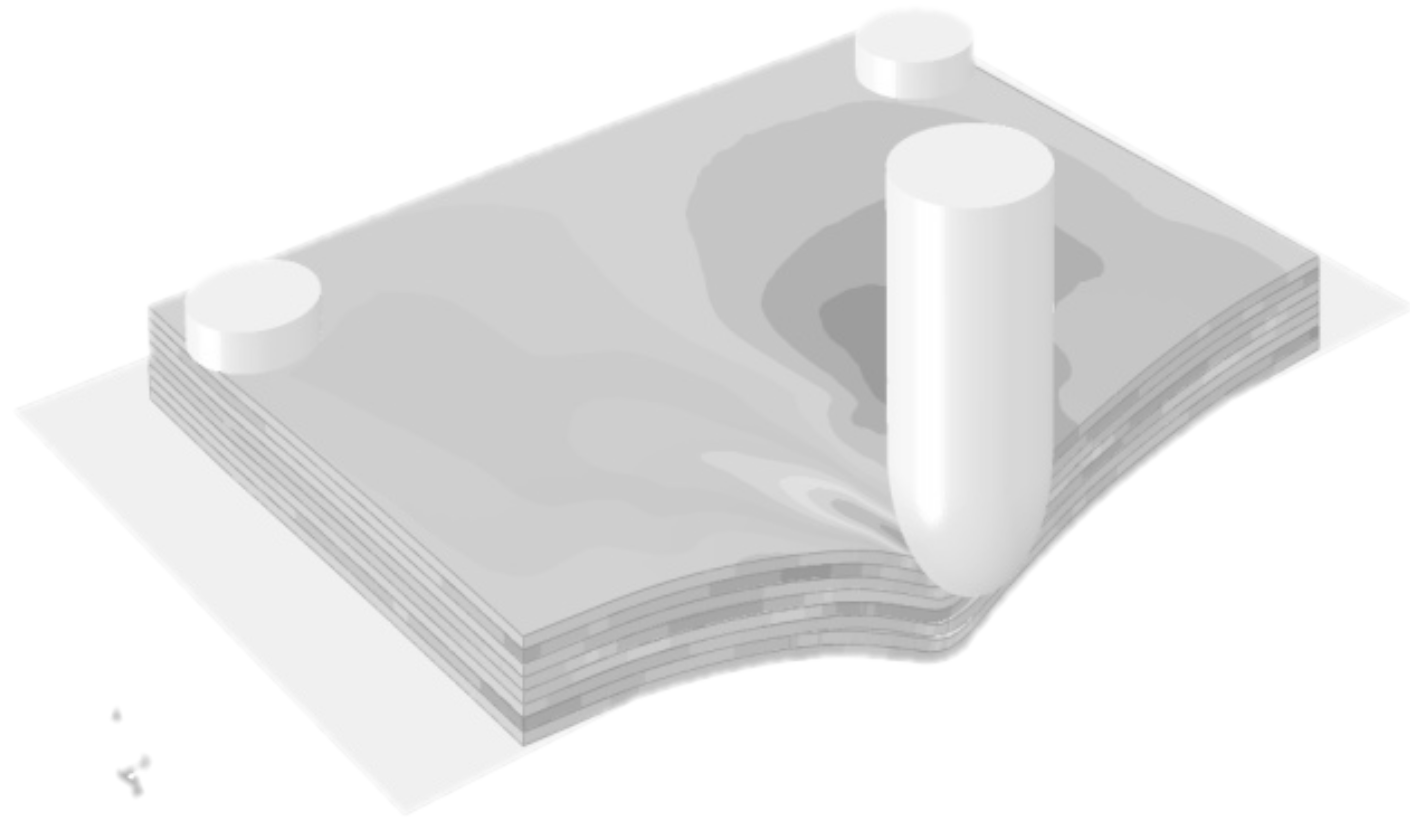




Digital twin of the tomography system

Josep Costa¹, Laura Carreras¹, Adrià Julià²

¹AMADE

² Graphics and Imaging Laboratory (GILAB)

Universitat de Girona



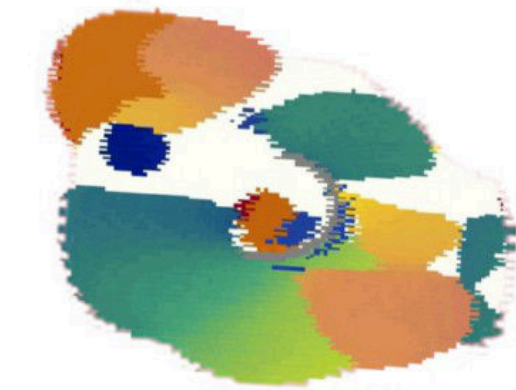
Table of contents

- Motivation. Tomography for CAI specimens.
- Methodology. The digital twin.
- Laminography analysis.
- Conclusions.

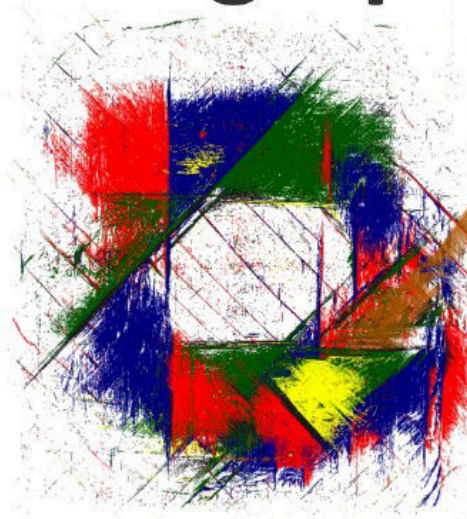
Motivation. Tomography and Composites.

- ❑ Tomography is currently a widely used Non-Destructive-Testing technique to study the microstructure and damage mechanisms of composites

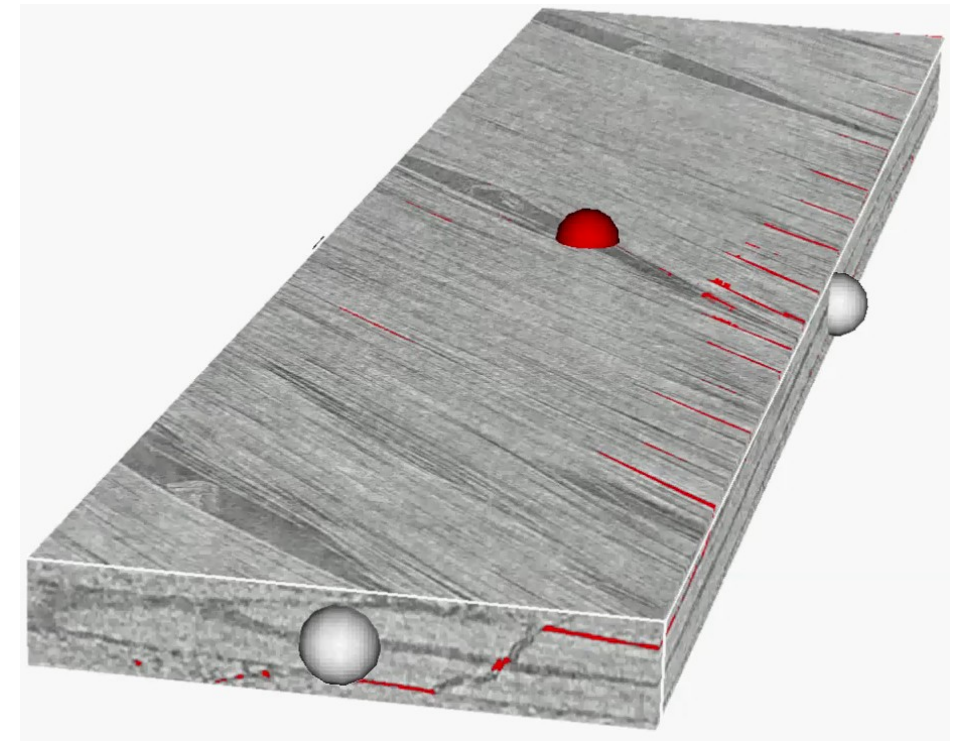
C-scan



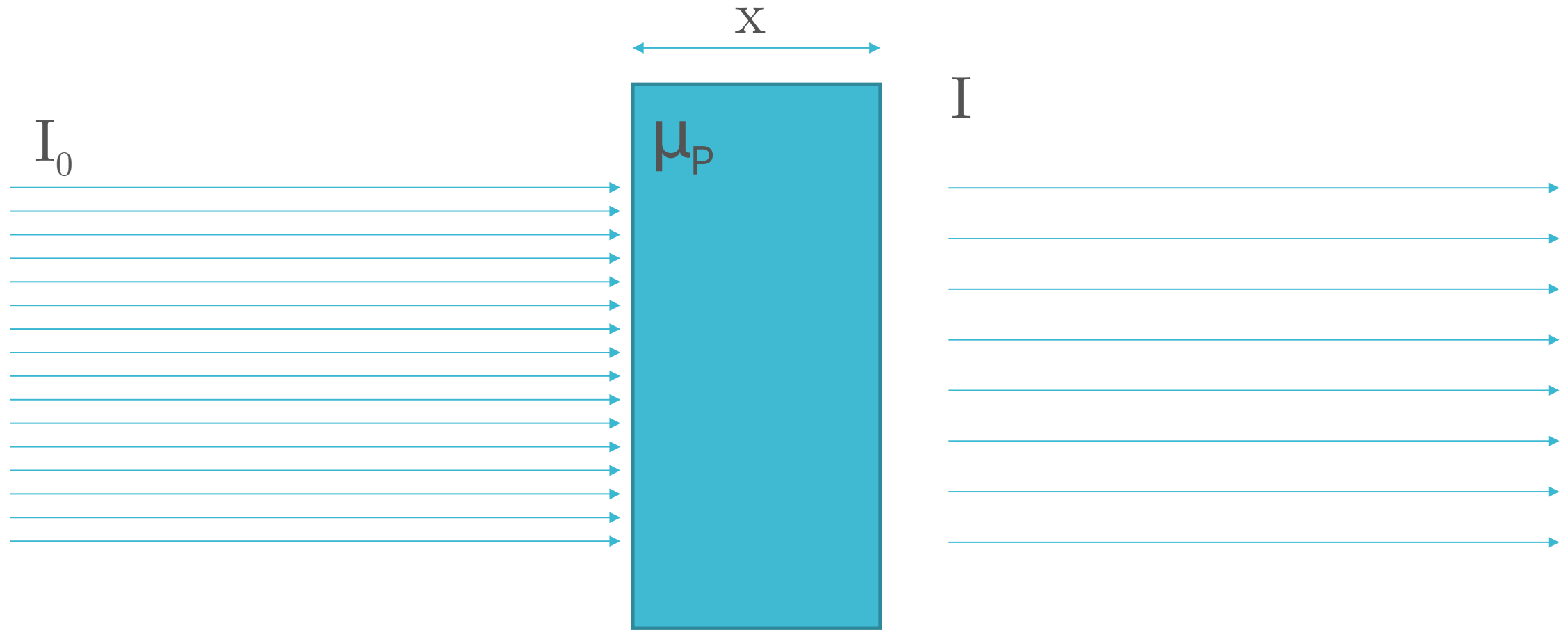
Tomography



10 mm

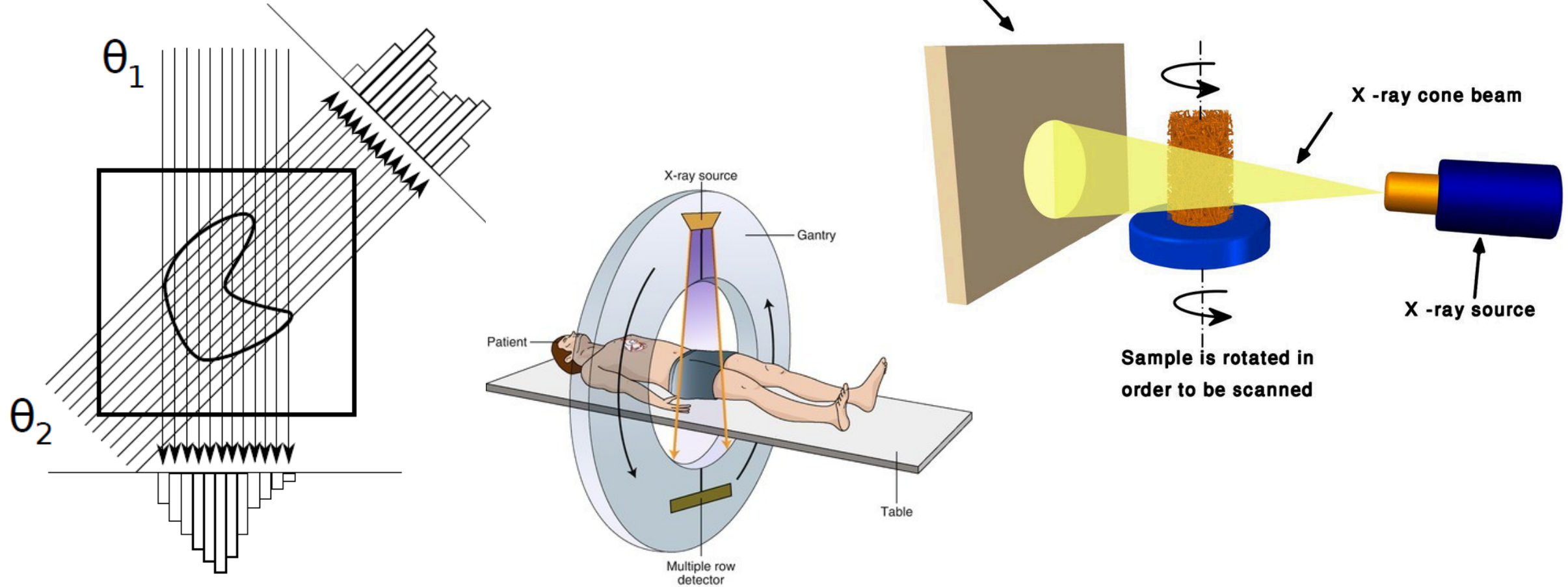


X-ray attenuation



$$I = I_0 e^{-\mu_p x}$$

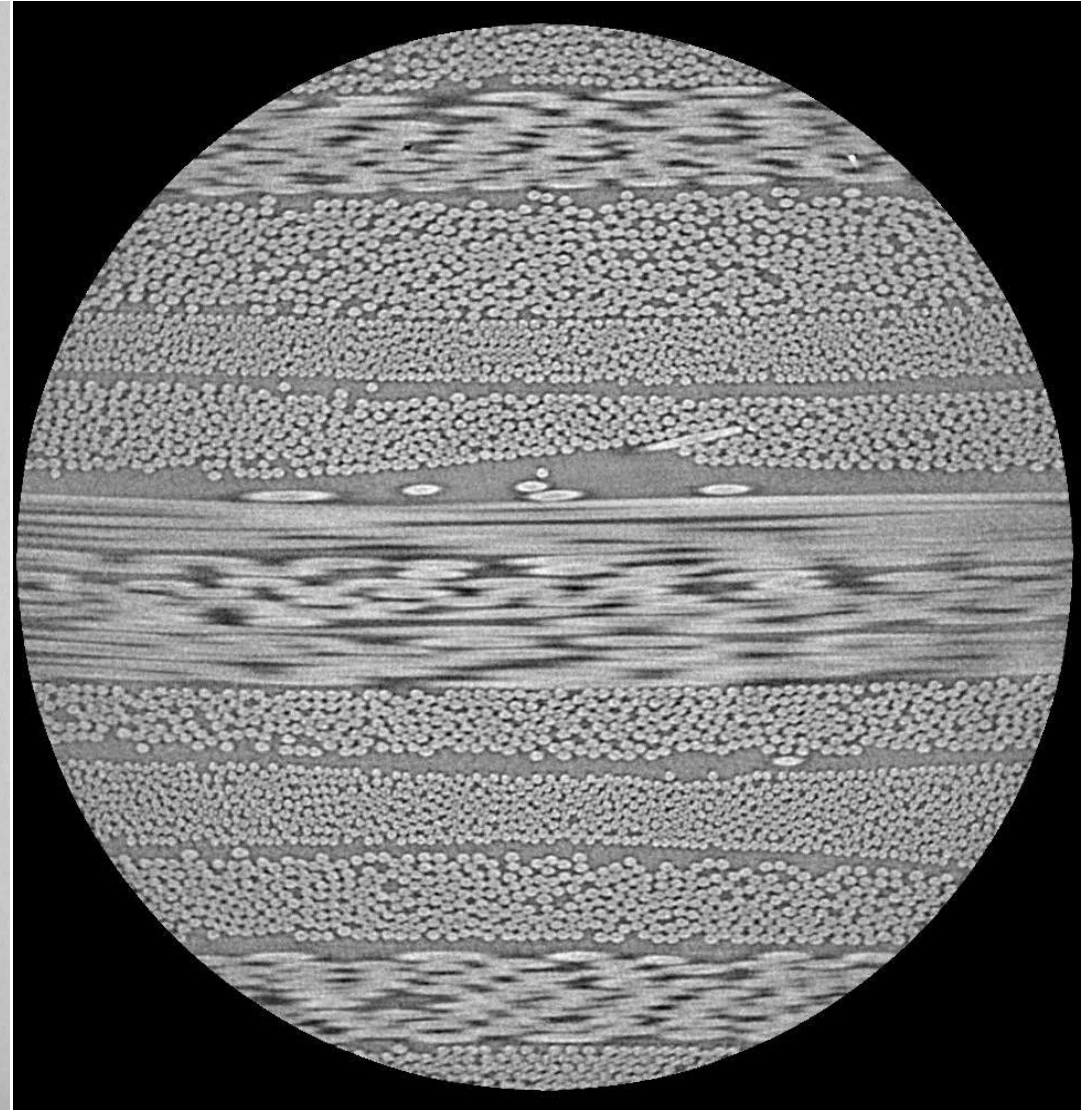
Motivation. The principle of tomography.



X-ray tomography

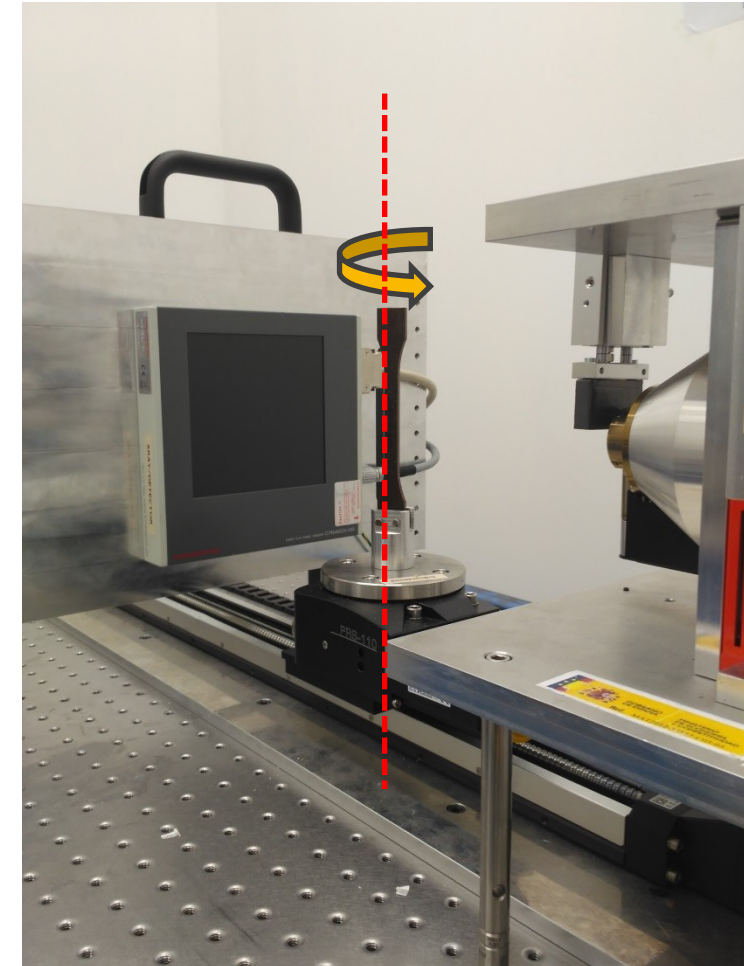
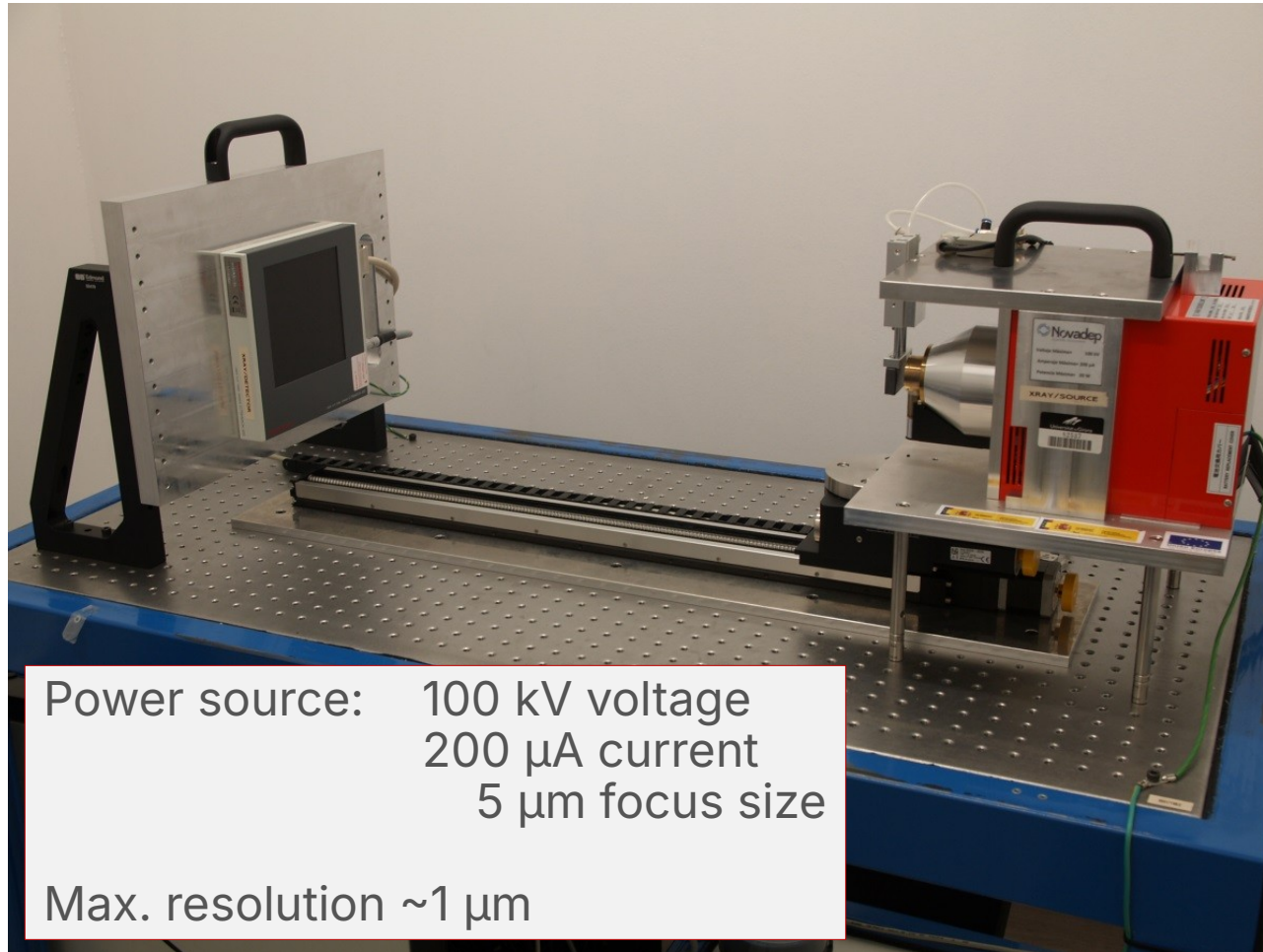


Acquisition

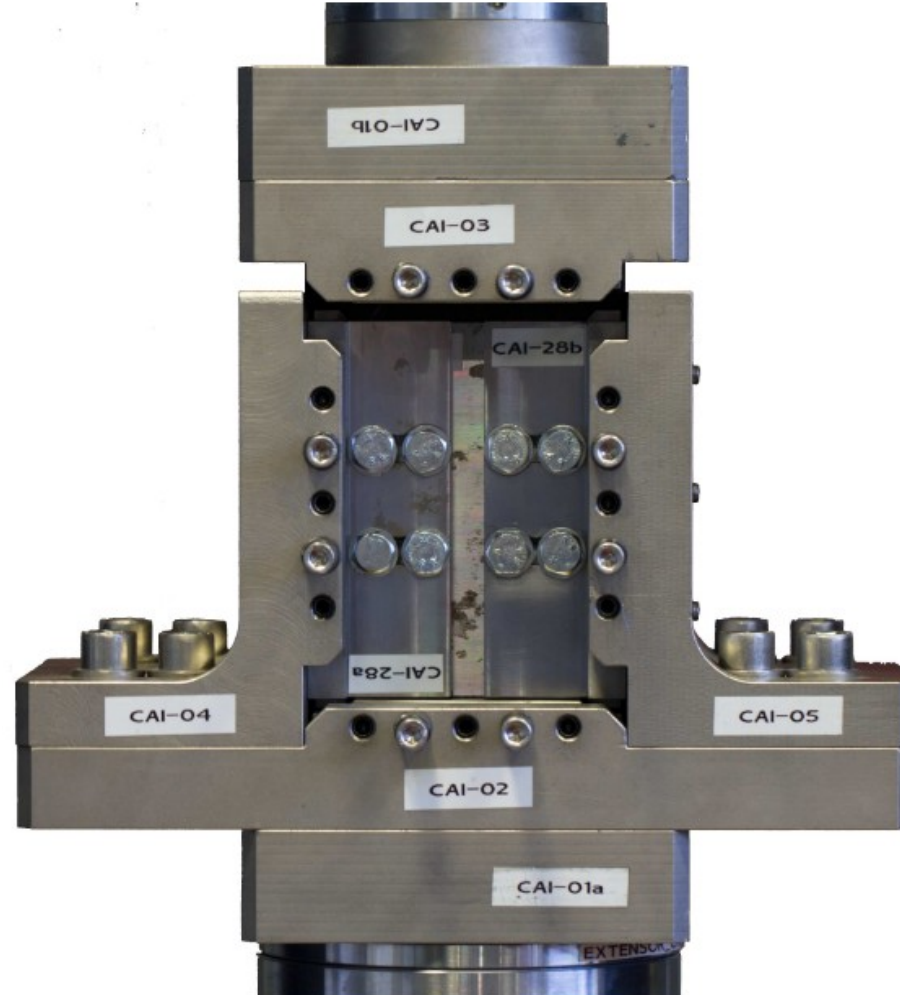
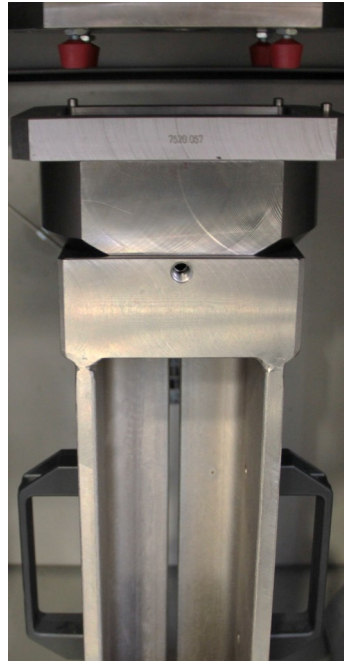
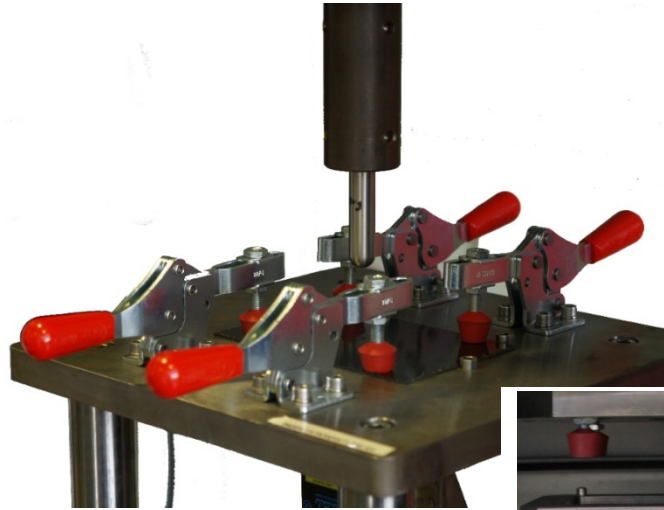


Result

Motivation. The tomography system at UdGirona



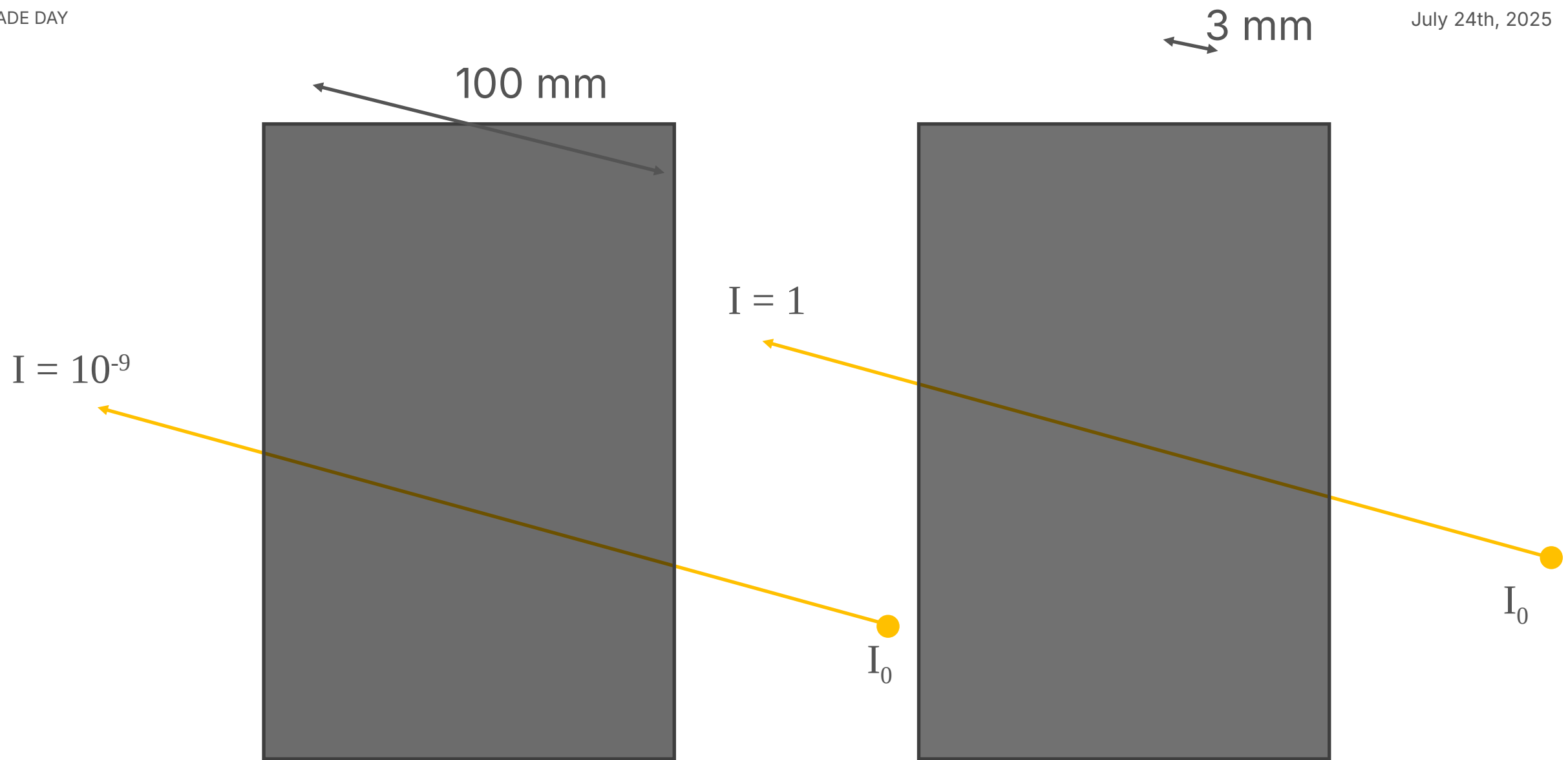
Motivation. CAI specimens.



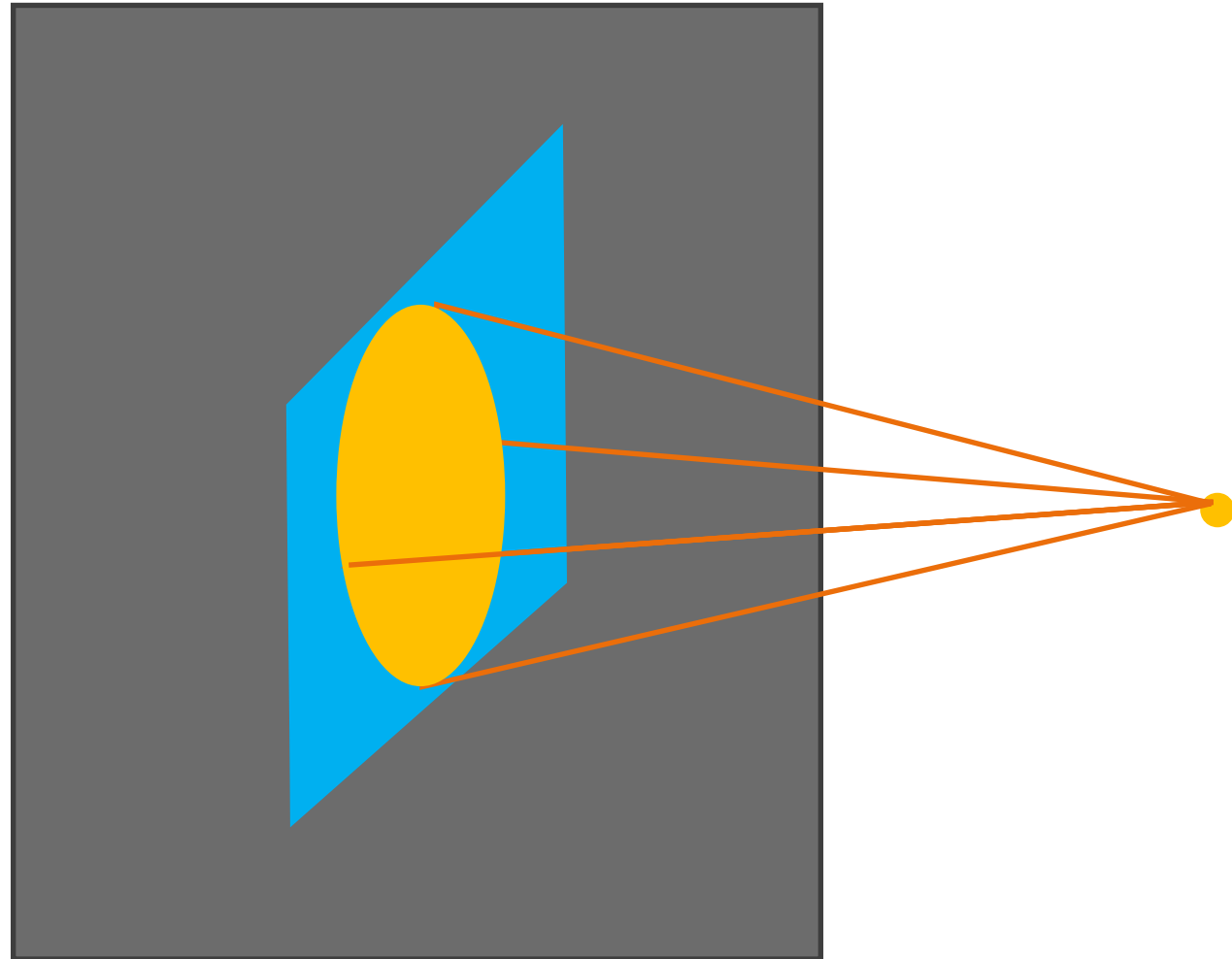
100 mm

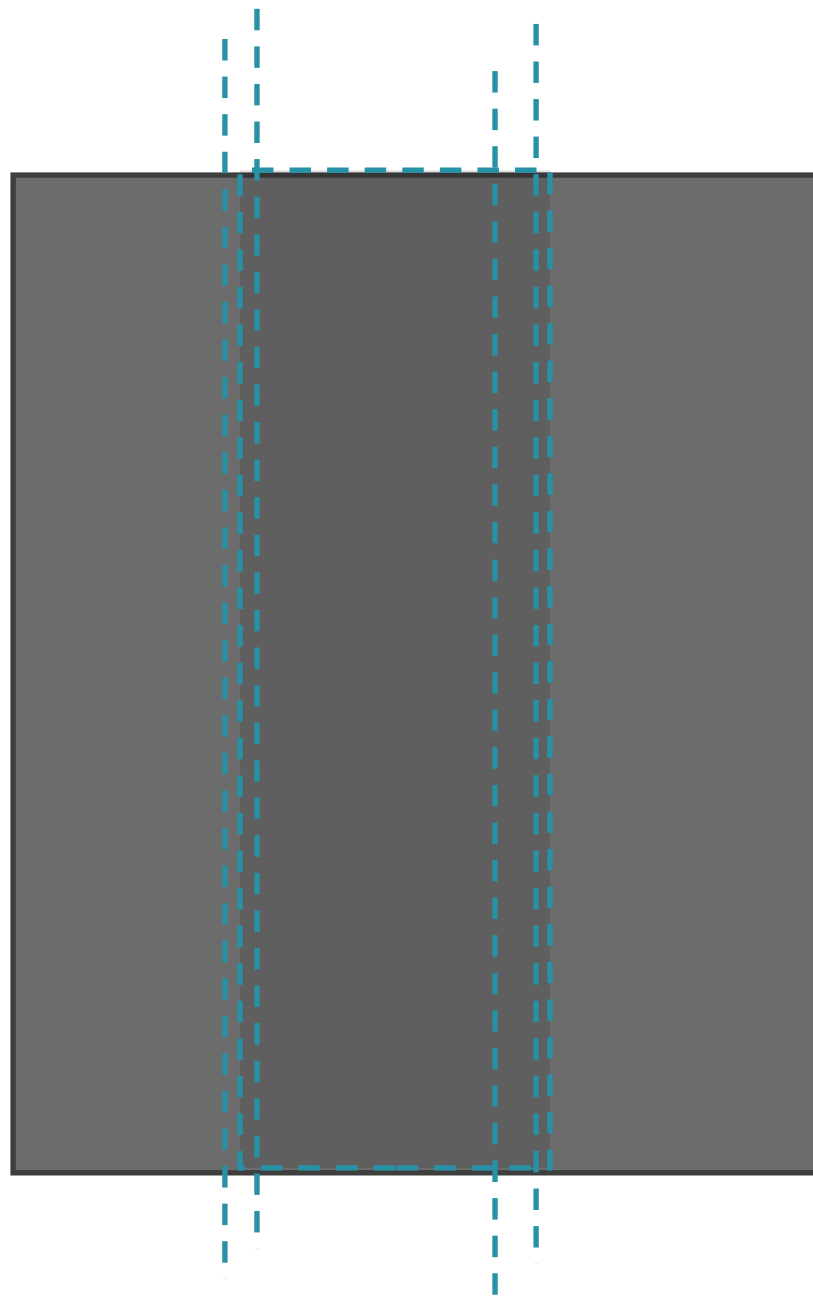
150 mm





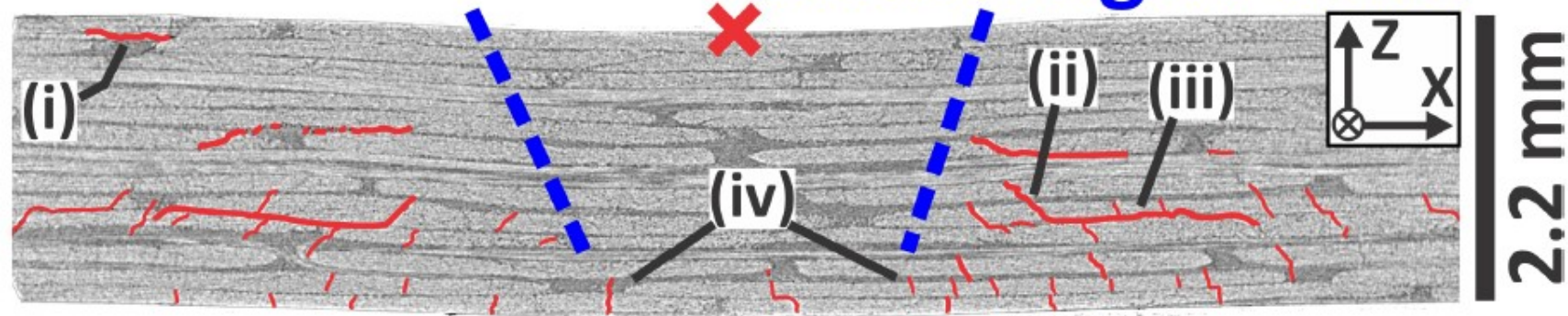
$$I = I_0 e^{-\mu \cdot L}$$





Damage scenario

Undamaged cone



(i) Fibre failure

(iii) Delamination



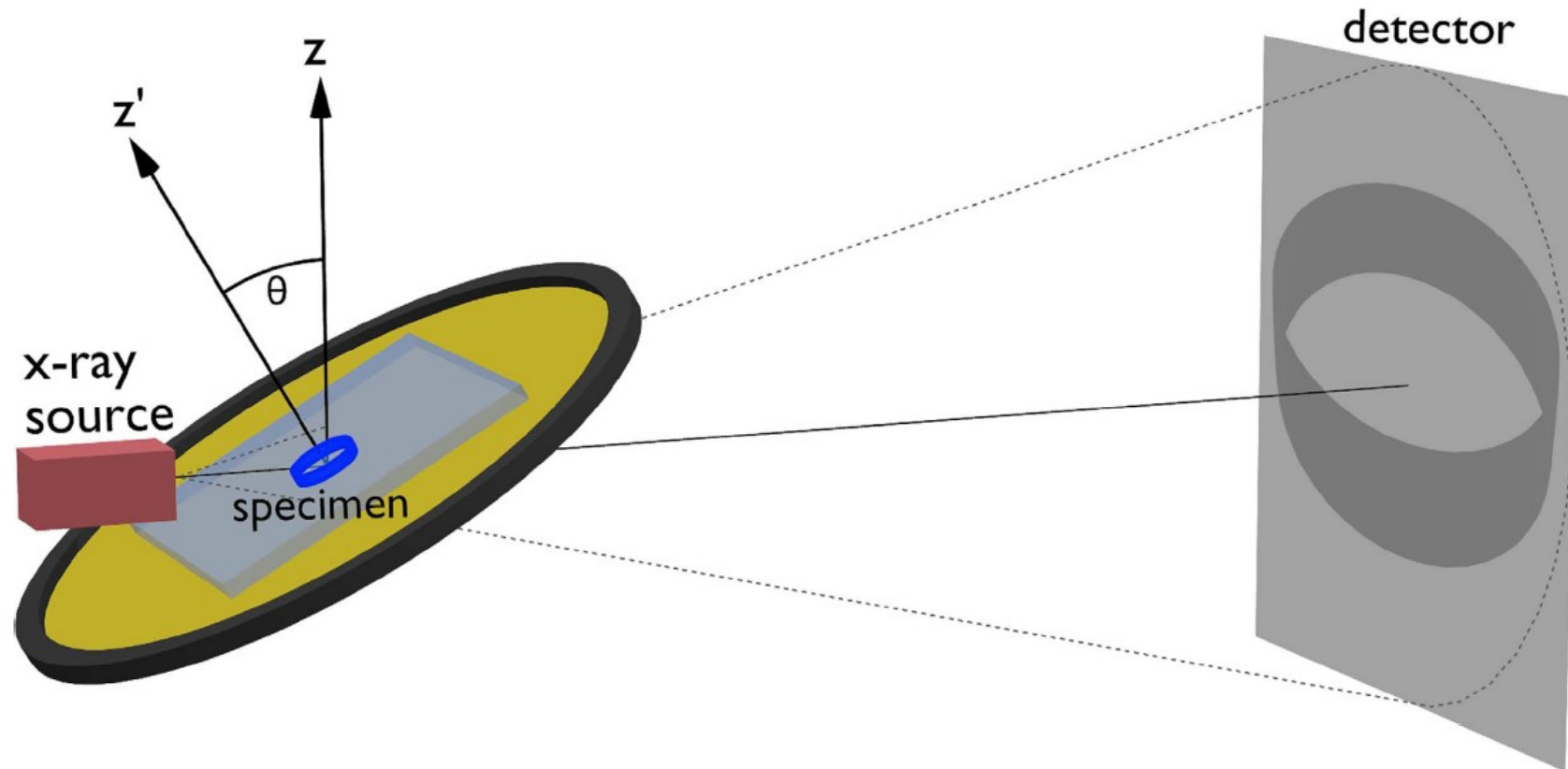
1000 μm



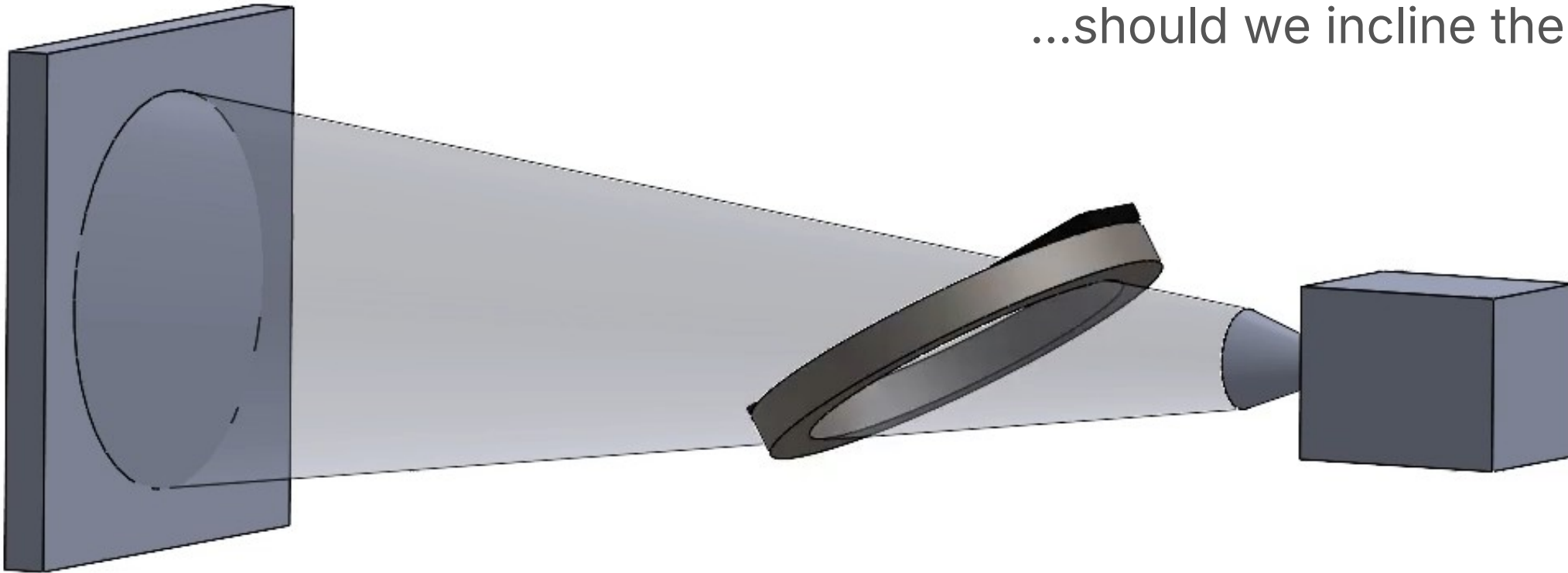
(ii) Shear crack

3000 μm

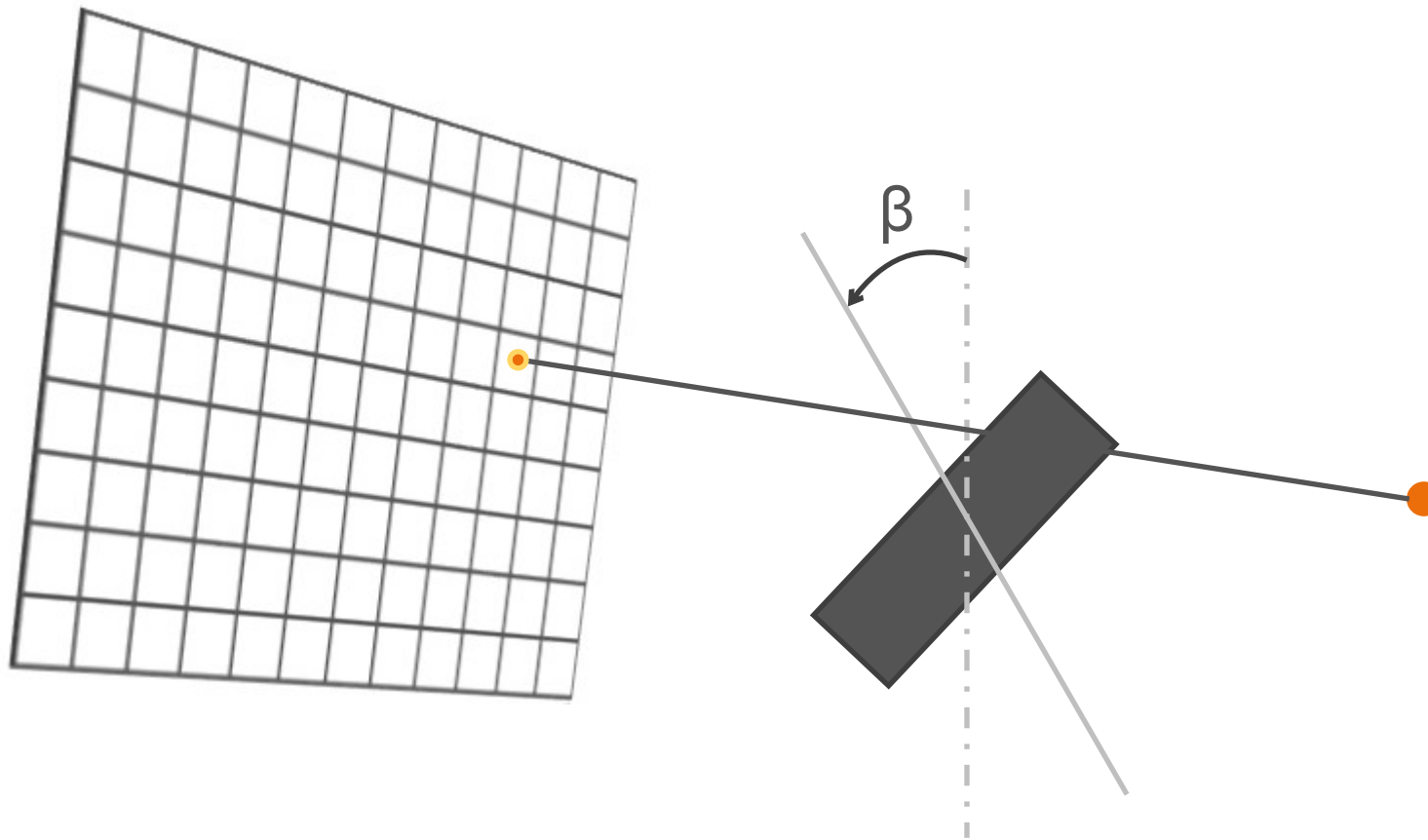
Motivation. Laminography



What inclination of the rotary table?
...resolution?
...should we incline the detector?



Methodology. A digital twin.

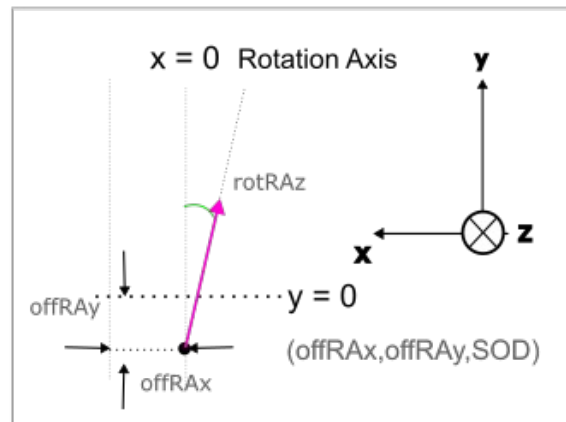
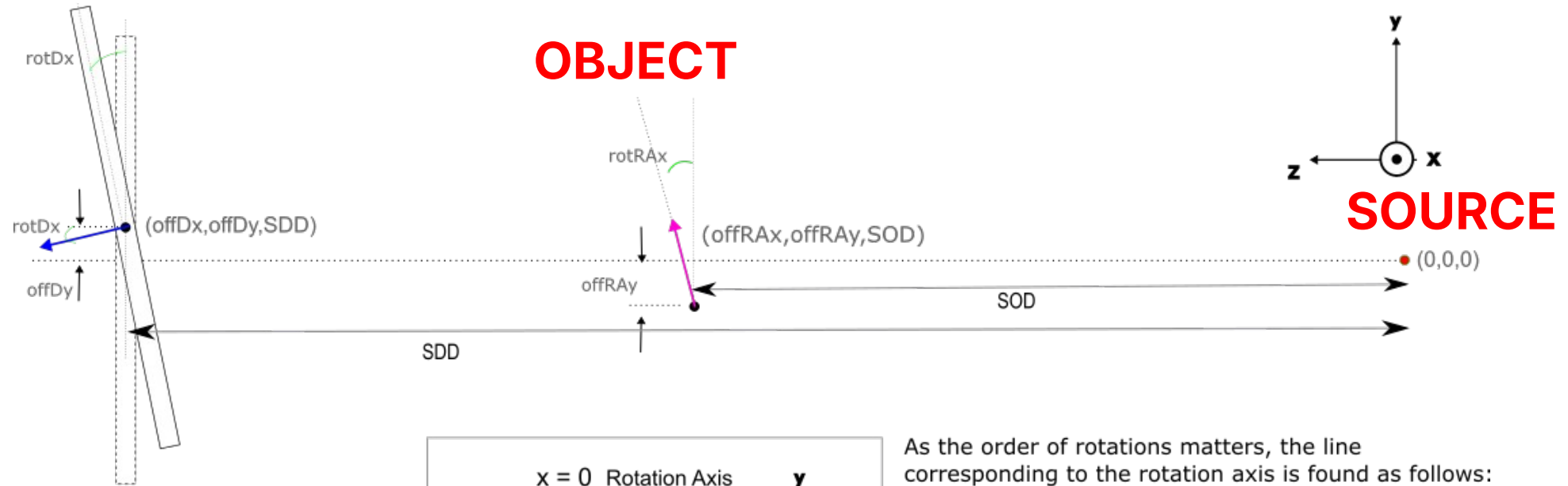


GENERATION OF VIRTUAL PROJECTIONS

- ❑ Calculation of the intensity reaching each pixel of the detector
- ❑ Geometry entirely parametrized
- ❑ Virtual specimen (phantom)
- ❑ Matlab script

Methodology. A digital twin.

DETECTOR

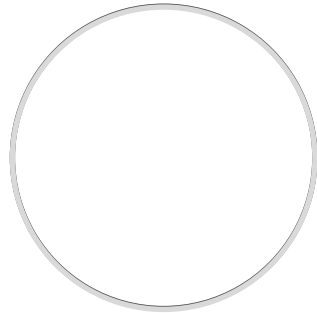
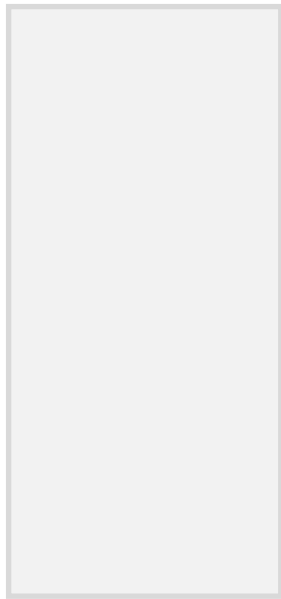


As the order of rotations matters, the line corresponding to the rotation axis is found as follows:

- 1) Initial line corresponding to a vertical line, $n=(0,1,0)$ passing through $(0,0,0)$
- 2) Rotation around x -axis
- 3) Rotation around z -axis
- 4) Translation from $(0,0,0)$ to $(\text{offRAx}, \text{offRAy}, \text{SOD})$

Methodology. A digital twin. The specimen

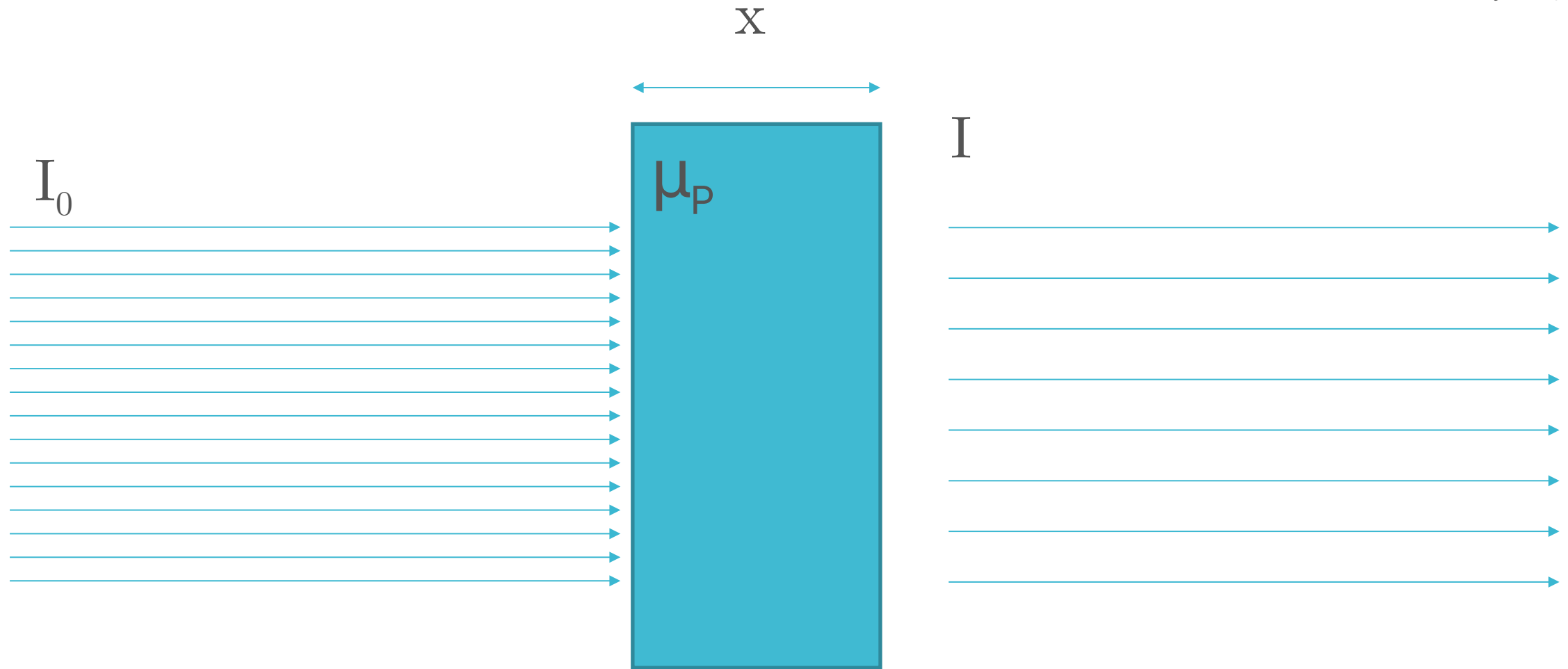
- ▣ Combination of parallelepipeds and spheres



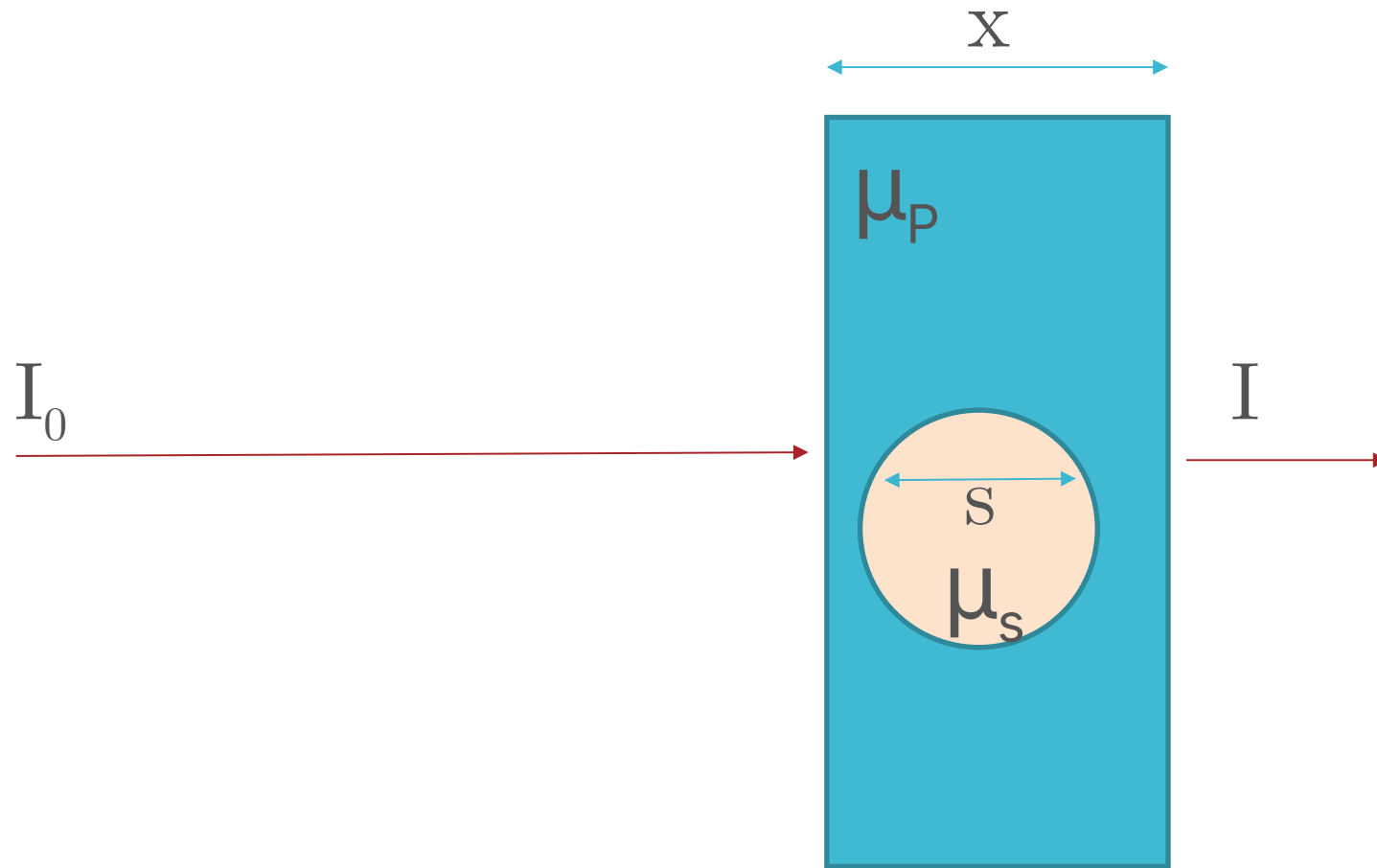
Slabs

Laminates

"Gruyere" slabs
(spheres embedded in the
rectangular prism)



$$I = I_0 e^{-\mu_p x}$$



$$I = I_0 e^{-[\mu_p(x-s) + \mu_s s]} = I_0 e^{-[\mu_p x + (\mu_s - \mu_p)s]}$$

Ideal vs real

- ❑ The source focus size
- ❑ X-ray spectrum
- ❑ Attenuating media
- ❑ Noise
- ❑ Sensor drifts
- ❑ Defective pixels
- ❑ Detector linearity
- ❑ Detector uniformity

Ideal

Zero

Monochromatic

2 homogeneous media

No

No

No

Ideal

Ideal

Real

5-50 microns

Broad spectrum

2 media with scatter

Yes

Yes

Yes

Not ideal

Not ideal

Methodology

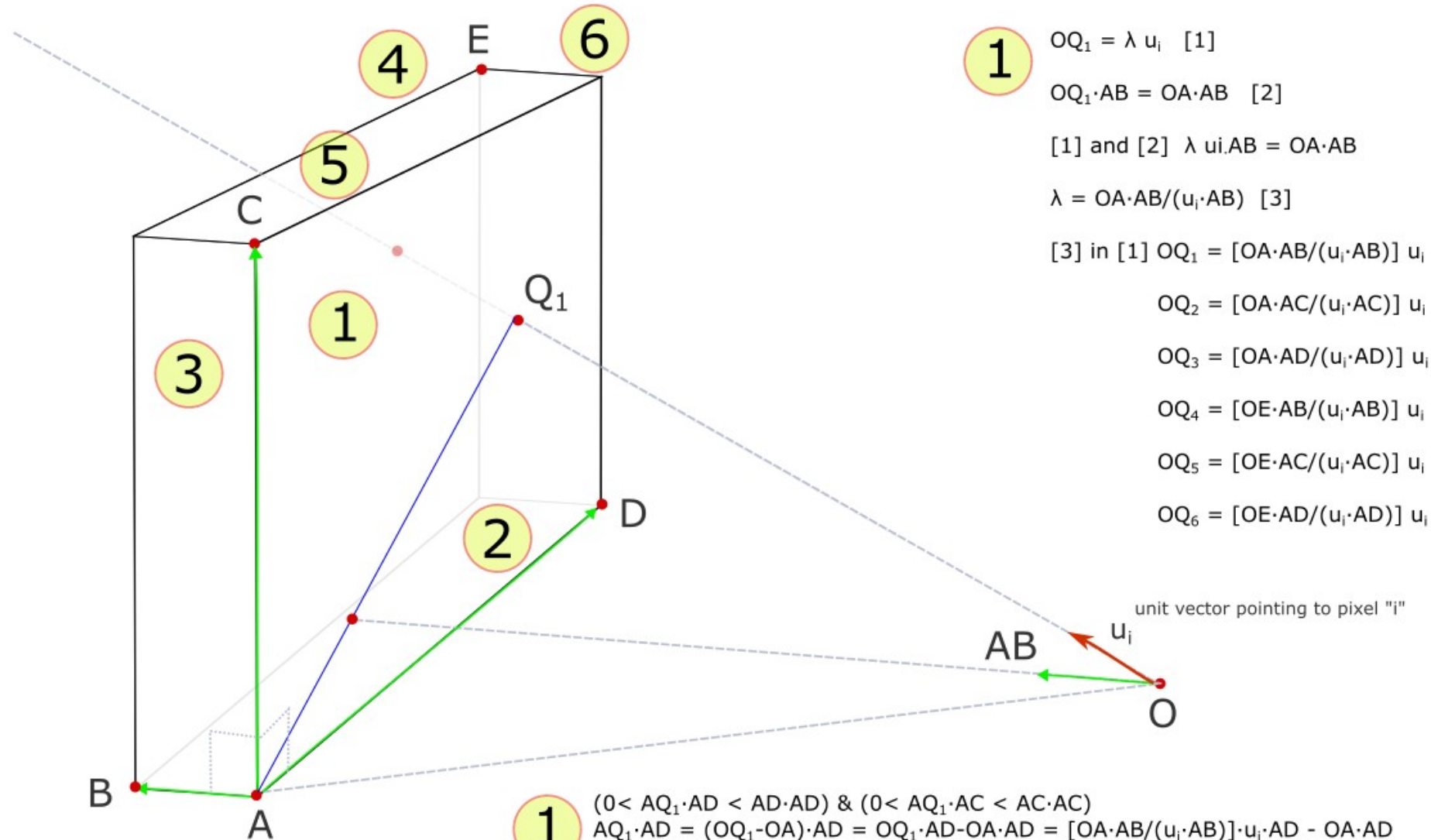
- ❑ Number of projections: 1200 projections
- ❑ Detector: 1120 × 1672 pixels
12 × 12 cm (50 × 50 μm pixel size)
- ❑ Specimen size: 100 × 25 × 4 mm, 1000 spheres of 3 diameters: 3, 1.5, 0.75 mm
- ❑ SOD (Subject-Object-Distance): 60 mm
- ❑ SDD (Subject-Detector-Distance): 220 mm

Methodology

- ❑ Number of projections: **1200** projections
- ❑ Detector: **1120** x **1672** pixels
12 × 12 cm (100 × 100 μm pixel size)
- ❑ Specimen size: 100 × 25 × 4 mm, **1000** spheres of 3 diameters: 3, 1.5, 0.75 mm
- ❑ SOD (Subject-Object-Distance): 60 mm
- ❑ SDD (Subject-Detector-Distance): 220 mm

2.247.168.000.000 beam calculations

Two trillion, two hundred forty-seven billion, one hundred sixty-eight million



1 $OQ_1 = \lambda u_i$ [1]

$OQ_1 \cdot AB = OA \cdot AB$ [2]

[1] and [2] $\lambda u_i \cdot AB = OA \cdot AB$

$\lambda = OA \cdot AB / (u_i \cdot AB)$ [3]

[3] in [1] $OQ_1 = [OA \cdot AB / (u_i \cdot AB)] u_i$

$OQ_2 = [OA \cdot AC / (u_i \cdot AC)] u_i$

$OQ_3 = [OA \cdot AD / (u_i \cdot AD)] u_i$

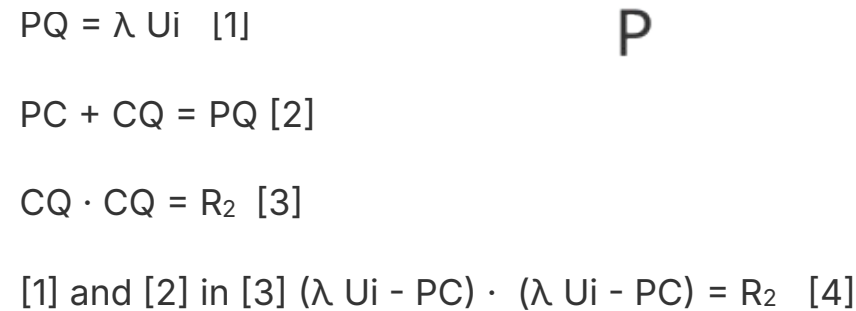
$OQ_4 = [OE \cdot AB / (u_i \cdot AB)] u_i$

$OQ_5 = [OE \cdot AC / (u_i \cdot AC)] u_i$

$OQ_6 = [OE \cdot AD / (u_i \cdot AD)] u_i$

1 $(0 < AQ_1 \cdot AD < AD \cdot AD) \ \& \ (0 < AQ_1 \cdot AC < AC \cdot AC)$
 $AQ_1 \cdot AD = (OQ_1 - OA) \cdot AD = OQ_1 \cdot AD - OA \cdot AD = [OA \cdot AB / (u_i \cdot AB)] \cdot u_i \cdot AD - OA \cdot AD$
 $AQ_1 \cdot AC = (OQ_1 - OA) \cdot AC = OQ_1 \cdot AC - OA \cdot AC = [OA \cdot AB / (u_i \cdot AB)] \cdot u_i \cdot AC - OA \cdot AC$

4 $(0 < EQ_4 \cdot (-AD) < AD \cdot AD) \ \& \ (0 < EQ_4 \cdot (-AC) < AC \cdot AC)$
 $EQ_4 \cdot (-AD) = (OQ_4 - OE) \cdot (-AD) = -OQ_4 \cdot AD + OE \cdot AD = -[OE \cdot AB / (u_i \cdot AB)] \cdot u_i \cdot AD + OE \cdot AD$
 $EQ_4 \cdot (-AC) = (OQ_4 - OE) \cdot (-AC) = -OQ_4 \cdot AC + OE \cdot AC = -[OE \cdot AB / (u_i \cdot AB)] \cdot u_i \cdot AC + OE \cdot AC$



Assuming:

$$\begin{aligned} P &= (0, 0, 0) \\ C &= (C_x, C_y, C_z) \\ U_i &= (U_x, U_y, U_z) \end{aligned}$$

The equation [4] becomes:

$$A \lambda^2 + B \lambda + C = 0$$

with:

$$\begin{aligned} A &= U_i \cdot U_i \\ B &= -2 U_i \cdot PC \\ C &= PC \cdot PC - R^2 \end{aligned}$$

which has real solutions for:
 $B^2 \geq 4AC$

And the difference between solutions is:

$$\text{SQRT}(B^2 - 4 A C) / A$$

Recalling that $\mathbf{U}_i$ is a unit vector ($\mathbf{U}_i \cdot \mathbf{U}_i = 1$)

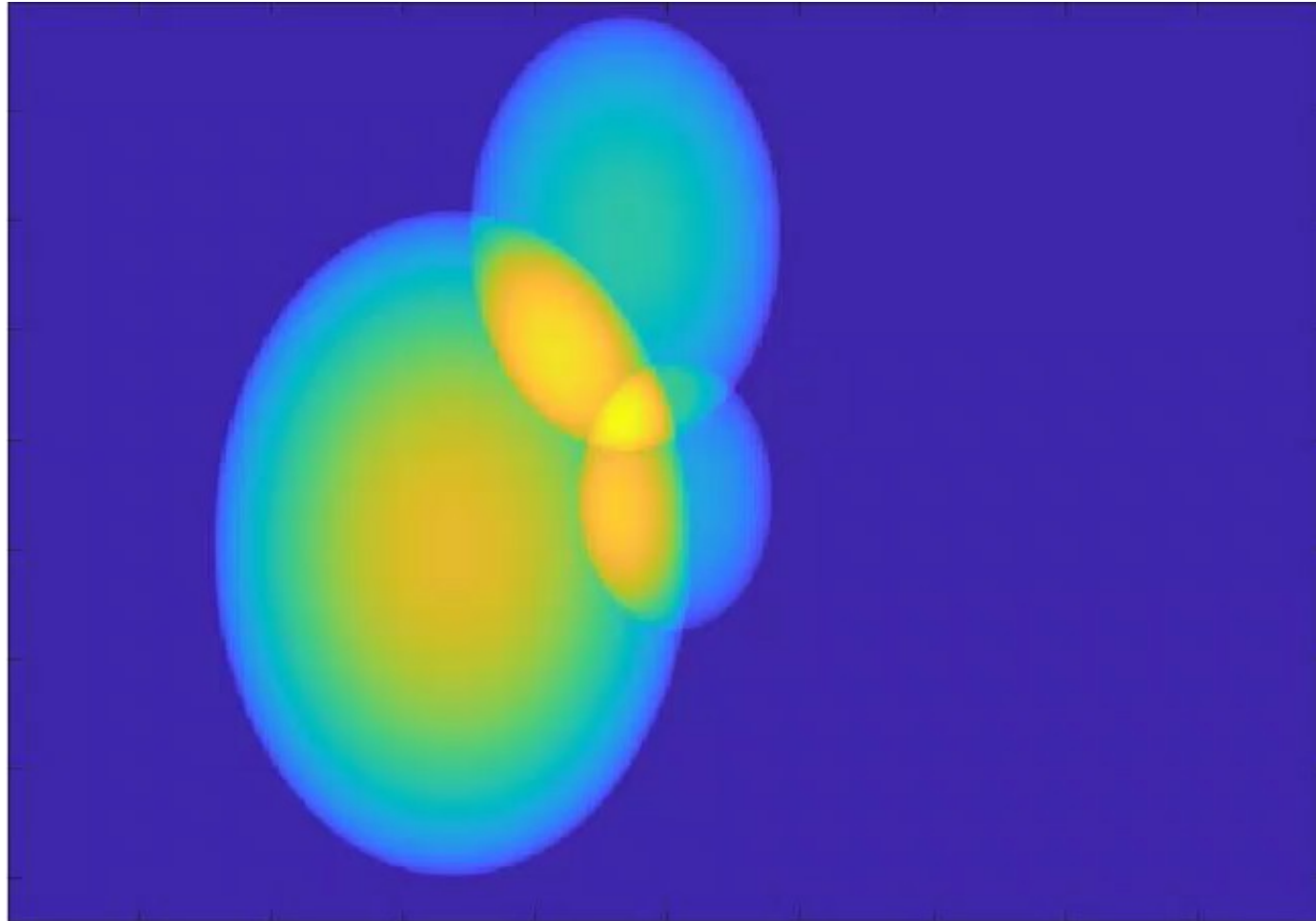
$$\lambda^2 - 2\lambda (U_i \cdot PC) + (PC \cdot PC - R^2) = 0$$

that has real solutions when:

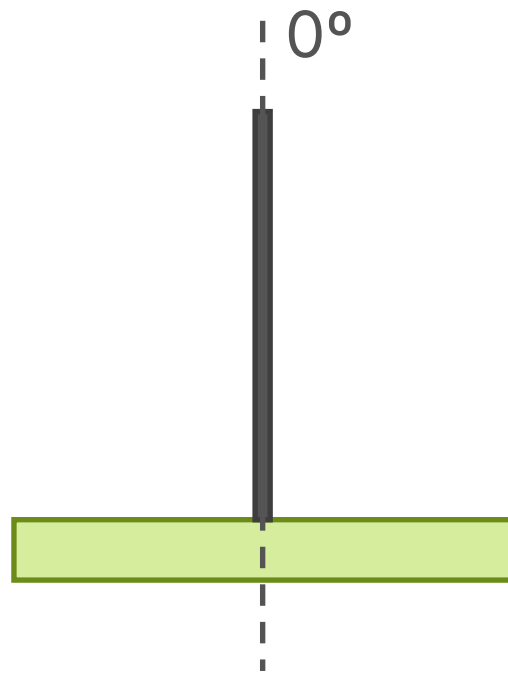
$$(U_i \cdot PC)^2 > PC \cdot PC - R^2$$

And the difference between solutions
(or the path of the beam across the sphere) is:

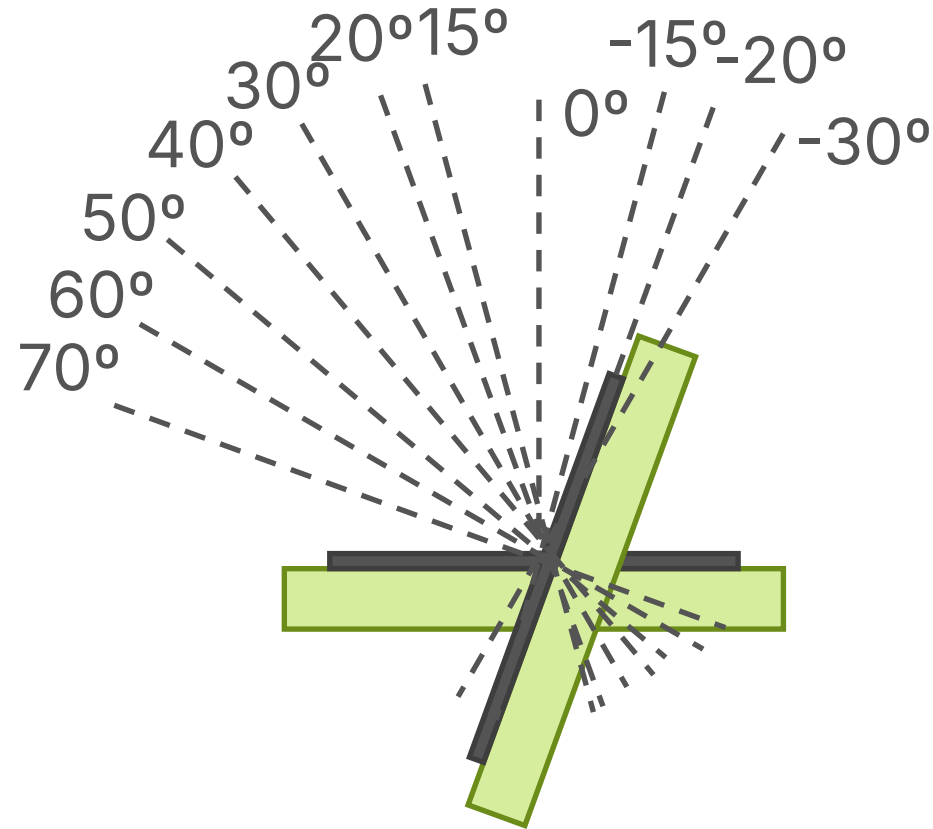
$$2\sqrt{(U_i \cdot PC)^2 - (PC \cdot PC - R^2)}$$



Methodology. Studied cases

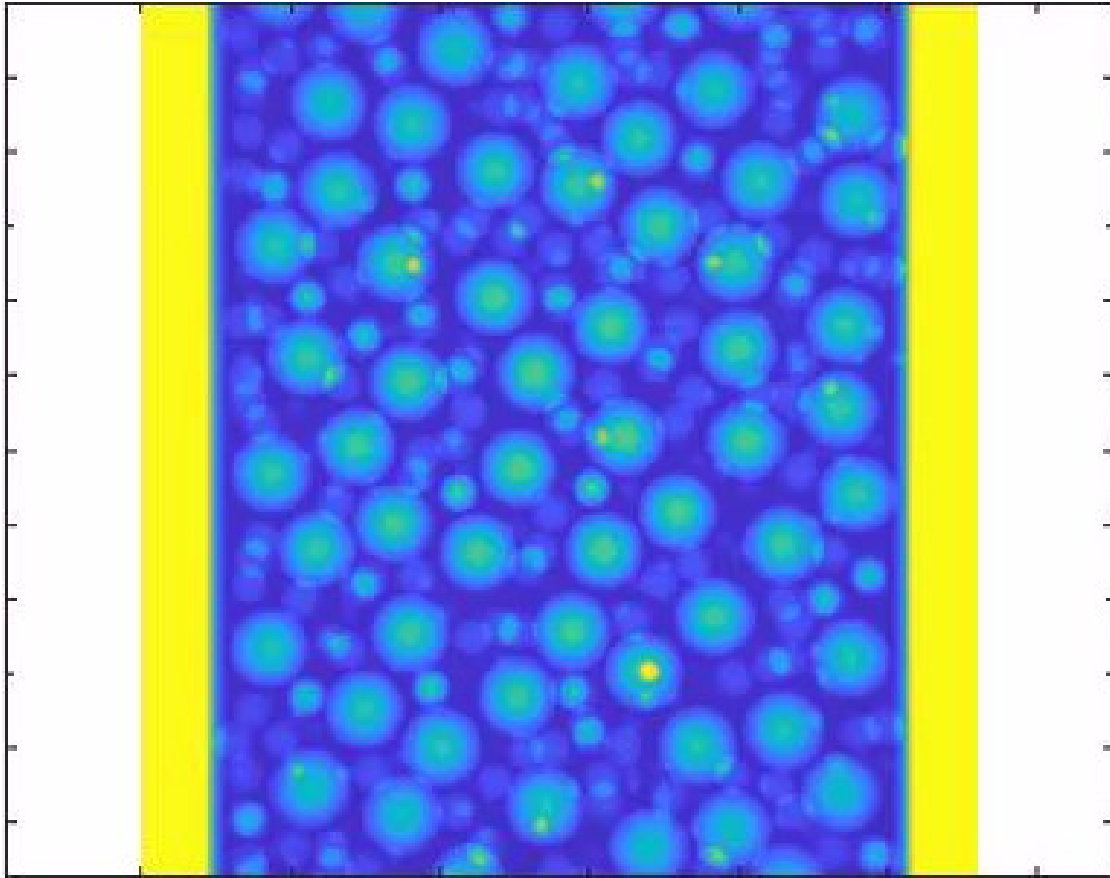


tomography

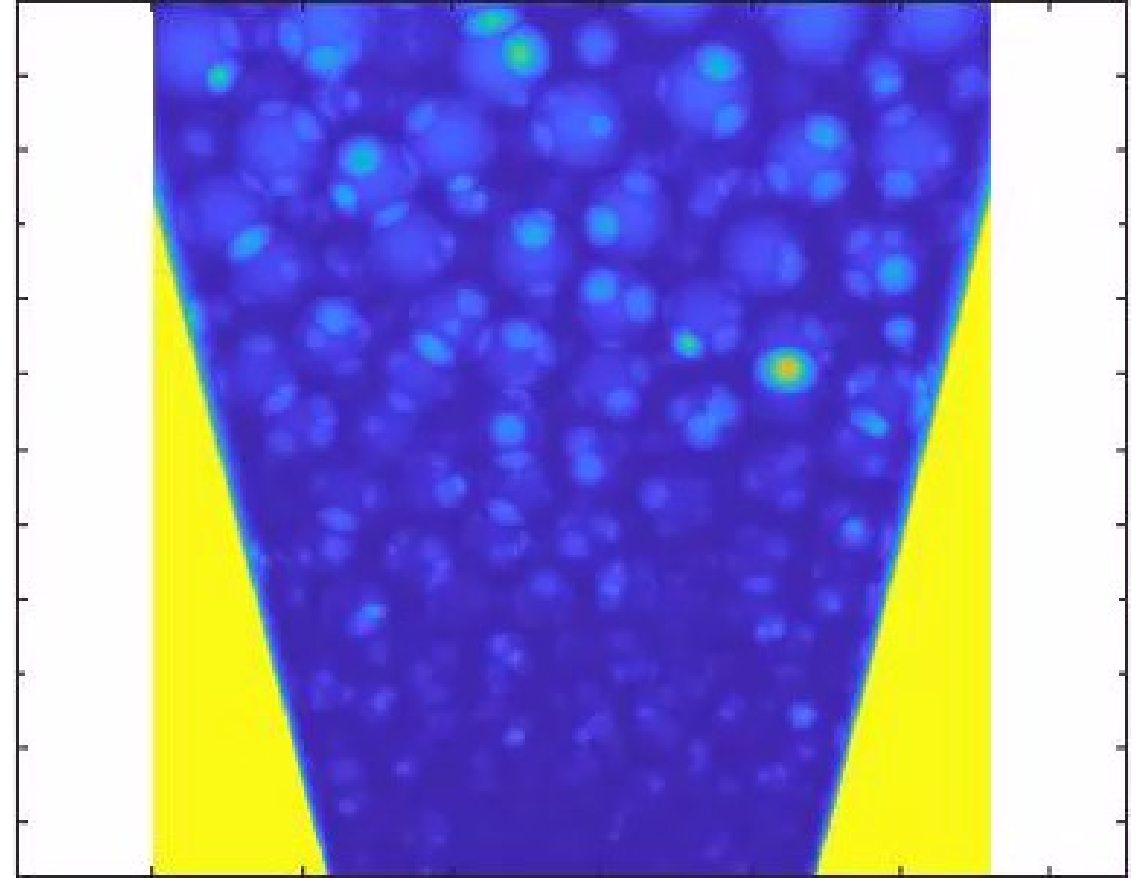


laminography

Results



Tomography



Laminography – 40°

Reconstruction

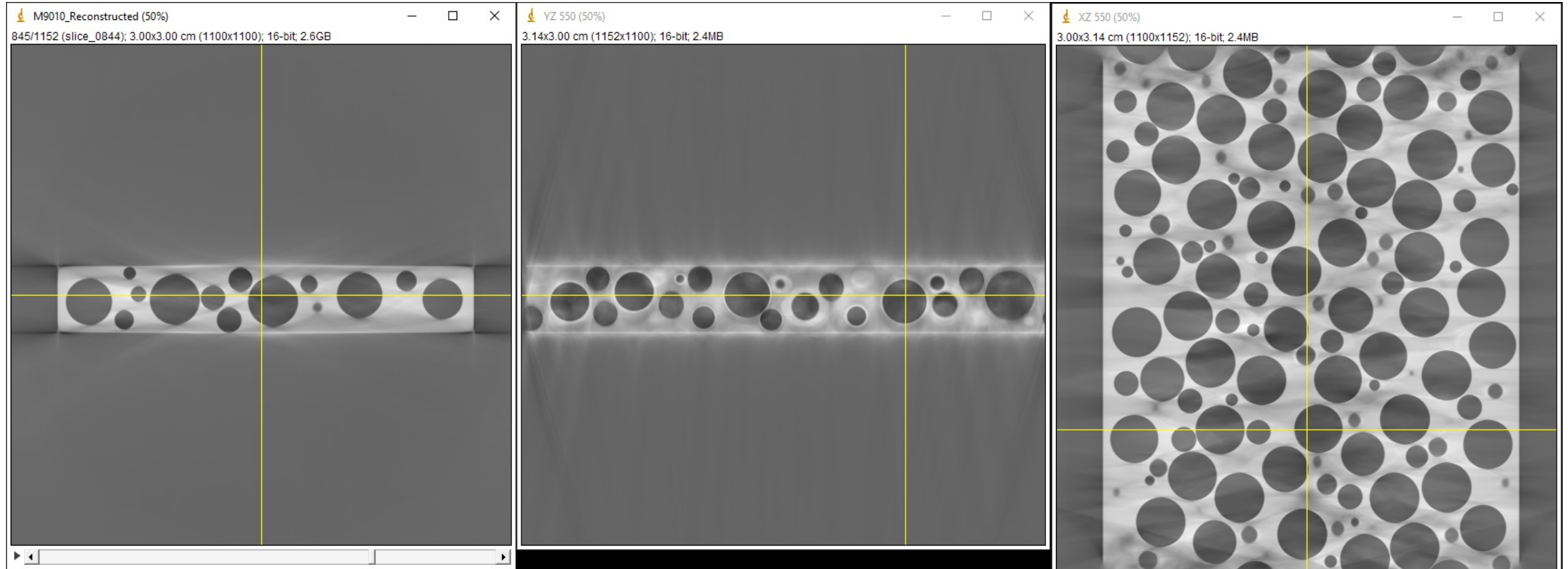
❑ X-AID reconstruction software from MITOS

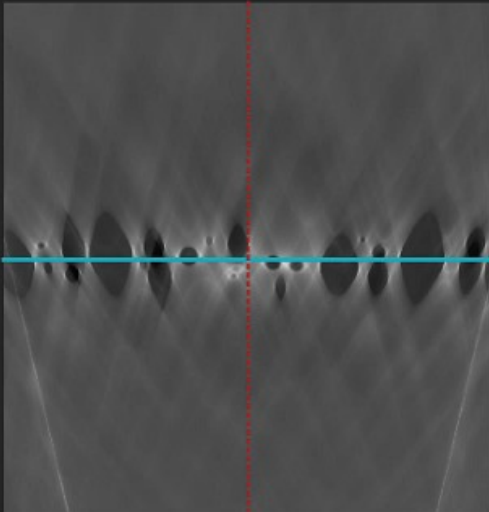
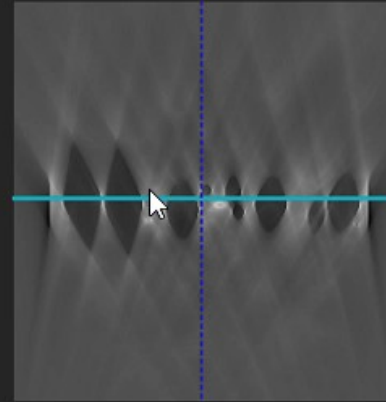
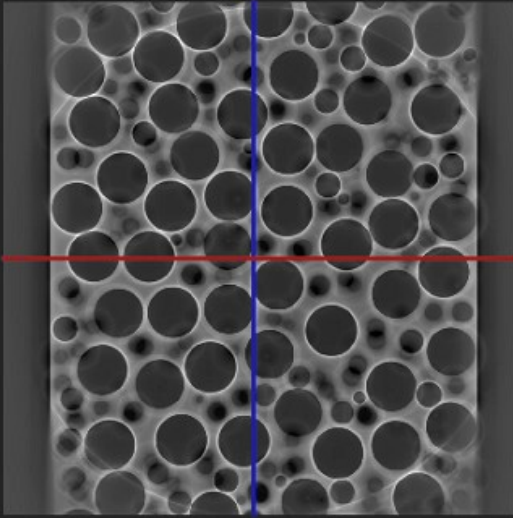
With laminography capabilities: Reconstruction of data from acquisition modes for flat objects like oblique/planar CT and linear/rotational laminography.



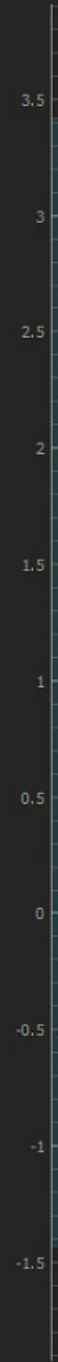
X-AID

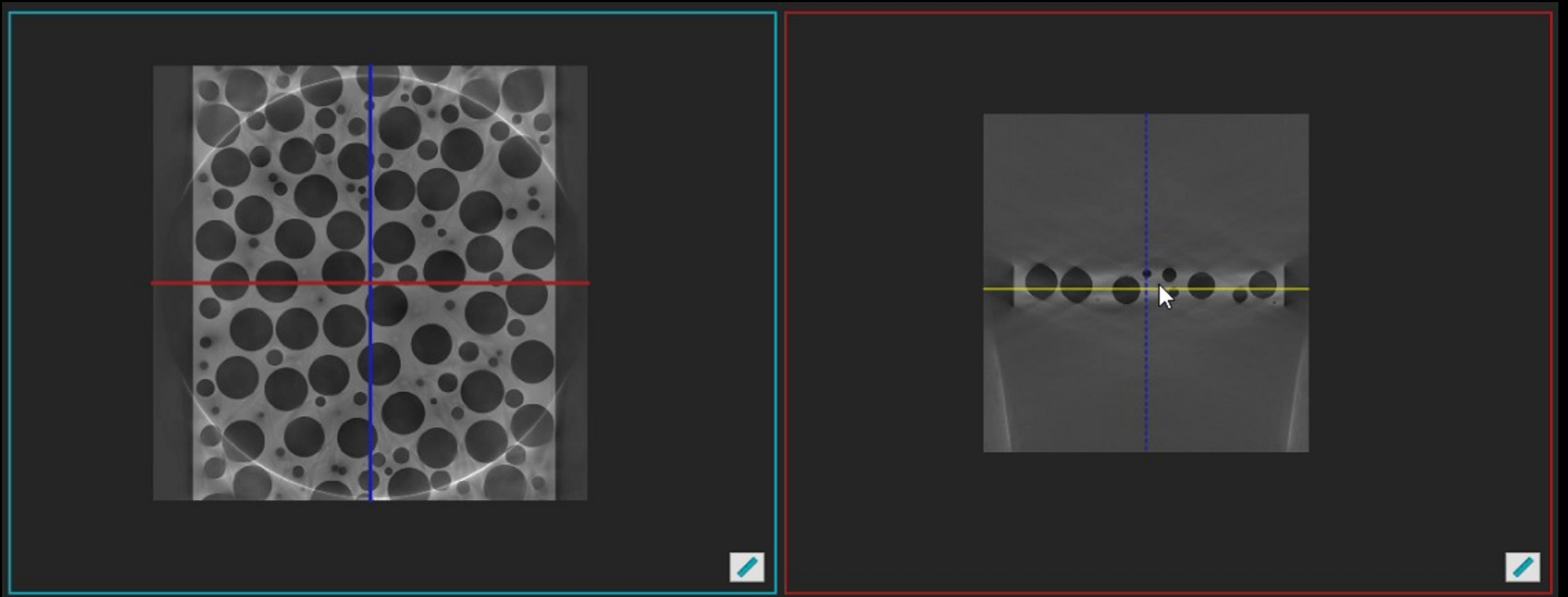
Software for scientific and industrial CT





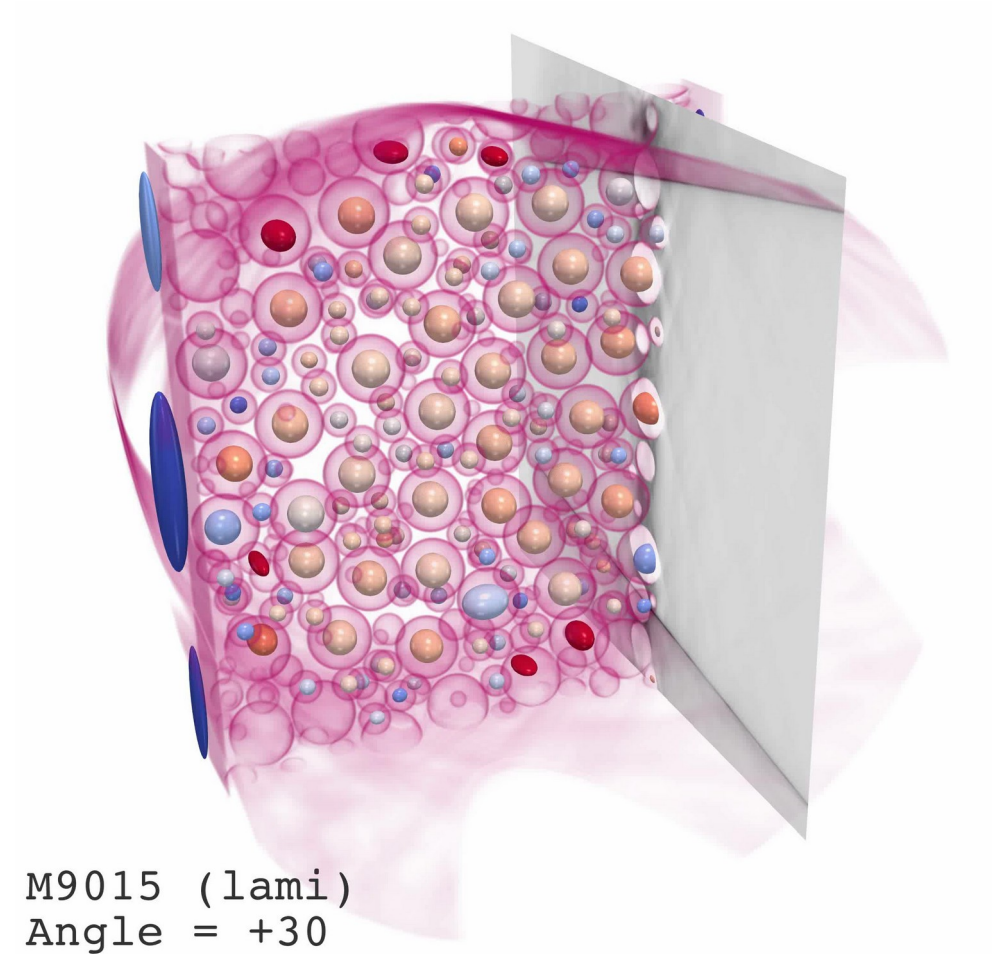
Laminography 70°



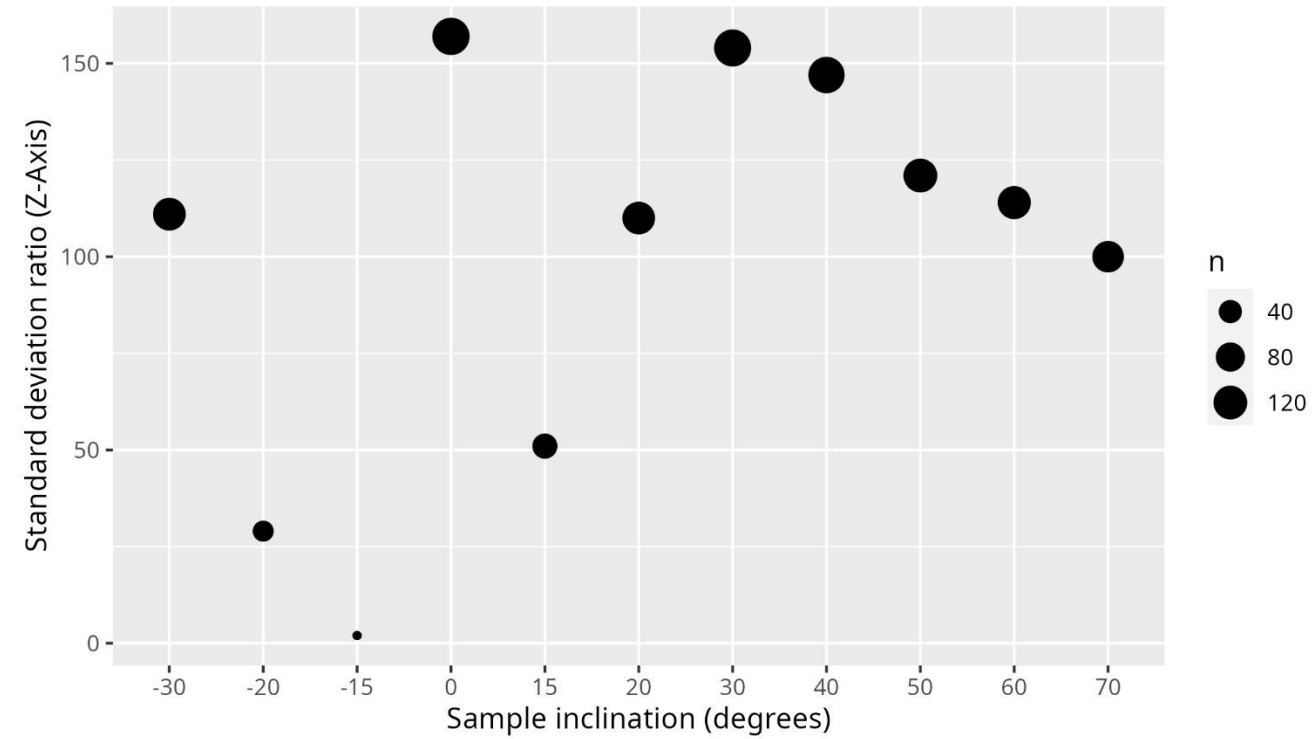
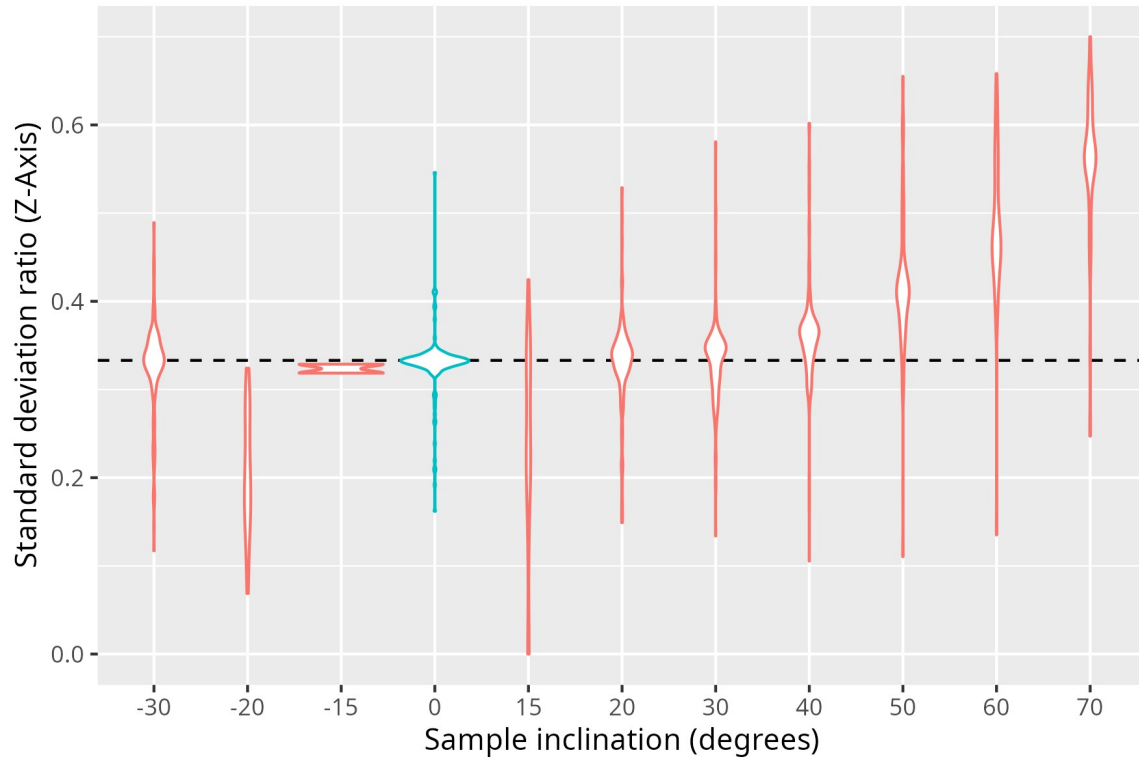


Laminography 30°

Analysis

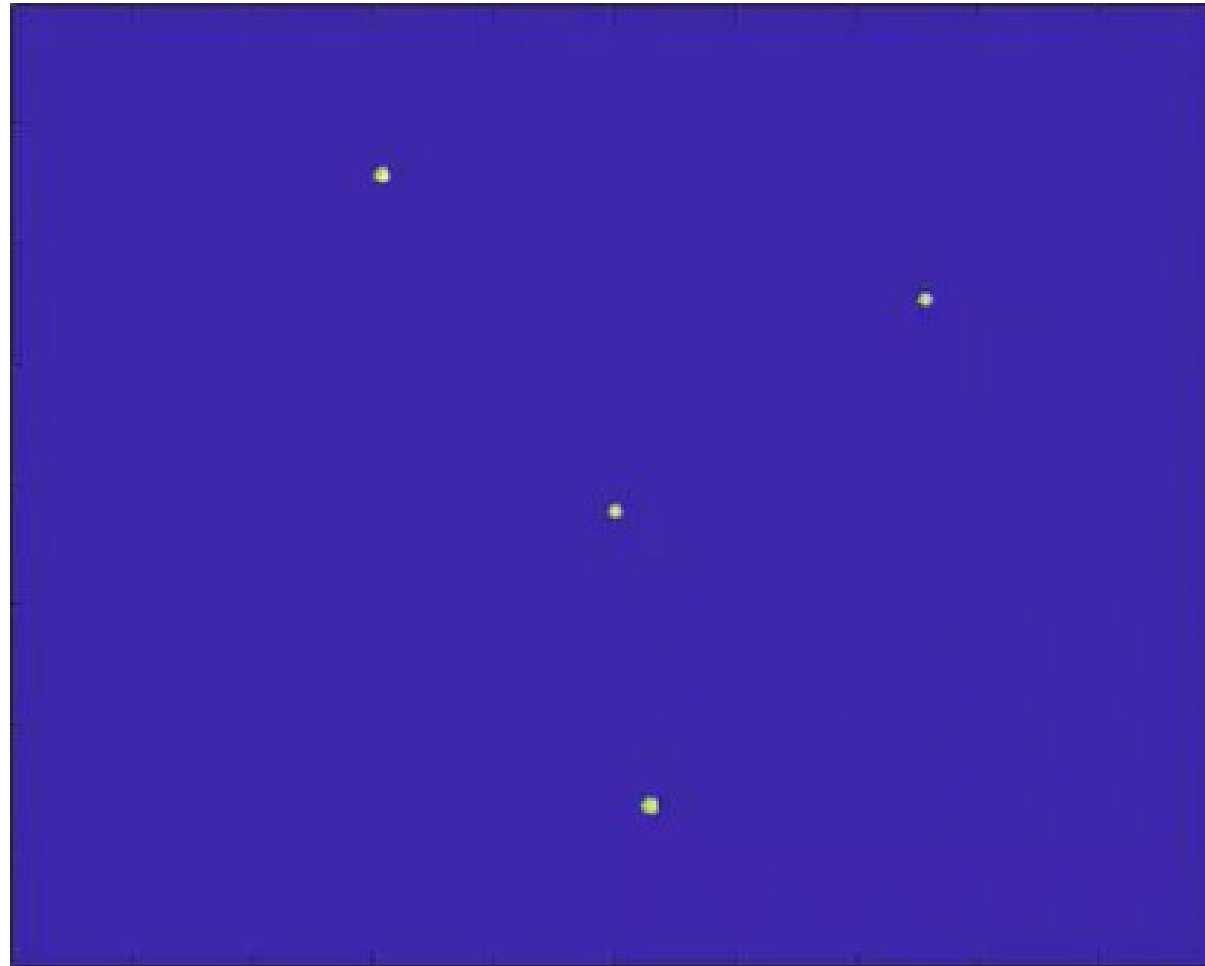


M9015 (lami)
Angle = +30



What else can we done with the digital twin?

- ❑ Anticipate the quality of the reconstruction of non-conventional specimens (large, thick, etc.)
- ❑ Support the decision of the parameters definition for the acquisition of projections (number of projections, etc.)
- ❑ Check the suitability of alternative reconstruction methods for particular specimens.
- ❑ Calibrate the real geometrical configuration of the system (source-object, source-detector distances, tilt of the rotation table, rotations and offset of the detector...)



Conclusions

- ❑ We have successfully developed a “digital twin” of the projection generation of a cone beam tomography system.
- ❑ It allows to simulate the most important geometrical parameters affecting the quality of the tomography.
- ❑ Reconstructions of the laminography with the explored configurations are not satisfactory. The least bad results are obtained at 30° . The study should continue.
- ❑ The usefulness of the “digital twin” goes much beyond the laminography feasibility study: geometrical calibration, ideal resolution, assessment of reconstruction algorithms, etc.
- ❑ Matlab parallel computing ...



<http://amade.udg.edu>

testlab.amade@udg.edu

