Single-nanometer focusing of hard X-rays using adaptive optical system

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Current status of X-ray mirror development for coming coherent-X-ray

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Acknowledgement

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Background and today's contents

3rd generation SR facilities widely contribute to many S&T fields.
4th generation facility (XFEL) has already been here.

Highly brilliant X-ray is not particular, now.

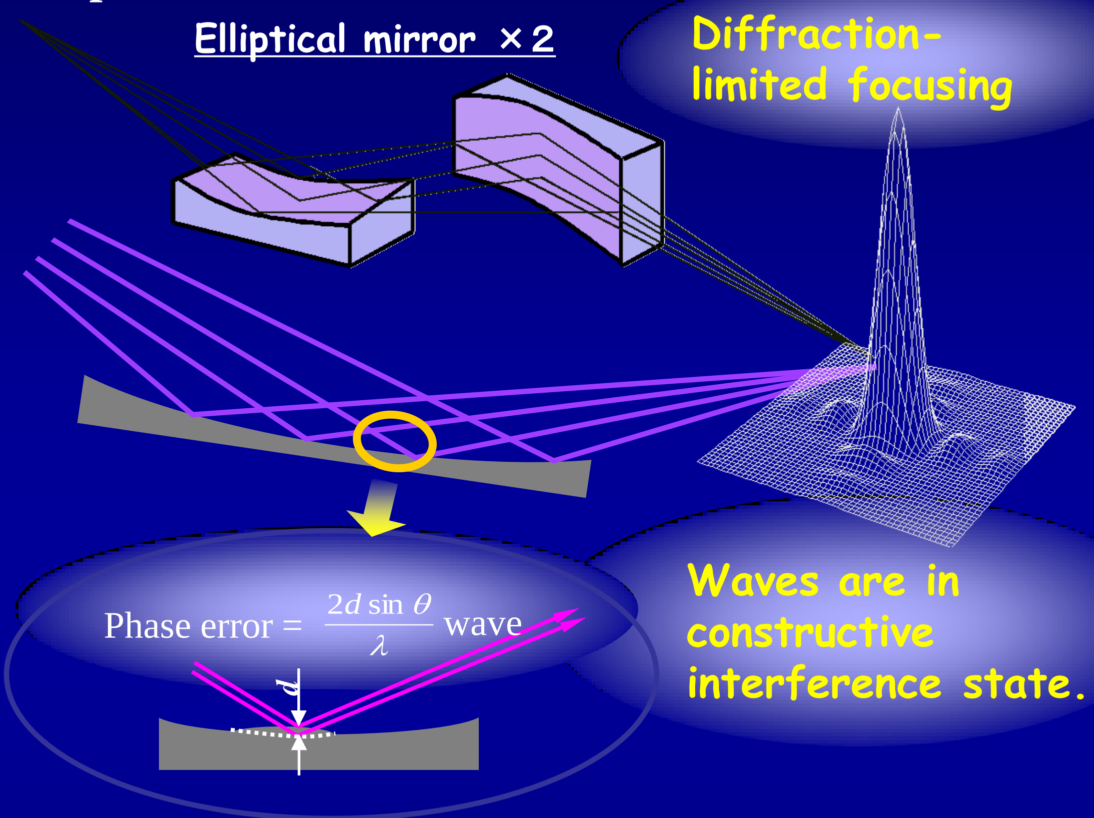
How should mirror optic contribute to coherent X-ray optical system?

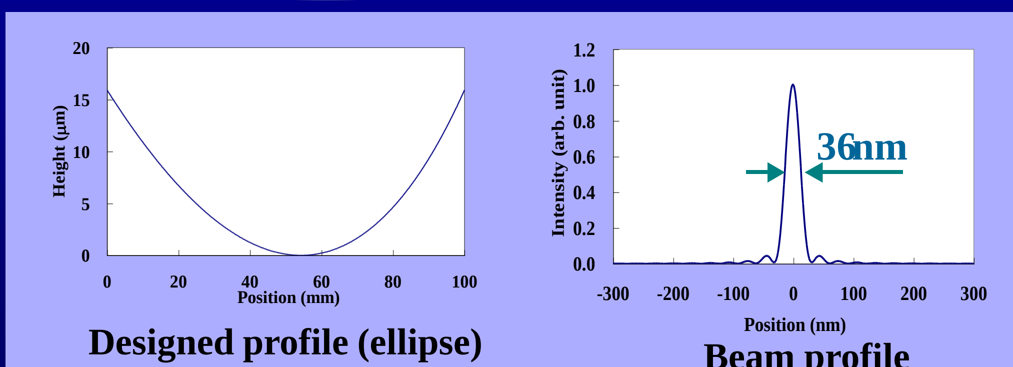
Current research targets

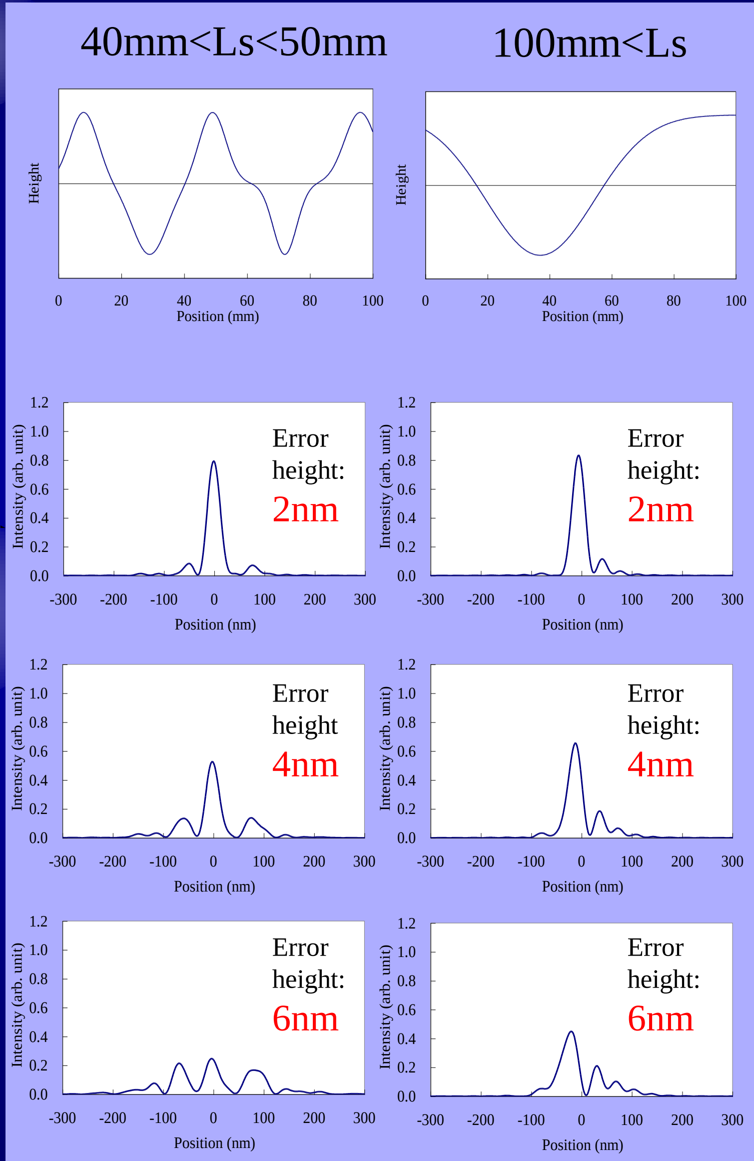
1. Focusing down to sub-10nm (including brief introduction of sub-50nm focusing)
2. Full-field, achromatic and high-resolution imaging of incoherent X-rays
3. Focused and full coherent X-ray illumination for diffraction microscopy

Required accuracy for nano-focusing under D-limited condition

Kirkpatrick-Baez mirrors







Fabrication and figure testing technologies of Osaka University

◎ Plasma CVM (chemical vaporization machining)

→ Rough figuring (Rapid figuring with 10nm (P-V) level accuracy)

K. Yamamura et al., Rev. Sci. Instrum. 71 (2000), 4627

◎ EEM (elastic emission machining)

→ Final figuring and smoothing (Fine figuring with atomically smoothing)

K. Yamauchi et al., Rev. Sci. Instrum. 73 (2002), 4028

◎ MSI (microstitching interferometry)

→ Figure tester with spatial resolution close to 0.01mm

K. Yamauchi et al., Rev. Sci. Instrum. 74 (2003), 2894

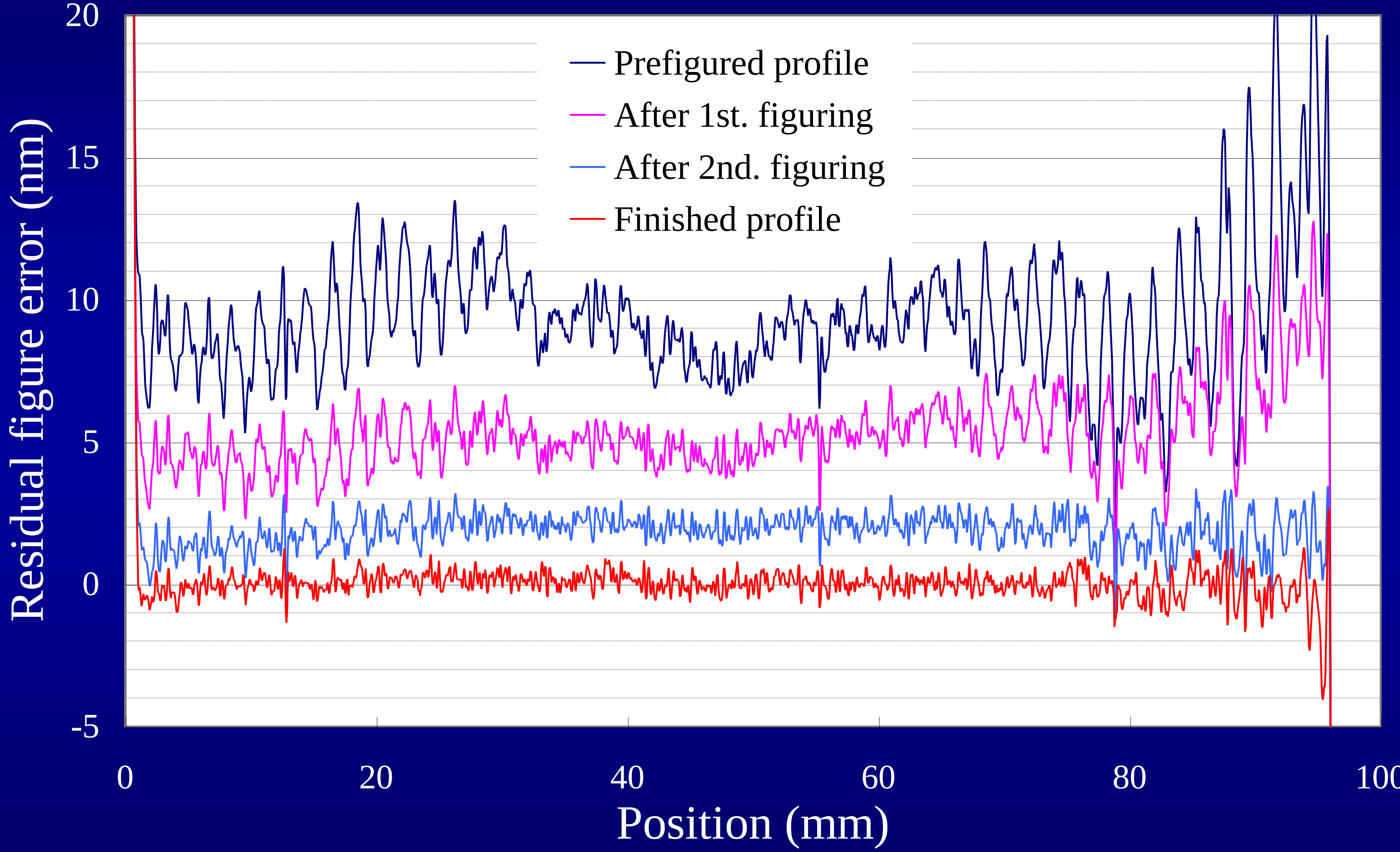
◎ RADSI (relative-angle determinable stitching interferometry)

→ Figure tester for steeply curved ellipse of large NA mirror

H. Mimura et al., Rev. Sci. Instrum. 76 (2005), 045102

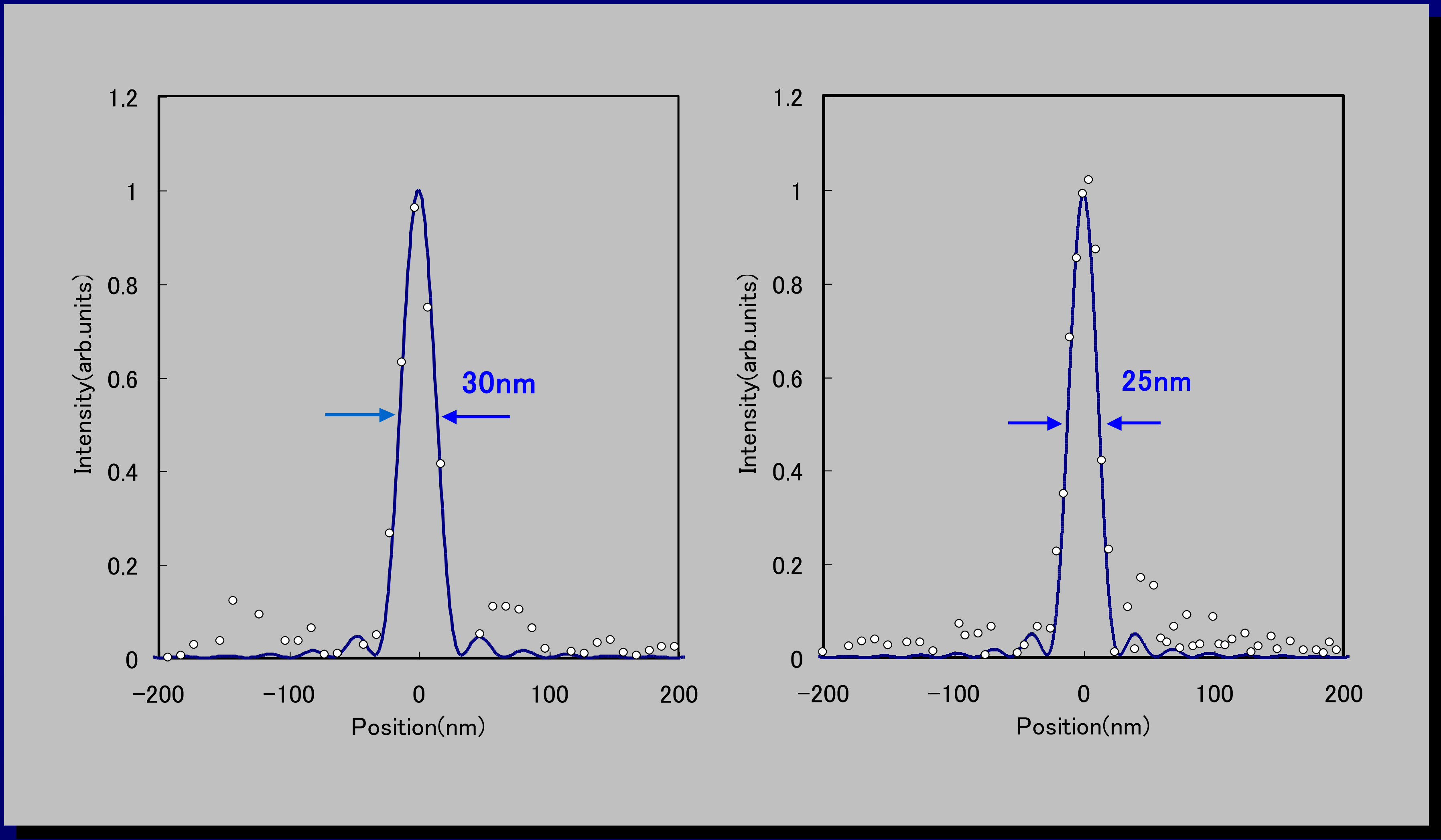
JTEC URL http://www.j-tec.co.jp

Typical deterministic figuring properties using EEM



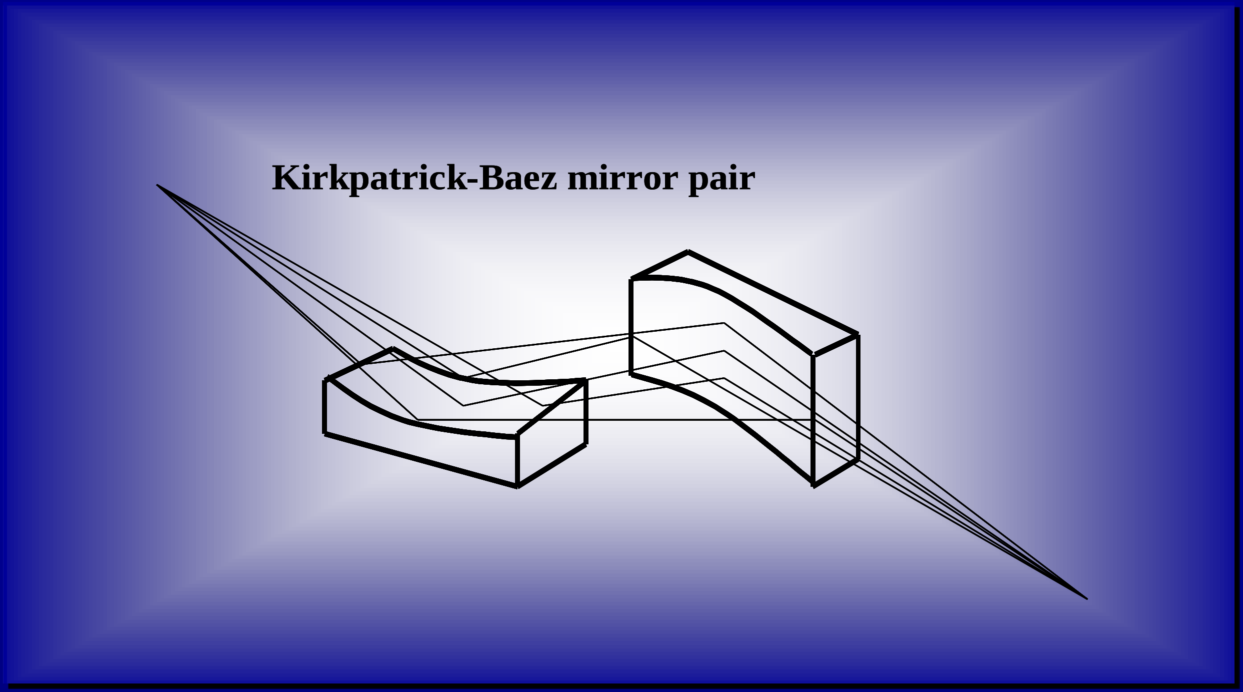
Sub-30nm focusing (2006)

Smallest size in hard-X-ray realized by total reflection achromatic mirror optics (focusing under diffraction limited condition)

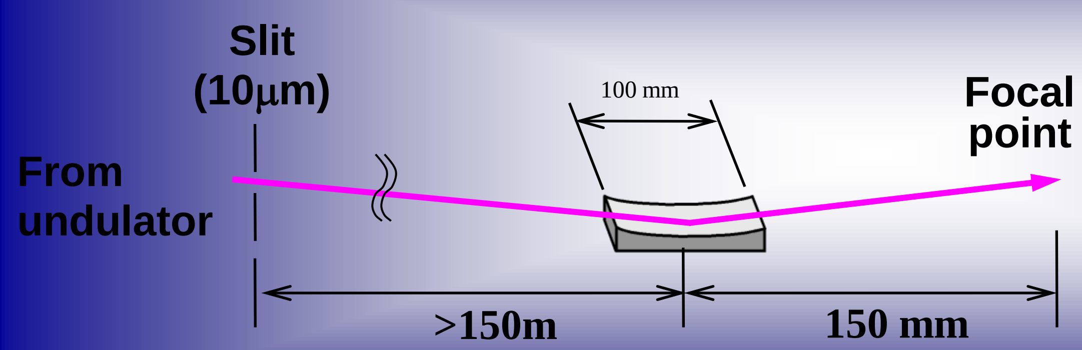


Mimura et al., APL (2007)

"Hard-X-ray sub-10nm focusing and realization of high-resolution X-ray microscopy"



To realize Sub-10nm focusing K-B mirrors

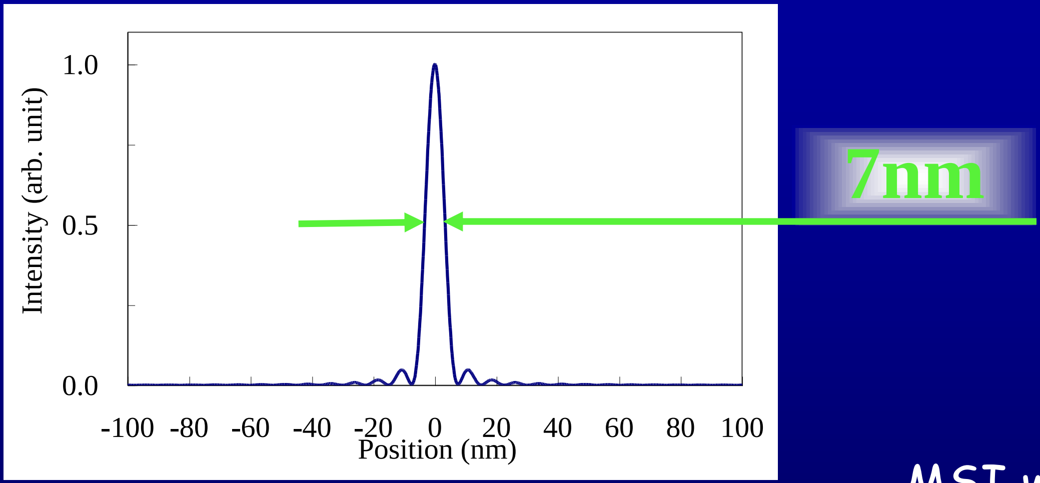


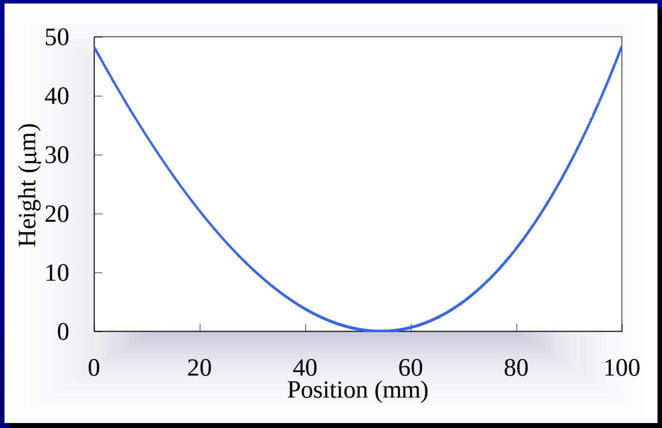
X-ray energy : 20keV

Focal length : 150mm

Acceptance width : 1.1mm

Incidence angle : 11.1mrad

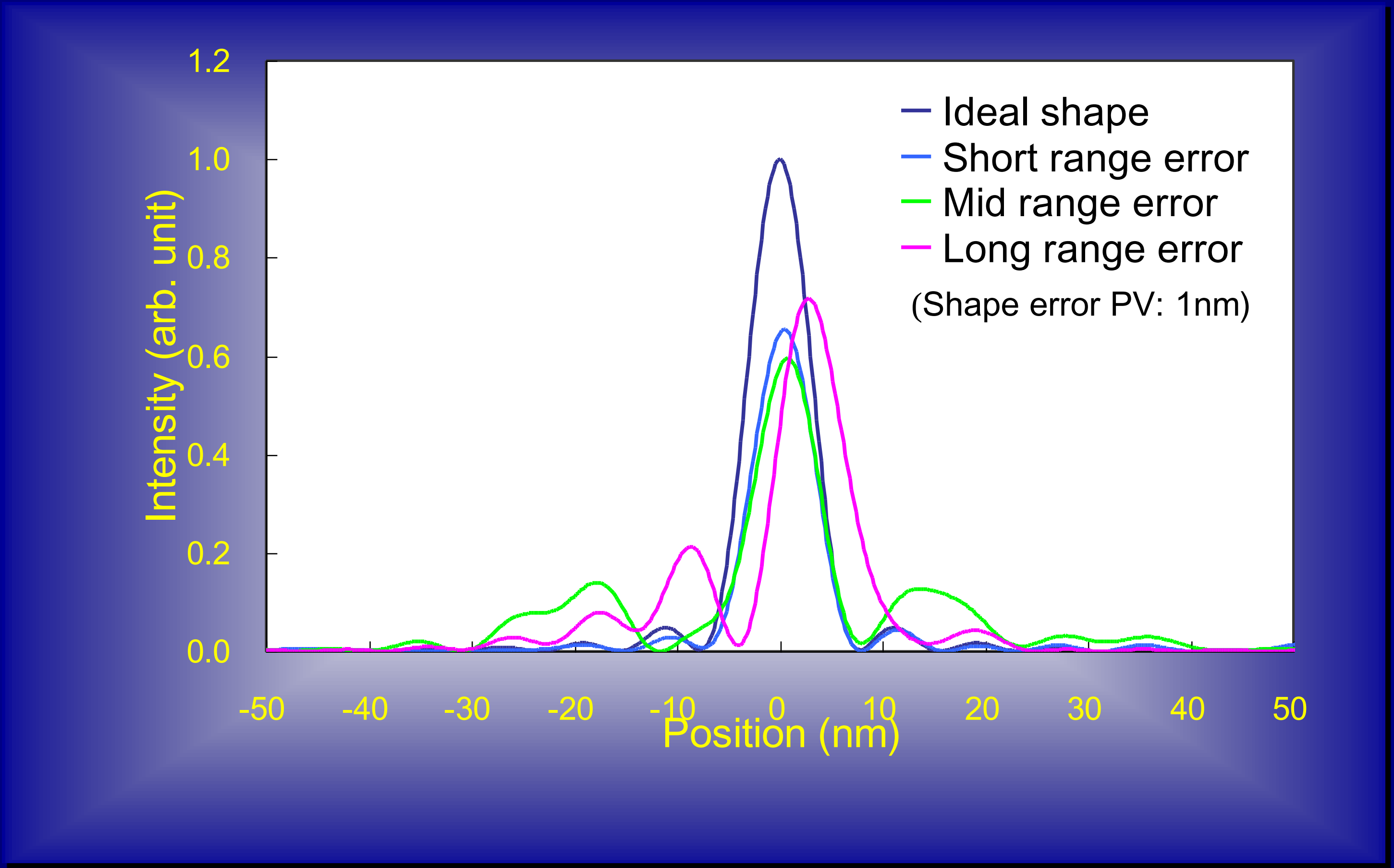




MSI with RADSI and EEM can prepare the surface figure with 1nm (P-V) accuracy.

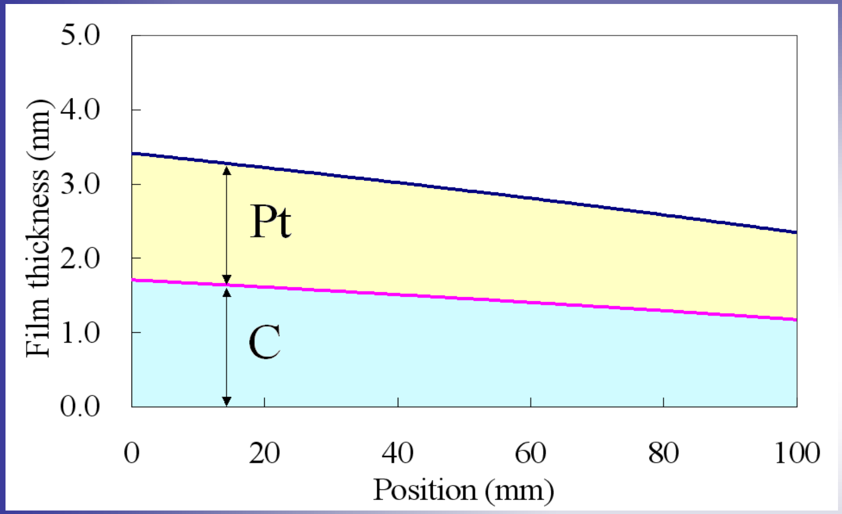
Estimation of required accuracy

@20keV Mirror length: 100mm, Focal length: 150mm

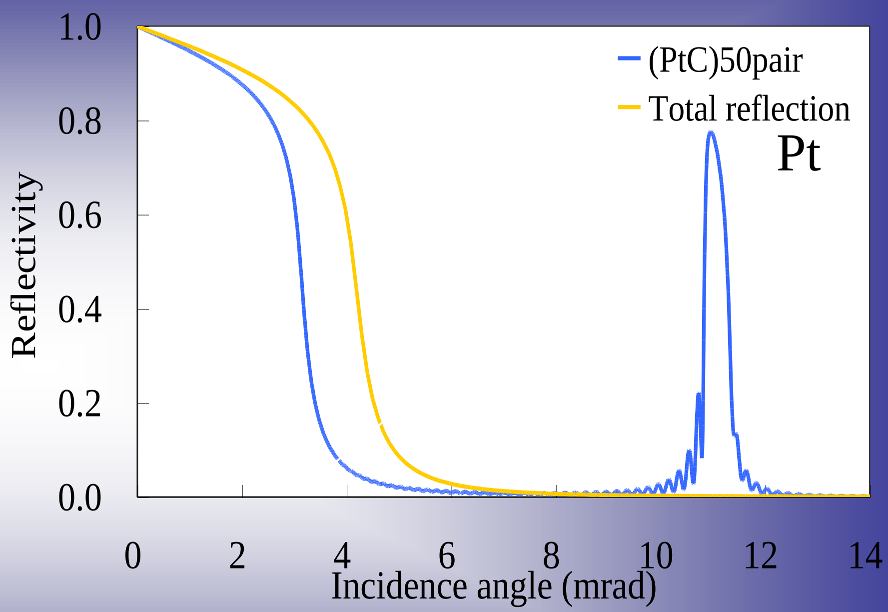


<u>Figure error of 1nm is not allowable</u>

Multi-layer technology is needed to realize large NA



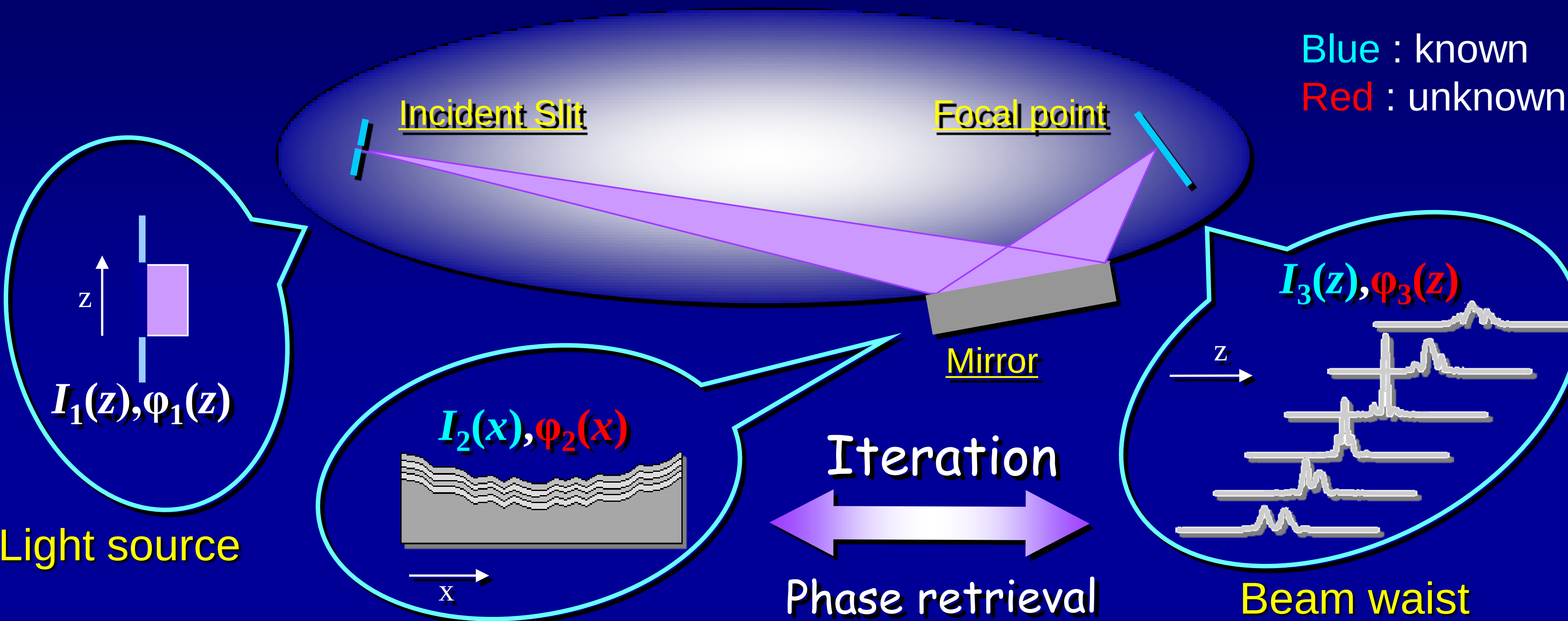
Graded multi-layer



Reflectivity

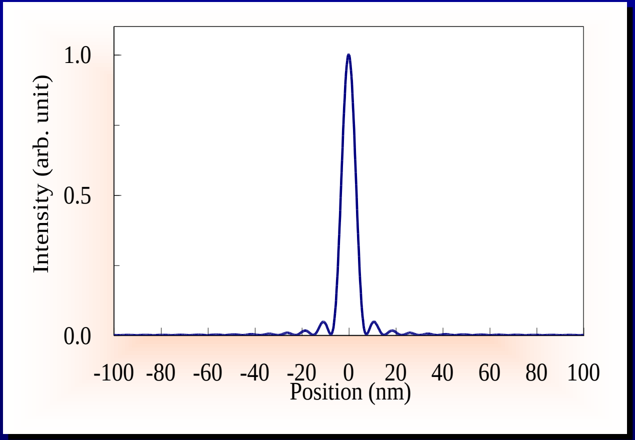
Not only figure error but also thickness deviation of the multilayer induce wavefront phase error.

At-wavelength phase-retrieval interferometry



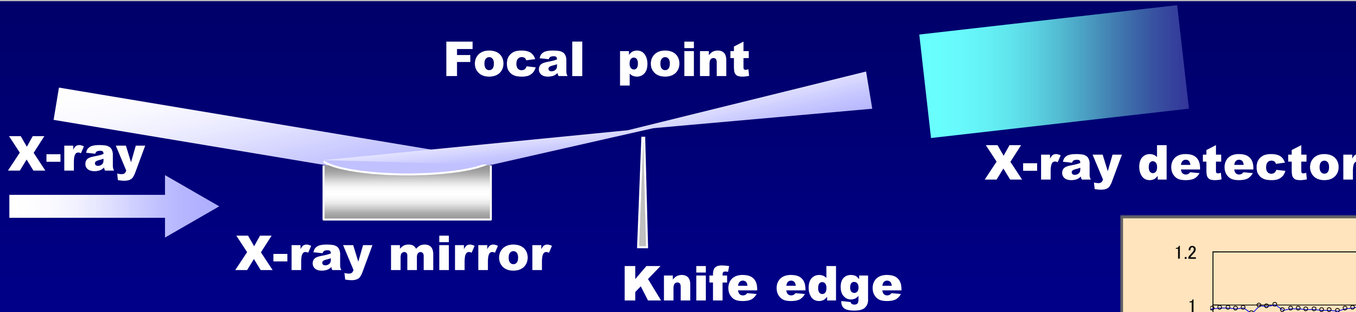
Mirror surface
(Phase error includes surface figure and ML thickness errors)

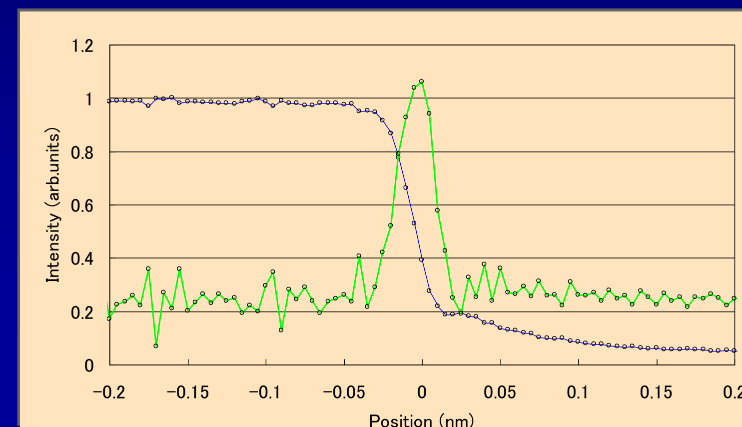
Phase error compensation



K. Yamauchi,
SPIE's Optics and Photonics 2005

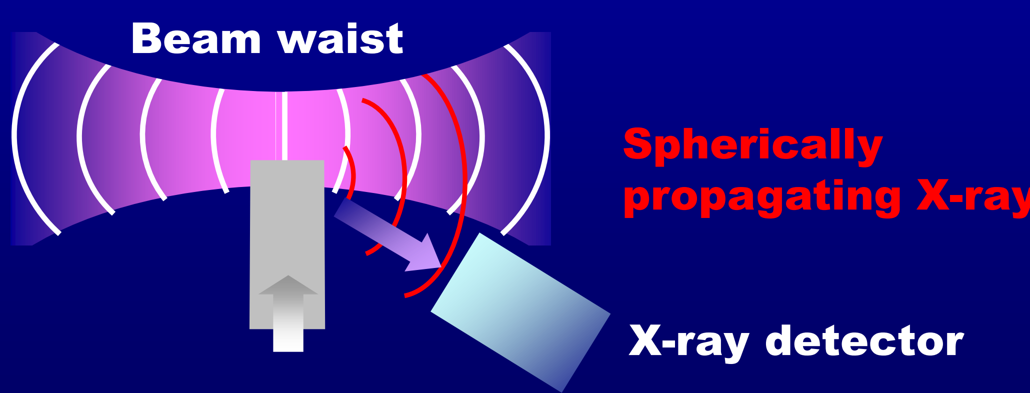
New knife-edge method





Conventional knife-edge method

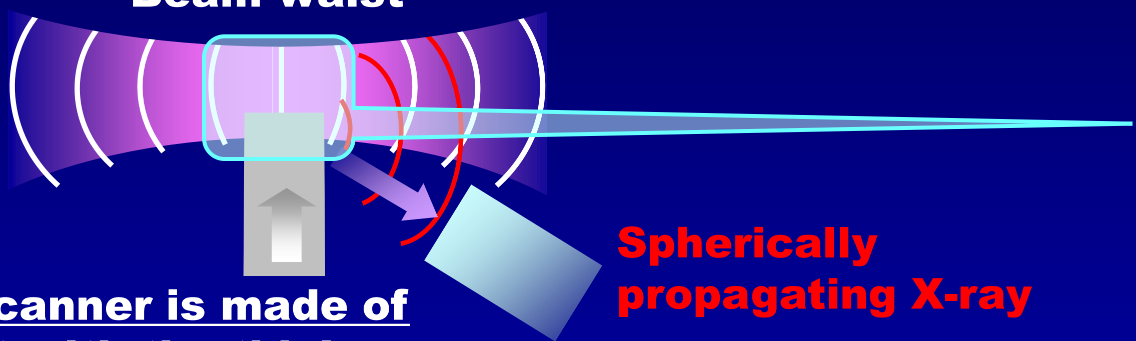
New method



Mimura et al.
Phys. Rev. A (2008)

Details of the new knife-edge method

Beam waist

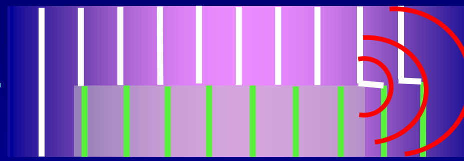


Scanner is made of Pt with the thickness of 2.5μm.

Spherically propagating X-ray

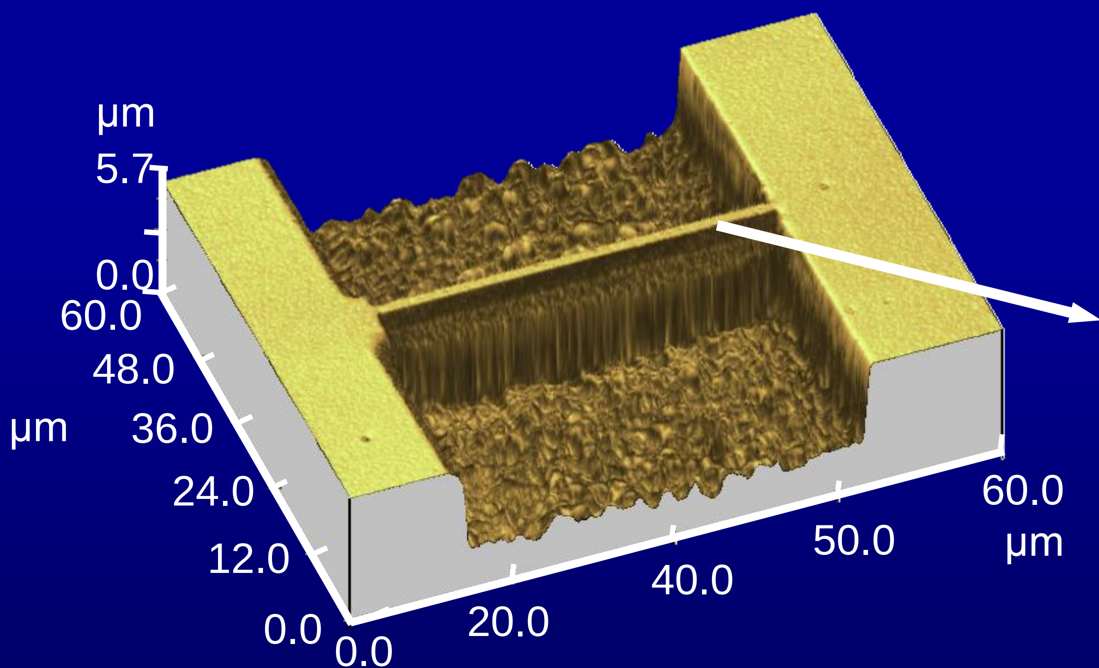
X-ray detector

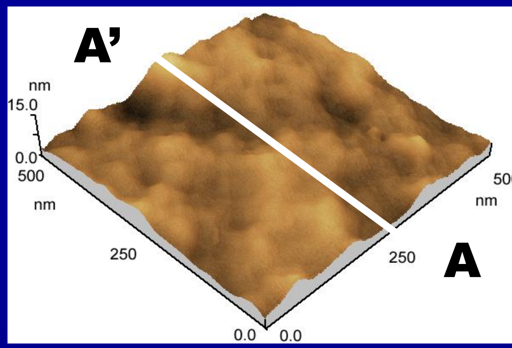
Scanner is acting as a phase object



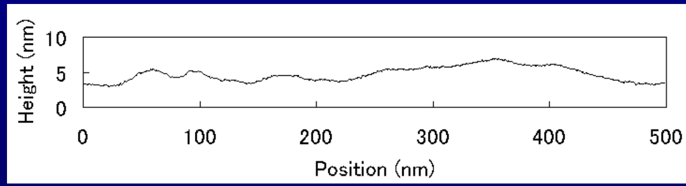
Modified wavefront

Phase is shifted with λ/2.





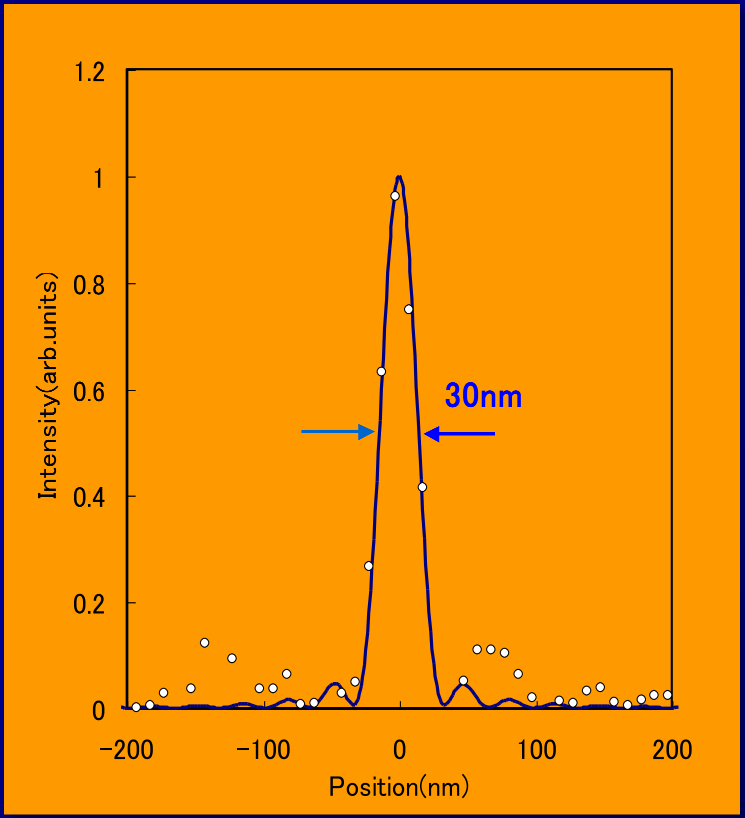
Microroughness at the bridge



A-A' profile

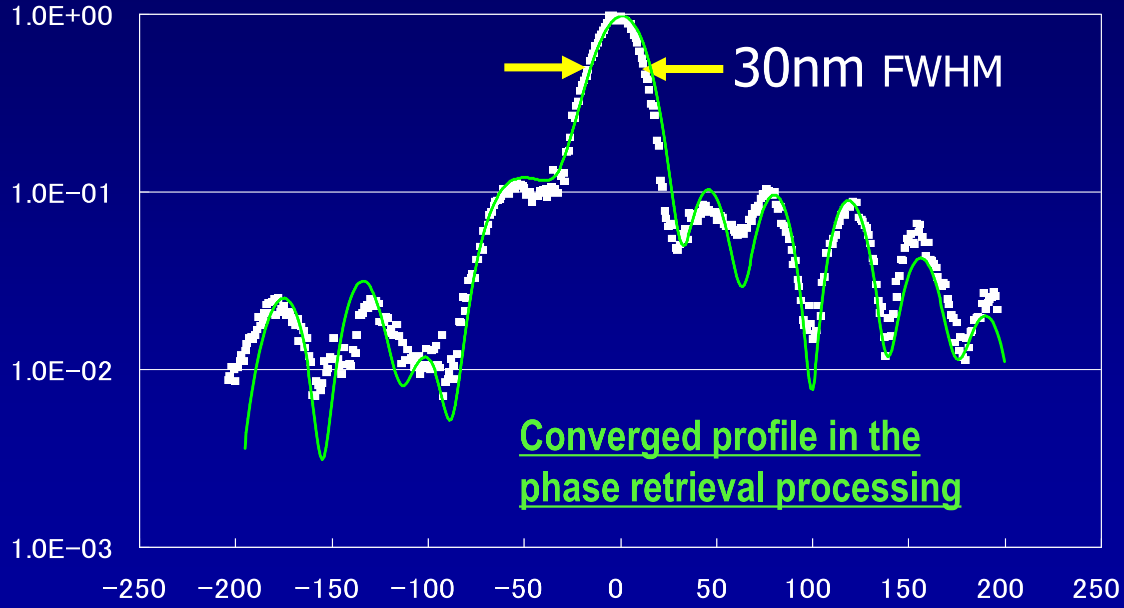
30nm-focusing mirror was employed

for a demonstration of the proposed at-wavelength measurement

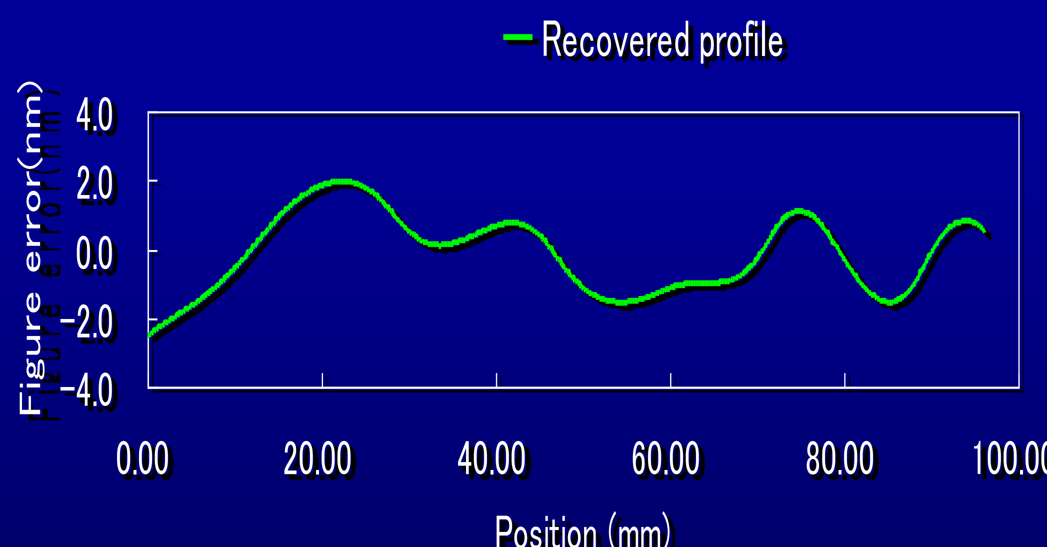


- Not a multilayer optic.
- Surface is coated by Pt.

Performance of phase retrieval



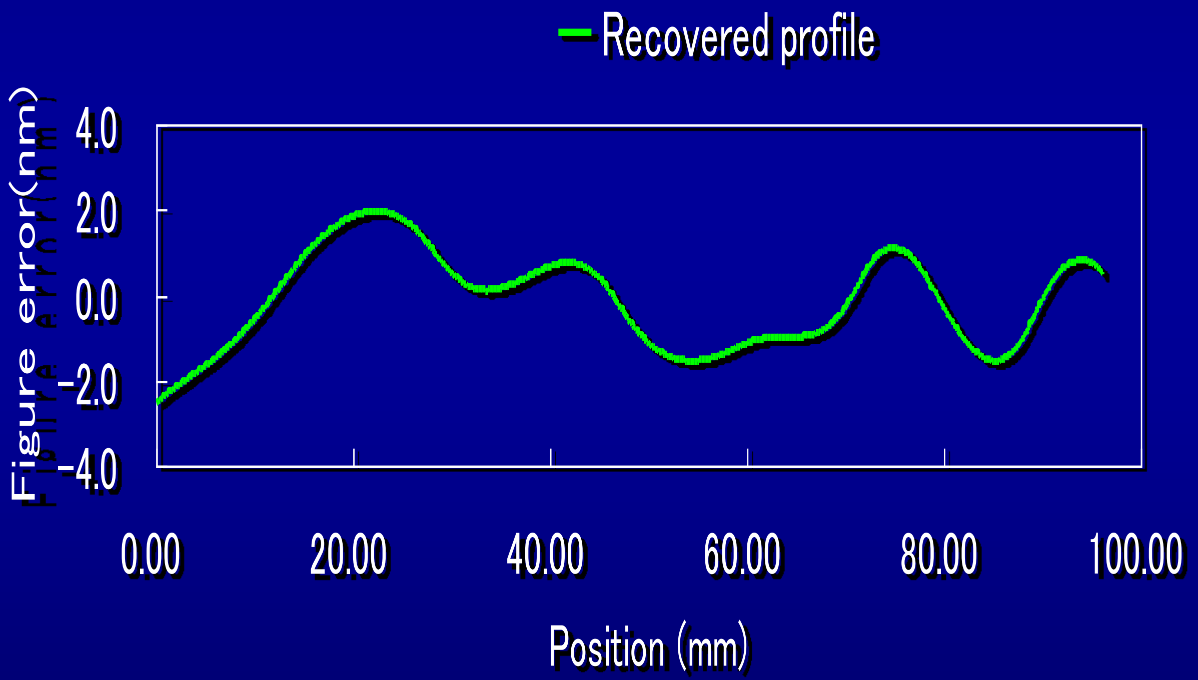
Measured beam profile



Mimura et al.
Phys. Rev. A (2008)

Verification

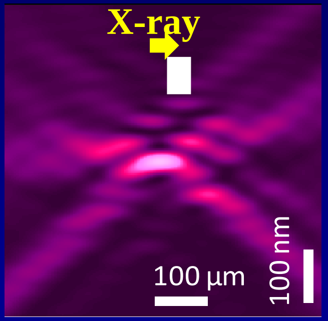
To verify the reliability of the recovered phase error profile, we actually refigured the mirror by differential deposition method (G. Ice) using the recovered profile.



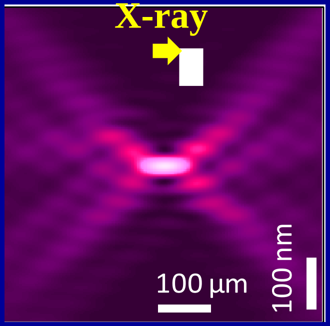
Focused beam profiles before and after DD

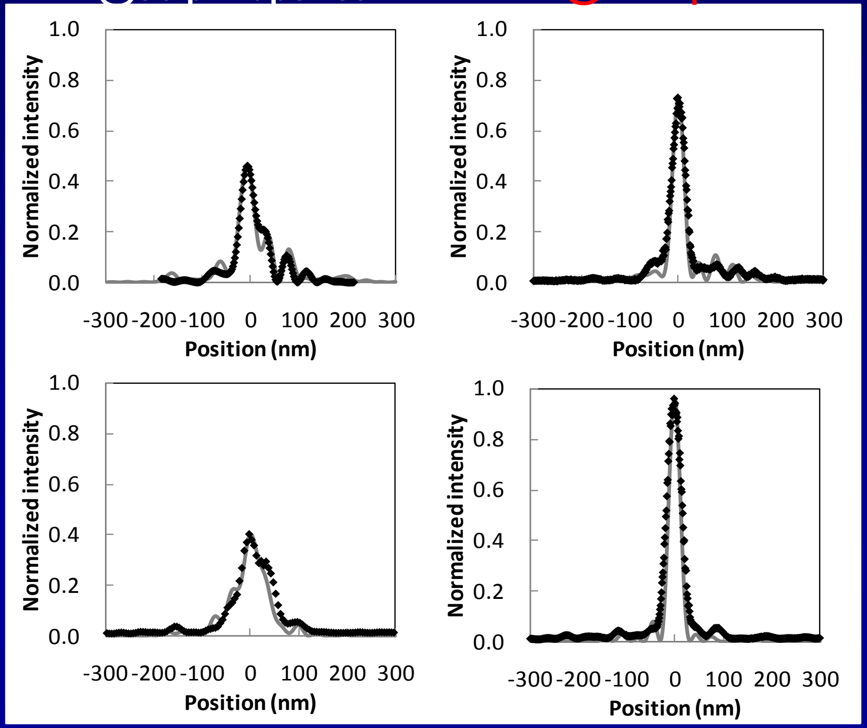
@50 µm upstream | @focal plane

Before DD

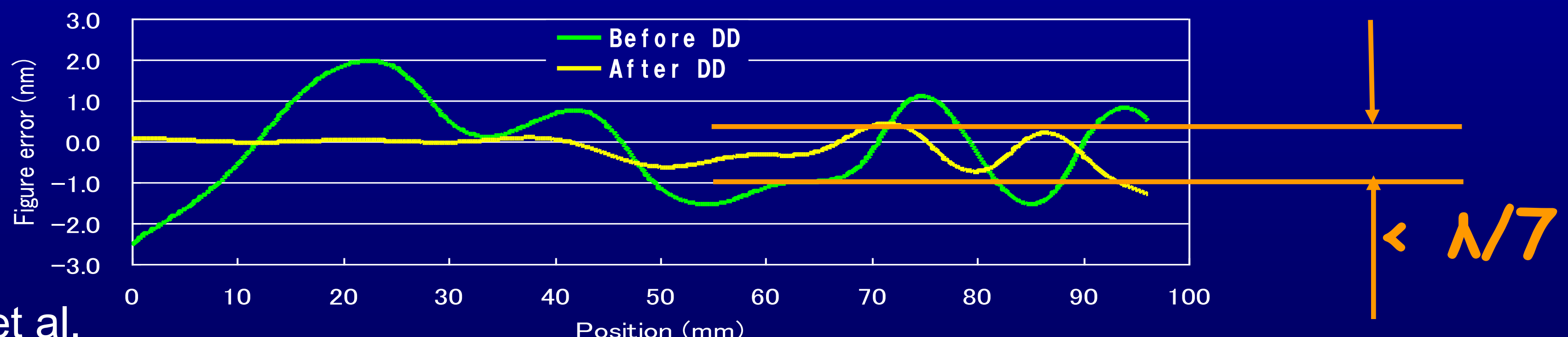


After DD



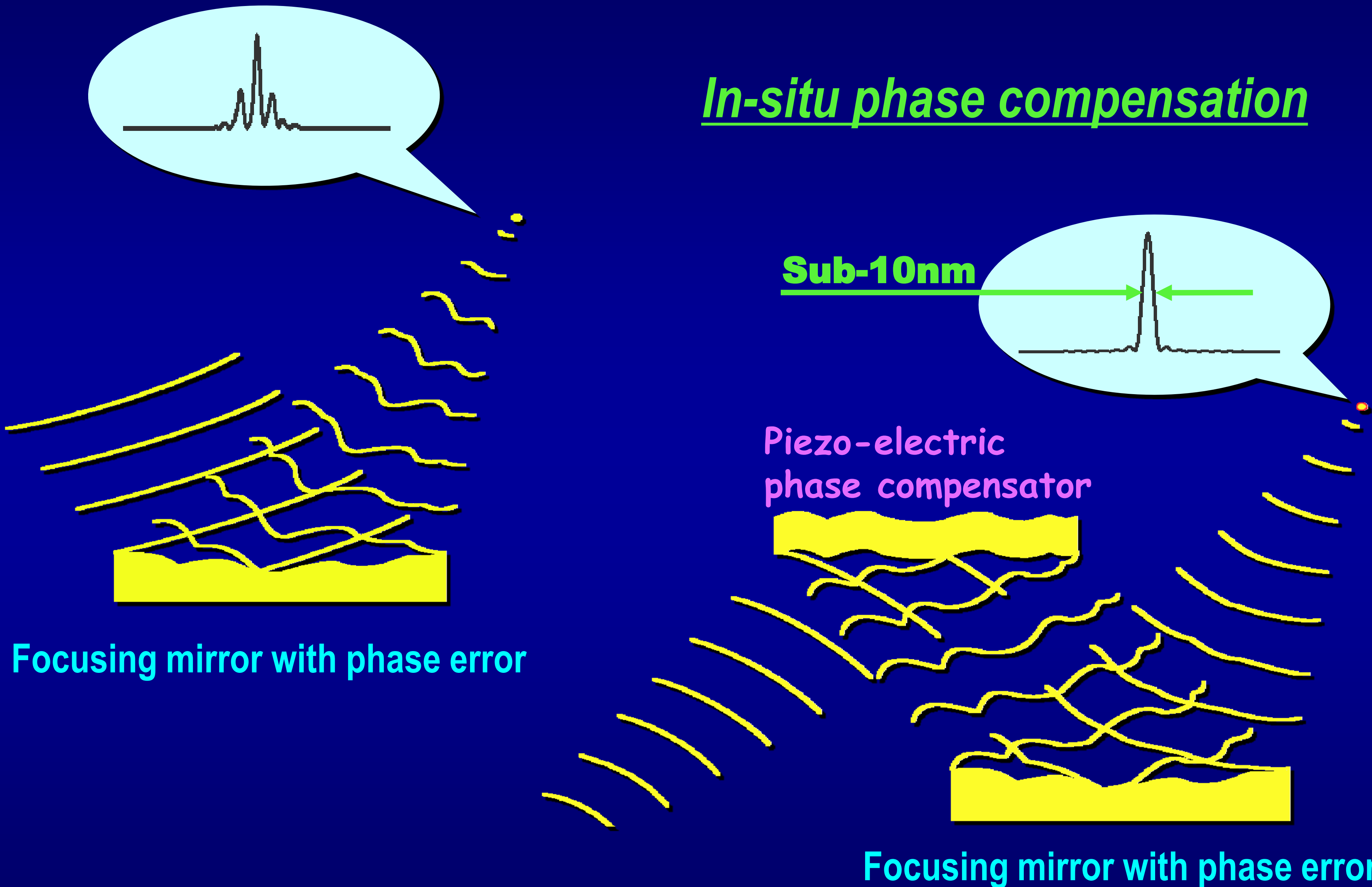


Comparison between the wave fields before and after phase compensation



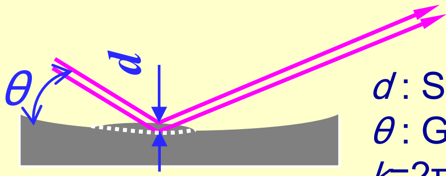
Handa et al.
SIA(2008)

On-line compensation of wavefront

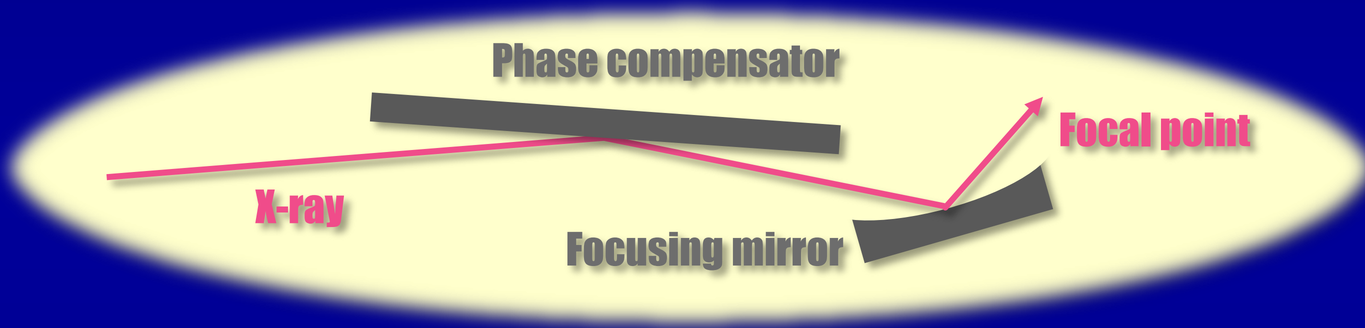


Design concept

Phase error = $2kd\sin\theta$



d : Shape error
θ : Glancing angle
$k=2\pi/\lambda$: Wave number



★ **Glancing angle of compensator mirror is N times smaller.**
(However, Consequently the length of the compensator becomes longer)

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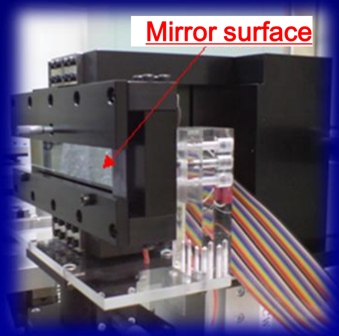
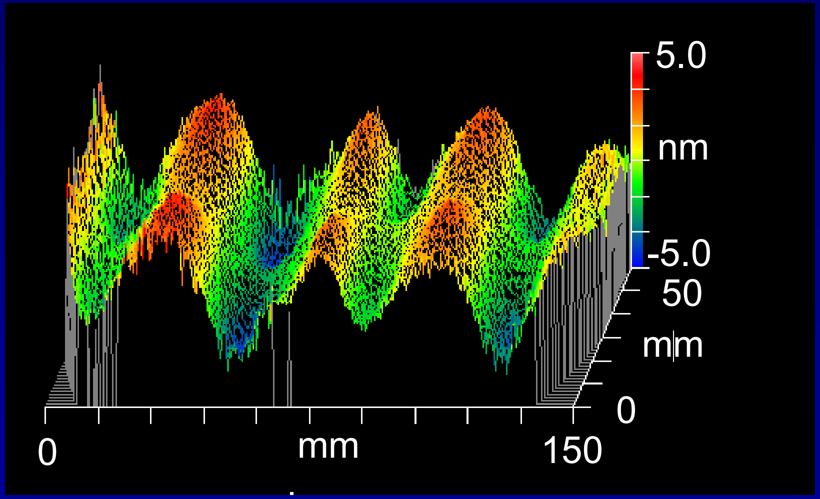
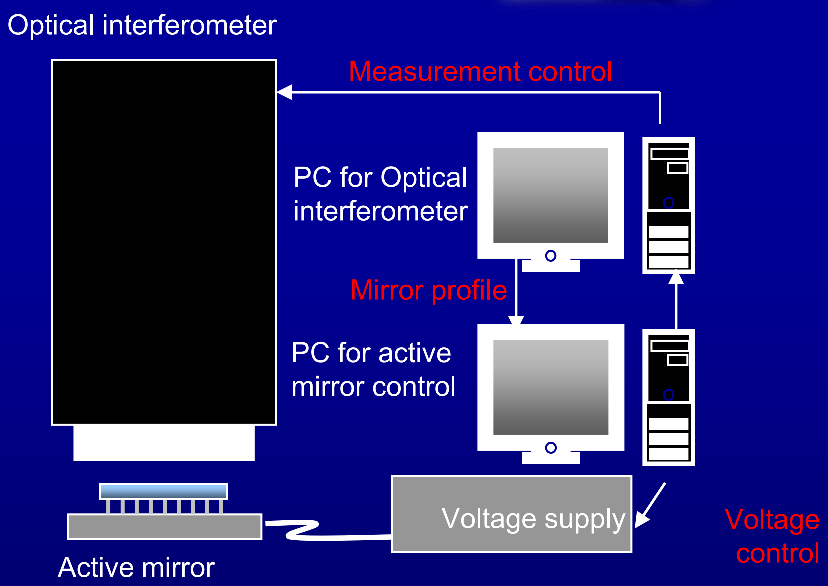
Required figure accuracy of the compensator mirror becomes N times lower.

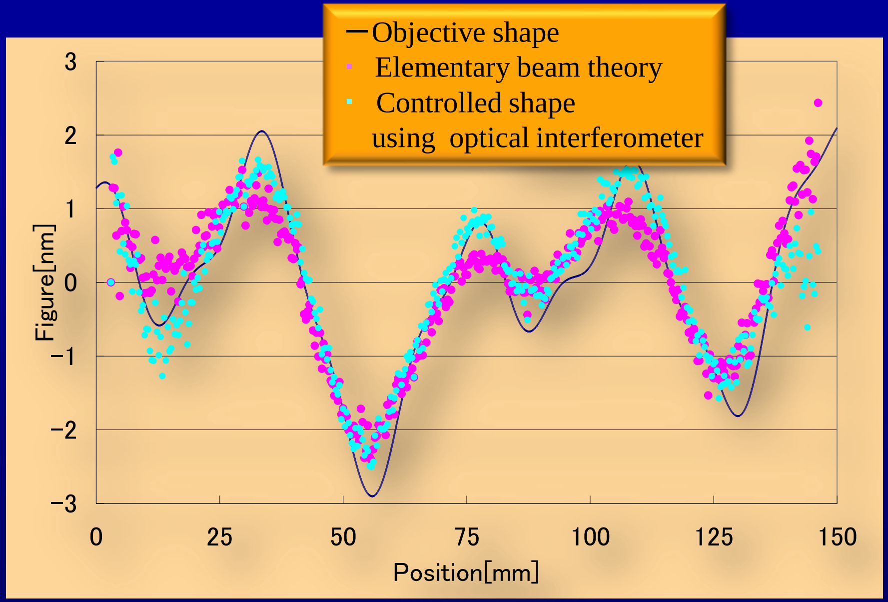
Phase compensator





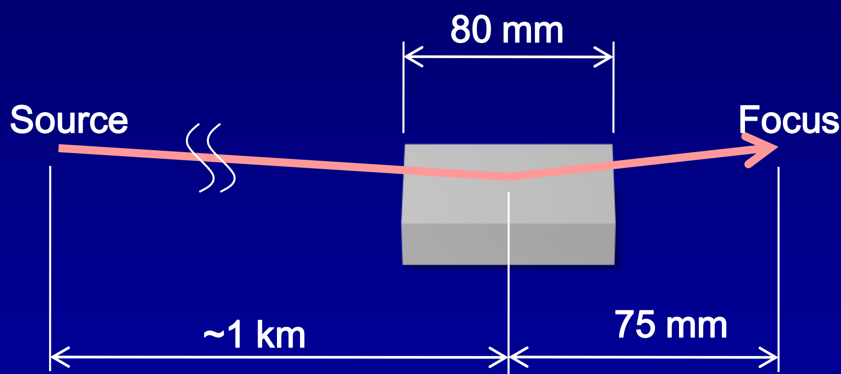


Feedback system



Kimura et al.,
SPIE O&P (2008), Jpn. J. Appl. Phys (2009)

Sub-10nm focusing mirror



X-ray energy : 20 keV
Mirror length : 80 mm
Focal distance : 75 mm
Glancing angle : 7.0 mrad
Multilayer material : $[Pt/C]_{20}$
Substrate material : quartz glass

$$\Lambda = \frac{\lambda}{2\sqrt{n^2 - \cos^2\theta}}$$

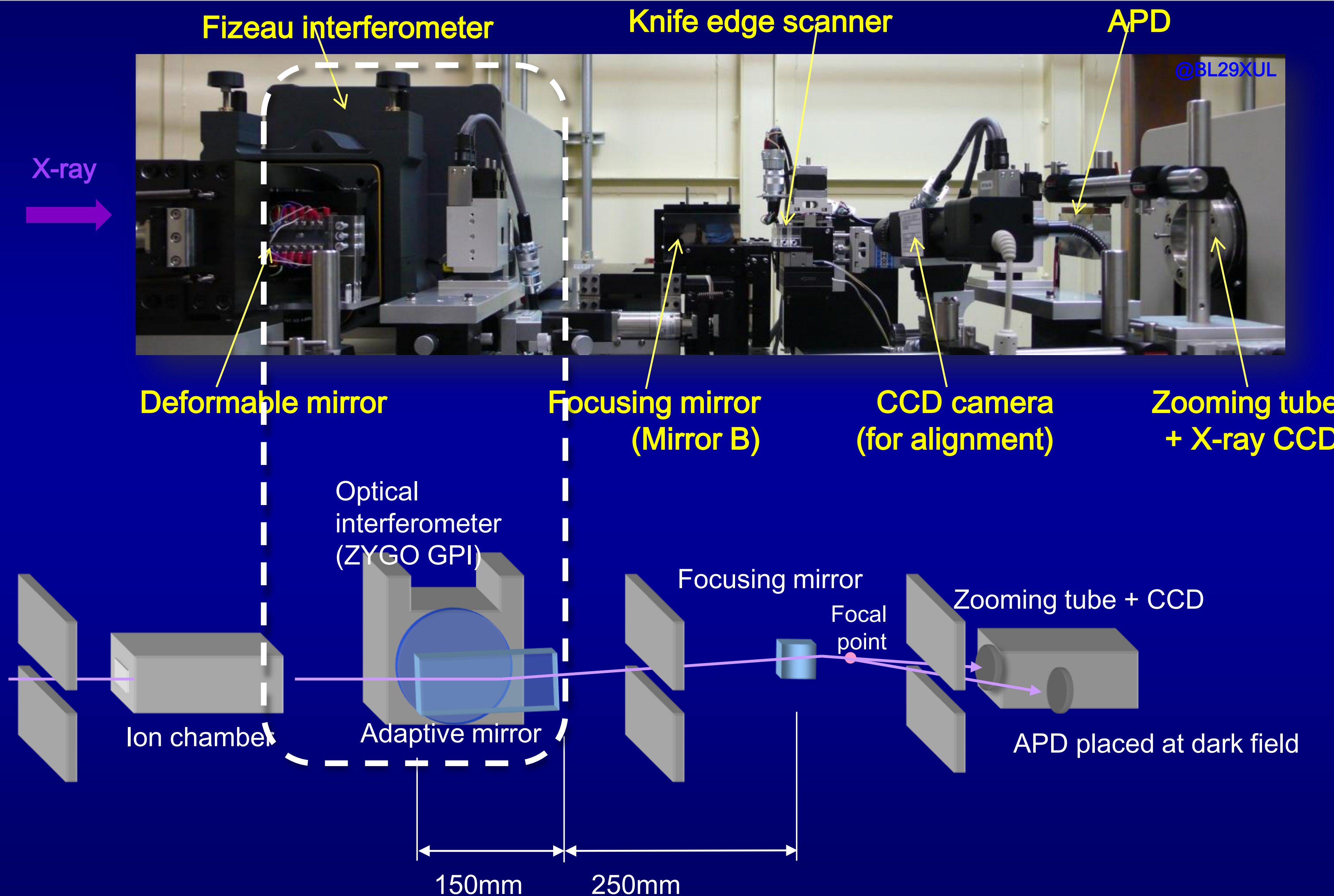
Λ : d-space
λ : X-ray wavelength
n : Index
θ : Glancing angle

EEM Machine

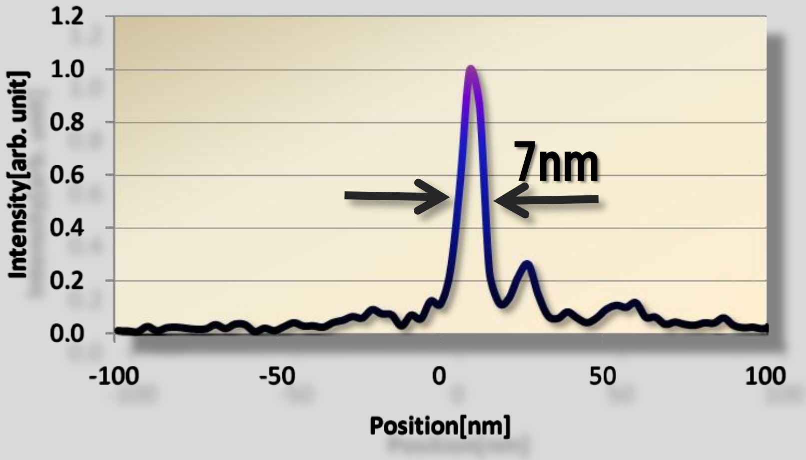
Micro- and RAD- Stitching Optical Interferometry

Laterally-Graded Multilayer Coater

Optical configuration for active phase compensation

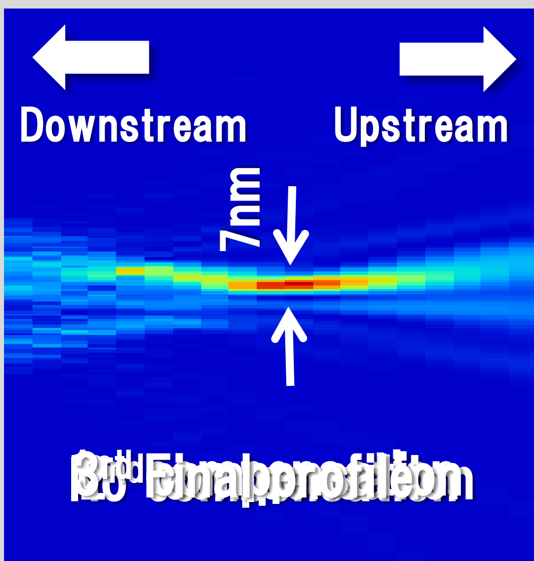


Sub-10nm focusing by using phase compensator



Profile at focal point

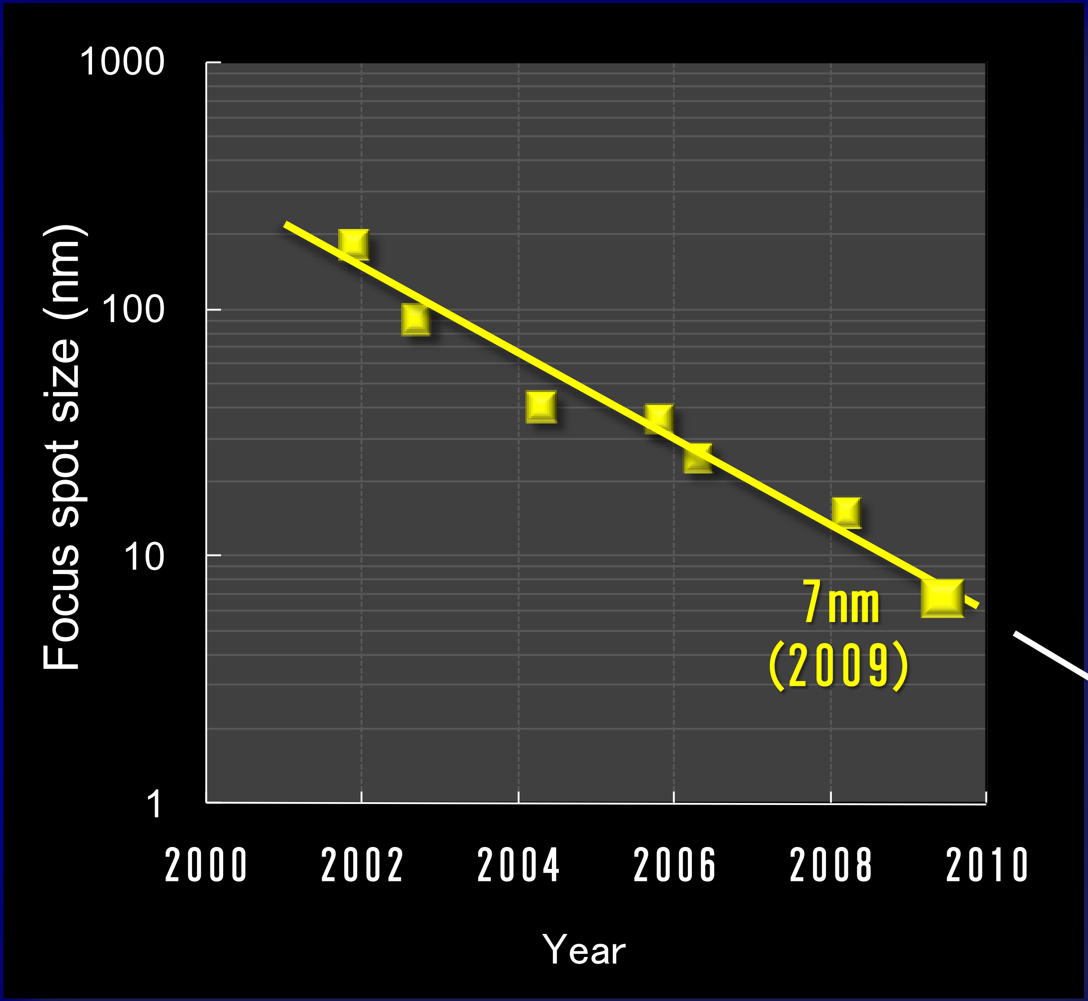
Compensated phase profile
(shape of compensation mirror)



Maximum phase compensated here was λ/2.
λ was 0.06 nm.

Beam waist structure

Nature Phys. (2010)



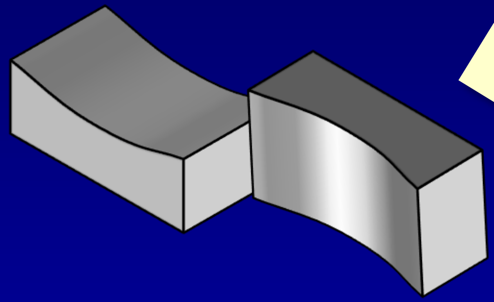
2014

IC

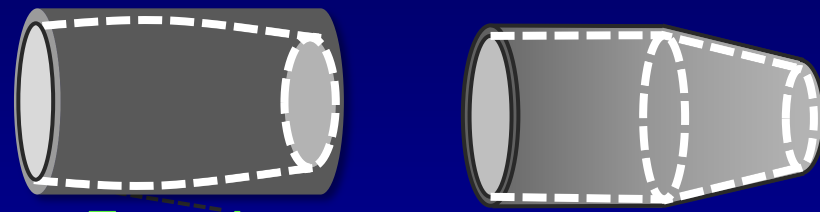
This is the smallest light beam human-made.

Achromatic imaging device (AKB Mirrors)

KB mirrors



Total reflection axial-symmetric optics



Focusing

Imaging

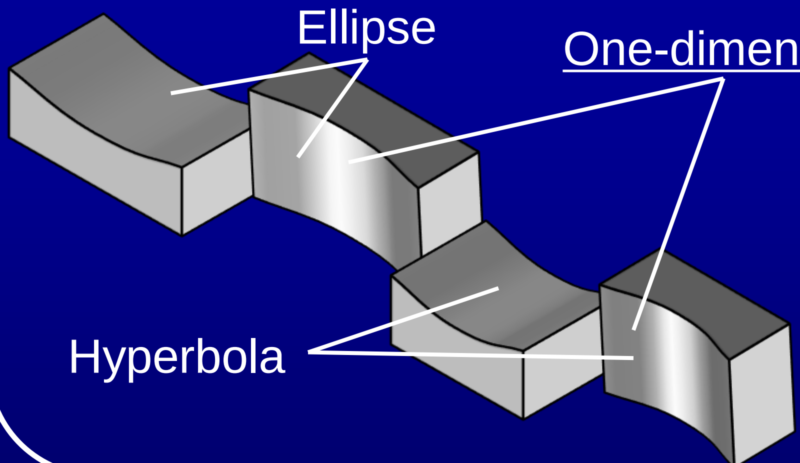
Wolter mirror

easy to fabricate

It fills Abbe's sine condition

Advanced Kirkpatrick−Baez mirrors

R. Kodama et al., *Optics Letters* **21** (17), 1321-1323 (1996).



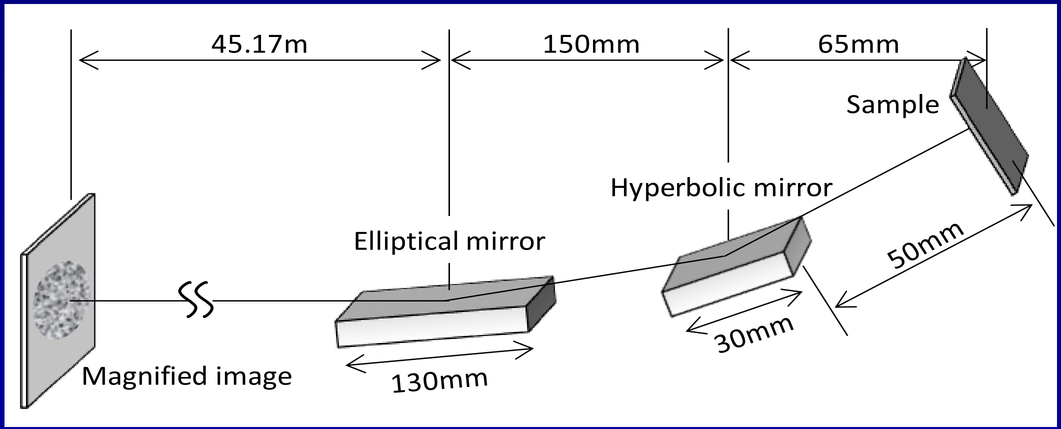
☆**Advantage**

- Wide field of view
- Easy fabrication

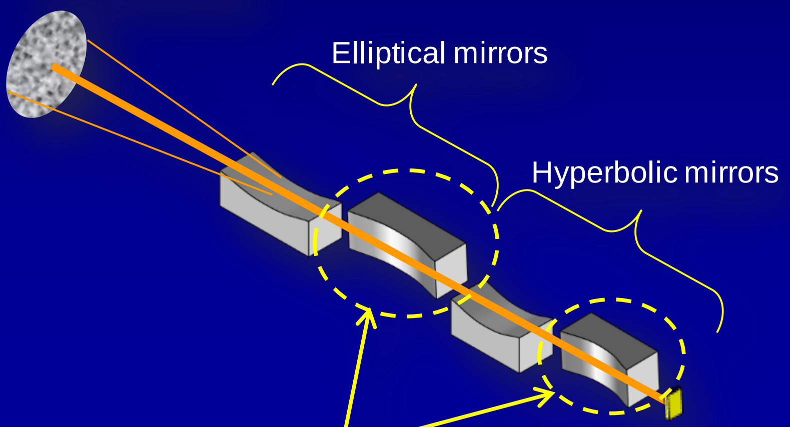
We tried to realize AKB mirrors having diffraction-limited performance.

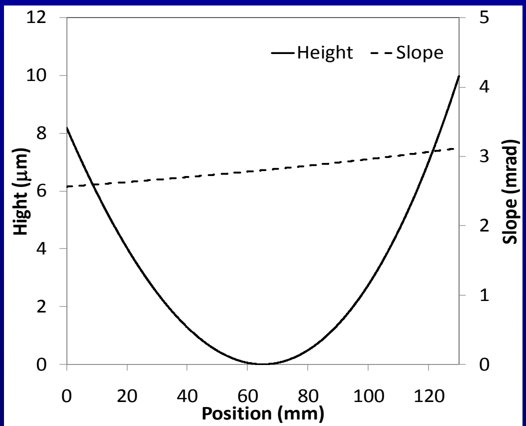
1-dimentional Wolter mirror system

Magnification: 385x , Size of the point spread function: 43nm

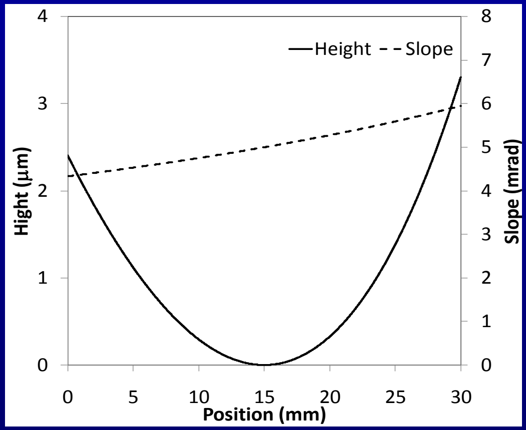


Optical system of a one-dimensional Wolter optics



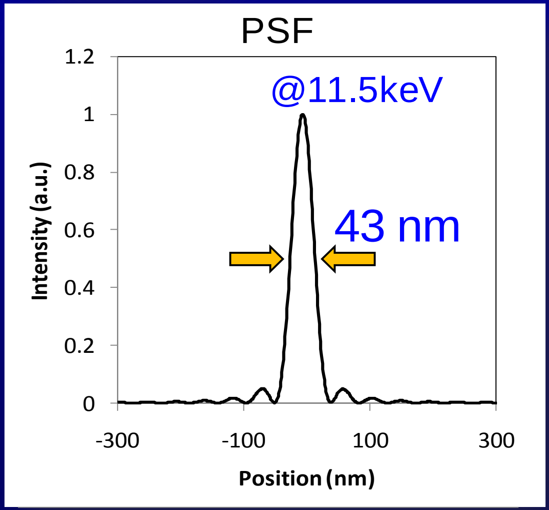


Elliptical mirror



Hyperbolic mirror

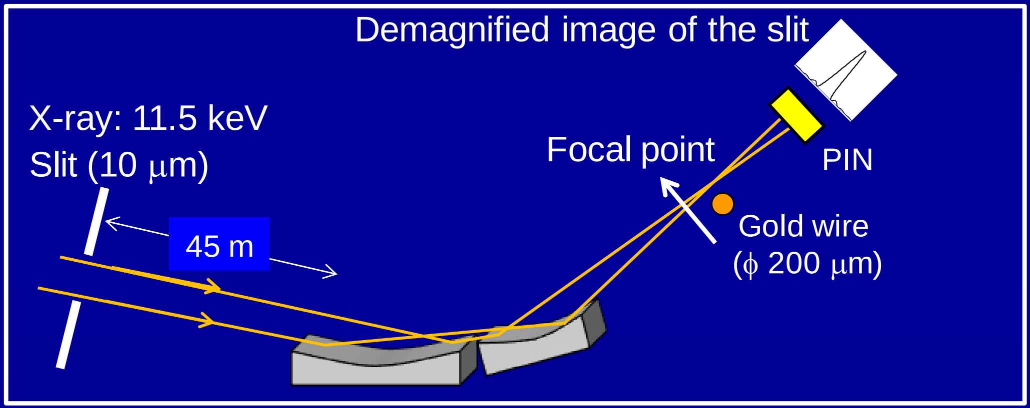
Mirror figures

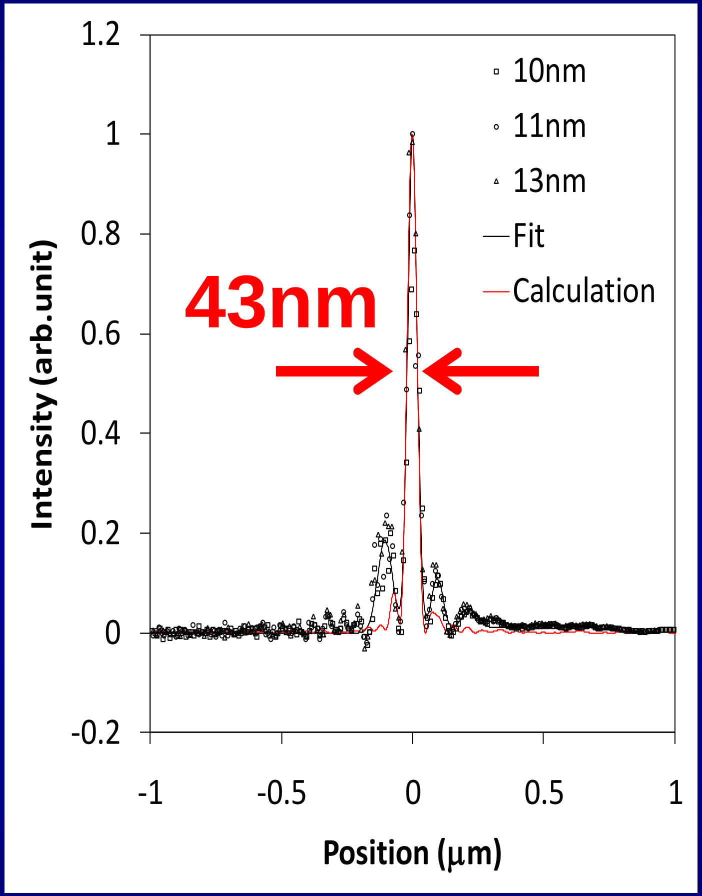


Spatial resolution test

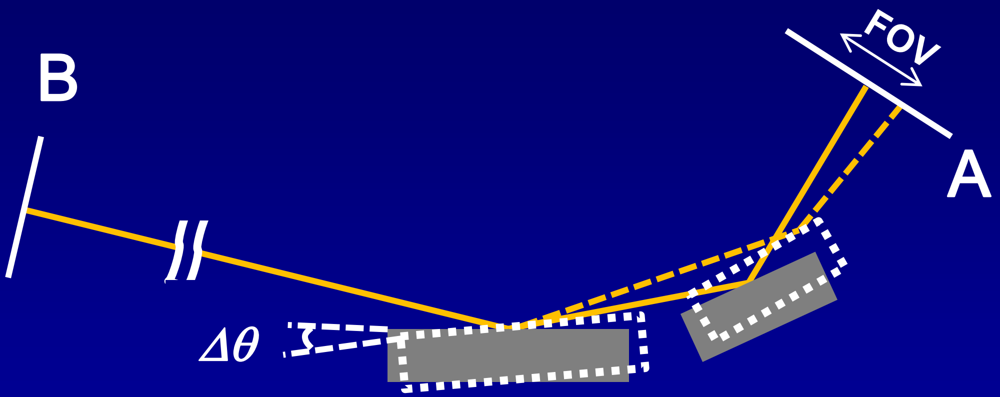
Point spread function measurement

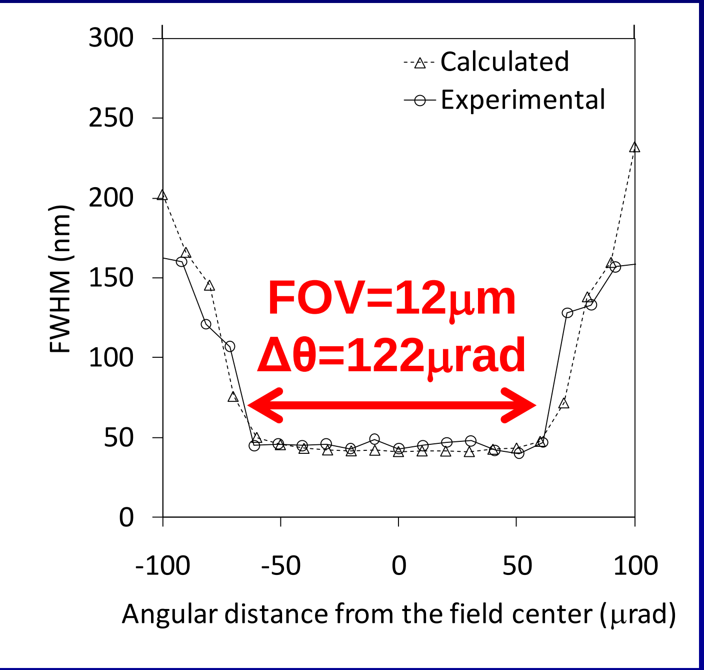
Demagnifed imaging system





Evaluation of FOV



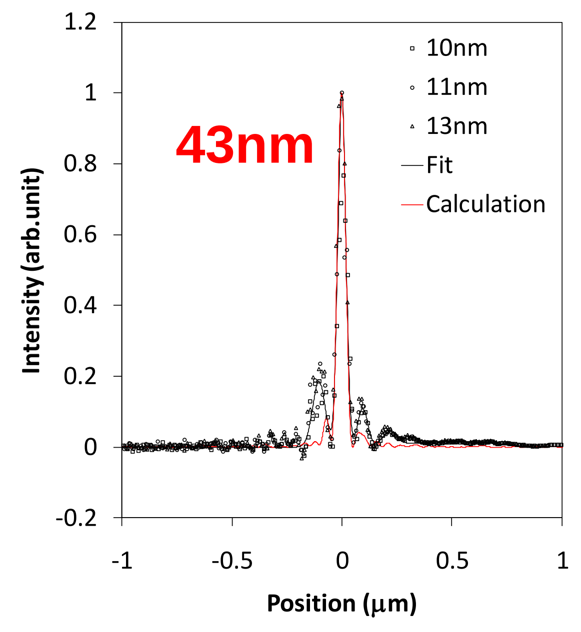


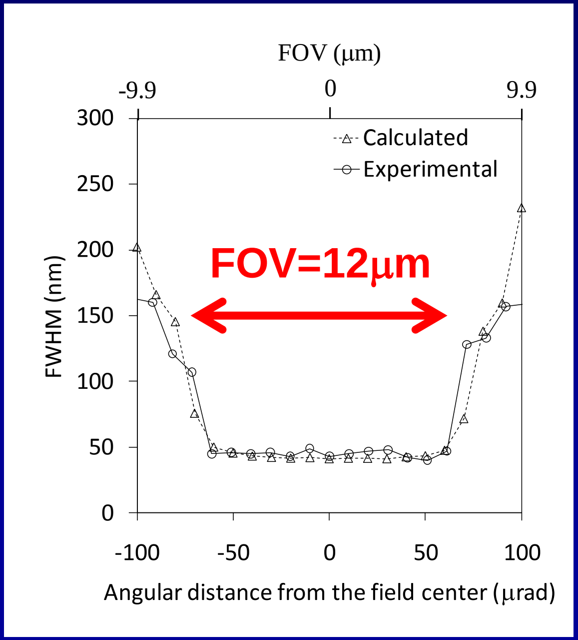
- To evaluate a field of view (FOV), we measured beam size on plane A by changing the glancing angle (Δθ).
- This procedure is equivalent to shifting relevant points on the planes A and B.

◆**Very wide angular width (Δθ) of 122 μrad was obtained.**

◆**It is equivalent to the FOV of 12μm.**

Summary of AKB development



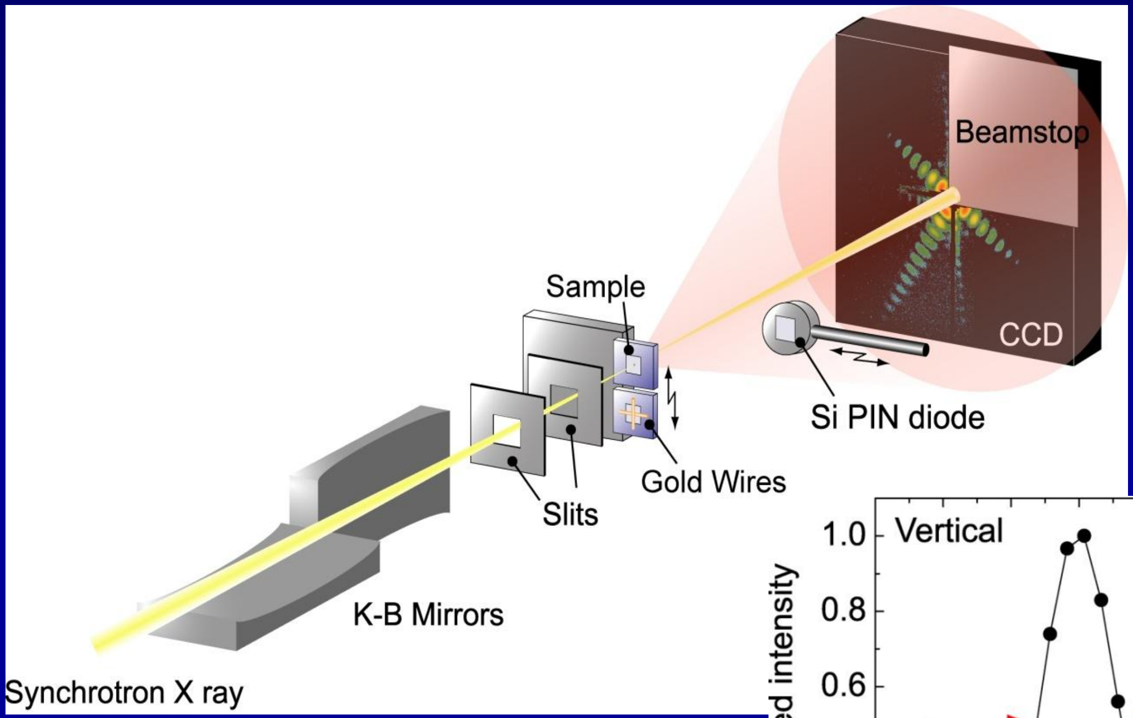


1-dimensional Wolter mirror demonstrated theoretically expected performances both in the resolution and FOV!

Matsuyama et al., Optics Lett (2010)

AKB optics will be indispensable optics especially in coming XFEL experiment.

Focused x-ray illumination for diffraction microscopy

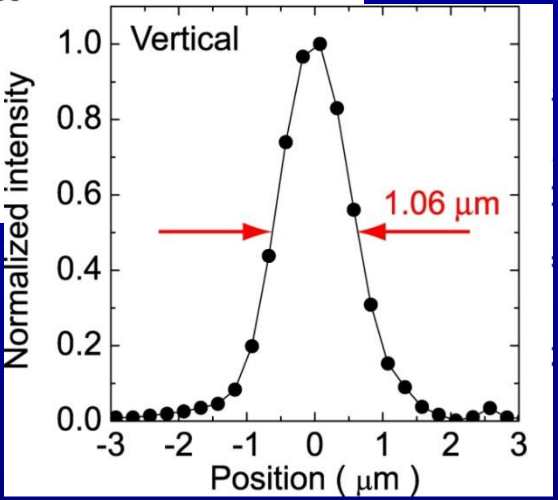


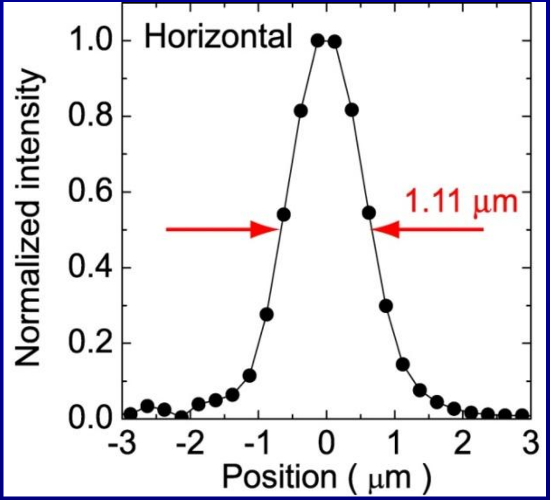
@SPring-8 BL29XUL

How wide area in k-space can we observe?

We must heighten the photon density at sample.

Beam profiles

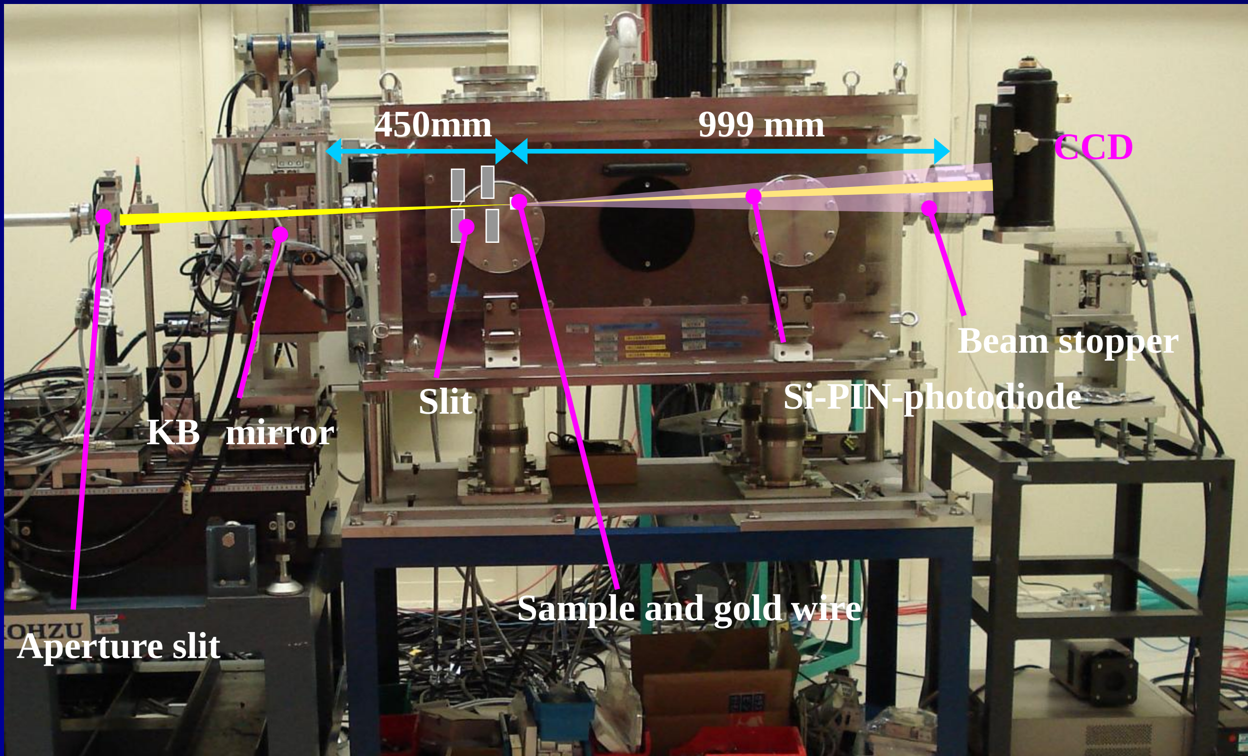




- Spot size: ~ 1 μm
- Photon density: ~ 1.0×10^4 photons/nm^2/s

➡ More than 100 times larger

Set-up and samples



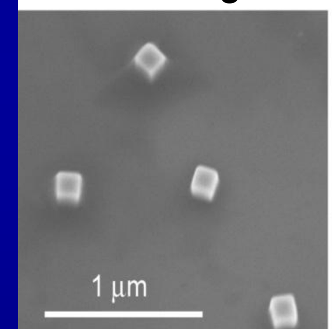
Science 298, 2176 (2002)

Shape-Controlle Synthesis of Gol an Silver Nanoparticles

Yugang Sun an Younan Xia*

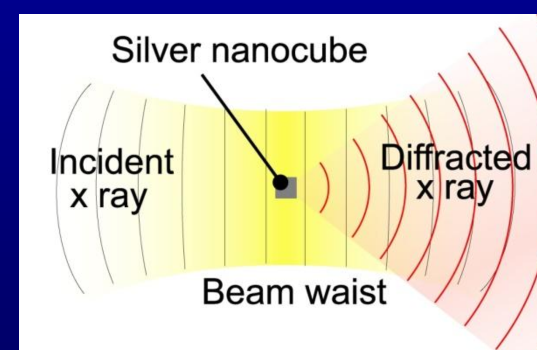
Monodisperse samples o silver nanocubes were synthesized in large quantities by reducing silver nitrate with ethylene glycol in the presence o poly(vinyl pyrrolidone) (PVP). These cubes were single crystals and were characterized by a slightly truncated shape bounded by {100}, {110}, and {111} facets. The presence o PVP and its molar ratio (in terms o repeating unit) relative to silver nitrate both played important roles in determining the geometric shape and size o the product. The silver cubes could serve as sacrificial templates to generate single-crystalline nanoboxes o gold: hollow polyhedra bounded by six {100} and eight {111} facets. Controlling the size, shape, and structure o metal nanoparticles is technologically important because o the strong correlation between these parameters and optical, electrical, and catalytic properties.

SEM image



Ag nanocube

～100 nm



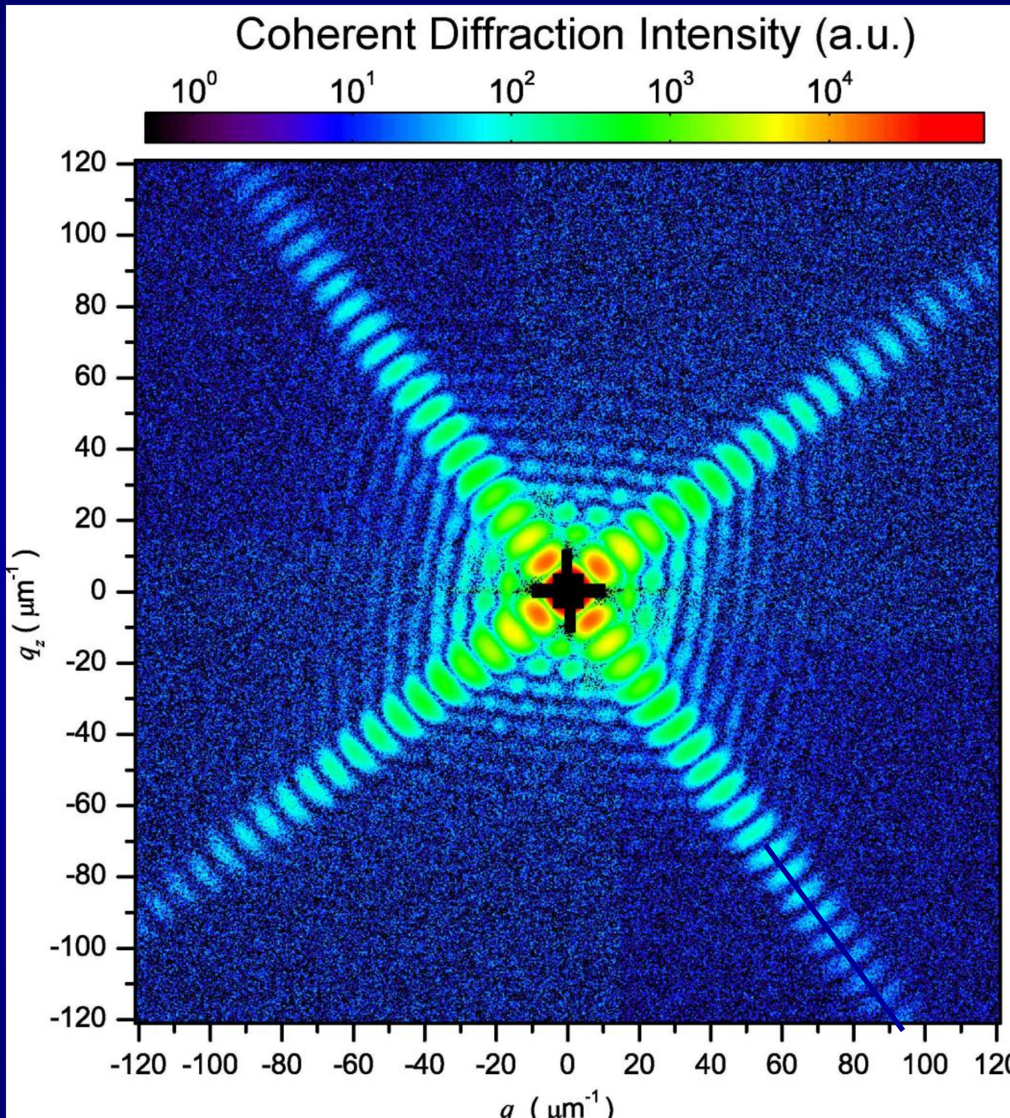
◆X-ray energy： 12keV

◆Working distance： 450mm

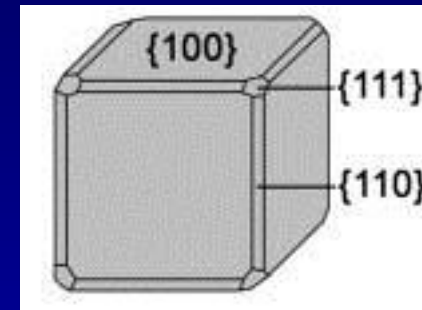
◆Camera length： 999mm

◆ CCD (Princeton Instruments PI-LCX:1300)

Pixel size: 20μm
1300×1340 pixels



Exposure time：800sec, 1.5×10^{11} Photons to the cube

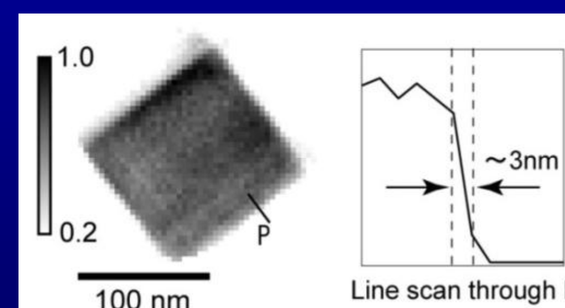


$$|q| = 2\sin(\Theta/2)/\lambda$$

λ: wavelength

Θ: Scattering angle

Sinc function: $\dfrac{\sin(\alpha q)}{\alpha q}$



Y.Takahashi et al., Phys. Rev. B 80, 054103 (2009).

Summary

- Achromatic total-reflection mirrors realized sub-30nm focusing of hard X-rays.
- In-site wavefront correction are promising techniques to construct highly accurate optical system of hard X-rays.

- KB mirrors could reach sub-10nm focusing.
- AKB mirrors enable achromatic imaging of incoherent x-rays with sub-50nm-resolution.
- KB mirrors could condense x-rays with preserving coherency and could heighten the spatial resolution of diffraction microscopy up to sub-5nm.