X-ray imaging based on small-angle X-ray scattering using spatial coherence of parametric X-ray radiation

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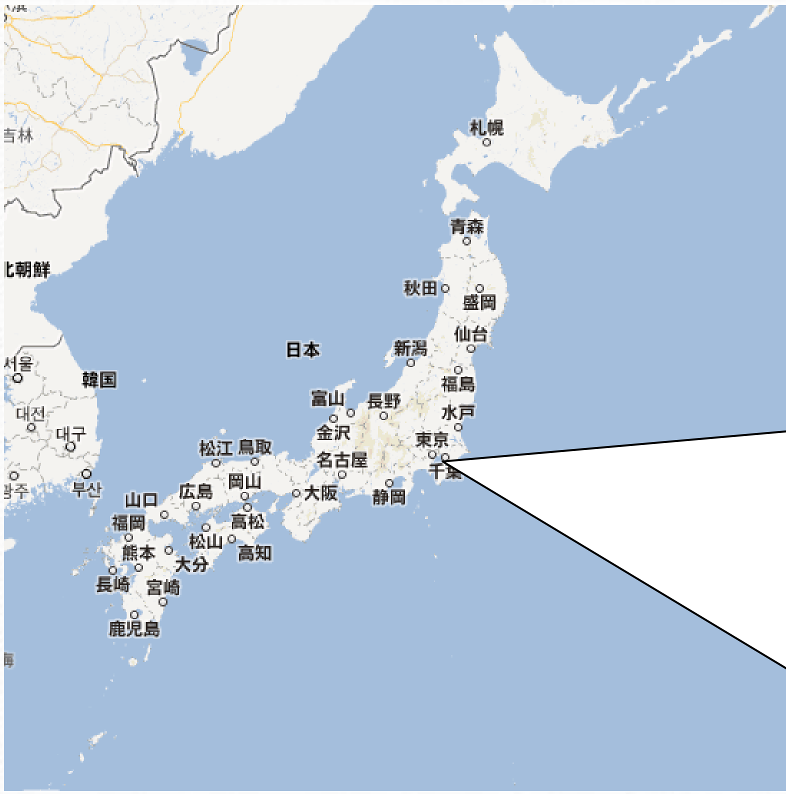
Outline

- LEBRA facility at Nihon University & the LEBRA-PXR source
- Diffraction-enhanced imaging (DEI) using the LEBRA-PXR source
- Imaging technique based on small-angle X-ray scattering (SAXS)
- Summary & prospects

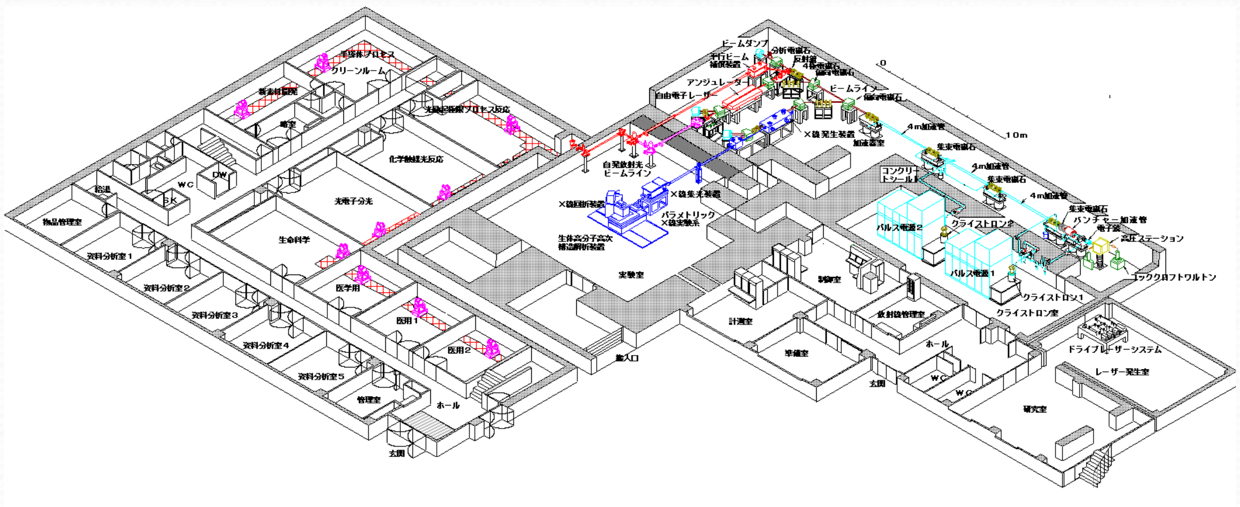
Nihon University



Funabashi, Chiba

LEBRA facility

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



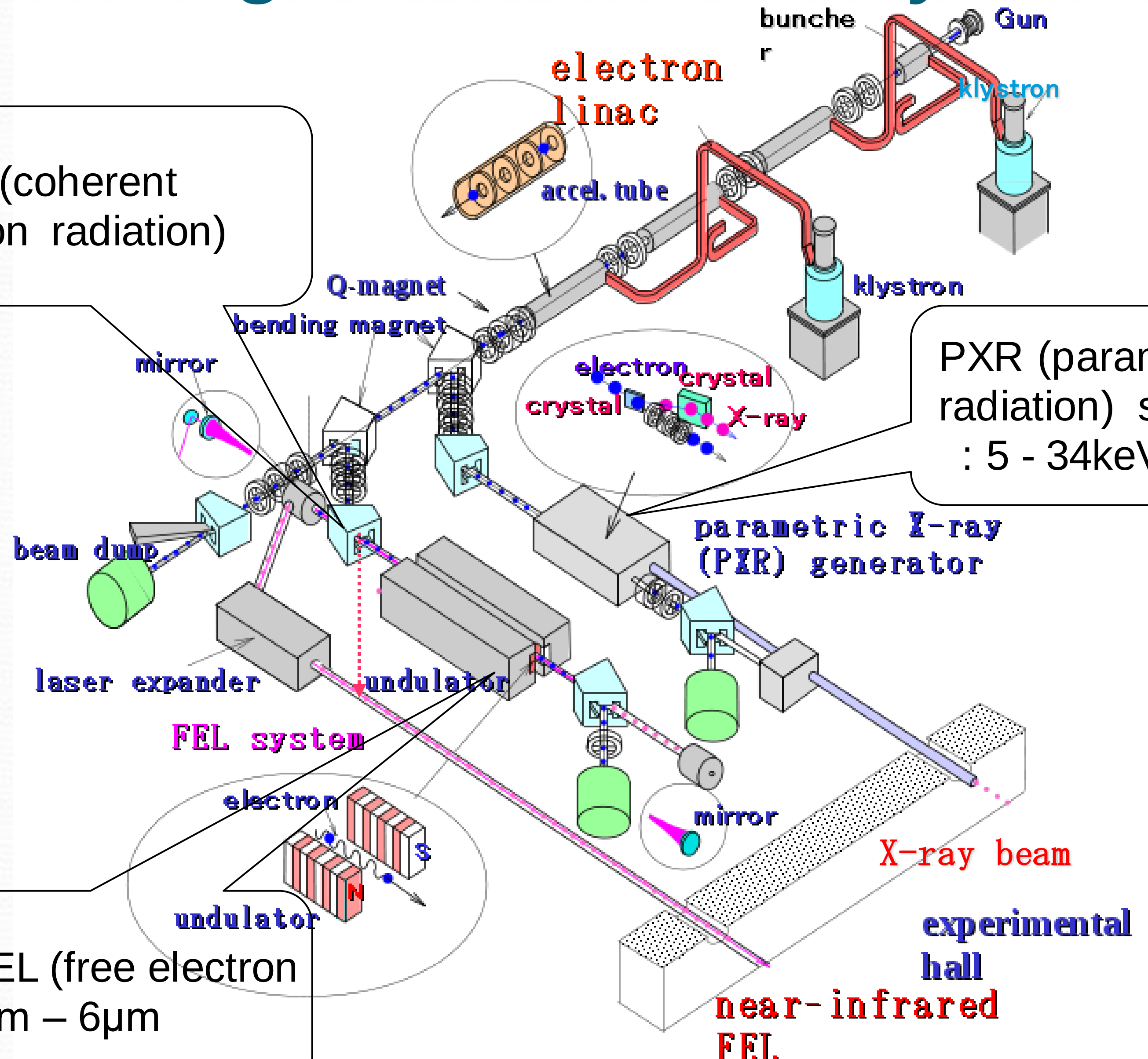
Tunable light-source facility based on
a conventional S-band electron linac

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

Tunable light source facility

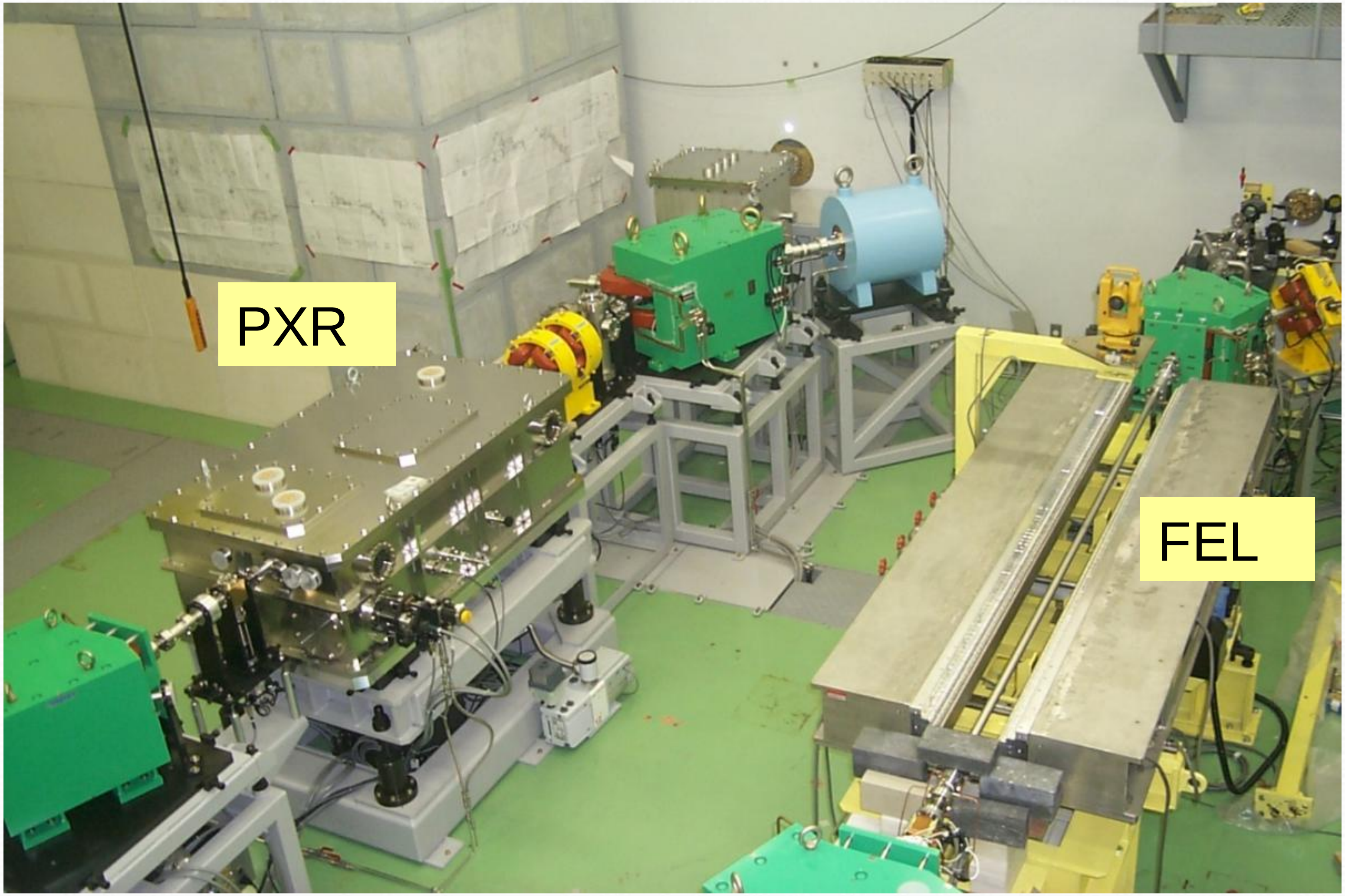
THz-CSR (coherent synchrotron radiation)

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

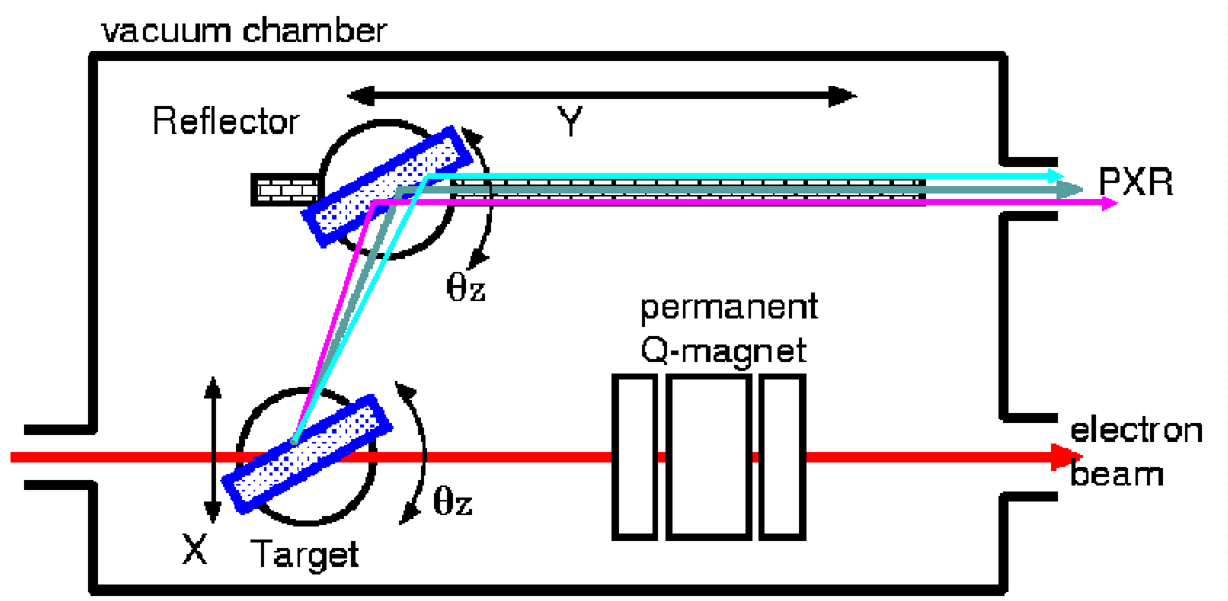


infrared FEL (free electron laser) : 1μm – 6μm

Beamlines (PXR & FEL)



Double crystal system for PXR

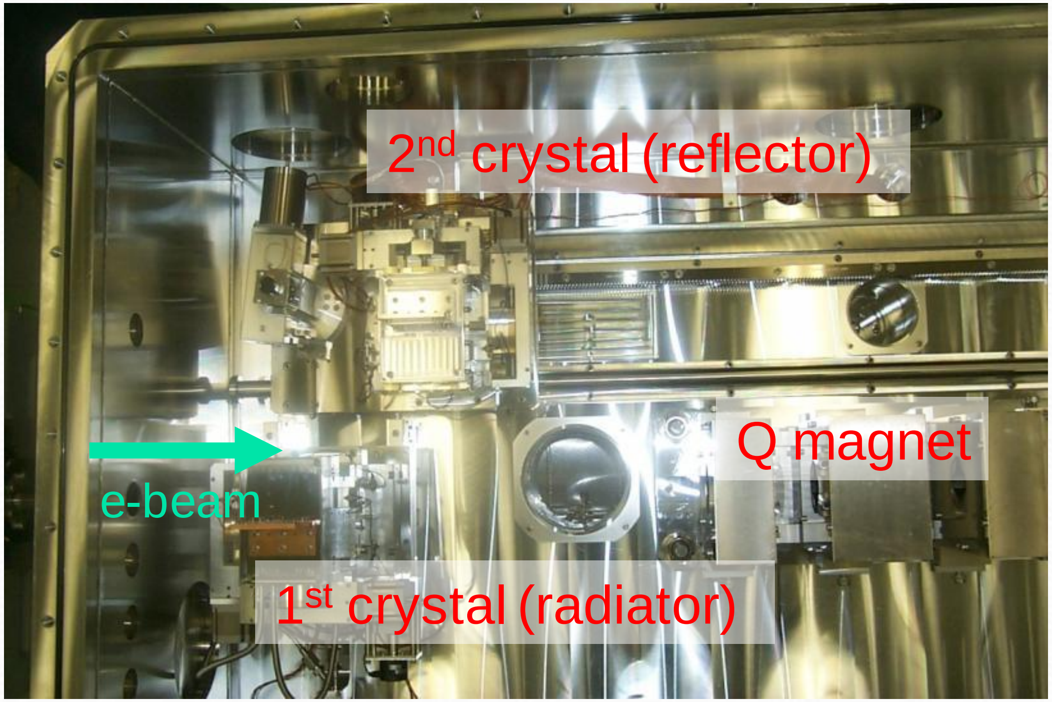


To actualize an X-ray source based on PXR, a double crystal system was proposed and developed.

The 1^{st} crystal is a target of electron beam and a radiator of PXR.

The 2^{nd} crystal is a reflector to transport PXR through a fixed exit port penetrating 2m shield wall.

Radiator of the PXR source



PXR radiator: 0.2mm thick Si perfect crystal wafer
reflector: 5mm thick Si perfect crystal plate
crystal plane:
Si(111) for 5 – 20keV
Si(220) for 6.5 – 34keV

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 source

- X-ray energy does not depend on the electron energy but on the crystal arrangement (Bragg angle).

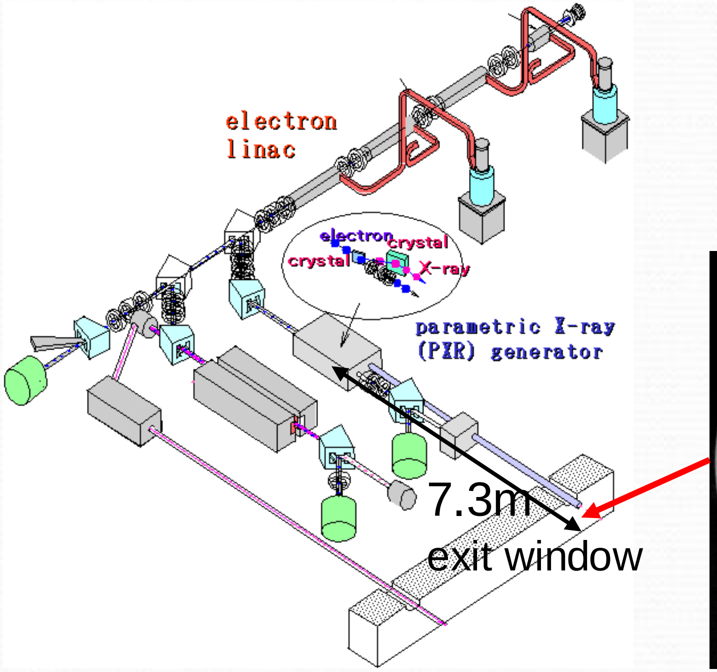
- Wide and continuous tunability

  Si(111): 5 - 20keV, Si(220): 6.5 - 34keV

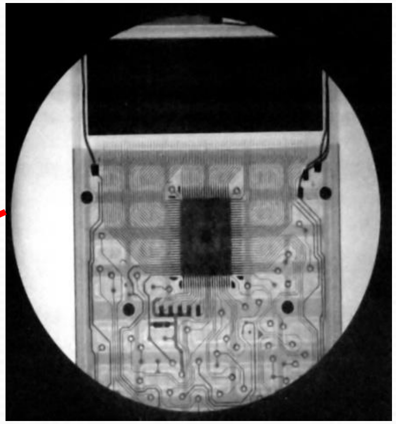
- Cone-beam depending on 1/γ
  Irradiation field of 100mm in diameter at the exit window
  (distance from the source to the window: 7.3m)

- PXR beam has energy dispersion (spatial chirp) along the horizontal direction.

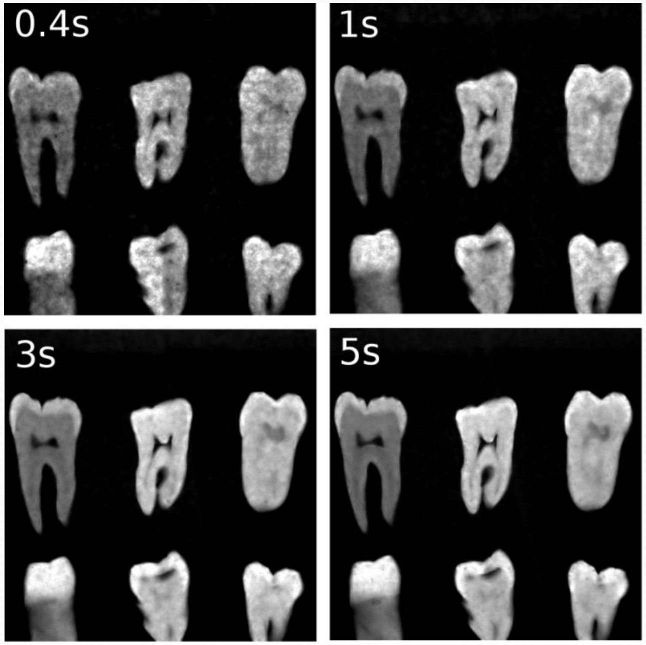
X-ray imaging (absorption contrast)



diameter: 100mm

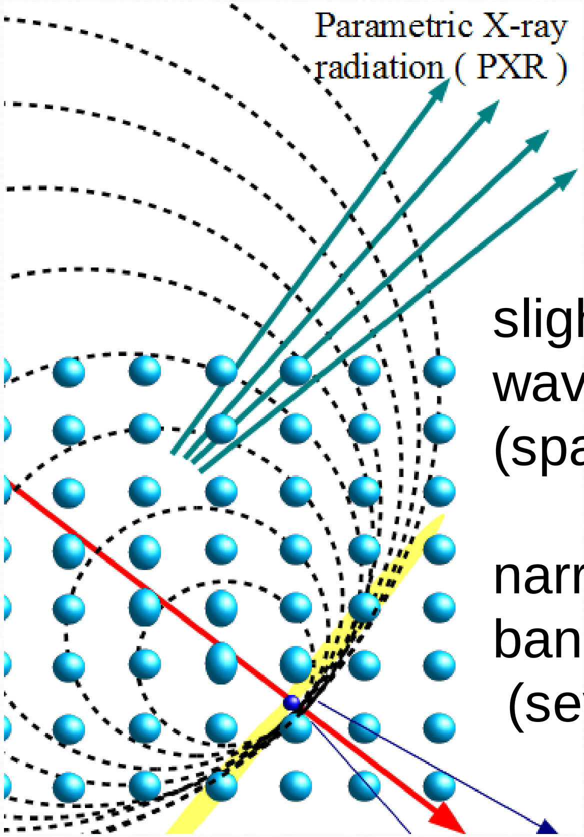


PXR radiator: Si(111)
PXR energy: 17.5keV (center)
e-beam: 2.6uA (average)
sample: calculator
detector: imaging plate (IP)
exposure: 10s



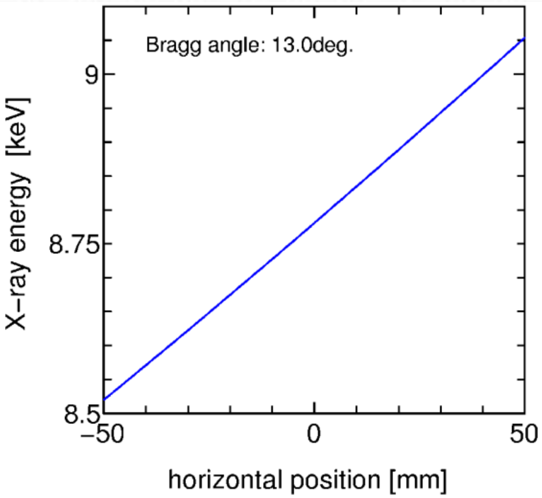
PXR radiator: Si(111)
PXR energy: 17.5keV (center)
e-beam: 2.6uA (average)
sample: human tooth
detector: flat panel detector (FPD)

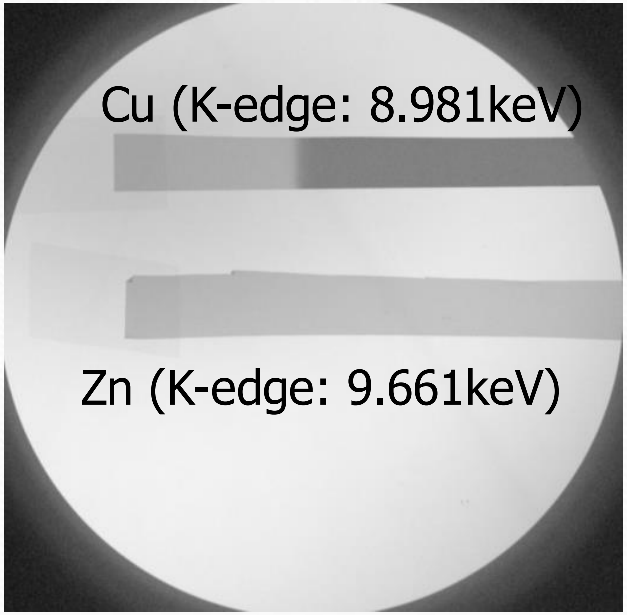
Spatial chirp of PXR beam



slight & continuous wavelength-shift (spatial chirp)

narrow local bandwidth (several eV)

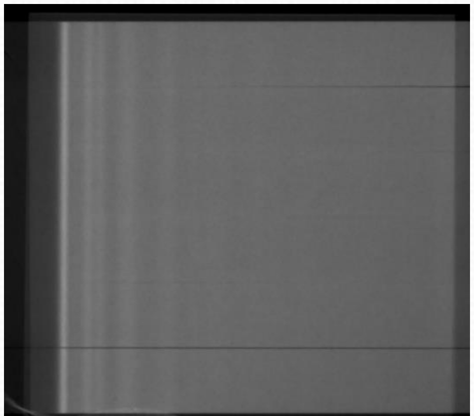




Wave front of PXR is different from both plane wave and spherical wave.

Typical result of DXAFS experiment

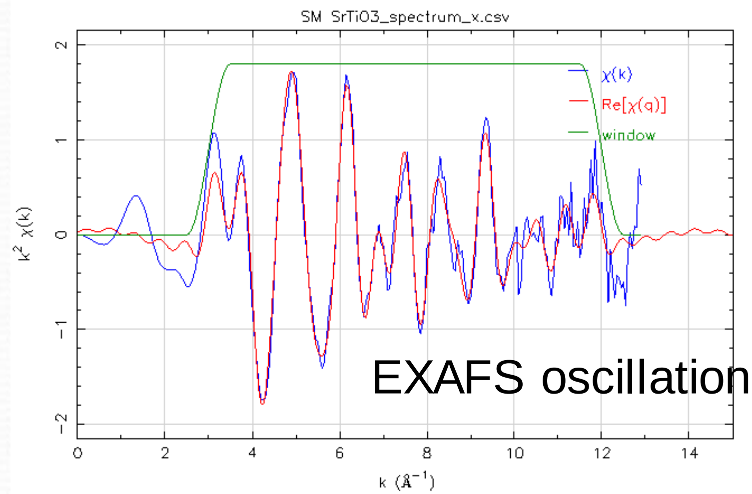
"Spatial chirp" can be used for dispersive X-ray fine structure analysis.

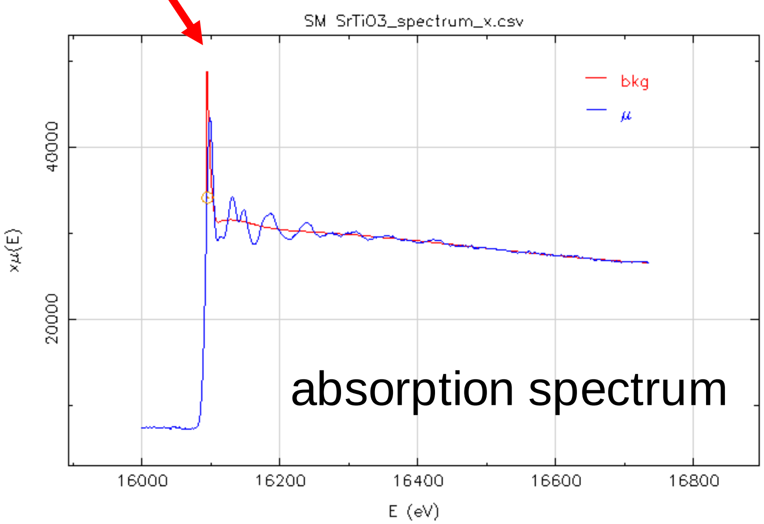


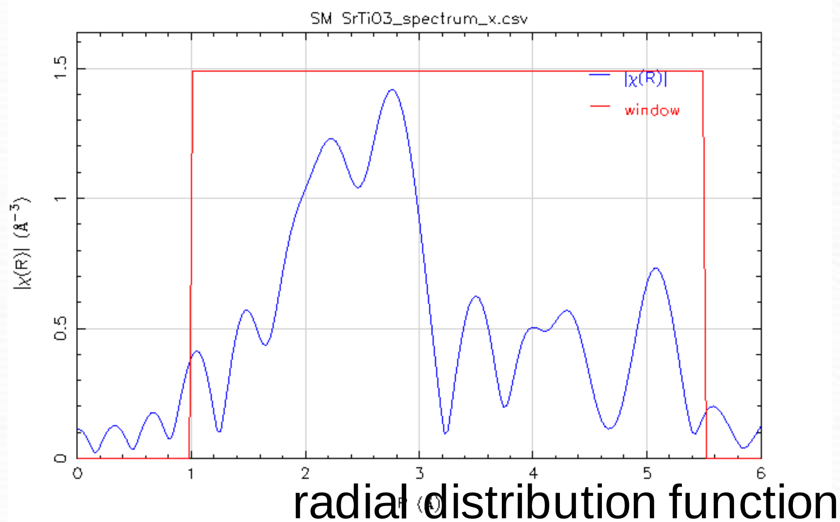
sample
$SrTiO_3$ (white pigments)

measurement time
30min

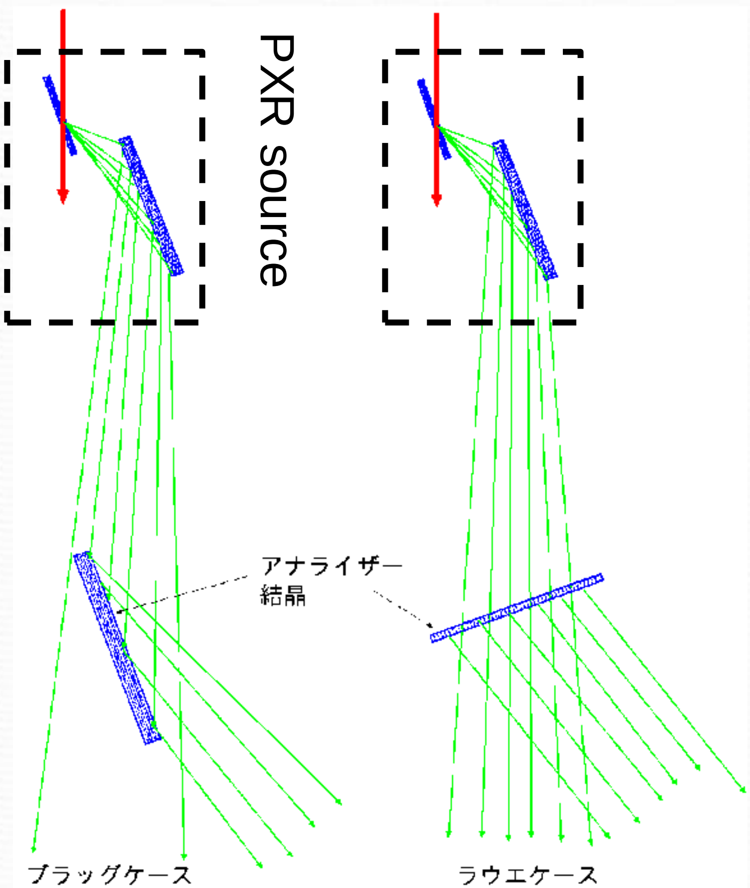
detector: Imaging plate



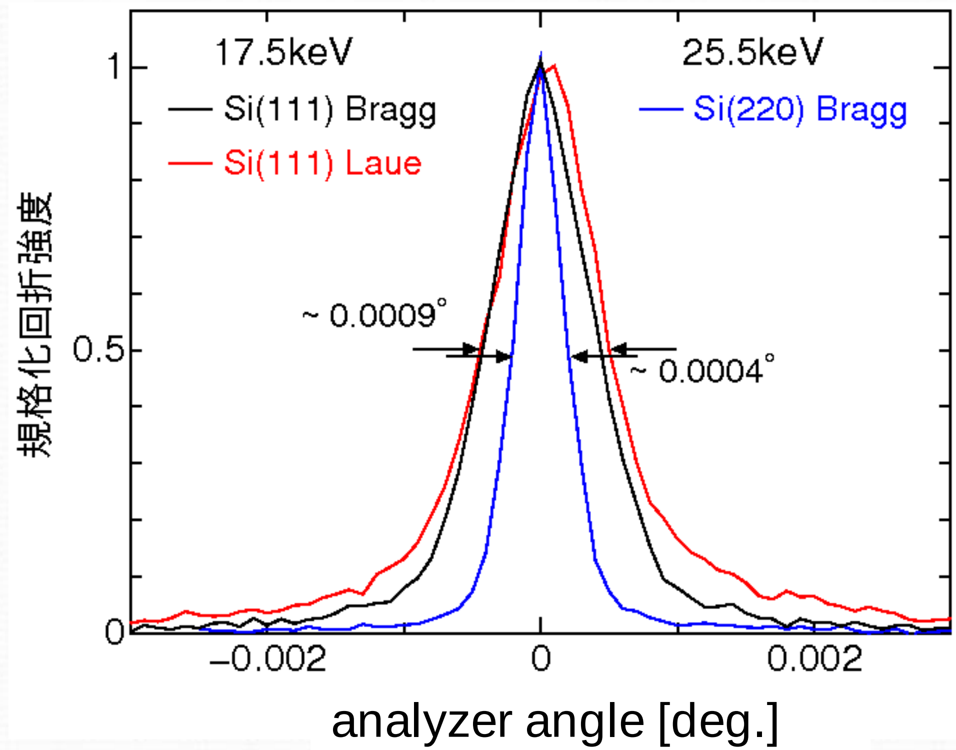




(+, -, +) arrangement



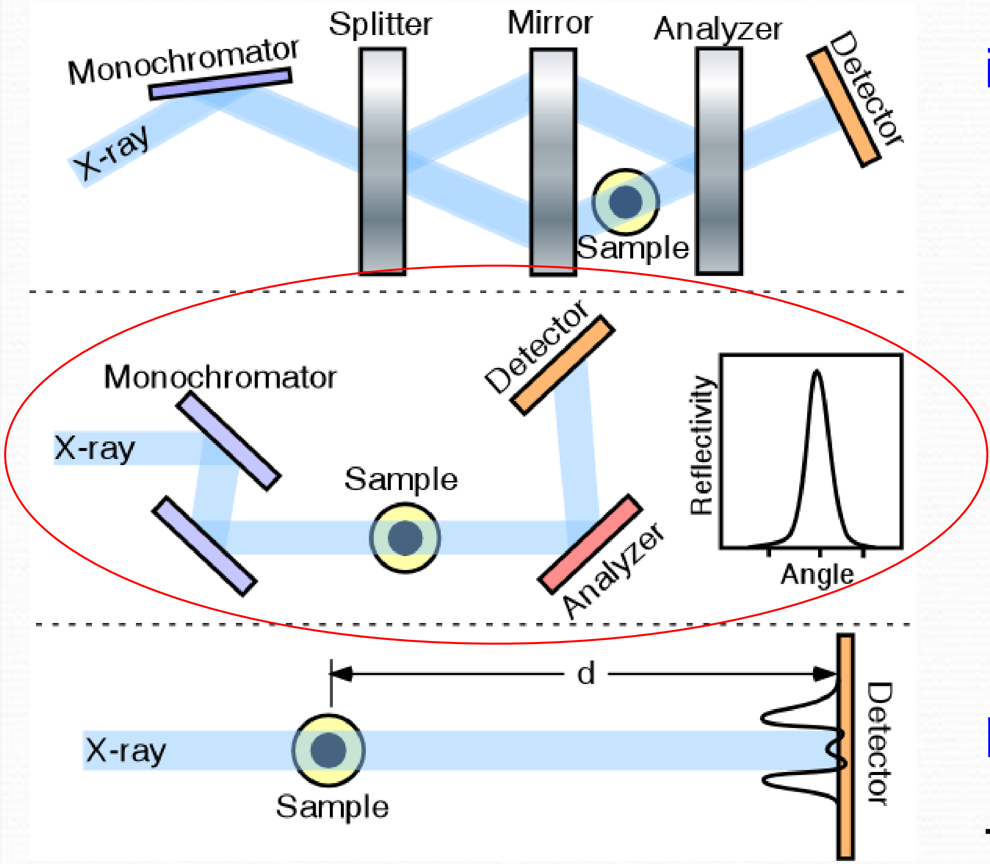
Bragg case Laue case



Bragg angle:
- larger for longer wavelengths
- smaller for shorter wavelengths

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)

Phase-contrast X-ray imaging



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

interferometer-based technique

Si perfect crystal interferometer

Talbot interferometer

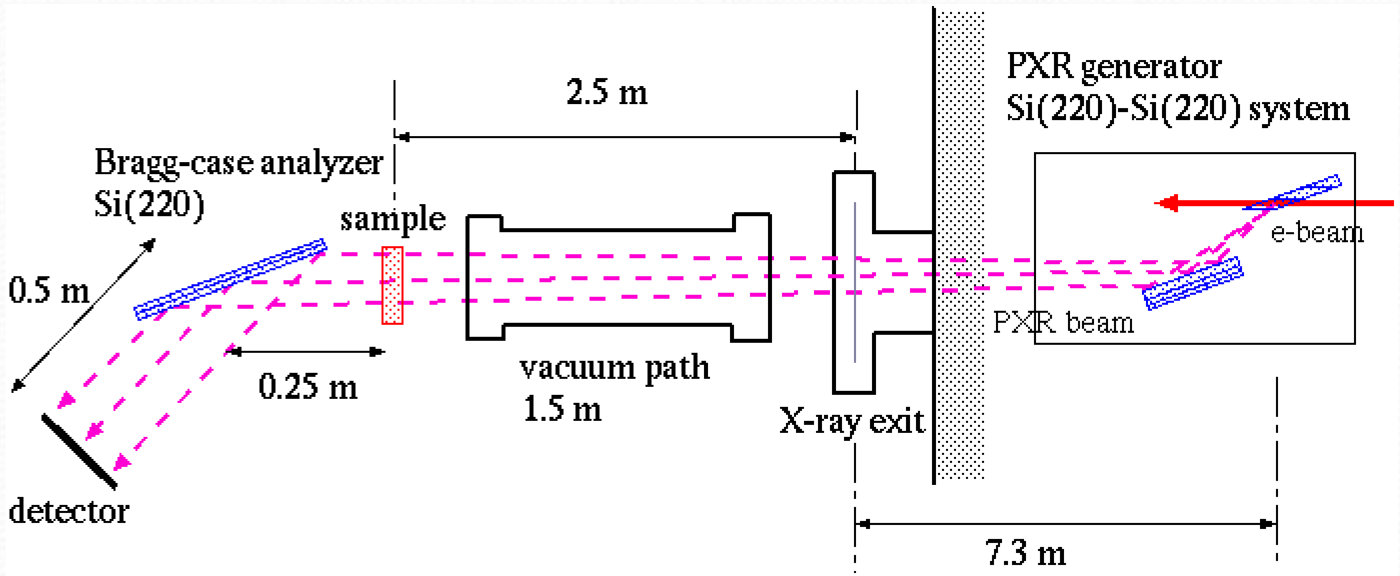
analyzer-based technique

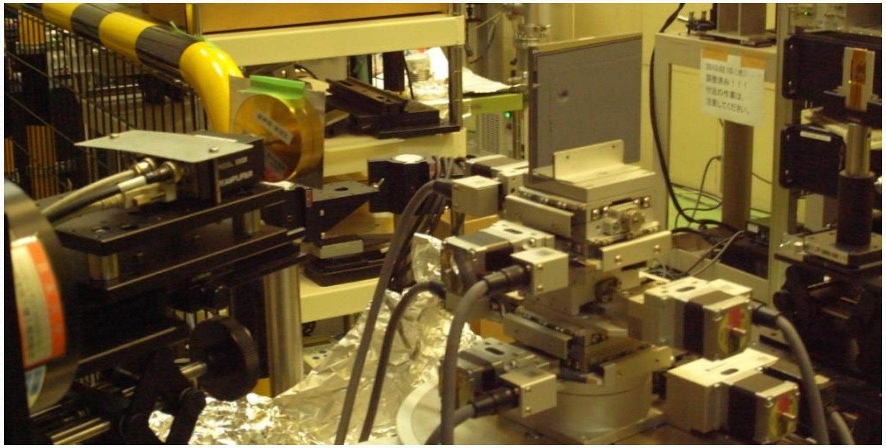
DEI: diffraction-enhanced imaging

propagation-based technique

The narrow diffraction width means that DEI is possible using PXR.

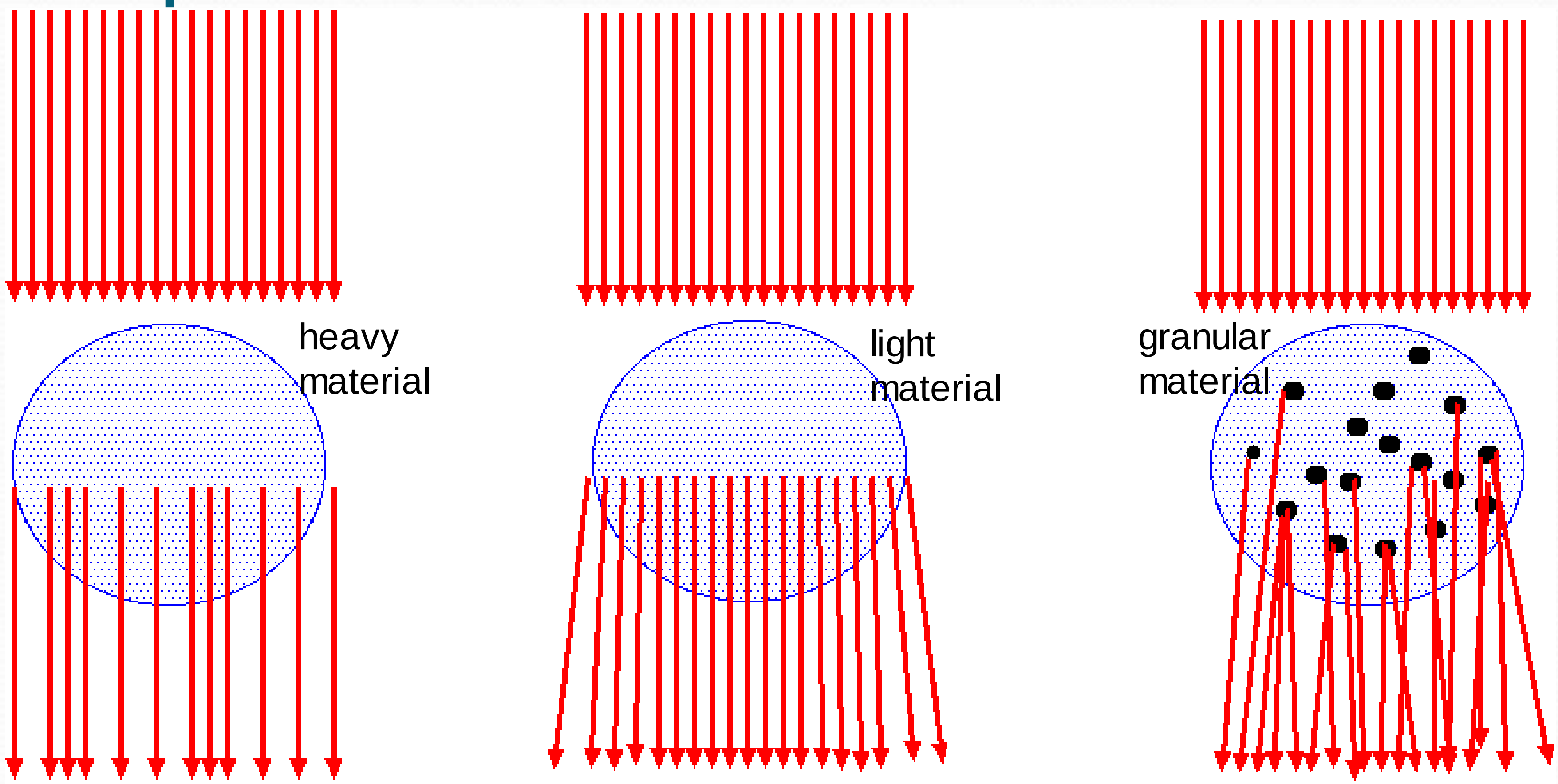
Setup of DEI experiments





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 sample materials

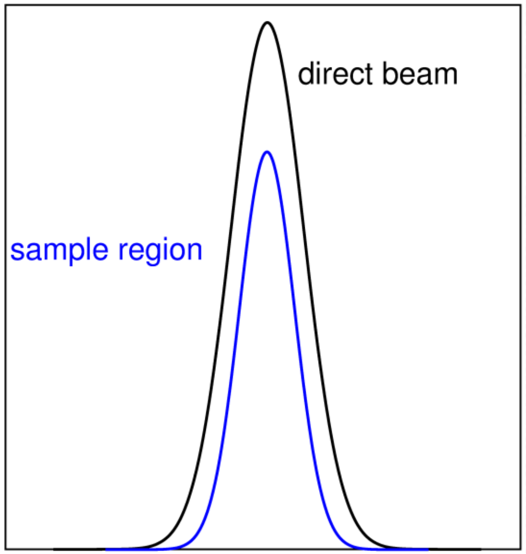


absorption
(amplitude attenuation)

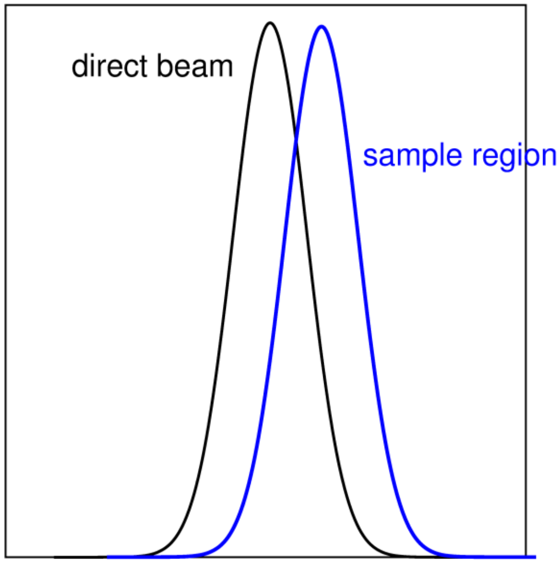
refraction
(phase shift)

small angle X-ray
scattering (SAXS)

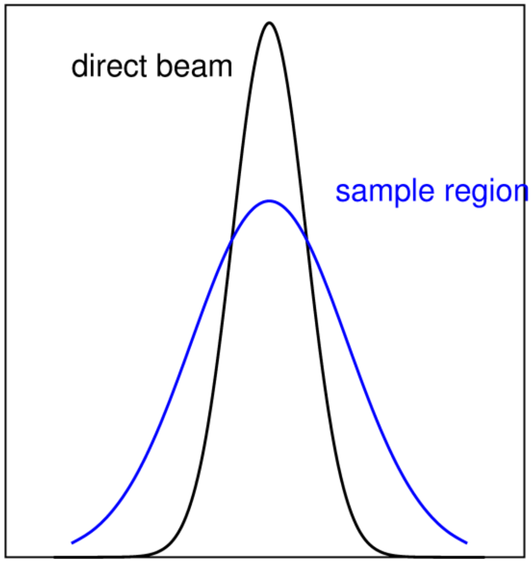
Transformation of rocking-curve shapes



absorption:
reduction of the area
of the curve



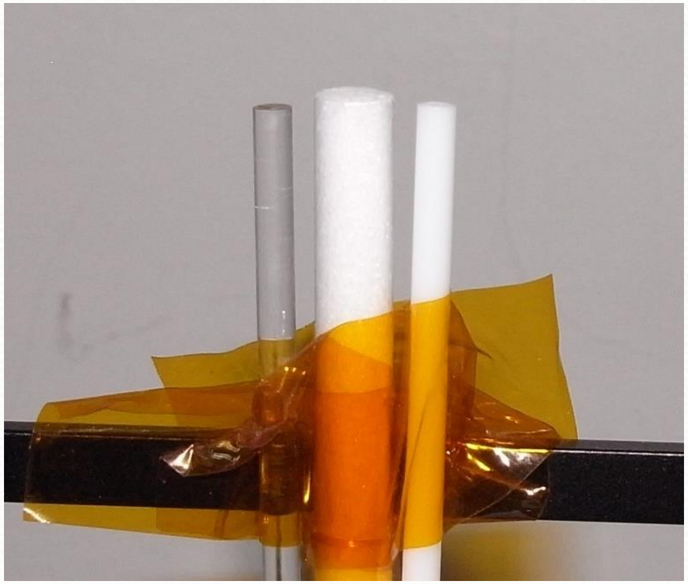
refraction:
shift of the center
of the curve



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

The angular resolution for refraction and scattering
depends on the diffraction width of the analyzer crystal.

Experiment for demonstration



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

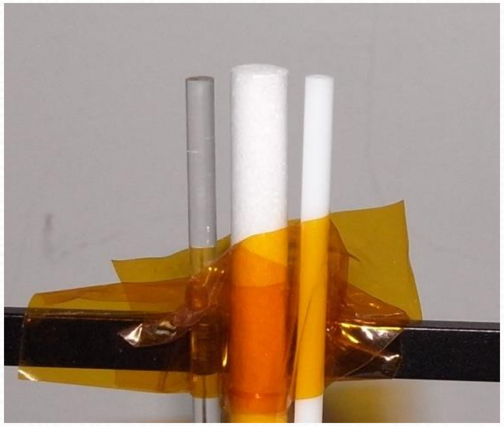
styrene-foam rod (6mm in dia.)
density: 0.16 g/cm^3

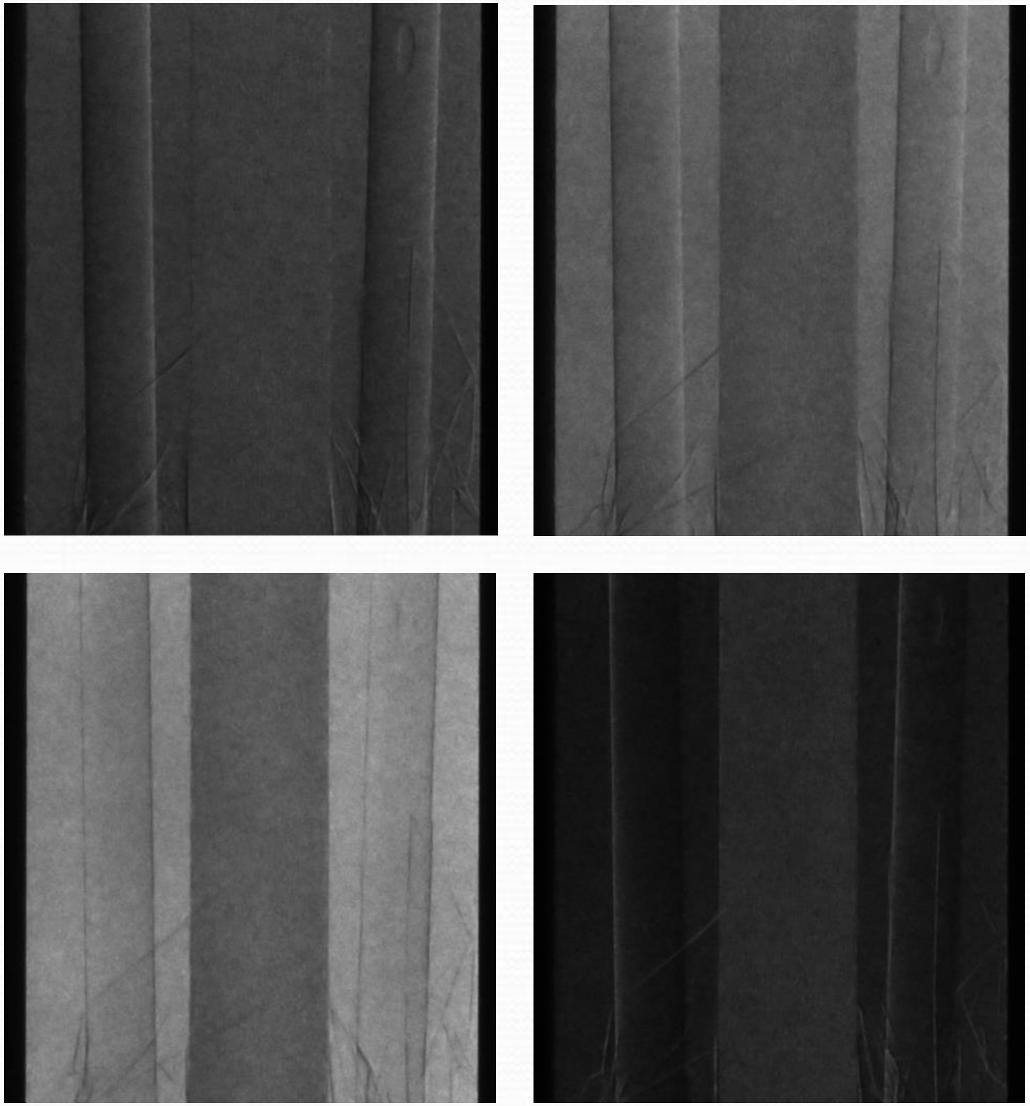
polystyrene rod (3mm in dia.)
density: 0.986 g/cm^3

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

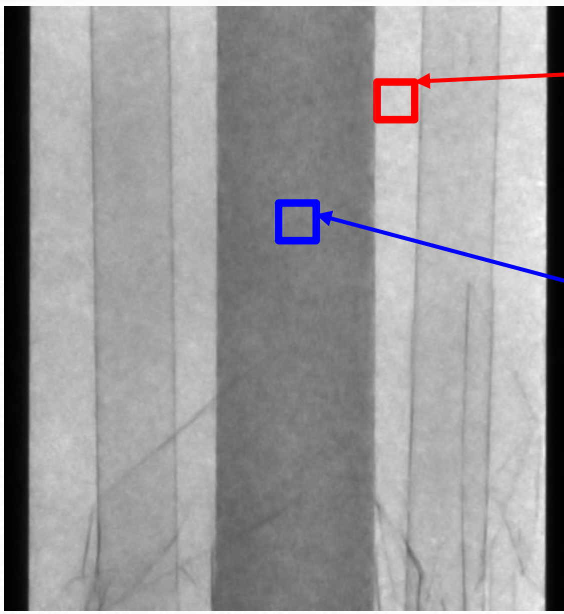
Result of DEI measurement

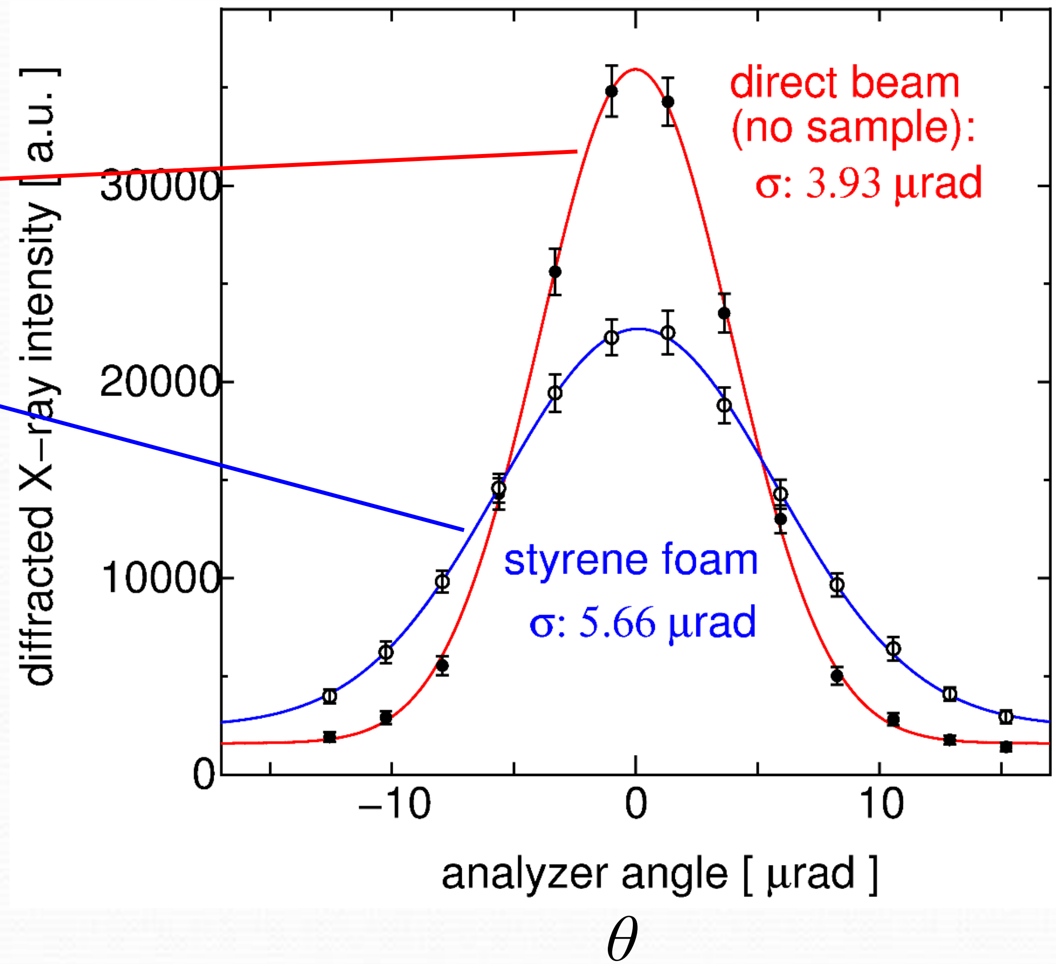




The DEI image contrast varies according to the analyzer angle.

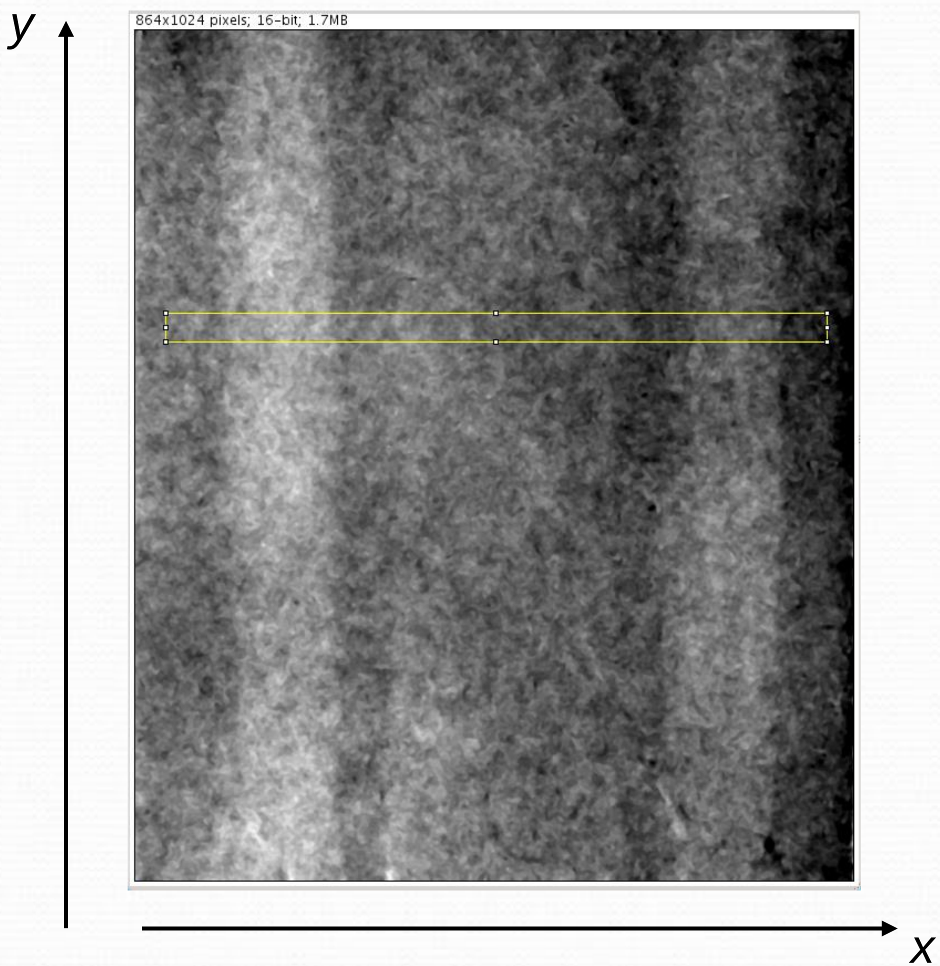
Rocking curves at each ROI





13 DEI images were taken
by using an X-ray CCD
(Q.E. @25.5keV ~ 10%)
Each exposure time: 15min

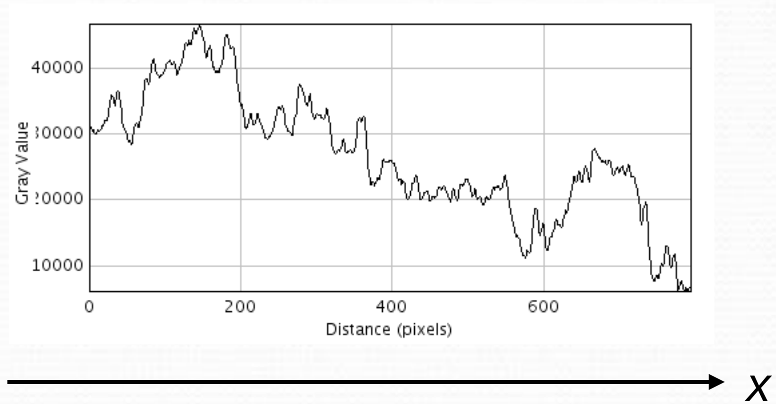
absorption-contrast image



complex refraction index:

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

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



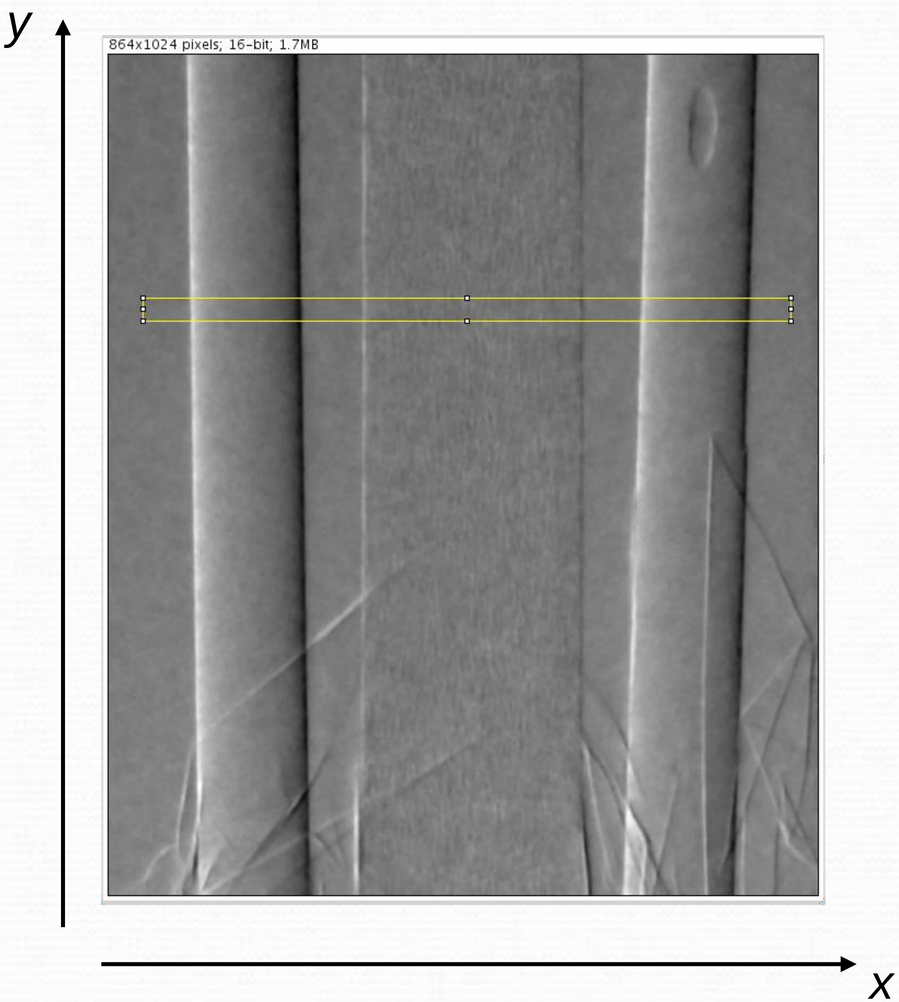
Integral with respect to θ

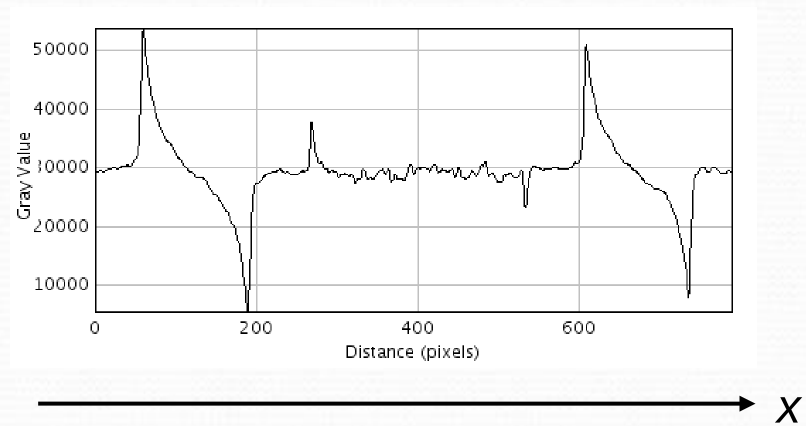
$I_{abs} = \sum I(x,y,\theta)$

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

$\propto \rho(x,y)$

phase-gradient image



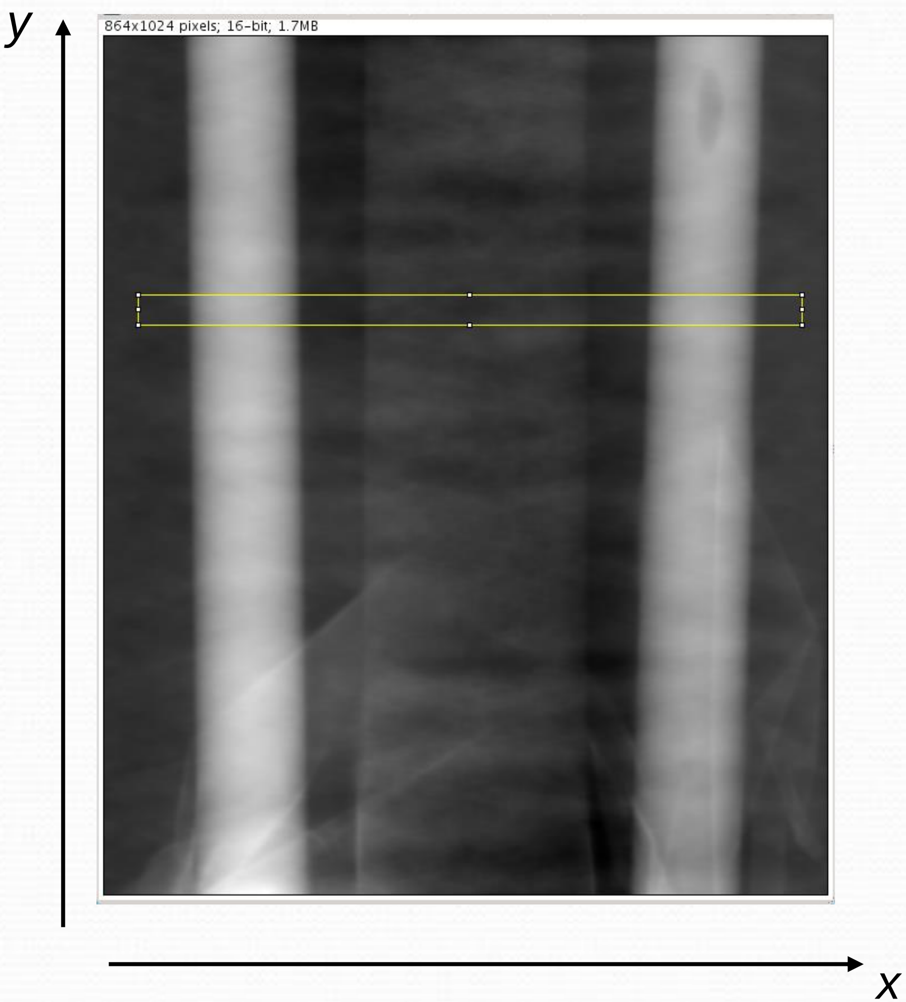


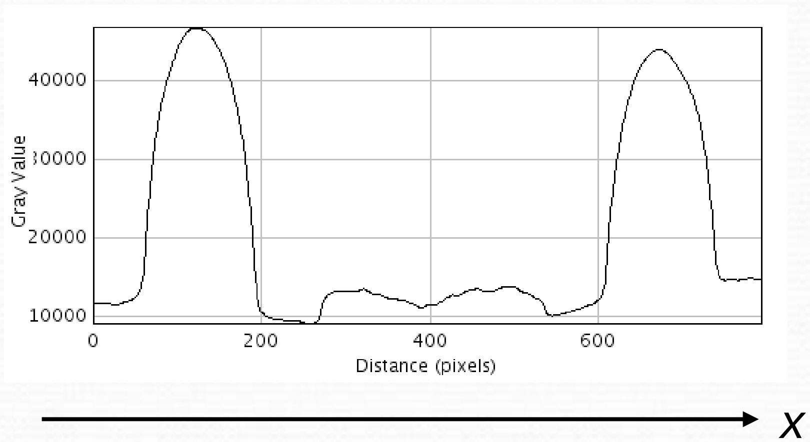
phase-gradient
(refraction-contrast) map

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

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

phase image



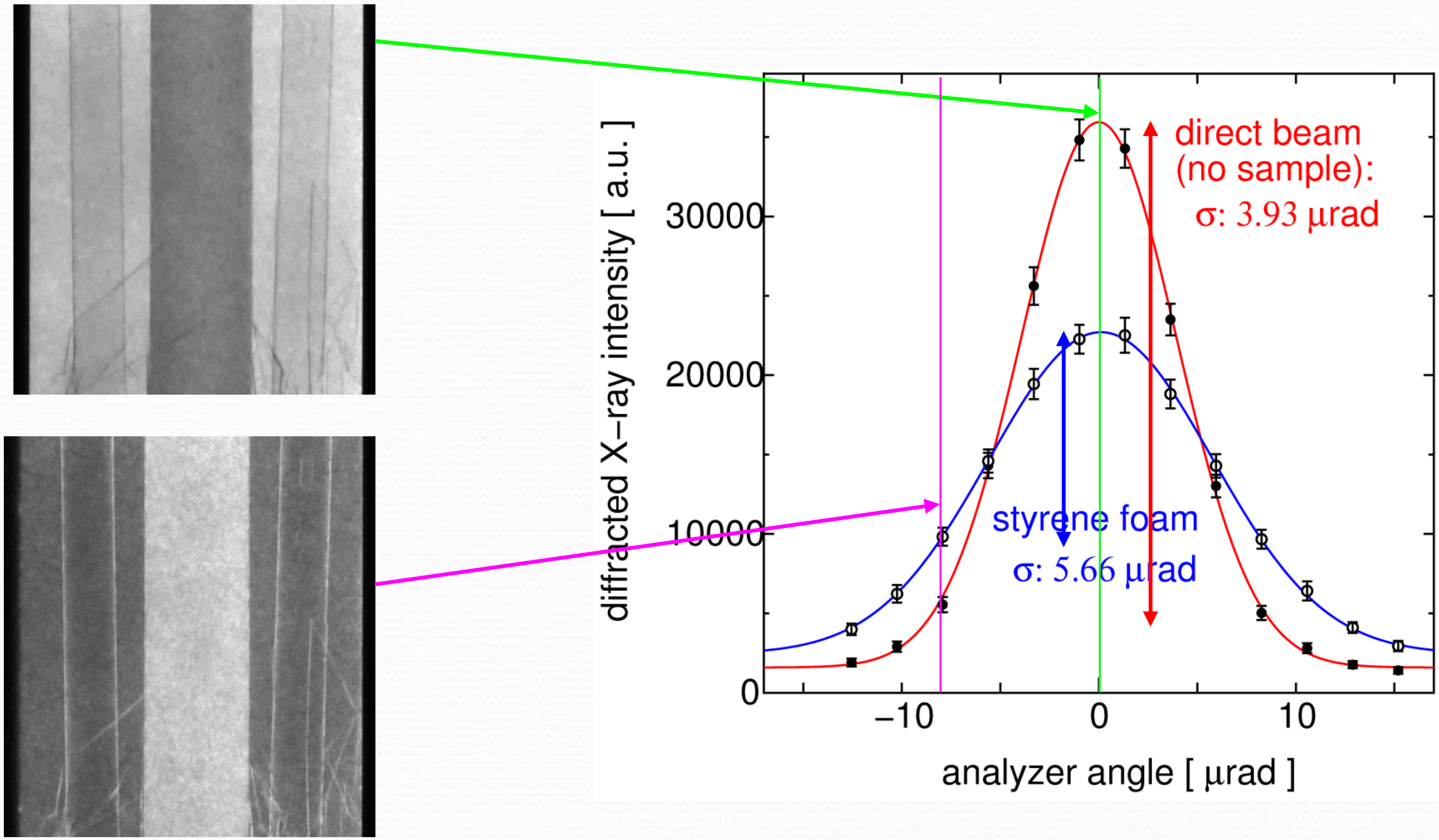


phase map

$$\delta(x,y) = \int \partial\delta(x,y) \,/\partial x \, dx$$

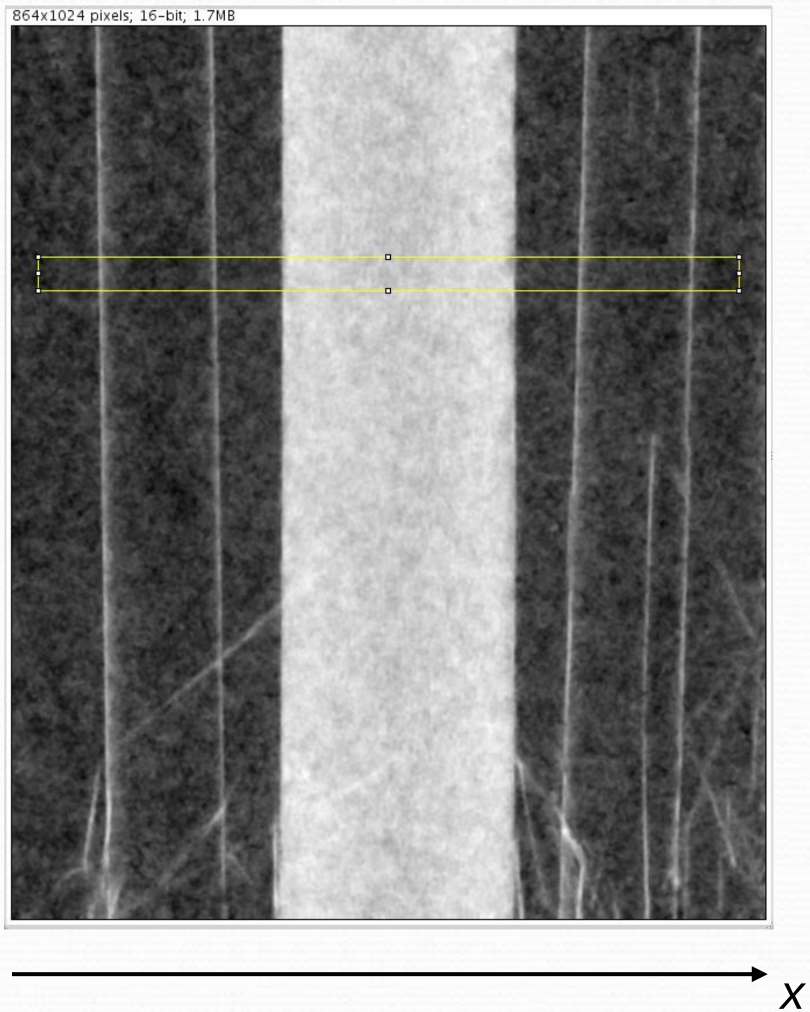
$$\propto \rho(x,y)$$

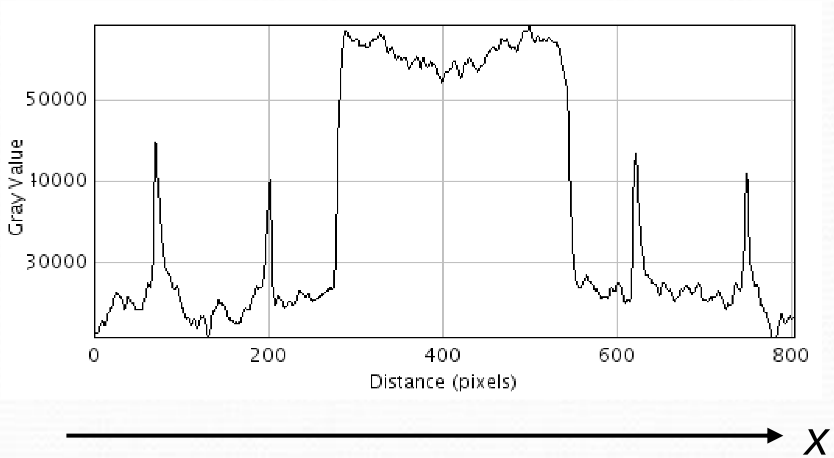
Visibility contrast due to SAXS effect



visibility contrast: $I(x,y, \theta=0) - I(x,y, \theta=2\sigma)$

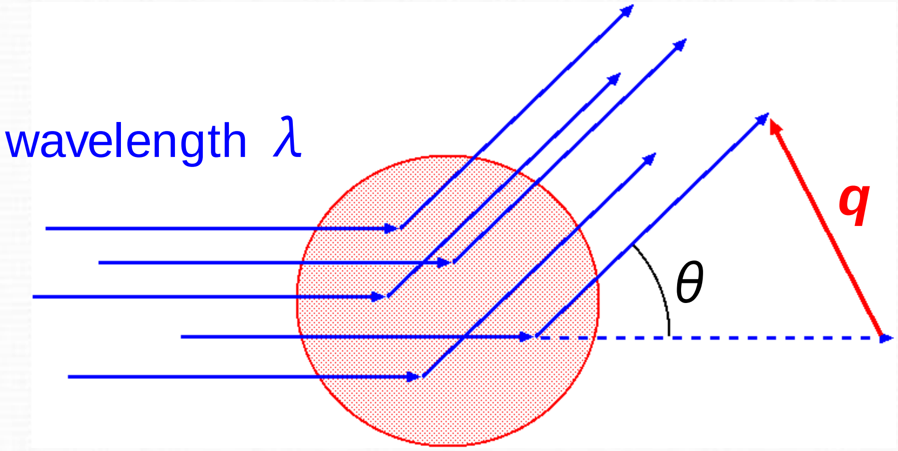
SAXS-based (visibility-contrast) image





the contrast is sensitive to the styrene-foam region independently of the density and the shape of the sample.

Small angle X-ray scattering (SAXS)

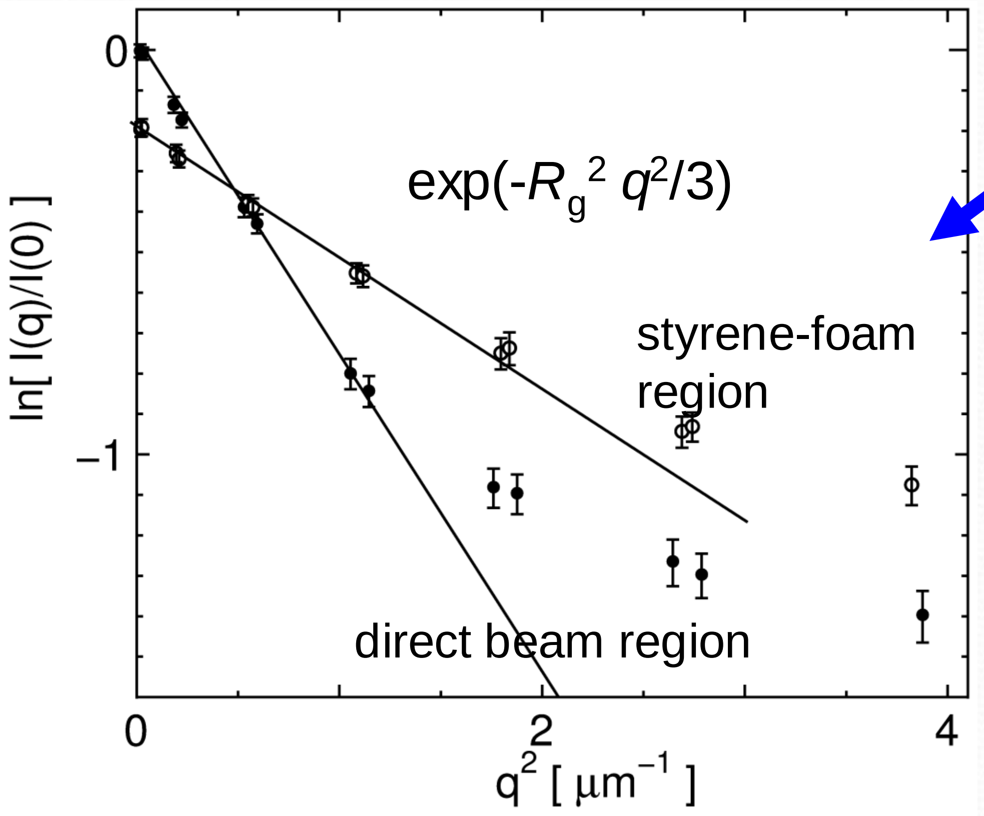


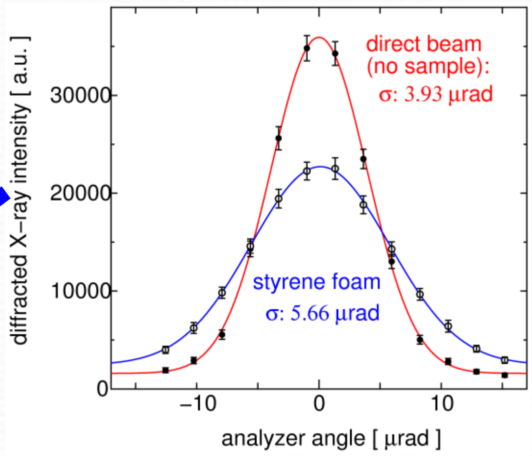
$q = |\,\boldsymbol{q}\,|$
$= (\,4\pi\,/\,\lambda\,)\,\sin(\theta/2)$

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

R_g : inertial (gyration) radius

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.

Summary

- Combining the cone-like divergence and the spatial chirp of PXR allows DEI using a PXR beam in the (+,-,+) arrangement.
- X-ray refraction and small-angle X-ray scattering (SAXS) due to sample materials can be measured simultaneously by the DEI method.
- DEI experiments using PXR successfully demonstrated that SAXS-based imaging is sensitive to micro structures of sample materials smaller than the pixel size of the image sensor.
- PXR beam has a sufficiently high spatial coherence to detect scattering angles in the range of micro-radian.

Prospects for application

SAXS based imaging is very sensitive to micro structures of sample materials.

expected application:

- analysis for material science

    nano-material, liquid crystal, …

- Analysis for bio-chemical science

    macromolecular, protein, ...

- pathological examination

    tissue fibrosis, ...

Acknowledgements

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Thank you for your kind attention !!