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

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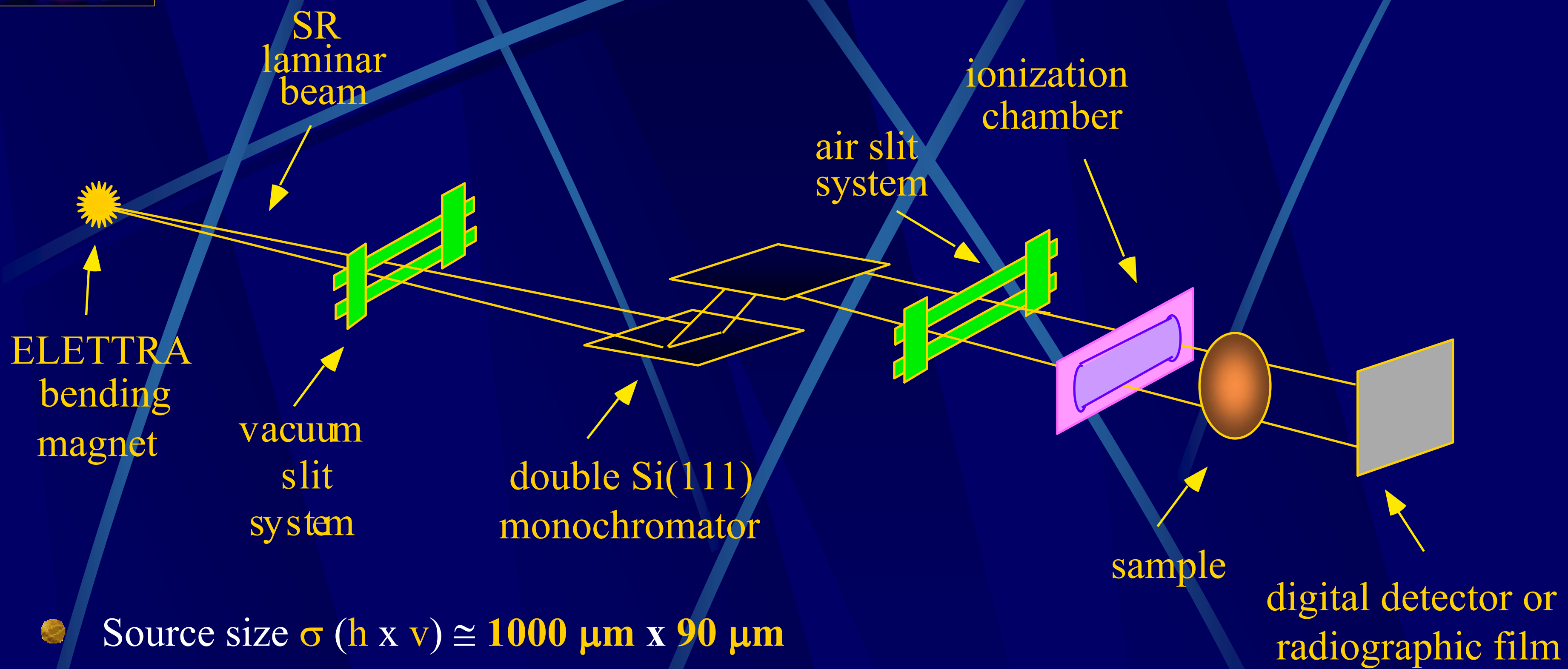
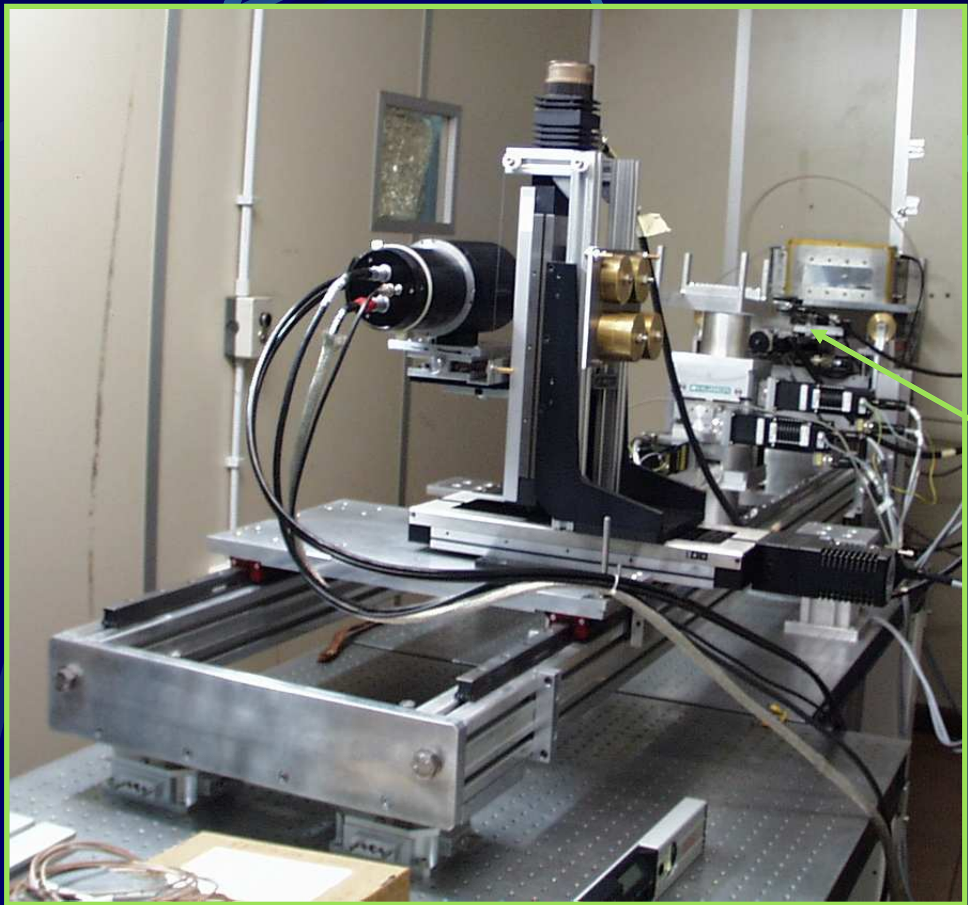
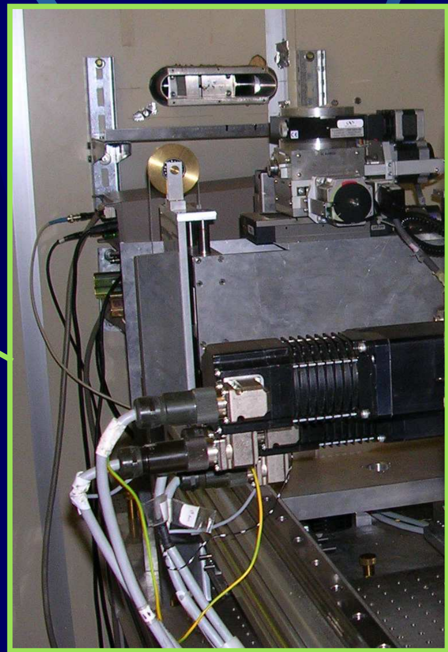
The SYRMEP beamline



- Source size σ (h x v) ≅ **1000 μm x 90 μm**
- Source-to-sample distance: **D ≅ 24 m**
- Beam size at sample (h x v) ≅ **150 mm x 6 mm**
- Energy range: **8 ÷ 35 keV**, Bandwidth **$\Delta\lambda/\lambda \cong 2\times10^{-3}$**
- Typical fluxes at 15 keV ≅ $2 * 10^8$ phot./mm^2 s (@ 2 GeV, 300 mA)
  $7 * 10^8$ phot./mm^2 s (@ 2.4 GeV, 180 mA)

The experimantal hutch at SYRMEP





X-ray imaging at a 3rd 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** (<≈ 1 μm at SYRMEP)
  → possibility of **big sample-to-detector distances** (<≈ 1 m at SYRMEP)
  → **high** spatial **coherence** of the X-ray beam (**L_c ≅ 10 μm @ 15 keV**)

Phase-sensitive techniques

SR X-ray imaging studies

Medical imaging:

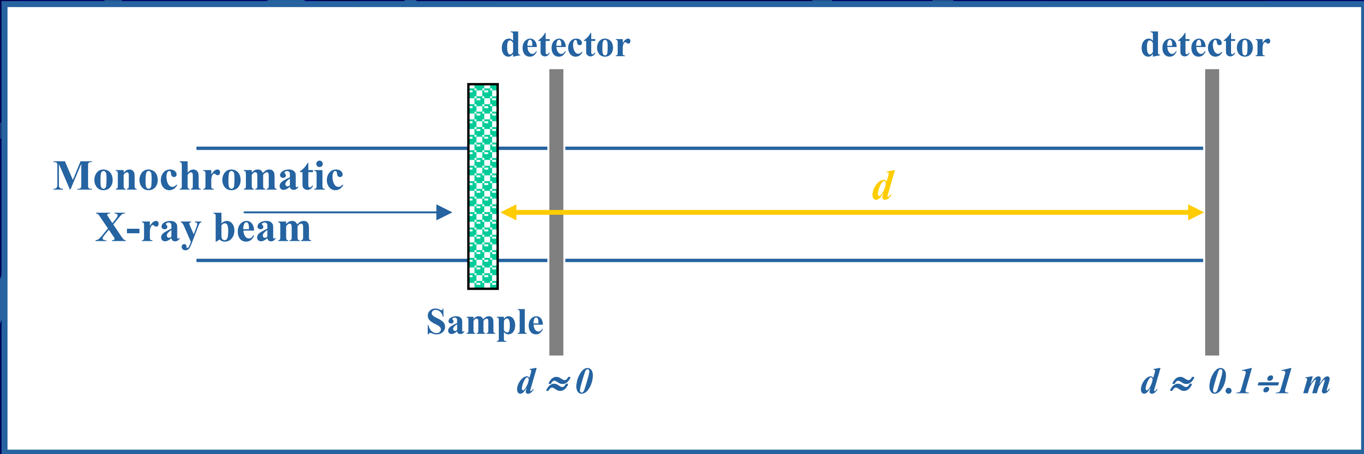
→ bones, dental implants
→ mammography
→ tissues ….

Material science imaging:

→ crystals
→ rocks and minerals
→ food science
→ archeological samples
→ engineering science ….

The X-ray imaging techniques

Absorption and Phase Contrast (PC) Radiography



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

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

n = 1 - δ - iβ : refraction index

μ = 4π β / λ : linear absorption coeff.

c : object size // to beam direction

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

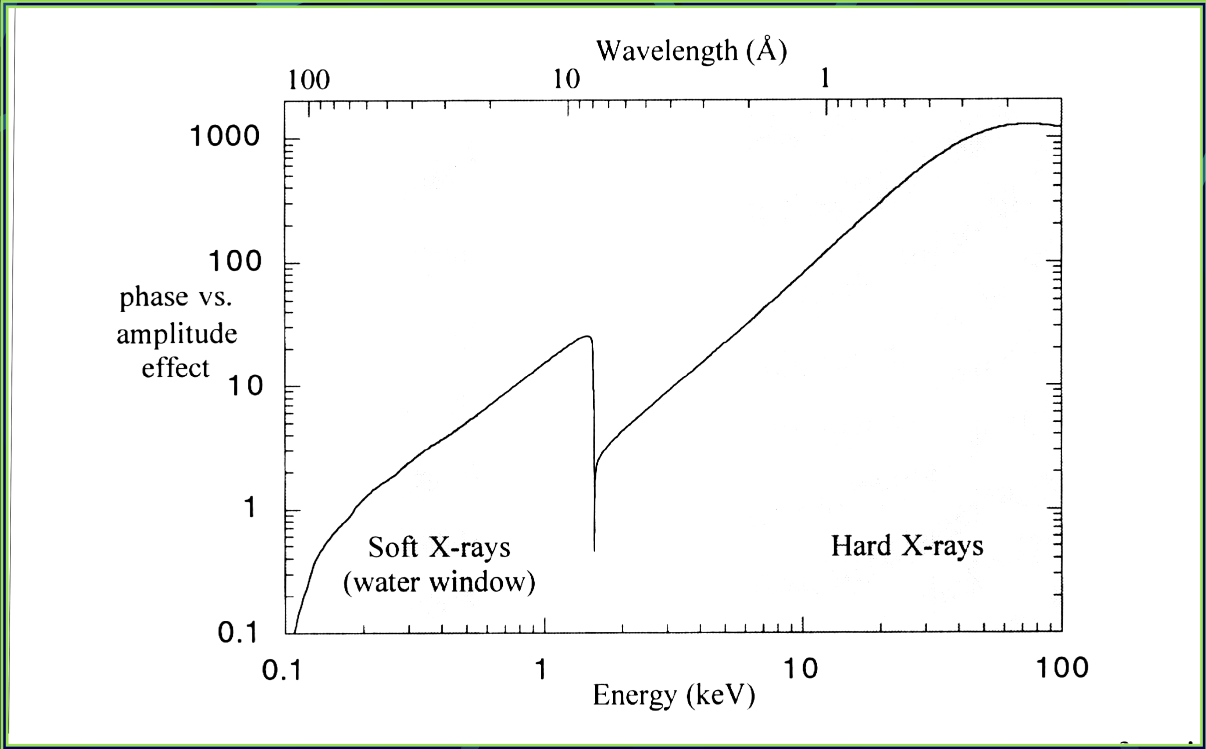
$r \cong a \Rightarrow$ *holographic regime*

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

a : object size ⊥ to beam direction

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

Absorption vs. Phase Contrast

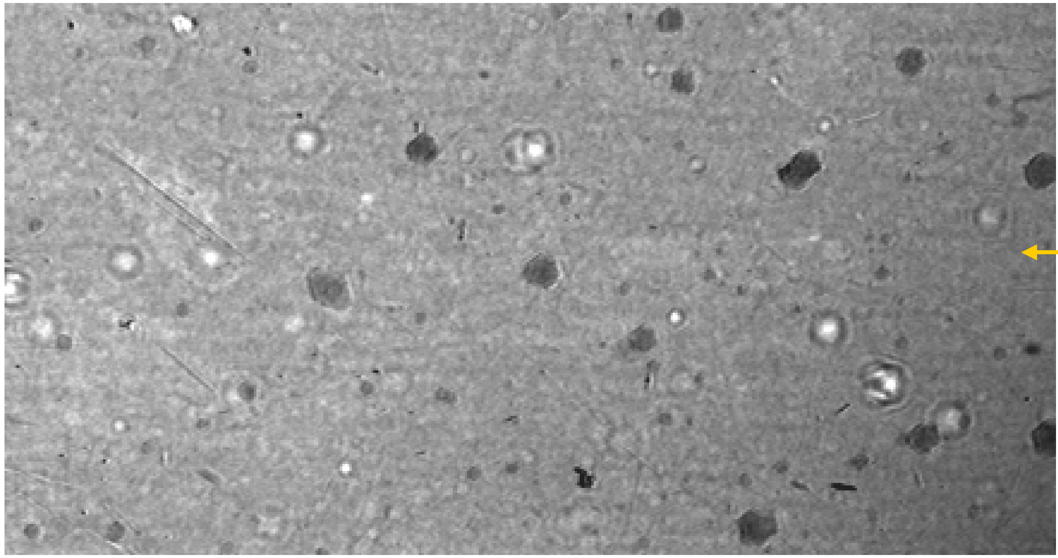


- Analysis of **materials**
  → **with weak absorption** with respect to hard X-rays
  → **producing significant variations of** X-rays **optical path**

Radiographs of an AlPdMn grain recorded at the ESRF (France)

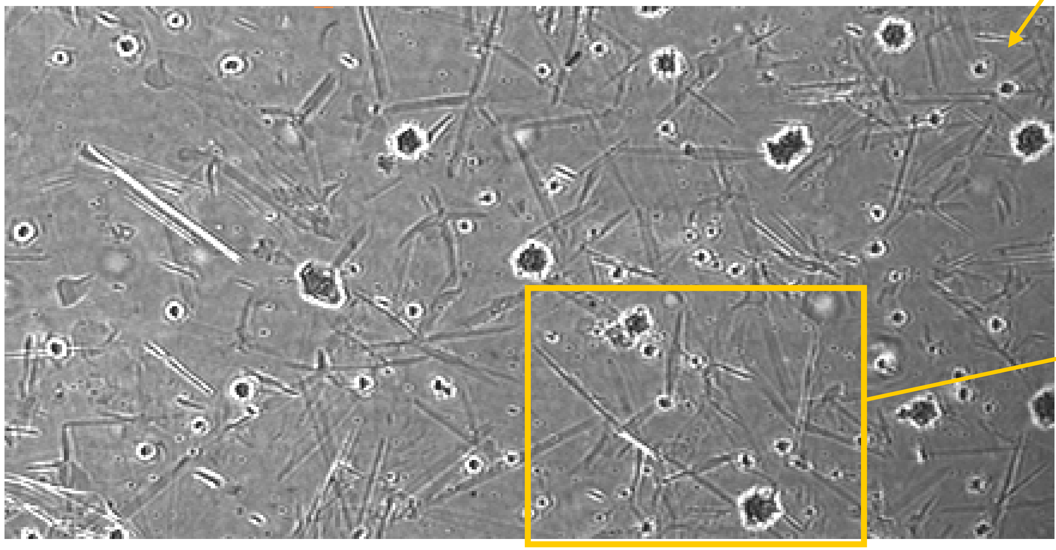
L. Mancini, PhD Thesis, 1998

Absorption radiograph



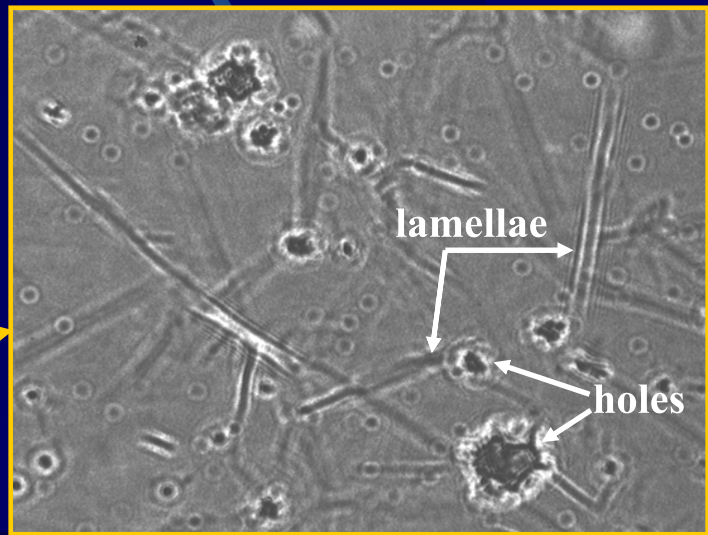
d = 2 cm

Phase radiograph



400 µm

d = 50 cm



200 µm

Vertical source size σ estimation from PCR of a nylon wire

Sample: **Nylon wire (120 µm Ø)**

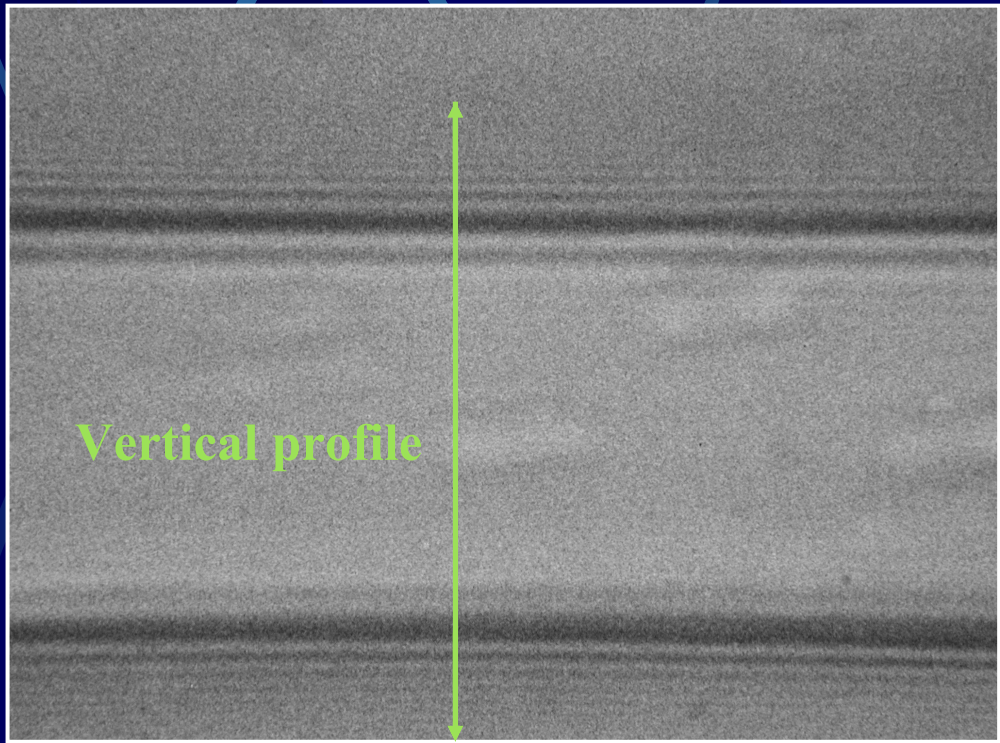
E = 10 keV

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

d **= 1 m**

D = 24 m

Detector: **1 µm resolution film**



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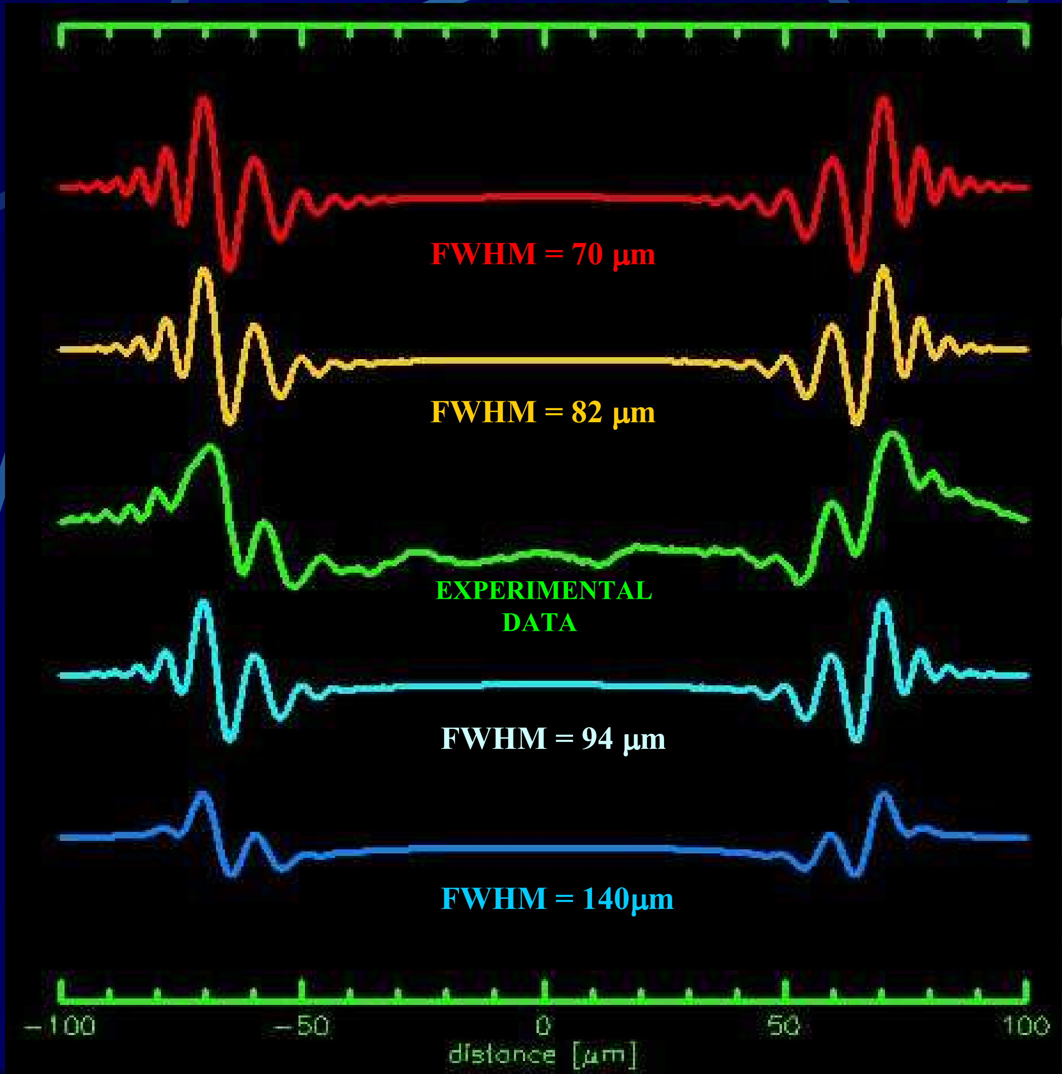
Experimental and simulated profiles for different σ values



Nylon wire (120 µm Ø)
E = 10 keV
d = 1 m

σ < ≅ 90-100 µm

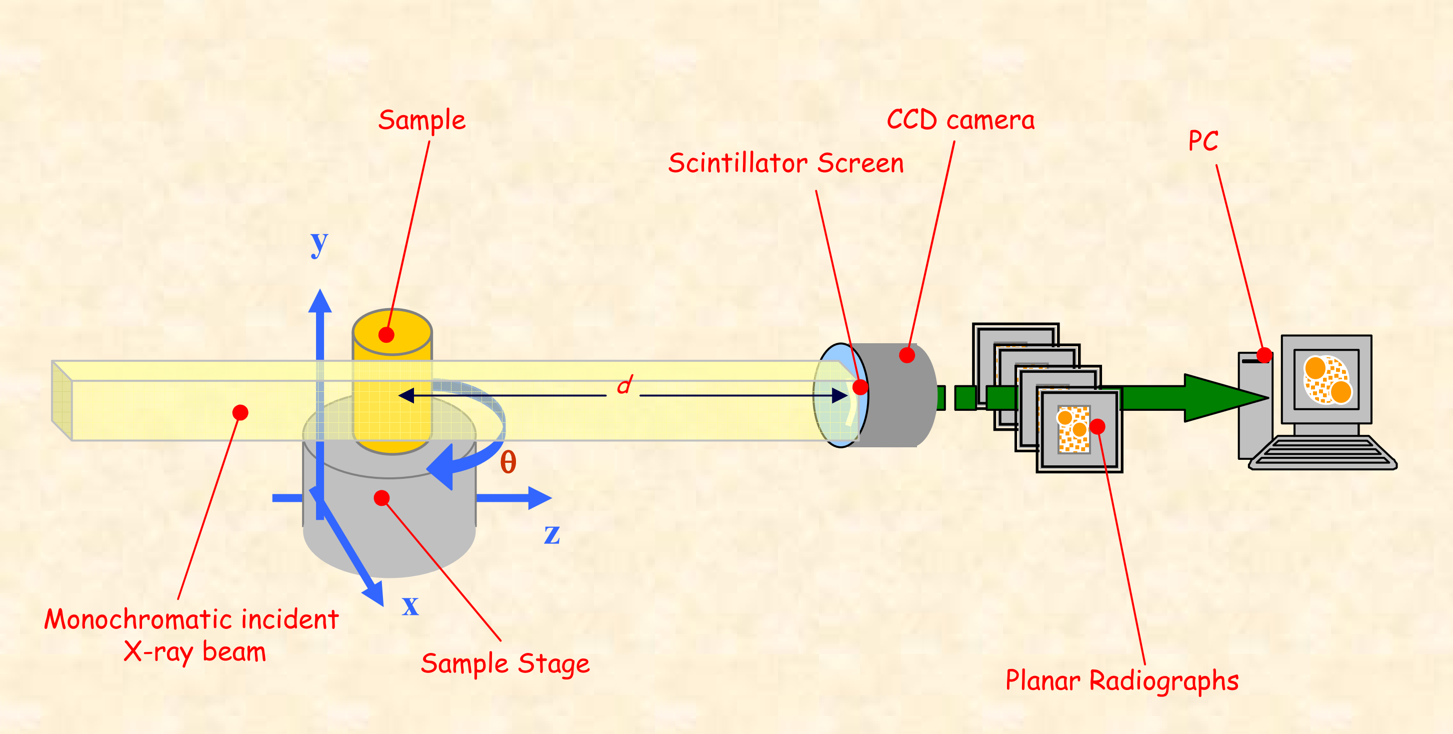
Results

- **Spatial resolution $\rho = \sigma d / D <\cong 1\ \mu m$ up to $d = 0.3$ m**
  $\cong 4\ \mu m$ at $d = 1$ m

- Possibility to work at **big sample-to-detector distances: $D >\approx 1$ m**

- **High transverse coherence of the beam: $L_c = \lambda D / (2\sigma) \cong 10\ \mu m$**

The principle of computed microtomography



CCD camera: 2048x2048 pixels^2, pixel size: 14 μm, FOV: 28x28 mm^2

- **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

- 1:1 Optics
  - 20 (40) µm thick IS
  - effective pixel size: 14 µm
  - PSF ~ 30 (50) µm

- Photonic science
  - 2048 x 2048 pixel
  - each pixel 14 x 14 μm^2

- 11:40 (Magnifying) Optics
  - ~ 5 µm thick IS
  - effective pixel size: 3.85 µm
  - PSF ~ 13 µm

SR X-ray imaging

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

→ growth processes
→ mechanical and thermal treatments
→ phase transitions ….

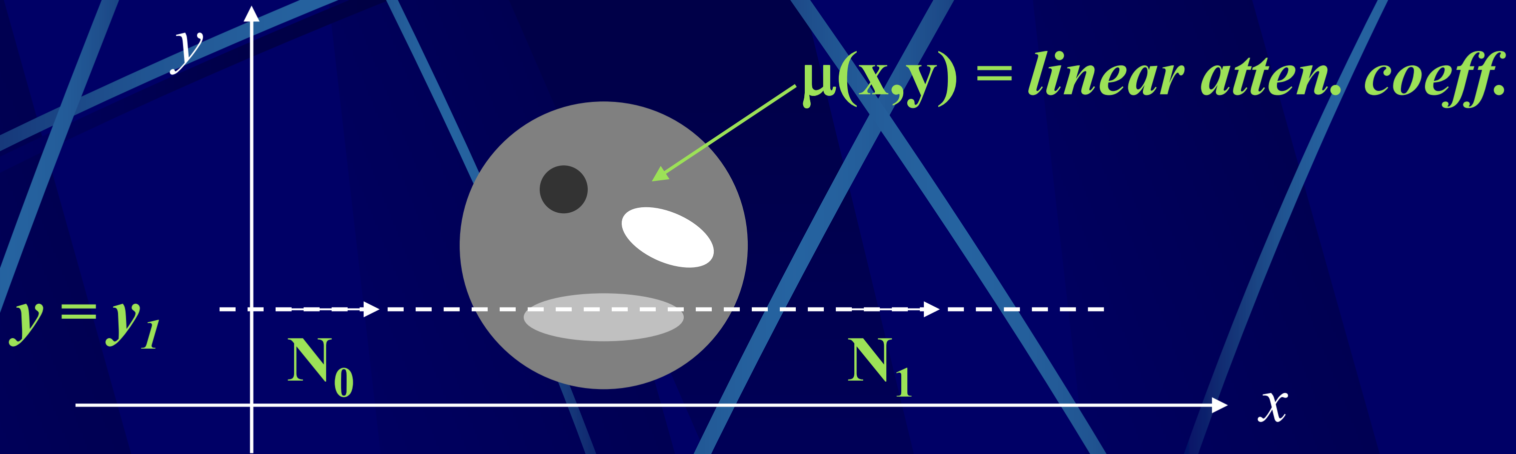
The aim

to investigate the relationship between microstructural

and physical properties

Principles of transmission X-ray μ-CT

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



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

$\ln (N_0 / N_1)= \int_{path} \mu(x,y_1)\, dx = \mathbf{P_\theta(t)}$ (((θ,t)) 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 μ(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 $\mu(x,y)$.

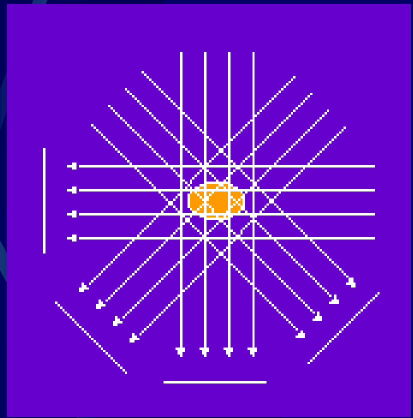
A projection is formed by combining a set of line integrals. The simplest projection is a collection of parallel ray integrals at a given angle (θ).

The **Fourier Slice Theorem** demonstrates that the Fourier transform of a parallel projection of an image of $\mu(x,y)$ taken at an angle θ 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

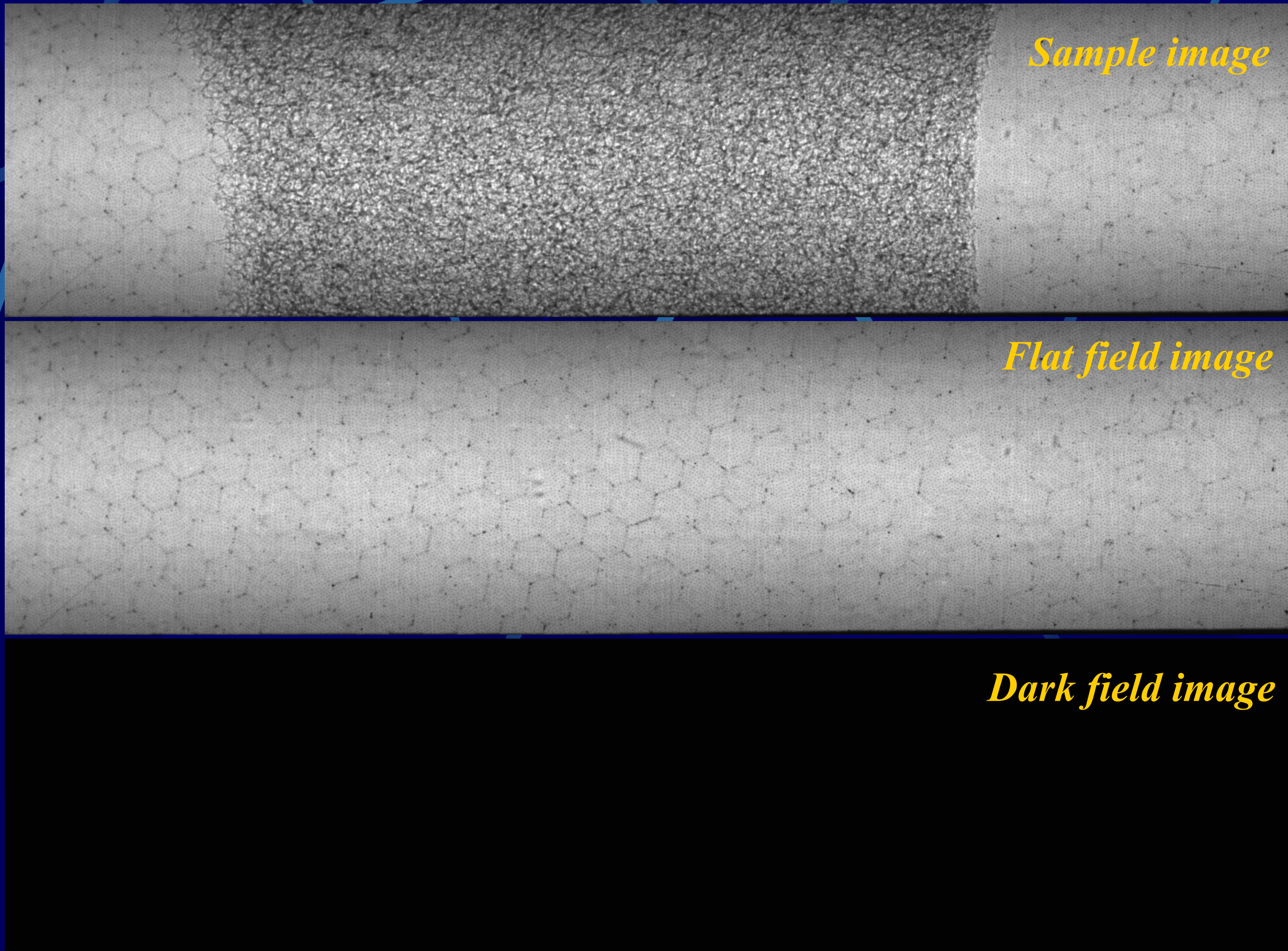
- Planar radiographs are elaborated by a **reconstruction procedure**:
  → **filtered backprojection** algorithm *[Herman, 1980]*
  → for each projection an **intensity map** is recorded in the xy detector plane
  → projections are submitted to **filtering procedures**
  → each intensity map is **back projected** along the normal to the projection itself
  → finally, the intensities are added for all the projections



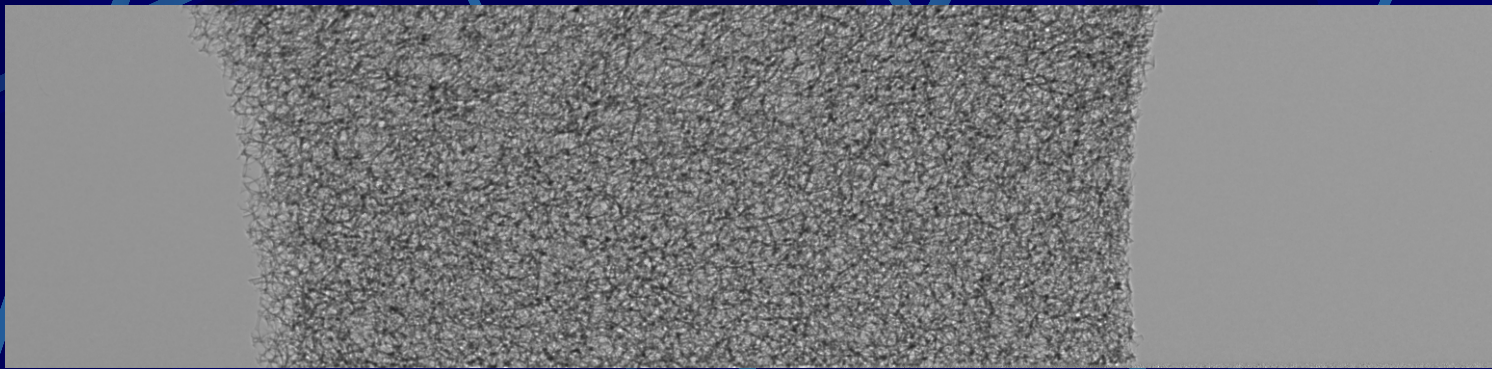
- Reconstructed slices are then treated by a **rendering procedure**:
  → 2D slices visualized as **Stack**
  → 3D views of the sample can be obtained (**Volume rendering**)

- Rendered images can be elaborated applying filters, false colors, **segmentation tools** to extract quantitative information.

Recording of tomographic images

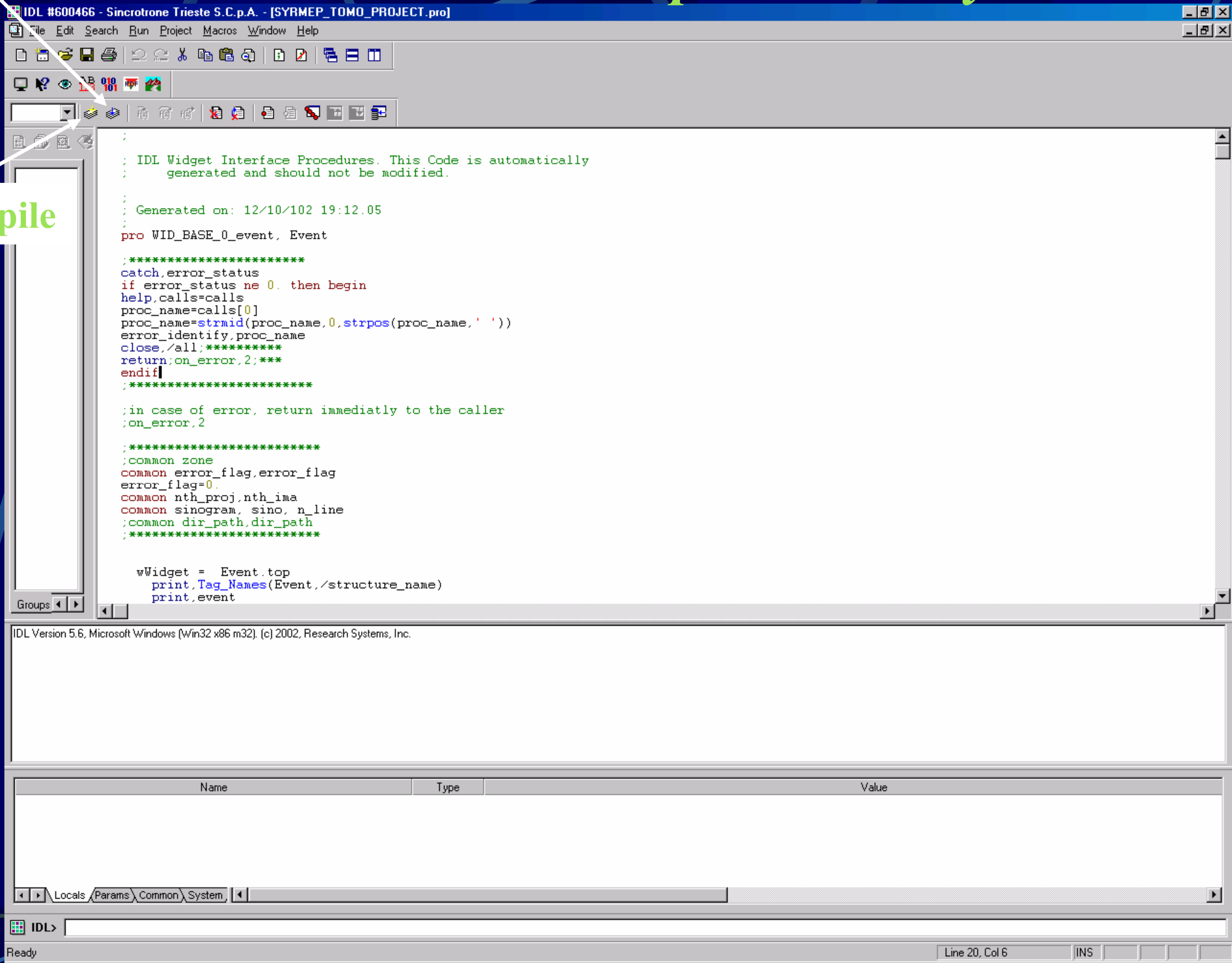


Flat procedure for the tomographic images

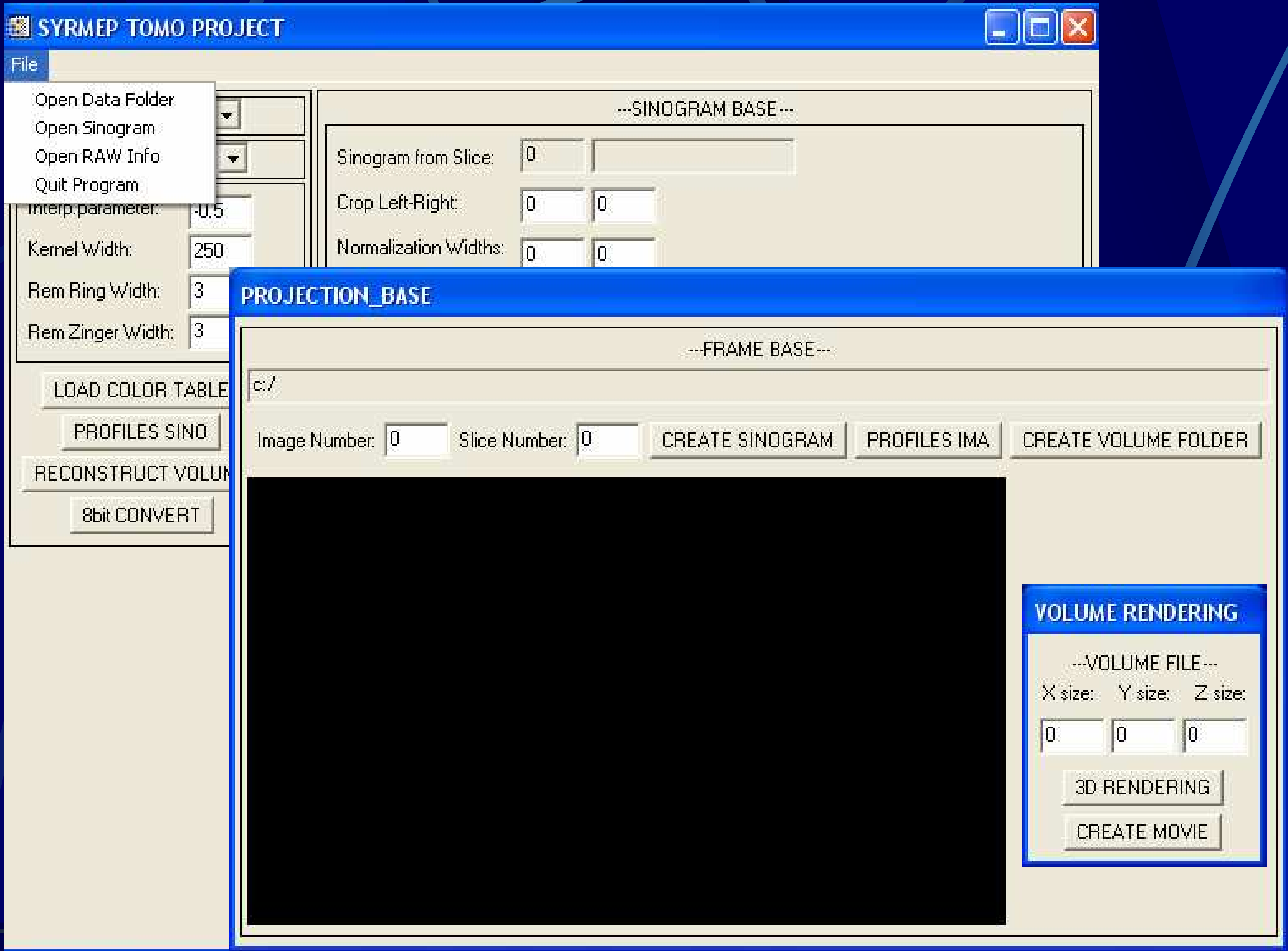


$$I_{flatted} = (I_{sample} - I_{dark})/(I_{flat} - I_{dark})$$

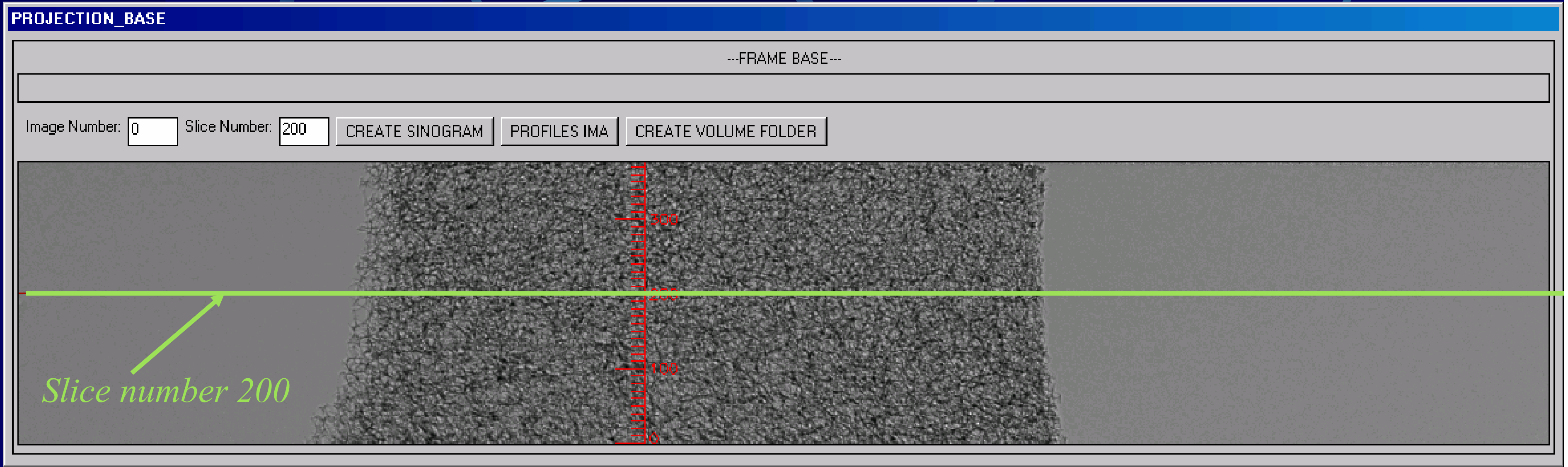
The reconstruction procedure by IDL

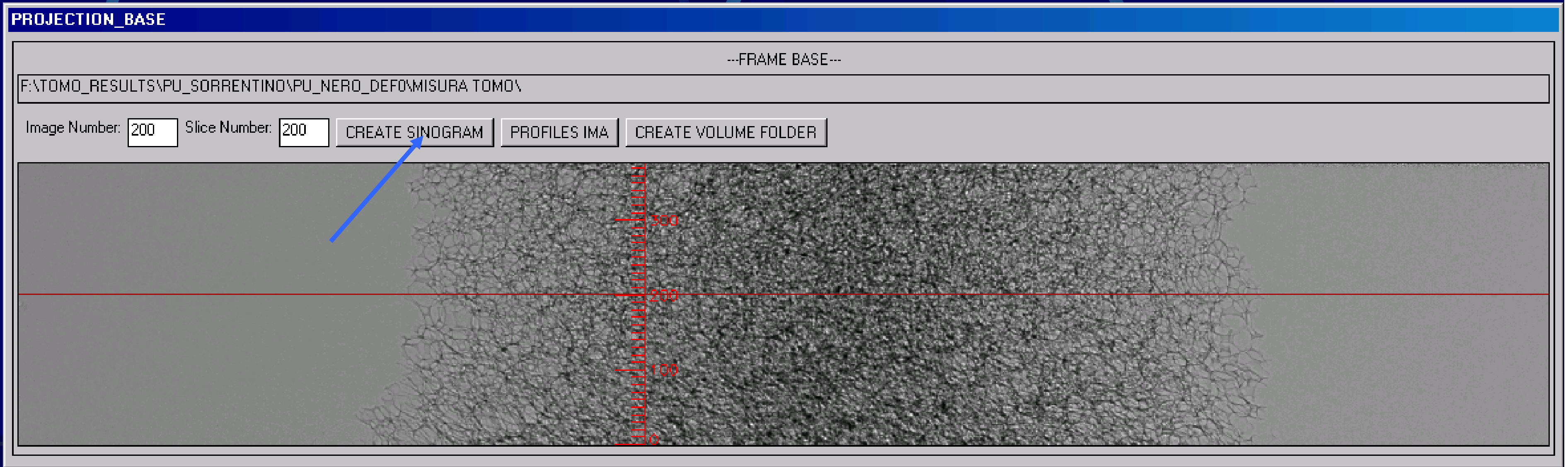


Starting of the reconstruction procedure

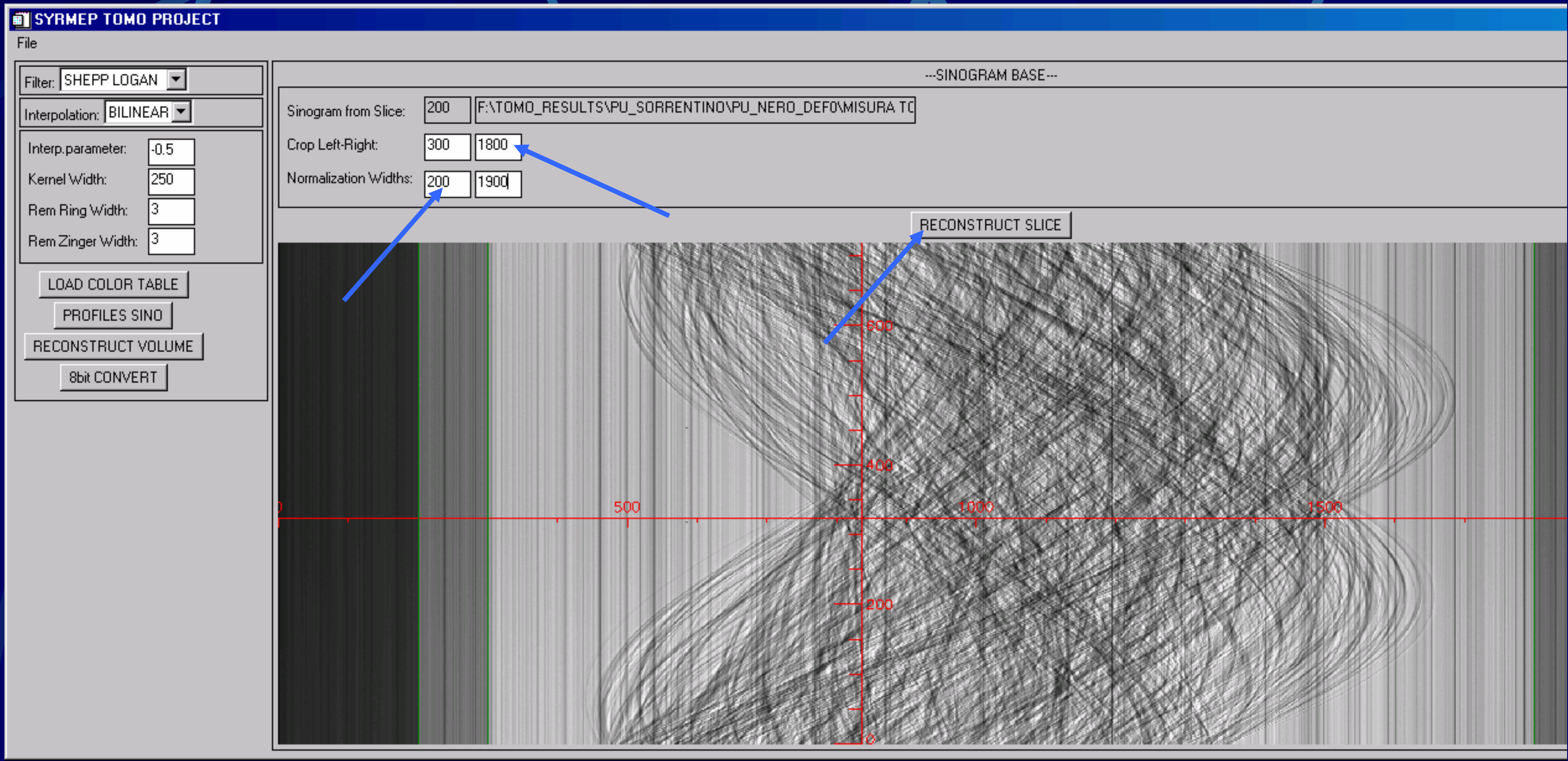


Choice of the slice to reconstruct

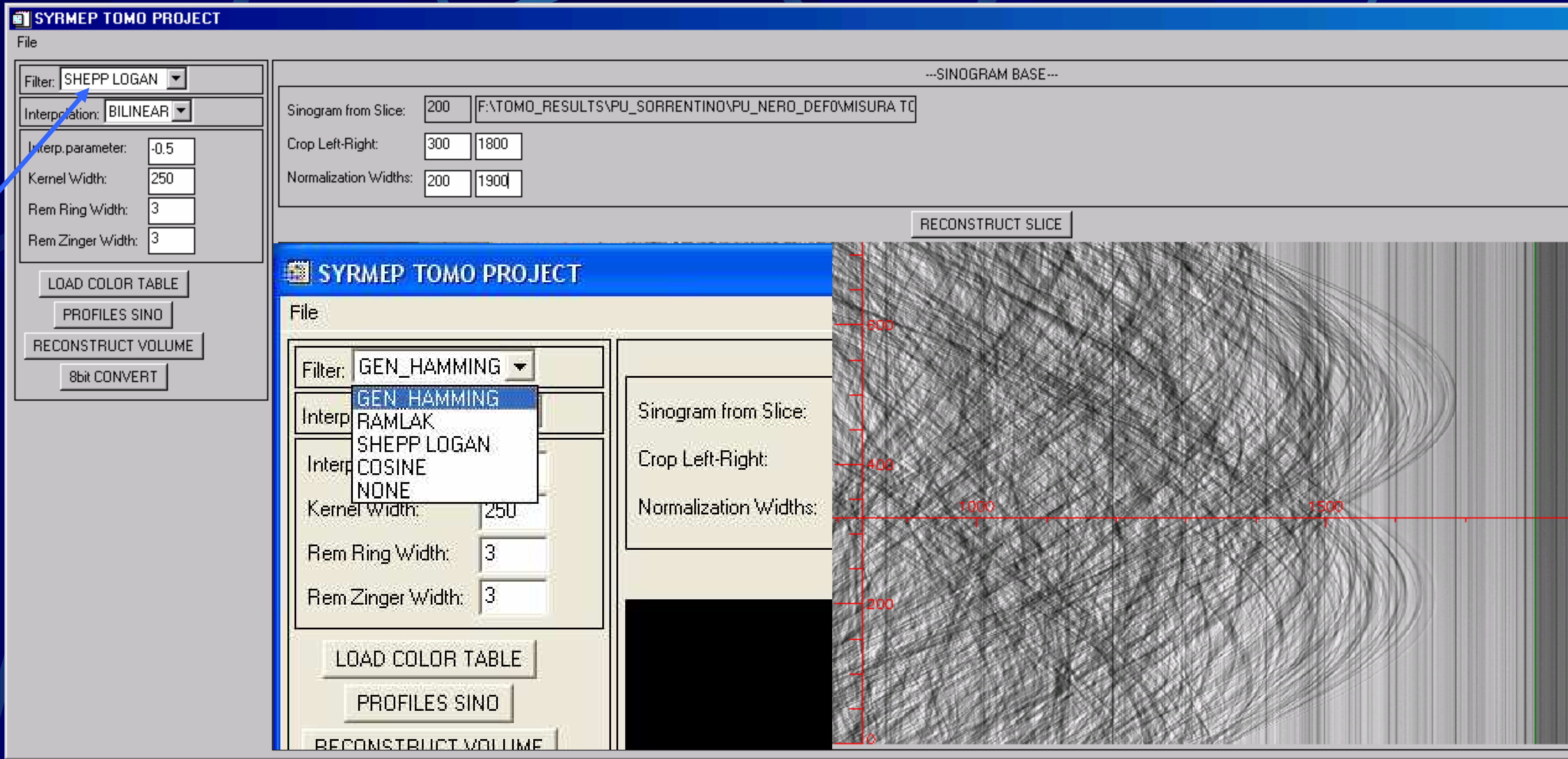




Creation of the sinogram

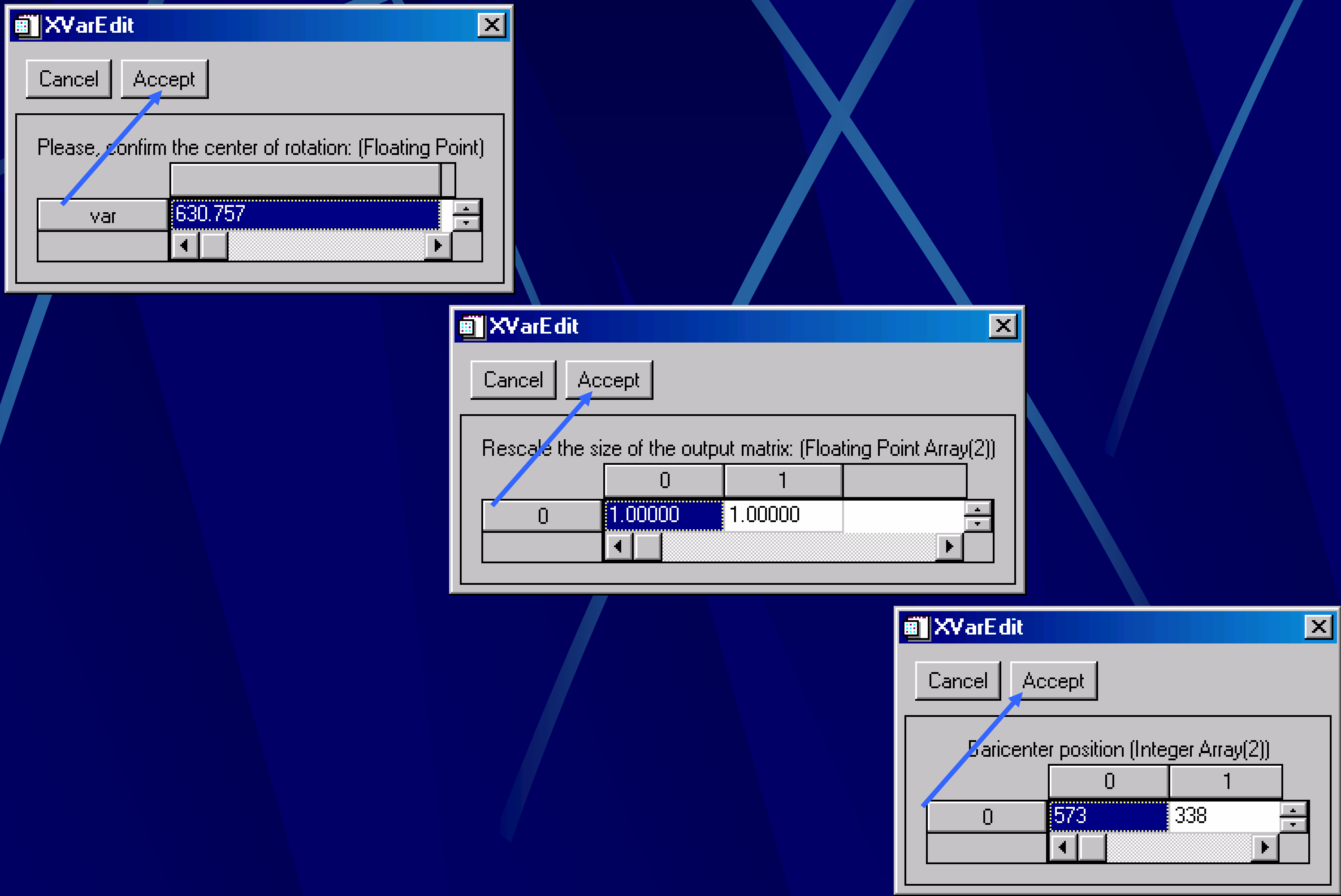


Filtering procedure

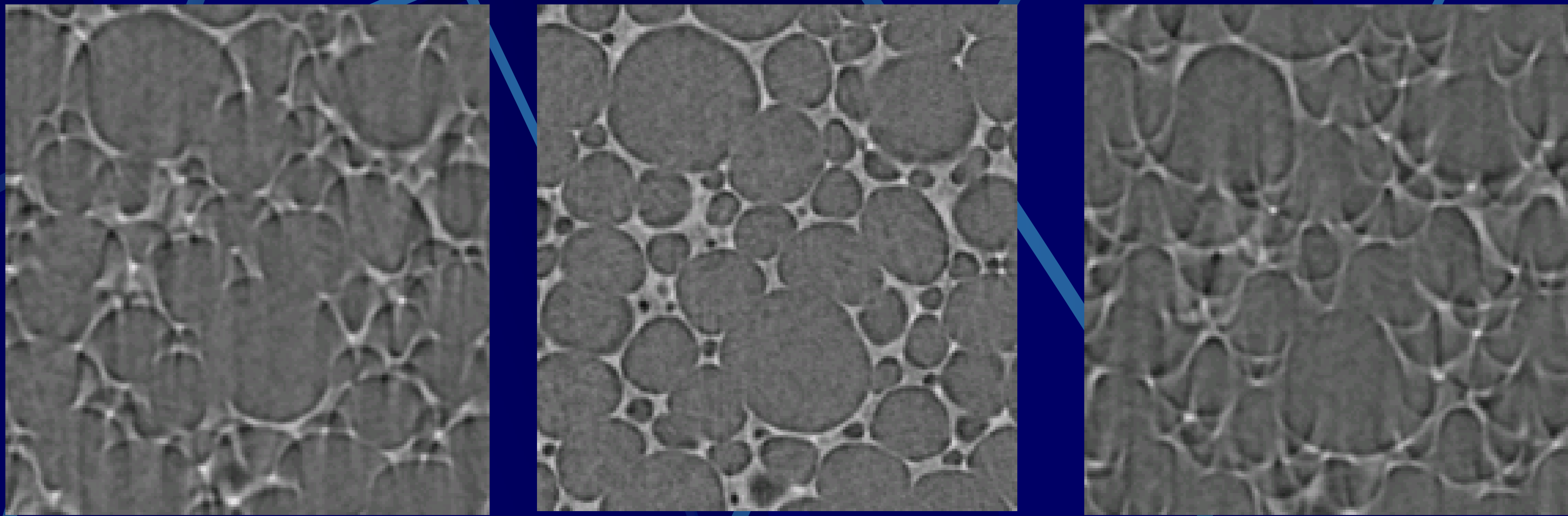


If in the reconstruction the backprojection is done without filtering the sinogram first, the resulting image is very blurry. In practice one always filters the sinogram before the backprojection. In this example the sinogram will be filtered using a Shepp-Logan filter, which is an edge-sharpening filter.

Choice of the reconstruction parameters



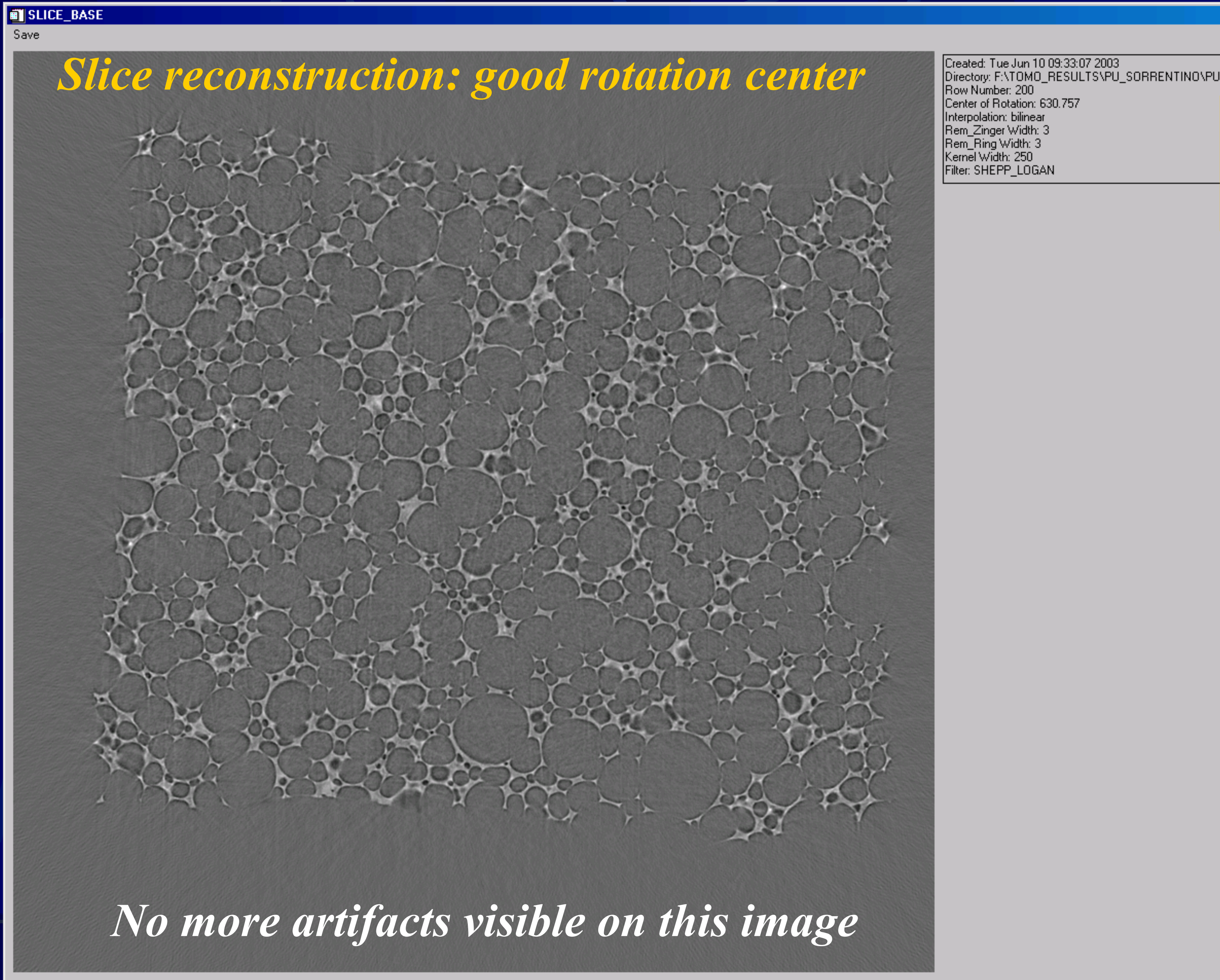
Slice reconstruction: optimization of the rotation center



C = 624.750 ***C = 630.750*** ***C = 638.750***

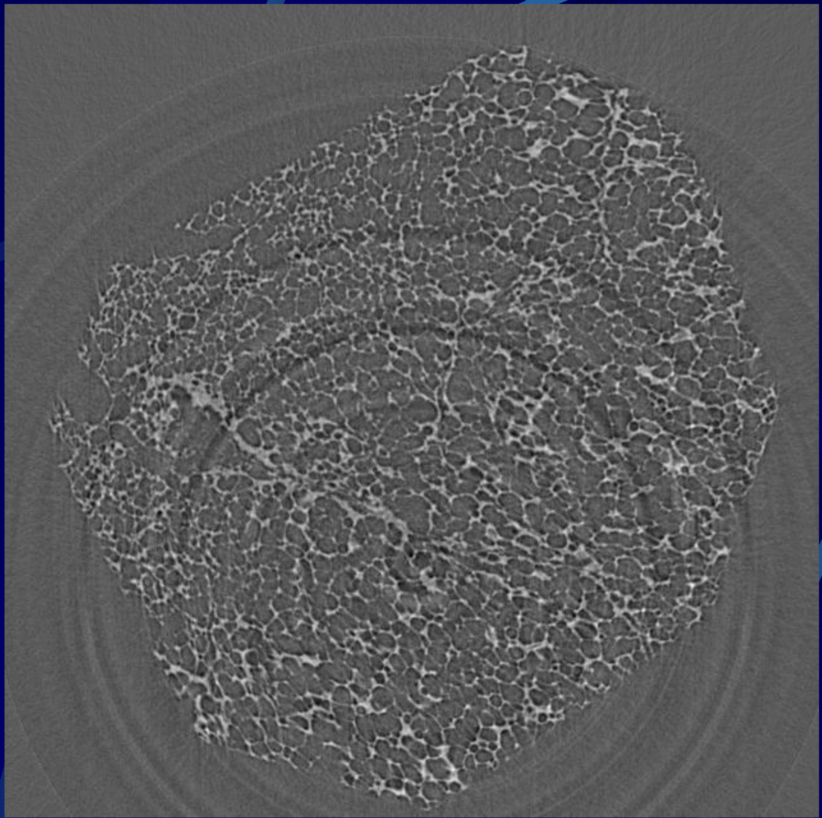
A poor centering causes **arc artifacts**. An automated centering procedure gives a sinogram which is better centered on the rotation axis by determining the center-of-gravity of each row in the sinogram, and fitting this center-of-gravity array to a sin wave. The symmetry axis of the fitted sin wave 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 reconstruction: good rotation center



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 a thin cylinder centered on the rotation axis in the real object.

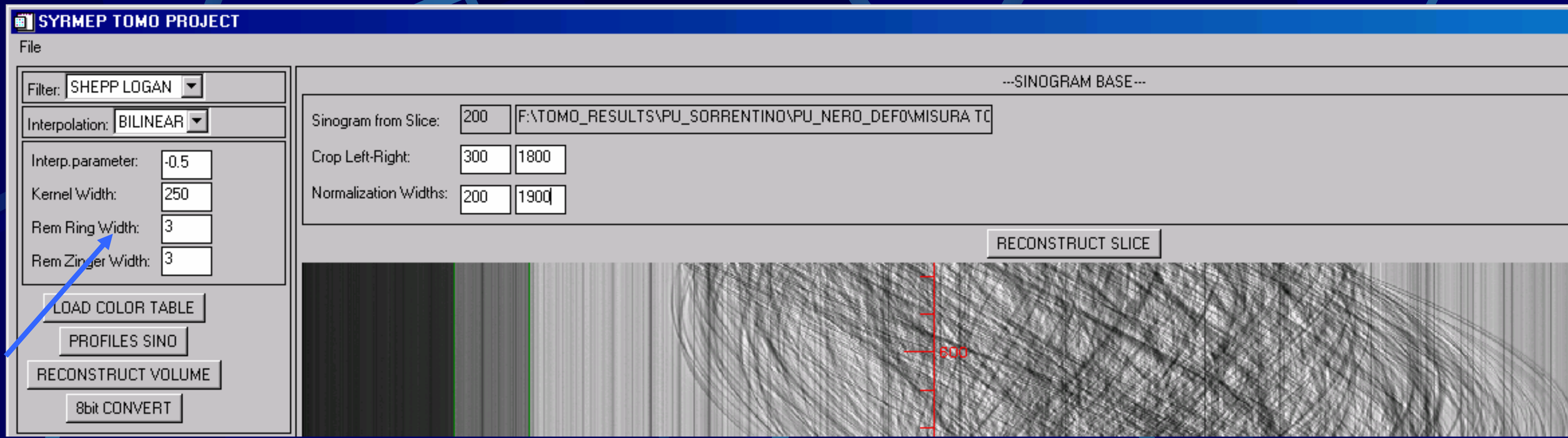
The causes of these vertical stripes in the sinogram can include the following:

→ 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?

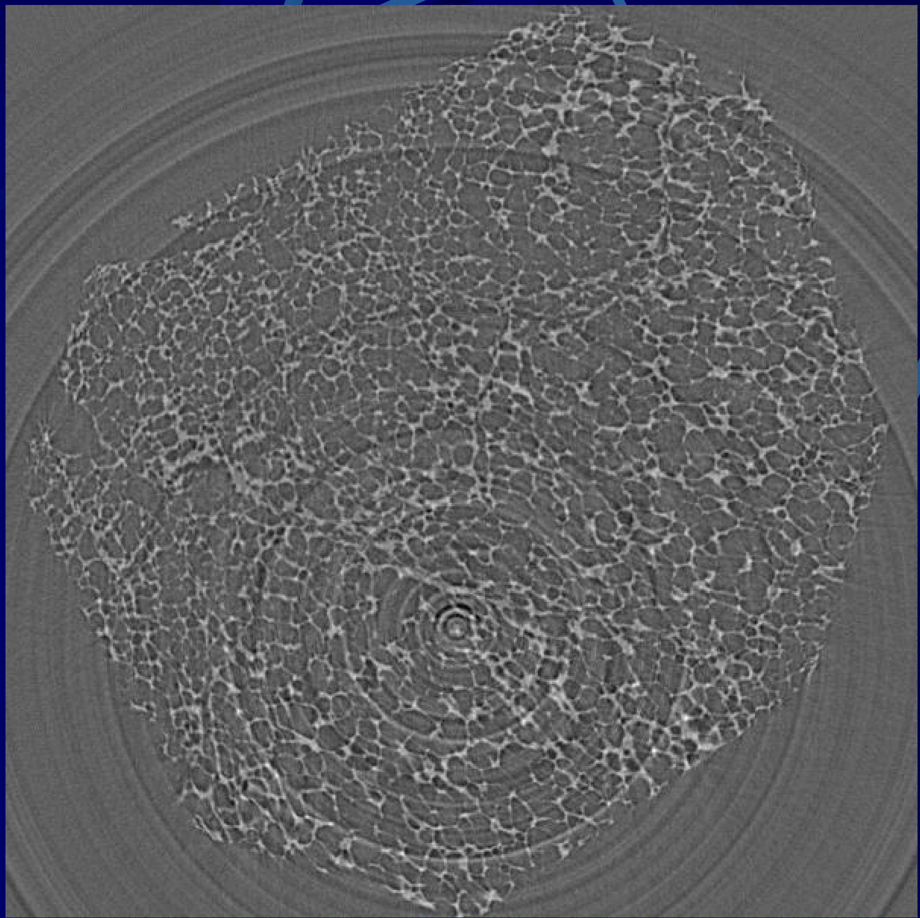


→ Compute the **average row of the sinogram** by summing down each column and dividing by the number of rows. This **average row** should have very little high-frequency content, since real objects will be moving in the sinogram, and will be blurred out when computing the average row.

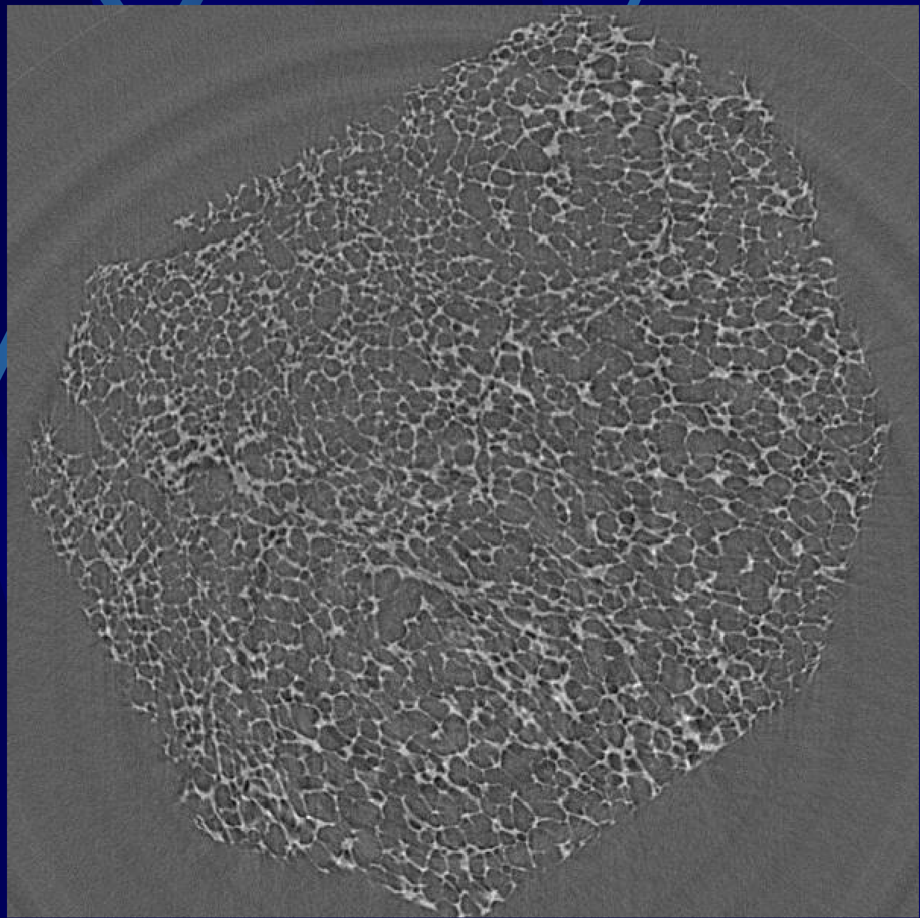
→ Compute the magnitude of these detector anomalies by subtracting a smoothed version of the average row from the average row.

→ 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



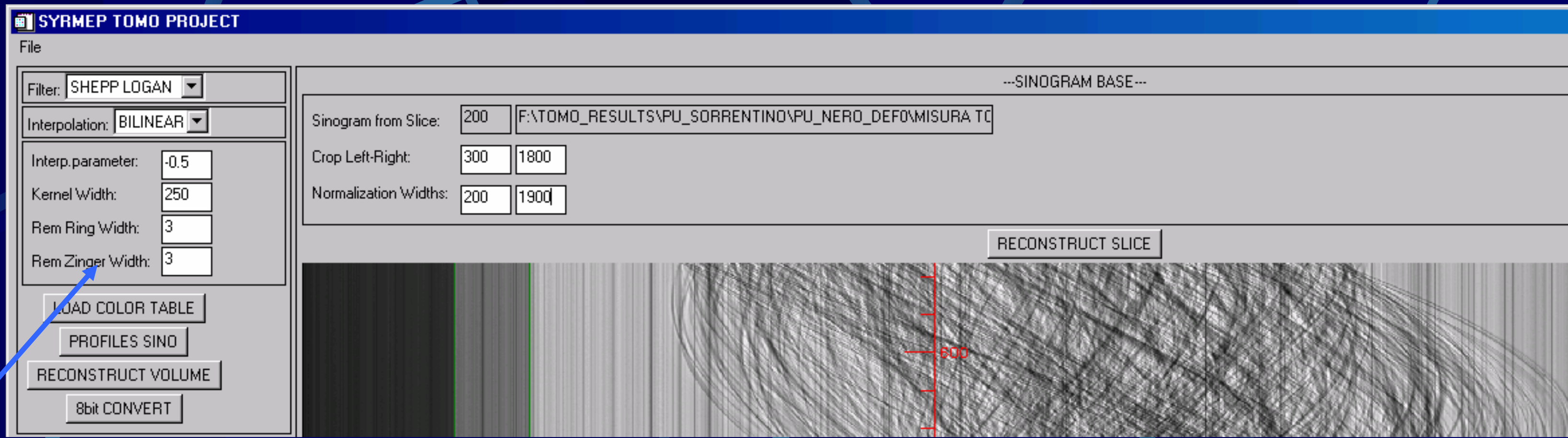
After

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?



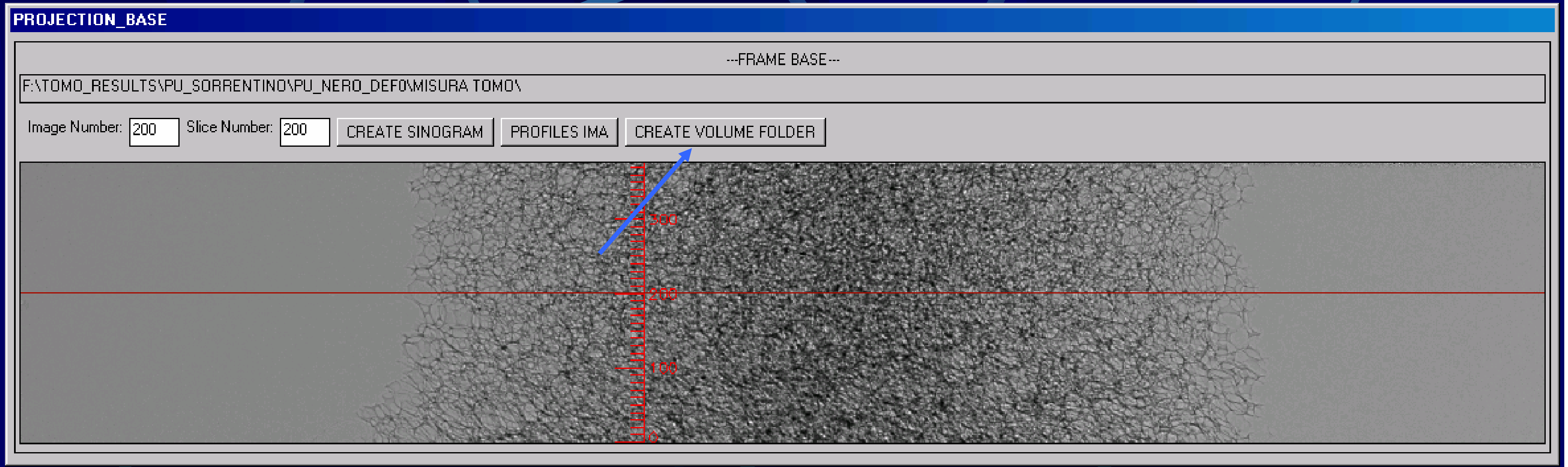
→ Smooth the raw image with a low-pass filter

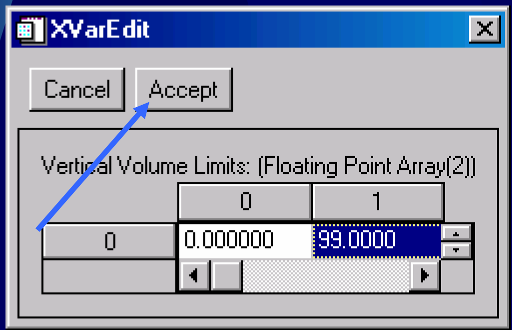
→ Subtract the raw image from the smoothed image

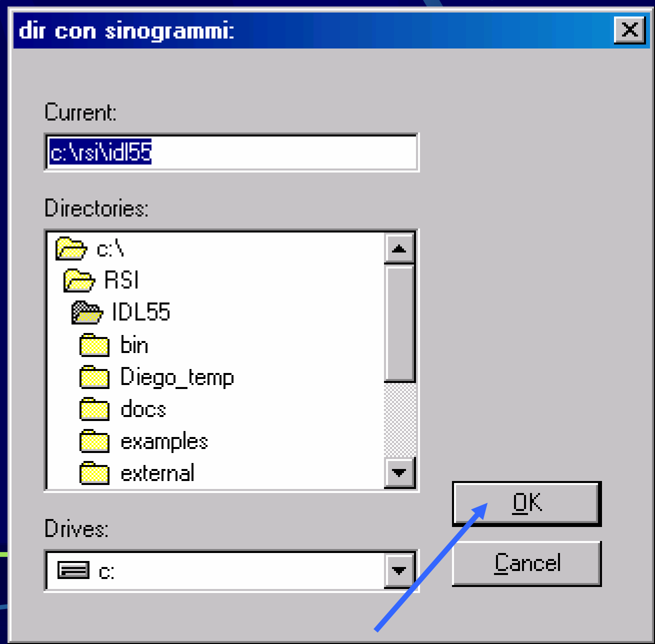
→ Divide the difference image from step 2 by the smoothed image to produce an image of anomalous pixels on a relative scale

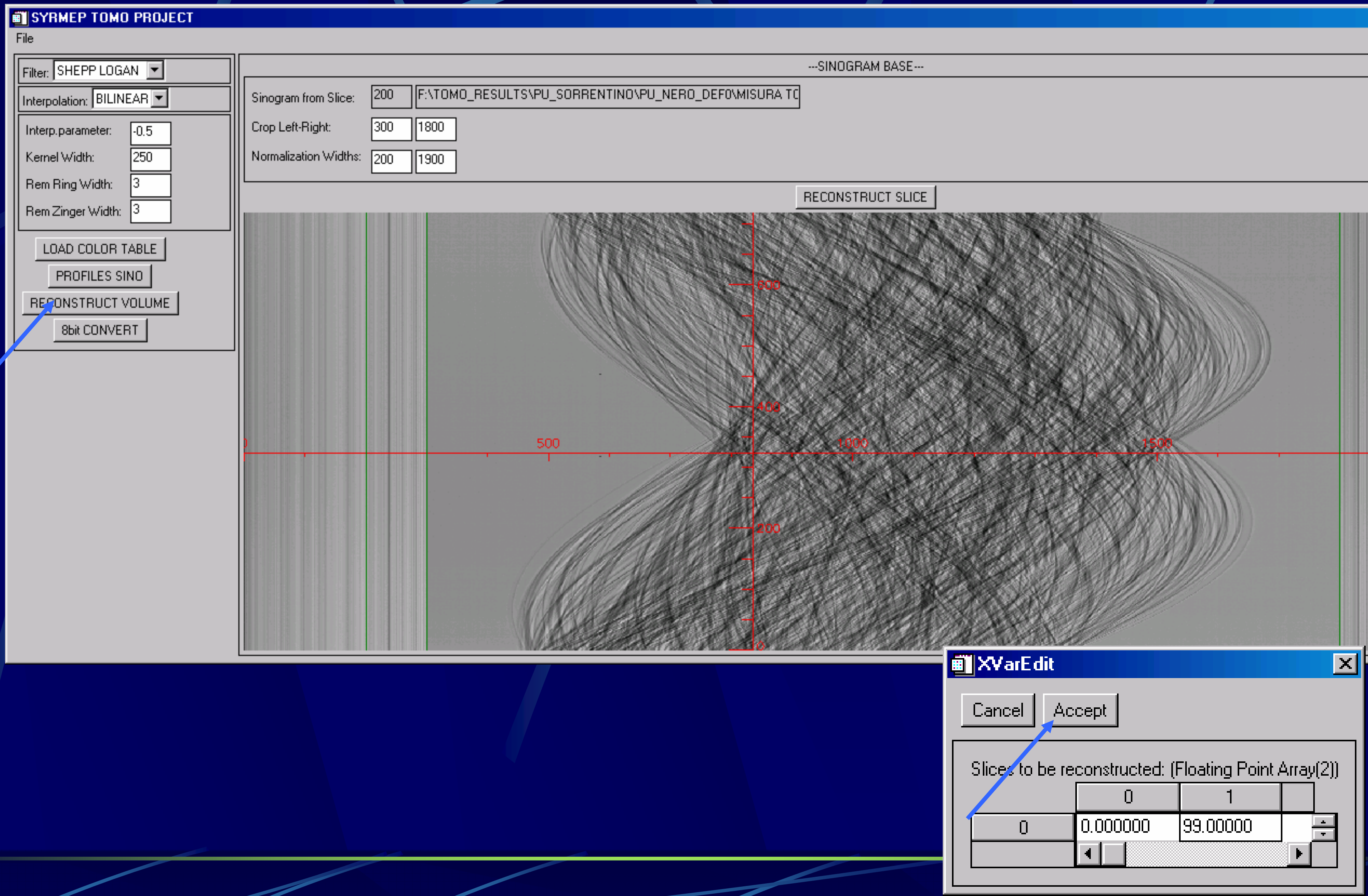
→ Any pixels in the image from step 3 which are greater than a threshold value (typically 1.2) are defined to be zingers. The intensity of zinger pixel at location N is replaced by the average intensity of the pixels at location N-2 and N+2. Pixels N-1 and N+1 are not used because some zingers affect 2 adjacent pixels.

Volume reconstruction

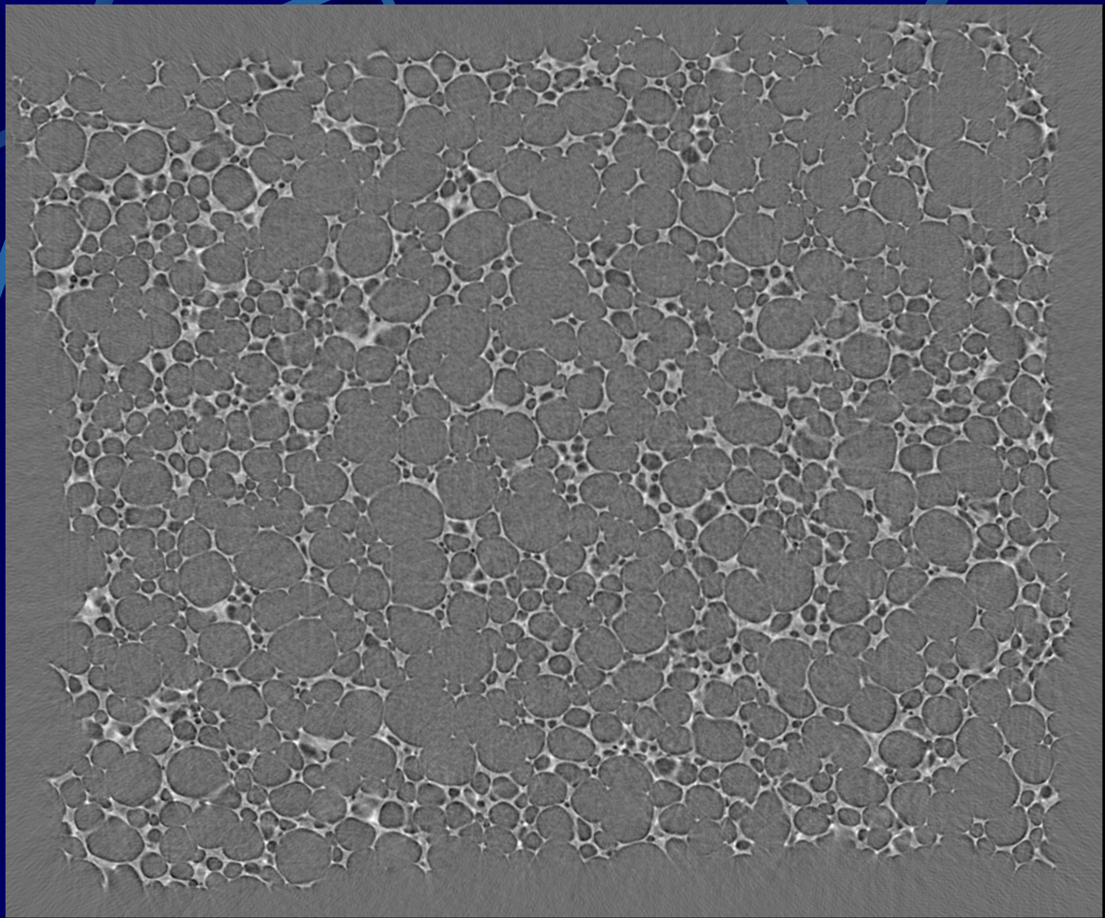







SYRMEP TOMO PROJECT
File
Filter: SHEPP LOGAN
Interpolation: BILINEAR
Interp.parameter: -0.5
Kernel Width: 250
Rem Ring Width: 3
Rem Zinger Width: 3
LOAD COLOR TABLE
PROFILES SINO
RECONSTRUCT VOLUME
8bit CONVERT
---SINOGRAM BASE---
Sinogram from Slice: 200 F:\TOMO_RESULTS\PU_SORRENTINO\PU_NERO_DEFO\MISURA TO
Crop Left-Right: 300 1800
Normalization Widths: 200 1900
RECONSTRUCT SLICE
600
400
200
0
500
1000
1500
XVarEdit
Cancel
Accept
Slices to be reconstructed: (Floating Point Array(2))
0
1
0
0.000000
99.00000

Data visualization: stack of 2D images

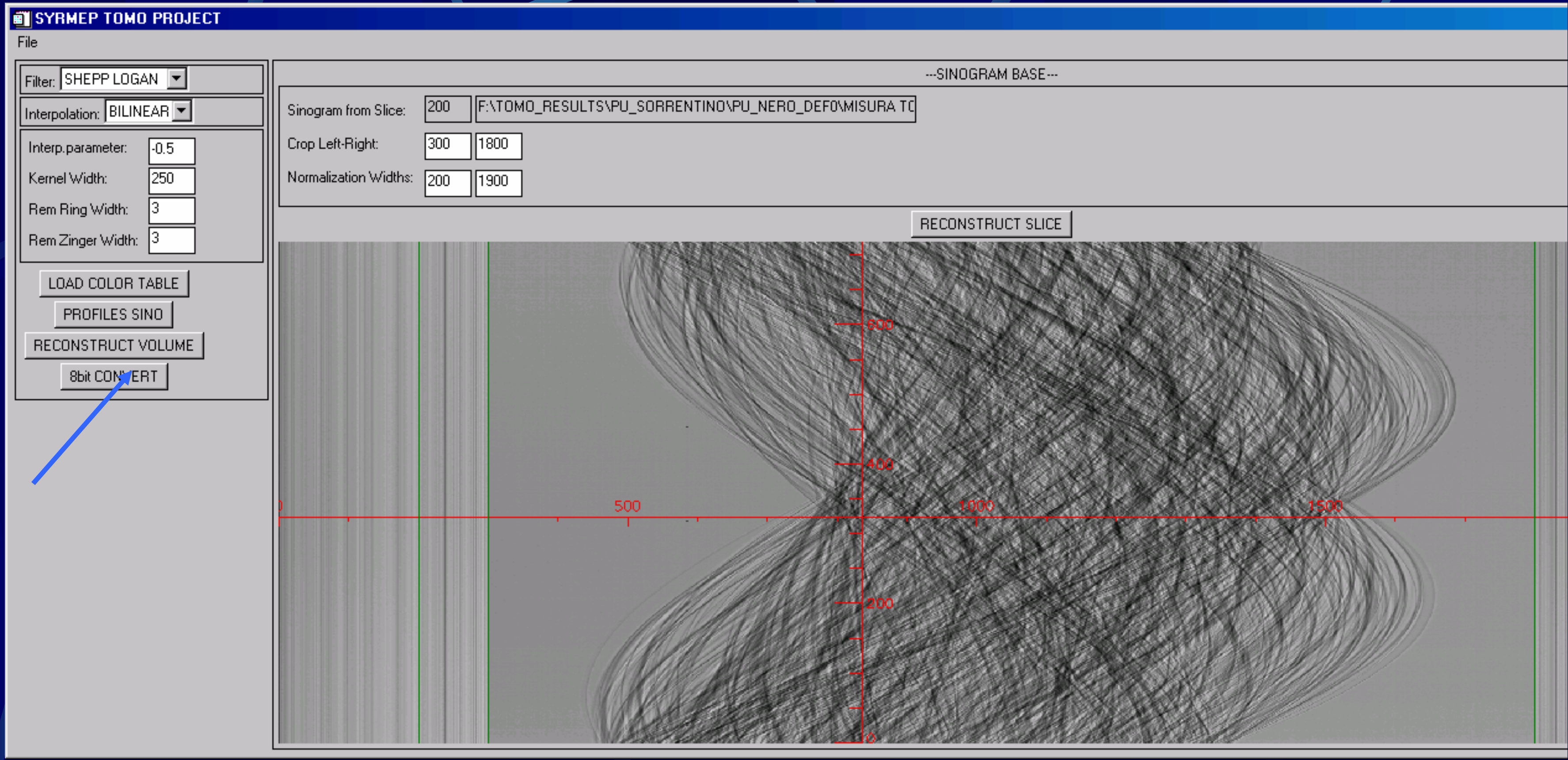


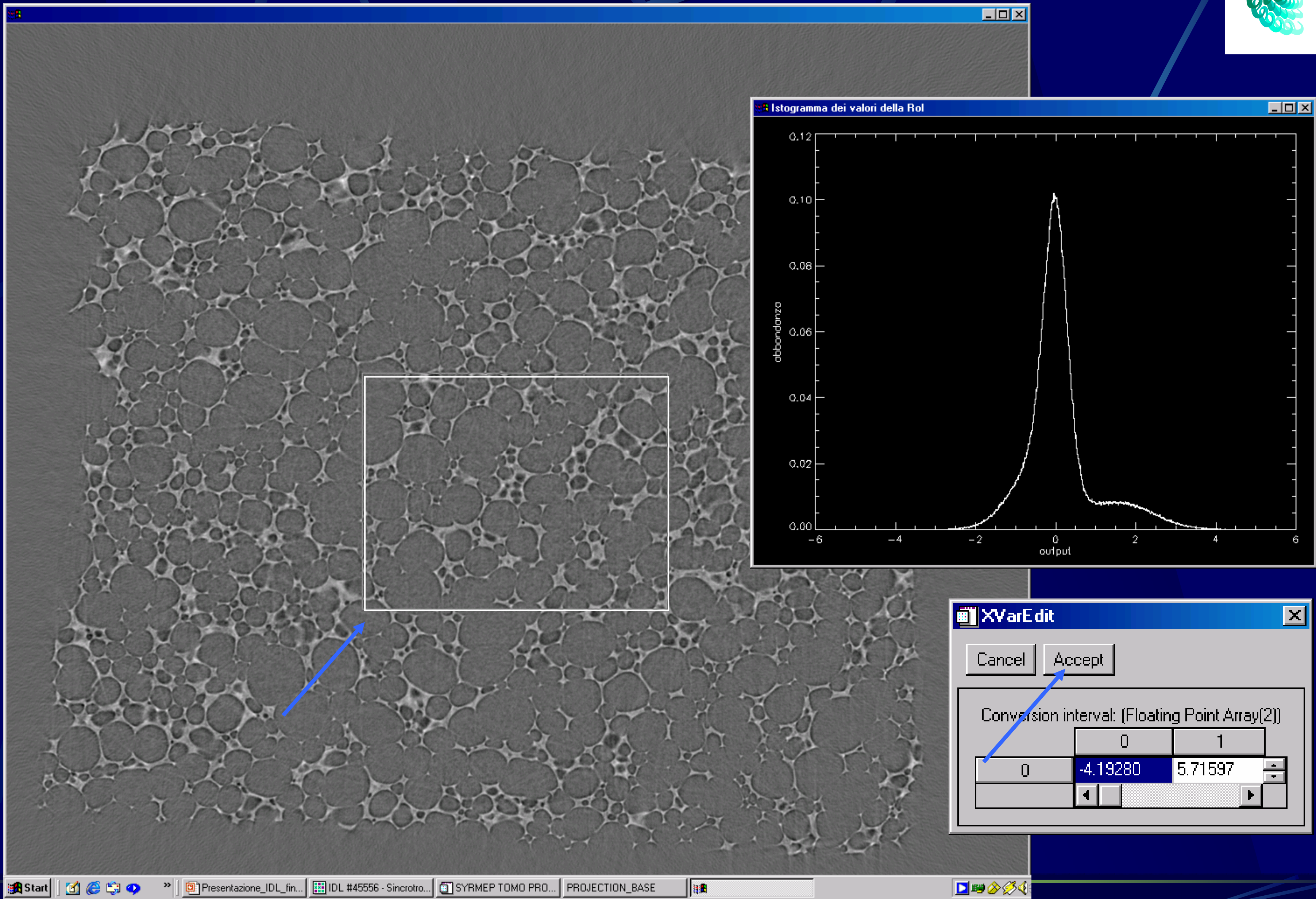
E = 12 keV
d = 32.5 cm

1 mm

Reconstructed stack of 100 slices

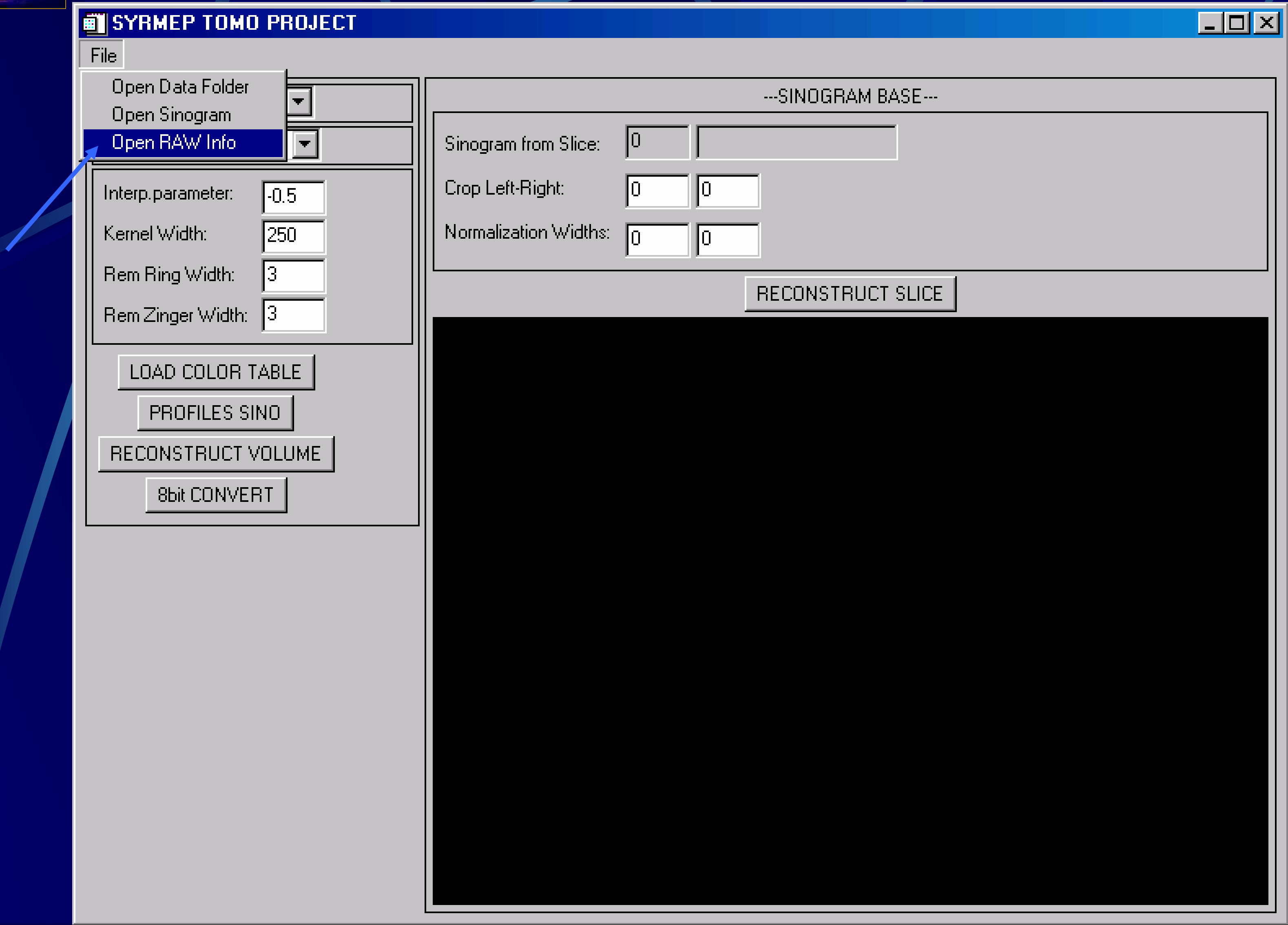
8bit .raw volume creation



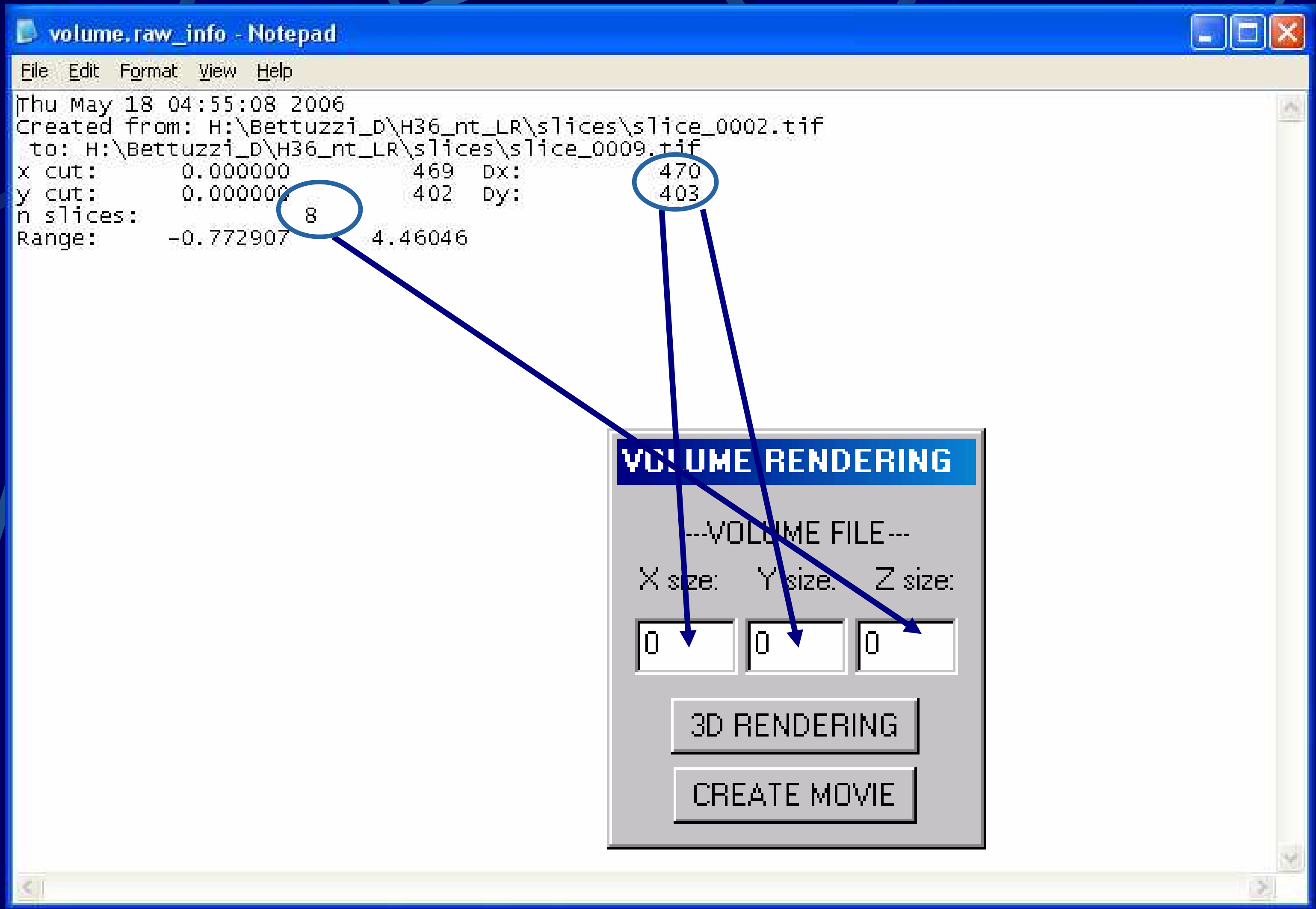


Istogramma dei valori della RoI
0.12
0.10
0.08
0.06
0.04
0.02
0.00
abbondanza
−6
−4
−2
0
2
4
6
output
XVarEdit
Cancel
Accept
Conversion interval: [Floating Point Array(2)]
0
1
0
-4.19280
5.71597
Start
Presentazione_IDL_fin...
IDL #45556 - Sincrotro...
SYRMEP TOMO PRO...
PROJECTION_BASE

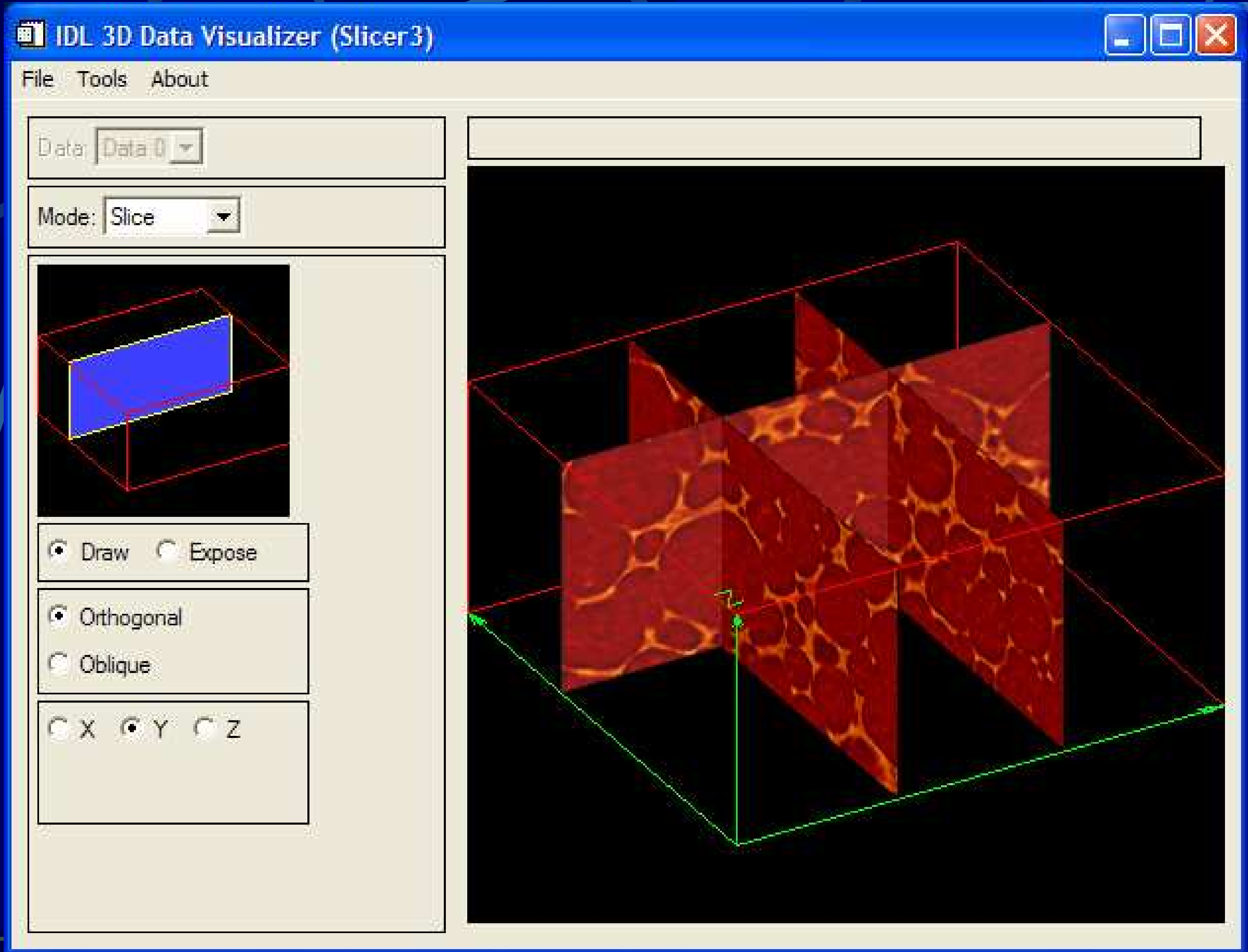
Data visualization: volume rendering



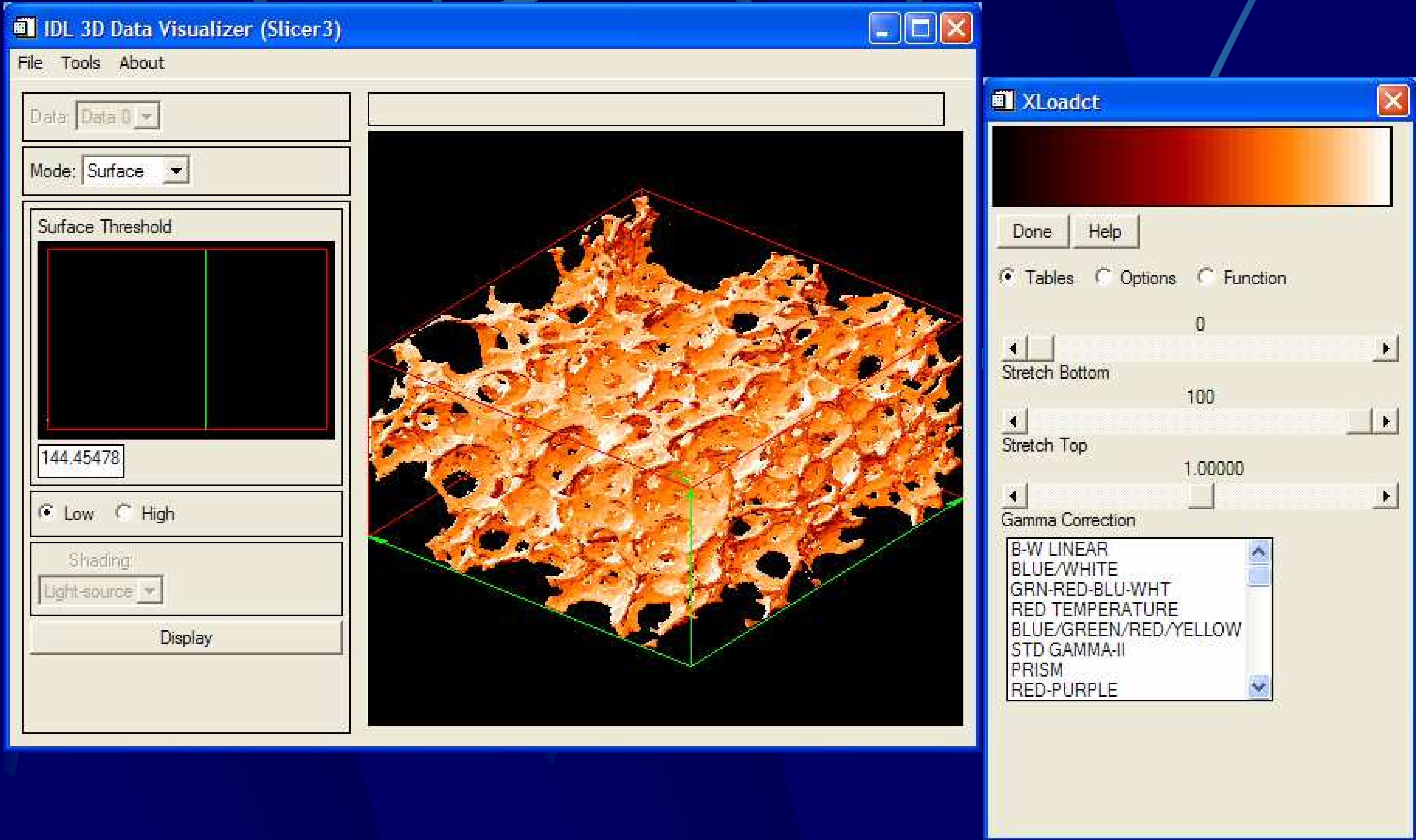
Volume rendering procedure



Slice visualizer



Isosurface rendering



Volume rendering

Virtual cut of the sample

(3.2 x 3.0 x 1.4) mm^3