T = \frac{I}{I_o}$$

thin scintillator

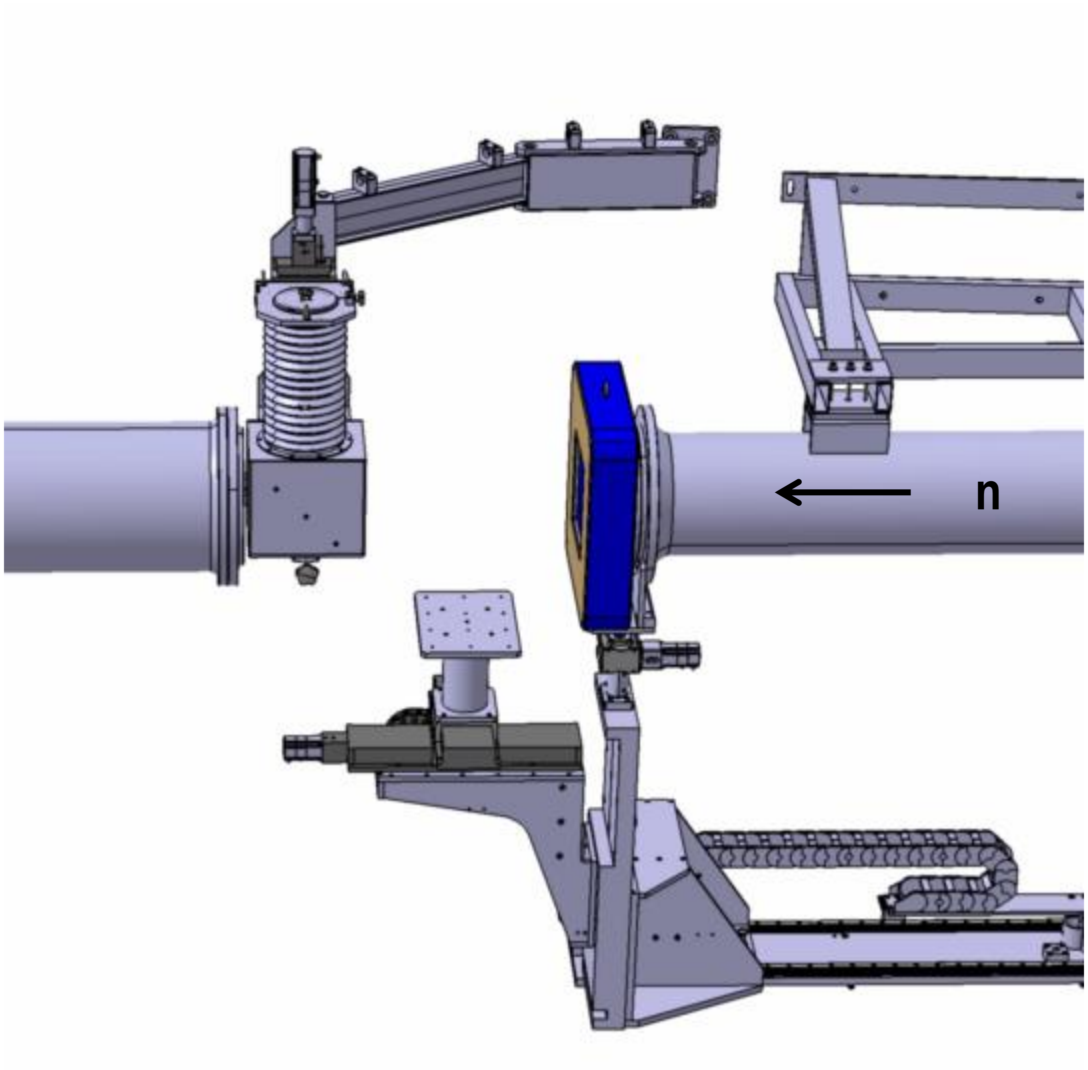
$$A = 1 - e^{-\Sigma f}$$

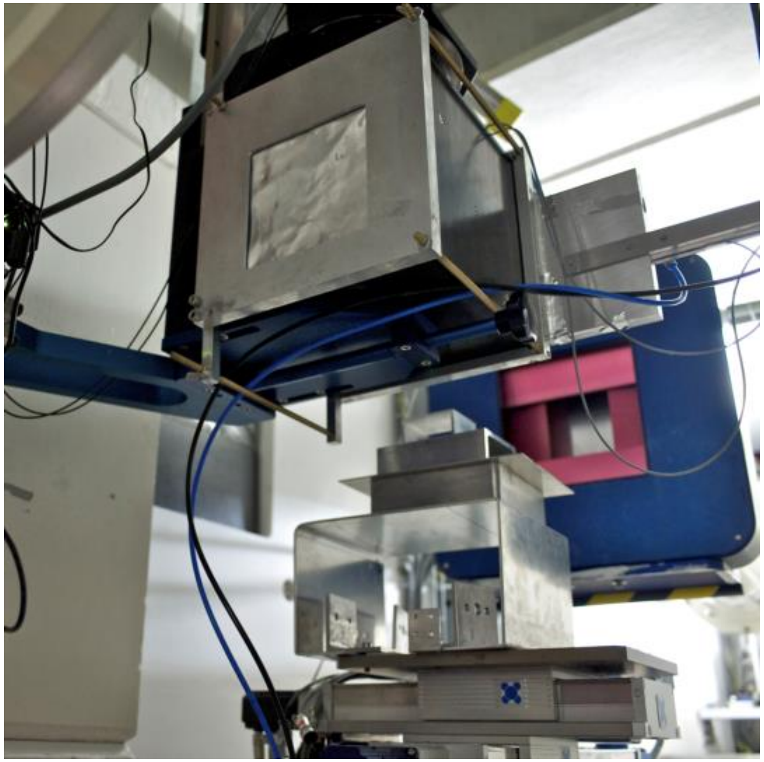
sample scattering

detector back scattering

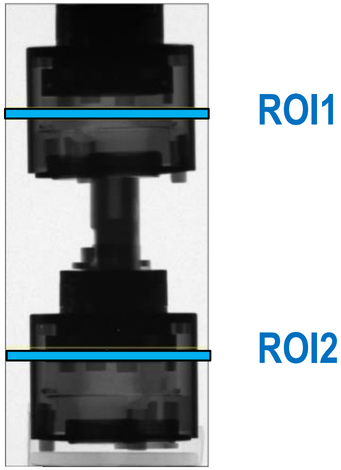
1 LOR: line of response

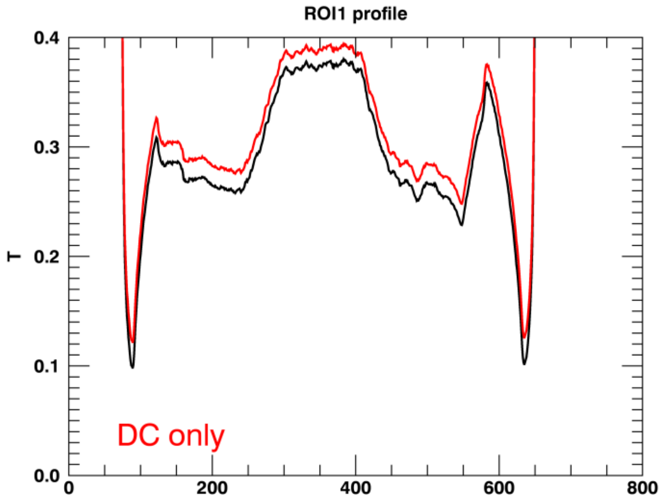
Typical camera detector setup: NEUTRA Pos 2

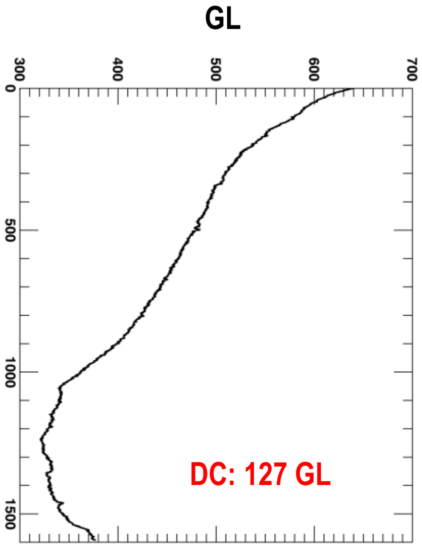


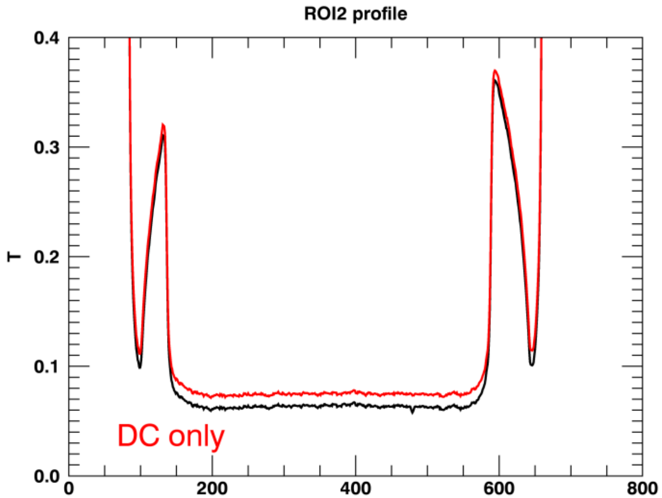


Detector backscattering estimate with black body

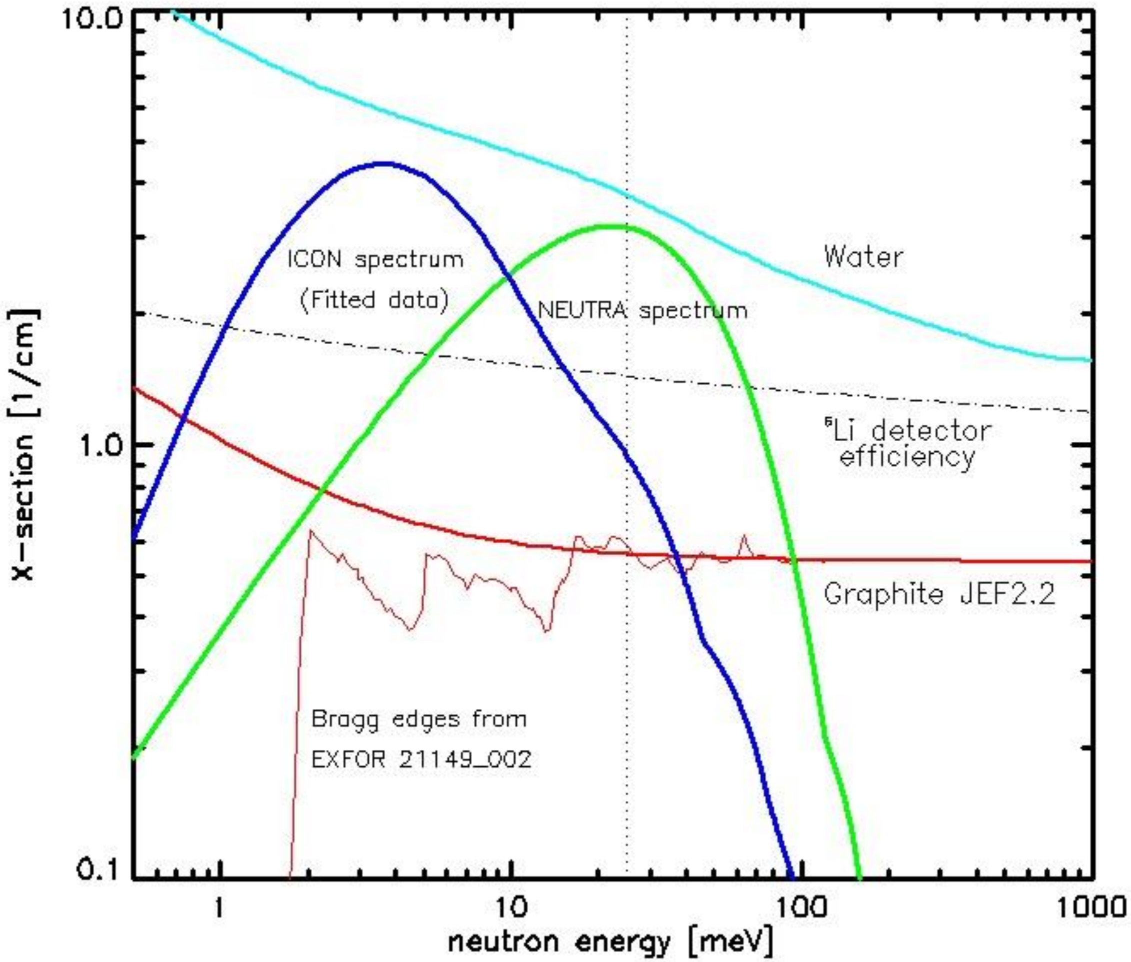








Cold and thermal neutron energy spectra



Requirements for quantitative neutron tomography ?

In order to be quantitative the exponential law of neutron attenuation should hold for every line of response !

$$I(\rho,\theta) = I_o \, e^{-\int_{-\infty}^{+\infty} \Sigma(x,y) ds} \qquad (1)$$

Main violations are due to (see introductory presentation M Morgano):

1. Scattering of neutrons in the sample and in the detector.
2. Use of a polychromatic neutron beam, effect of „beam hardening“.

Spectral effects

Let's redefine the uncollided neutron flux per energy interval as I(x,E). Then it can be shown, that for every small energy interval dE the exponential attenuation law is valid:

$$I(x,E)dE = I_o(E)dE \exp[-\Sigma(E)\, x] \tag{1}$$

For a known incident energy spectrum $I_o(E)$ we can average over energy

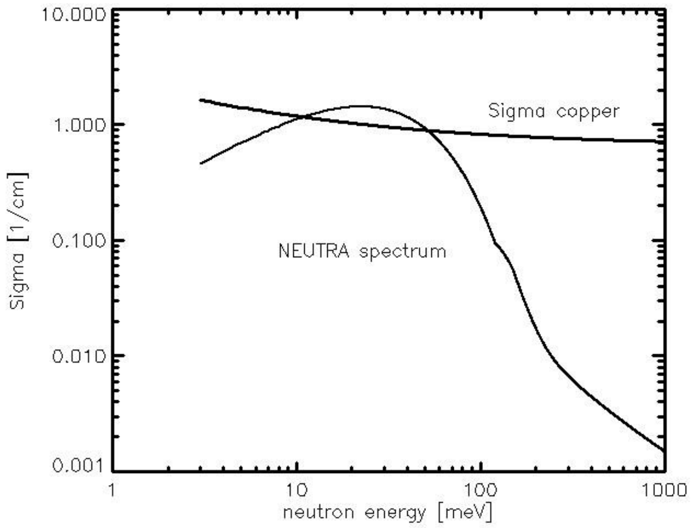
$$< I(t) > = \int_{E_{\min}}^{E_{\max}} I(t,E)\, dE = \int_{E_{\min}}^{E_{\max}} I_o(E) \exp[-\Sigma(E)\, t]\; dE \tag{2}$$

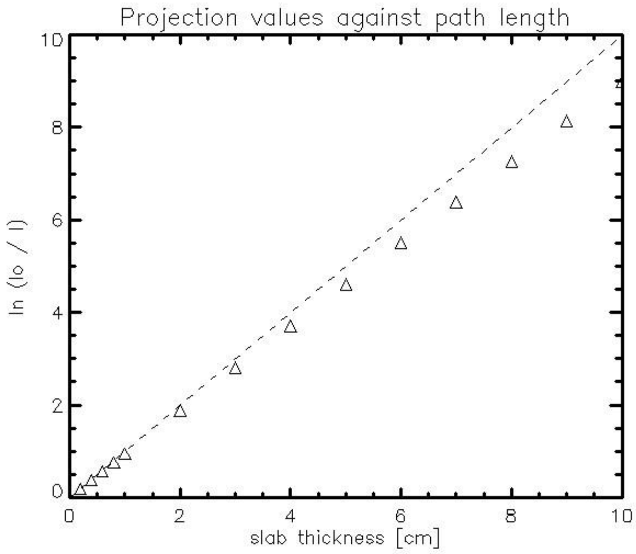
We can calculate the total intensity of the uncollided exiting beam after traversing the distance t in a slab, by integrating over the whole energy spectrum e.g. with E_{min}= 3 meV, E_{max}= 1 eV.

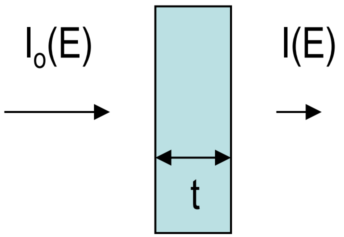
$$< I(t) > = < I_o > \exp[- < \Sigma > t] \quad \therefore \quad < \Sigma > = \frac{-\ln \dfrac{< I(t) >}{< I_o >}}{t} \tag{3}$$

Using equation (2) and the known energy dependence of the cross section we can calculate an energy averaged cross section <Σ>, that would be measured by an ideal detector registering the uncollided flux component only. This spectrum averaged effective cross section <Σ> is calculated from equation (3).

Beam hardening in neutron tomography ?



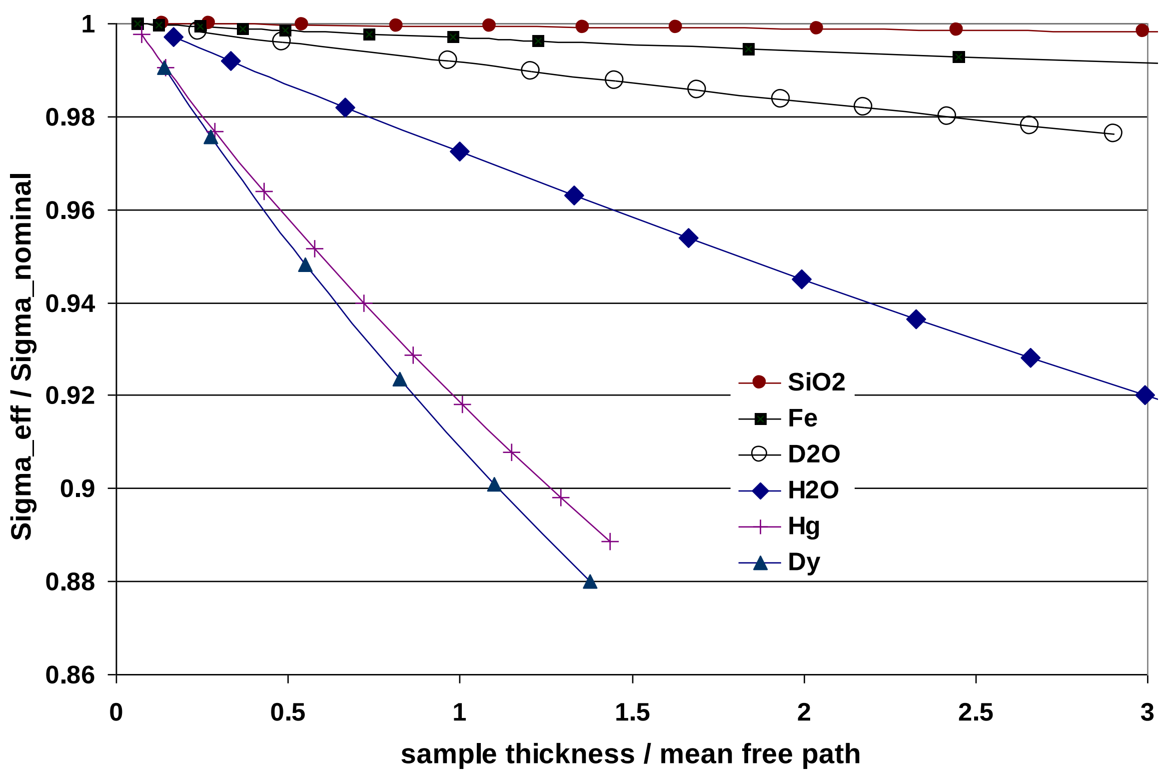


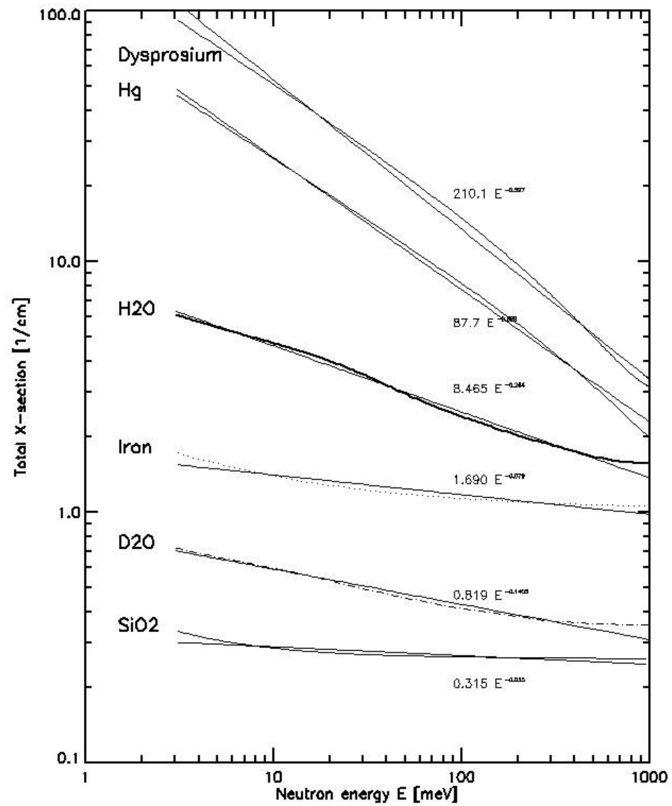


Effective <Σ> value depends on material penetration length t !

$$< \Sigma > = \frac{-\ln \frac{< I(t) >}{< I_o >}}{t}$$

Magnitude of beam hardening in a thermal neutron-spectrum for selected elements and compounds

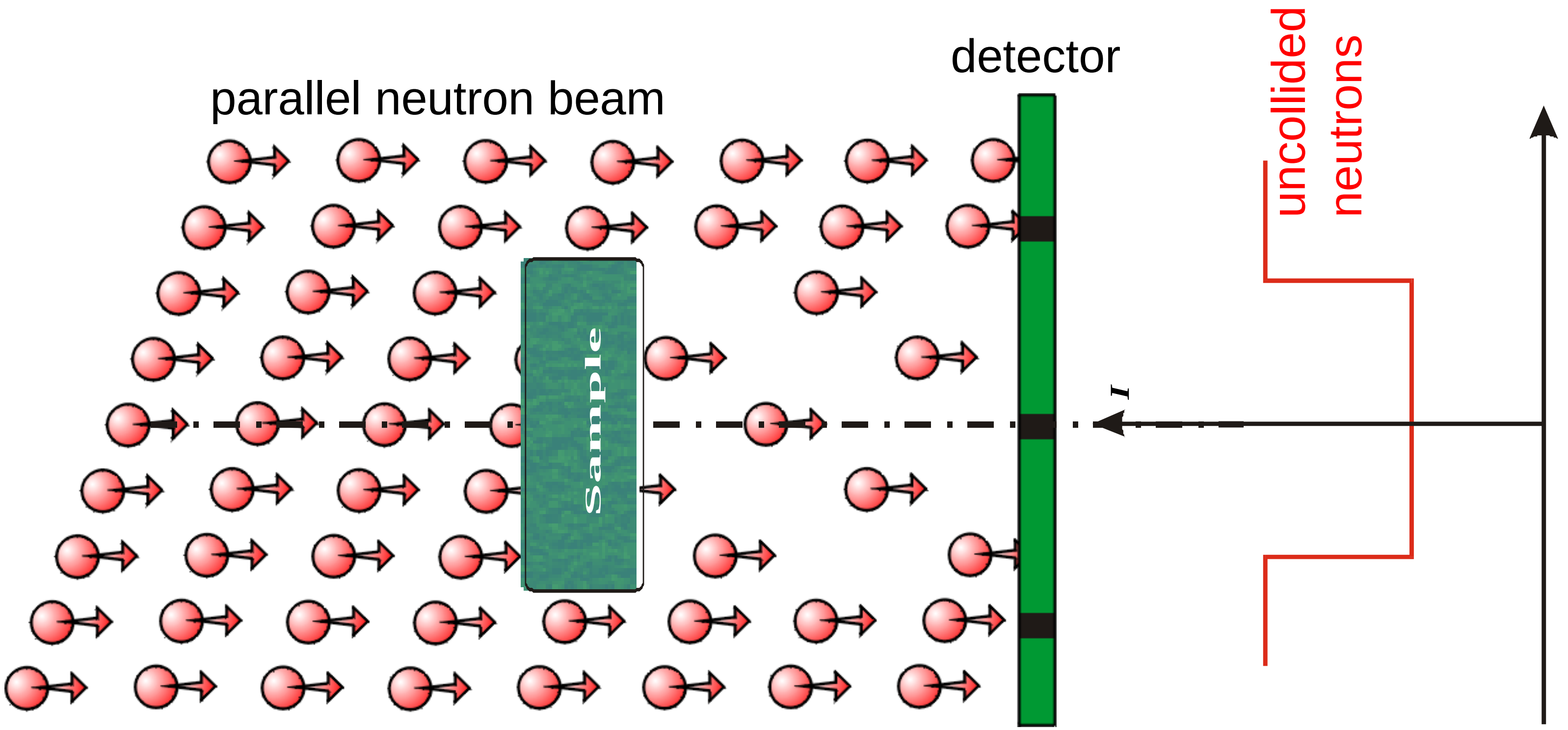




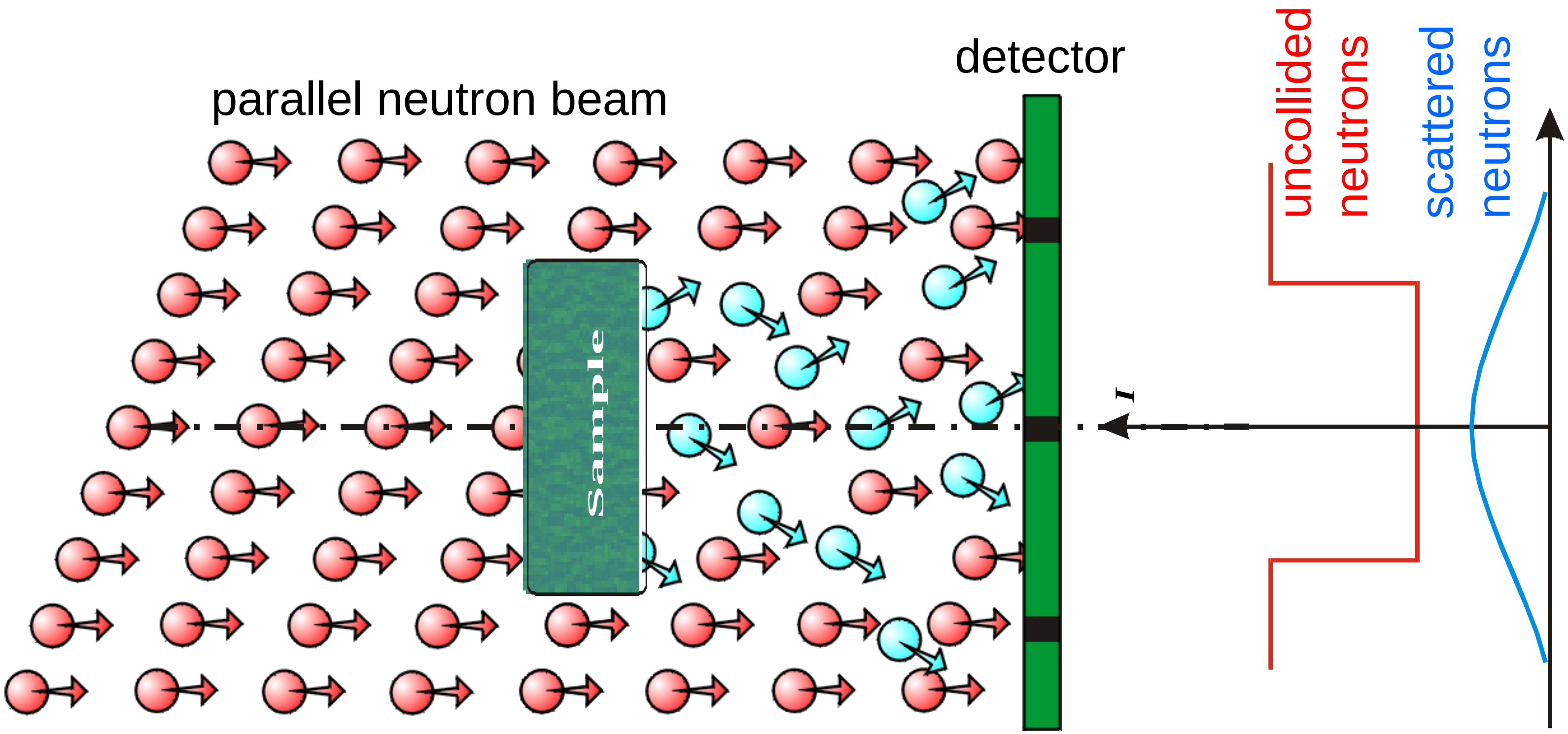
Effect not negligible for neutron absorber materials and H_2O !

Correlation: beam hardening increases with steepness of $\Sigma(E)$

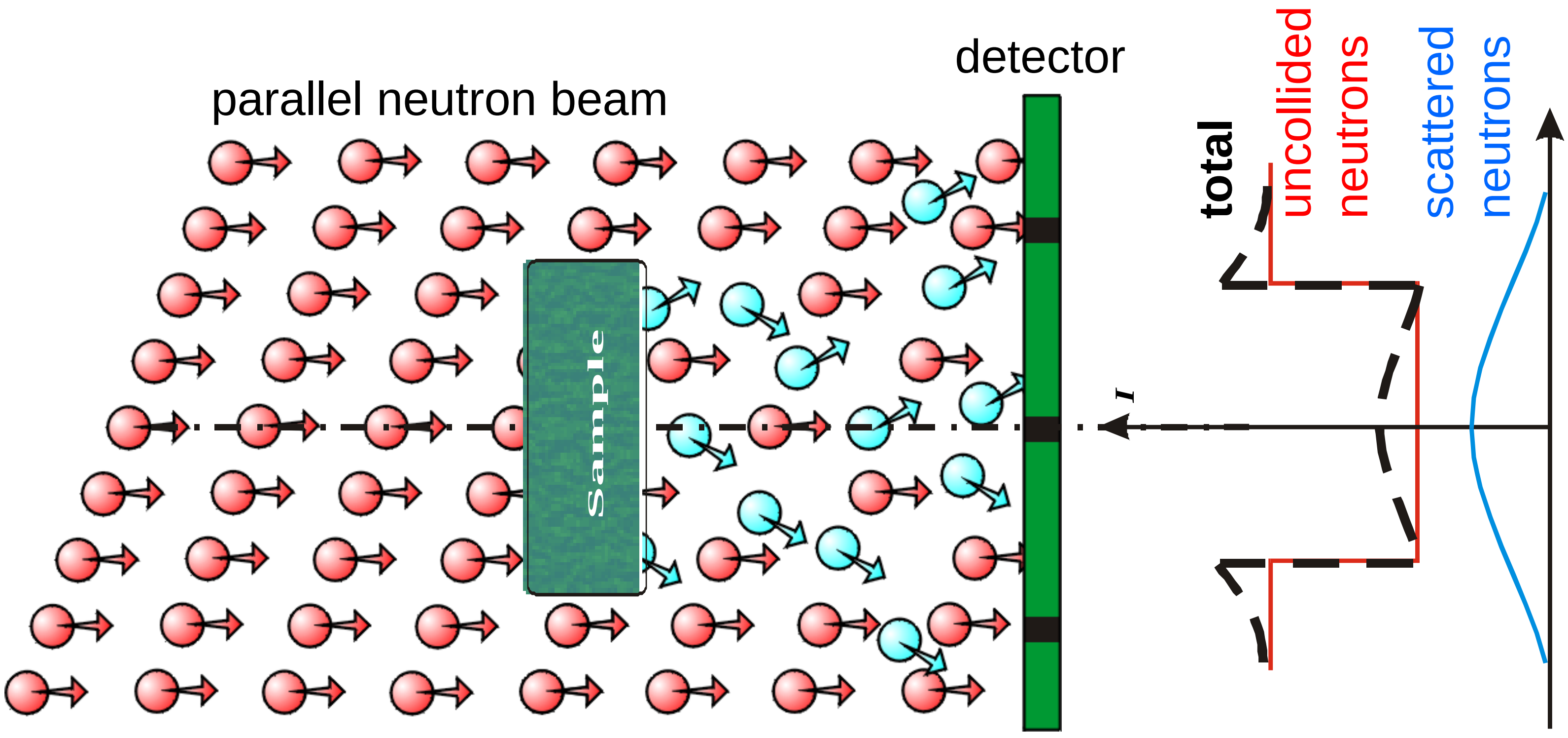
Neutron scattering – Build-up effect in NR



Neutron scattering – Build-up effect in NR



Neutron scattering – Build-up effect in NR



Thesis R Hassanein 2006: QNI correction tool

DISS. ETH NO. 16809

CORRECTION METHODS FOR THE
QUANTITATIVE EVALUATION OF
THERMAL NEUTRON TOMOGRAPHY

A dissertation submitted to the

SWISS FEDERAL INSTITUTE OF TECHNOLOGY ZURICH

for the degree of

Doctor of Sciences

presented by

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Dr. Eberhard Lehmann, co-examiner
Prof. Dr. Peter Böni, co-examiner

2006

Program implemented in IDL
Executable running with IDL virtual machine.
QNI version 1.0 (2006) available on request from PSI.
No updates, no support, no helpline !

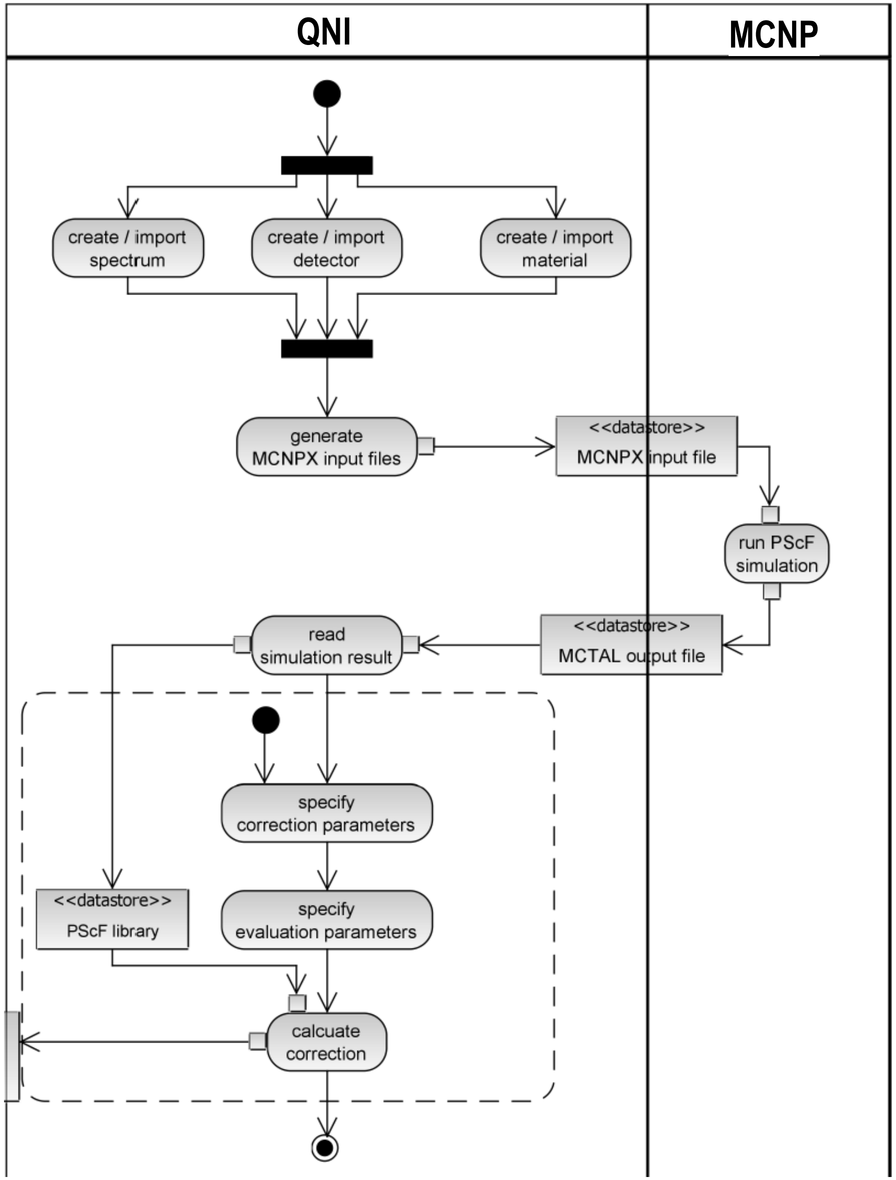
http://e-collection.ethbib.ethz.ch/cgi-bin/show.pl?type=diss&nr=16809

QNI Framework

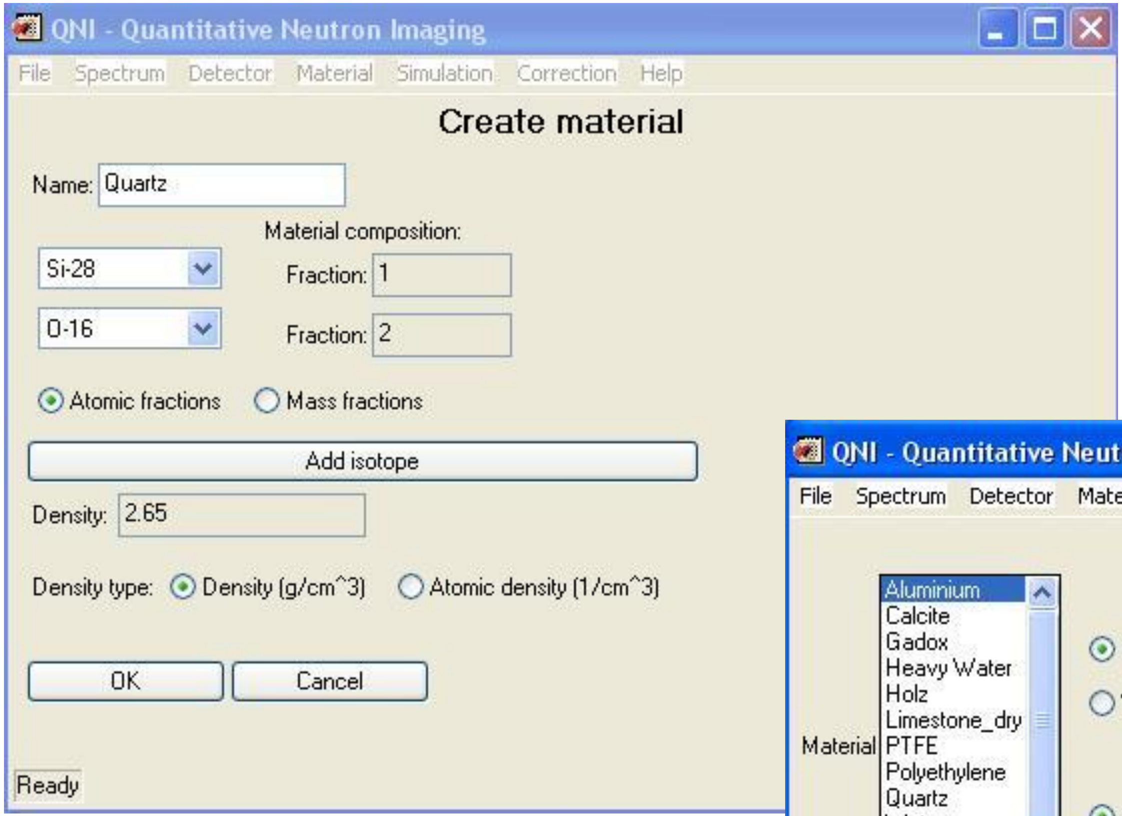
Facility, scintillator and sample material properties

Calculate point spread function parameters with MCNP

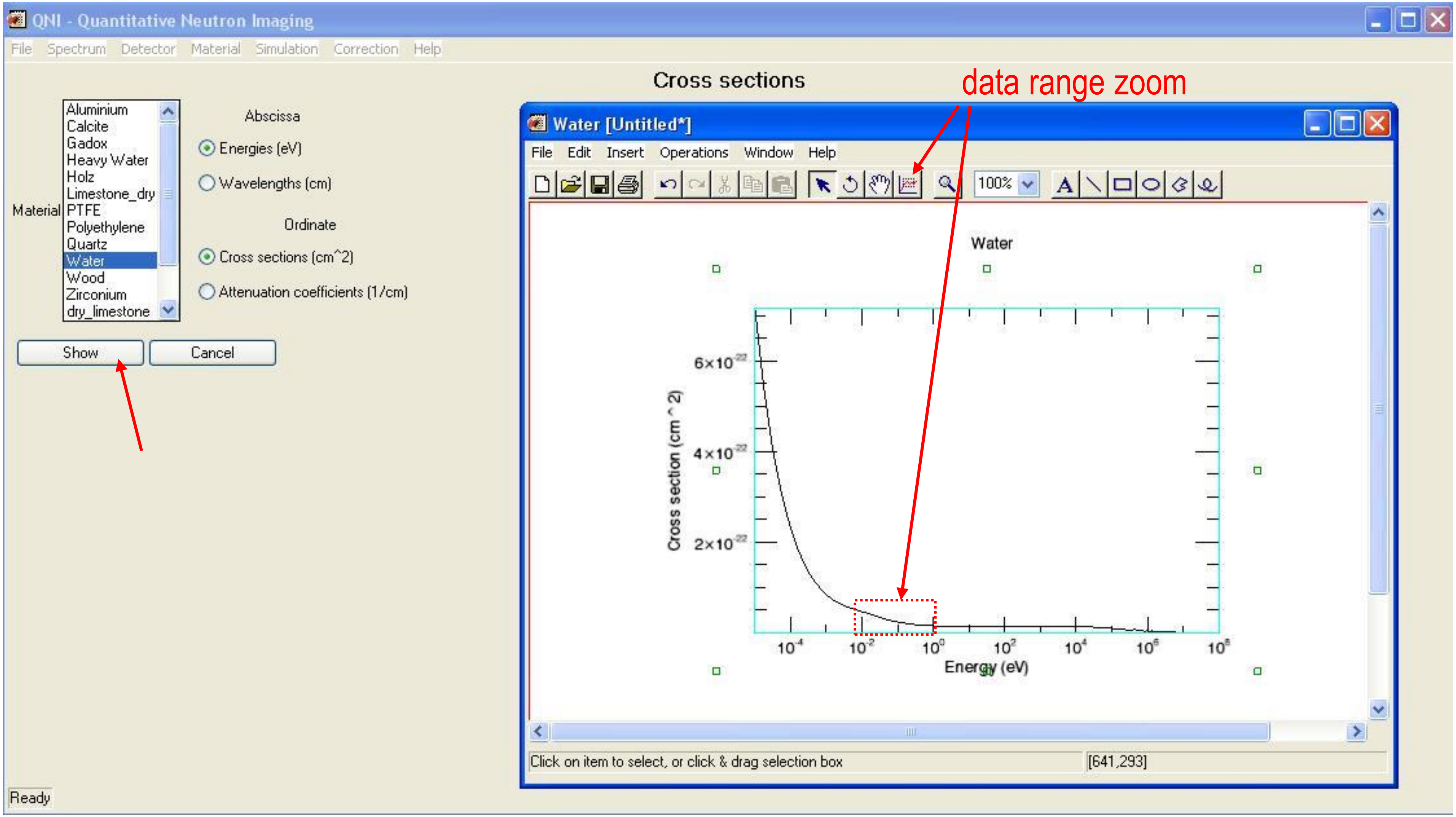
Iteratively calculate corrections considering detector background & sample scattering



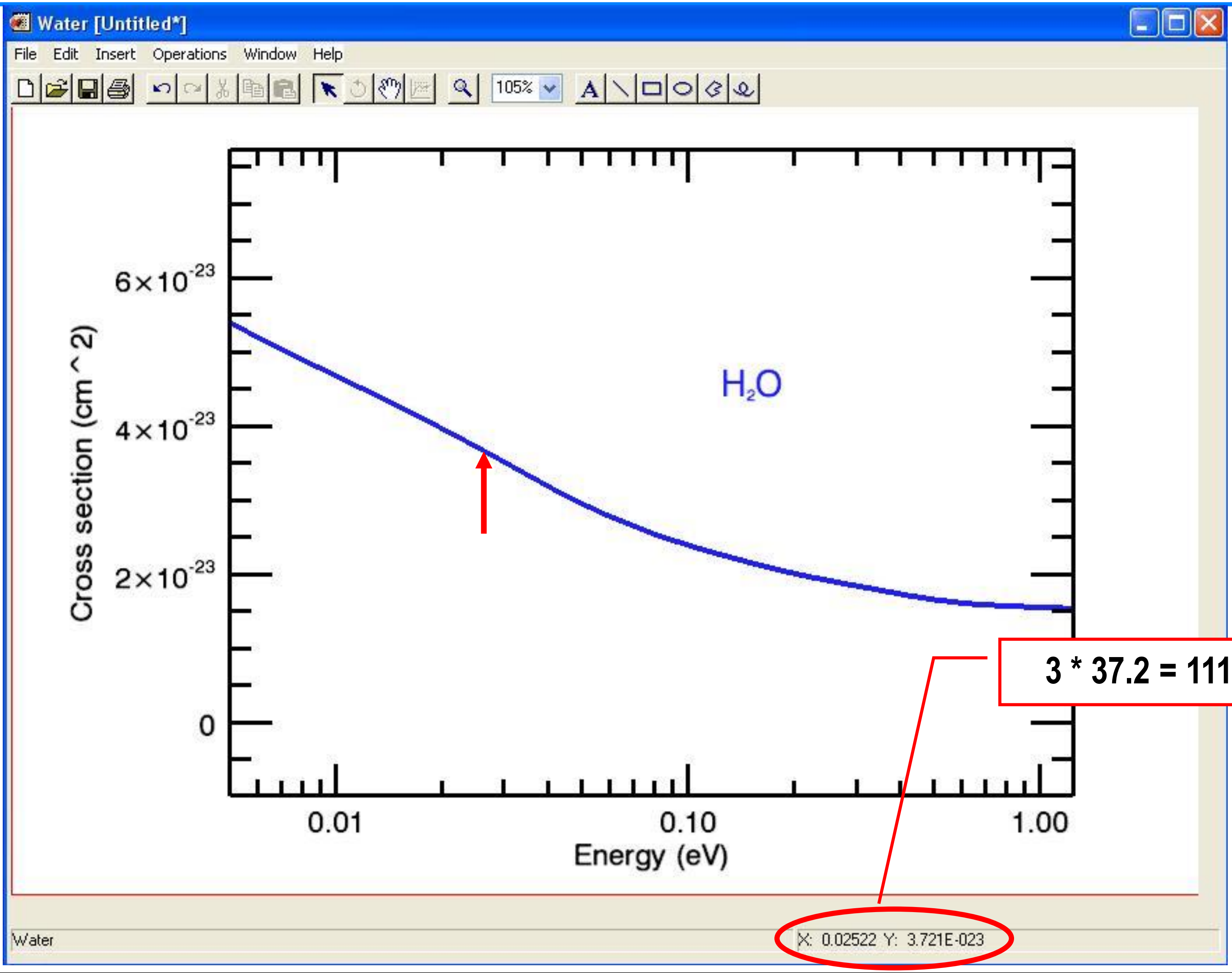
QNI: Material cross section library (data from MCNPX)



QNI: Quantitative Neutron Imaging correction tool

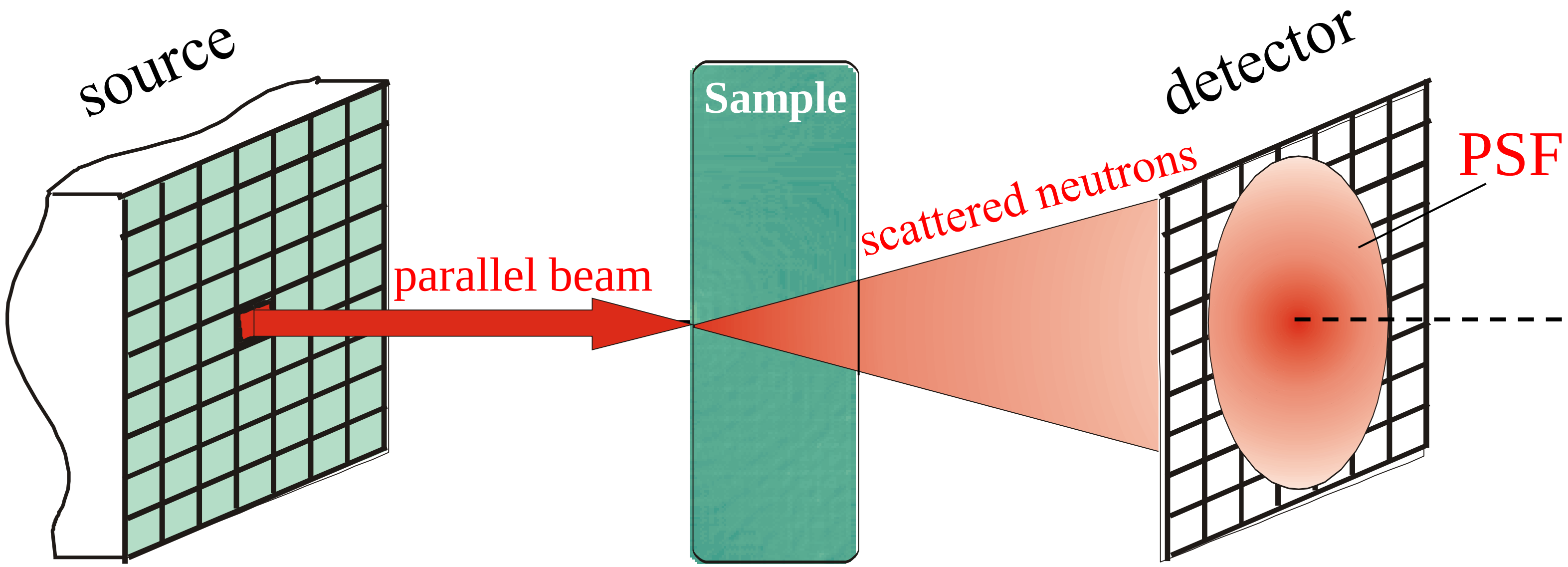


QNI: H_2O cross section at 25 [meV]



3 * 37.2 = 111.6 [b]

Monte Carlo simulations – Model



Monte Carlo simulation – Model

Neutron spectrum

Beam divergence

Sample material

Material thickness

Sample-detector distance

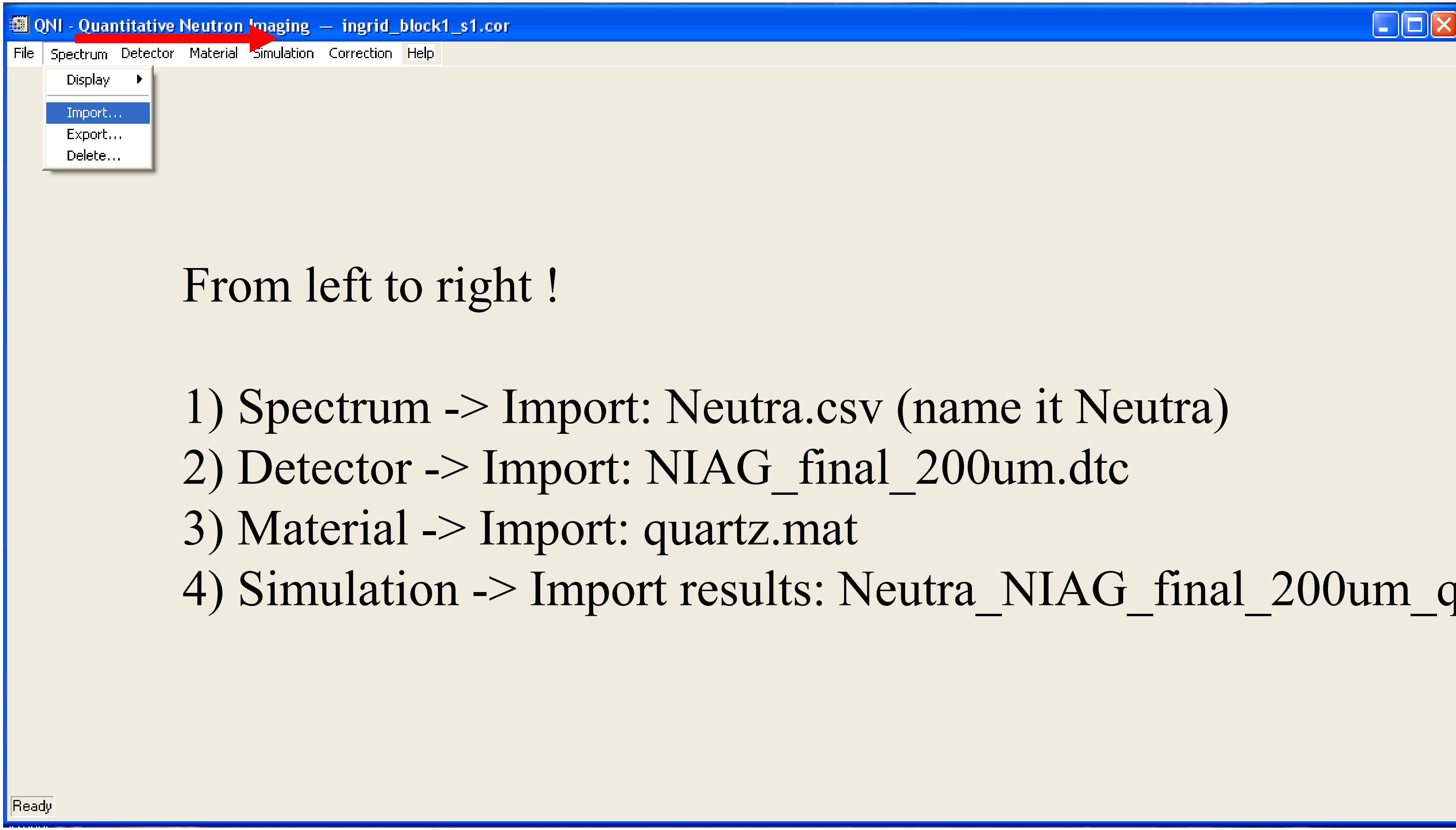
→ MCNP →

PSF

or

PScF

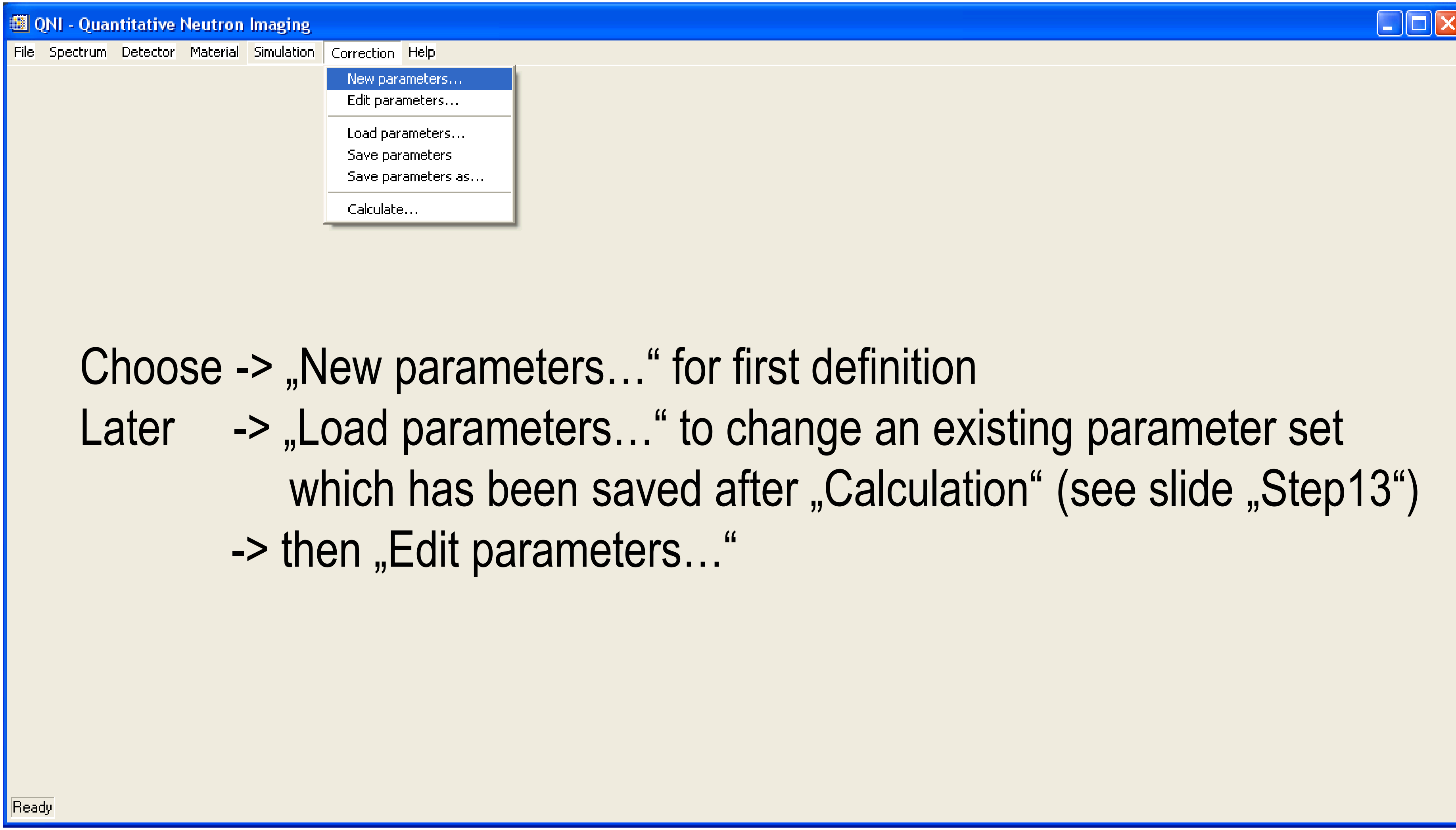
Setting up the problem



From left to right !

1) Spectrum -> Import: Neutra.csv (name it Neutra)
2) Detector -> Import: NIAG_final_200um.dtc
3) Material -> Import: quartz.mat
4) Simulation -> Import results: Neutra_NIAG_final_200um_qua

Set up correction parameters

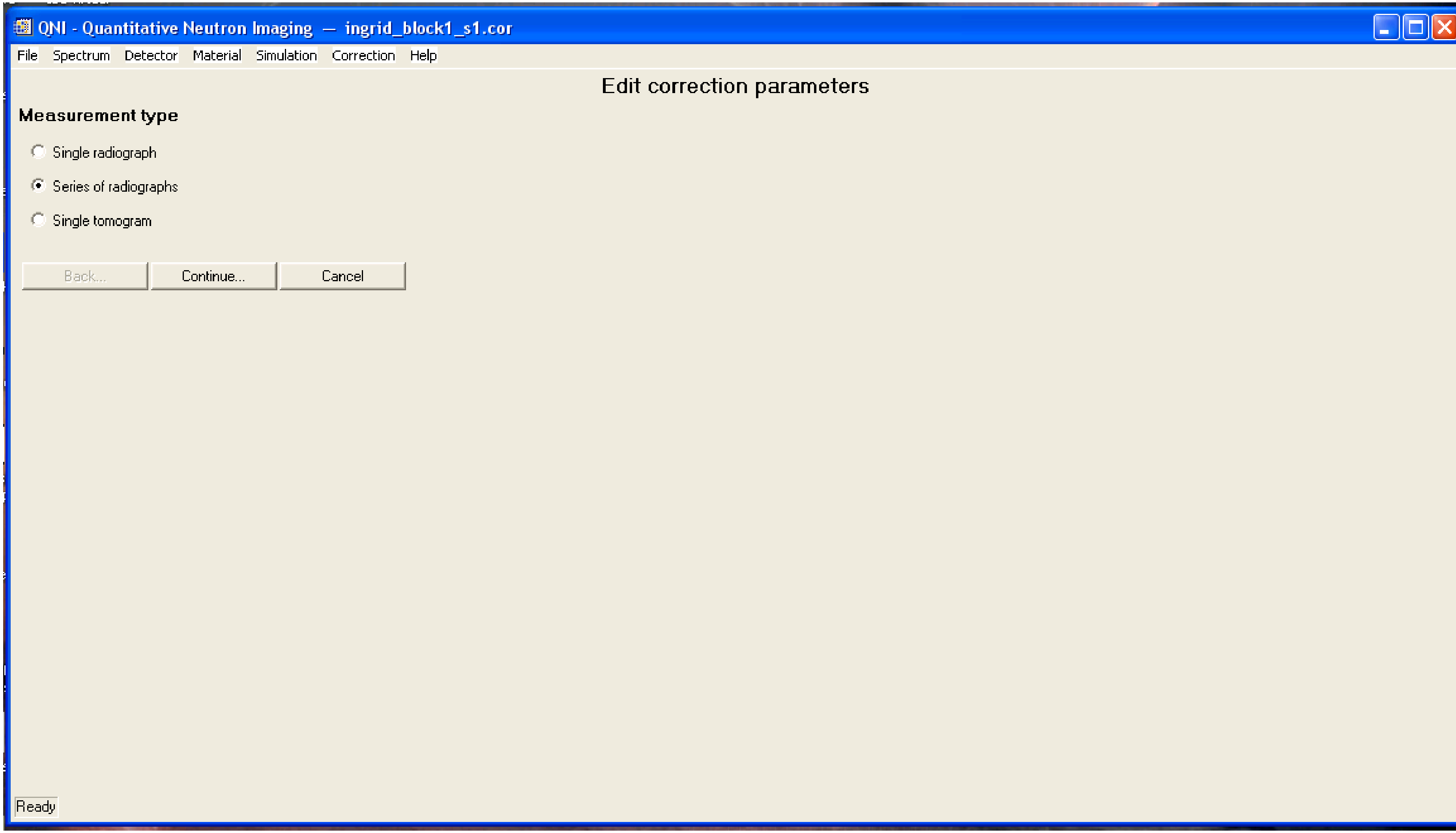


Choose -> „New parameters…“ for first definition

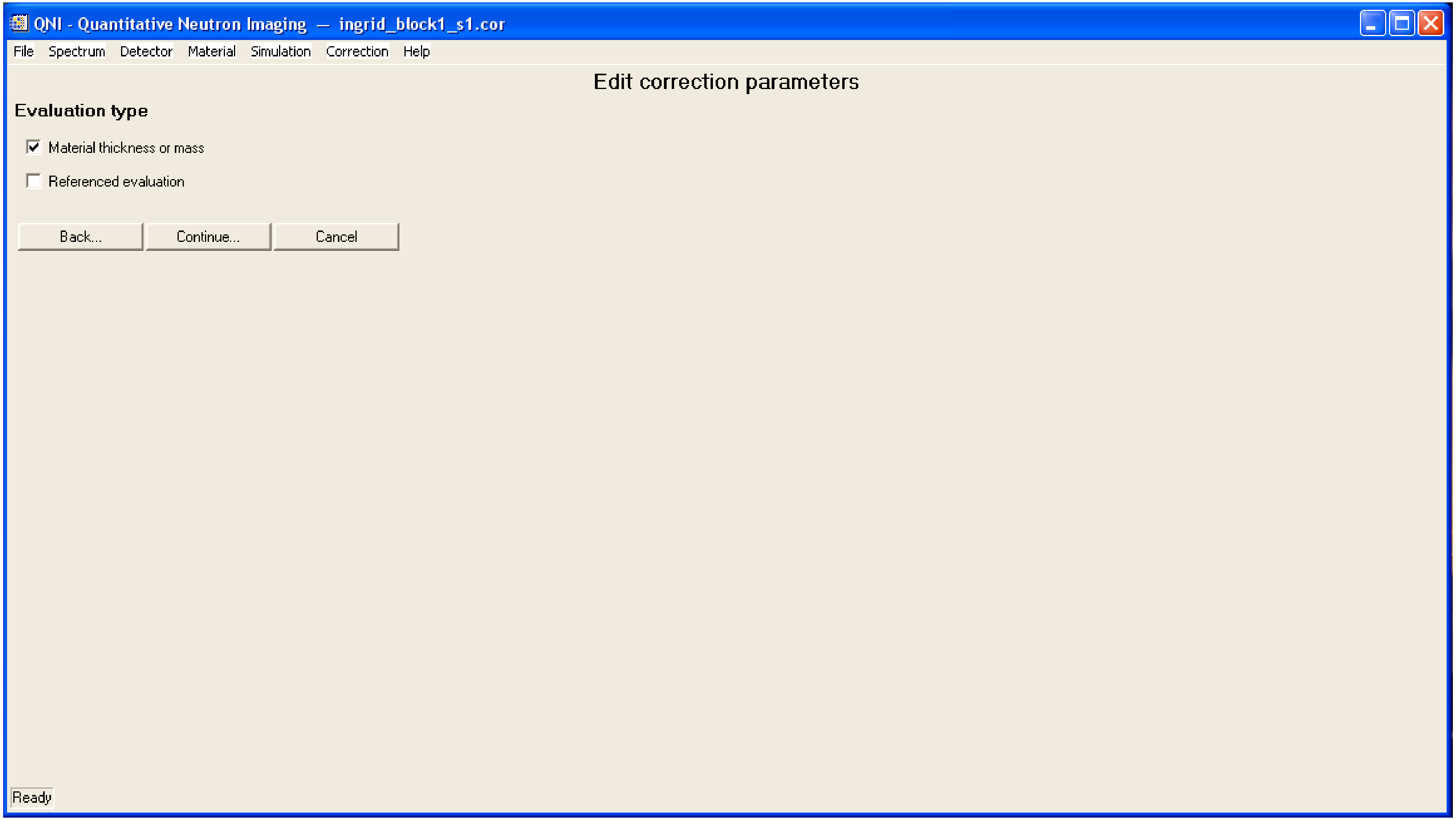
Later -> „Load parameters…“ to change an existing parameter set which has been saved after „Calculation“ (see slide „Step13“)

-> then „Edit parameters…“

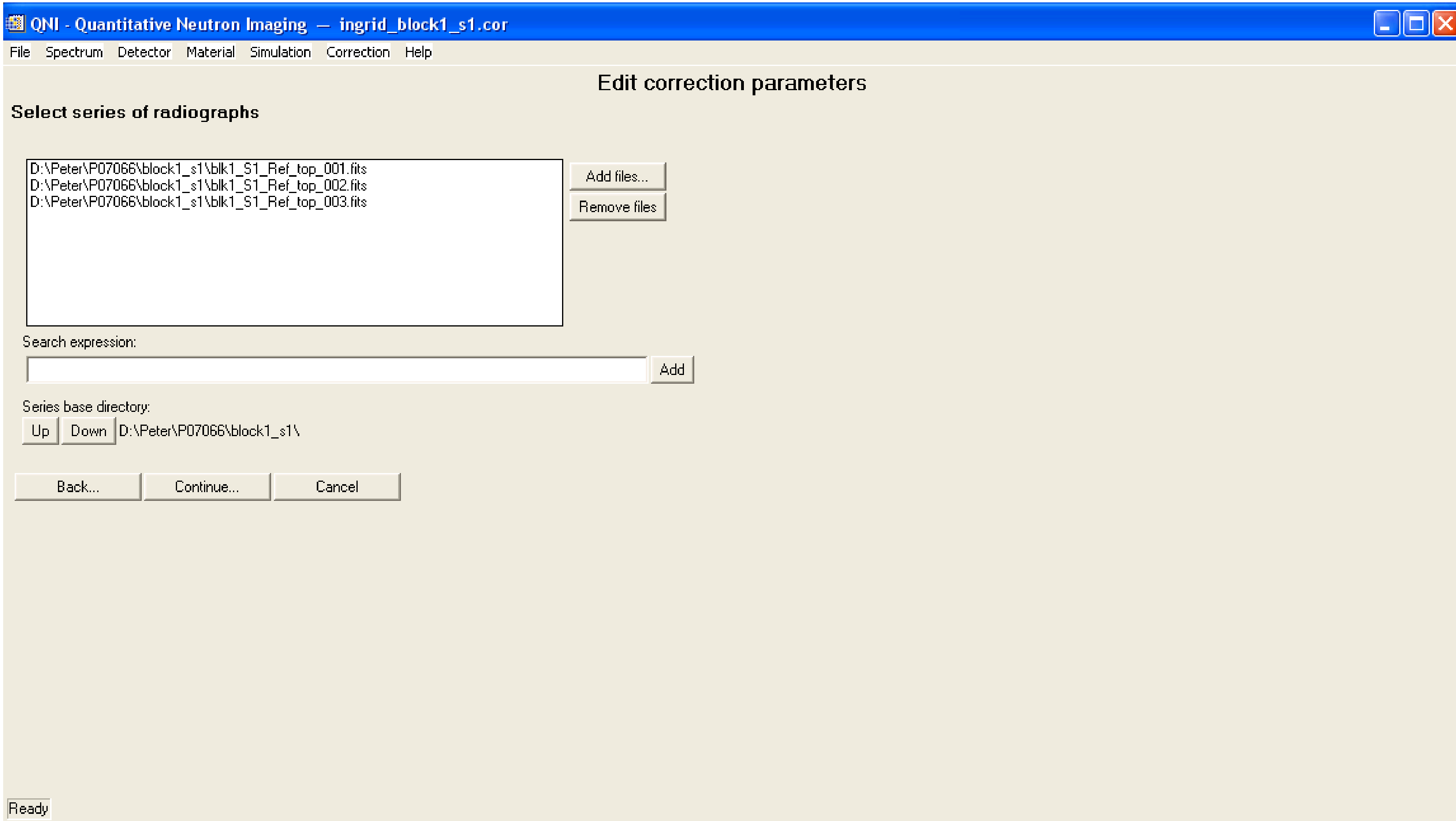
Correction parameters step by step



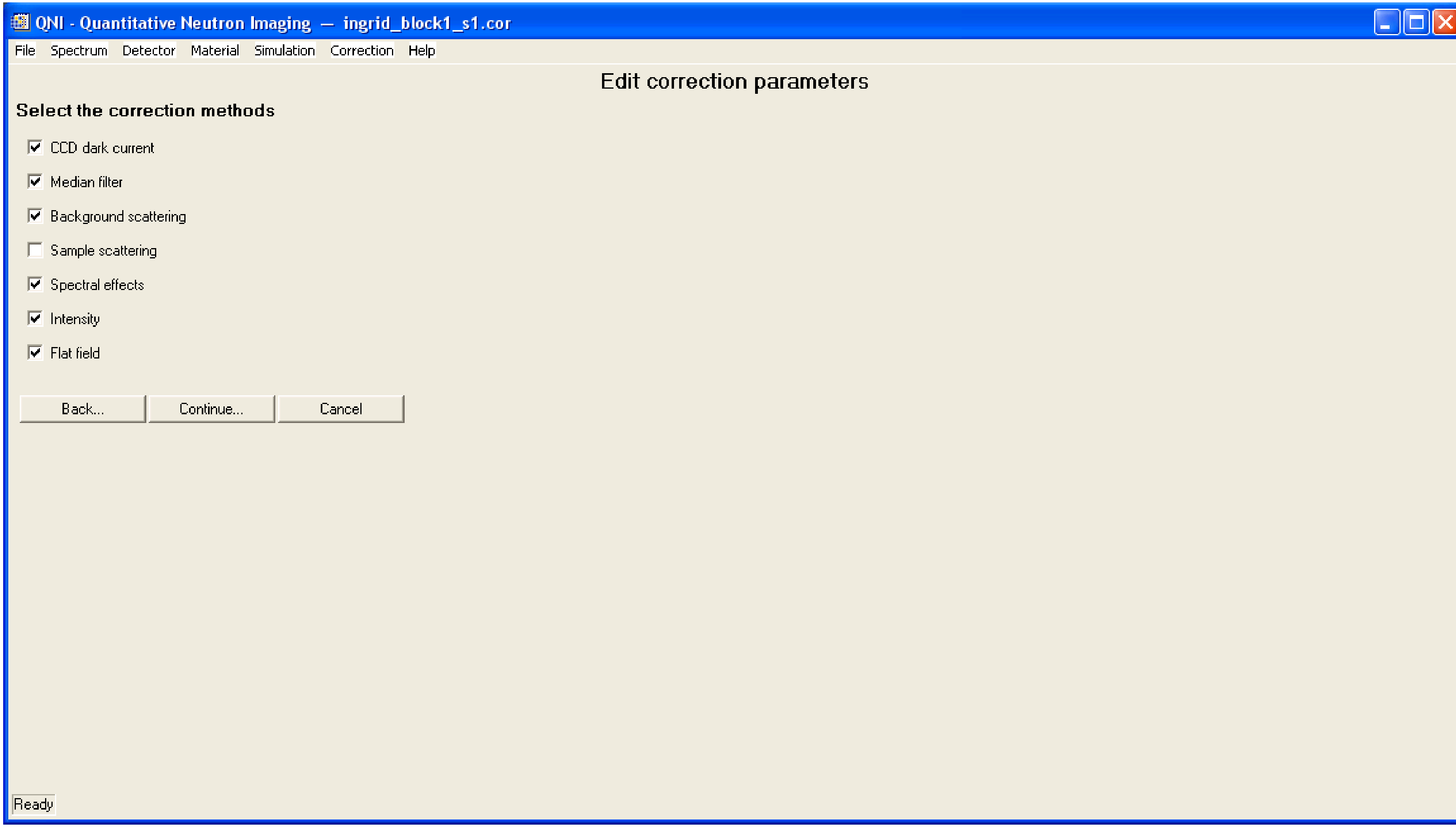
Step 2


QNI - Quantitative Neutron Imaging — ingrid_block1_s1.cor
File Spectrum Detector Material Simulation Correction Help
Edit correction parameters
Evaluation type
Material thickness or mass
Referenced evaluation
Back...
Continue...
Cancel
Ready

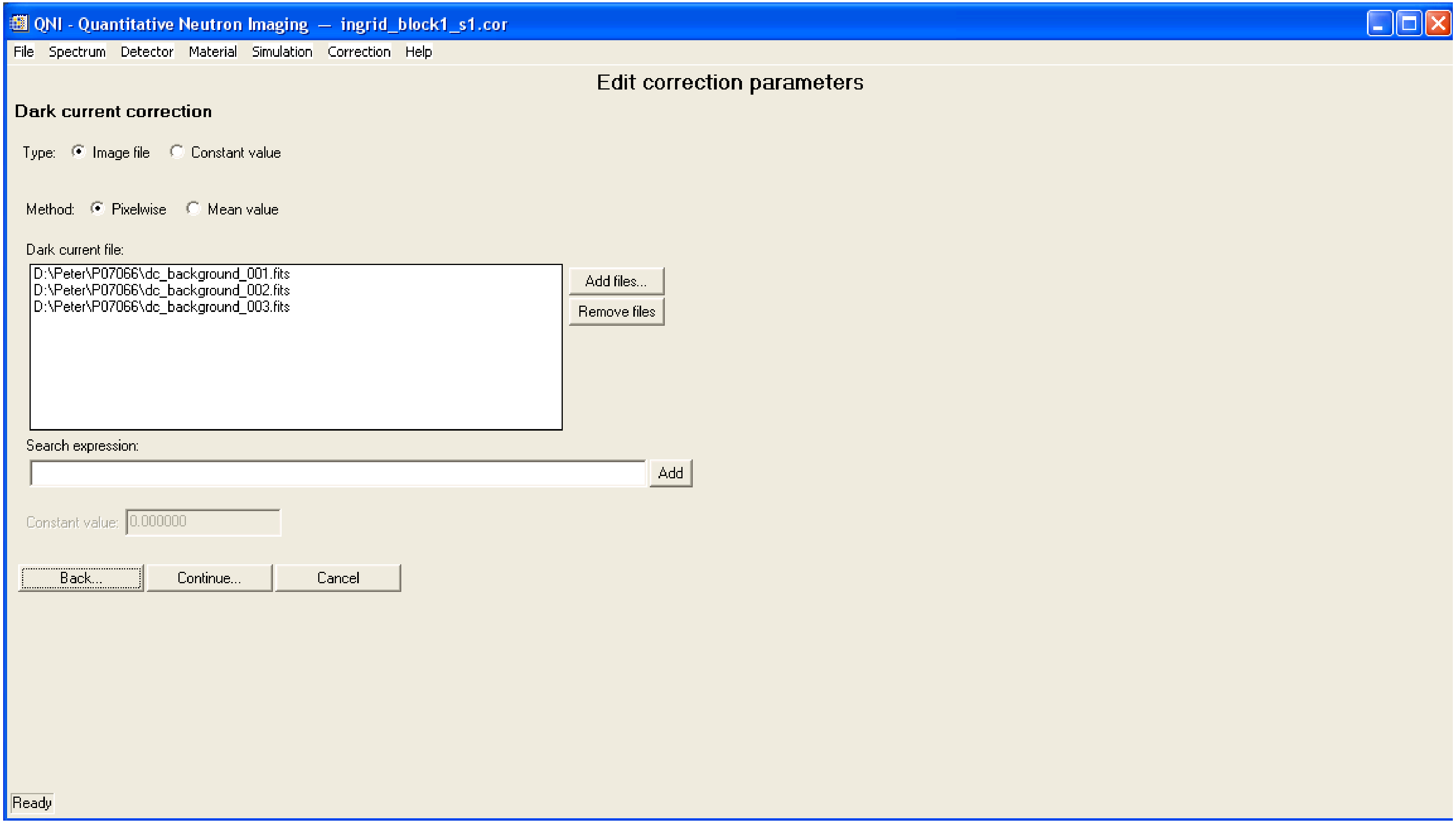
Step 3


QNI - Quantitative Neutron Imaging — ingrid_block1_s1.cor
File Spectrum Detector Material Simulation Correction Help
Edit correction parameters
Select series of radiographs
D:\Peter\P07066\block1_s1\blk1_S1_Ref_top_001.fits
D:\Peter\P07066\block1_s1\blk1_S1_Ref_top_002.fits
D:\Peter\P07066\block1_s1\blk1_S1_Ref_top_003.fits
Add files...
Remove files
Search expression:
Add
Series base directory:
Up
Down
D:\Peter\P07066\block1_s1\
Back...
Continue...
Cancel
Ready

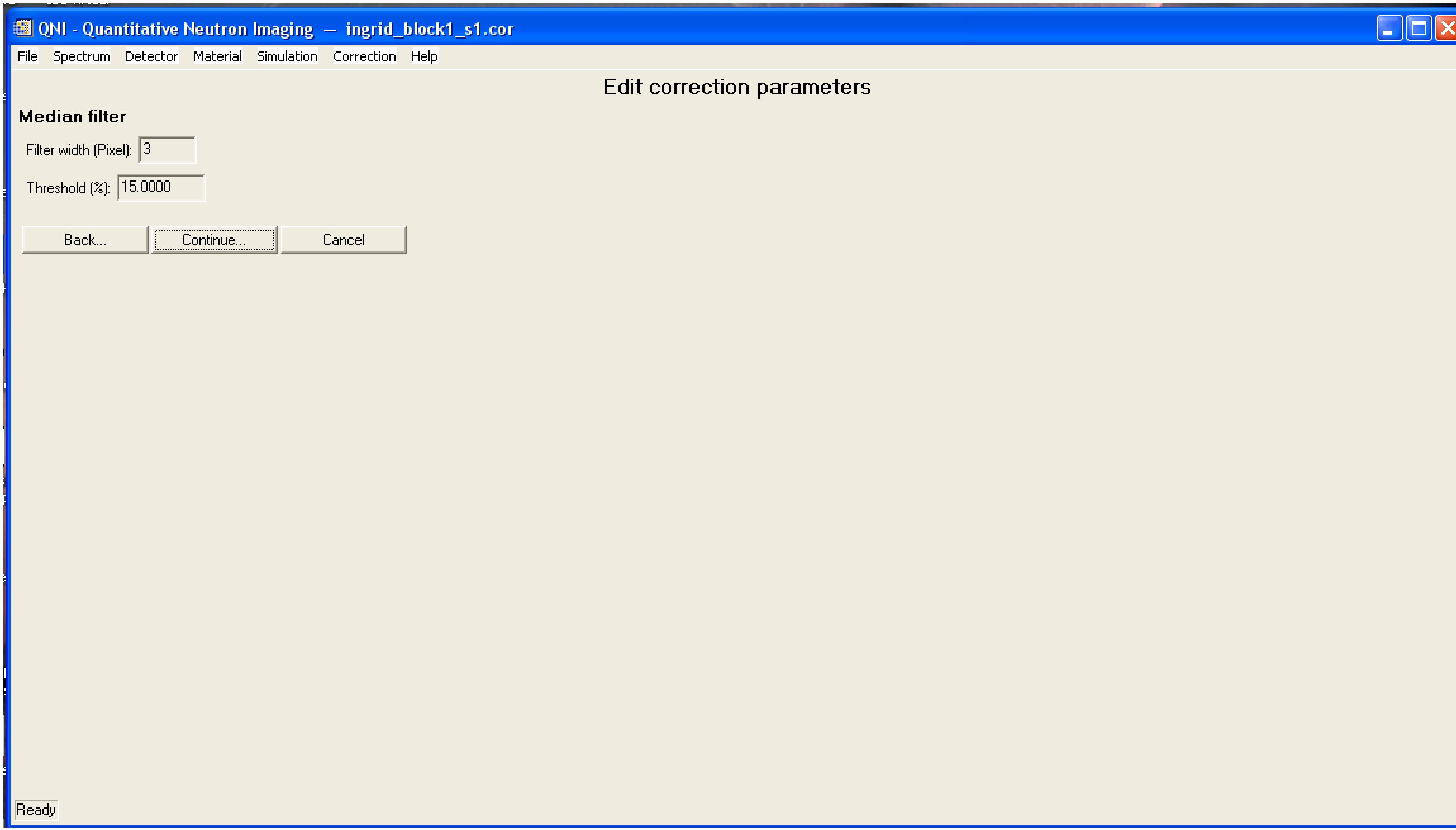
Step 4


QNI - Quantitative Neutron Imaging — ingrid_block1_s1.cor
File Spectrum Detector Material Simulation Correction Help
Edit correction parameters
Select the correction methods
CCD dark current
Median filter
Background scattering
Sample scattering
Spectral effects
Intensity
Flat field
Back...
Continue...
Cancel
Ready

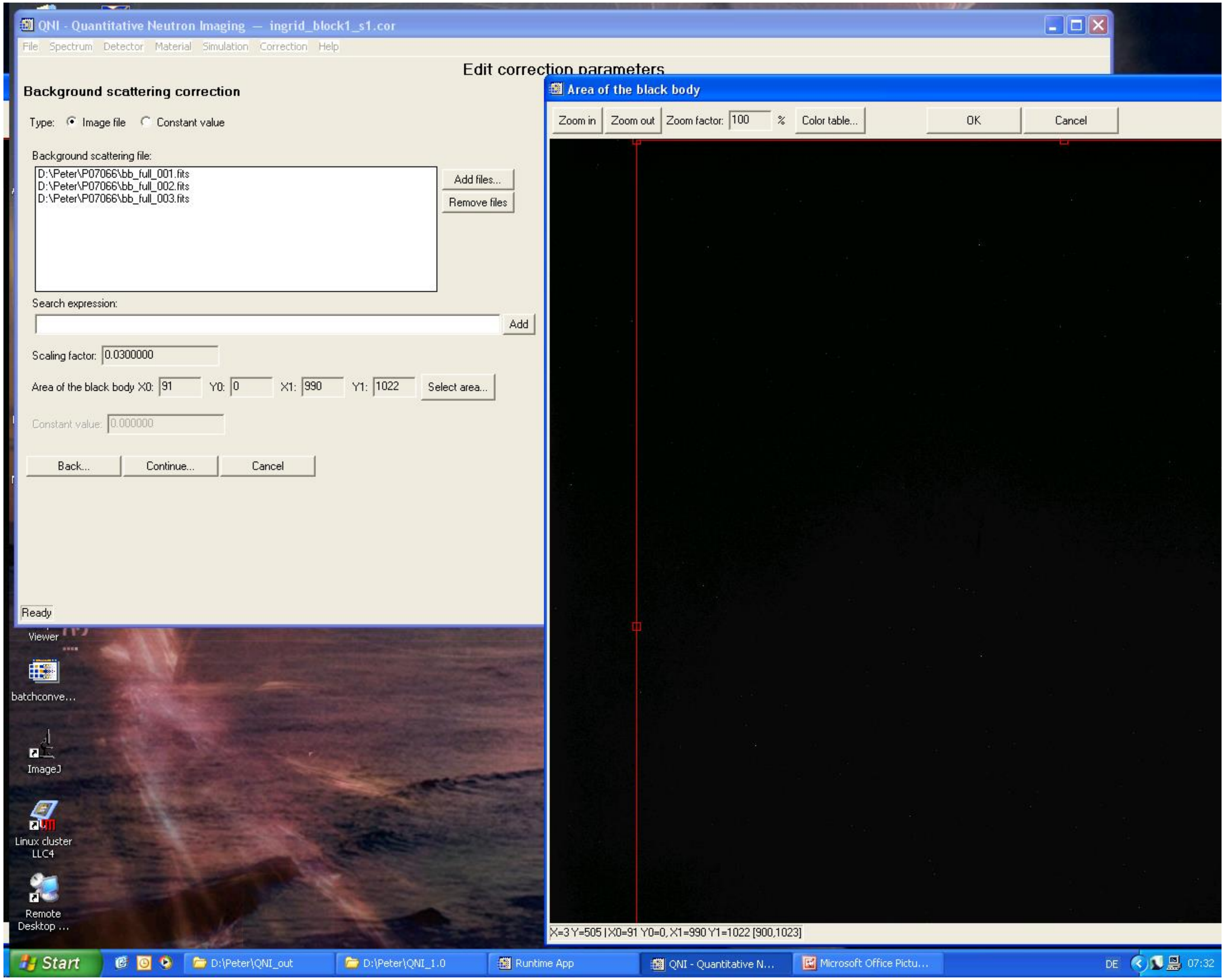
Step 5


QNI - Quantitative Neutron Imaging — ingrid_block1_s1.cor
File Spectrum Detector Material Simulation Correction Help
Edit correction parameters
Dark current correction
Type: Image file Constant value
Method: Pixelwise Mean value
Dark current file:
D:\Peter\P07066\dc_background_001.fits
D:\Peter\P07066\dc_background_002.fits
D:\Peter\P07066\dc_background_003.fits
Add files...
Remove files
Search expression:
Add
Constant value: 0.000000
Back...
Continue...
Cancel
Ready

Step 6

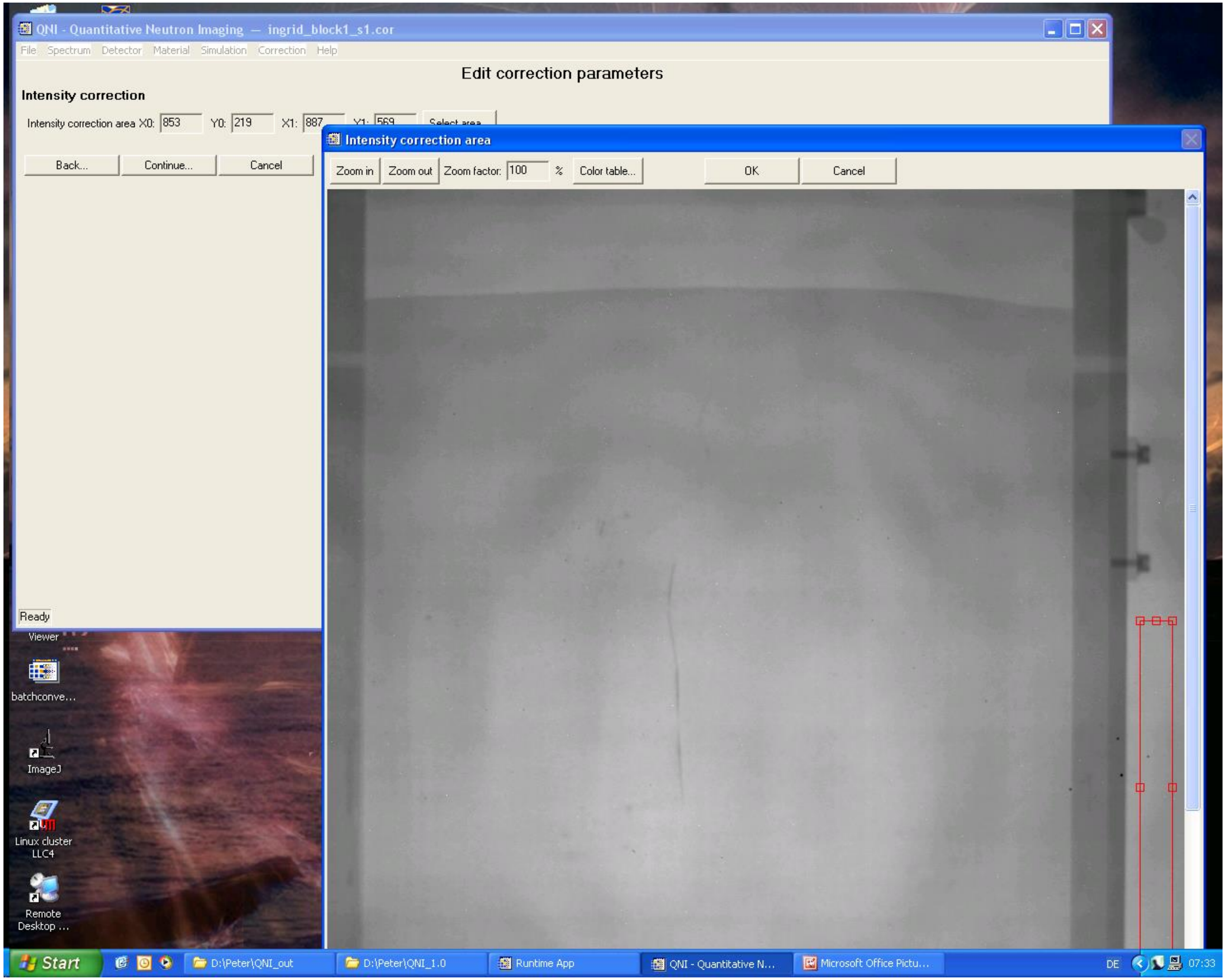

QNI - Quantitative Neutron Imaging — ingrid_block1_s1.cor
File Spectrum Detector Material Simulation Correction Help
Edit correction parameters
Median filter
Filter width (Pixel): 3
Threshold (%): 15.0000
Back...
Continue...
Cancel
Ready

Step 7



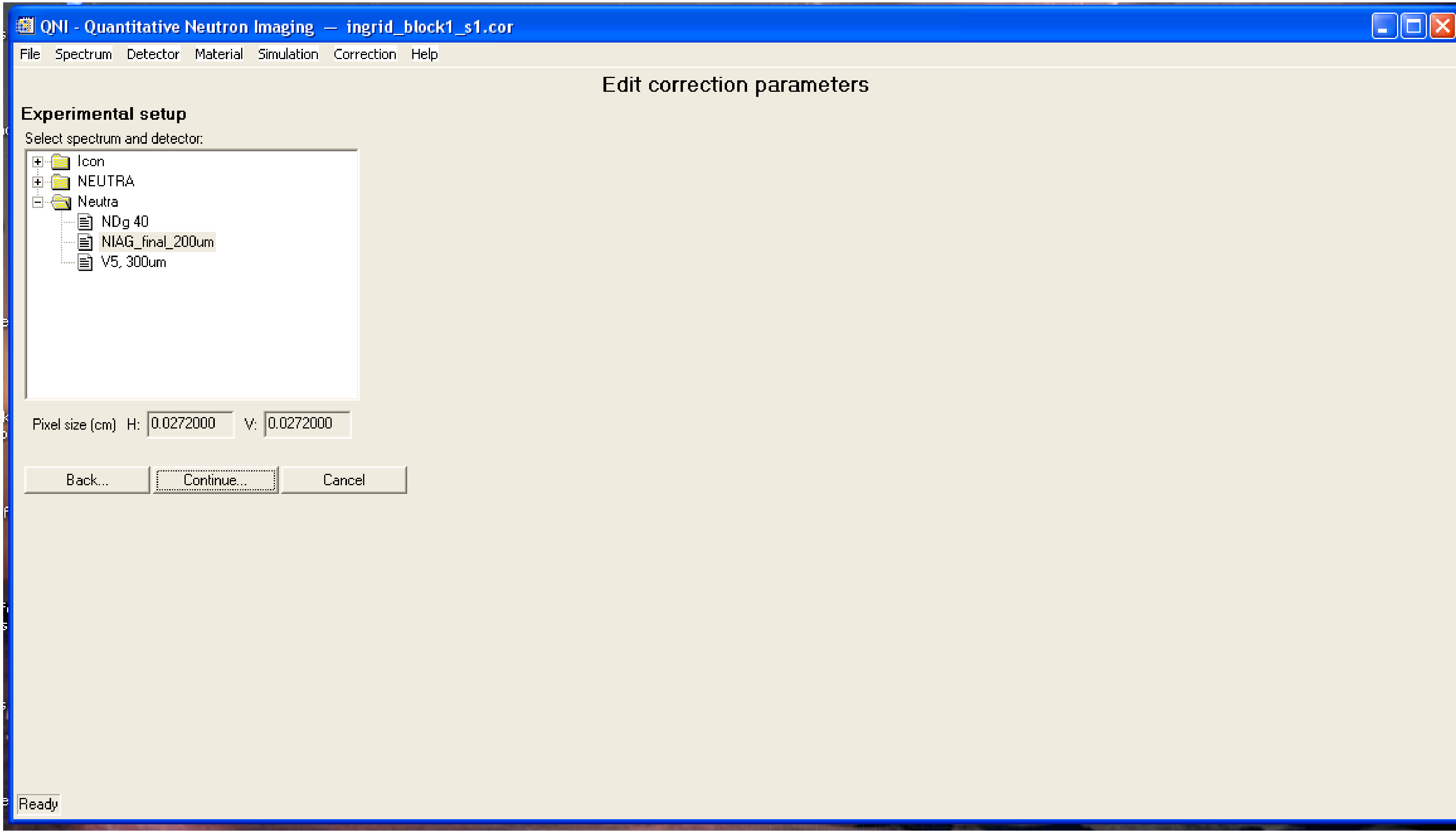
QNI - Quantitative Neutron Imaging — ingrid_block1_s1.cor
File Spectrum Detector Material Simulation Correction Help
Edit correction parameters
Background scattering correction
Type: Image file Constant value
Background scattering file:
D:\Peter\P07066\bb_full_001.fits
D:\Peter\P07066\bb_full_002.fits
D:\Peter\P07066\bb_full_003.fits
Add files...
Remove files
Search expression:
Add
Scaling factor: 0.0300000
Area of the black body X0: 91 Y0: 0 X1: 990 Y1: 1022
Select area...
Constant value: 0.000000
Back...
Continue...
Cancel
Ready
Area of the black body
Zoom in
Zoom out
Zoom factor: 100 %
Color table...
OK
Cancel
X=3 Y=505 | X0=91 Y0=0, X1=990 Y1=1022 [900,1023]
Start
D:\Peter\QNI_out
D:\Peter\QNI_1.0
Runtime App
QNI - Quantitative N...
Microsoft Office Pictu...
DE
07:32

Step 8

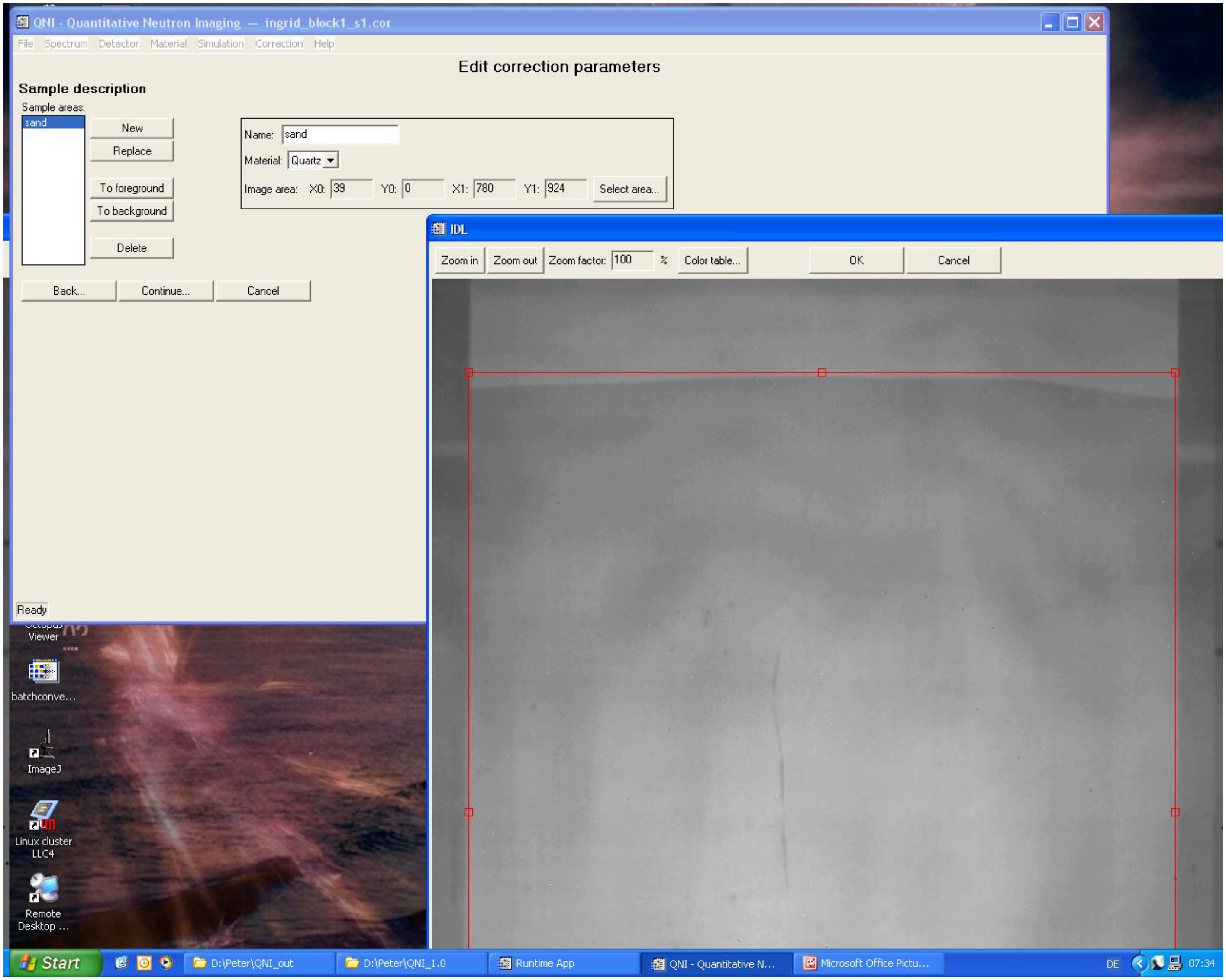


QNI - Quantitative Neutron Imaging — ingrid_block1_s1.cor
File Spectrum Detector Material Simulation Correction Help
Edit correction parameters
Intensity correction
Intensity correction area X0: 853 Y0: 219 X1: 887
Back... Continue... Cancel
Ready
Intensity correction area
Zoom in Zoom out Zoom factor: 100 % Color table... OK Cancel
batchconve...
ImageJ
Linux cluster LLC4
Remote Desktop ...
Start
D:\Peter\QNI_out
D:\Peter\QNI_1.0
Runtime App
QNI - Quantitative N...
Microsoft Office Pictu...
DE 07:33

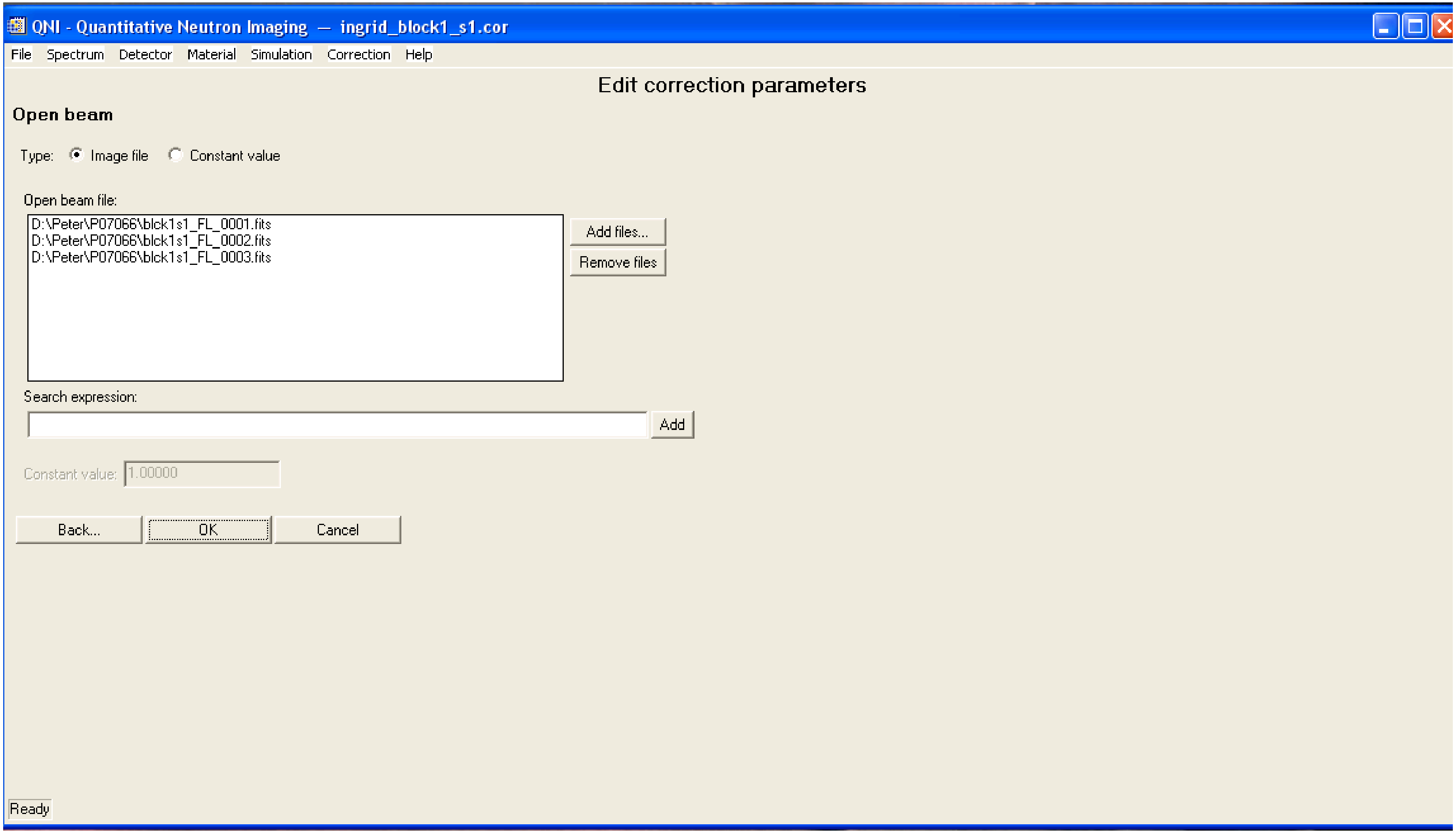
Step 9


QNI - Quantitative Neutron Imaging — ingrid_block1_s1.cor
File Spectrum Detector Material Simulation Correction Help
Edit correction parameters
Experimental setup
Select spectrum and detector:
Icon
NEUTRA
Neutra
NDg 40
NIAG_final_200um
V5, 300um
Pixel size (cm) H: 0.0272000 V: 0.0272000
Back...
Continue...
Cancel
Ready

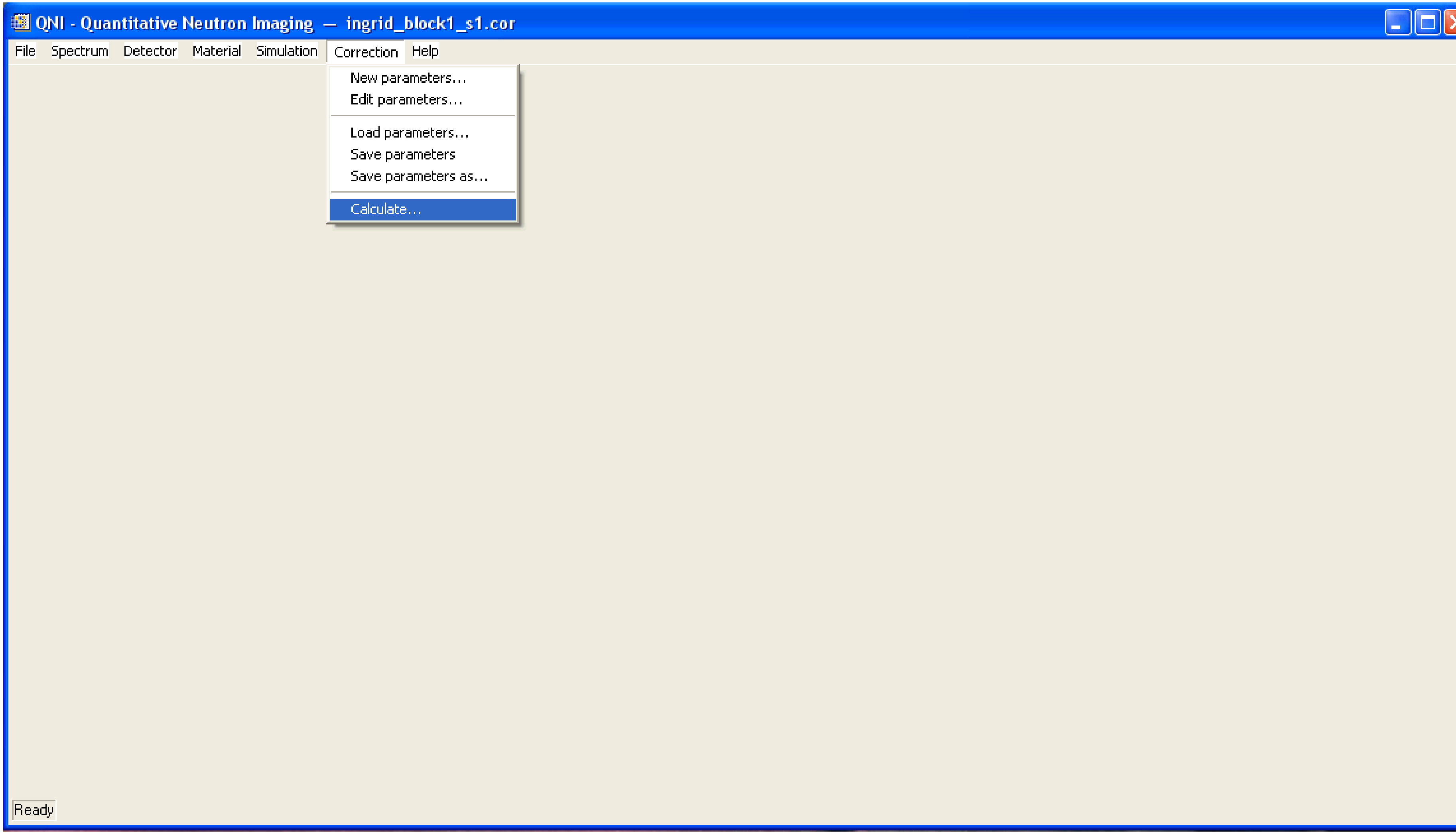
Step 10


QNI - Quantitative Neutron Imaging — ingrid_block1_s1.cor
File Spectrum Detector Material Simulation Correction Help
Edit correction parameters
Sample description
Sample areas:
sand
New
Replace
To foreground
To background
Delete
Name: sand
Material: Quartz
Image area: X0: 39 Y0: 0 X1: 780 Y1: 924
Select area...
Back...
Continue...
Cancel
Ready
IDL
Zoom in
Zoom out
Zoom factor: 100 %
Color table...
OK
Cancel
batchconve...
ImageJ
Linux cluster LLC4
Remote Desktop ...
Start
D:\Peter\QNI_out
D:\Peter\QNI_1.0
Runtime App
QNI - Quantitative N...
Microsoft Office Pictu...
DE
07:34

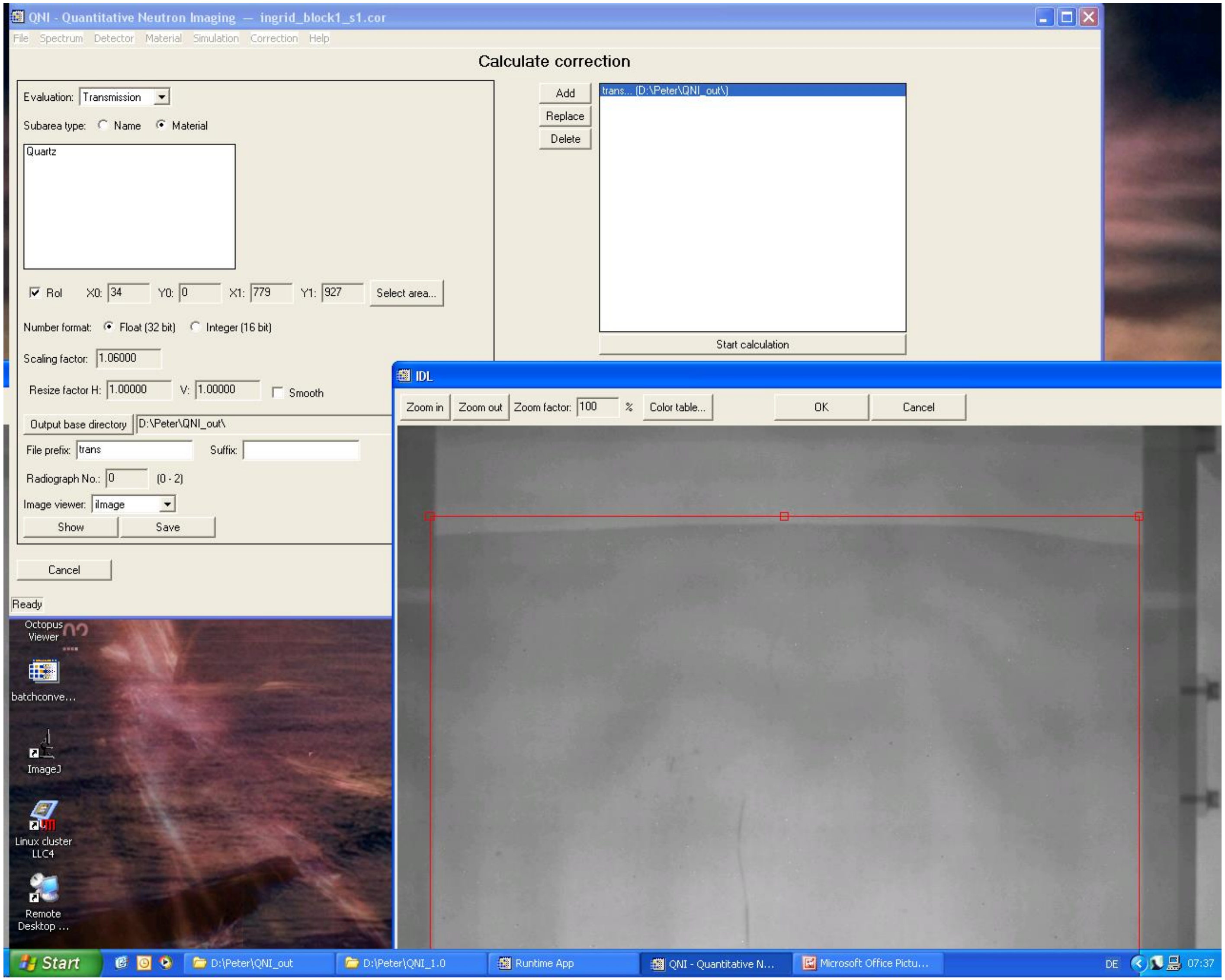
Step 11


QNI - Quantitative Neutron Imaging — ingrid_block1_s1.cor
File Spectrum Detector Material Simulation Correction Help
Edit correction parameters
Open beam
Type: Image file Constant value
Open beam file:
D:\Peter\P07066\blck1s1_FL_0001.fits
D:\Peter\P07066\blck1s1_FL_0002.fits
D:\Peter\P07066\blck1s1_FL_0003.fits
Add files...
Remove files
Search expression:
Add
Constant value: 1.00000
Back...
OK
Cancel
Ready

Step 12


QNI - Quantitative Neutron Imaging — ingrid_block1_s1.cor
File
Spectrum
Detector
Material
Simulation
Correction
Help
New parameters...
Edit parameters...
Load parameters...
Save parameters
Save parameters as...
Calculate...
Ready

Step 13


QNI - Quantitative Neutron Imaging — ingrid_block1_s1.cor
File Spectrum Detector Material Simulation Correction Help
Calculate correction
Evaluation: Transmission
Subarea type: Name Material
Quartz
RoI X0: 34 Y0: 0 X1: 779 Y1: 927 Select area...
Number format: Float (32 bit) Integer (16 bit)
Scaling factor: 1.06000
Resize factor H: 1.00000 V: 1.00000 Smooth
Output base directory D:\Peter\QNI_out\
File prefix: trans Suffix:
Radiograph No.: 0 (0 - 2)
Image viewer: iImage
Show
Save
Cancel
Ready
Add
Replace
Delete
trans... (D:\Peter\QNI_out\)
Start calculation
IDL
Zoom in
Zoom out
Zoom factor: 100 %
Color table...
OK
Cancel
Octopus Viewer
batchconve...
ImageJ
Linux cluster LLC4
Remote Desktop ...
Start
D:\Peter\QNI_out
D:\Peter\QNI_1.0
Runtime App
QNI - Quantitative N...
Microsoft Office Pictu...
DE
07:37

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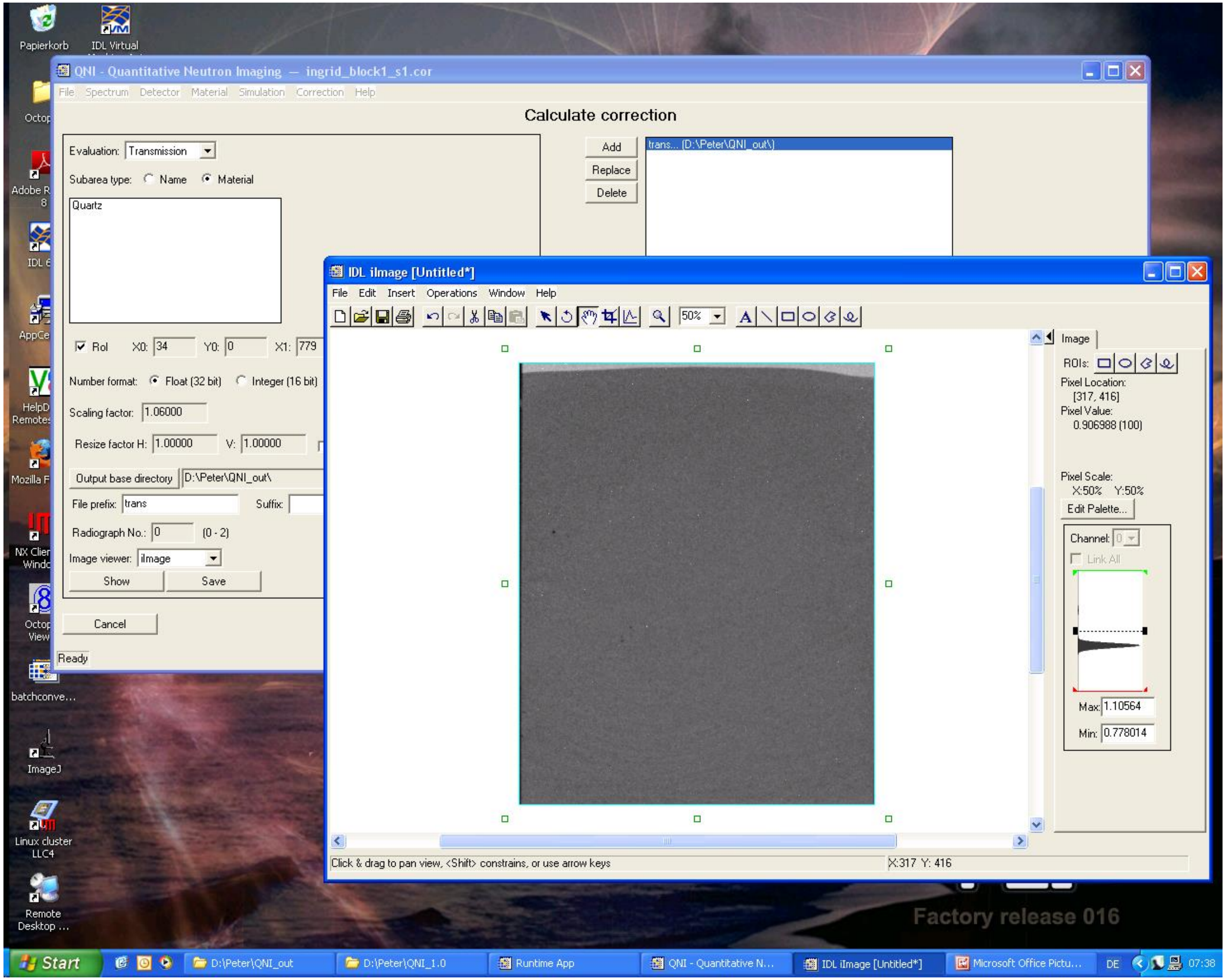
Step 14



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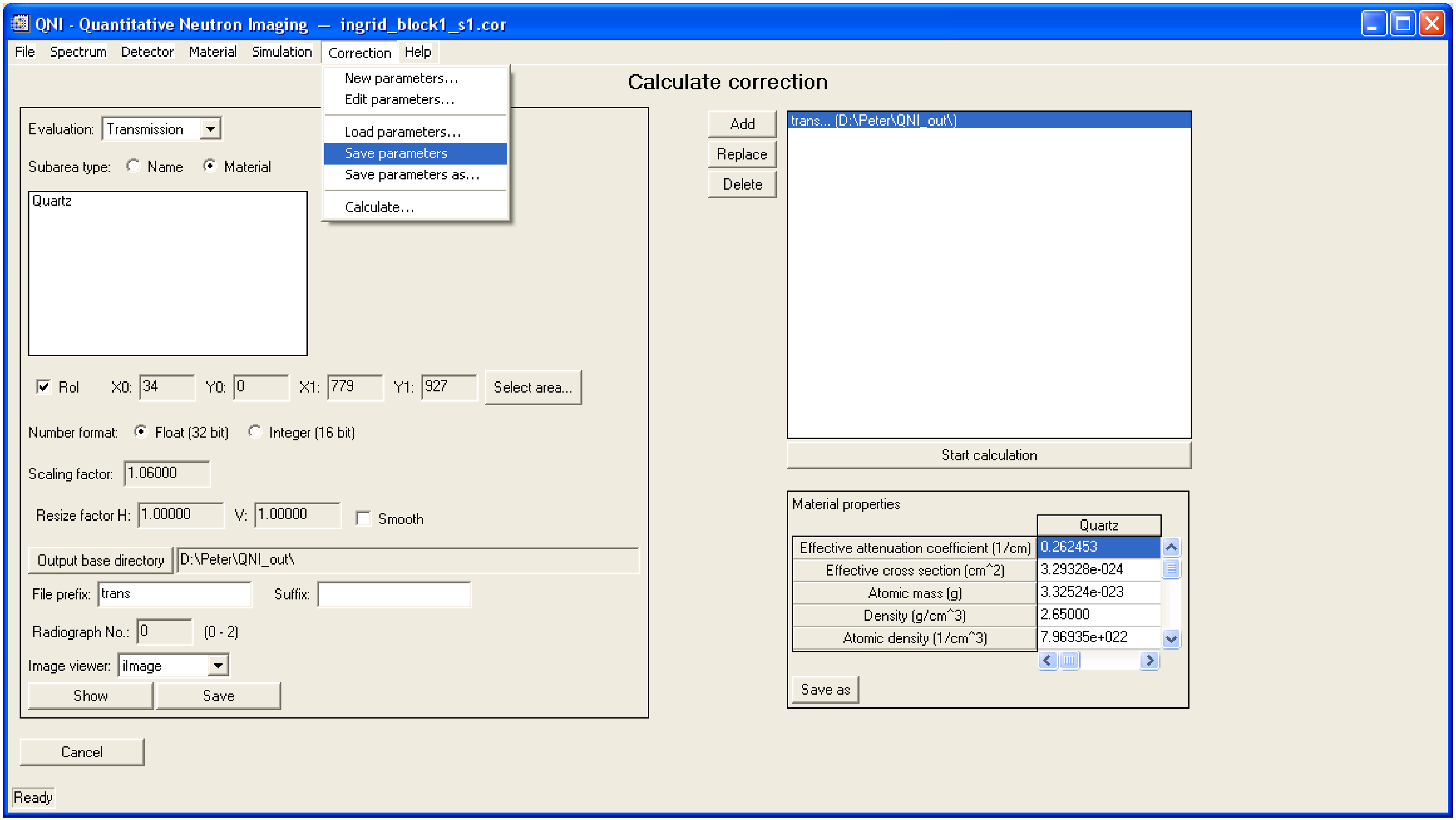
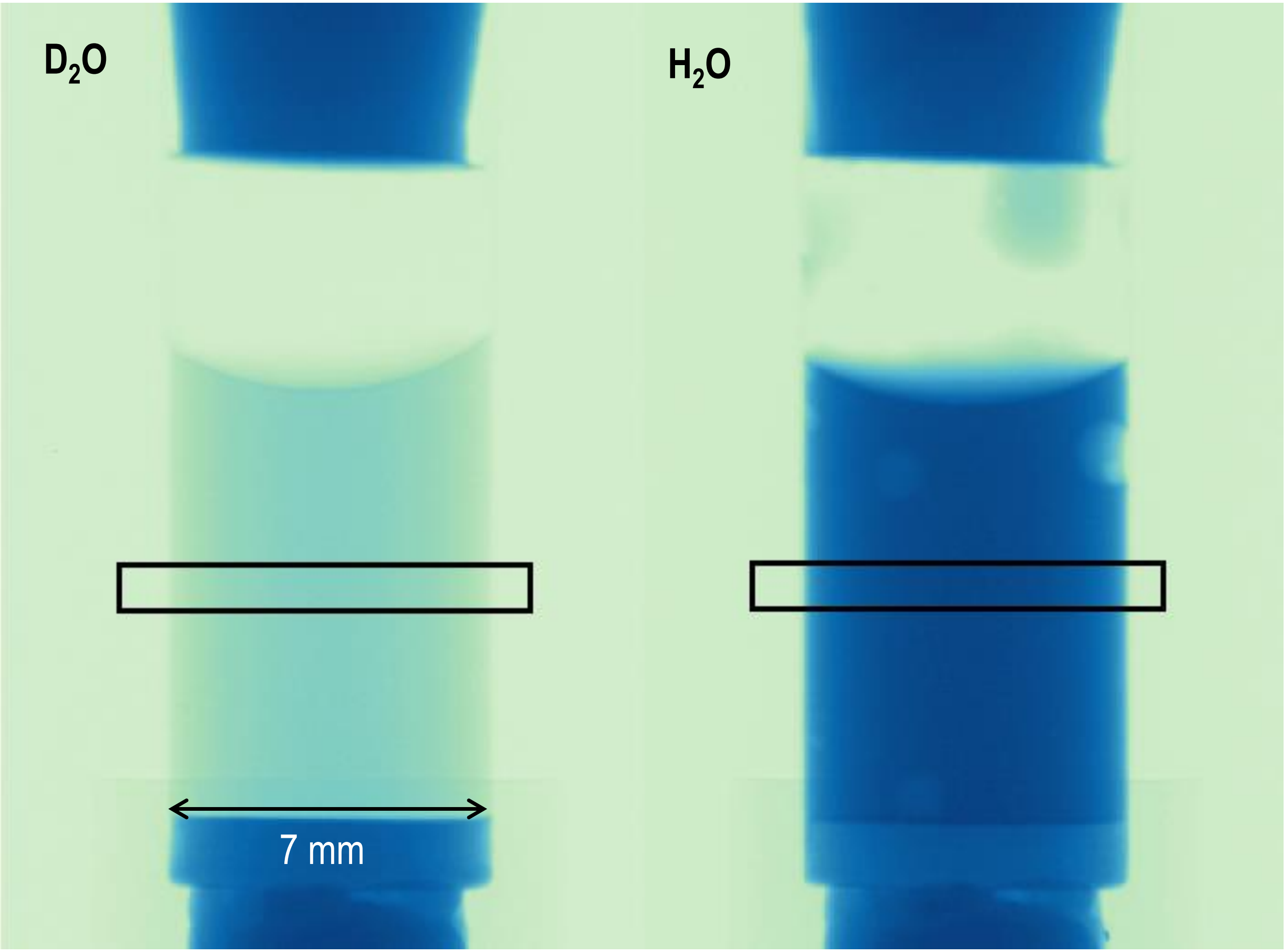
Step 15

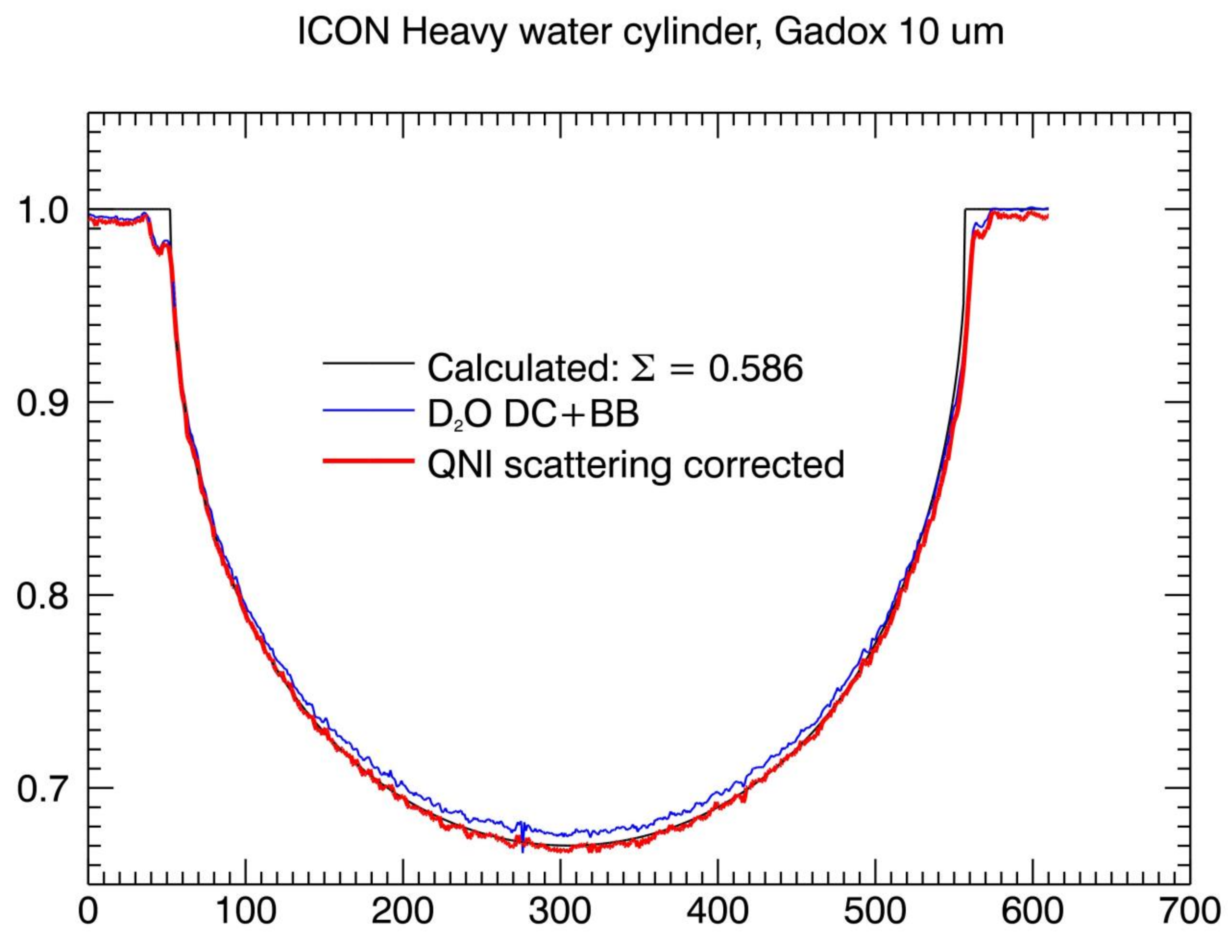


Effect of scattering correction in H_2O & D_2O

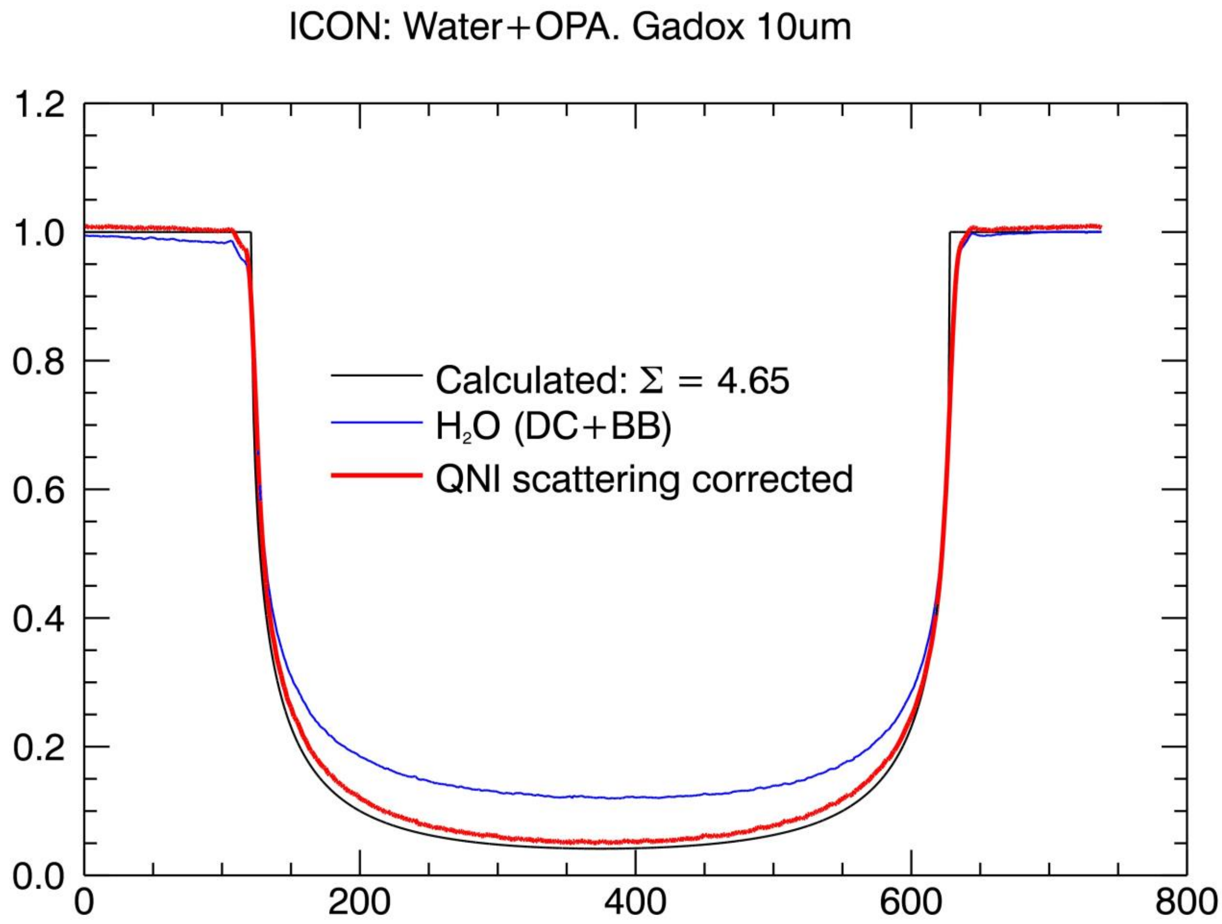


Measurements with μ-setup at ICON

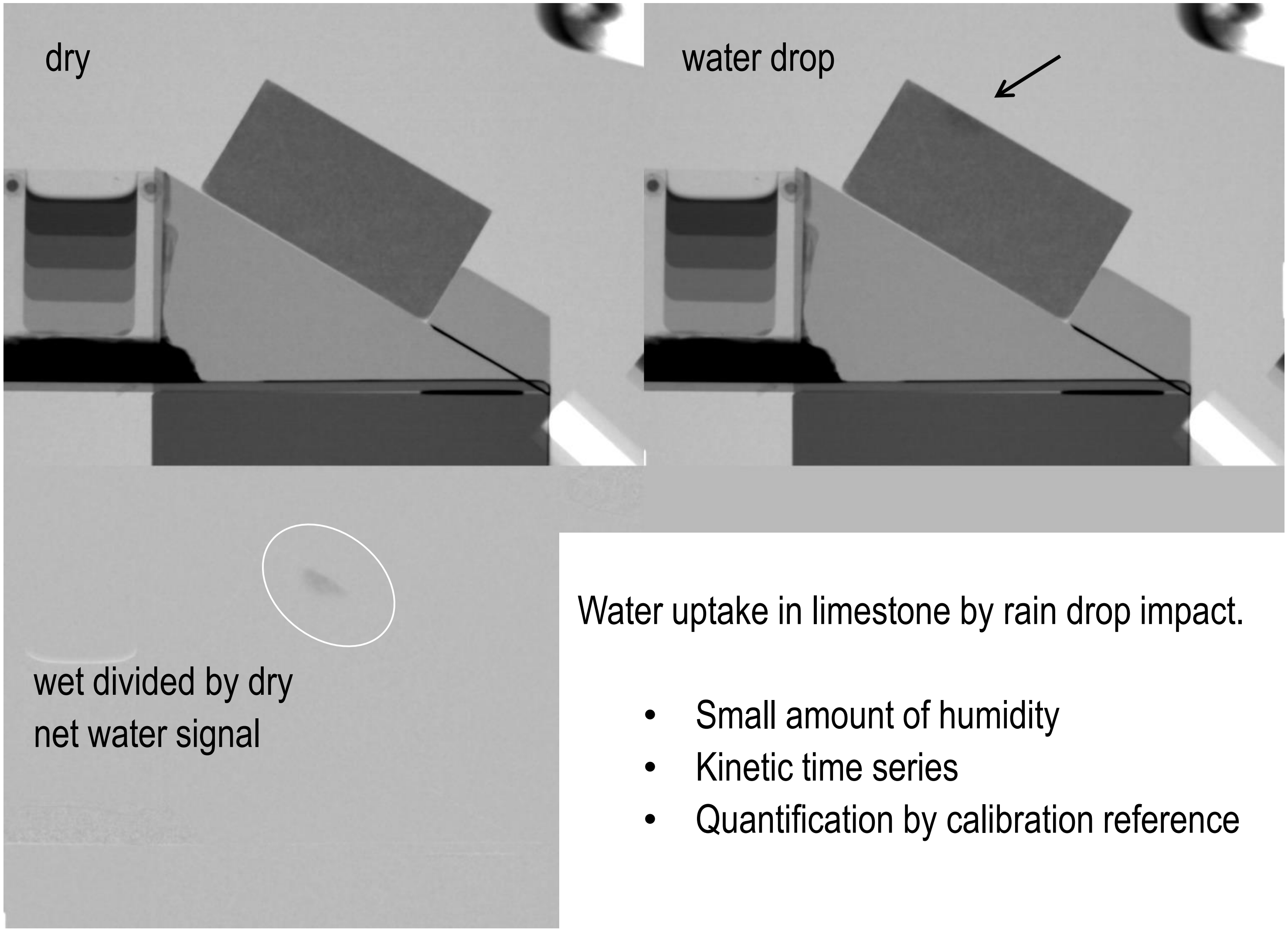
Profile across D_2O cylinder



Scattering correction of cylinder containing H_2O and Opalinus



Referenced evaluation with calibration step wedge



Water uptake in limestone by rain drop impact.

- Small amount of humidity
- Kinetic time series
- Quantification by calibration reference

Net humidity gain/loss from wet and dry projections

$$T_w = \frac{I_w}{I_{ow}} = e^{-(\Sigma_w t_w + \Sigma_d t_d)}$$

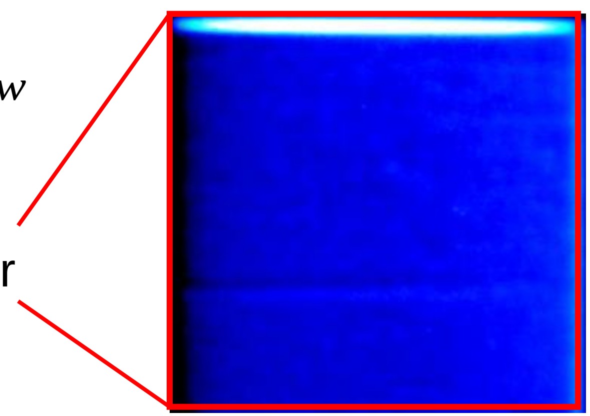
Transmission of wet state T_w

$$T_d = \frac{I_d}{I_{od}} = e^{-\Sigma_d t_d}$$

Transmission of „dry“ state T_d

$$\frac{T_w}{T_d} = e^{-\Sigma_w t_w} \qquad \therefore -\ln\left(\frac{T_w}{T_d}\right) = \Sigma_w t_w$$

Referencing wet to „dry“ T



Assuming $\sum_w = 3.6$ [1/cm] and summing over results in mass of water lost [g]

Some hints for quantification

- Quantification starts with setting up the experiment correctly: e.g. choosing the appropriate scintillator, field of view and pixel-size, what are the measures to reduce neutron and/or γ-ray background, assess sample transmission before deciding on sample size, is imaging frame rate used in accordance with a sufficient signal-to-noise ratio,…

- If you know what you want to quantify, then think of additional independent measures e.g. measure the sample weight before/after or during the neutron-imaging sequence with a balance in-situ or at least at the start and end of the imaging sequence. Are additional standard references needed ?

- Think about the neutron image evaluation procedure before starting the measurements: e.g. how to assess the backgrounds. If a referenced evaluation is looked for, make sure that sample registration with the reference is guaranteed. If the sample shape changes during the experiment by swelling or shrinking, think of how this will affect a referenced evaluation. Do you need additional markers for sample registration ?

- When using the QNI framework make sure to perform all the required measurements and determine the sample to detector distance.

Questions from the audience ?

Thank you for your attention !

PSI neutron imaging links

NIAG: http://www.psi.ch/niag

NEUTRA: http://www.psi.ch/sinq/neutra

ICON: http://www.psi.ch/sinq/icon