Simultaneous K-edge subtraction tomography for strontium tracer using parametric X-ray radiation

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Collaborators

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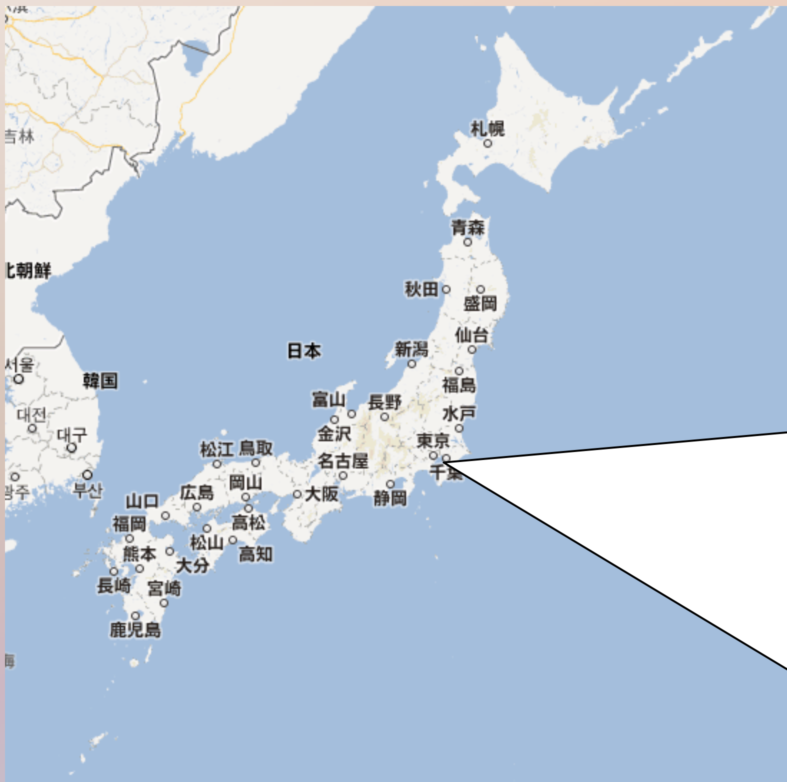
Outlines

- Status of LEBRA-PXR source
- Advanced imaging using the PXR source
- Computed Tomography using PXR
- Temporal-KES (K-edge subtraction) method
- Simultaneous-KES method based on PXR
- Summary

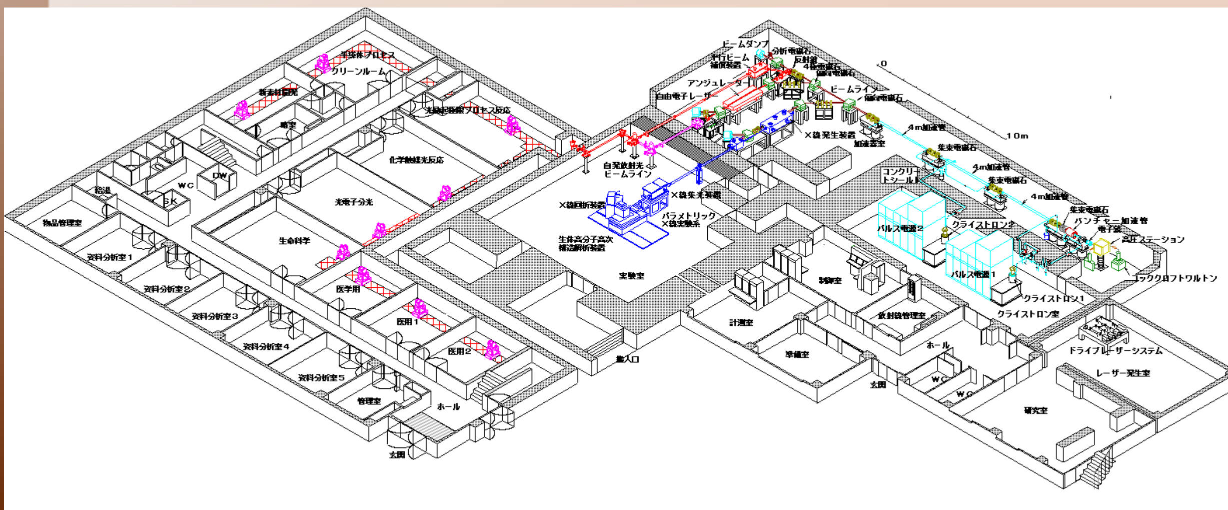
Nihon University



Funabashi, Chiba

LEBRA facility

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



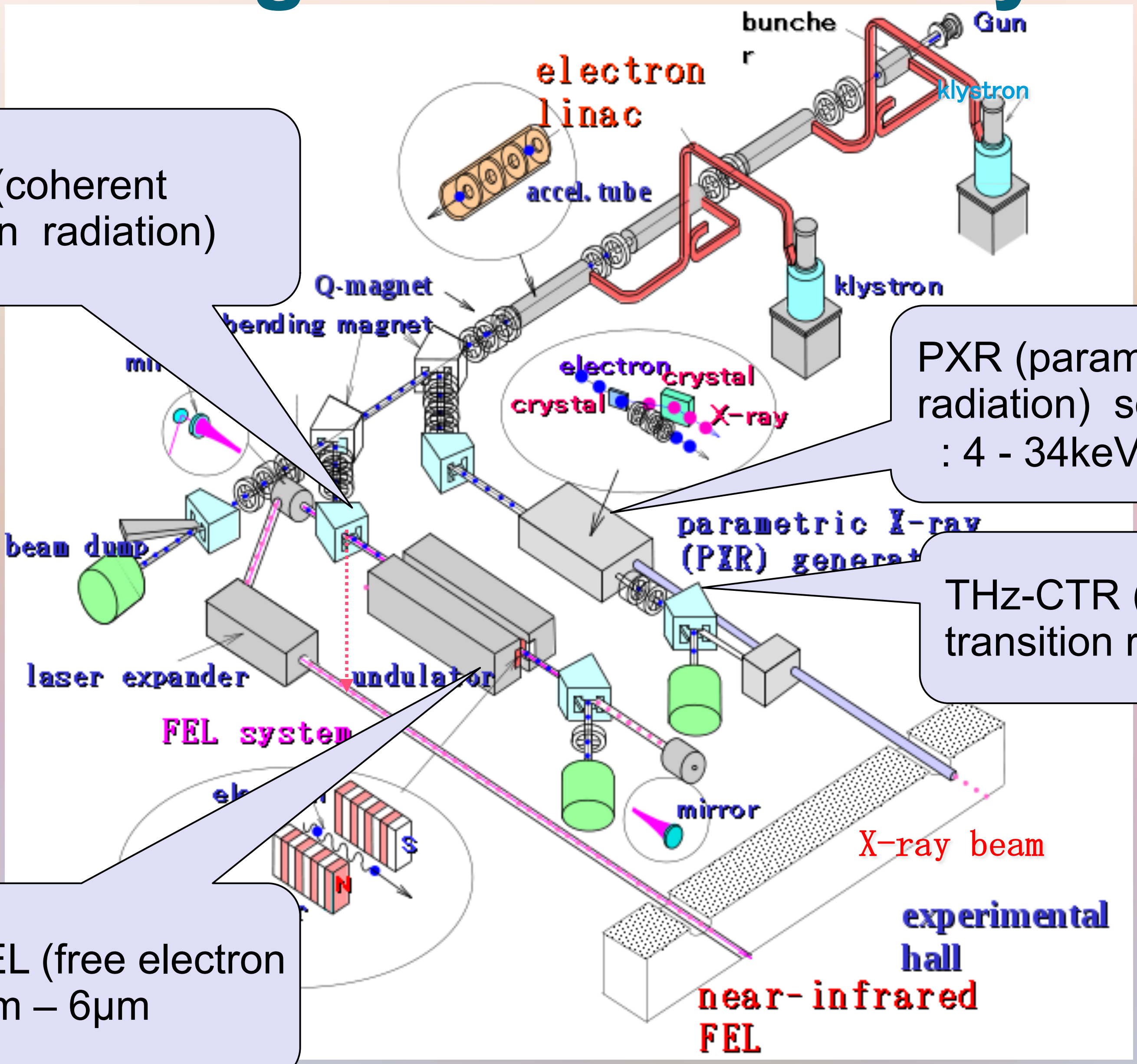
Coherent light-source facility based on
a conventional S-band electron linac

elctron energy: 125MeV(max.), 100MeV(typ.)
average current : 5μA (max.), 1 – 3 μA(typ.)

Specification of LEBRA Linac

electron energy	50 – 100 MeV
accelerating frequency	2856 MHz
bunch length (rms)	0.5 – 3 ps
bunch charge	~ 40 pC
macropulse duration	4 - 20 μs
macropulse beam current	~ 130 mA
macropulse repetition rate	2 – 5 pps
average beam current	< 5 ? A
beam emittance	< 20π mm mrad

Tunable light source facility



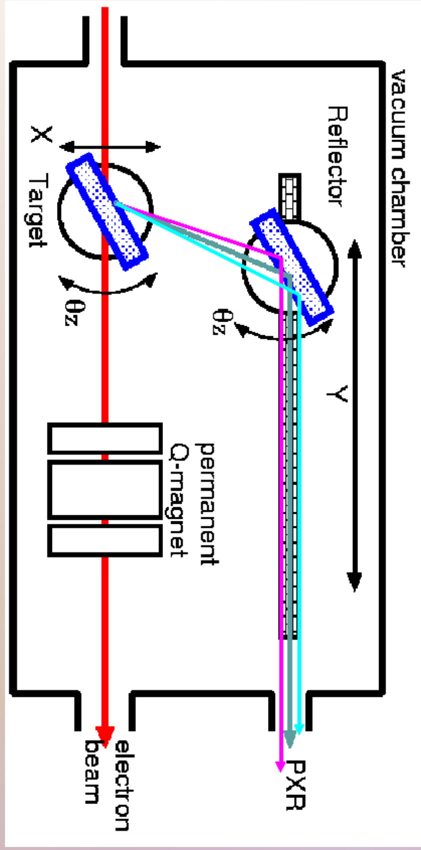
THz-CSR (coherent synchrotron radiation)

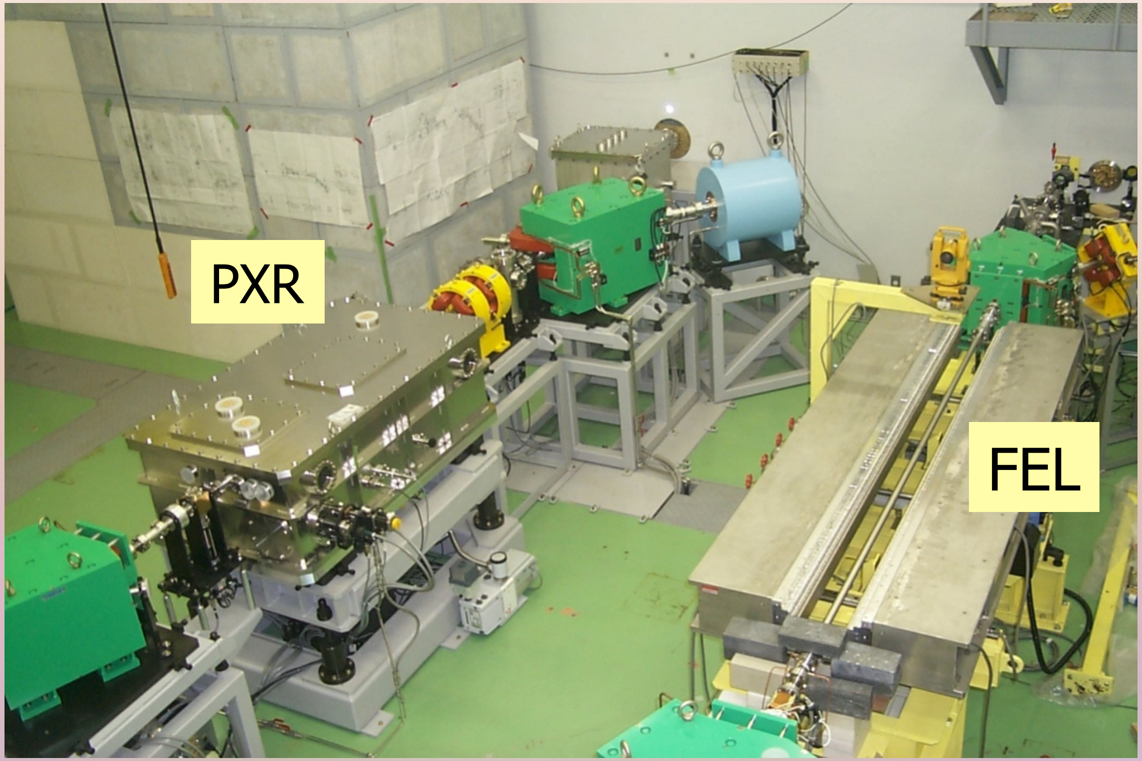
PXR (parametric X-ray radiation) source
: 4 - 34keV

THz-CTR (coherent transition radiation)

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

LEBRA facility: beamlines (FEL & PXR)





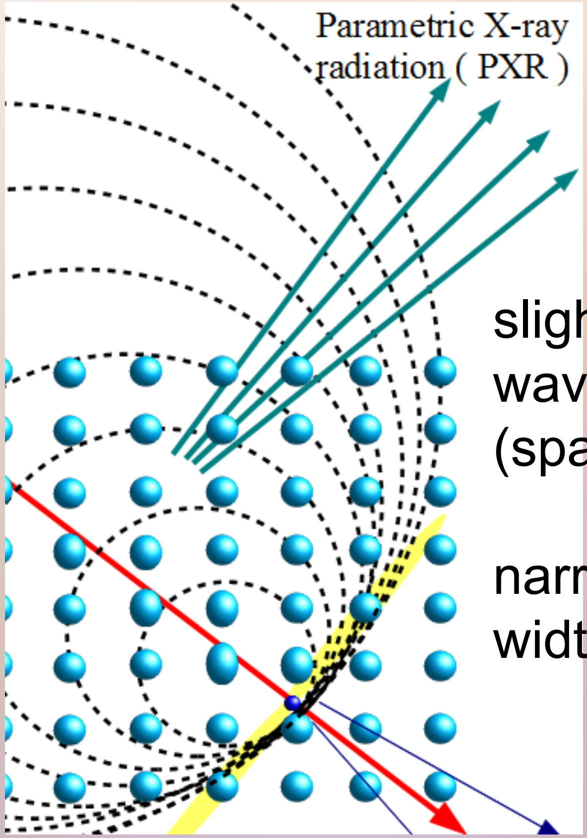
Free electron laser (FEL): 1 ?m– 6 ?m (near-IR)

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

Status of LEBRA-PXR source

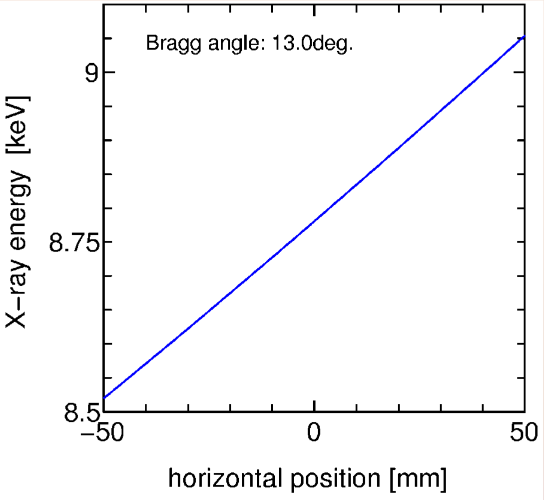
electron energy	100 MeV
X-ray radiator (target)	Si crystal plate
source size (e-beam spot on target)	0.5 – 1mm in dia.
X-ray energy range	Si(111): 4 – 20 keV Si(220): 6.5 – 34 keV
irradiation port	100 mm in dia.
total photon rate	$\geq 10^7$ /s @17.5keV

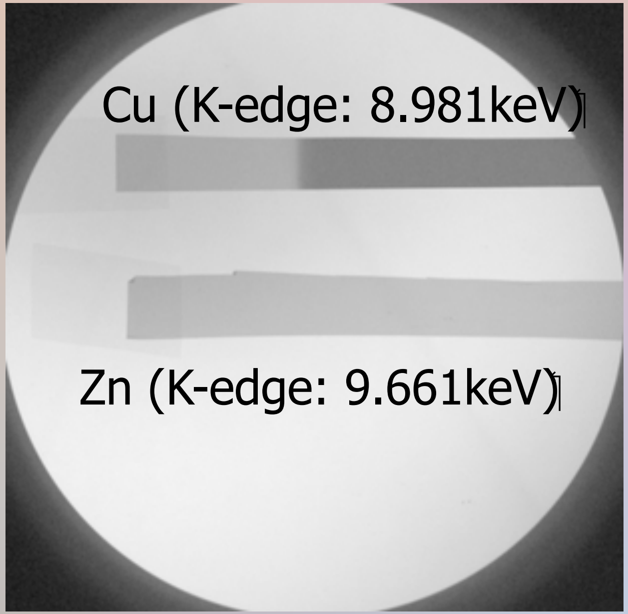
Spatial chirp of PXR beam



slight & continuous wavelength-shift (spatial chirp)

narrow local spectral width (several eV)





Wave front of PXR is different from both plane wave and spherical wave.

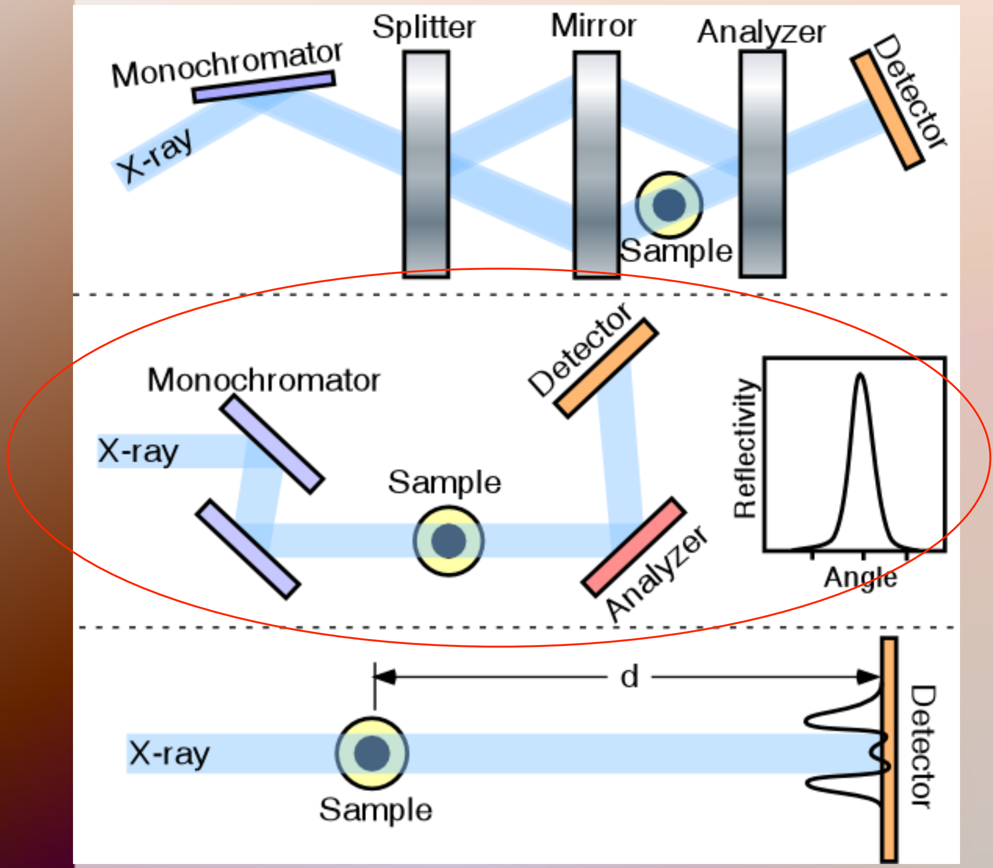
Feature of LEBRA-PXR

- Monochromaticity
  - energy dispersion (spatial chirp) ~ 10%
  - local band width ~ 0.1% (several eV)
- Tunability
  - continuous selection of the center energy
- Large irradiation area
  - 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) contrast
  contrast 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

Phase-contrast X-ray imaging



interferometer-based technique

Si perfect crystal interferometer

Talbot interferometer

analyzer-based technique

DEI: diffraction-enhanced imaging

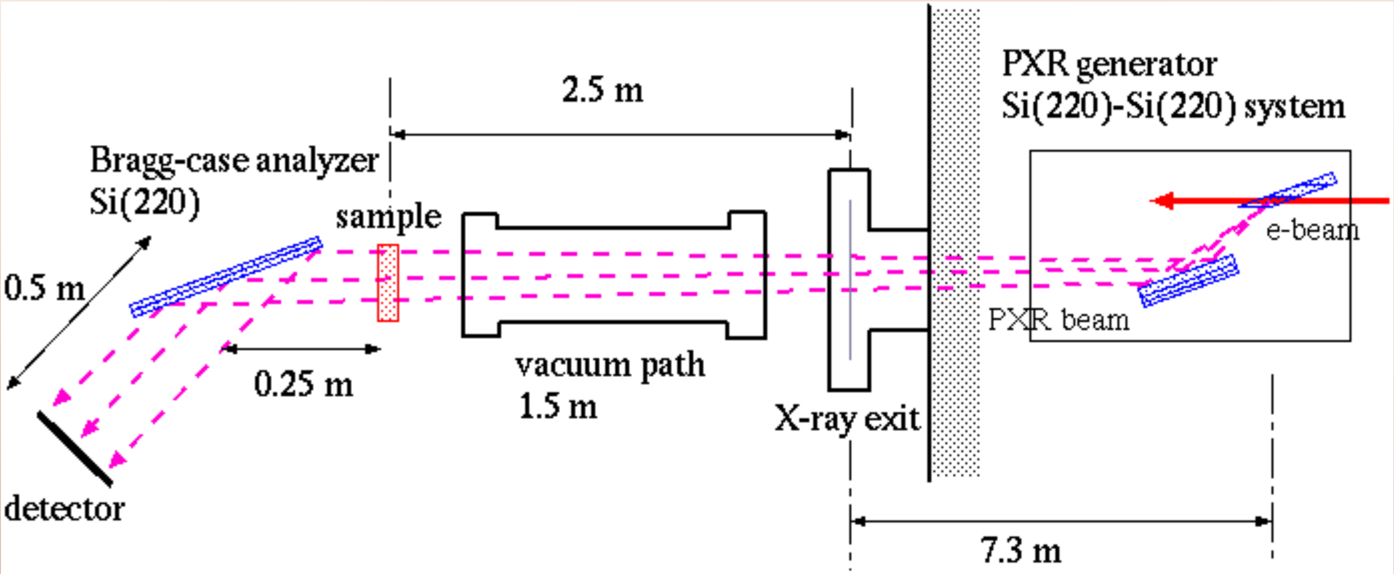
propagation-based technique

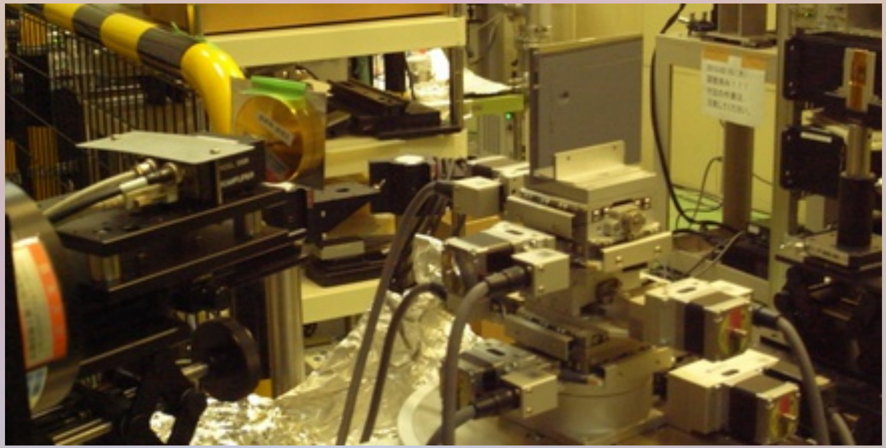
R. Fitzgerald: Phys. Today 53 (2000) 23

DEI is possible using PXR.

Setup of DEI experiments

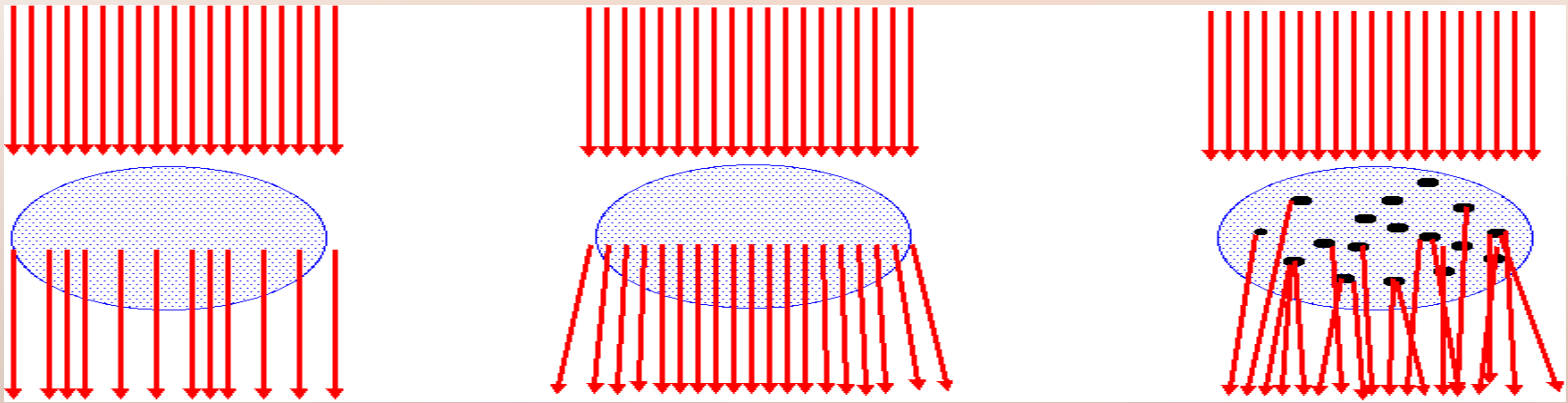
top view

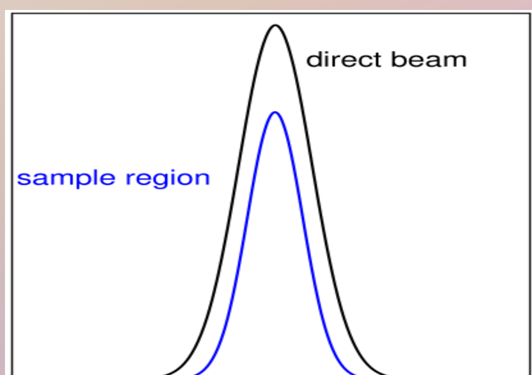




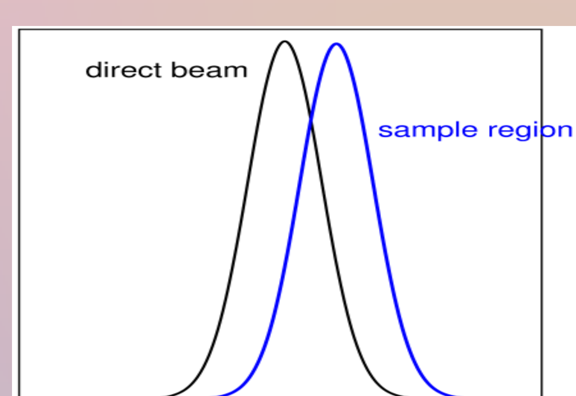
Due to the extension of cone-beam, a wide irradiation field can be obtained without asymmetric analyzer.
The distance between the PXR source and the sample is shorter than 10m.

Interaction between X-rays and material

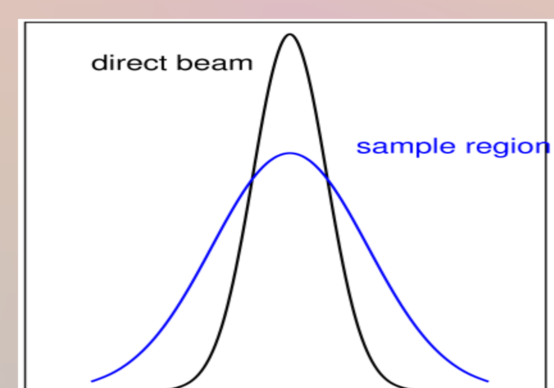




absorption (amplitude attenuation): reduction of the peak area

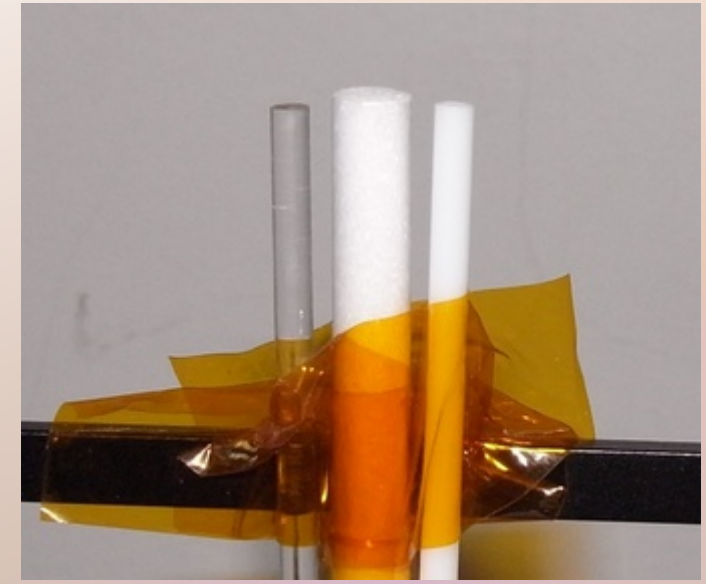


refraction (phase shift): shift of the center position



small-angle scattering (SAXS): reduction of the peak height (or peak broadening)

Experiment for demonstration



Sample:
acrylic rod (3mm in dia.)
density: 1.17 g/cm^3

styrene-foam rod (6mm in dia.)
density: 0.16 g/cm^3

polystyrene rod (3mm in dia.)
density: 0.986 g/cm^3

PXR source:
radiator-reflector: Si(220)-Si(220)
electron energy: 100MeV
average beam current: 3μA
PXR energy: 25.5keV
photon rate: ~ 10^6 /s /100mm in dia.

DEI measurement setup:
analyzer: Si(220)
160mm x 35mm x 5mm
angular step: 0.4625 μrad
image sensor: X-ray CCD
(Q.E. @25.5keV ~ 10%)
pixel size: 24μm x 24μm

Image contrast

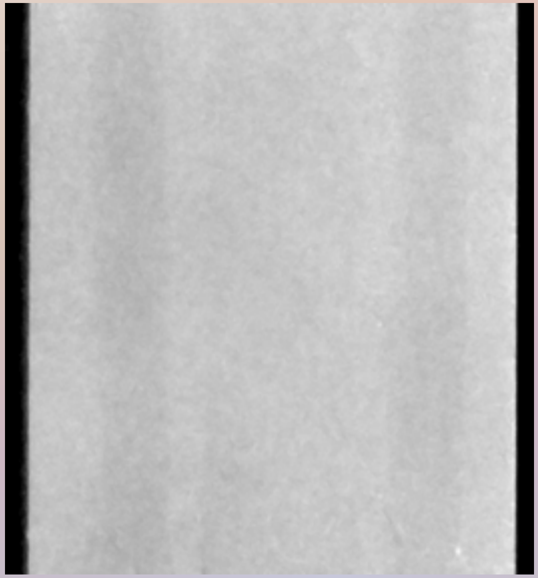
sample:

acrylic rod, styrene-foam rod, polystyrene rod

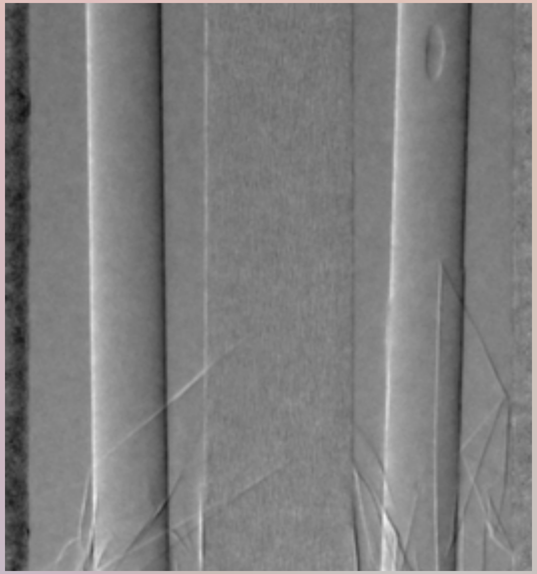
PXR energy: 25.5 keV

Phase contrast is much stronger than absorption contrast.

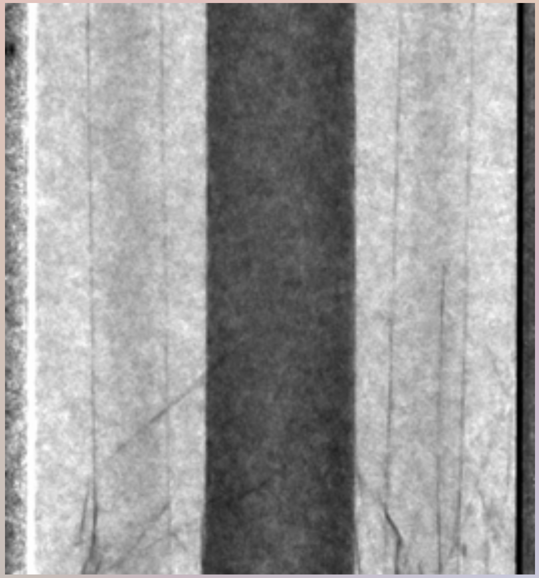
SAXS imaging is sensitive to micro structures of sample material smaller than 1-micron.



absorption

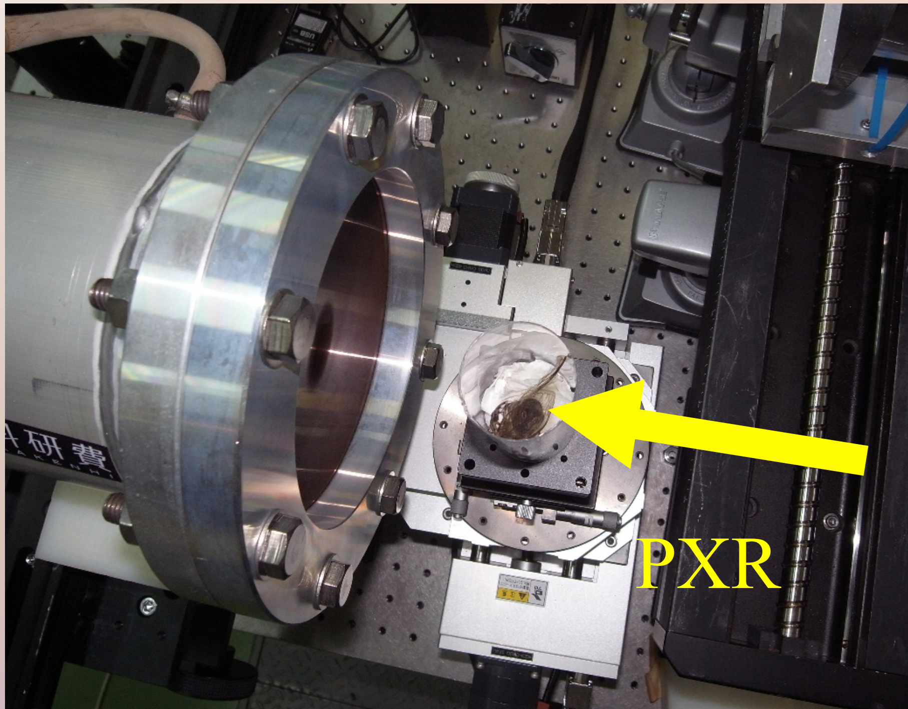


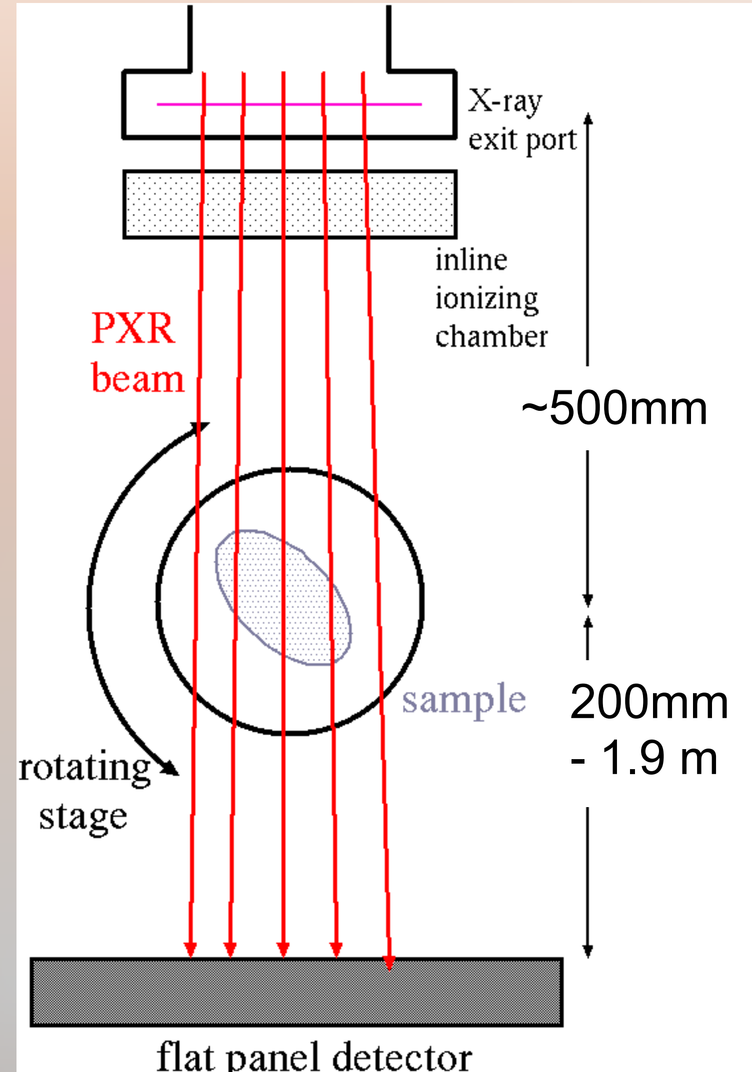
refraction
（phase gradient map）



small-angle scattering
（SAXS contrast）

Setup for CT experiment using PXR



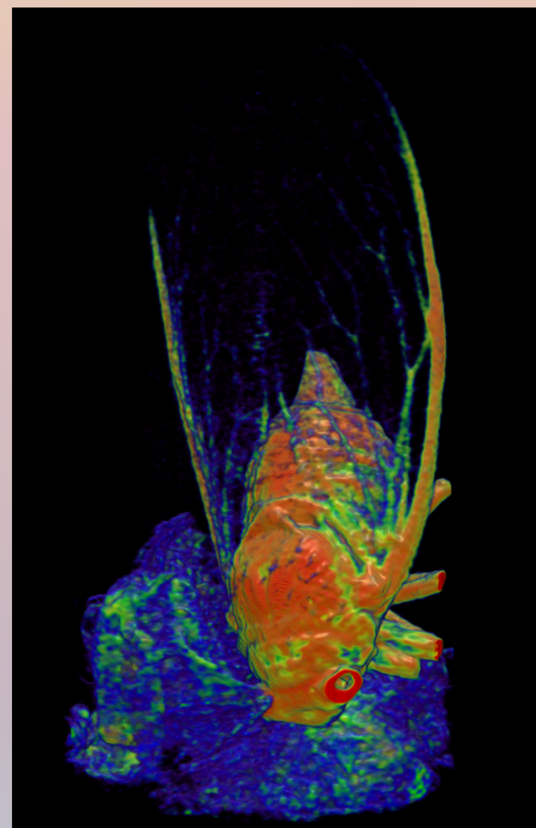


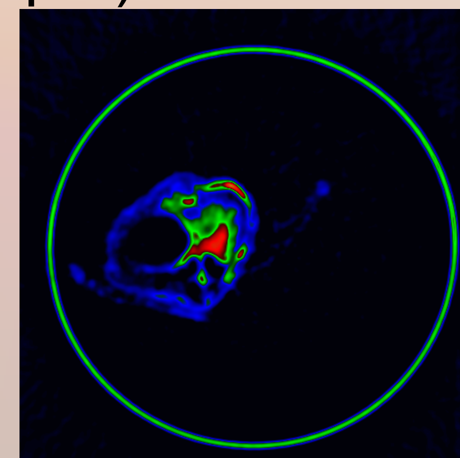
vacuum
path

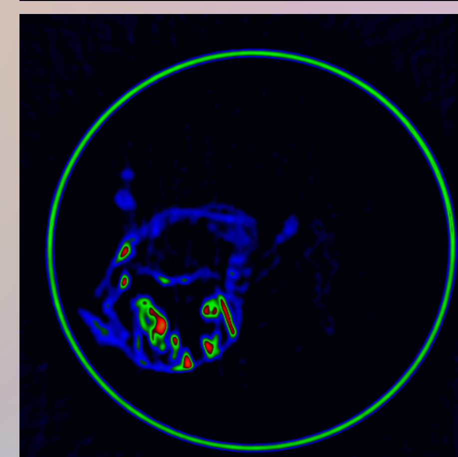
sample &
rotating stage
(0 – 180 deg.)

CT image using PXR

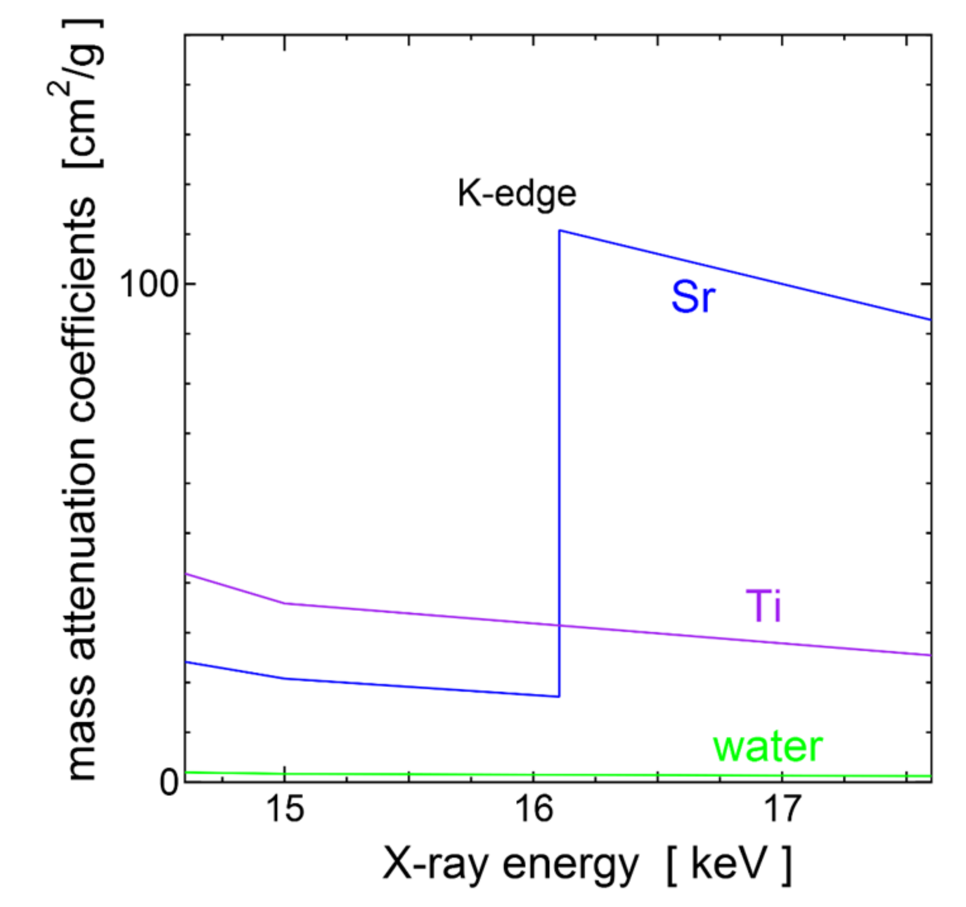
PXR source: Si(220) PXR energy: 15keV
sample: cicada (insect)
measurement time: 20s x 600 (3 hours 20min)
FPD: Shad-o-Box 1280HS (pixel size: 100μm)







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



At the K-shell absorption edge of strontium, the X-ray absorption power drastically changes at only the place where strontium exists.

Sr K-edge: 16.105 keV

Element detection (Sr)

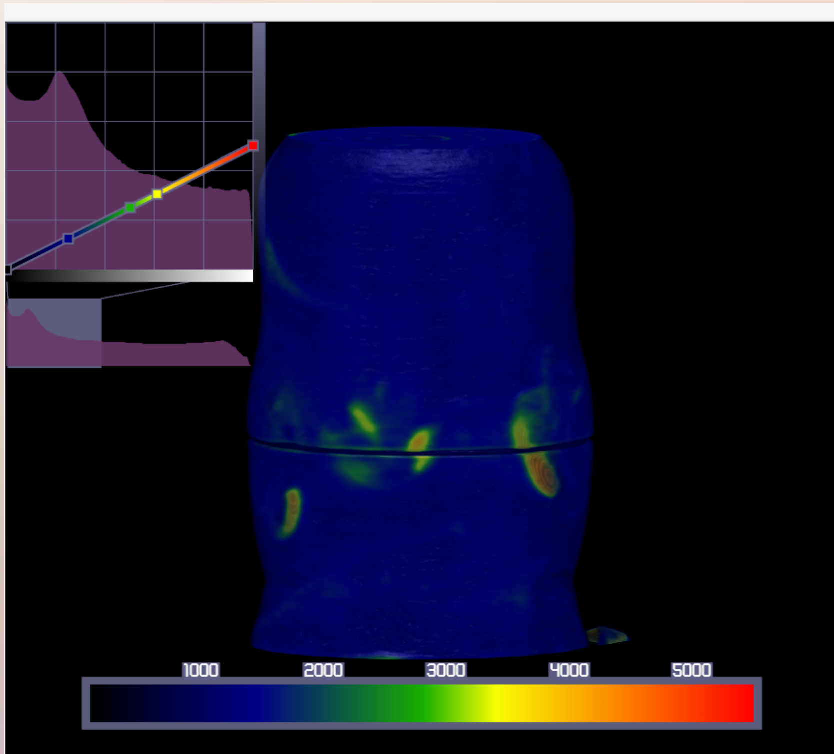
Sample:
matryoshka doll
(3 layers)

material: wood
diameter: 34mm
height: 55mm

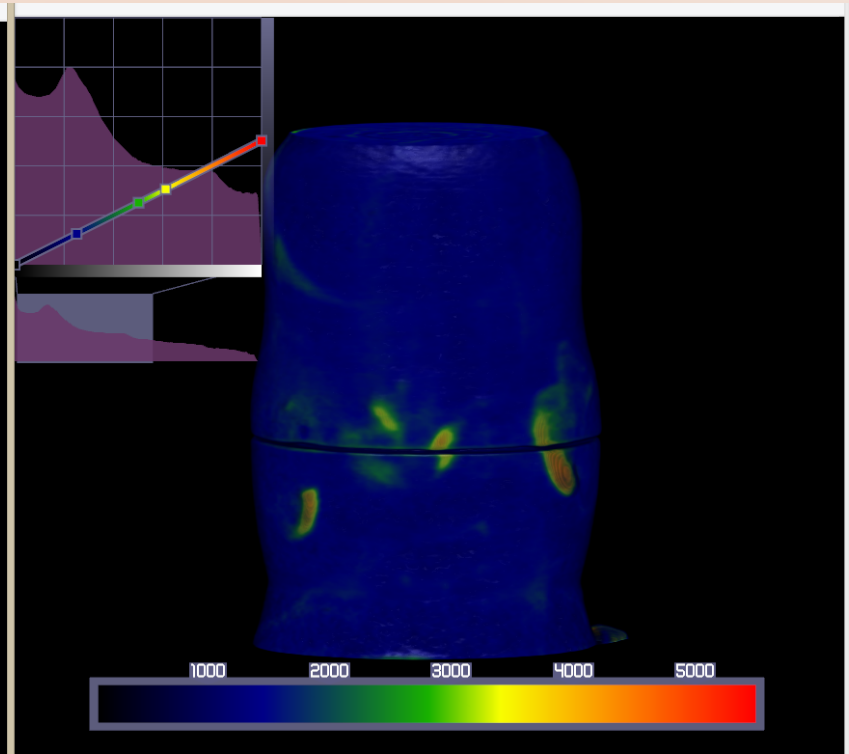
polyethylene pellets containing $SrTiO_3$ (STO) (white pigment)

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

Effect of K-shell absorption edge



16.7 keV



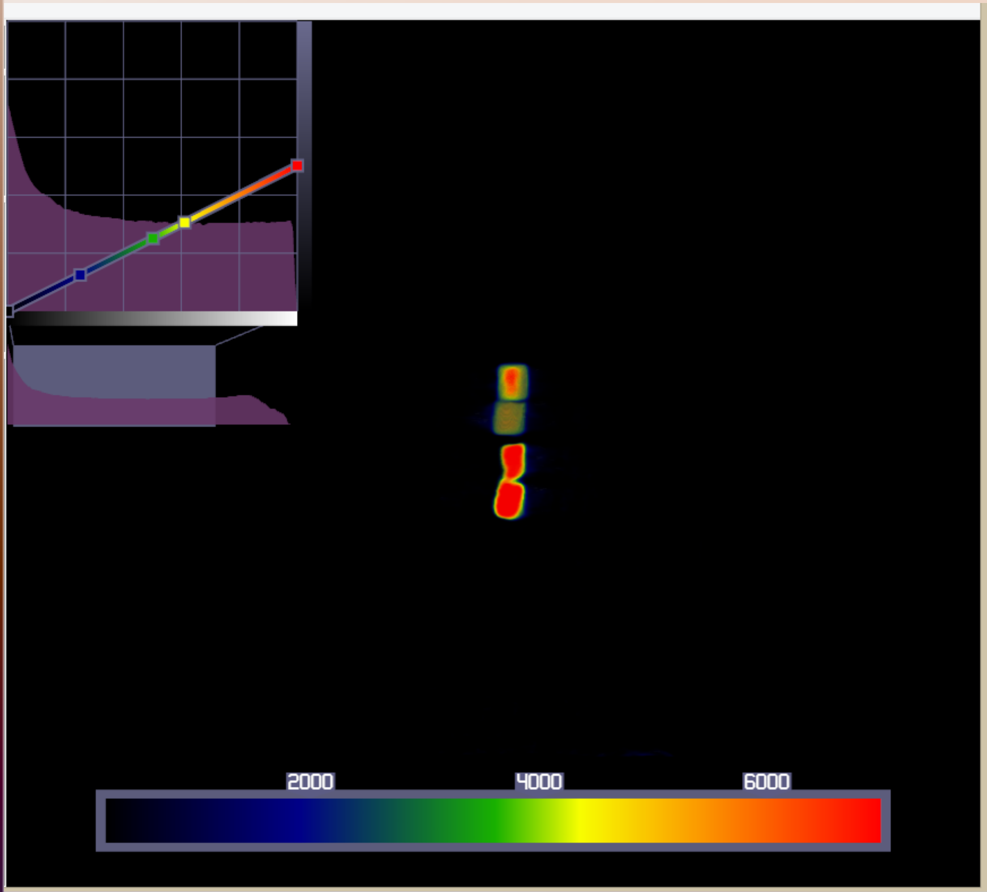
15.5 keV

Sr K-shell absorption edge: 16.1 keV

each measurement time: 1 hr (360 projections)

Both image contrasts are normalized at the wooden region.

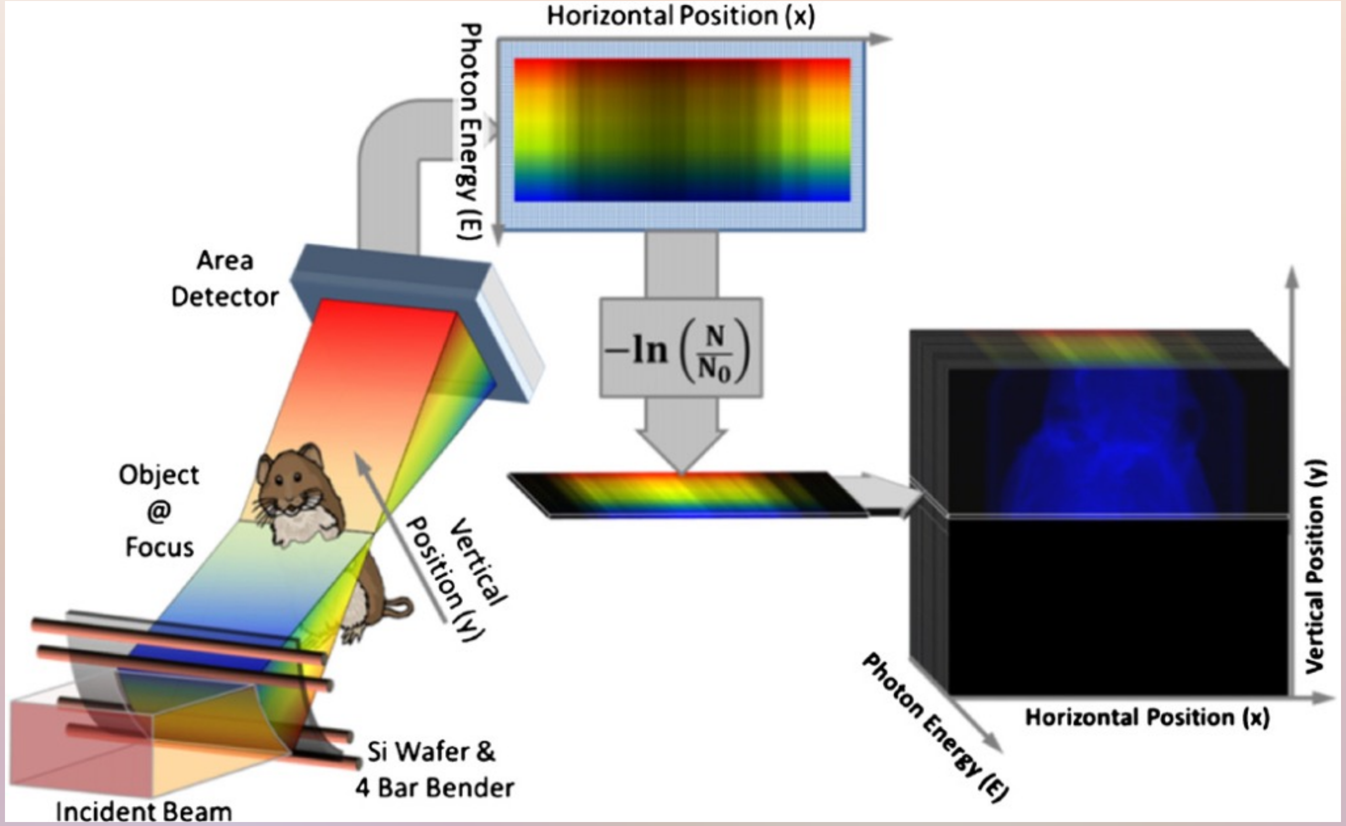
K-edge subtraction (KES) method



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

In this case, the datasets of CT were separately acquired. This method, therefore, is referred to as temporal K-edge subtraction (KES).

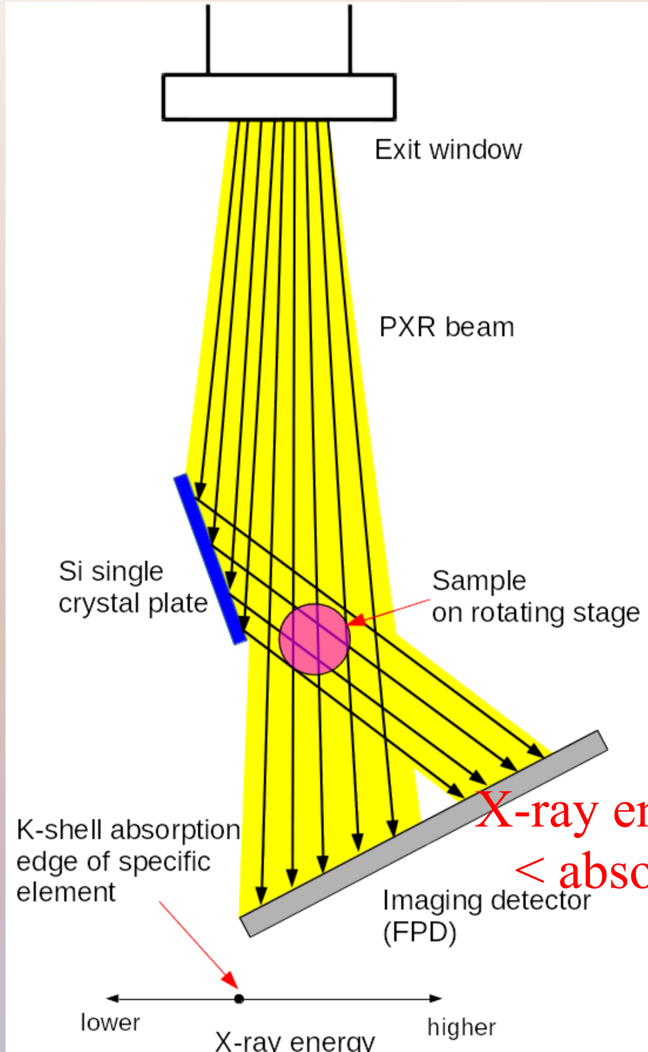
spectral-KES using SR source



Y. Zhu, et al., Phys. Med. Biol. 59 (2014) 2485–2503.

Simultaneous KES method is developed at Canadian Light Source using bent crystal optics. They call the method “spectral-KES method”.

Simultaneous-KES CT using PXR



X-ray energy
< absorption edge

X-ray energy
> absorption edge

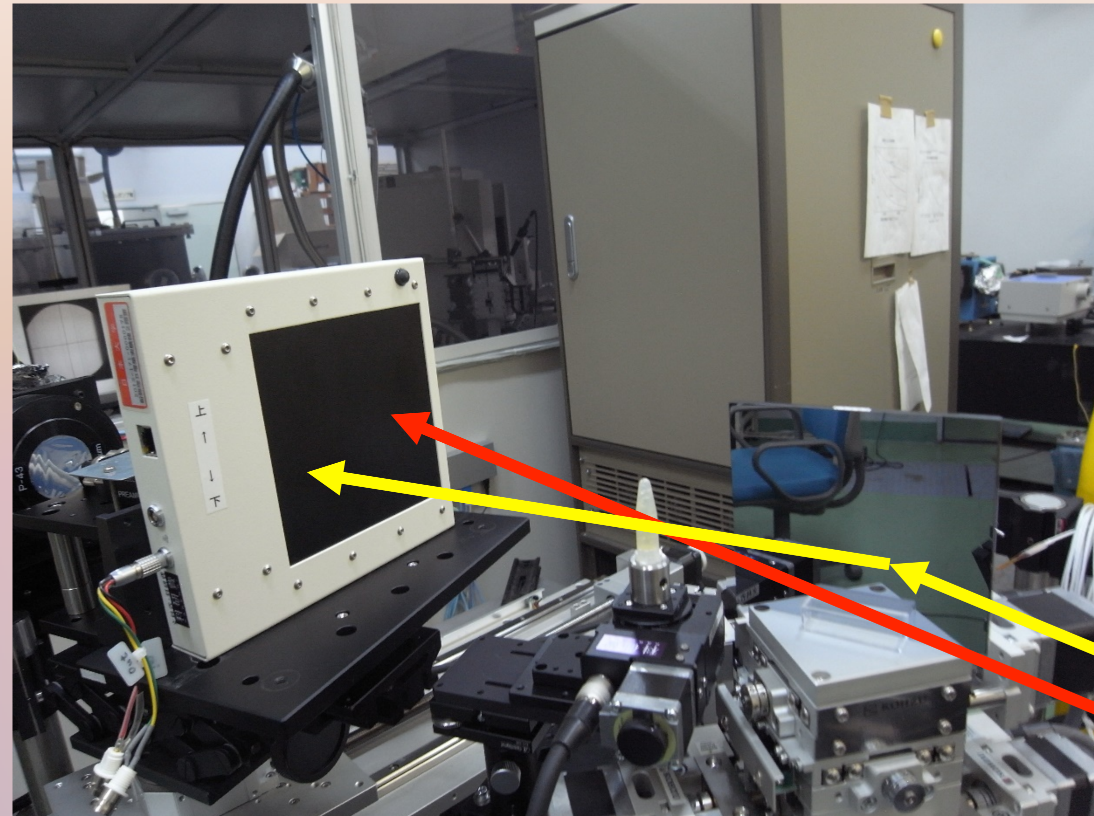
Using the spatial chirp property of PXR, crossing two beams having slightly different energies can be formed using DEI setup.

The 2-color beams can be used for simultaneous KES when the center energy of the PXR beam is adjusted to the K-edge energy of a specific element.

Moreover, KES-CT is possible by rotating the sample.

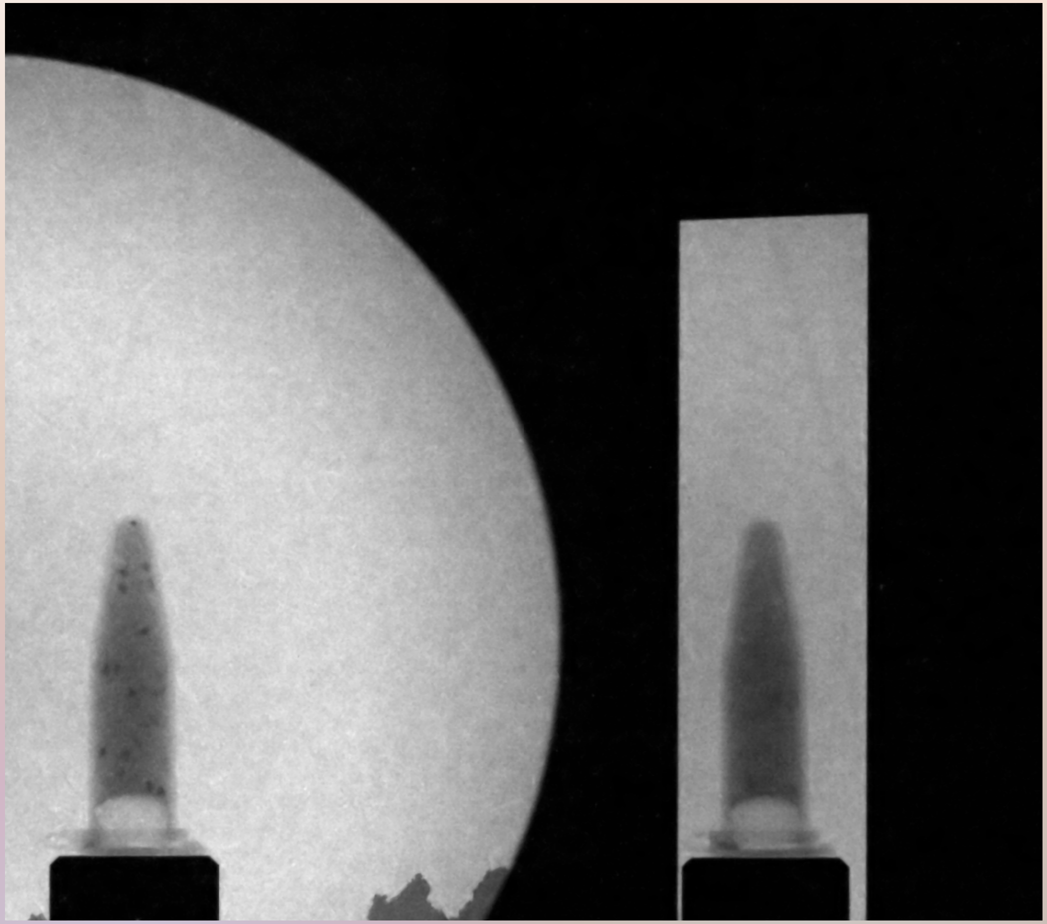
Setup for KES-CT experiment

sample:
epoxy resin
+
polyethylene fragments colored with $SrTiO_3$ (STO)



PXR source & DEI analyzer: Si(220)
PXR energy: 16.105 keV
FPD: Shad-o-Box 1280HS
(pixel size: 100μm)

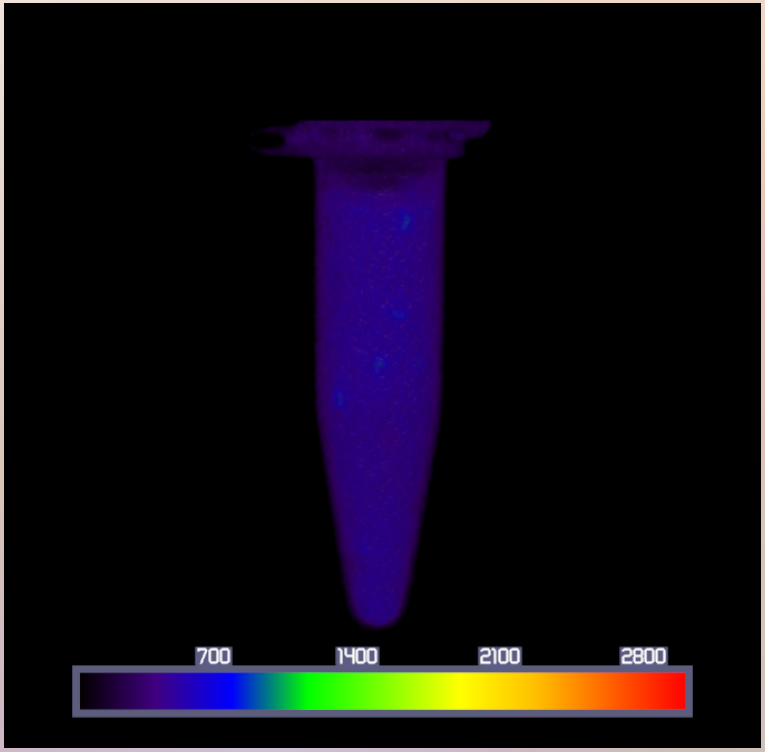
Simultaneous KES-CT using PXR



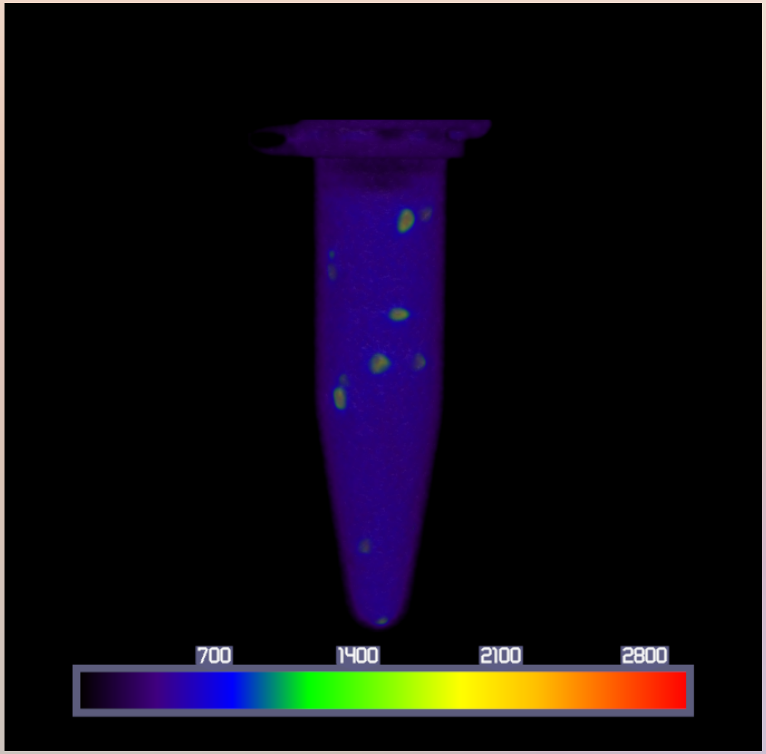
X-ray reflectivity of the Si(220) analyzer crystal ~ 75%

projection images: 360 (angular step: 0.5 deg.)
each exposure time: 20s
total measurement time: 2 hours

3D reconstruction from KES-CT data



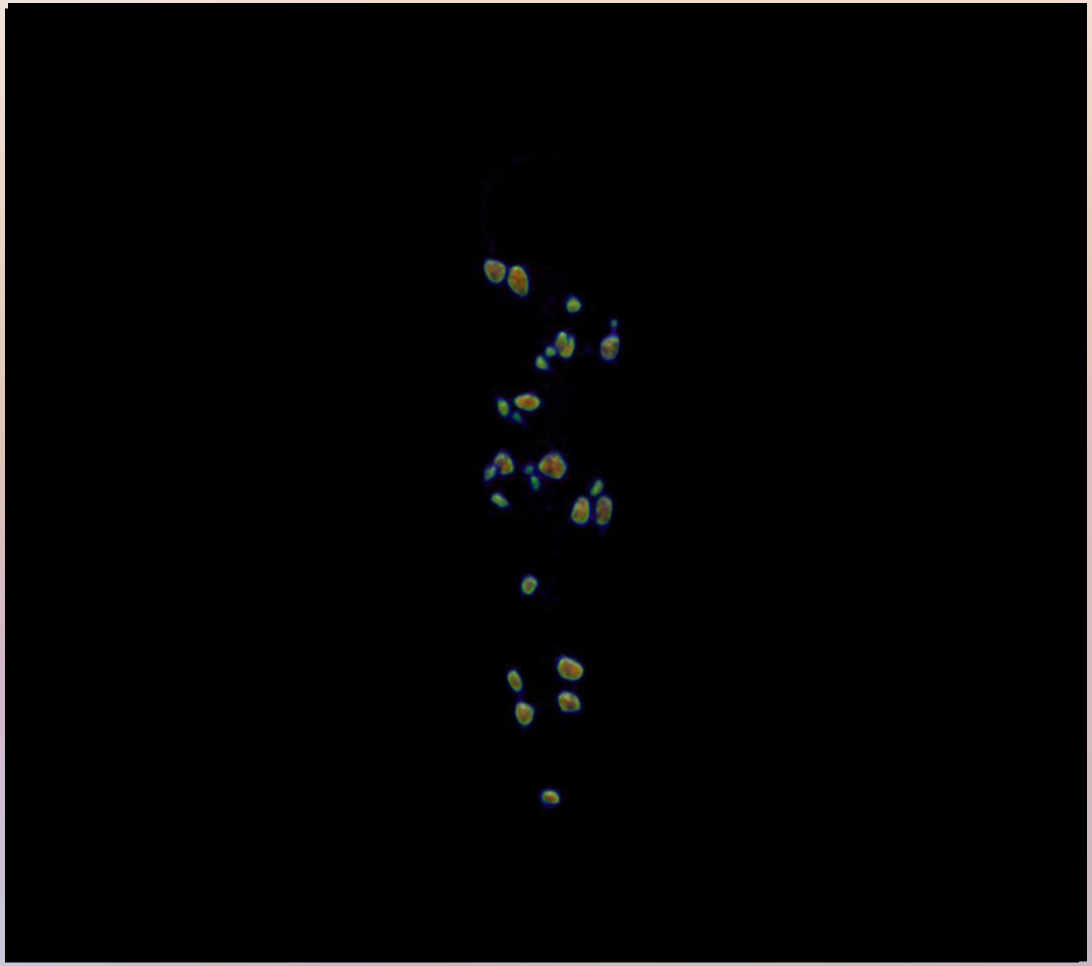
lower than Sr K-edge
~ 16.0 keV



higher than Sr K-edge
~ 16.2 keV

Both image contrasts are normalized at the region of epoxy resin.

Sr distribution obtained by KES-CT



Sr distribution is calculated as subtraction of two CT images.

Summary

- KES method is useful for the detection of specific element.
- Simultaneous-KES method is one of the current topics in the field of advanced X-ray imaging.
- Combining DEI technique and the energy selectivity of PXR makes it possible to realize simultaneous KES without bent-crystal monochrometer.
- We demonstrated that simultaneous KES-CT using PXR has a capability to detect strontium distribution in a light material sample.
- PXR-KES has a competitive edge in the field of element imaging against other X-ray sources such as SR sources.

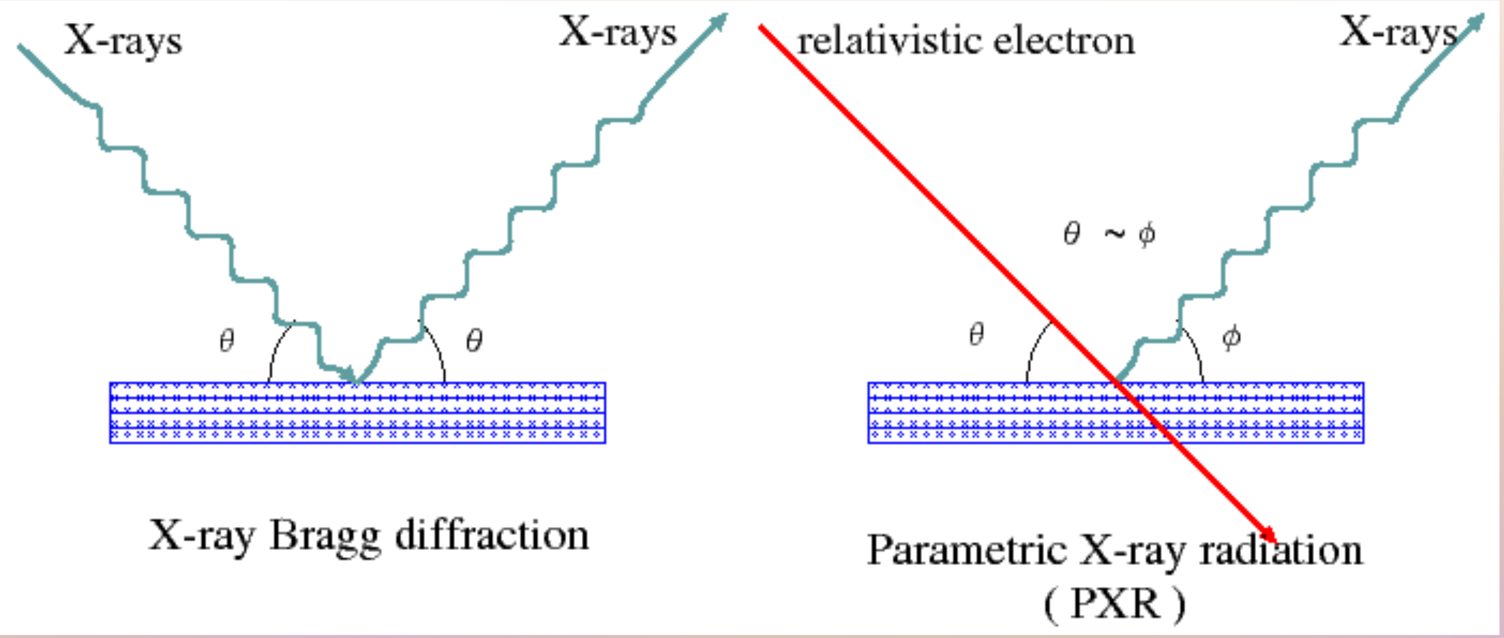
Acknowledgements

MEXT.KAKENHI (25286087&16K05008)

Thank you for your kind attention !!

Appendix

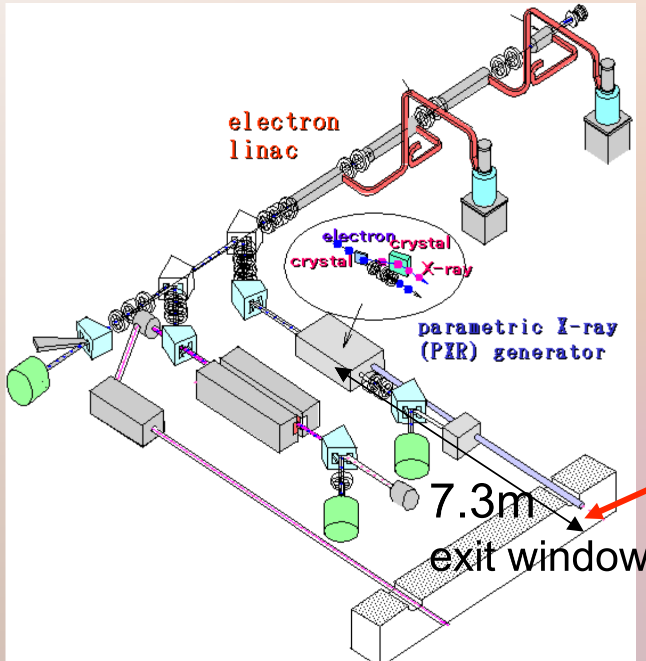
What is PXR?



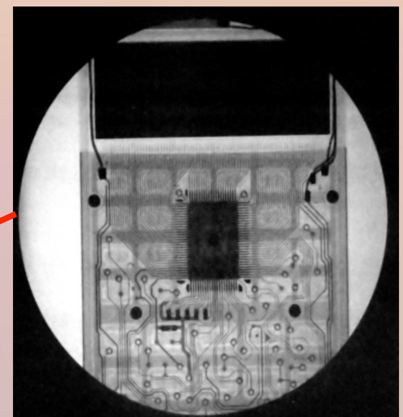
PXR: Parametric X-ray Radiation

PXR is apparently similar to X-ray Bragg diffraction.
The phenomenon corresponds to Bragg diffraction for virtual photons accompanying the incident electron.
The X-ray energy is tunable depending on the Bragg angle.

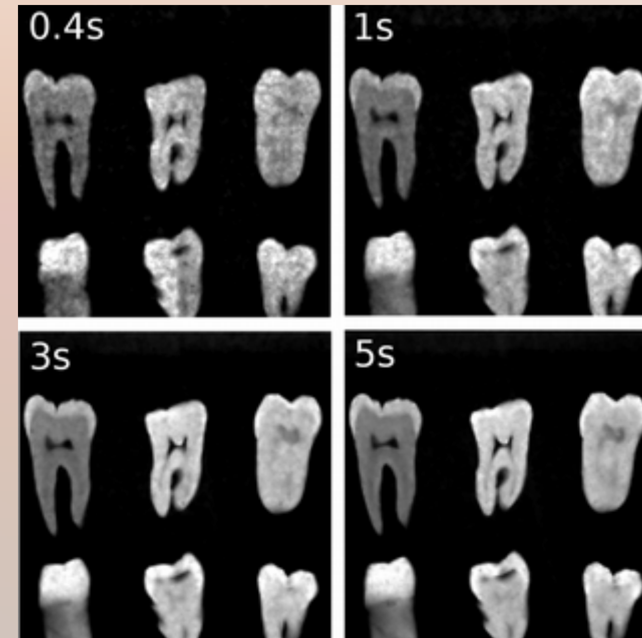
X-ray imaging (absorption contrast)



diameter: 100mm

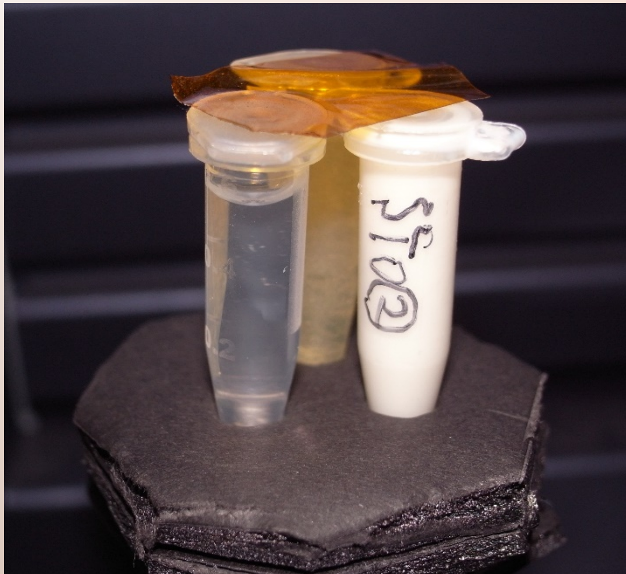


PXR radiator: Si(111)
PXR energy: 17.5keV (center)
e-beam: 2.6uA (average)
sample: calculator
detector: imaging plate (IP)
exposure: 10s



PXR radiator: Si(111)
PXR energy: 17.5keV (center)
e-beam: 2.6uA (average)
sample: human tooth
detector: flat panel detector (FPD)

Sample 2



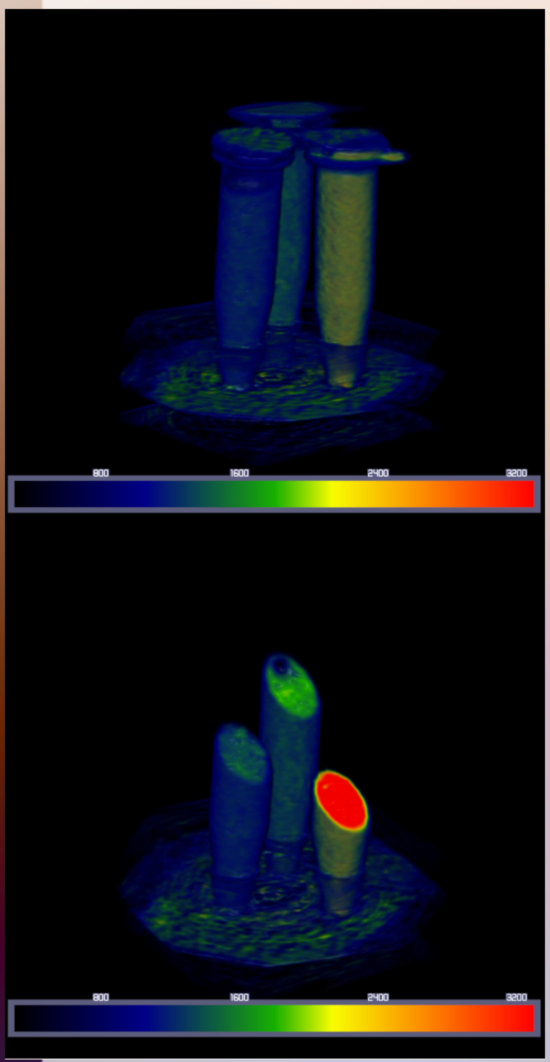
Experiment for a material with lower concentration of Sr

ethanol
  density: 0.79 g/cm^3

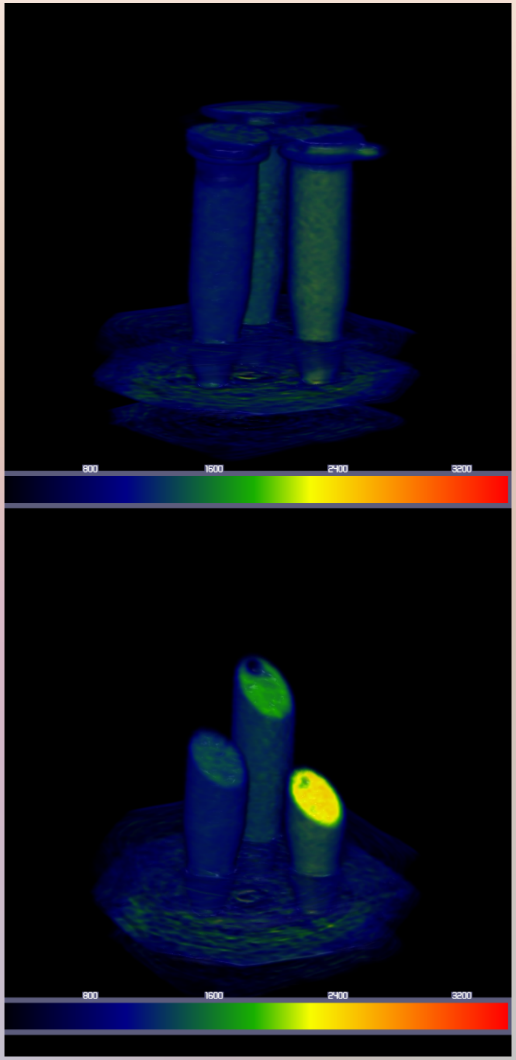
epoxy resin
  density: ~ 1.2 g/cm^3

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

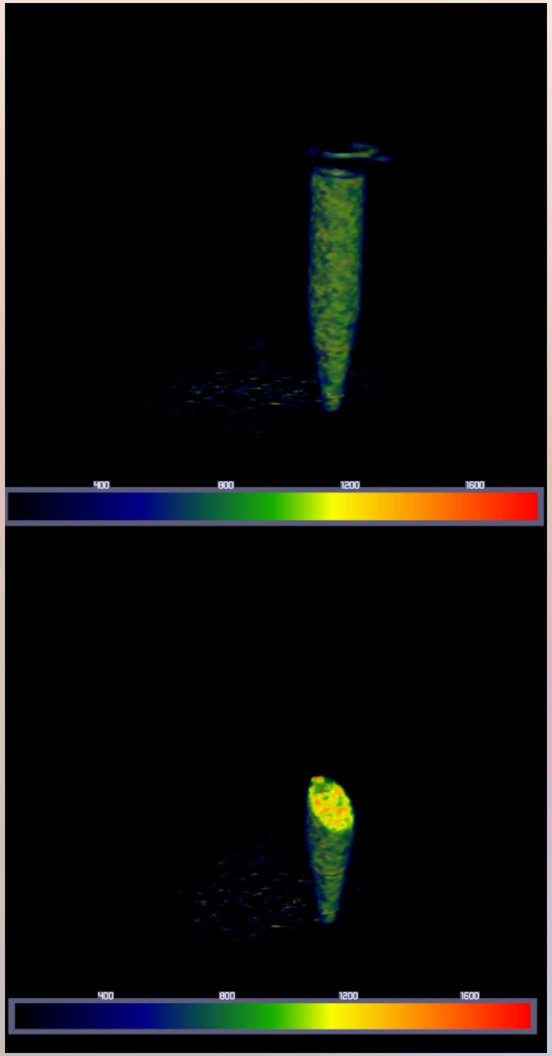
Comparison of 3D distributions



16.6 keV



15.6 keV



difference

Result of reconstructions

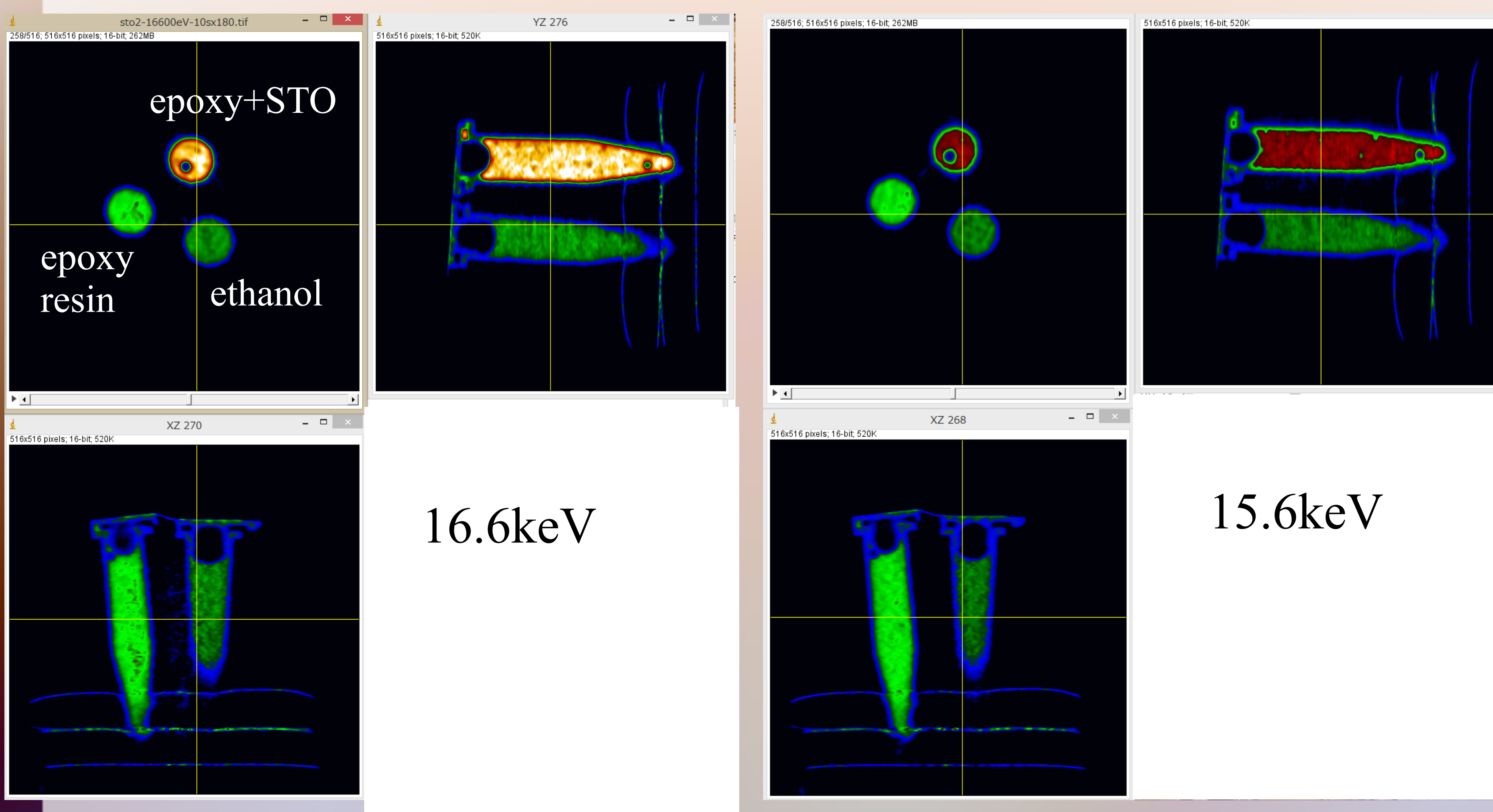
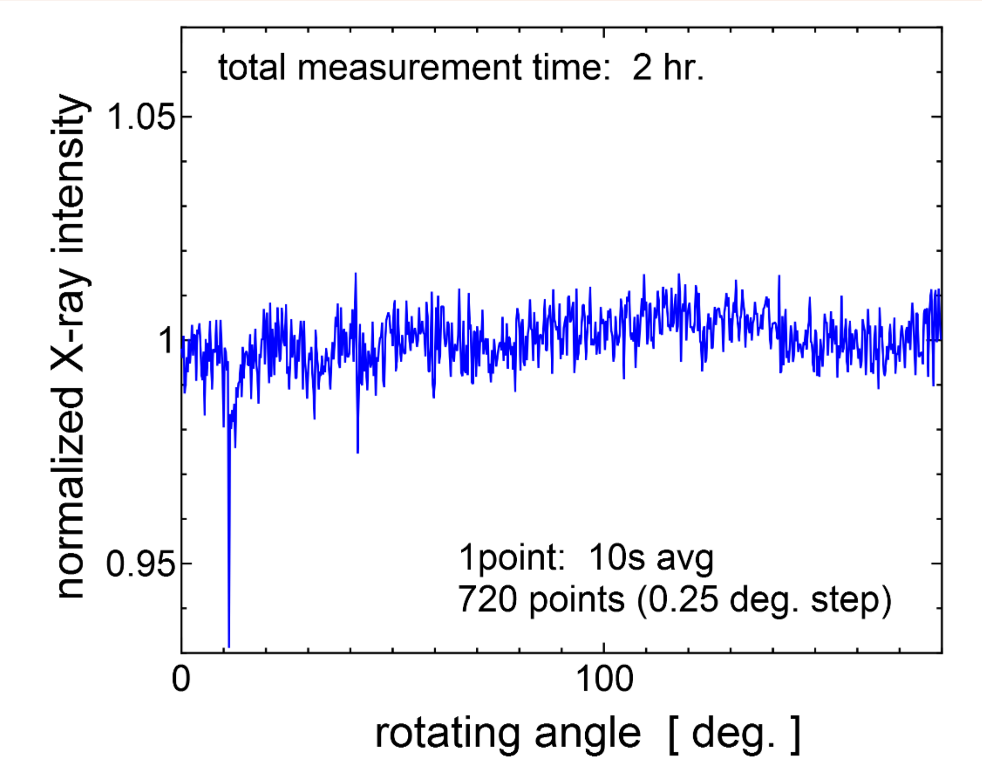


Image contrasts are normalized at the region of ethanol.

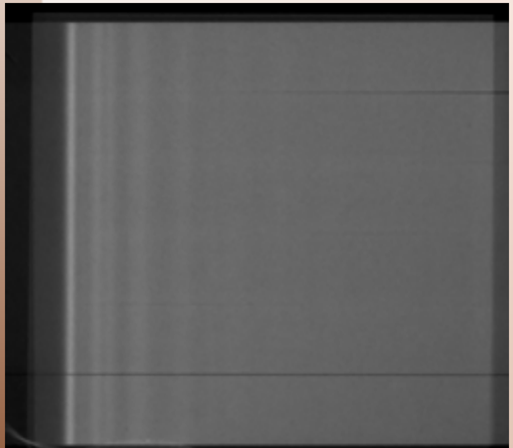
Stability of PXR beam



Long term stability of the PXR intensity was achieved except rare RF faults.

The stability is a great advantage in computed tomography (CT) experiments.

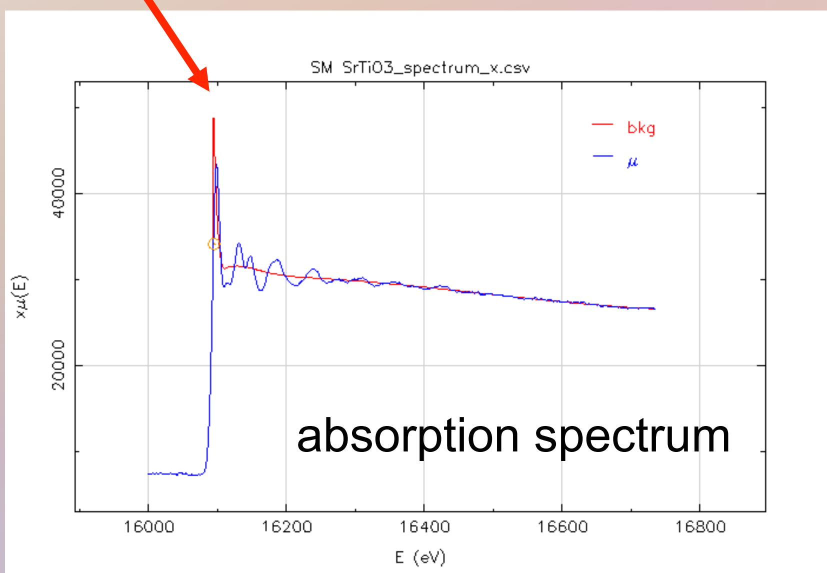
Typical result of DXAFS experiment

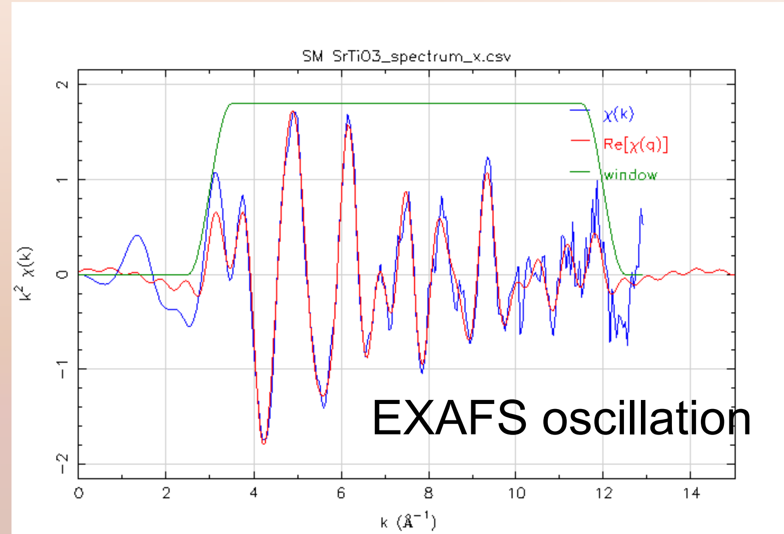


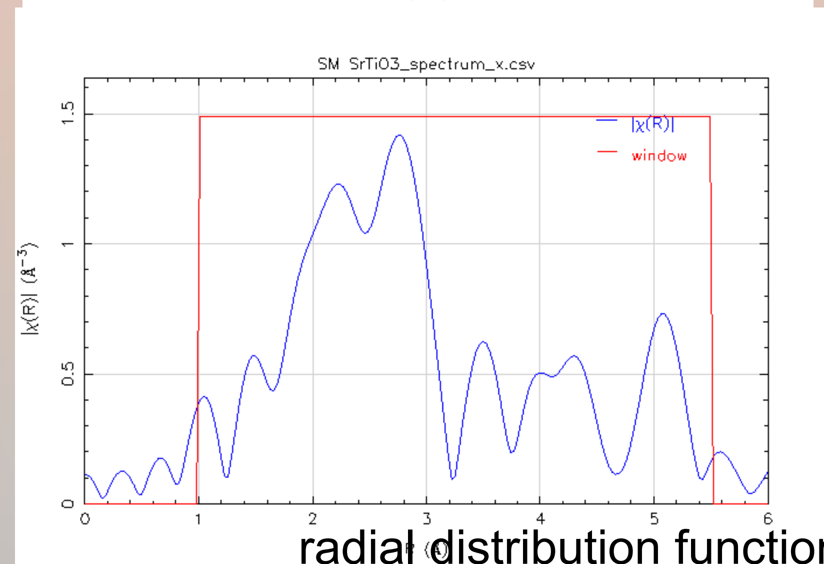
sample
$SrTiO_3$ (white pigments)

measurement time
30min

detector: Imaging plate

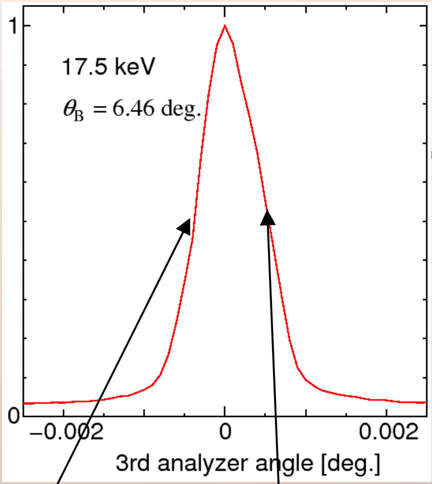


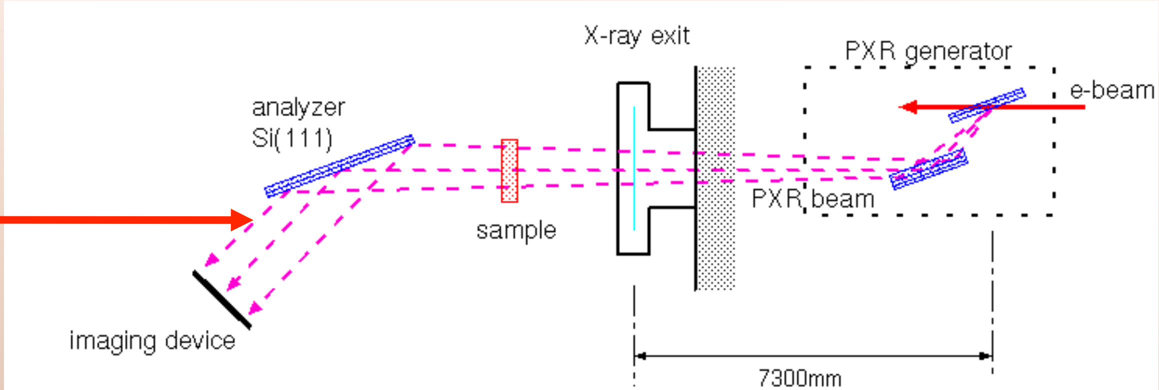




Time- resolved XAFS measurement can be expected using the linac-based source.

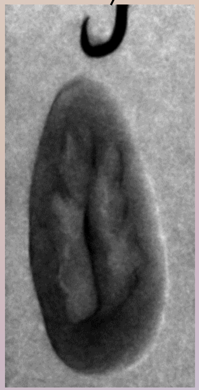
Diffraction Enhanced Imaging (DEI)



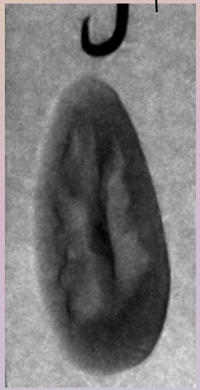


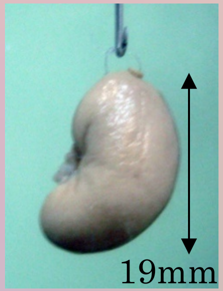
Analyzer-based Phase-contrast imaging
(DEI: Diffraction-enhanced imaging)

A

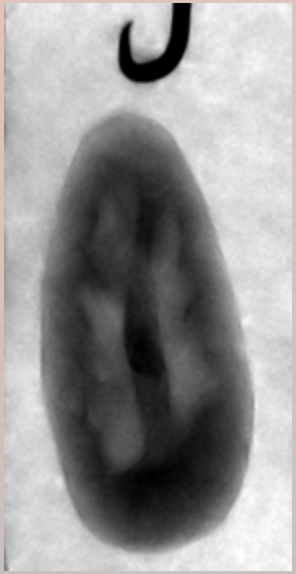


B





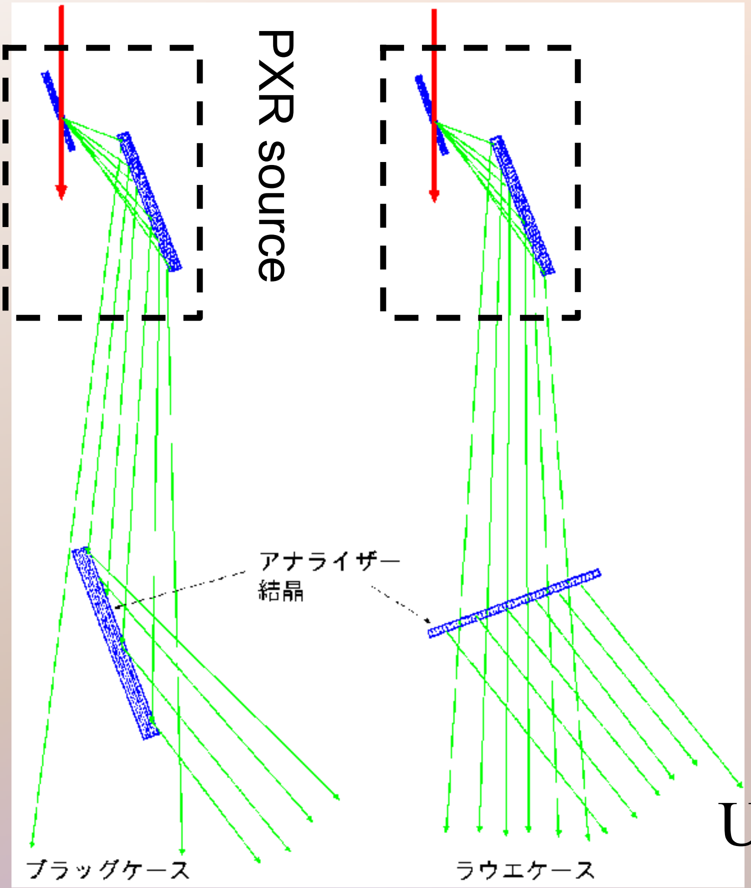
kidney of mouse



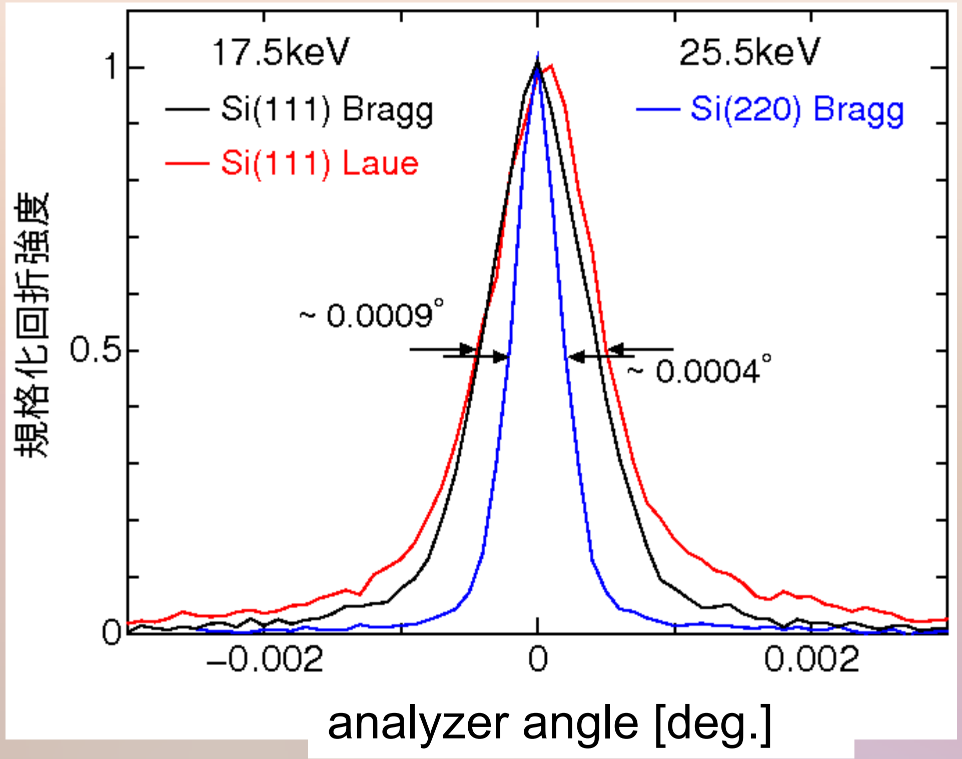
A+B:
absorption contrast

A-B:
phase contrast

(+, -, +) arrangement



Bragg case Laue case

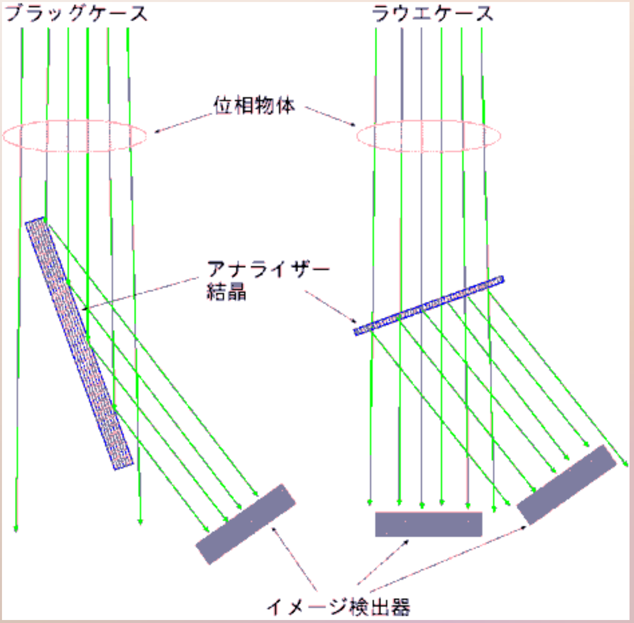


Using a 3rd analyzer crystal in the (+,-,+) arrangement, the whole of a PXR beam can be diffracted with a narrow angular width despite the cone-beam. (pseudo-plane wave)

Bragg angle:

- larger for longer wavelengths
- smaller for shorter wavelengths

DEI in a Laue case

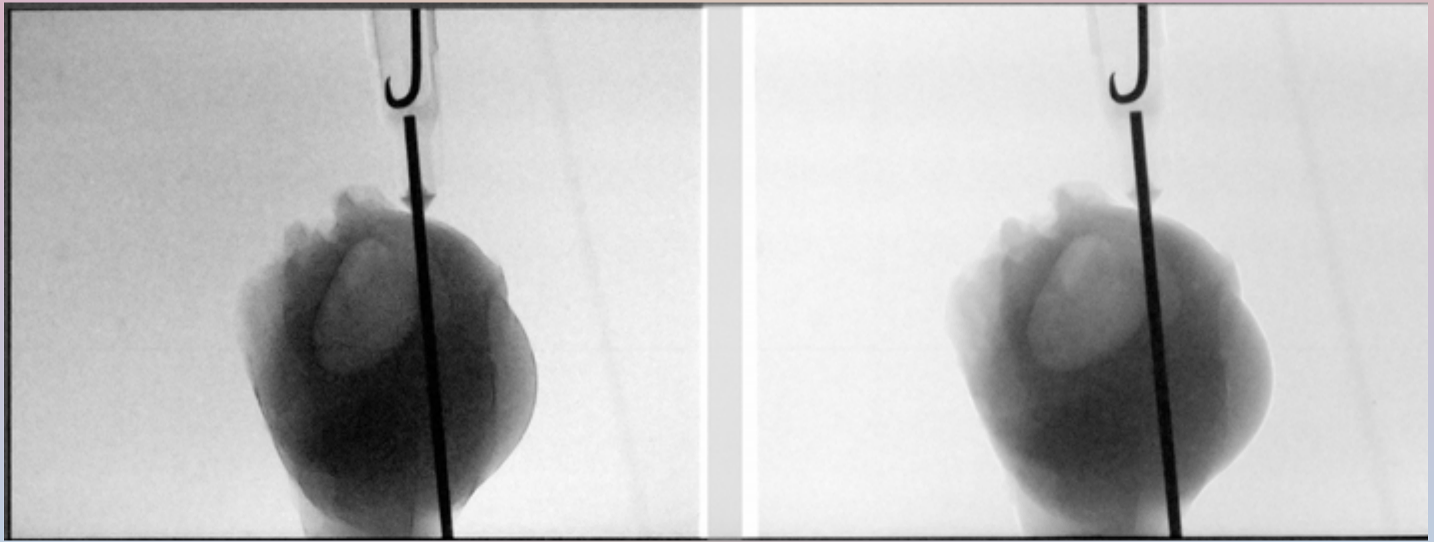


The irradiation field of DEI is limited by the size of the analyzer crystal.

Using an analyzer in a Laue case, the active area of 50mm x 50mm is actually available.

PXR radiator:
Si(220)
PXR energy:
17.5keV

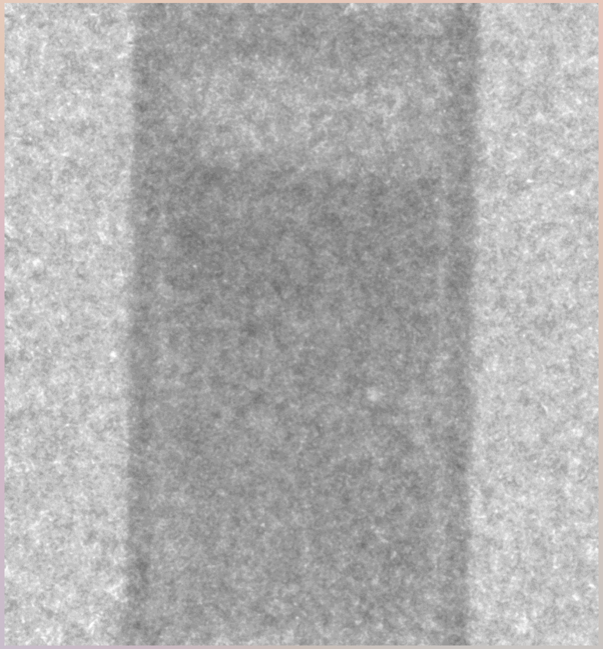
sample:
pig eyeball



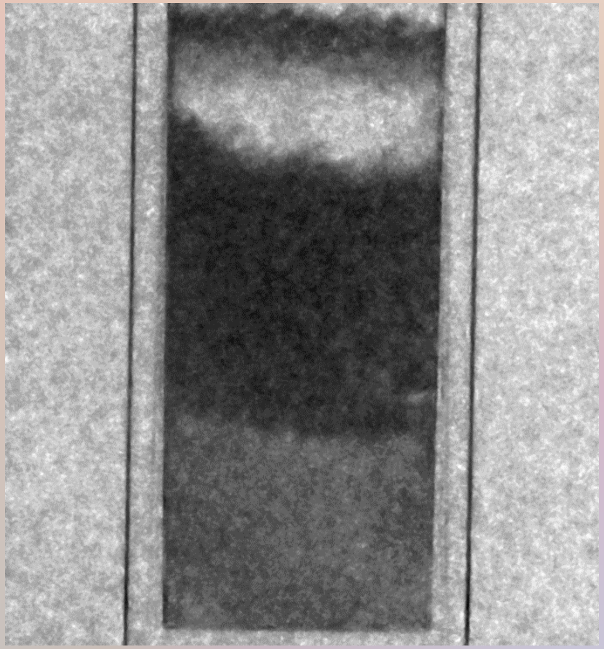
SAXS contrast image

experimental condition:
PXR radiator: Si(220)
PXR energy: 23keV
sample: silica standard particles（φ1μm, φ0.2μm）
X-ray camera: I.I. CCD （QE ≲ 10%）

silica powder
upper layer:
0.2μm in dia.
lower layer:
1.0μm in dia.



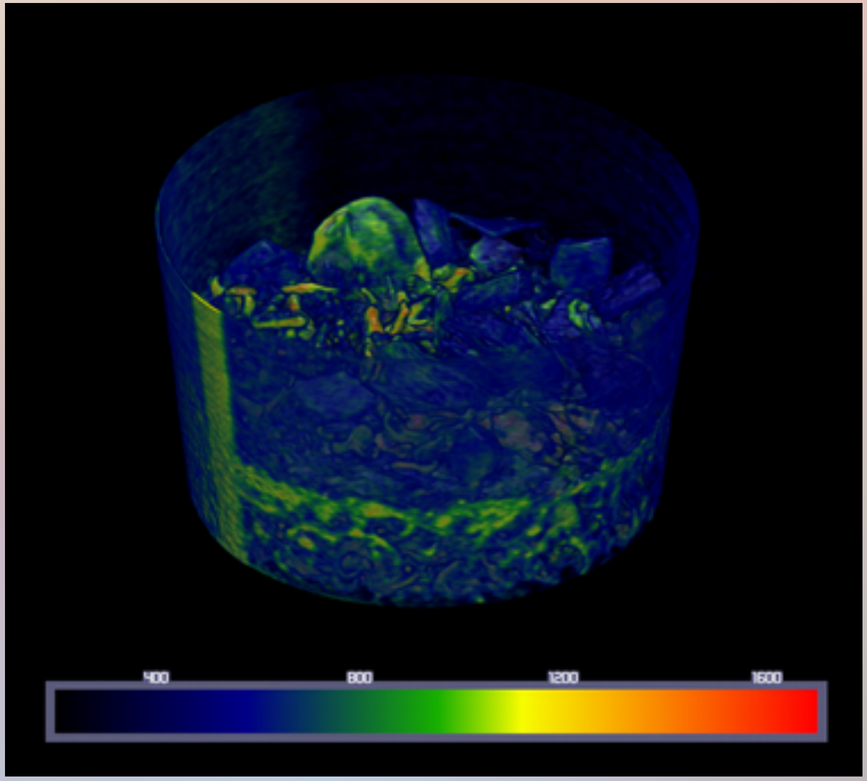
absorption contrast image

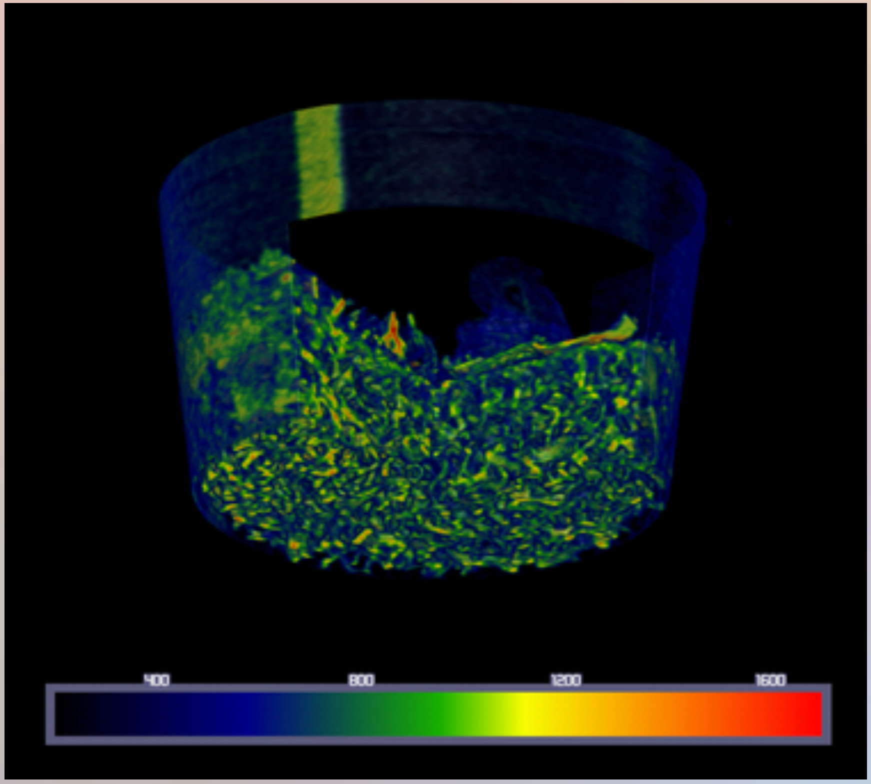


SAXS contrast image

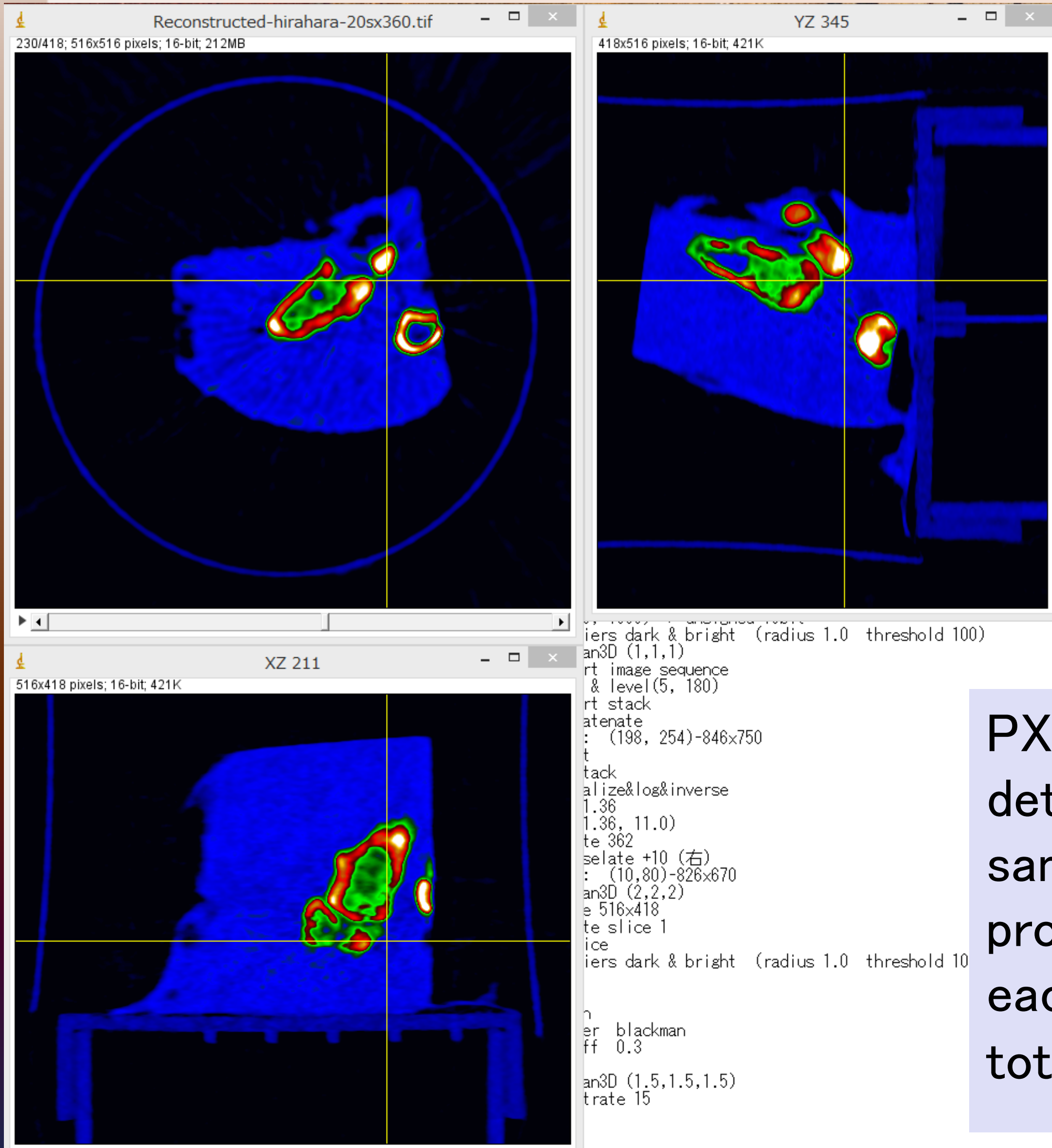
Large sample & Higher X-ray energy

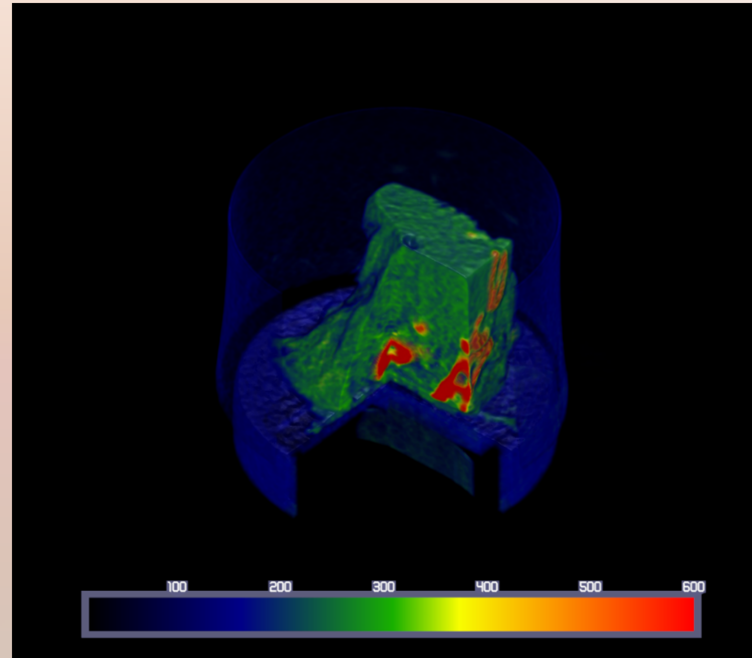
PXR source: Si(220)　　PXRenergy: 27keV
sample: CUP-Noodle （~90mm in diameter）
measurement time: 20s x 360 (2 hours)
FPD: Shad-o-Box 1280 HS （pixel size: 100μm）





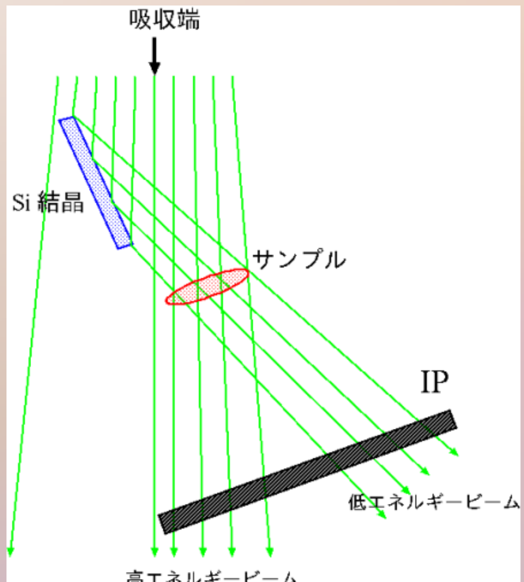
CT image of biological sample

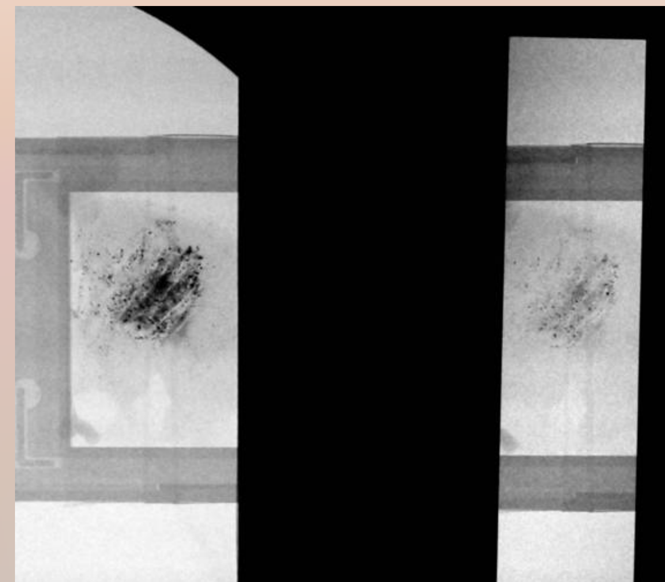




PXR: 25keV
detector: Shad-o-Box 1280HS
sample: tumor of dog forefoot
projection images: 360
each exposure time: 20s
total measurement time: 2 hours

Arsenic detection using 2-color X-ray beams

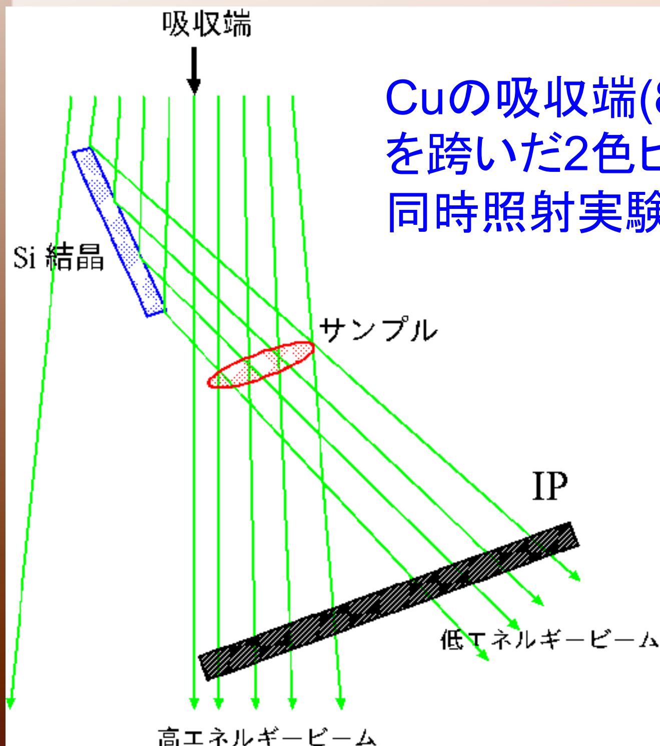




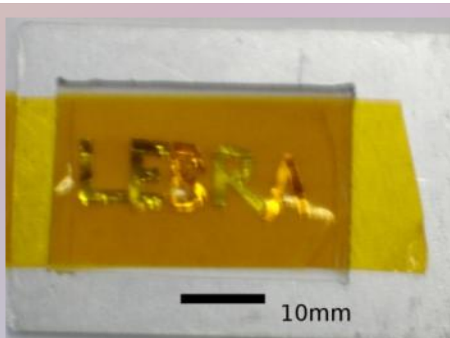
日本大学学術研究助成金（総合研究）

2010-3-13

2色同時撮像による元素イメージング



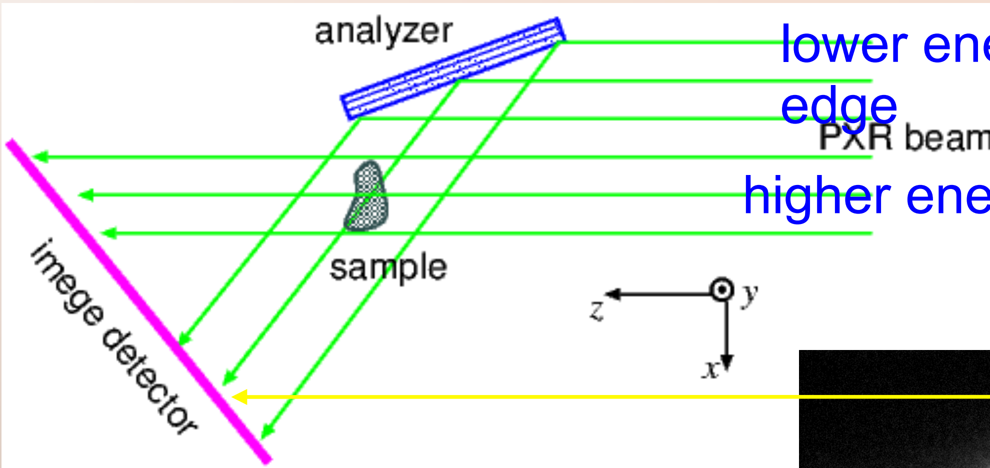
Cuの吸収端(8.98keV)を跨いだ2色ビーム同時照射実験



L : Ni (20μm)
E : Ni-Cu (10μm)
B, A : Cu (20μm)
R : Zn (25μm)

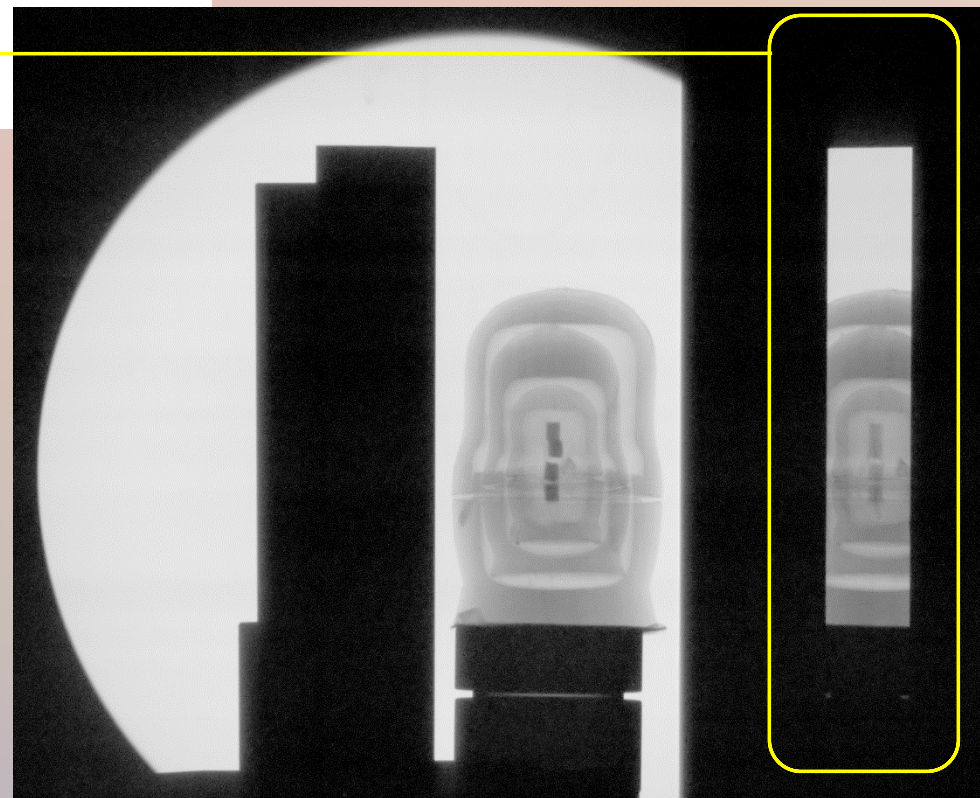
元素(Cu)検出を実証

Stereoscopic X-ray imaging



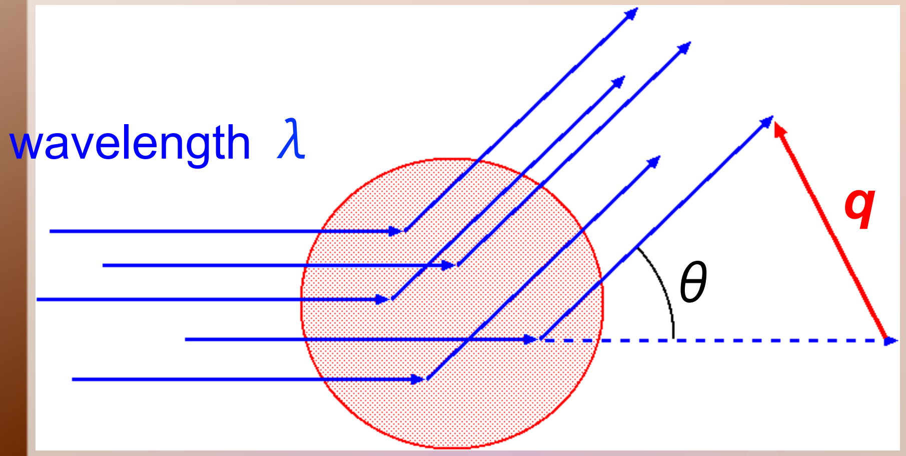
lower energy than Sr K-edge

higher energy than Sr K-edge



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

Small angle X-ray scattering (SAXS)

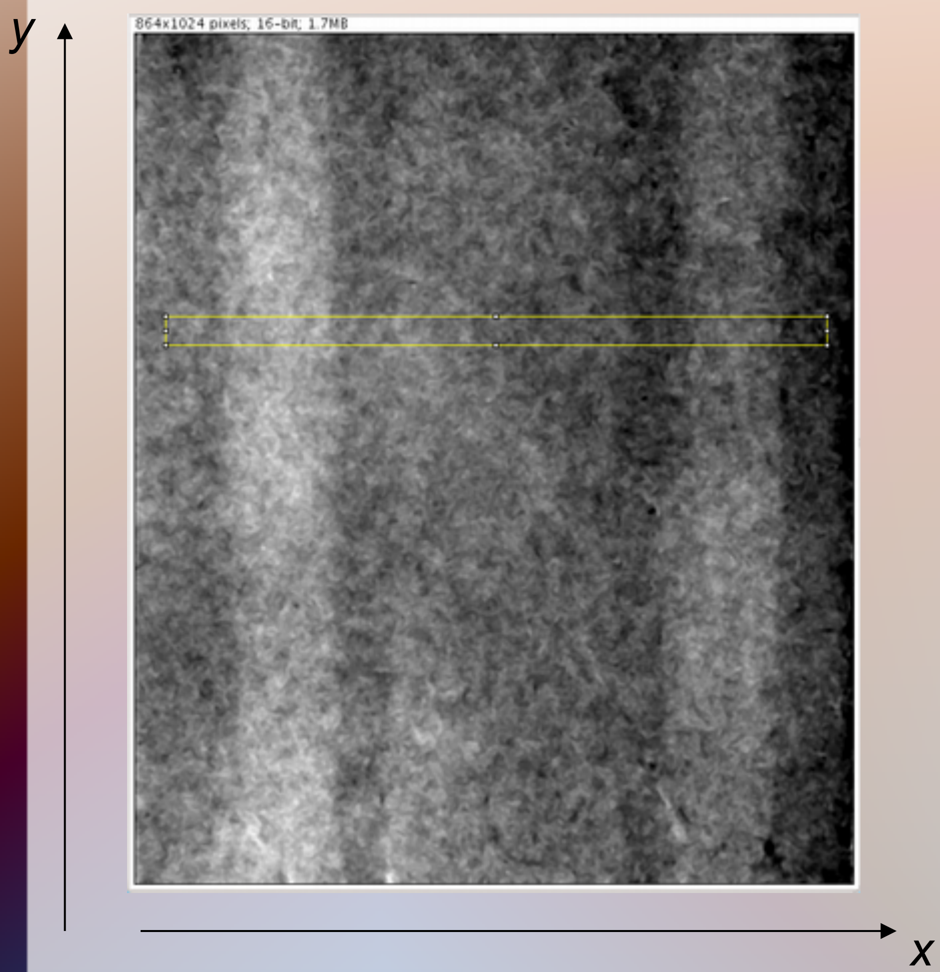


$$q = |\boldsymbol{q}| = (4\pi/\lambda)\sin(\theta/2)$$

Guinier approximation: $$I(q) = I_0 \exp\left(-\frac{1}{3} R_g^2 q^2\right)$$

R_g : inertial (gyration) radius

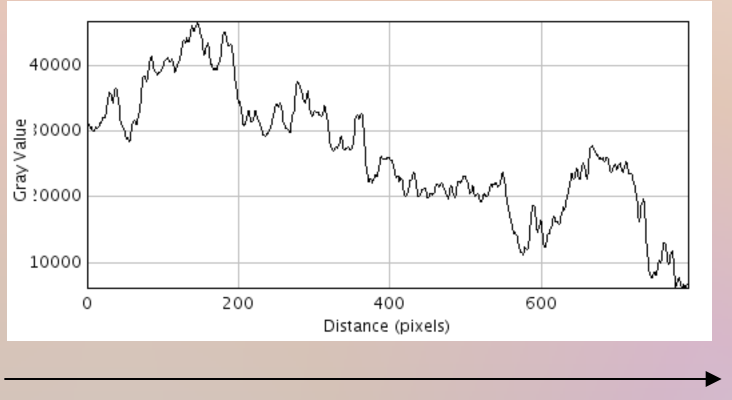
absorption-contrast image



complex refraction index:

$n(x,y) = 1 - \delta(x,y) + i\,\beta(x,y)$

$\delta, \beta \propto \rho$: density



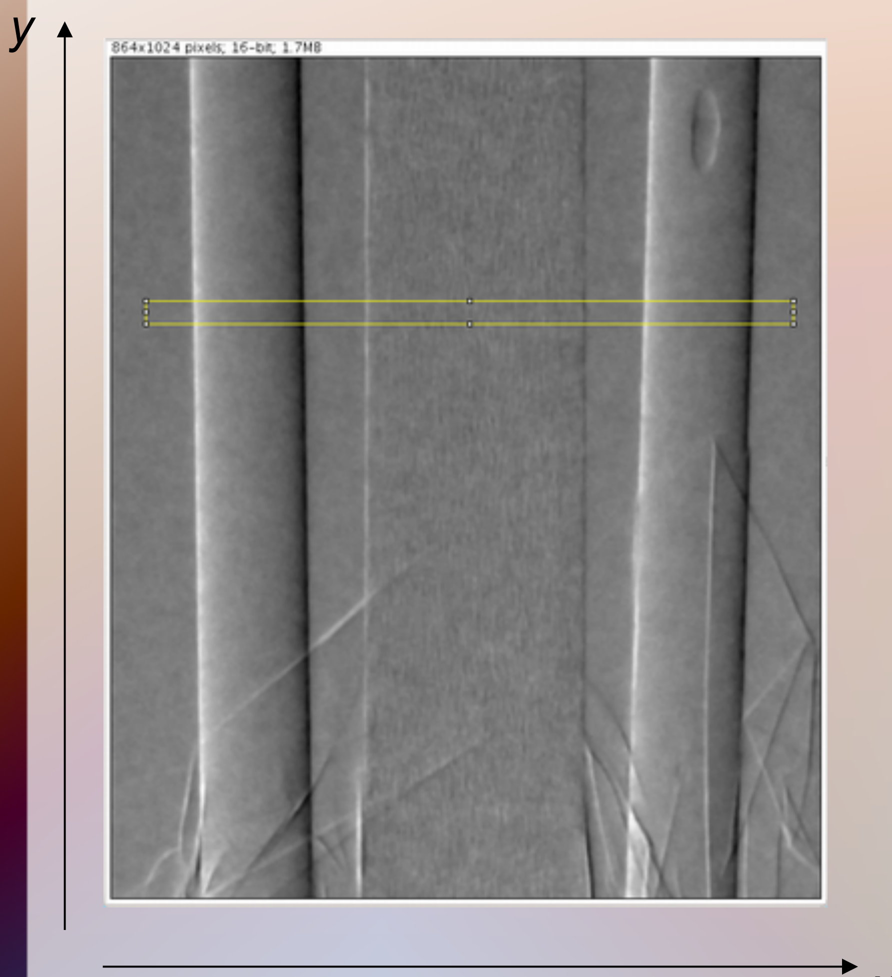
Integral with respect to θ

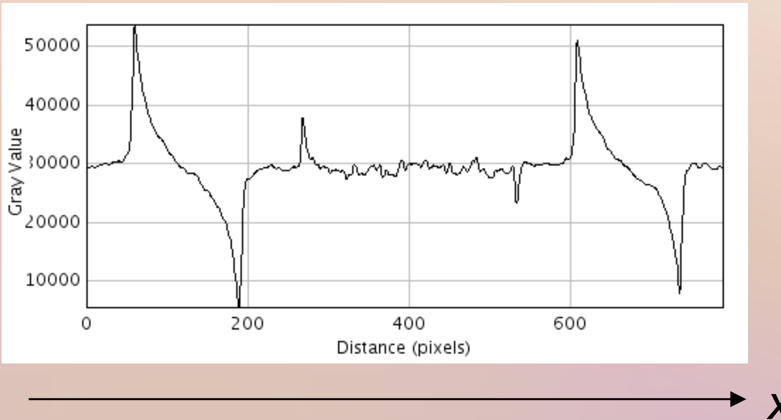
$I_{abs} = \sum I(x,y,\theta)$

$\ln(I_{abs}(x,y)/I_0) \propto \beta(x,y)$

$\propto \rho(x,y)$

phase-gradient image



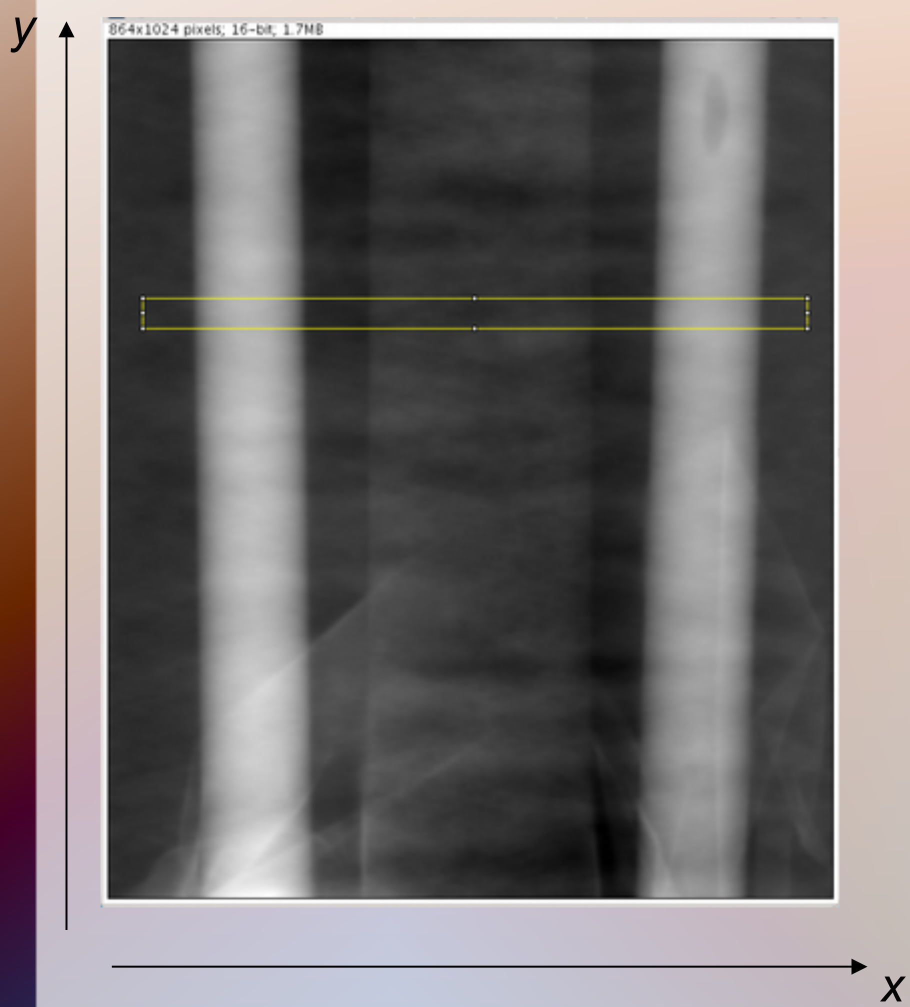


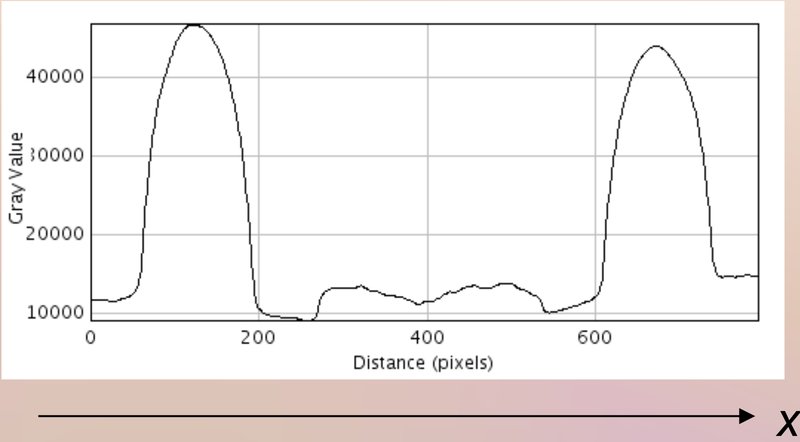
phase-gradient
(refraction-contrast) map

$$\sum \theta\, I(x,y,\theta) / \sum I(x,y,\theta)$$

$$\propto \;\; \partial\delta(x,y)/\partial x$$

phase image



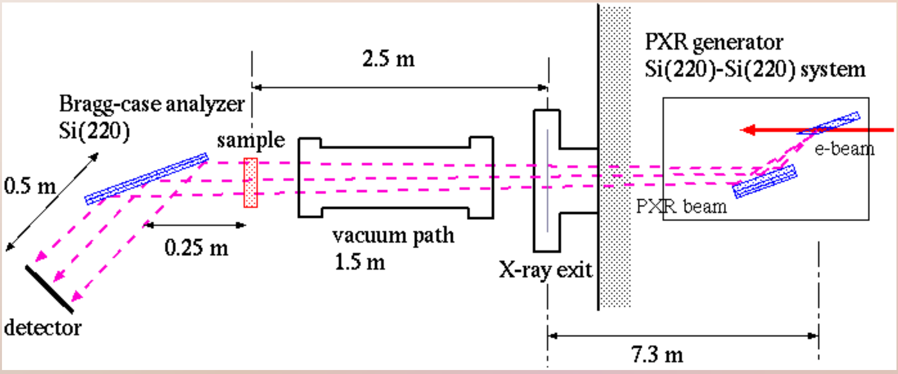


phase map

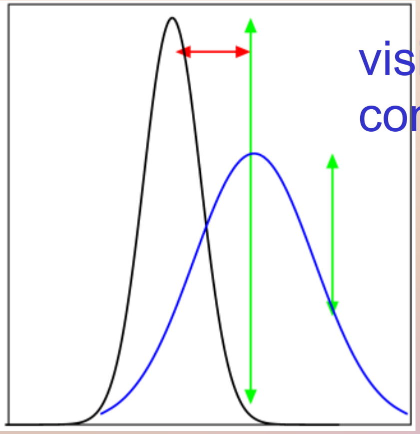
$$\delta(x,y) = \int \partial\delta(x,y)\,/\partial x\ \mathrm{d}x$$

$$\propto\ \rho(x,y)$$

diffraction-enhanced imaging

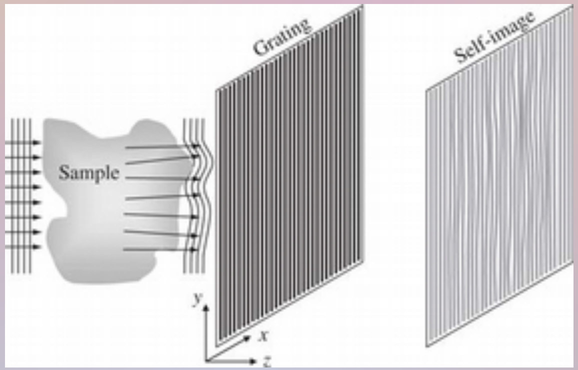


phase contrast



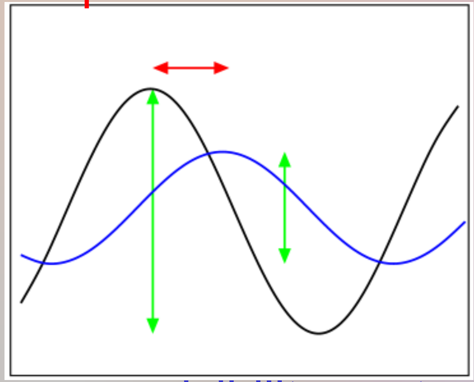
visibility contrast

Talbot interferometer imaging



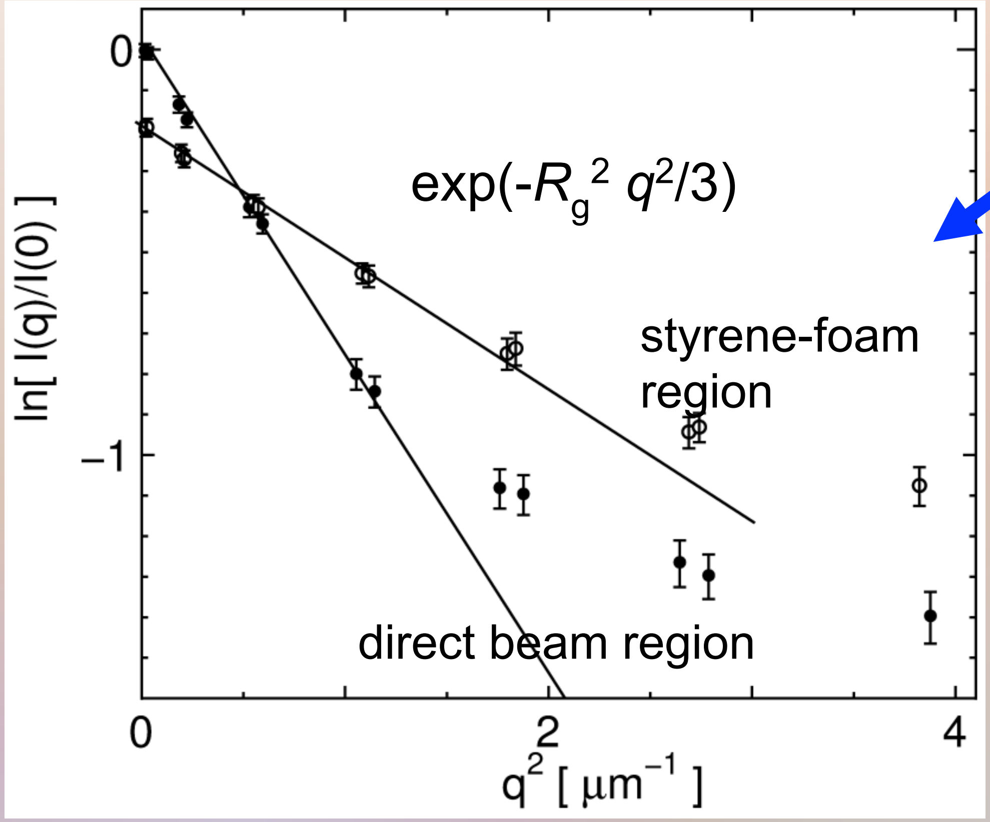
A. Momose et al.: JJAP 42 (2003) L866.

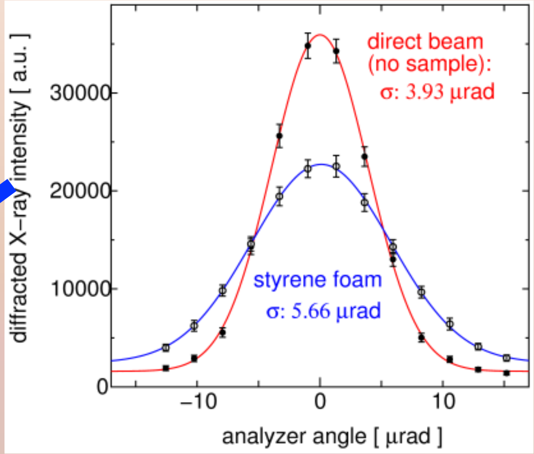
phase contrast



visibility contrast

Guinier plot





inertial radius

$R_g \sim 1\mu m$

< pixel size (24 μm)

$$q = (4\pi / \lambda\ ) \sin(\theta/2)$$

For more exact estimation, the sample thickness has to be optimized.