GDR 3544
Sciences du bois

La microtomographie à rayons X pour le bois

Outils, usages et perspectives

Eric BADEL

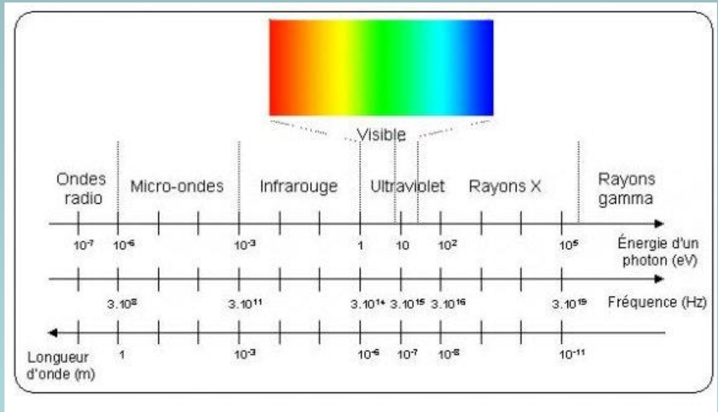
U.M.R. PIAF

UMR PIAF, INRA-UBP 5 chemin de Beaulieu, Clermont Ferrand

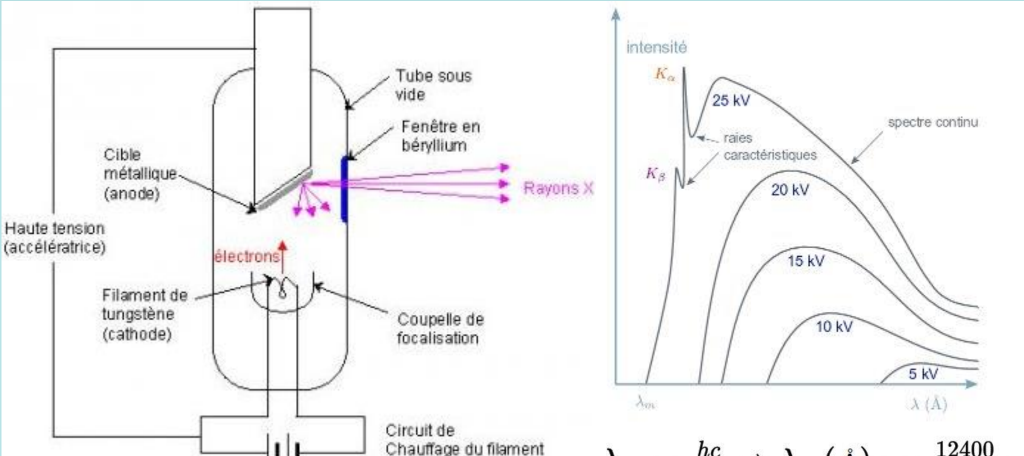
ALIMENTATION
AGRICULTURE
ENVIRONNEMENT

Rayonnement X

Le rayonnement X est une onde électromagnétique résultant de l'accélération d'électrons



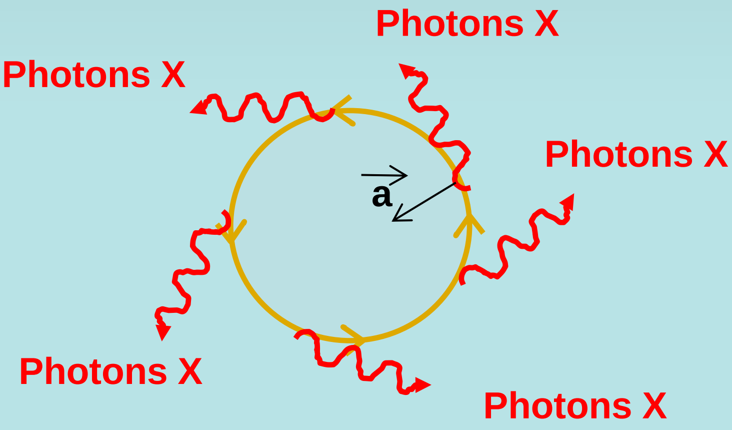
Freinage sur une anode + exitation de la cible (tube X)



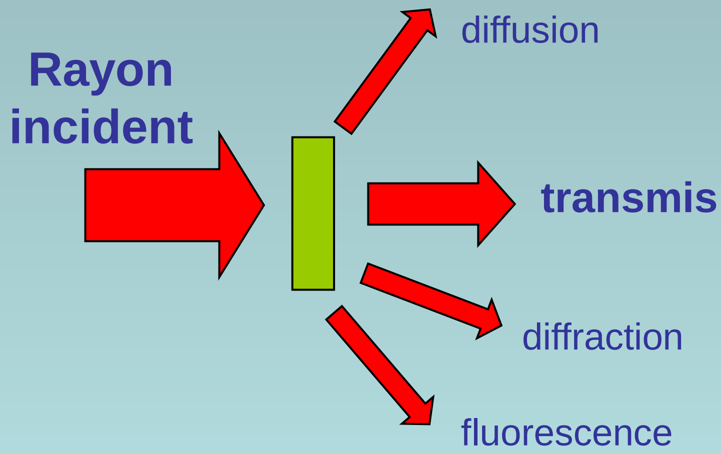
$$\lambda_m = \frac{hc}{eV} \Rightarrow \lambda_m(\text{Å}) = \frac{12400}{V(\text{volts})}$$

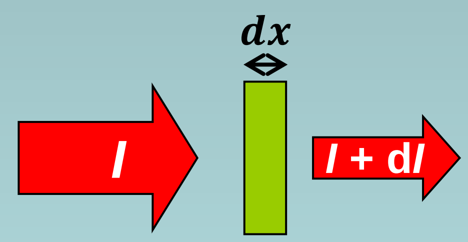
ΔV

Accélération centrifuge (synchrotron)

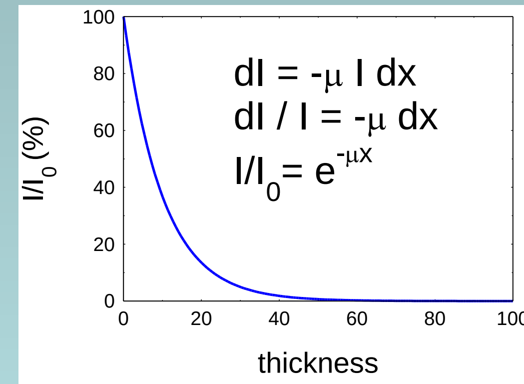


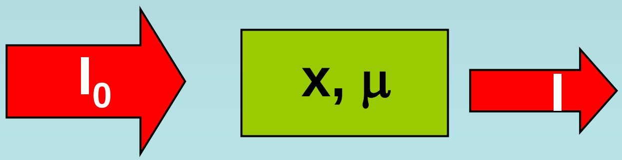
Atténuation des rayons X par la matière





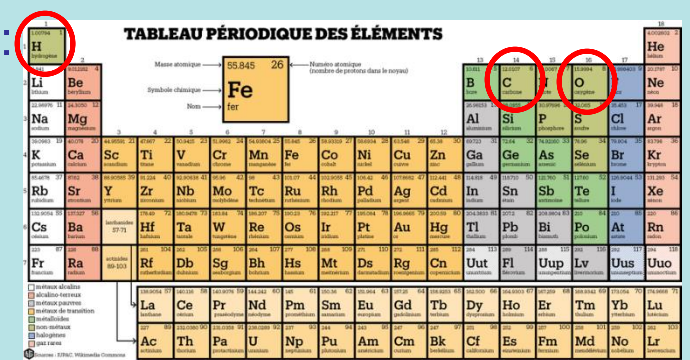
$$dI = -\mu \, I \, dx$$





$$ln(\frac{I}{I_0}) = -\mu \, X$$

μ : l'atténuation des rayons X par la matière dépend de:
- le numéro atomique des constituants chimiques (Z^3)
- la densité de la matière
- l'énergie du rayonnement incident !!!

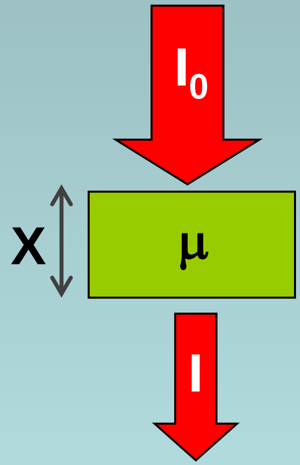


Bois : cellulose $C_6H_{12}O_6$ peu atténuant

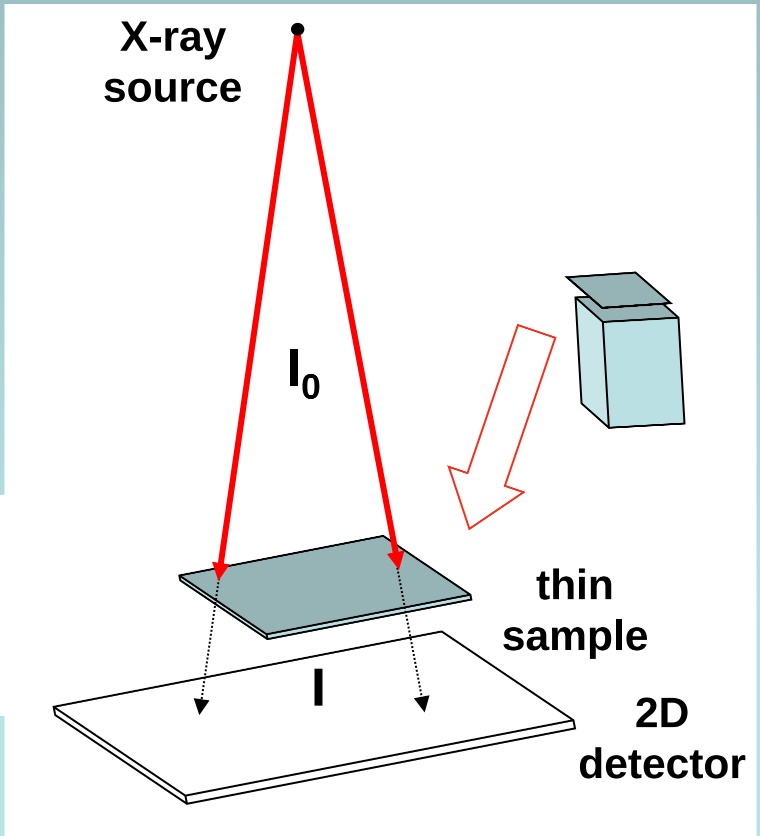
Choix du rayonnement incident

Projection simple 2D : la radiographie X

Röntgen 1895

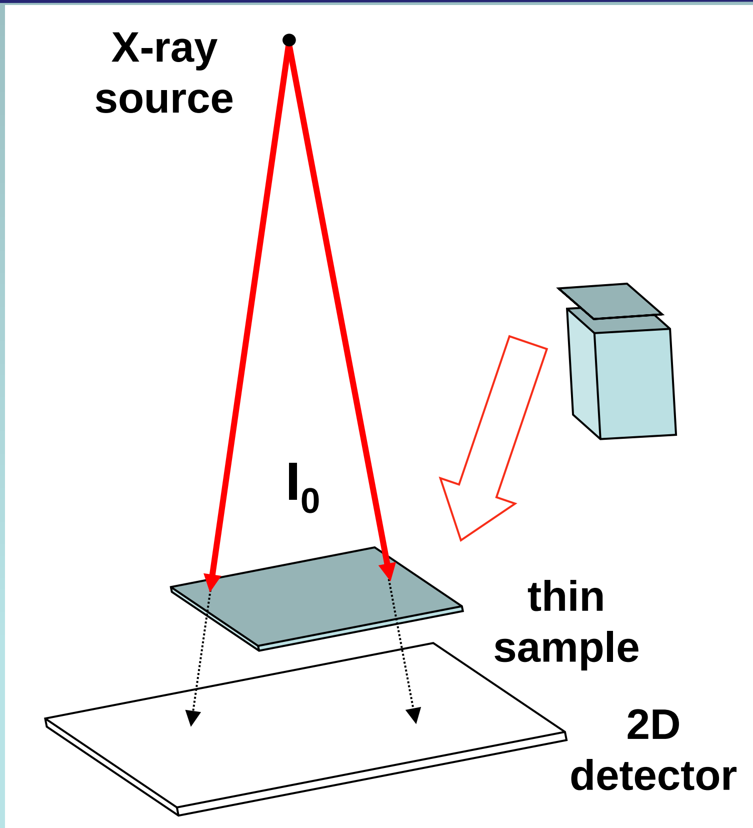


$$ln\left(\frac{I}{I_0}\right) = -\mu\, X$$



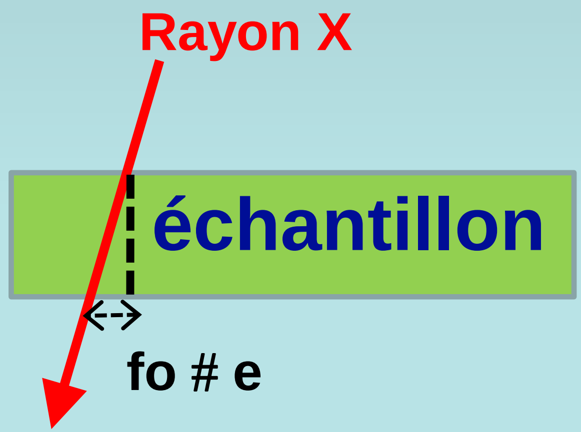
- information intégrative sur l'épaisseur de l'échantillon
- ce que l'on mesure : **μ X**

Projection simple 2D : la radiographie X
Résolution et limites



$$resolution\ pixel = \frac{resolution\ detecteur}{M}$$

$$M = \frac{|source - échantillon|}{|source - détécteur|}$$

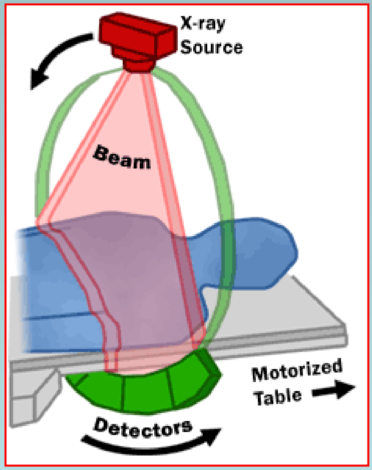


- Flou « échantillon » lié à l'épaisseur de l'échantillon et amplifié par le grossissement
- Résolution spatiale définie par celle du détecteur et le grossissement X

- **Solution: échantillon très fin**

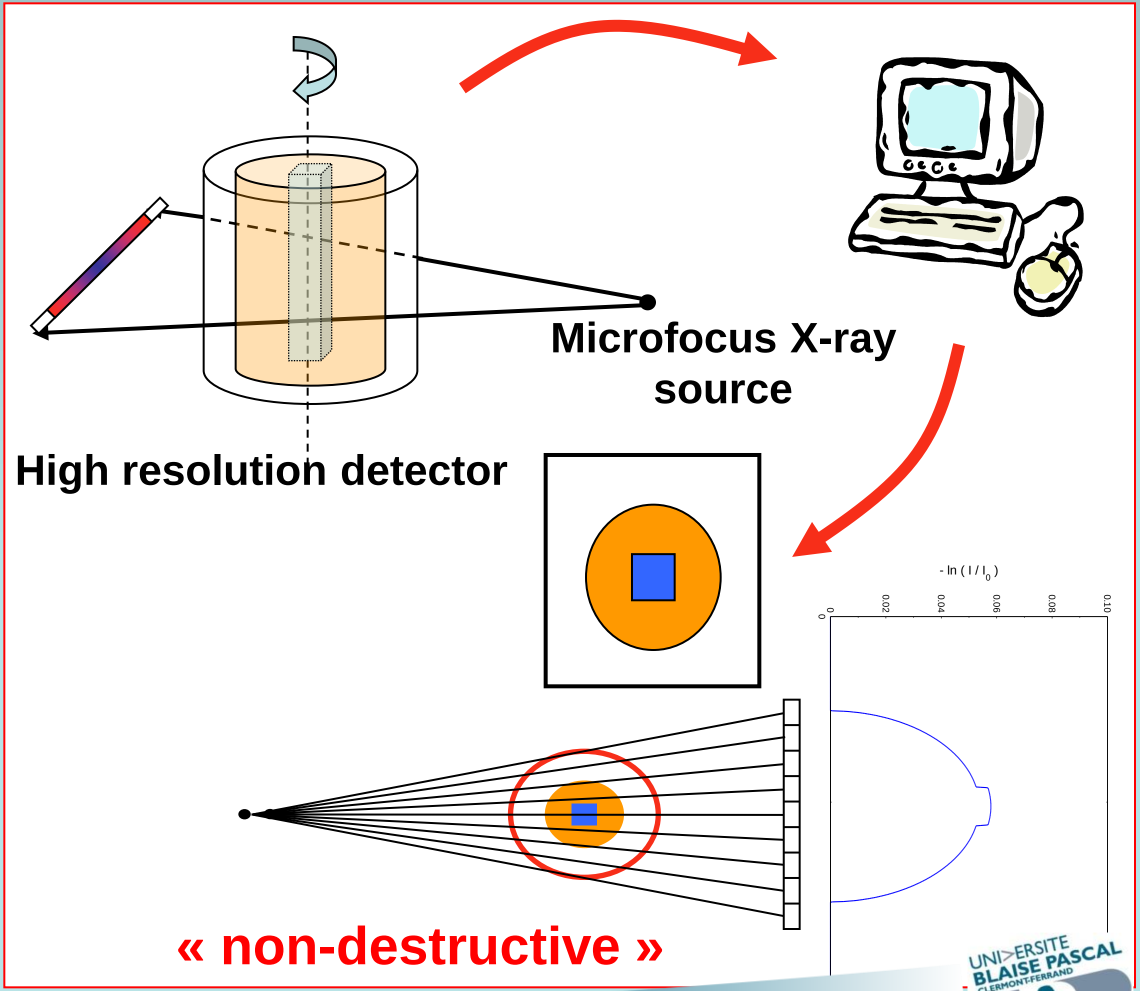
(micro)tomographie à rayons X 2D

Scanner médical

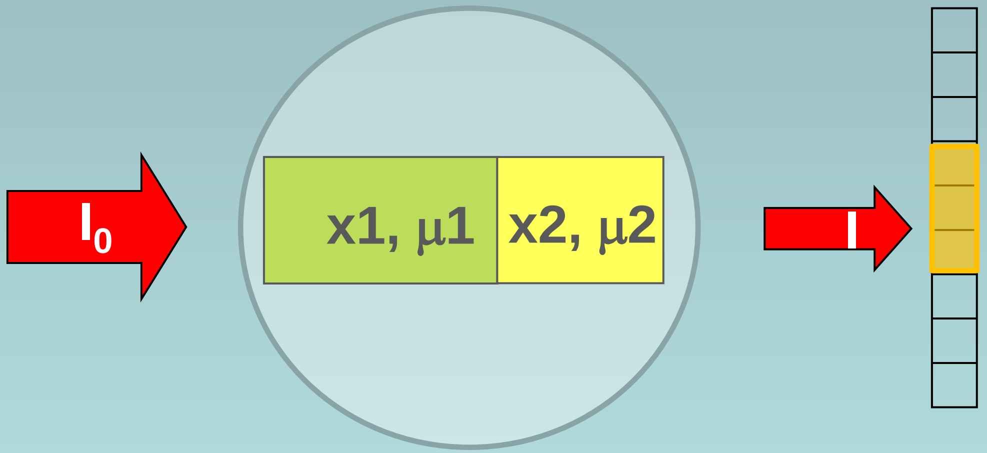


J. Ruelle (INRA-Nancy)

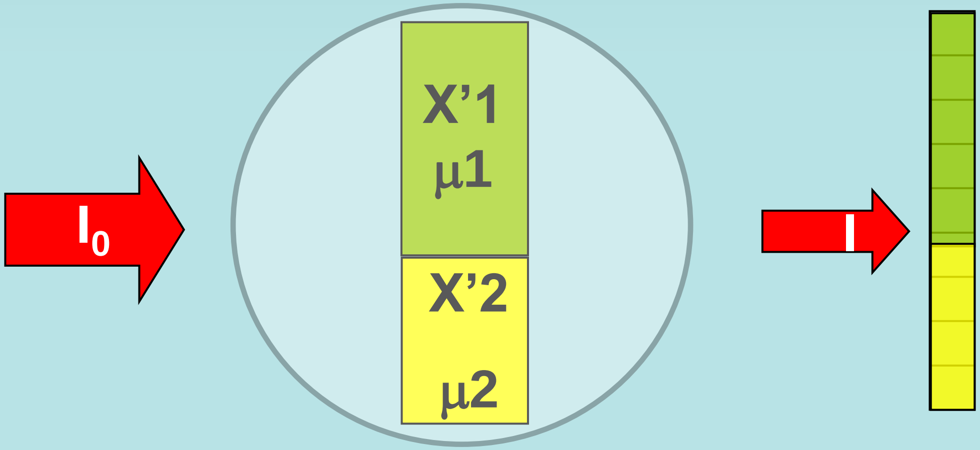
Microtomographie 2D (haute résolution)



Reconstruction tomographique (2D)



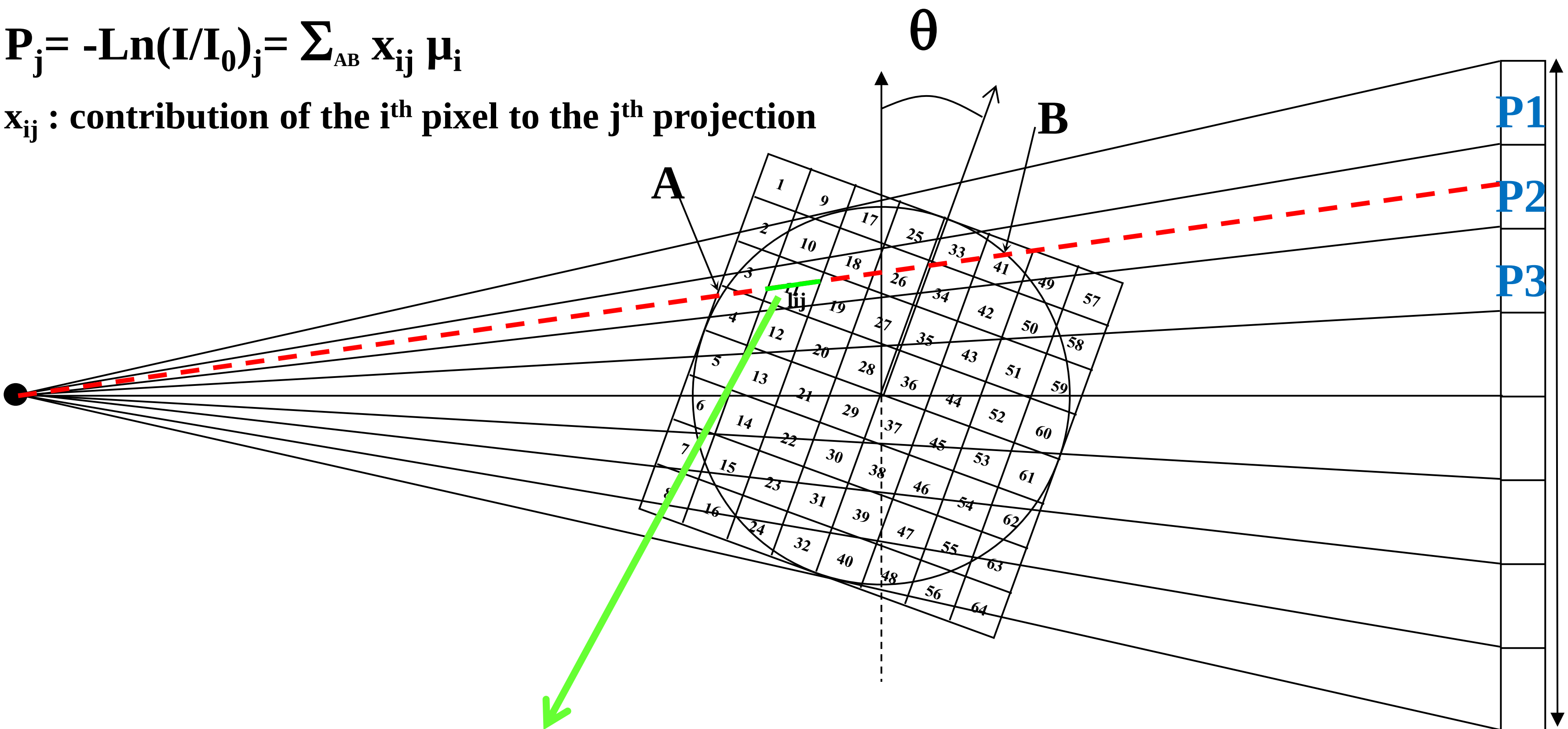
$$P = -Ln(I/I_0) = x_1\,\mu_1 + x_2\,\mu_2$$



Reconstruction tomographique (2D)

$P_j = -Ln(I/I_0)_j = \Sigma_{AB}\, x_{ij}\, \mu_i$

x_{ij} : contribution of the i[th] pixel to the j[th] projection



$P_2 = -Ln(I/I_0)_2 = x_{4,2}\, \mu_4 + x_{11,2}\, \mu_{11} + x_{19,2}\, \mu_{19} + x_{18,2}\, \mu_{18} + x_{26,2}\, \mu_{26} + x_{33,2}\, \mu_{33} + x_{41,2}\, \mu_{41}$

- Experimental measurements
- Unknowns
- Geometrical computation

Reconstruction tomographique (2D)

$\theta=0°$

$P_1 = -Ln(I/I_0)_1 = \Sigma\, x_{i1}\, \mu_i$

$P_2 = -Ln(I/I_0)_2 = \Sigma\, x_{i2}\, \mu_i$

⋮

$P_N = -Ln(I/I_0)_N = \Sigma\, x_{iN}\, \mu_i$

⋮

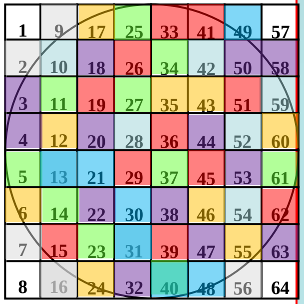
$\theta=360°$

Exemple :

- **Nombre de detecteurs: 1000**
- **Inconnues : carré de 1000 x 1000**
- **Nombre d'équations : nb de détecteurs x nombre d'incréments de rotation**

- **Méthodes algébriques :**

Système à 1 000 000 inconnues à résoudre avec 1 000000 équations

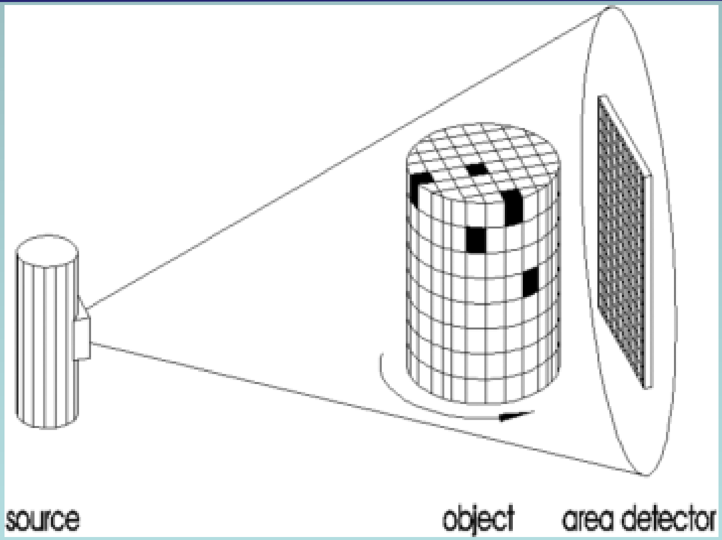


- **Transformée de Fourier**

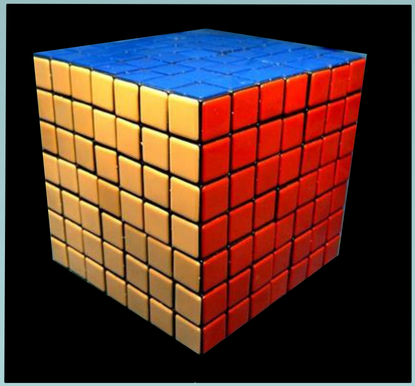
Algo de Felkamp, etc…

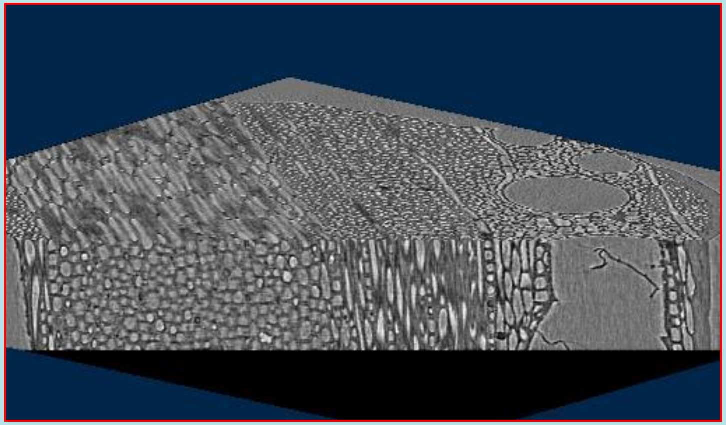
- **Résultat : une cartographie 2 D des coefficients d'atténuation μ_i dépendants de la nature du rayon incident**

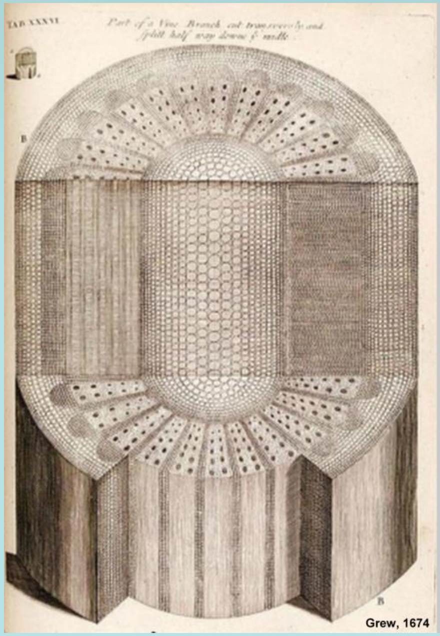
Microtomographie 3D



1000 à 2000 projections sur 360°





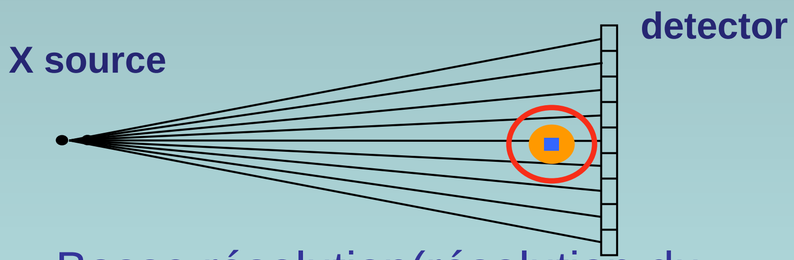


Grew (1674) first light microscope

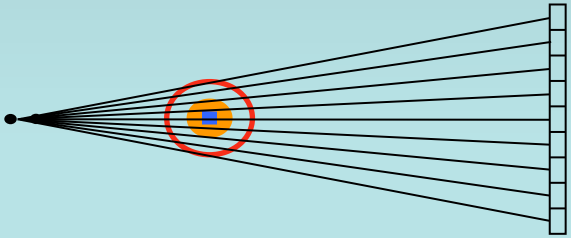
Badel *et al* (2014) X-ray micro-CT sc

Contraintes

Champ d'observation vs résolution



Basse résolution(résolution du détecteur)

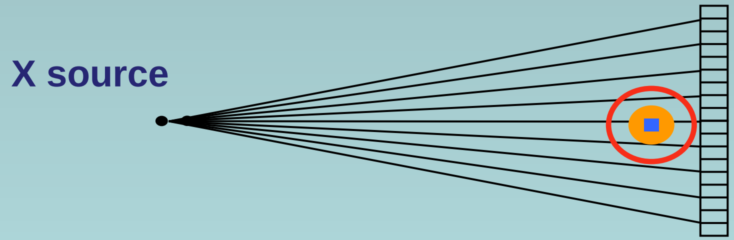


Haute résolution (grossissement ***M***)

$$pixel\ resolution = \frac{detector\ resolution}{M}$$

$$M = \frac{|source - detector|}{|source - sample|}$$

Résolution spatiale vs temps d'acquisition



Petits détecteurs:

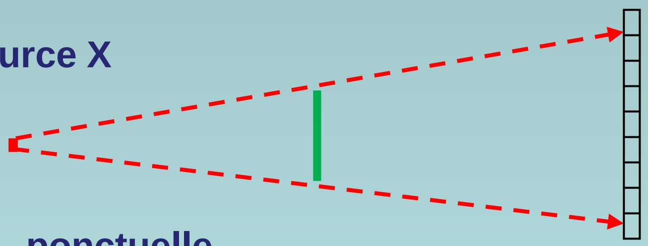
- Faible signal (faible S/B)
- Compensation par des projections de longue durée
- Beaucoup de projections

Contraintes

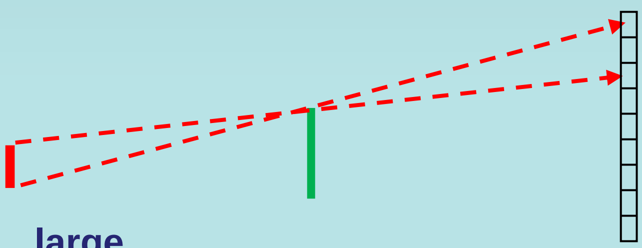
Résolution spatiale vs type de source

detector

Source X



- **ponctuelle**



- **large**

$$flou\ pixel = diamètre\ du\ spot \times M$$

Rayonnement Synchrotron:
- Très haut flux
- Faisceau parallèle (monochromatique ou non)
- Détecteurs à très haute résolution spatiale

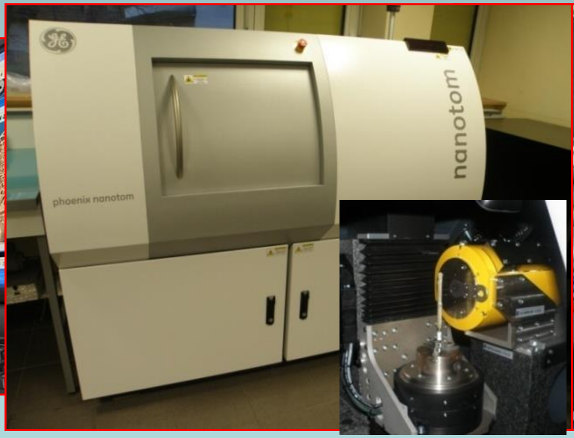
- Haute résolution
- Scans rapides
- Toujours le compromis résolution spatiale vs champ d'observation

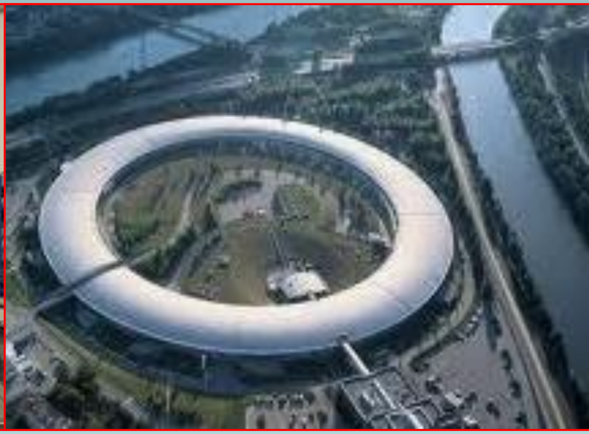
Les outils (2D->3D)

Scanner médical

J. ruelle

Les outils (2D->3D)

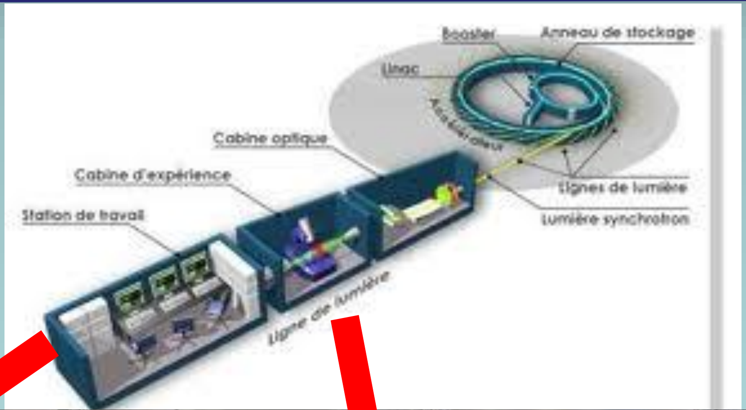




Small lab device | **Lab device** | **Synchrotrons facilities**

X-ray	Polychromatic	Polychromatic	Monochromatic
Beam	Divergent	Divergent	Parallel
Spatial resolution	5-10 microns	1 micron	0.3 micron
Max sample size	4-5 cm	10-20 cm	1 mm
File size	16 Go	32 Go	64 Go or more
Scan time	10 min to 1 hour	10 min to 1 hour	1 s to few minutes

The synchrotron lights

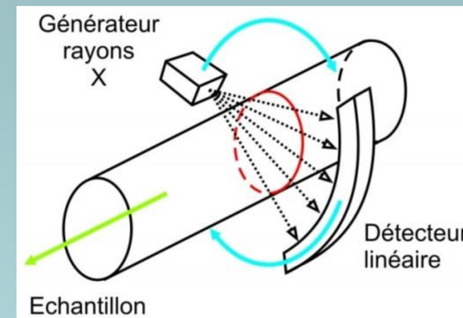


Applications sur le bois

X ray medical scanner for Wood inspection

J. ruelle

Gros objets

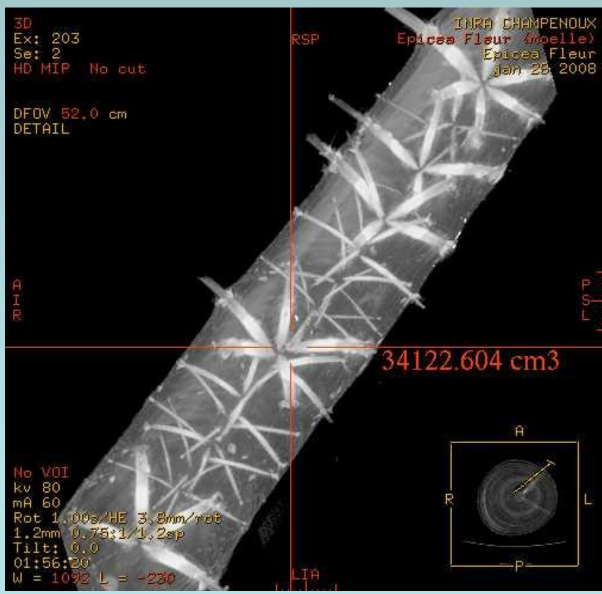


Interpolation entre les tranches -> 3D

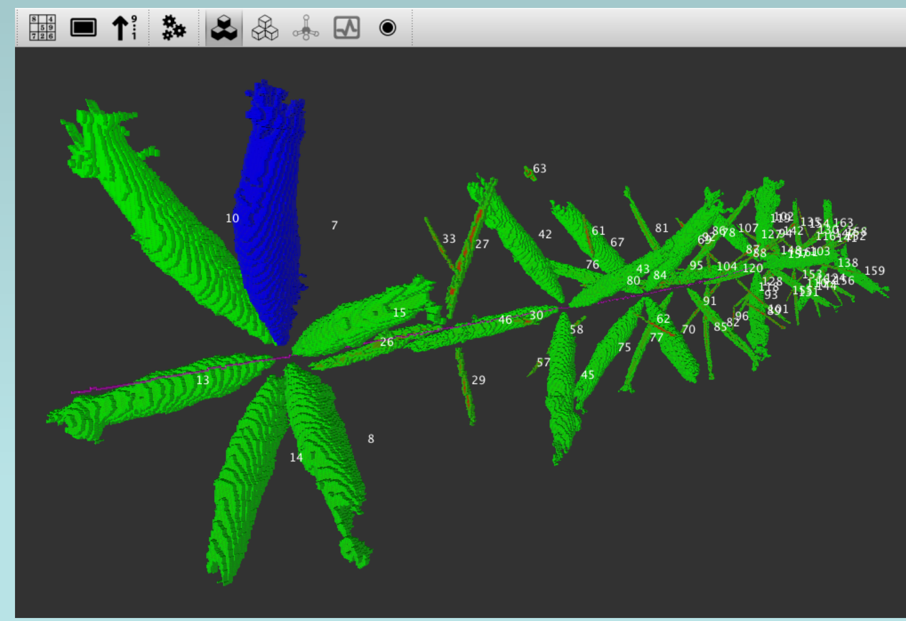
Application : structures du tronc

Détection de noeuds

Exemple : épicea



3D view built from 2D slices stacking



3D rendering of automatic nodes detection

Application : structures du tronc

Etude de la croissance primaire par détection automatique des trajectoires de la moelle

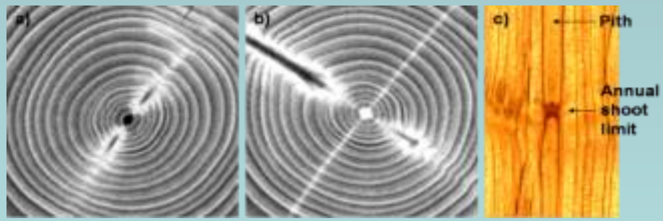
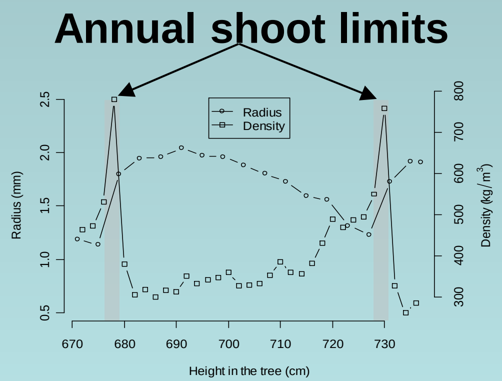
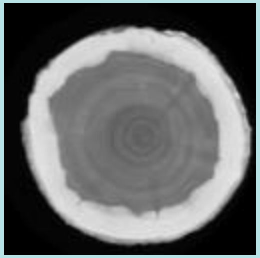


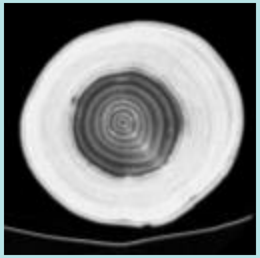
Illustration de la variation de densité de la moelle au niveau des unités de croissance primaire



Distinction aubier / duramen par le biais de la densité et de l'humidité relative du bois



épicéa



sapin

Attention à la composition chimique. Les calibrations ne fonctionnent (théoriquement) que si on a calibré avec le même composant !

$C_6H_{12}O_6 + H_2O$

Tomodensitométrie : Principe et mise en œuvre

Calibration pour la mesure de densité

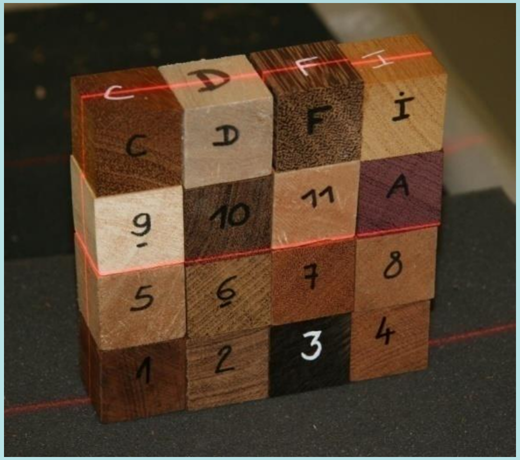
Valeurs Hounsfield

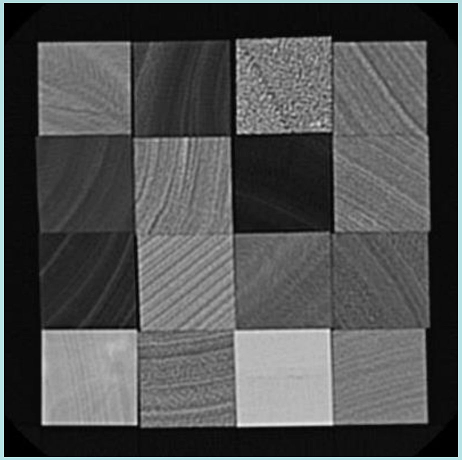
-1000 (air) | 0 (eau) | +1000 (os)

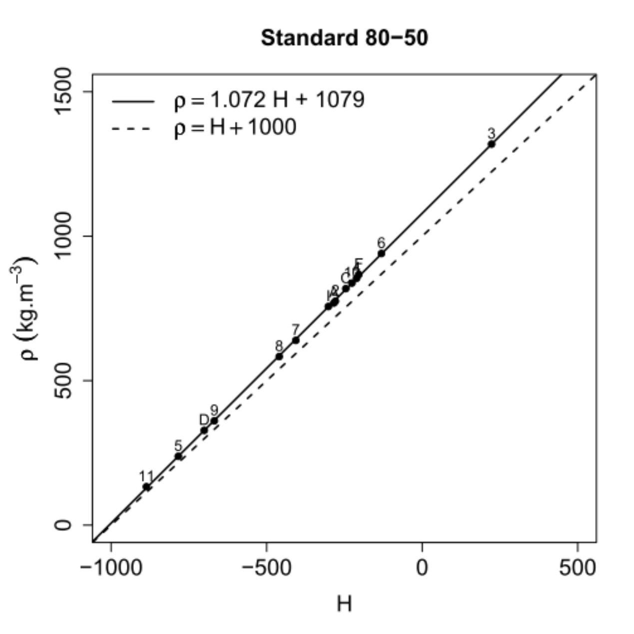
Epicéa

Douglas

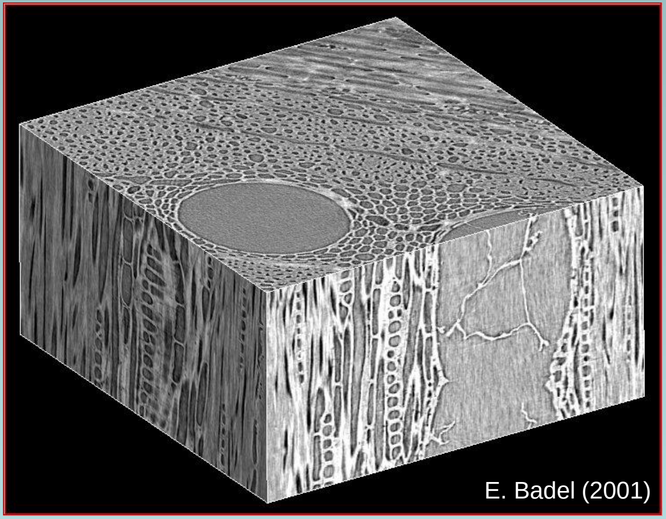
Chêne

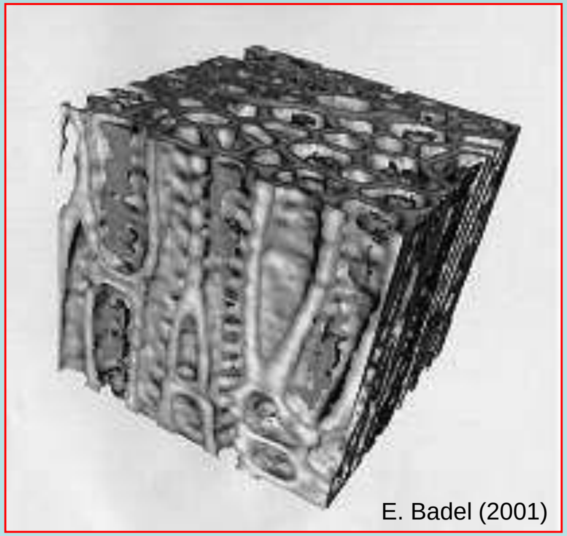




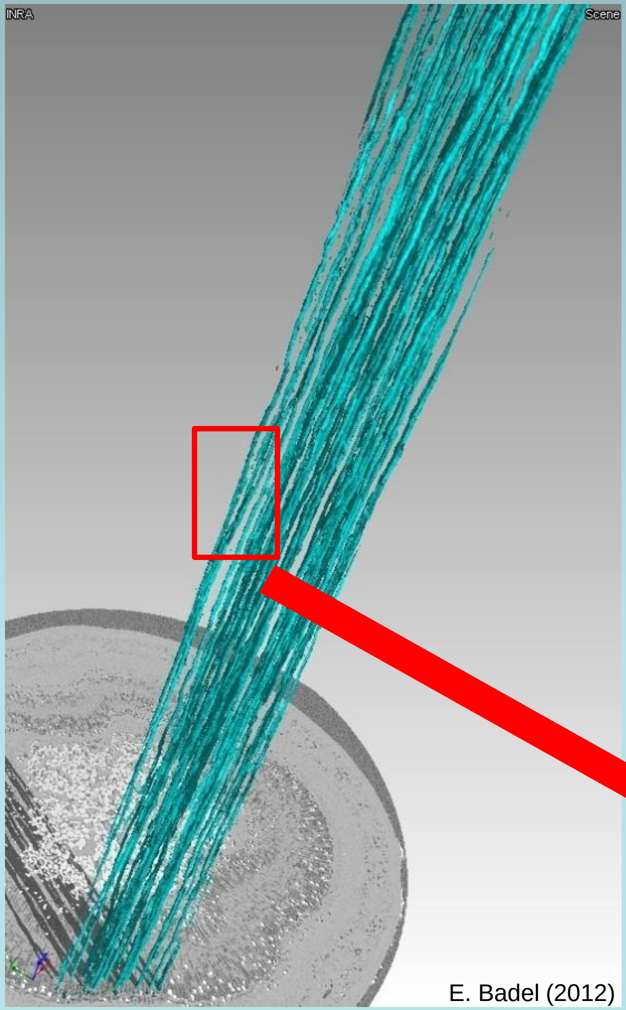


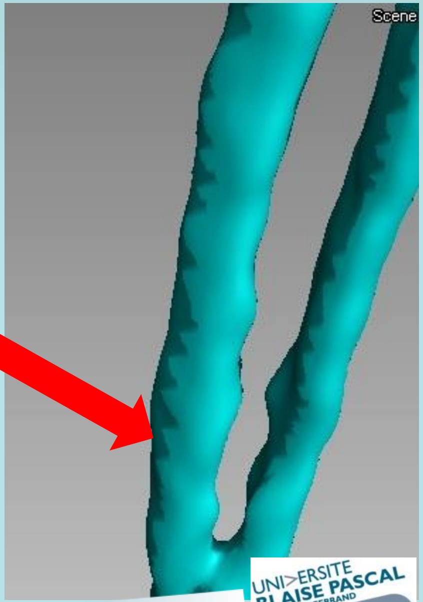
µCT: Structure anatomique 3D du bois





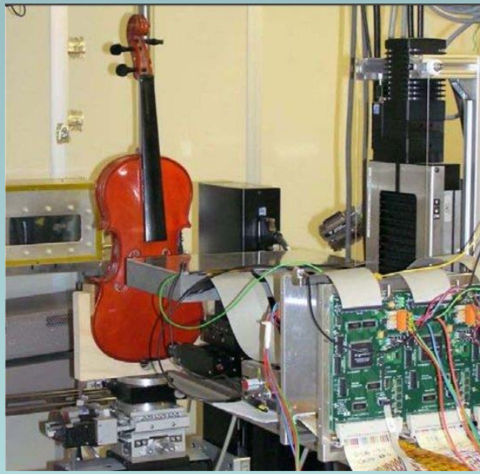
Parois cellulaires

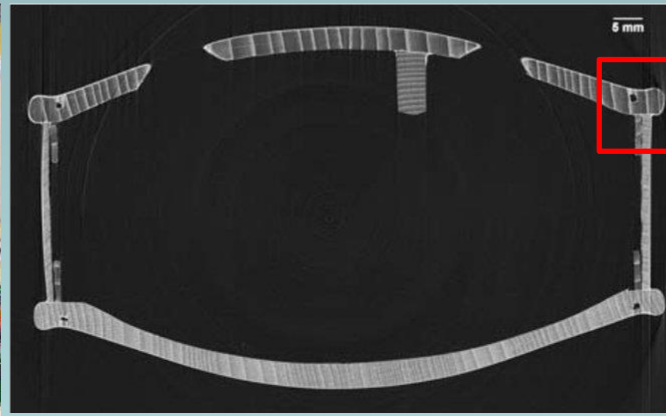




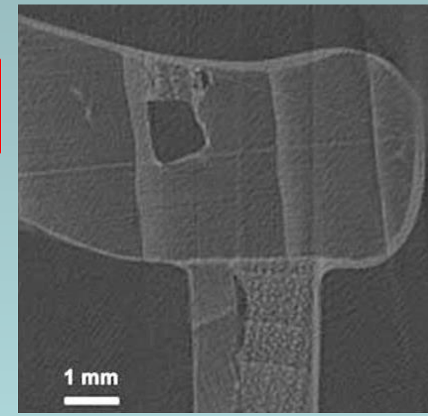
Réseau hydraulique

Visualisation 3D d'objets (en bois)



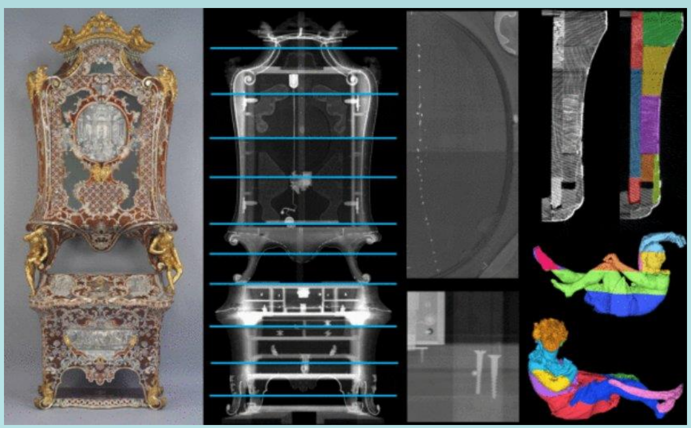


Rigon 2010



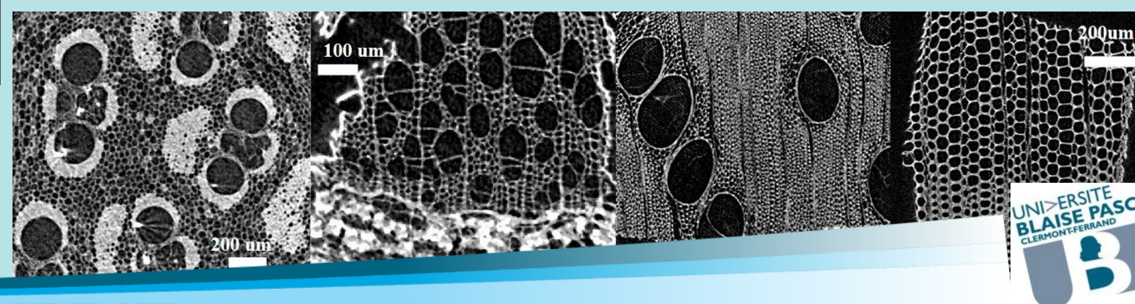
Rigon 2010

Vatican 2015



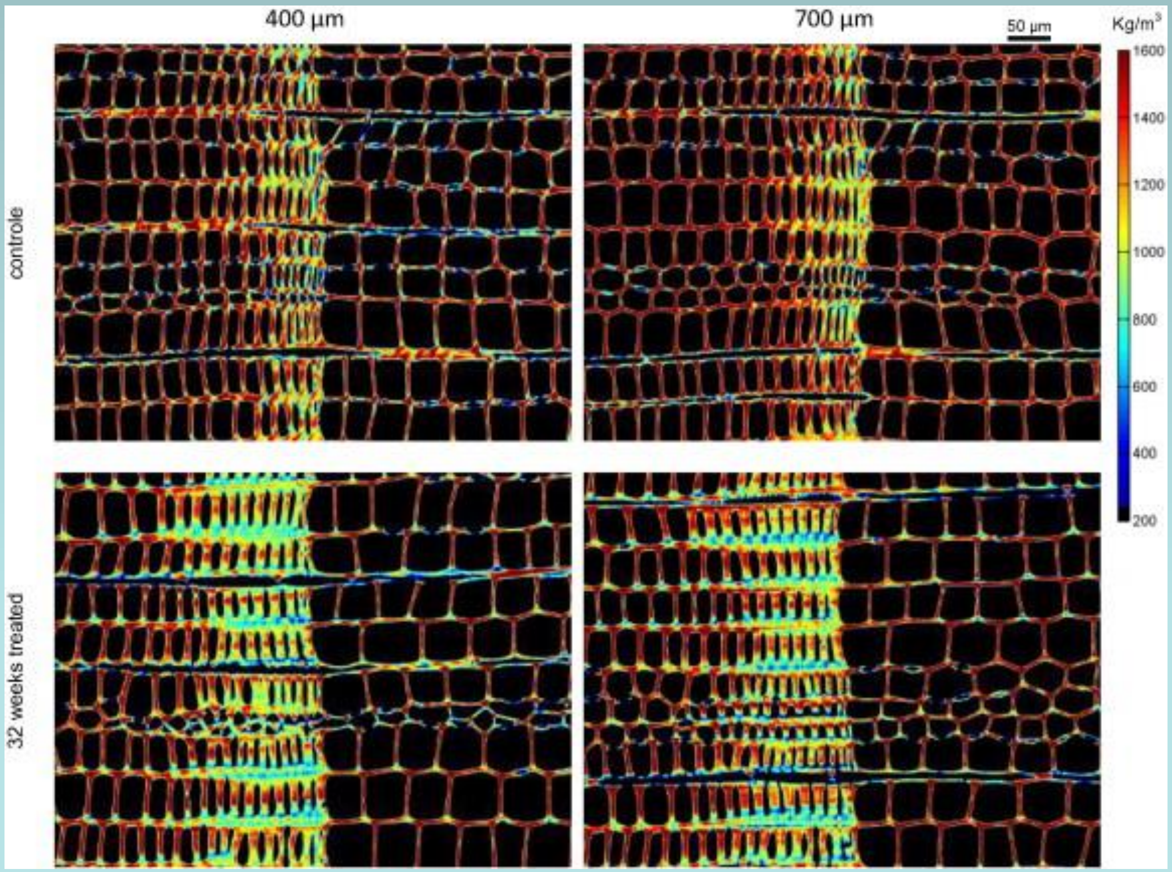
Re 2014

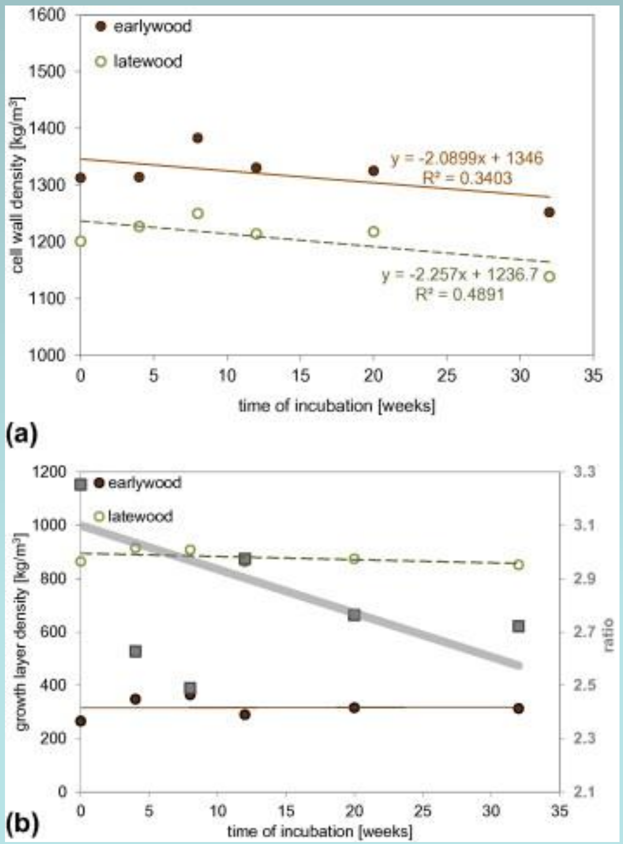
- Structure interne
- Secret de fabrication
- Eventuelles réparations
- Aide à la restauration : défauts(fissures….)
- Anatomie du bois : détermination d'essences



Suivis de procédés

Biological degradation : effect of chemical of thermal treatments



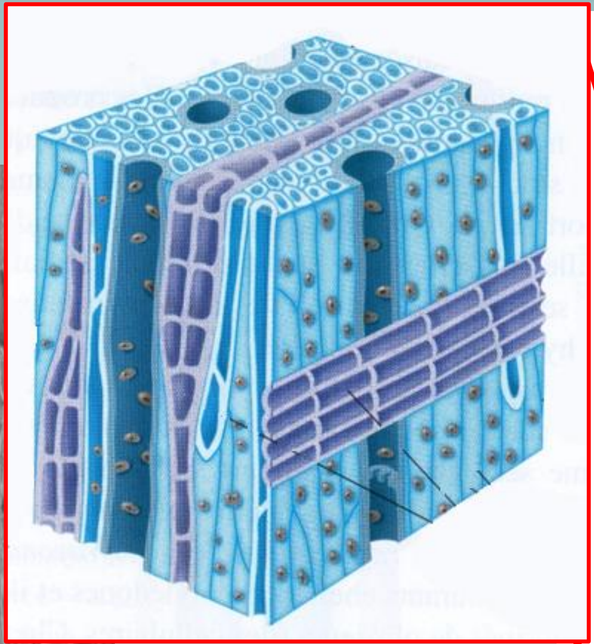


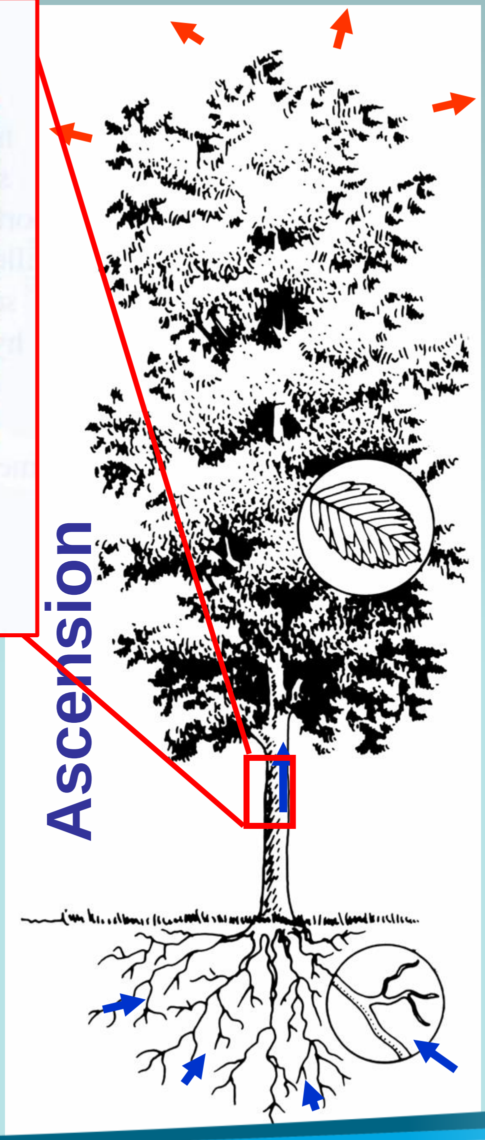
(Gilani et al, 2014)

Transverse section of Norway spruce wood showing density distribution at different tomographic slices of untreated (top) and wood treated for 32 weeks with Physisporinus vitreus (bottom). Degradation was more significant in latewood.

Attention au rayonnement ionisant sur le vivant

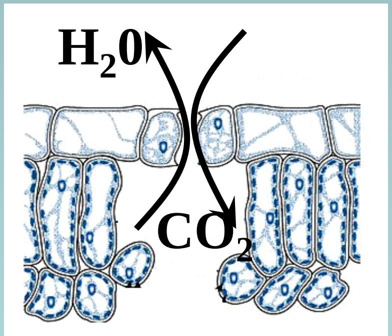
U.M.R. PIAF





Evaporation

Ascension



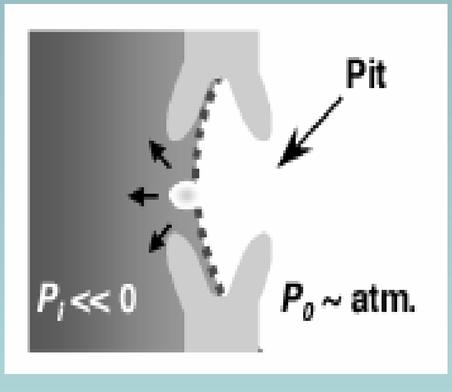
embolism

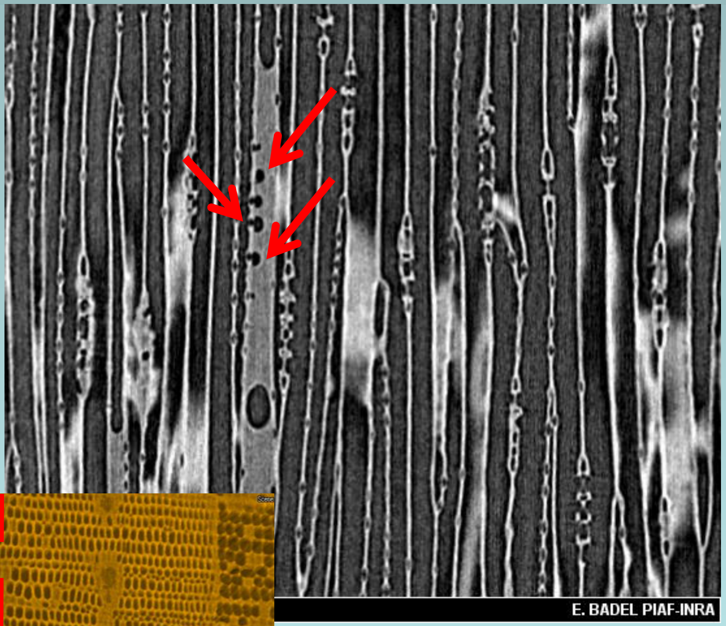
H. Cochard

Xylem under tension

Absorption

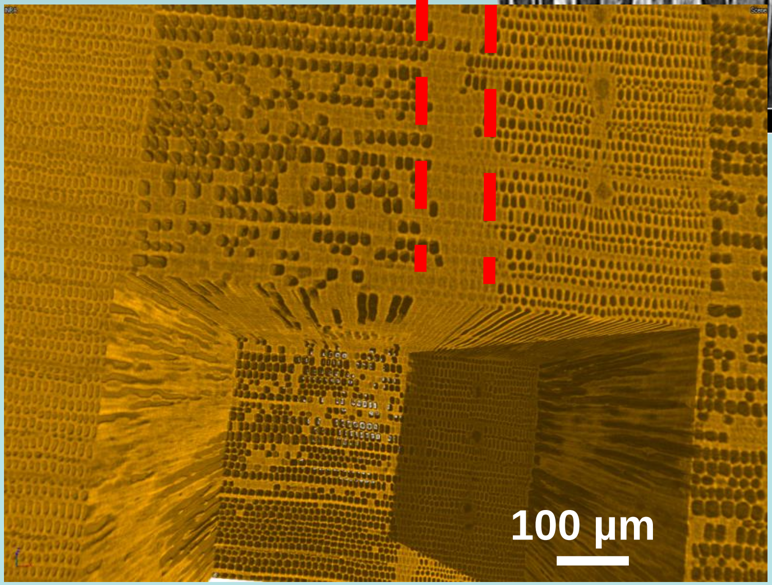
Mesure et localisation de l'embolie



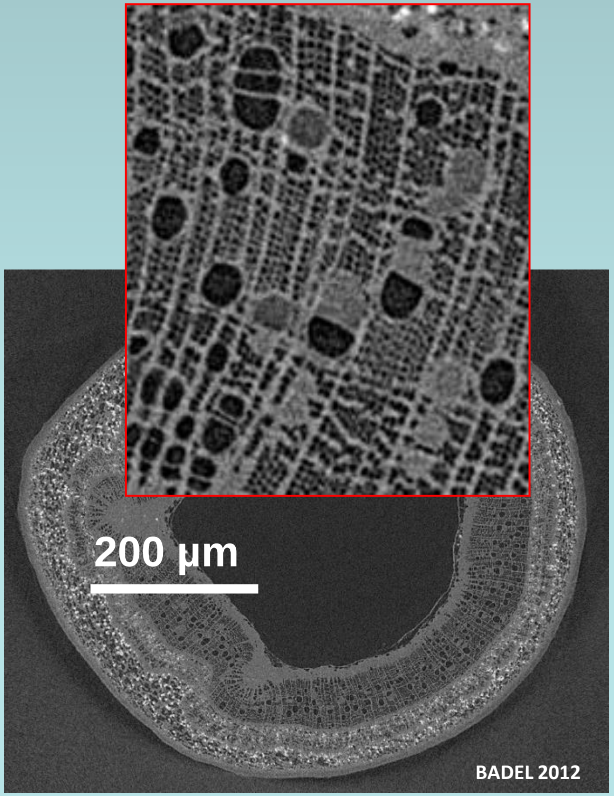


Pinus sylvestris

Douglas

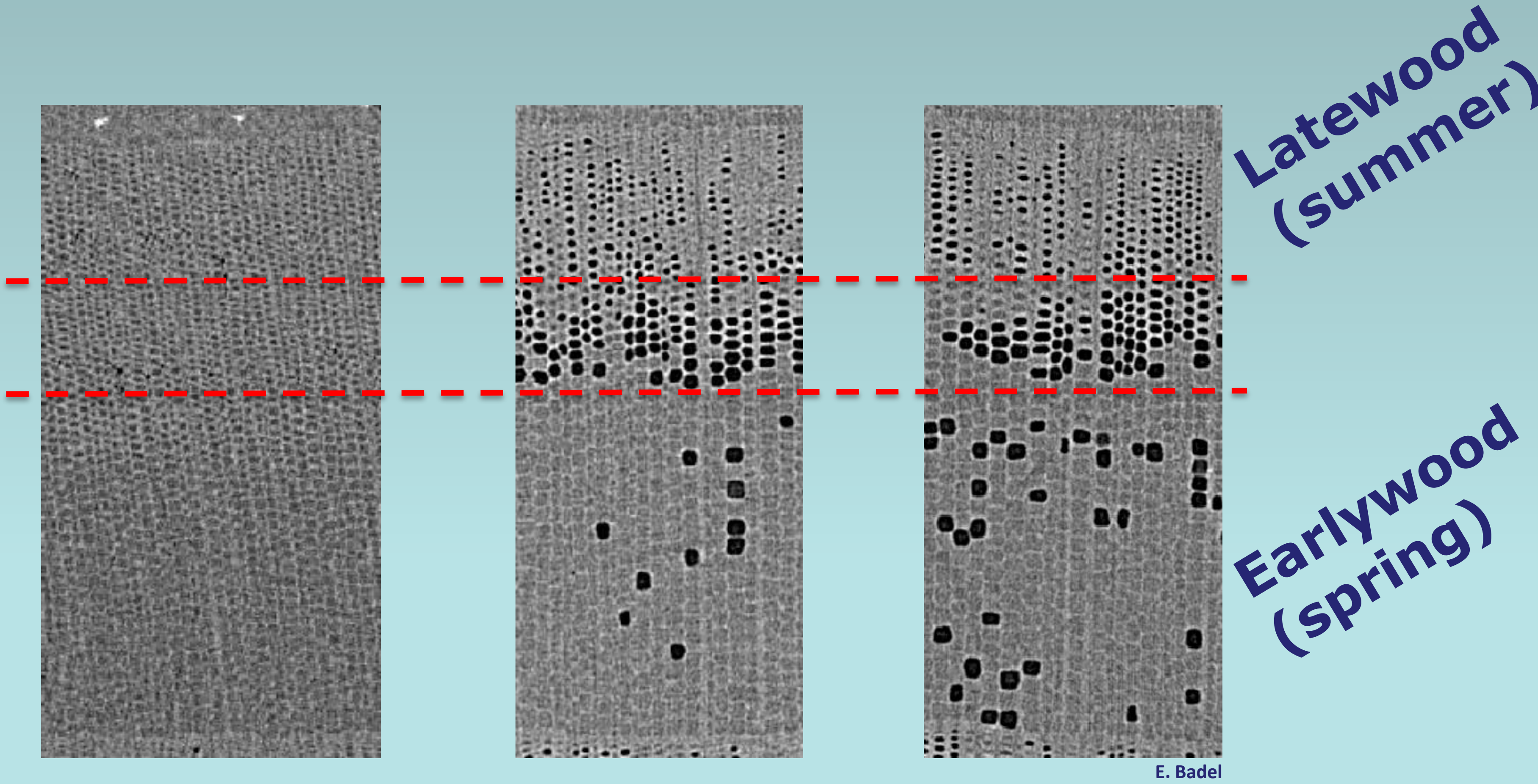


(Dalla Salda et al, JPH 2015)



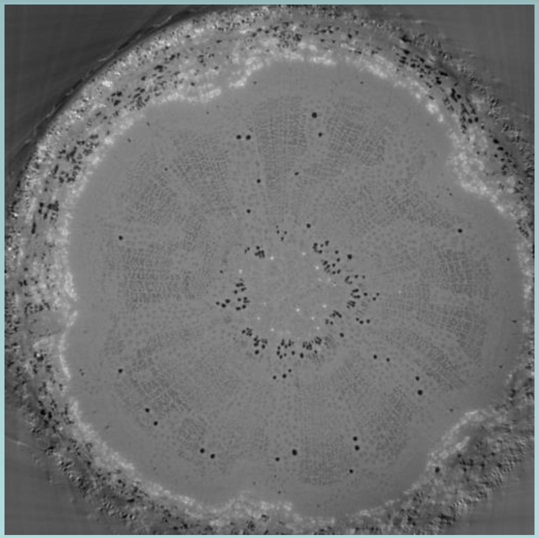
Walnut tree

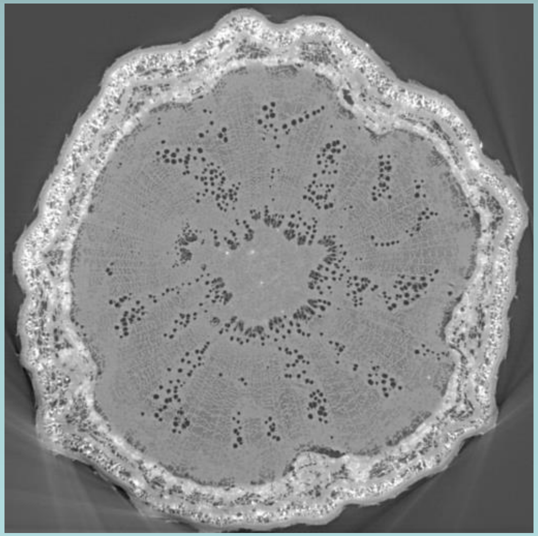
In situ dynamic embolism measurements

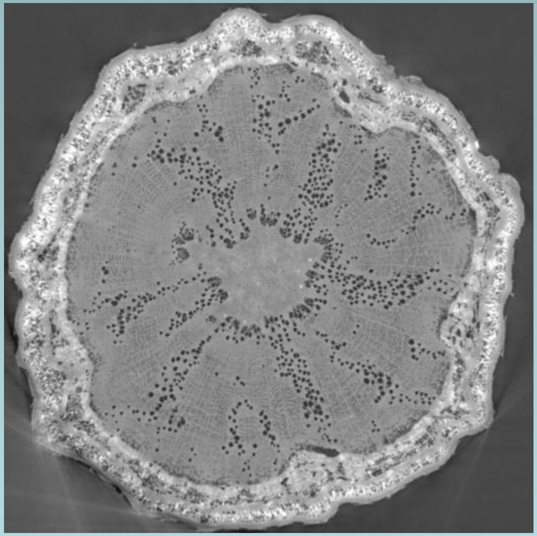


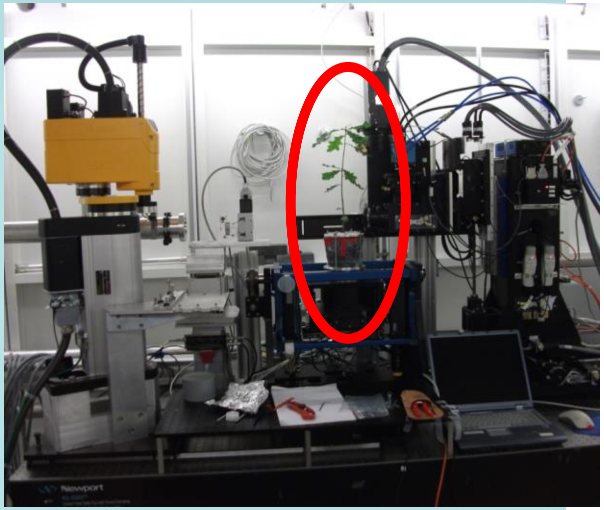
Initial state (0 MPa) **-2 MPa** **-2.5 MPa**

In situ dynamic embolism measurements

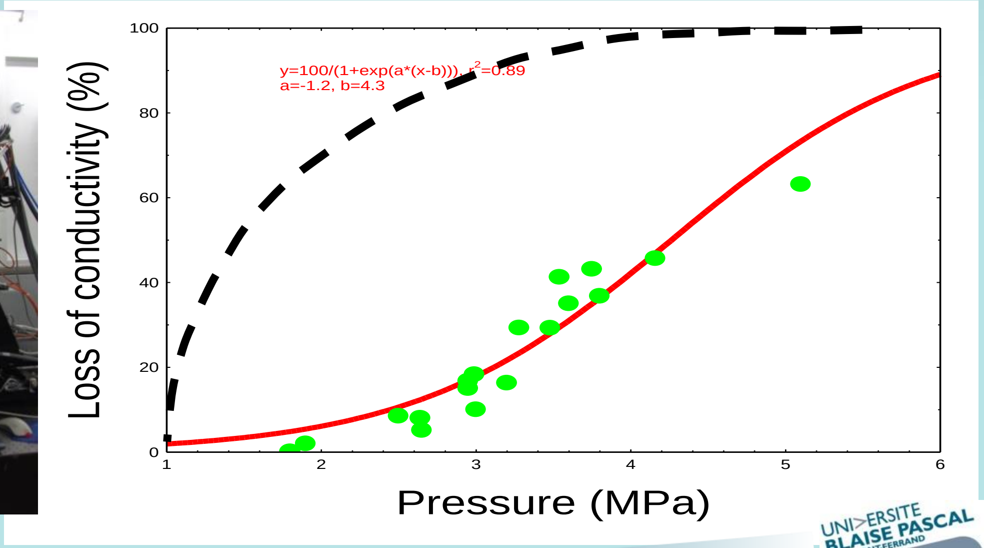




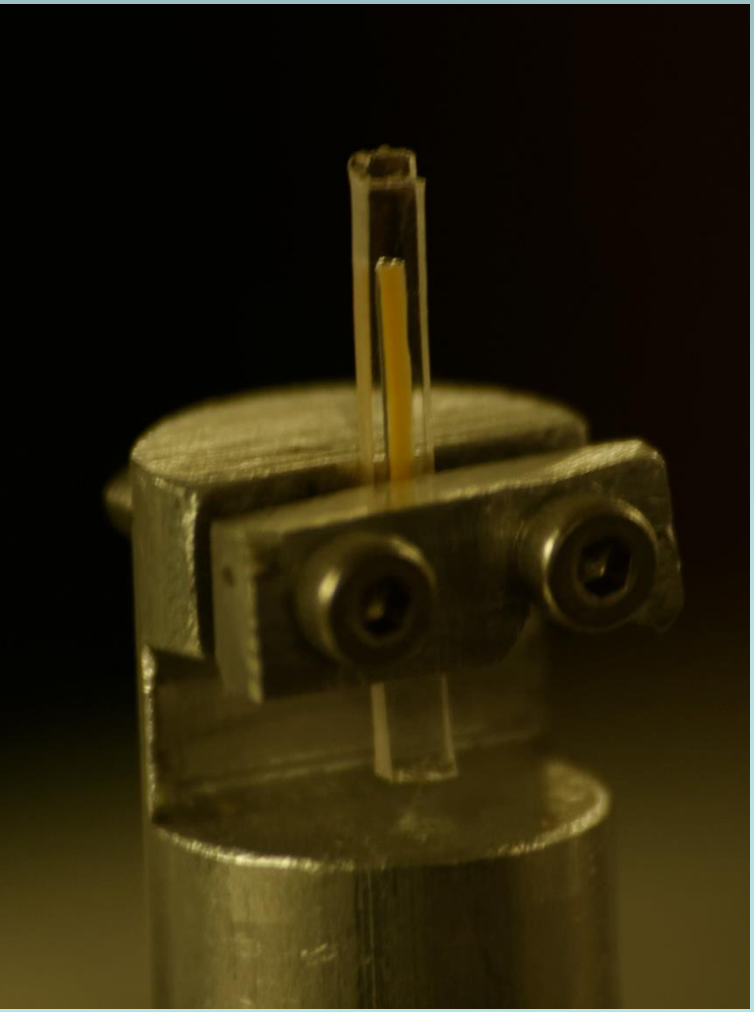


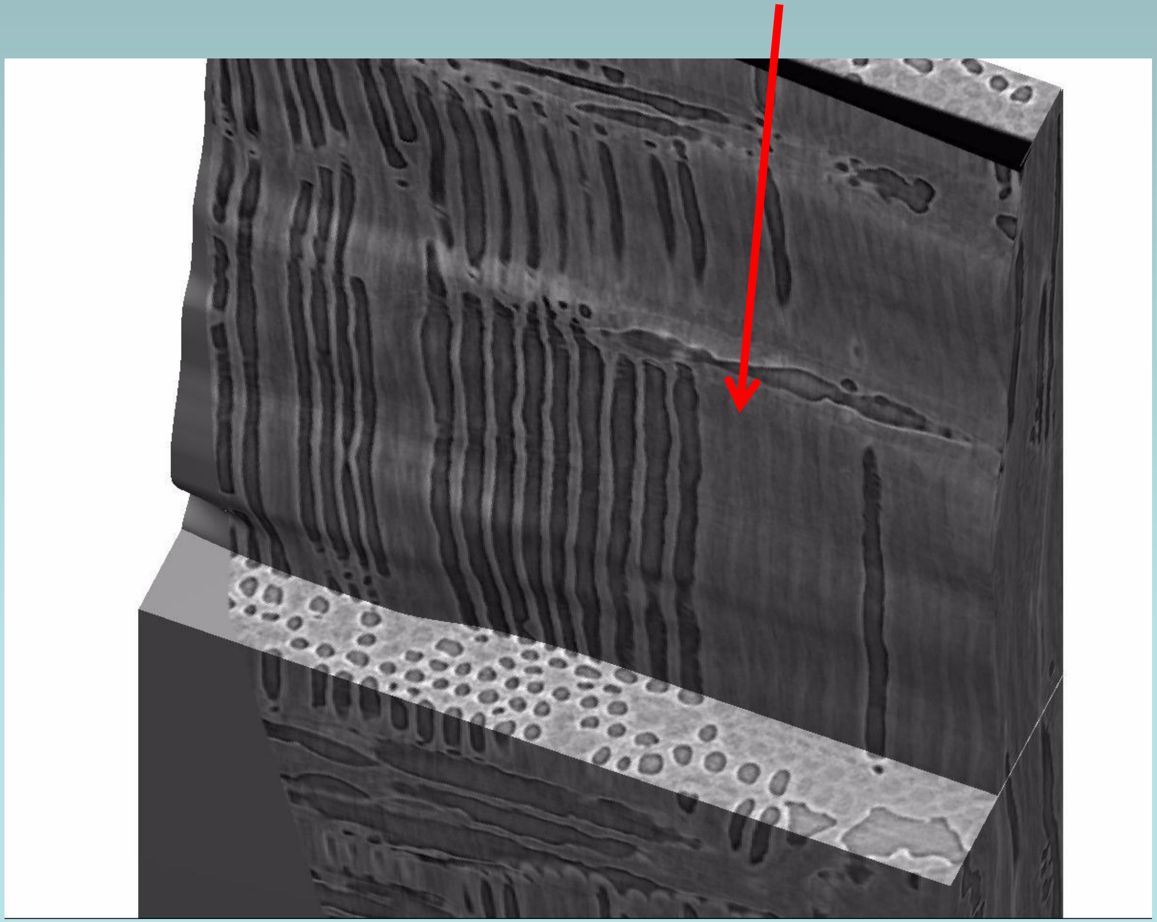


J. ruelle



FAST-TOMO : Visualisation rapide de l'embolie (4D)





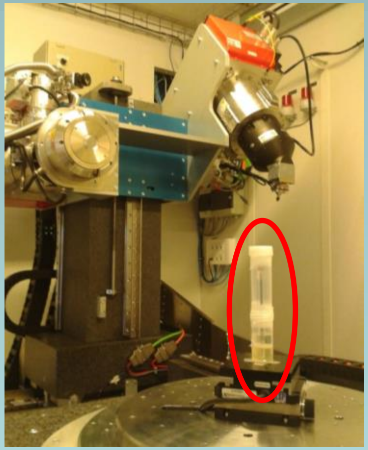
Scans de 1 seconde

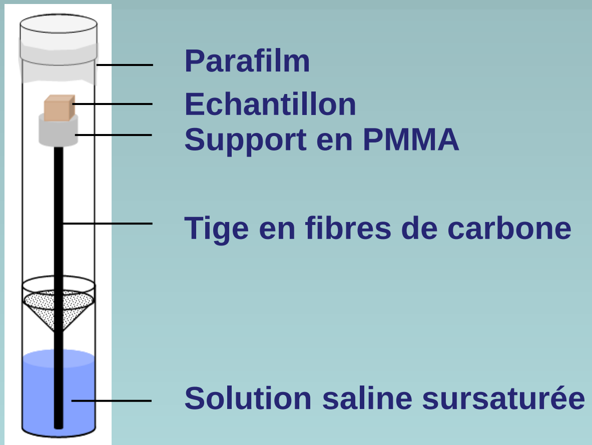
(Ponomarenko et al 2016)

Retrait du bois

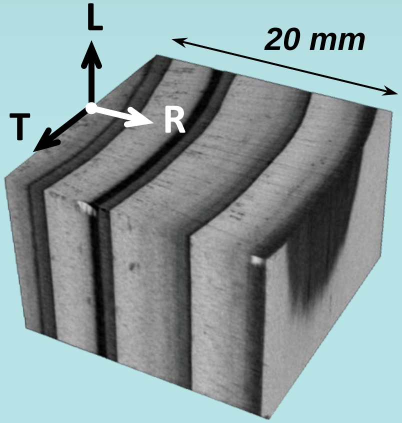
Scans for different moisture contents:

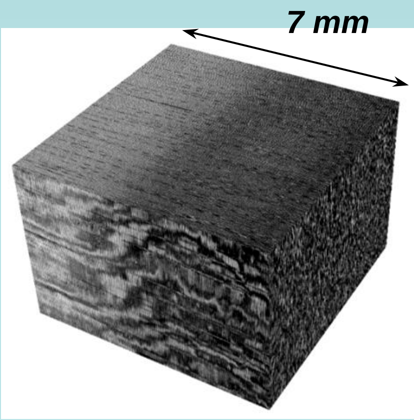
- macroscopic measurements
- X-ray scan
- volumic images correlation
- multiscale observations

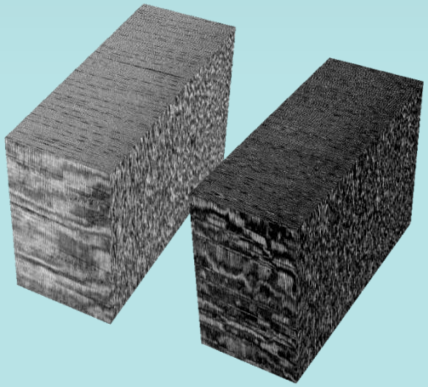


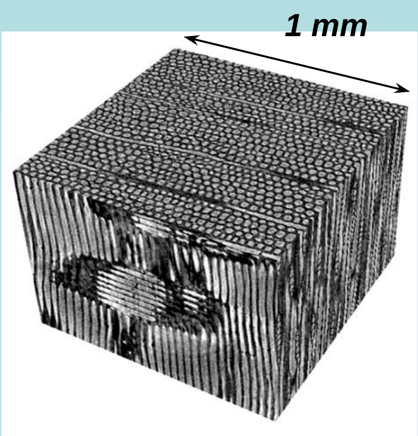


Tomographie RX de laboratoire — **Tomographie RX synchrotron**









Succession de cernes — *Résolution 52 µm*

Cerne — **Bois initial et bois final** — *Résolution 8 µm*

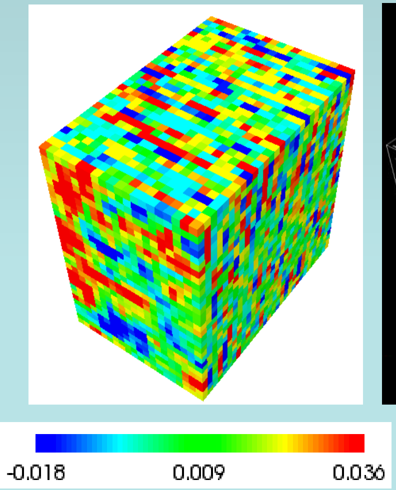
Cellules — *Résolution 0,87 µm*

Retrait du bois

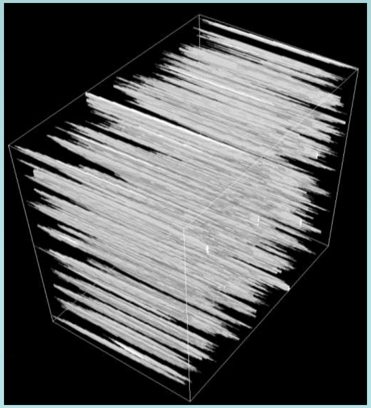
- **Etat 0 : humidité relative de 44%**
- **Etat 1 : humidité relative de 80%**

Déformations moyennes 0 → 1 : $\begin{bmatrix} 0{,}3\% & 0 & 0 \\ 0 & \boxed{0{,}9\%} & 0 \\ 0 & 0 & 0{,}2\% \end{bmatrix}_{(R,T,L)}$

Mesures de champ $\varepsilon_{tangentielle}$



Structure anatomique



M. Bonnet

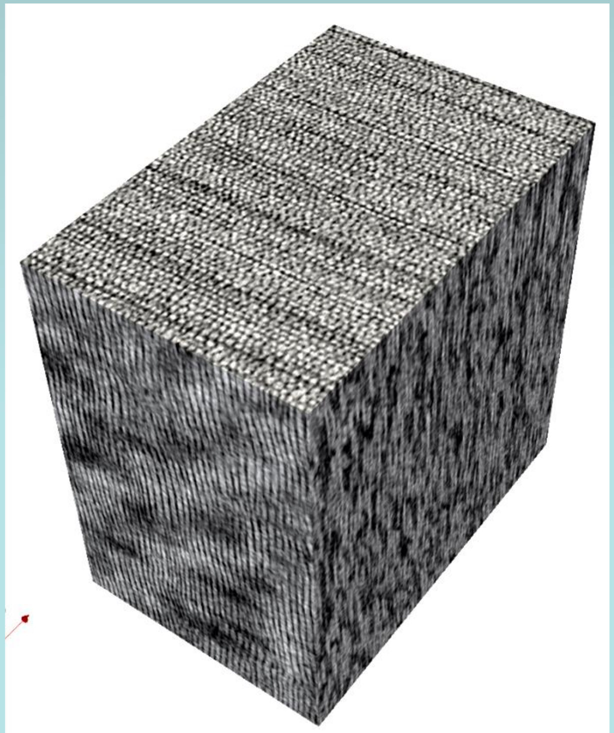
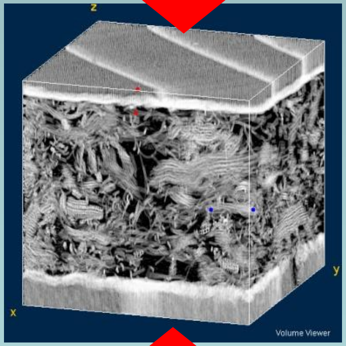
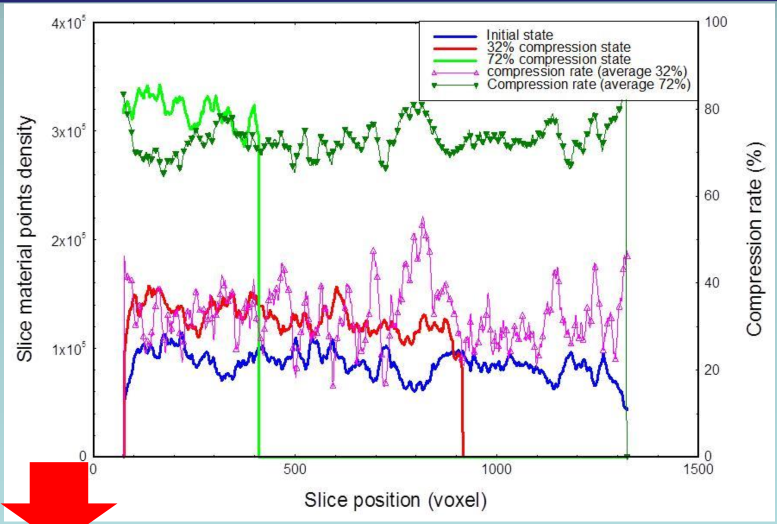


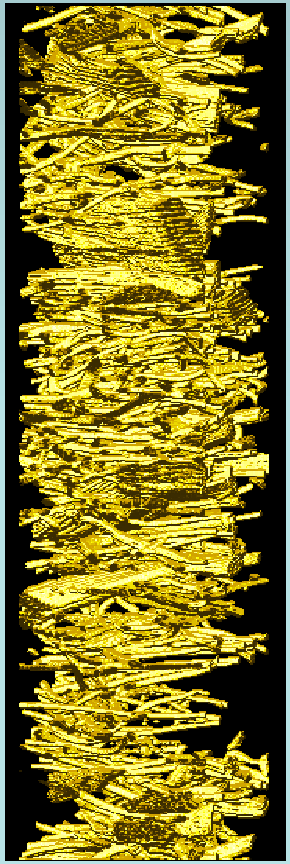
Image 3D de la région d'intérêt analysée par corrélation d'images (bois initial de Douglas, résolution 8 µm)

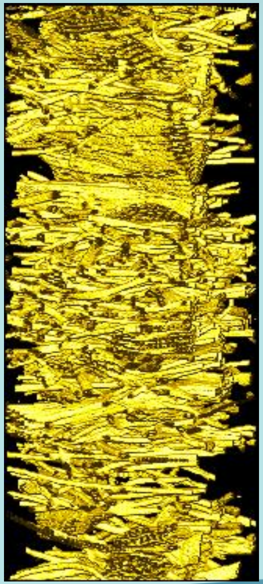
Cf exp. P. Doumalin et JC Dupré + atelier

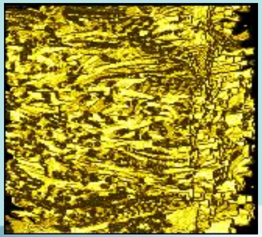
Essais mécaniques compression d'un panneau de fibres











(Badel et al 2008)

Essais mécaniques : compression d'un panneau de fibres

Correlation d'images pour mesure de champ de déplacement : DVC method

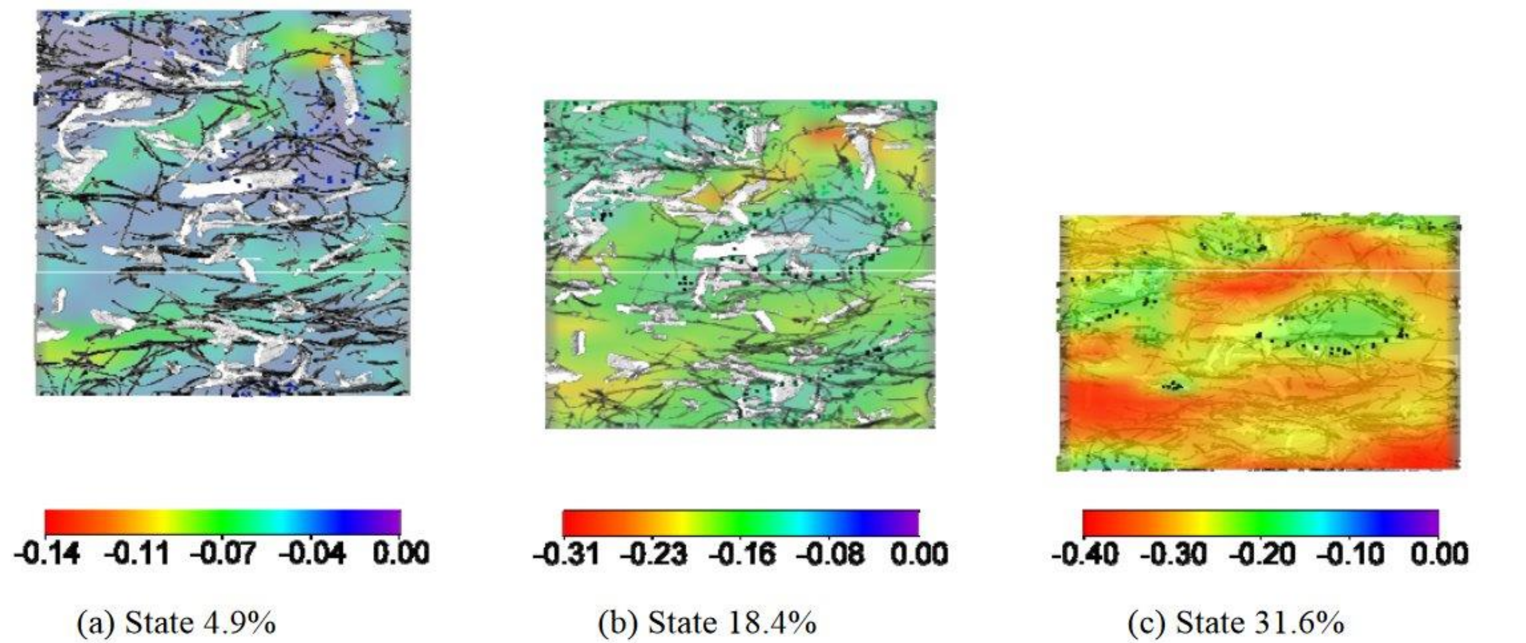
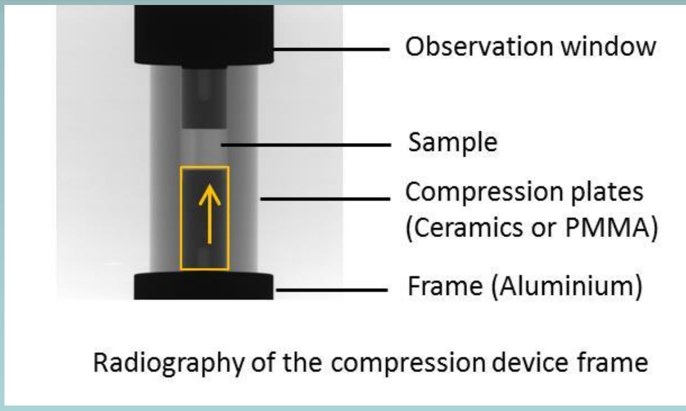


FIG. 7 : Superposition of microstructure (white = wood, black = PES) with Ezz strain for one slice, dashed lines represent less deformed zones

Cf exp. P. Doumalin et JC Dupré + atelier

(Tran et al 2013)

Essais mécaniques : compression radial de bois massif

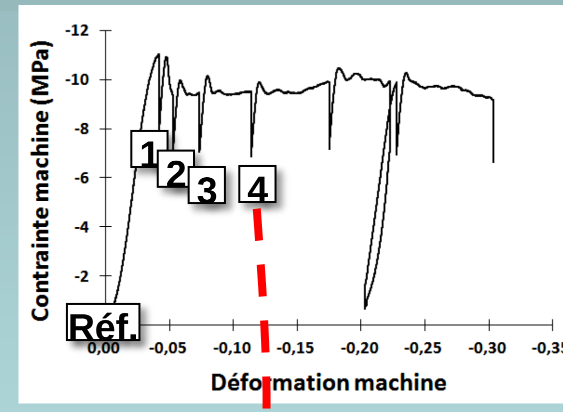


Radiography of the compression device frame

Species: Douglas

Scale: earlywood cell

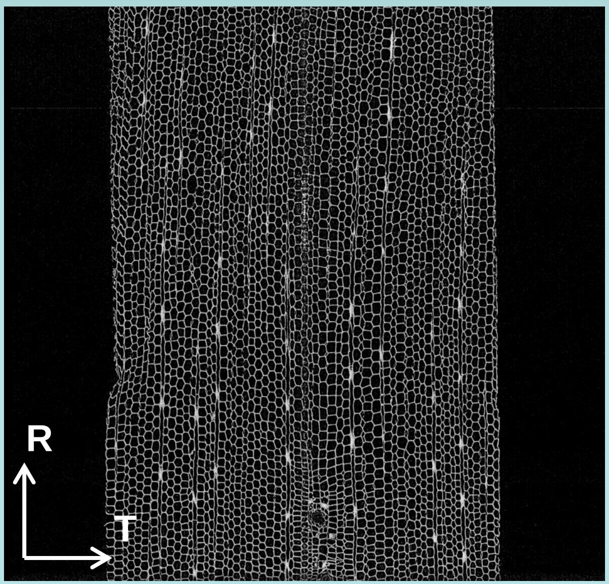
Mechanical testing: radial compression



M. Bonnet

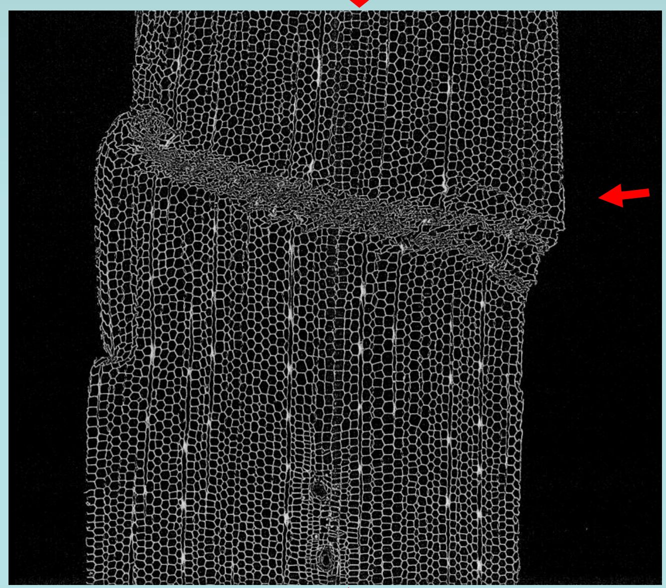
2,7 mm

,3 mm



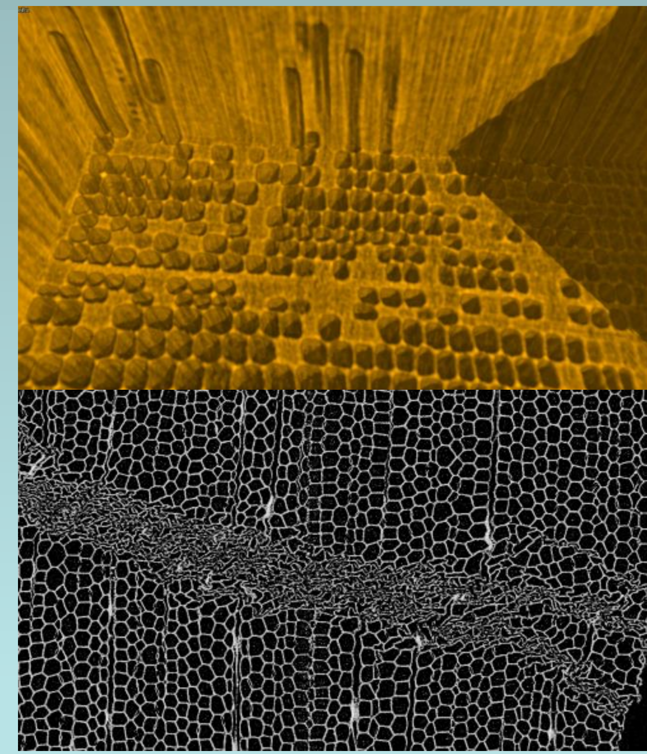
M. Bonnet

Initial



step n° 4

Conclusions

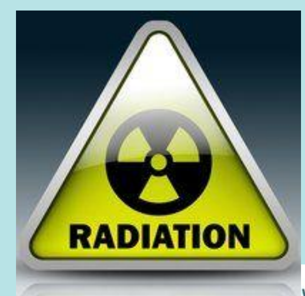


- Beaucoup d’applications pour le matériau bois : structure, détection de noeuds, de défauts sanitaires (pourriture, attaques de xylophages..), fissuration, etc..

- Des évolutions technologiques permanentes (résolution, champ, vitesse…)

- Outils d’observation non destructive pour la mesure de déformation mécanique (retrait hydrique lors du séchage, comportement mécanique…)

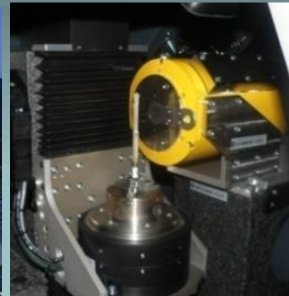
- Difficile de maitriser température + humidité au sein d’un microtomographe (conditionnement d’échantillons végétaux



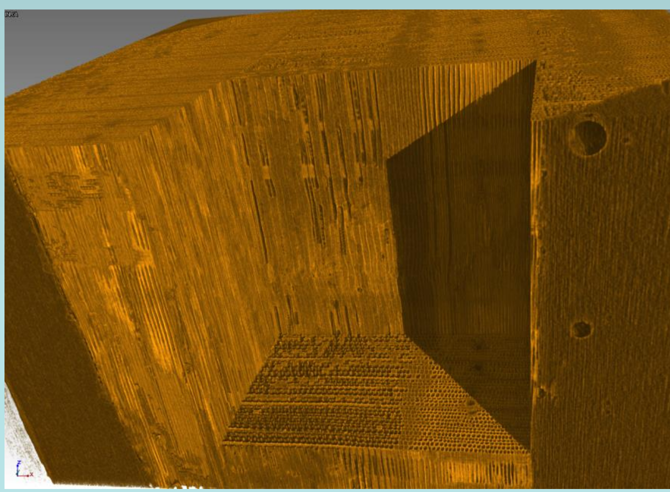
- Encore peu d’appareils “grand champ” ou portables
- Ne pas oublier l’imagerie RMN pour l’observation de l’eau

- Attention aux effets des rayonnements sur le vivant

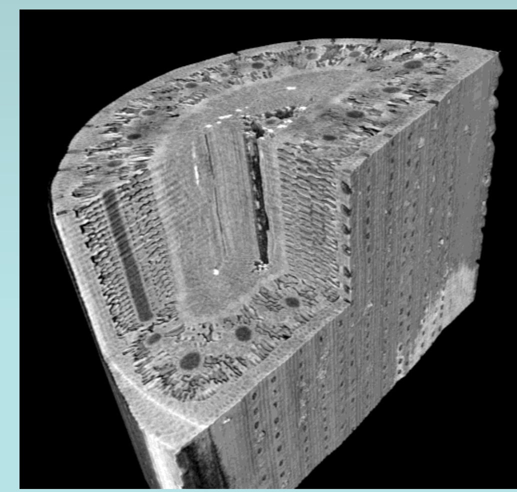
- On n’a pas parlé de : tomographie de diffusion, bi-energie….



Merci de votre attention



Un doute ?
Faites un test !



U.M.R. PIAF