Element-sensitive Computed Tomography by Fine Tuning of PXR-based X-ray Source

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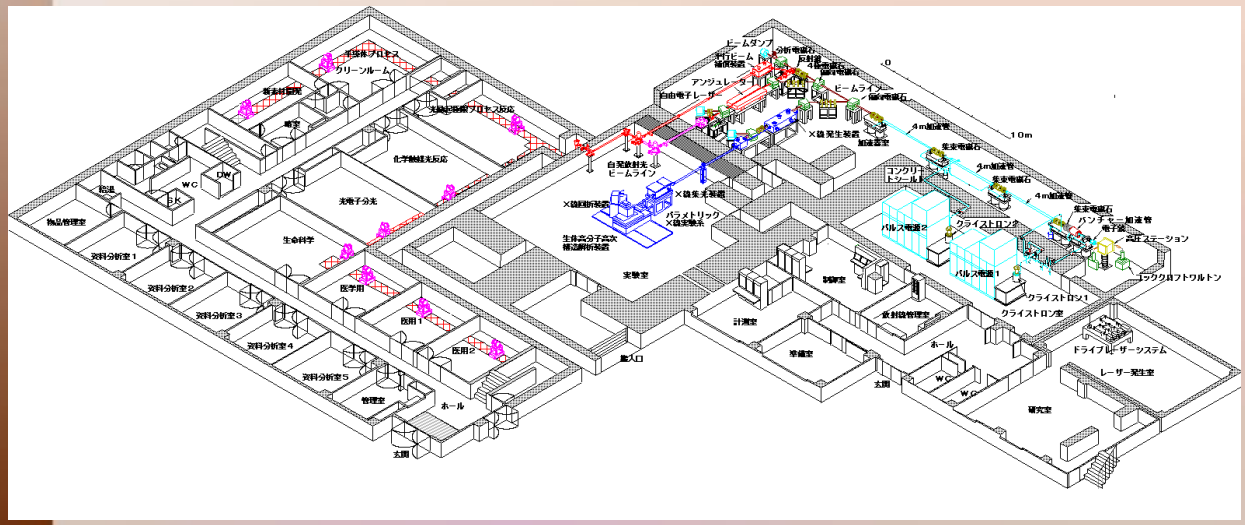
LEBRA facility of Nihon University

LEBRA: **L**aboratory for **E**lectron **B**eam **R**esearch & **A**pplication

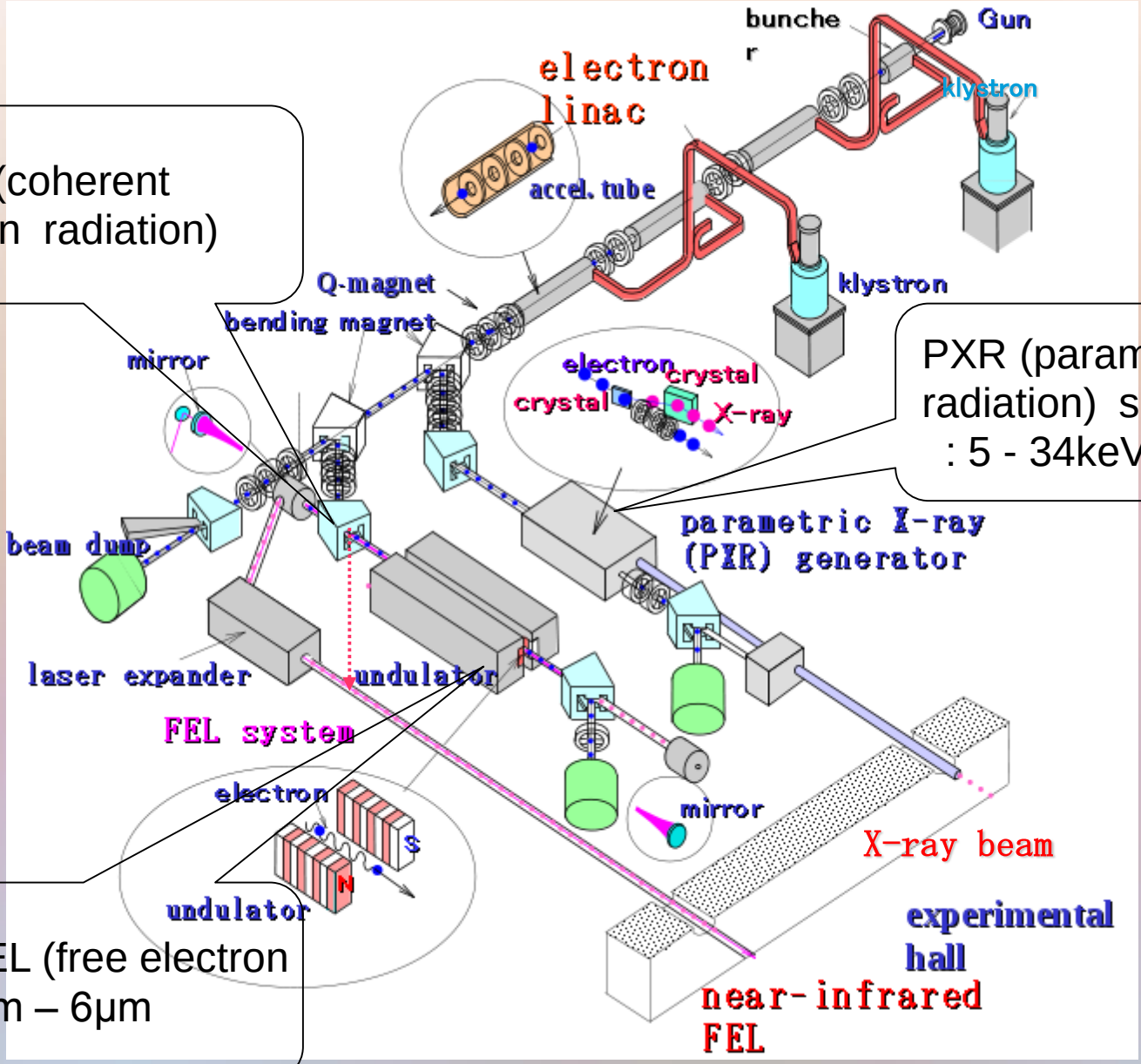


Tunable light-source facility based on
a conventional S-band electron linac

elctron energy: 125MeV(max.), 100MeV(typ.)
average current : 5μA (max.), 1 – 2 μA(typ.)

Tunable light source facility

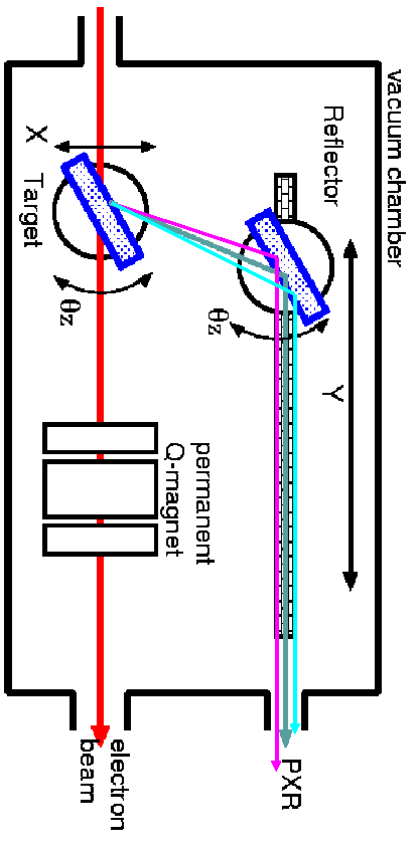
THz-CSR (coherent synchrotron radiation)

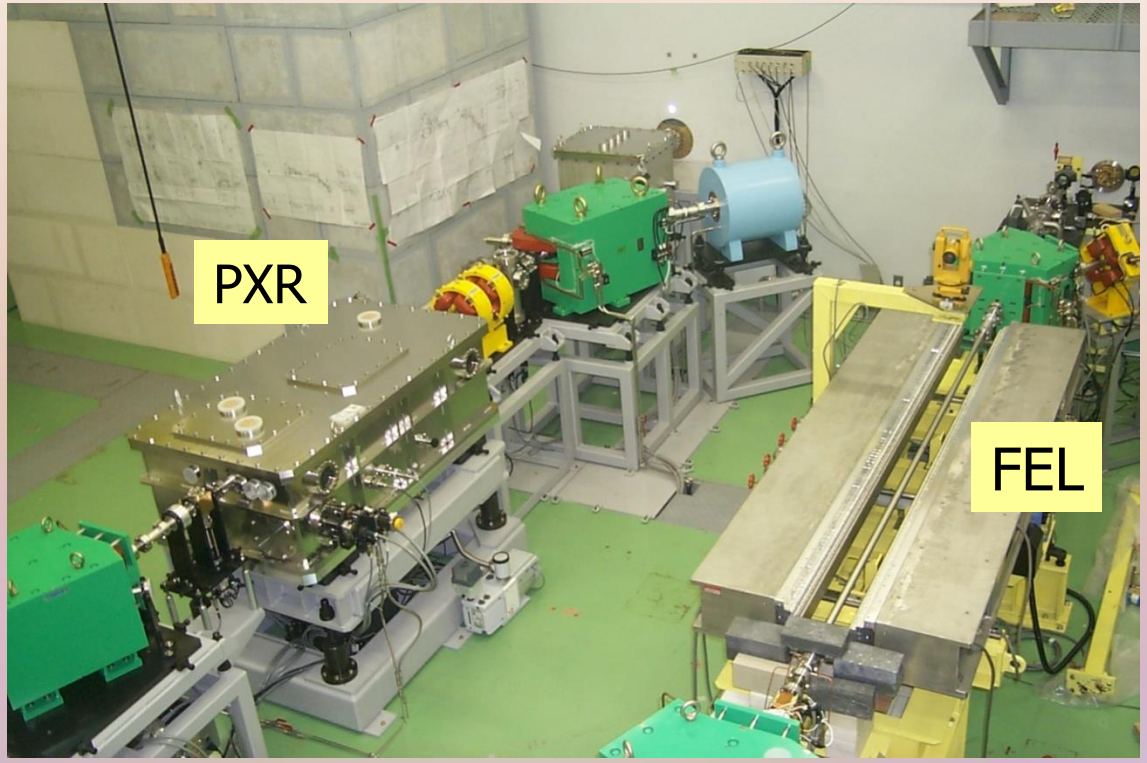


PXR (parametric X-ray radiation) source : 5 - 34keV

infrared FEL (free electron laser) : 1μm – 6μm

LEBRA facility: beamlines (FEL & PXR)





Free electron laser (FEL): 1 μm– 6 μm (near-IR)

Parametric X-ray radiation (PXR): double-crystal system

Status of LEBRA-PXR source

electron energy	**100 MeV**
accelerating frequency	**2856 MHz**
bunch length	**~3.5 ps**
macropulse duration	**4 - 10 μs**
macropulse beam current	**~130 mA**
repetition rate	**2 – 5 pps**
average beam current	**1 - 3 μA**
electron beam size	**0.5 – 1mm in dia.**
X-ray energy range	**Si(111): 5 – 20 keV**
	Si(220): 6.5 – 34 keV
irradiation field	**100 mm in dia.**
total photon rate	**$\geq 10^7$ /s @17.5keV**

Feature of LEBRA-PXR

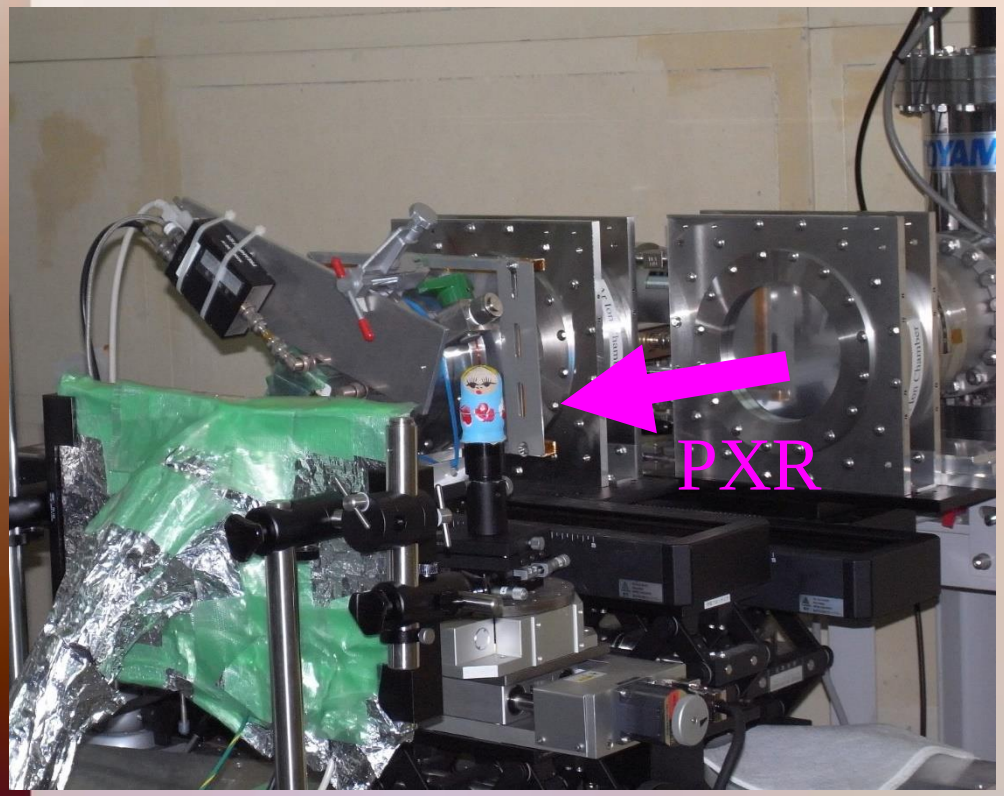
- Monochromaticity
  - energy dispersion (spatial chirp) ~ 10%
  - local band width ~ 0.1% (several eV)
- Tunability
  - continuous selection of the center energy
- Large irradiation field
  - at least 100mm in diameter
  - cone-beam depending on $1/\gamma$
- Spatial coherence
  - phase-contrast imaging is actually possible
- Stability
  - X-ray stability depends only on the linac condition

Application of LEBRA-PXR source

- Conventional imaging
  monochromaticity & tunability
- Diffraction-enhanced imaging
  refraction (phase-gradient) based phase contrast imaging based on small-angle scattering (SAXS)
- X-ray absorption fine structure (XAFS)
  energy dispersive type XAFS analysis
- Computed tomography (CT)
  monochromaticity & tunability
  propagation-based phase contrast effect

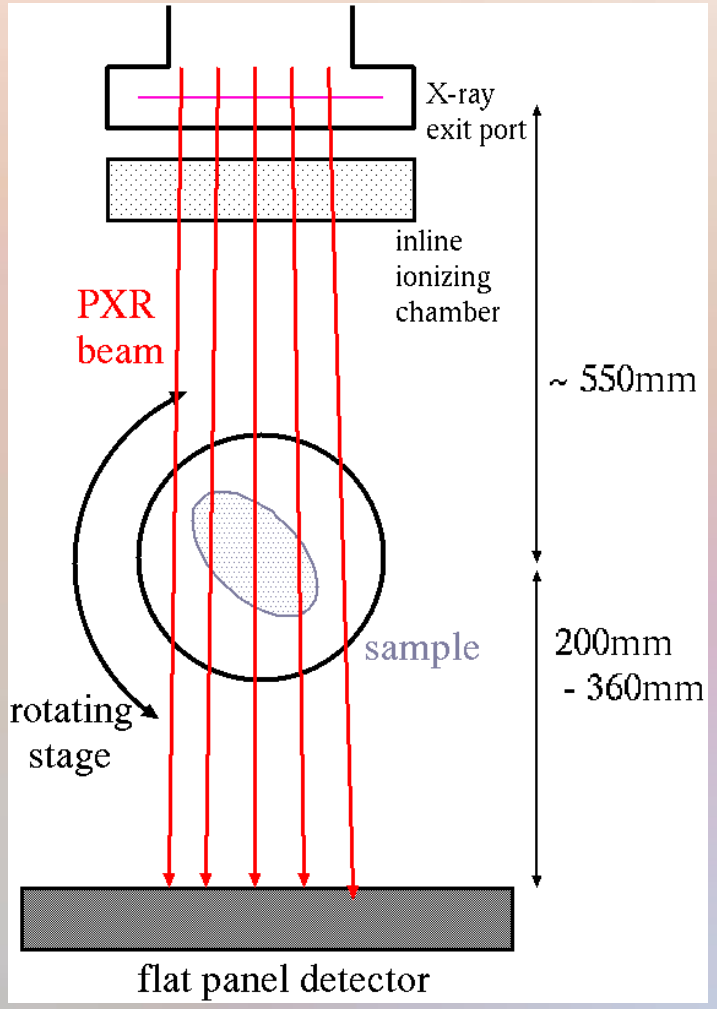
Setup for Computed Tomography Experiments

PXR source: Si(111)



FPD

sample &
rotating stage
(0 – 180 deg.)



Flat Panel Detector (FPD)

HAMAMATSU
C9728DK-10

Specification

scintillator: CsI (165μmt)

sensor: CMOS

pixel size: 50 μm x 50 μm

number of pixels: 1032 x 1032

active area: 51.6mm x 51.6mm

frame rate: 0.1 - 3 f/s

resolution: 10 line pairs/mm

X-ray absorption efficiency:

~ 85% @ 18keV

Sample 1

Sample:
matryoshka doll
(3 layers)

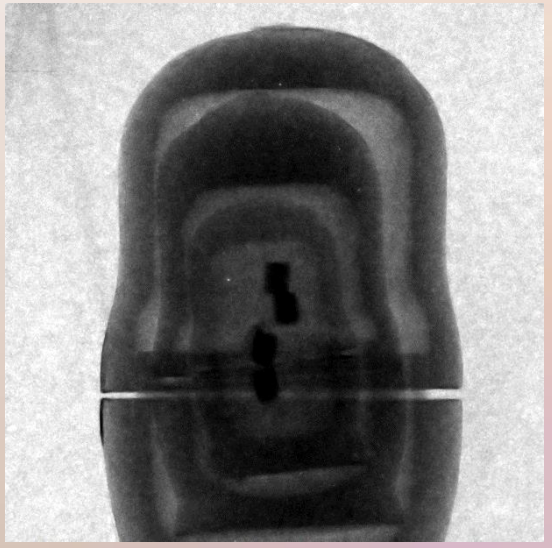
material: wood
diameter: 34mm
height: 55mm

polyethylene pellets containing $SrTiO_3$ (STO) (white pigment)

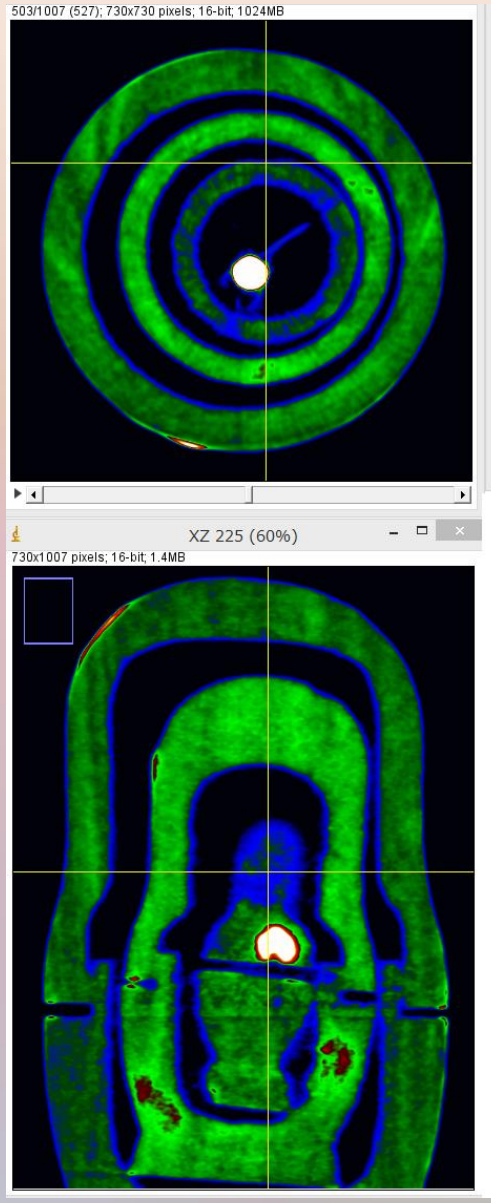
density: 1.0 g/cm^3
Sr: 4.8 wt %

2hr CT-scan experiment

projection image



PXR energy: 16.5keV
detector: FPD
exposure time: 10 s

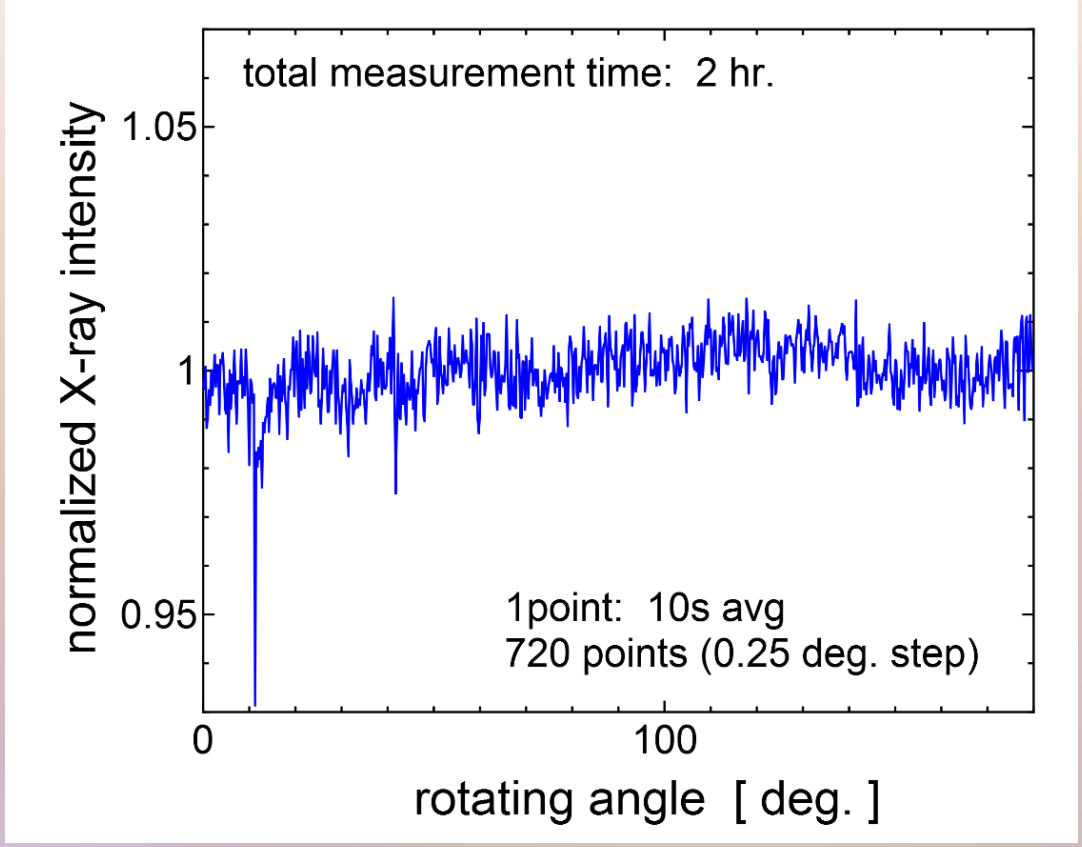


reconstructed 3D image

projection: 720
angular step: 0.25 deg.

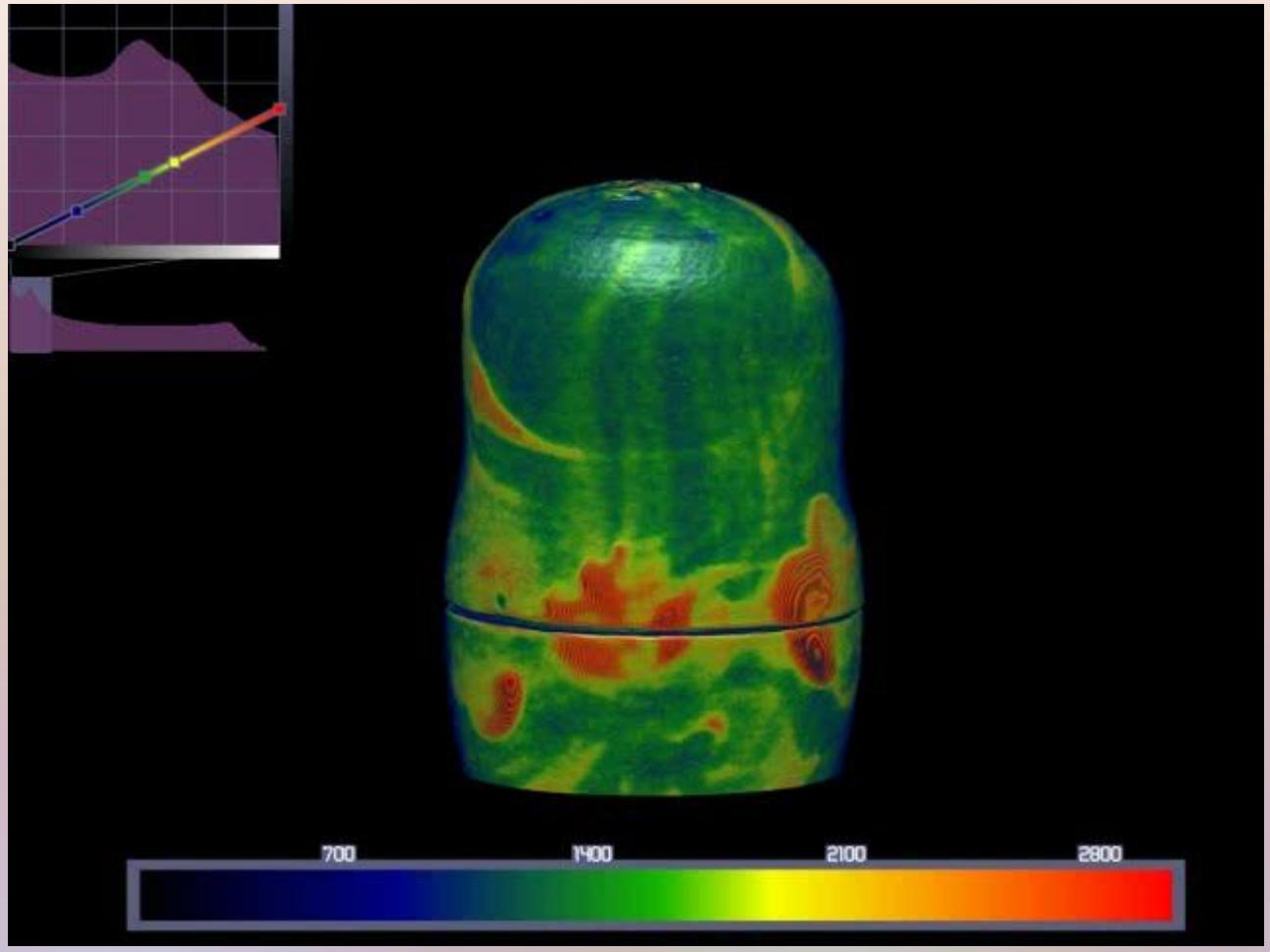
total measurement time:
2 hrs (net)

Stability of PXR beam



The PXR intensity was sufficiently stable during the CT experiment.

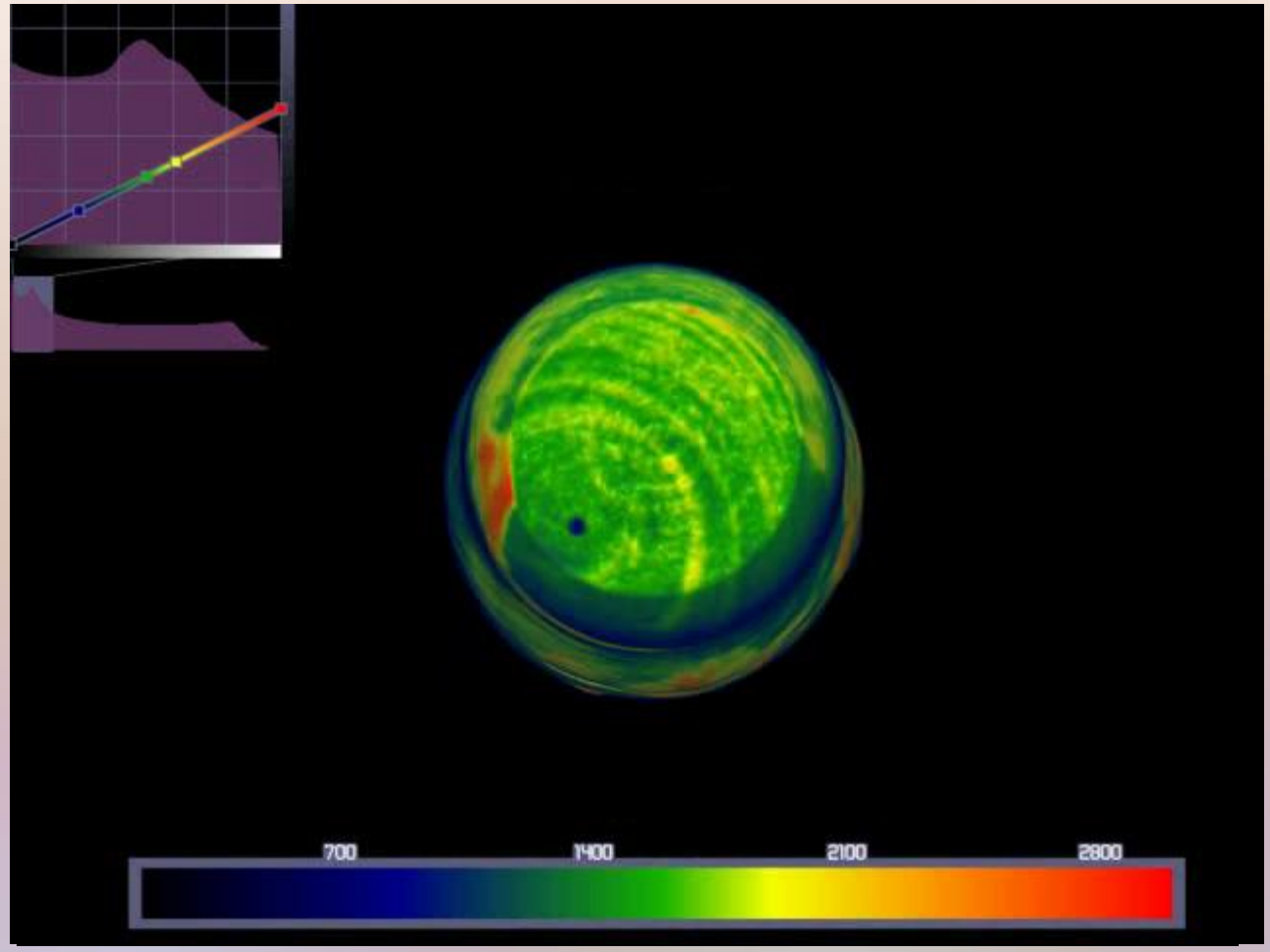
3D volume rendering



reconstruction algorithm:

conventional filtered back projection (FBP)

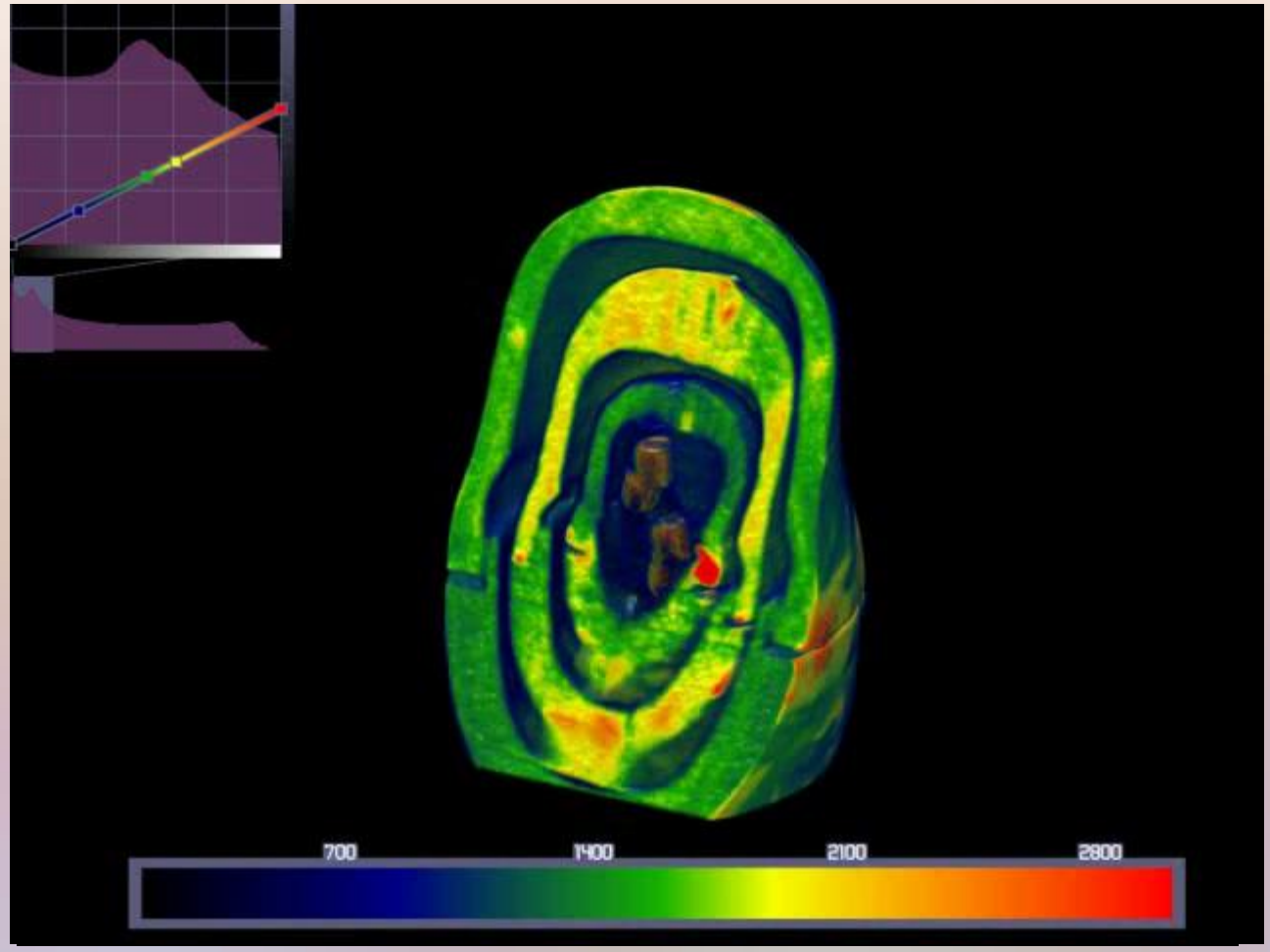
3D volume rendering



reconstruction algorithm:

conventional filtered back projection (FBP)

3D volume rendering

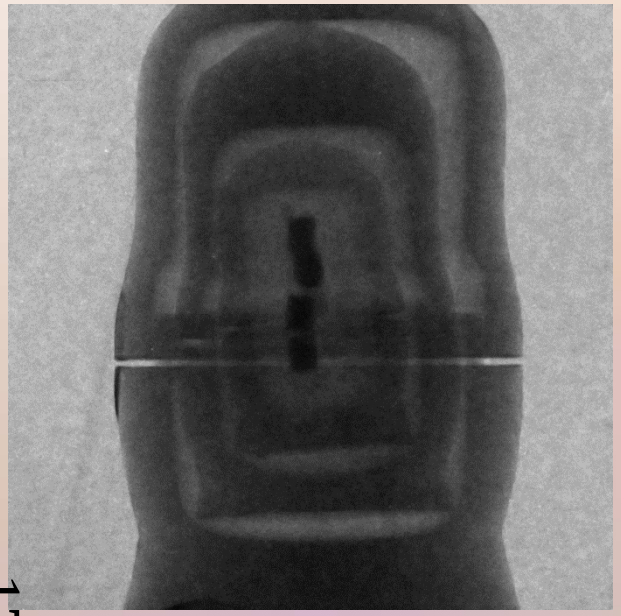


reconstruction algorithm:

conventional filtered back projection (FBP)

2-color CT across the Sr K-shell edge

higher energy



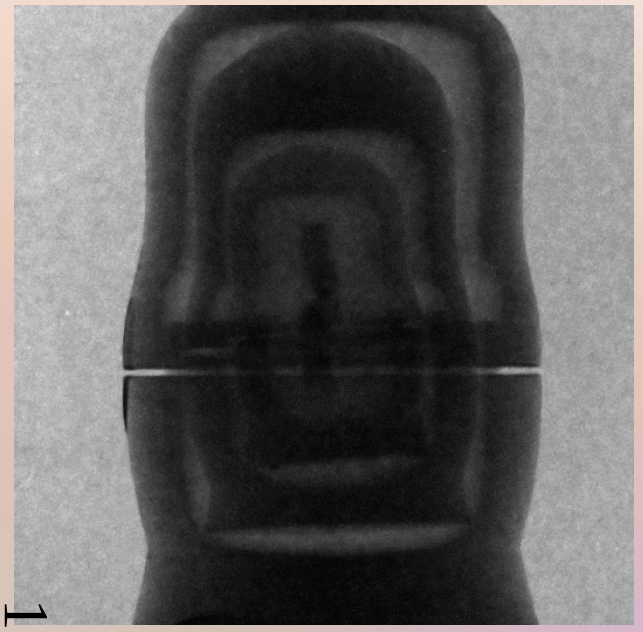
17.13keV

center
16.7keV

16.27keV

Sr K-edge: 16.1keV

lower energy



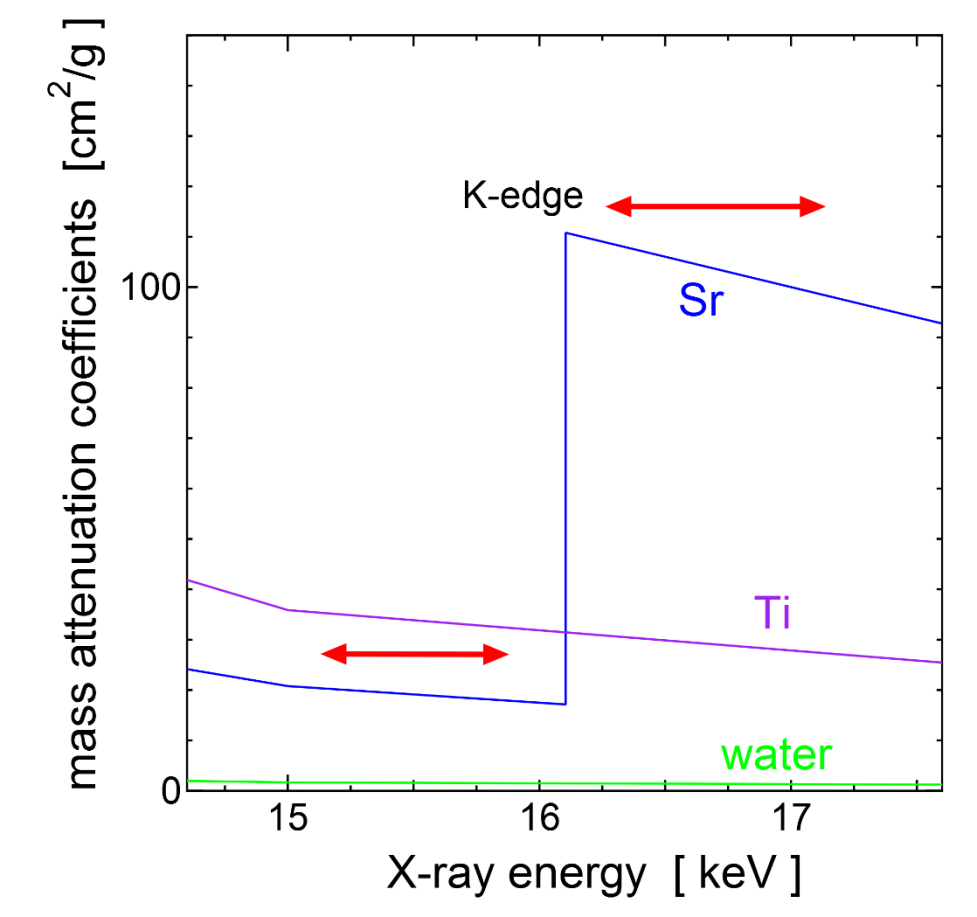
15.87keV

center
15.5keV

15.13keV

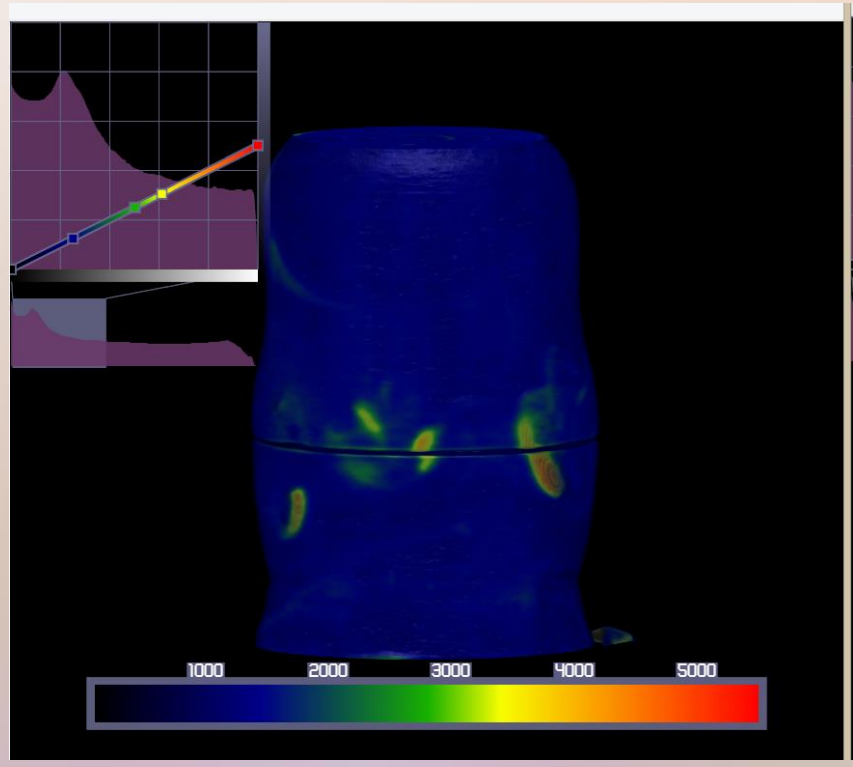
To obtain strontium distribution distinguished from other heavy elements, 2-color CT scans were carried out.

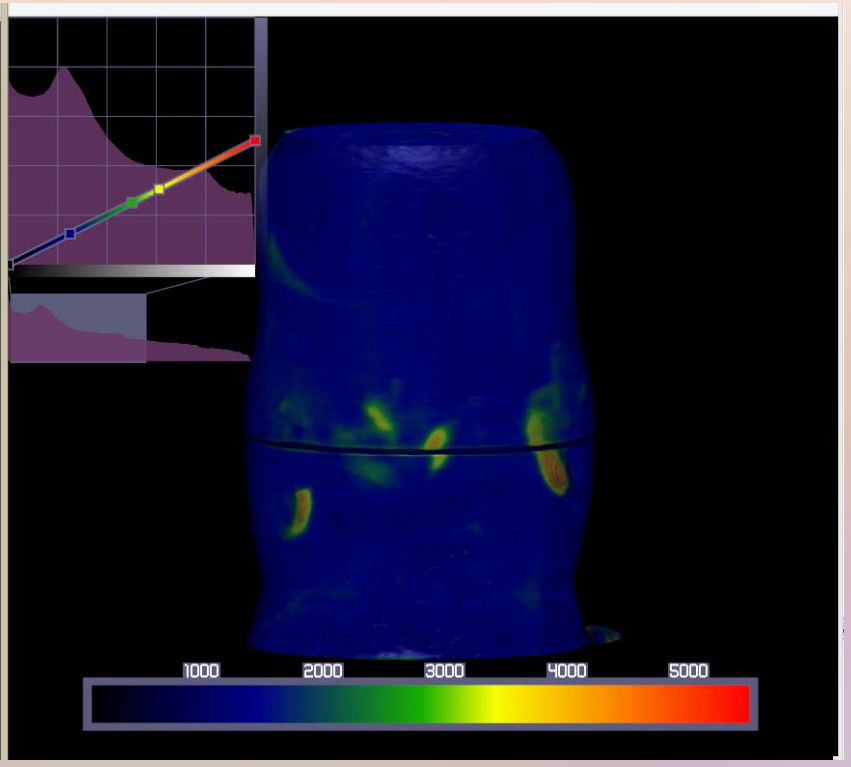
X-ray attenuation around the K-shell edge of Sr



The effect of the X-ray energy variation due to the spatial chirp of the PXR beam may be negligible because of the average effect of rotating the object by 180 deg.

Comparison of 3D distributions



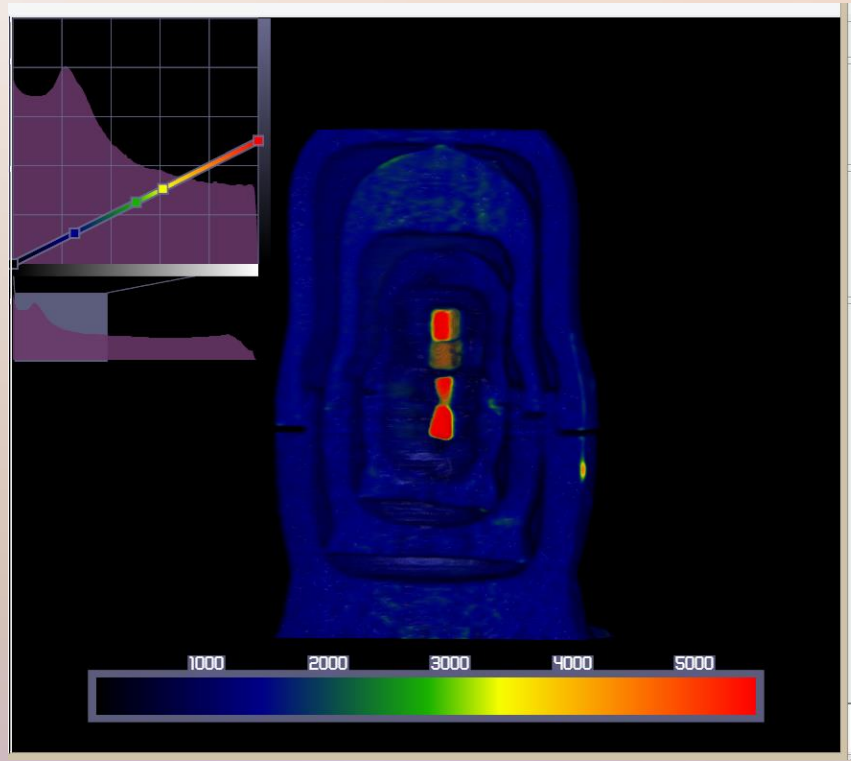


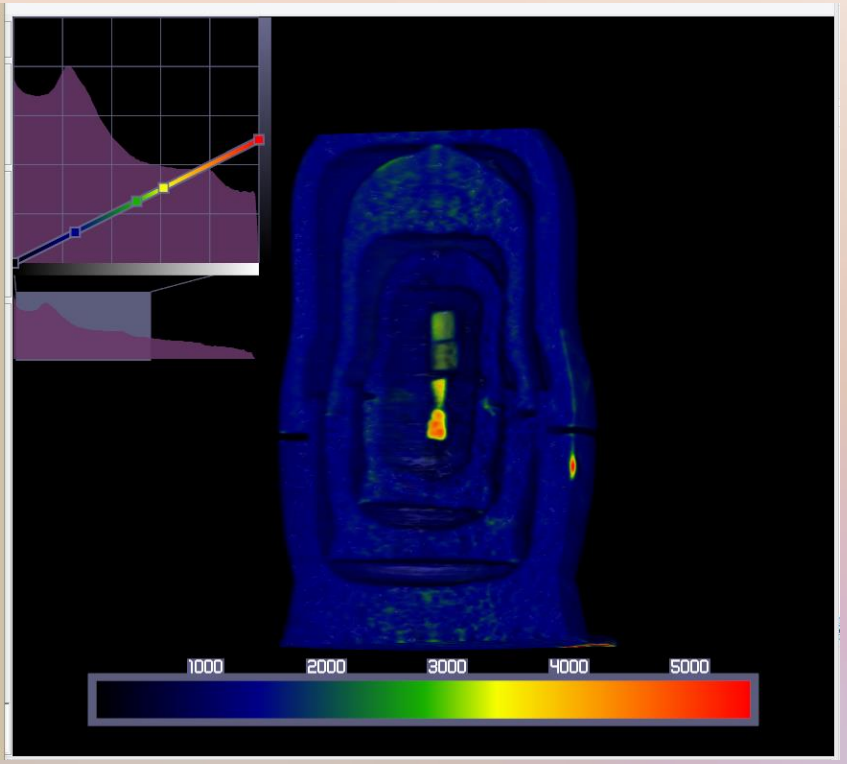
16.7 keV

15.5 keV

each measurement time: 1 hr (360 projections)
Both image contrasts are normalized at the wooden region.

Comparison of 3D distributions



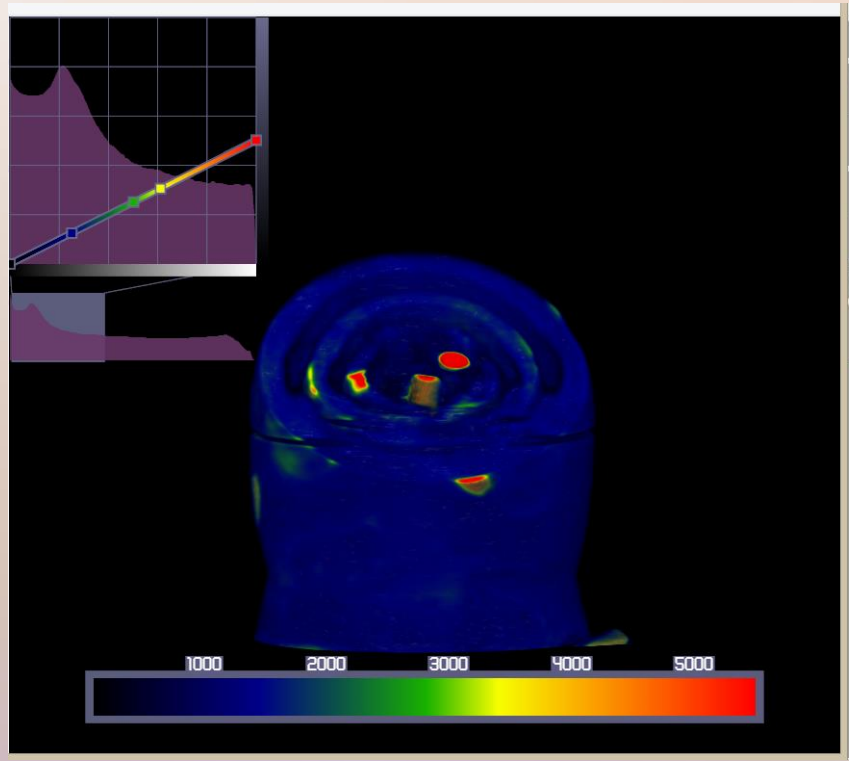


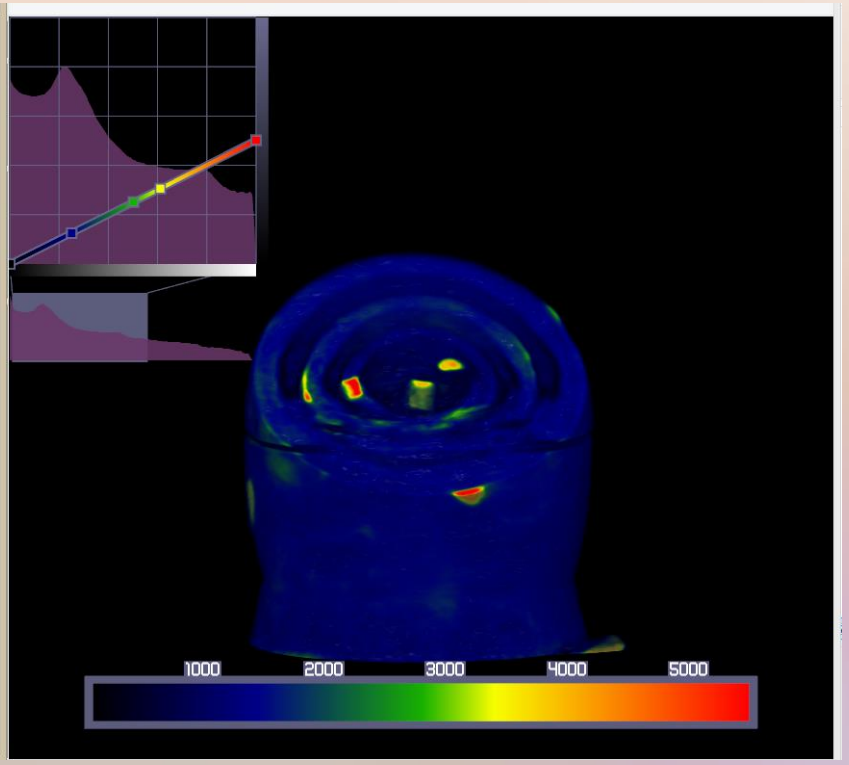
16.7 keV

15.5 keV

each measurement time: 1 hr (360 projections)
Both image contrasts are normalized at the wooden region.

Comparison of 3D distributions



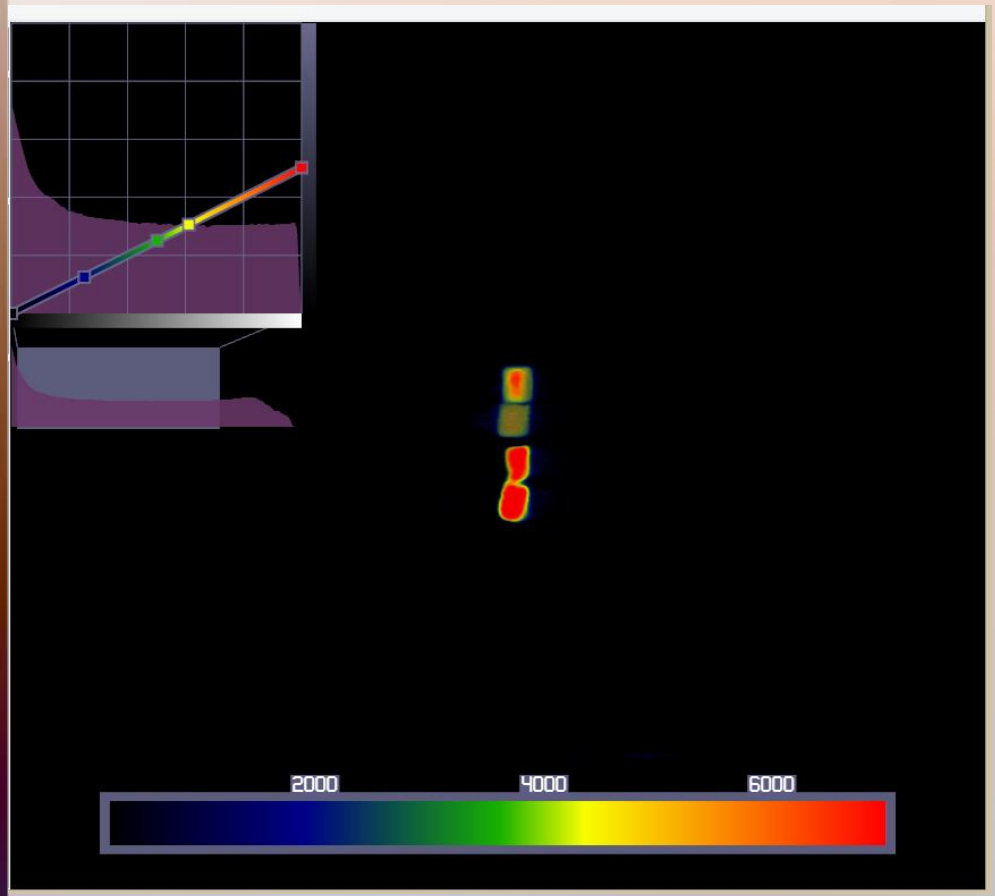


16.7 keV

15.5 keV

each measurement time: 1 hr (360 projections)
Both image contrasts are normalized at the wooden region.

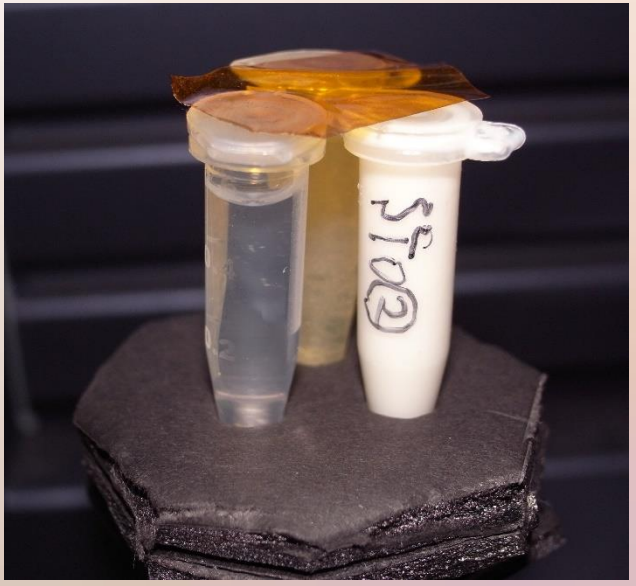
3D distribution of Sr

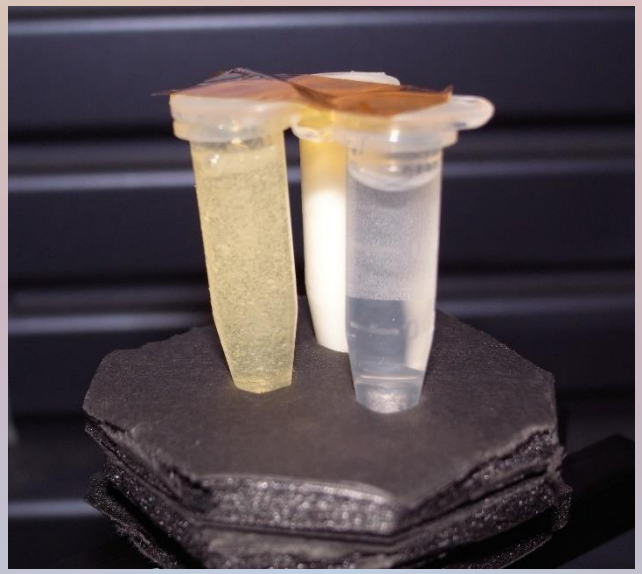


The 3D distribution of Sr element is obtained as difference between the tomographic images of 16.7keV and 15.5keV.

The experimental data are sufficiently reliable to cancel the contribution of other elements.

Sample 2





Experiment for a material with lower concentration of Sr

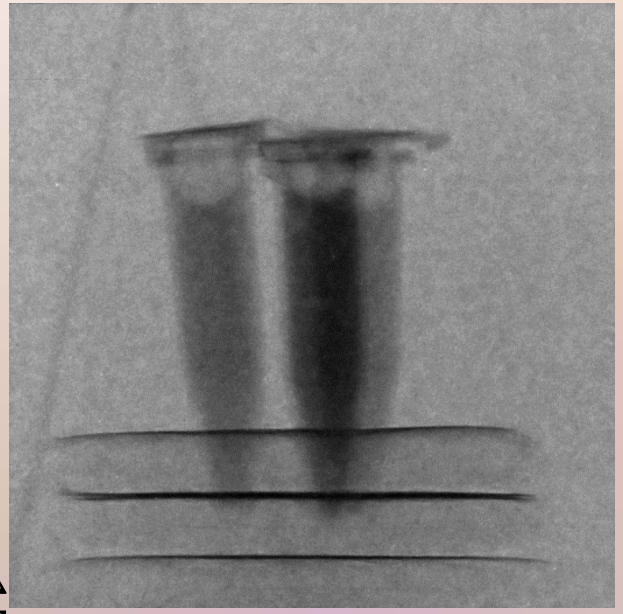
ethanol
density: 0.79 g/cm^3

epoxy resin
density: ~ 1.2 g/cm^3

epoxy resin + $SrTiO_3$ (STO)
density: ~ 1.2 g/cm^3
Sr: 0.6 wt %

2-color CT across the Sr K-shell edge

higher energy



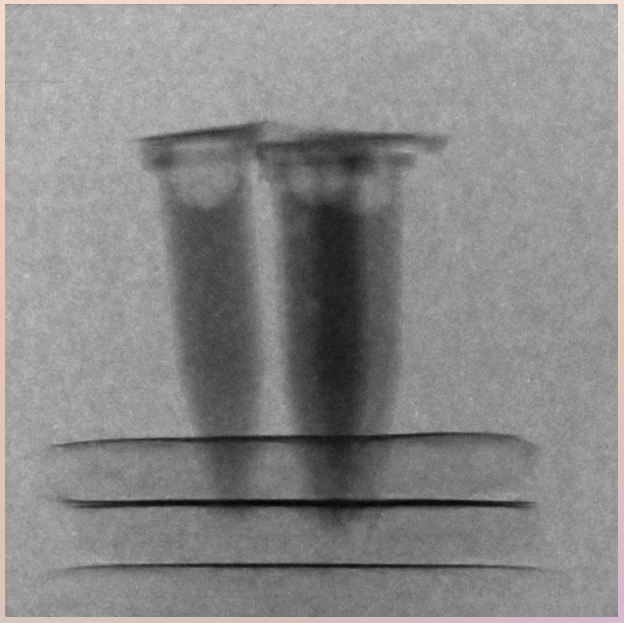
17.03keV

center
16.6keV

16.17keV

Sr K-edge: 16.1keV

lower energy



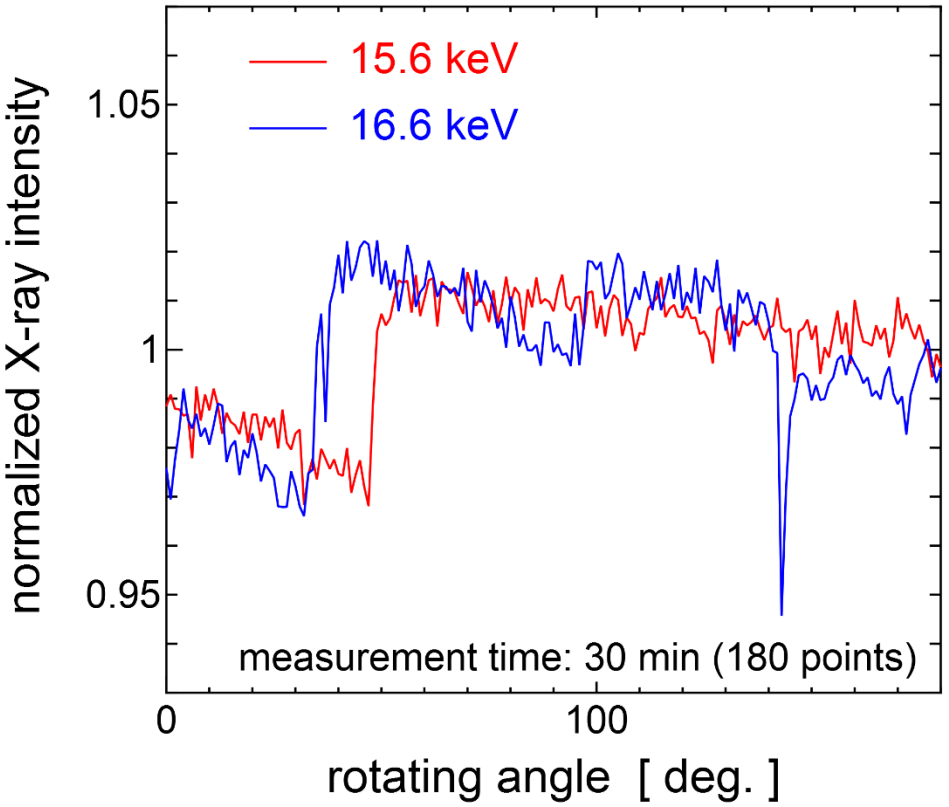
15.98keV

center
15.6keV

15.22keV

exposure time of each projection image: 10s
projection: 180 (each measurement time: 30min)

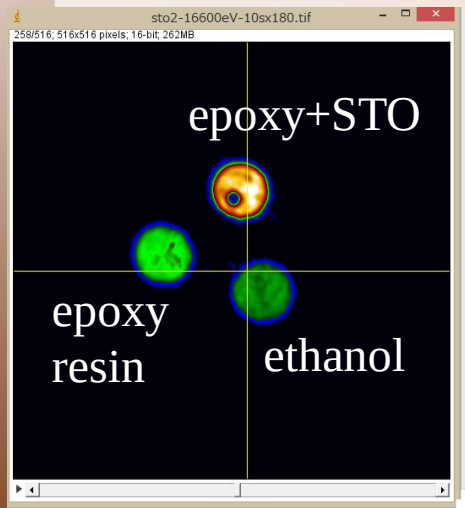
X-ray Stability during the measurement

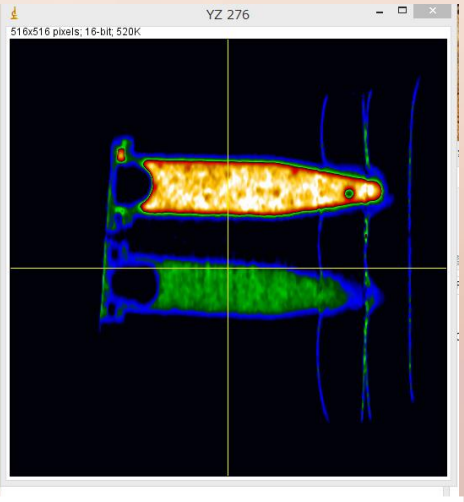


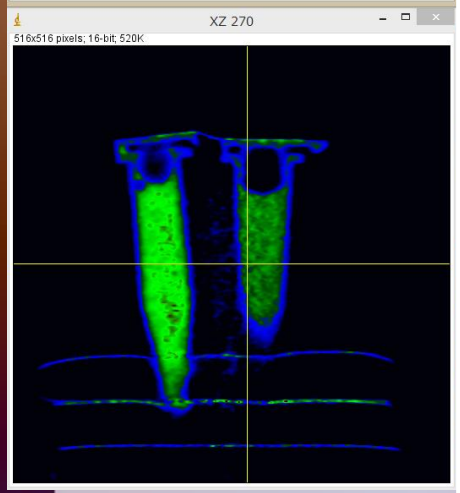
Intensity fluctuation of the incident X-rays during each measurement was less than 5%.

(At that time, the linac had a trouble with the injector vacuum.)

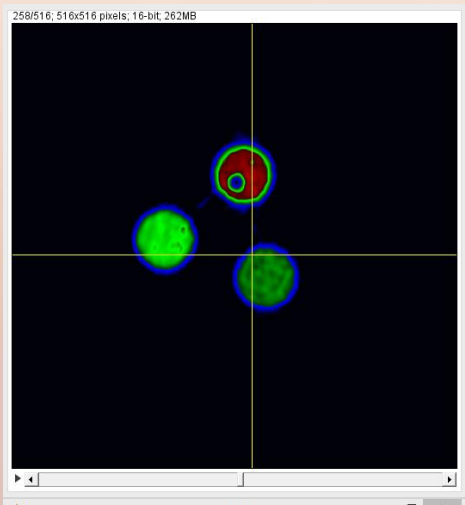
Result of reconstructions

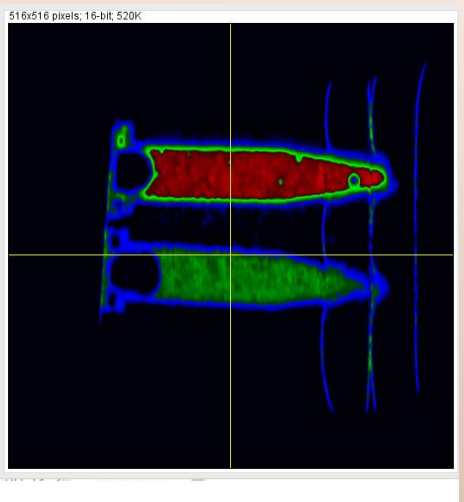


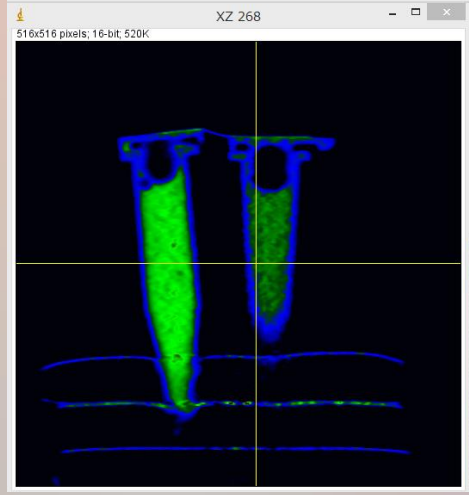




16.6keV



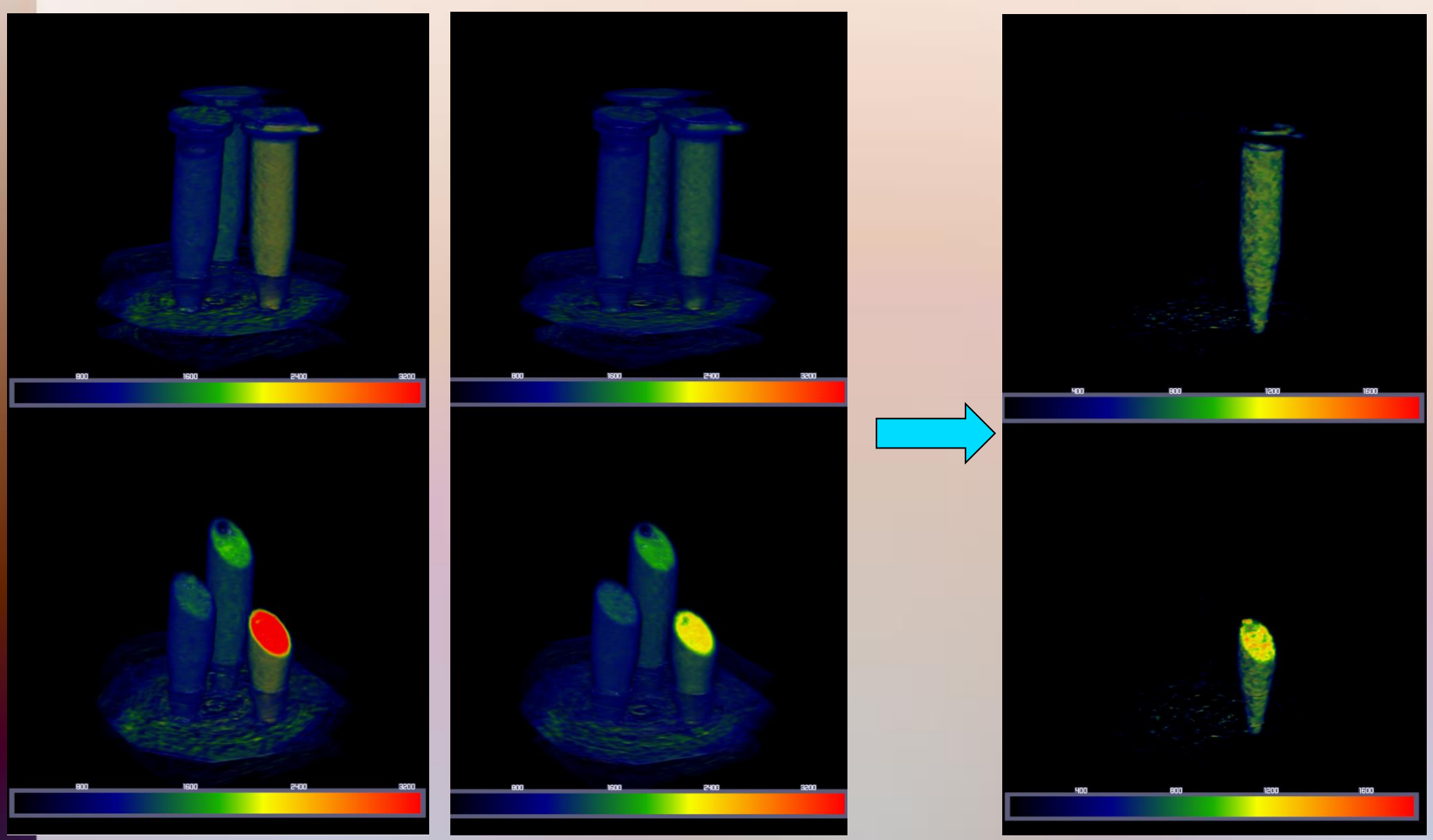




15.6keV

Image contrasts are normalized at the region of ethanol.

Comparison of 3D distributions

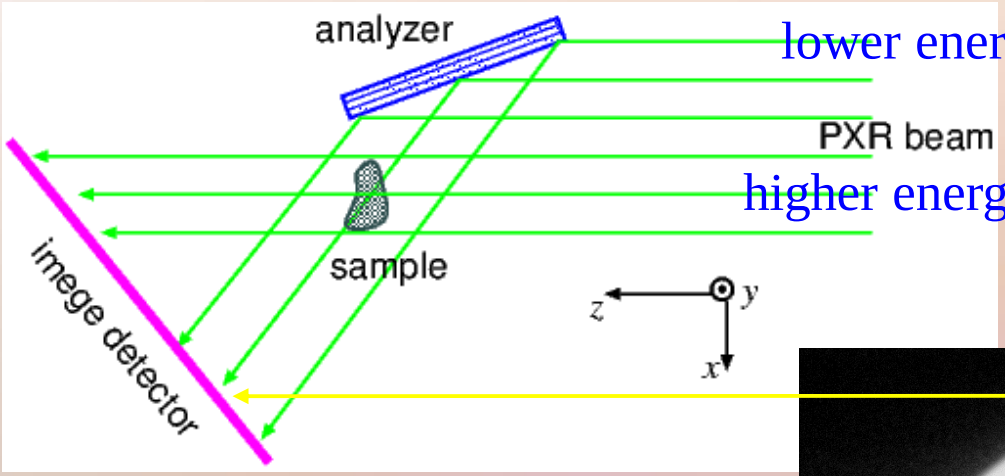


16.6 keV

15.6 keV

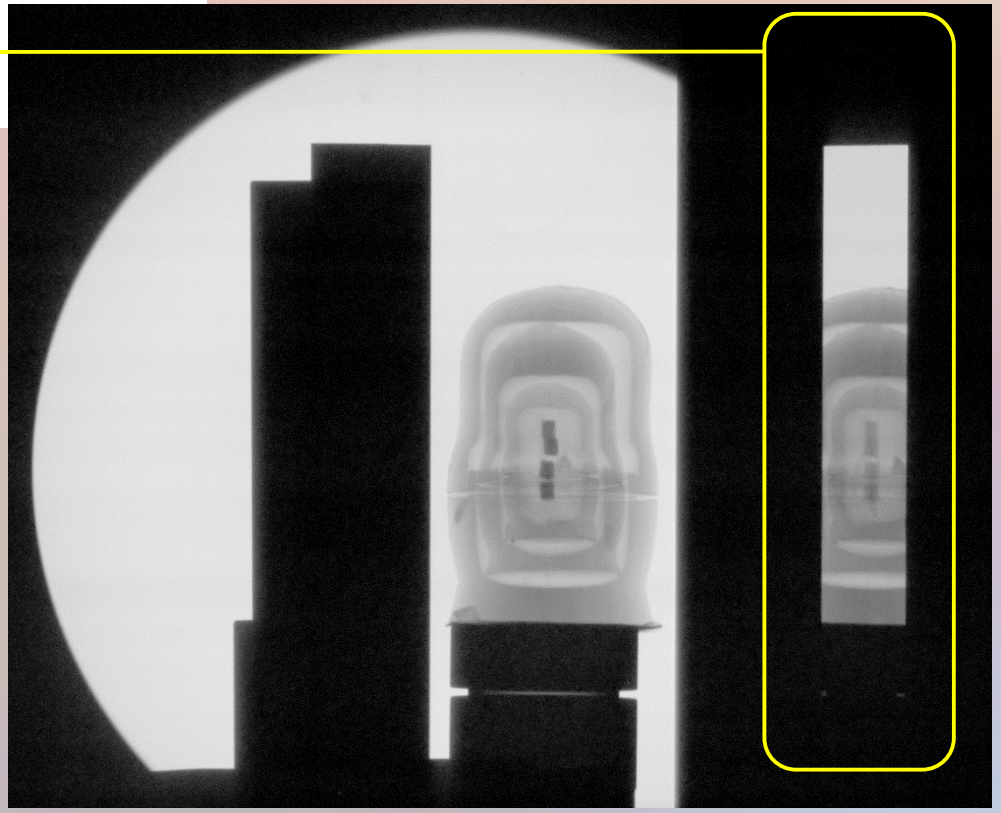
difference

Stereoscopic X-ray imaging



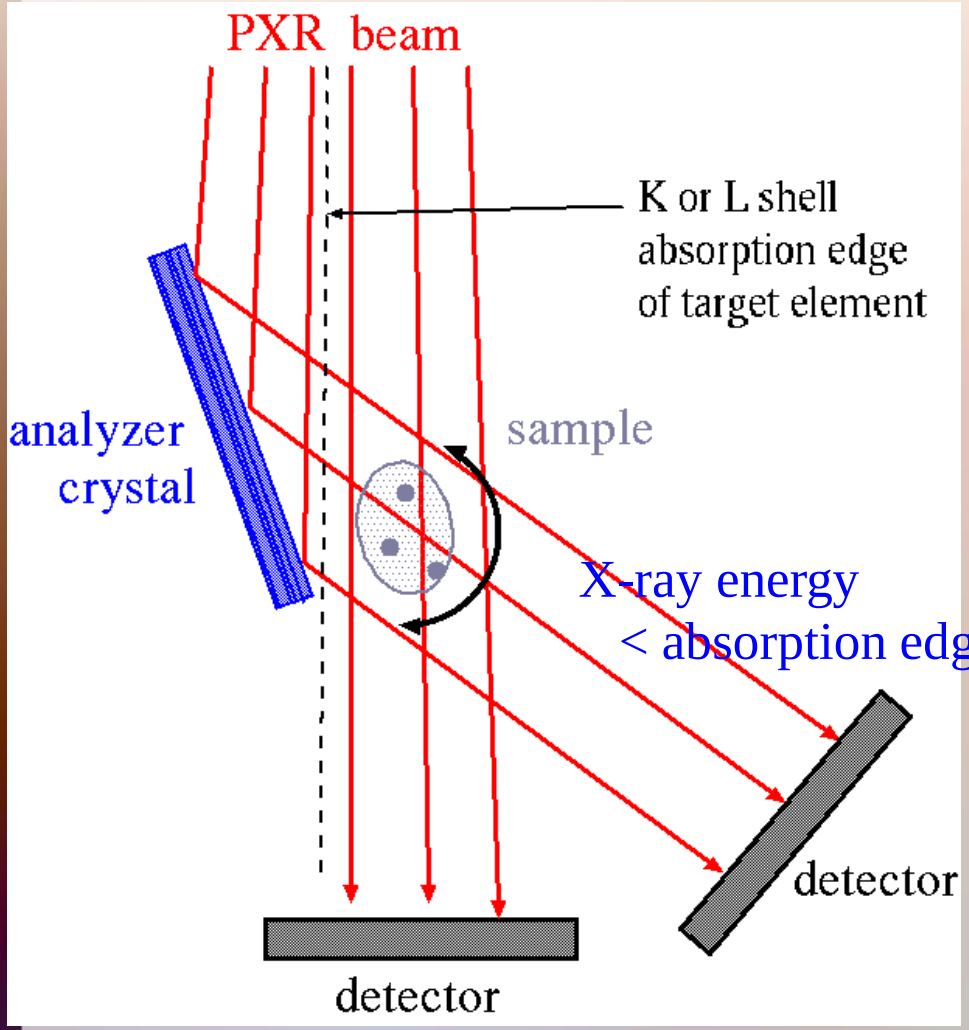
lower energy than Sr K-edge

higher energy than Sr K-edge



The technique of analyzer-based phase contrast imaging allows dichromatic crossing beam of X-rays with respect to the absorption edge of specific element.
It is useful for the element detection.

Simultaneous dichromatic CT for element detection



The distribution of a target element could be obtained using dichromatic crossing beam.

Now, we are preparing a new image detector and a compact rotating stage for such experiments.

Summary

- The LEBRA-PXR source is sufficiently stable for monochromatic CT scan of 2hrs.
- Comparison between the tomographic images obtained using the PXR beam of 15.5keV and 16.7keV gave the information of Sr element in the deep area of the specimen.
- 3D distribution of 0.6wt% Sr was successfully obtained by this 2-color CT scan experiment across the K-shell absorption edge.
- The technique realizes depth-direction analysis on specific element in samples.
- Experiments of simultaneous dichromatic CT-scans are projected as an advanced application of PXR.

Acknowledgements

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Thank you for your kind attention !!