X-ray imaging/tomographic measurements of water transport and swelling deformation in bentonite

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Beacon kick-off seminar
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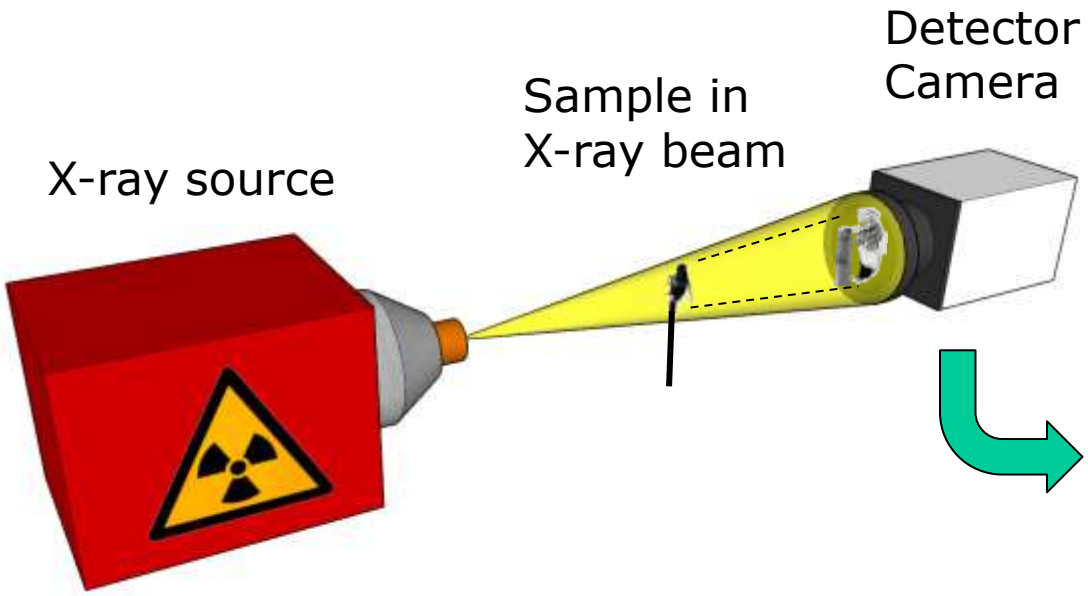
Introduction

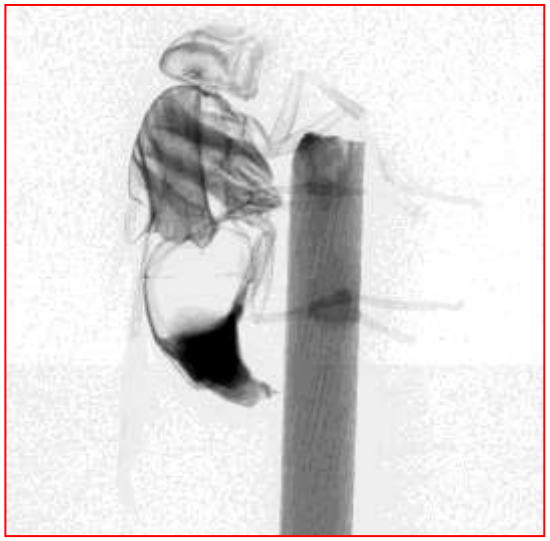
- Report of previous work carried out in finnish national program KYT2018 (project THEBES) and EU/FP7 framework (project BELBar)
- General goals:
  - To develop non-intrusive experimental methods based on X-ray tomography/imaging that can be used to gain information on water transport and swelling dynamics of bentonite.
  - To produce detailed and well characterized data on wetting/swelling processes and thereby to support modelling of bentonite buffer behaviour and erosion process.
- Two techniques developed and used for measuring deformation and water content in wetting bentonite
  - X-ray imaging method (1D + time / 2D + time)
  - X-ray tomographic method (3D + time)

THEBES BELBaR EURATOM

X-ray imaging

- X-ray imaging is based on attenuation of X-rays in material: Attenuation rouhgly proportional to mass density

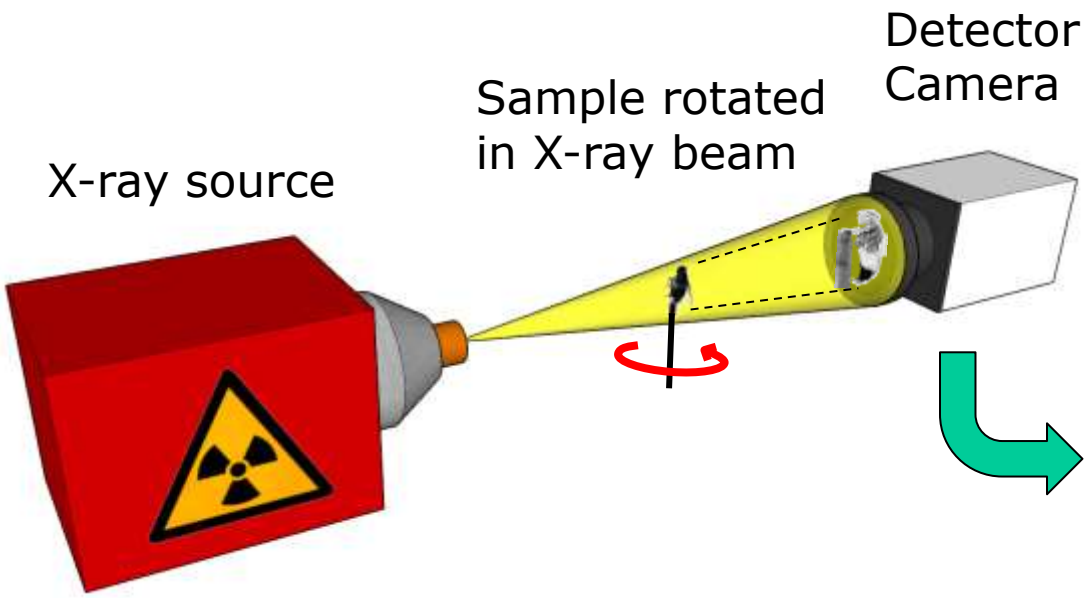




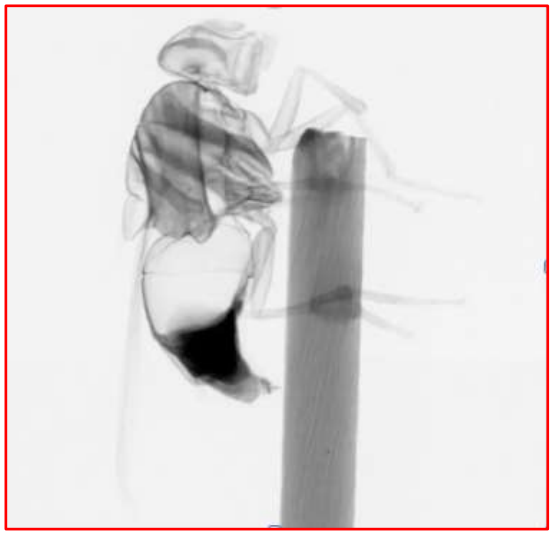
Gray-scale value
∝ integrated X-ray
attenuation profile

X-ray tomography

- A number of X-ray images (~10^3) taken from different directionds



Multiple X-ray images (~10^3)



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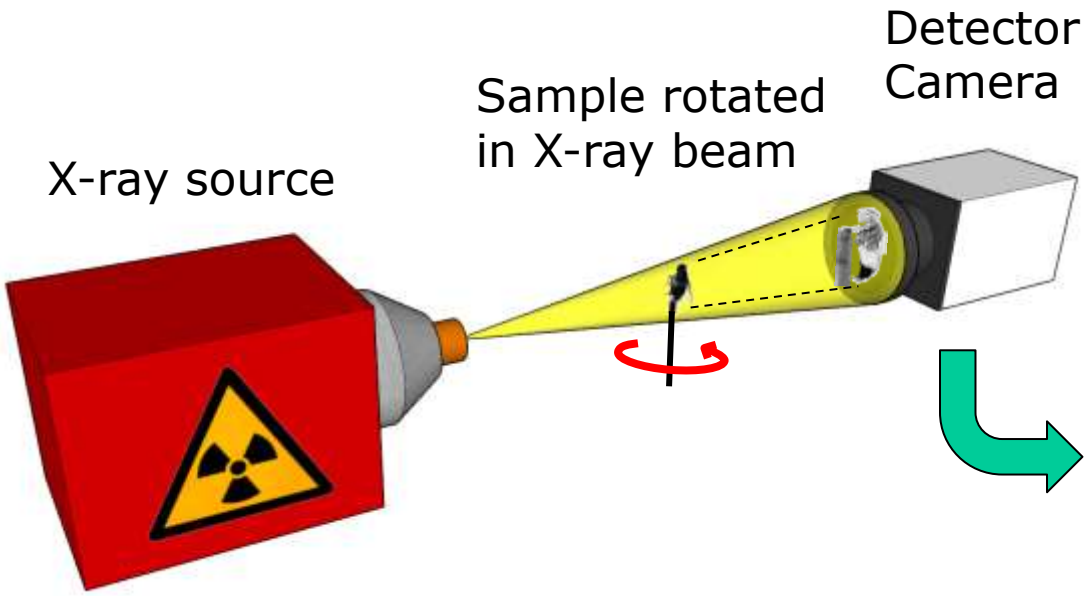

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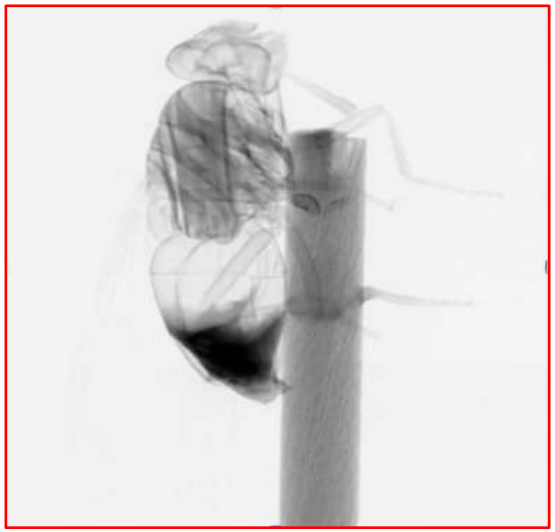

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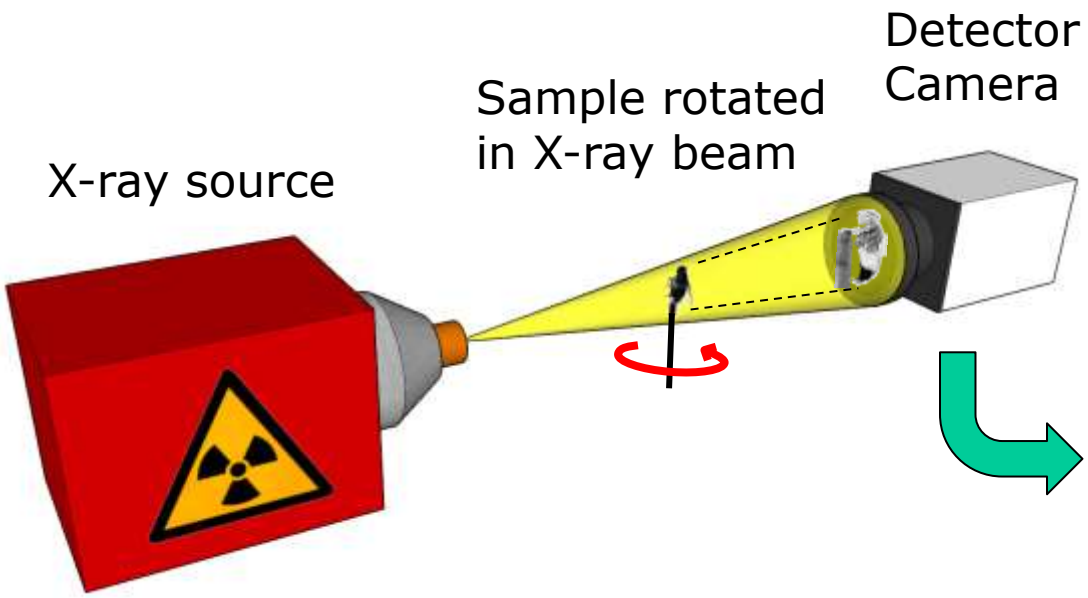

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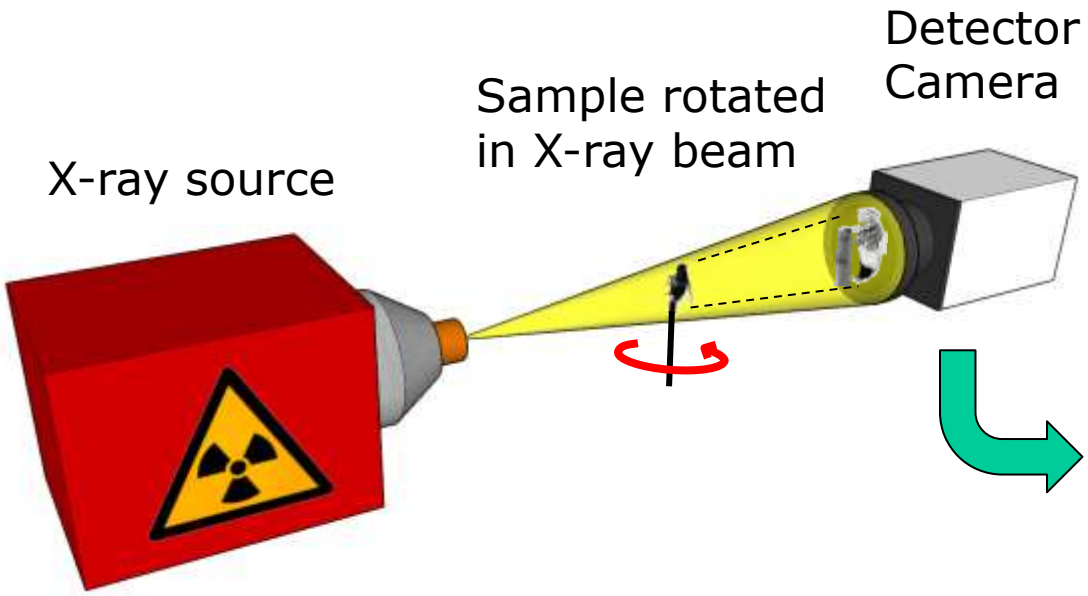

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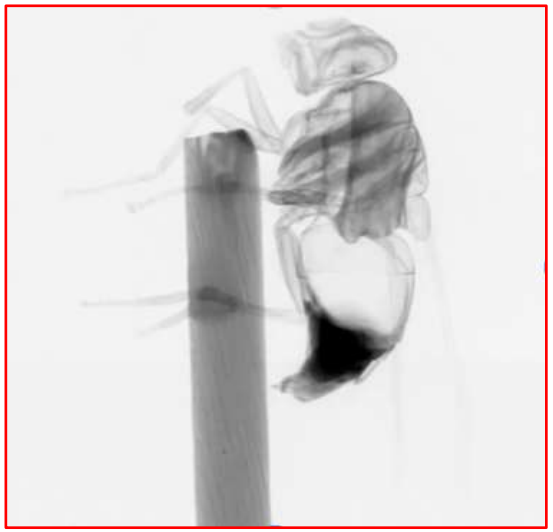
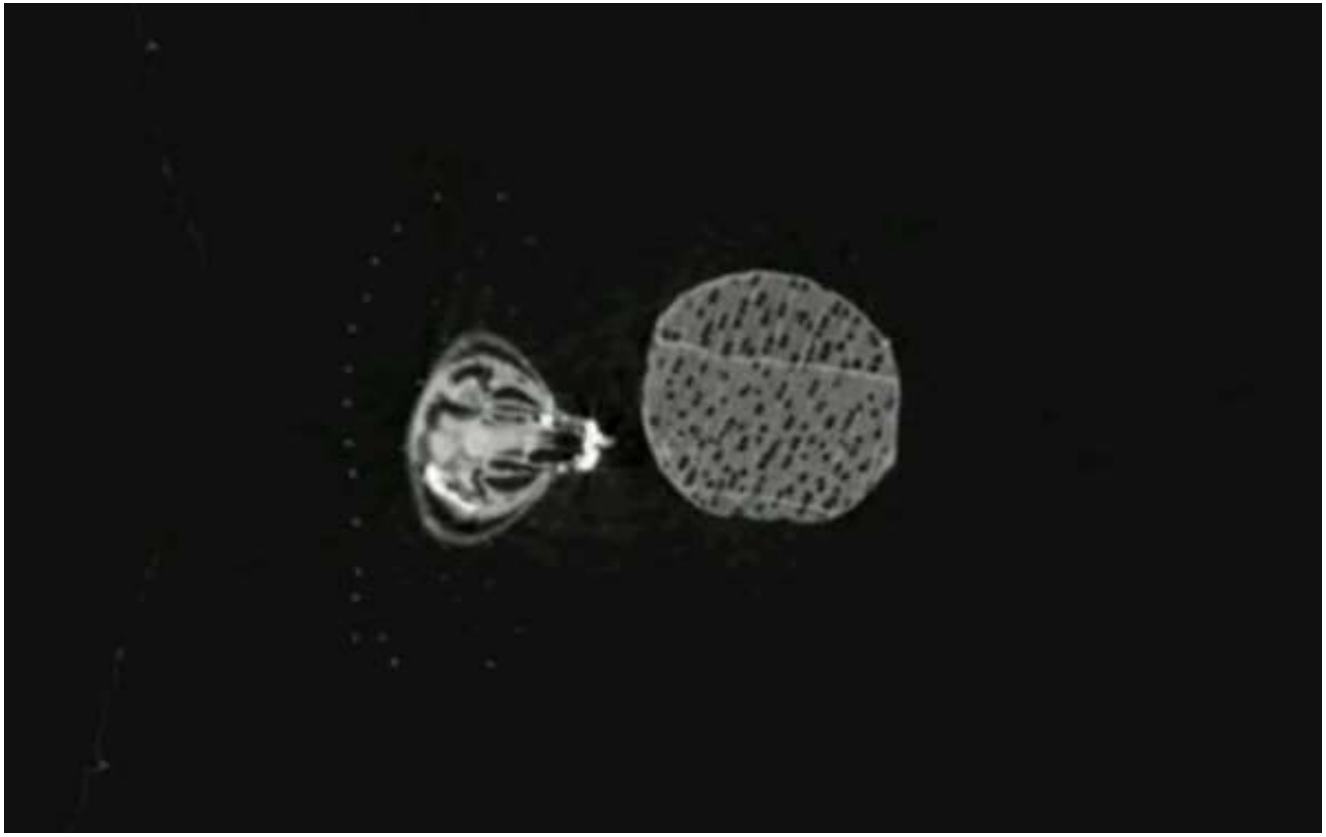


Computer reconstruction

- Layered images (~10^3 horizontal 'slices' of the object)



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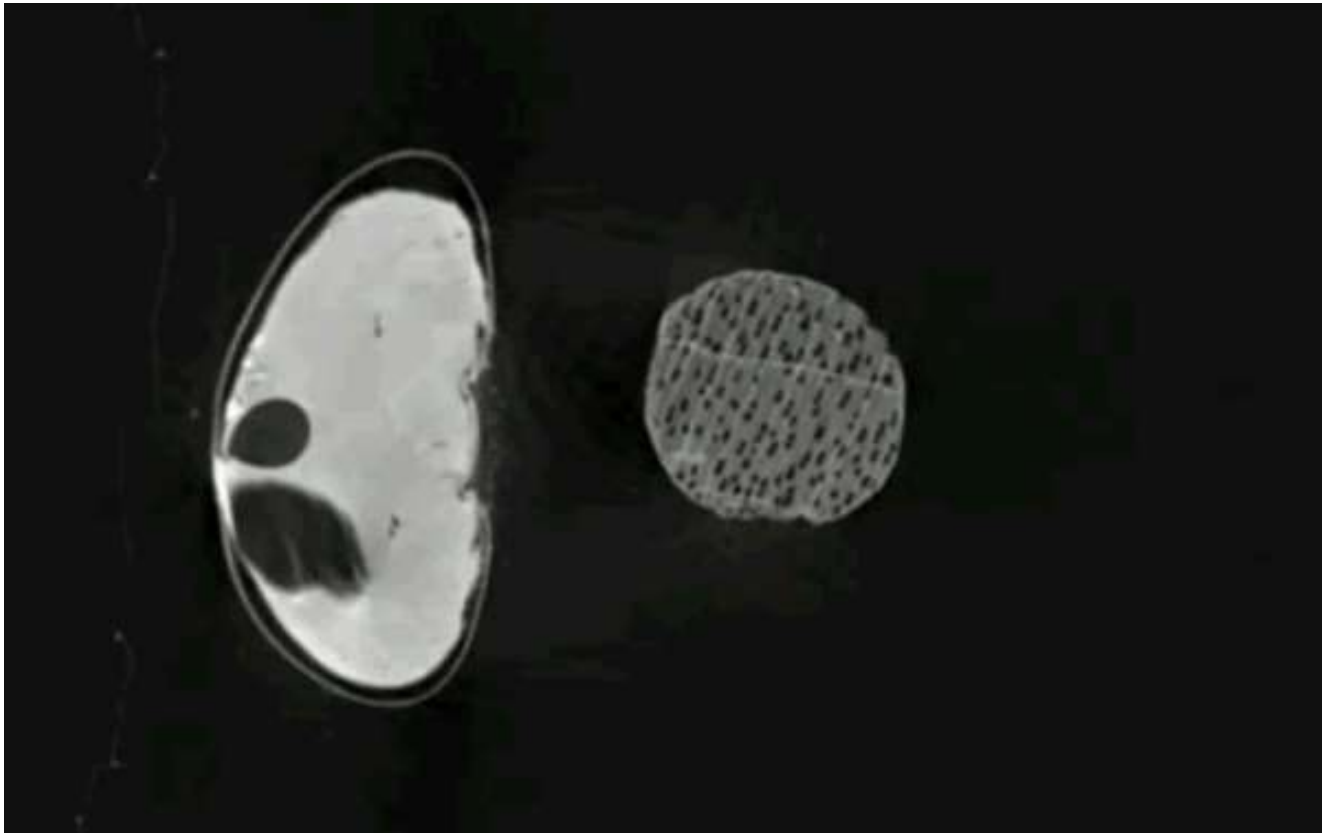

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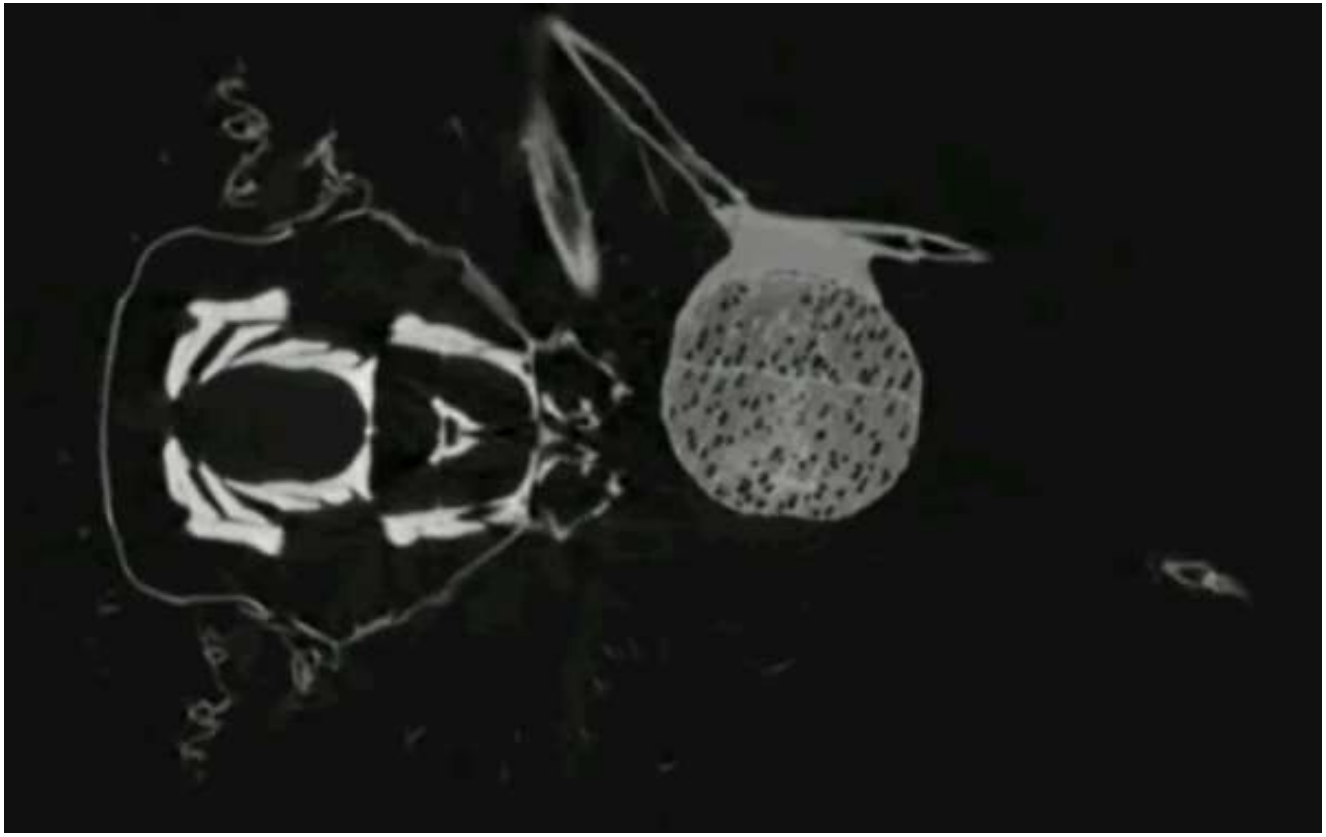

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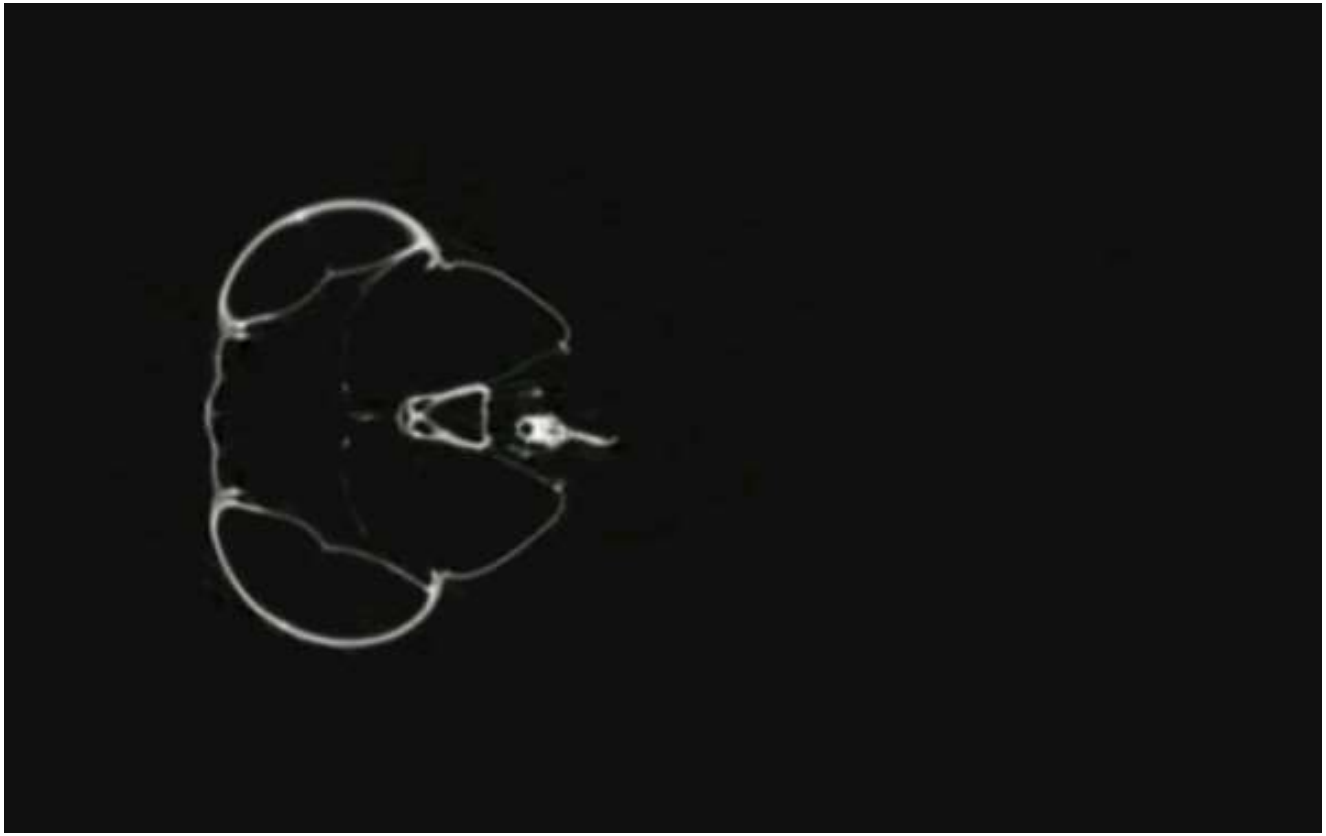

Rendered image

- The actual 3D structure in digital numerical form.

Rendered image

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Rendered image

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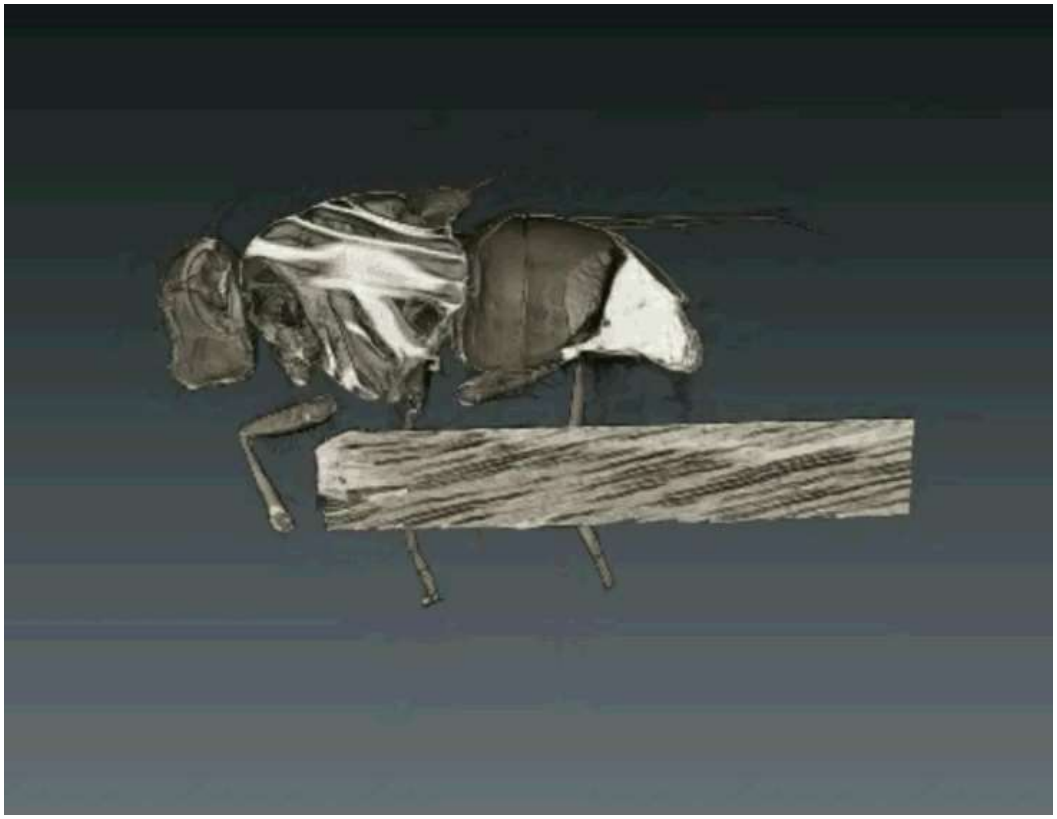
Rendered image

- The actual 3D structure in digital numerical form.
- Gray-scale value of a voxel ∝ local attenuation coefficient
- Enables quantitative analysis of the 3D structure!



X-ray tomography laboratory at JyU

- SkyScan 1172 microCT
  - sample size 2 mm - 50 mm
  - resolution 5 µm
  - X-ray energy 20 keV – 100 keV
- Xradia (Zeiss) microCT
  - sample size 0.6 mm - 6 mm
  - resolution 1 µm
- Xradia (Zeiss) nanoCT
  - sample size 15 µm or 60 µm
  - resolution 50 nm or 150 nm

SkyScan 1172 µCT

Xradia nCT and Xradia µCT

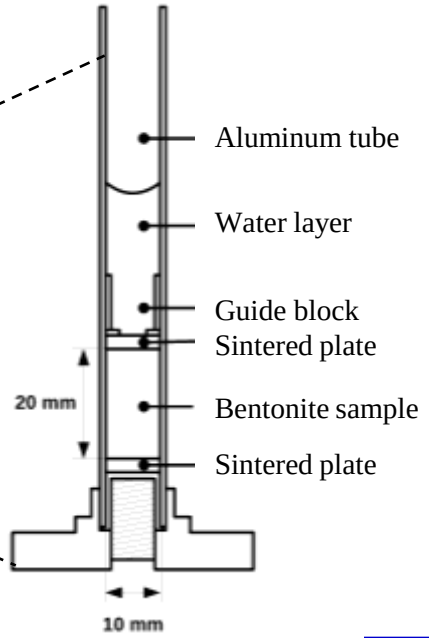
X-ray imaging study of free swelling in a narrow channel

- Bentonite sample doped with small marker particles compacted in an aluminum tube
- Water (0.1 M NaCl) added on top of the sample which is allowed to swell freely upwards.
- Wetting/swelling monitored by X-ray imaging.

Xray
motion picture

Tomographic scanner
(SkyScan 1172)

Sample holder
(aluminum tube)



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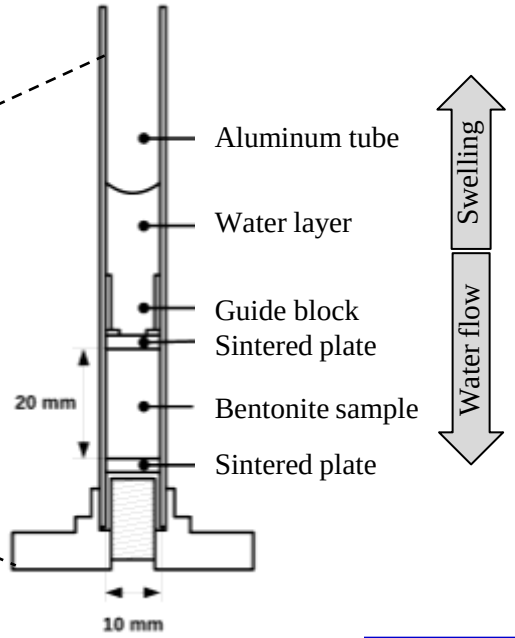


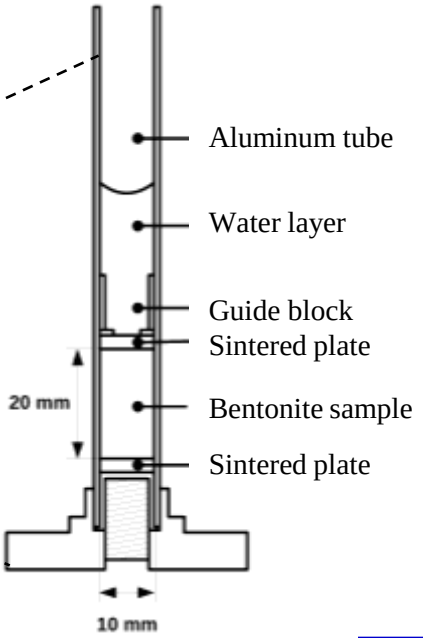
X-ray imaging study of free swelling in a narrow channel

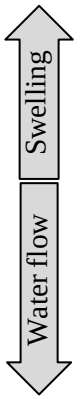
- Bentonite sample doped with small marker particles compacted in an aluminum tube
- Water (0.1 M NaCl) added on top of the sample which is allowed to swell freely upwards.
- Wetting/swelling monitored by X-ray imaging (typically for 4 days).

Xray
motion picture

Tomographic scanner
(SkyScan 1172)

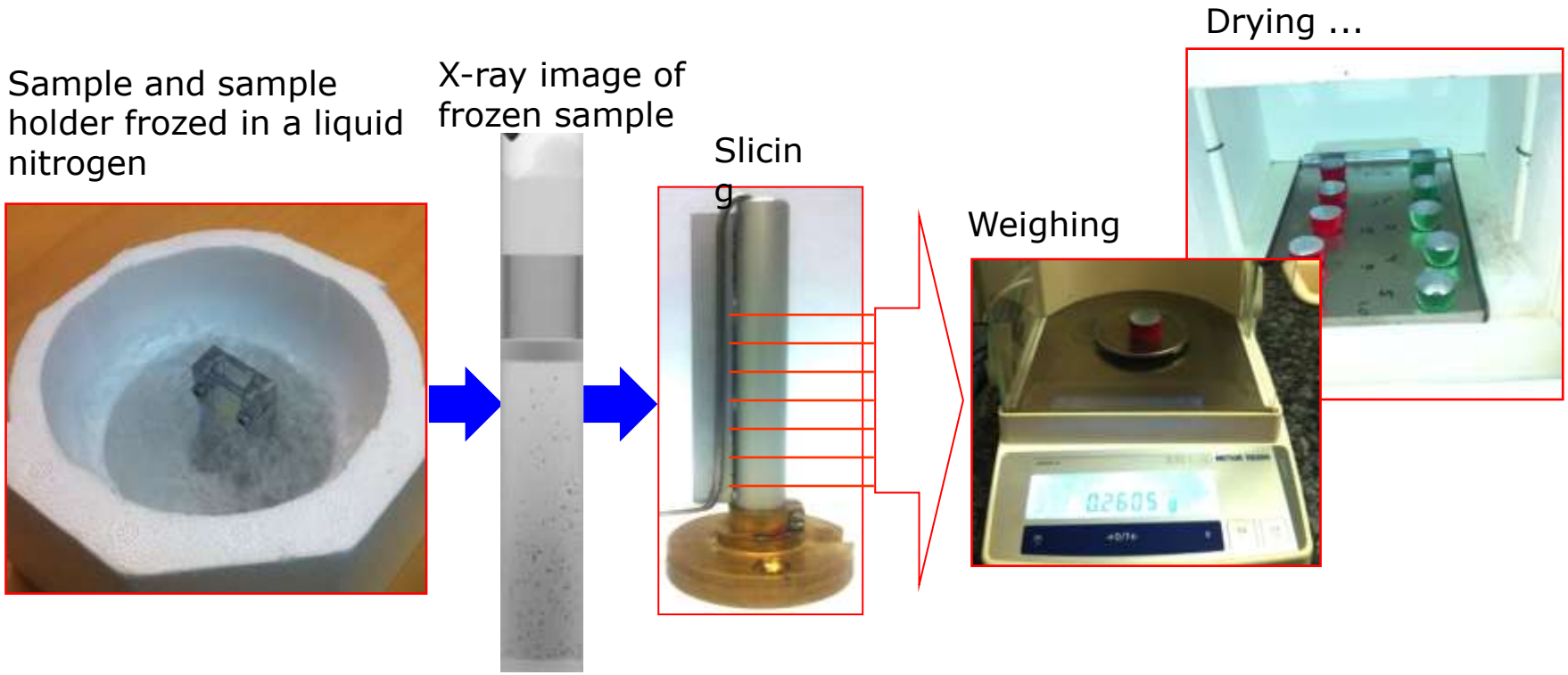
Sample holder
(aluminum tube)



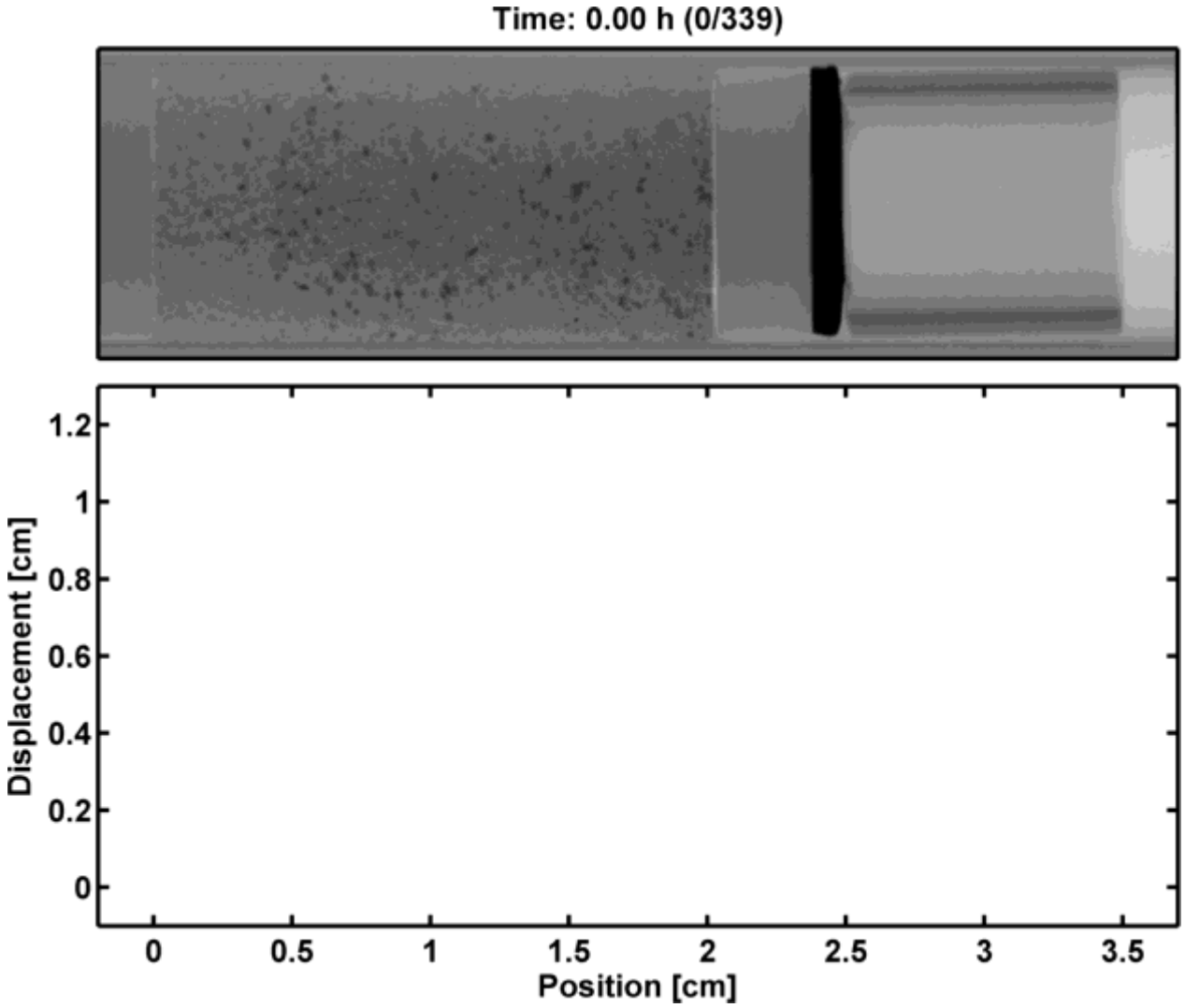


Calibration of X-ray image grey scale (attenuation coefficient)

- Post mortem gravimetric dry density and water content measurement.
- Calibration of x-ray image grey scale to local solid and water content.



Free swelling of MX80 – Deformation analysis



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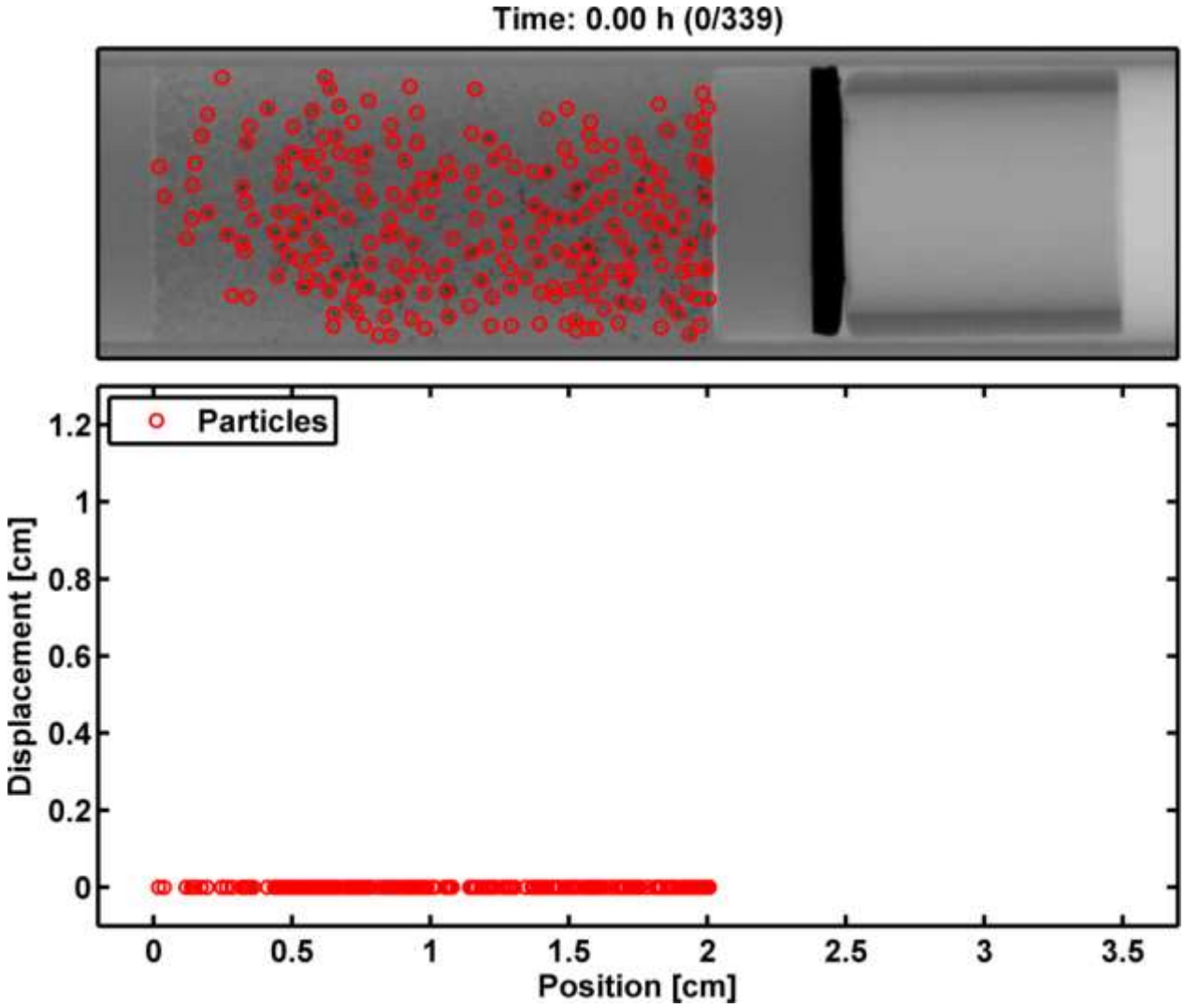

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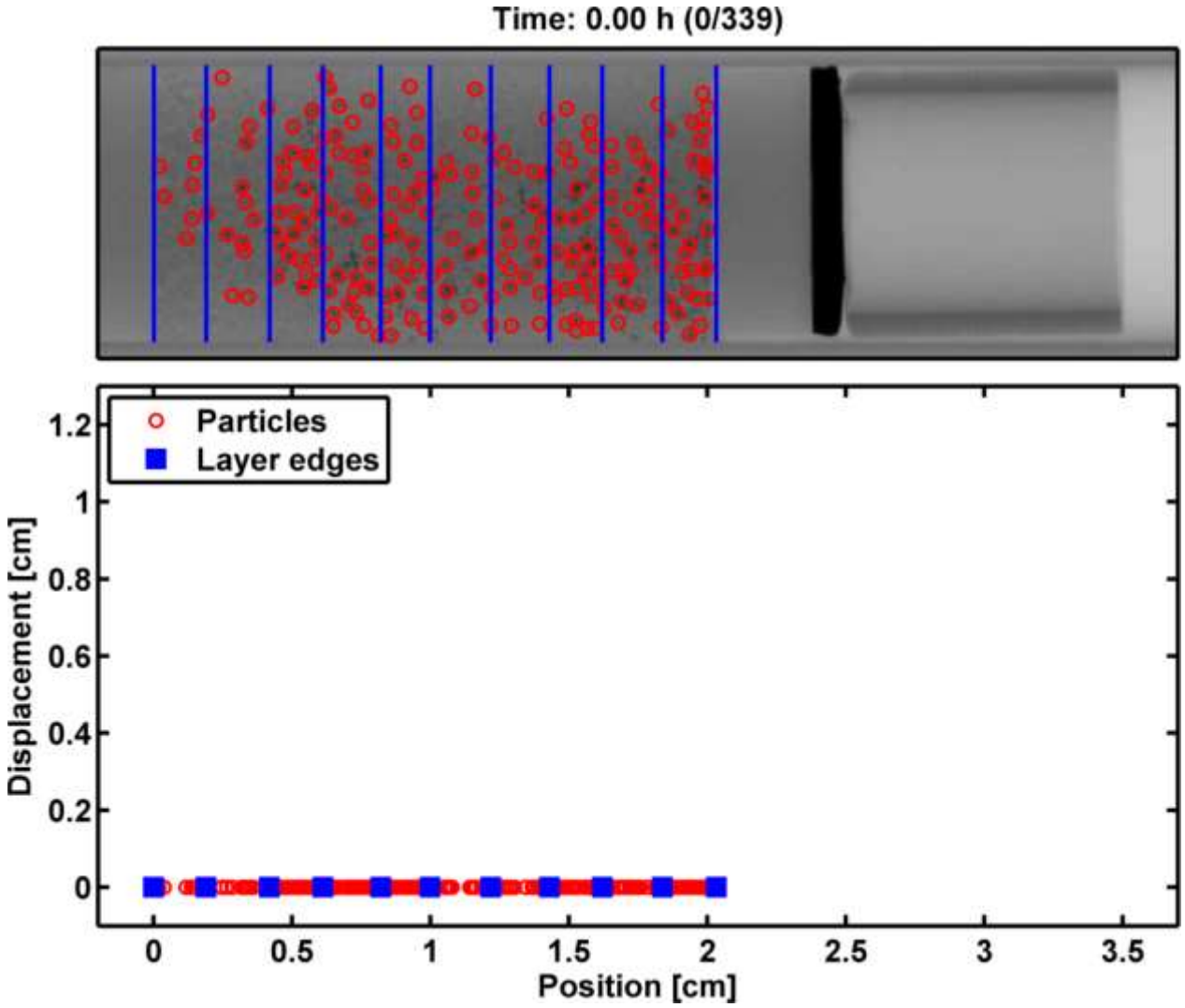

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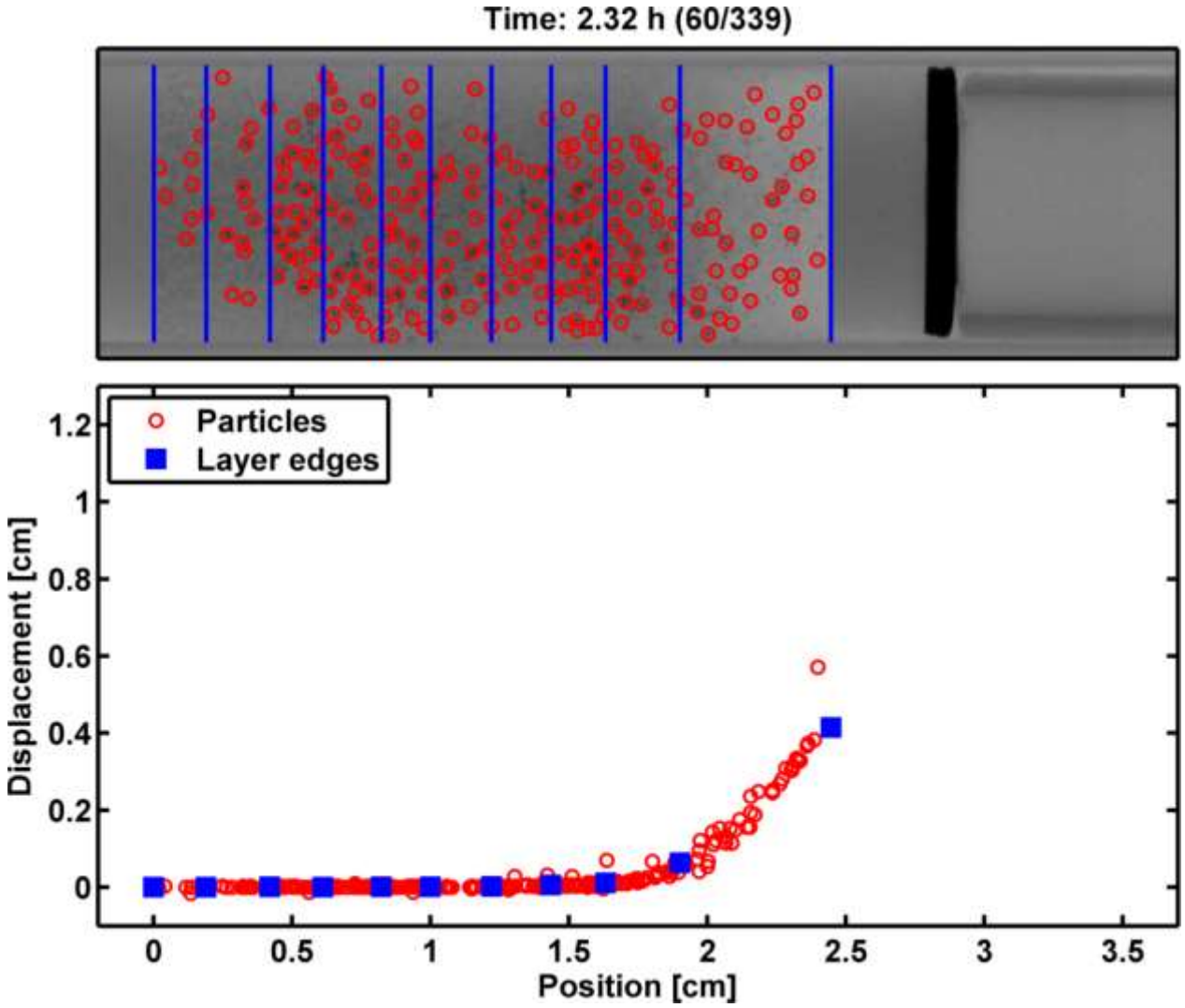

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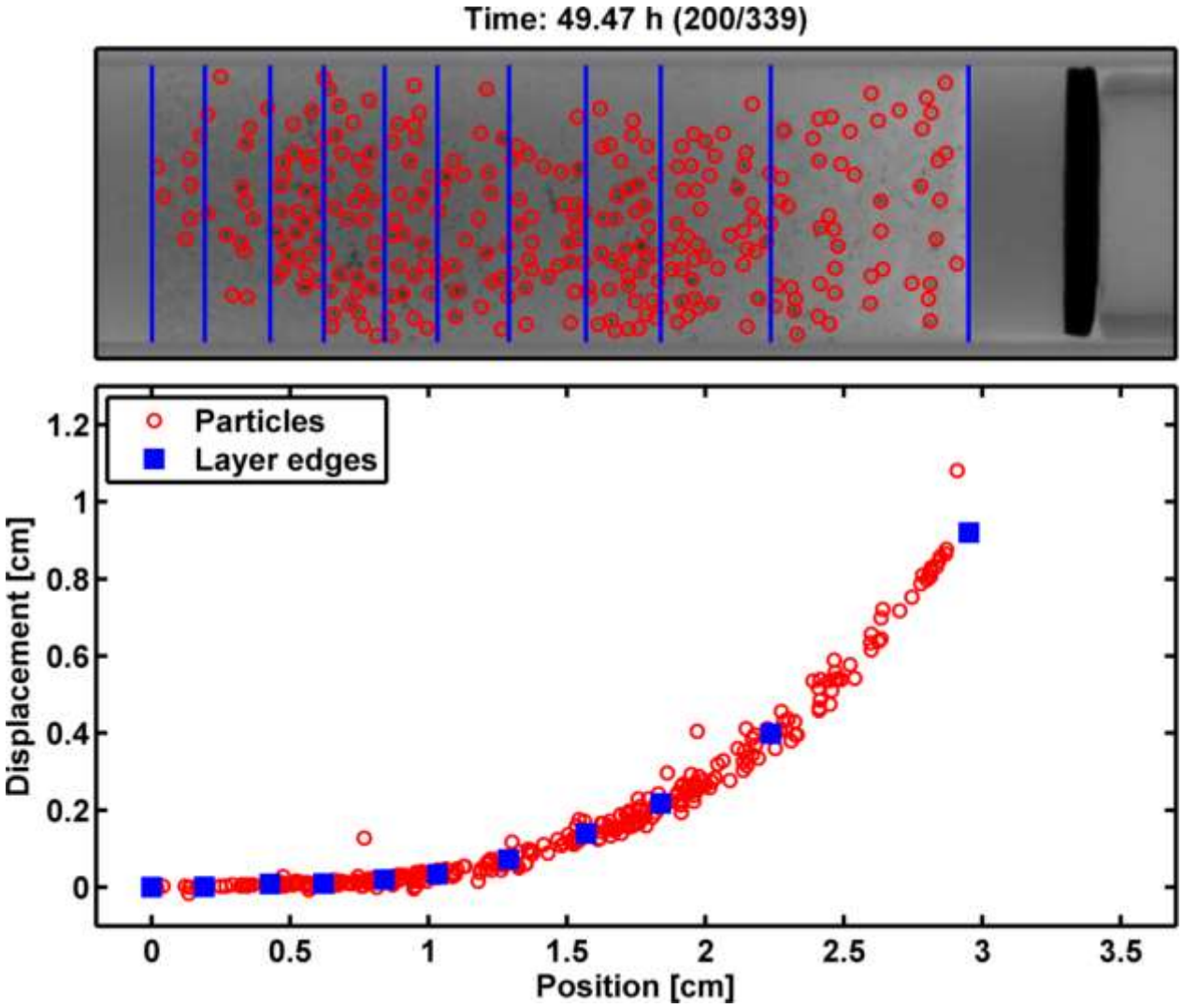

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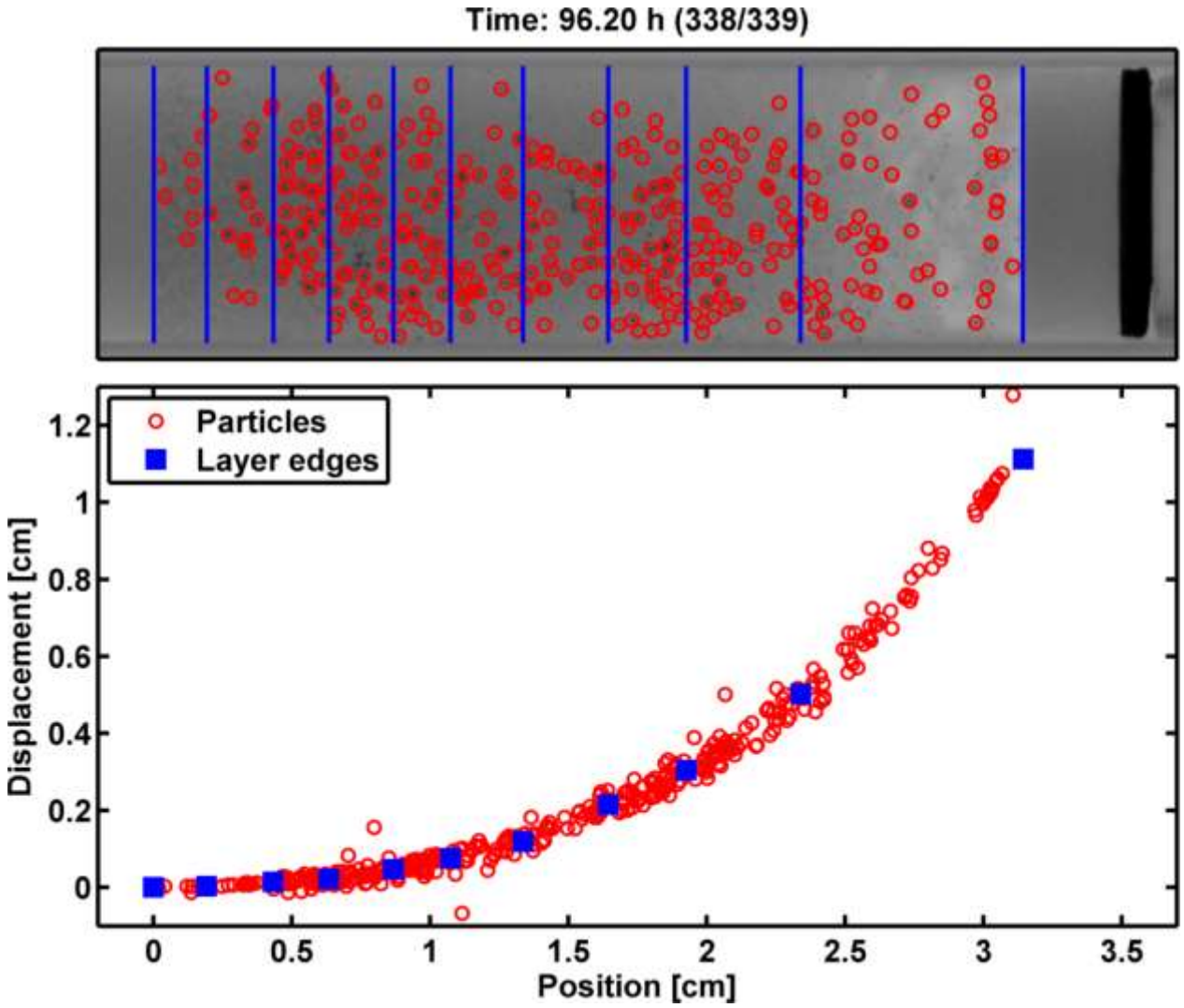
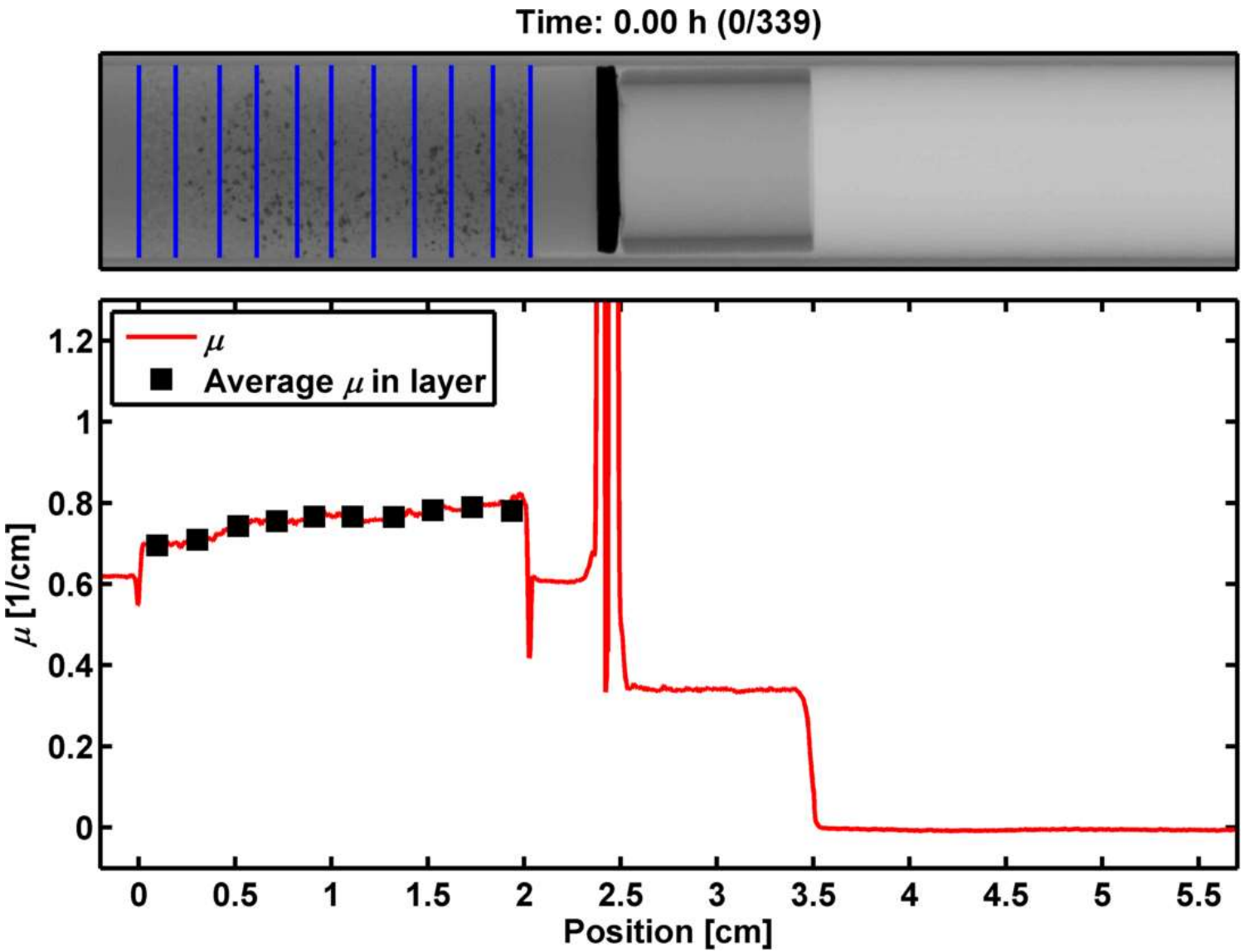


Dry density distribution

$\rho_b(z,t)$

Free swelling of MX80 – Attenuation coefficient



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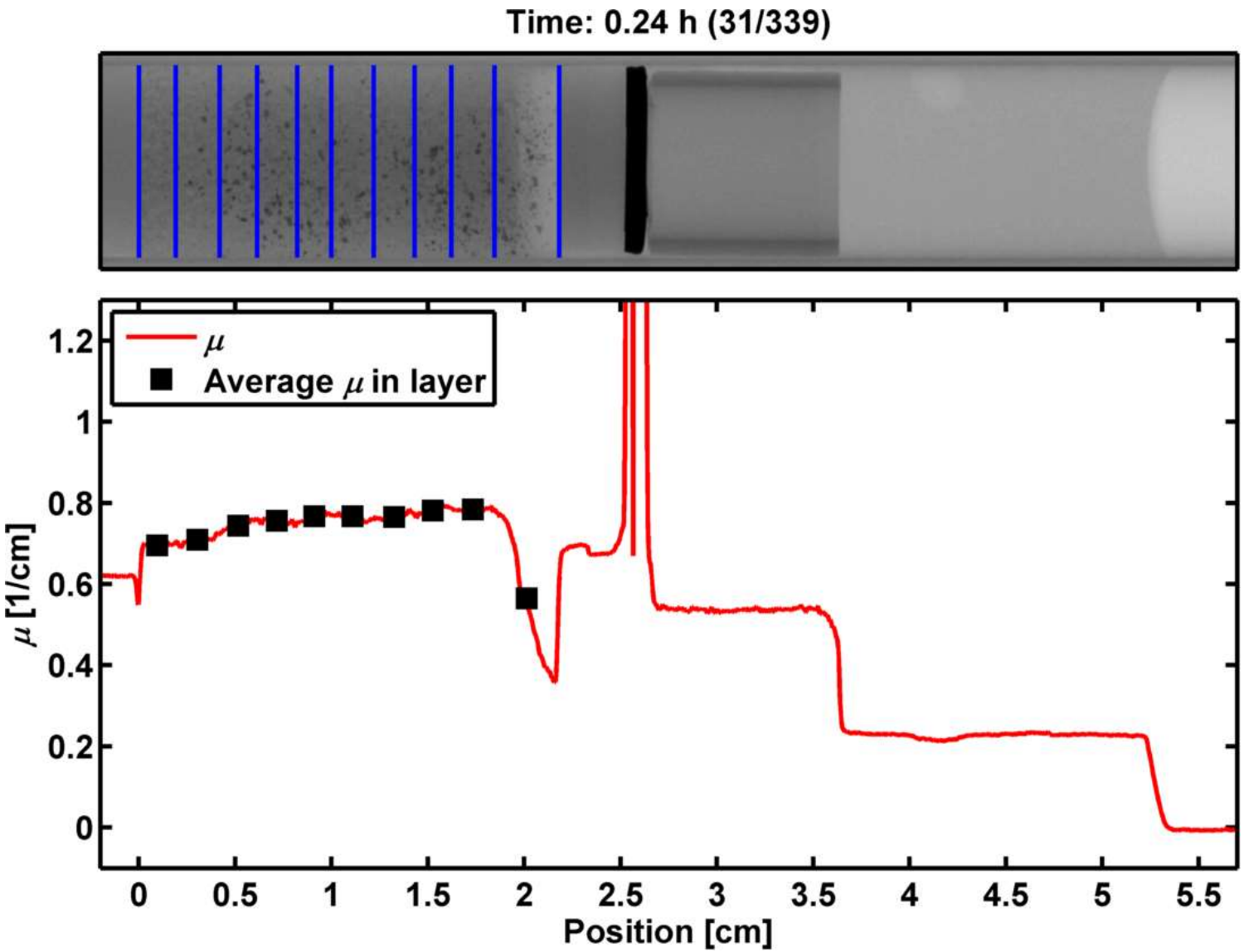

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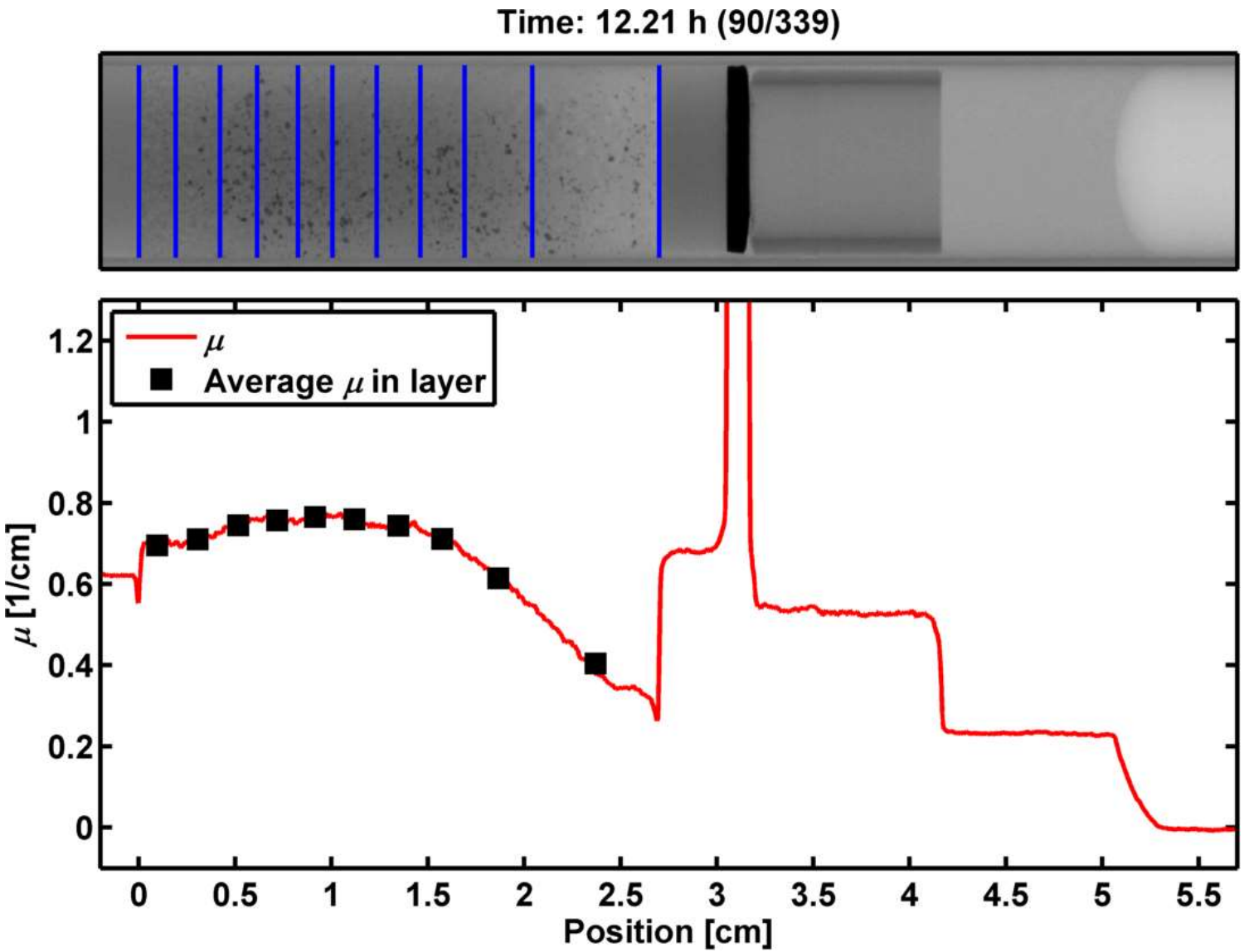

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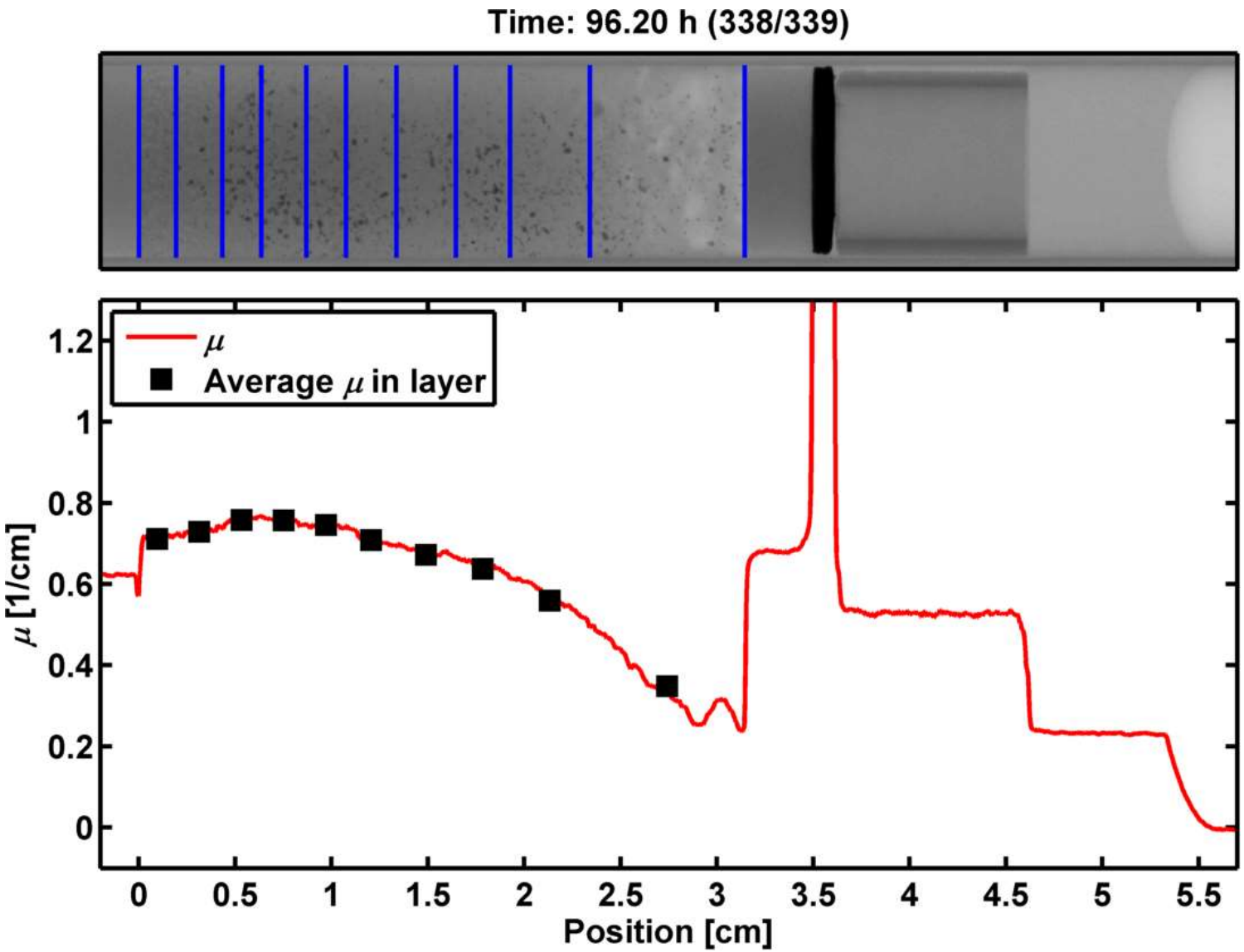


Free swelling of MX80 – Water content analysis

- Linear attenuation coefficient μ of the wetting sample depends on dry density ρ_b and water content ρ_w as

$$\mu = C_b\rho_b + C_w\rho_w$$

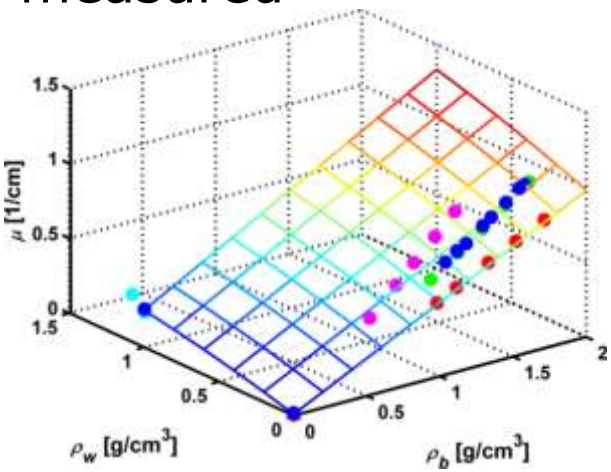
Dry density distribution

➡ $\rho_b(z,t)$

- Here:
  - $\mu(z,t)$ given by X-ray image gray scale value
  - $\rho_b(z,t)$ given by initial dry density and measured displacement field
  - C_b and C_w obtained from calibration data (gravimetric measurement)

Water content distribution

➡ $\rho_w(z,t) = (\mu(z,t) - C_b\rho_b(z,t))/C_w$

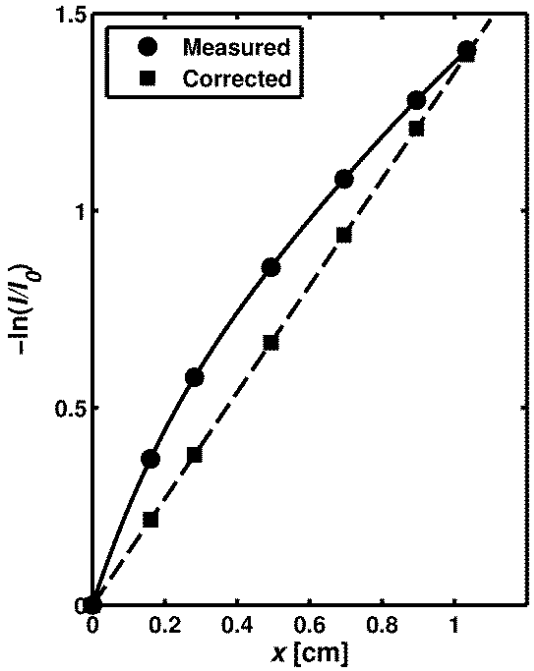


Calibration data

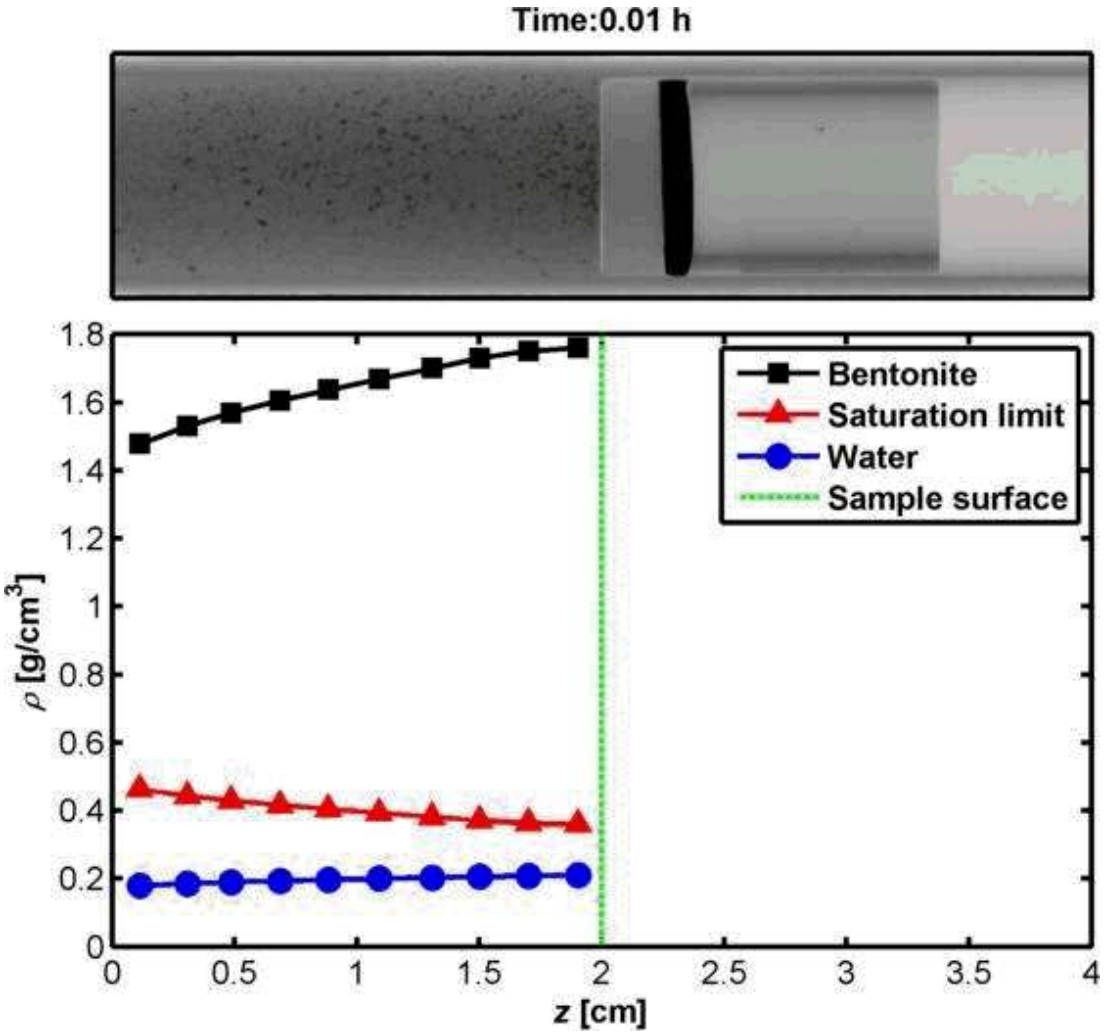
Correcting imaging errors and artefacts (crux of the method)

- Errors caused by polychromatic energy spectrum of the X-ray tube and its angular/temporal variations must be carefully corrected for.

- Dynamic flat field correction based on X-ray images of aluminum step wedge phantom taken between X-ray images of the sample.



Free swelling of MX80 – Results: $\rho_b(x,t)$ and $\rho_w(x,t)$



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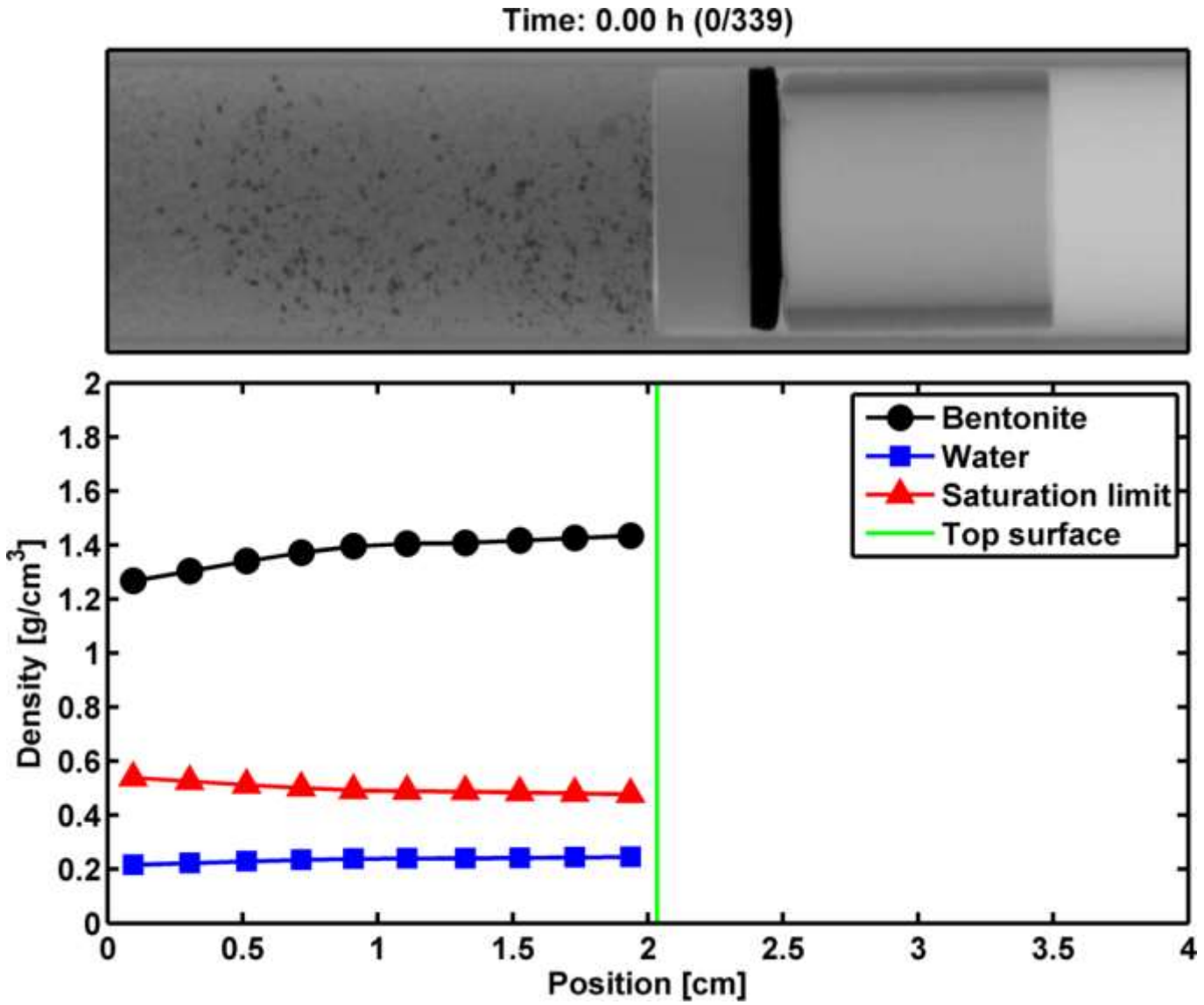

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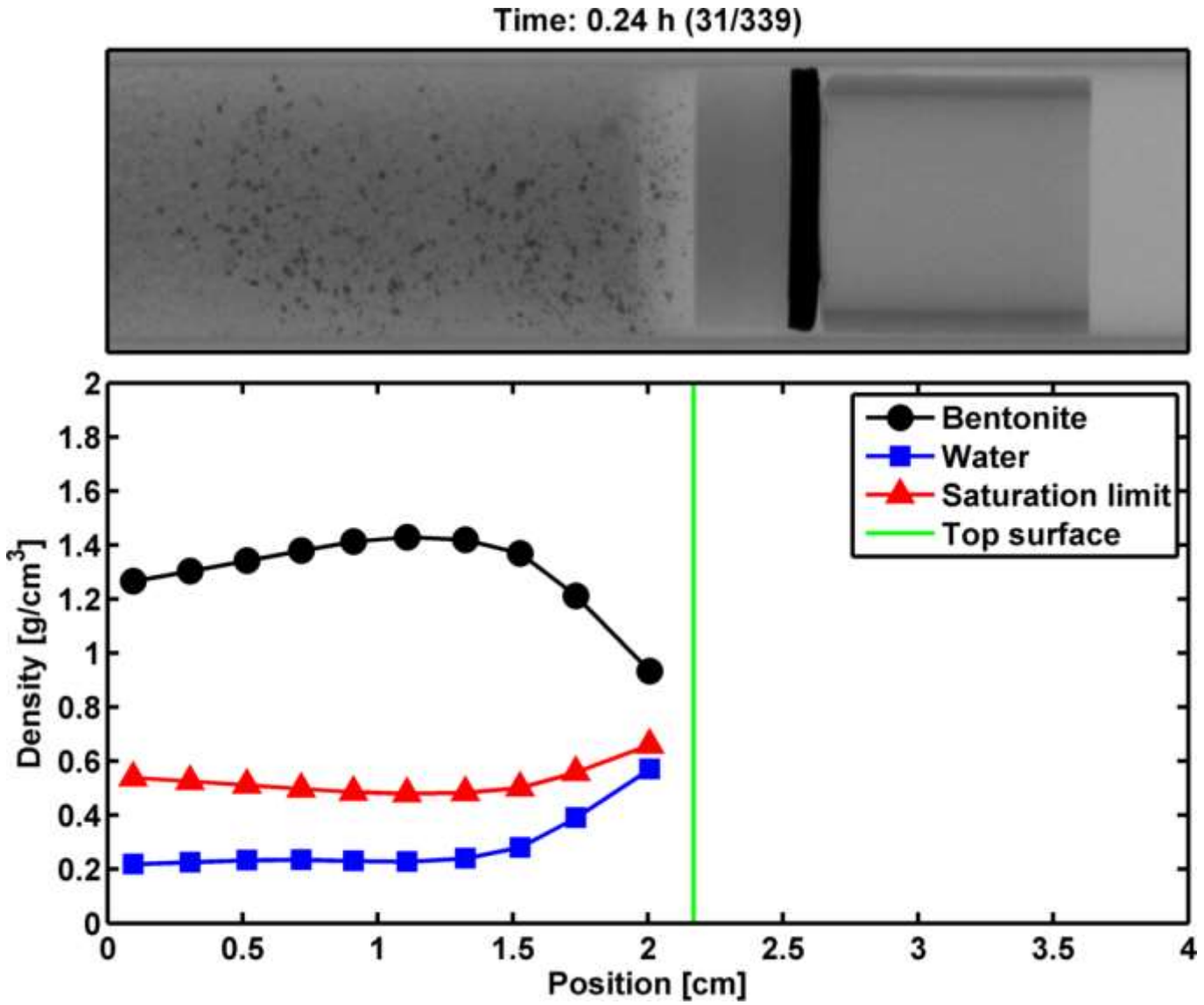

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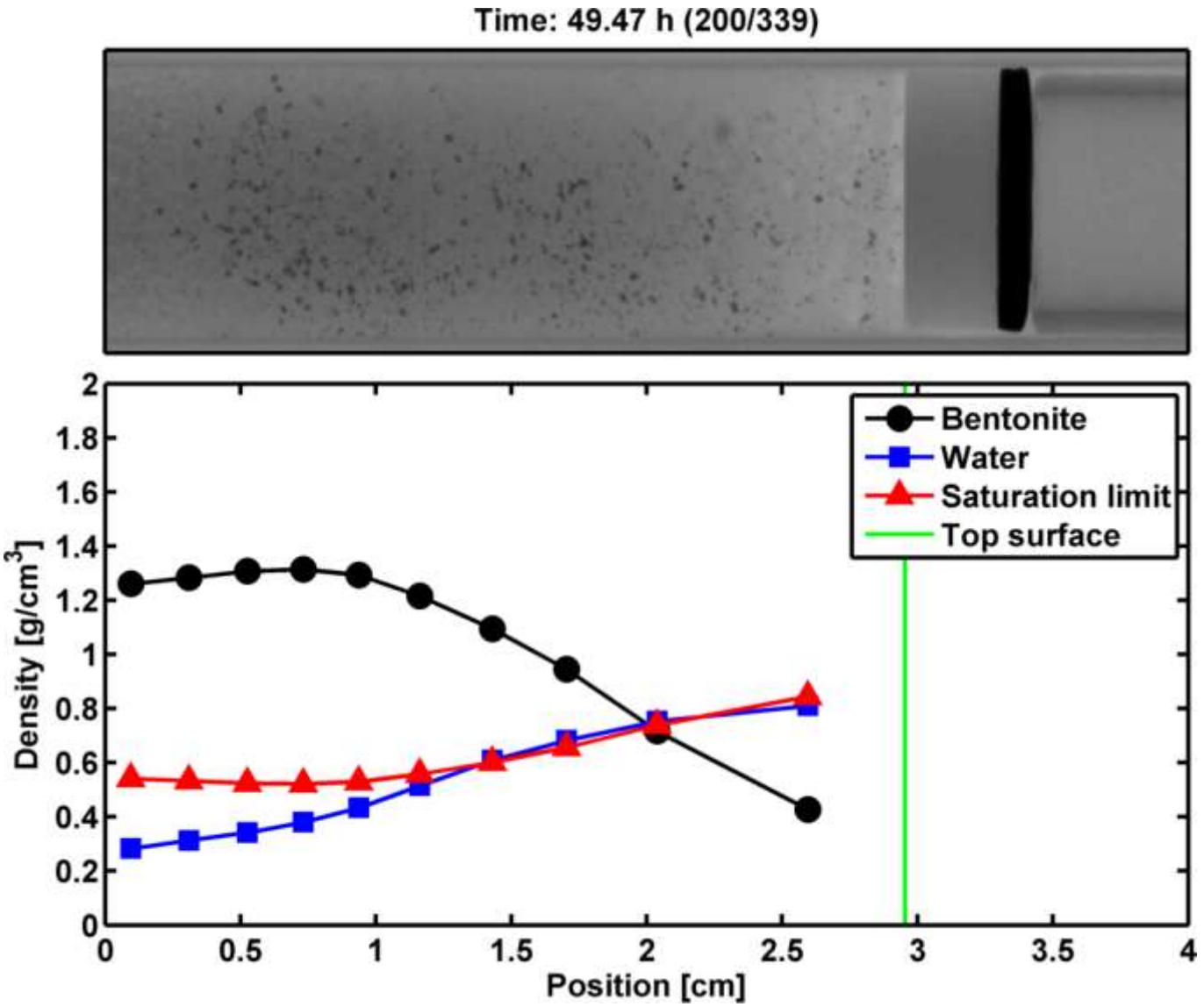

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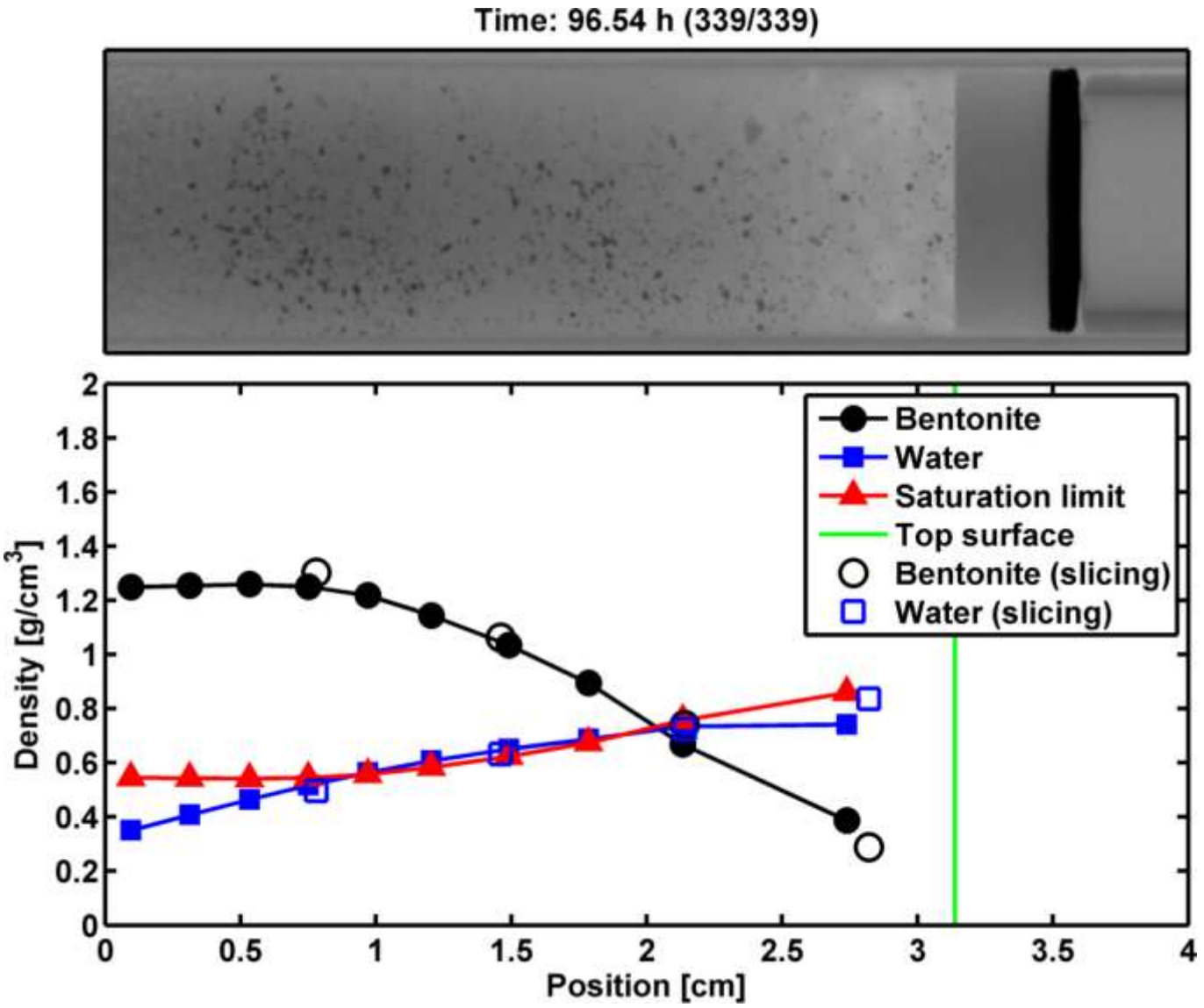


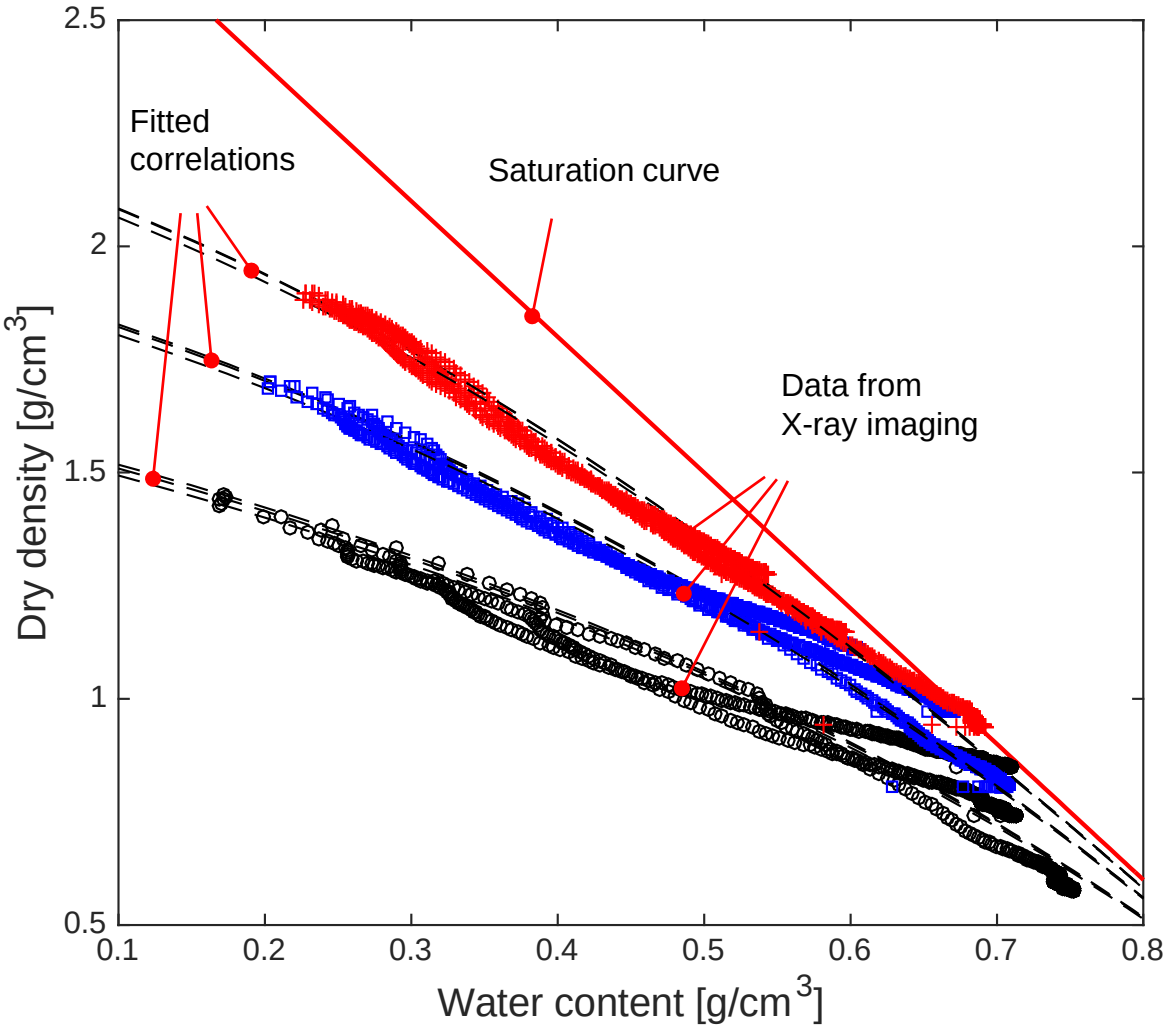
Free swelling experiments. Summary

Table 1: Number of experiments done.

	Initial water content		
Initial dry density	w_0 = 12%	w_0 = 17%	w_0 = 24%
ρ_b = 1.90 g/cm³	2	2	-
ρ_b = 1.65 g/cm³	2	2	2
ρ_b = 1.40 g/cm³	2	2	2

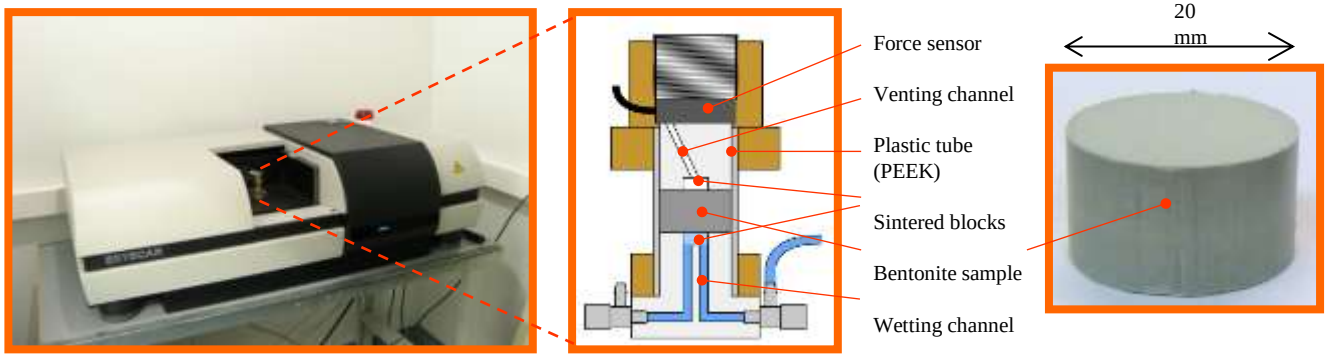
- Repeatability and accuracy reasonably good.
- Data is available for model validation etc.

Free swelling of MX80 – Results: Free swelling curves

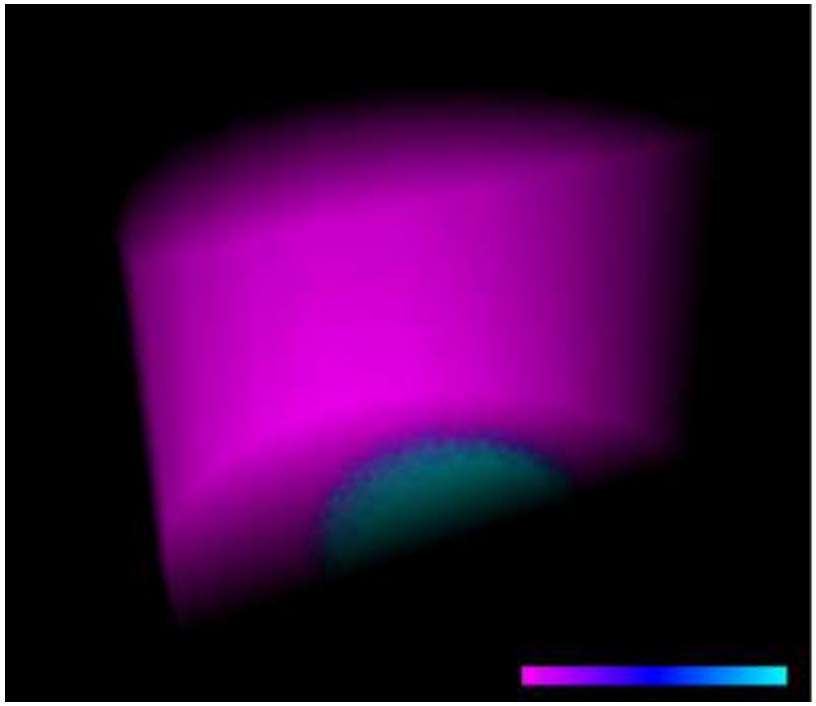


4D tomography : Monitoring wetting/swelling process

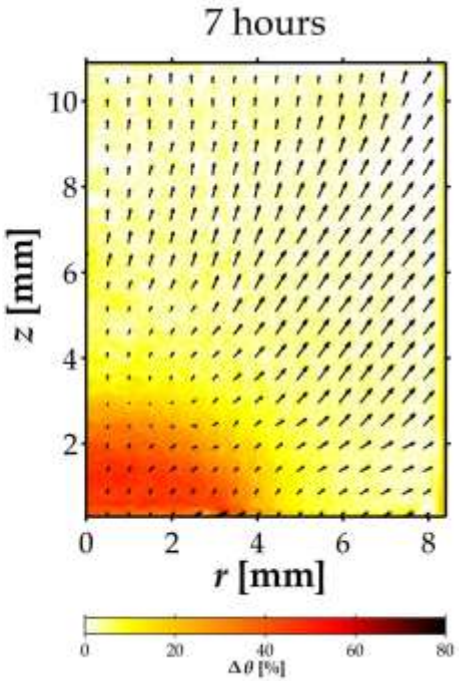
X-ray tomographic scanner, sample holder and a material sample (compacted bentonite).



Diffusive water transport



Water content and displacement due to swelling (averaged over azimuthal angle)



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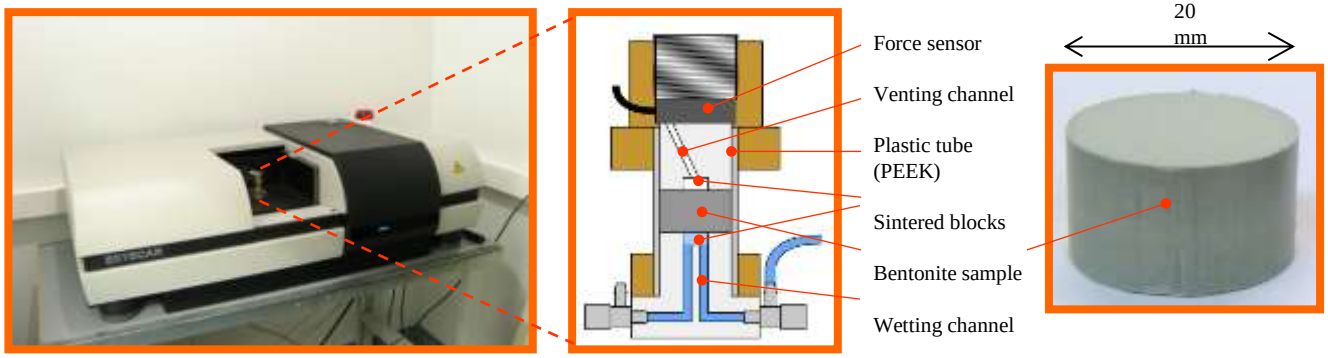

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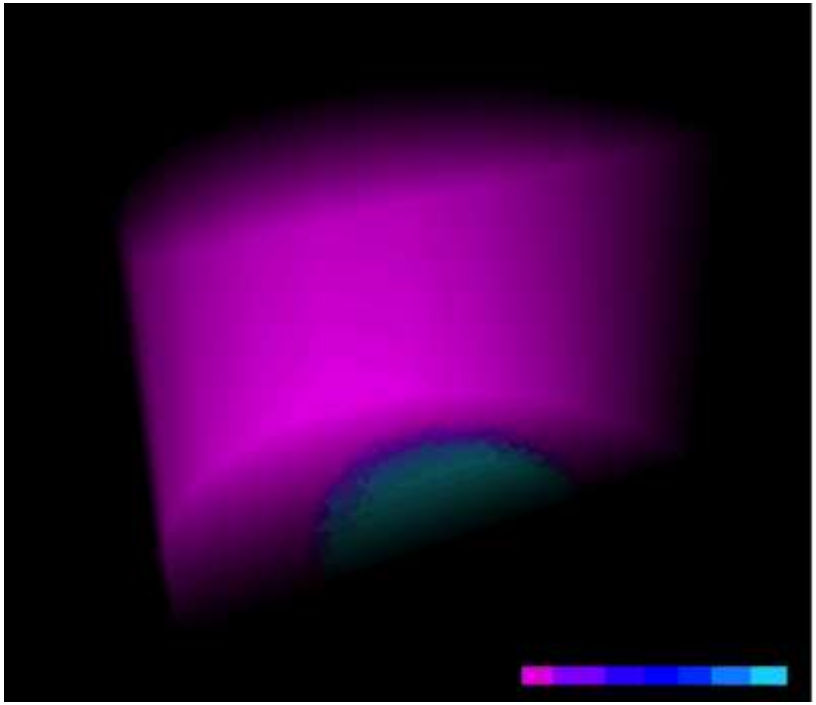

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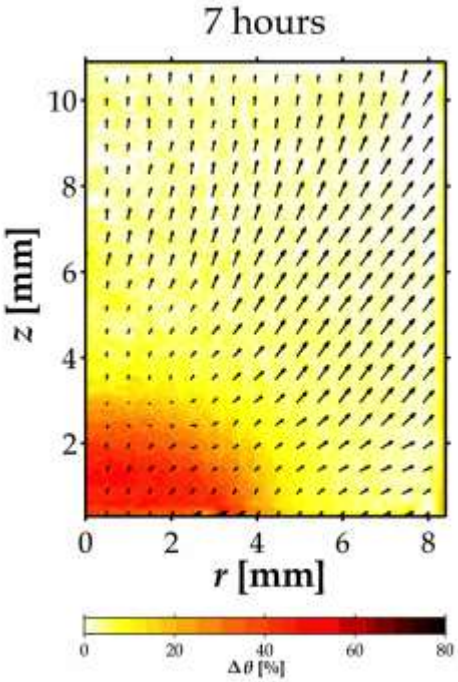

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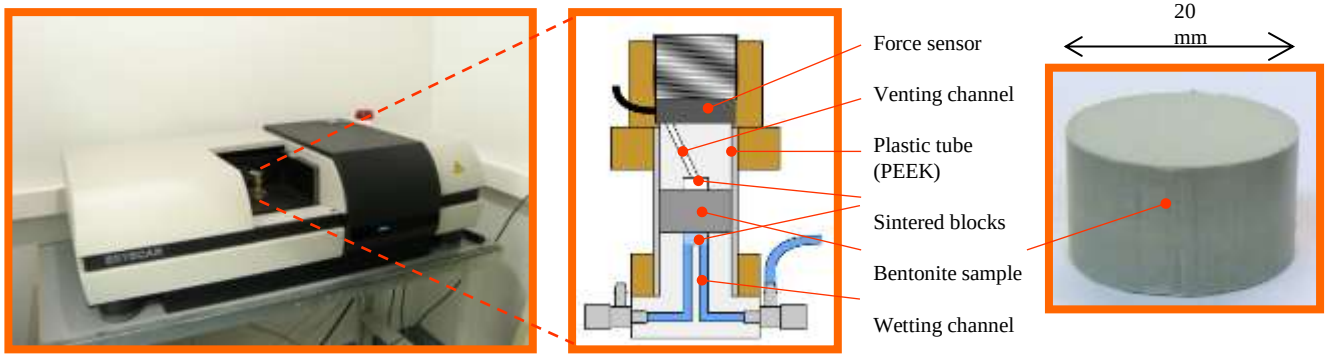

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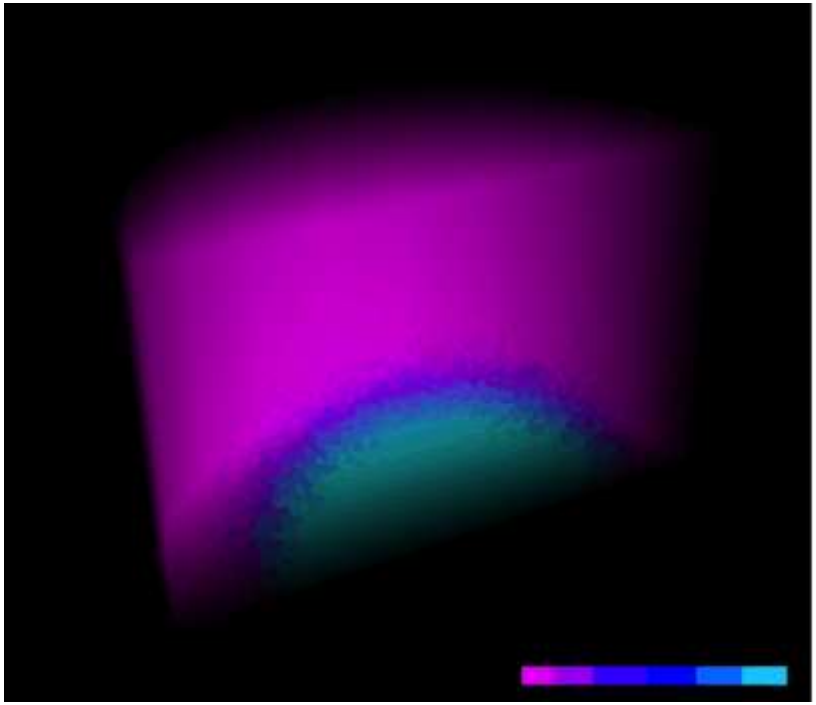

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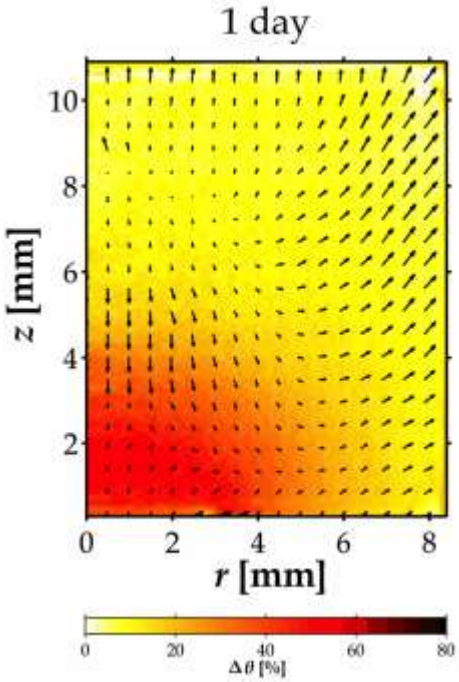

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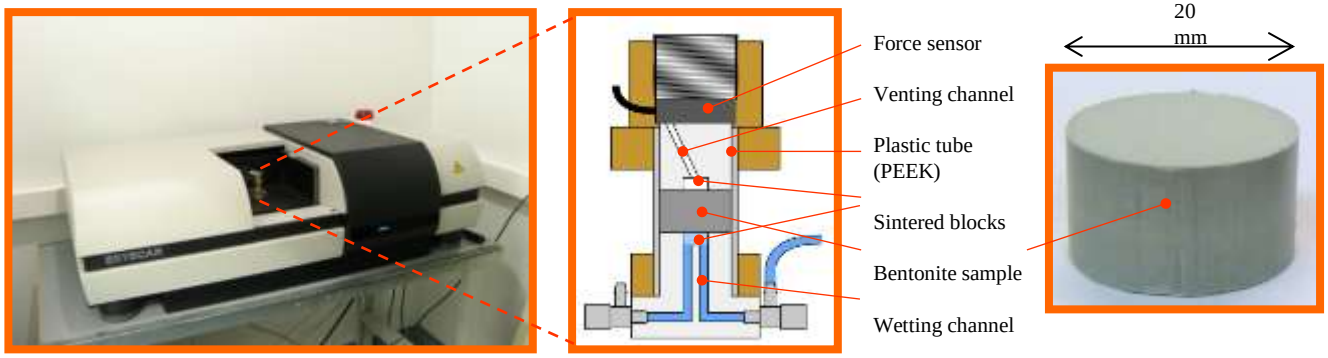
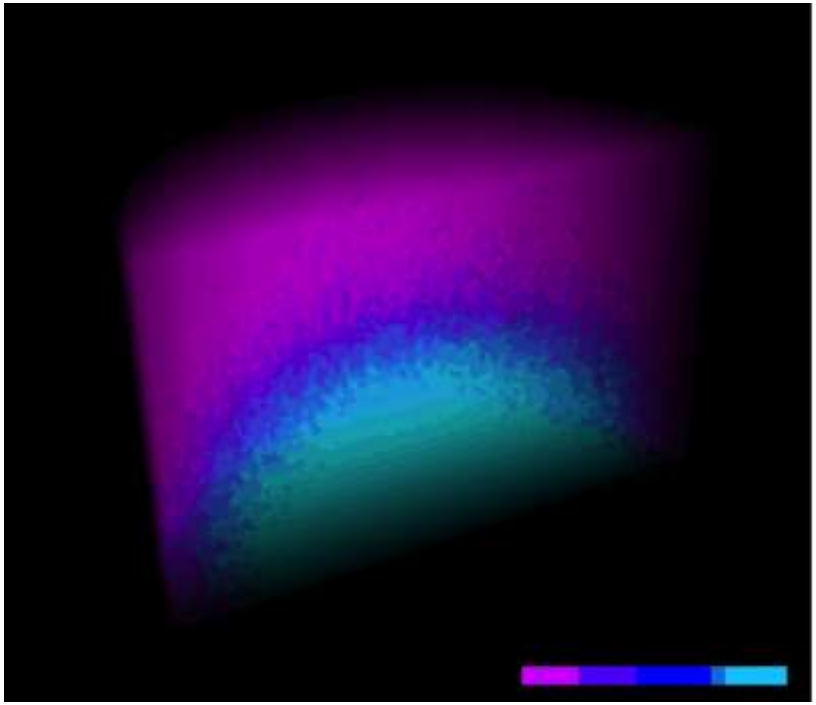
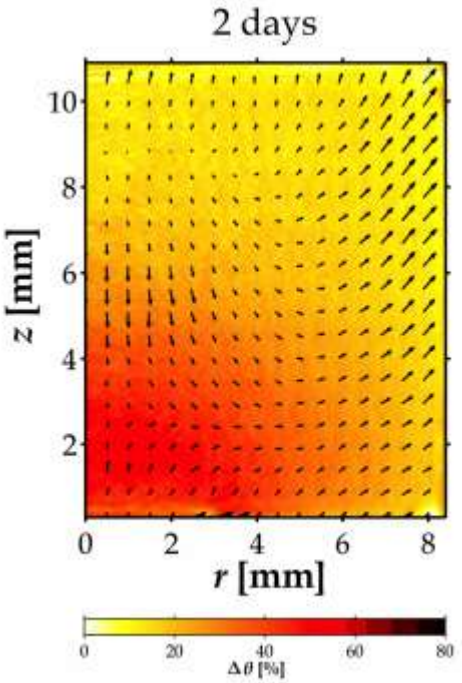


Diffusive water transport

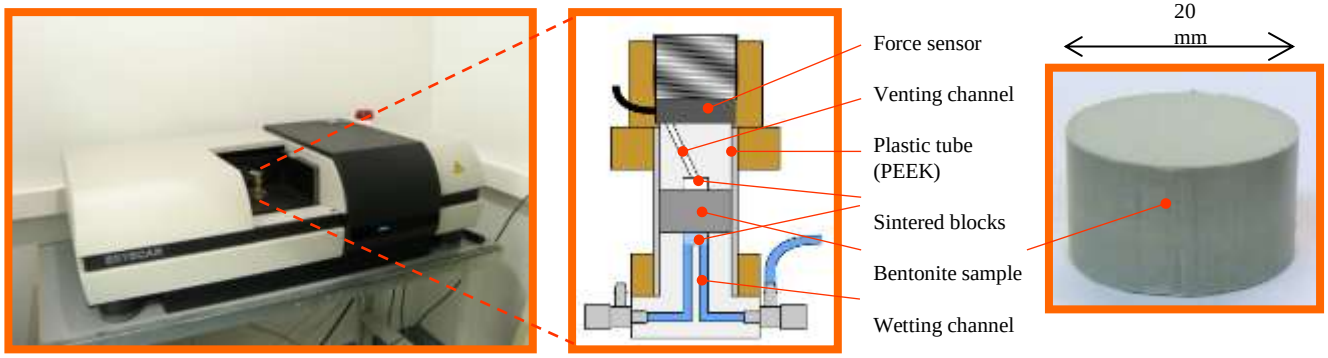


Water content and displacement due to swelling (averaged over azimuthal angle)

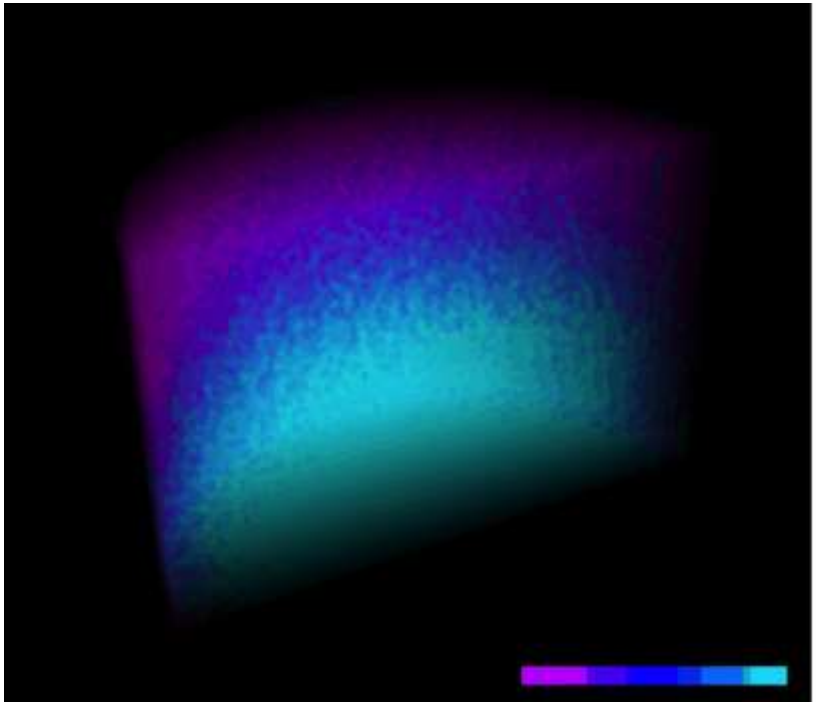


4D tomography : Monitoring wetting/swelling process

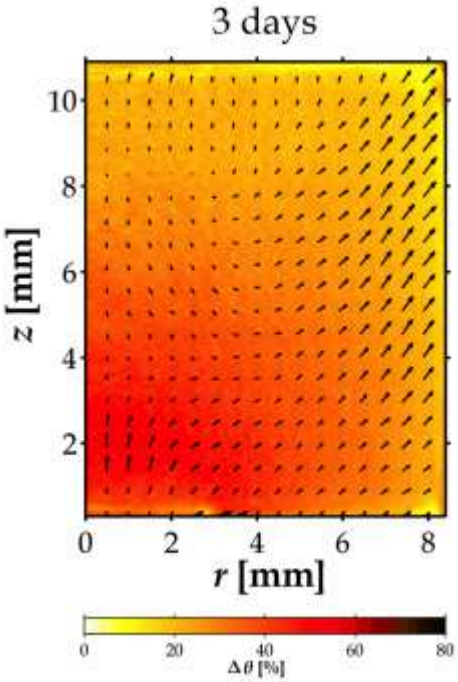
X-ray tomographic scanner, sample holder and a material sample (compacted bentonite).



Diffusive water transport



Water content and displacement due to swelling (averaged over azimuthal angle)



4D tomography : Monitoring wetting/swelling process

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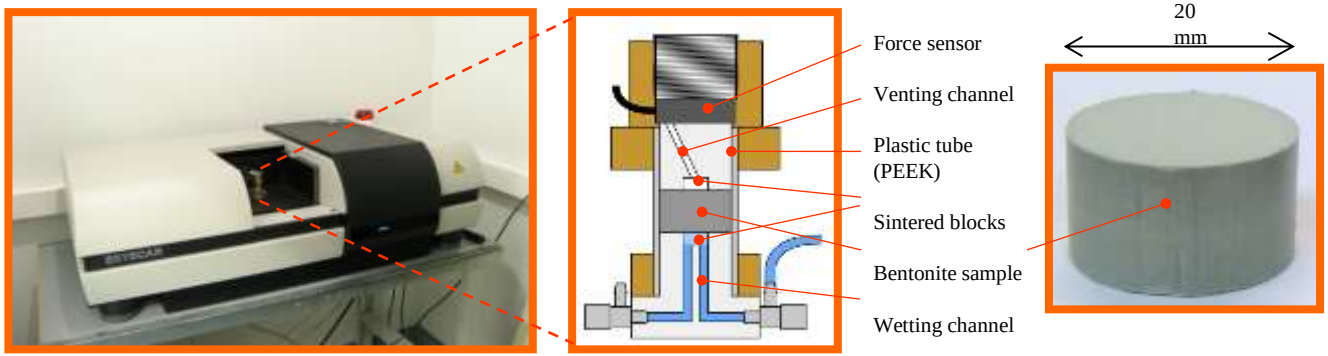
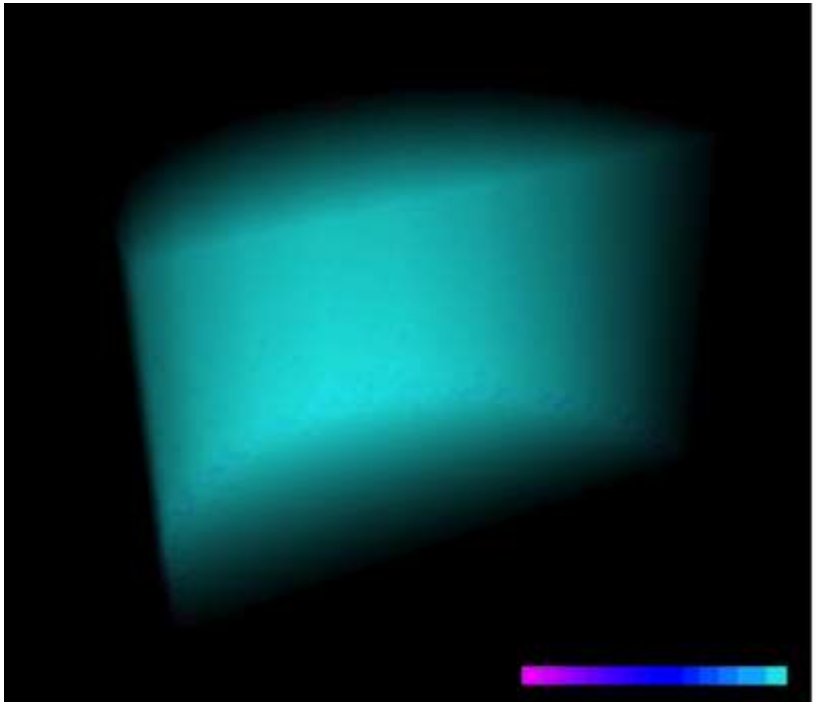
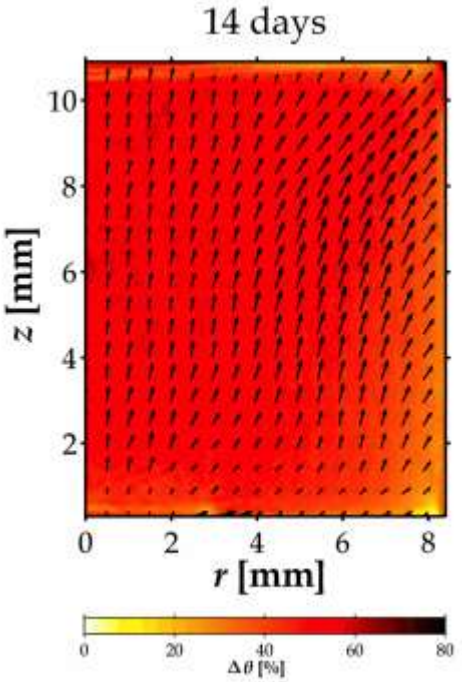


Diffusive water transport



Water content and displacement due to swelling (averaged over azimuthal angle)



Conclusions

- Two non-destructive methods, based on X-ray imaging and tomography, have been successfully used for monitoring wetting and swelling behaviour of bentonite.
- Repeatability and accuracy reasonably good.
- Extensive set of free swelling experiments has been carried out in 2016 and the data is available for model validation etc.
- Ongoing (THEBES project): 1D wetting experiments in closed volume using X-ray imaging.

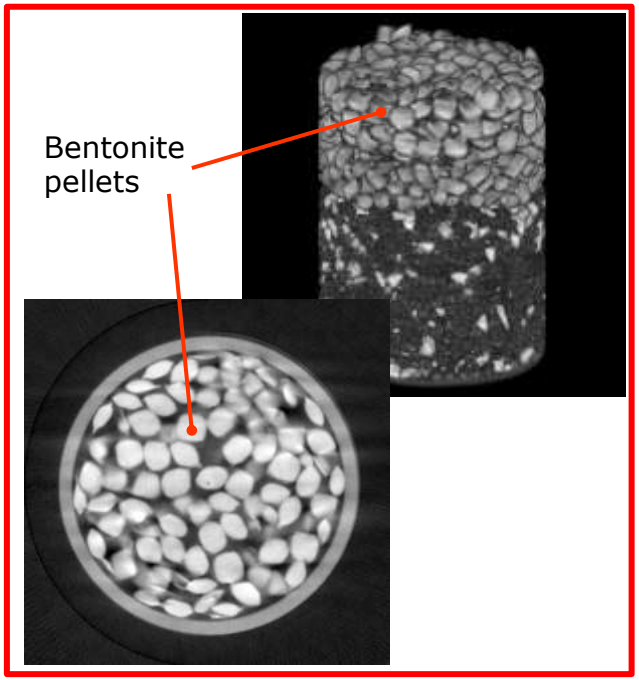
Future prospects / Beacon

- A medical X-ray source will be used to study homogenization with larger sample size

Linac X-ray source, 6-20 MeV

Sample chamber design
-Diameter 100 mm.

First test image
(tomography with 6 MeV X-rays)



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