Optics considerations for APS-U

Xianbo Shi
Optics Group
Advanced Photon Source

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Outline

- Introduction
- Focusing high energy X-rays
- Coherence preservation
- Summary

Introduction

APS-U
High brightness
Small emittance
Partial/full coherence

→ **Beamline Optics** →

Experimental Techniques
High resolution, nm focus
High flux density
High coherent flux

↑ **New Science**

Questions being asked about APS-U:

- New Beamlines:
  - Beamline scheme
  - Optics specification
- Existing Beamlines:
  - Readiness of current beamline optics for the APS upgrade

- Beam profile (size, shape, depth)
- Beam intensity, flux
- Coherence property

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X-ray focusing limits

- X-ray source demagnification: $\frac{q}{p}S$
- Partially coherent beam: electron beam + undulator radiation
  - Electron:

APS-U 324 bunch: $\sigma_x = 21.5\ \mu\text{m}, \sigma_y = 4\ \mu\text{m}, \sigma_x' = 3.1\ \mu\text{rad}, \sigma_y' = 1.7\ \mu\text{rad}$

Current APS: $\sigma_x = 274\ \mu\text{m}, \sigma_y = 10\ \mu\text{m}, \sigma_x' = 11\ \mu\text{rad}, \sigma_y' = 3.6\ \mu\text{rad}$

  - Photon: Undulator: L = 2.4 m

$$\sigma_r = \frac{1}{2\pi}\sqrt{2L\lambda},\ \ \sigma_r' = \sqrt{\frac{\lambda}{2L}}$$

Energy (keV)	20	50	100
σ_r (μm)	2.75	1.74	1.23
σ_r' (μrad)	3.59	2.27	1.61

  - Total beam size

$$\Sigma_x = \sqrt{\sigma_x^2 + \sigma_r^2}$$

$$\Sigma_y = \sqrt{\sigma_y^2 + \sigma_r^2}$$

$$\Sigma_x' = \sqrt{\sigma_x'^2 + \sigma_r'^2}$$

$$\Sigma_y' = \sqrt{\sigma_y'^2 + \sigma_r'^2}$$

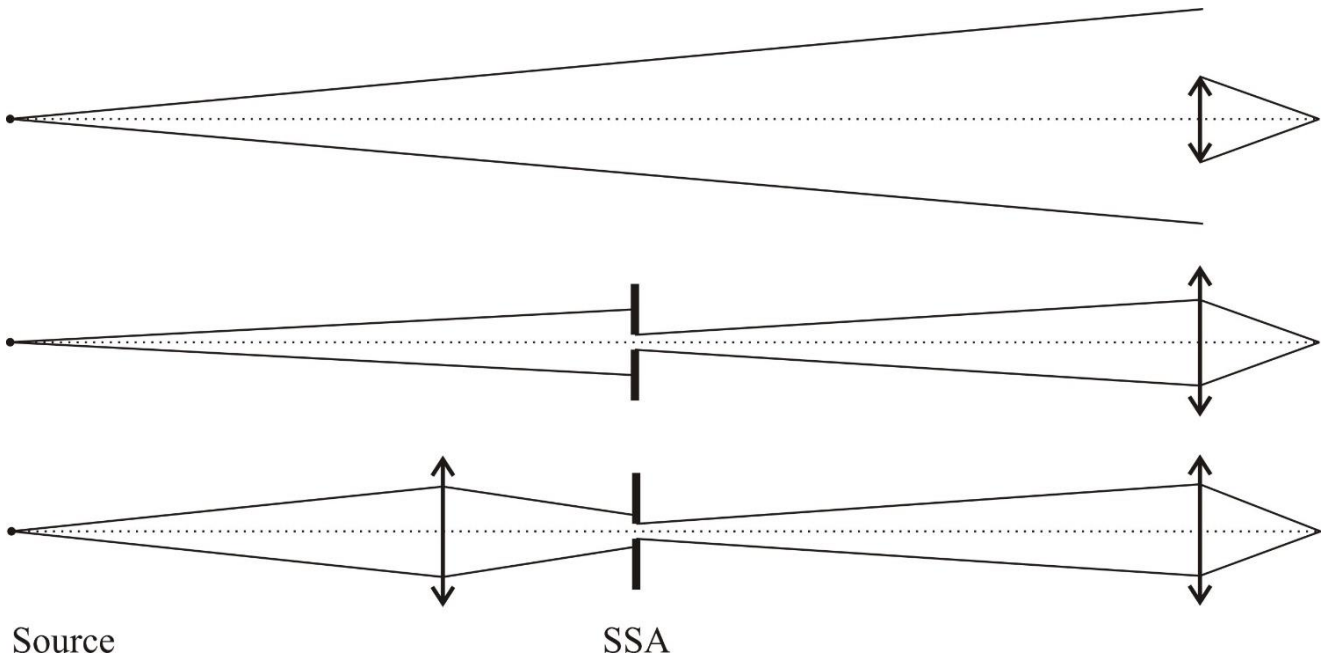
	APS-U 324 bunch			Current APS		
Energy (keV)	20	50	100	20	50	100
Σ_x (μm)	21.7	21.6	21.5	274	274	274
Σ_y (μm)	4.9	4.4	4.2	11	10	10
Σ'_x (μrad)	4.7	3.8	3.5	12	11	11
Σ'_y (μrad)	4.0	2.8	2.3	5.1	4.2	3.9

X-ray focusing limits

- Experimental limitations
  - Working distance

    e.g., W = 70 mm, for a 70 m long beamline, demag >= 1/1000
  - Degree of coherence: aperture and redefine source

    Coherence vs flux vs focal size (sample size)



Optics limitation at high energies

- Diffraction limits of optics: numerical aperture
  - Total reflection mirrors:

$$D_{dif} = \frac{0.88\lambda q}{l\,\theta}, \qquad q = \frac{l}{2} + W$$

Proximity of the elliptical mirror

Energy (keV)	20	50	100
Material	Rh	Pt	Pt
θ (mrad)	3.0	1.5	0.65

  - Multilayer mirrors:

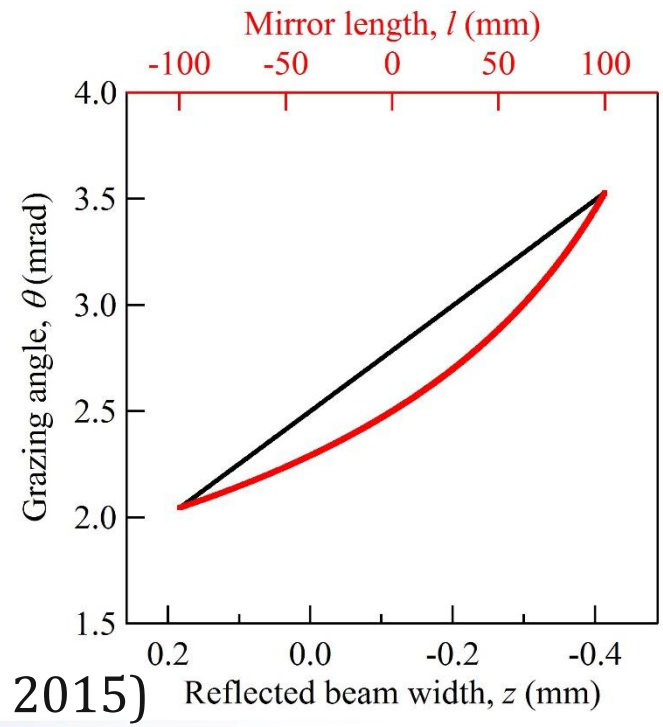
    θ can be a factor of 4 larger
  - CRLs:

    200 nm focusing with etched Si
  - Kinoform lens

    200 nm focusing at 1-ID at 51 keV
  - MLL:

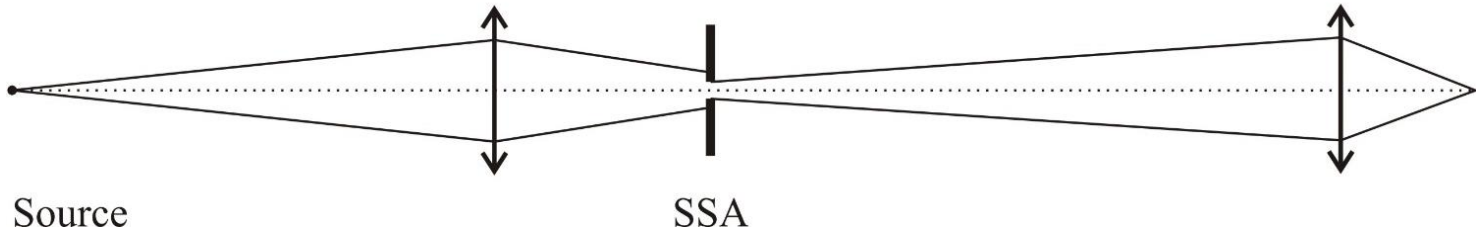
    In favor of high energy, wedged

    8 nm at 17 keV (Scientific Report 5, 2015)



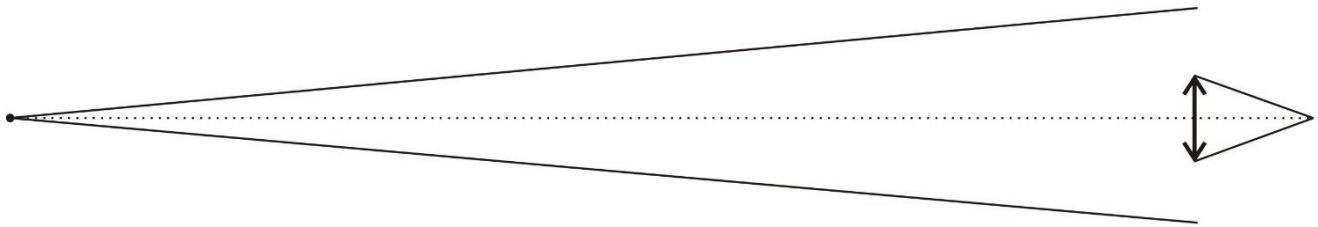
Other issues

- Optics aberration (e.g., mirror figure error)
  - <0.1 μrad, <1 nm, higher requirements for high energies
  - JTEC mirror <0.05 μrad
- Vibration
  - Source vibration
  - Mono vibration: 0.1 μrad at 30 m gives 6 μm virtual source vibration, which is larger than the APS-U source size
  - Improve mono stability and use secondary source



Example:

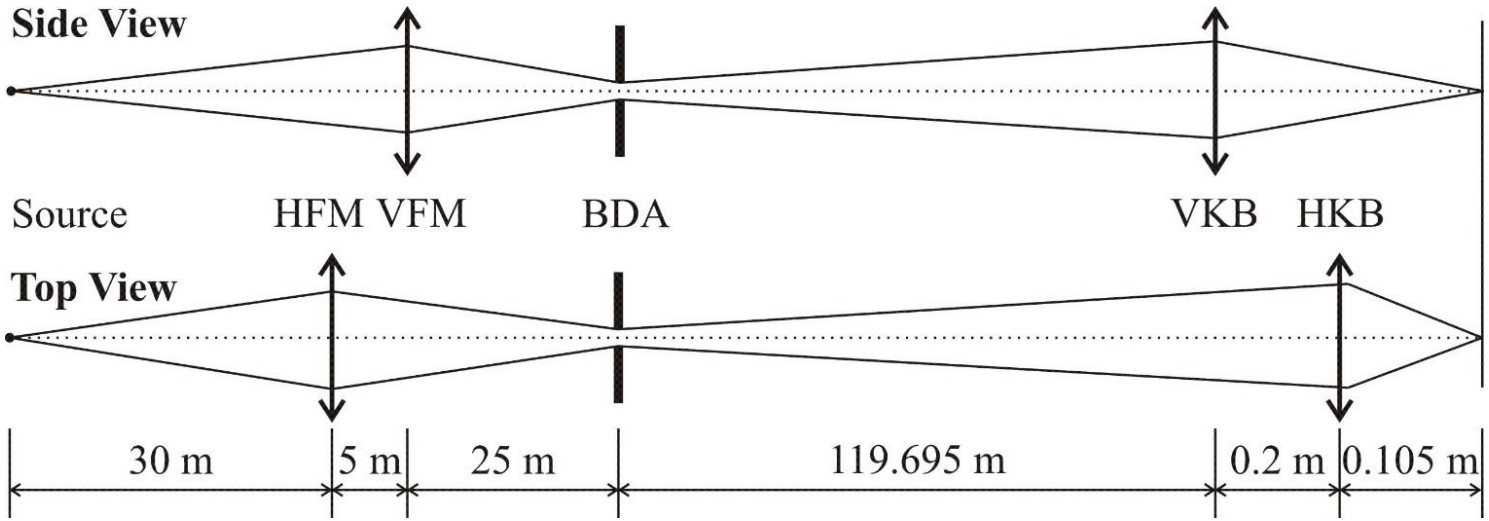
- Coherence focusing: p = 70 m, W = 100 mm



	MBA 324 bunch mode		
Energy (keV)	20	50	100
Focal size (nm)	109×41	101×34	108×35
Transmission	2.9%	1%	0.6%
Flux (ph/s/0.1%BW)	3.9e13	1.4e12	6.8e10

(P28.0+P23.5-L480-Rev2)

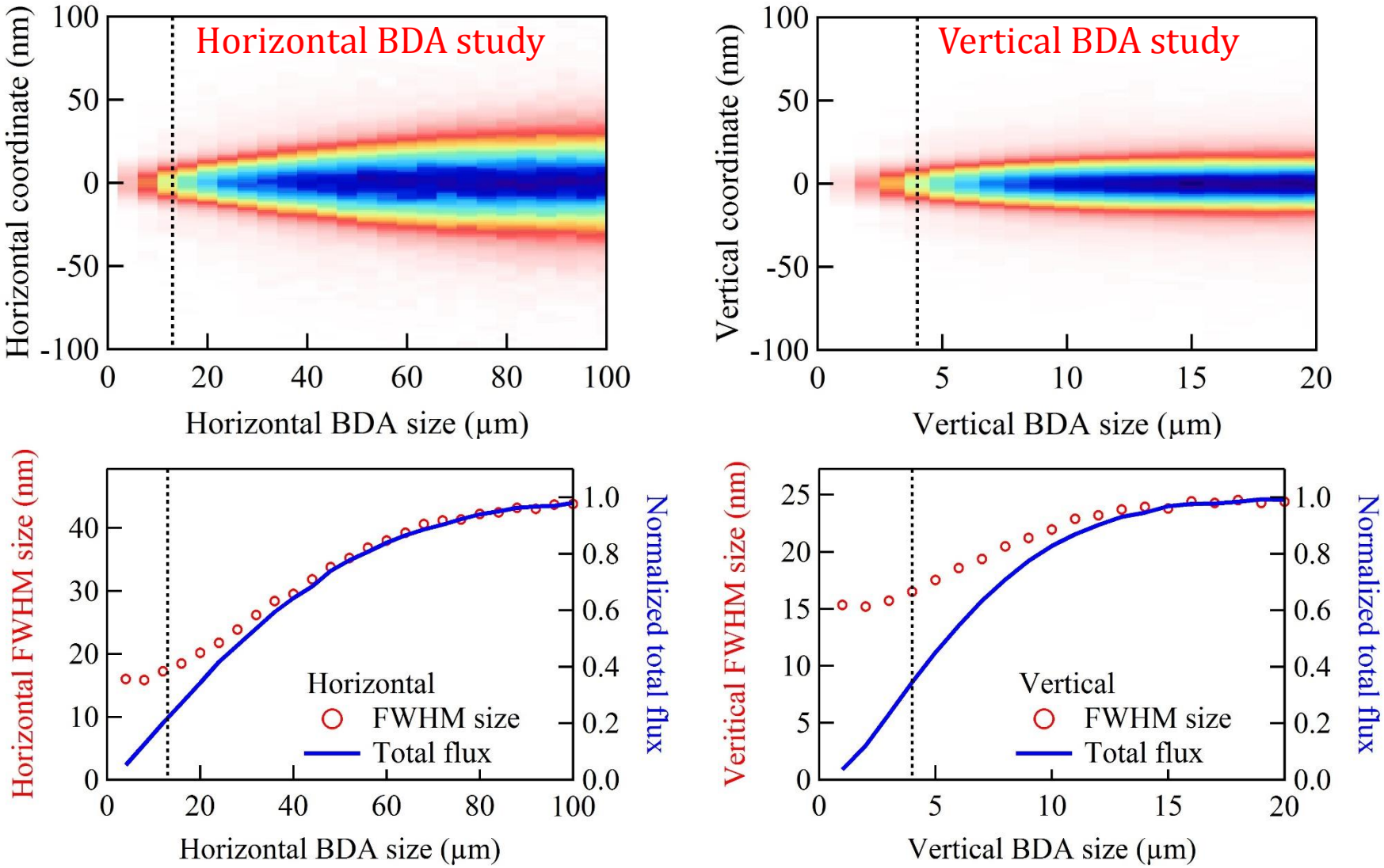
ISN beamline: APS-U



- Source APS-U 324 bunch: 2.4 m long undulator, E = 25 keV
  - Σ_x = 21.5 μm, Σ_y = 4.6 μm, Σ'_x = 4.5 μrad, Σ'_y = 3.7 μrad
- HFM, VFM: 400 mm long, 2.5 mrad grazing angle
- BDA: 12 × 4 μm^2 (h × v) → wide open
- VKB: 300 mm long, 2.5 mrad grazing angle
- HKB: 100 mm long, 2.5 mrad grazing angle

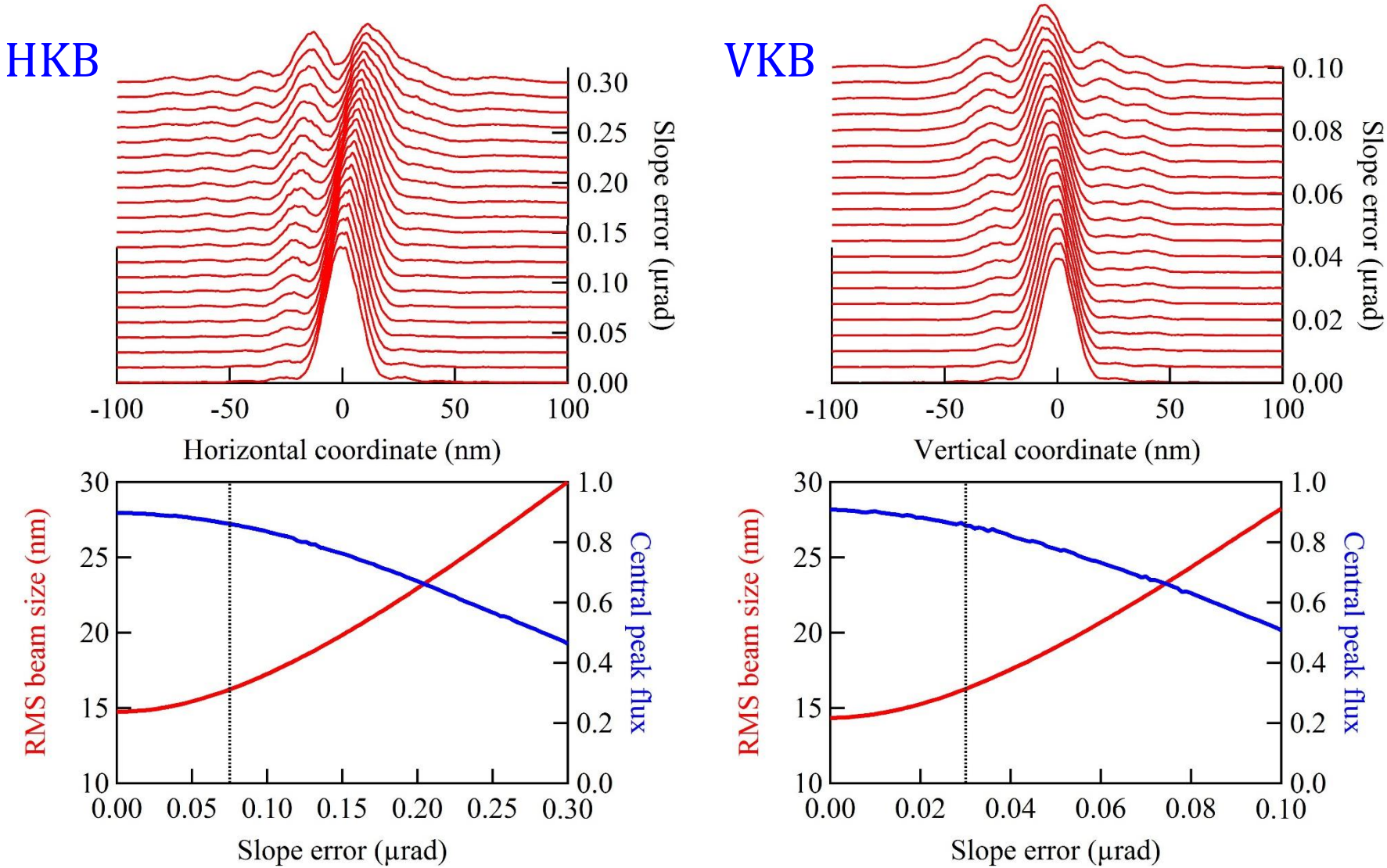
ISN beamline: APS-U

HYBRID code



Diffraction limited BDA size: H < 13 μm, V < 4 μm

ISN beamline: APS-U



Mirror slope error: HKB < 0.08 μrad, VKB < 0.03 μrad

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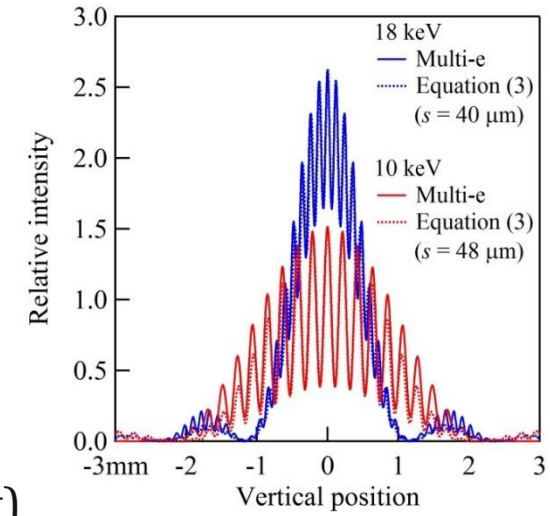
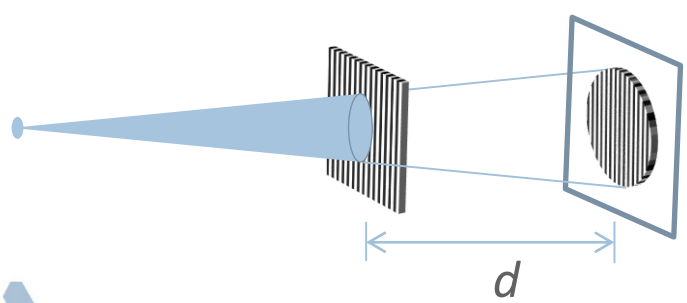
Coherence simulation and characterization

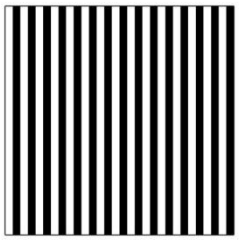
- Estimate from beam size: $A_c = \frac{4}{\pi}\left(\frac{\lambda f}{D}\right)^2$, $M = \frac{A_D}{A_c}$
- Simulate the mutual coherence function
  - SRW
  - Codes under development
- Simulate coherence measurements
  - Single-slit or Double-slits experiments →
  - Grating interferometry
    - Talbot self-imaging distance

$$d_{talbot} = \frac{1}{\eta}\frac{np^2}{2\lambda}$$ (n = 1, 3, 5, …, η = 1 for π/2 grating)

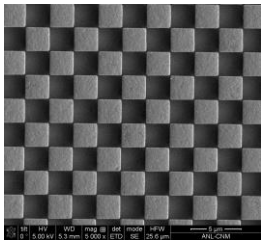
    - The image contrast drop as a function of *d*, which is a measurement of transverse coherence of the source.







1D



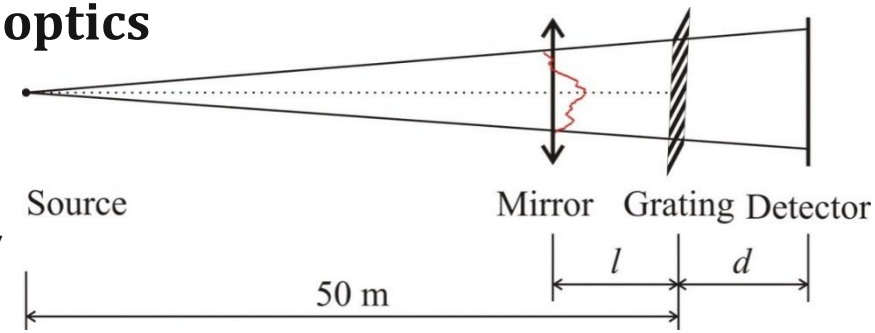
2D

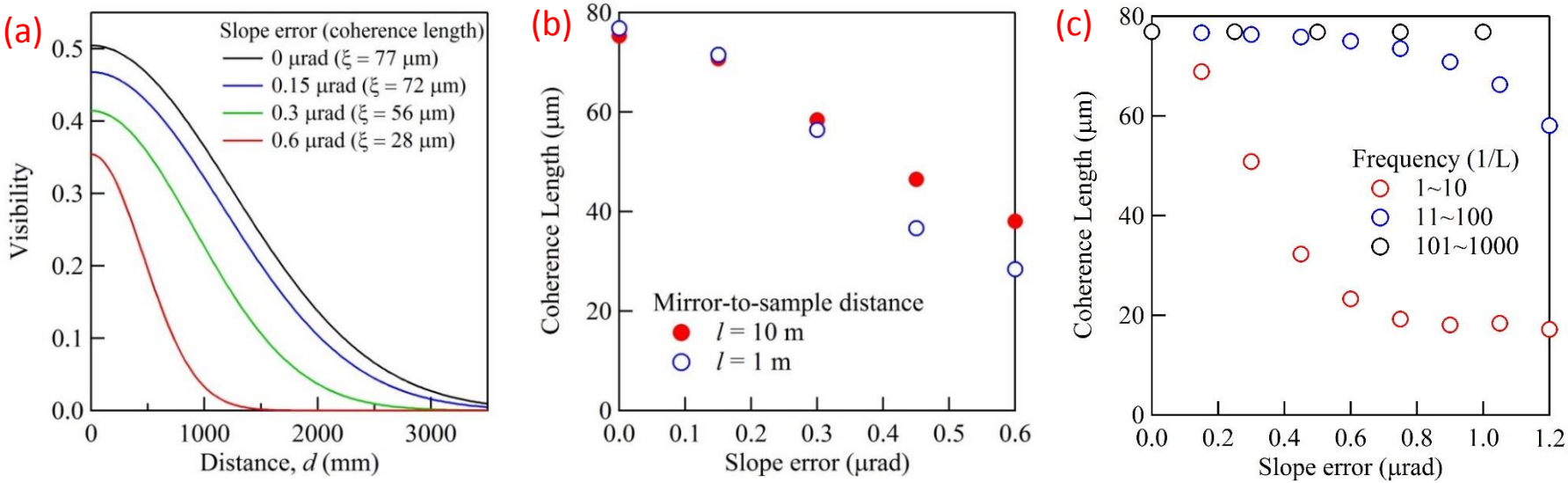
Strategic LDRD

Marathe, S., et al., *Opt. Express*, ***22,*** 14041 (2014).

Coherence simulation

- **Coherence and wavefront preserving optics**
  - APS-U source (48 bunch):
    - Electron: σ_v = 10.9 μm, σ'_v = 3.8 μrad
    - ID: 28 mm undulator, 2.4 m, K = 0.67
    - Photon energy: 10 keV

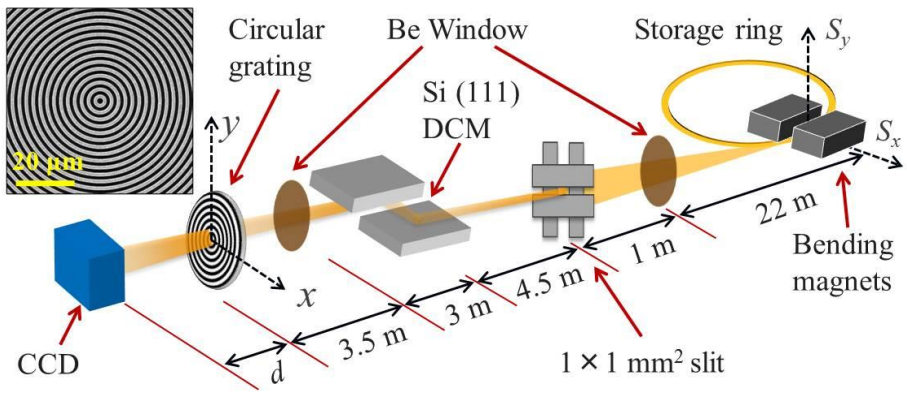


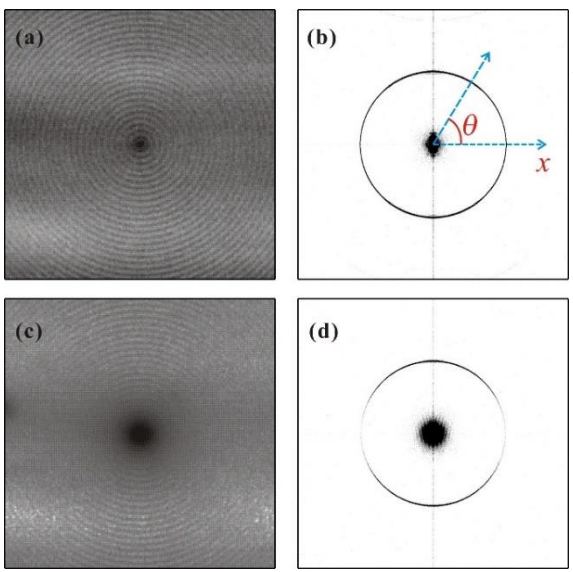


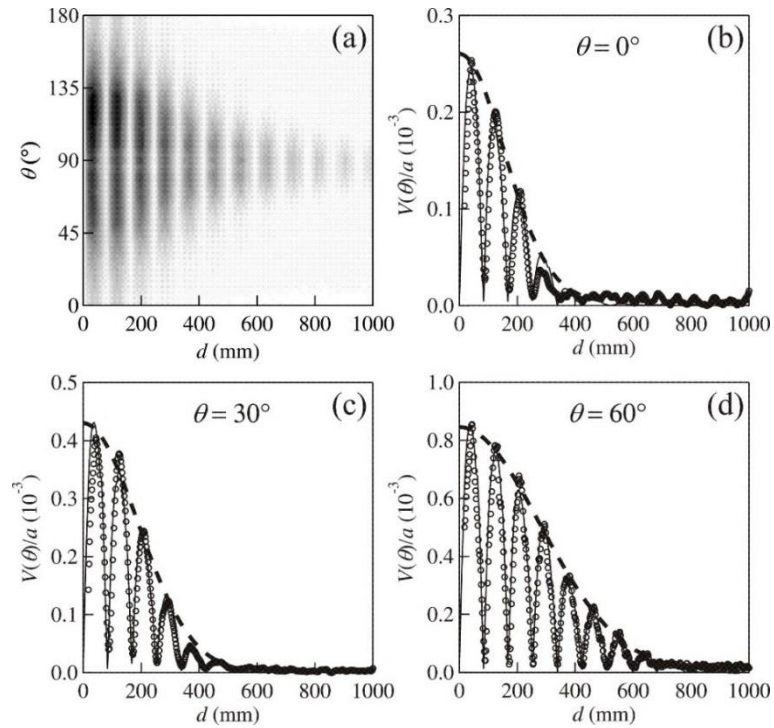
(a) Visibility decay as a function of distances *d* with different mirror slope errors. (b) Coherence length ξ as a function of mirror figure error. (c) Mirror frequency dependence of coherence degradation.

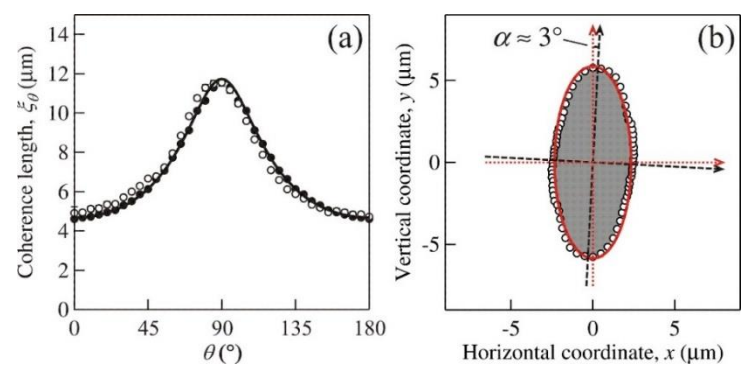
Coherence characterization

- **Circular grating interferometry**









Shi, X., et al., *Appl. Phys. Lett.*, ***105,*** 041116 (2014).

Summary (take-home message)

- The optics requirement for APS-U is challenging but not impossible.
- Preparing for the APS upgrade, the simulation code *HYBRID* has been developed and is being used for general beamline design. Other codes are either available or under development for special beamline design needs.
- We are looking forward to collaborate with beamline scientists and user to design and optimize new/current beamlines, and to perform front-to-end simulations for advanced experimental design.
- To preserve the beam wavefront and coherence, R&D on optics vibration and figure error reduction is needed for the APS-U. Beam characterization tools are under development.
- The ongoing APS beamline measurements (Ruben Reininger, Xianbo Shi, Yingbo Shi) will help the beamline transition to APS-U.
- An ID beamline for optics testing is essential and the key.

High-Energy X-Ray Focusing Workgroup

- Focusing above 50 keV.
- Micron/Submicron High-Energy X-Ray Focusing
  - (Multilayer) mirrors
  - CRLs, Saw-tooth lenses
  - Kinoforms
  - MLL and MZP
- (Sub-)Millimeter High-Energy X-Ray Focusing with Bent Crystals
  - Sagittally/meridionally bent Laue/ Bragg crystals and combinations.
- Future development and possible R&D efforts were suggested

High Energy Focusing Optics

X-ray Science Division

Advanced Photon Source

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Xianbo Shi (chair)
Sarvjit D. Shastri
Chris J. Benmore
Karena W. Chapman
Gregory J. Halder
Yang Ren
Xianghui Xiao
Jonathan D. Almer
Ruben Reininger
Raymond P. Conley
Xianrong Huang
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Thank you!