At-wavelength metrology of X-ray optics

__Hongchang Wang__, Sebastien Berujon, John Sutter, Kawal Sawhney

Diamond Light Source

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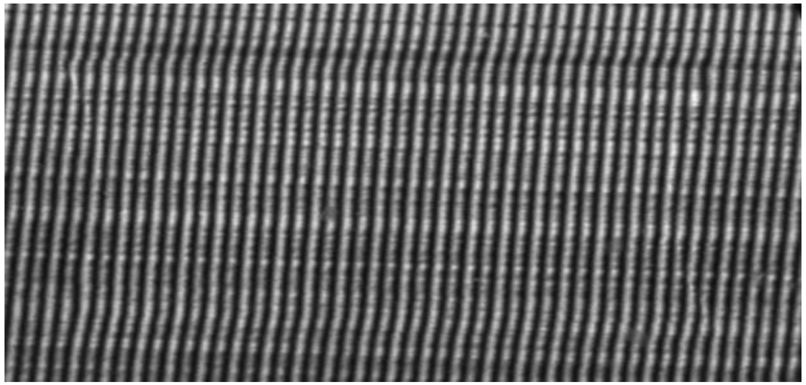
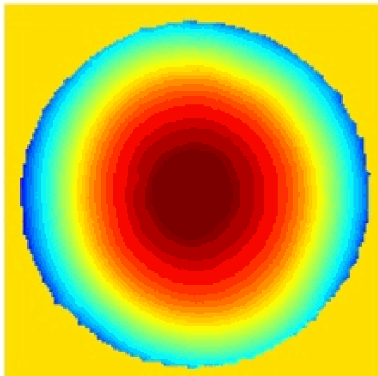
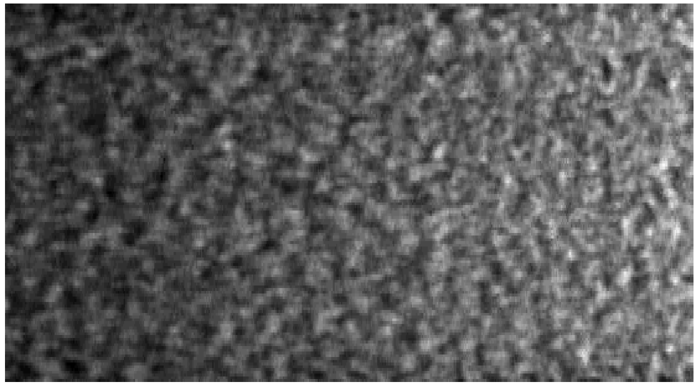
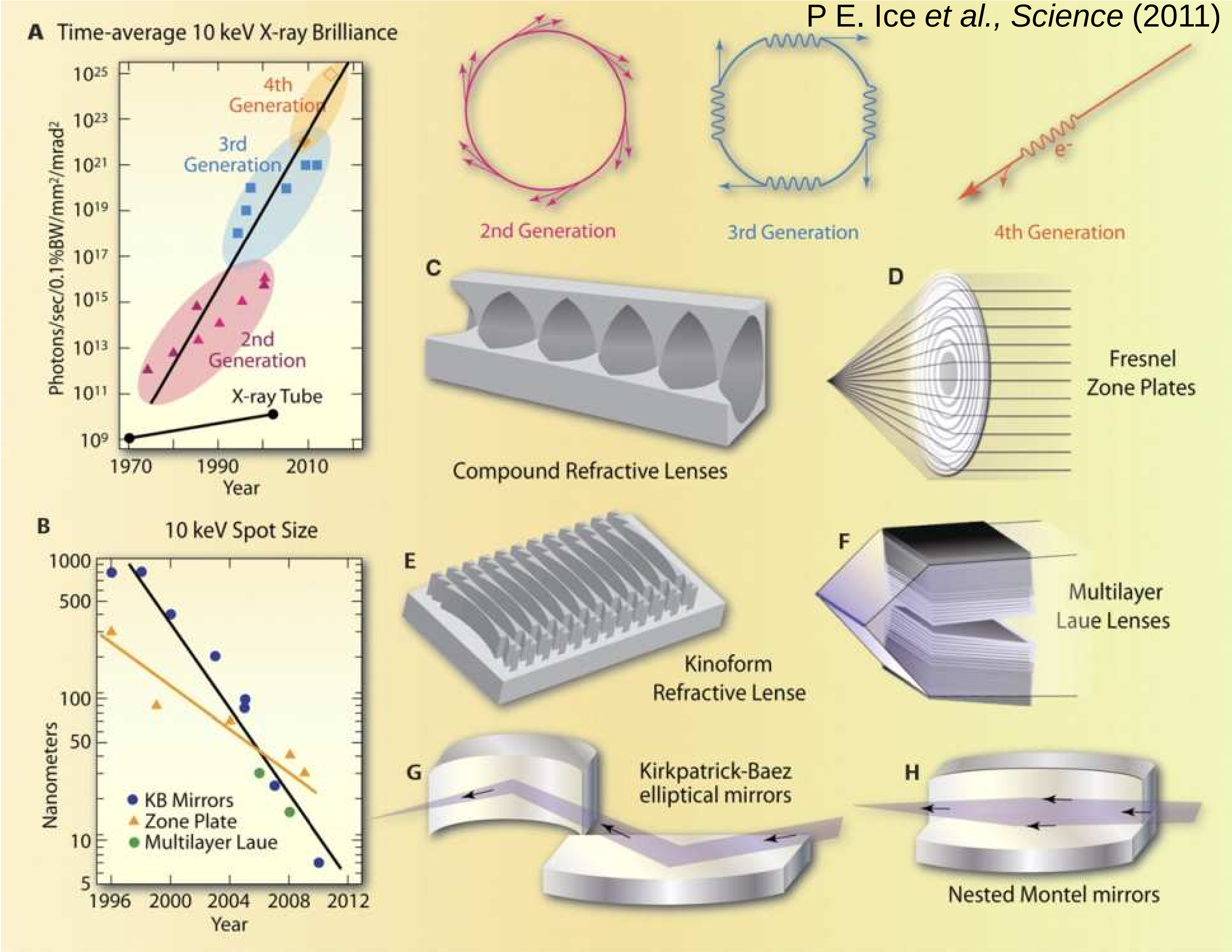
kawal.sawhney@diamond.ac.uk

Meadow 2013, Trieste, Italy

X-ray optics



If you can't measure it, you can't improve it!

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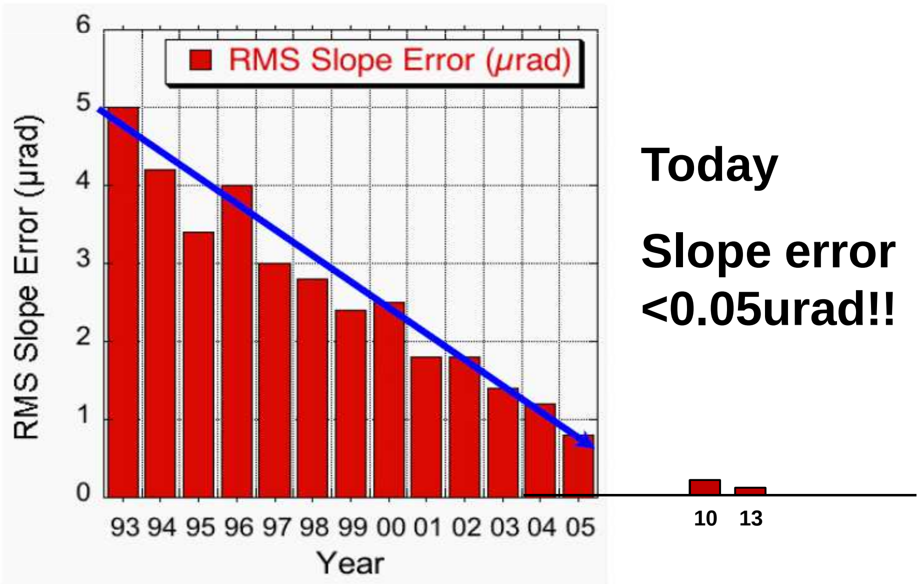
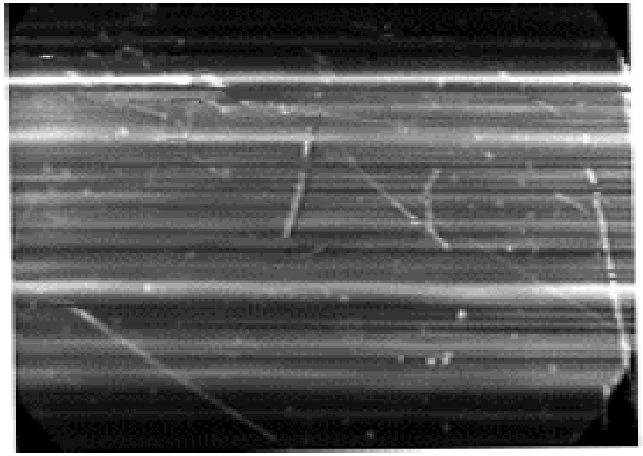
X-ray Mirrors



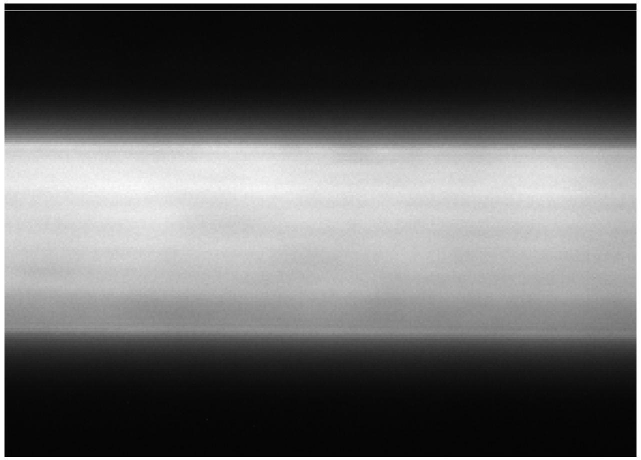
Today

Slope error <0.05urad!!

Summary courtesy of L. Assoufid by compiling data from APS, ESRF and Spring-8, (2005)



L. Assoufid, et al (1998)



K. Sawhney, et al (2013)

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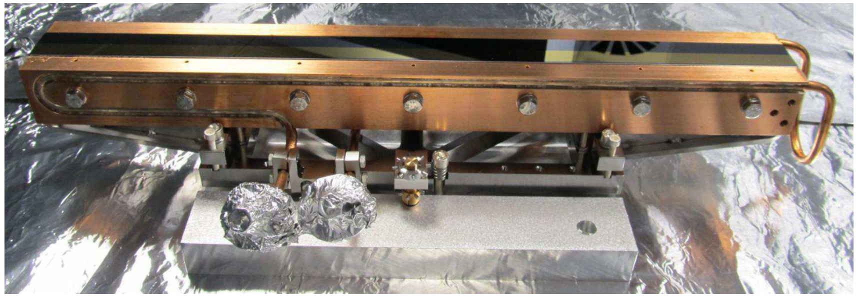
Limiting factor for synchrotron optics

Mechanics & clamps



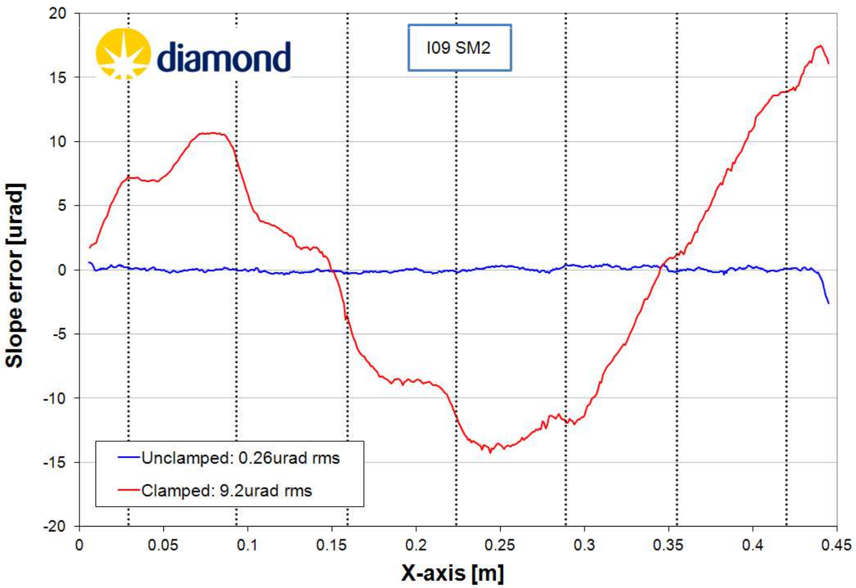
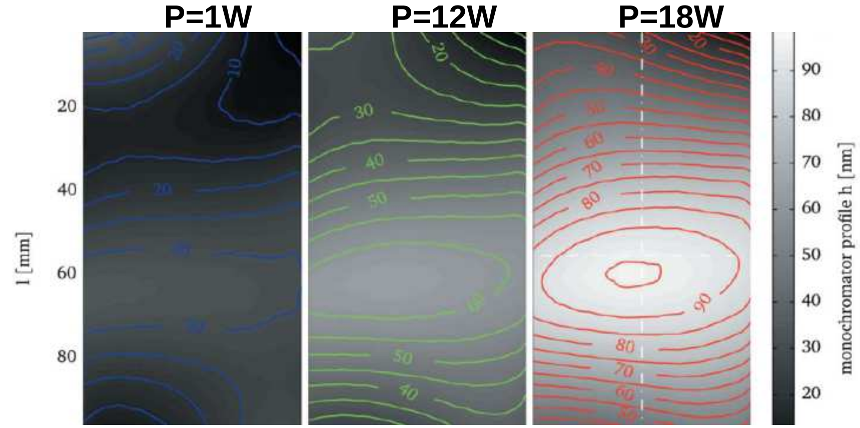


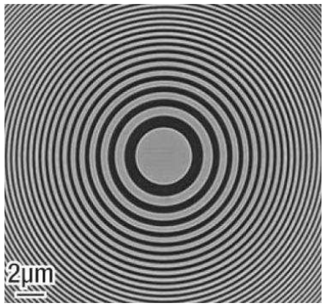
Image Courtesy of Simon Alcock

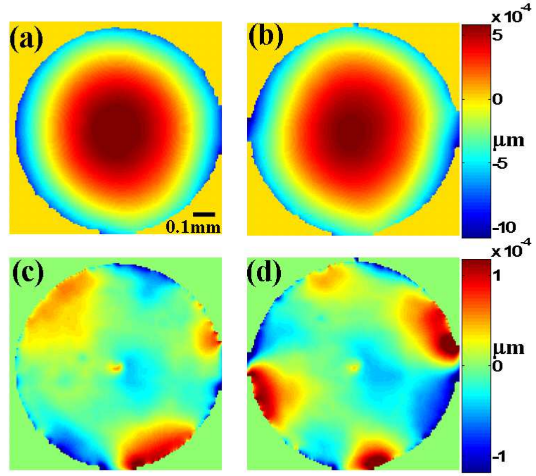
Heat load deformation



S. Rutishauser, et al J. Syn. Rad. (2013).

Wavefront distortion from incoming bean





H. Wang, et al., Opt. Lett. (2013)

Ex-situ Metrology instruments at Diamond

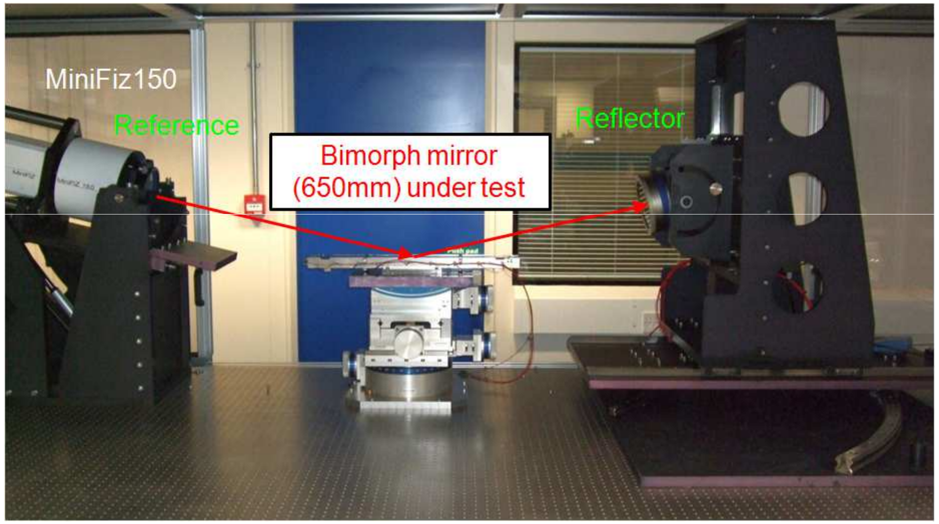
Fizeau interferometer

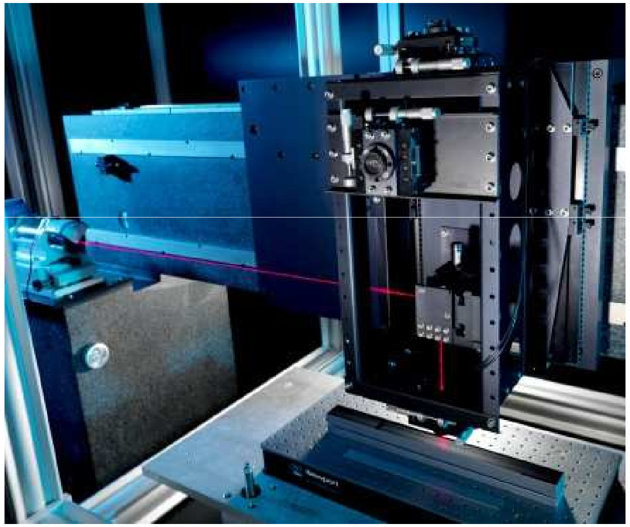
Pros:

- 3-D height measurement
- Beam diameter: 150mm
- Lateral scan size: 150mm – 1500mm
- Planar & spheric testing accuracy: λ/100 PV

Diamond-NOM

- Slope measurement
- Lateral scan size: 1500mm
- Lateral resolution: <1mm
- Repeatability <50nrad





Cons:

☹ Reference Flat calibration

☹ Dedicated curved reference surface

☹ Slow acquisition (10min – 1 day)

☹ 1D line profiles (RoC >7m)

S. Alcock., et al, Nucl. Instrum. & Meths., A 616, 224 (2010)

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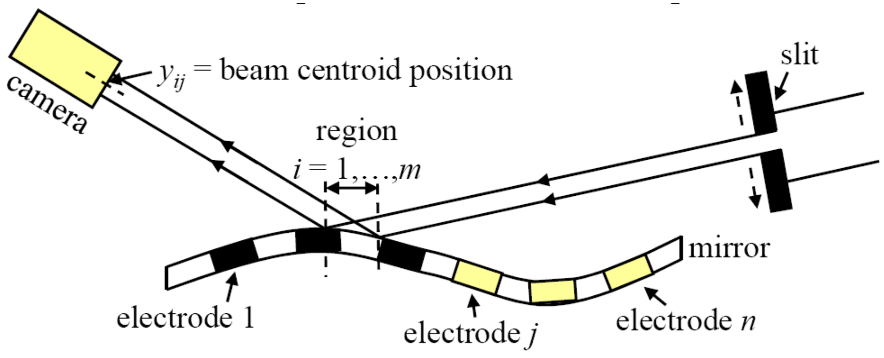
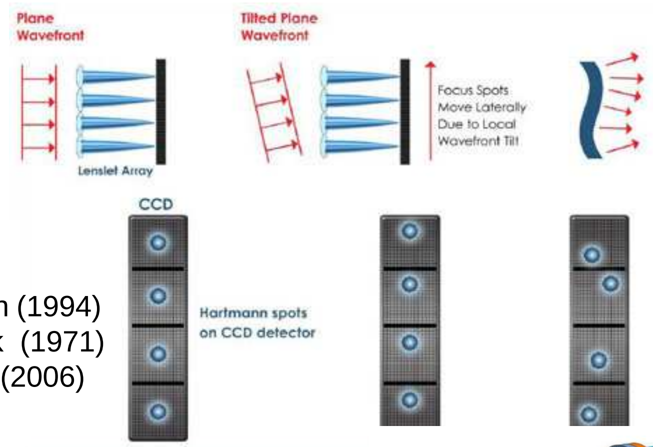


O. Hignette e al., SPIE, (1997); J. Sutter, et al, J. Syn. Rad. (2012)

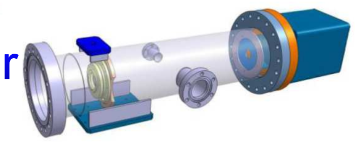
Image from http://www.bostonmicromachines.com



•J. Hartmann (1994)
•R. V. Shack (1971)
•P. Mercere (2006)

Pencil beam scan

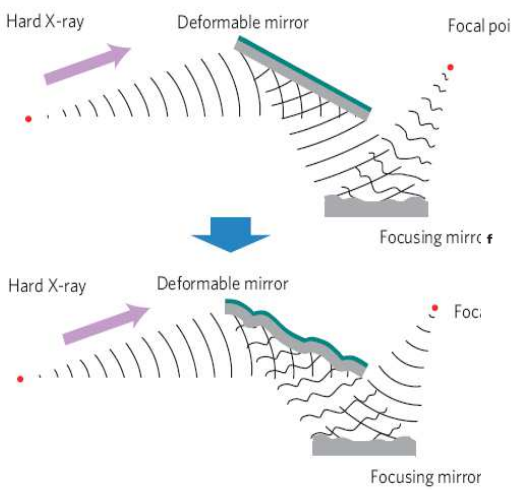
Hartmann wavefront sensor

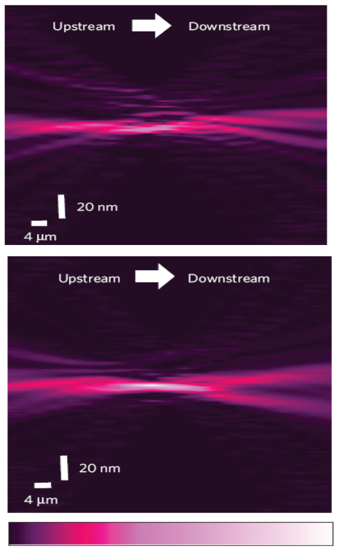


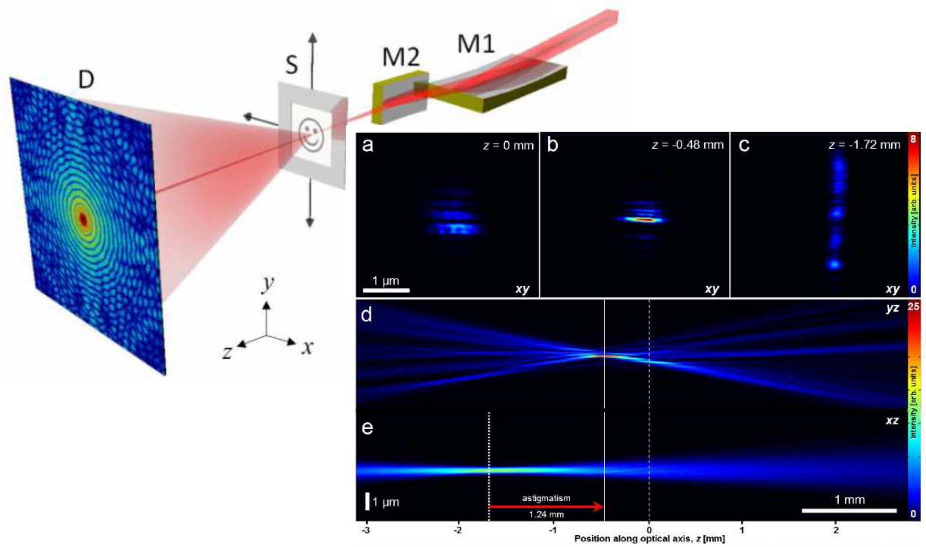
At-wavelength metrology

Phase-retrieval

Ptychographic coherent diffractive imaging







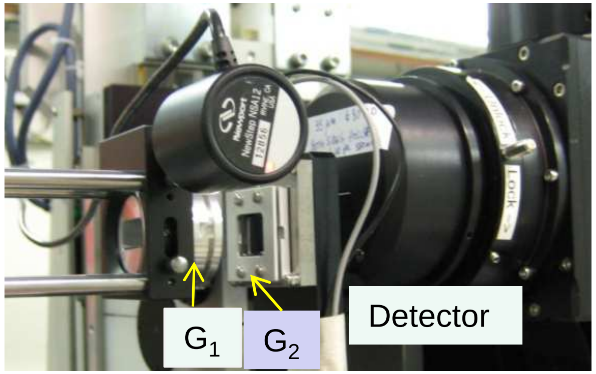
H Yumoto et al., Rev. Sci. Instrum. (2006);H Mimura *et al., Nature Phys.* (2010);

C. M. Kewish,, et al., Opt. Express (2010)

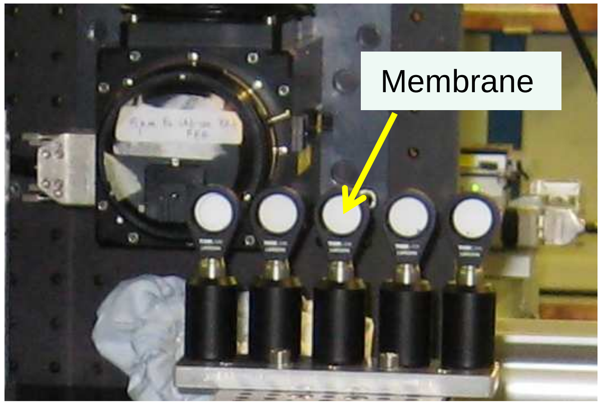
At-wavelength Metrology at Diamond

1. Pencil beam technique

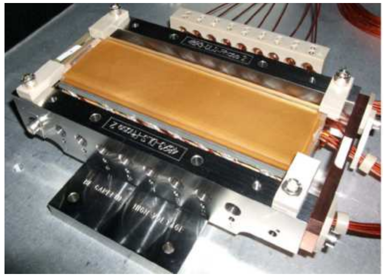
2. Grating shearing interferometer



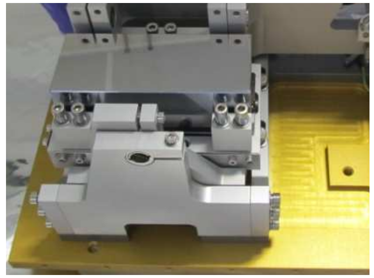
3. X-ray Speckle Based Technique



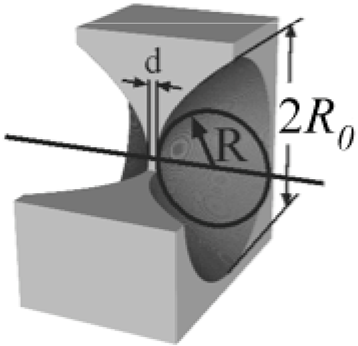
Bimorph mirror



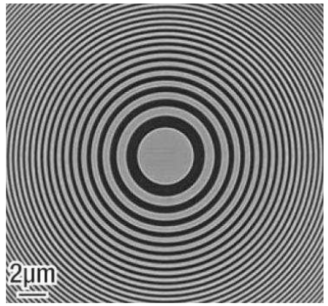
K-B mirror



Refracting Optics



Diffracting Optics



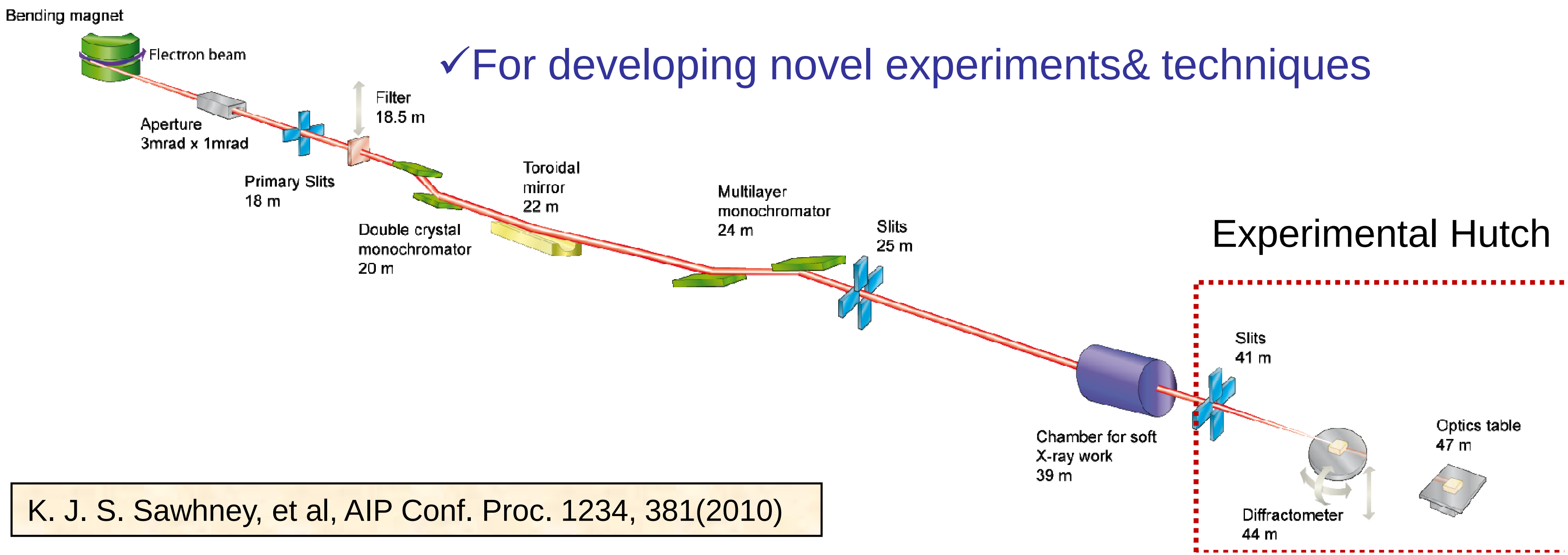
1. H. Wang, et al., Opt. Lett. 38, 827(2013)
2. S. Bérujon, et al ., Appl. Phys. Lett. 102. 154105 (2013).
3. S. Berujon, et al., Opt. Lett. 37, 1622 (2012)
4. S. Berujon, et al., Opt. Lett. 37, 4464 (2012)
5. S. Bérujon, et al., Phys. Rev. Lett. 108, 158102 (2012)
6. S. Bérujon, et al ., Phys. Rev. A. 86. 063813 (2012).
7. H. Wang, et al., Opt. Express 19, 16550 (2011)…….

Diamond B16 Test beamline

- Monochromator: DCM, DMM and Channel-Cut crystal
- Large energy range (2keV~40keV)
- Various beam mode: White beam, Pink beam, Mono beam
- Variable beam size (sub-µm~10mm)
- Flexibility & versatility to enable wide range of experiment

✓For testing optics& detectors

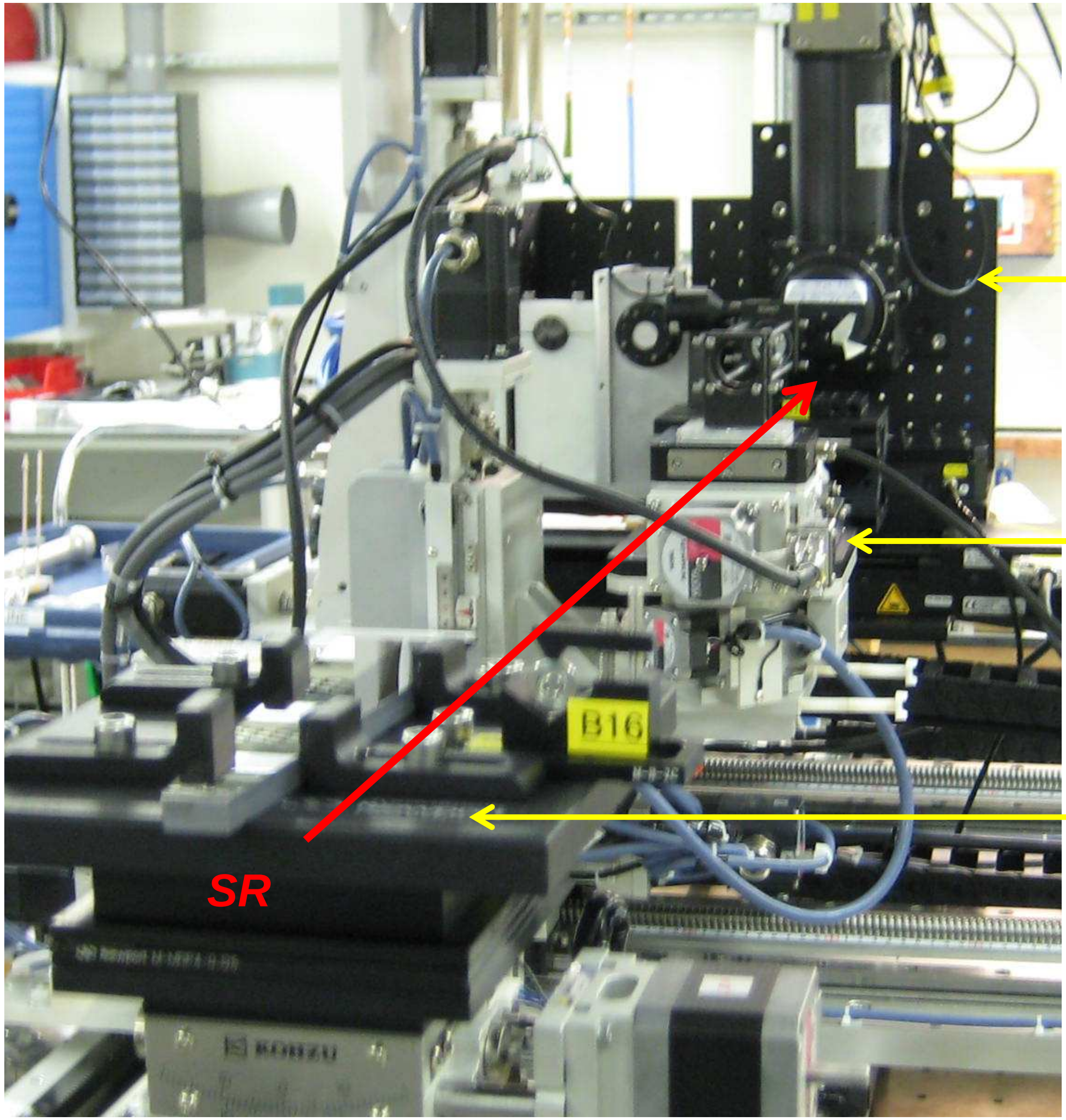
✓For developing novel experiments& techniques



K. J. S. Sawhney, et al, AIP Conf. Proc. 1234, 381(2010)

Diamond B16 Test beamline

Setup on Versatile Optics Table in B16 Experimental Hutch



Detectors

High Res. X-ray Camera

- PCO 4000 large area camera
- Objectives:
  - -20X: 0.45 µm/pixel
  - -10X: 0.90 µm/pixel

Mini-FDI: 6.4µm/pix

Diagnostic

Grating Interferometer

Membrane

……..

Optics

Mirrors, CRLs, FZP

……..

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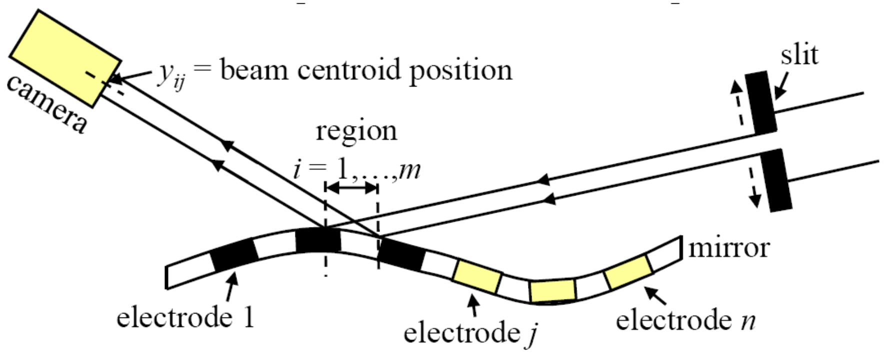
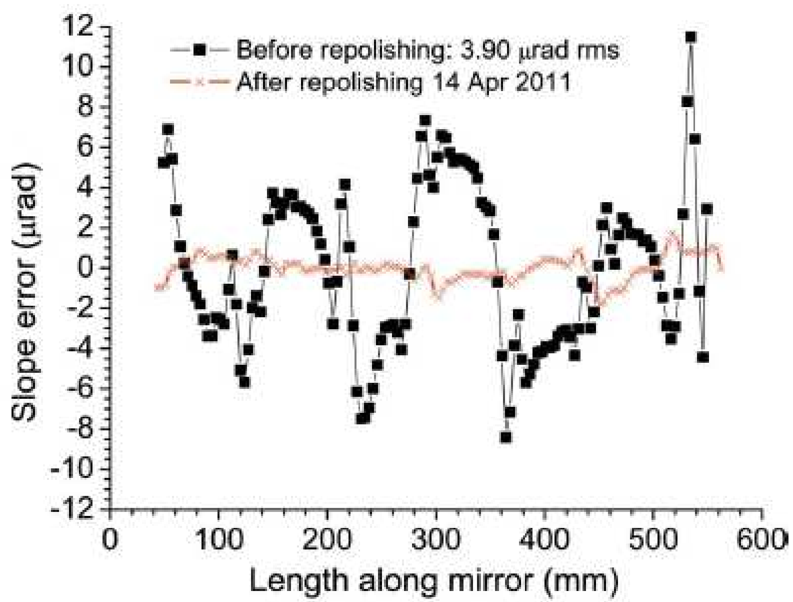
In-situ metrology with Pencil beam technique



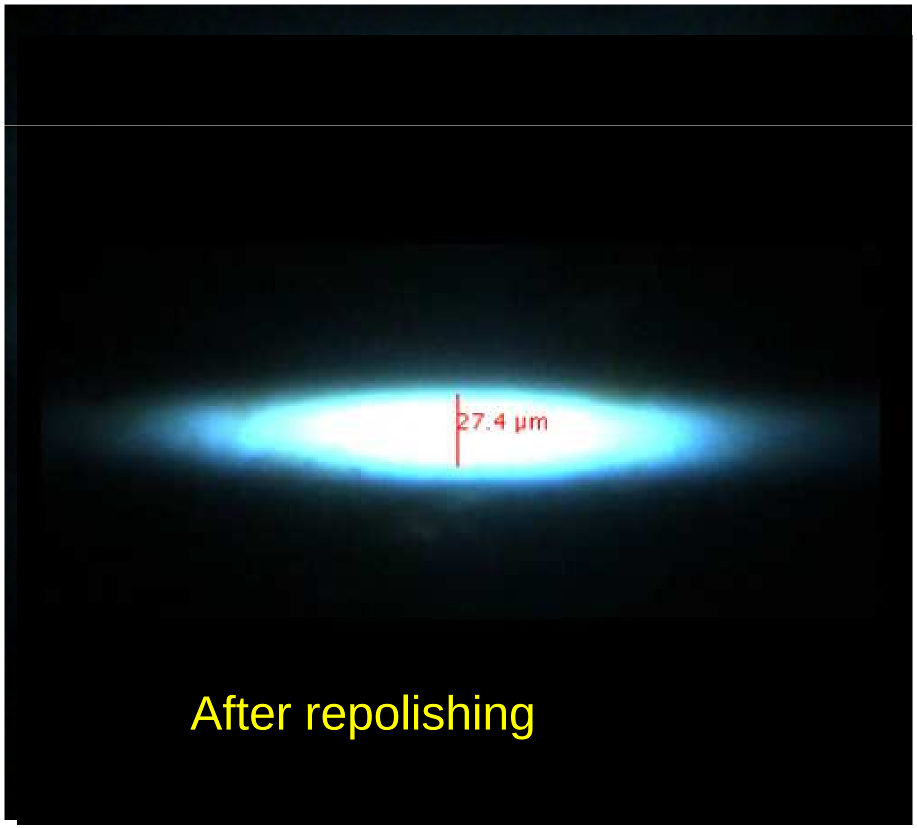
Schematic of the in situ pencil-beam procedure

Repolishing	slope error (r.m.s.)	Vertical beam size (FWHM)
Before	4 µrad	80 µm
After	0.4 µrad	27 µm

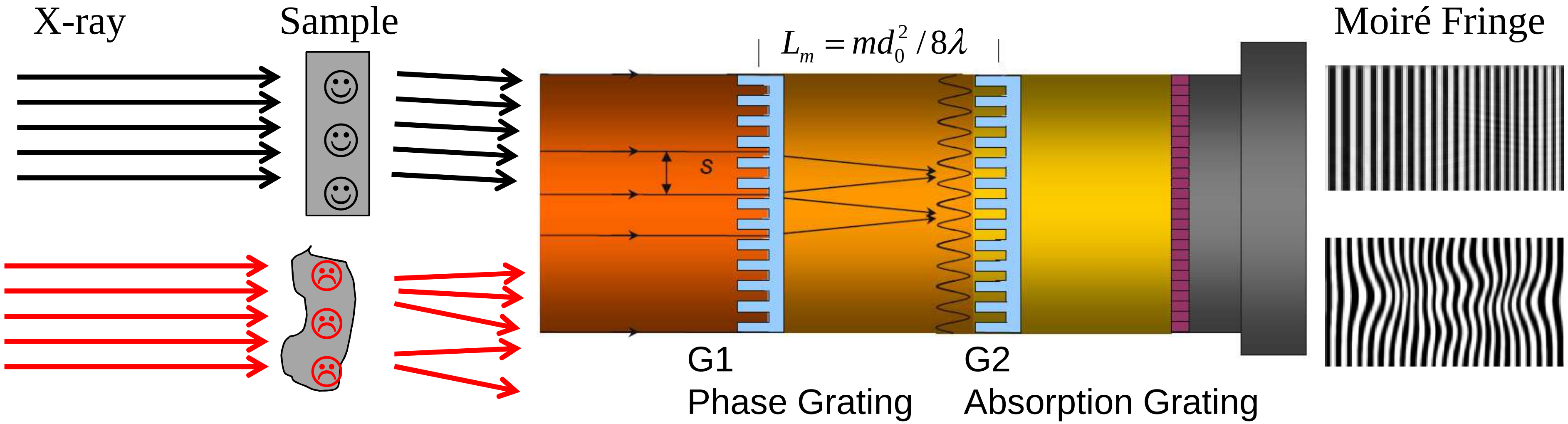
Vertical focusing mirror Slope Error



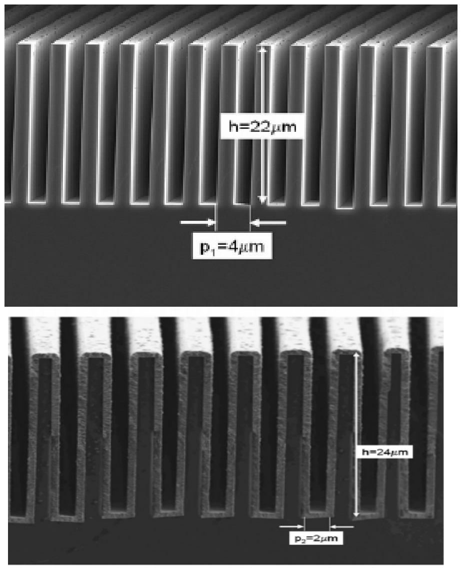
J. Sutter, et al, J. Syn. Rad. 19 , 960 (2012)



Grating Interferometer



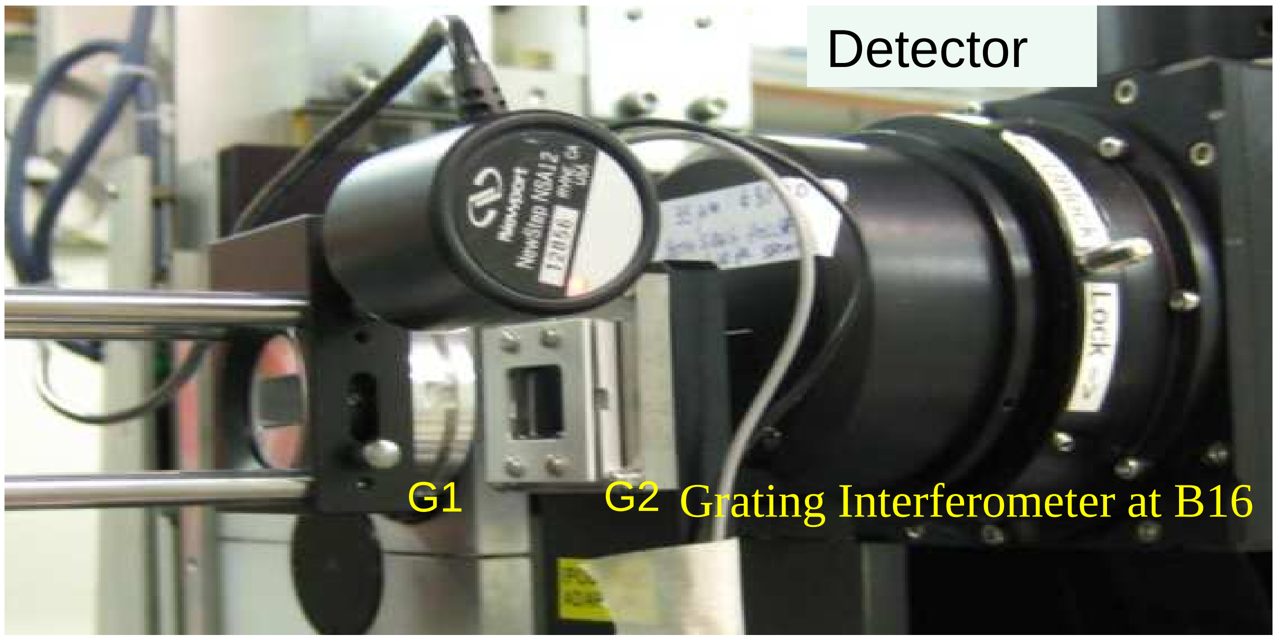
C. David et *al., Appl. Phys. Lett.* (2002); A. Momose et al., Japn. J. Appl. Phys. (2005); T. Weithamp et al., Opt. Exp. (2005)



G1

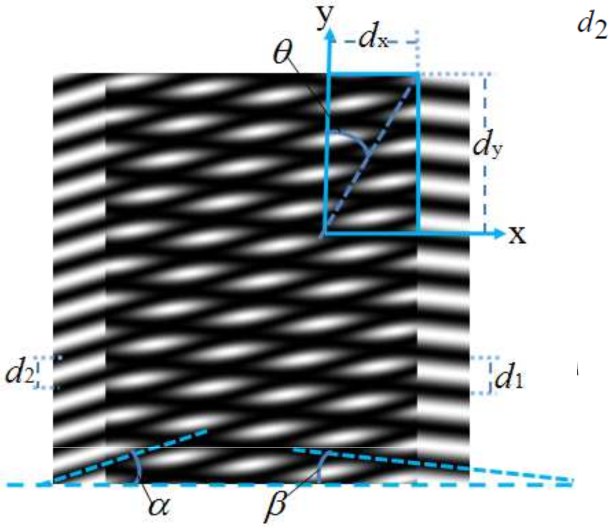
G2

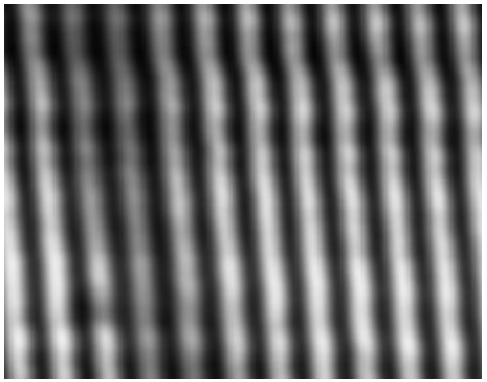
Grating Image Courtesy of C. David, (2007)

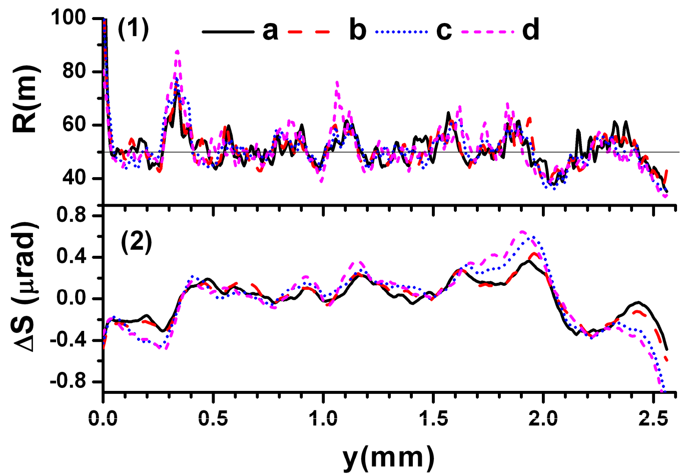


Rotating shearing interferometer

H. Wang, et al., Opt. Express 19, 16550 (2011).



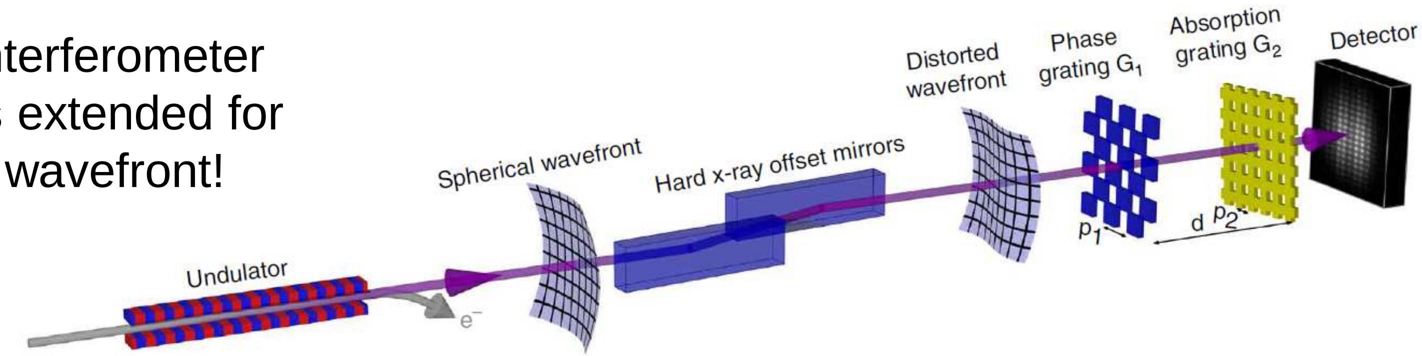




$$\gamma_y = \cos\alpha - \sqrt{\kappa^2 - (\gamma_x - \sin\alpha)^2}$$

Moiré fringe period d and fringe angle θ is changing when G_1 is rotating

The rotating interferometer technique was extended for exploring FEL wavefront!



S. Rutishauser, et al Nat Commun 3, 947 (2012).

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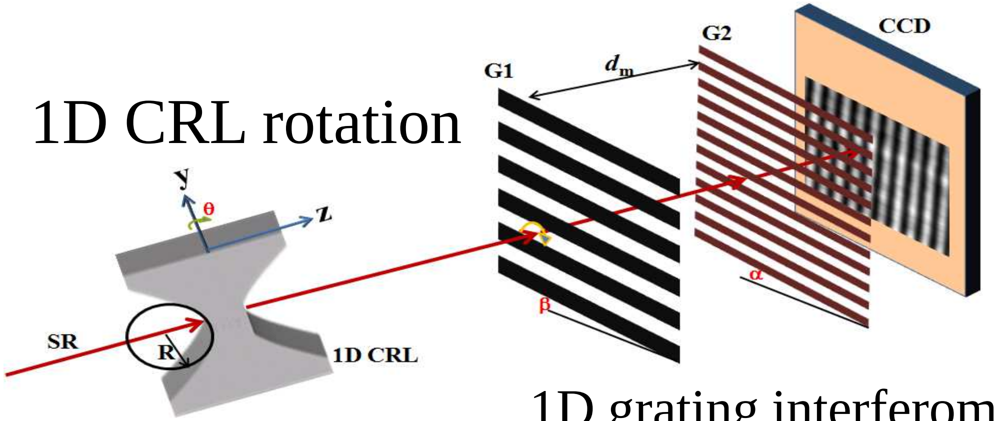
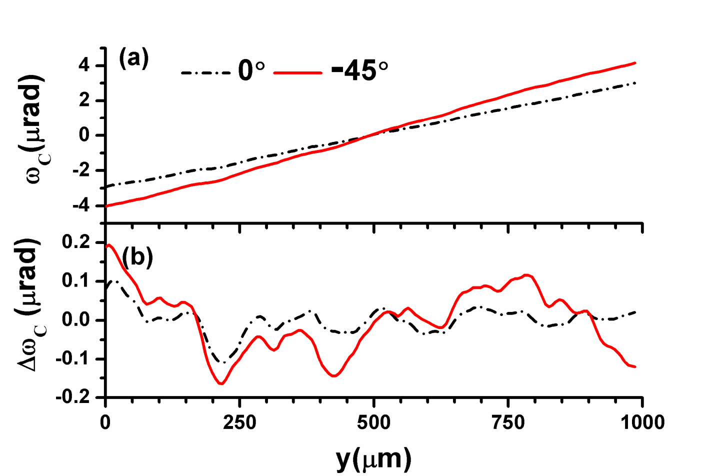
Refracting Optics— 1D CRL

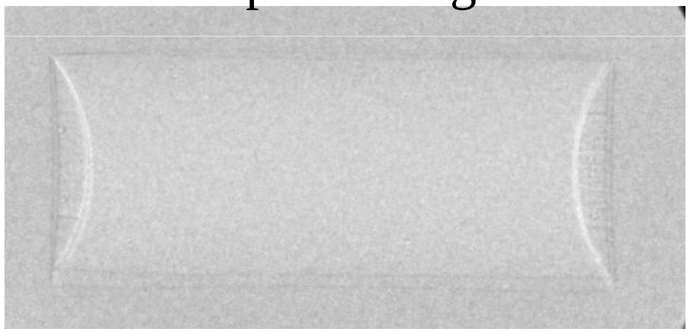
1D CRL rotation



1D grating interferometer



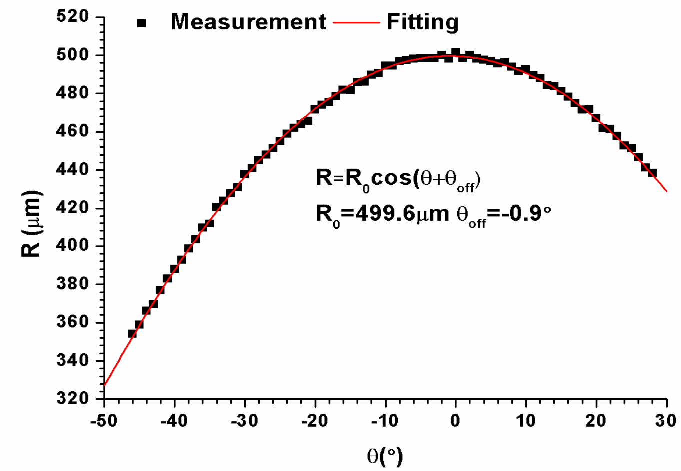
Absorption Image



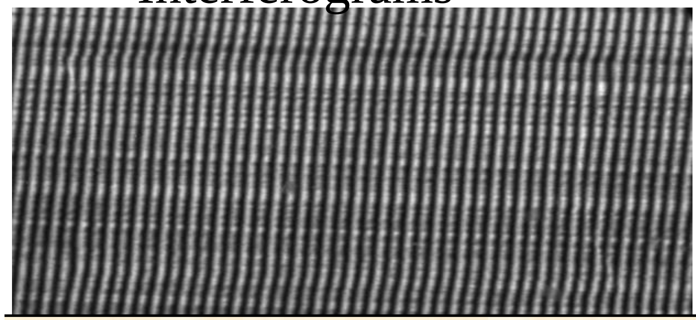
$$f = \frac{NR}{2\delta} = \frac{NR_0 \cos(\theta}{2\delta}$$

$$\omega_y \approx \tan \omega_y = \frac{y}{f}$$

$$R = 2\delta f$$



Interferograms



N: Number of lens

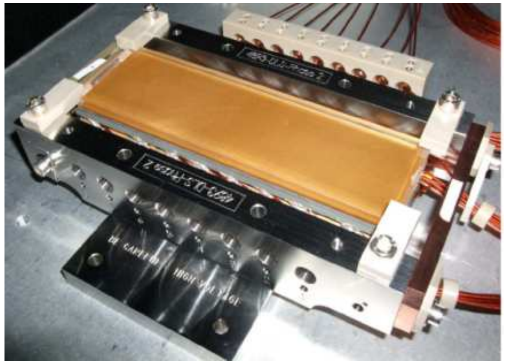
R: Apex radius

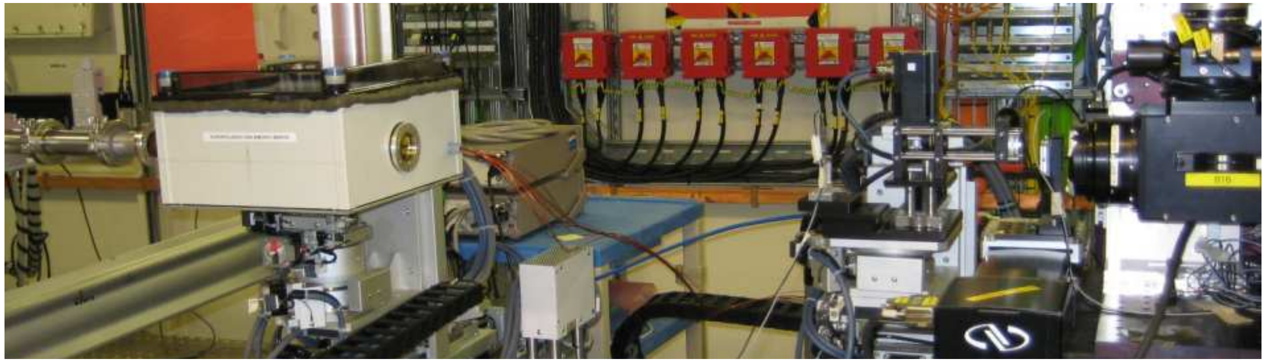
δ : refractive index of the beryllium

H. Wang, et al., AIP Conf. Proc.1466, 223-228 (2012).

1D CRL lenses for vertical focusing, Hard X-ray Nanoprobe Beamline, Yong Chu, NSLS-II

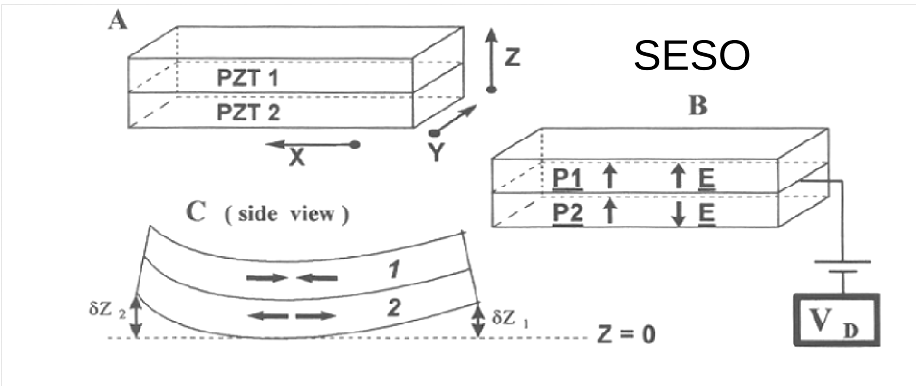
Super polished bimorph mirror





Elliptical **:**p = 46m;q = **400**mm;θ = **3**mrad, 8 piezo electrodes, L=150 mm (120mm EEM)

Bimorph Active Mirrors



By applying appropriate voltages to the bimorph piezos, both global figure & localised figure errors can be dynamically adjusted

Super-polishing

Elastic Emission Machining (EEM): J-tec

Remove middle & high spatial frequency roughness

Figuring with sub nanometre-level accuracy by numerically controlled elastic emission machining,

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

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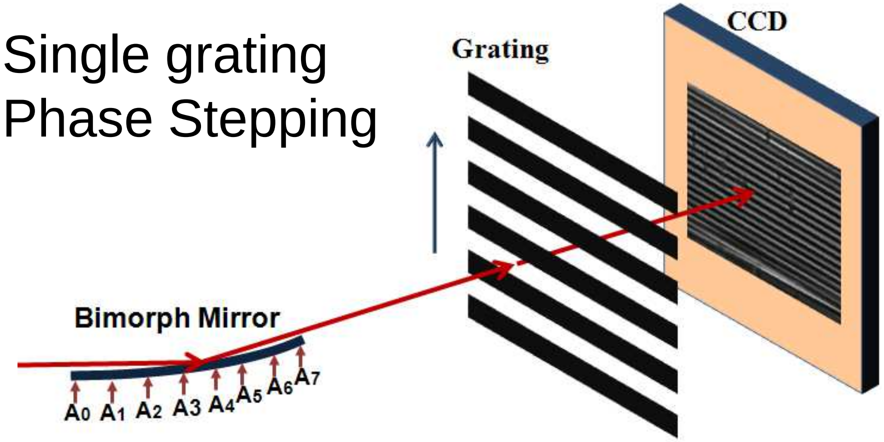
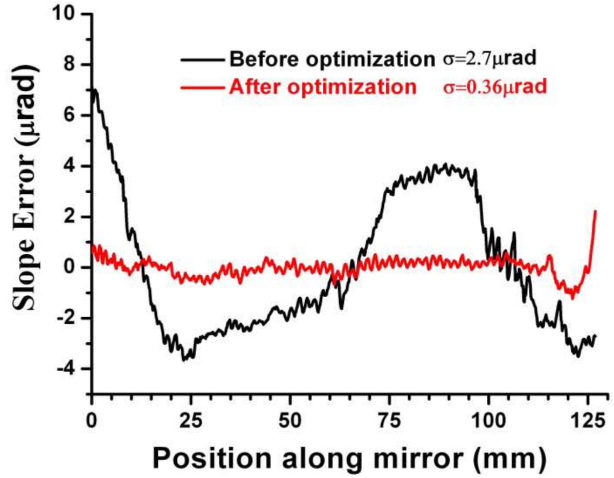
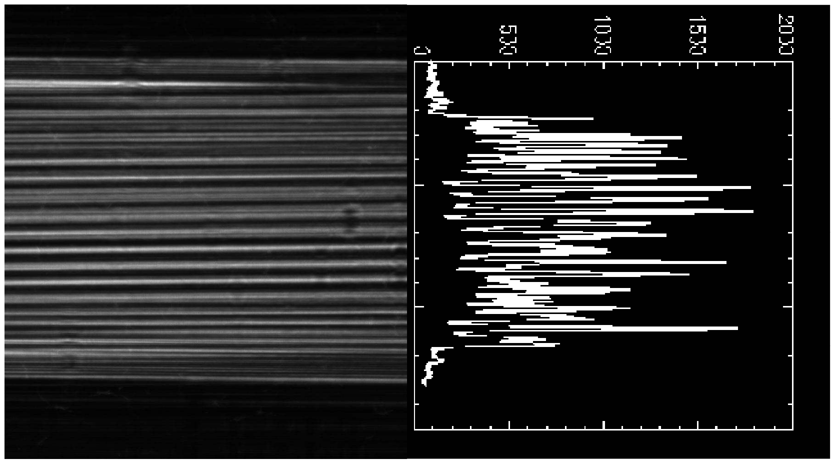
Super polished bimorph mirror

Single grating
Phase Stepping

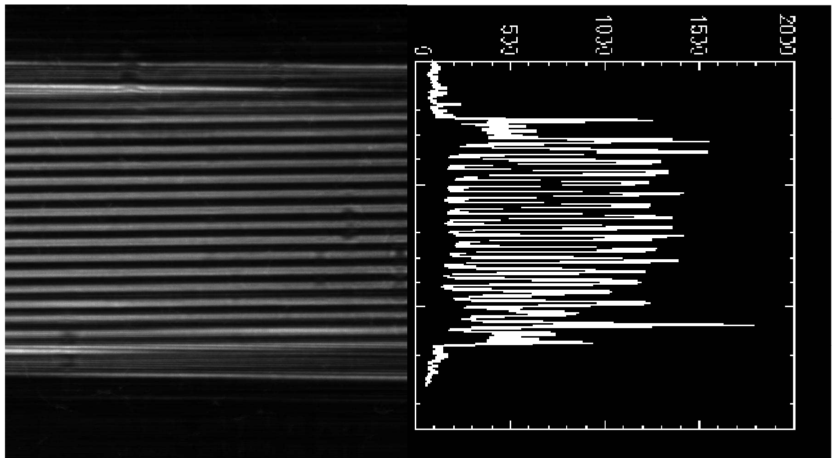




Before Optimization



After Optimization



H. Wang et al, Paper in Submission, (2013)

Diffracting Optics— Fresnel Zone Plate

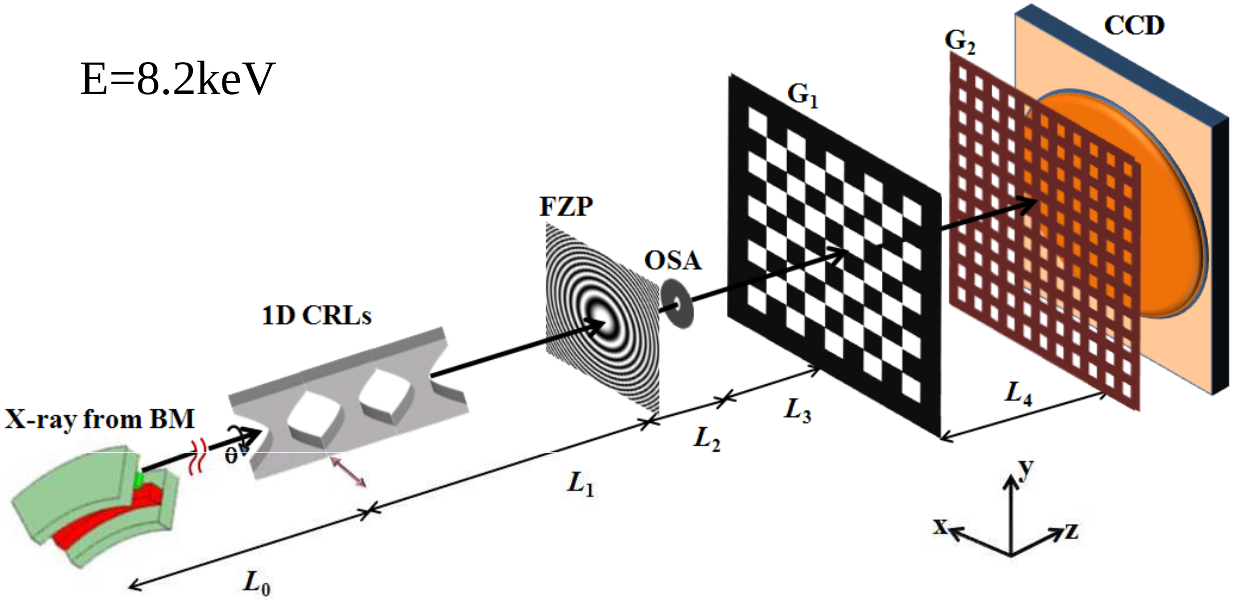
2D grating interferometer

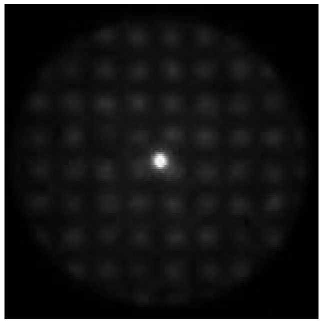
1D CRL stack
N=6 R=500 μm

Zone plate
D=200μm Δr=100nm

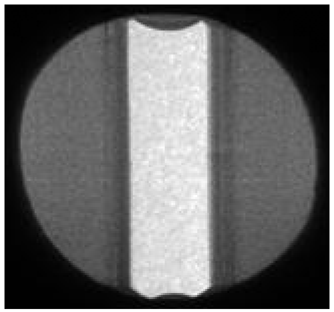
2D Gratings
G1: p1=2.576 μm
G2: p2=2.000 μm
L4=60mm (5th Order)

E=8.2keV





2D Moiré fringe



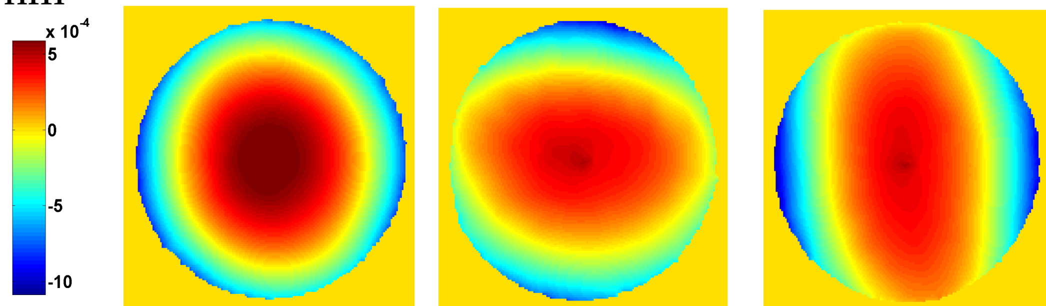
1D CRL Rotate

nm

no CRLs

CRLs 0°

CRLs 90°



Wavefront

H. Wang, et al., Opt. Lett. 38, 827(2013)

diamond

X-ray Speckle BasedTechnique

Principle: Modulate incoming wavefront with speckle and then use digital correlation algorithms to follow the displacement of small subsets of speckle between images.

Near field speckle theory
Speckle grains do not change in size and shape over distance D^2/λ

R. Cerbino et al., Nature Physics (2008)

Membrane:
SiC abrasive paper
Organic filters
Grain size D: 0.1um~50um

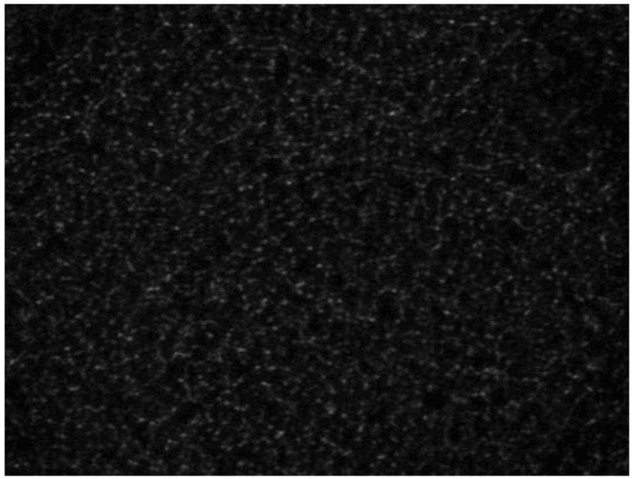
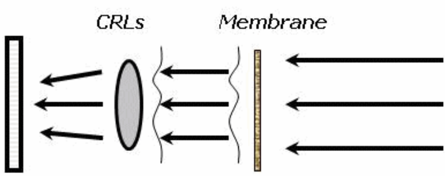
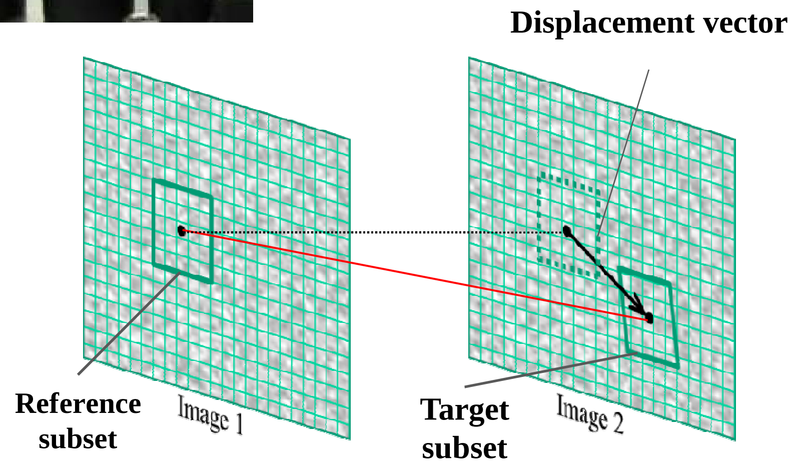


Image Courtesy of L. Peverini





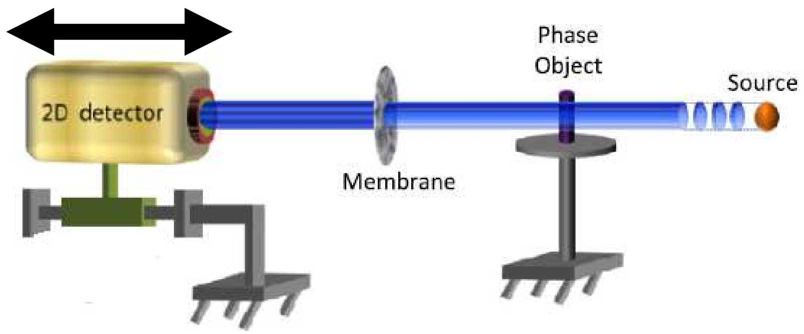
•Digital Image Correlation (DIC) algorithm

S. Bérujon, et al., Phys. Rev. Lett. 108, 158102 (2012)

ESRF diamond

Wavefront reconstruction

Absolute Mode: Move detector

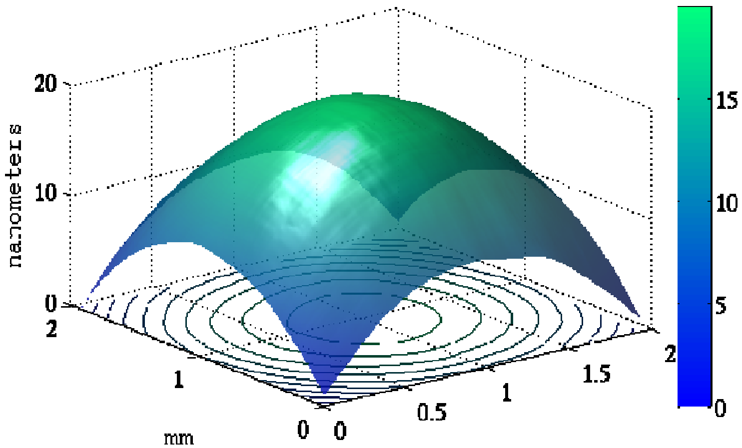


E = 14.5 keV (Theory: R=47.5 m)

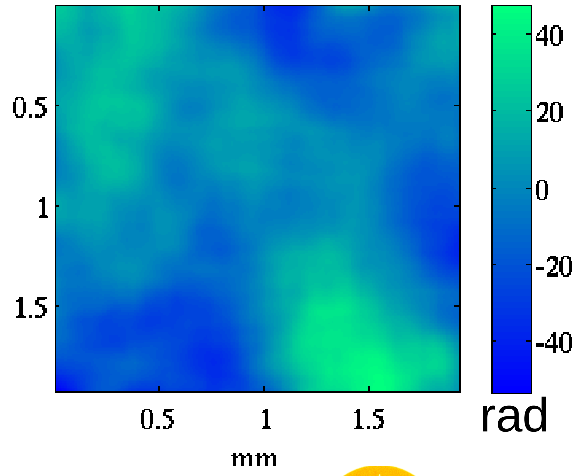
Shape of the beam: ellipsoidal
R_v = 49.7 m
R_h = 48.8 m

Asymmetric beam:
Monochromator Heat bump ?

B16 Beam wavefront



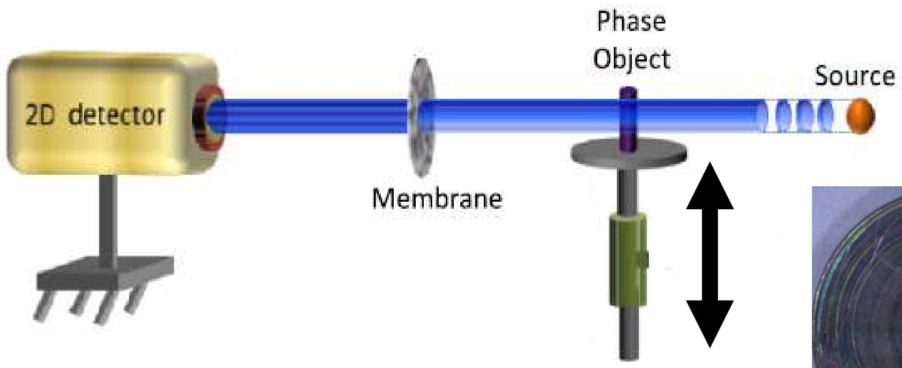
Distortion from perfect ellipsoid

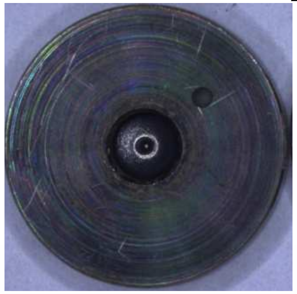


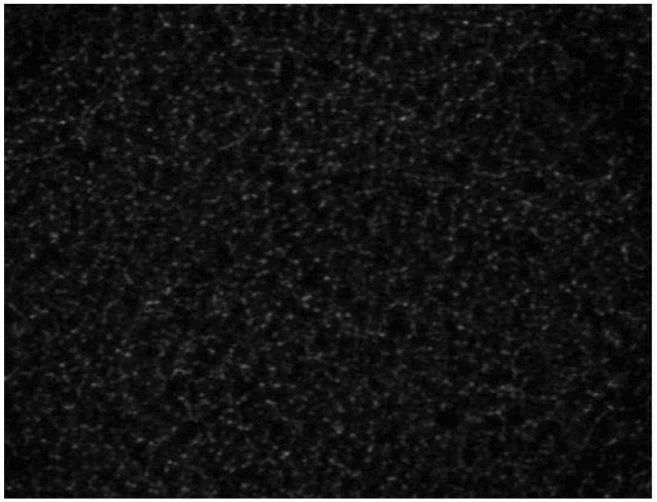
S. Bérujon, et al., Phys. Rev. Lett. 108, 158102 (2012)

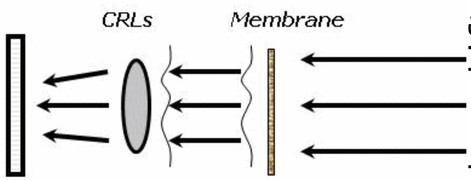
Refracting Optics— 2D CRL

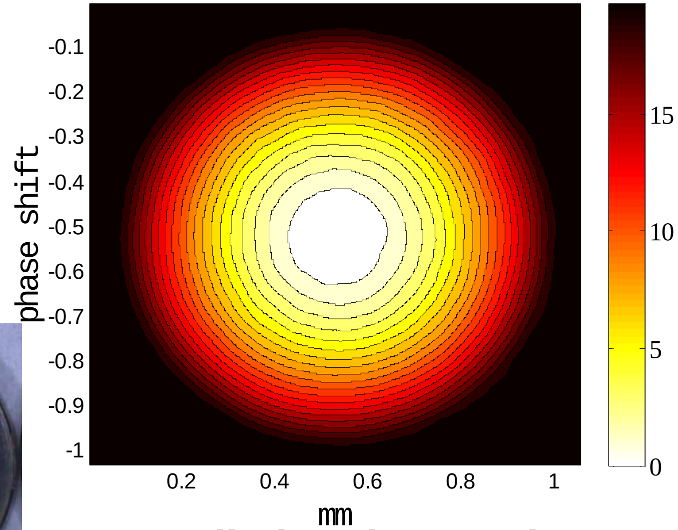
Differential Mode: Move Sample



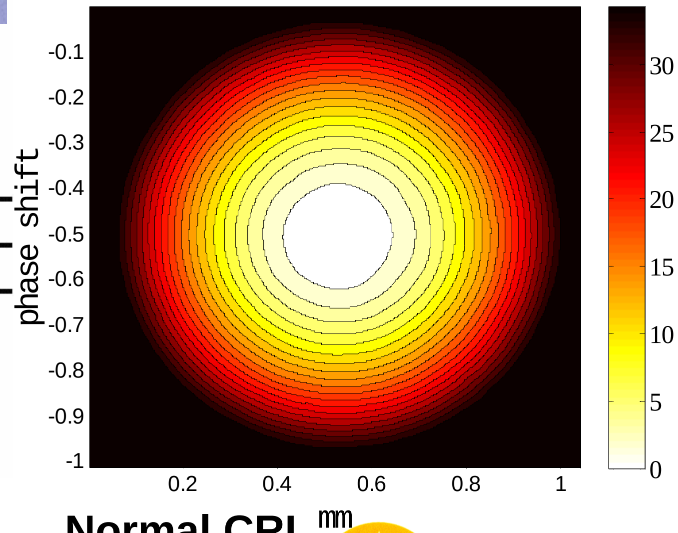








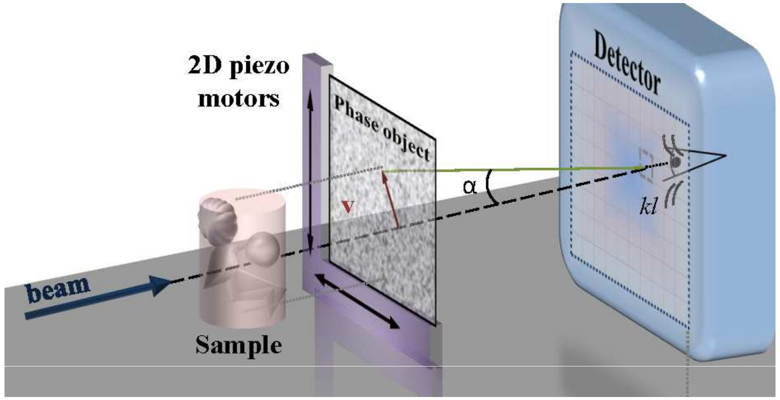
Irradiation damaged CRL



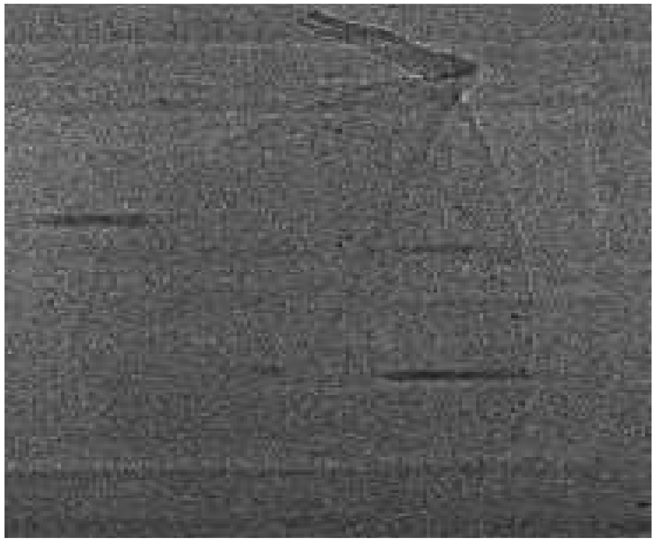
Normal CRL

Extension to Generalized Scheme

Scanning Mode: Scan Membrane

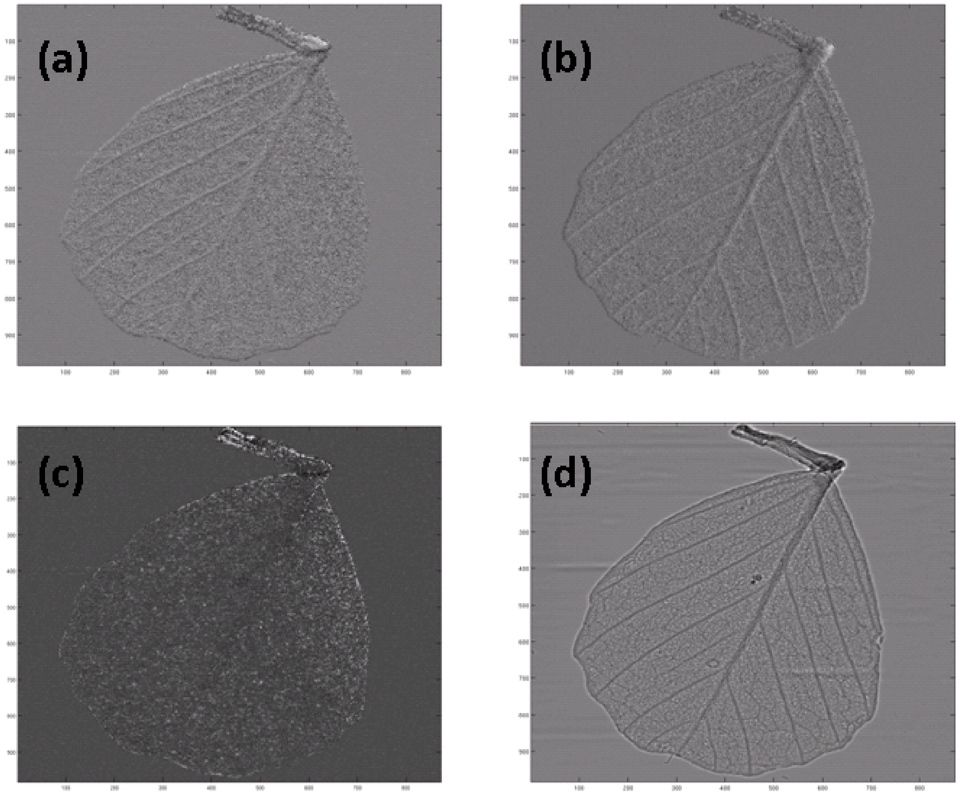


2D raster scan



Vertical gradients

Horizontal differential



Dark field image

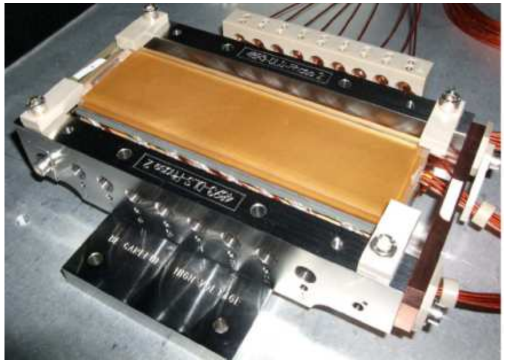
Absorption image

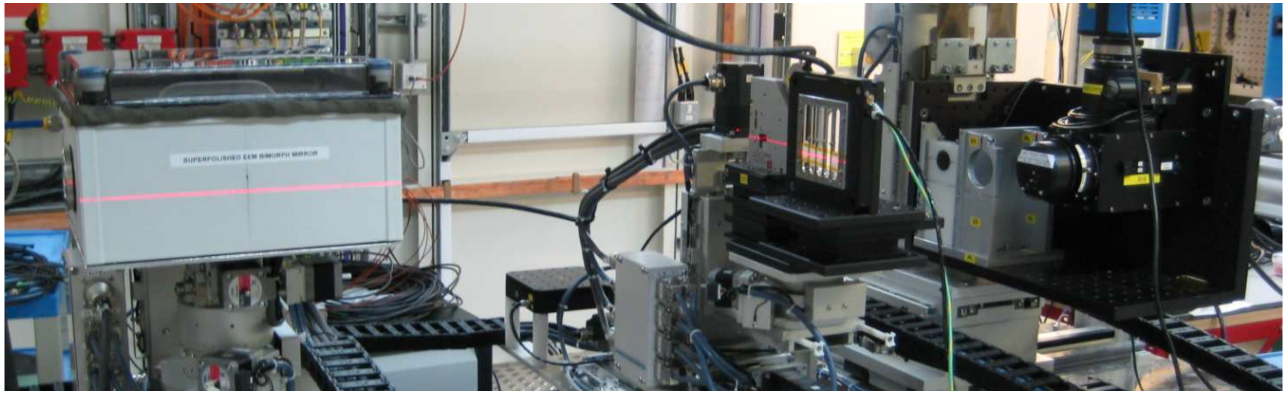
✓From grating to speckle

✓Phase image + Dark field image

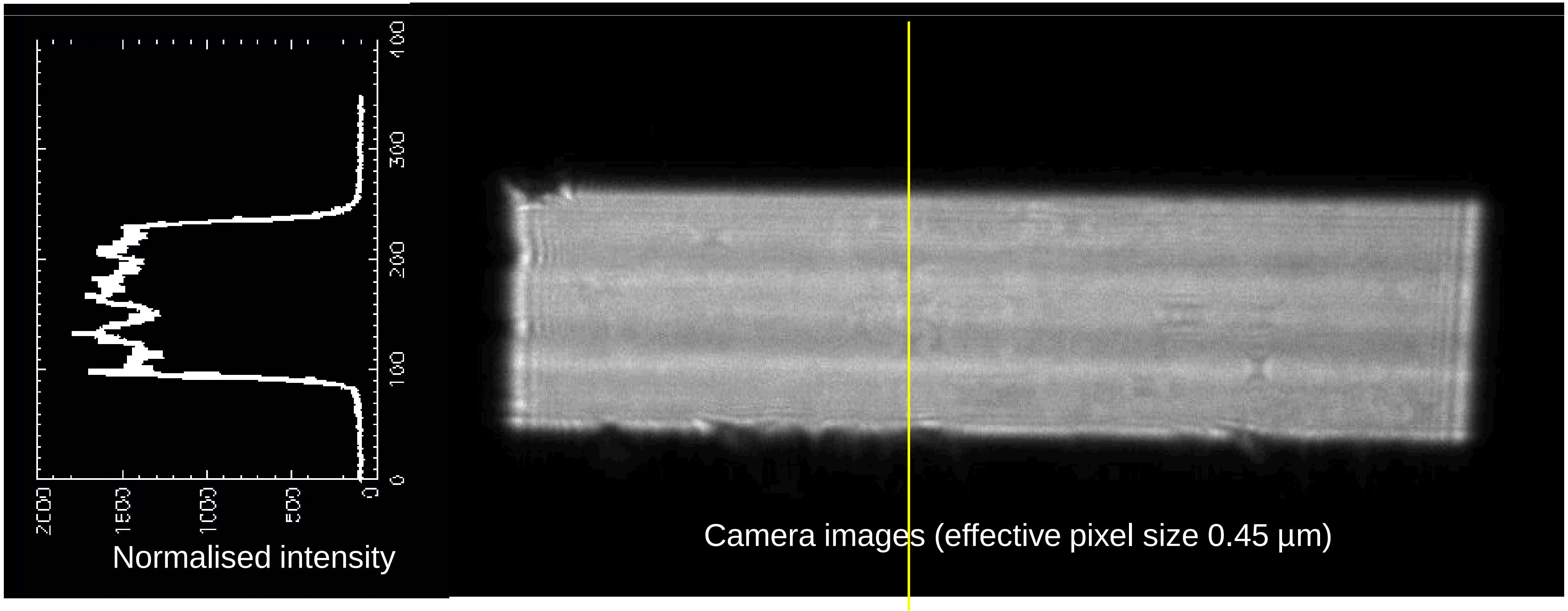
S. Bérujon, et al ., Phys. Rev. A. 86. 063813 (2012).

Super polished bimorph mirror



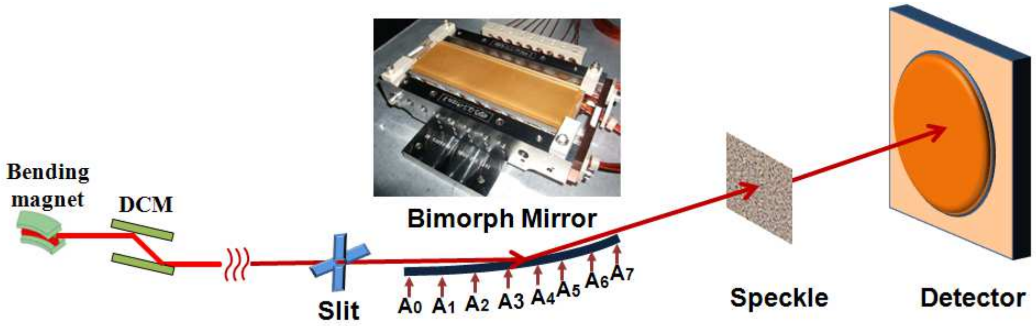


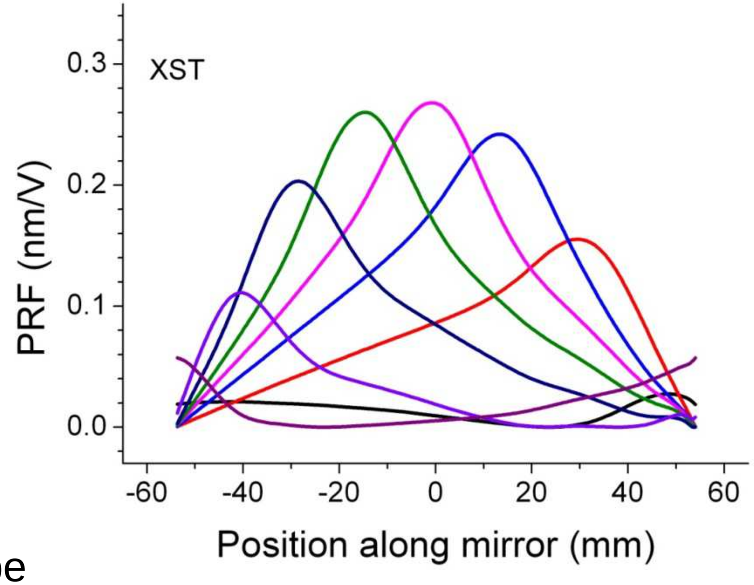
Elliptical **:**p = 46m;q = **400**mm;θ = **3**mrad, 8 piezo electrodes, L=150 mm (120mm EEM)



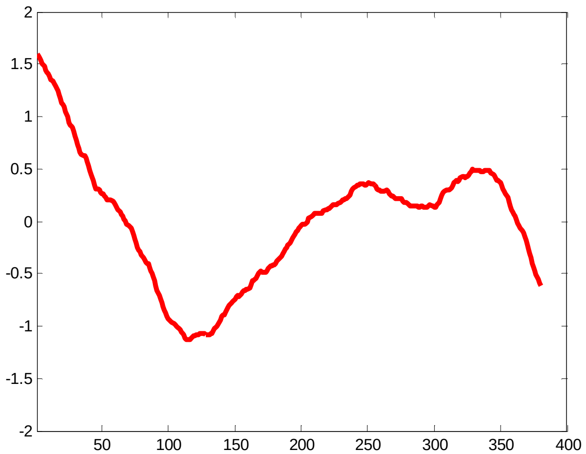
Super polished bimorph mirror: focus

Elliptical **:**p = 46m;q = **400**mm;θ = **3**mrad

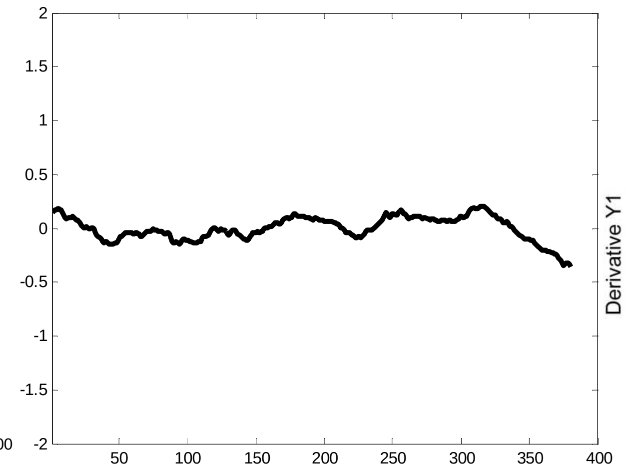


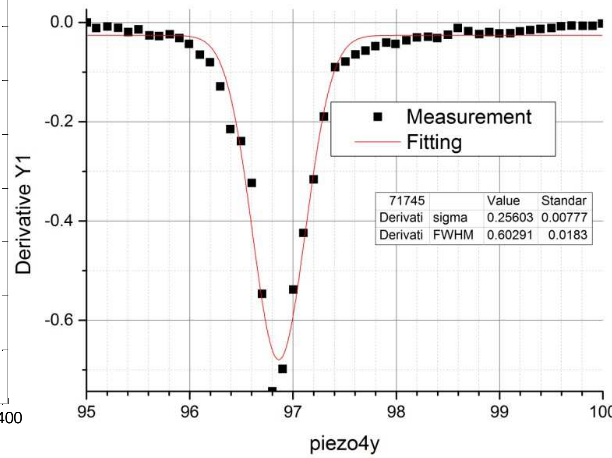


Before Optimisation
Slope Error= 0.87urad

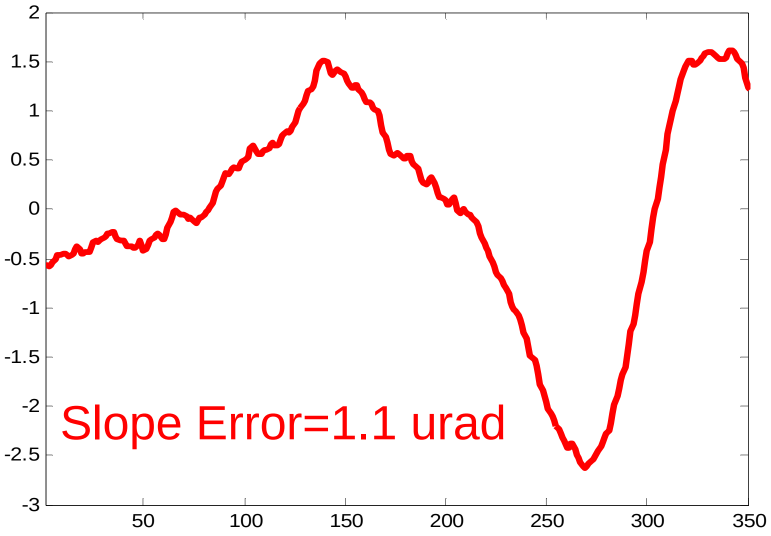


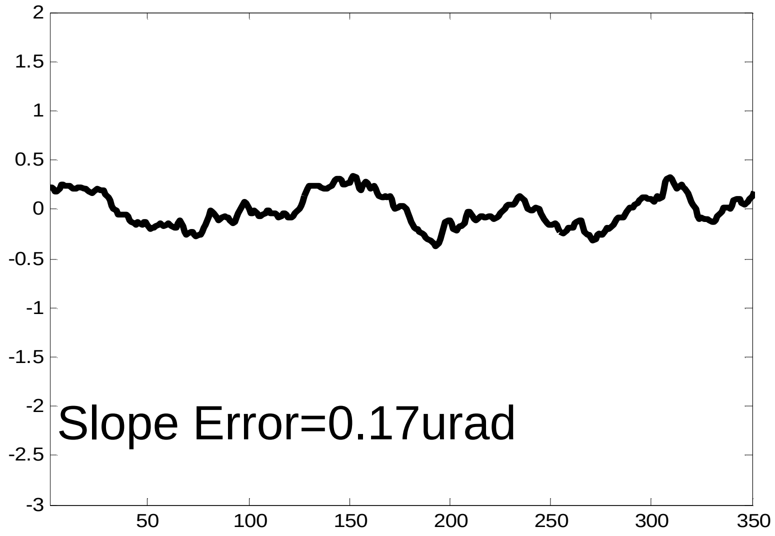
After Optimisation :Slope
Error= 0.11urad





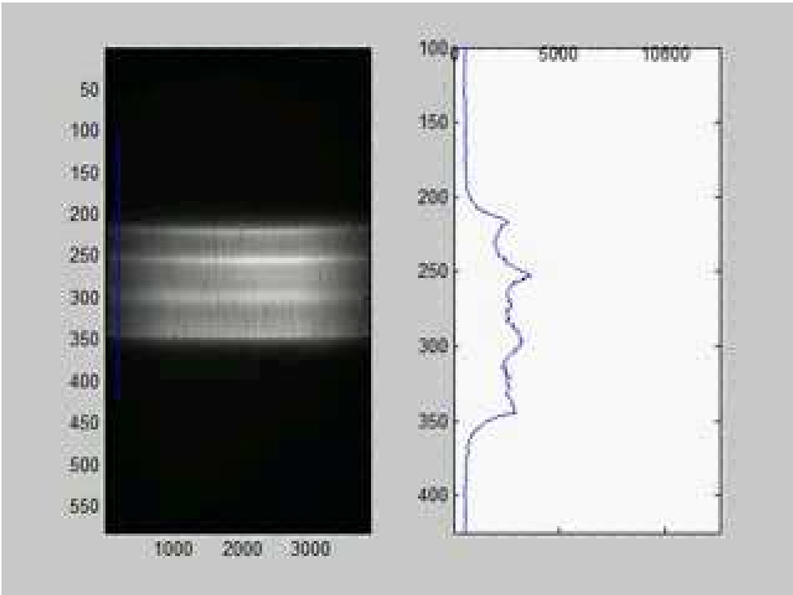
Super polished bimorph mirror: defocus

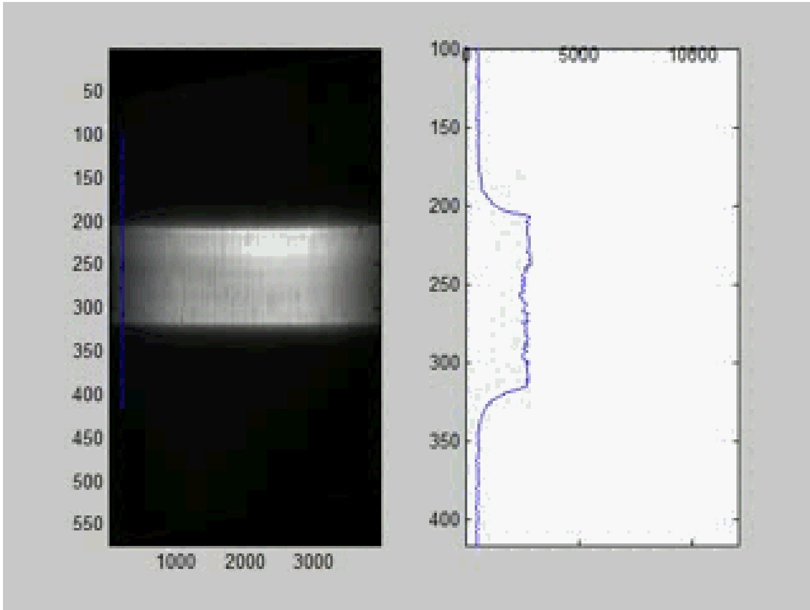




Pencil beam scan

Speckle scan





Summary

At-wavelength metrology

-Moderate requirements on coherence

-Sub-micro->nano-radians accuracy

-Compact and easily be installed

-Fast measurement

Future work

-Improve the sensitivity

-Test strong curved mirrors

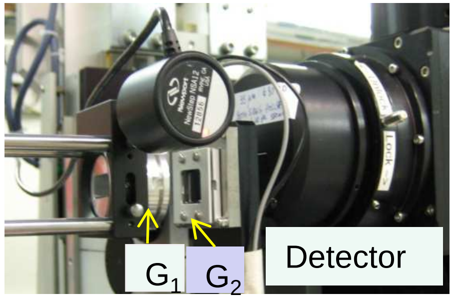
-Compact test instrument/Auto-alignment

-X-ray lab source

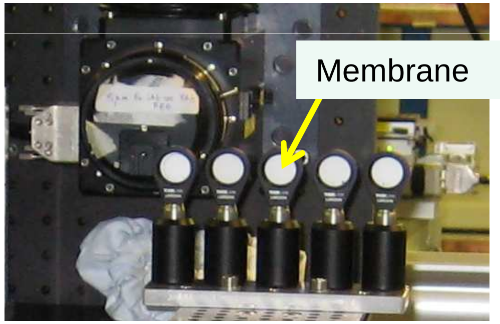
-X-FEL

-……..

Grating Interferometer



Speckle Based technique



Acknowledgements

Thanks to…

- Diamond Light Source

  Optics & Metrology Group

  Kawal Sawhney, Sébastien Berujon, Simon Alcock and John Sutter

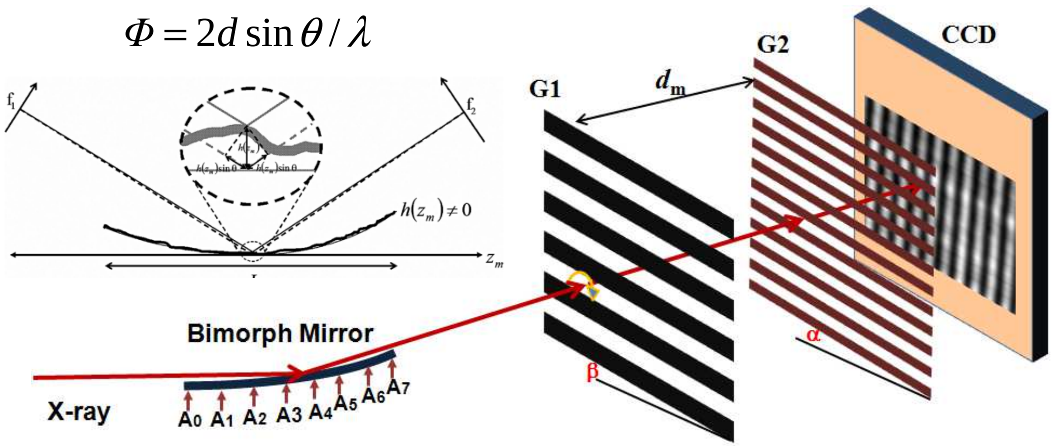
  Andrew Malandain, Stewart Scott, Slava Kachkanov and Igor Dolbnya……

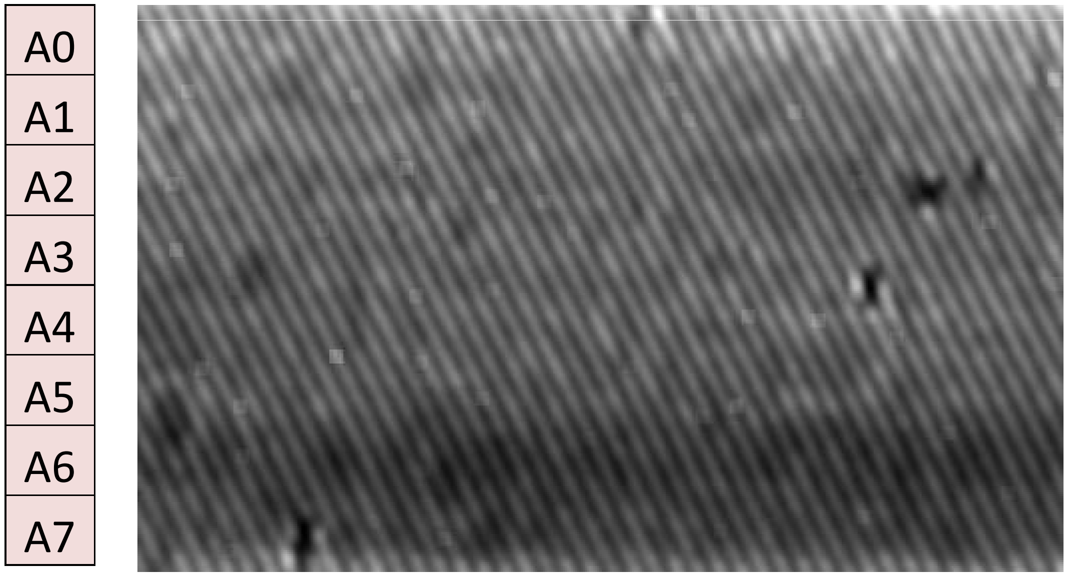
- PSI (Christian David, Simon Rutishauser)
- NSLS II (Yong Chu, Hanfei Yan)
- ESRF (Eric Ziegler)

diamond

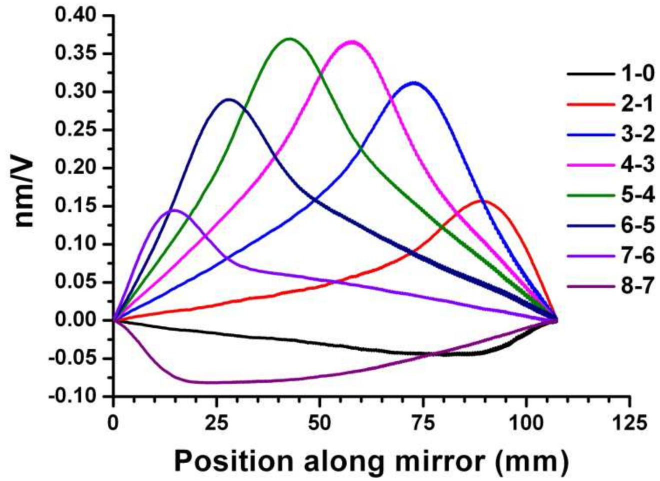
Super polished bimorph mirror

$$\Phi = 2d\sin\theta/\lambda$$

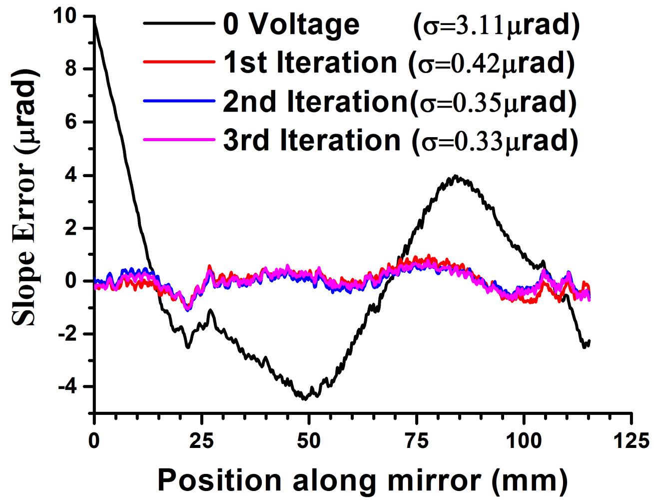




Piezo Response Function (PRF)

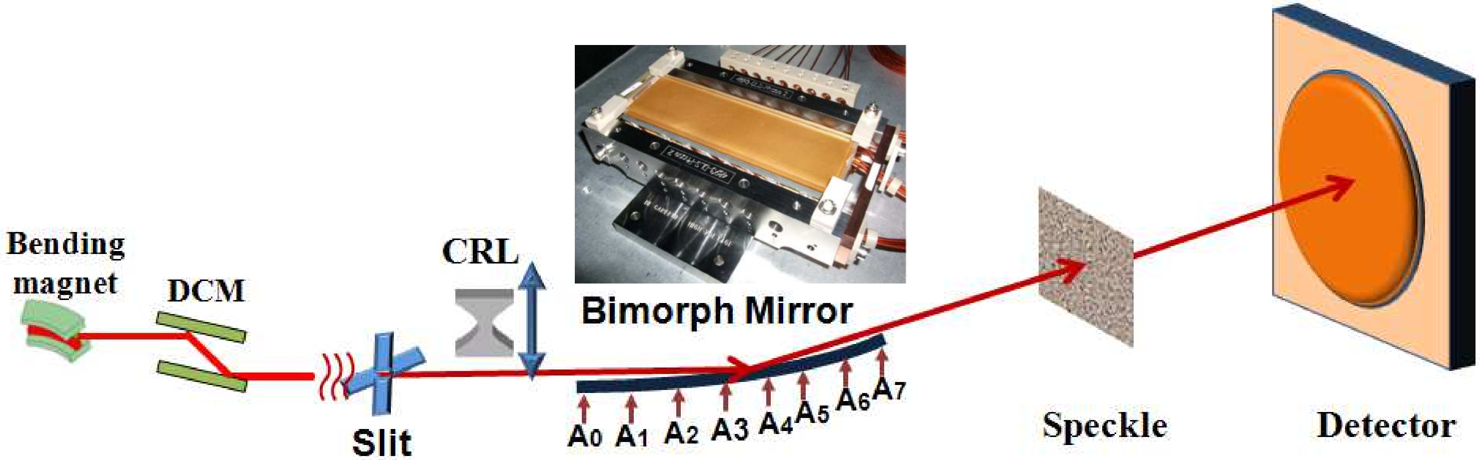


Wavefront Slope error

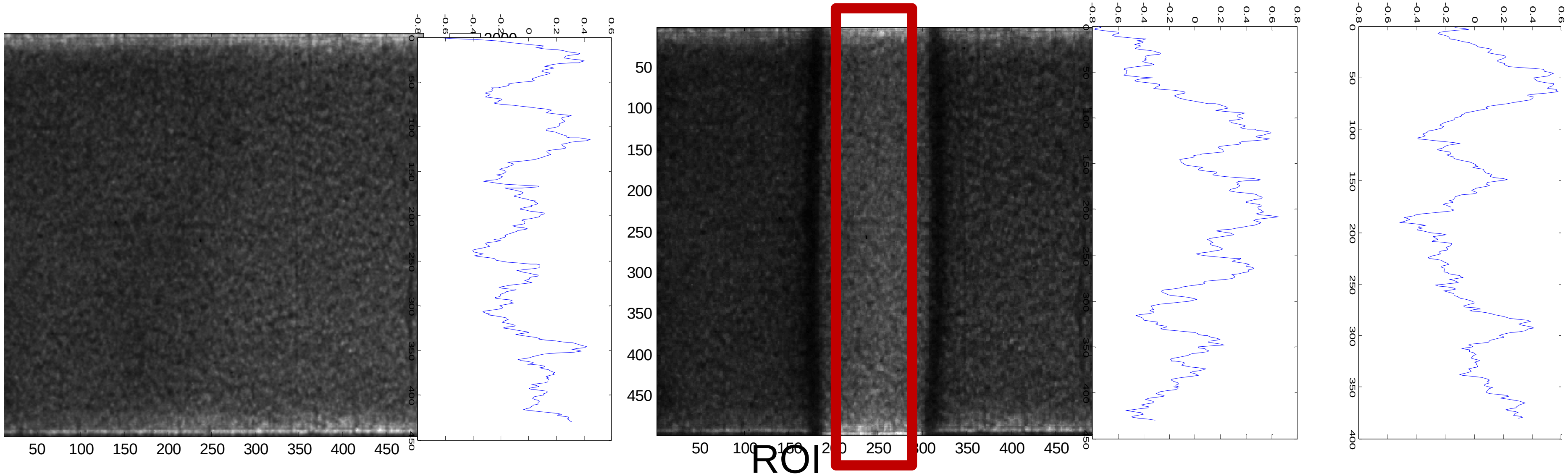


H. Wang et al, Paper in Submission, (2013)

Super polished bimorph mirror: wavefront correction



Slope Error: 0.20urad → Before correction 0.34urad → After: 0.24urad



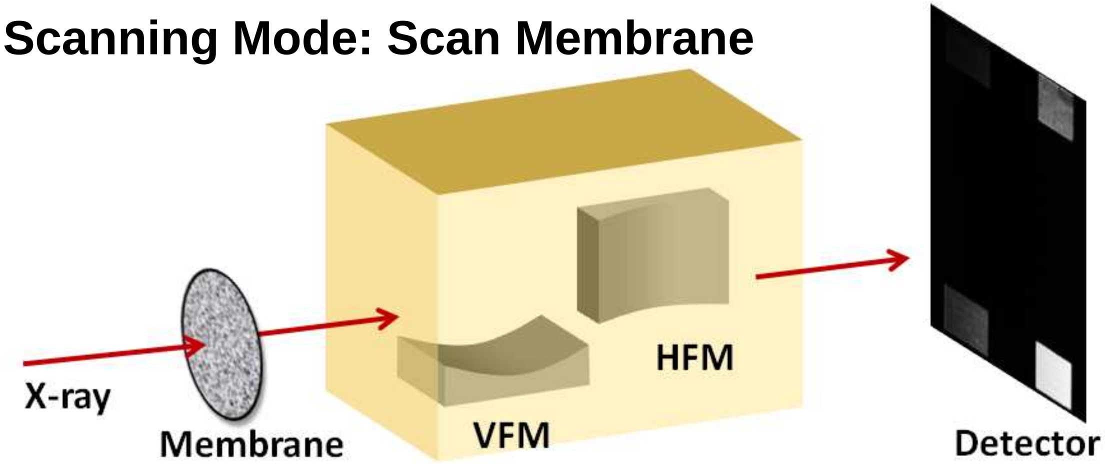
Without CRL

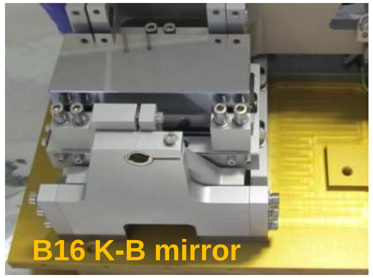
With CRL

H. Wang et al, Paper in preparation, (2013)

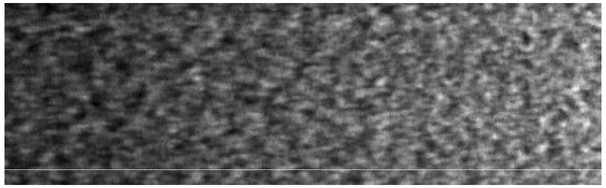
Characterization for K-B mirror

Scanning Mode: Scan Membrane



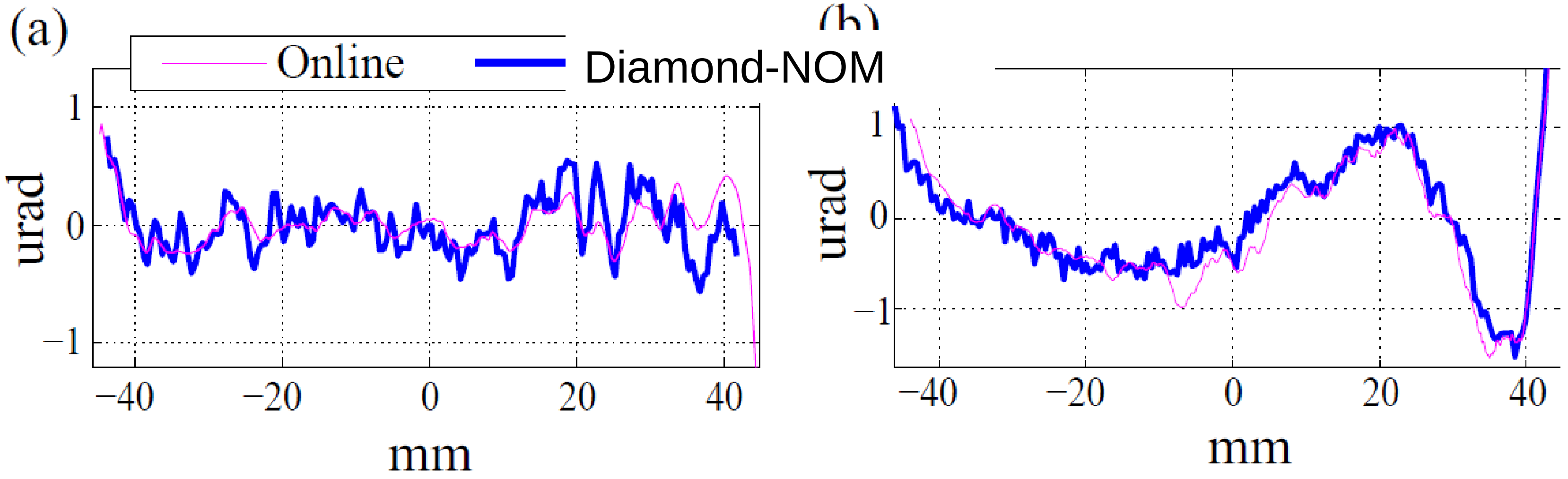


Horizontal Scan for HFM



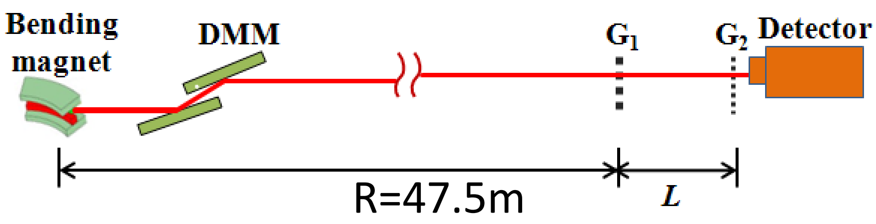
VFM **:**p = 47m;q = **235**mm;θ = **3**mrad

HFM **:**p = 47m;q = **125**mm;θ = **3**mrad



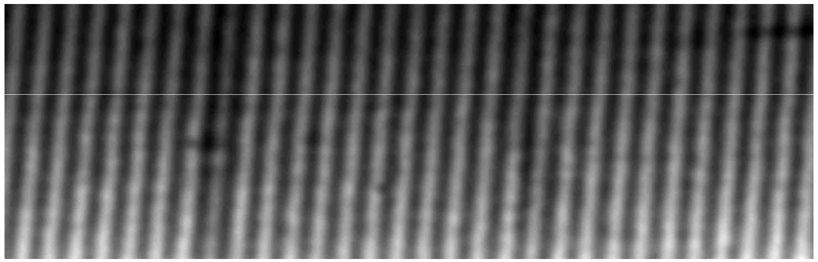
S. Berujon et al, Optics Letters., 37, 4464-6, (2012); S. Berujon et al, Paper in submission, (2013)

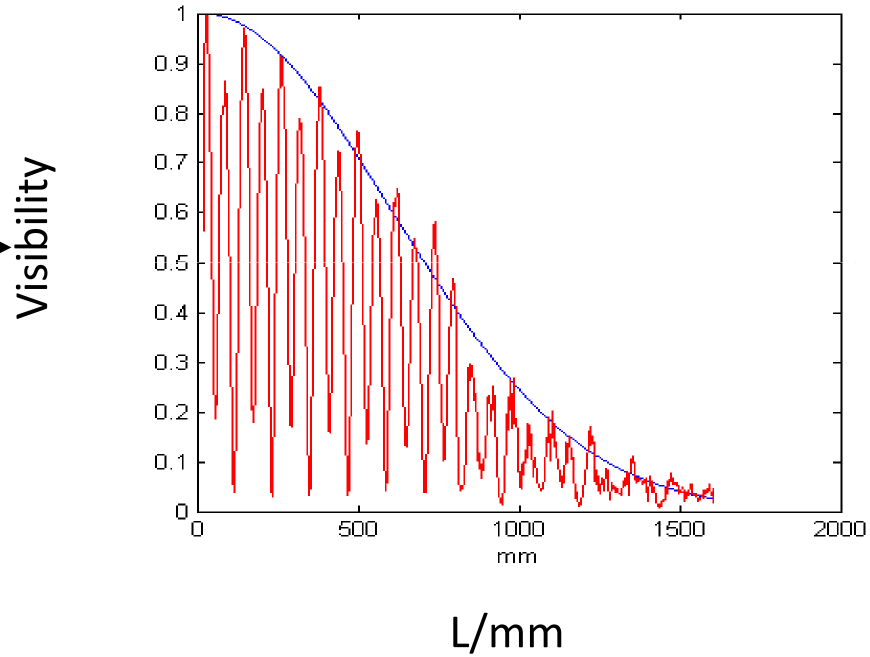
Coherence length measurement at B16



Double Multilayer Monochromator (DMM)

E = 18 keV   Tablot distance $L_m = m\dfrac{d_0^2}{8\lambda}$





$$|\gamma(x,y)| = \gamma_0 \exp(-x^2/2\xi_x^2 - y^2/2\xi_y^2)$$

F. Pfeiffer et al, Phys. Rev. Lett. (2005)

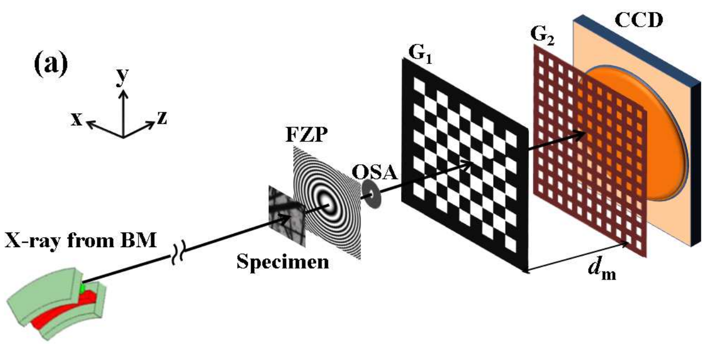
Transverse Coherence length $\xi_y = \lambda R / 2\pi\sigma_y$

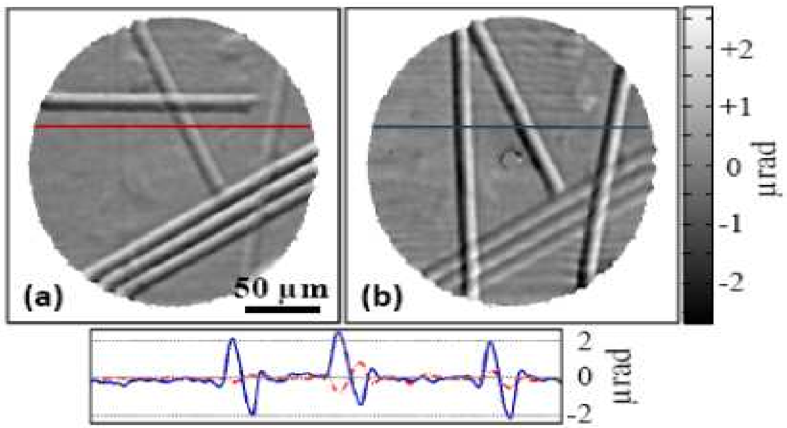
H. Wang et al, Paper in Preparetion, (2013)

	Coherence length	Vertical Source Size
Measurement	ξ_y =21 μm	σ_y=24.8 μm (rms)
Theory	ξ_y =22 μm	σ_y=23.5 μm (rms)

X-ray phase contrast imaging

2D grating interferometer

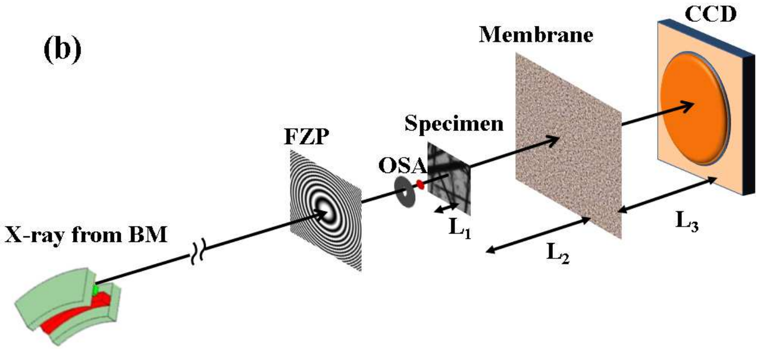




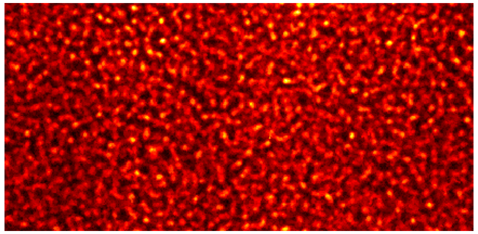
(a) vertical gradient, (b) horizontal gradient

S. Berujon, H Wang et al., Opt. Lett. 37, 1622 (2012)

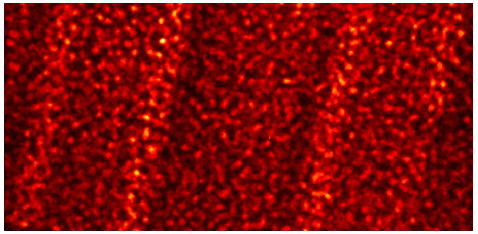
X-ray Speckle Based technique

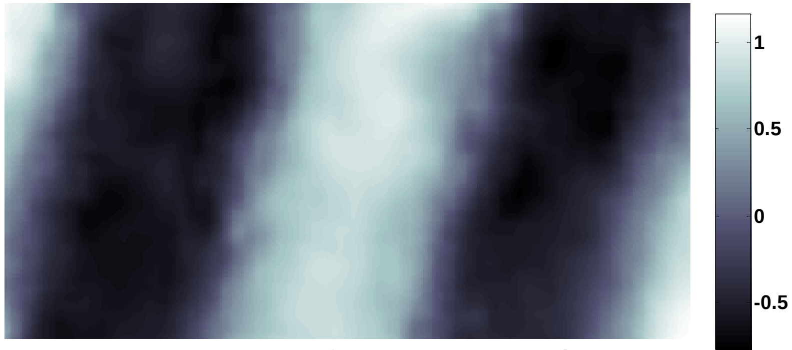


Flat Field Speckle Pattern



Carbon Fiber Speckle Pattern





Wavefront construction

S. Bérujon, H Wang et al ., Appl. Phys. Lett. 102. 154105 (2013).