Emerging Scientific Opportunities with X-Ray Imaging at SPring-8

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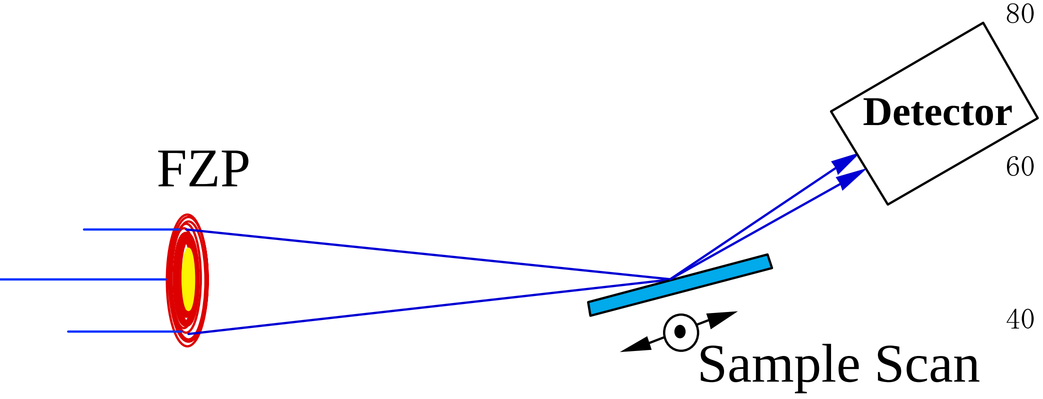
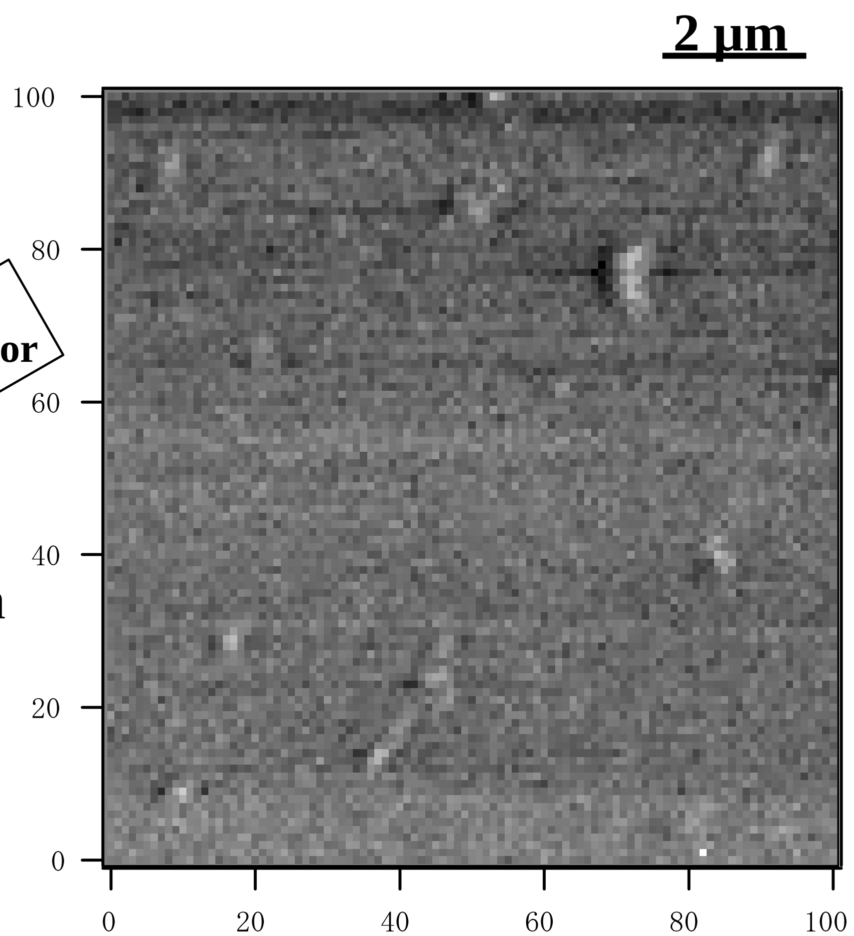


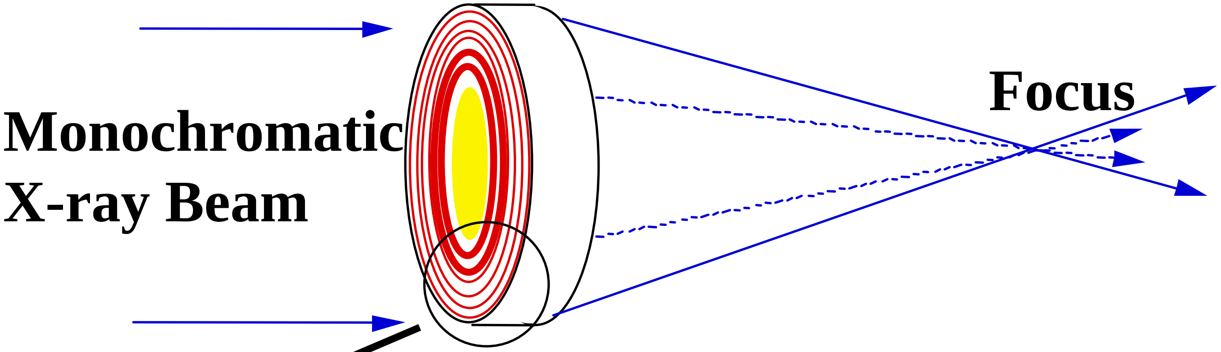
Experimental Setup

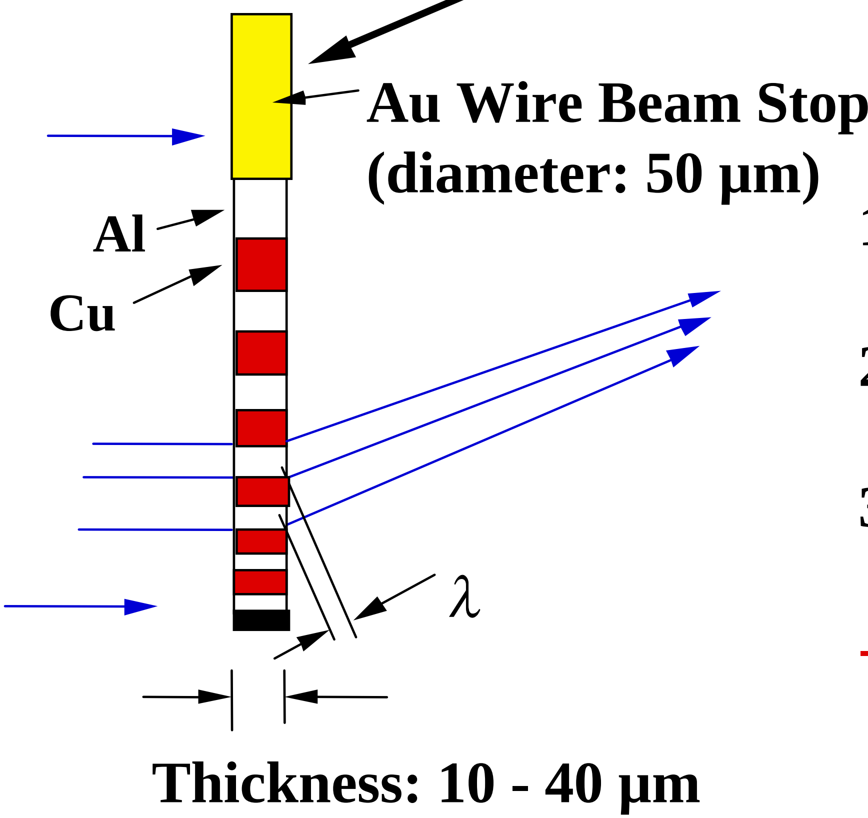


Measured Topograph

Si 001 wafer, 9.85 keV, 004 Bragg Reflection,
101 x 101 pixels, 100 nm x 100 nm pixel, 0.3 s/pixel.

Scanning Diffraction-topography using Microbeam with 120 nm probe size. @BL20XU



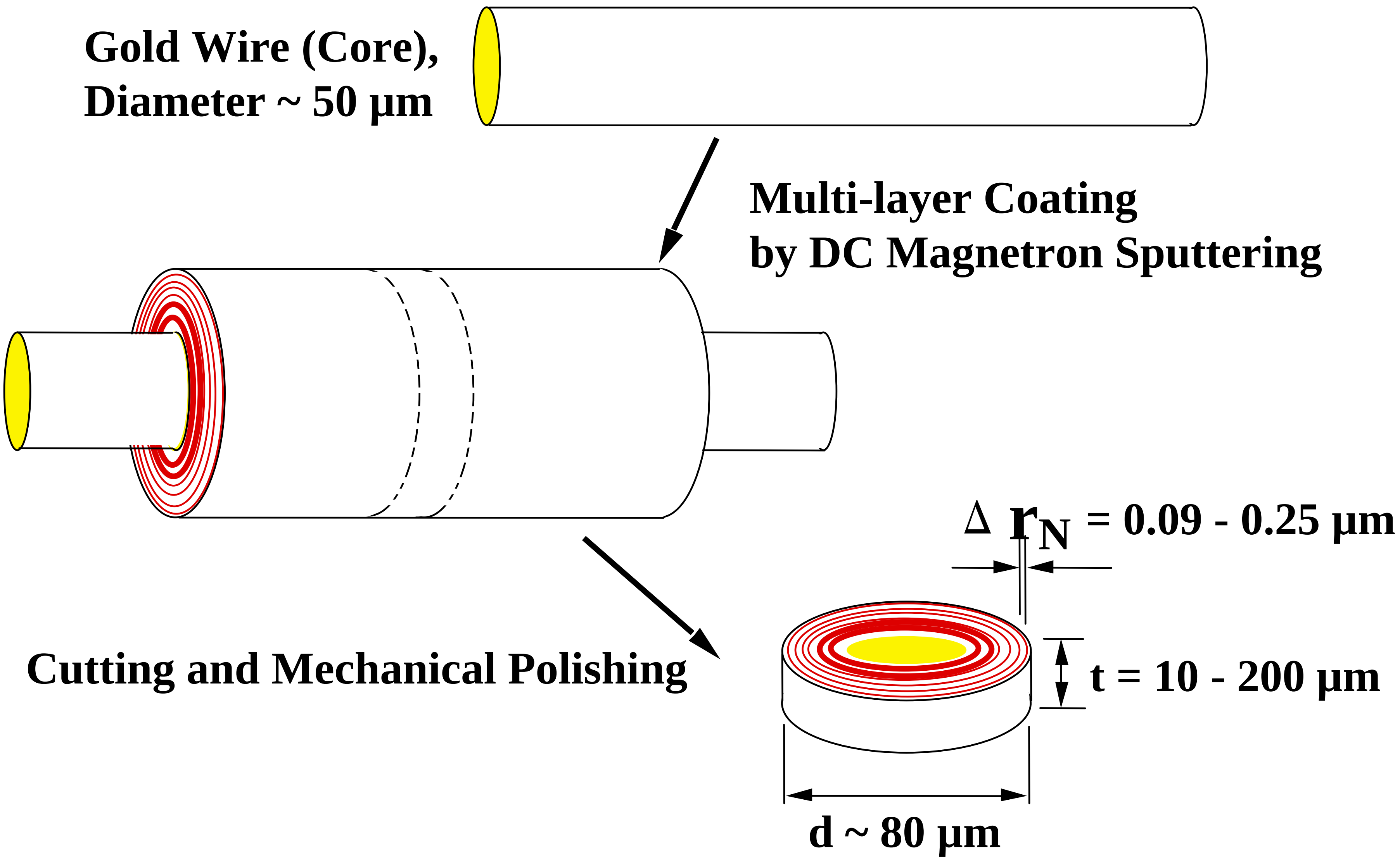


Advantages of SS-FZP

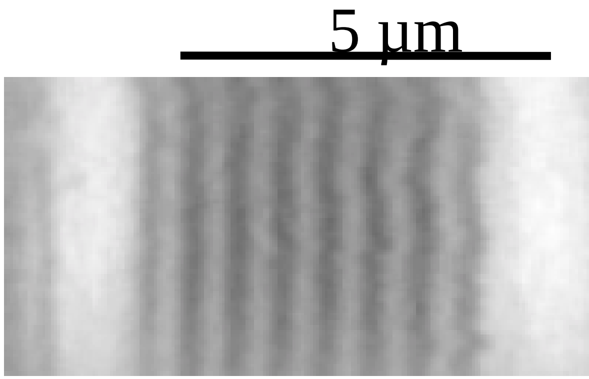
1. **High Aspect Ratio**
   Zone Height/Zone Width > 100.
2. **Narrow Zone Width**
   < 100 nm.
3. **Thickness**
   No Thickness Limit.

--> High Energy (~ 100 keV) Optics.

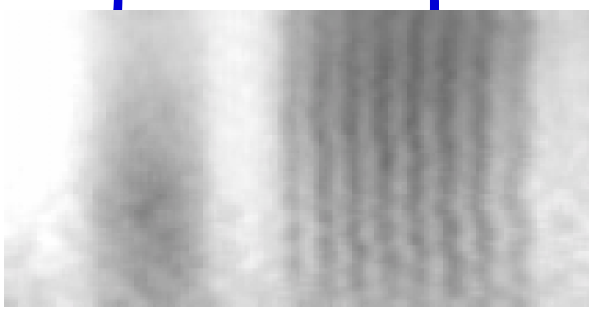
Schematic View of Sputtered-sliced Zone Plate



Fabrication Process of Sputtered-sliced Fresnel Zone Plates

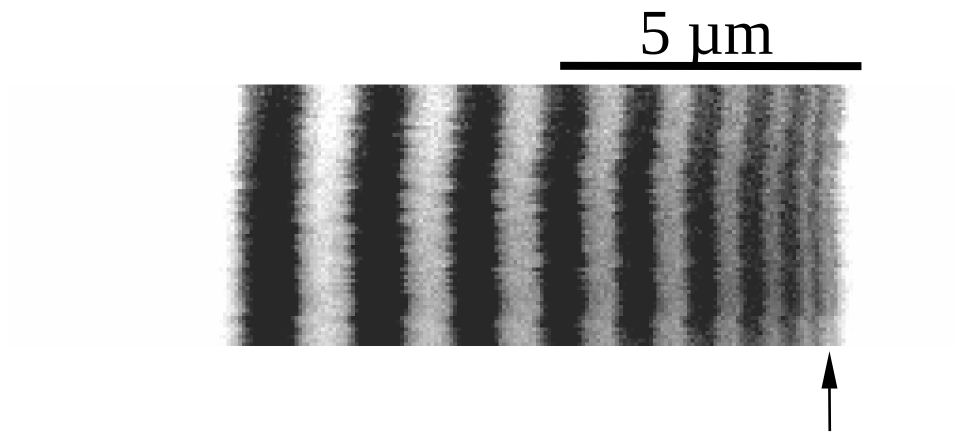


0.3 µm line & space



0.2 µm line & space

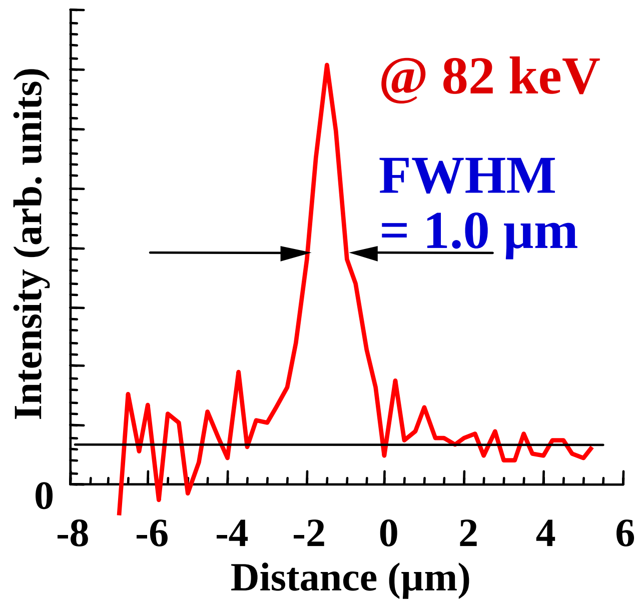
X-ray wavelength: 1.4 Å,
128 x 64 pixels,
0.0625 µm/pixel,
Dwell time: 0.4s/pixel.



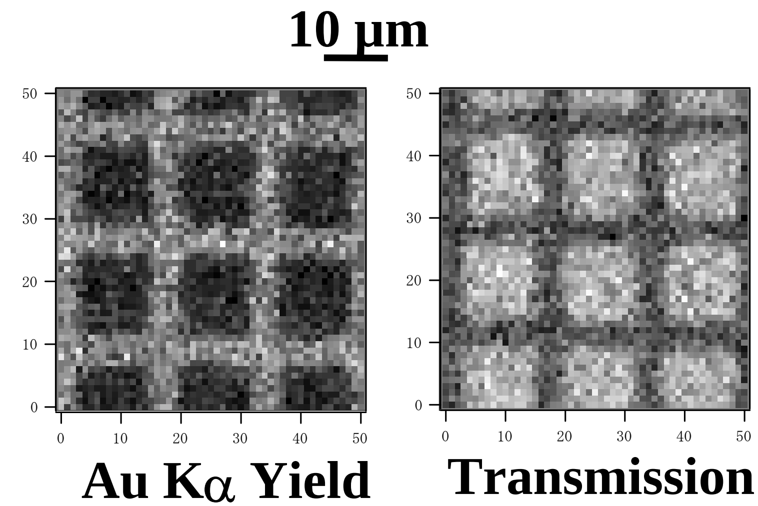
0.1 µm line & space

X-ray wavelength: 1.0 Å,
256 x 70 pixel,
0.0625 µm/pixels,
Dwell time: 0.4s/pixel.

Scanning Microscopic Image of Resolution Test Pattern



Focused Beam Profiles measured by Knife-edge Scan



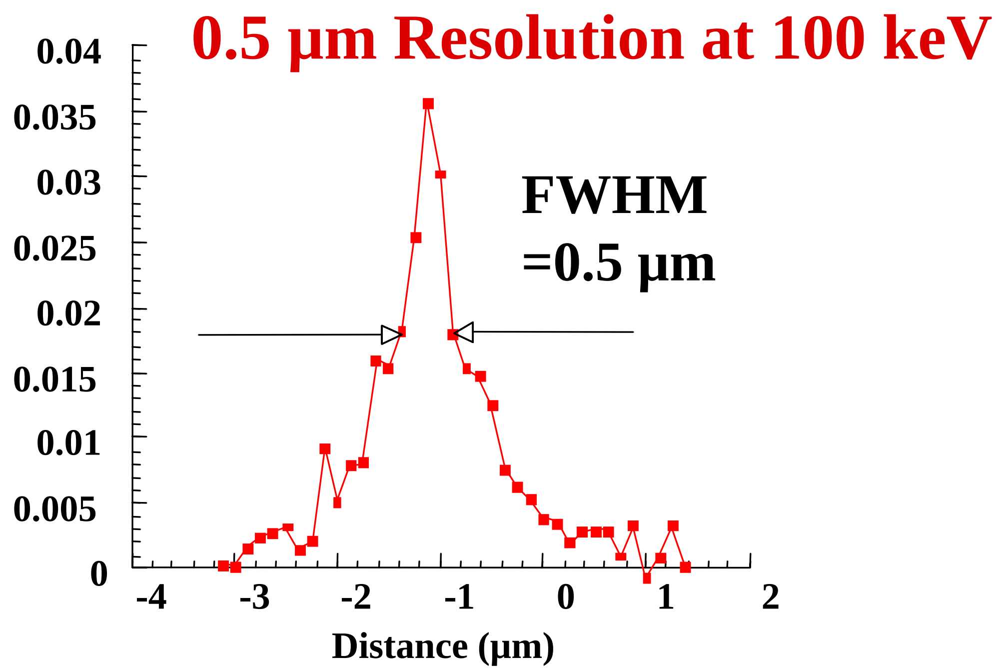
Scanning Microscopic Image

X-ray Energy: 82 keV (0.151 Å), f ~ 700 mm,
Cu/Al sputtered-sliced FZP (50 layers),
Core (center beam stop): Au 50 µm in diameter,
Outermost zone width: 0.15 µm,
Thickness: ~ 40 µm.

Sample: gold mesh (1500 lines/inch),
X-ray Energy: 82 keV ,
51 x 51 pixels,
1 µm/pixel,
Dwell time: 2 s/pixel,
CdZnTe-detector for fluorescent X-rays.

Microfocusing/scanning microscopy with SS-FZP at 82 keV

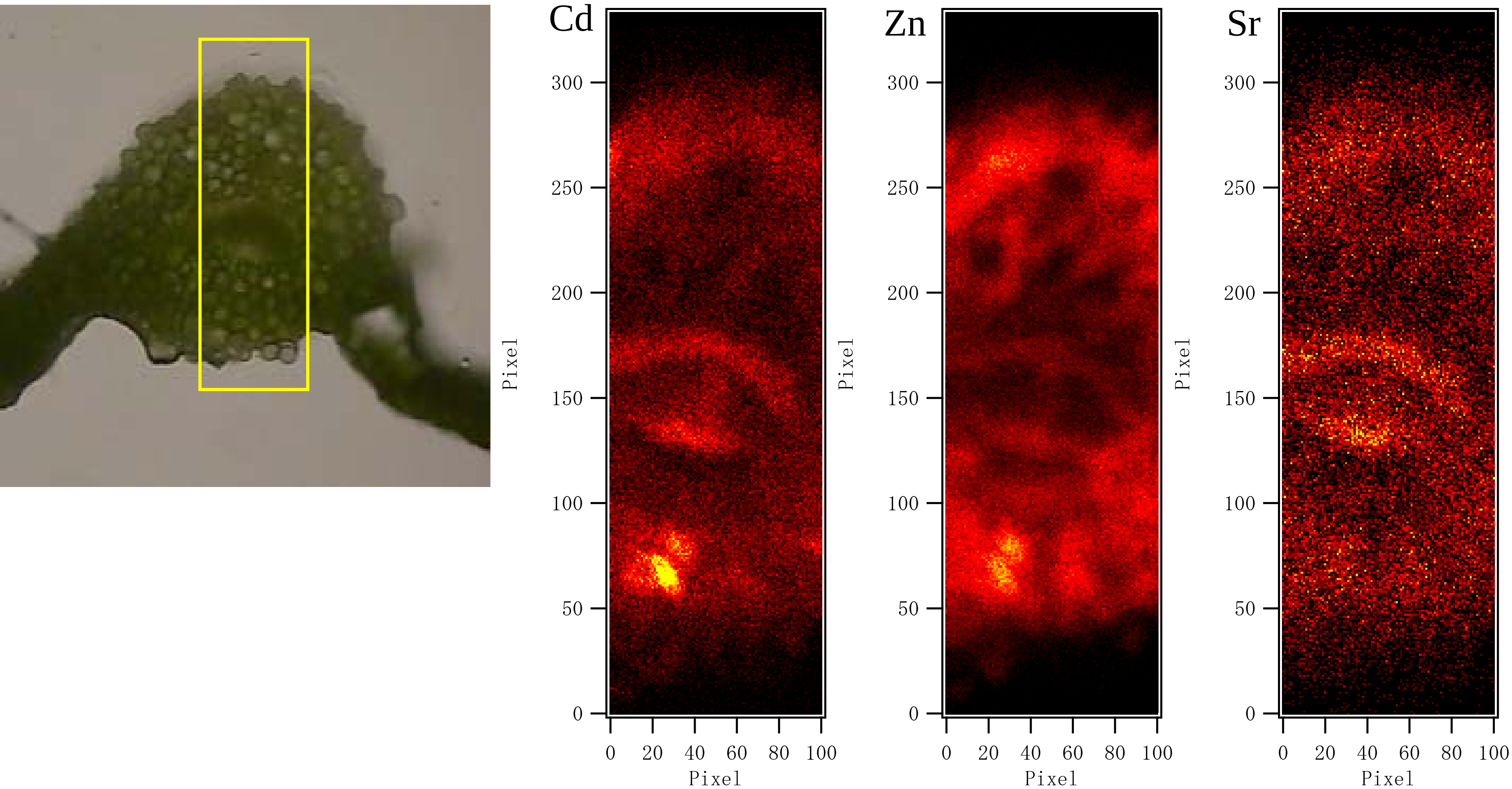
Diffraction efficiency: 15%



Microbeam with Sputtered-sliced FZP

Focused Beam Profile Measured by Edge-scan @BL20XU

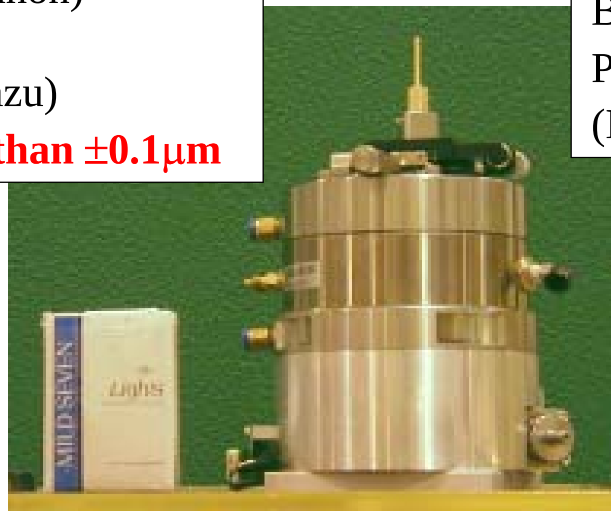
X-ray wavelength: 0.124 Å (100 keV), f ~ 900 mm,
Cu/Al sputtered-sliced FZP (70 layers),
Core (beam stop): Au 50 µm in diameter,
Outermost zone width: 0.16 µm,
Thickness: ~ 180 µm.



XRF imaging of a cross section of a leaf which belongs to cruciferous plant.
Measurement condition: X-ray energy=37 keV, pixel size=3 μm x 3 μm, exposure time=0.2 sec/pixel.

@ BL37XU

Air bearing
AB-80R(Canon)
Rotation stage
RA-10(Kohzu)
Wobble is less than ±0.1μm

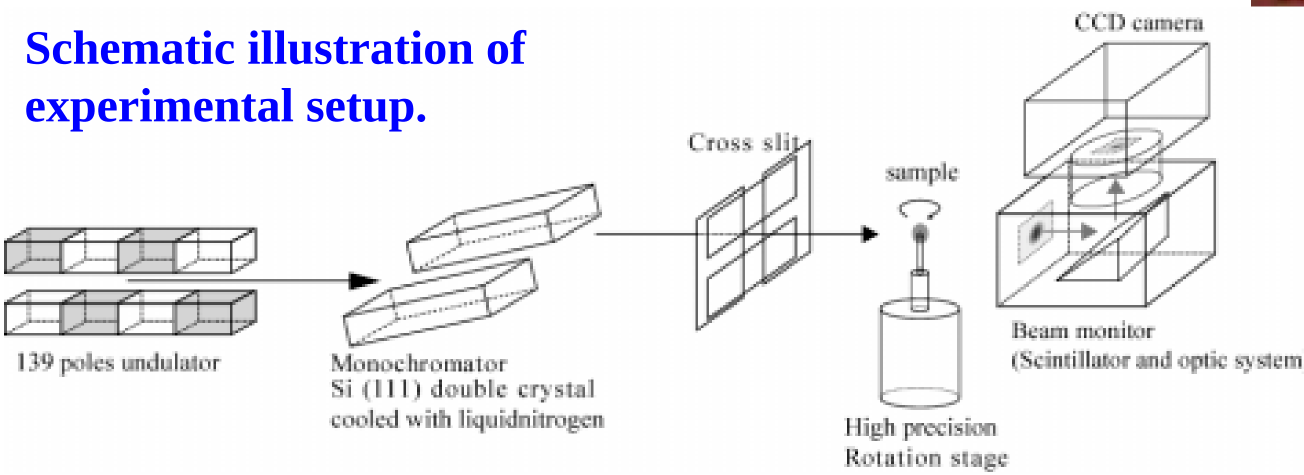


High precision rotation stage.

CCD camera: C4880-10-14A
Beammonitor: AA50(x20, x10)
Pixel size: 0.5μm, 1.0μm
(Hamamatsu photonics K.K.)

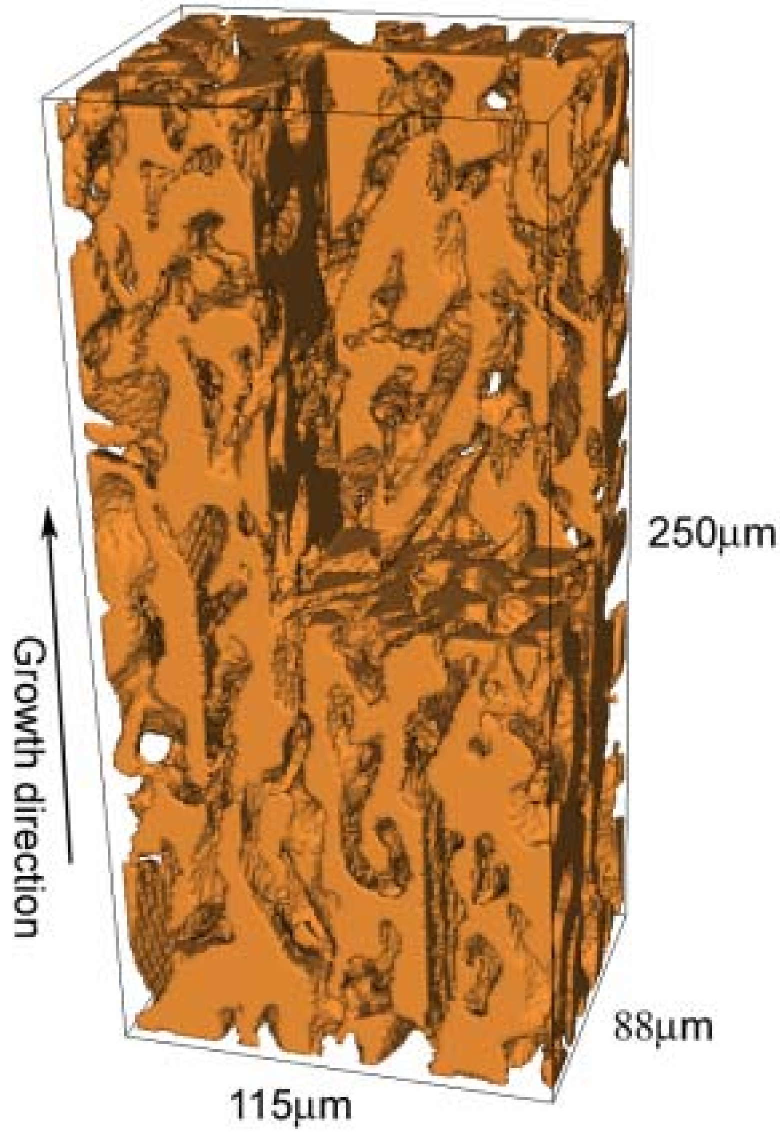
High resolution detector.

Schematic illustration of experimental setup.



X-ray micro-tomography (3-D imaging with SP-μCT 47XU)

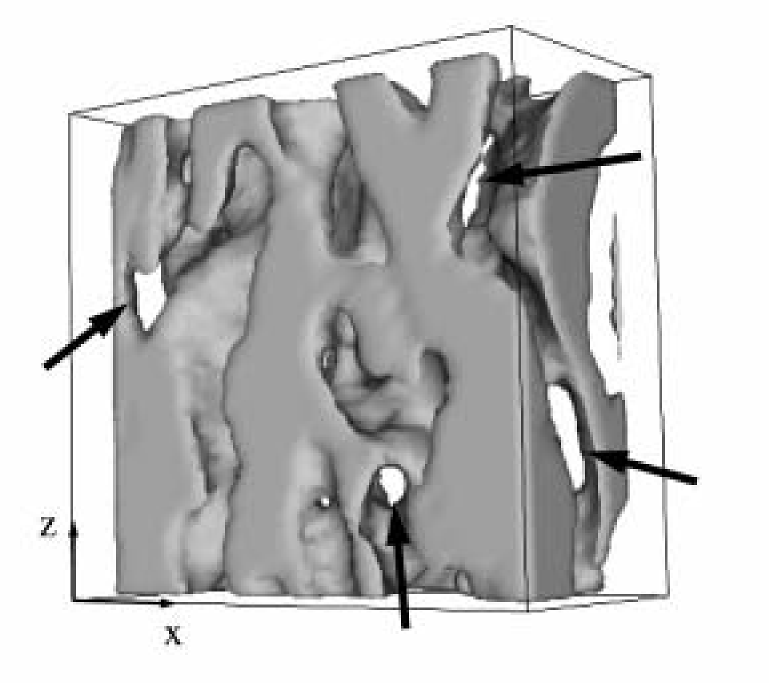
Investigations of Al_2O_3-YAG eutectic structure and their network structure.



Unidirectionally solidified Al2O3-based eutectic composites have excellent mechanical properties at high temperatures. For example, Al2O3-YAG (Y3Al5O12, yttrium-aluminum-garnet) eutectic composites exhibit excellent mechanical properties from room temperature to 2073K in an air atmosphere and are candidates for high temperature use. The mechanical properties of the above mentioned composites are closely related to their solidified structures. 3D observation shows that the constituent phases with faceted interfaces are three-dimensionally continuous and are complexly entangled with each other. 3D structure obtained by micro X-ray CT allows us to discuss evolution of the eutectic structure during the solidification and origin of the excellent mechanical properties.

3-D image of Al_2O_3-YAG eutectic structure

Network structure in Al_2O_3-YAG eutectic composite

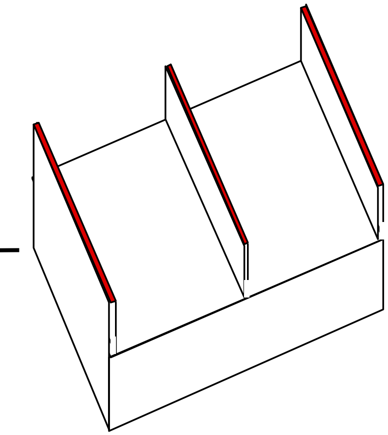


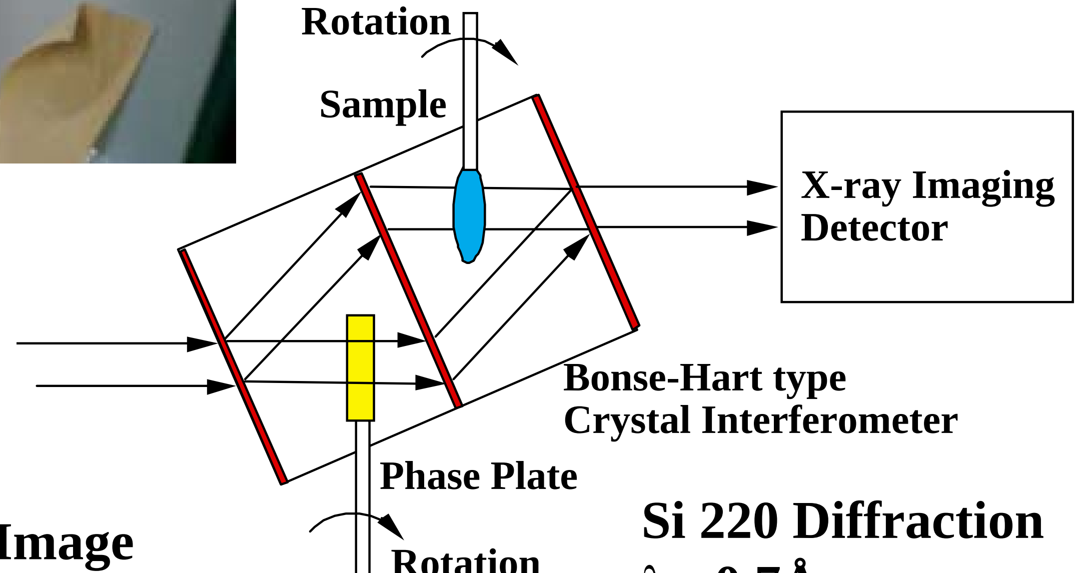
59 x 28 x 52 μm

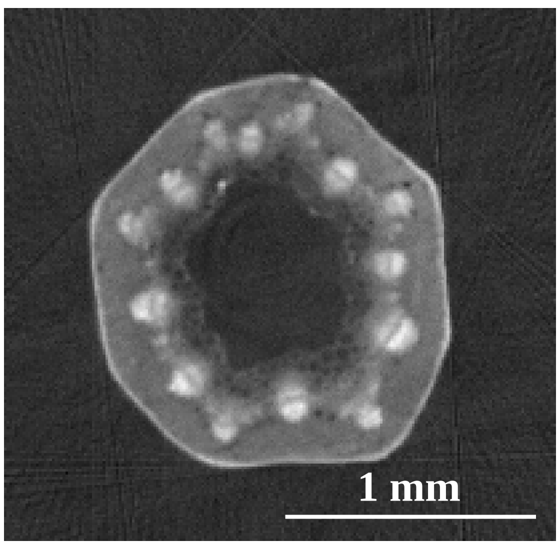
YAG phase is removed from 3D reconstructed image. Holes of the Al_2O_3 phase indicates Al_2O_3 and YAG phases are entangled each other. No holes are observed in conventional eutectic structures of metallic alloys.

Composition: Al_2O_3-18.5mol%Y_2O_3
Growth rate : 0.5mm/h

X-ray energy:	25keV
Projection:	750 frames
Resolution:	0.5μm/pixel







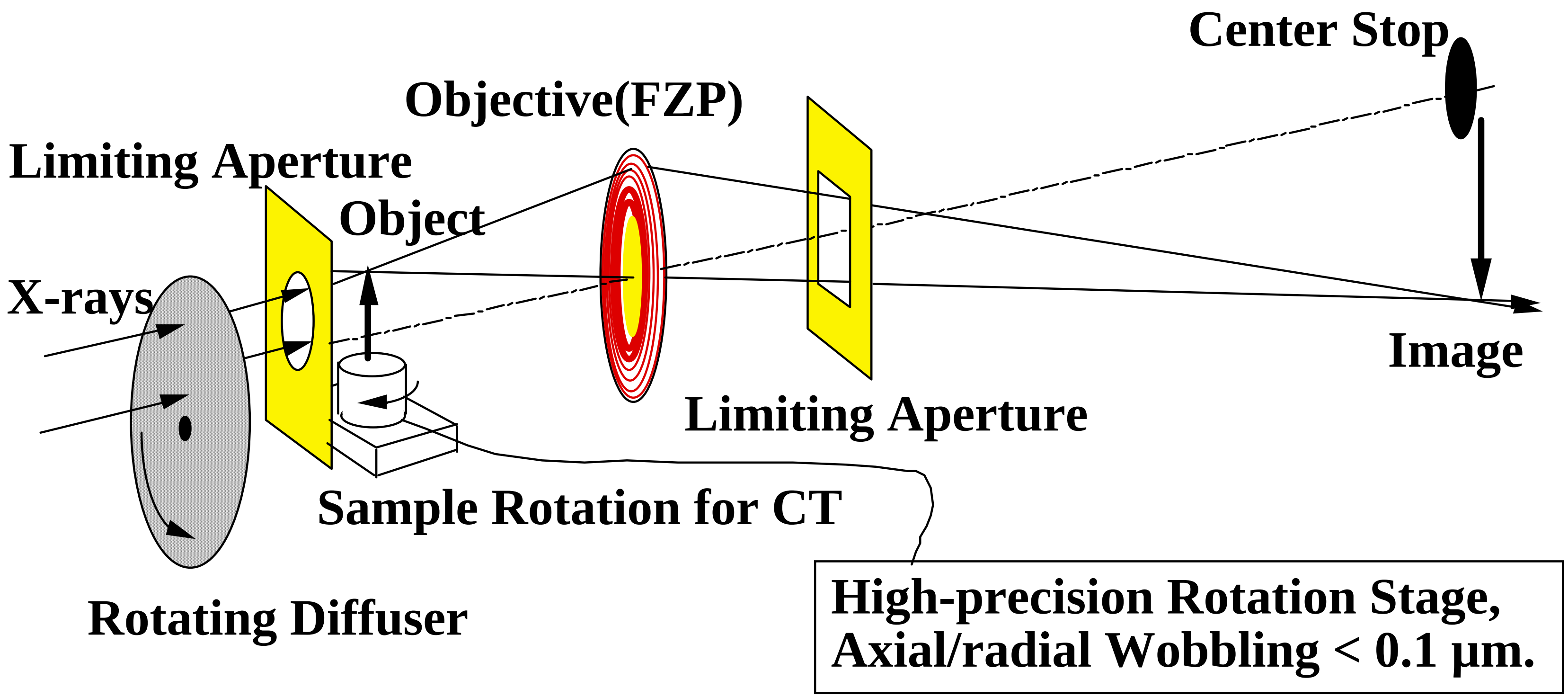
Test Image

Si 220 Diffraction

λ= 0.7Å

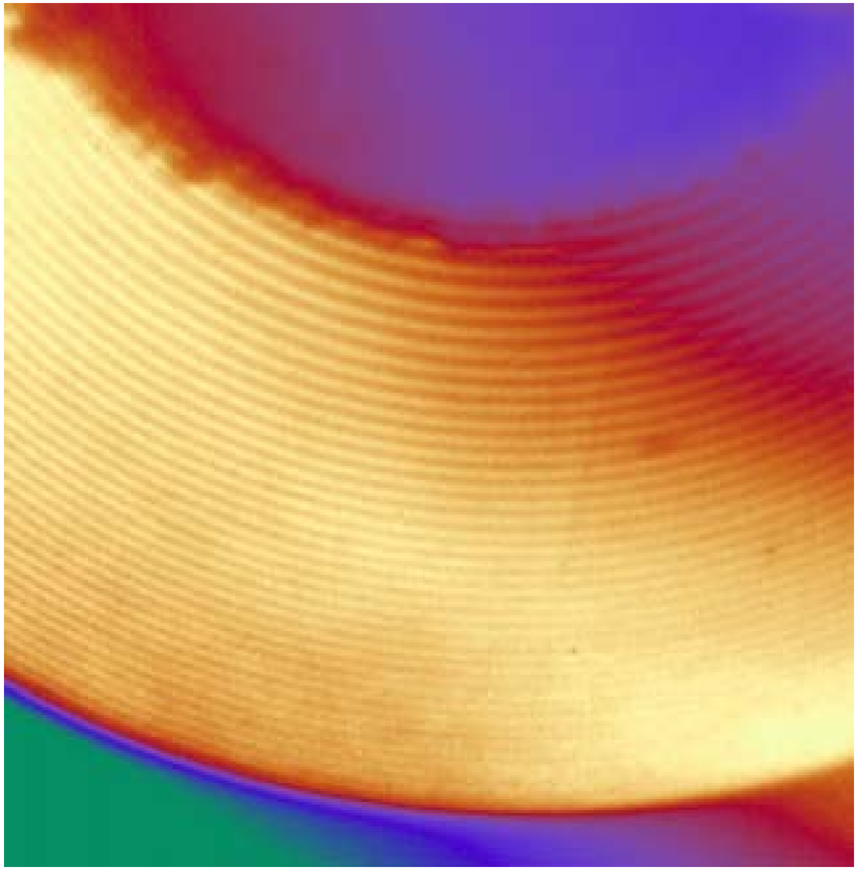
Field of View ~ 6mm

Phase-contrast CT using Bonse-Hart Interferometer at BL20XU



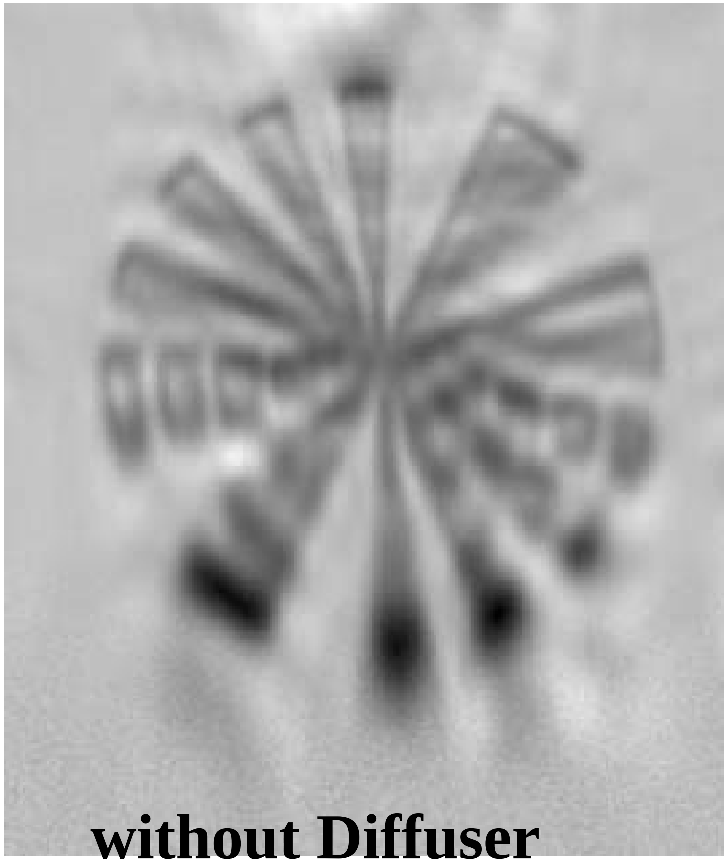
Schematic Diagram Experimental Setup
for Imaging Microscopy and Micro-tomography

@ BL47XU

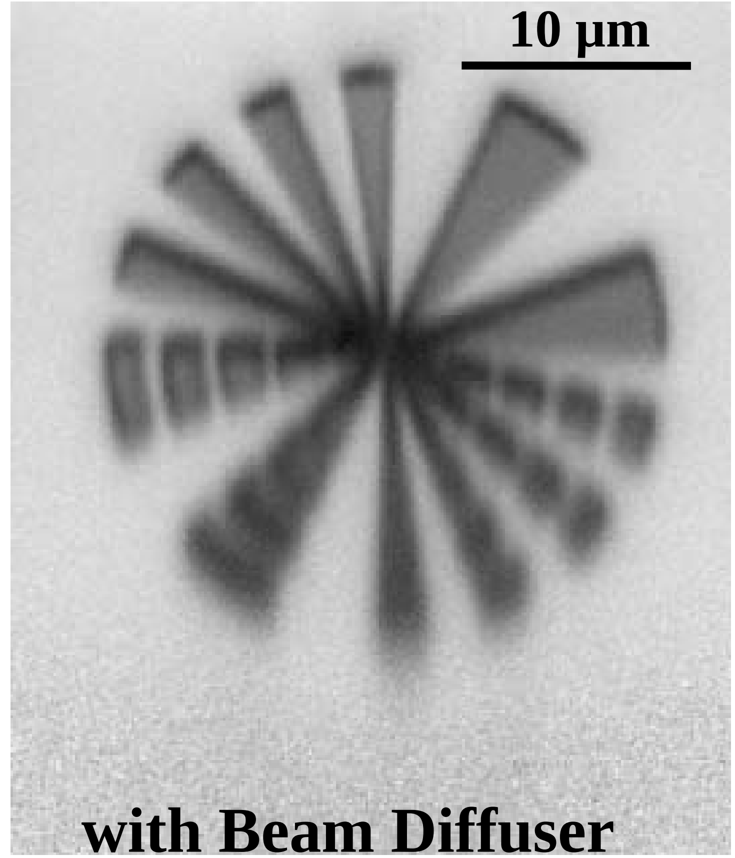


Imaging Microscopy

Objective &Sample:FZP with 0.25 μm outermost zone width, X-ray Energy: 8 keV.



without Diffuser
- Coherent Illumination -

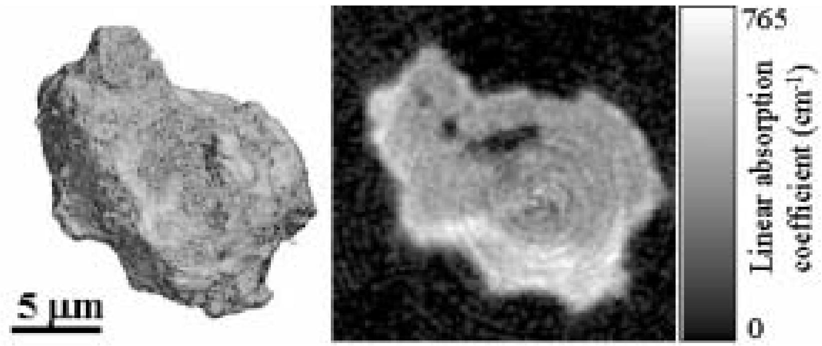


with Beam Diffuser
- Incoherent Illumination-

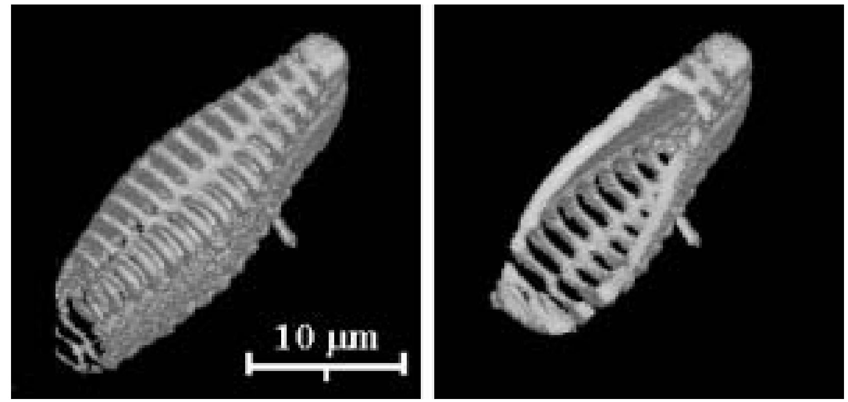
Imaging Microscopy with FZP Objective
- Effect of Beam Diffuser -

X-ray energy: 8 keV

Control of coherence is important!

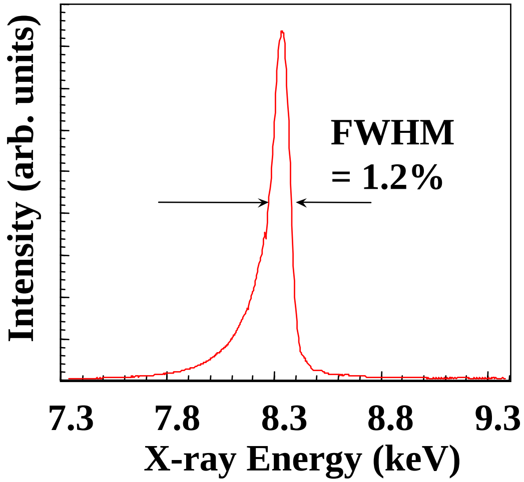


Stony Meteorite Allende
8 keV, x7.61, BM3(x10), voxel size 0.13 µm.
100 projection, exposure time:15 s/projection.



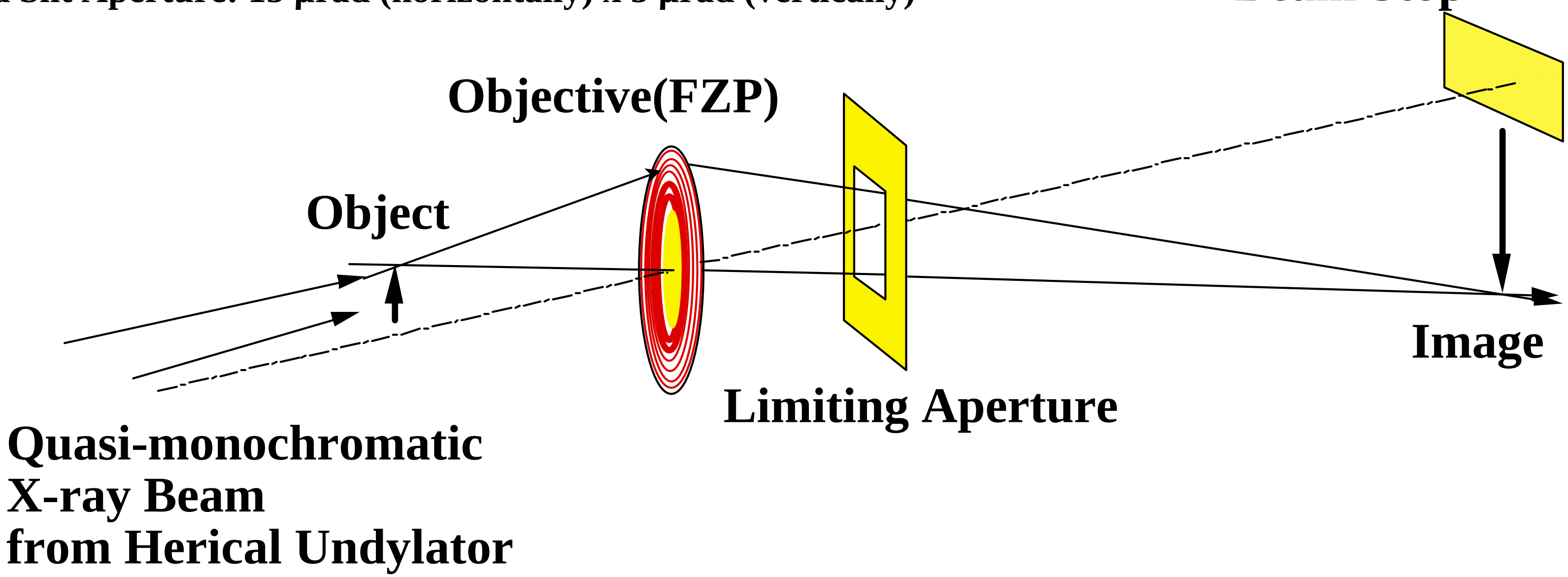
Diatom "Achnanthidium lanceolata"
8 keV, x10, BM3(x10), voxel size 0.1 µm.
360 projection, exposure time: 60 s/projection.

X-ray Micro-tomography using Imaging Optics with Fresnel Zone Plate Objective



Hard X-ray Imaging Microscopy with Fresnel Zone Plate Objective & Quasi-monochromatic Undulator Radiation

Measured Spectra of Undulator Radiation
Front-end Slit Aperture: 15 μrad (horizontally) x 5 μrad (vertically)



Experimental Setup at BL40XU SPring-8

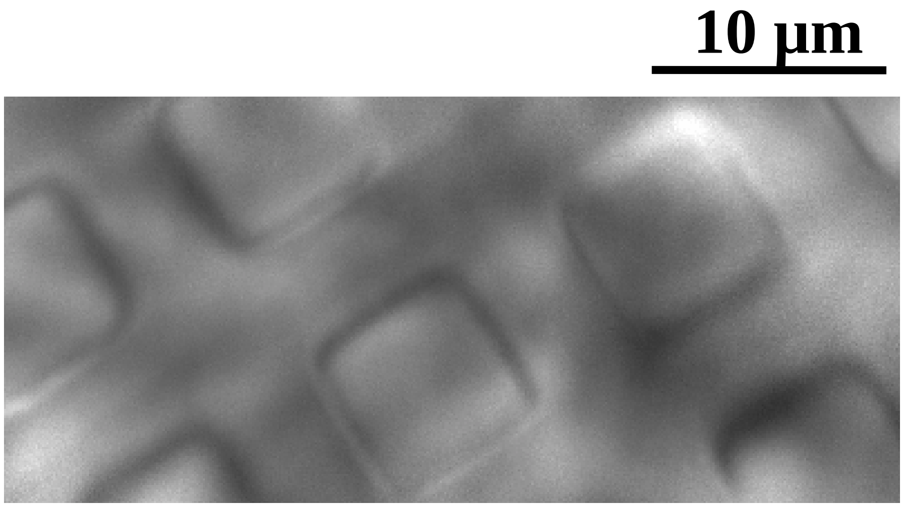
BL40XU of SPring-8 (High Flux Beamline)

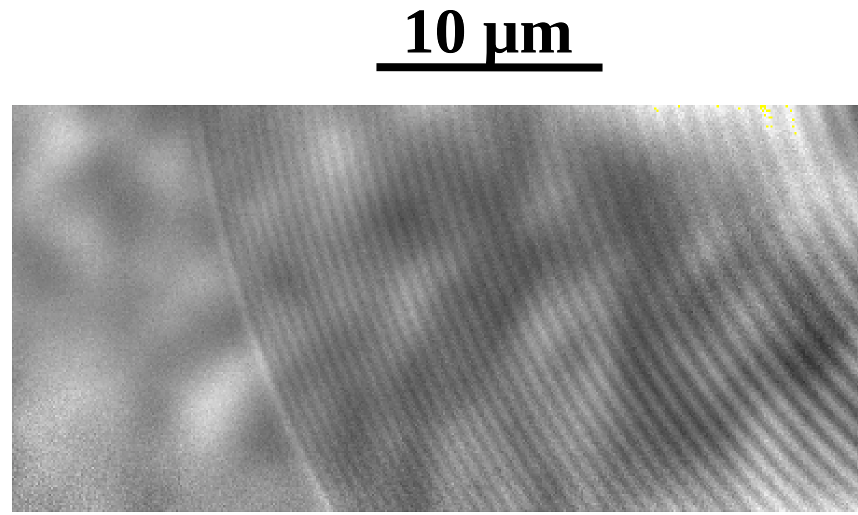
1. Undulator radiation without monochromator, $\Delta\lambda/\lambda$ ~ 1%.
2. Helical Undulator --> Suppression of higher order,
3. Condenser Optics: K-B mirror

Available flux ~ 1000 times conventional beamlines (undulator beamlines with crystal monochromator).

Requirement on monochromaticity for Fresnel zone plate ~ Number of Fresnel zone.
--->$\Delta\lambda/\lambda$ ~ N (number of Fresnel zone)

Use of direct undulator radiation, $\Delta\lambda/\lambda$ ~ 100.
X-ray imaging microscopy with sub-µm resolution and milli-second exposure time!





Object: Cu mesh, 2000 lines/inch

Object: Fresnel zone plate, 0.25 μm outermost zone width

Image of test object

Objective: FZP, 0.25 μm outermost zone width, 100 zones,
Magnification: 11.3,
X-ray energy: 8.34 keV,
Exposure time: 1.5 ms (Single Shot)

Hard X-ray Imaging Microscopy with Fresnel Zone Plate Objective & Quasi-monochromatic Undulator Radiation at BL40XU

Summary and Future Project

1. Microbeam, Scanning Microscopy, Imaging Microscopy
   submicron - 60 nm resolution in hard X-ray region.
2. Micro-CT, XRF Analysis/imaging, topography, micro-diffraction.

~ 50% of general users @BL20B2 & 47XU is micro-CT,
~ 80% of XRF users @BL37XU is microbeam analysis.

Wide varieties of spatial resolution and FoV(field of view) are required.
  Spatial resolution: 10 µm - 100 nm, FoV: 100 mm -.
  Macroscopic -> intermediate -> microscopic -> nano-scopic!

Future,
  1. Spatial Resolution: 10 nm @4 - 100 keV.
  2. Variable field and spatial resolution are required for general use.