



# Synchrotron X-ray computed microtomography: procedures for image reconstruction and analysis

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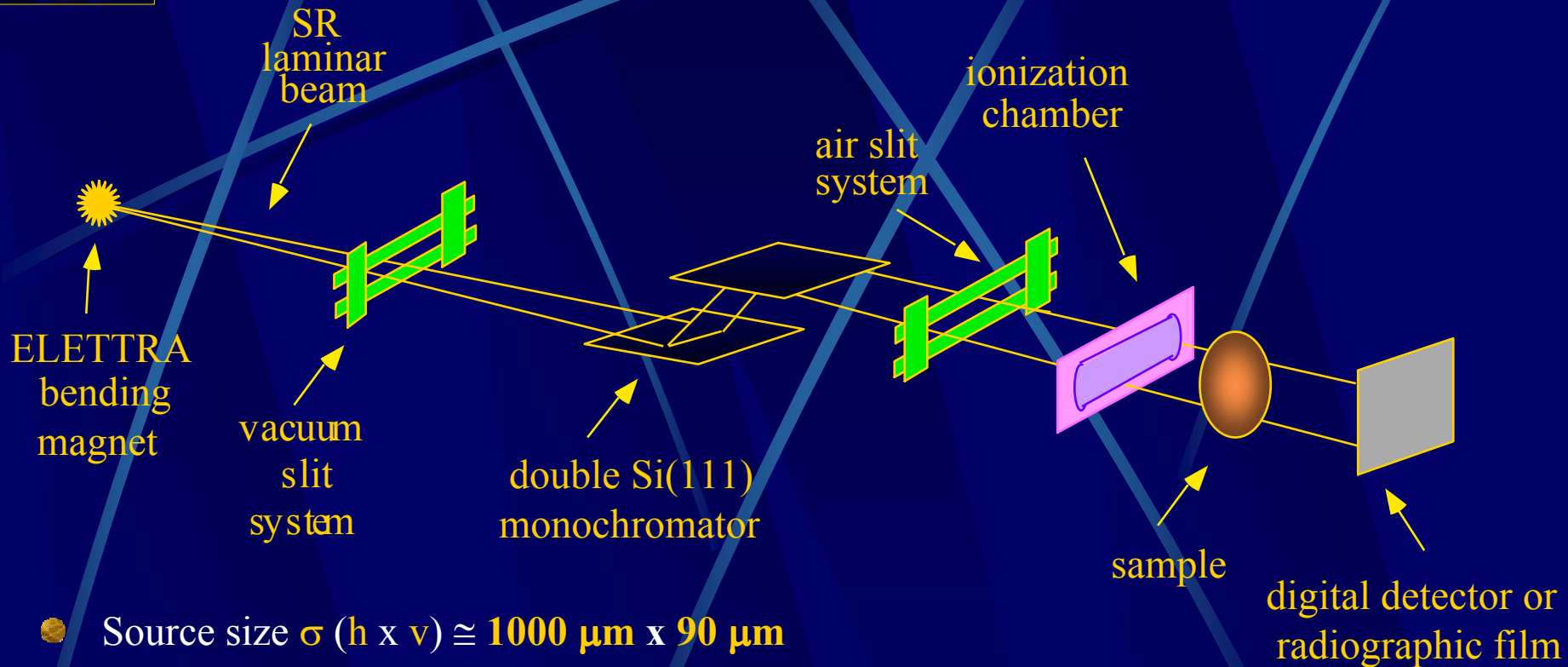
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<sup>3</sup>*University of Trieste*



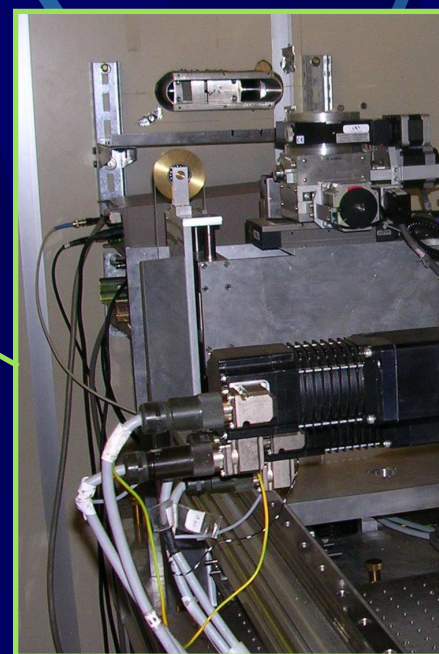
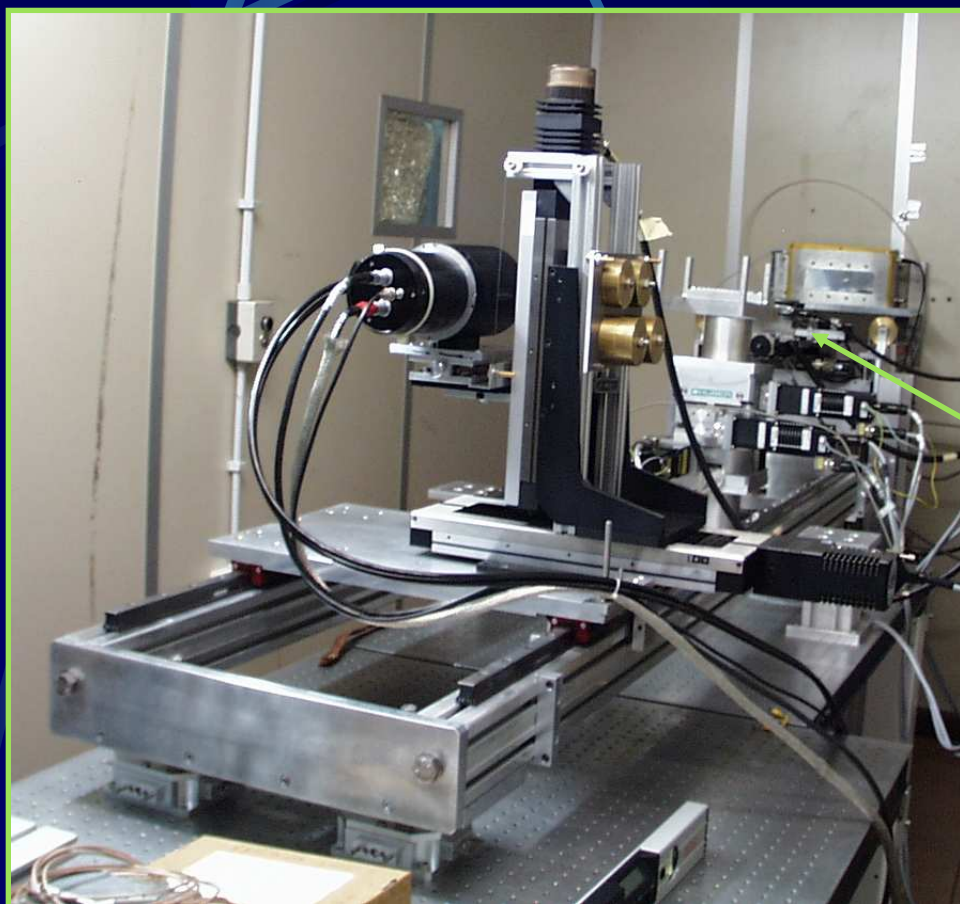
# The SYRMEP beamline



- Source size  $\sigma$  ( $h \times v$ )  $\cong 1000 \mu\text{m} \times 90 \mu\text{m}$
- Source-to-sample distance:  $D \cong 24 \text{ m}$
- Beam size at sample ( $h \times v$ )  $\cong 150 \text{ mm} \times 6 \text{ mm}$
- Energy range:  $8 \div 35 \text{ keV}$ , Bandwidth  $\Delta\lambda/\lambda \cong 2 \times 10^{-3}$
- Typical fluxes at 15 keV  $\cong 2 * 10^8 \text{ phot./mm}^2 \text{ s}$  (@ 2 GeV, 300 mA)  
 $7 * 10^8 \text{ phot./mm}^2 \text{ s}$  (@ 2.4 GeV, 180 mA)



# The experimental hutch at SYRMEP





## X-ray imaging at a 3<sup>rd</sup> generation SR facility

- **high** energy photons and high **flux**
  - **heavy** and/or **bulky samples** in transmission geometry
  - **tunability** in a large energy range
  - **short** exposure times
- small **angular source size** and big **source-to-sample distance**
  - **high spatial resolution** ( $< \approx 1 \mu\text{m}$  at SYRMEP)
  - possibility of **big sample-to-detector distances** ( $< \approx 1 \text{ m}$  at SYRMEP)
  - **high spatial coherence** of the X-ray beam ( $L_c \cong 10 \mu\text{m}$  @ 15 keV)



*Phase-sensitive techniques*





## *SR X-ray imaging studies*

### **Medical imaging:**

- bones, dental implants
- mammography
- tissues ....

### **Material science imaging:**

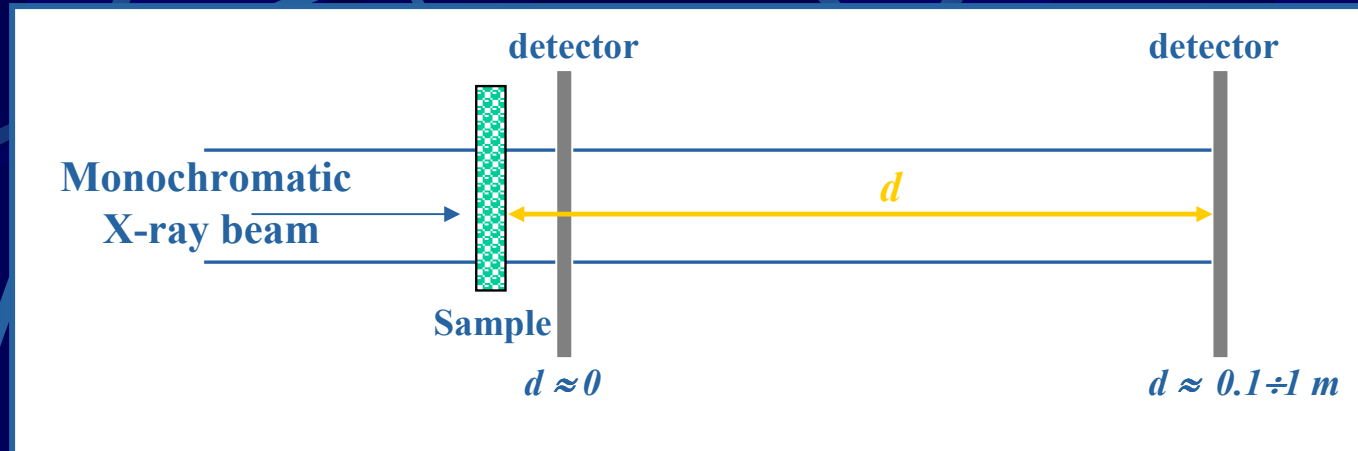
- crystals
- rocks and minerals
- food science
- archeological samples
- engineering science ....



# **The X-ray imaging techniques**



# Absorption and Phase Contrast (PC) Radiography



$$(\Delta I/I)_{\text{abs}} = e^{-c \Delta \mu} - 1$$

$$\Delta \phi = 2\pi c \Delta \delta / \lambda$$

$r \ll a \Rightarrow$  *edge detection regime*

$r \cong a \Rightarrow$  *holographic regime*

$r \gg a \Rightarrow$  *Fraunhofer diffraction*

$\mathbf{n} = 1 - \delta - i\beta$  : refraction index

$\mu = 4\pi \beta / \lambda$  : linear absorption coeff.

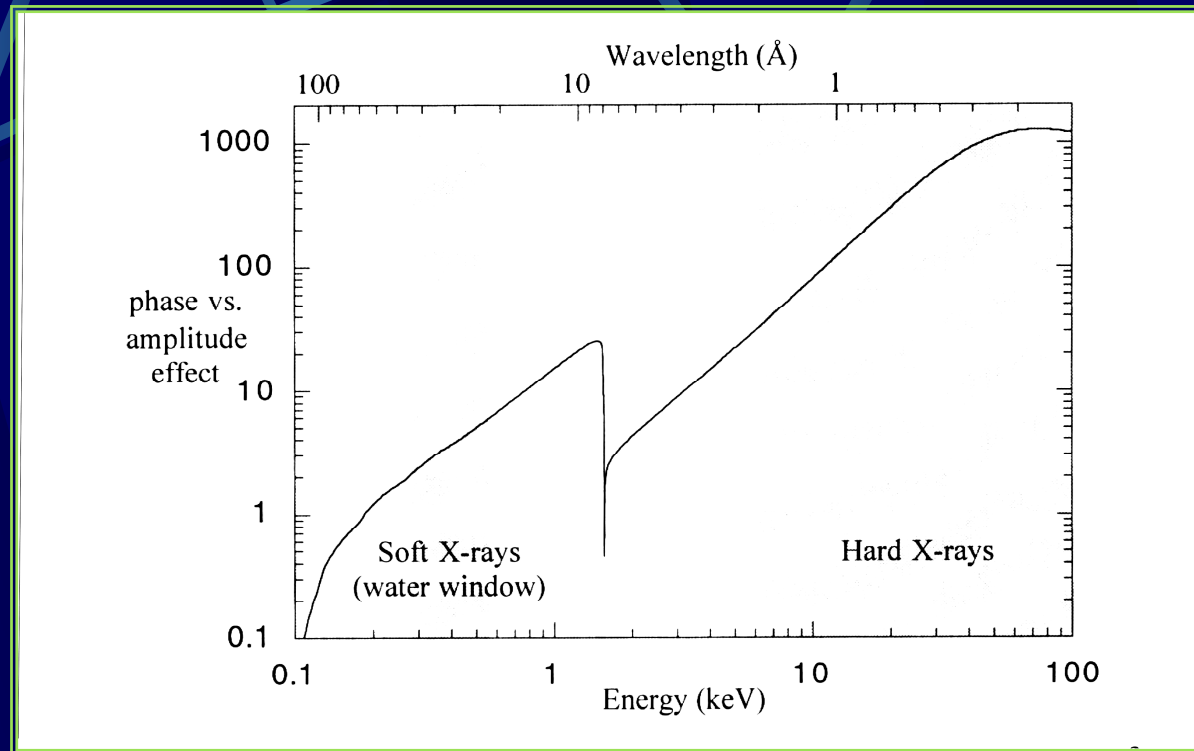
$c$  : object size // to beam direction

$a$  : object size  $\perp$  to beam direction

$r = (\lambda d)^{1/2}$  : first Fresnel zone radius



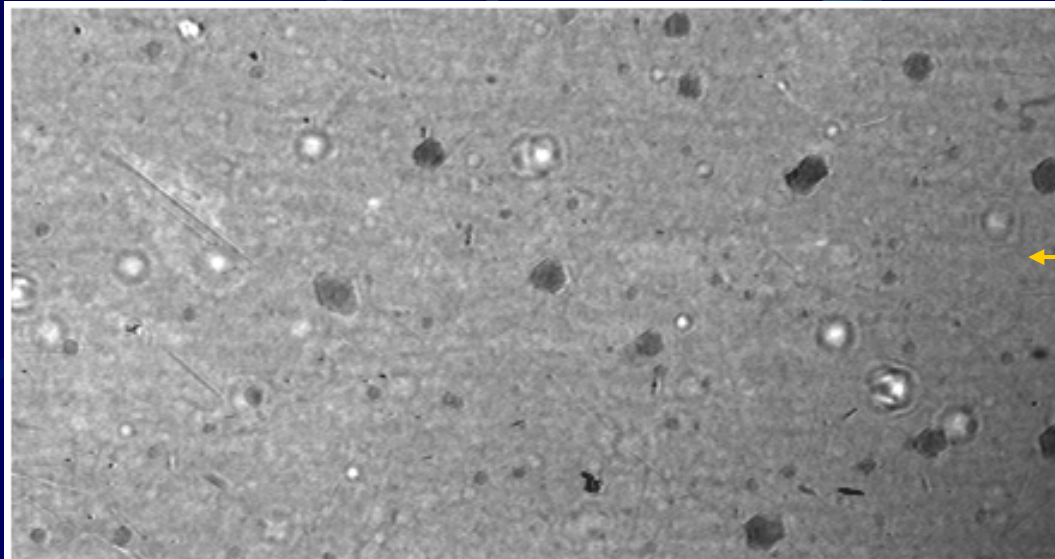
## Absorption vs. Phase Contrast



- Analysis of materials
  - with **weak absorption** with respect to hard X-rays
  - producing **significant variations of X-rays optical path**

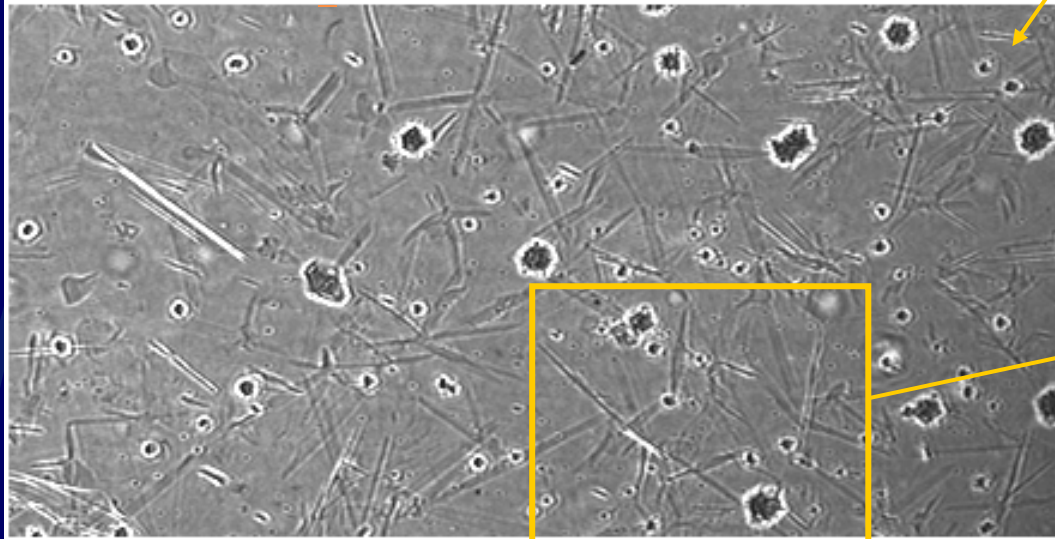


L. Mancini, PhD Thesis, 1998



Absorption radiograph

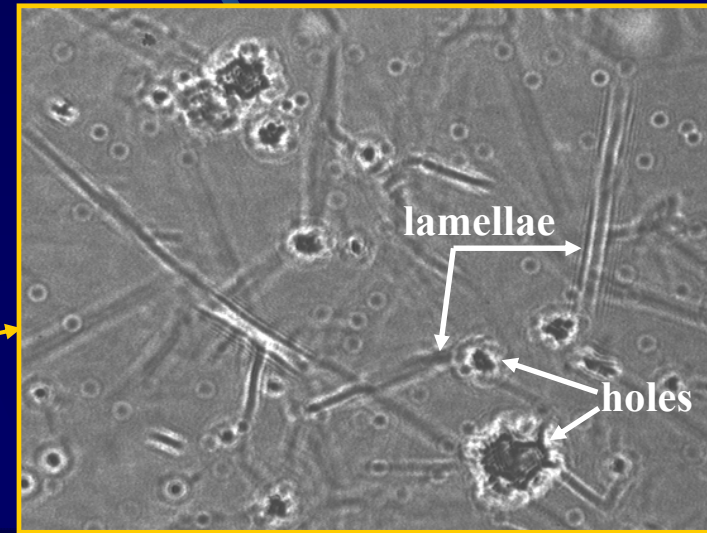
$d = 2 \text{ cm}$



Phase radiograph

$d = 50 \text{ cm}$

400  $\mu\text{m}$



lamellae

holes

200  $\mu\text{m}$



## *Vertical source size $\sigma$ estimation from PCR of a nylon wire*

**Sample:** Nylon wire (120  $\mu\text{m}$   $\emptyset$ )

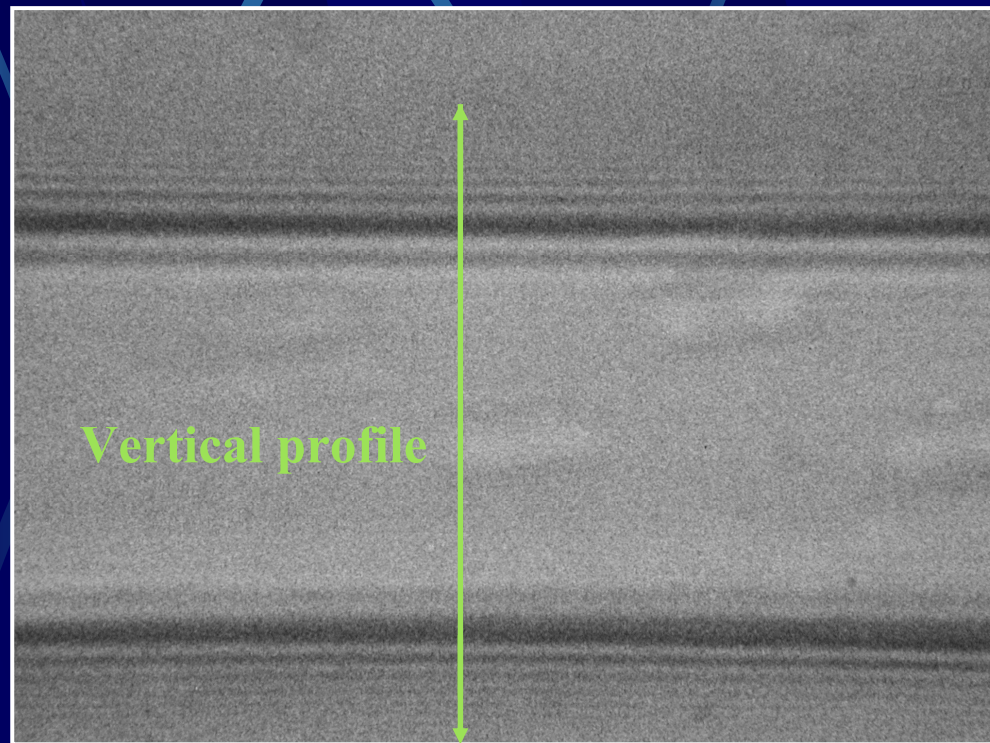
**E = 10 keV**

**Refraction index:**  $\delta = 2.55 \times 10^{-6}$ ,  $\beta = 2.72 \times 10^{-9}$

**d = 1 m**

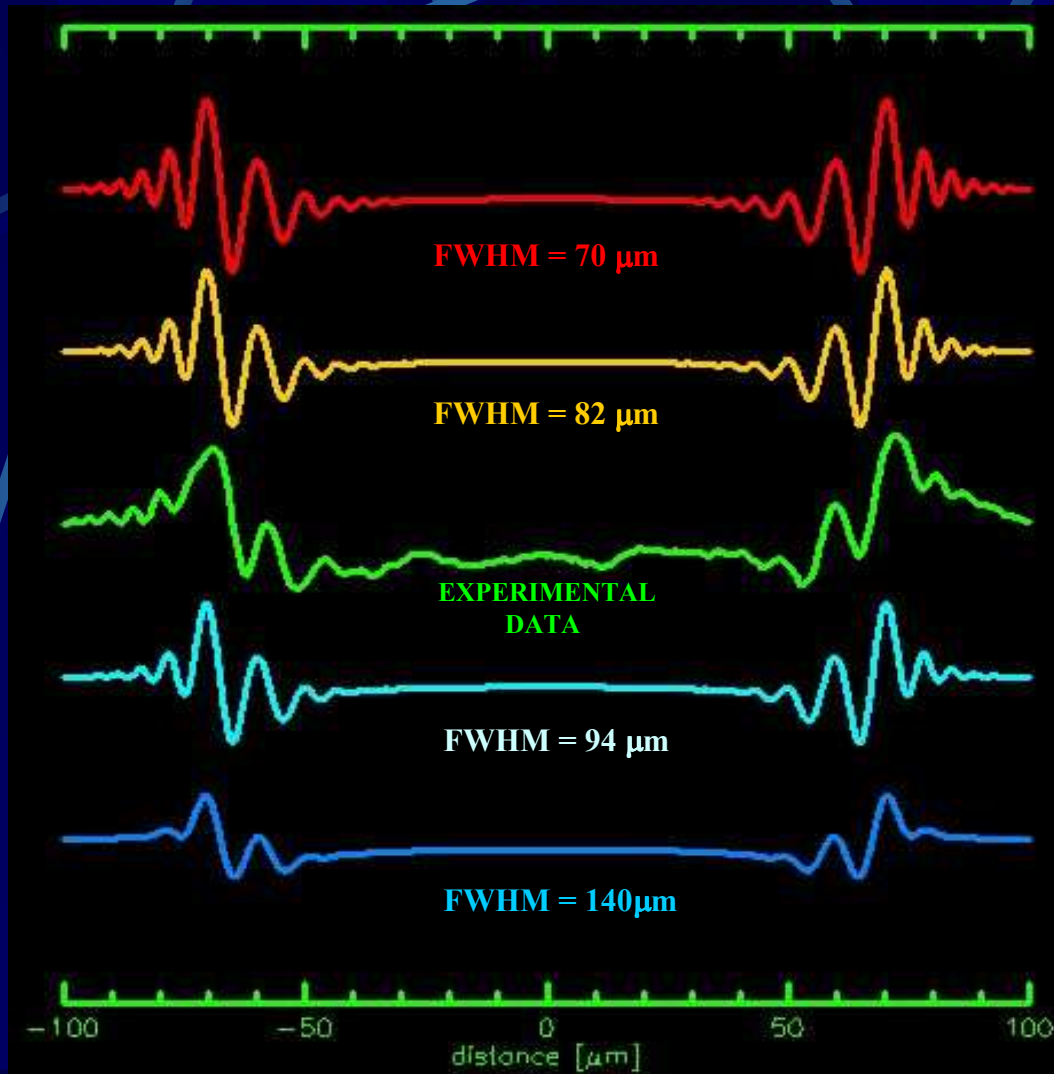
**D = 24 m**

**Detector:** 1  $\mu\text{m}$  resolution film





## Experimental and simulated profiles for different $\sigma$ values



Nylon wire (120  $\mu\text{m}$   $\emptyset$ )  
E = 10 keV  
d = 1 m



$\sigma < \cong 90\text{-}100 \mu\text{m}$





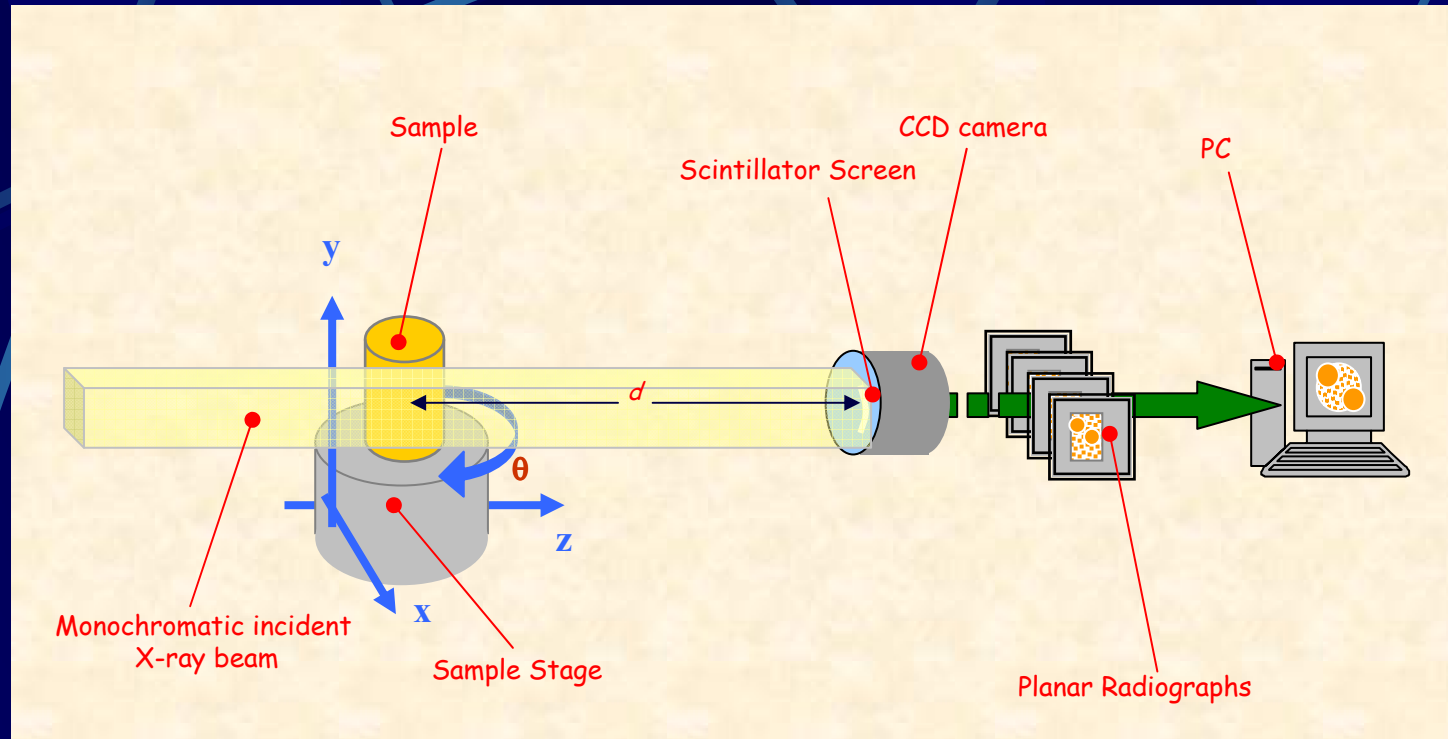
## *Results*

- **Spatial resolution  $\rho = \sigma d / D < \cong 1 \mu\text{m}$  up to  $d = 0.3 \text{ m}$   
 $\cong 4 \mu\text{m}$  at  $d = 1 \text{ m}$**
- Possibility to work at **big sample-to-detector distances:  $D > \approx 1 \text{ m}$**
- **High transverse coherence of the beam:  $L_c = \lambda D / (2 \sigma) \cong 10 \mu\text{m}$**





# The principle of computed microtomography



**CCD camera:** 2048x2048 pixels<sup>2</sup>, pixel size: 14  $\mu\text{m}$ , FOV: 28x28 mm<sup>2</sup>

- Precious for investigation of internal features **without** sample **sectioning**:
  - in many cases the **sectioning procedure** modifies the structures under analysis
  - the sample can be after **studied by other** experimental **techniques**,
  - or submitted to several **treatments** (mechanical, thermal, etc...)



## CCD Detector & Optics



- Photonic science
  - 2048 x 2048 pixel
  - each pixel  $14 \times 14 \mu\text{m}^2$



- 1:1 Optics
  - 20 (40)  $\mu\text{m}$  thick IS
  - effective pixel size: 14  $\mu\text{m}$
  - PSF  $\sim 30$  (50)  $\mu\text{m}$



- 11:40 (Magnifying) Optics
  - $\sim 5 \mu\text{m}$  thick IS
  - effective pixel size: 3.85  $\mu\text{m}$
  - PSF  $\sim 13 \mu\text{m}$



## *SR X-ray imaging*

*In-situ* and *ex-situ* experiments in a large range of materials:

- growth processes
- mechanical and thermal treatments
- phase transitions ....

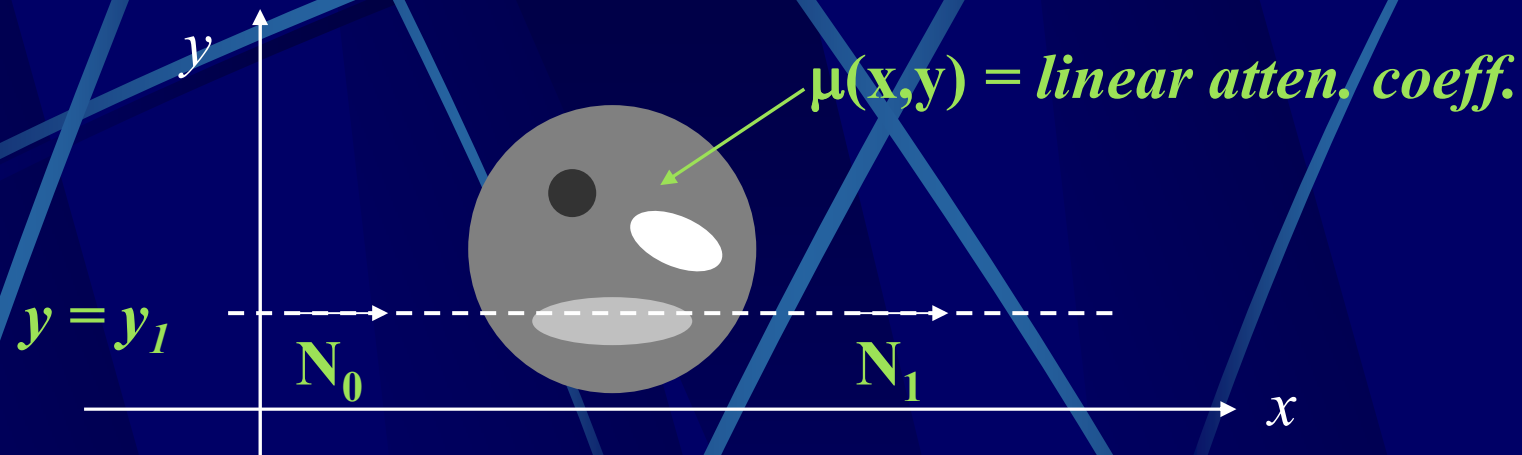
### **The aim**

to investigate the **relationship** between **microstructural**  
and **physical** properties



# Principles of transmission X-ray $\mu$ -CT

Kak A.C., Slaney M., IEEE Press, 1987



$$N_1 = N_0 \exp\left[- \int_{\text{path}} \mu(x, y_1) dx\right] \quad (\text{Beer-Lambert law})$$

$$\ln(N_0 / N_1) = \int_{\text{path}} \mu(x, y_1) dx = \mathbf{P}_{\theta}(\mathbf{t}) \quad ((\theta, \mathbf{t}) \text{ polar coordin.})$$

Repeating such a measurement along a sufficient number of straight lines within the same slice delivers the Radon transform of the object. The inverse of the Radon transform allows to reconstruct the  $\mu(x,y)$  map of the slice.





## *The Fourier Slice Theorem*

*Kak A.C., Slaney M., IEEE Press, 1987*

A line integral  $P_{\theta}(t)$  represents the integral of the  $\mu(x,y)$  of the object along a line.  $P_{\theta}(t)$  is known as the Radon transform of the function  $\mu(x,y)$ .

A projection is formed by combining a set of line integrals. The simplest projection is a collection of parallel ray integrals at a given angle ( $\theta$ ).

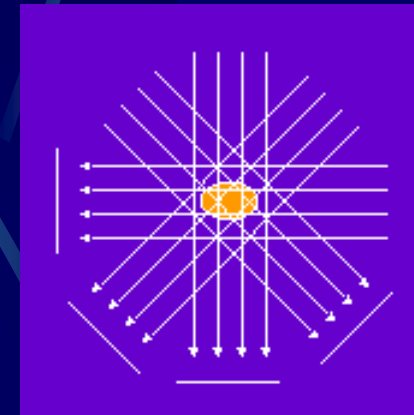
**The Fourier Slice Theorem** demonstrates that the Fourier transform of a parallel projection of an image of  $\mu(x,y)$  taken at an angle  $\theta$  gives a slice of the 2D transform of the object function.

Then, given the projection data, it should be possible to estimate the object by simply performing a 2D inverse Fourier transform.



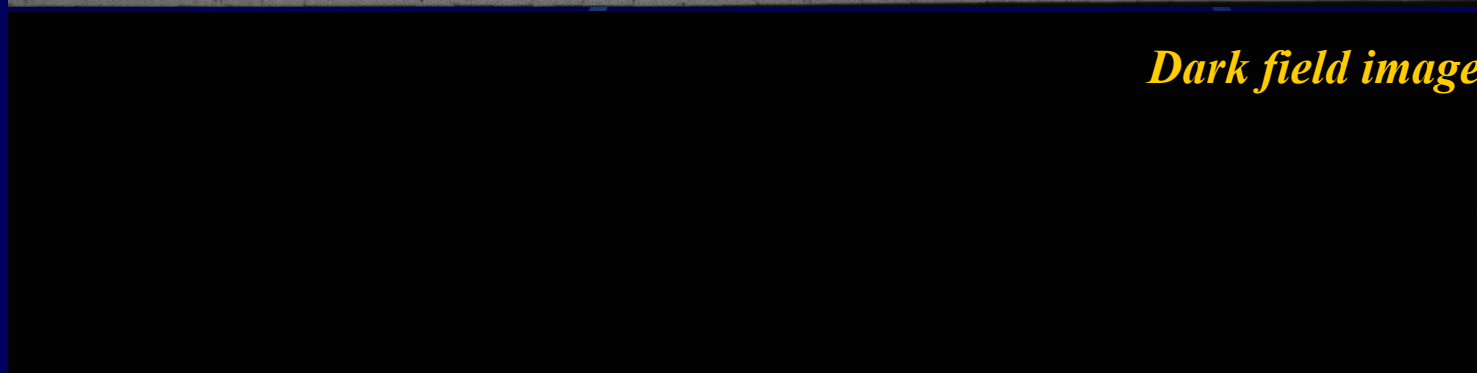
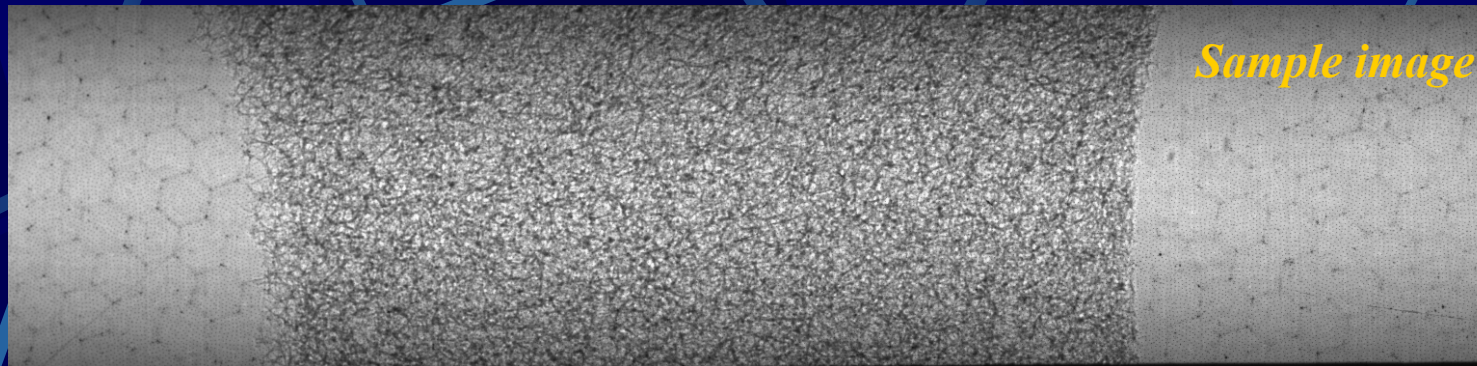
## *Elaboration of tomographic images*

- Planar radiographs are elaborated by a **reconstruction procedure**:
  - **filtered backprojection** algorithm [Herman, 1980]
  - for each projection an **intensity map** is recorded in the xy detector plane
  - projections are submitted to **filtering procedures**
  - each intensity map is **back projected** along the normal to the projection itself
  - finally, the intensities are added for all the projections
- Reconstructed slices are then treated by a **rendering procedure**:
  - 2D slices visualized as **Stack**
  - 3D views of the sample can be obtained (**Volume rendering**)
- Rendered images can be elaborated applying filters, false colors, **segmentation tools** to extract quantitative information.





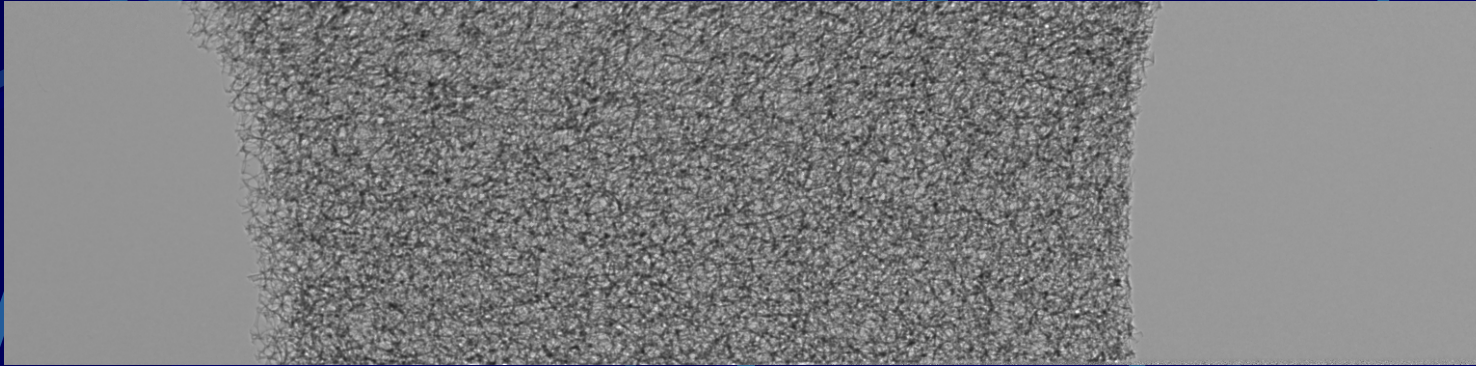
## *Recording of tomographic images*







## *Flat procedure for the tomographic images*



$$I_{flatted} = (I_{sample} - I_{dark}) / (I_{flat} - I_{dark})$$







## Starting of the reconstruction procedure

The screenshot displays the SYRMEP TOMO PROJECT software interface. The main window is titled "SYRMEP TOMO PROJECT" and features a menu bar with "File" open. The menu options include "Open Data Folder", "Open Sinogram", "Open RAW Info", and "Quit Program". Below the menu, there are several input fields: "interp.parameter:" (value: -0.5), "Kernel Width:" (value: 250), "Rem Ring Width:" (value: 3), and "Rem Zinger Width:" (value: 3). A "File" menu is also visible, listing "LOAD COLOR TABLE", "PROFILES SINO", "RECONSTRUCT VOLUM", and "8bit CONVERT".

The "PROJECTION\_BASE" dialog box is open, showing a path field with "c:/". Below the path field, there are input fields for "Image Number:" (value: 0) and "Slice Number:" (value: 0). To the right of these fields are three buttons: "CREATE SINOGRAM", "PROFILES IMA", and "CREATE VOLUME FOLDER".

At the bottom right of the dialog box, there is a "VOLUME RENDERING" section. It contains a field for "--VOLUME FILE--" and three input fields for "X size:", "Y size:", and "Z size:", all with a value of 0. Below these fields are two buttons: "3D RENDERING" and "CREATE MOVIE".



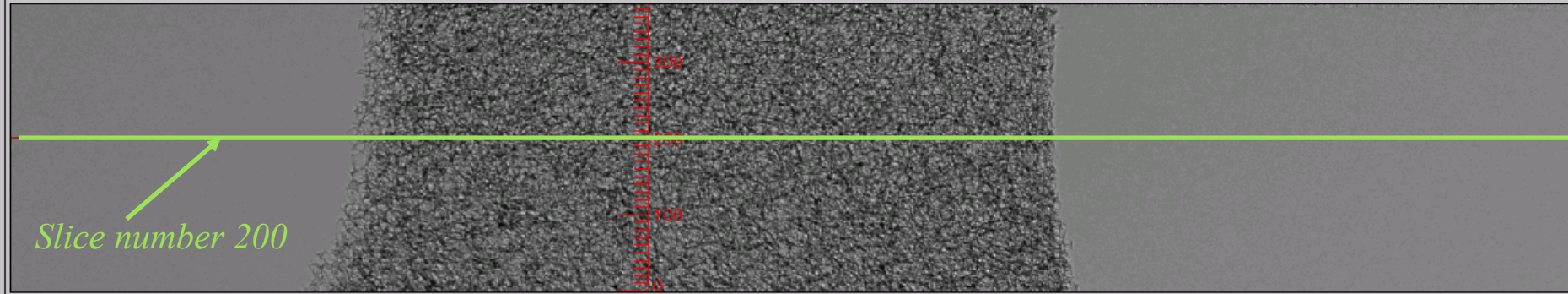
# Choice of the slice to reconstruct



PROJECTION\_BASE

--FRAME BASE--

Image Number:  Slice Number:

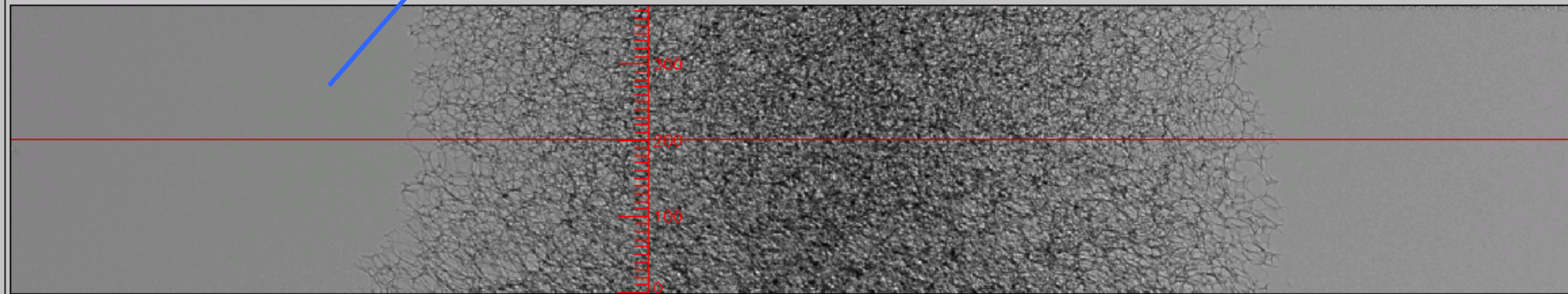


PROJECTION\_BASE

--FRAME BASE--

F:\ATOMO\_RESULTS\PU\_SORRENTINO\PU\_NERO\_DEFOVMISURA TOMO\

Image Number:  Slice Number:







# Creation of the sinogram



**SYRMEP TOMO PROJECT**

File

Filter: SHEPP LOGAN

Interpolation: BILINEAR

Interp. parameter: -0.5

Kernel Width: 250

Rem Ring Width: 3

Rem Zinger Width: 3

LOAD COLOR TABLE

PROFILES SINO

RECONSTRUCT VOLUME

8bit CONVERT

---SINOGRAM BASE---

Sinogram from Slice: 200 F:\TOMO\_RESULTS\PU\_SORRENTINO\PU\_NERO\_DEF0\MISURA TC

Crop Left-Right: 300 1800

Normalization Widths: 200 1900

RECONSTRUCT SLICE



## Filtering procedure

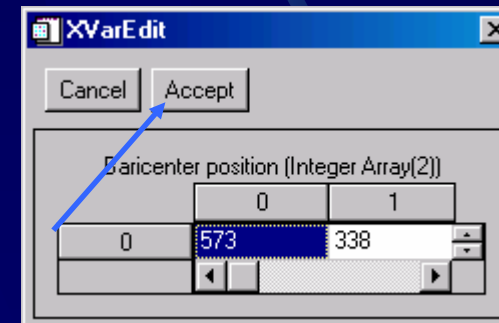
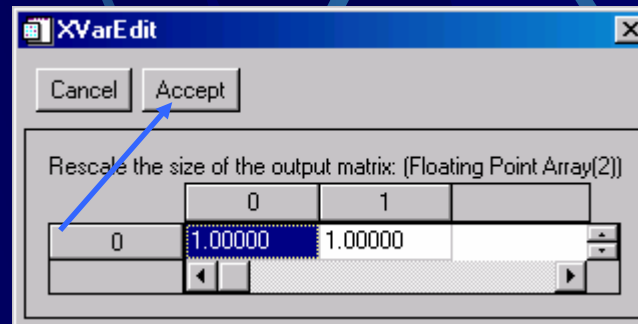
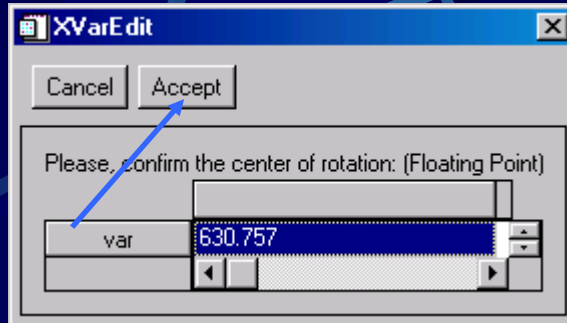
The screenshot displays the SYRMEP TOMO PROJECT software interface. The top window shows the 'Filter' dropdown set to 'SHEPP LOGAN' and the 'Interpolation' dropdown set to 'BILINEAR'. The 'Sinogram from Slice' is set to '200' and the file path is 'F:\TOMO\_RESULTS\PU\_SORRENTINO\PU\_NERO\_DEF0\MISURA TC'. The 'Crop Left-Right' is set to '300' and '1800', and 'Normalization Widths' are '200' and '1900'. A 'RECONSTRUCT SLICE' button is visible. The bottom window shows the 'Filter' dropdown set to 'GEN\_HAMMING' with a dropdown menu open showing options: 'GEN\_HAMMING', 'RAMLAK', 'SHEPP LOGAN', 'COSINE', and 'NONE'. The 'Sinogram from Slice' is '200', 'Crop Left-Right' is '300' and '1800', and 'Normalization Widths' are '200' and '1900'. A 'RECONSTRUCT VOLUME' button is visible. The main plot area shows a sinogram with a vertical axis labeled '200', '400', and '600', and a horizontal axis with '1000' and '1500' marked. The plot shows a dense, noisy pattern of lines.

If in the reconstruction the backprojection is done without filtering the sinogram first, the resulting image is very blurry. In practice **one always filters the sinogram before the backprojection**. In this example the sinogram will be filtered using a **Shepp-Logan filter**, which is an edge-sharpening filter.



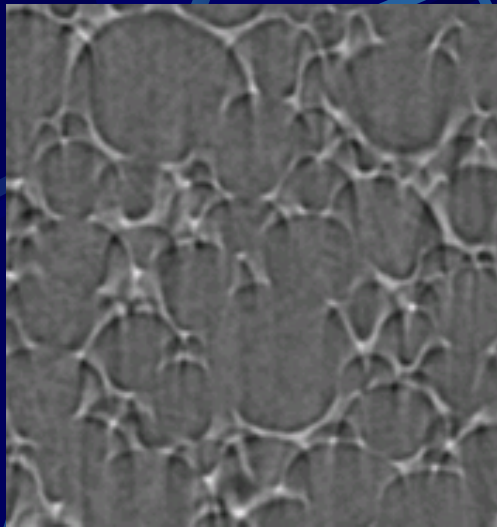


## Choice of the reconstruction parameters

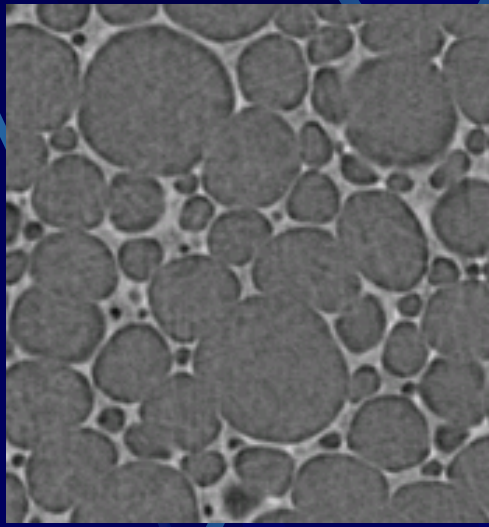




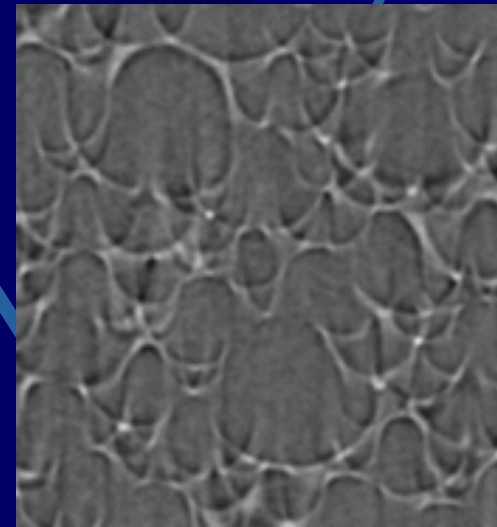
## *Slice reconstruction: optimization of the rotation center*



$C = 624.750$



$C = 630.750$



$C = 638.750$

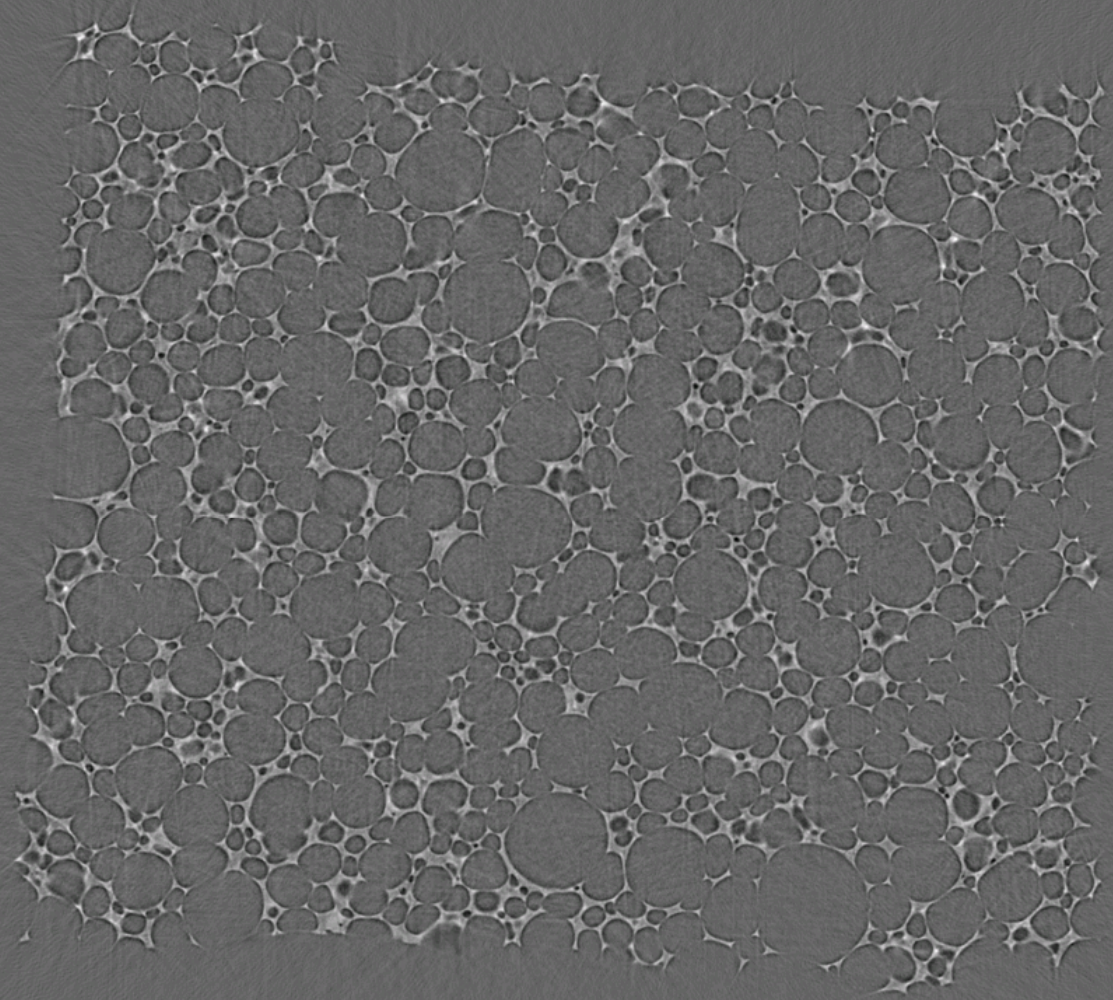
A poor centering causes **arc artifacts**. An automated centering procedure gives a sinogram which is better centered on the rotation axis by determining the center-of-gravity of each row in the sinogram, and fitting this center-of-gravity array to a sin wave. The symmetry axis of the fitted sin wave is the rotation axis. The sinogram is then shifted left or right so that the rotation axis is exactly on the center column of the sinogram array.





SLICE\_BASE  
Save

# *Slice reconstruction: good rotation center*

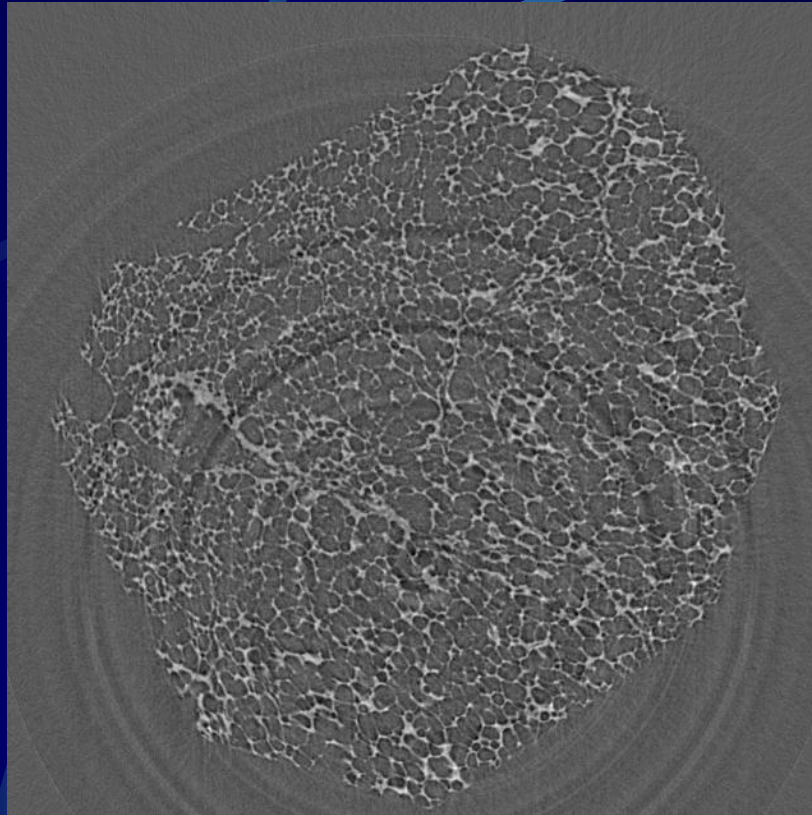


Created: Tue Jun 10 09:33:07 2003  
Directory: F:\TOMO\_RESULTS\PU\_SORRENTINO\PU  
Row Number: 200  
Center of Rotation: 630.757  
Interpolation: bilinear  
Rem\_Zinger Width: 3  
Rem\_Ring Width: 3  
Kernel Width: 250  
Filter: SHEPP\_LOGAN

*No more artifacts visible on this image*



## *Ring artifacts reduction*



The ring artifacts are due to drifts or non-linearities in the detector response.

A bad detector element will show up as a vertical stripe in the sinogram.

Two vertical lines in the sinogram would appear as a thin cylinder centered on the rotation axis in the real object.

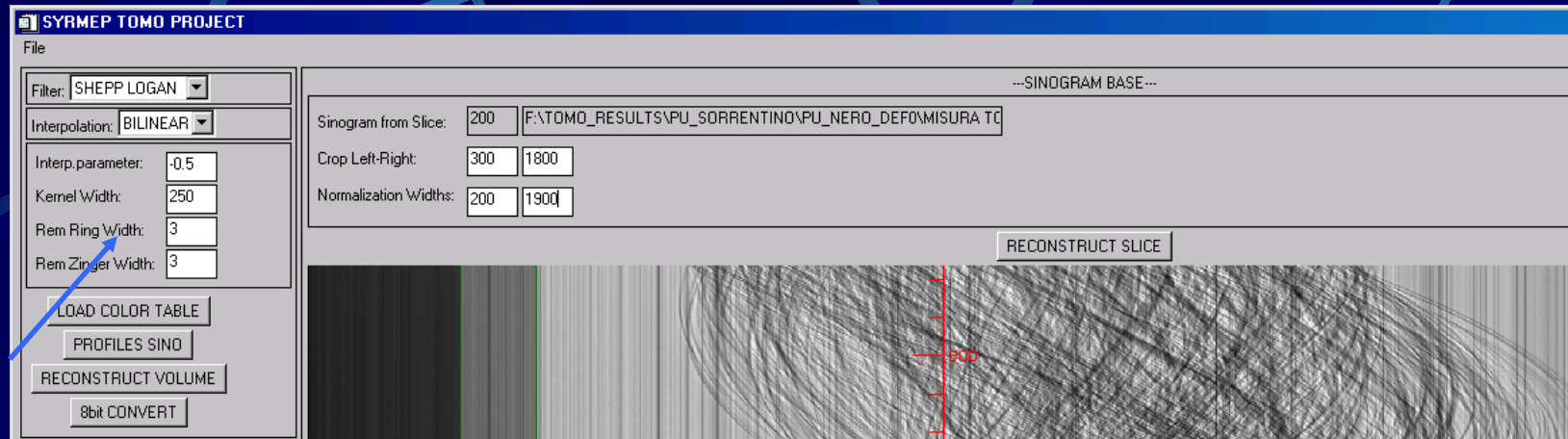
The causes of these vertical stripes in the sinogram can include the following:

- Drifts in the detector element sensitivity in between white-field calibrations
- Non-linear detector element response
- Higher energy harmonics in the incident beam





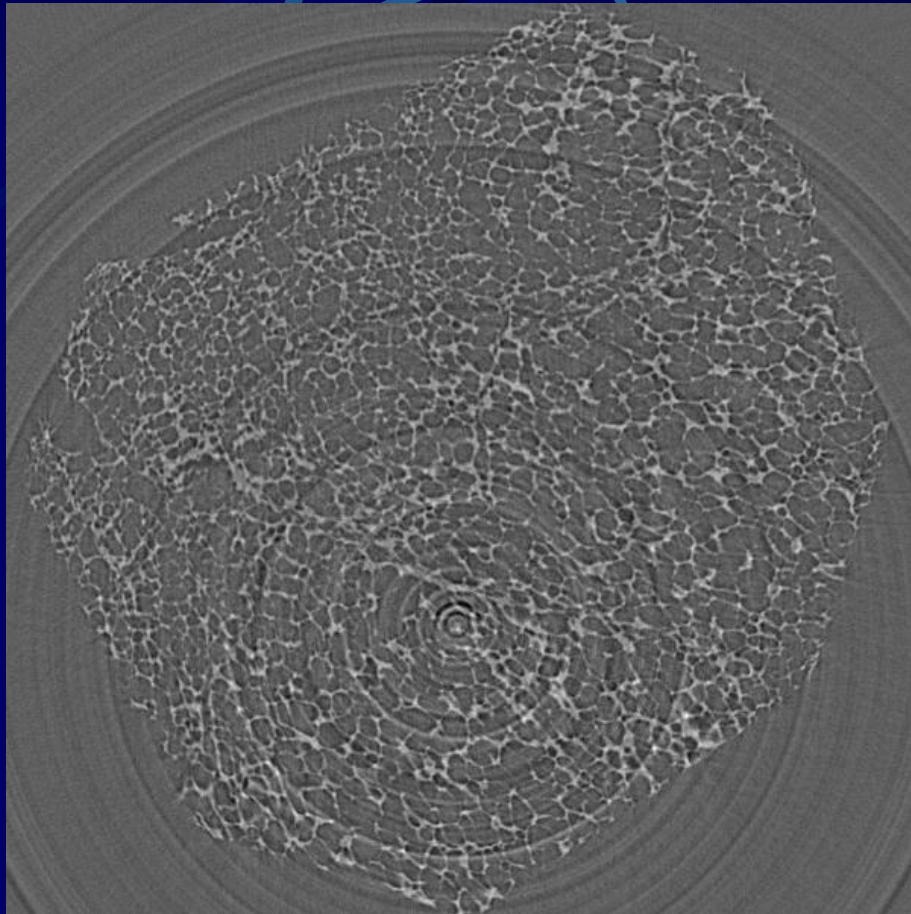
## How to reduce the ring artifacts?



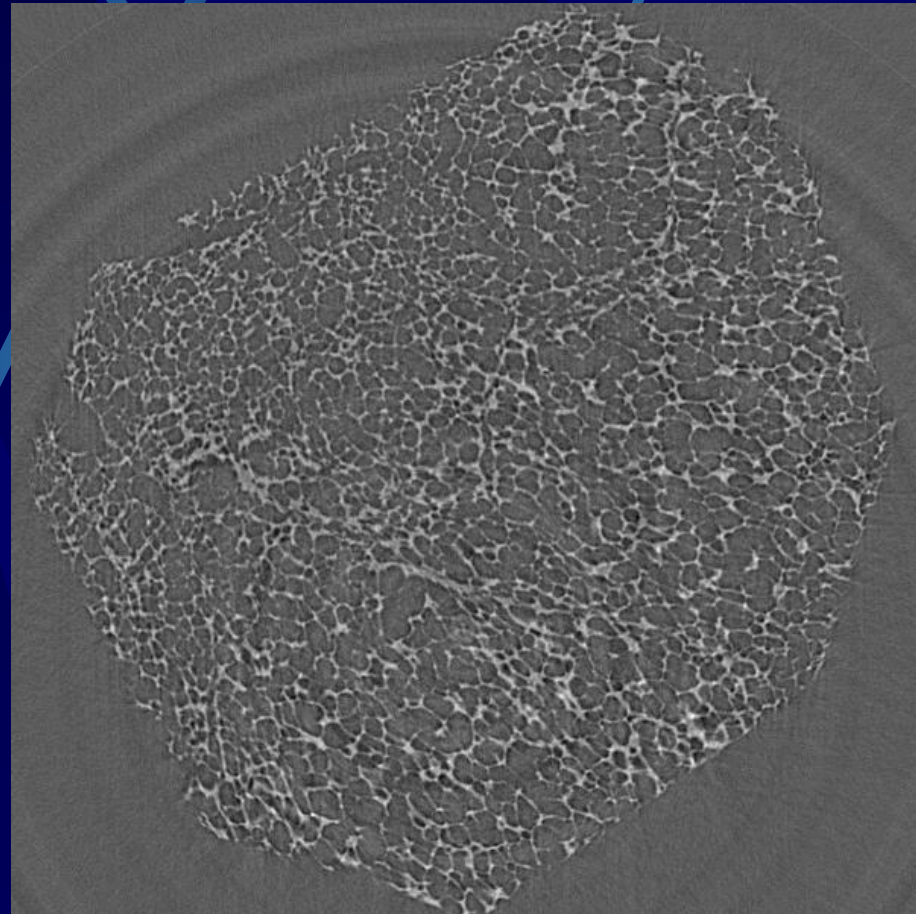
- Compute the **average row of the sinogram** by summing down each column and dividing by the number of rows. This **average row** should have very little high-frequency content, since real objects will be moving in the sinogram, and will be blurred out when computing the average row.
- Compute the magnitude of these detector anomalies **by subtracting a smoothed version of the average row** from the average row.
- **Subtract the result** of previous step, the detector anomalies, **from each row in the sinogram**. This results in a sinogram with much less vertical striping.



## *Result of the ring artifacts reduction*



**Before**



**After**



## *Zinger removal*

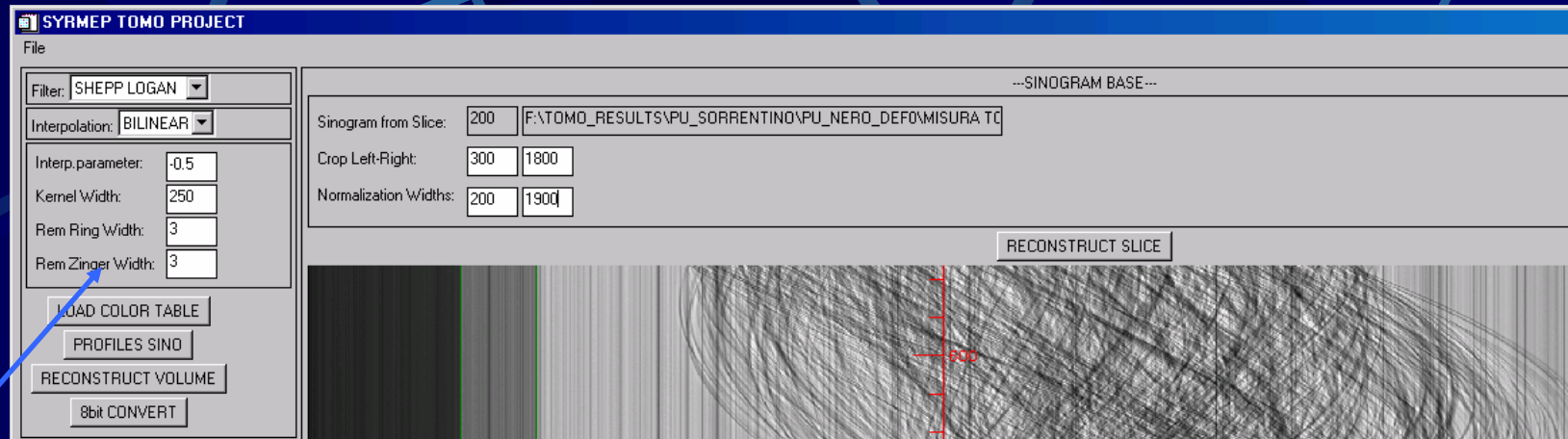
A close look to the reconstructed slice can also reveal perfectly straight, bright lines at random orientations in the image. These bright lines, which look like scratches, are due to **zingers**, or anomalously bright pixels, in the raw images. These zingers are caused by cosmic rays or scattered X-rays hitting the CCD chip directly, causing large energy deposition relative to the visible light photons from the scintillator crystal.

**Eliminating these zingers** is best done when the raw data and white field images are first read in.





## How to remove zingers?



- Smooth the raw image with a low-pass filter
- Subtract the raw image from the smoothed image
- Divide the difference image from step 2 by the smoothed image to produce an image of anomalous pixels on a relative scale
- Any pixels in the image from step 3 which are greater than a threshold value (typically 1.2) are defined to be zingers. The intensity of zinger pixel at location  $N$  is replaced by the average intensity of the pixels at location  $N-2$  and  $N+2$ . Pixels  $N-1$  and  $N+1$  are not used because some zingers affect 2 adjacent pixels.





# Volume reconstruction



PROJECTION\_BASE

--FRAME BASE--

F:\TOMO\_RESULTS\PU\_SORRENTINO\PU\_NERO\_DEF0\MISURA TOMO\

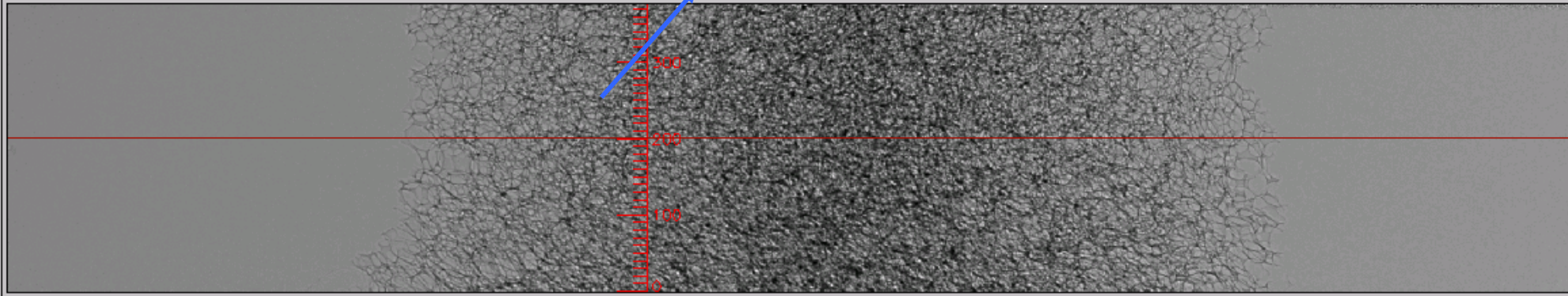
Image Number: 200

Slice Number: 200

CREATE SINOGRAM

PROFILES IMA

CREATE VOLUME FOLDER



**XVarEdit**

Cancel Accept

Vertical Volume Limits: (Floating Point Array(2))

	0	1
0	0.000000	99.0000

**dir con sinogrammi:**

Current:  
c:\rsi\idl55

Directories:

- c:\
- RSI
- IDL55
- bin
- Diego\_temp
- docs
- examples
- external

Drives:  
c:

OK Cancel



**SYRMEP TOMO PROJECT**

File

Filter: SHEPP LOGAN

Interpolation: BILINEAR

Interp.parameter: -0.5

Kernel Width: 250

Rem Ring Width: 3

Rem Zinger Width: 3

LOAD COLOR TABLE

PROFILES SINO

RECONSTRUCT VOLUME

8bit CONVERT

---SINOGRAM BASE---

Sinogram from Slice: 200 F:\TOMO\_RESULTS\PU\_SORRENTINO\PU\_NERO\_DEF\MISURA TC

Crop Left-Right: 300 1800

Normalization Widths: 200 1900

RECONSTRUCT SLICE

**XVarEdit**

Cancel Accept

Slices to be reconstructed: (Floating Point Array(2))

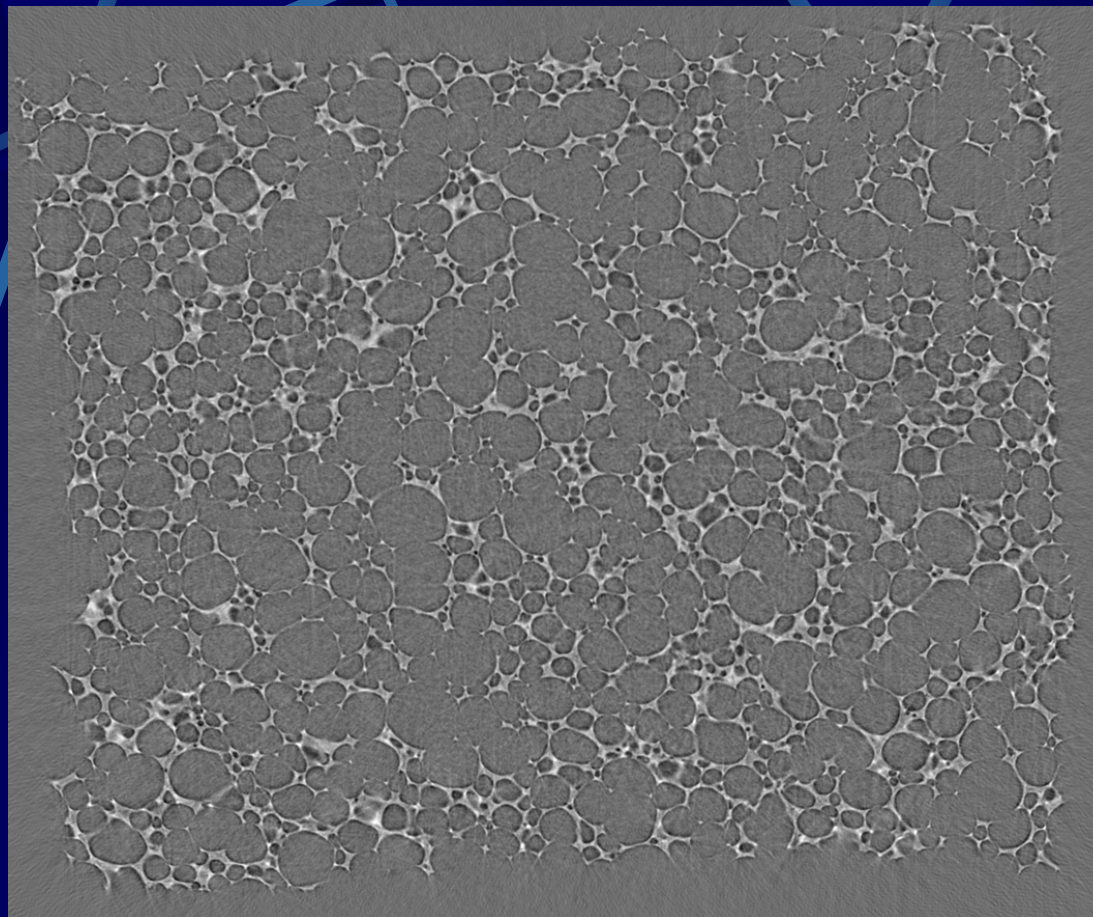
	0	1	
0	0.000000	99.000000	

Navigation buttons: left arrow, right arrow





## *Data visualization: stack of 2D images*



$E = 12 \text{ keV}$   
 $d = 32.5 \text{ cm}$

1 mm

*Reconstructed stack of 100 slices*



# 8bit .raw volume creation



**SYRMEP TOMO PROJECT**

File

Filter: SHEPP LOGAN

Interpolation: BILINEAR

Interp. parameter: -0.5

Kernel Width: 250

Rem Ring Width: 3

Rem Zinger Width: 3

LOAD COLOR TABLE

PROFILES SINO

RECONSTRUCT VOLUME

8bit CONVERT

---SINOGRAM BASE---

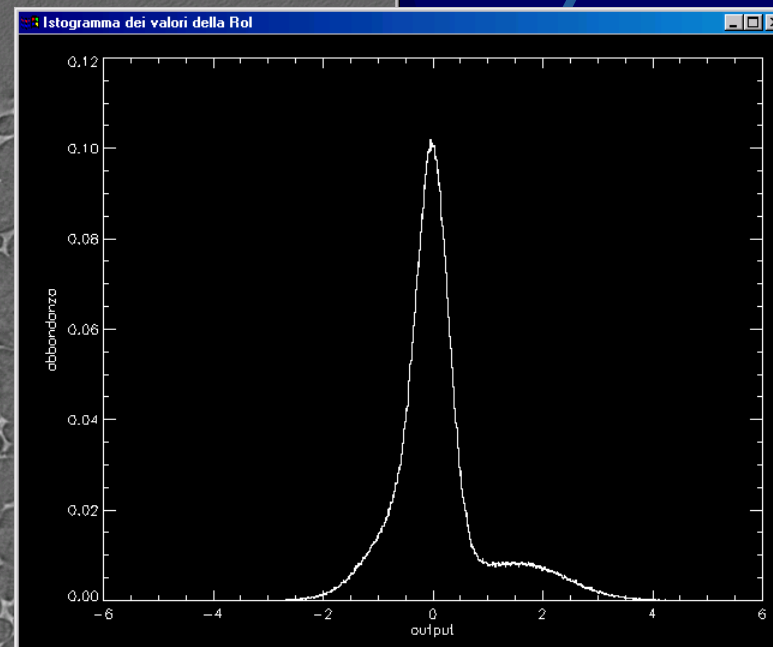
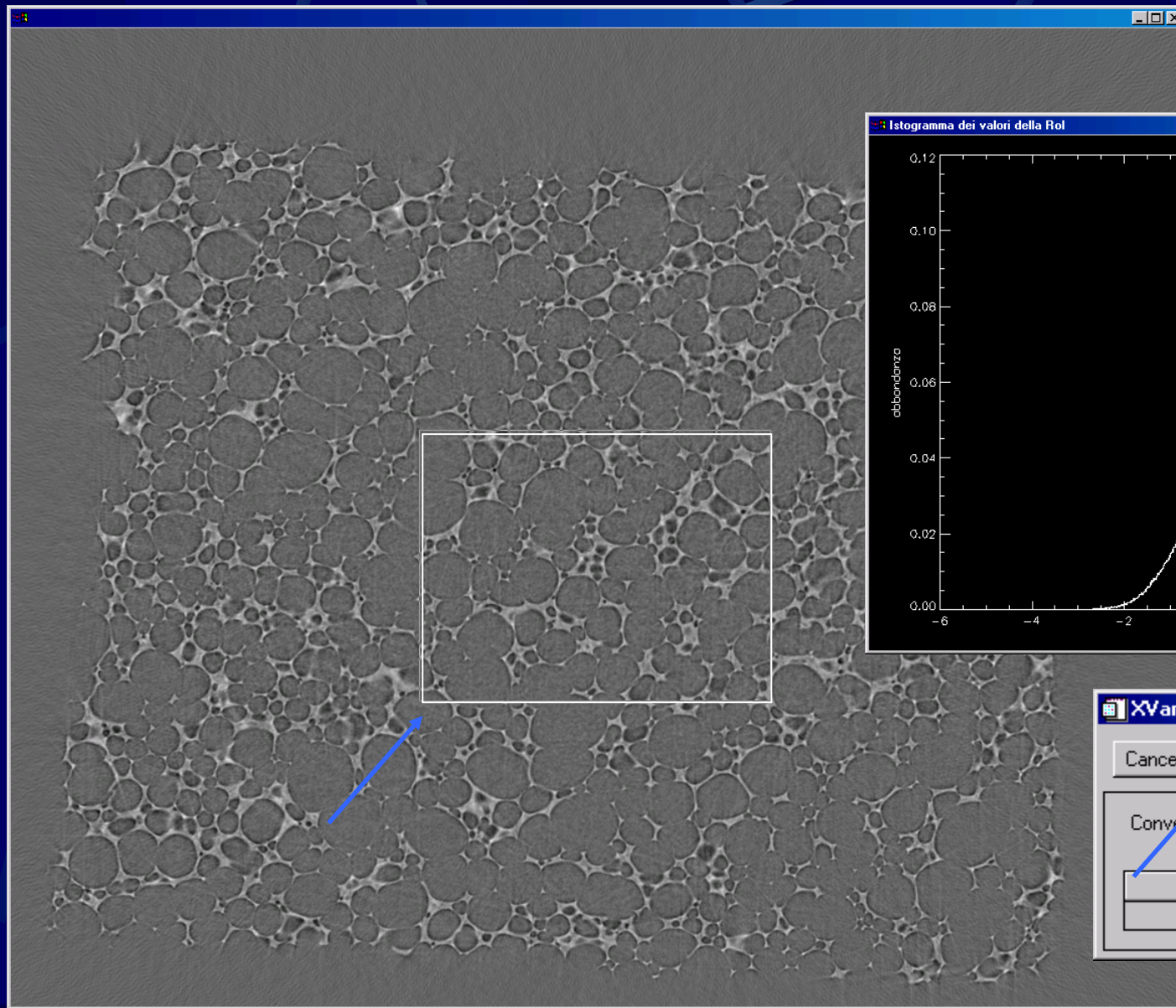
Sinogram from Slice: 200 F:\TOMO\_RESULTS\PU\_SORRENTINO\PU\_NERO\_DEF\MISURA TC

Crop Left-Right: 300 1800

Normalization Widths: 200 1900

RECONSTRUCT SLICE





XVarEdit

Cancel Accept

Conversion interval: (Floating Point Array(2))

	0	1
0	-4.19280	5.71597



# Data visualization: volume rendering



**SYRMEP TOMO PROJECT**

File

- Open Data Folder
- Open Sinogram
- Open RAW Info**

Interp.parameter:

Kernel Width:

Rem Ring Width:

Rem Zinger Width:

LOAD COLOR TABLE

PROFILES SIND

RECONSTRUCT VOLUME

8bit CONVERT

---SINOGRAM BASE---

Sinogram from Slice:

Crop Left-Right:

Normalization Widths:

RECONSTRUCT SLICE



# Volume rendering procedure

volume.raw\_info - Notepad

```
File Edit Format View Help
|Thu May 18 04:55:08 2006
Created from: H:\Bettuzzi_D\H36_nt_LR\slices\slice_0002.tif
to: H:\Bettuzzi_D\H36_nt_LR\slices\slice_0009.tif
x cut: 0.000000 469 Dx: 470
y cut: 0.000000 402 Dy: 403
n slices: 8
Range: -0.772907 4.46046
```

**VOLUME RENDERING**

---VOLUME FILE---

X size: Y size: Z size:

0 0 0

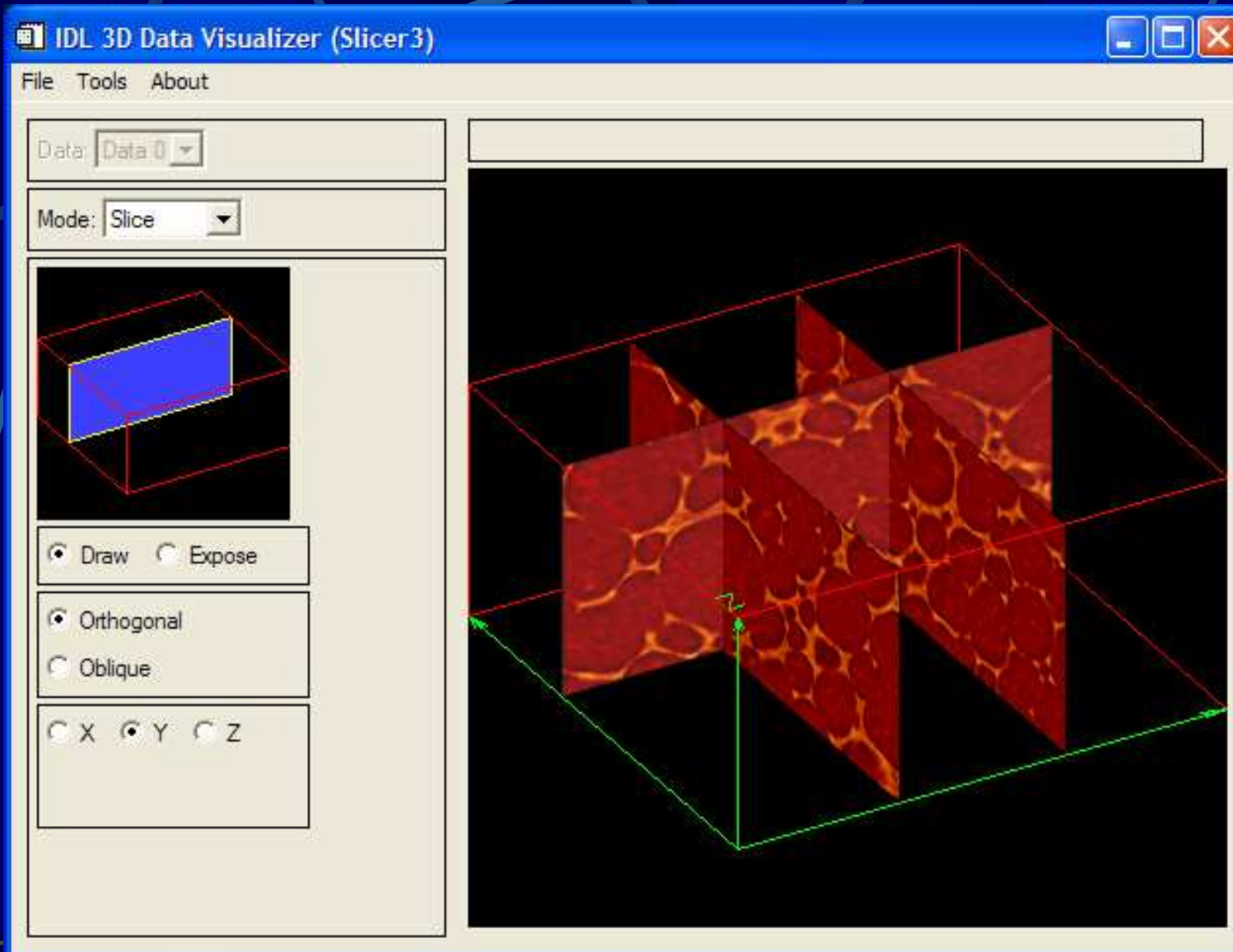
3D RENDERING

CREATE MOVIE



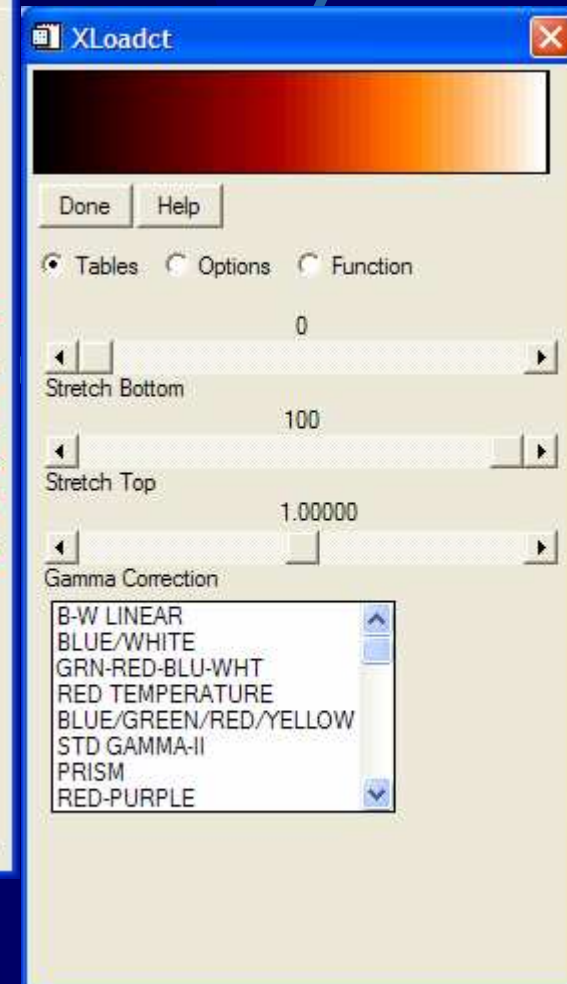
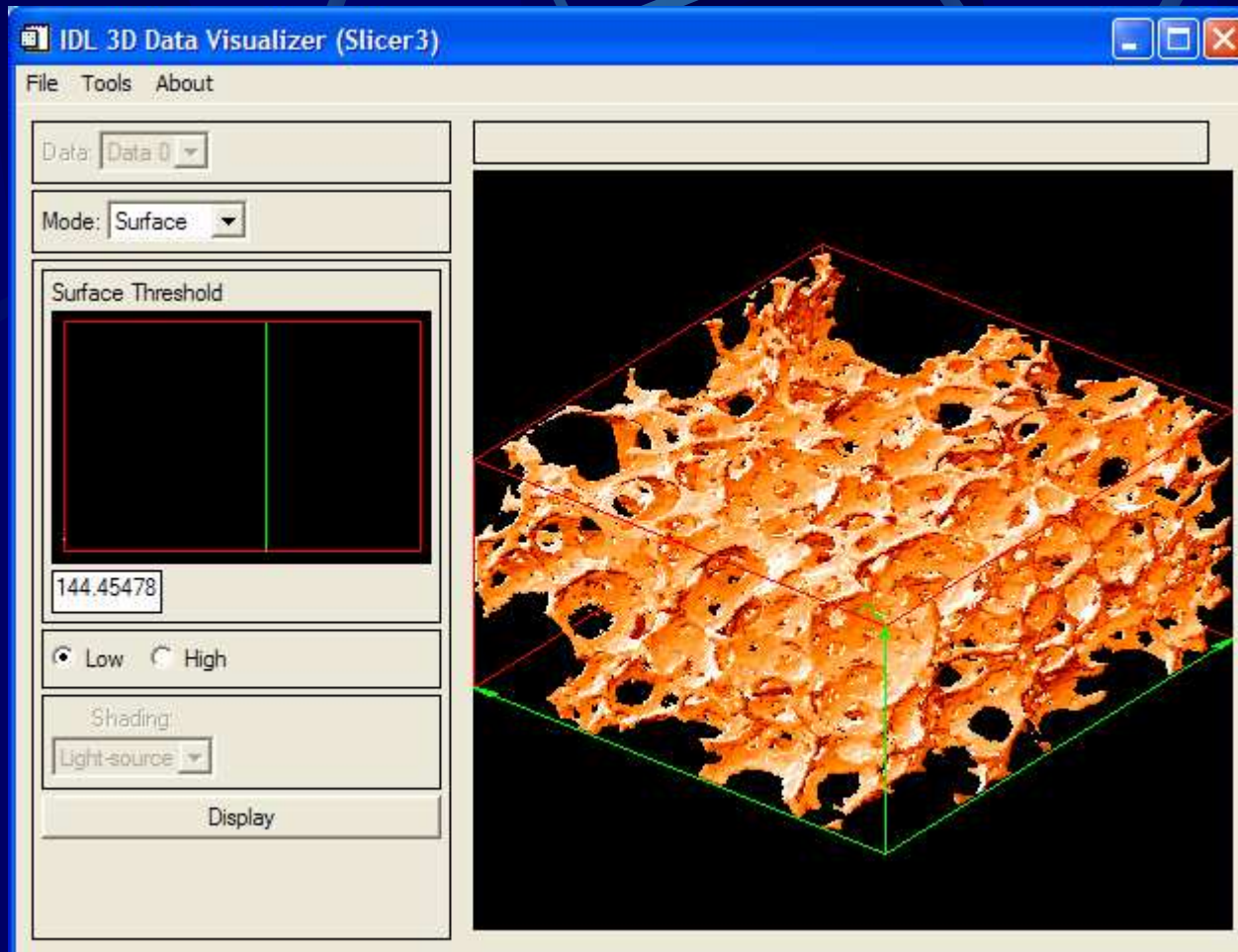


# Slice visualizer





# Isosurface rendering





*Volume rendering*  
Virtual cut of the sample  
(3.2 x 3.0 x 1.4) mm<sup>3</sup>

