Current status and development of nanofocusing system at SACLA

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Background

2-satage nanofocusing system (50 nm and sub-10 nm)

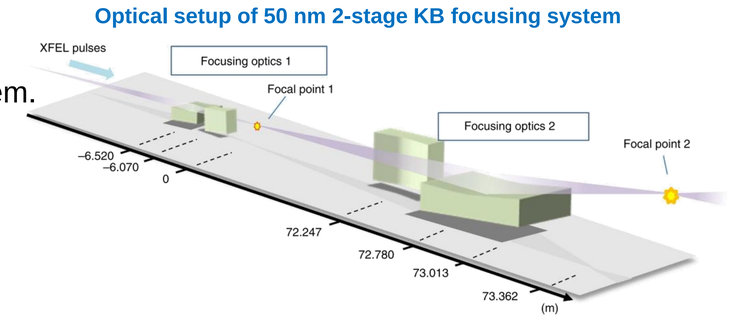
- ✓ Large demagnification factor with compact facility
- ✓ High NA with small divergence of XFEL
- ✓ Unique X-ay sciences were investigated using the 50 nm focusing system.

K. Tamasaku *et al.*, Nat. Photon. 8, 313 (2014).
H. Yoneda *et al.*, Nature, 524, 446 (2015).

However,,,

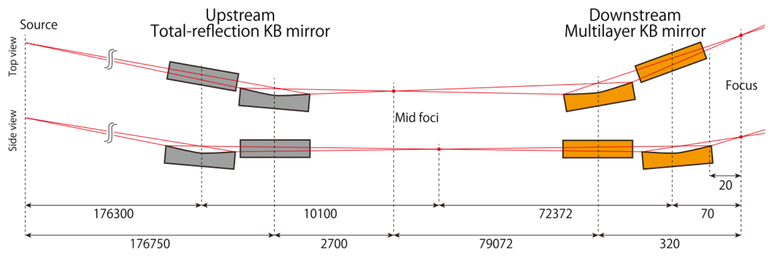
- ✓ Designed before SACLA lasing.
  - ┗ Source position was assumed to be the exit of last undulator.
- ✓ Difficult tuning, but short life time of fine focus
- ✓ Throughput < 10 % (Slightly small acceptable aperture)

Optical setup of 50 nm 2-stage KB focusing system



H. Mimura *et al.*, Nat. Commun. 5, 3539 (2014).

Arrangement of sub-10 nm 2-stage KB focusing system



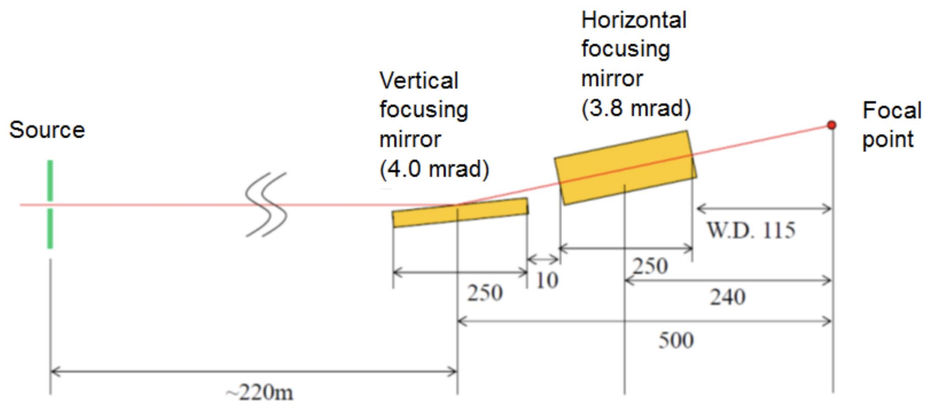
S. Matsuyama *et al.*, Sci. Rep. 8, 17440 (2018).

→ One-stage nanofocusing systems (300 exa & new sub-10) have been developed.

300 exa: 100~ nm focusing system (installed in summer 2017)

Optical design

✓ The system consists of **1-stage KB optics**.

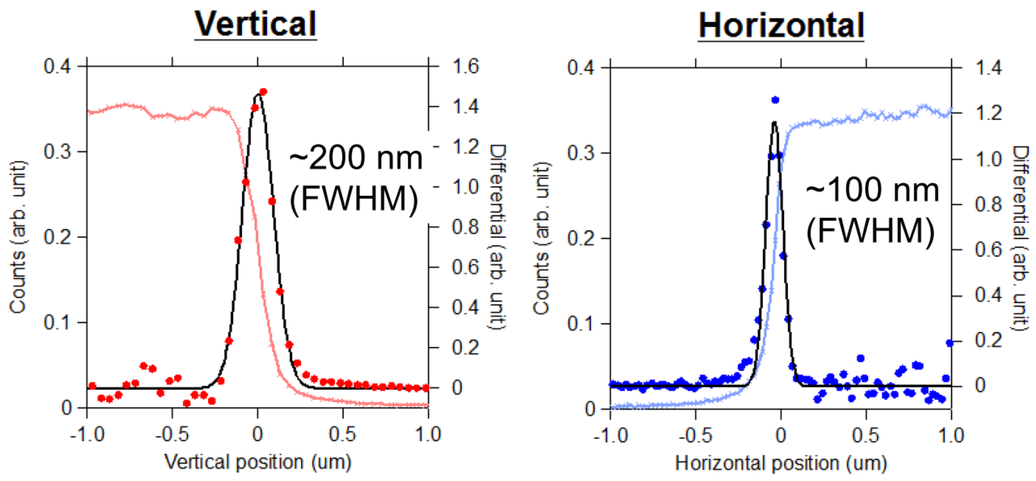


Upstream mirror (Vertical)
- Source-mirror distance: 220 m
- Focal length: 500 mm
- Incident angle: 4.0 mrad
- Mirror length: 250 mm
- Spatial acceptance: 1 mm
- Numerical aperture: 1.0 × 10^{-3}
  →Focus size (diffraction-limit): 45 nm @ 12keV
- Demagnification factor: 440
  →Focus size (geometrical): *~180 nm
- **Focus size (total): ~200 nm**

Downstream mirror (Horizontal)
- Source-mirror distance: 220 m
- Focal length: 240 mm
- Incident angle: 3.8 mrad
- Mirror length: 250 mm
- Spatial acceptance: 0.95 mm
- Numerical aperture: 2.4 × 10^{-3}
  →Focus size (diffraction-limit): 23 nm @ 12keV
- Demagnification factor: 918
  →Focus size (geometrical): *~87 nm
- **Focus size (total): ~100 nm**

* The parameters depend on the source condition of SACLA

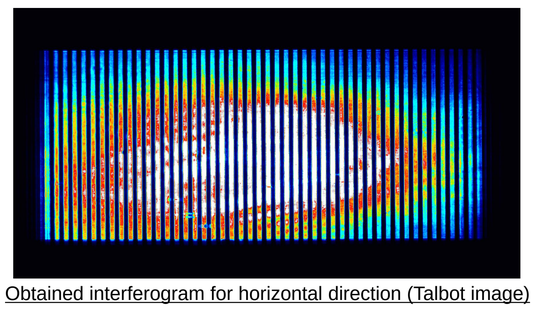
Typical focusing profile @ BL3 (EH5)



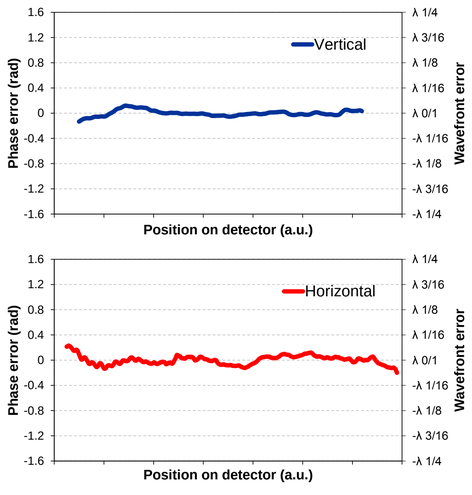
Specification

- Focus size (average): 200 nm (V) × 100 nm (H)
- Intensity: ~**3×10^{20} (=300 exa) W/cm^2**
- Rayleigh length: ~30 μm
- Throughput: ~25 %
- Tolerance of incident angle error: 1~2 μrad
- Cut-off energy: 12 keV
- Tuning time for mirrors: ~2 hours
- Lifetime of focus: > 10 hours
- Sample: Foil, Liquid jets, Gas chamber, etc.

Wavefront errors measured by grating-interferometer



Obtained interferogram for horizontal direction (Talbot image)



✓ **Wavefront errors < 0.4 rad (λ/16)**
  ┗Accuracy of the system was extremely high.

Unique studies are expected

✓ Nonlinear X-ray physics: XFEL-pumped Ka laser, X-ray saturable absorption, etc.

c.f. H. Yoneda *et al*., Nature Commun., 5, 5080 (2014).

✓ Diffraction measurement: fs-damage observation, etc.

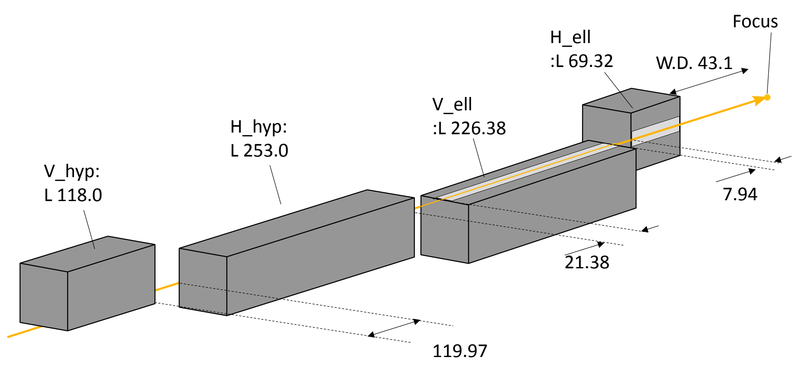
c.f. I. Inoue *et al.,* Proc. Natl. Acad. Sci. USA. 113, 1492-1497 (2016).

New sub-10 nm focusing system (under development)

Optical design

✓ The system consists of 1-stage **Wolter III-advanced KB optics**.

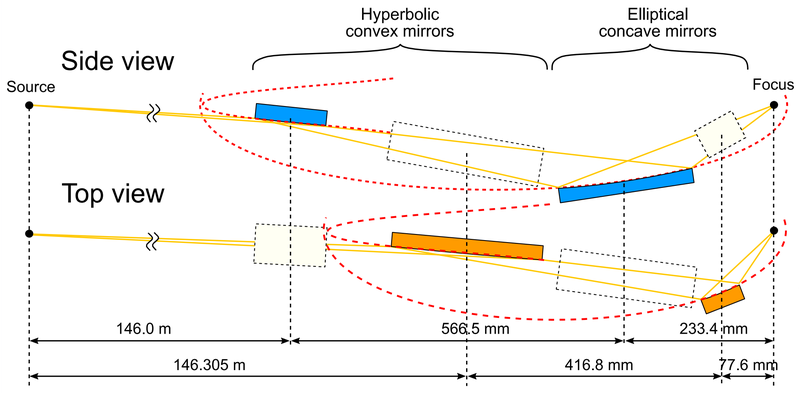
J. Yamada *et al.*, Appl. Opt. 56(4), 967 (2017).
J. Yamada *et al.*, Opt. Express 27(3), 3429 (2019).



Parameters of new sub-10 nm focusing system

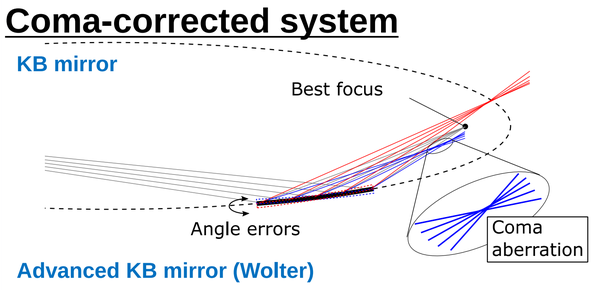
	Horizontal		Vertical	
	Hyp	Ell	Hyp	Ell
Glancing angles (mrad)	1.95	23.4	3.8	18.9
Coating	Single layer	Multilayer	Single layer	Multilayer
NA	10.2 × 10^{-3}		9.5 × 10^{-3}	
Acceptance (μm)	490		440	
Demagnification	6037~**7773***		4435~**6052***	
X-ray energy (keV)	9.1			
Designed reflectivity (%)	~ 50.8 (@ σ =0.25)			
Expected focus size (nm)	**6.4** ~ 8.6*		**7.2** ~ 8.9*	
Intensity (W/cm^2)	$10^{21\sim22}$			

* The parameters depend on the source condition of SACLA
(source size: σ16~20 (V), σ25~32 (H) μm
source-mirror: 107~146 (V), 146~188 (H) m
estimated by past experiments)

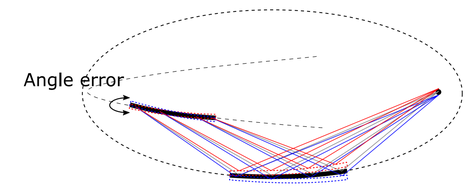


Coma-corrected system

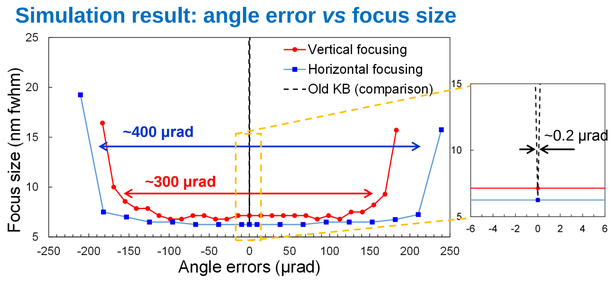
KB mirror



Advanced KB mirror (Wolter)

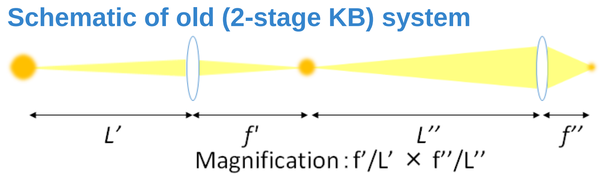


Simulation result: angle error *vs* focus size

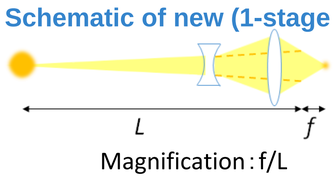


Compact but large demag.

Schematic of old (2-stage KB) system



Schematic of new (1-stage advanced KB) system



✓ To focus the XFEL source (~60 μm) down to 10nm, demag. factor of 6000~ is necessary.

✓ **Demag. factor of > 6000** is available with the **~145 m source-mirror distance** in new system.

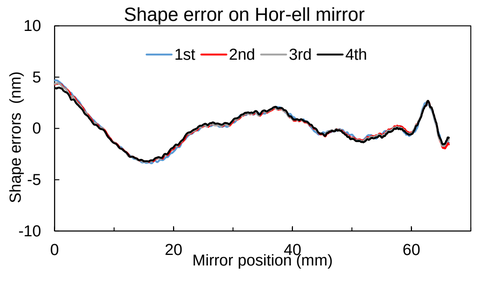
Results of 1st commissioning @ SPring-8

✓ 1-dimensional (horizontal) focusing test was performed.

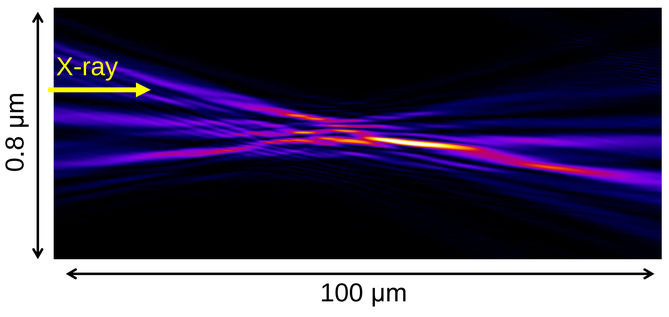
✓ **Alignment time was ~2 hours** with good repeatability and stability.

✓ Shape accuracy of mirror was 4~5 nm PV, characterized by grating-interferometer.
  ┗ Goal is ~1 nm PV. Mirrors will be re-polished.

Mirror shape error estimated by measured wavefront



Calculated focusing intensity based on measured wavefront



Mirrors are still under developments.
The system will be installed to BL3 (EH4c) in 2020 summer~.