Computed Tomography for Light Materials Using Monochromatic X-ray Beam Produced by Parametric X-ray Radiation

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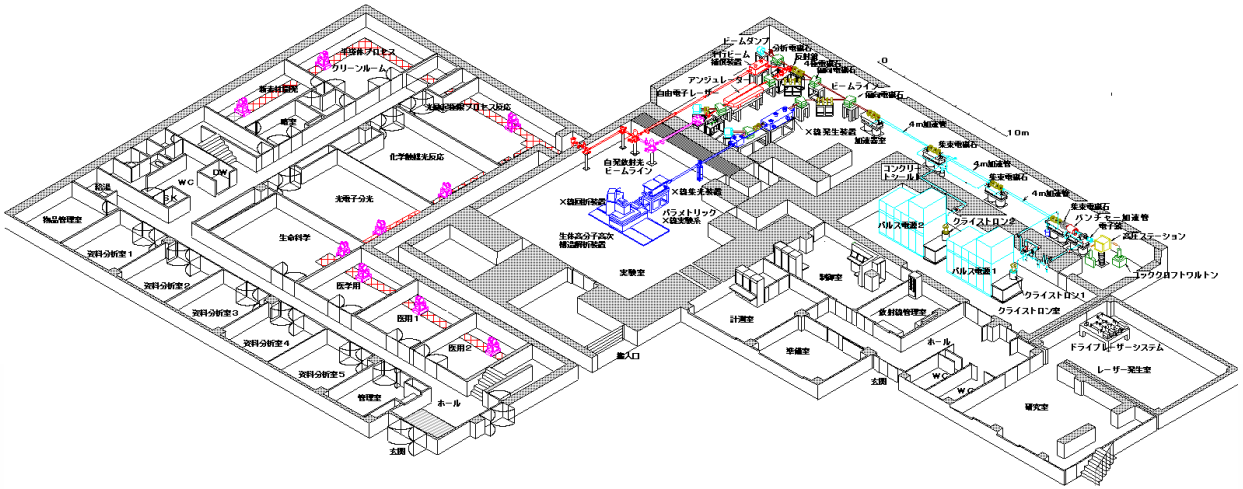
LEBRA facility of Nihon University

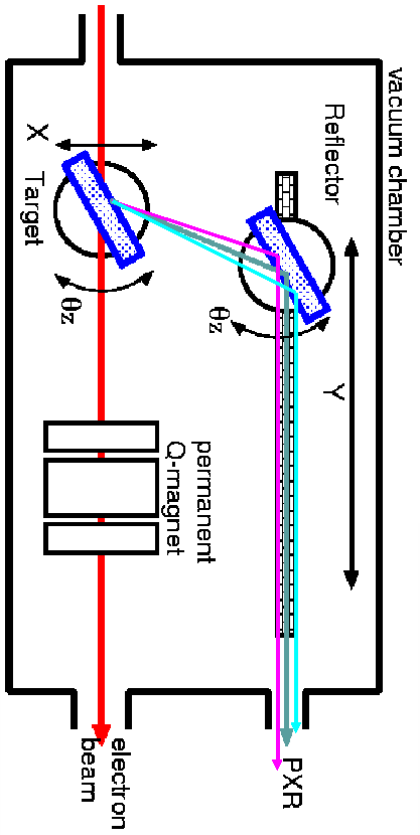
LEBRA: **L**aboratory for **E**lectron **B**eam **R**esearch & **A**pplication

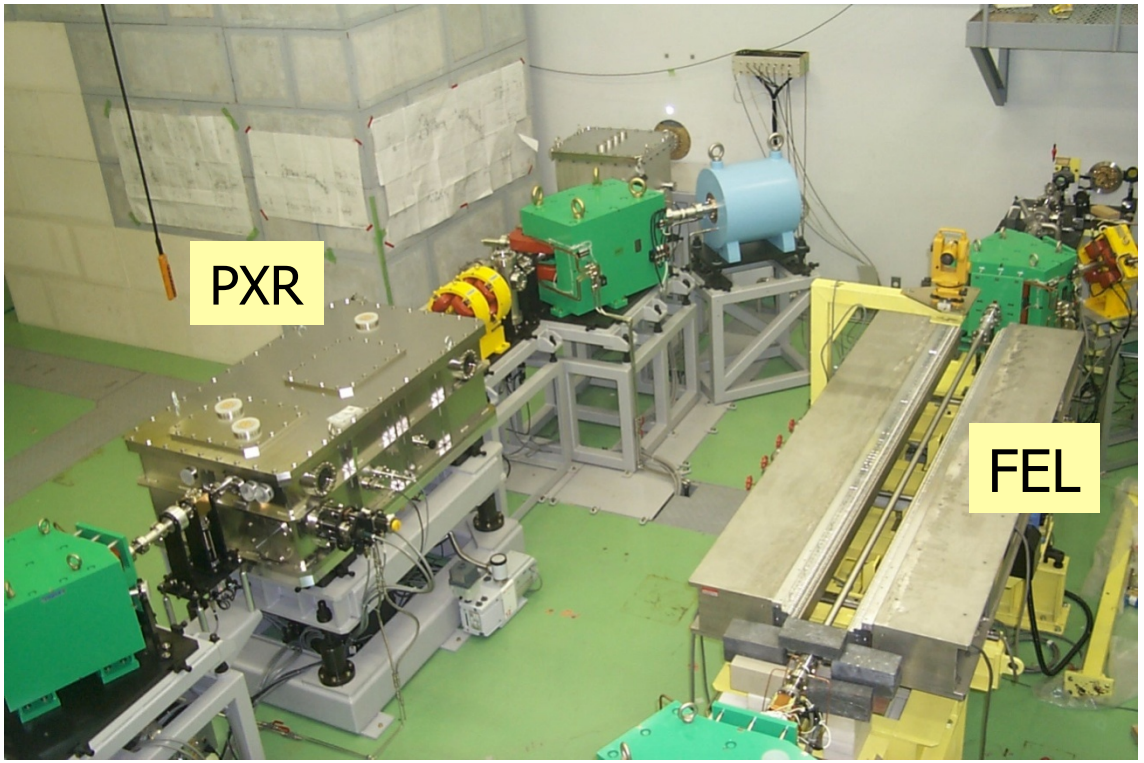


Tunable light-source facility based on
a conventional S-band electron linac

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

LEBRA facility: beamlines (FEL & PXR)





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

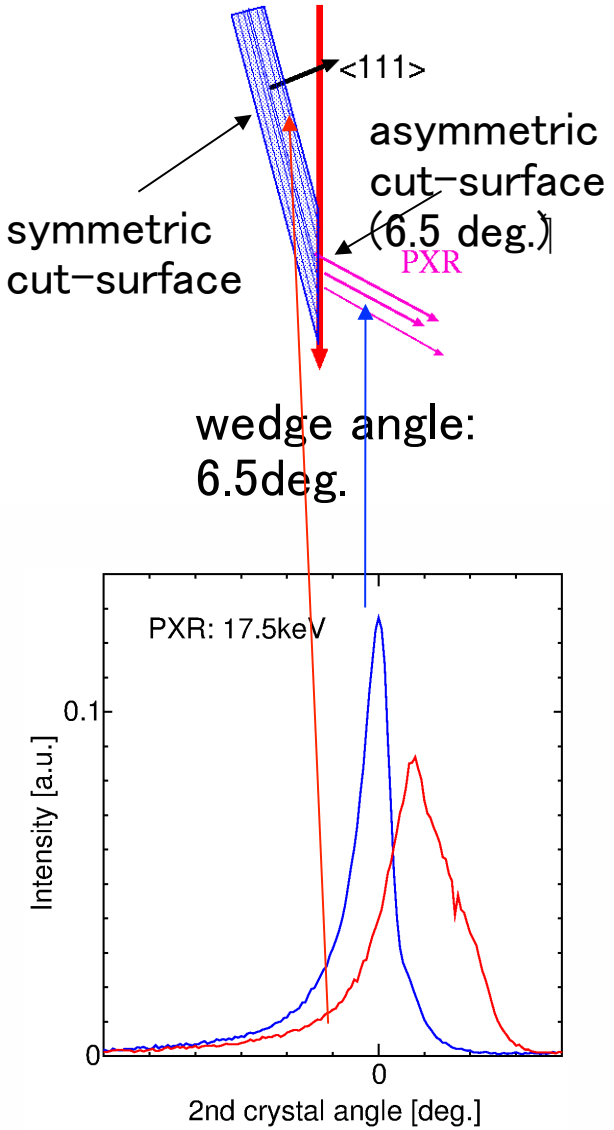
Parametric X-ray radiation (PXR): double-crystal system

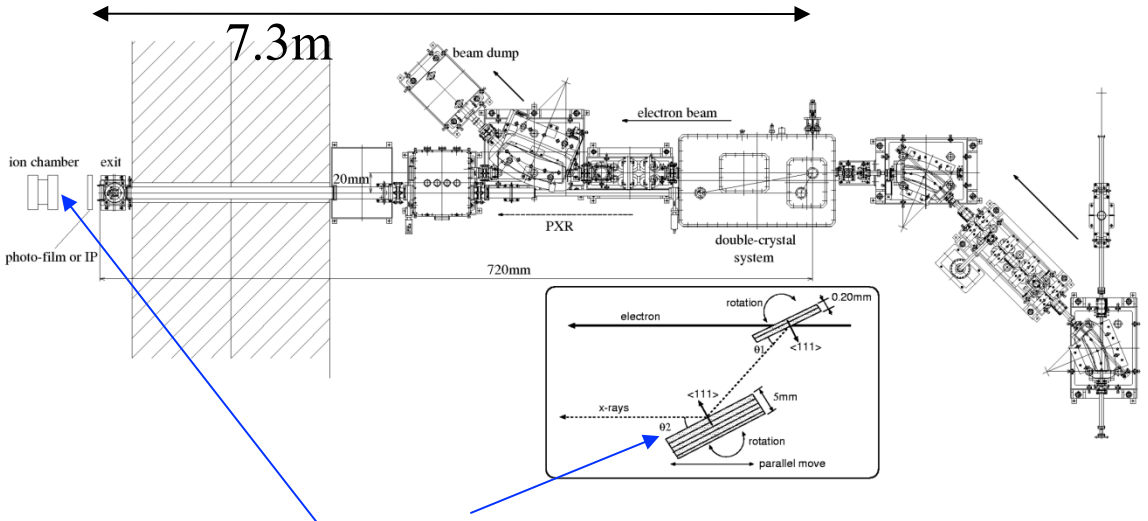
Status of LEBRA-PXR (typ.)

- Electron beam energy: 100MeV
- Macro pulse of e-beam : ~130mA, 4 – 5 μs, 5pps
- Average e-beam current: 2~3 μA
- X-ray energy: 5 – 34keV

  (Si(111): 5 – 20keV, Si(220): 6.5 – 34keV)
- Irradiation field: 100mm in diameter @ exit port
- Total photon rate: ~ 10^7 photon/s @ 17.5keV
- Application: imaging, XAFS, radiobiology, ...

Wedge-shaped target crystal





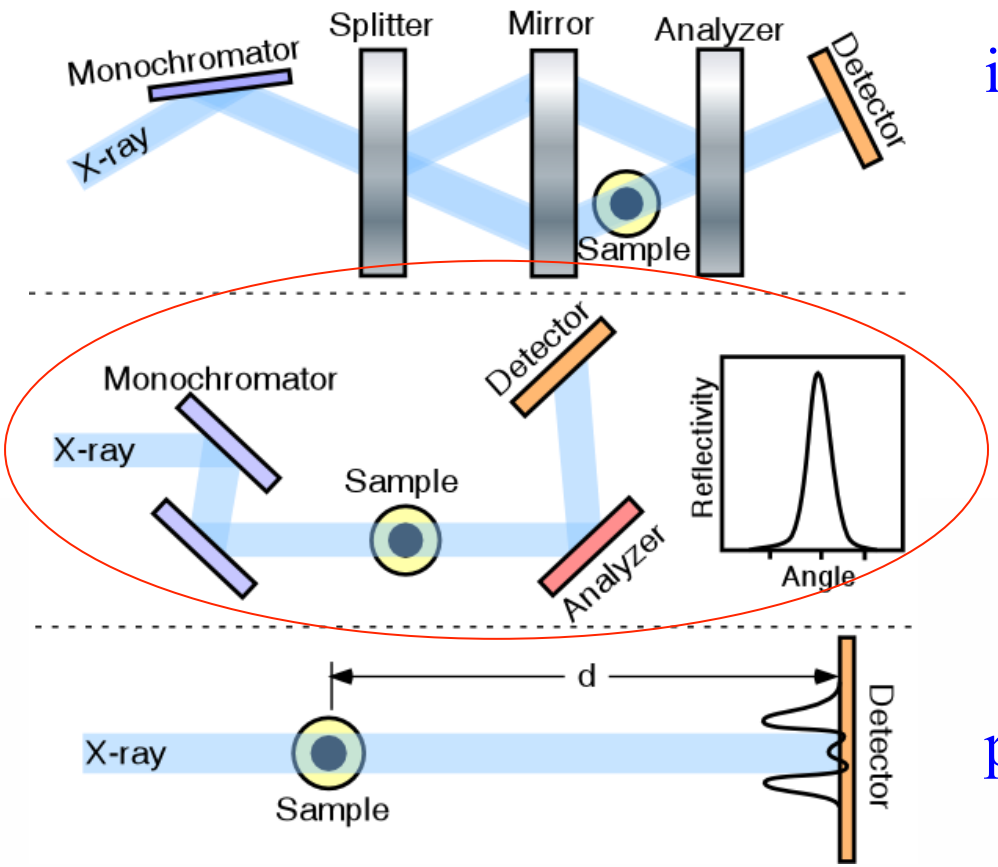
rocking curve measurement
@ 2nd crystal in the PXR generator

Wedge-shaped target crystals were adopted for the PXR source.
The wavefront of PXR from the asymmetric cut-surface seems to be more uniform than that from symmetric cut-surface.

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

Phase-contrast(sensitive) X-ray imaging



interferometer-based technique

analyzer-based technique

propagation-based technique

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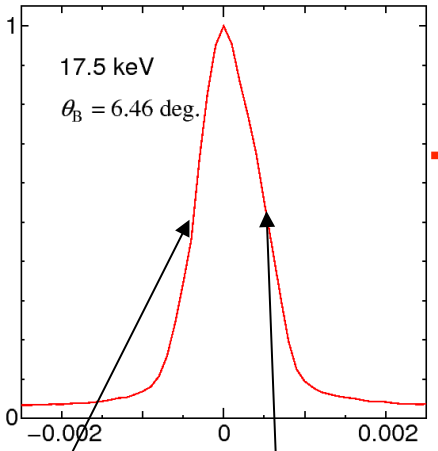
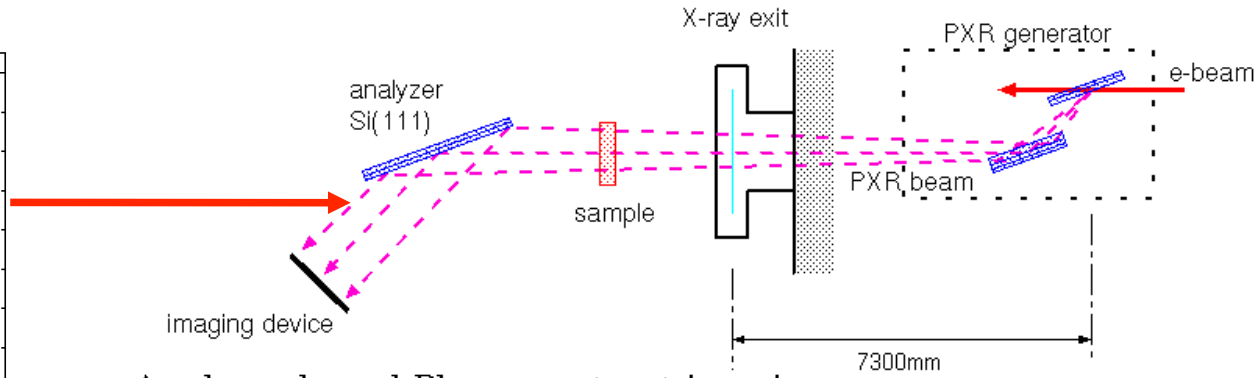
The methods require X-ray beams with excellent spatial coherence.

Diffraction Enhanced Imaging (DEI)

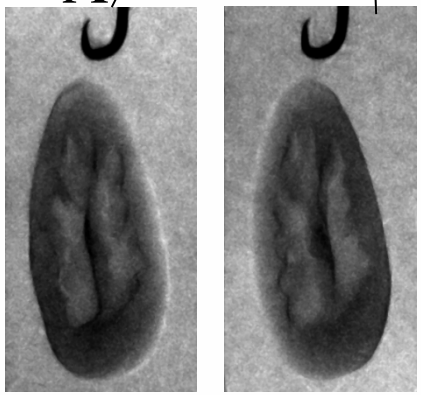


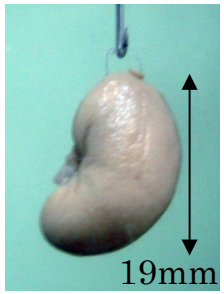


Analyzer-based Phase-contrast imaging
(DEI: Diffraction-enhanced imaging)

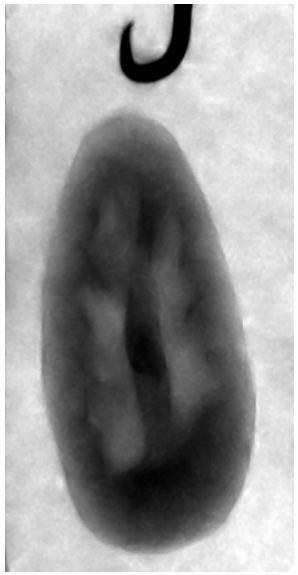
A

B

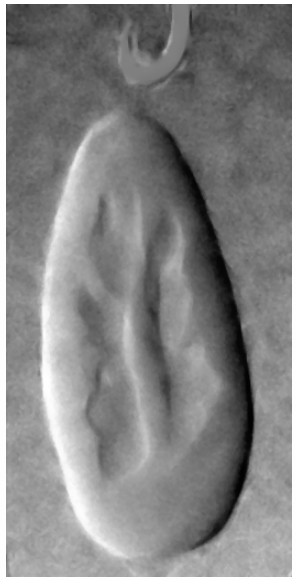




kidney of mouse



A+B:
absorption contrast



A-B:
phase contrast

Feature of LEBRA-PXR

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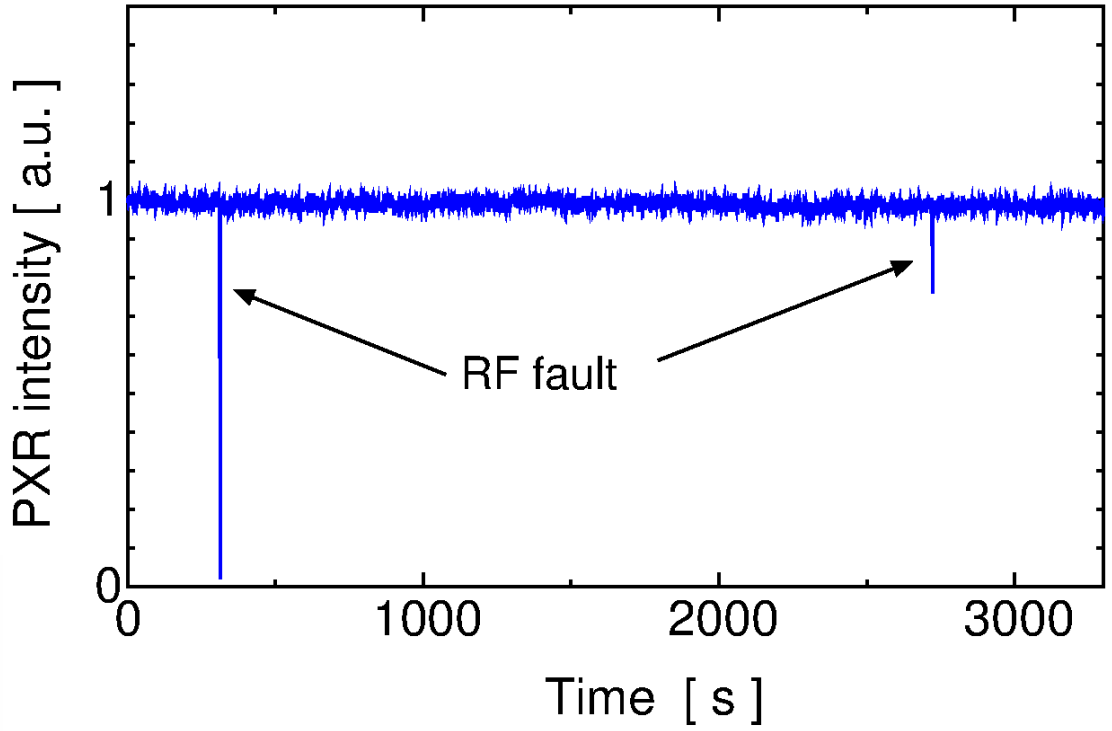
  - energy dispersion (spatial chirp) ~ 10%
  - local band width ~ 0.1% (several eV)
- Tunability
  - continuous selection of the center energy
- Large irradiation area
  - at least 100mm in diameter
  - cone-beam depending on $1/\gamma$
- Spatial coherence
  - phase-contrast imaging is actually possible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

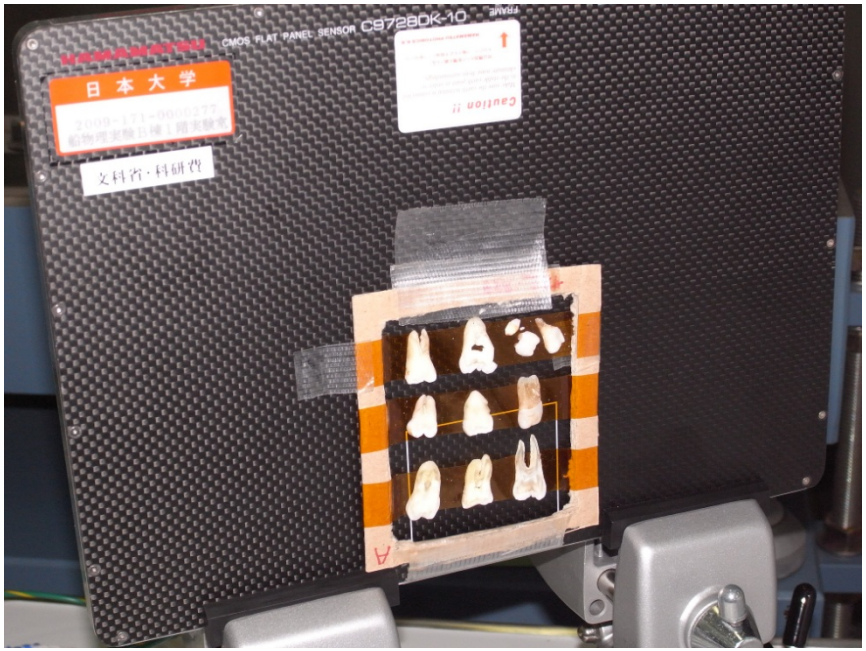
Stability of PXR beam



The precession of cooling water temperature was improved by 0.01deg. and long term stability of the PXR intensity was achieved except rare RF faults.

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

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

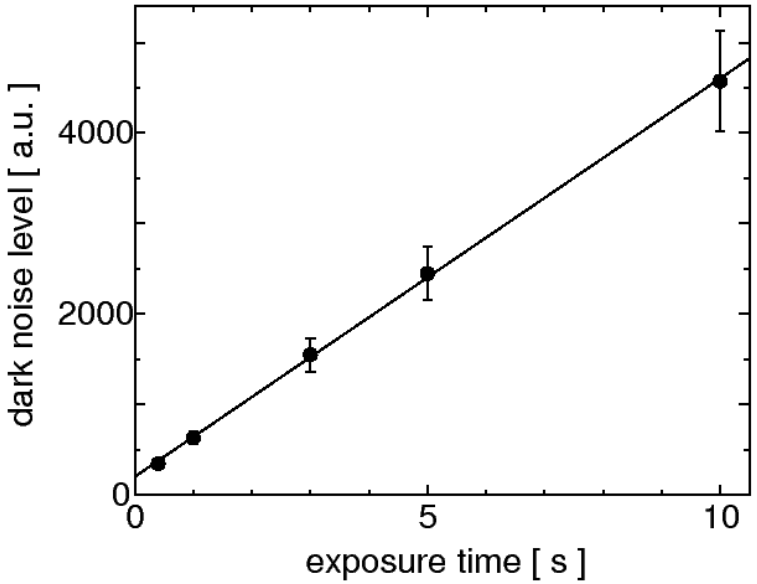
frame rate: 0.1 - 3 f/s

resolution: 10 line pairs/mm

X-ray absorption efficiency:

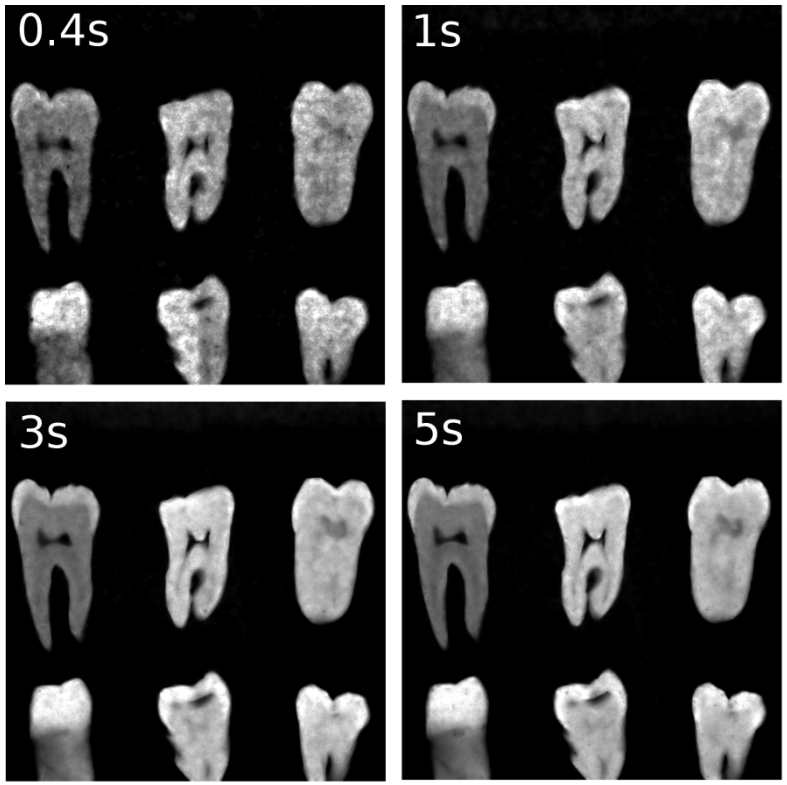
~ 85% @ 18keV

Performance of FPD



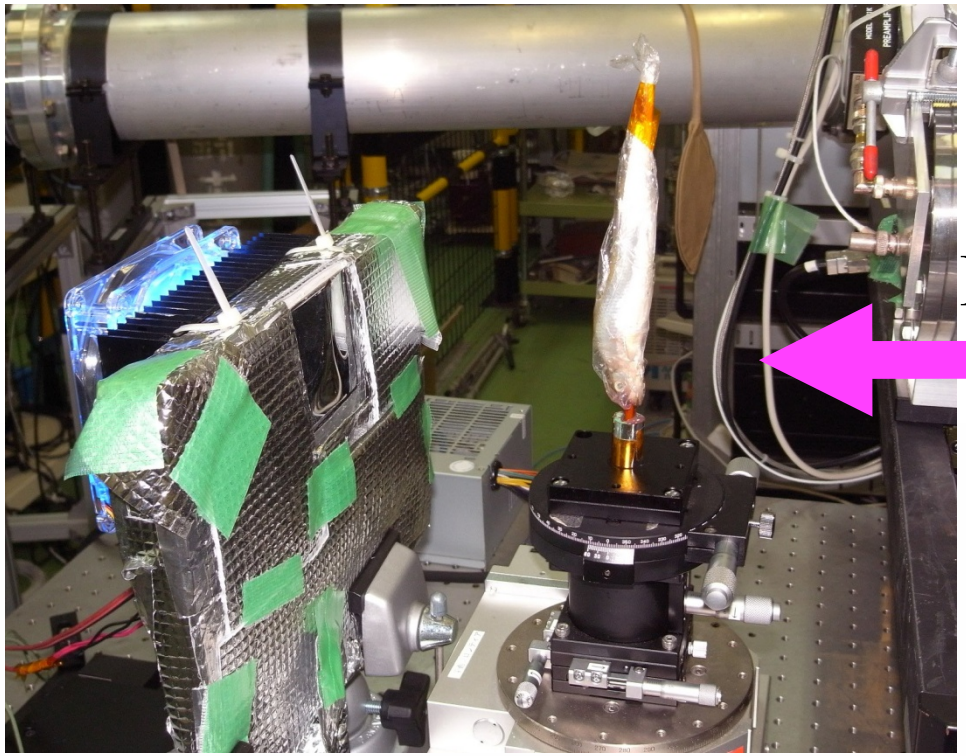
large dark noise has to be subtracted from raw images.

For the proper subtraction constant room temperature is required.



target: wedge-shaped
Si(111) (6.5deg.)
PXR: 17.5keV (grazing incidence)
e-beam: 2.6uA (average)
sample: human tooth

Setup for Computed Tomography Experiments

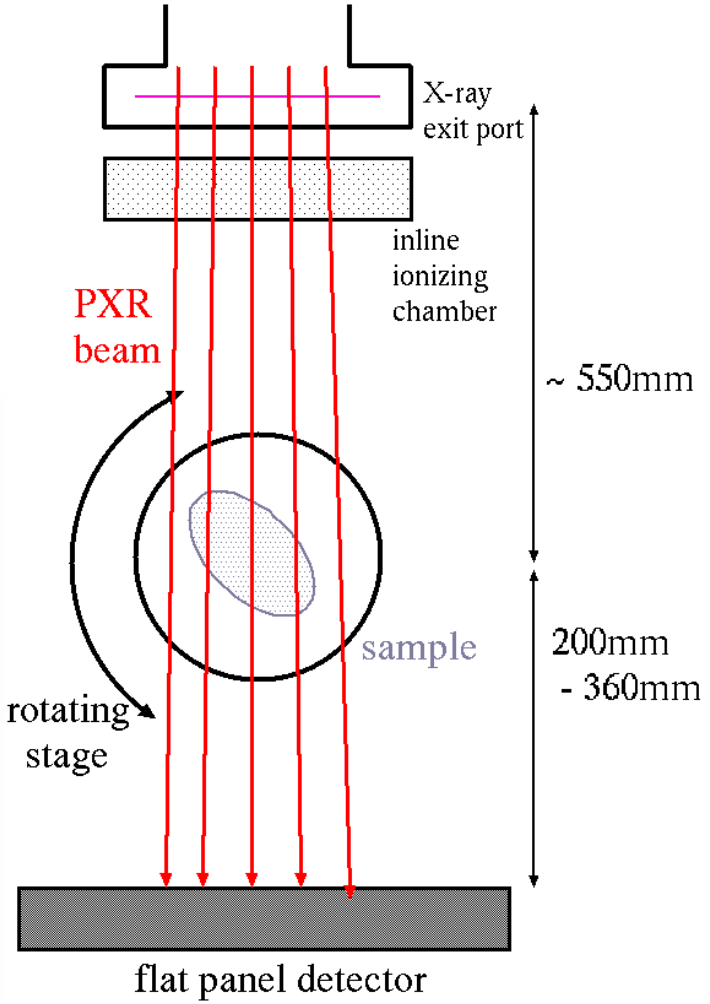


PXR

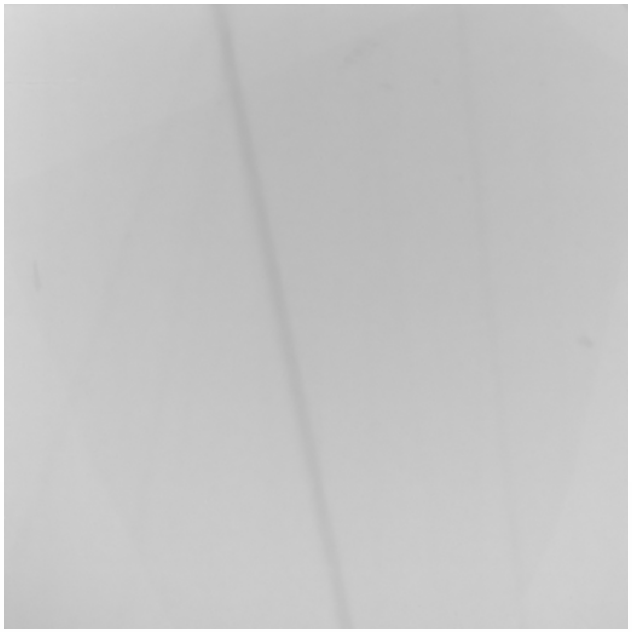
FPD

sample &
rotating stage
(0 – 180 deg.)

PXR source: Si(111)



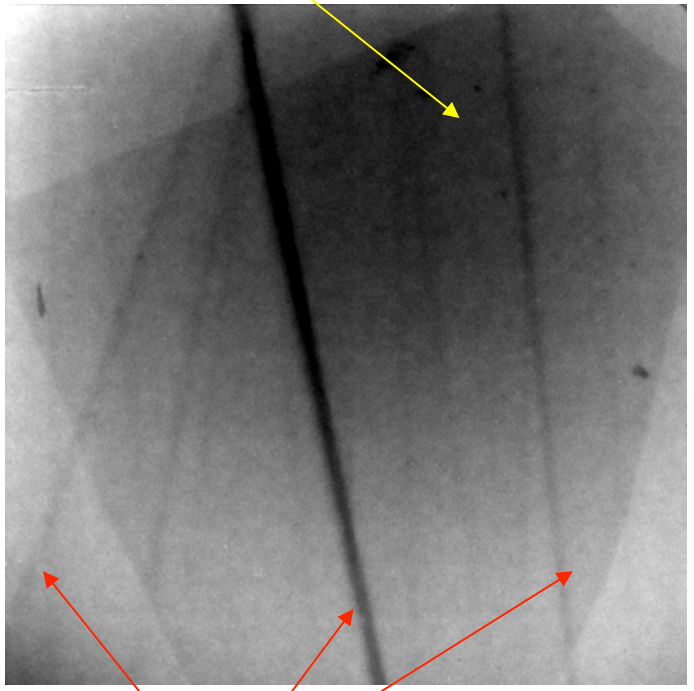
Shading correction



Intensity distribution in the PXR beam(I_0 image)

contrast enhancement

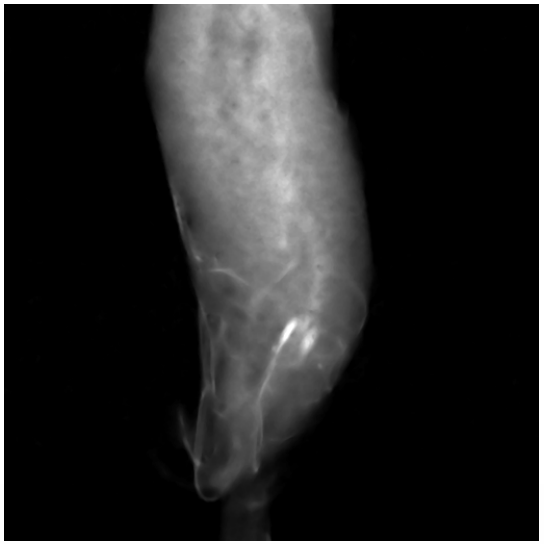
unknown trapezoid structure in the FPD



topograph caused by defects of the target and/or reflector Si crystals

Shading correction requires the linearity of the FPD and the stability of the PXR beam.

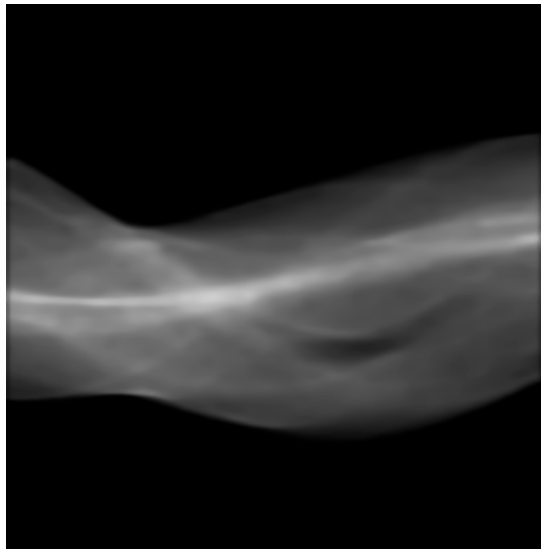
Process of Tomography

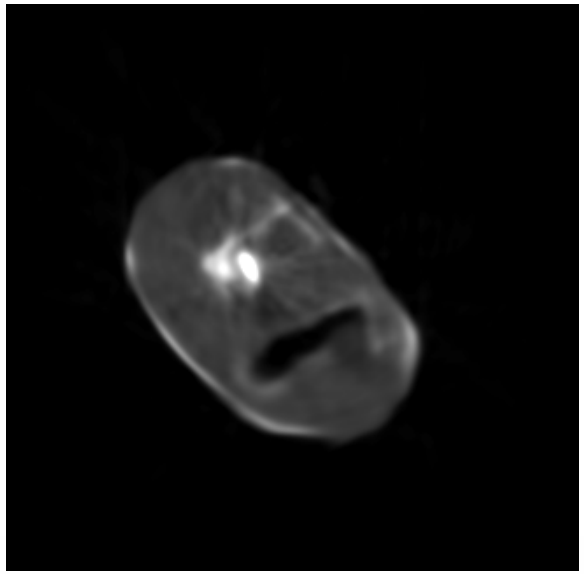


normalized projection images (divided by I_0 image)

60 – 360 image stack

sinogram





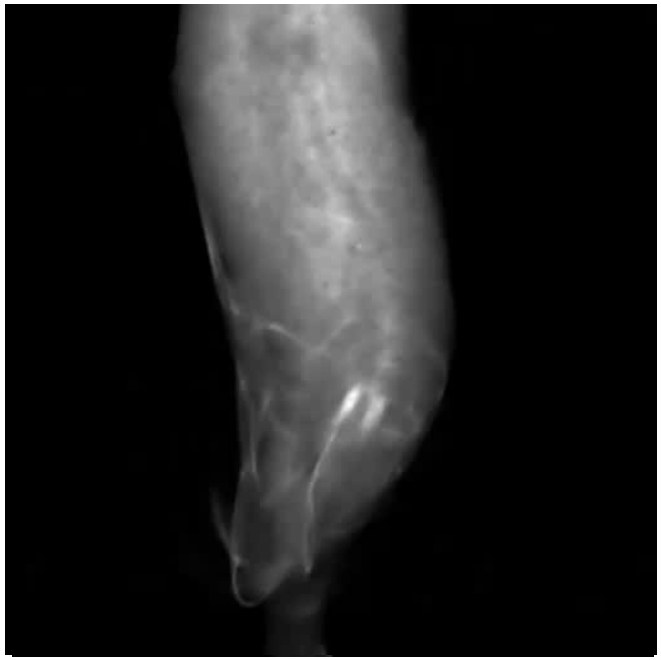
tomogram

back projection (Radon transform)

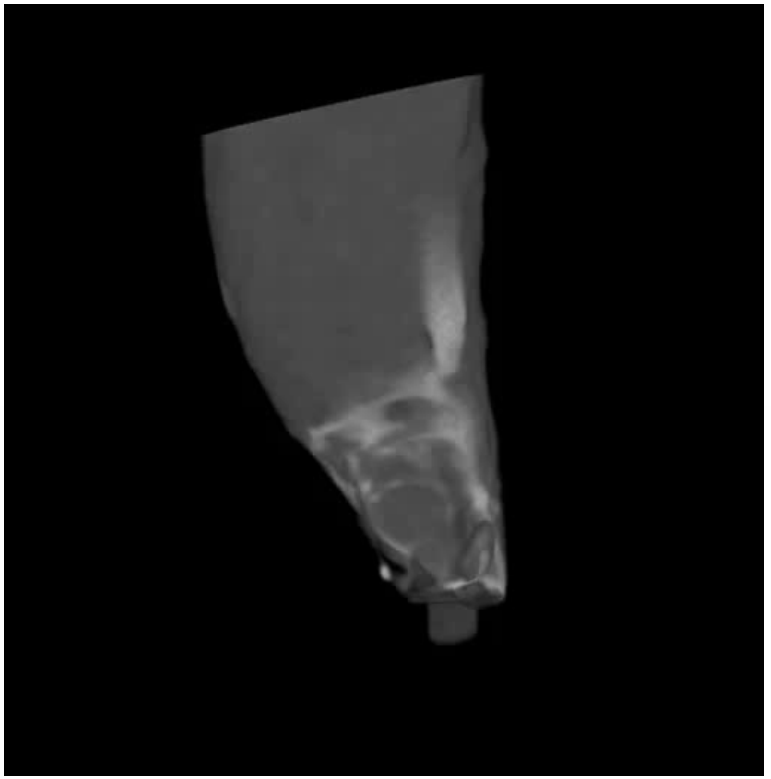
Typical result 1

Sample: fish
(hypomesus japonicus)

projection image



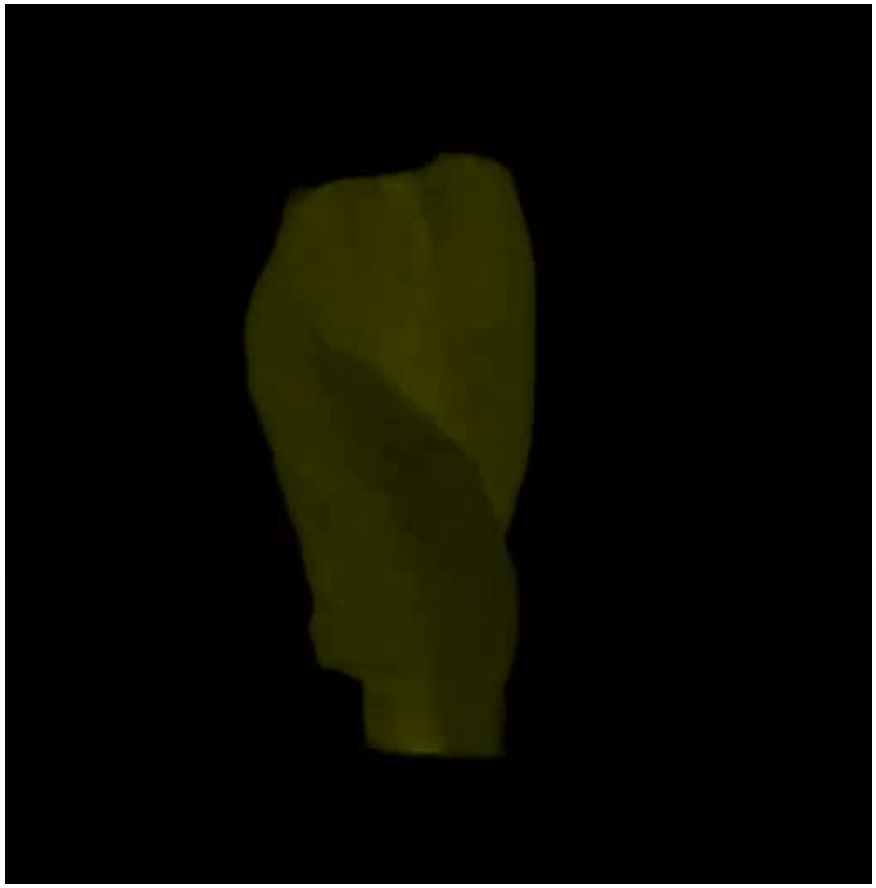
reconstructed 3D image



PXR energy: 19keV
10s exposure x 90 images
total measurement time: 15min (net)

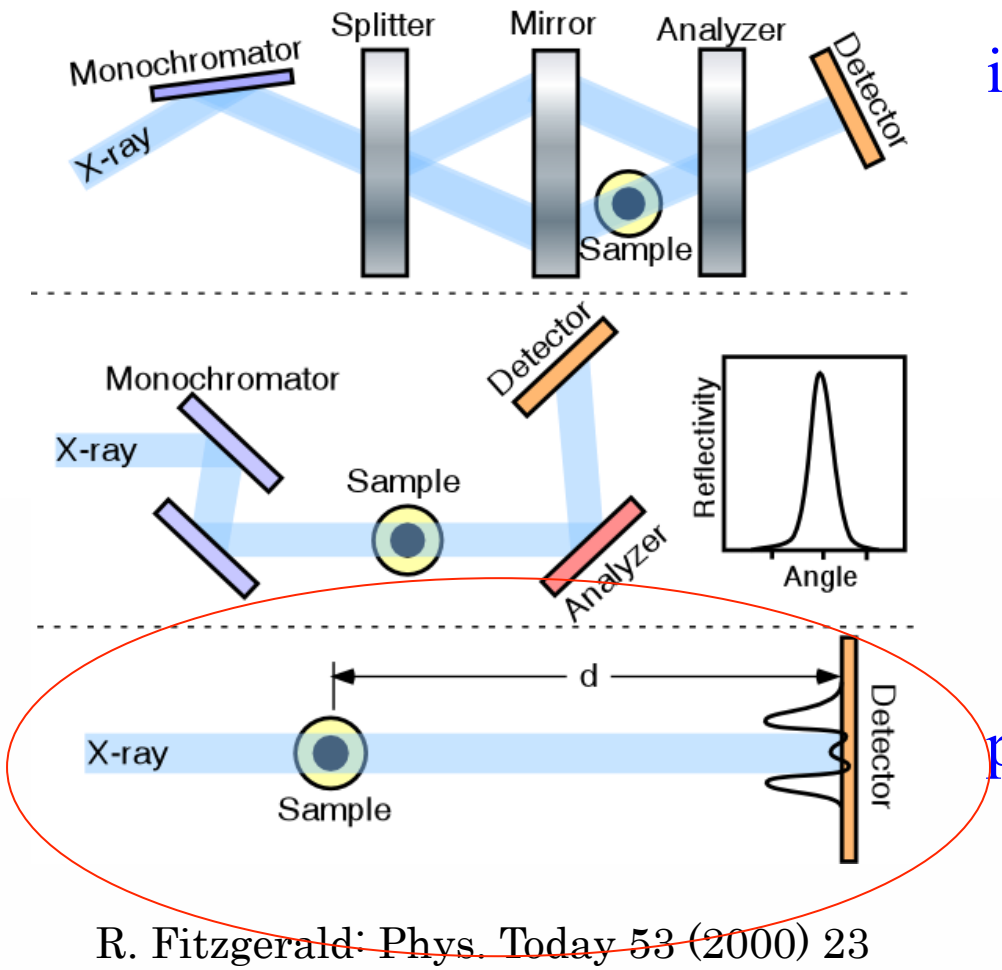
Typical result 2

sample: chicken wing



PXR energy: 17.5keV
5s exposure x 60 images
total measurement time:
5min (net)

Phase-contrast(sensitive) X-ray imaging



interferometer-based technique

analyzer-based technique

propagation-based technique

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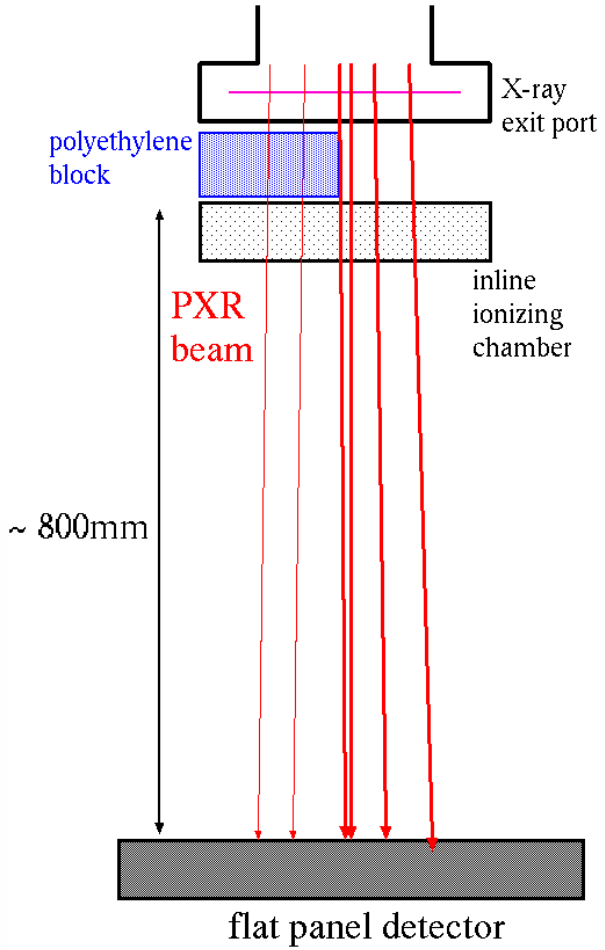
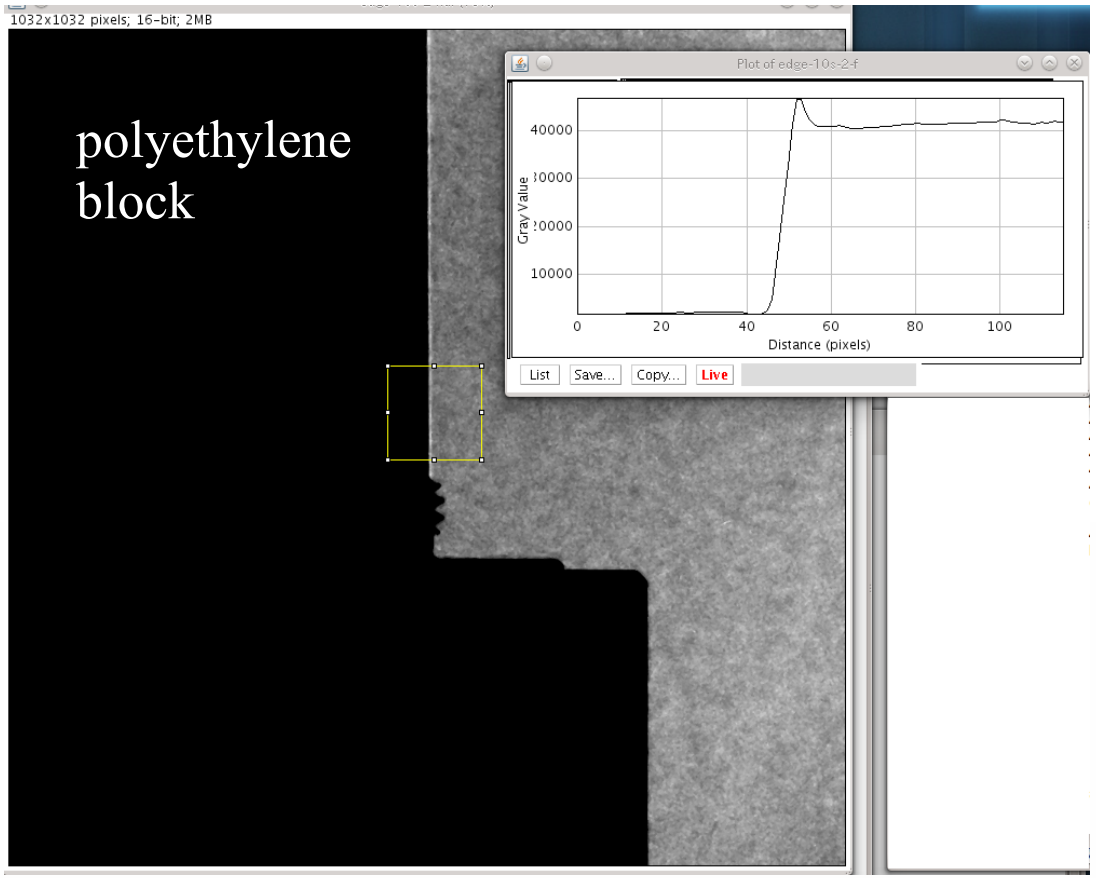
The methods require X-ray beams with excellent spatial coherence.

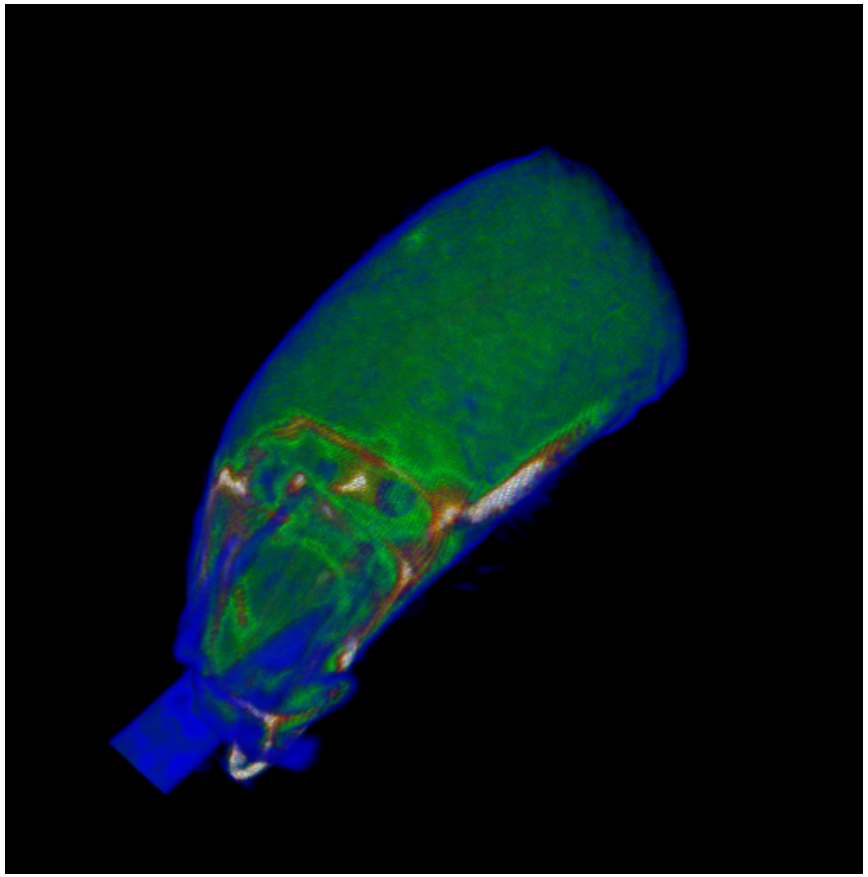
Edge-enhancement effect

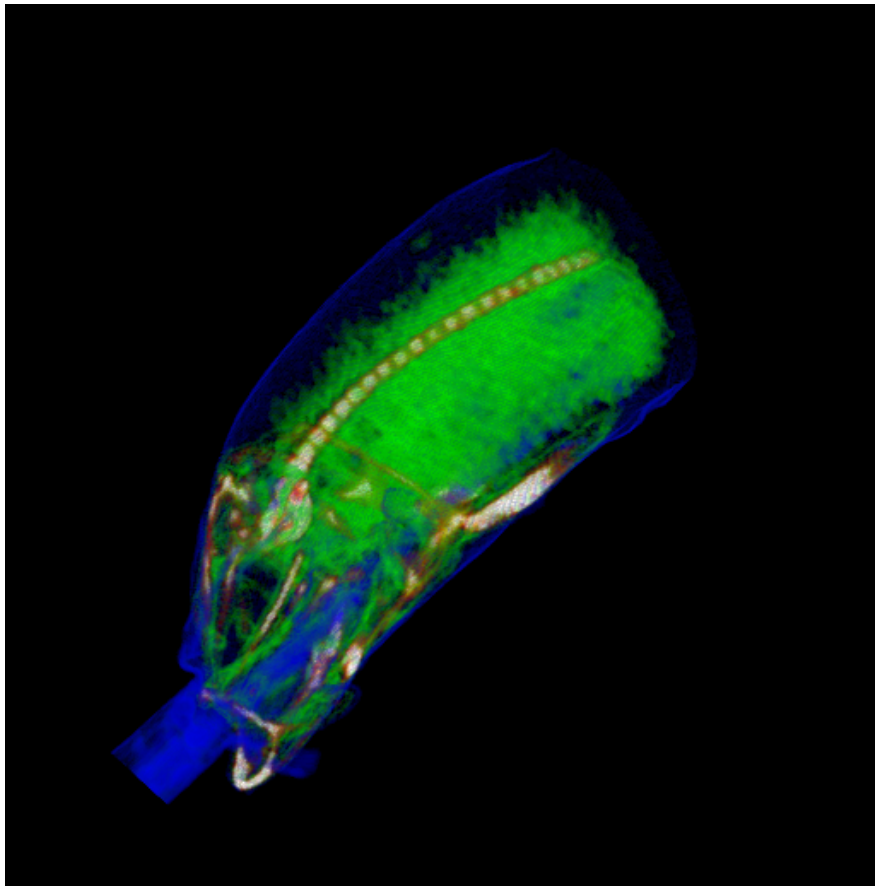




With a propagation distance of several 100 mm,
edge enhancement due to phase contrast is actually observed.

Sample1 (fish)

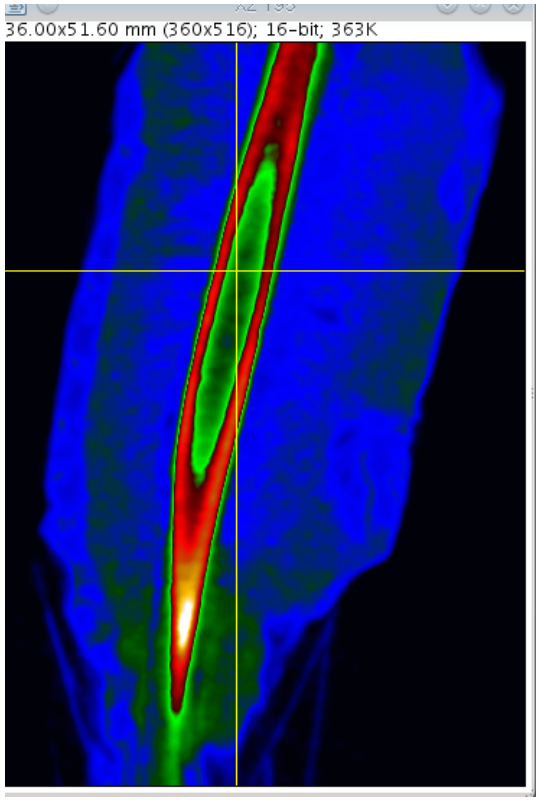


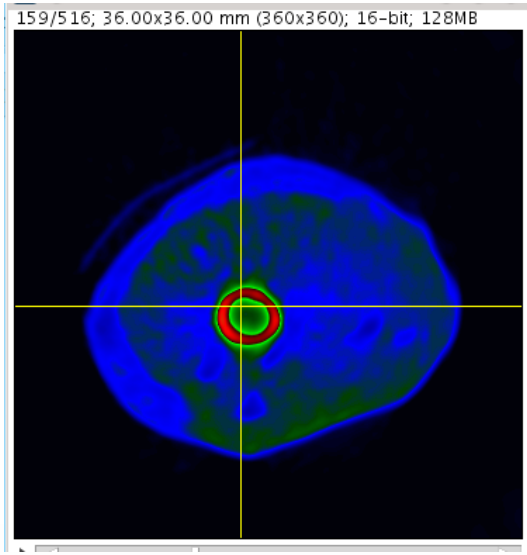


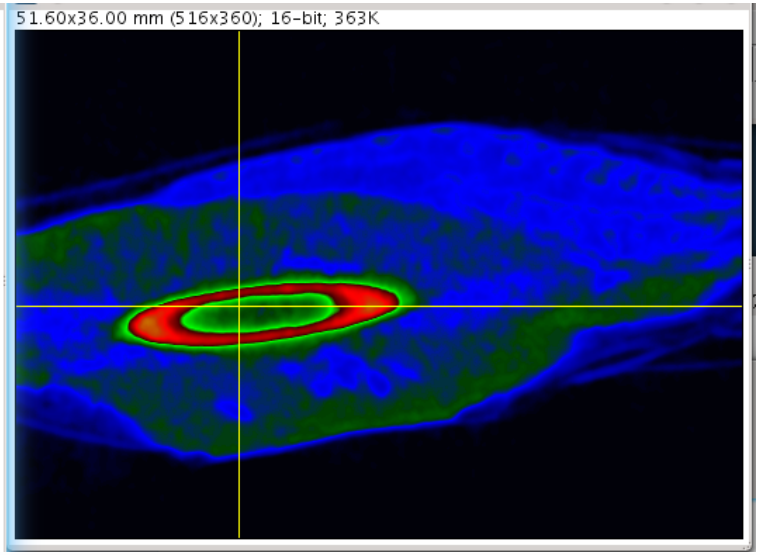
PXR energy: 17.5keV
30min measurement
(10s x 180 images)

outlines of the sample are clear and sharp.

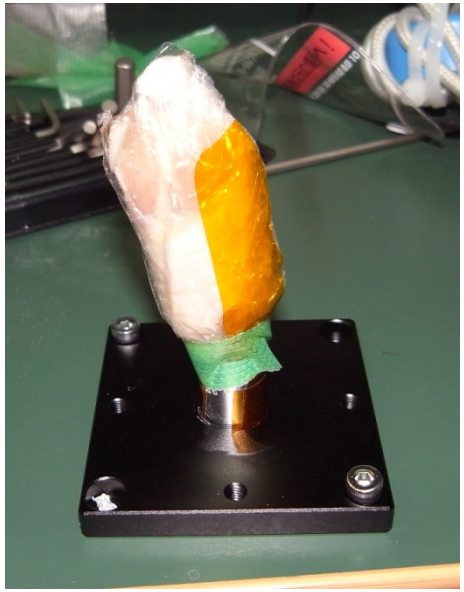
Sample2 (chicken wing)





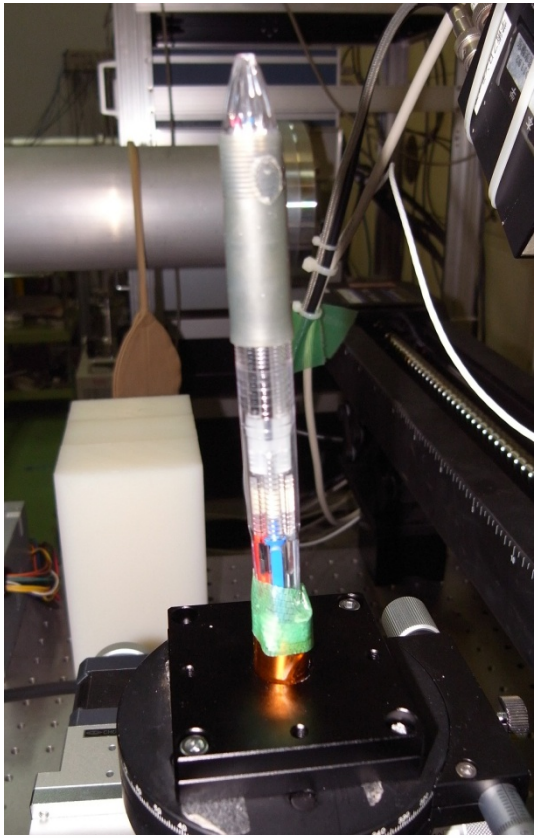


17.5keV
1 hour measurement
(10s x 360 images)

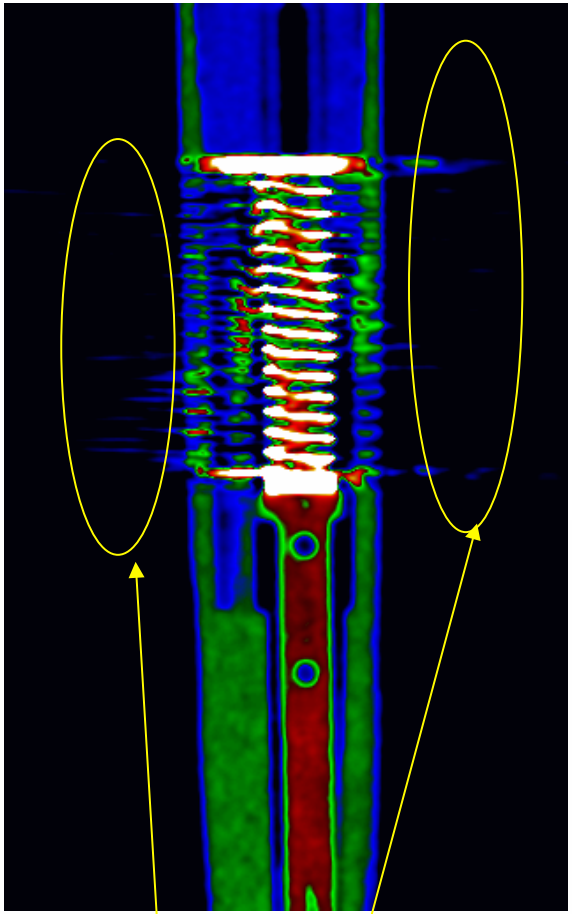


Muscles and adipose tissue can be distinguished; polyethylene wrappings and polyimide tape are visible.

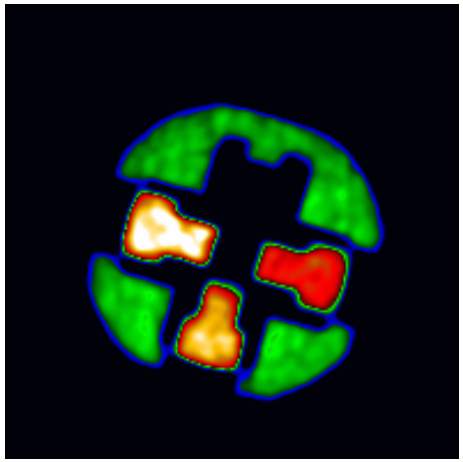
Sample3 (ballpoint pen)



17.5keV
1 hour measurement
(10s x 360 images)

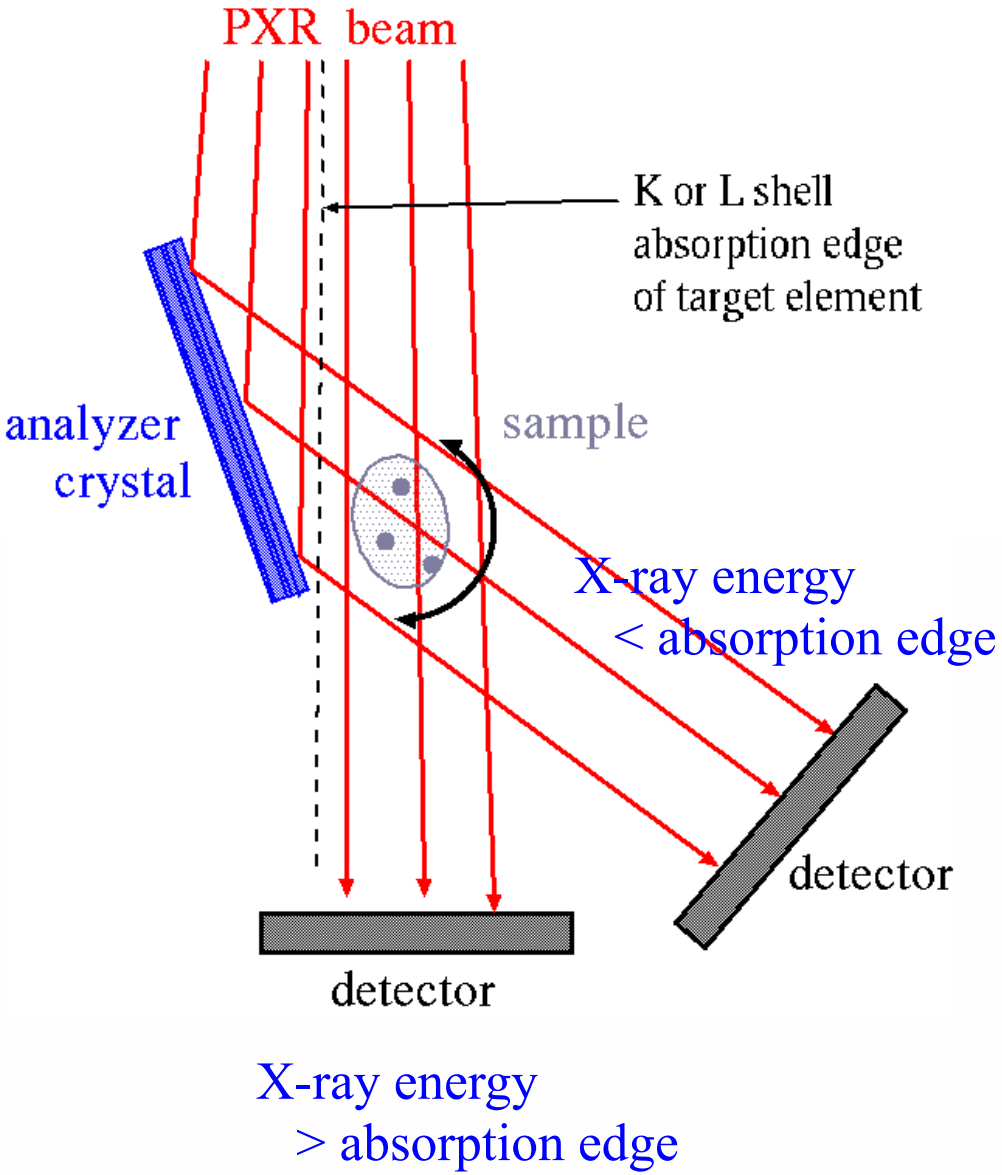


artifacts due to
heavy materials (springs)



The difference of pigment is observed; advantage of monochromatic X-ray

future: Element sensitive CT experiment



Using the spatial chirp in the PXR beam, we can implement element-sensitive CT experiments.

The distribution of a target element is obtained as the difference between 2 tomograms across the K or L-shell absorption edge energy.

Summary

- Using a FPD and the LEBRA-PXR source, monochromatic CT experiments on biological samples are possible.
- 3D tomographic images were actually obtained by 5 min measurement, and PXR beam is sufficiently stable during 1 hour measurement.
- For the reconstruction process, simple normalization is enough and effective due to the linearity of the FPD.
- Sharp outlines in CT images suggest the benefit of propagation-based phase contrast.
- Monochromatic CT is sensitive to the slight difference of the density in the samples.

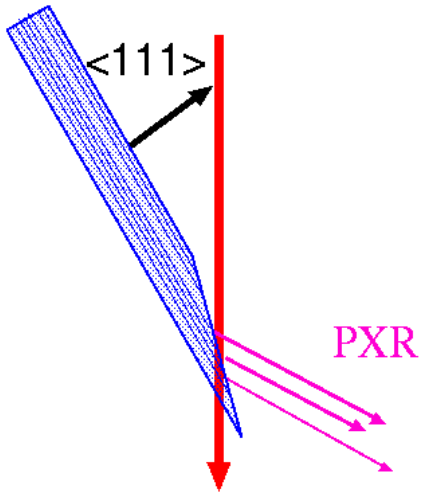
Acknowledgements

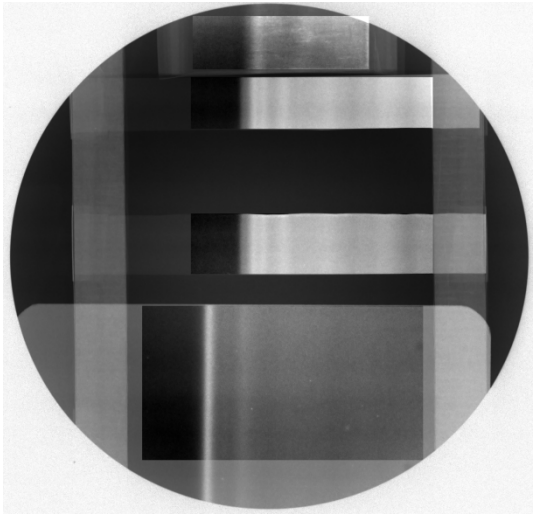
- Nihon University Multidisciplinary Research Grant for 2012 (Sogo: 12-19)
- MEXT.KAKENHI (24651105, 24560069)

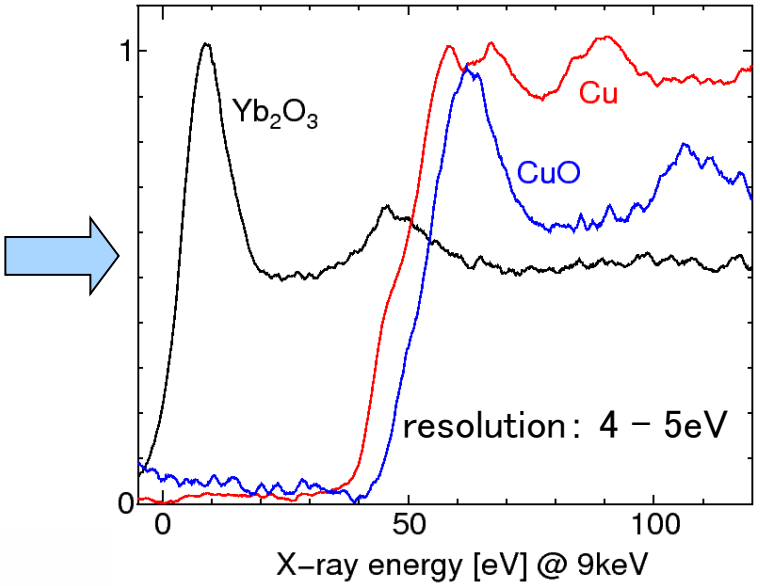
Thank you for your kind attention !!

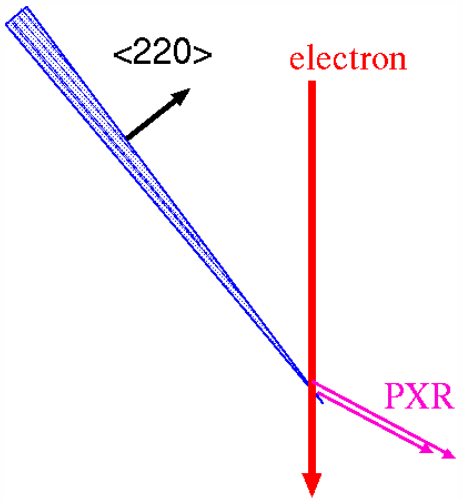
Appendix

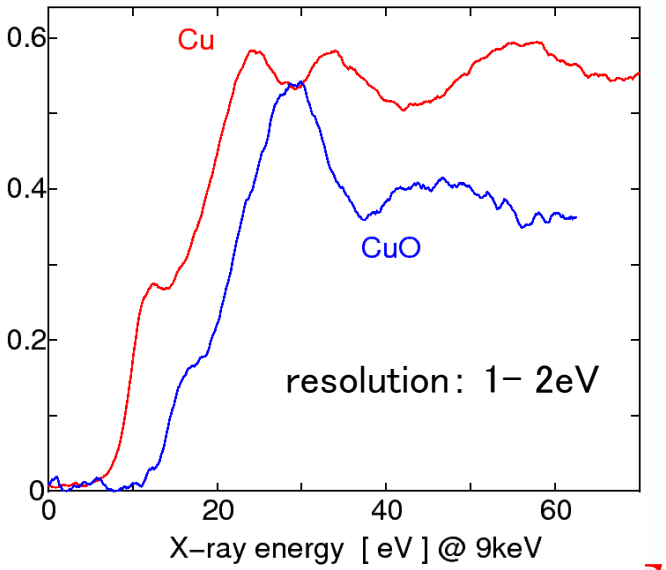
Dispersive XAFS (DXAFS)





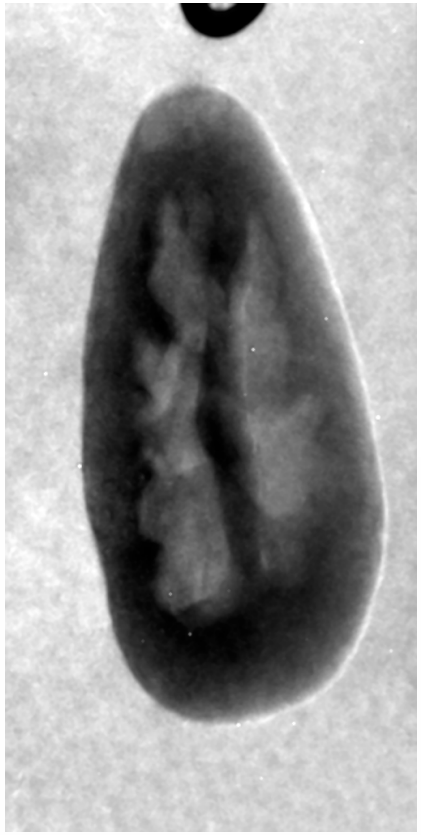




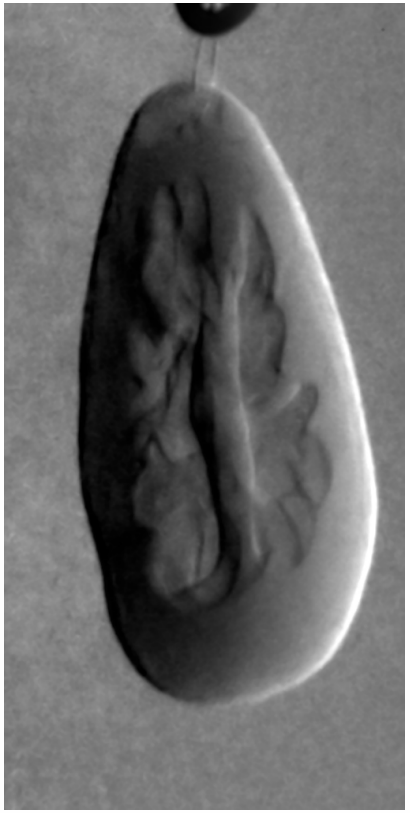


Typical result of DEI 2 (17.5keV)

kidney of mouse

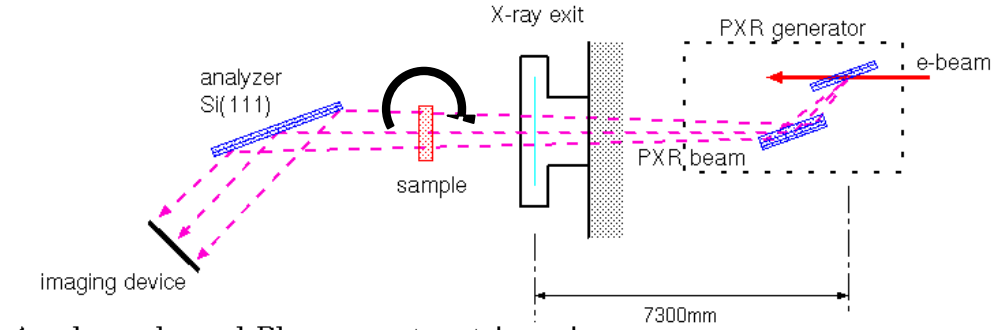


A+B
absorption

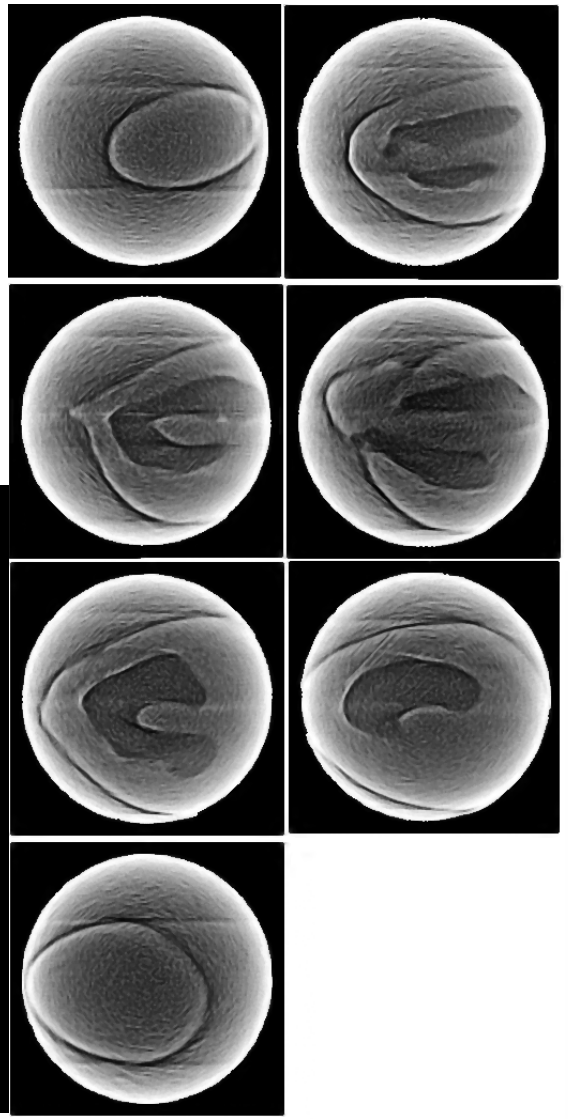


A-B
phase contrast

DEI-CT(computed tomography)



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



sample: mouse kidney
PXR energy: 17.5keV

angular step: 2 deg.
projection: 90 images
(180 DEI images)
measurement time (net)
30s x 2 x 90 = 5400s
= 90min

phase-contrast tomography calculated from DEI images