

Caractérisations tomographiques de mousses métalliques : Structure et propriétés mécaniques

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Intérêts de l'imagerie 3D par tomographie RX

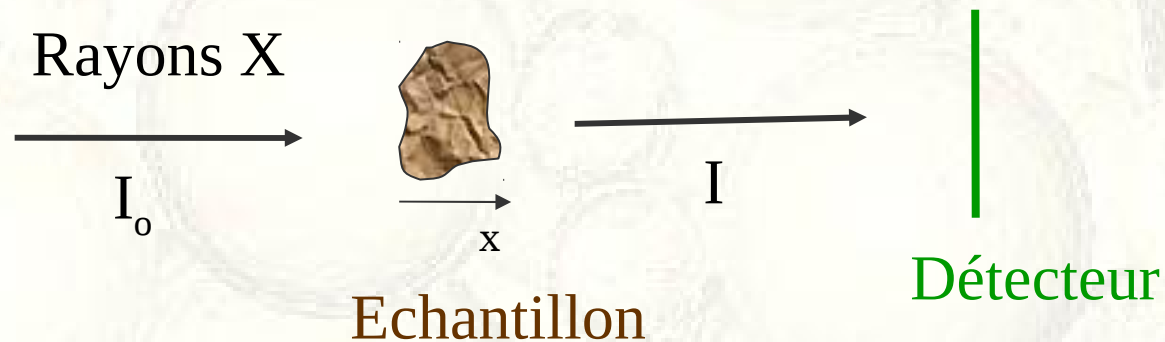
- Meilleure vision de la microstructure
 - Pas de règles stéréographiques à appliquer
 - Cas des formes complexes (percolation)
 - Accès à des paramètres inaccessibles en 2D (nombre)
- Pas de perturbation liée à la surface
 - Pas d'artefact de préparation
 - Pas de relaxation des contraintes (endo.)

Plan

- Principe
- Exemples
 - visualisation
 - quantification
 - Essais in-situ
- Conclusions & perspectives

Principe

La radiographie

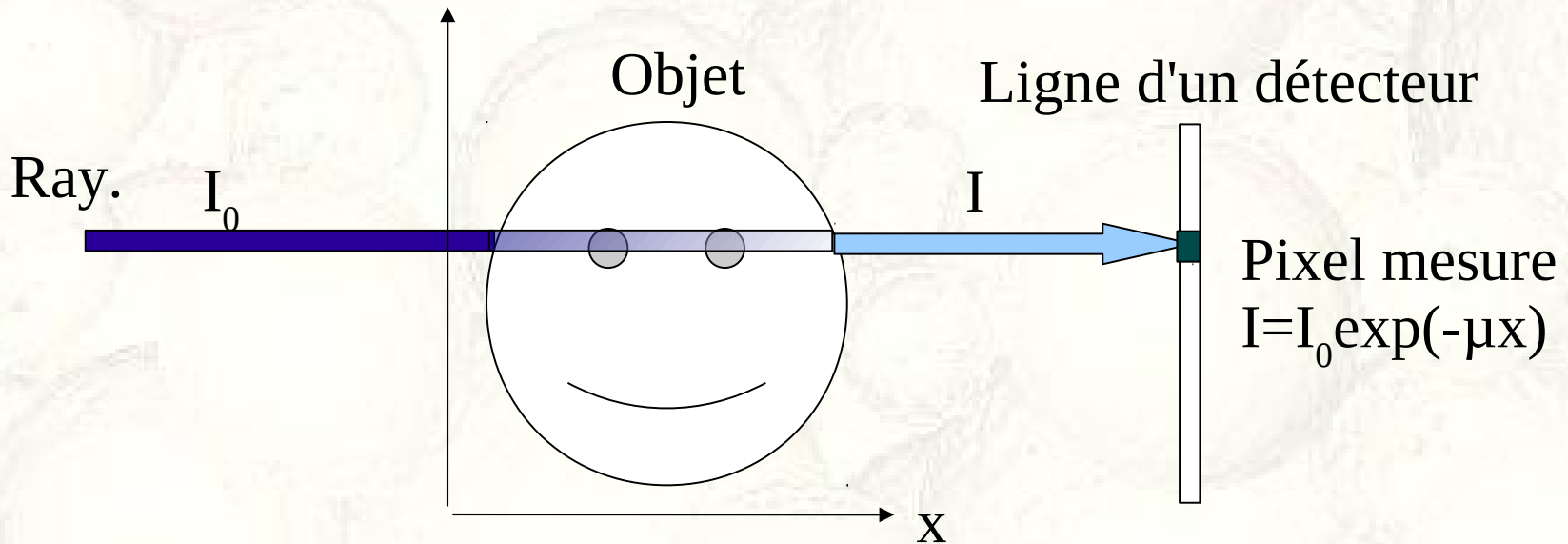


Loi de Lambert-Beer:

$$\frac{I}{I_0} = \exp \int -\mu dx$$

μ , coefficient d'atténuation linéaire

Principe



Ce qu'on a :



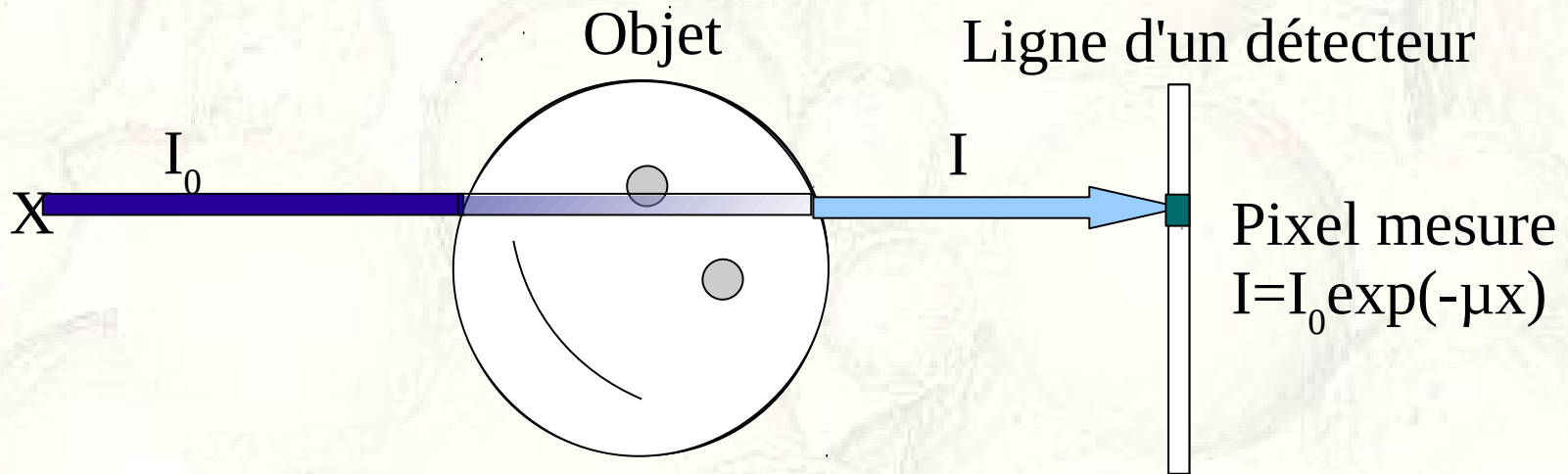
Intégrale de l'absorption μ
le long du trajet x

Ce qu'on
voudrait :



Valeur de μ en tout point
le long du trajet x

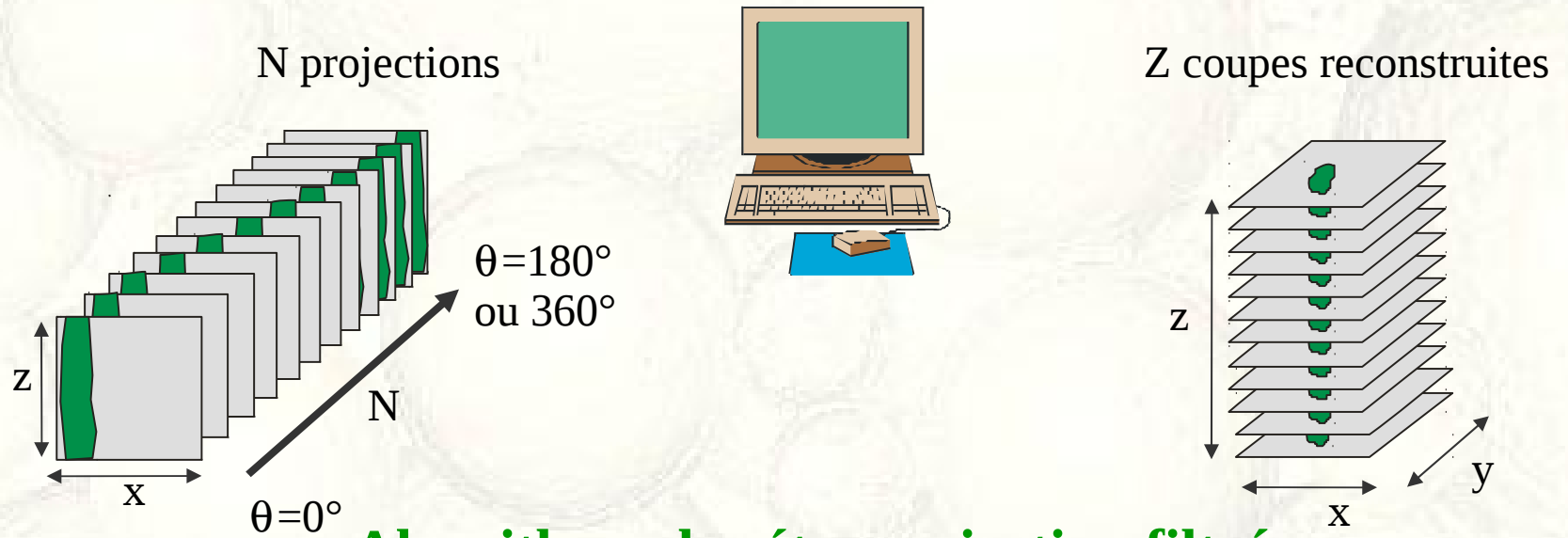
Principe



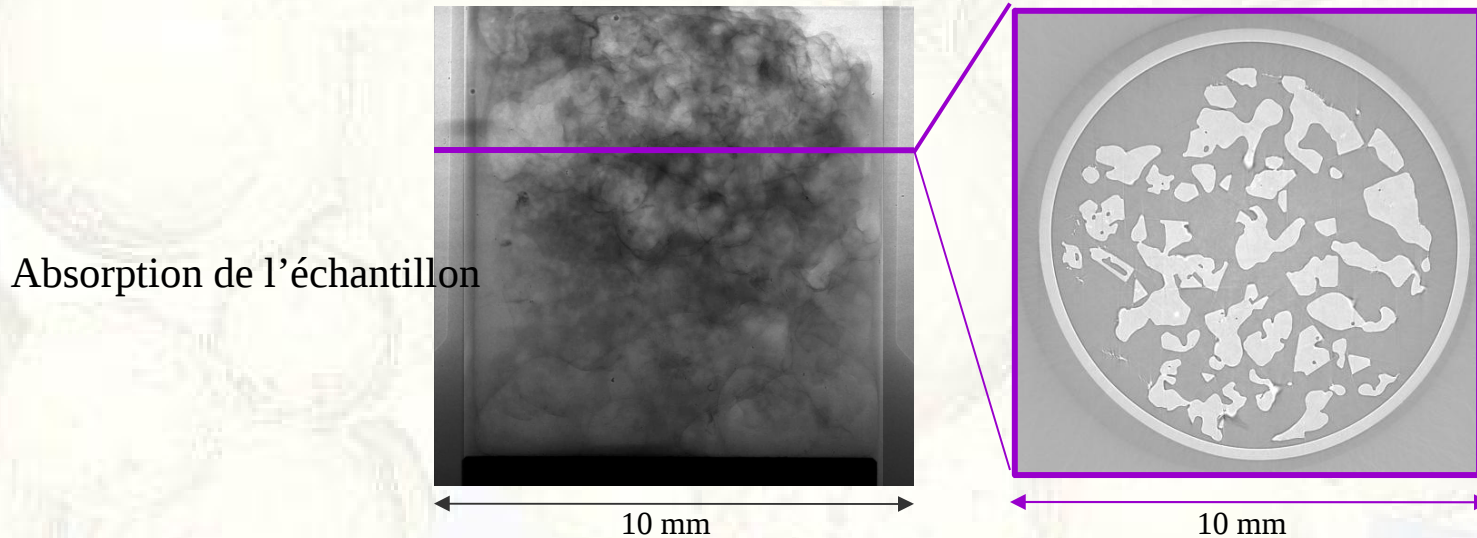
Solution, faire des images de l'objet sous plusieurs angles
+ reconstruction informatique

Calcul de la carte $\mu(x, y)$

Du 2D au 3D: Reconstruction tomographique



Algorithme de rétroprojection filtrée



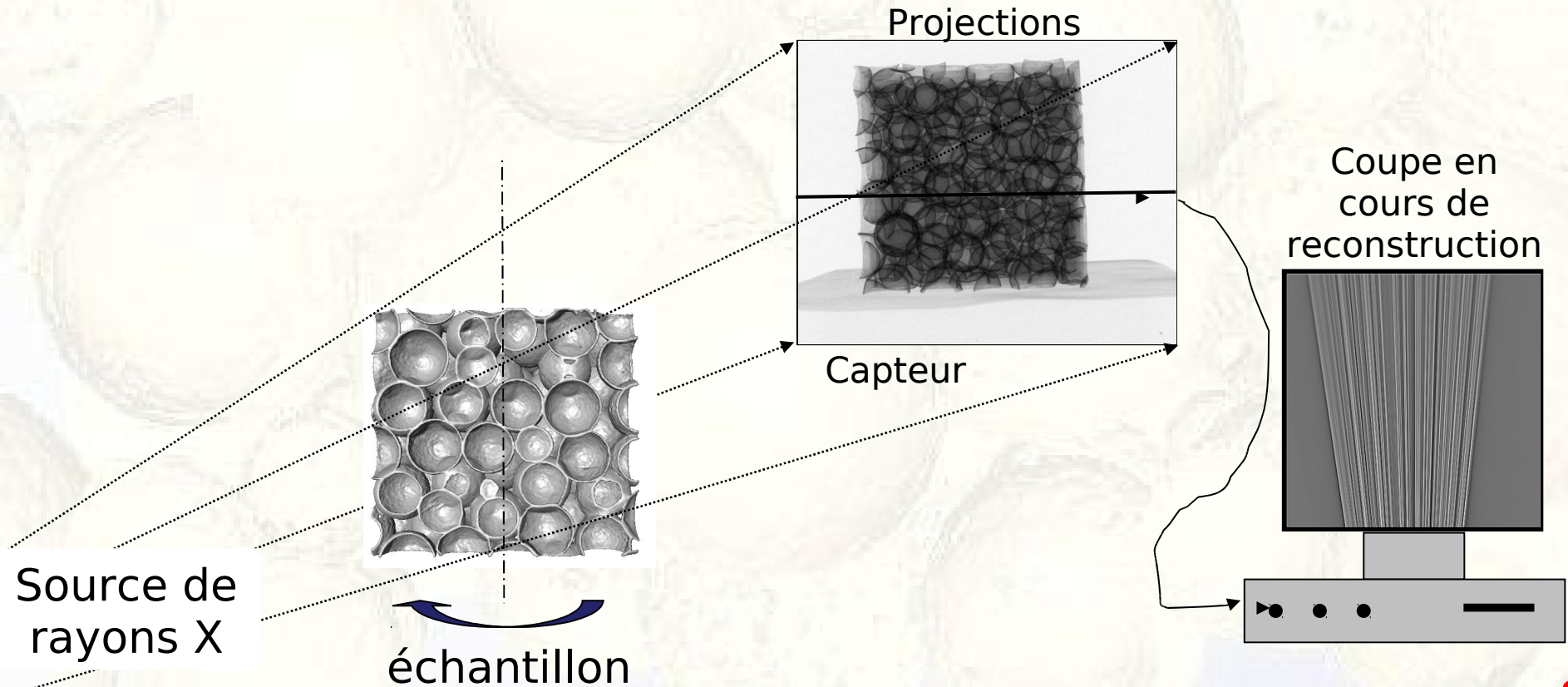
Dispositif

- source RX

- Table de rotation

- Detecteur RX

- Ordinateur reconstruction



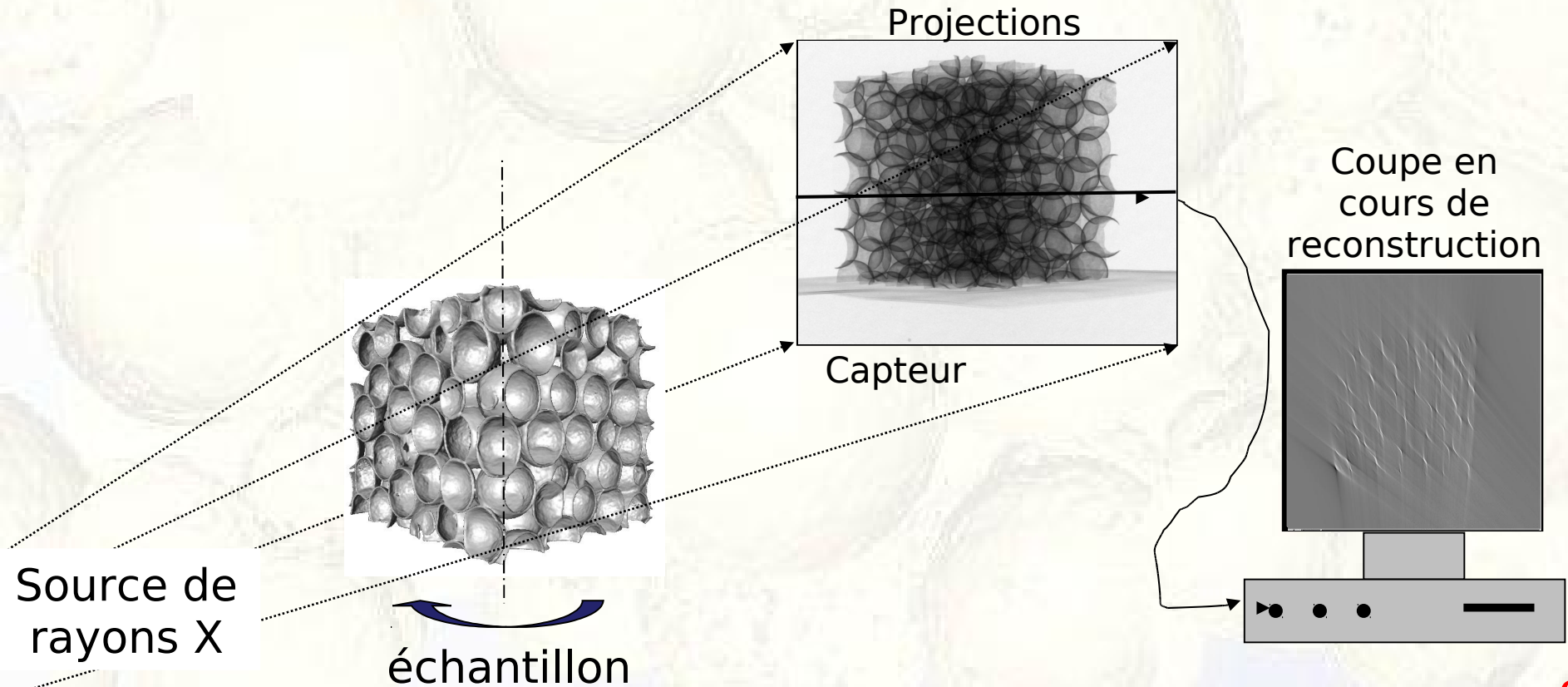
Dispositif

- source RX

- Table de rotation

- Detecteur RX

- Ordinateur reconstruction



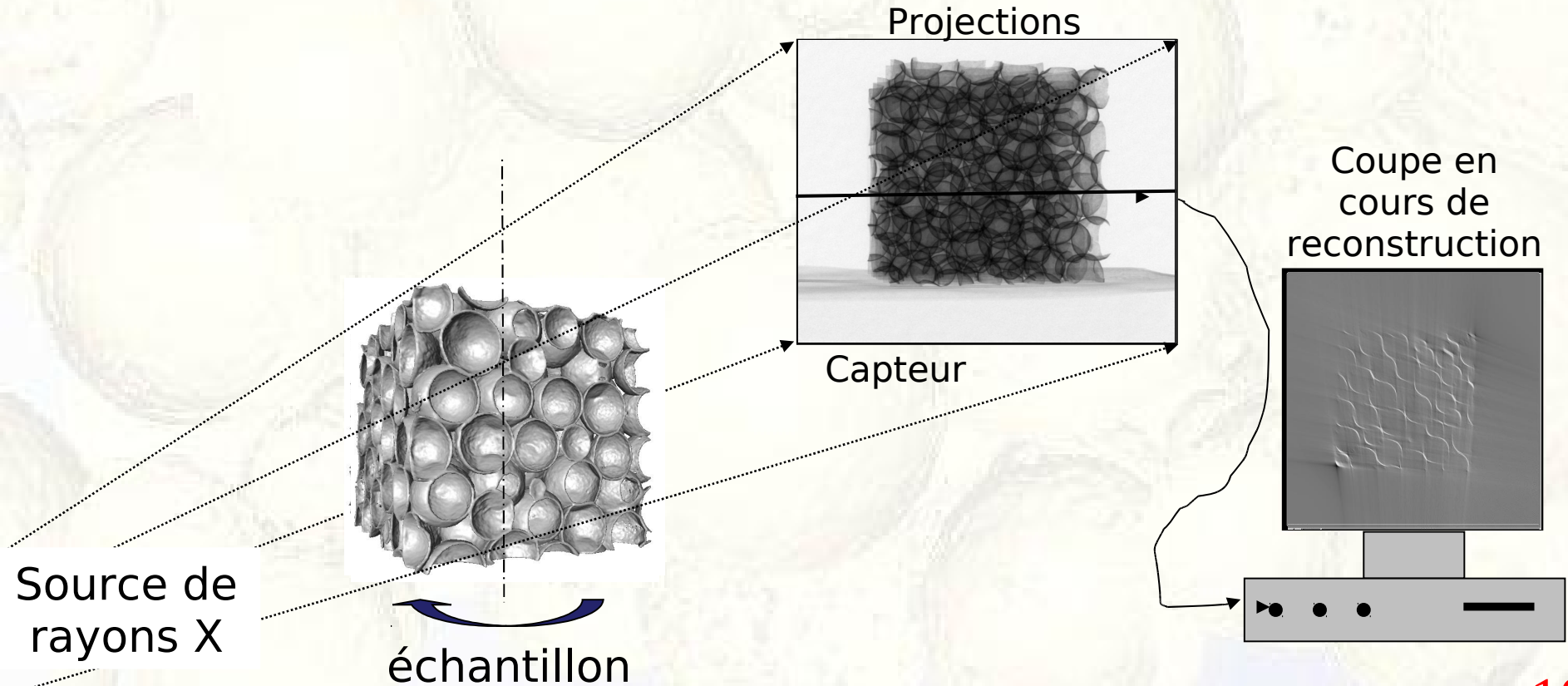
Dispositif

- source RX

- Table de rotation

- Detecteur RX

- Ordinateur reconstruction



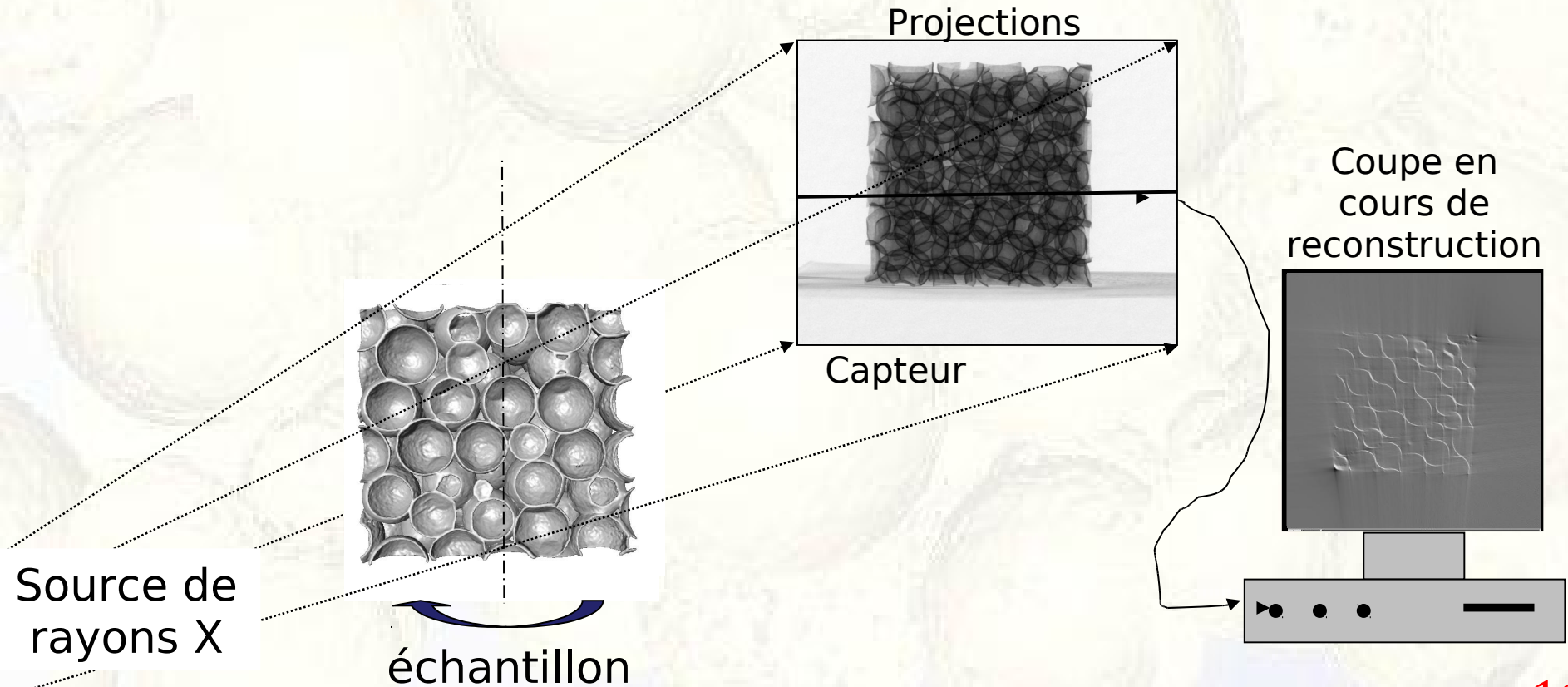
Dispositif

- source RX

- Table de rotation

- Detecteur RX

- Ordinateur reconstruction



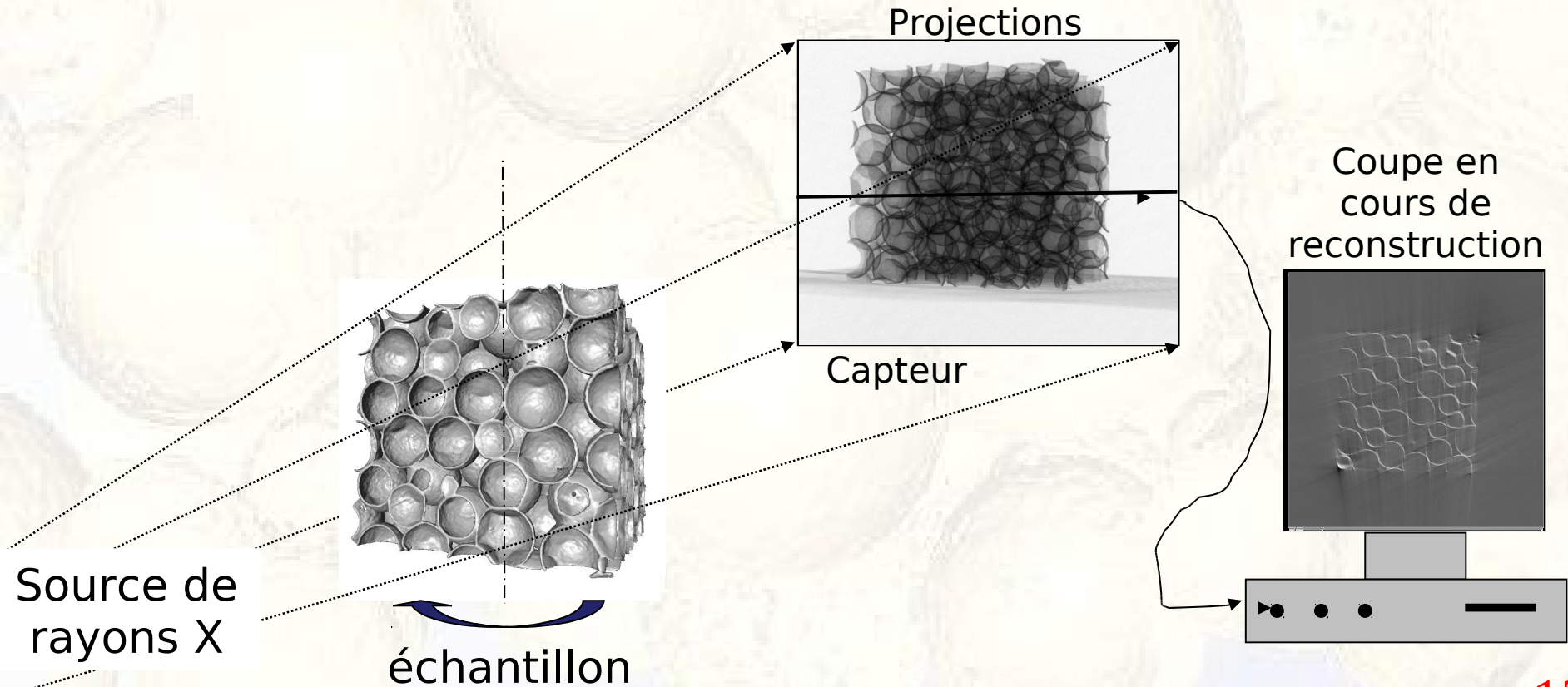
Dispositif

- source RX

- Table de rotation

- Detecteur RX

- Ordinateur reconstruction



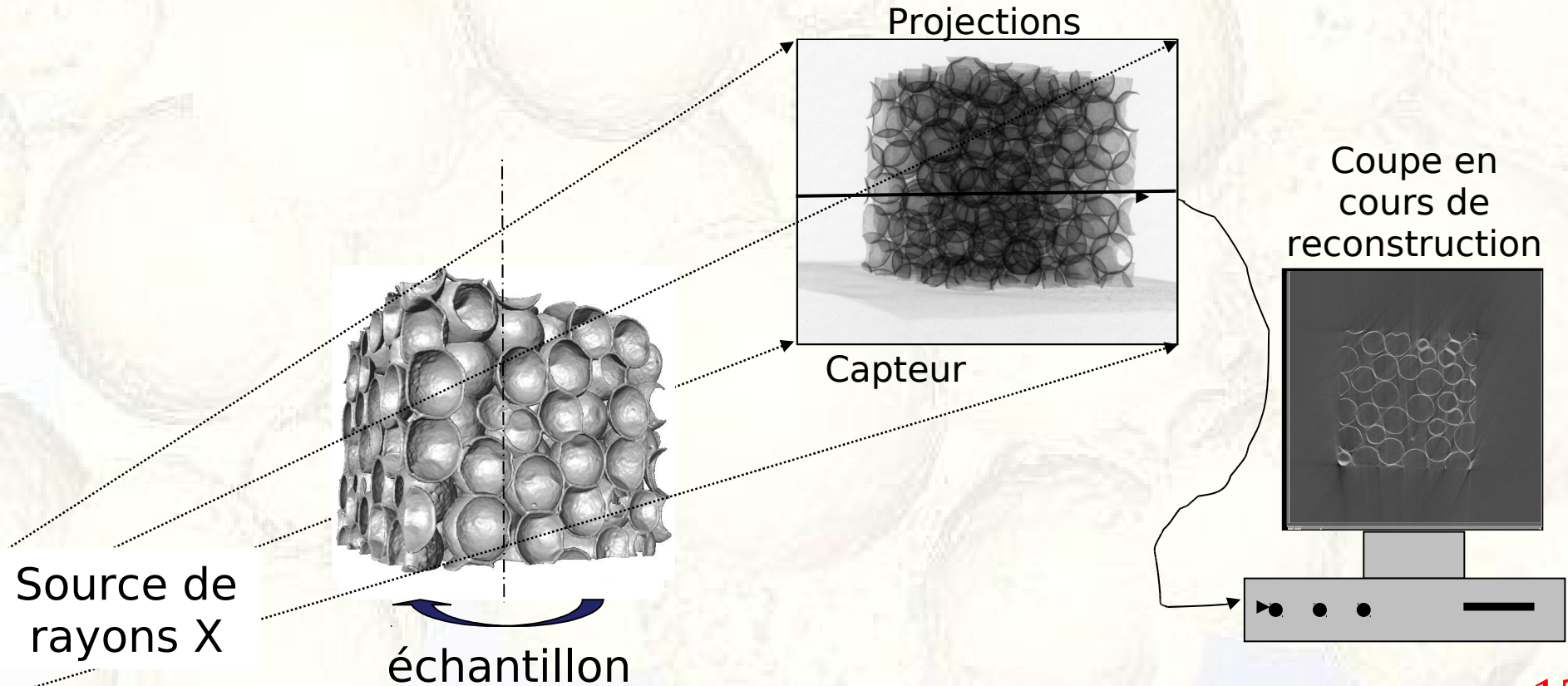
Dispositif

- source RX

- Table de rotation

- Detecteur RX

- Ordinateur reconstruction



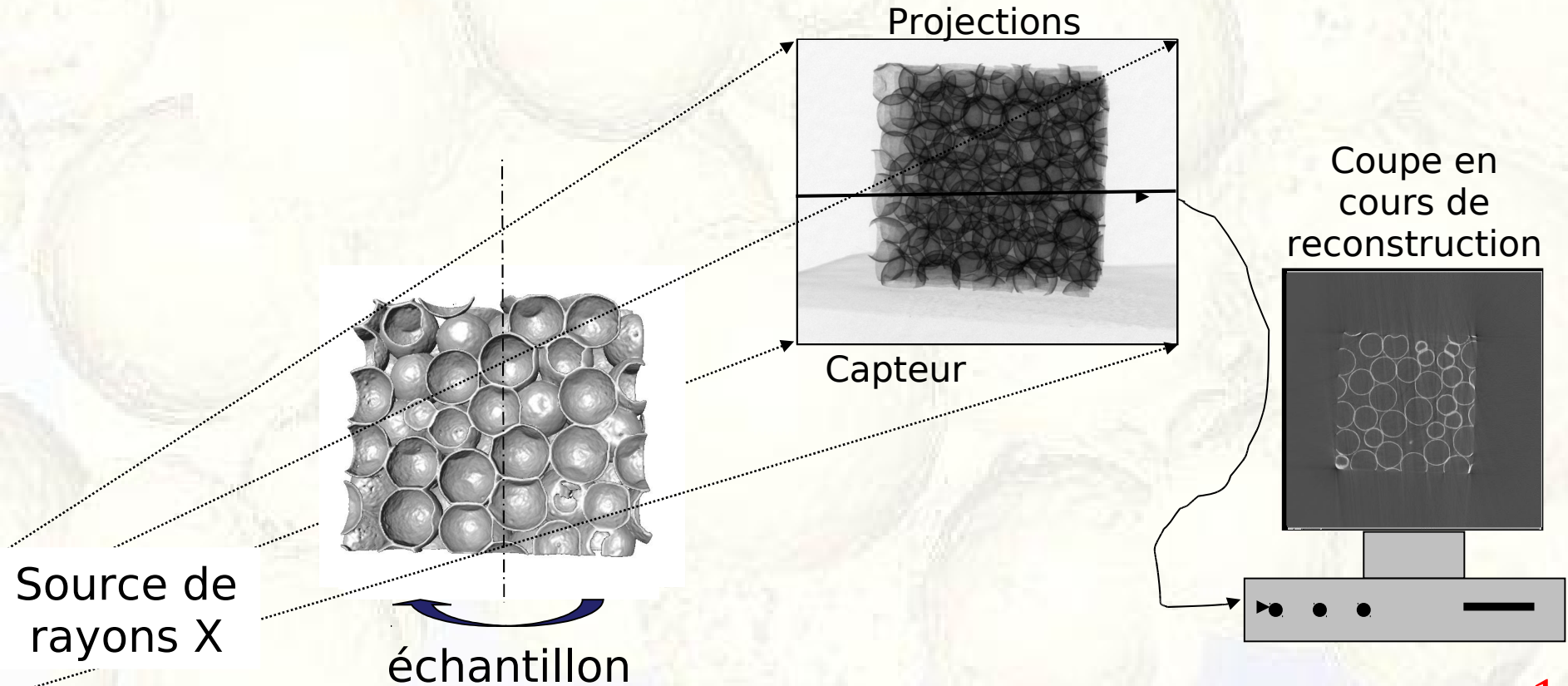
Dispositif

- source RX

- Table de rotation

- Detecteur RX

- Ordinateur reconstruction



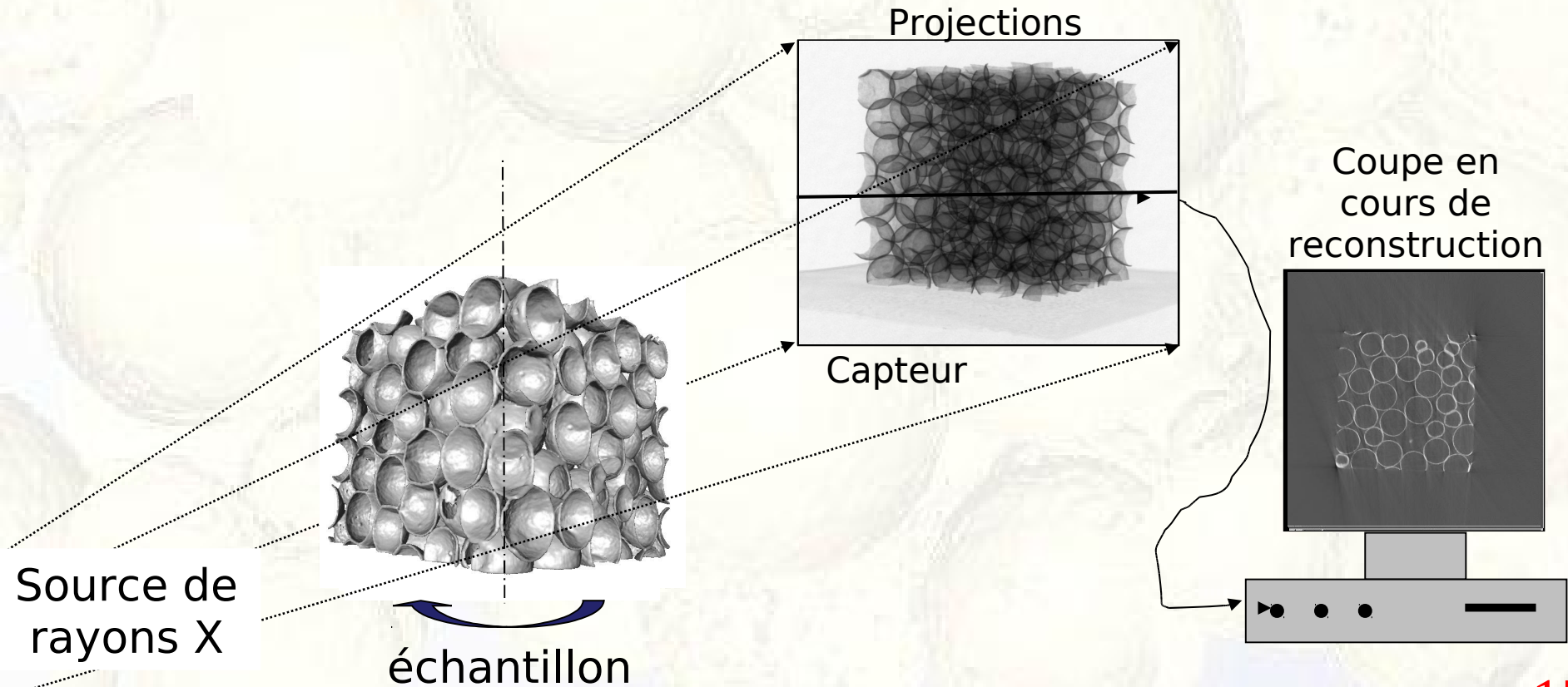
Dispositif

- source RX

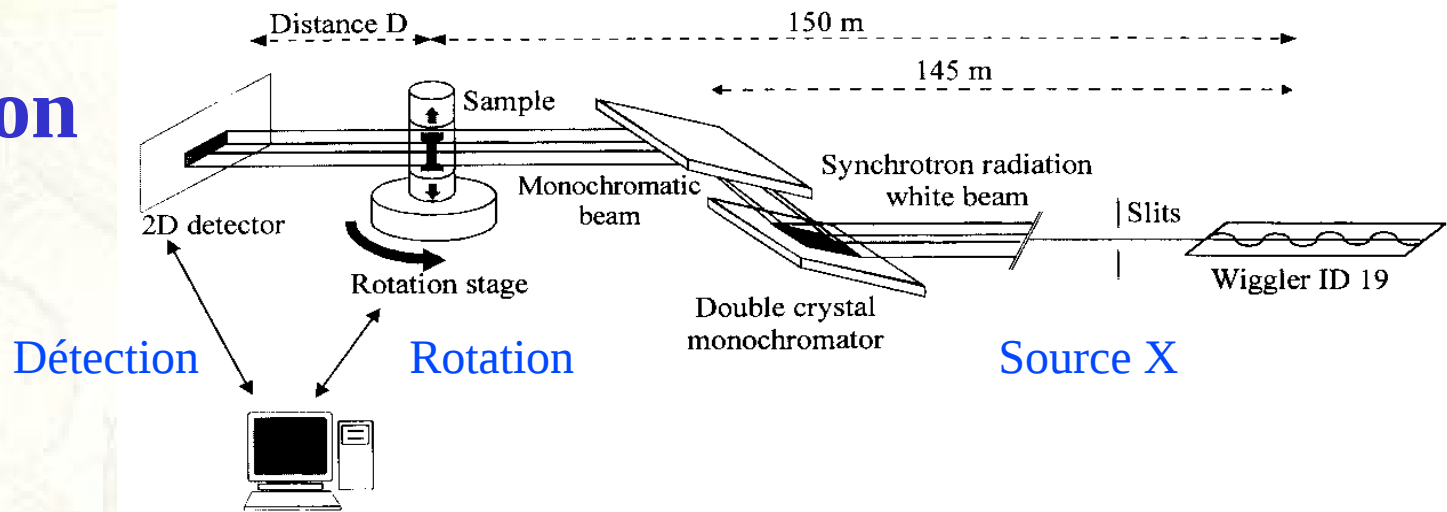
- Table de rotation

- Detecteur RX

- Ordinateur reconstruction



Synchrotron



Faisceau polychromatique
ou monochromatique

Resolution : 20 nm mini.

temps d'acquisition ~
moins d'1 seconde au
mini.

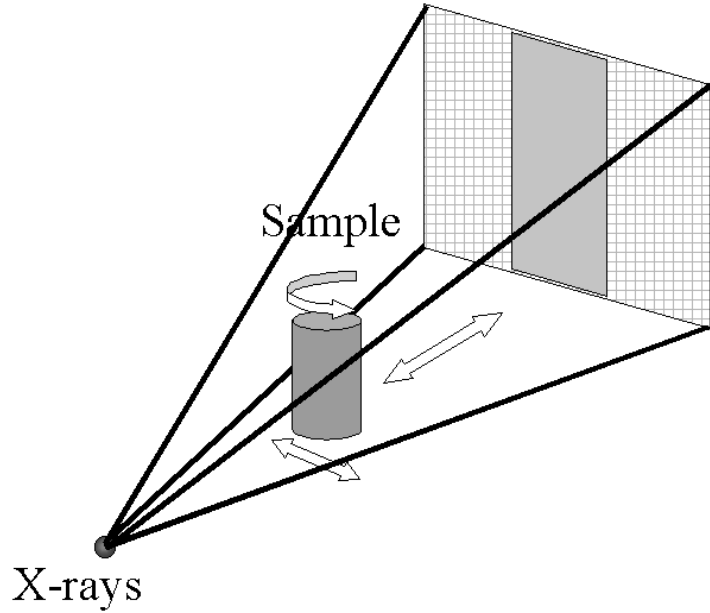
- moteurs et détecteurs très précis
- flux de photons important

Tomographe de laboratoire

Faisceau polychromatique

Resolution : 1 - 150 μm

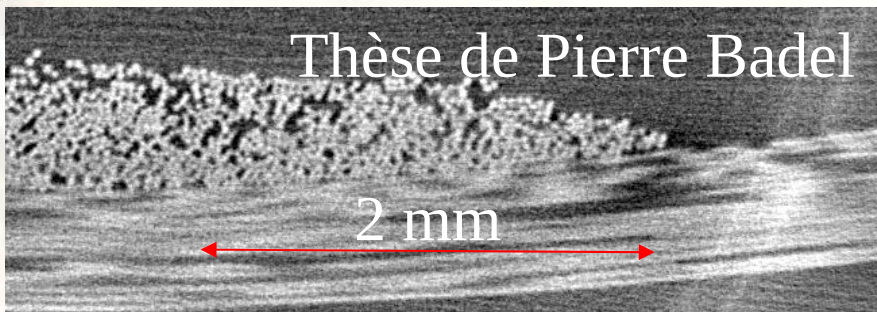
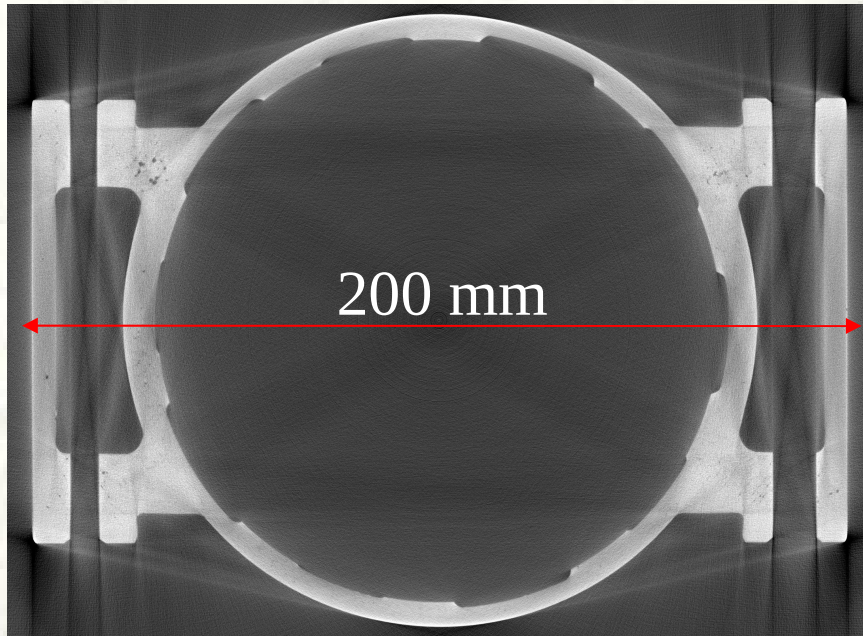
temps d'acquisition \sim 15 à
60 min.



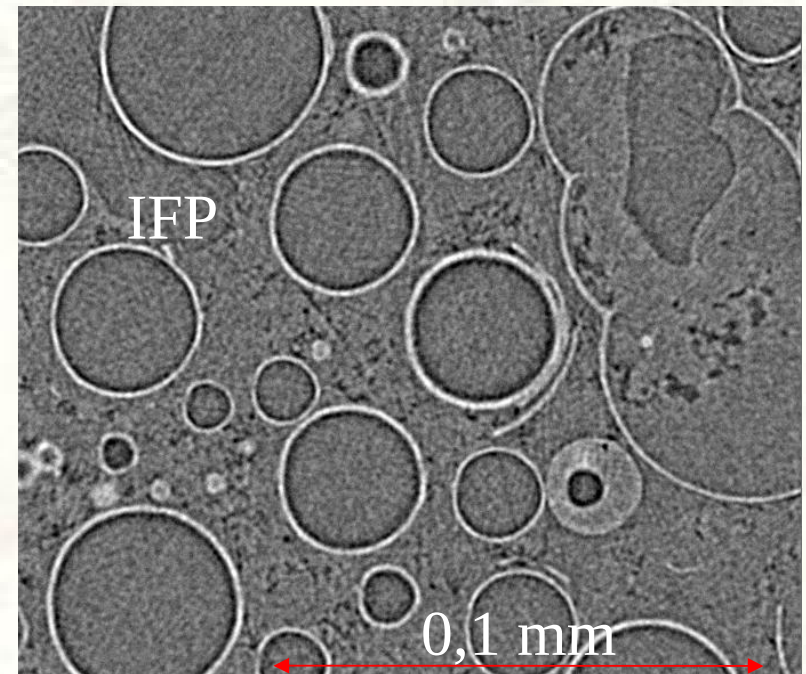
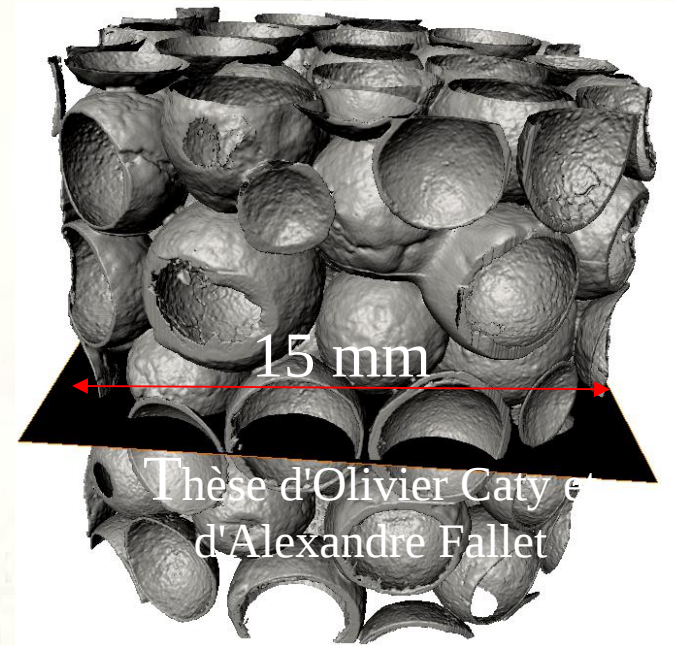
Phoenix V tome X
Detecteur Varian Paxscan
(1920x1536 pixels)
Tube RX à microfoyer
(taille source de \sim 1 à 4 μm)



Exemples absorption/résolution



1000 pixels



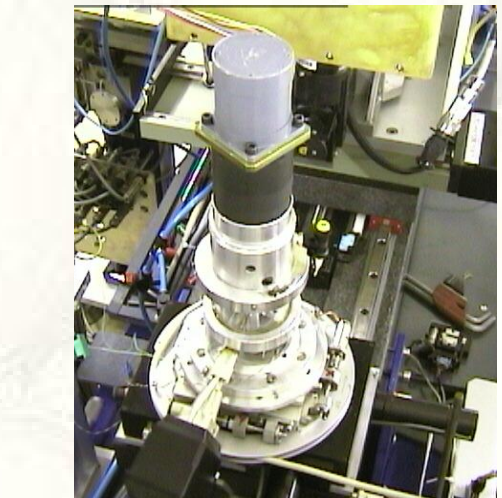
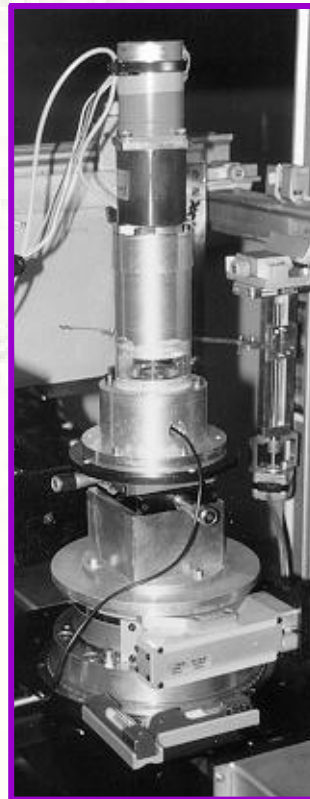
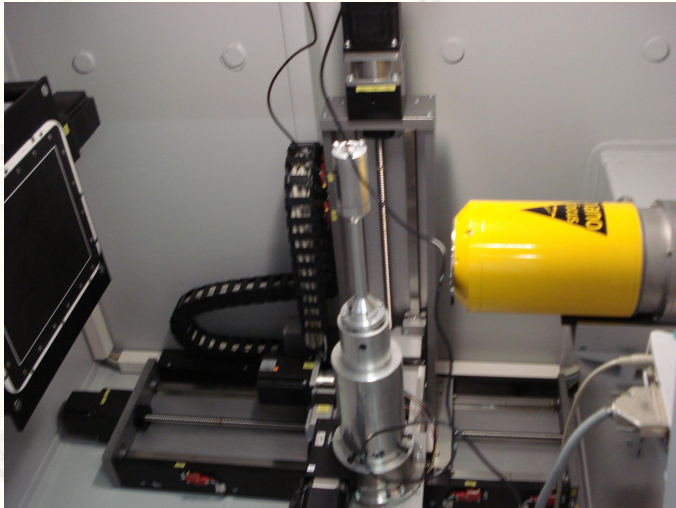
Environnement échantillon / essais in-situ

✓ **Traction/compression**

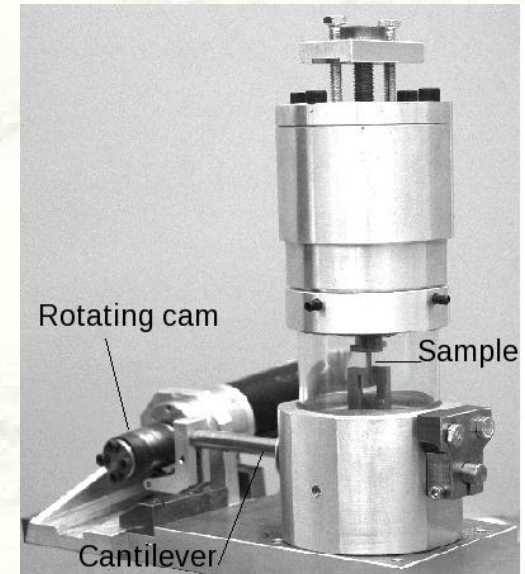
Jusqu'à 5000N

Vitesse : 0.1 $\mu\text{m/s}$ à qqs mm/s

dépl maxi : 10 à 15 mm



✓ **Traction à chaud**



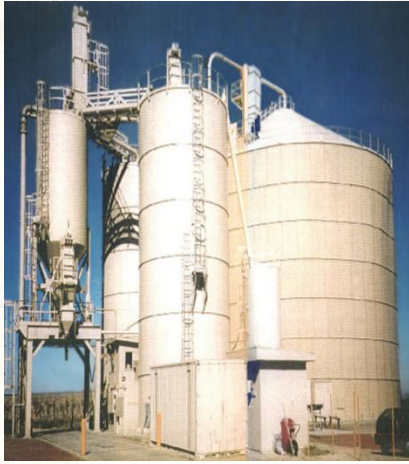
✓ **Four**

✓ **Double torsion**

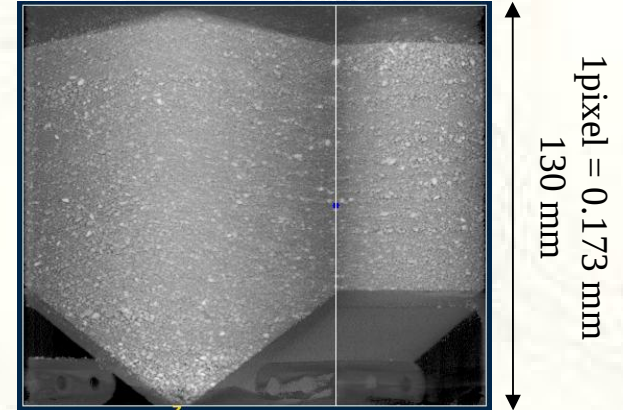
✓ **Platine cryogénique**

✓ **Fatigue**

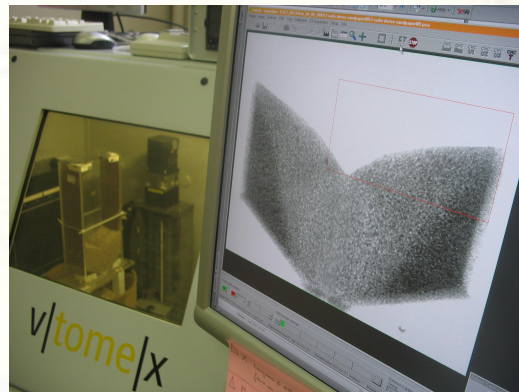
Écoulements gravitaires, cas des silos



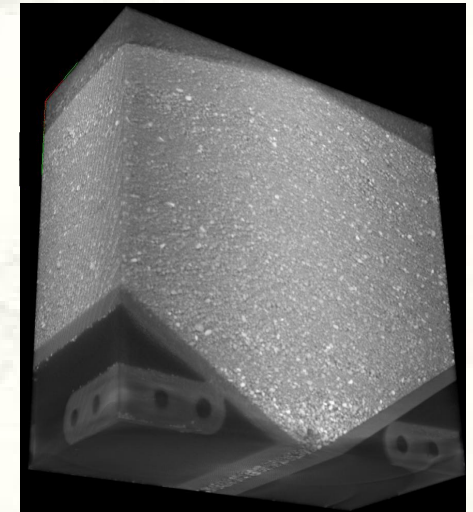
Reconstruction 3D
Tomographie X – état initial



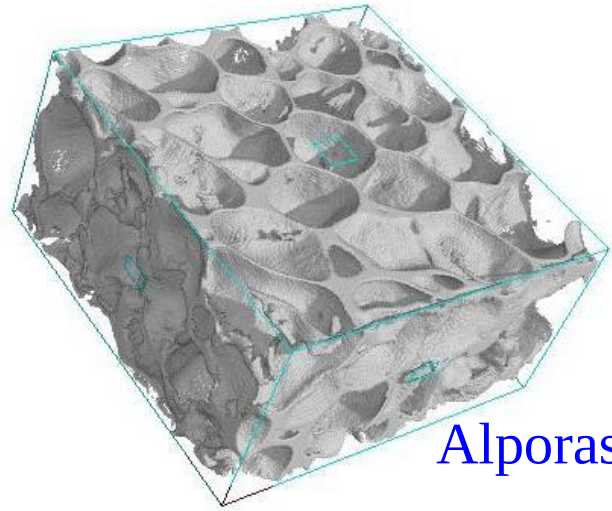
Silo modèle
dans le tomographe



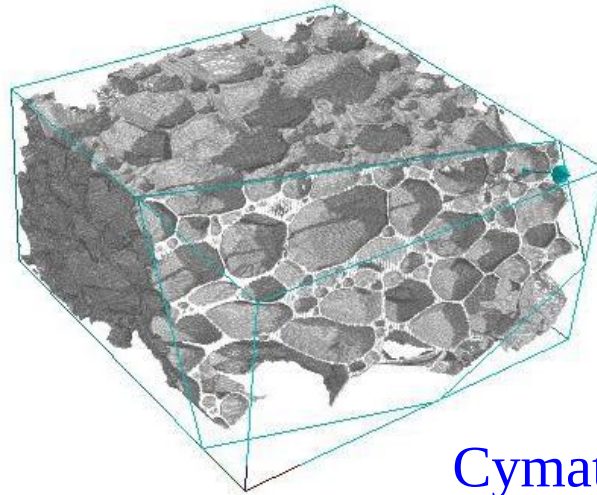
Radiographies 2D



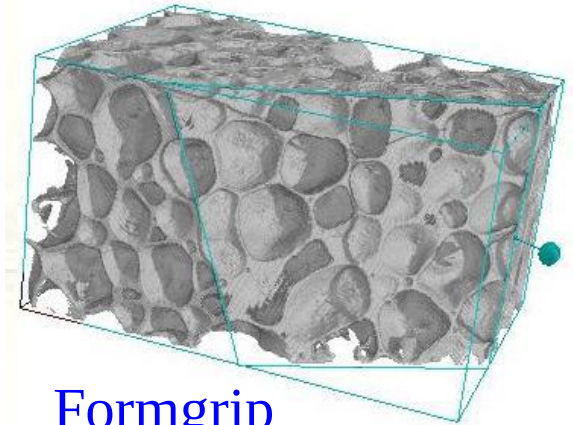
Analyses qualitatives



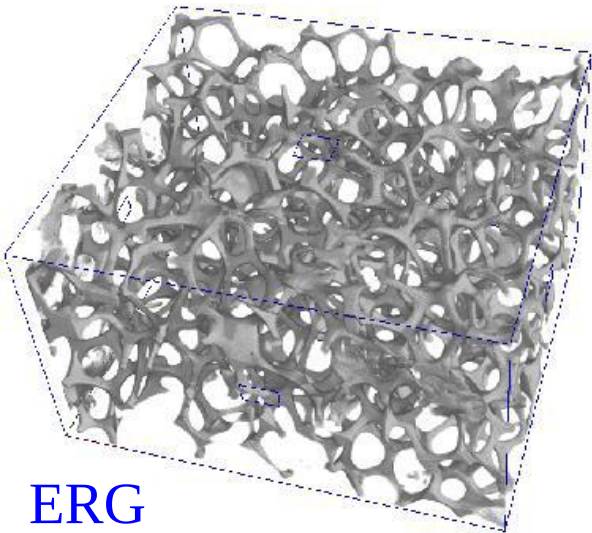
Alporas



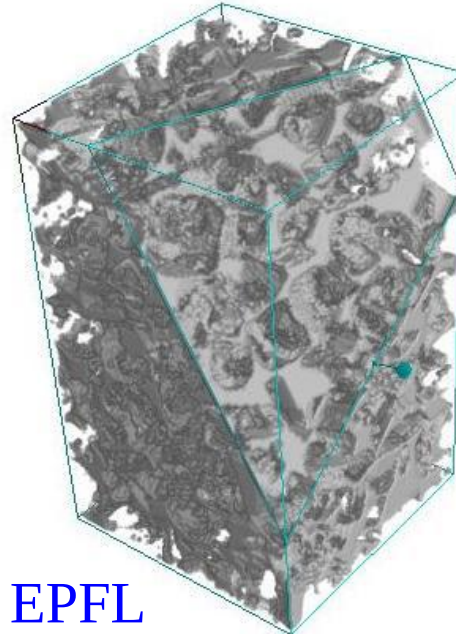
Cymat



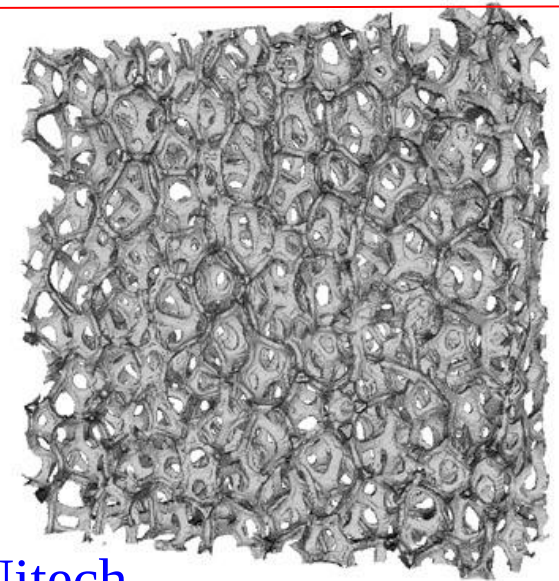
Formgrip



ERG



EPFL



Nitech

Analyses quantitatives

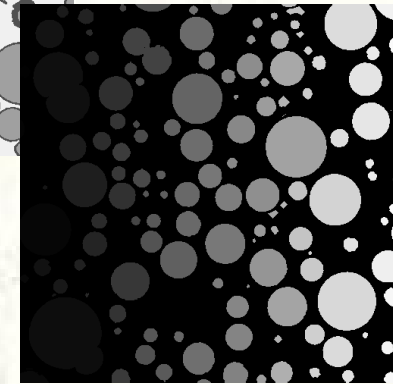
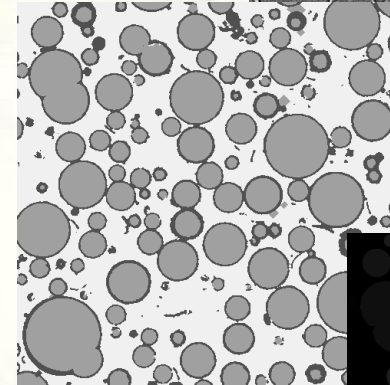
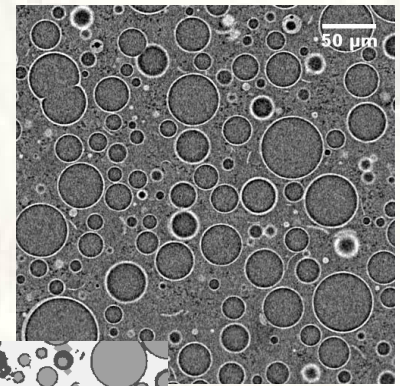
Analyse d'objets

- Cellules fermées

- Étiquetage

- Calcul des paramètres morphologiques des étiquettes

- Volume, surface, centre de gravité, forme
 - Moments d'inertie



| | Volume (µm ³) | Surface (µm ²) | sphericity | A (µm) | B (µm) | C (µm) | Fab | Fac | Fbc |
|---------------|------------------------------|-------------------------------|-------------|-----------|-----------|-----------|--------|--------|--------|
| Mean | 2,9077459 | 10,375430 | 0,815919327 | 0,8789 | 0,6151 | 0,4788 | 1,4506 | 1,8620 | 1,2869 |
| Min | 0,0231667 | 0,4270259 | 0,449953711 | 0,15 | 0,1534 | 0,1496 | 1 | 1 | 1,0042 |
| Max | 32,965457 | 69,509613 | 0,929263880 | 2,7035 | 1,7177 | 1,2292 | 4,5503 | 7,2048 | 2,4955 |
| VC (%) | 127,72% | 87,29% | 10,66% | 49,79% | 39,91% | 35,30% | 29,09% | 35,24% | 18,87% |

Number = 500 analysed particules (touching borders excluded)

Cellules ouvertes densité locale, épaisseur poutre, taille des cellules (qui doivent être fermées par morphologie mathématique)

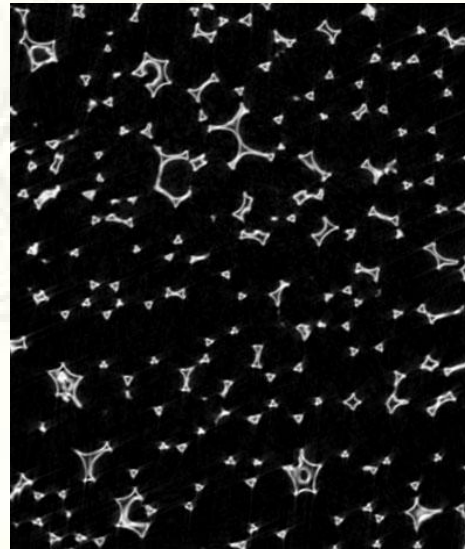
Nieh *et al.*

Dillard *et al.* (poster)



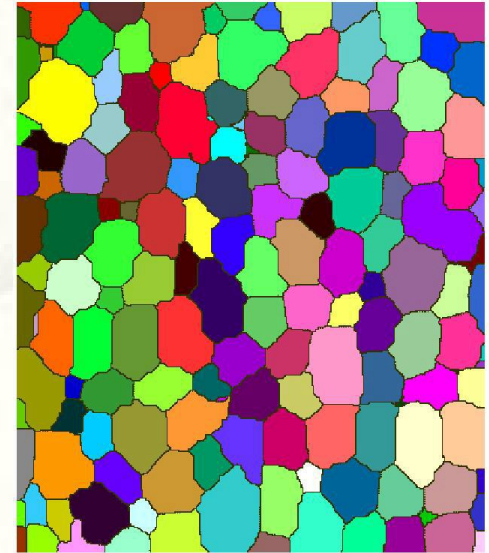
Fig. 3. Synchrotron tomographic image of AA6101 Al foam at a resolution of 23 μm . The structure is predominately open-celled. The rough surface of cell walls (edges) is a result of the casting process.

Raw material
section



2-D section

Segmented image
(watershed)



3-D calculation

ERG Al Foam

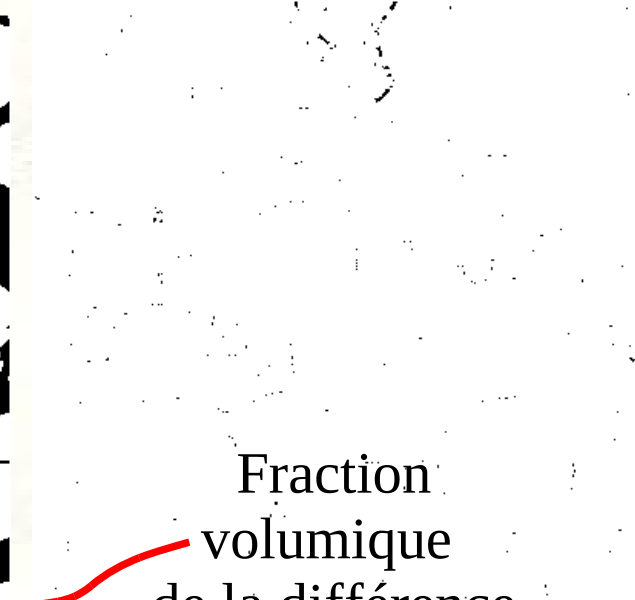
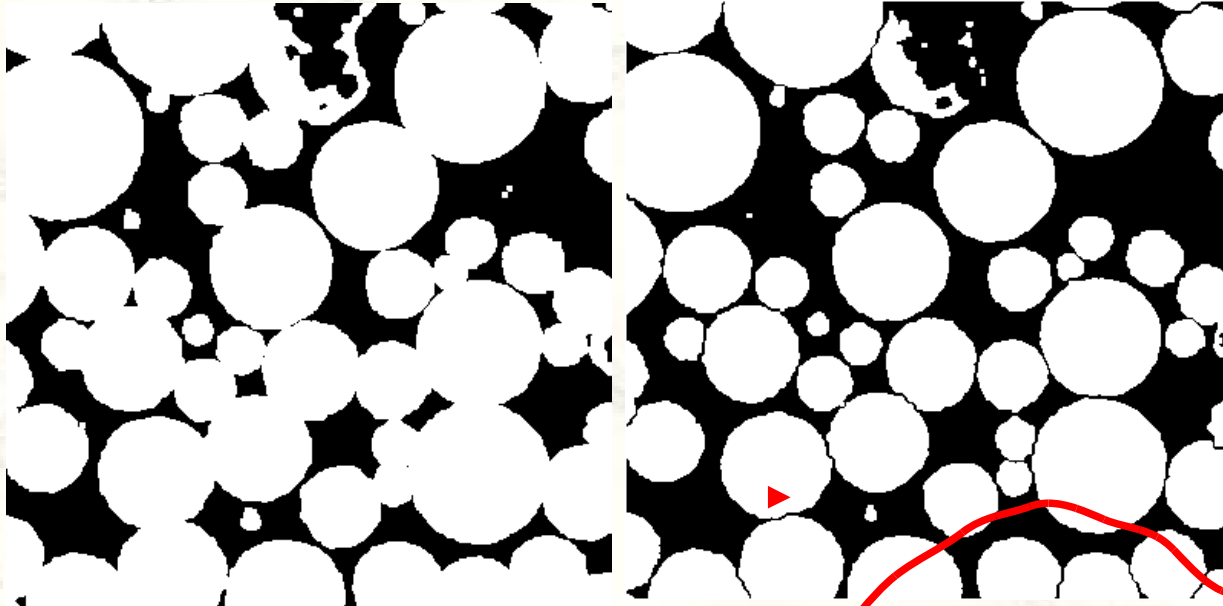
Nitech Ni Foam

Granulométrie 3D = Ouvertures successives

A = Initial

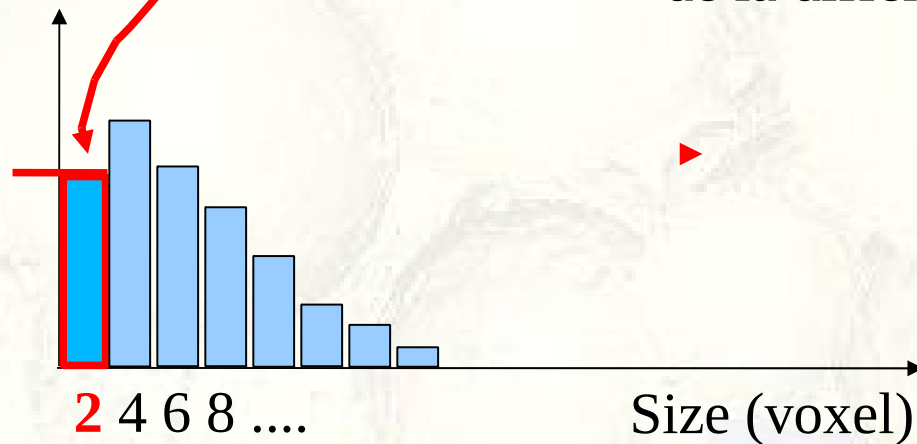
B = Initial + érosion +
dilatation **de taille 1**

Différence
entre A and B



Fraction de
matière (%)

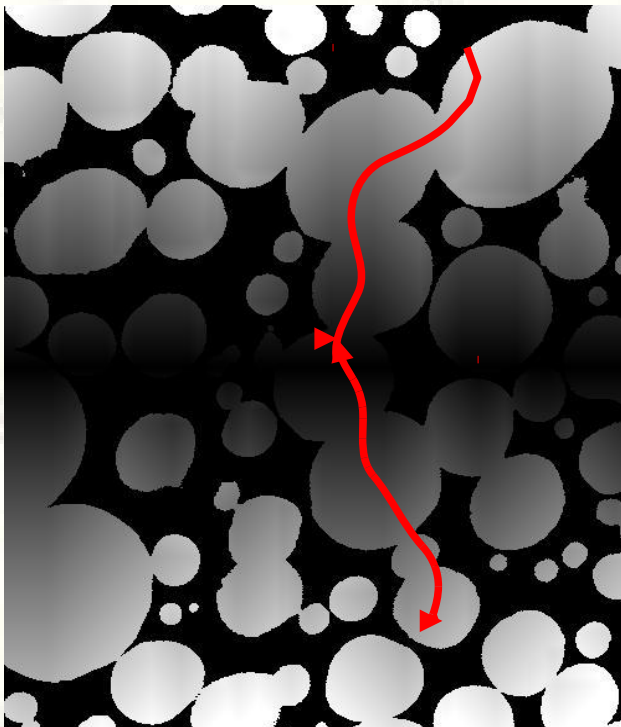
Fraction
volumique
de la différence



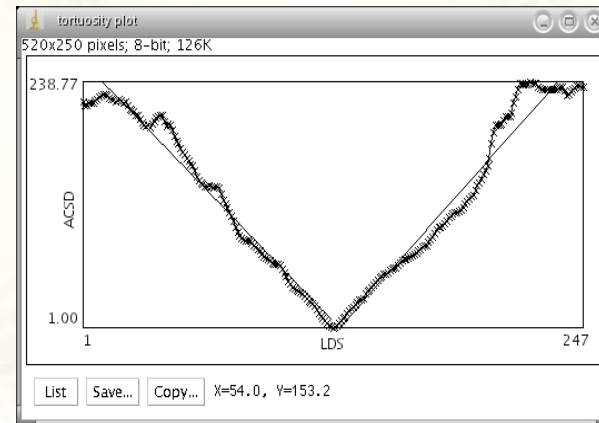
Connections

Nombre, Taille intersection, taille des voisins de chaque porosité...

Tortuosité



Tortuosité =
trajet réel / trajet direct

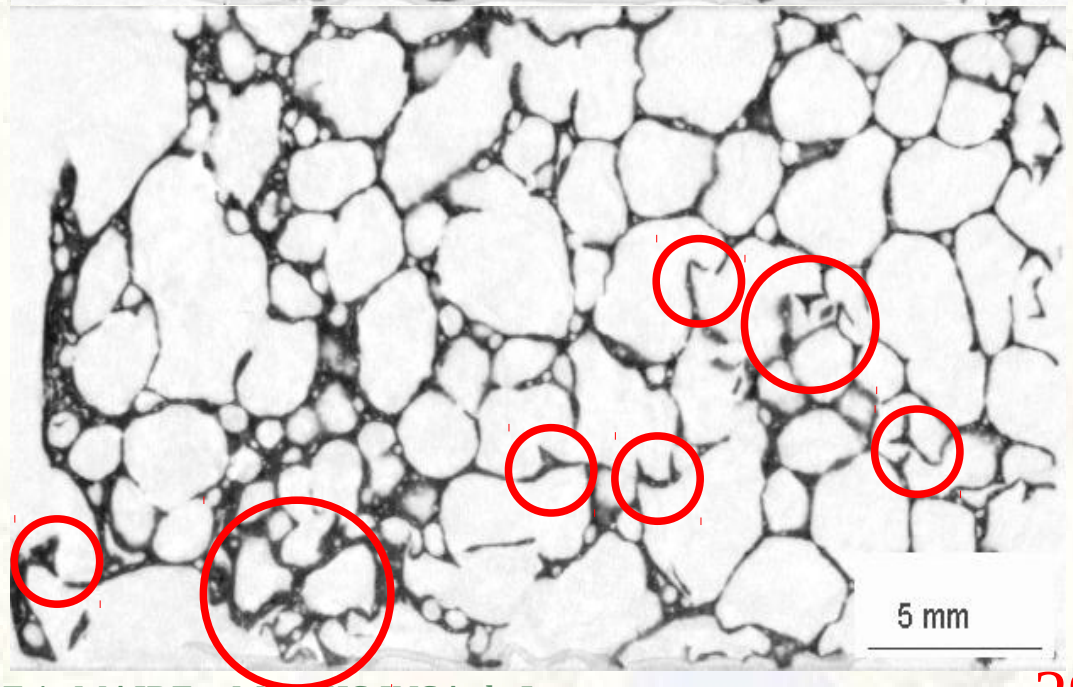
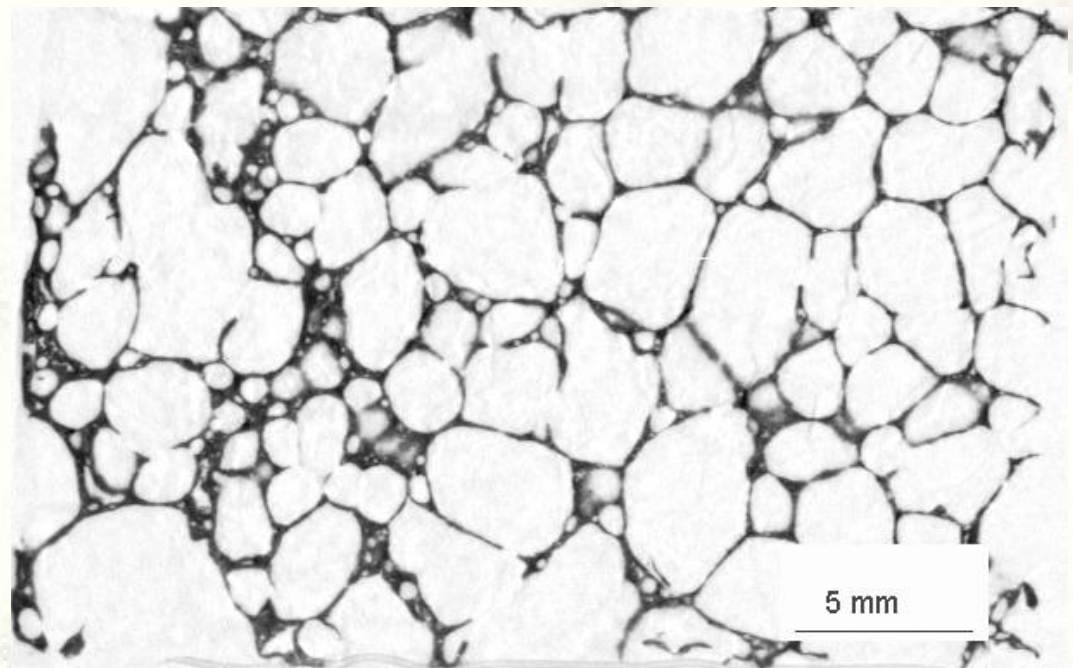


Essais in-situ

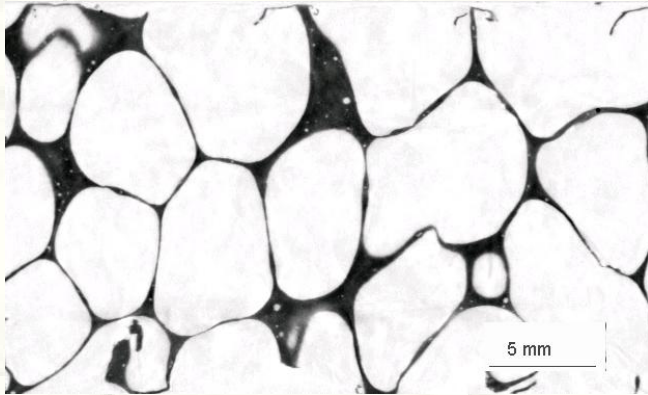
Deformation de mousses Al (compression)

IFAM

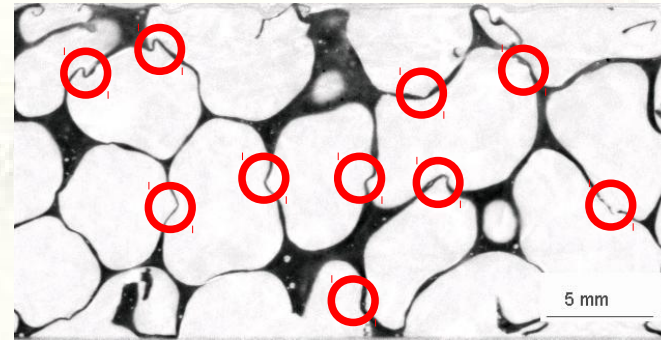
MRS bulletin 2003



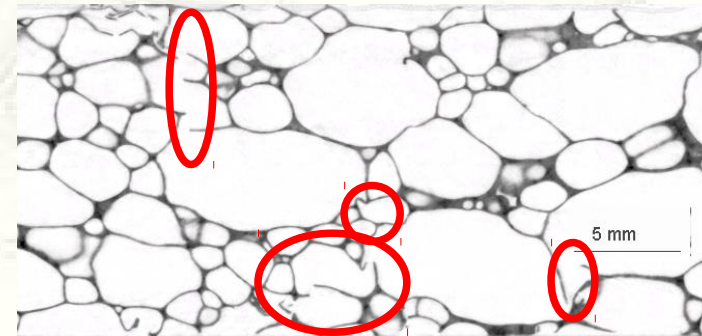
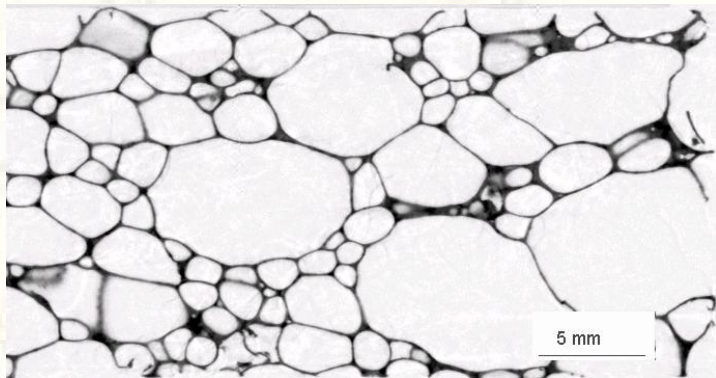
Initial



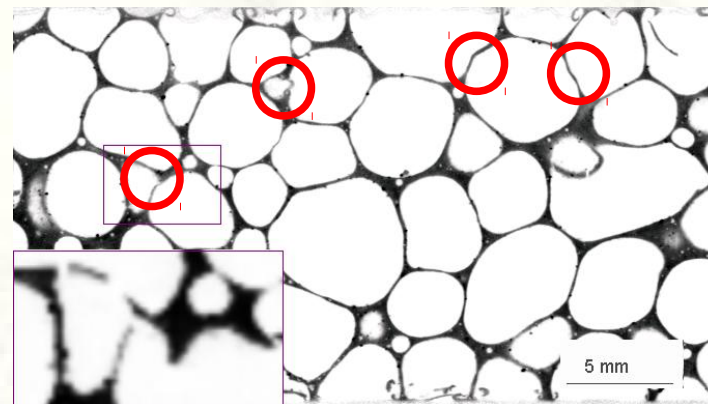
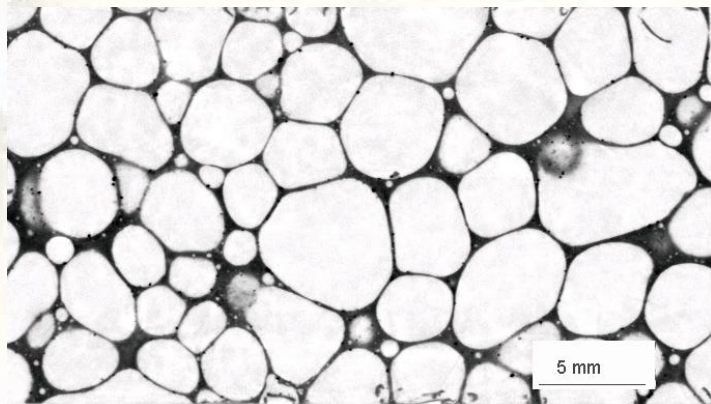
Deformé



Alporas

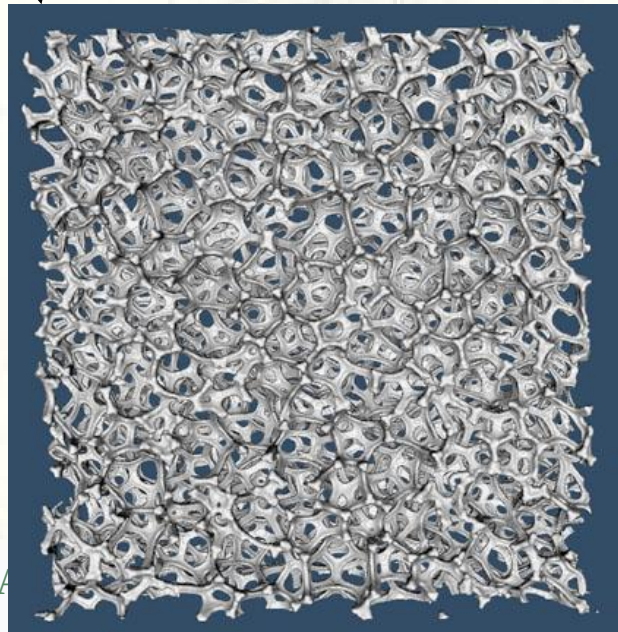
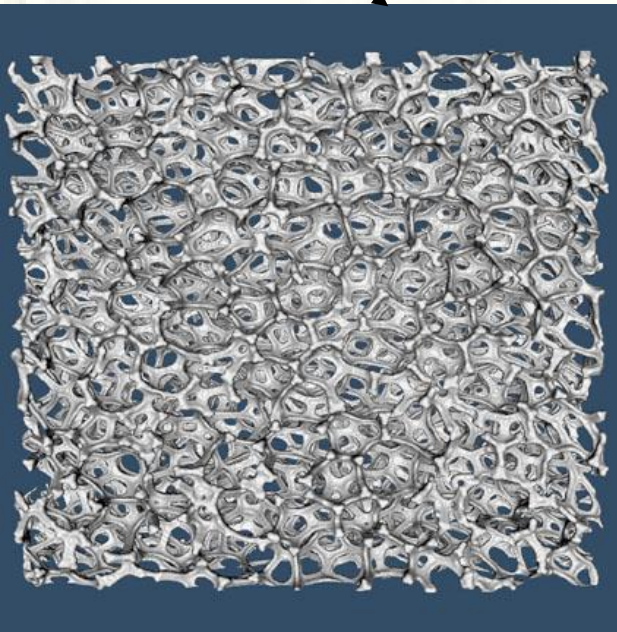
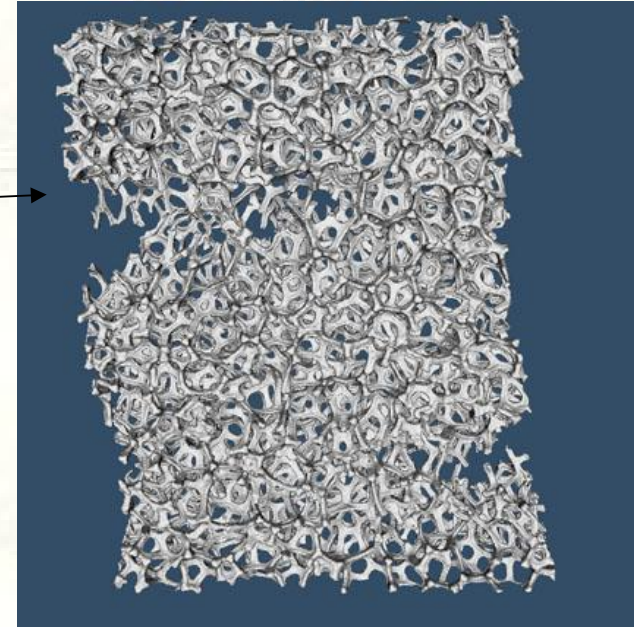
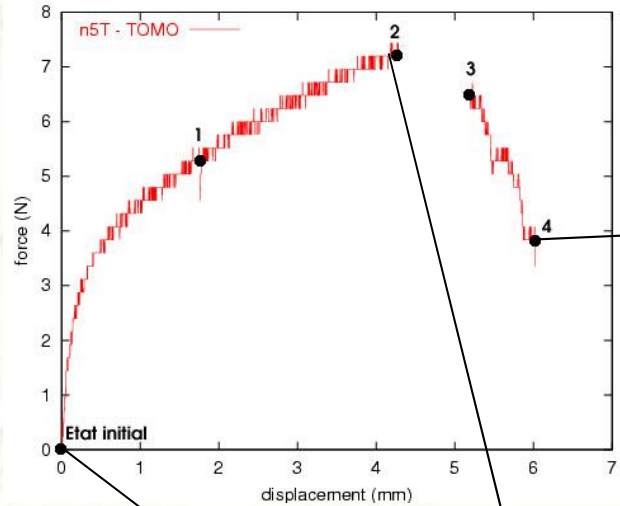


Cymat



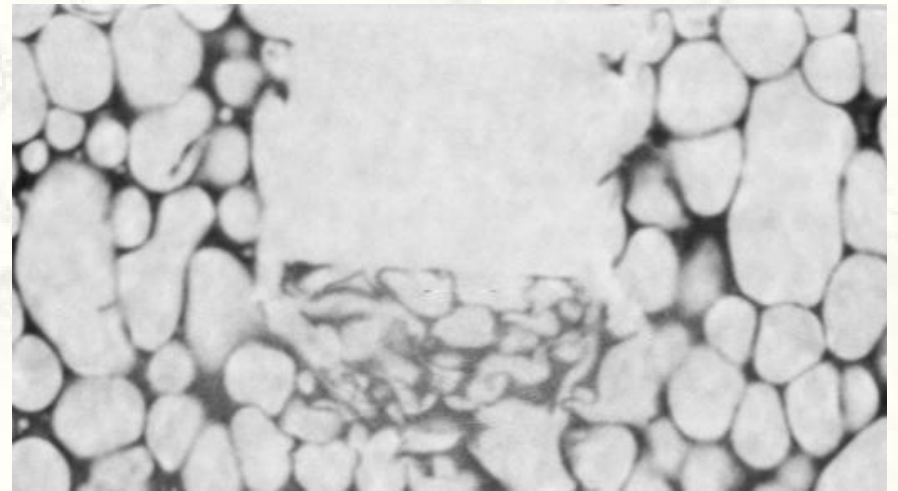
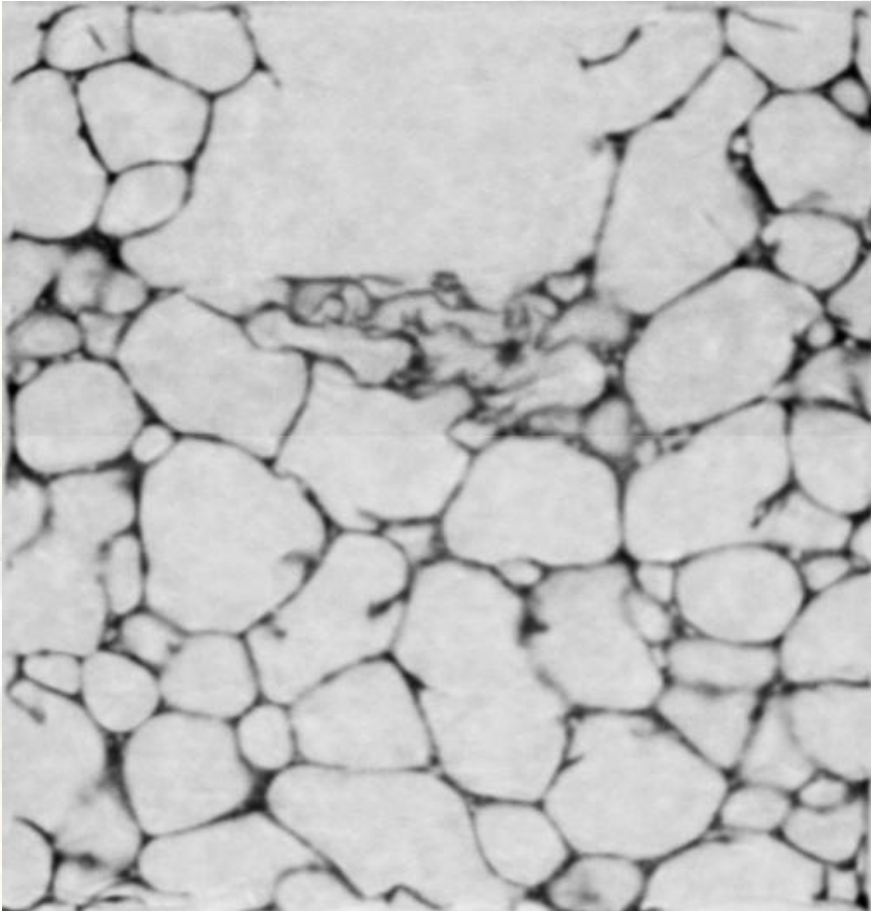
Formgrip

Deformation de mousses de nickel



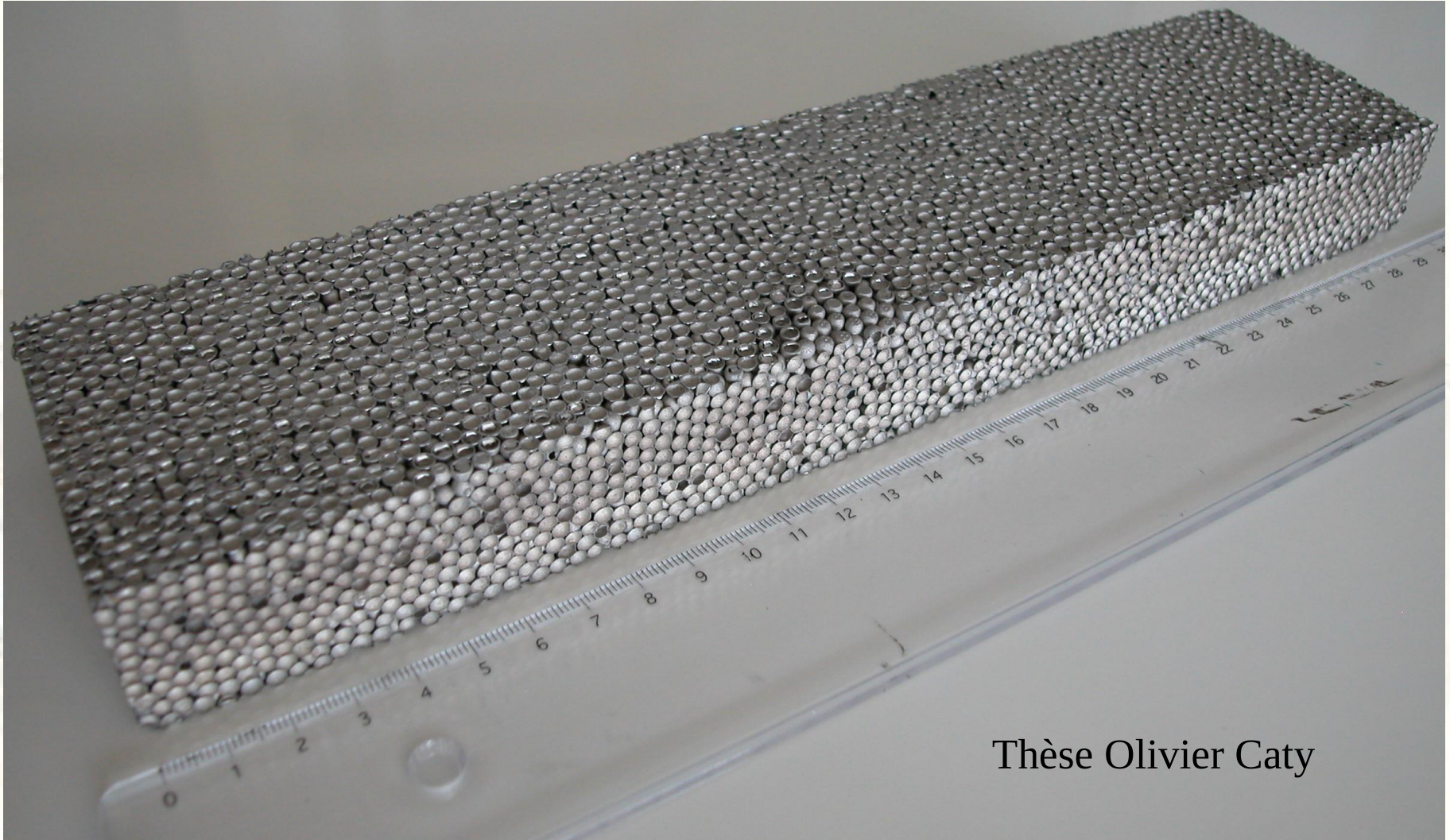
Dillard *et al.* *Phil Mag*

Indentation



Fatigue avec le tomographe de laboratoire

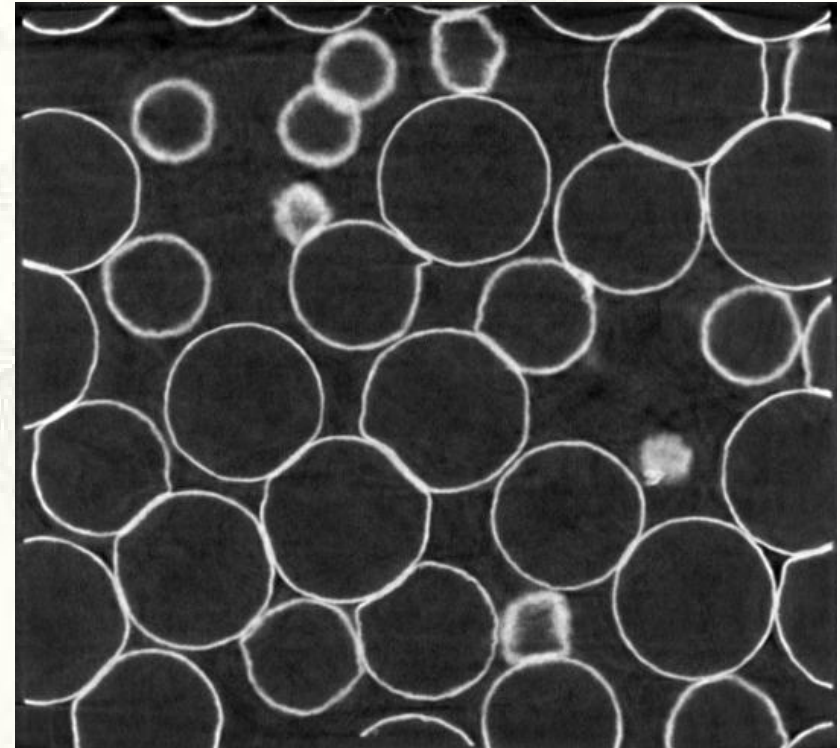
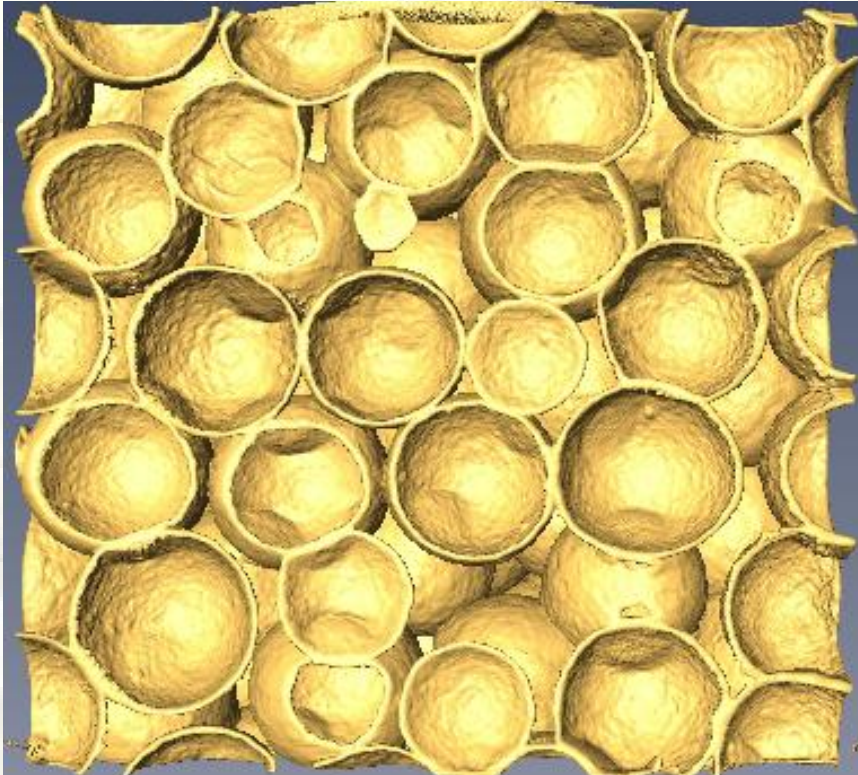
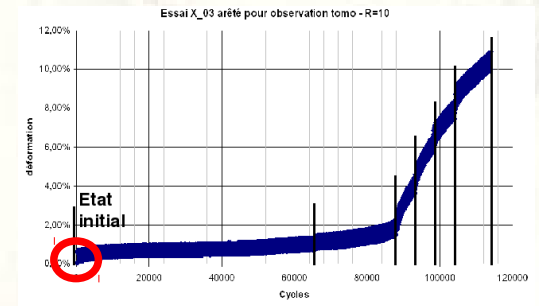
Exemple: empilement de sphères creuses



Thèse Olivier Caty

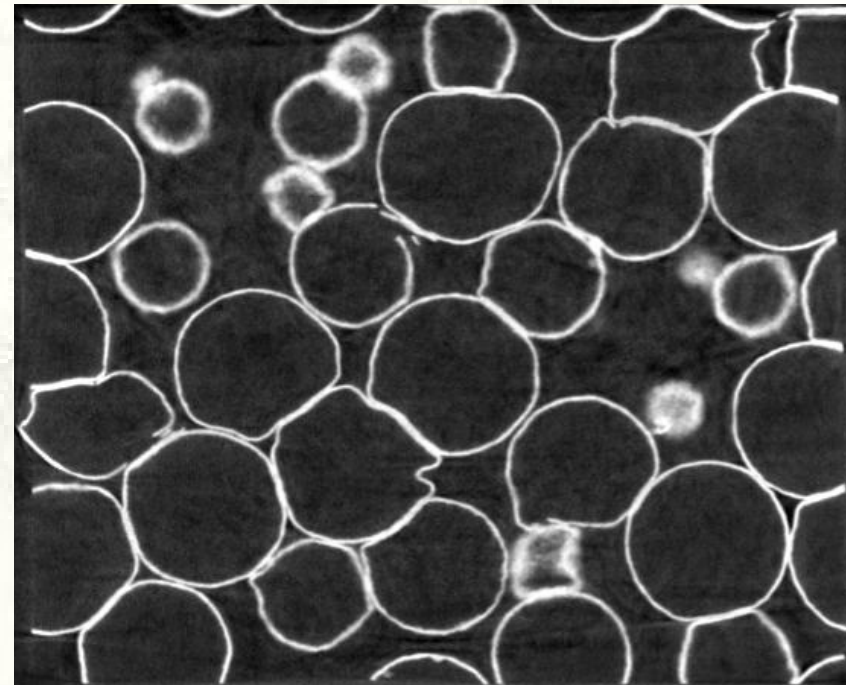
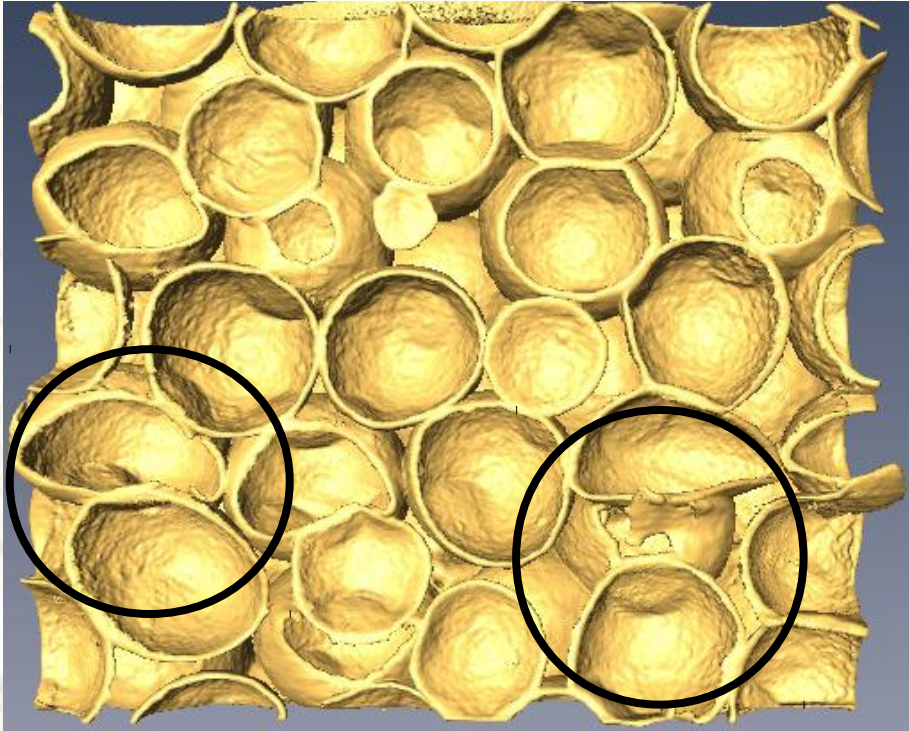
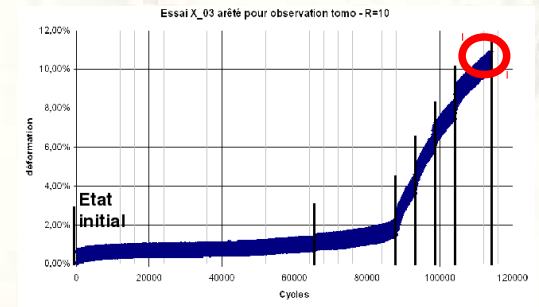
Mécanismes d'endommagement

$N = 0$



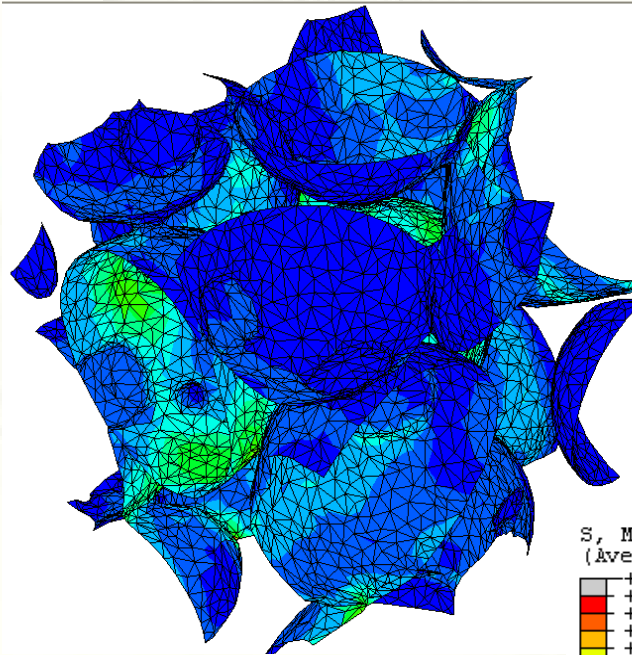
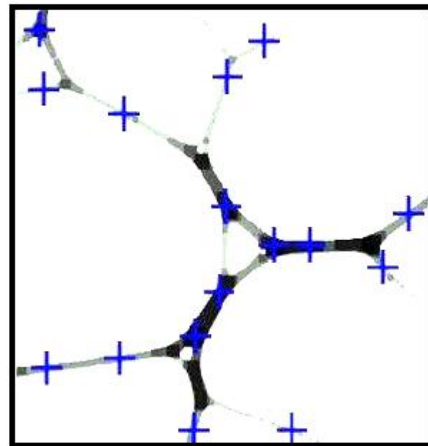
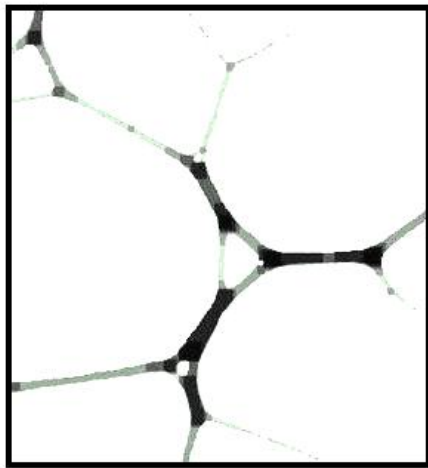
Mécanismes d'endommagement

N = 114500

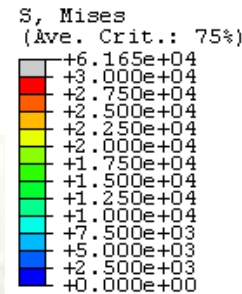
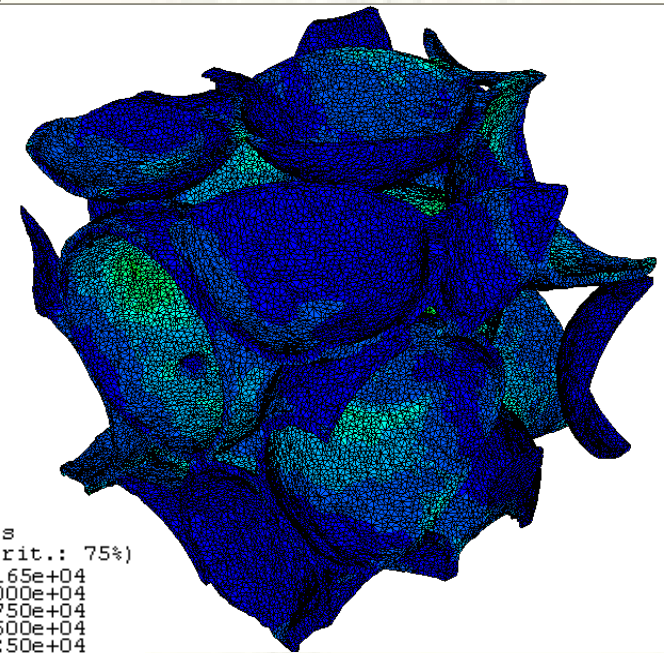


fissures !
bandes de déformations

Maillages coques avec épaisseurs récupérées sur les images



- Calcul en élasticité linéaire
- 7490 éléments coques triangulaires linéaires
- Durée calcul 11 s



- Calcul en élasticité linéaire
- 428000 éléments tétraédriques linéaires
- Durée calcul 114 s

Thèse O. Caty (MATEIS)

Conclusion

- Technique appropriée aux matériaux cellulaires
- Caractérisation de la microstructure
 - visualisation
 - quantification
 - Essais in-situ

Perspectives

- Résolution spatiale
- Résolution temporelle