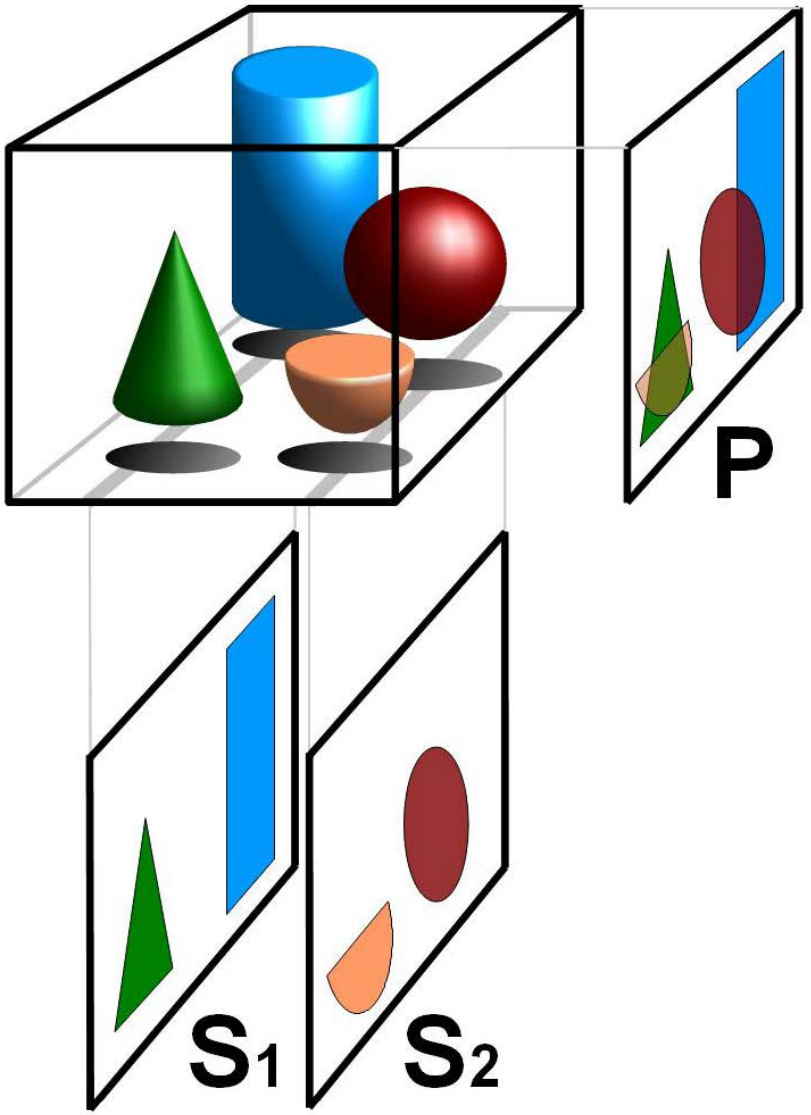
In situ Xray Computed Tomography
4D analysis of materials and structures

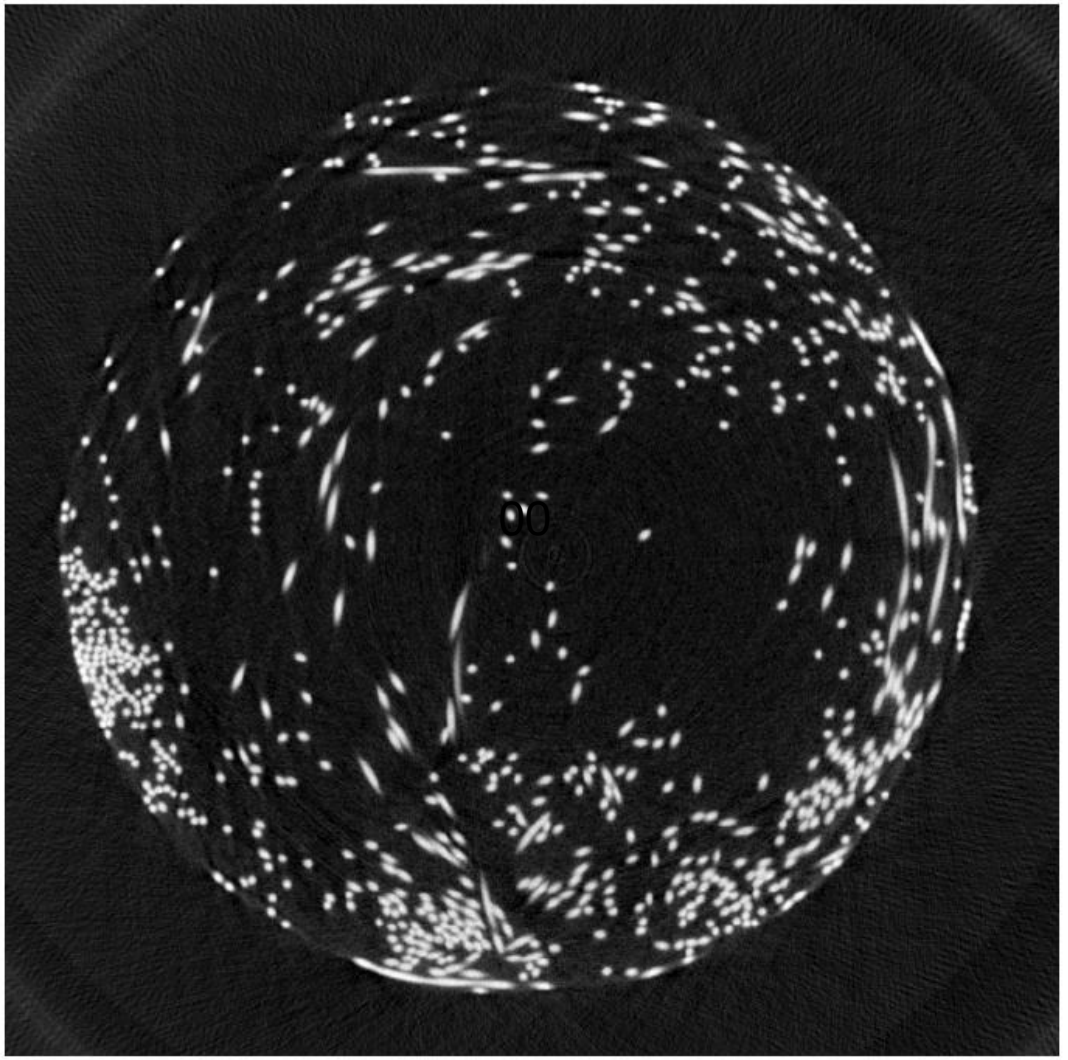
Eric Maire, J Adrien,
J Papillon, J Lachambre
Ch Le Bourlot, S Dancette
X Boulnat

Outline

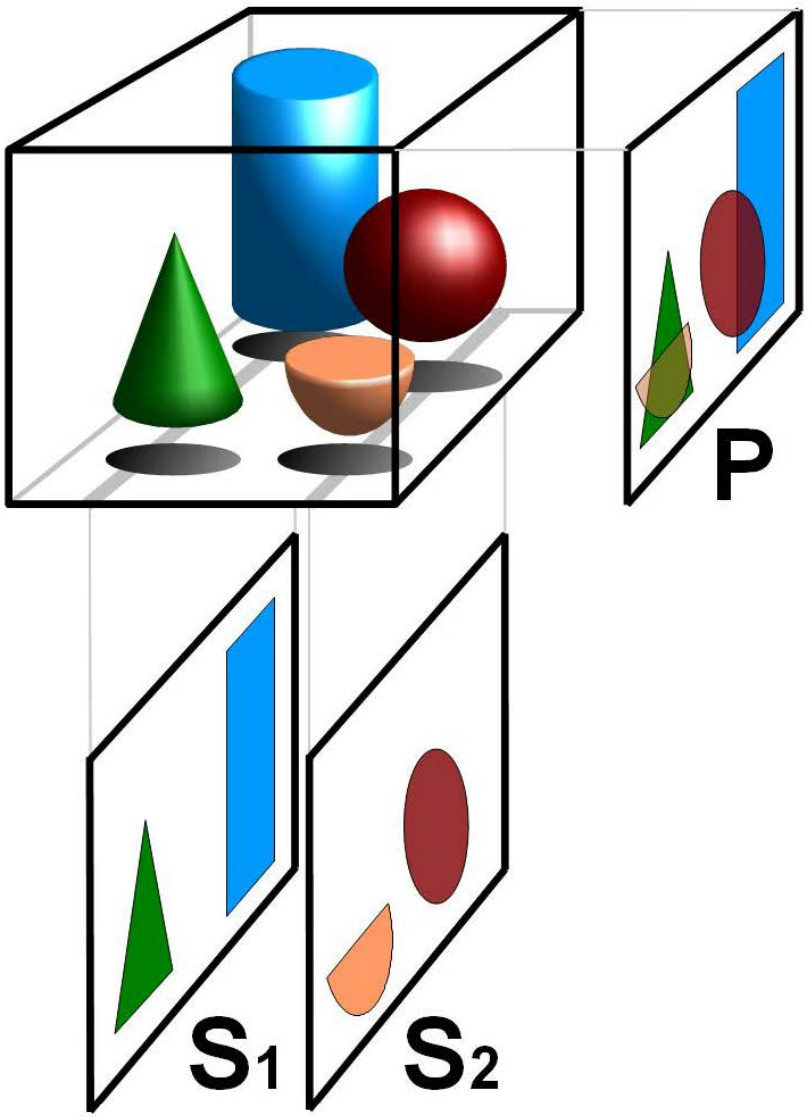
- Introduction
  - Motivation 2D, 3D, 4D
  - Principle of XRCT
  - In situ
- Examples
  - Fracture of sustainable energy related materials
  - Examples with Japanese colleagues
- Pushing the limits
  - Temporal
  - Spatial

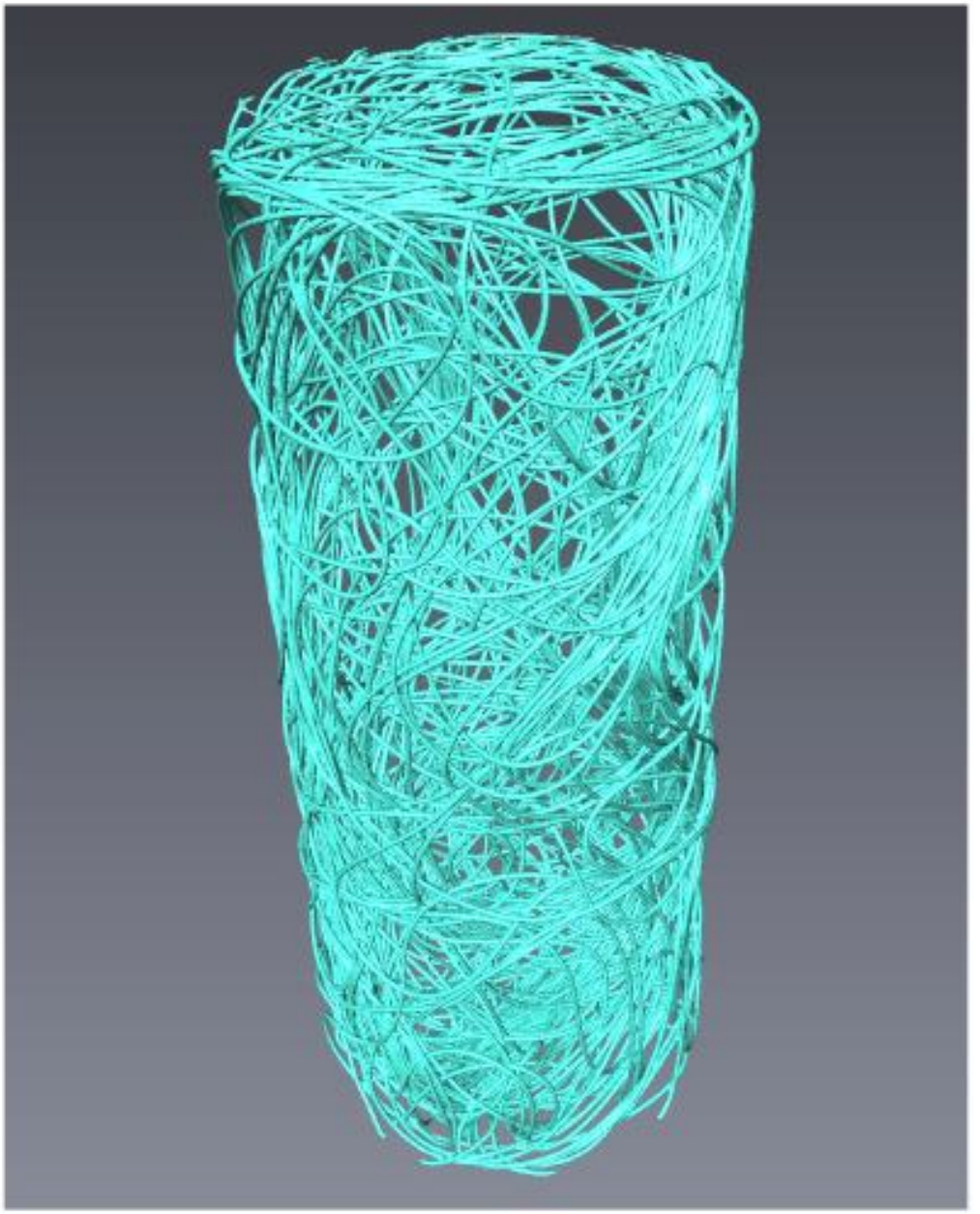
3D is better than 2D



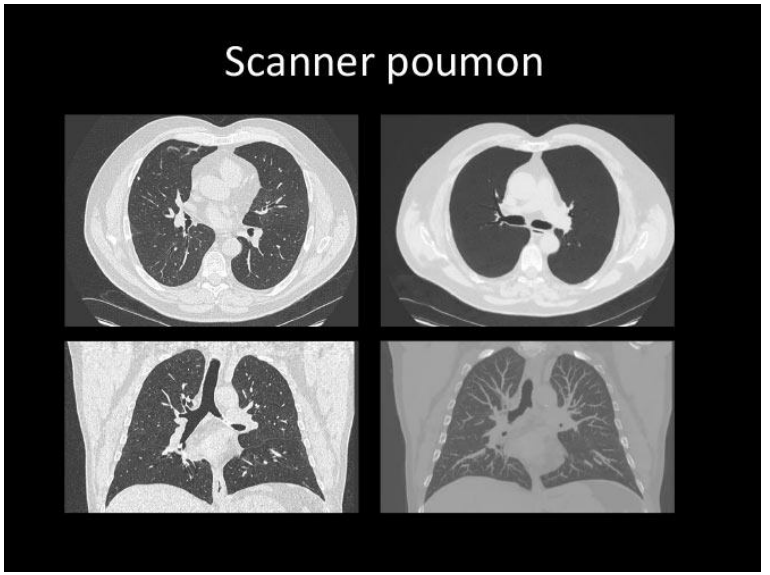


3D is better than 2D



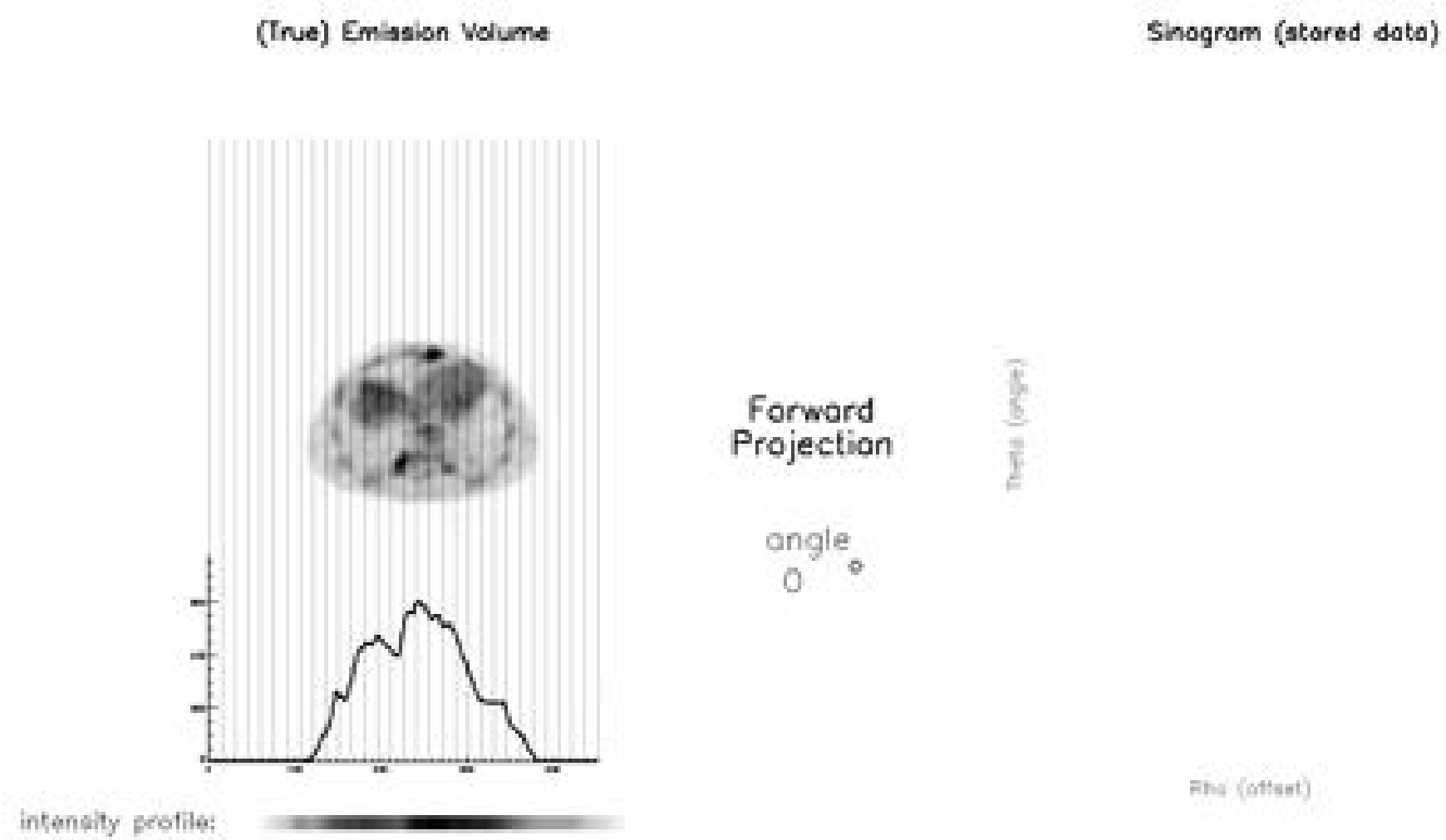


3D imaging is available : XRCT

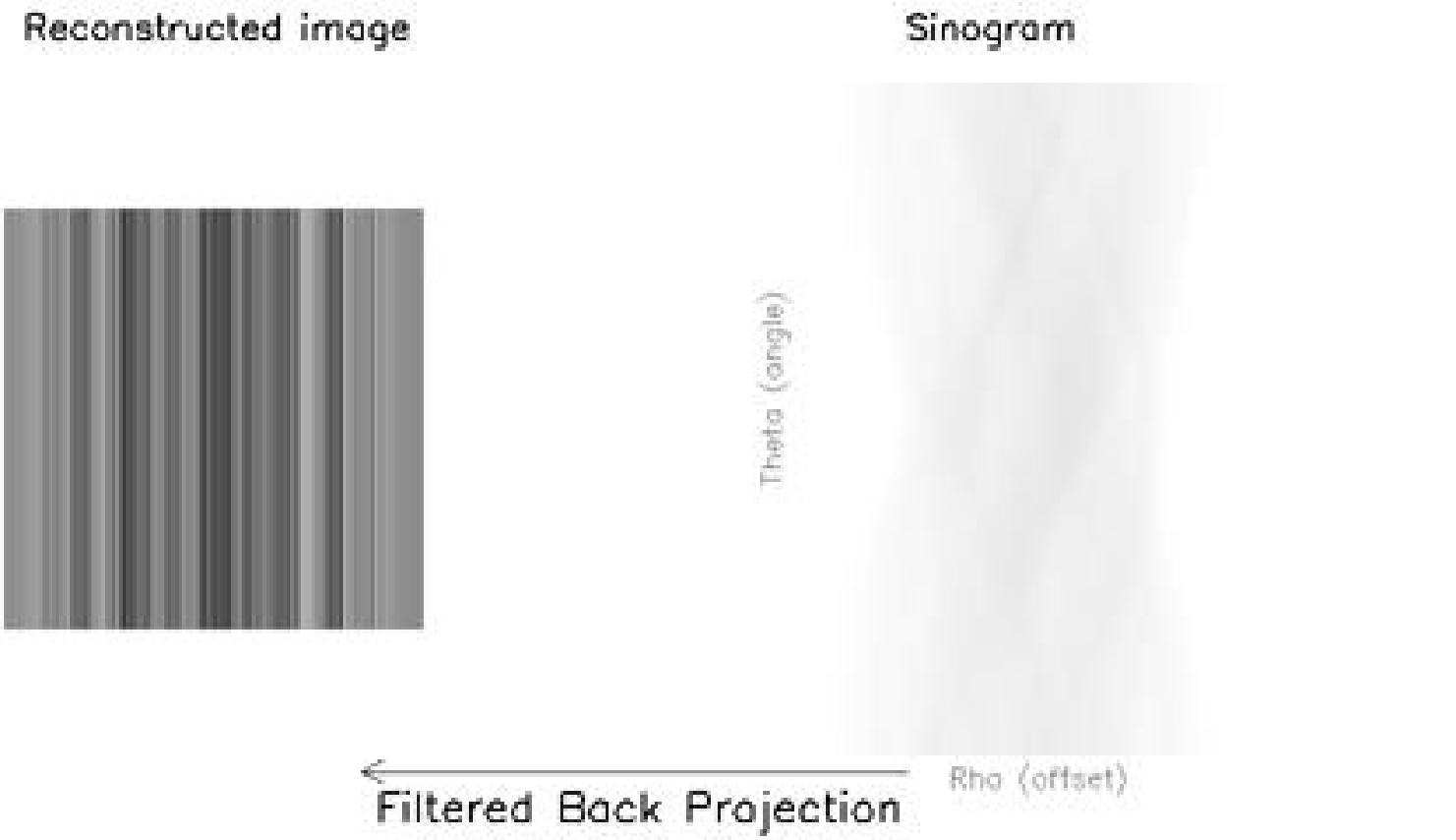


XRCT How does it work ?

Step 1 : acquisition

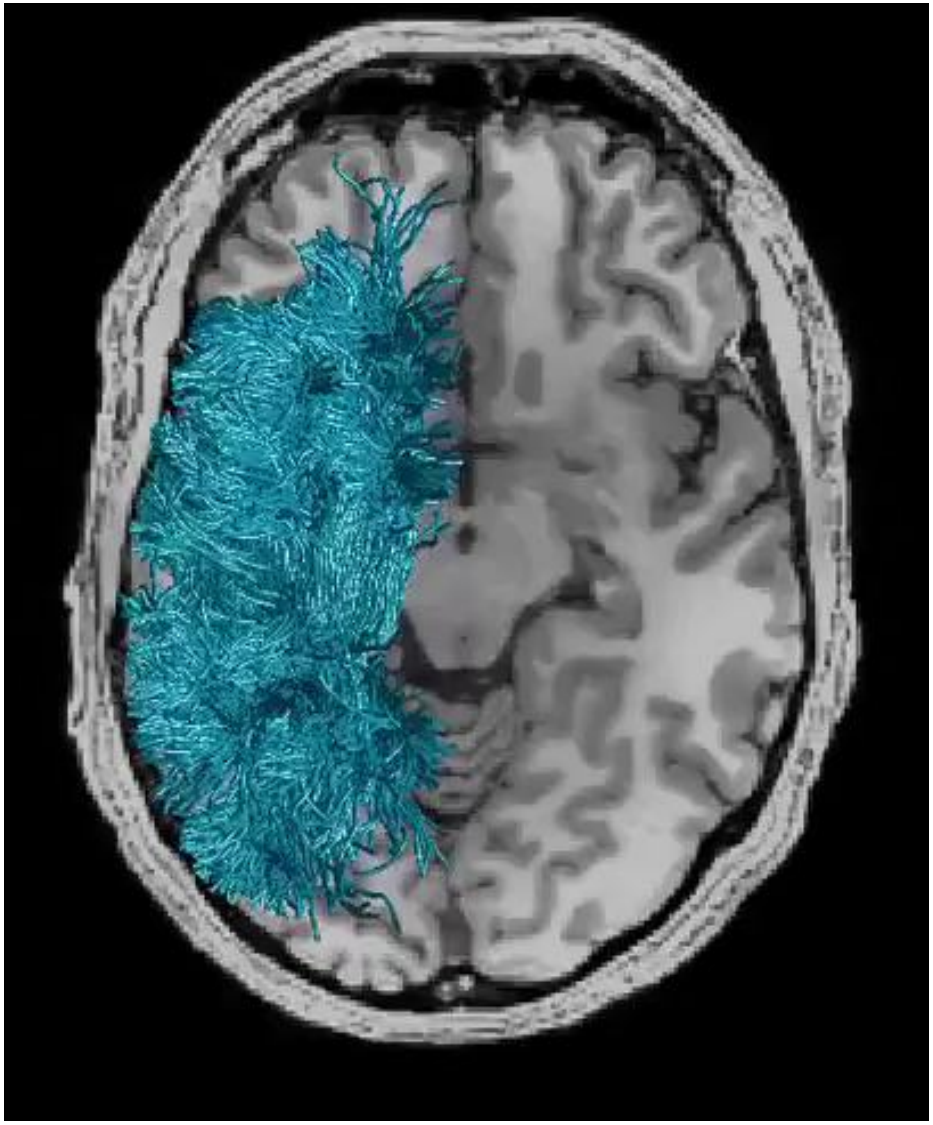


Step 2 : Reconstruction



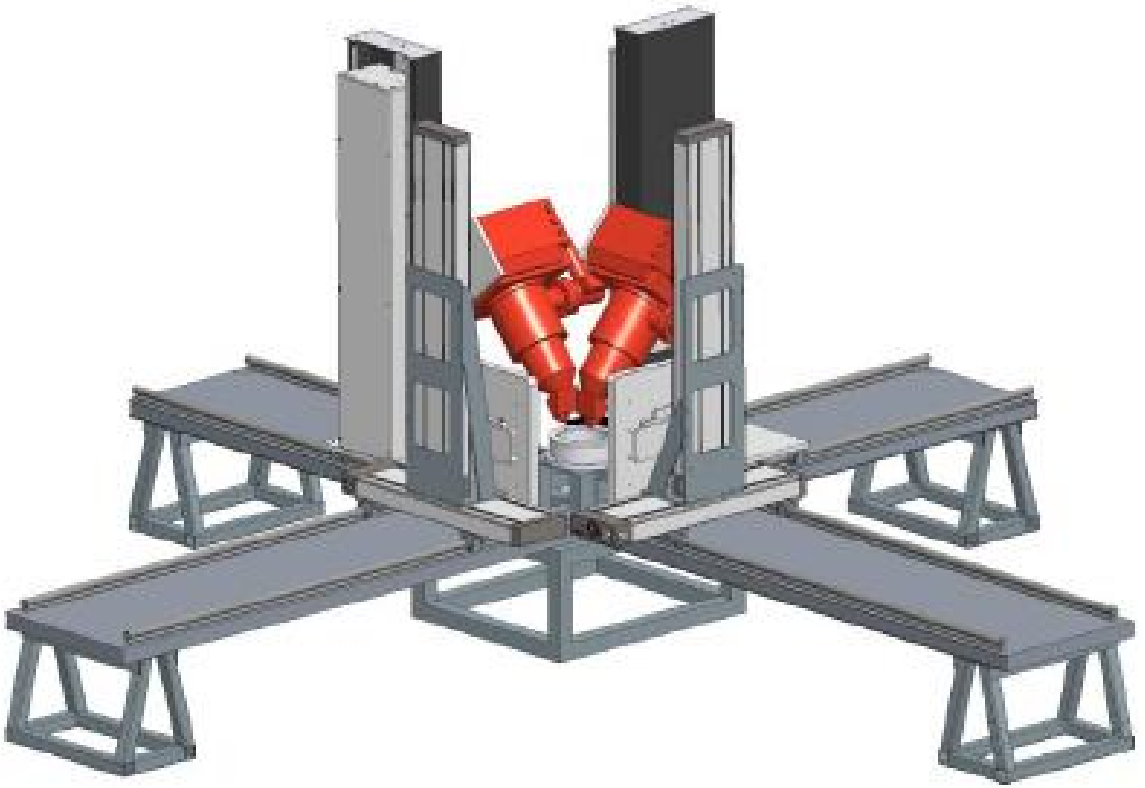
Result : 3D **volume**

- With a 2D detector, you can reconstruct
- **a stack of slices**
- **=**
- A 3D volume
- All you need is a SCANNER



Laboratory tomographs

Double blade High Energy
Aura DTHE



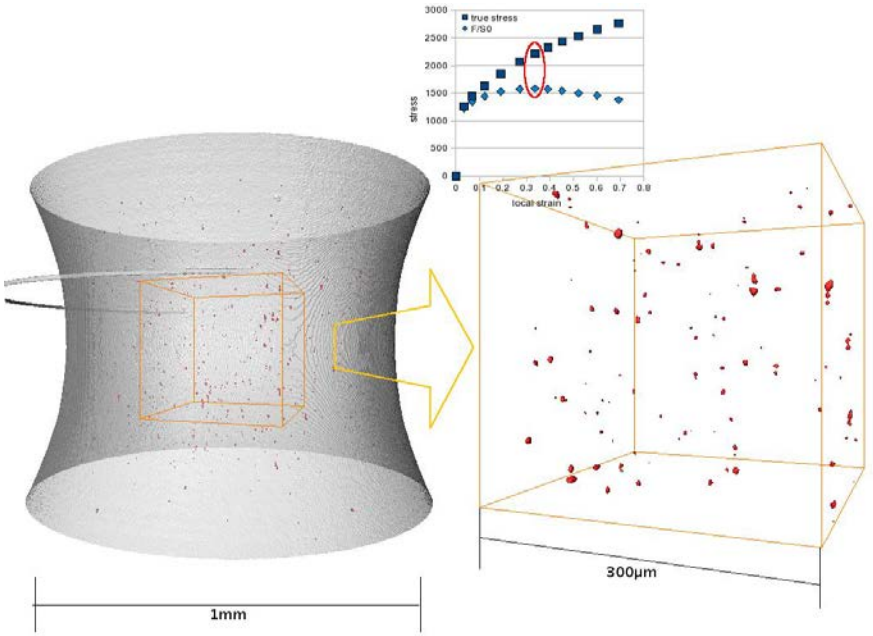
Synchrotron tomographs: high resolution

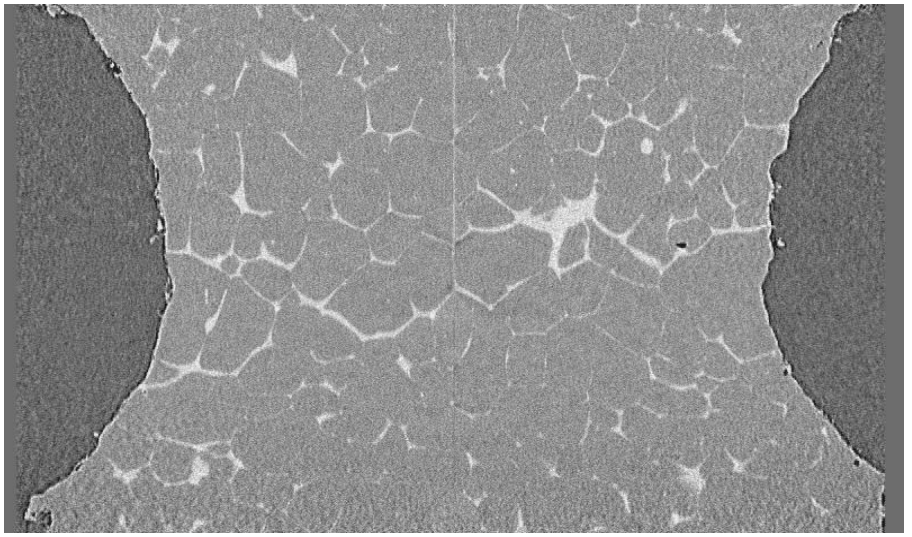
ID15 fast acquisition
ID16 Very high resolution

ID 19
-Home Page-

4D (3D + t) is better than 3D

- Non destructive 3D : calls for **in situ testing**

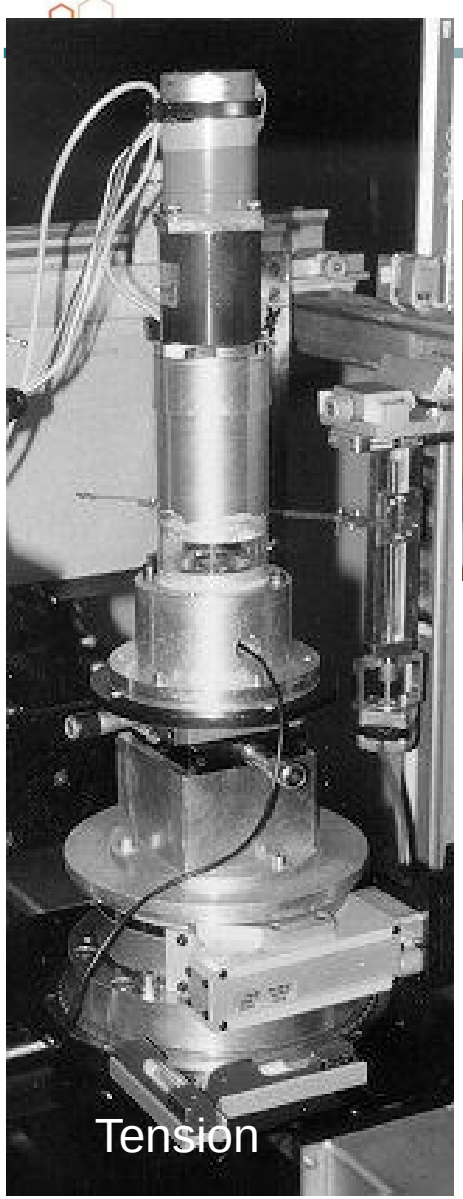


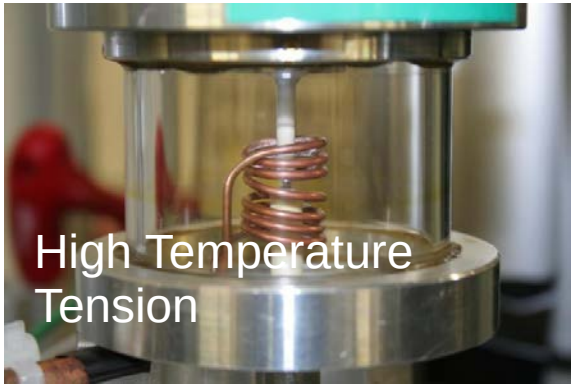


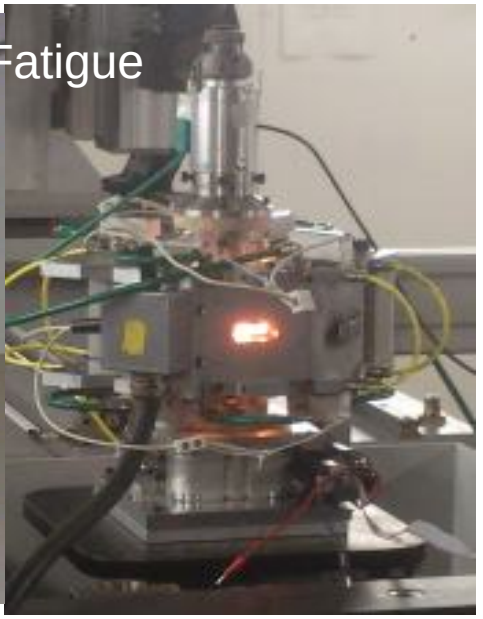
- All you need is a scanner + a loading device

Synchrotron

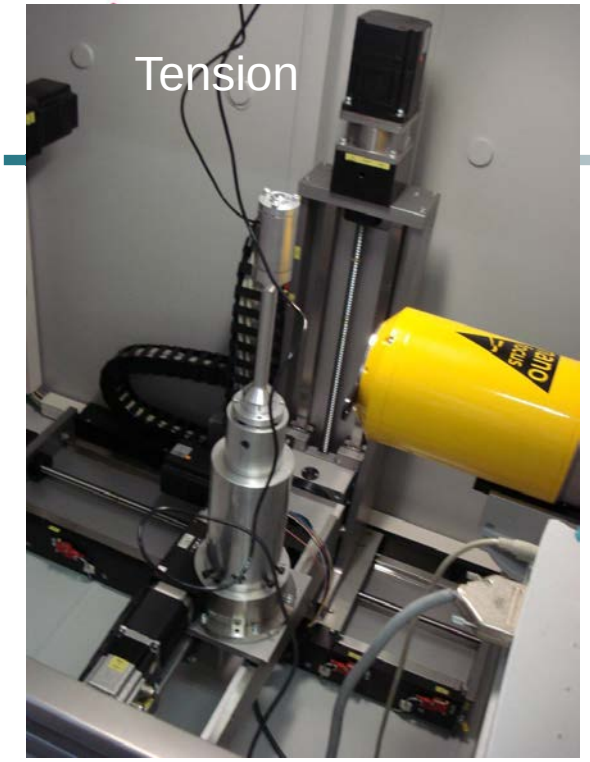
High Speed Tension

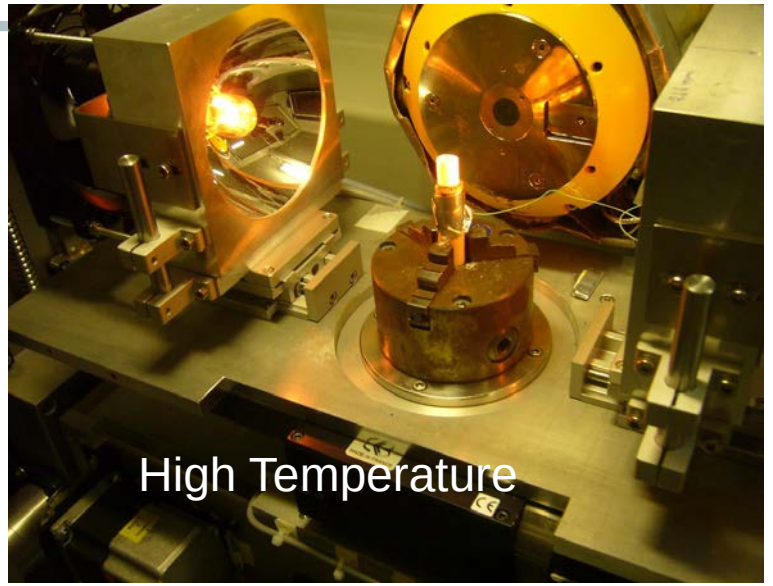




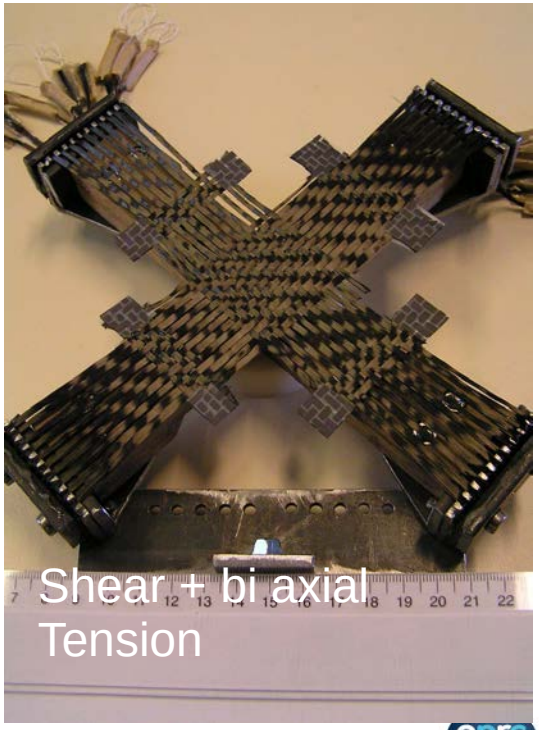


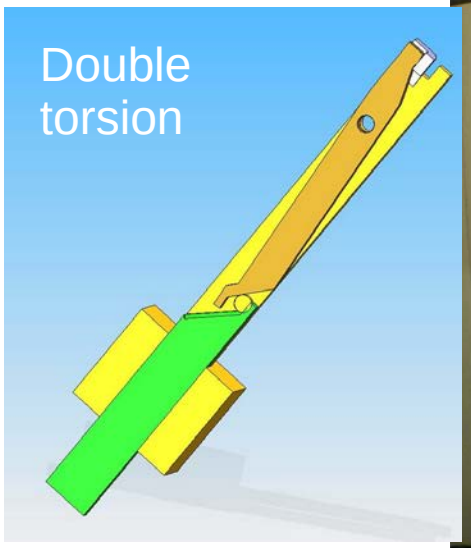
Lab CT


Tension


High Temperature


Low Temperature

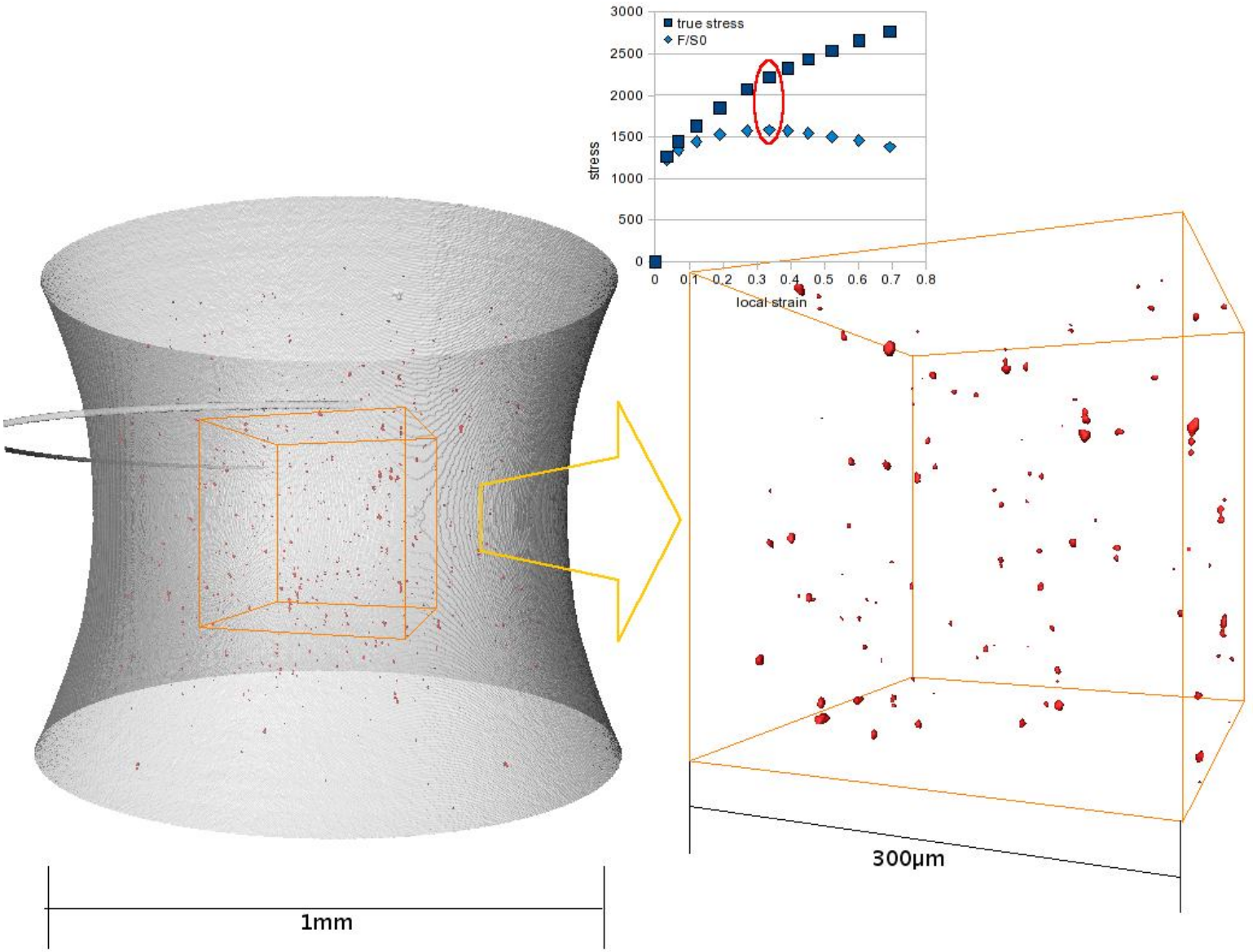

Shear + bi axial
Tension


Double
torsion


High pressure


Indentation

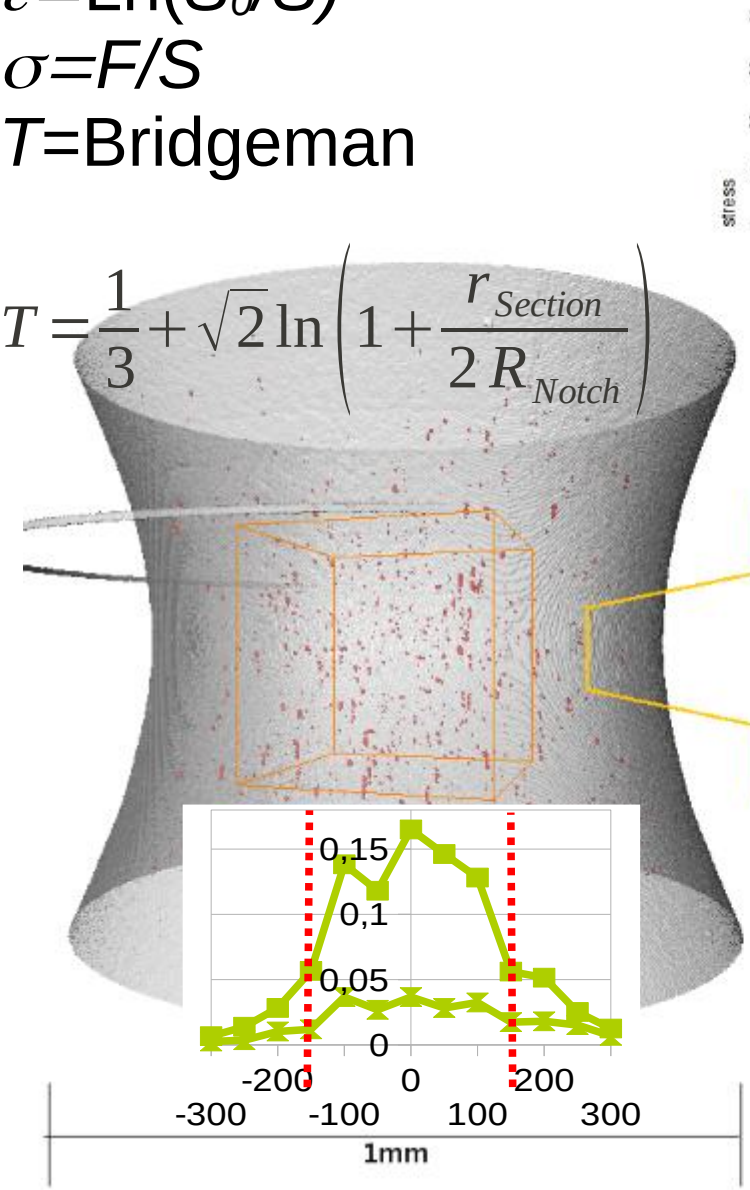
In situ mechanical tests

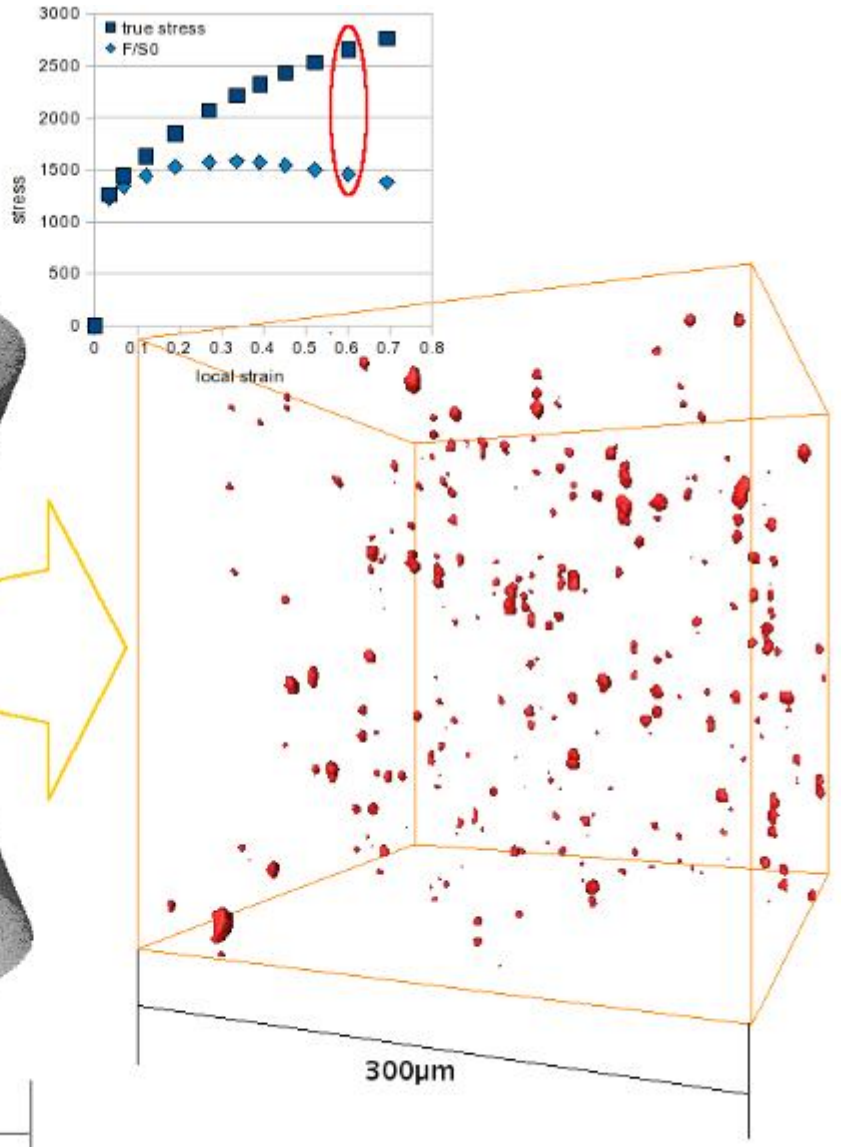


Typical output (2 types)

$S(z)$
$\varepsilon = \mathrm{Ln}(S_0/S)$
$\sigma = F/S$
T=Bridgeman

$$T = \frac{1}{3} + \sqrt{2}\ln\left(1 + \frac{r_{Section}}{2R_{Notch}}\right)$$



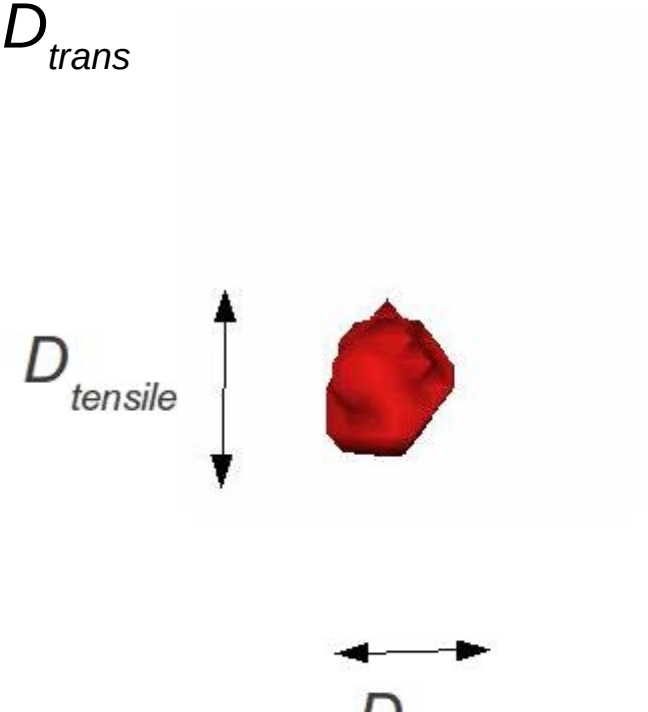


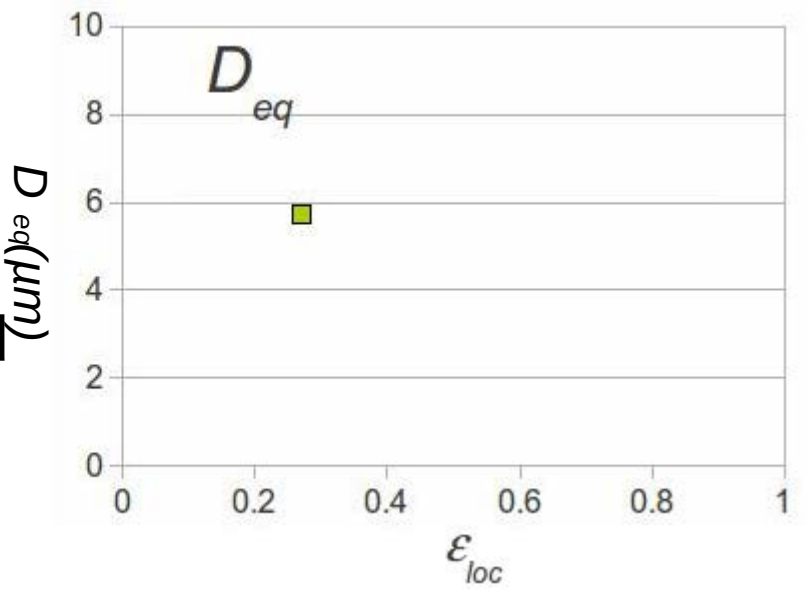
Damage Quantification In Small size Central cubes

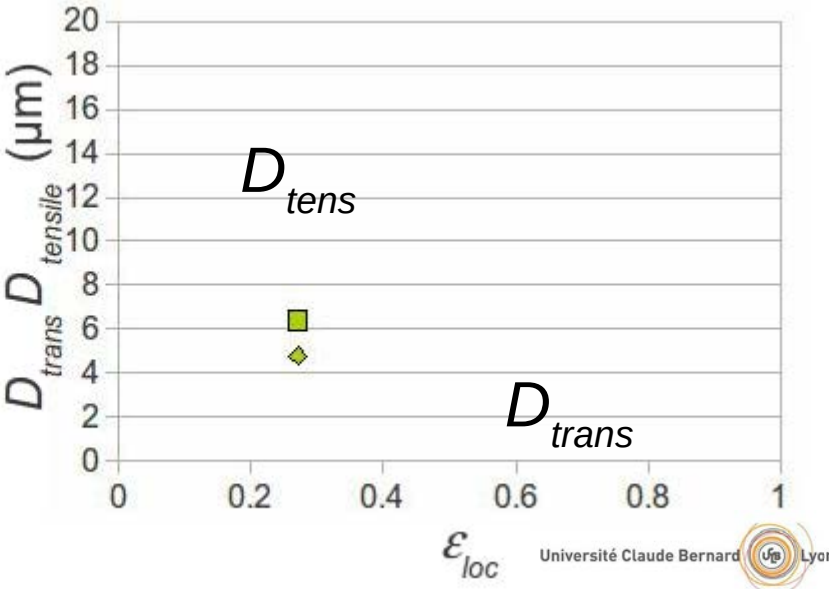
f... and more:
Nucleation: *N*
Growth: *R*
Coalescence:
Distance to neighbours

Growth (quantification)

- Volume increase : D_{eq} (cavity assumed to be spherical)
- Shape change : D_{tens} and D_{trans}







$$W = \frac{D_{tensile}}{D_{trans}}$$

With Japanese colleagues

Materials Science and Engineering A 528 (2011) 1512–1520

Contents lists available at ScienceDirect

Materials Science and Engineering A

journal homepage: www.elsevier.com/locate/msea

Room-temperature ductility of Ti–6Al–4V alloy with α′ martensite microstructure

Hiroaki Matsumoto[a,*], Hiroshi Yoneda[b], Kazuhisa Sato[a], Shingo Kurosu[a], Eric Maire[c], Damien Fabregue[c], Toyohiko J. Konno[a], Akihiko Chiba[a]

[a] Institute for Materials Research, Tohoku University, Japan
[b] Tohoku University, Japan
[c] Université de Lyon, INSA LYON, CNRS, MATEIS, France

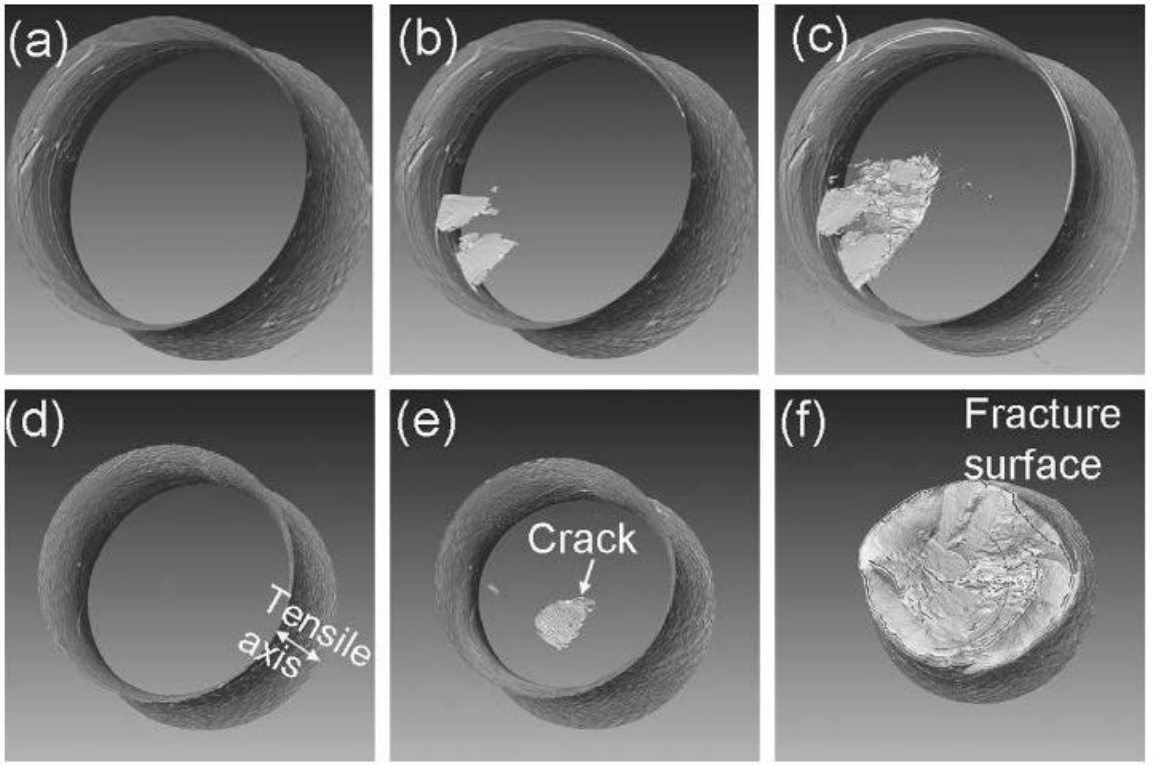


Fig. 5. X-ray microtomographs demonstrating the fracture behavior in 1373 K STQ (a–c) and 1223 K STQ (d–f). (a) and (d) show the microtomographs prior to cracking, (b), (c), and (e) show the microtomographs during crack propagation, and (f) shows the microtomograph after fracture.

Materials Characterization
Volume 116, June 2016, Pages 48-54

CoCrMo cellular structures made by Electron Beam Melting studied by local tomography and finite element modelling

Clémence Petit [a], Eric Maire [a], Sylvain Meille [a], Jérôme Adrien [a], Shingo Kurosu [b], Akihiko Chiba [b]

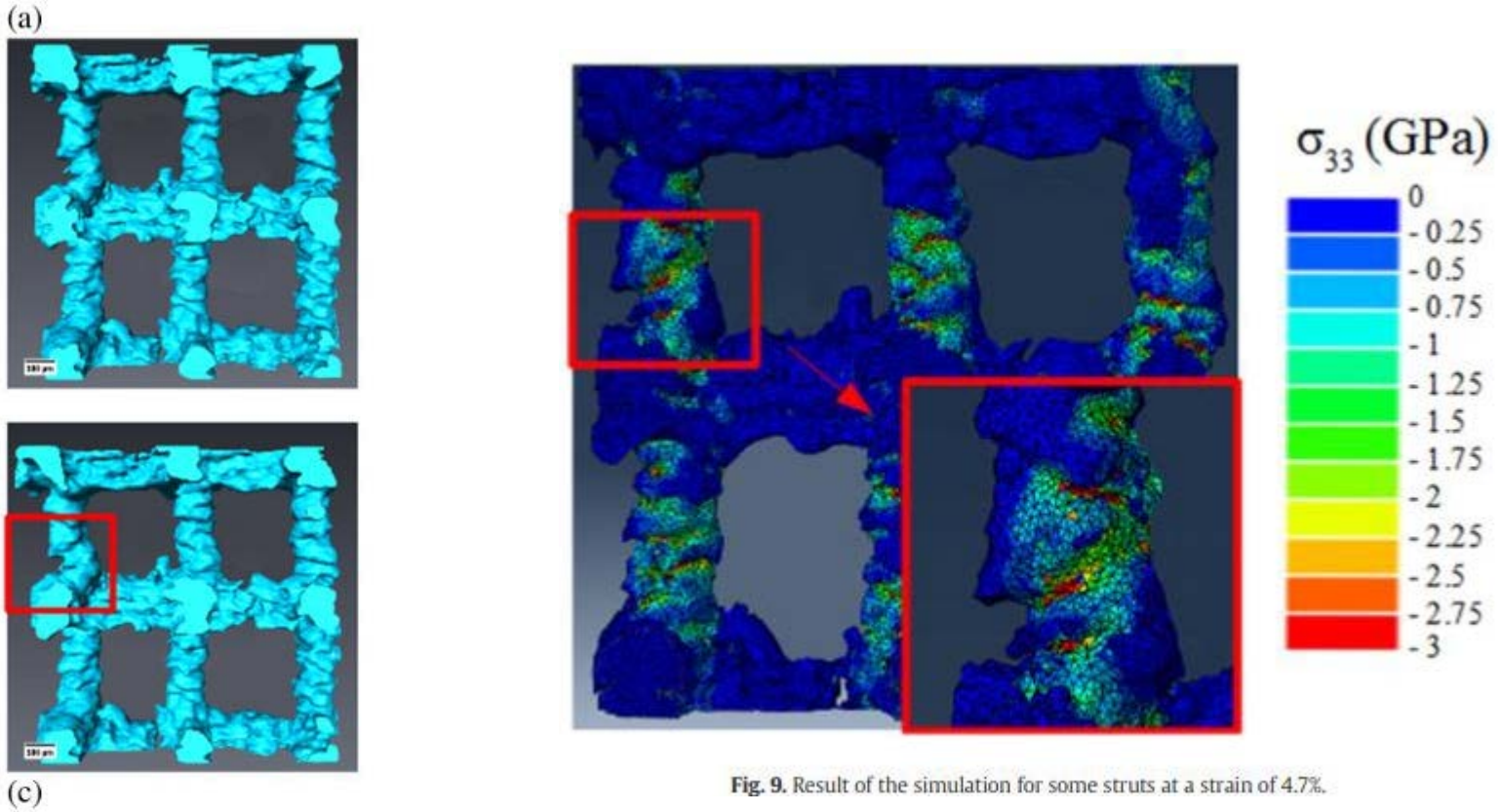


Fig. 9. Result of the simulation for some struts at a strain of 4.7%.

Contents lists available at ScienceDirect

Additive Manufacturing

journal homepage: www.elsevier.com/locate/addma

Solidification behavior and porosity in electron-beam powder bed fusion of Co–Cr–Mo alloys: Effect of carbon concentrations

Shoya Aota [a,b,1], Kenta Yamanaka [a,*], Manami Mori [a,c], Nobuyuki Sasaki [a,2], Jérôme Adrien [d], Eric Maire [d], Damien Fabrègue [d,e], Akihiko Chiba [a]

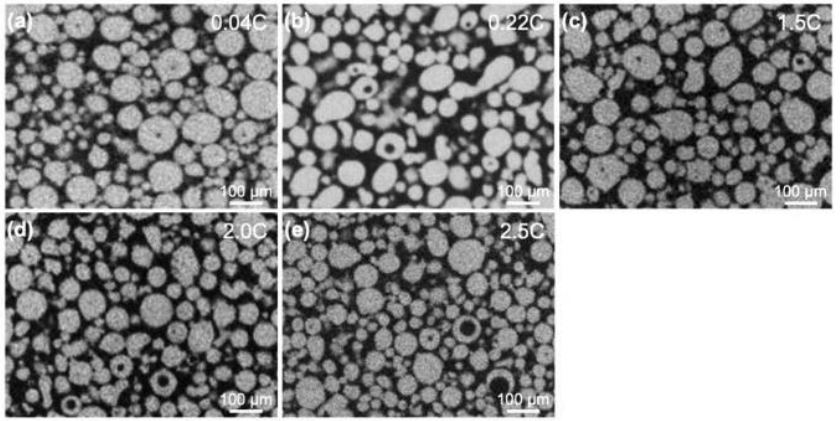
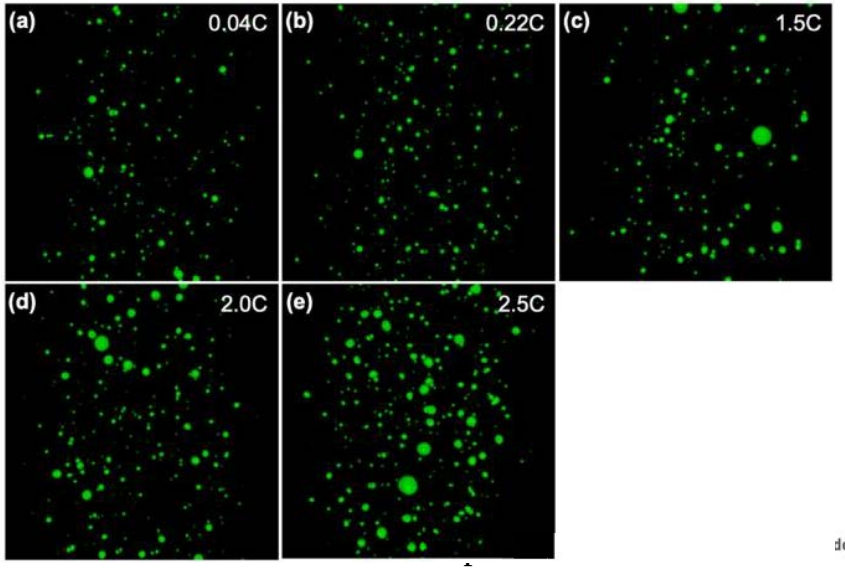


Fig. 5. Cross-sectional morphologies of (a) 0.04C, (b) 0.22C, (c) 1.5C, (d) 2.0C, and (e) 2.5C powders, as obtained by XCT.



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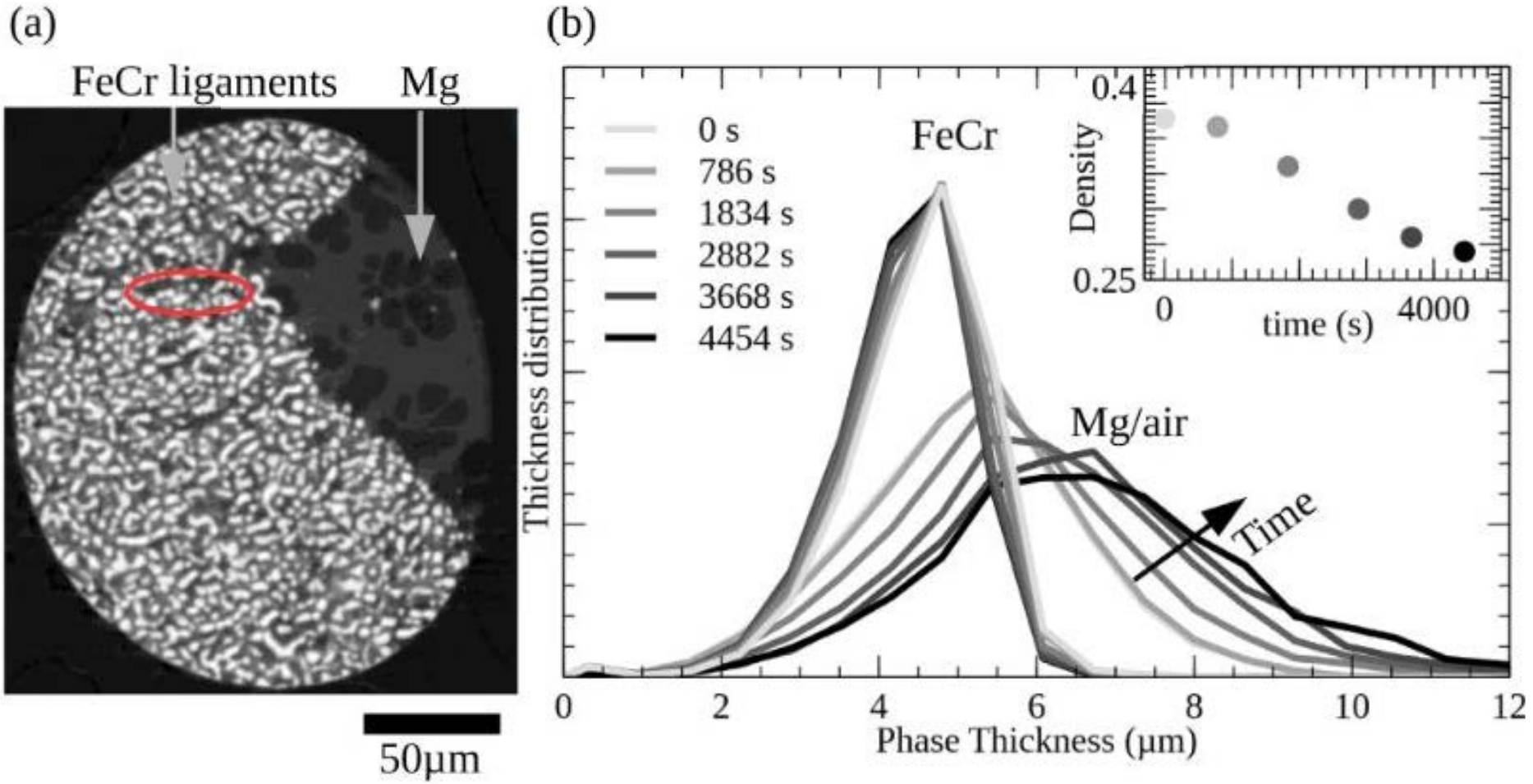
Materialia

journal homepage: www.elsevier.com/locate/mtla

Full Length Article

In situ observation of liquid metal dealloying and etching of porous FeCr by X-ray tomography and X-ray diffraction

Morgane Mokhtari[a,b,c,d], Christophe Le Bourlot[a,*], Jérome Adrien[a], Anne Bonnin[e], Wolfgang Ludwig[a,f], Pierre-Antoine Geslin[a,b], Takeshi Wada[b], Jannick Duchet-Rumeau[c], Hidemi Kato[b], Eric Maire[a]



materials

Article

Role of Hydrogen-Charging on Nucleation and Growth of Ductile Damage in Austenitic Stainless Steels

Eric Maire [1,*], Stanislas Grabon [1], Jérôme Adrien [1], Pablo Lorenzino [1], Yuki Asanuma [2], Osamu Takakuwa [3,4,5] and Hisao Matsunaga [3,4,6]

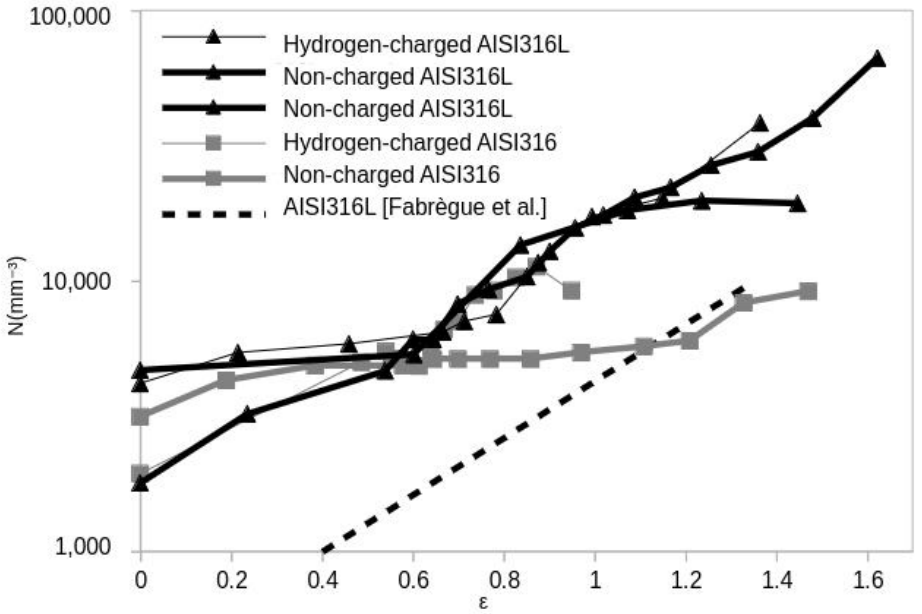
AISI316L

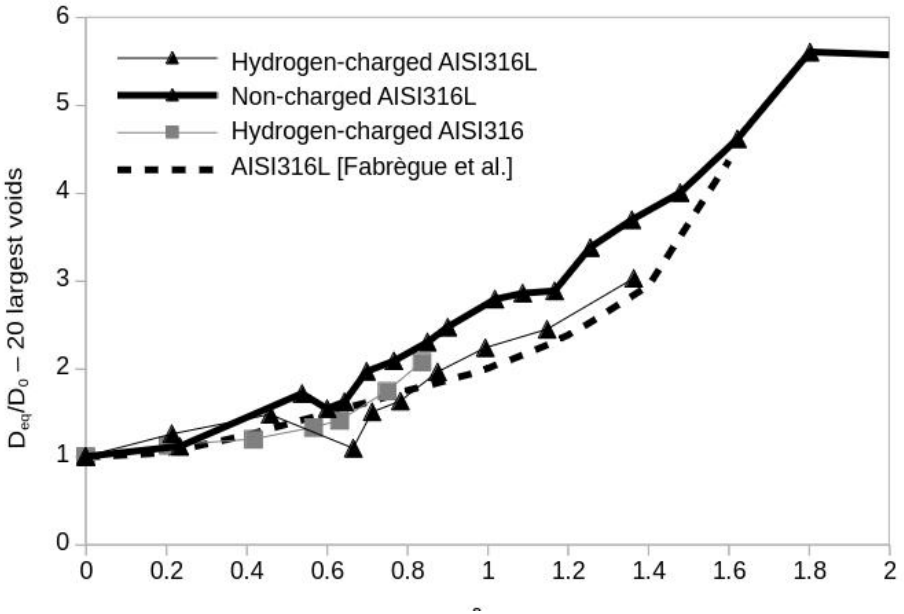
H2 Charged AISI316

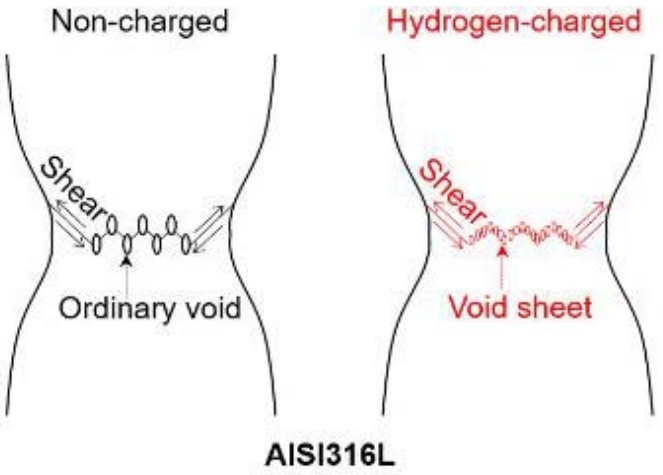
H2 Charged AISI316L

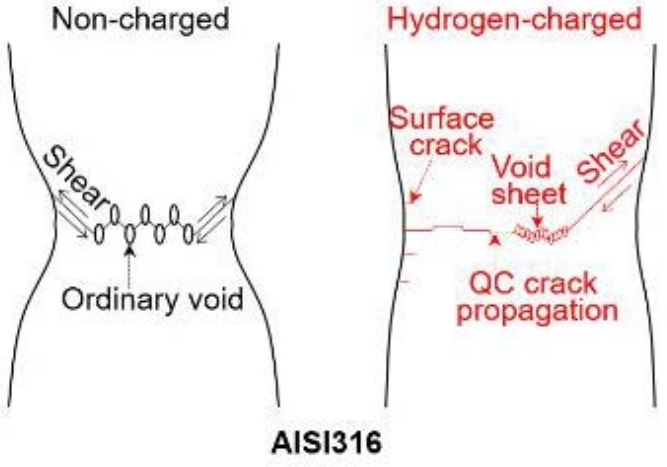
Quantification

- Nucleation and growth are similar









High acquisition speed
High resolution
(both are exclusive)

Pushing the temporal limits

Int J Fract (2016) 200:3–12
DOI 10.1007/s10704-016-0077-y

CrossMark

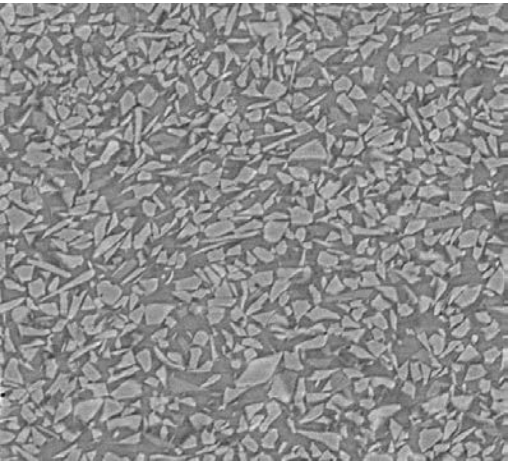
IUTAM PARIS 2015

20 Hz X-ray tomography during an in situ tensile test

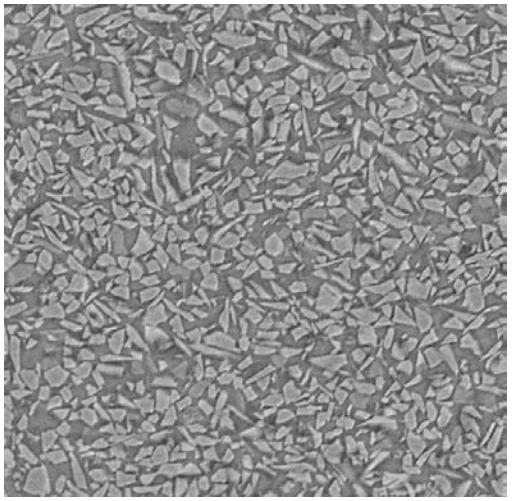
Eric Maire · Christophe Le Bourlot · Jérôme Adrien · Andreas Mortensen · Rajmund Mokso

Time for one scan :

5 minutes



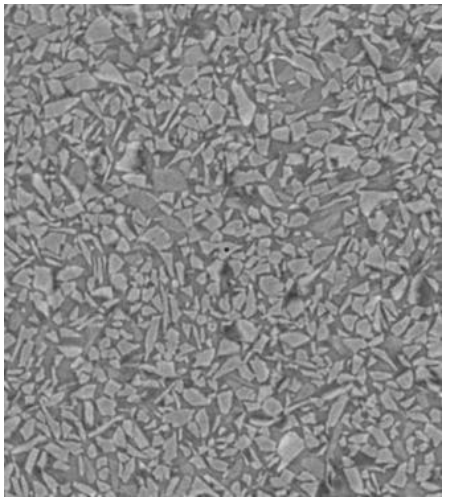
20 seconds



At ESRF ID15

0,16 second : tensile test

with $d\varepsilon/dt=10^{-3}\,s^{-1}$

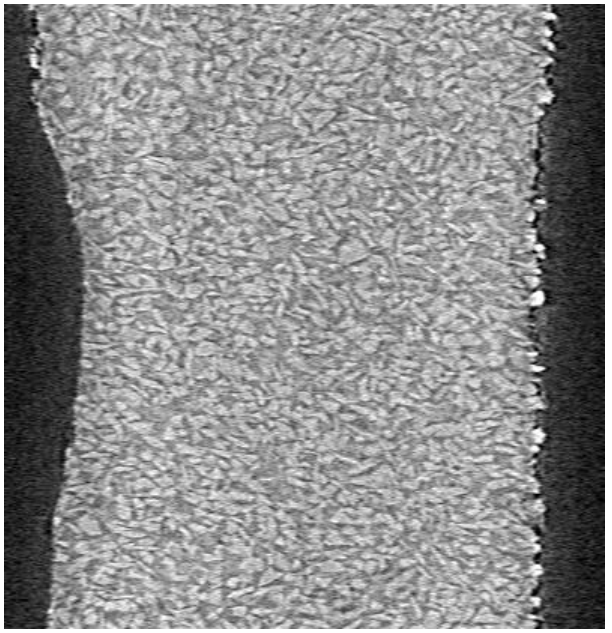


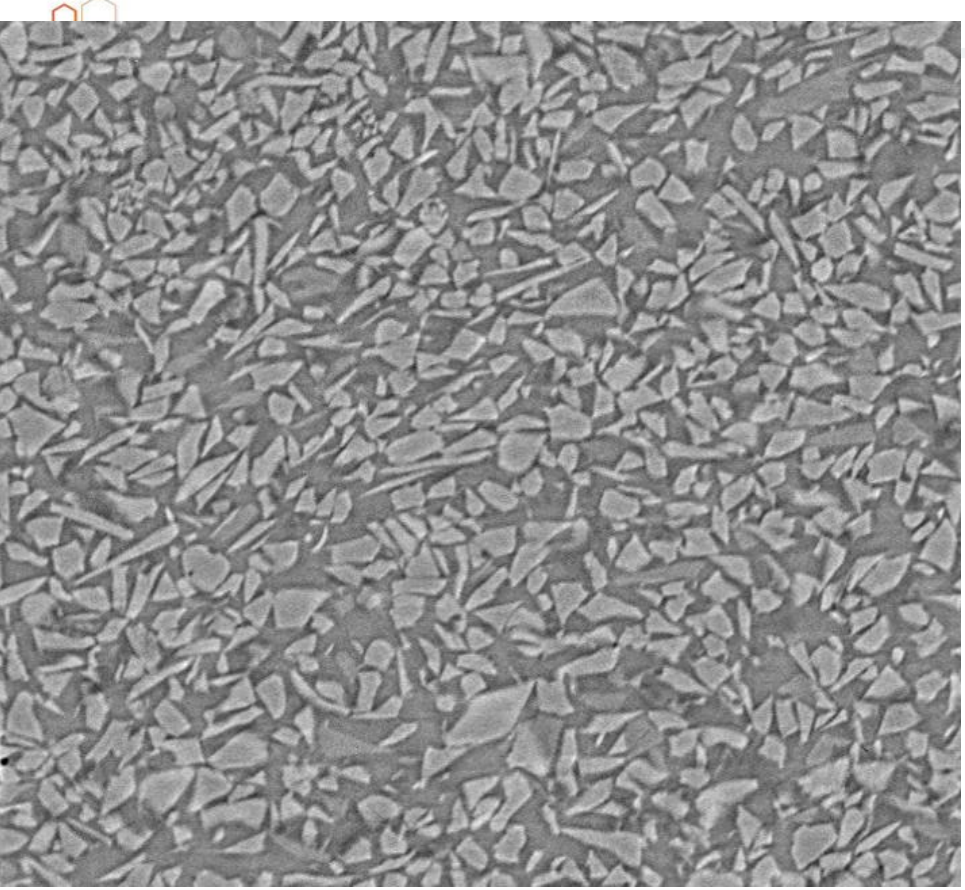
500 microns

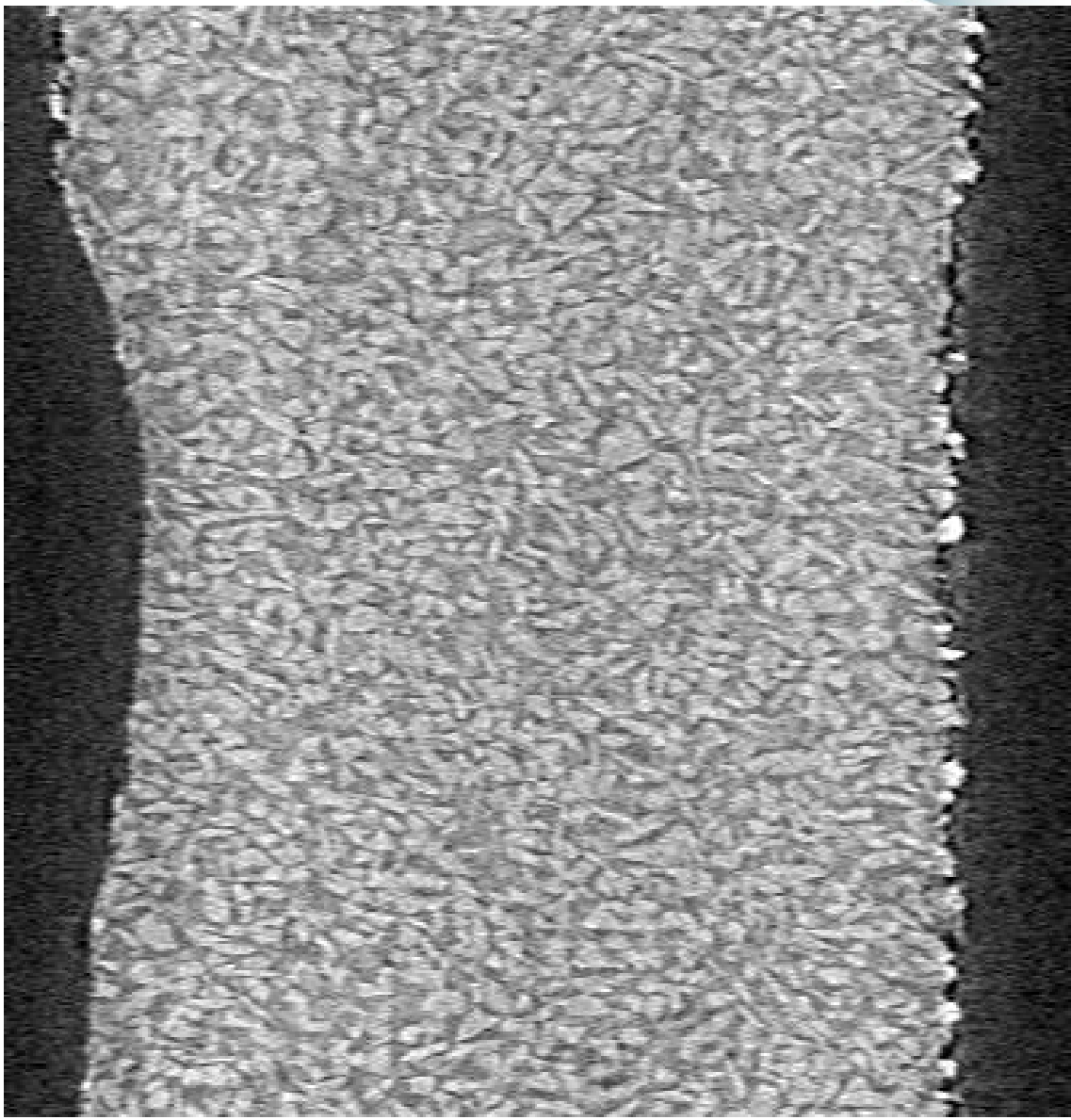
At SLS Tomcat

0,05 second tensile test

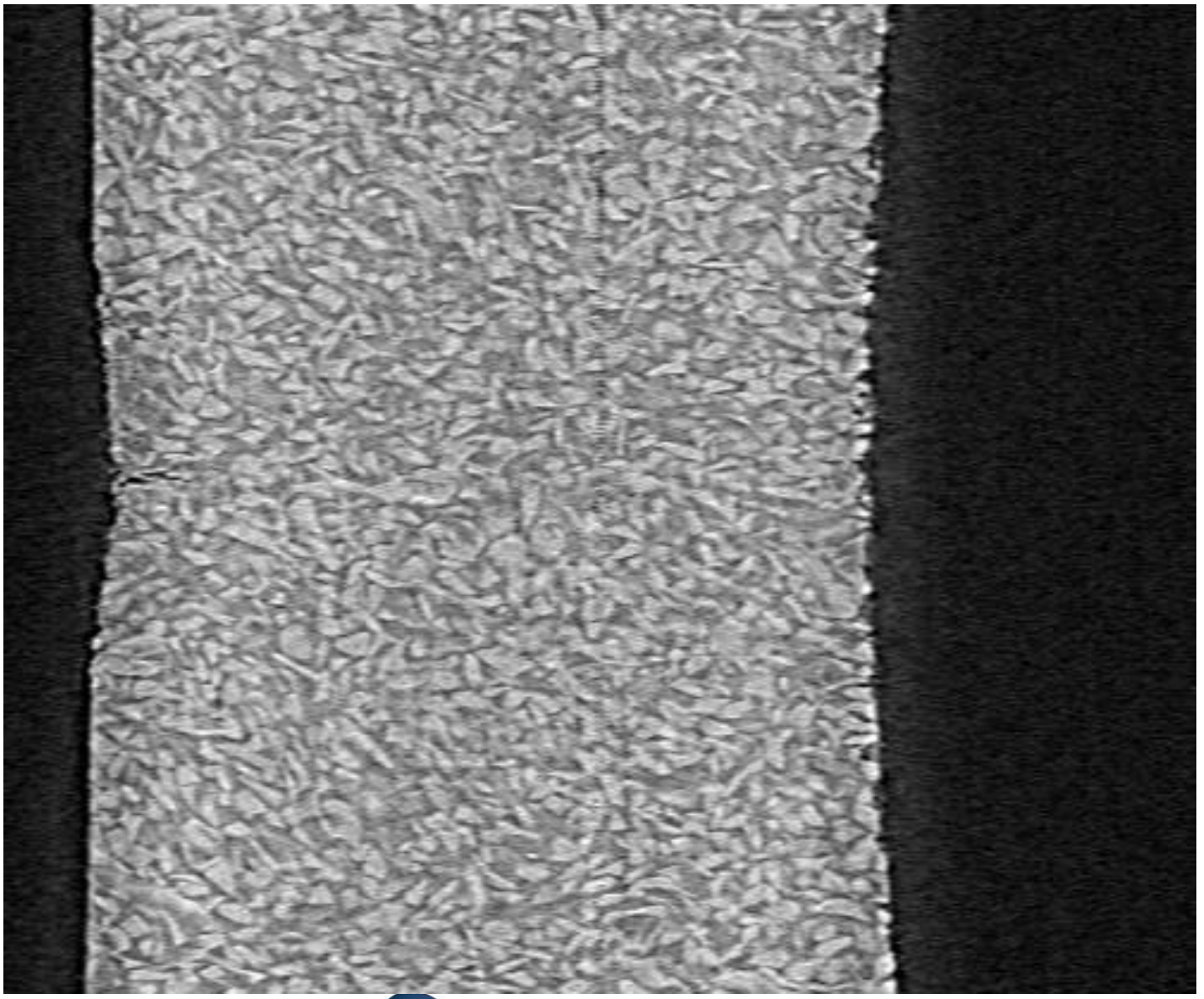
with $d\varepsilon/dt=10^{-3}\,s^{-1}$







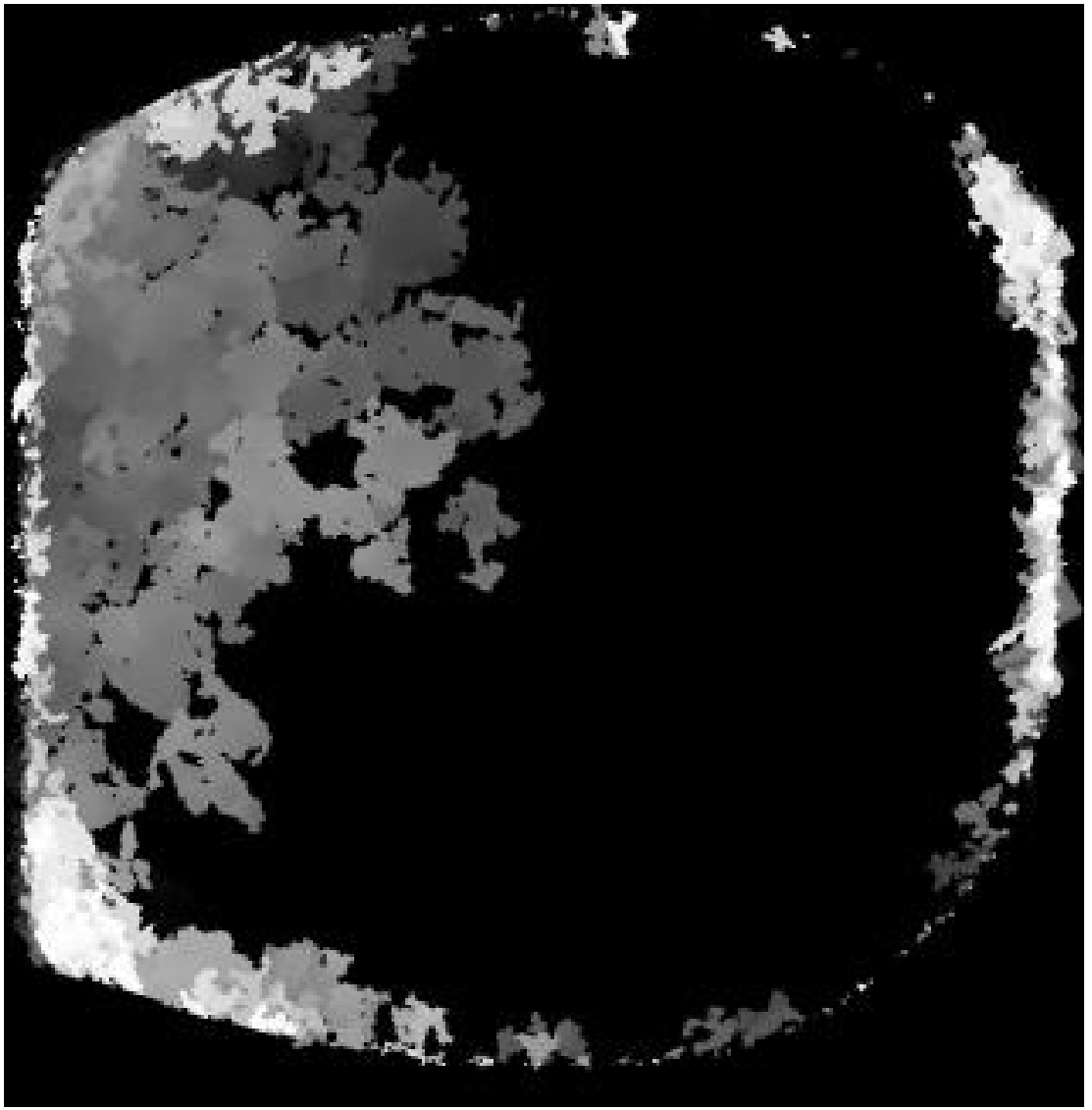
Fracture at 20 tomo per second



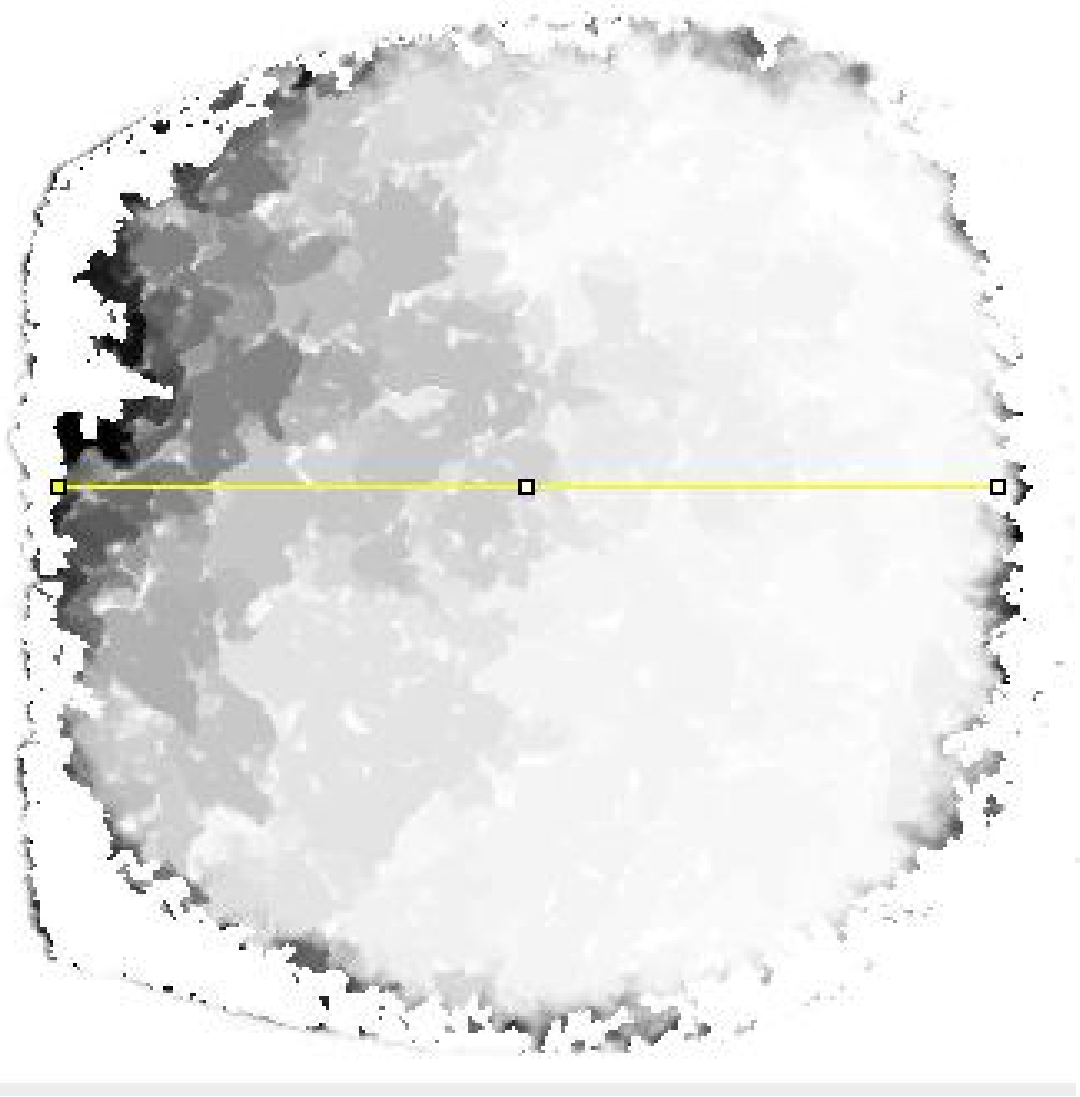
With R Mokso and C Schelputz

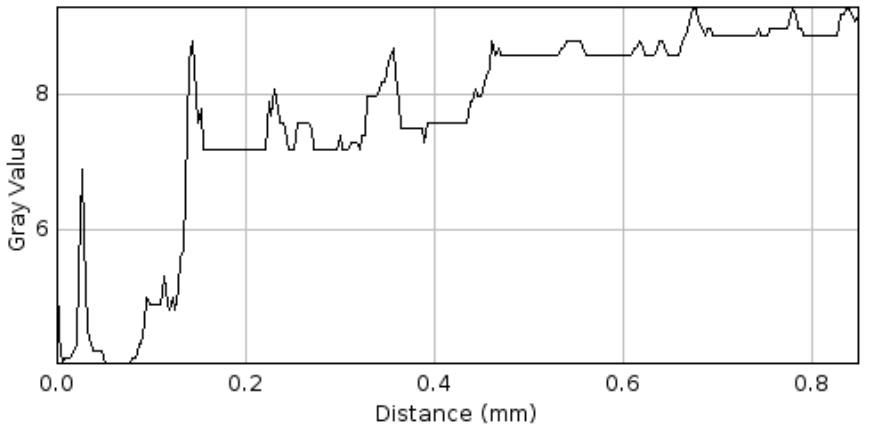
SLS TOMCAT

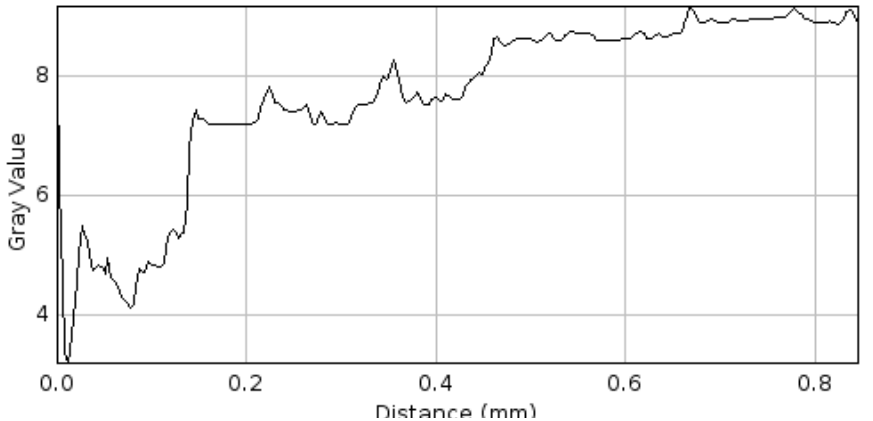
Crack propagation + altitude

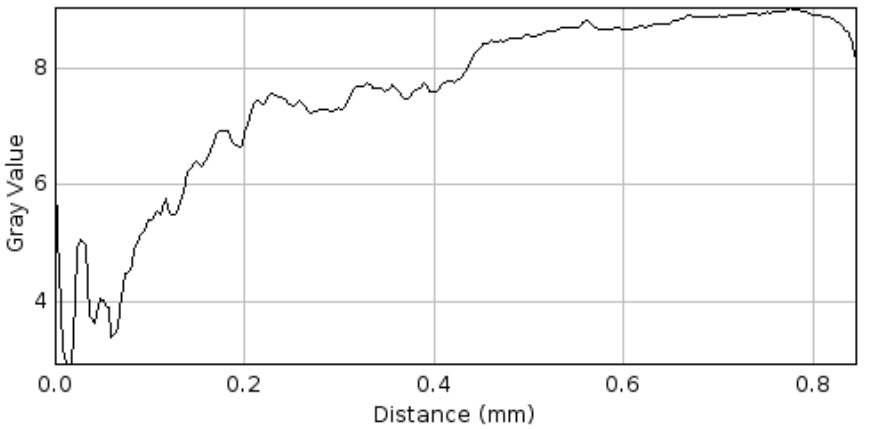


Time to destination

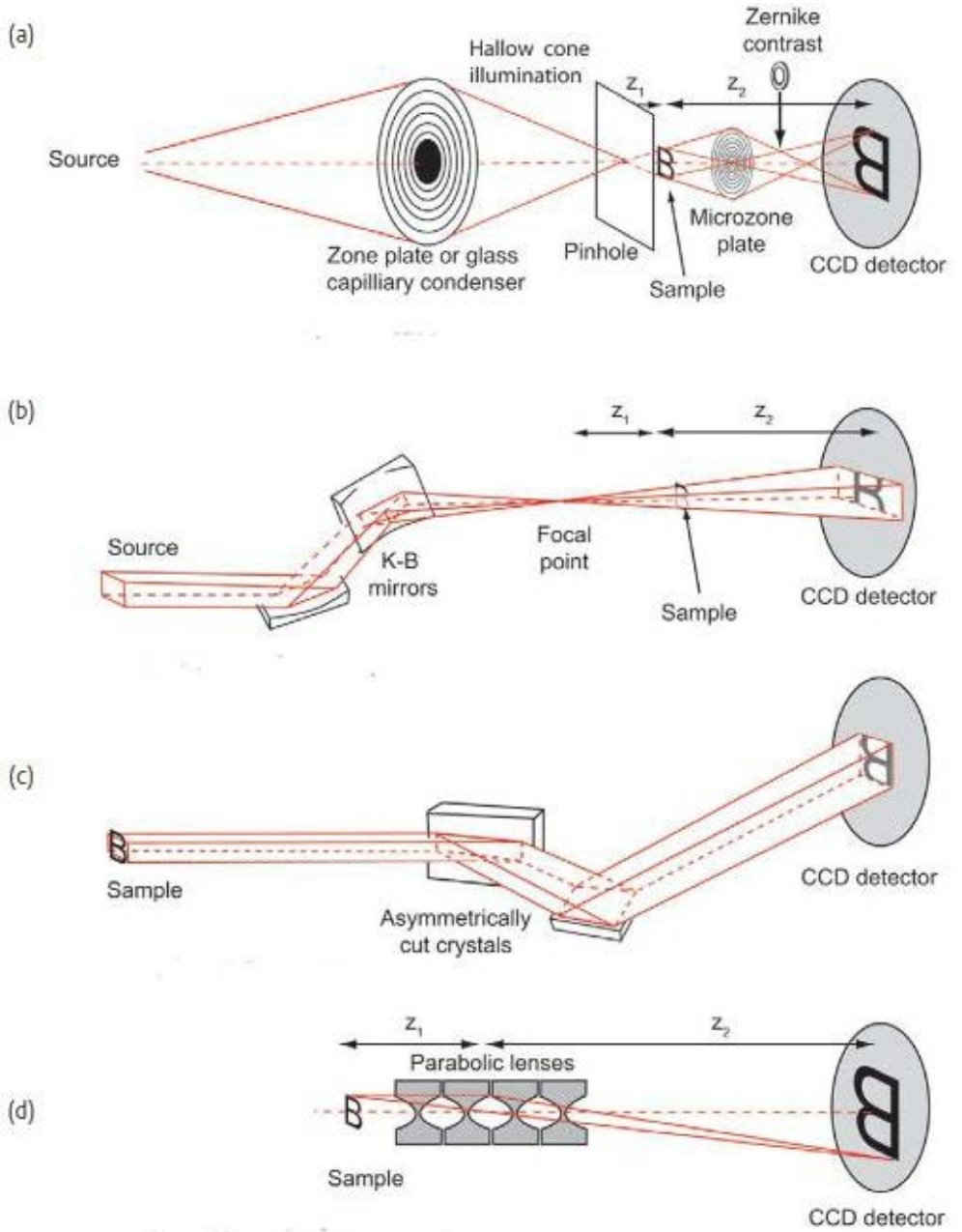






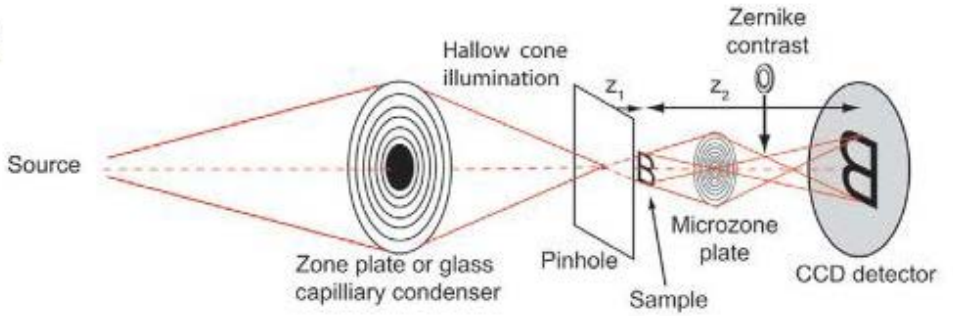


Pushing the spatial limits



PJ Withers
X Ray nanotomography

Pushing the spatial limits



RESEARCH ARTICLE | APRIL 05 2007

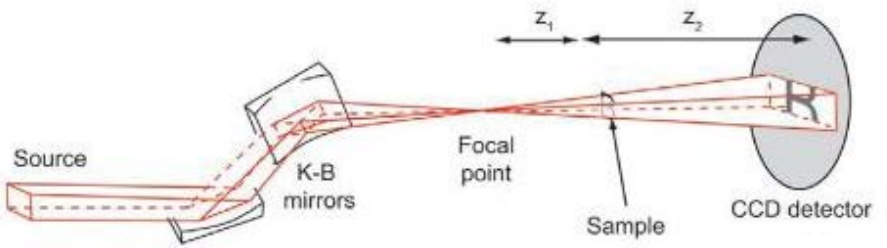
Nanoscale zoom tomography with hard x rays using Kirkpatrick-Baez optics

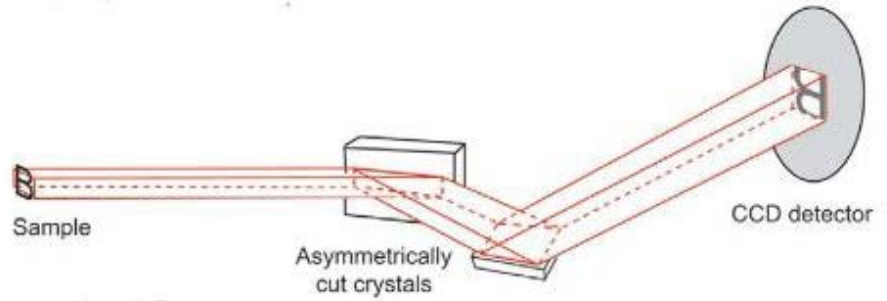
R. Mokso; P. Cloetens; E. Maire; W. Ludwig; J.-Y. Buffière

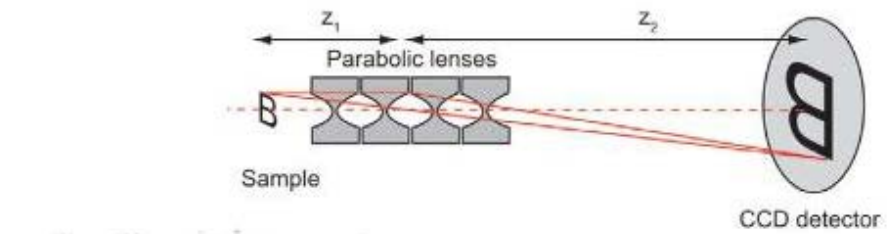
Check for updates

+ Author & Article Information

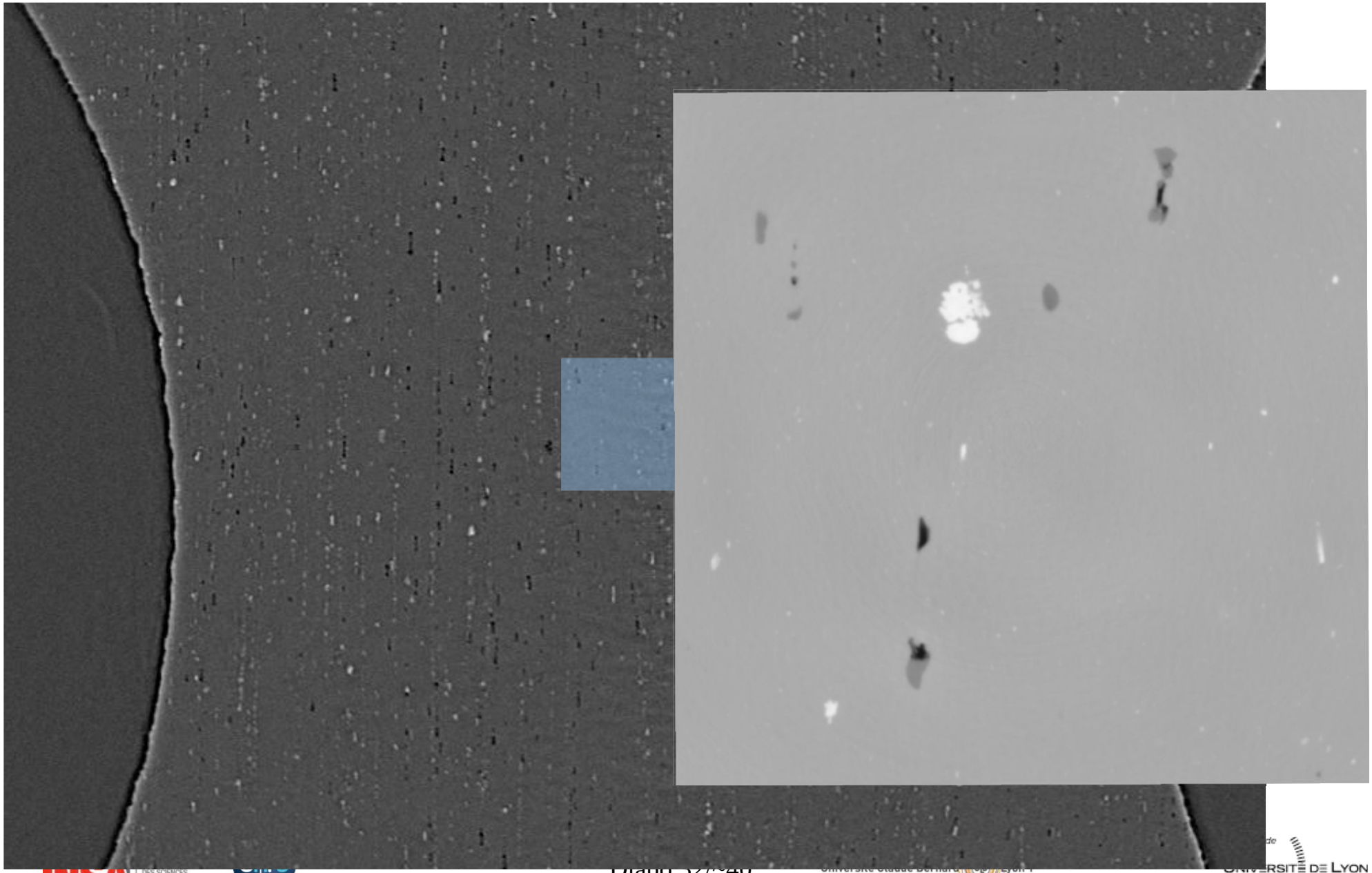
Appl. Phys. Lett. 90, 144104 (2007)





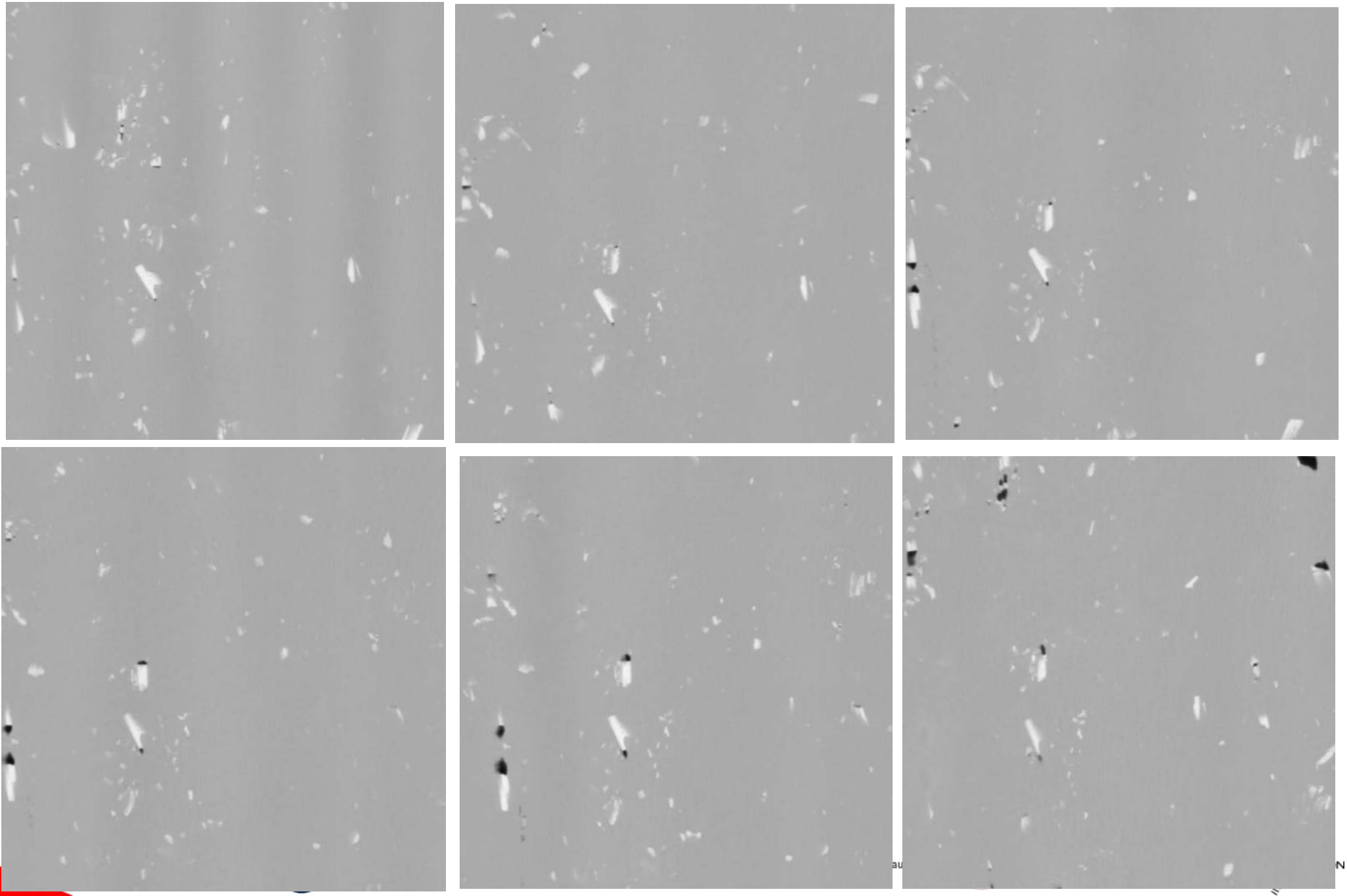


Aluminium alloys

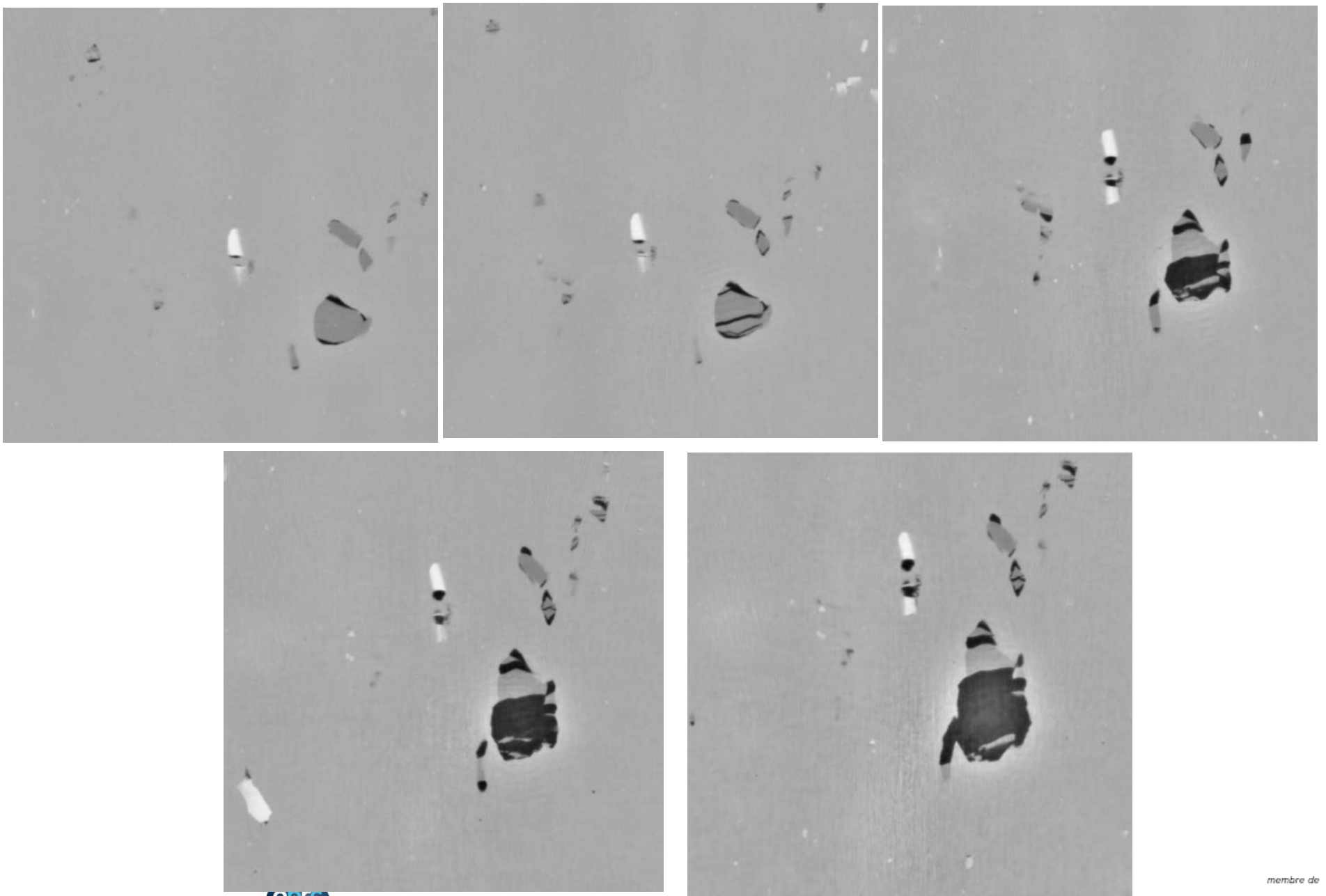


MatéIS

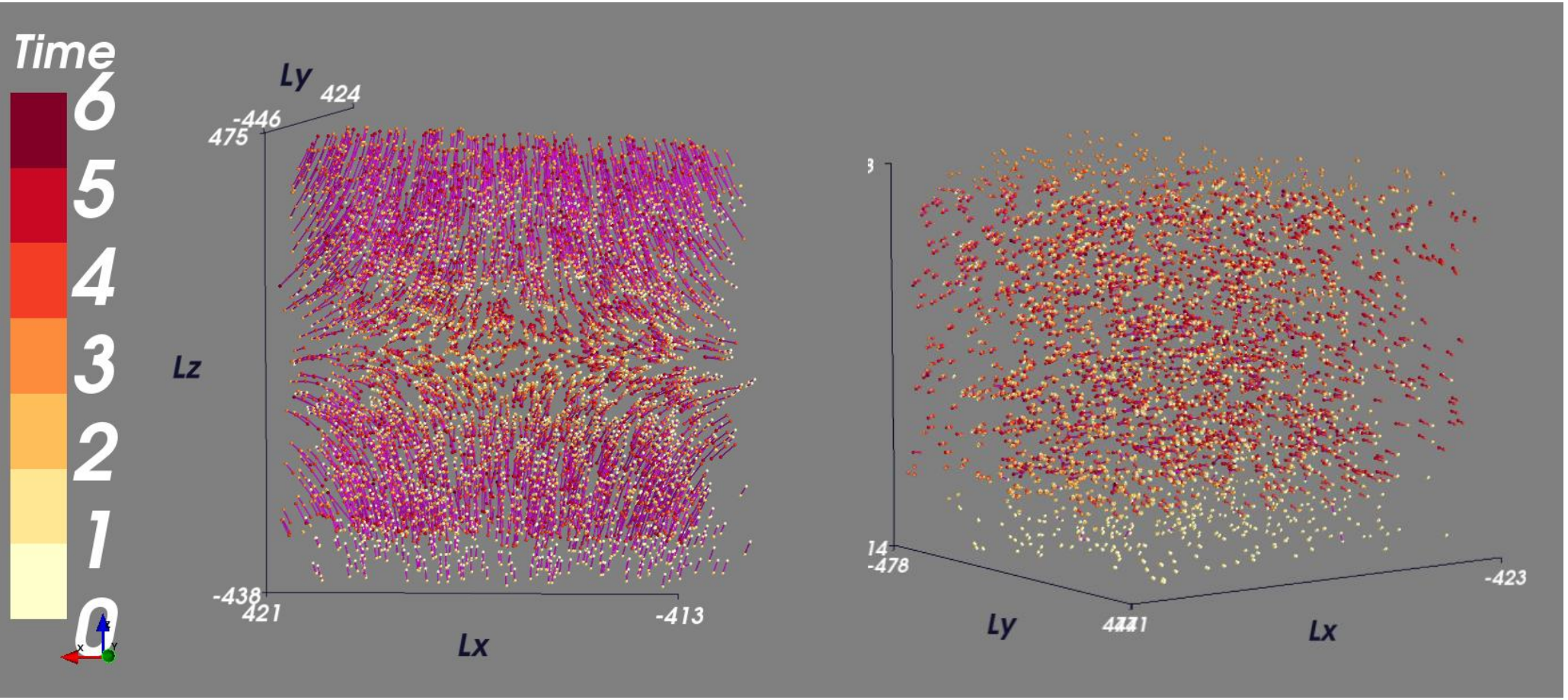
1200



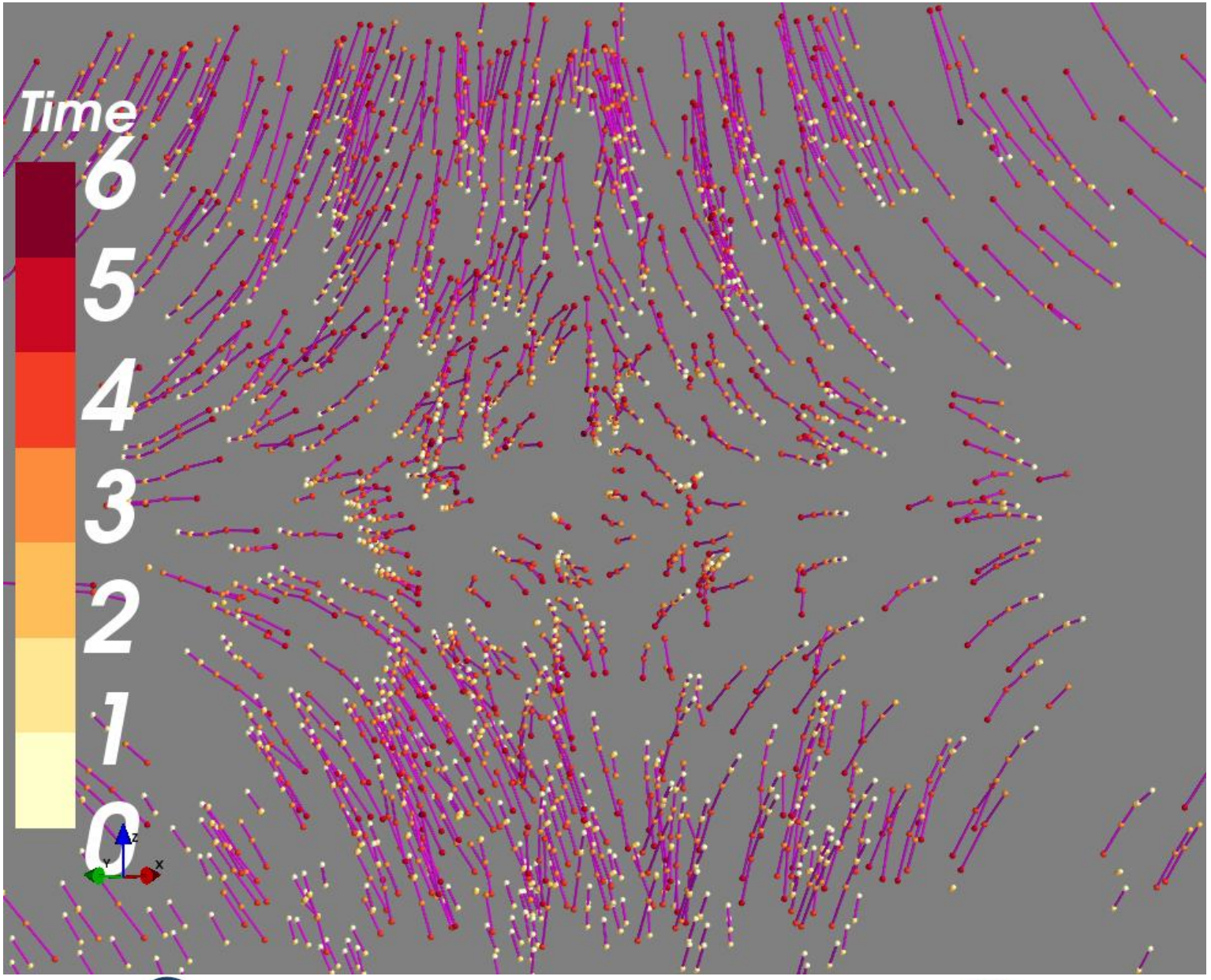
5182

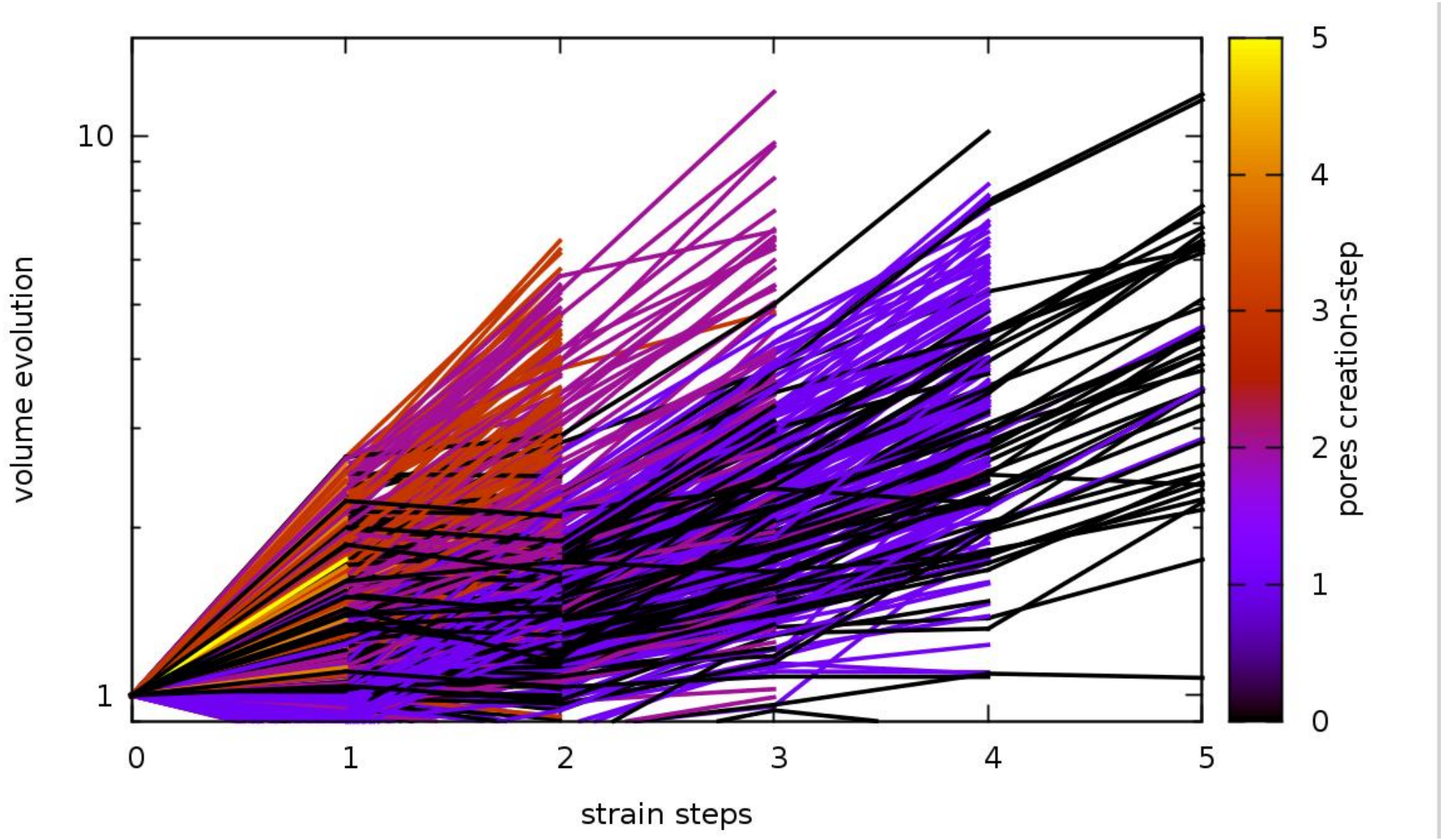


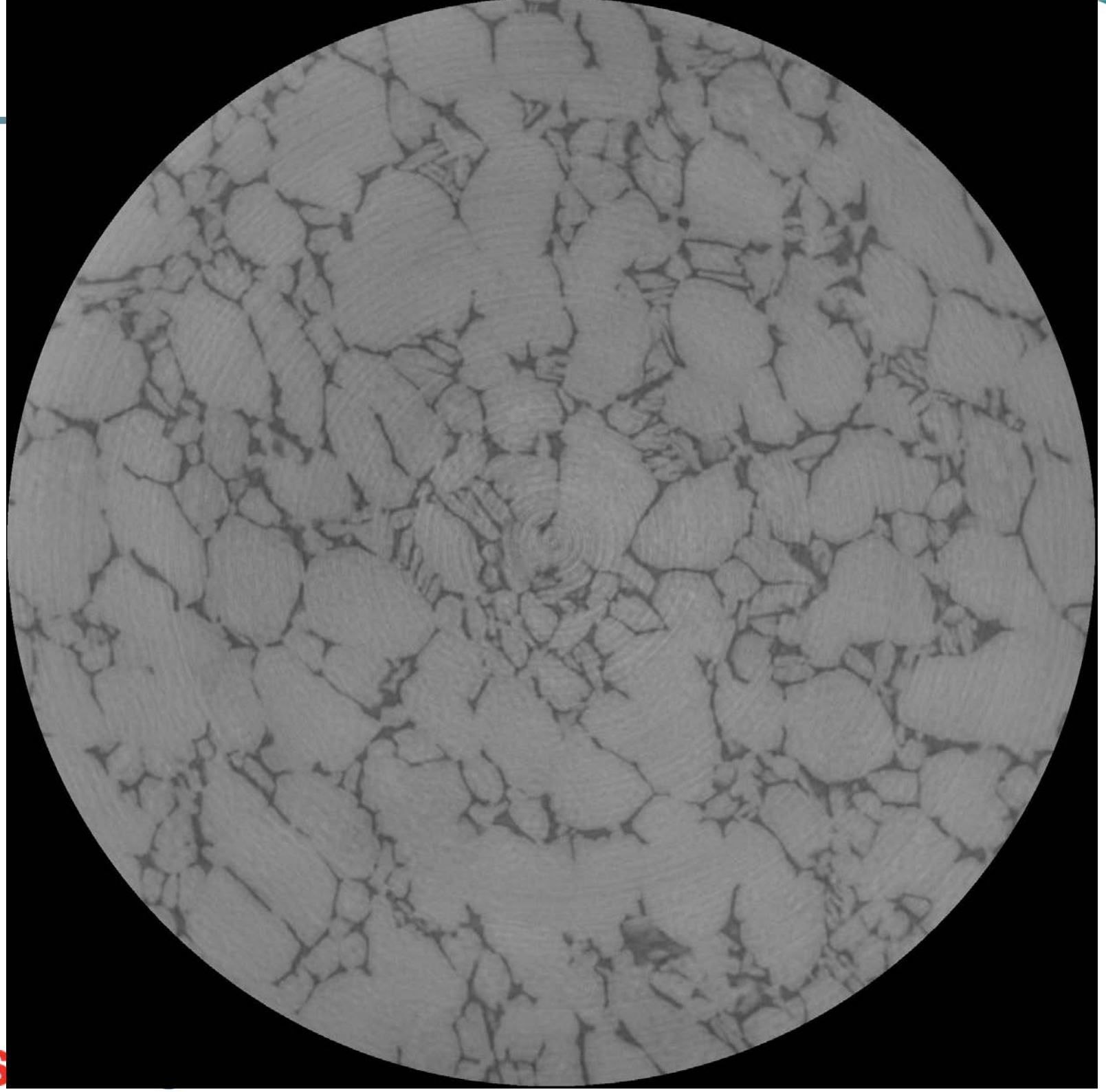
Tracking particles

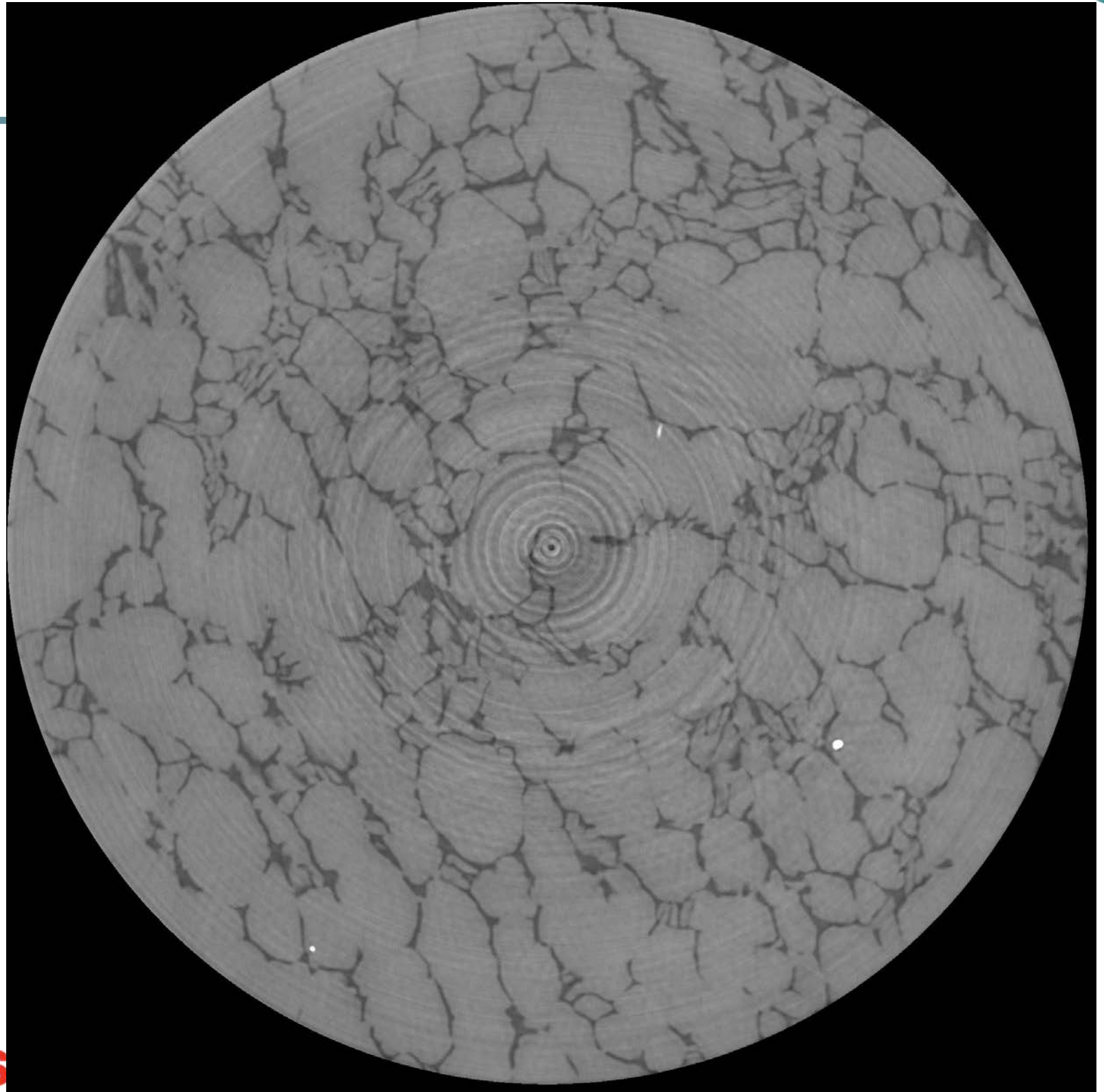


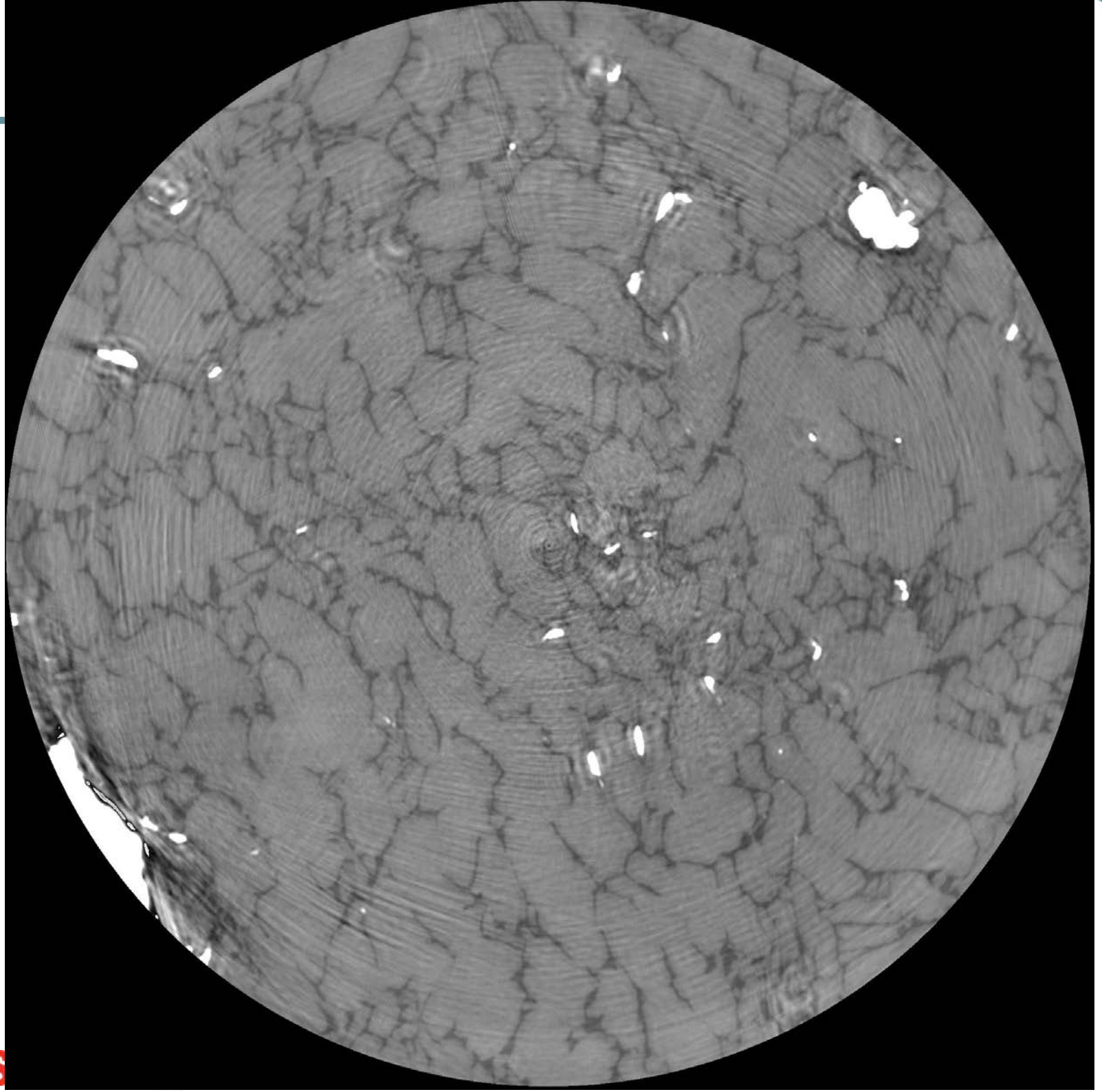
Pores




volume evolution
10
1
0
1
2
3
4
5
strain steps
pores creation-step
5
4
3
2
1
0







Conclusion

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Tomoscopy: Time-Resolved Tomography for Dynamic Processes in Materials

Francisco García-Moreno, Paul Hans Kamm, Tillmann Robert Neu, Felix Bülk, Mike Andreas Noack, Mareike Wegener, Nadine von der Eltz, Christian Matthias Schlepütz, Marco Stampanoni, and John Banhart*