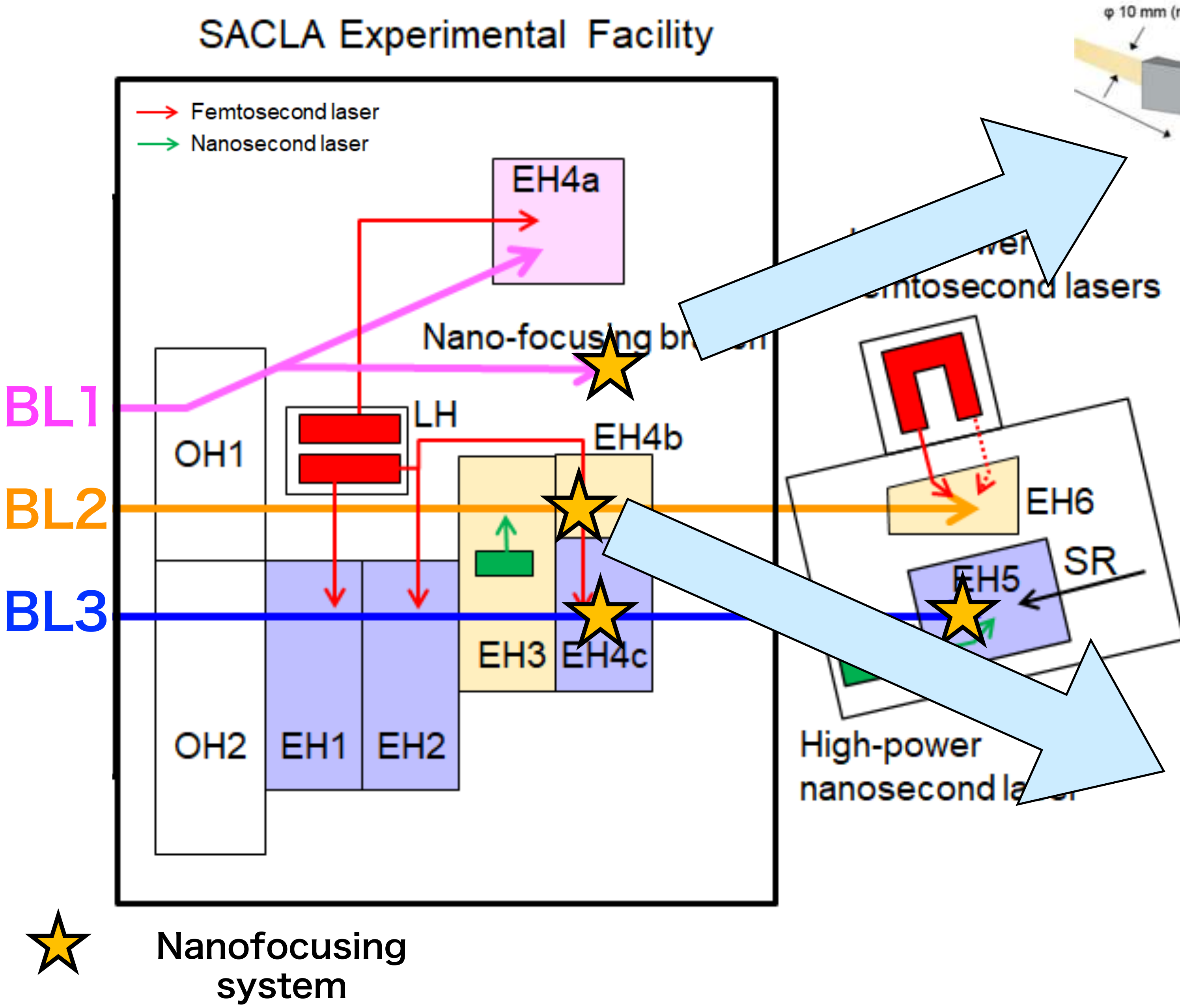
Specification and operation details of 100 nm & sub-10 nm focusing system at SACLA

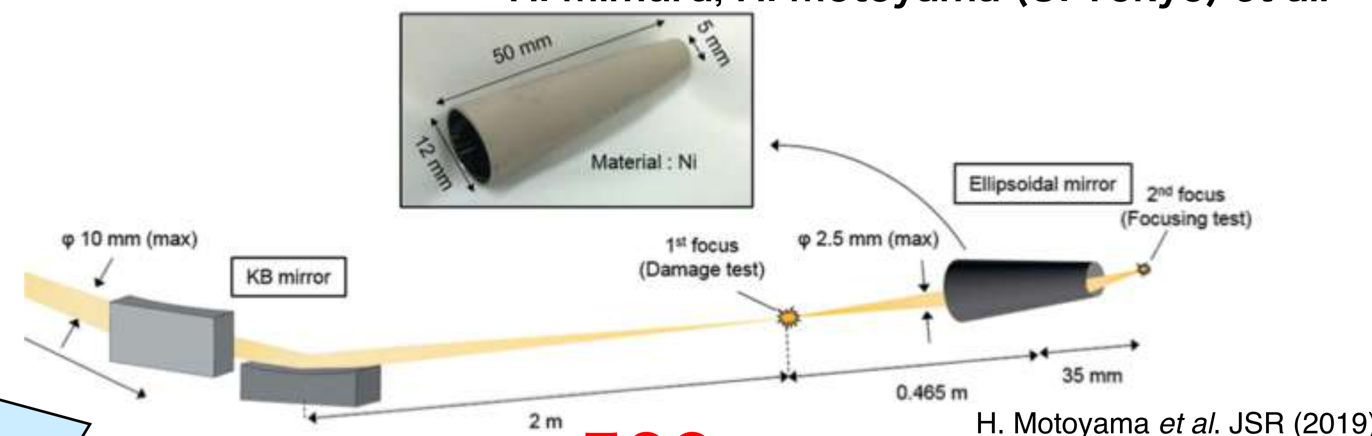
Jumpei Yamada (SACLA)

Nanofocusing system at SACLA



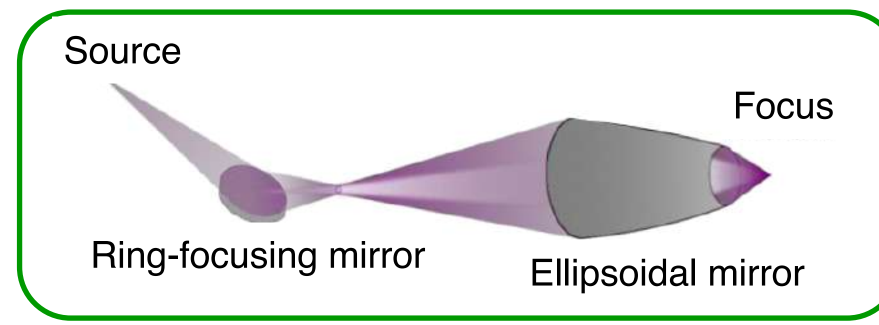
Soft X-ray nanofocusing

H. Mimura, H. Motoyama (U. Tokyo) *et al.*



H. Motoyama *et al.* JSR (2019)

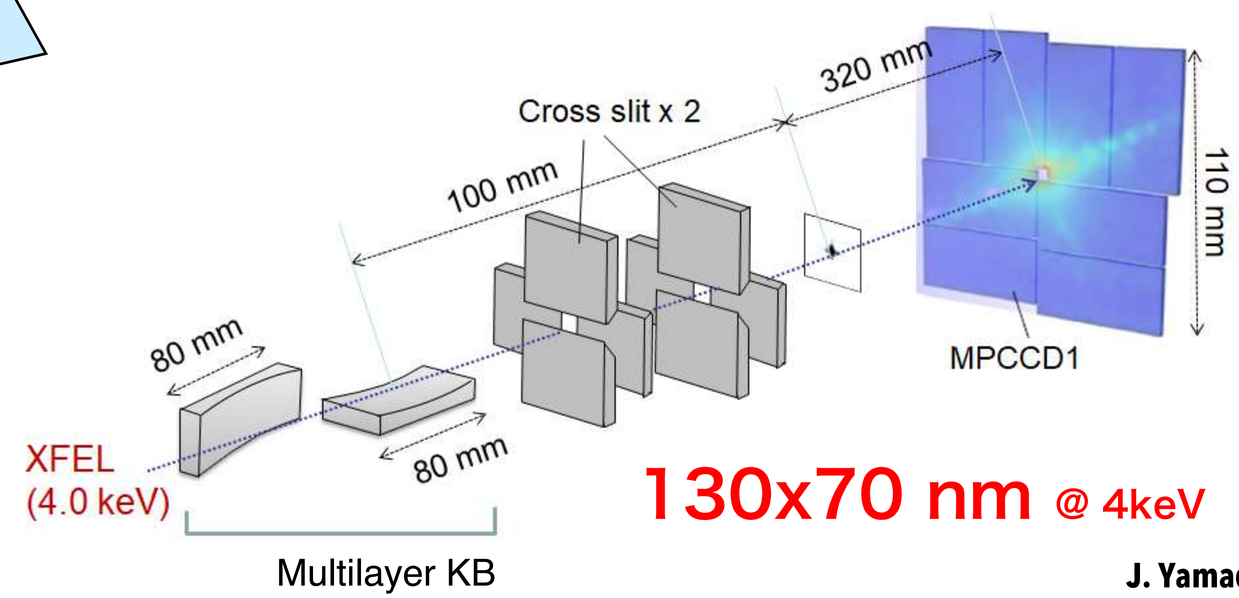
~500 nm @ 100~120eV



~50 nm @ 40~150eV is emerging

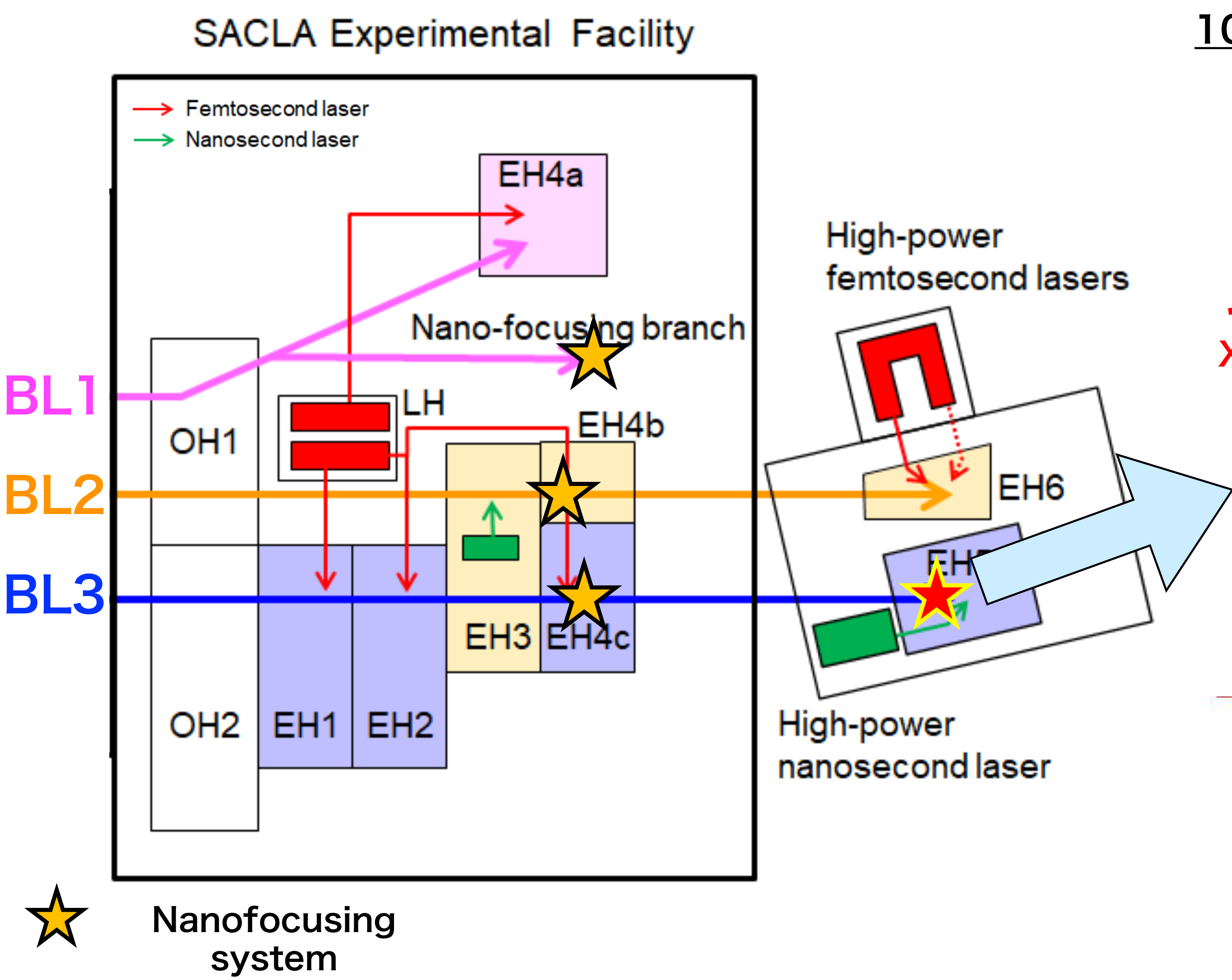
Nanofocusing for CDI (MAXIC-S)

H. Yumoto, T. Koyama, H. Ohashi (SACLA & SPring-8)
T. Kimura, A. Suzuki, Y. Nishino (Hokkaido U.), et al.

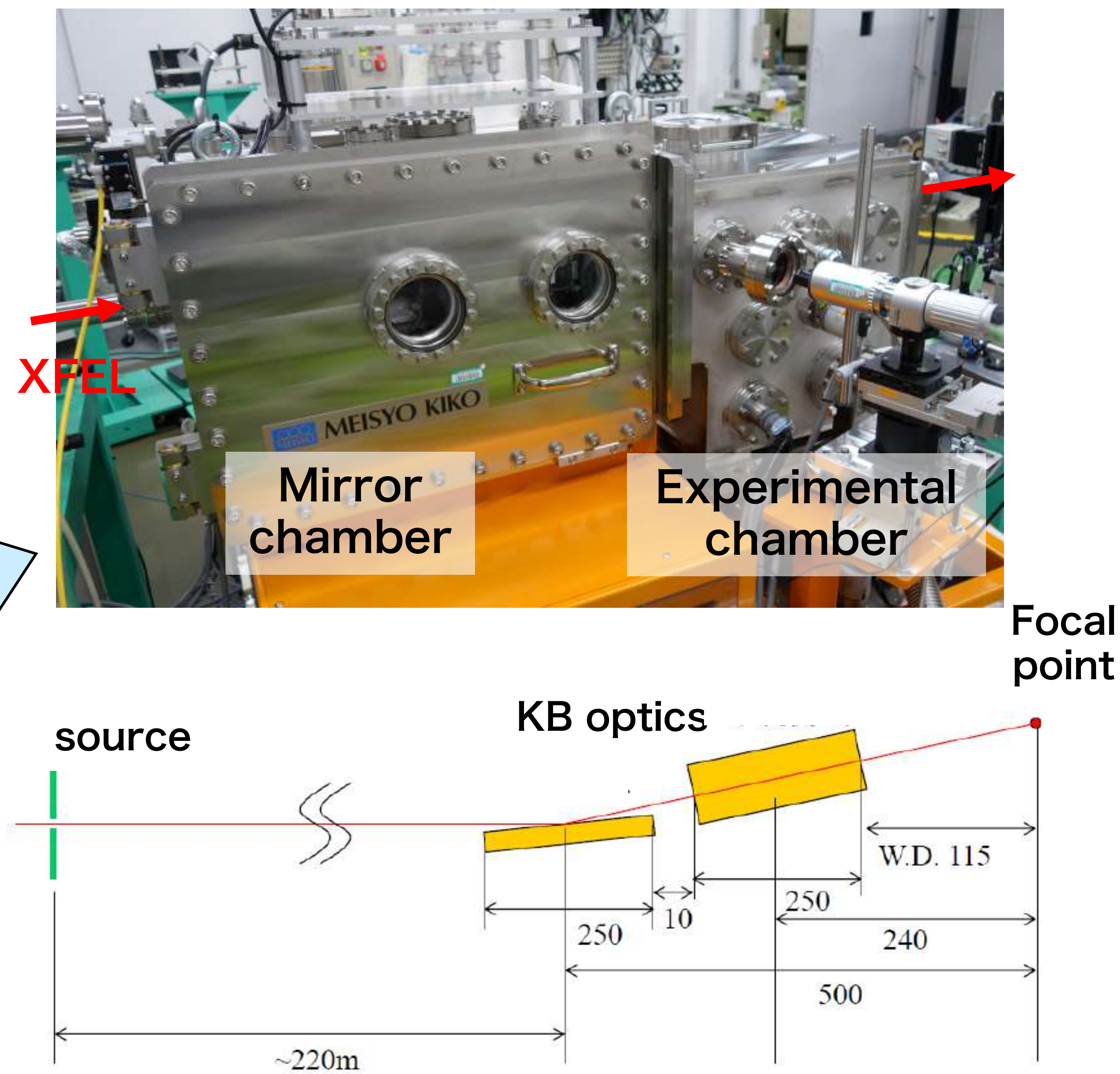


130x70 nm @ 4keV

Topics1: 100exa system



100-200 nm focusing @ 6-12keV (100exa)

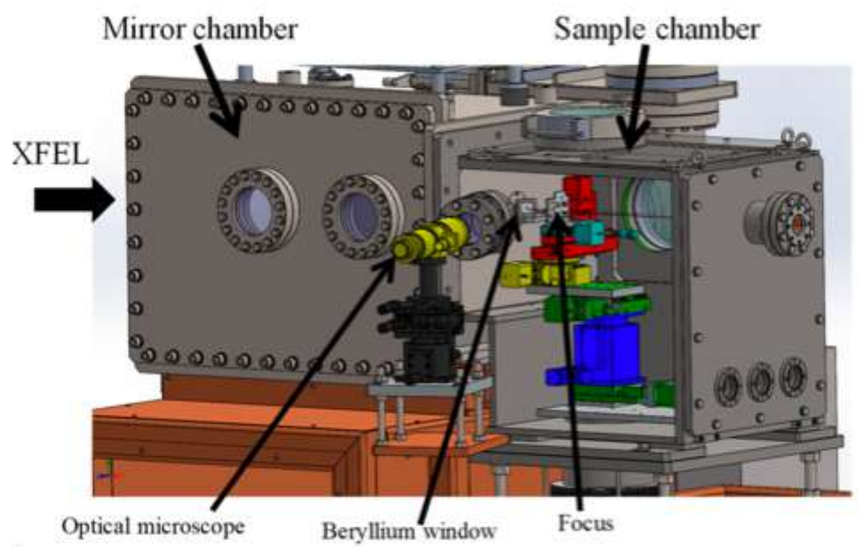


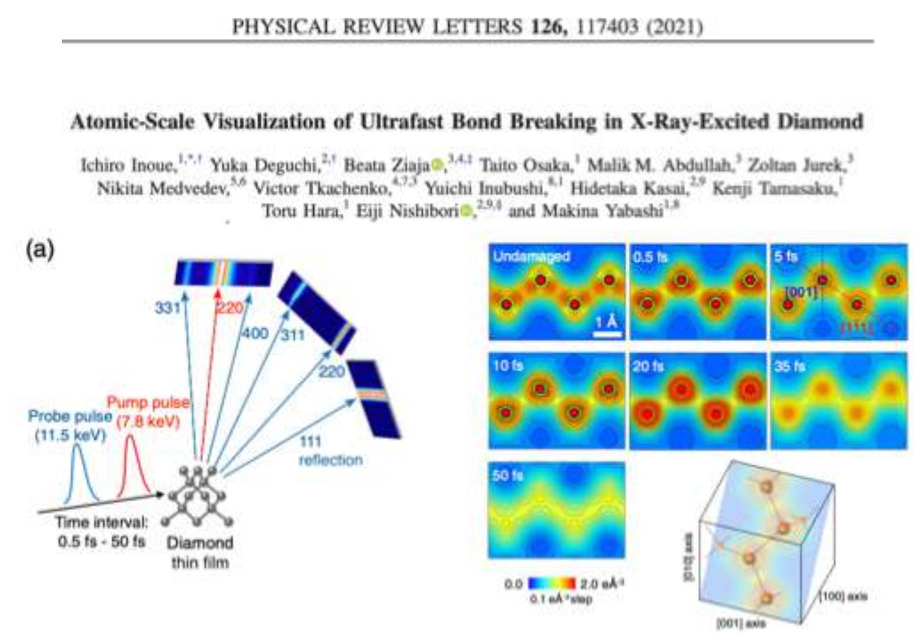
J. Yamada

100exa focusing system

XFEL 100-200 nm focusing with **10^{20} W/cm²** (=**100EW/cm²**)


Drs. Ohashi-san, Yumoto-san (JASRI)




PHYSICAL REVIEW LETTERS 126, 117403 (2021)

Atomic-Scale Visualization of Ultrafast Bond Breaking in X-Ray-Excited Diamond

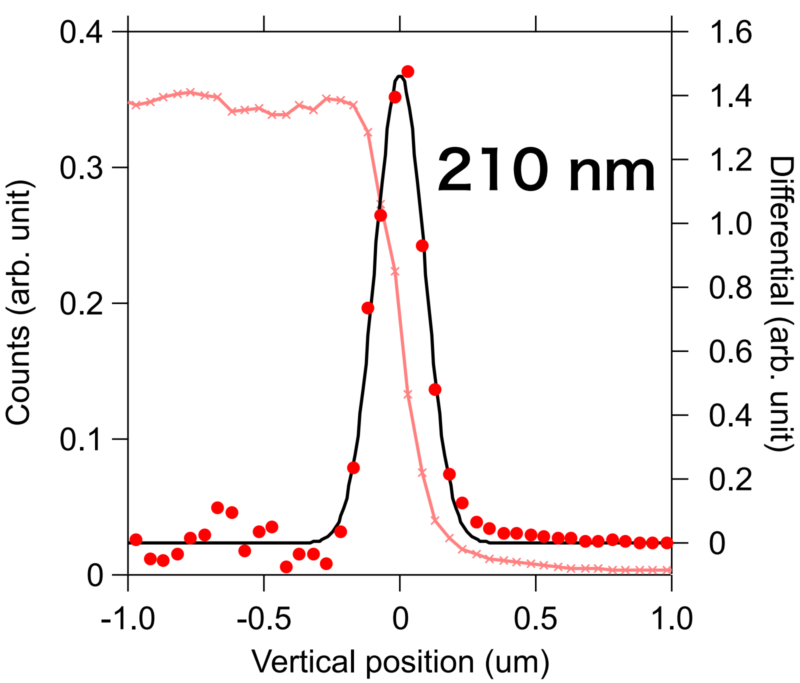
Ichiro Inoue, Yuka Deguchi, Beata Ziaja, Taito Osaka, Malik M. Abdullah, Zoltan Jurek, Nikita Medvedev, Victor Tkachenko, Yuichi Inubushi, Hidetaka Kasai, Kenji Tamasaku, Toru Hara, Eiji Nishibori and Makina Yabashi

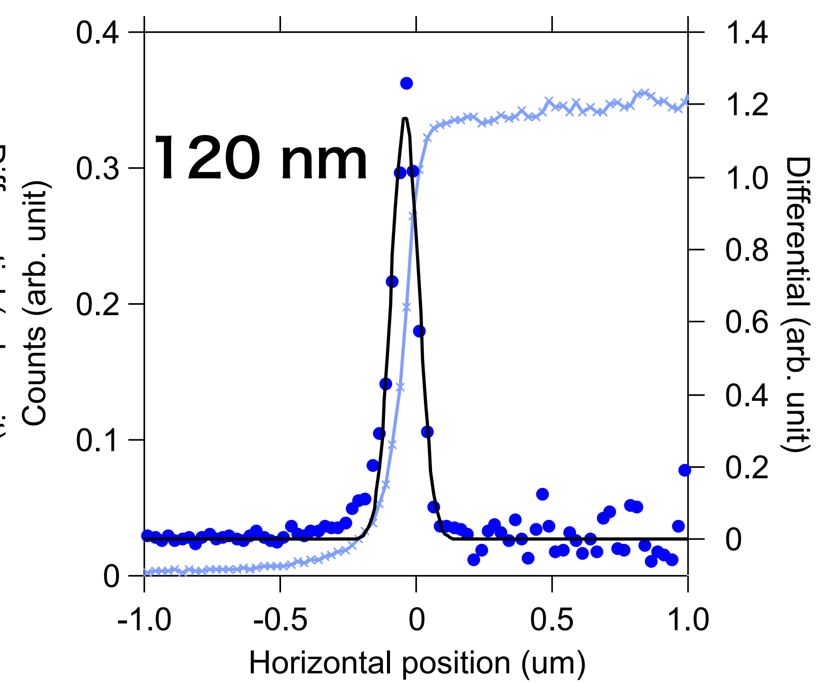
I. Inoue *et al.*, PRL **126** (2021)

Focus size

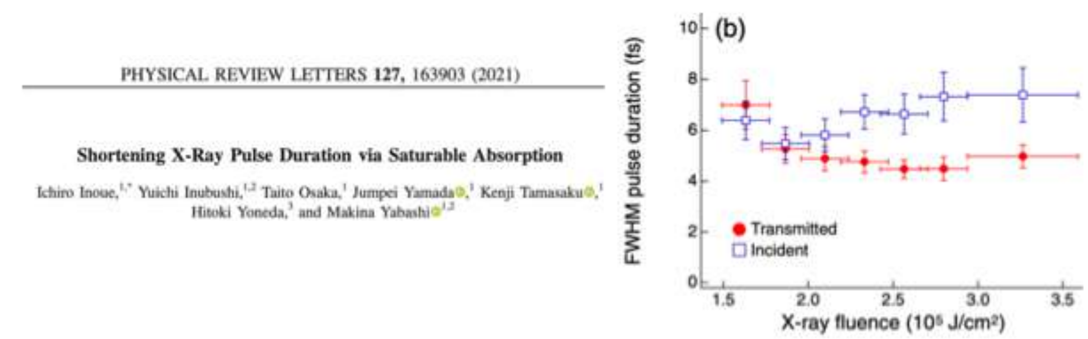
Vertical

Horizontal





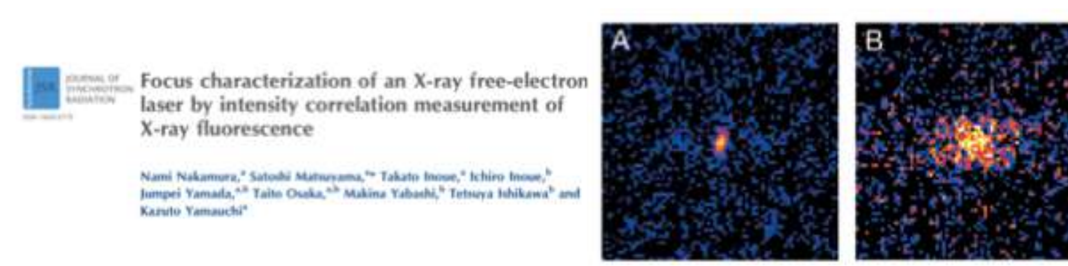
H. Yumoto *et al.*, Appl. Sci. (2020)


PHYSICAL REVIEW LETTERS 127, 163903 (2021)

Shortening X-Ray Pulse Duration via Saturable Absorption

Ichiro Inoue, Yuichi Inubushi, Taito Osaka, Jumpei Yamada, Kenji Tamasaku, Hitoki Yoneda, and Makina Yabashi

I. Inoue *et al.*, PRL **127** (2021)

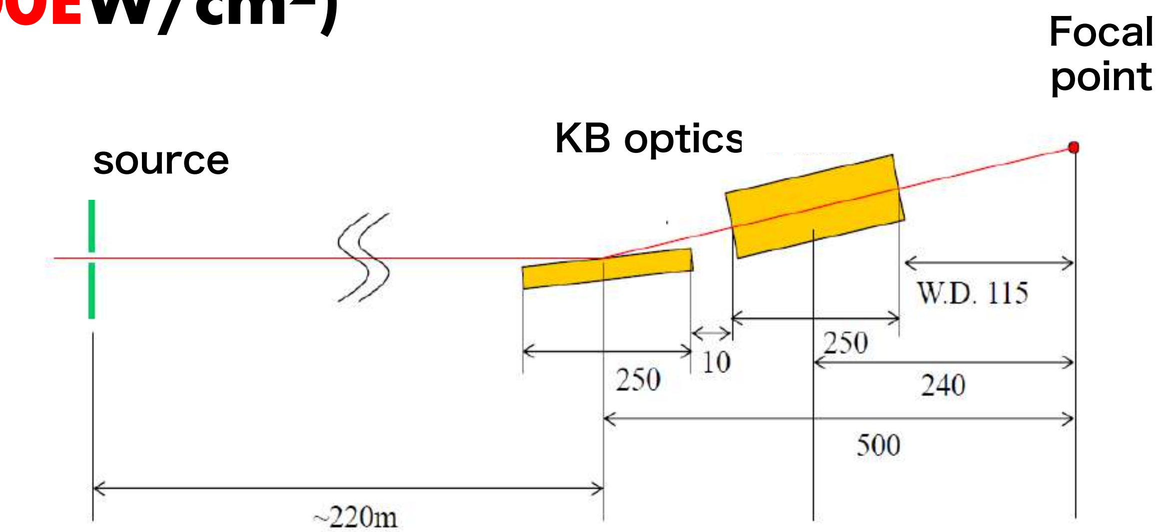

Focus characterization of an X-ray free-electron laser by intensity correlation measurement of X-ray fluorescence

Nami Nakamura, Satoshi Matsuyama, Takato Inoue, Ichiro Inoue, Jumpei Yamada, Taito Osaka, Makina Yabashi, Tetsuya Ishikawa and Kazuto Yamauchi

N. Nakamura *et al.*, JSR **27** (2020)

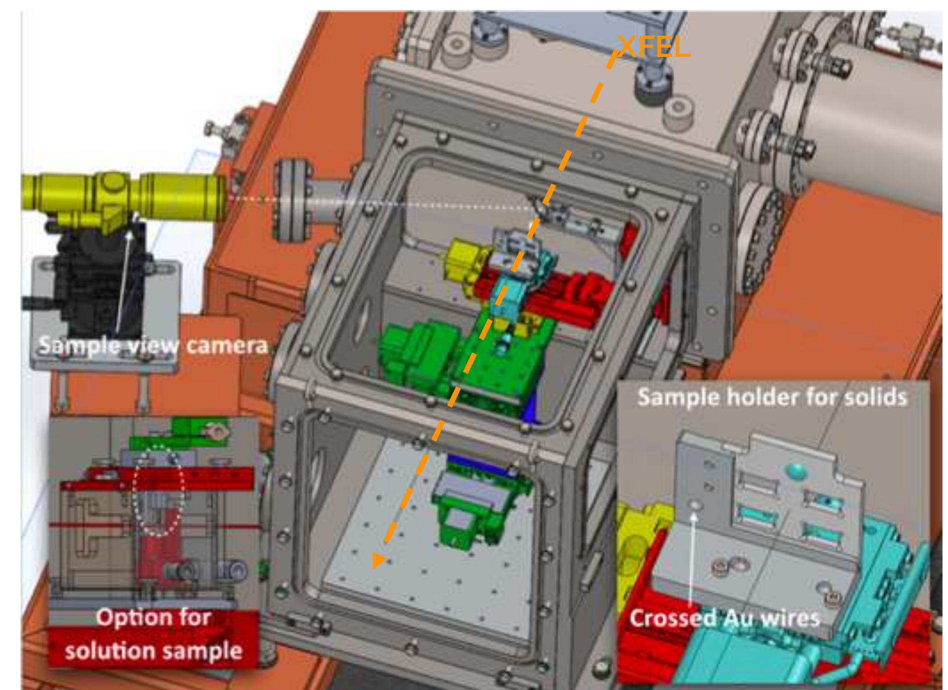
100exa focusing system

XFEL 100-200 nm focusing with 10^{20} W/cm² (=100EW/cm²)



Specification

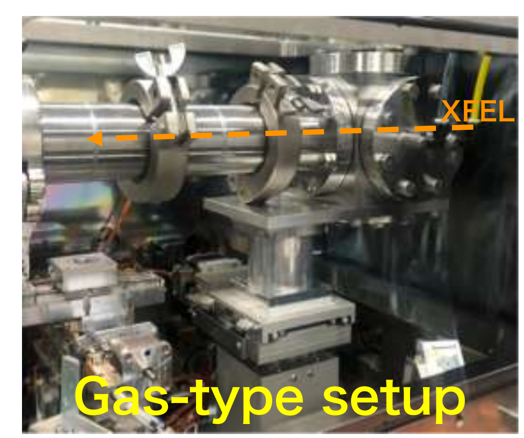
Photon energy :	<12 keV
Reflectivity:	>80 % @ 12keV
Acceptance:	~1 x 1 mm (cf. incident ~550 um fwhm)
Throughput:	>25% (including all BL-optics)
Sample type:	Solid (foil), liquid jet, gas, etc.
Focus size:	~100 nm x ~200 nm
Depth of focus:	~65 um
Tuning time:	4~5 hours (initial tuning) **2~3 hours (re-focusing)**
Lifetime of focus:	**~12 hours**

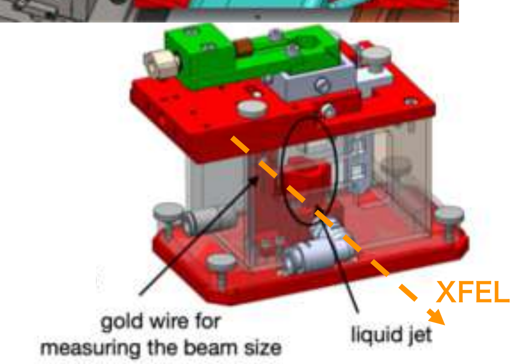


Issues

The measurements have been restricted by re-focusing
└ ~3h of interruption every 10~12h.

Re-focusing was just try-errors of wire-scanning
└ Less quantitative
└(BL staffs were exhausted…)



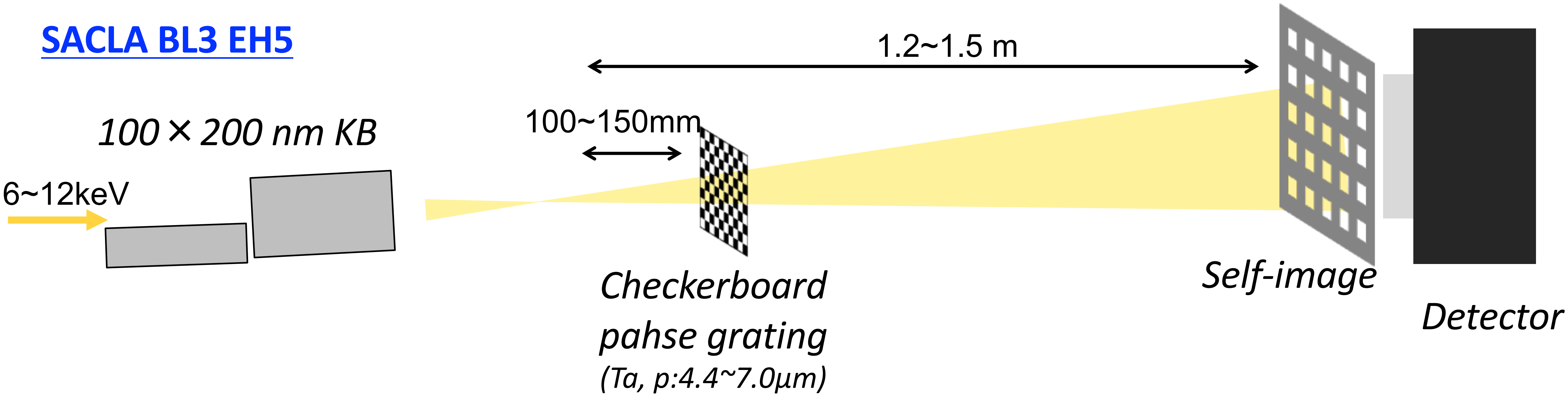


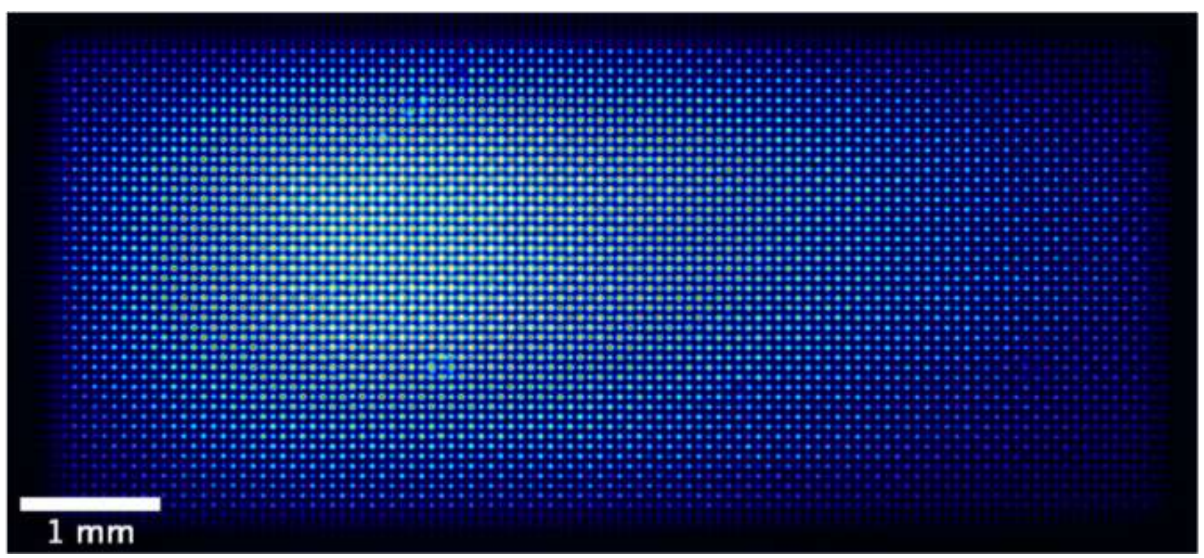
Liquid-type setup

J. Yamada

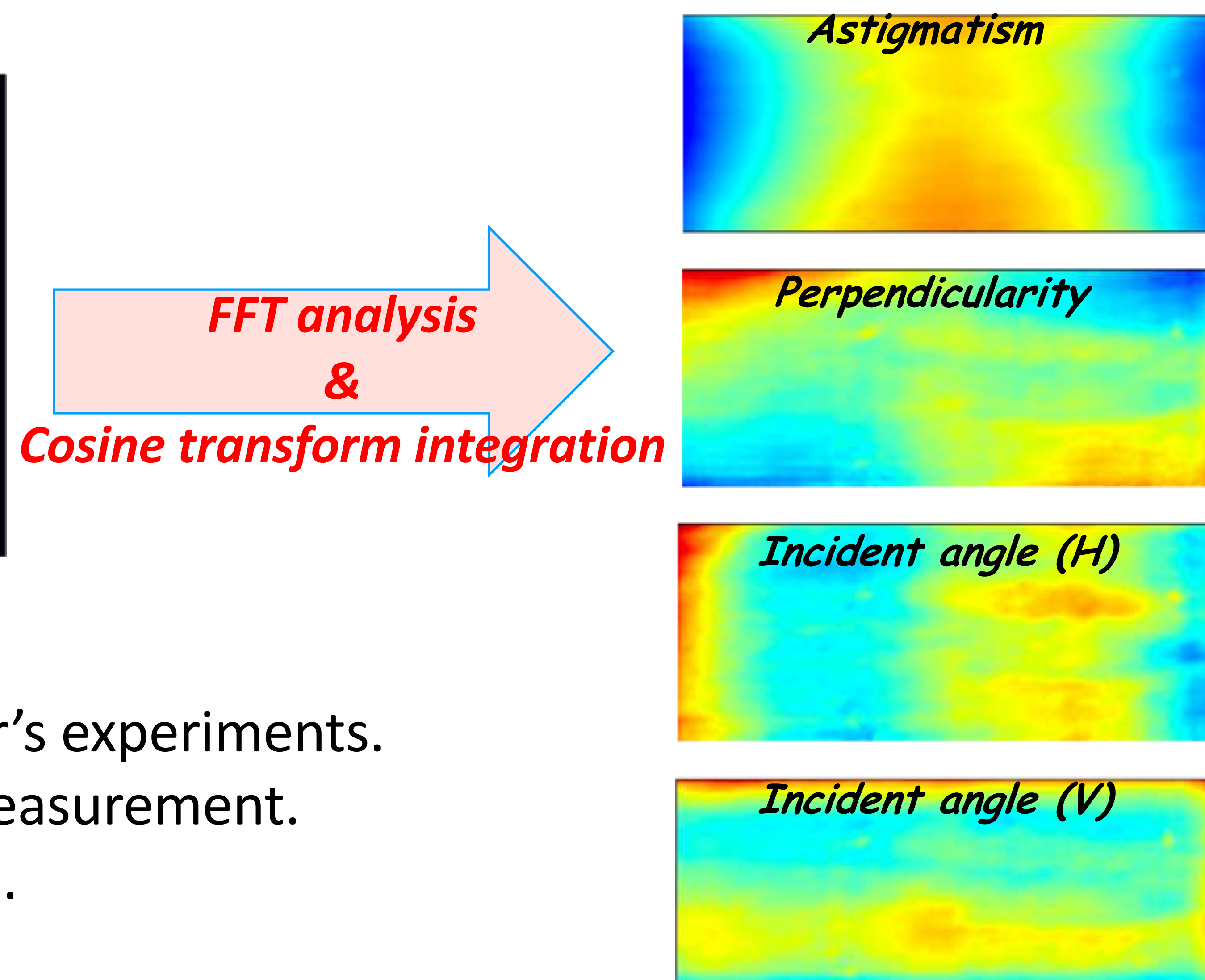
Automated optimization of 100exa: nanofocusing KB via wavefront measurement

SACLA BL3 EH5





Typical self-image

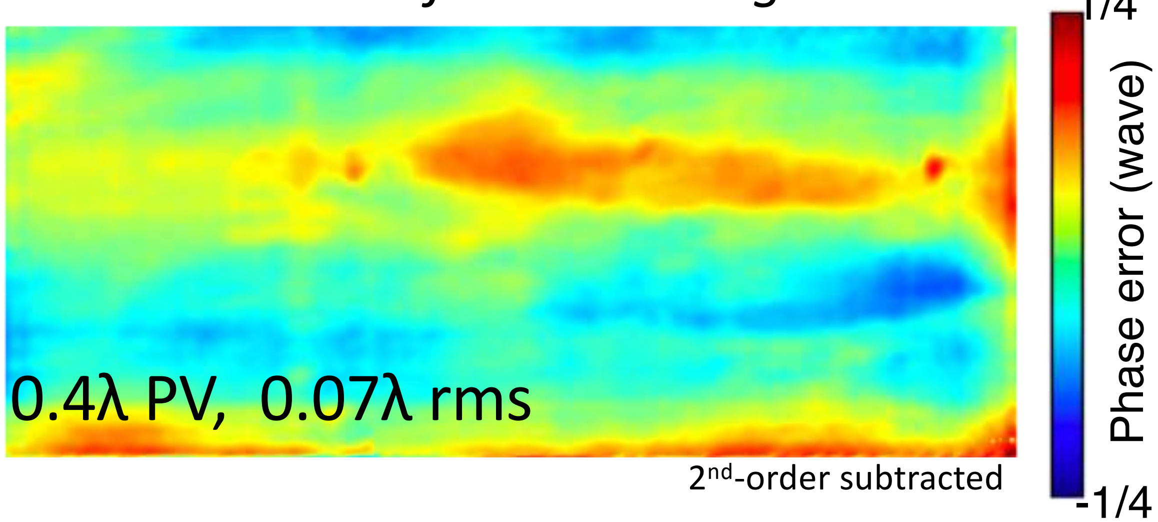


- ☑ Relatively compatible setup with user's experiments.
- ☑ Fast and less-chromatic wavefront measurement.
- ☑ Quantification of KB alignment errors.

Automated optimization of 100exa: nanofocusing KB via wavefront measurement

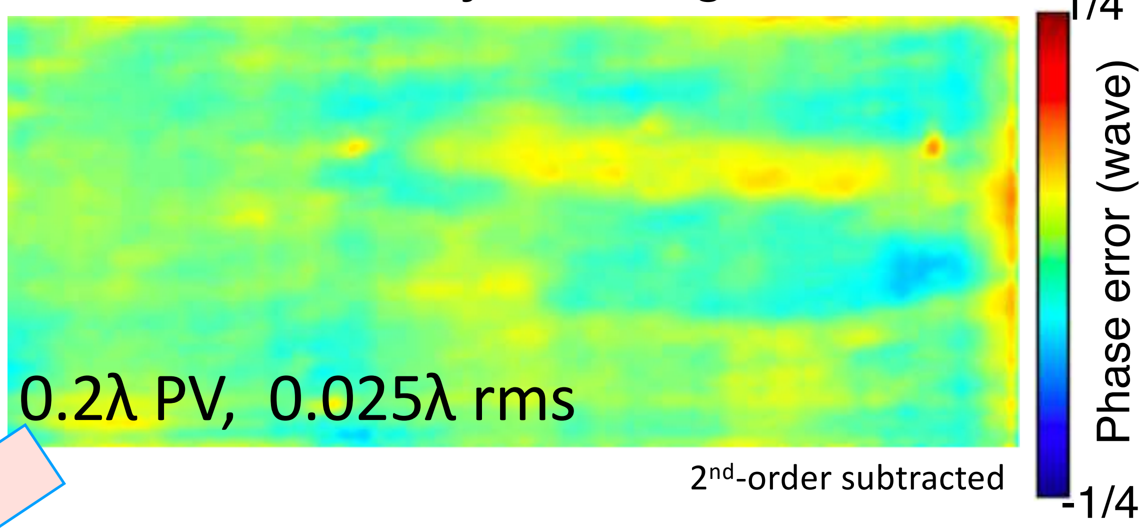
Performance Test @ 9.07 keV SASE

10 hours after the tuning



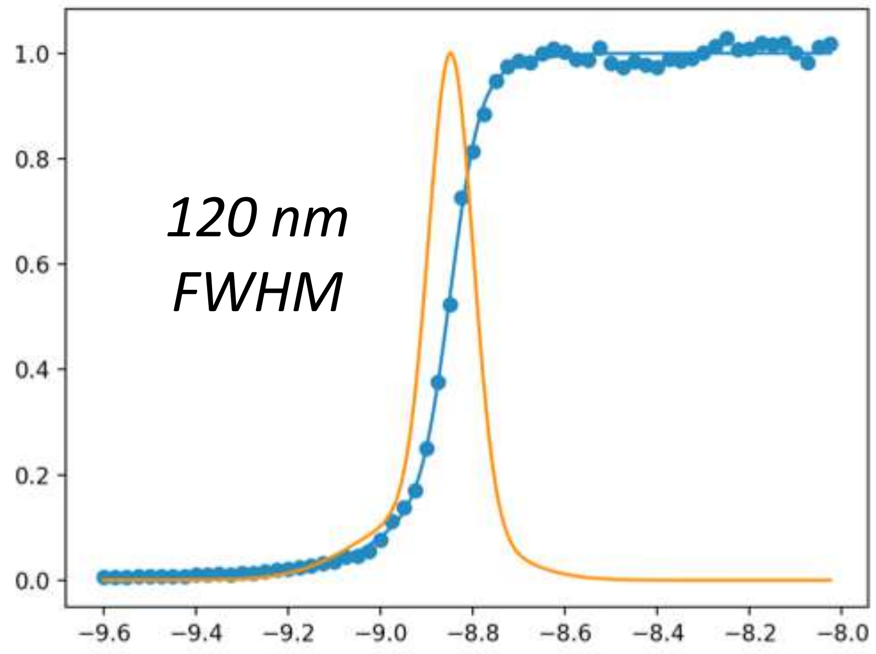
<10 min.
Auto-tuning

Result of re-tuning

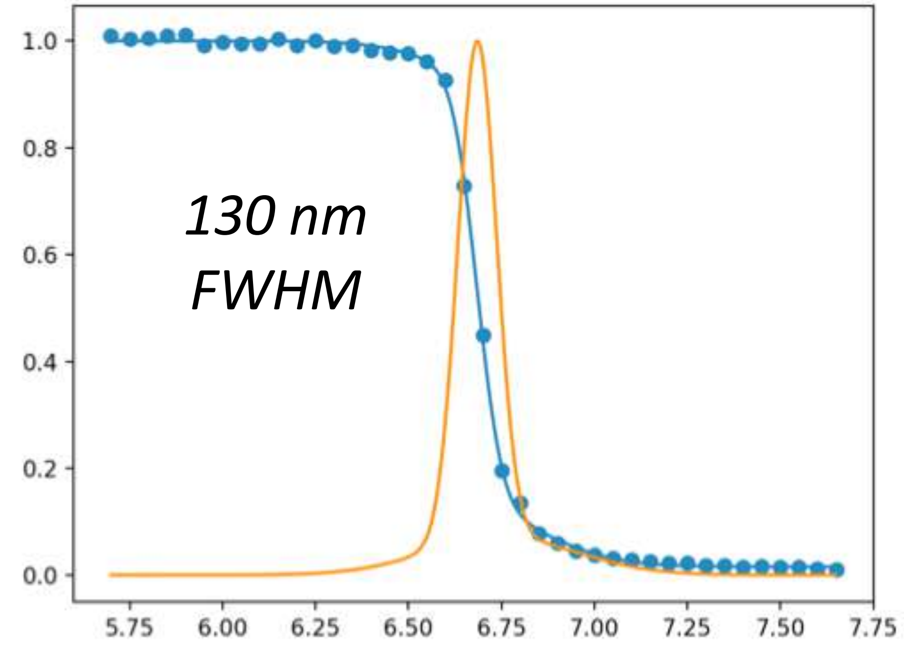


Cross-check with wire (knife-edge) scan

Horizontal



Vertical



☑ 2~10 min auto-refocusing is available by users themselves.

☑ The wavefront was consistent with the knife-edge scan.

J. Yamada

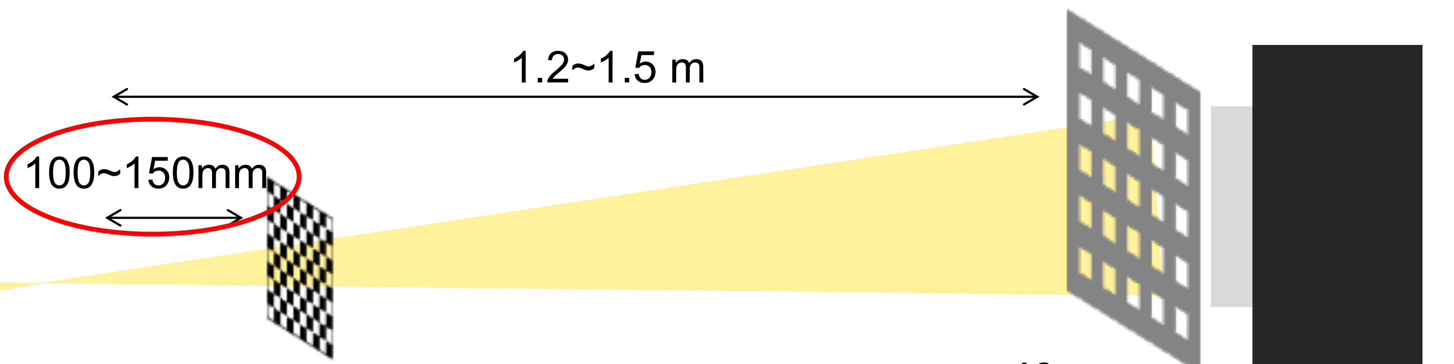
Topics1: 100exa system

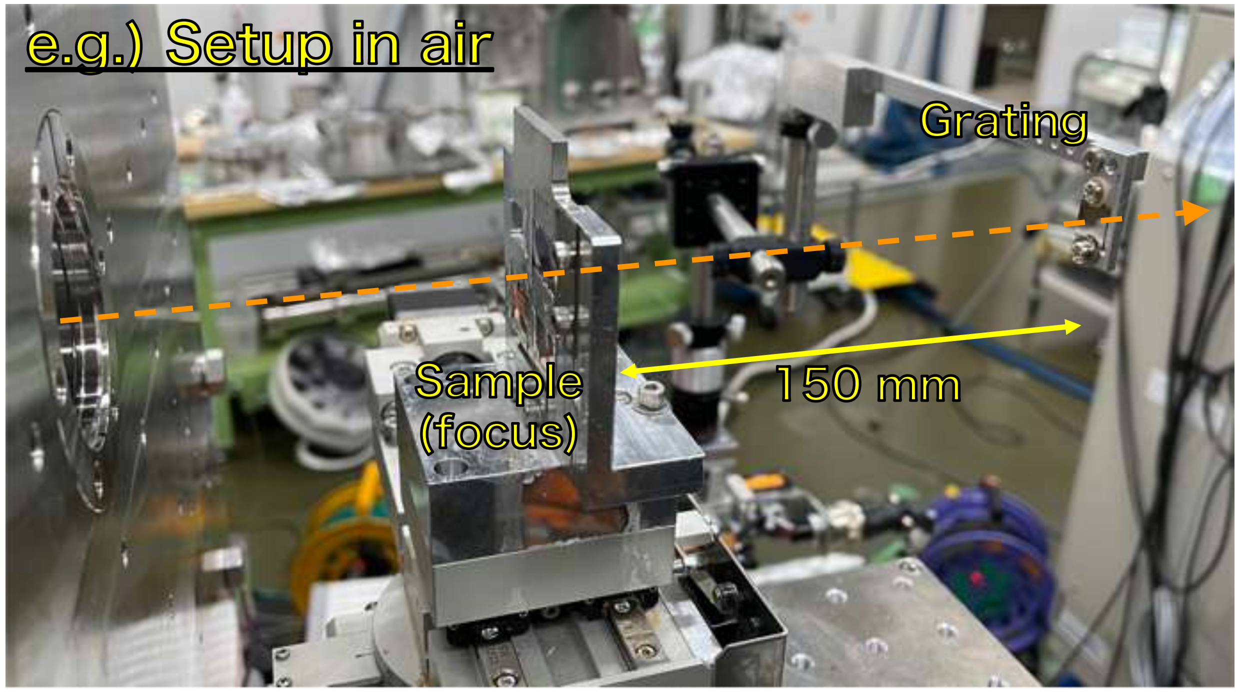
From SACLA side:

We recommend to use the grating-based auto-tuning system.

If acceptable, convenient & effective nanofocused XFEL will be available.

Requirement: Make space for the grating



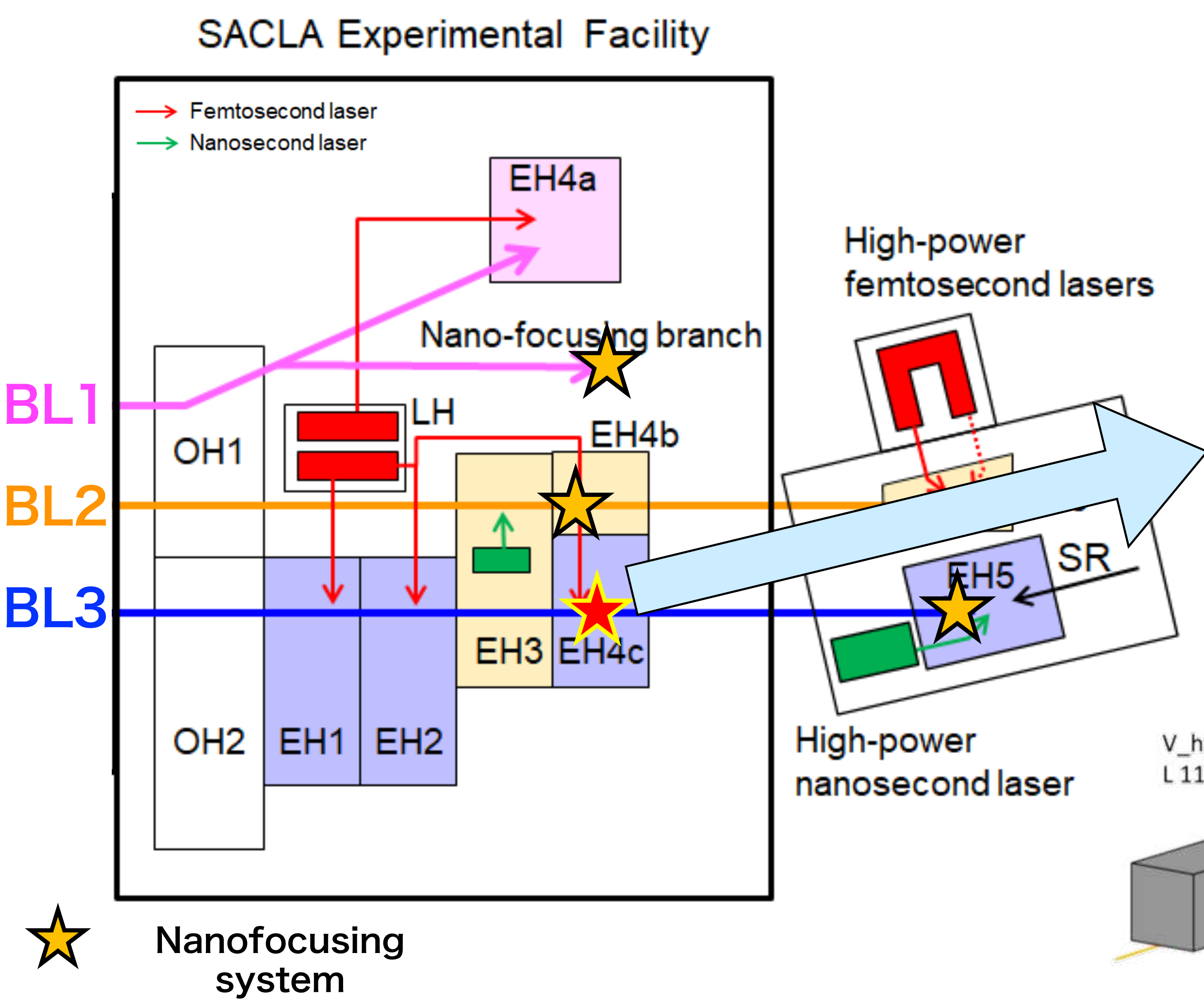


Photon Energy	5.50	5.75	6.00	6.25	6.50	6.75	7.00	7.25	7.50	7.75	8.00	8.25	8.50	8.75	9.00	9.25	9.50	9.75	10.00	10.25	10.50	10.75	11.00	11.25	11.50	11.75	12.00
Grating1: 4.4um								5/8	5/8	5/8	5/8	5/8	5/8	5/8	5/8	5/8	5/8	5/8	5/8	5/8	5/8	5/8	5/8	5/8	5/8	5/8	5/8
Grating2: 7um					3/8	3/8	3/8	3/8	3/8	3/8	3/8	3/8	3/8	3/8	3/8												
Grating3: 6.4um	5/8	5/8	5/8	5/8	5/8					3/8	3/8	3/8	3/8	3/8	3/8	3/8	3/8	3/8	3/8	3/8	3/8						

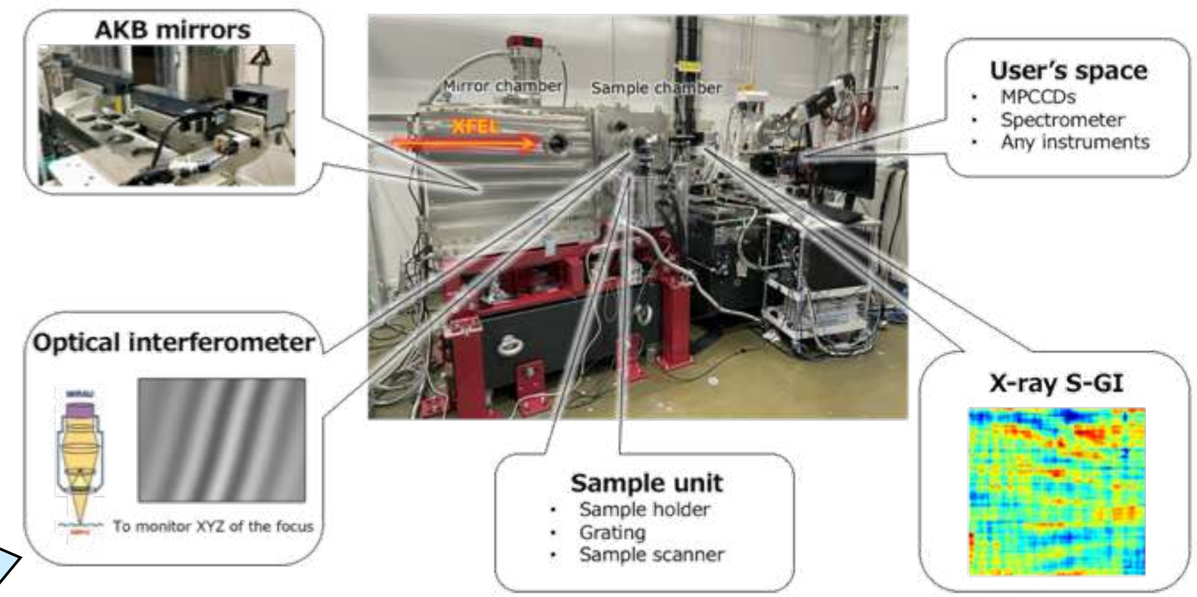
5/8 Talbot order (blue) 3/8 Talbot order (yellow)

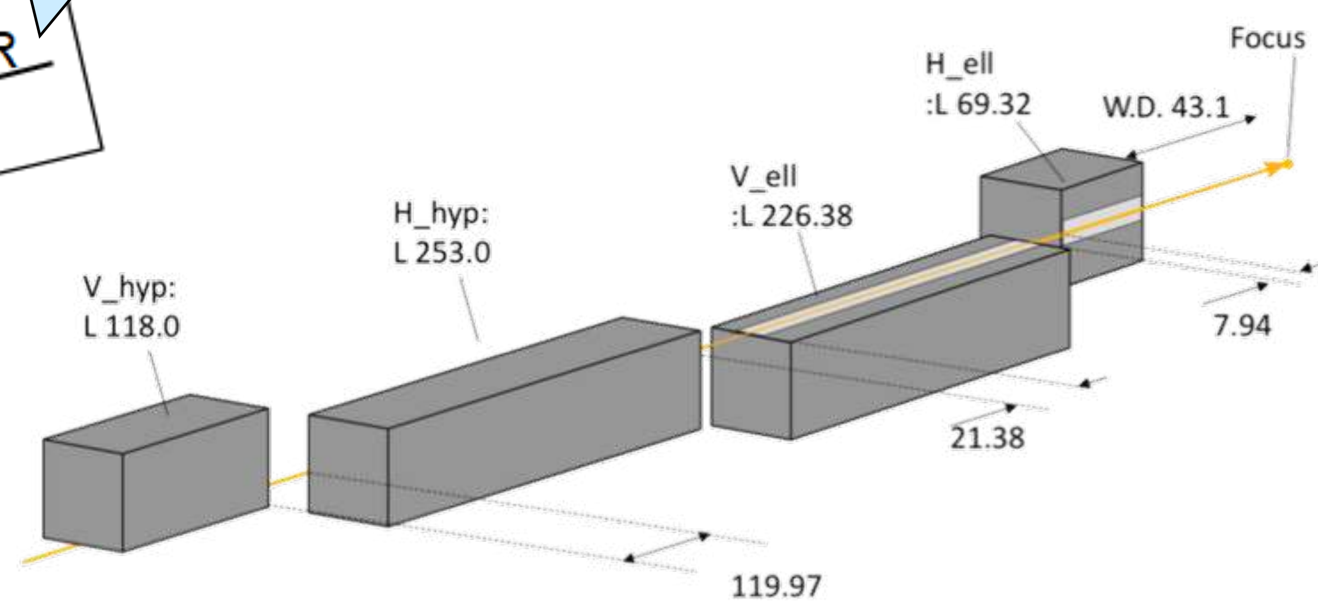
J. Yamada

Topics2: sub-10 nm system



Sub-10 nm focusing @ 9.1keV





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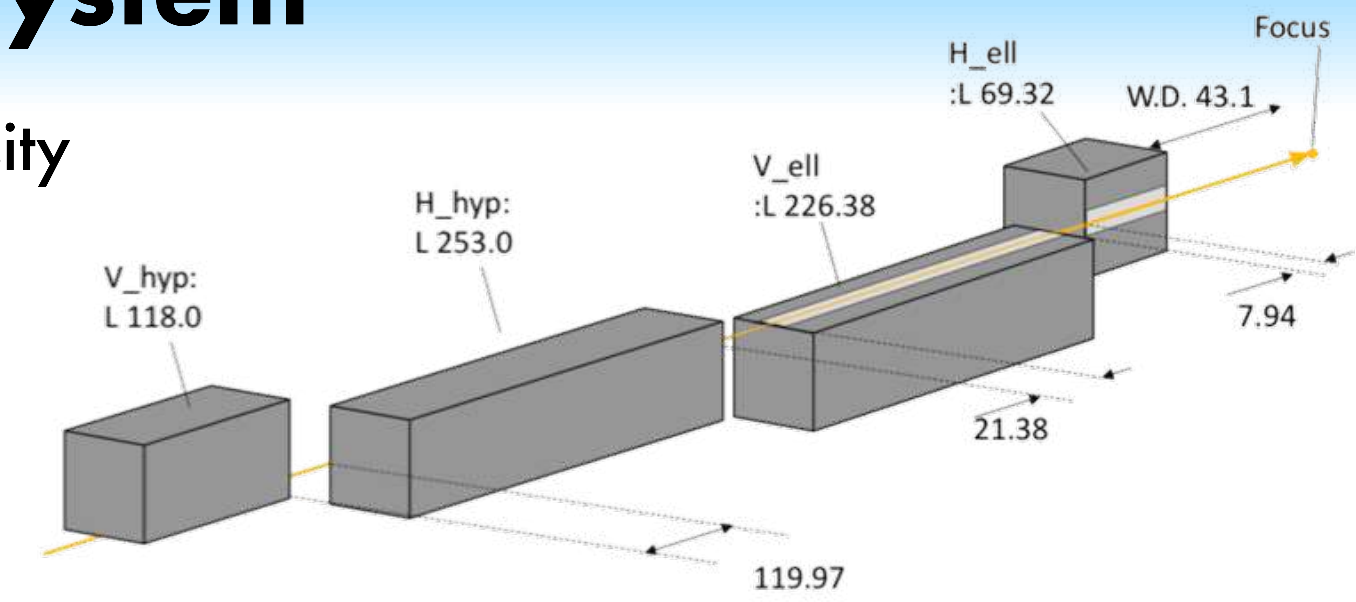
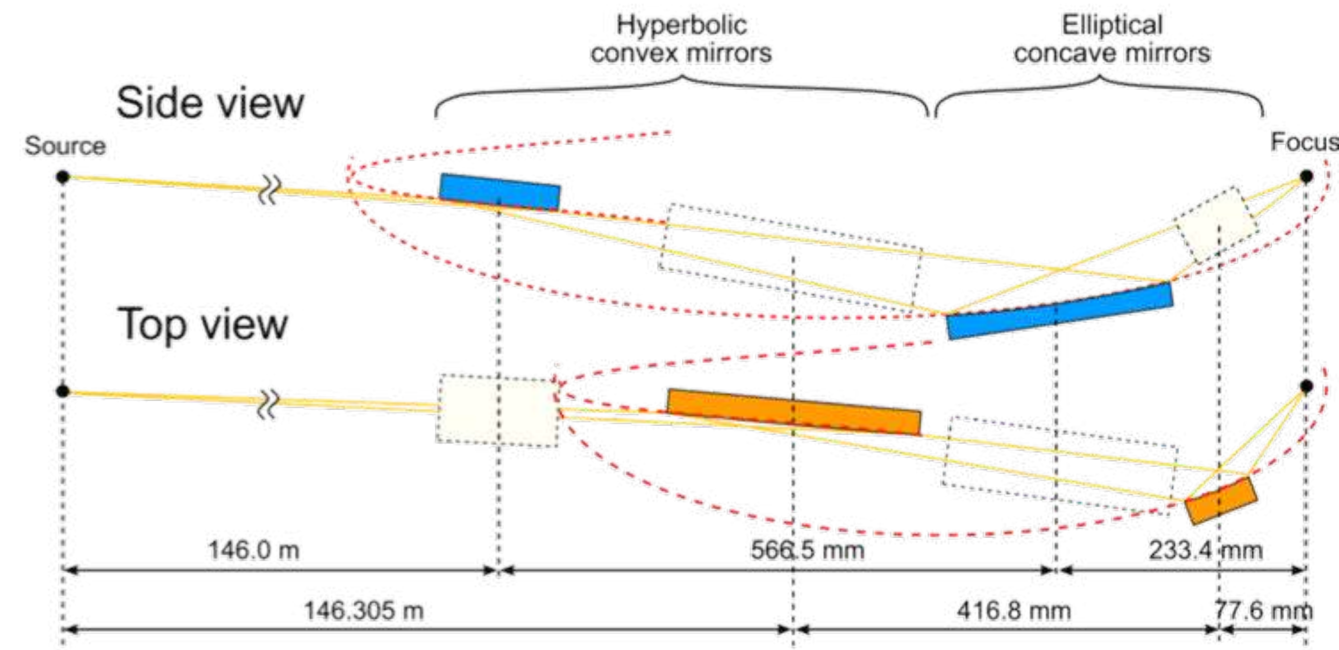
Sub-10 nm focusing system

XFEL **7 nm** focusing with **10^{22} W/cm^2** intensity



Specification

Photon energy :	9.124 keV (w/ multilayer b.w. 200eV)
Reflectivity:	39.6 %
Acceptance:	~500 x 500 µm (cf. incident ~380 um fwhm)
Throughput:	>15% (including all BL-optics)
Sample type:	Solid
Focus size:	6.6 nm x 7.1 nm
Depth of focus:	2 um
Tuning time:	currently ~12 hours (initial tuning) ~10 min by grating (re-focusing)
Lifetime of focus:	>10 hours

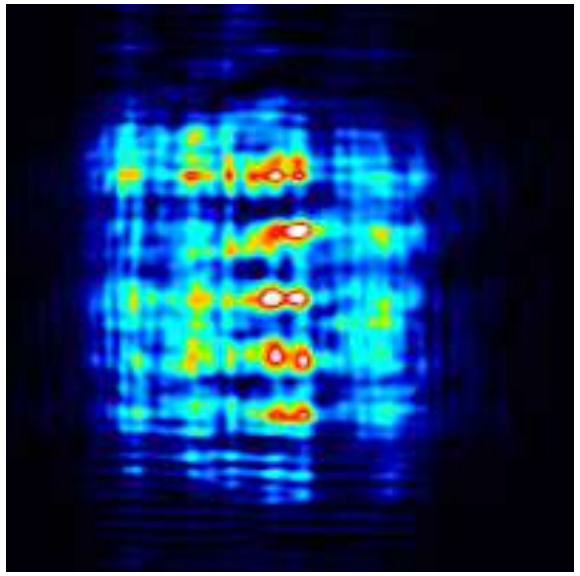


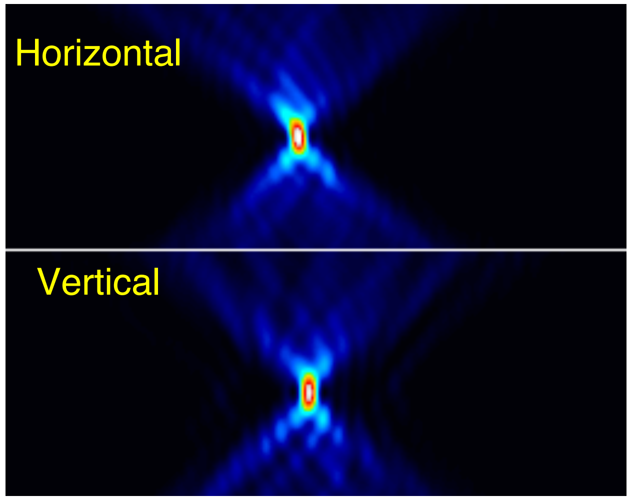
Issues & question

Is the focus truly sub-10 nm?

How to manage the narrow DoF of 2µm?

What science will open up?





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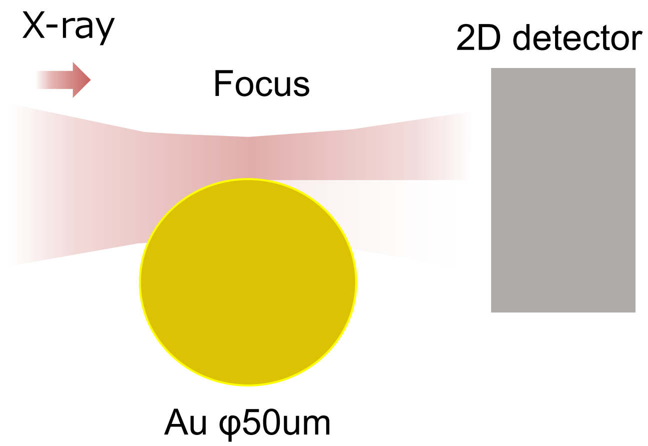
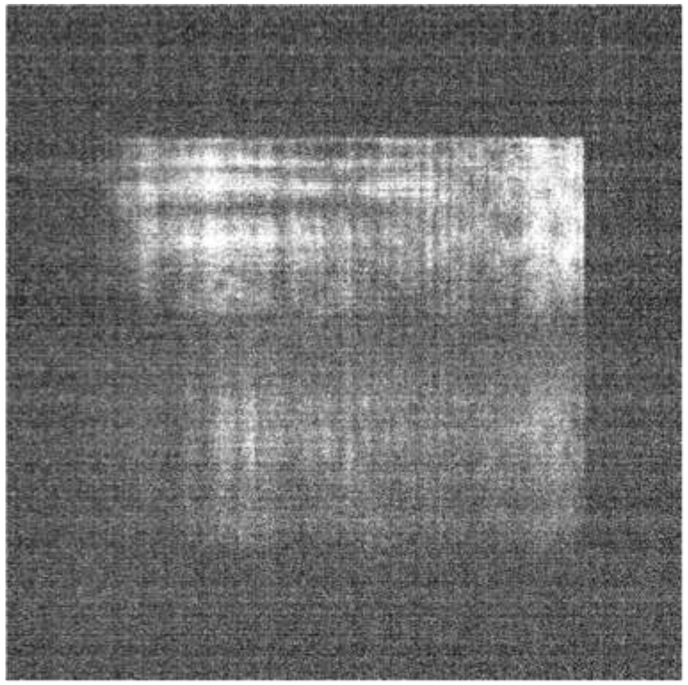
Focus characterization of sub-10 nm XFEL

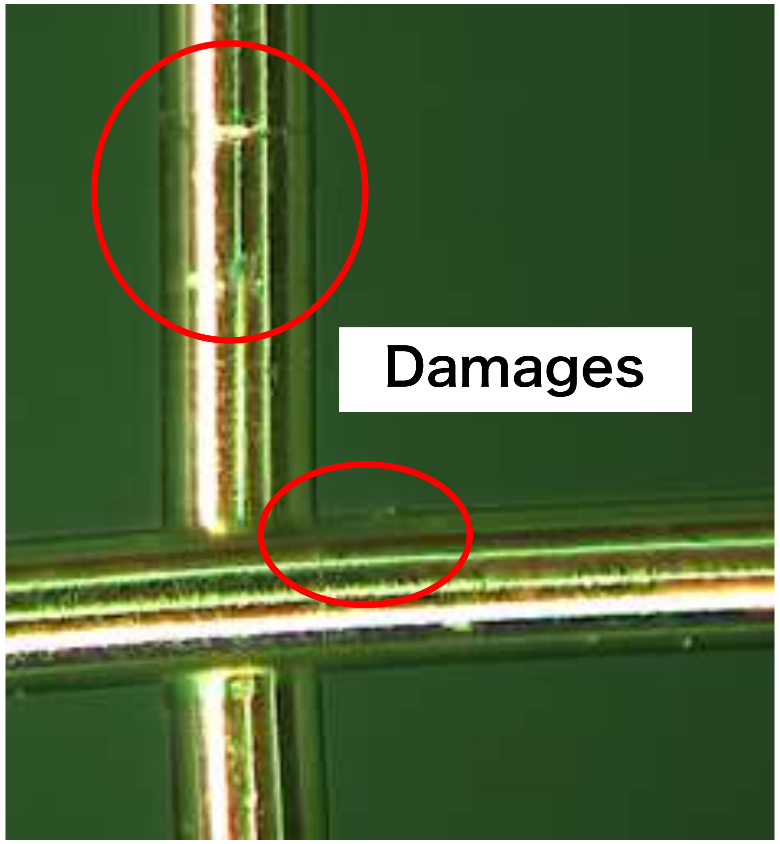
For the sub-10 nm XFEL beam, wire-scanning method is not realistic.

☑ Focus & samples vibration of ~20 nm





☑ sub-10 nm XFELs damage the wire



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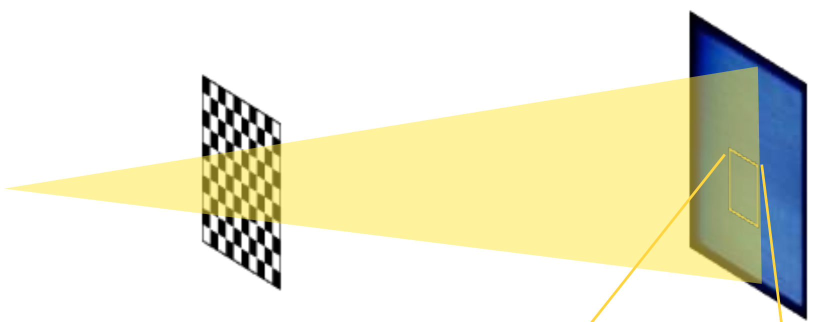
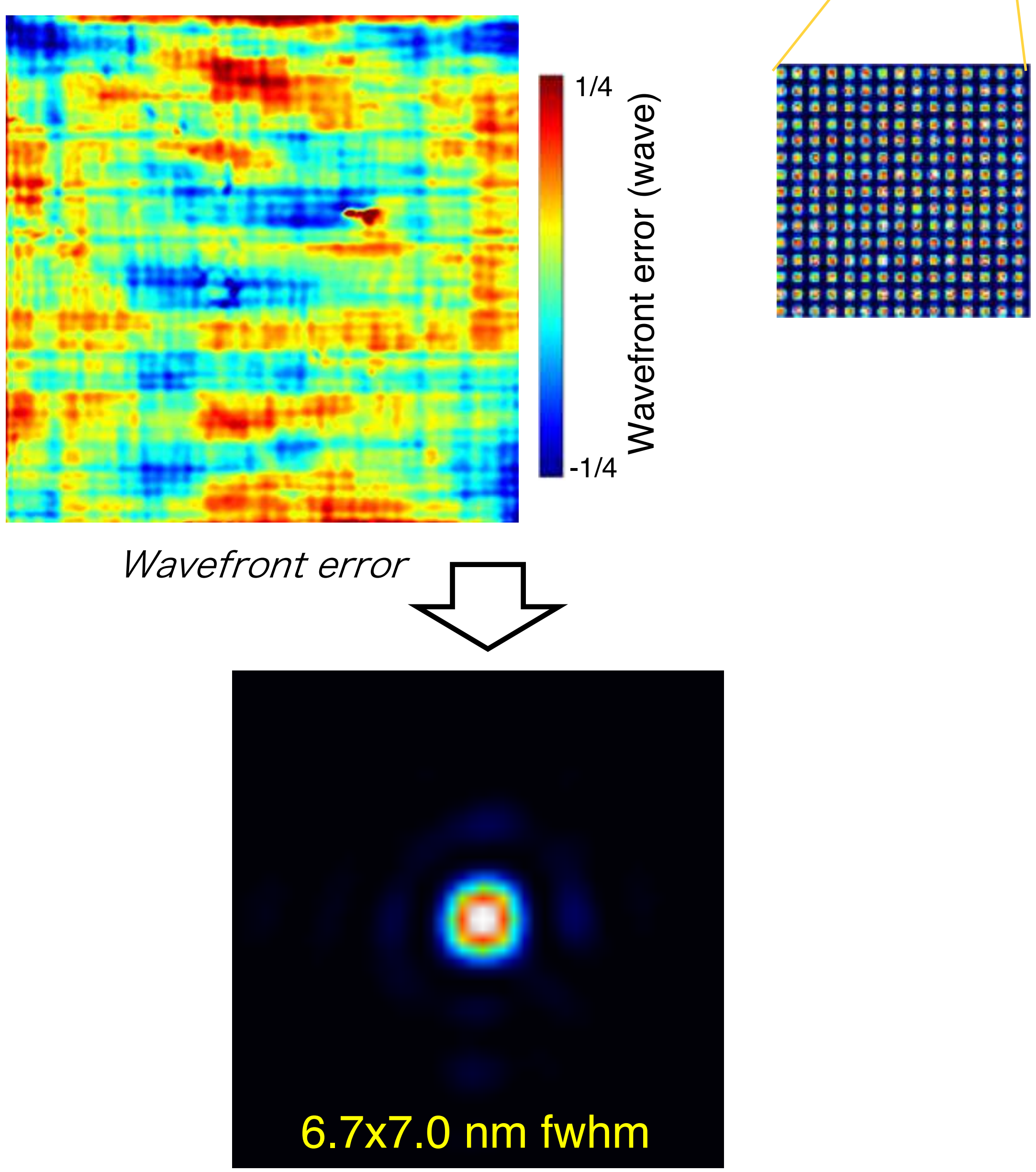
Focus characterization of sub-10 nm XFEL

Wavefront measurement by grating interferometer (75 shot-average)

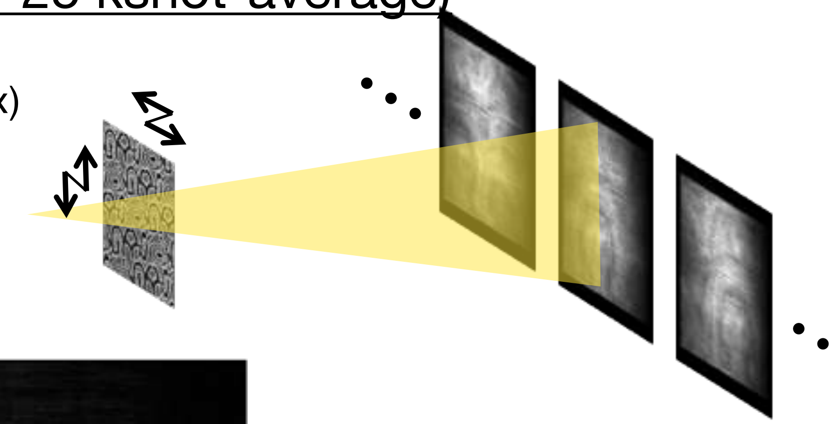
3um-pitch grating
Camera-length 0.45m
Focus-grating 8.4 mm

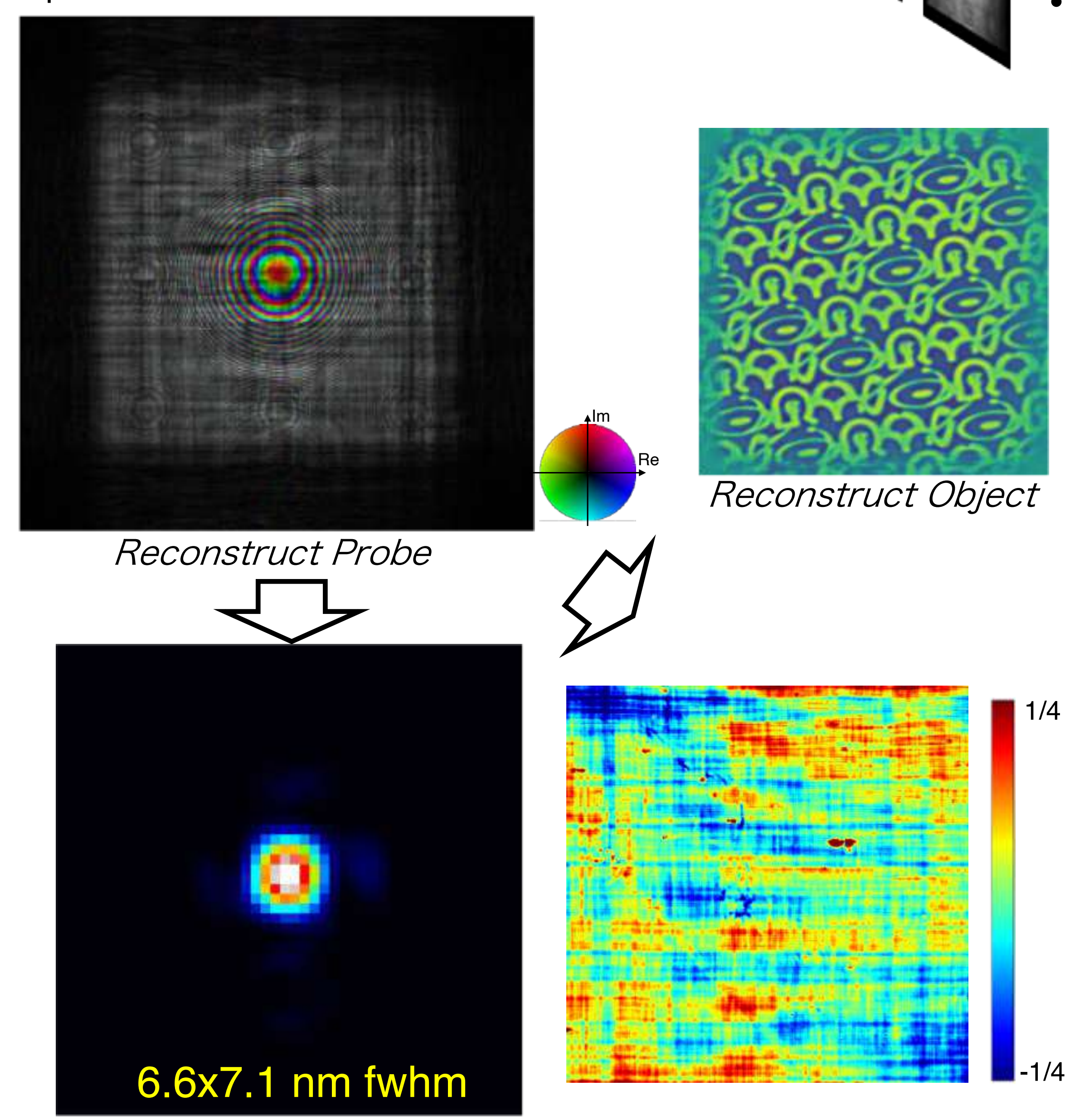




Ptychographic probe measurement (~25 kshot-average)

Sample: FIB etched pattern
Detector: MPCCD (50um/pix)
Camera length: 1.14 m
272nm step, 16 x 16 scan
120 um defocus
Attenuated w/ Si t0.8 mm
100 shots/position





s-GI & ptycho. consistently indicated 7nm focus size

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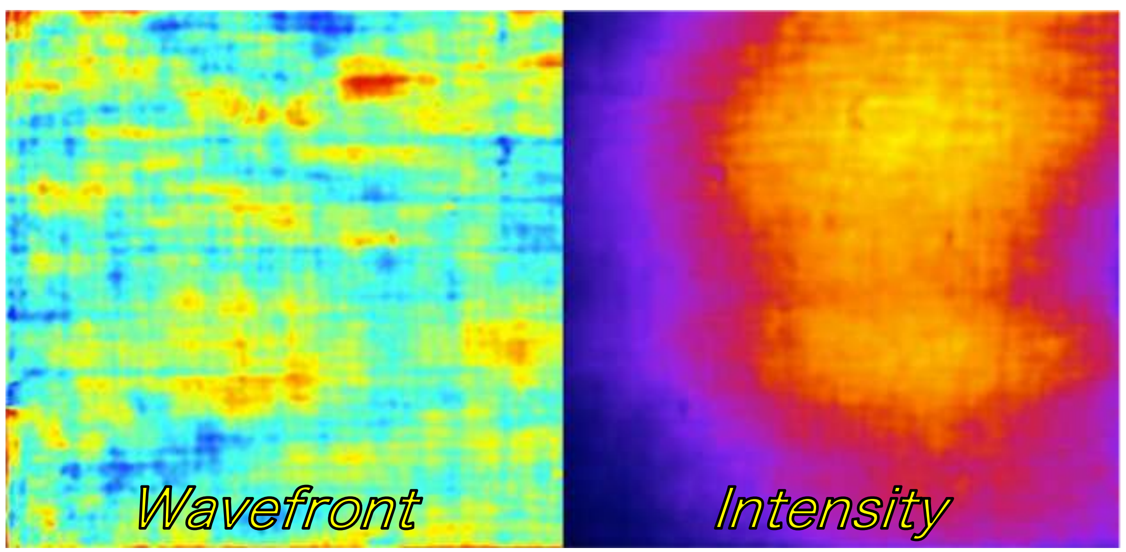
Pulse-to-pulse focus characterization

Single-shot wavefront measurement

30Hz image acquisition
by IMPERX-CMOS

courtesy of SACLA Eng. team



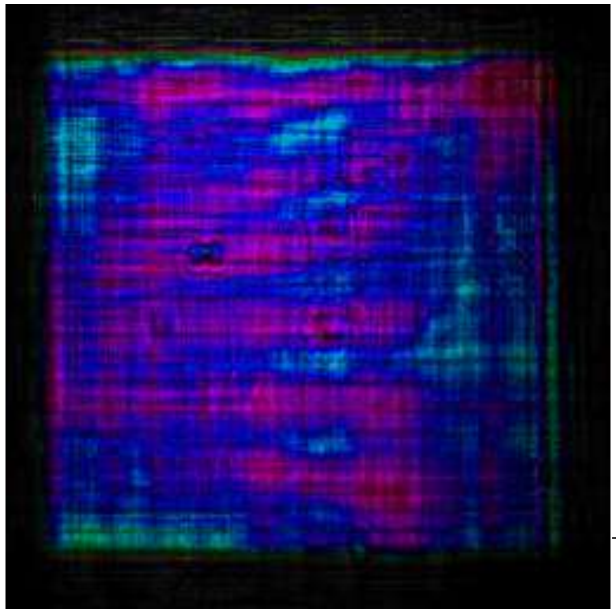
Single-shot characterization revealed almost stable wavefronts

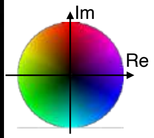
Near-field ptycho. w/ orthogonal probe relaxation

OPR: Orthogonal probe relaxation

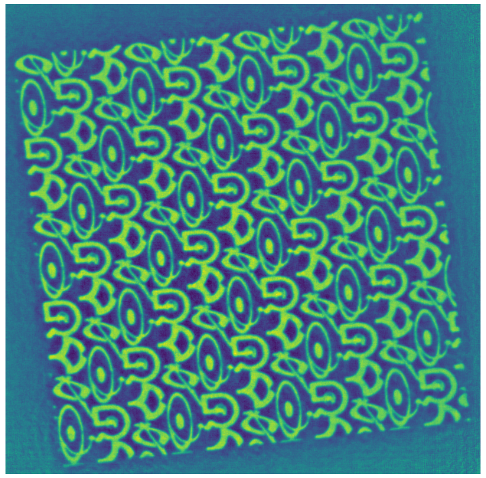
└individual probes for each of diffraction can be reconstructed

M. Odstrcil *et al*., Opt. Express (2016).
S. Sala *et al*., J. Appl. Cryst. (2020).

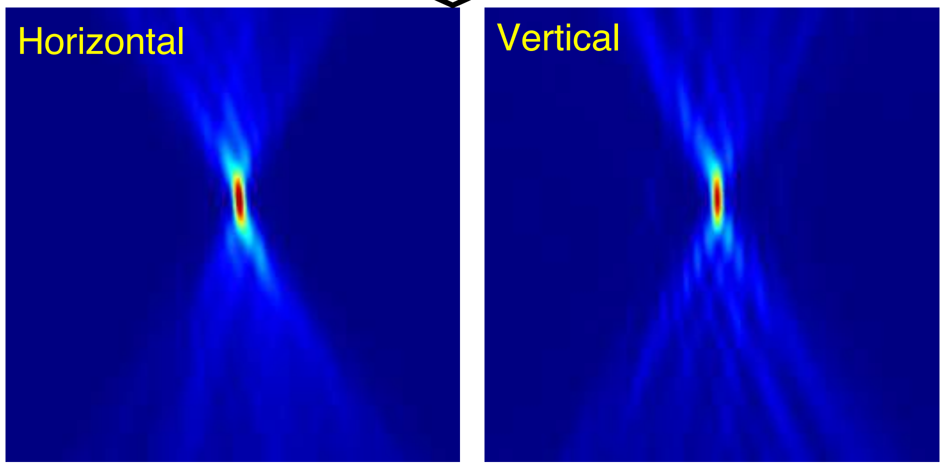




Reconstruct 196 Probes



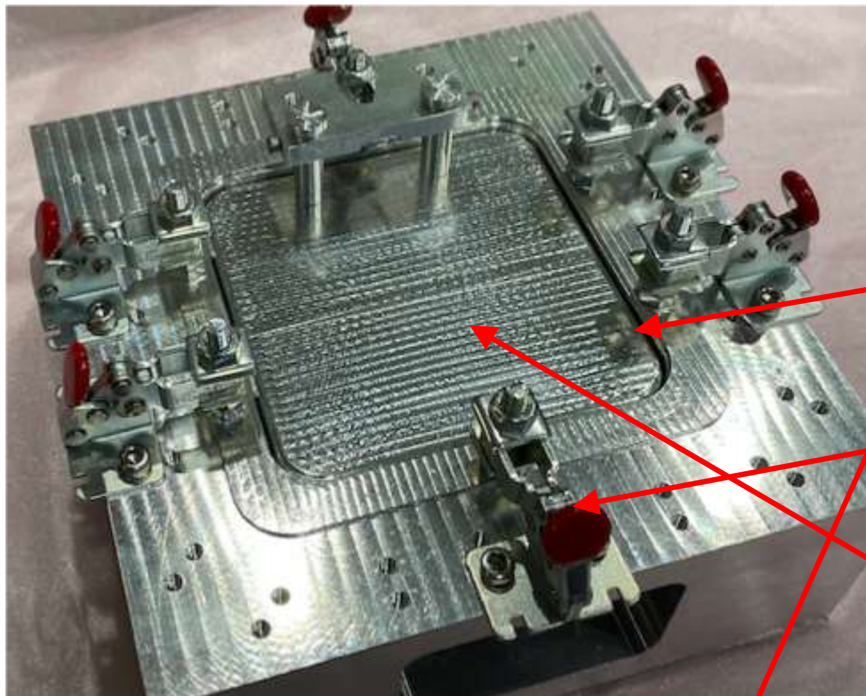
Reconstruct Object



How to manage the narrow DoF of 2μm

☑ The sample should be placed within a depth of focus of 2um

-> Sample tuner to tighten the film

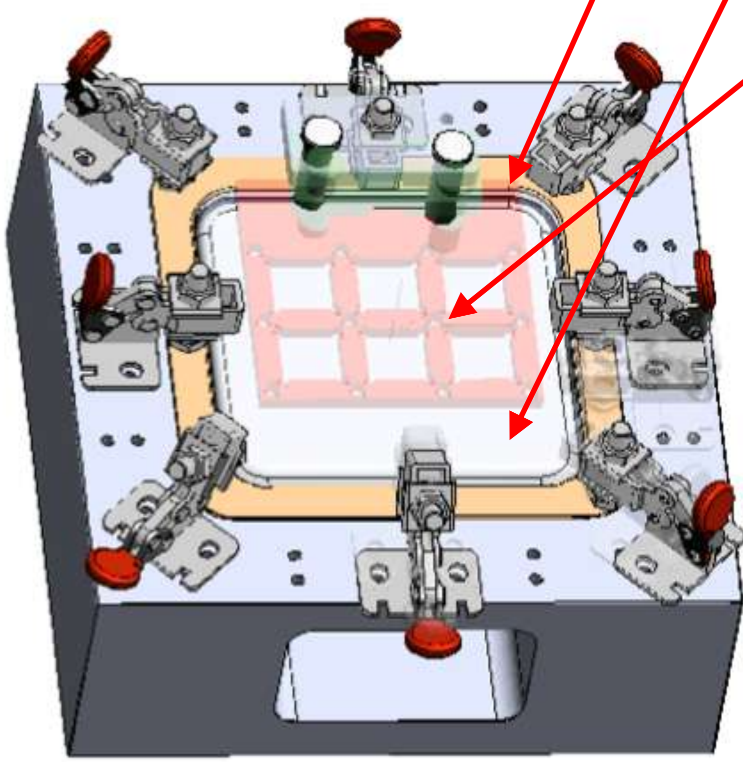


①Set a film

②clamp&hold

③Raise center stage
& apply tension

④Put the holder
& glue the film

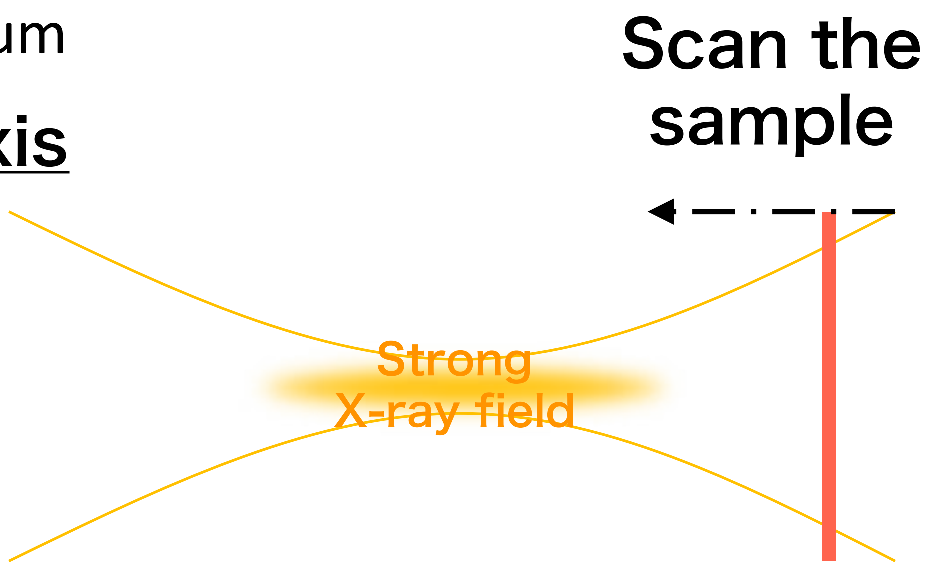


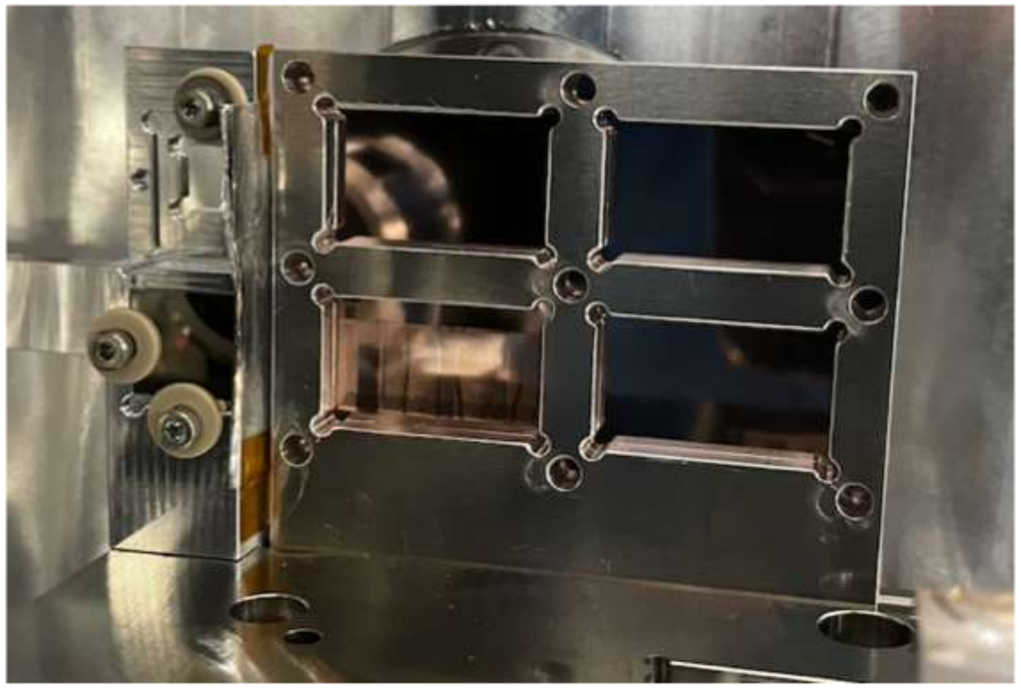
Example of tightened film

How to manage the narrow DoF of 2μm

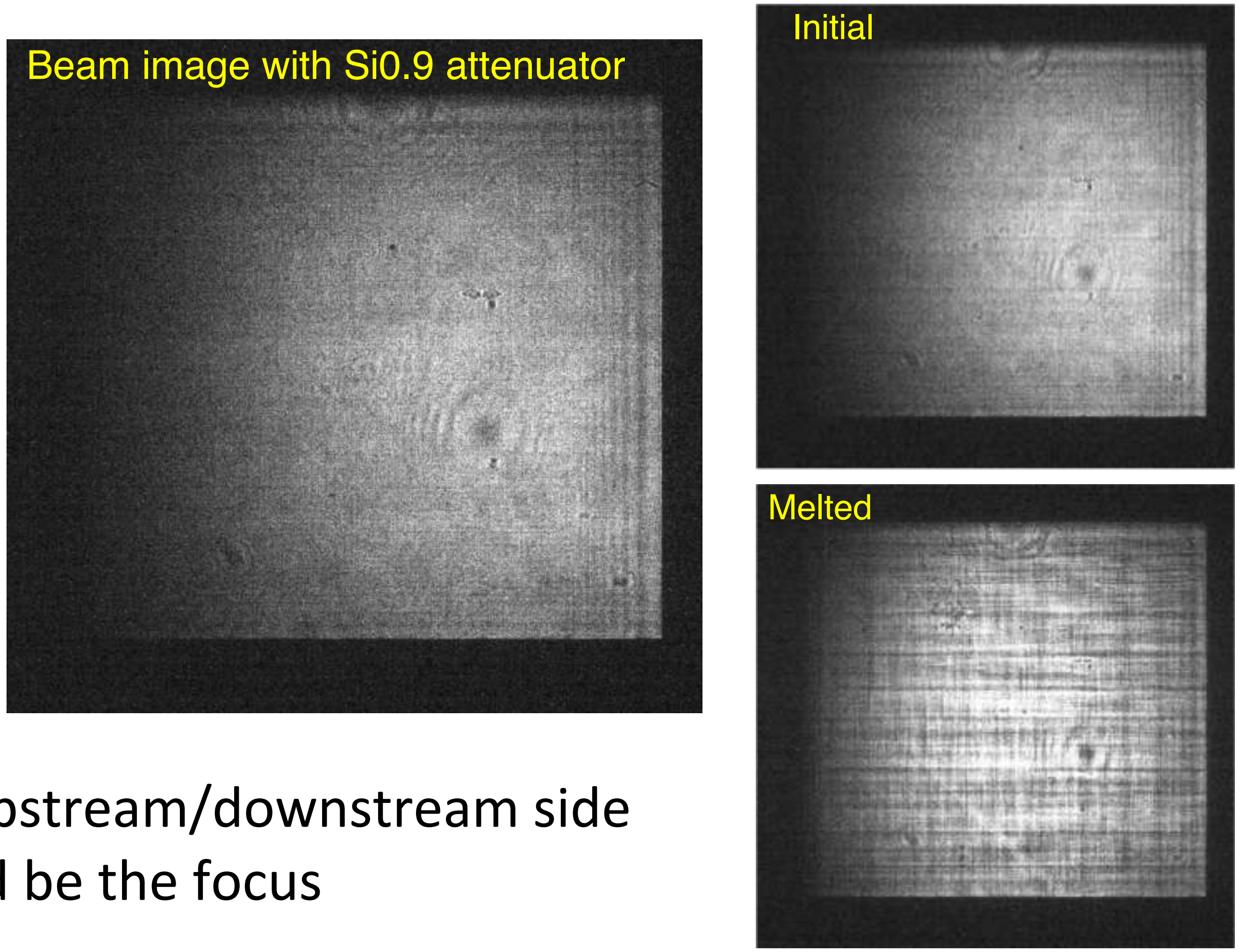
☑ The sample should be placed within a depth of focus of 2um

-> <u>Find the focus position along the optical axis</u>





Set the prepared sample to the scan stages



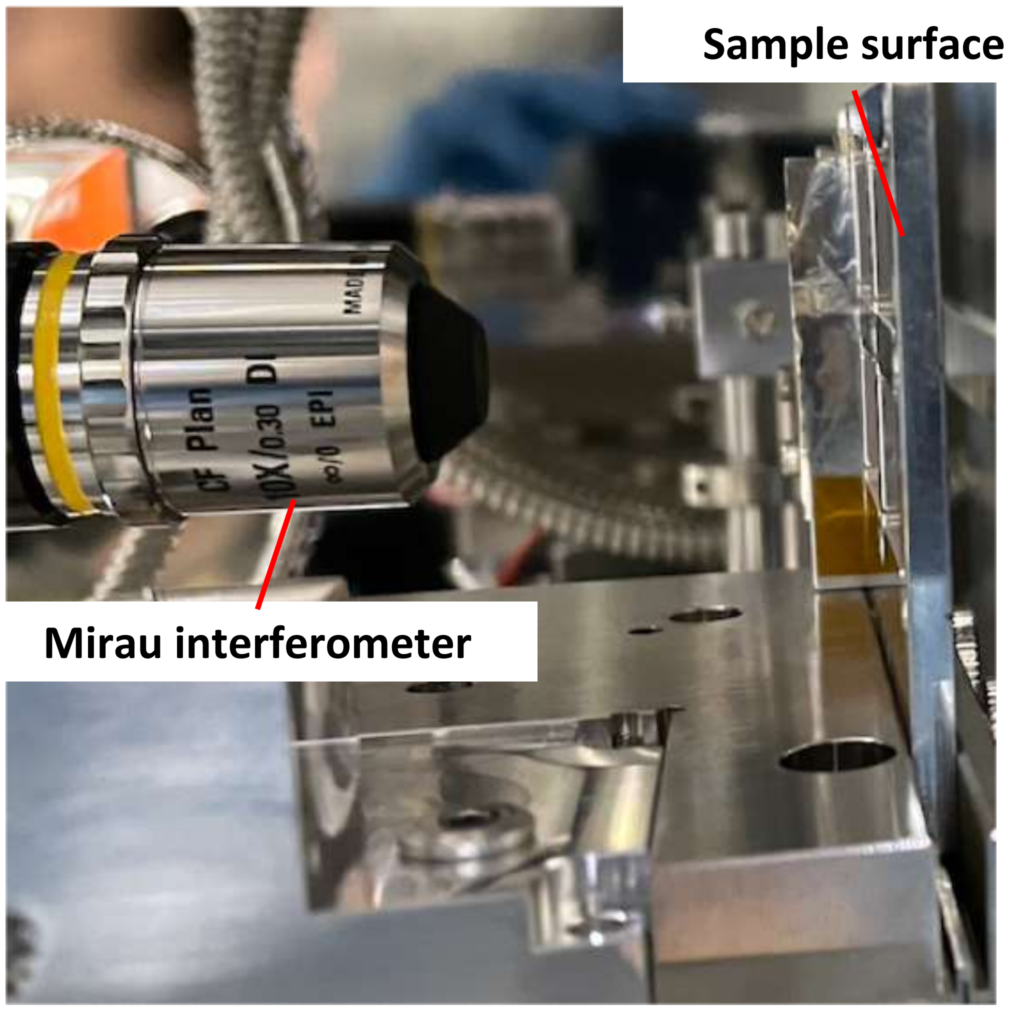
Search the ‘**melting position**’ from upstream/downstream side
Center of the melting position should be the focus

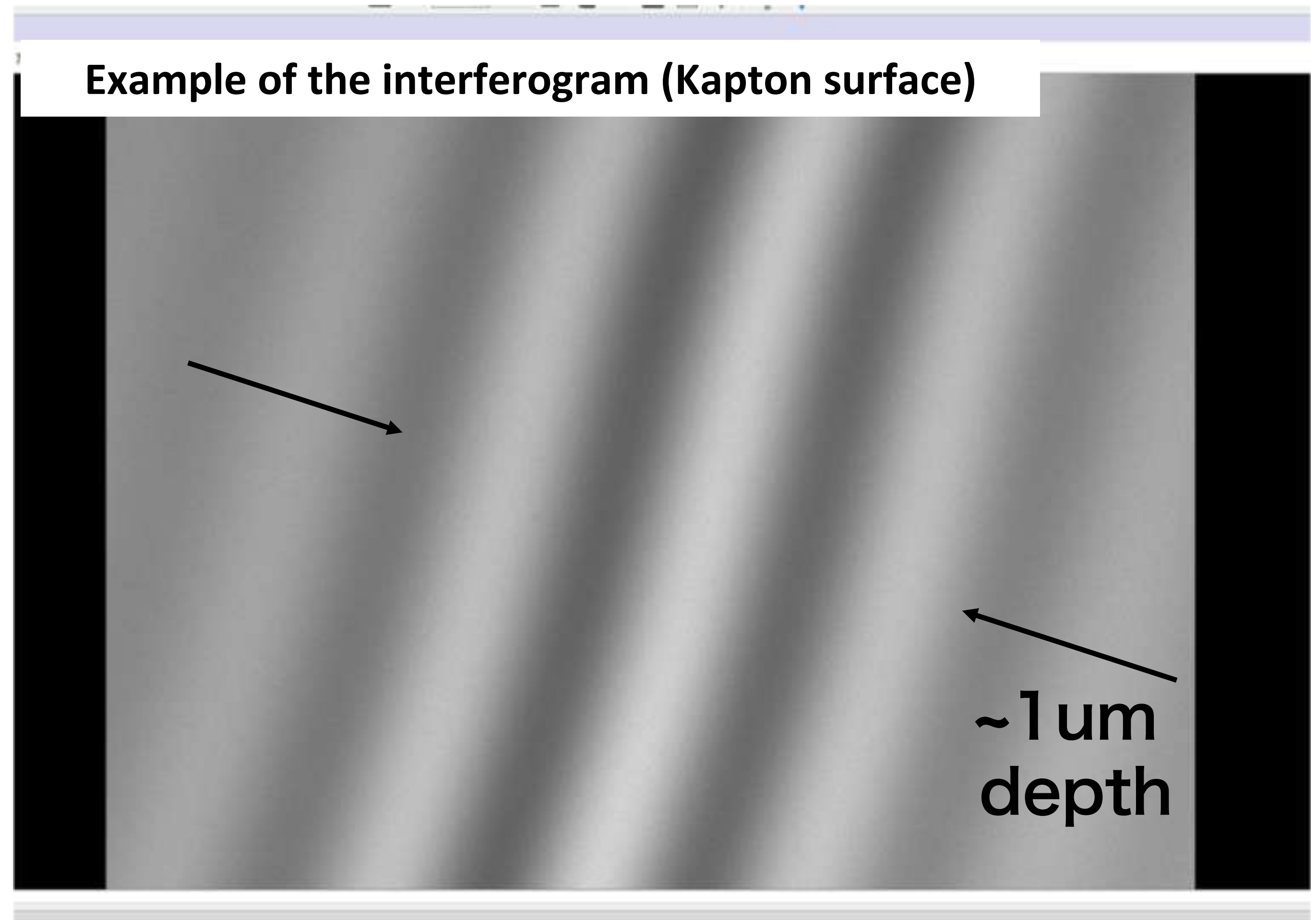
J. Yamada

How to manage the narrow DoF of 2μm

☑ The sample should be placed within a depth of focus of 2um

-> <u>Tune the sample rotation using sample monitor (optical interferometer)</u>





<u>The sample (tightened film) surface can be kept at the same position within 1~2 μm.</u>

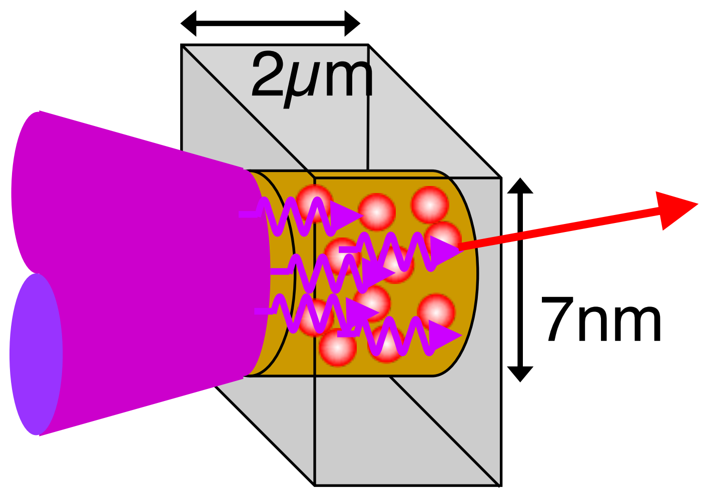
Targets of the sub-10nm XFEL

Expected Intensity/fluence   Pulse energy on mirrors : 255 μJ

$255\mu J \times 40\%_{\text{reflectivity}} \times 47\%_{\text{Power in fwhm}} / 7x7nm^2 / 7fs \approx$ **1.21×10^{22} W/cm^2**

3.27×10^{10} photons/shot => 5.83×10^{22} photons/cm^2

However,,,



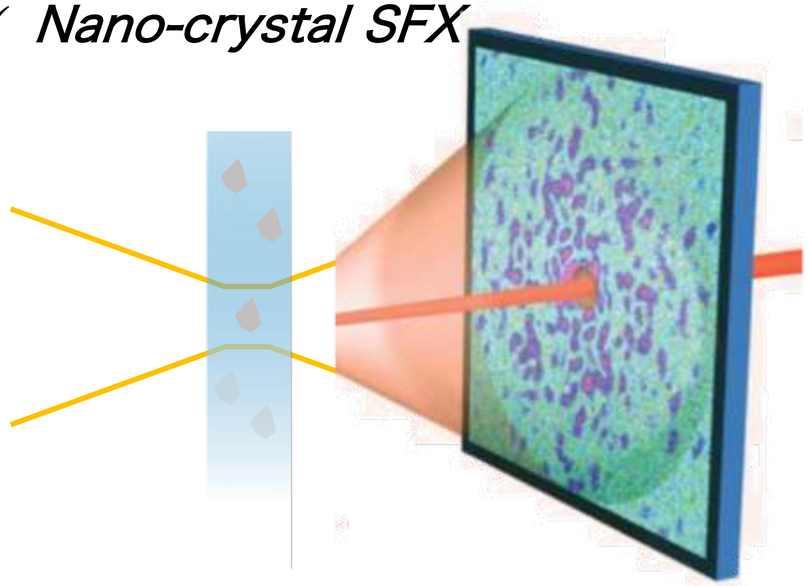
Number of atoms (Cu) in the focus: ~8.3×10^6

~1000 times less than photons

-> signals should be weak

Targets of the sub-10 nm XFEL (tentative)

✓ *Nano-crystal SFX*

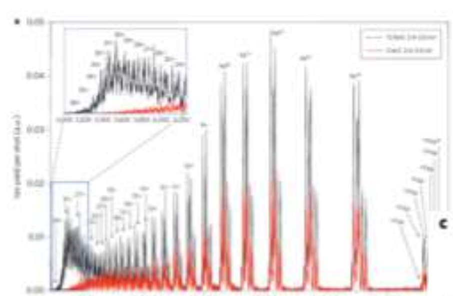


Shoot smaller samples w/ high flux

→**single-molecular imaging**

K. J. Gaffney & H. N. Chapman Science. (2007)

✓ *Nonlinear interaction*

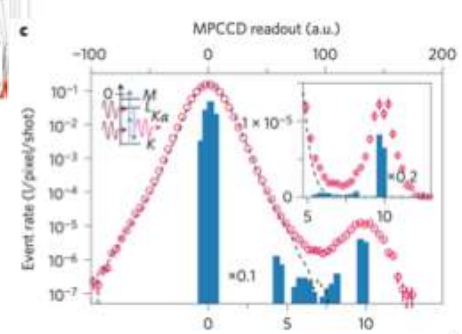


e.g.) Multi photoionization

B. Rudek, Nat. Photon. (2012)

e.g.) Multi-photon absorption

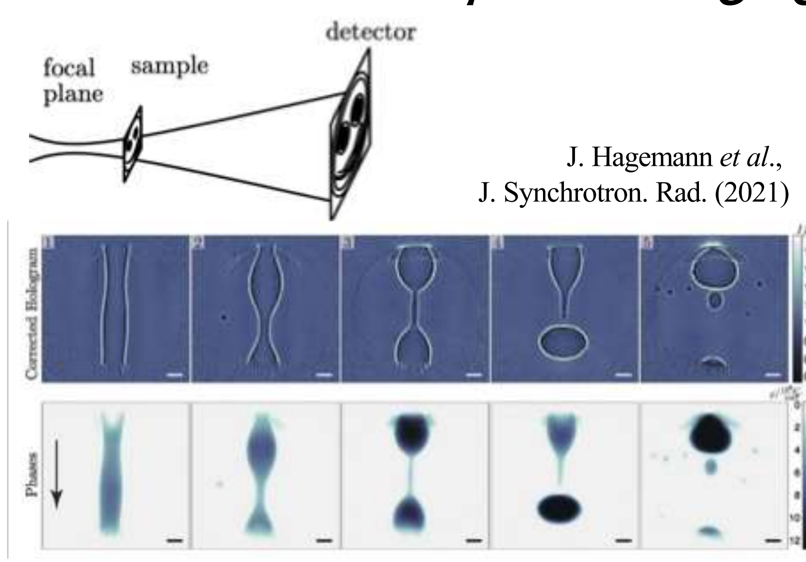
K. Tamasaku, Nat. Photon. (2014)



Signals $\propto \sigma \cdot I^{2\sim3}$

New phenomena of X-ray nonlinear optics

✓ *Nano-resolution phase imaging*



J. Hagemann *et al.*,
J. Synchrotron. Rad. (2021)

7-nm resolution
single-shot phase imaging

Topics2: sub-10 nm system

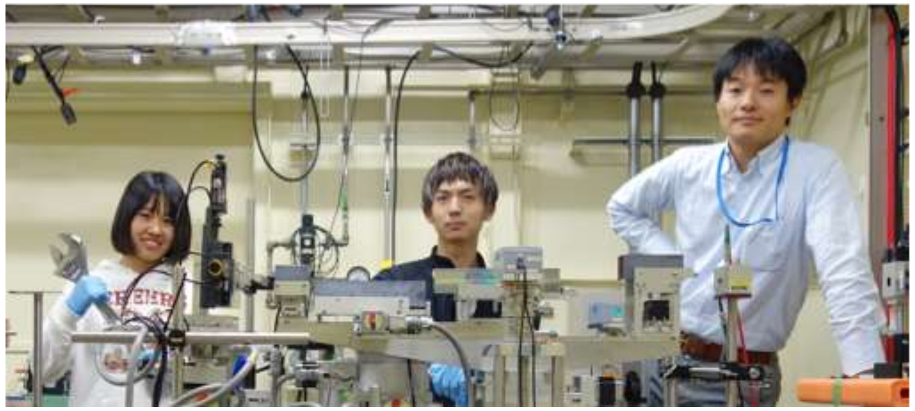
From SACLA side:

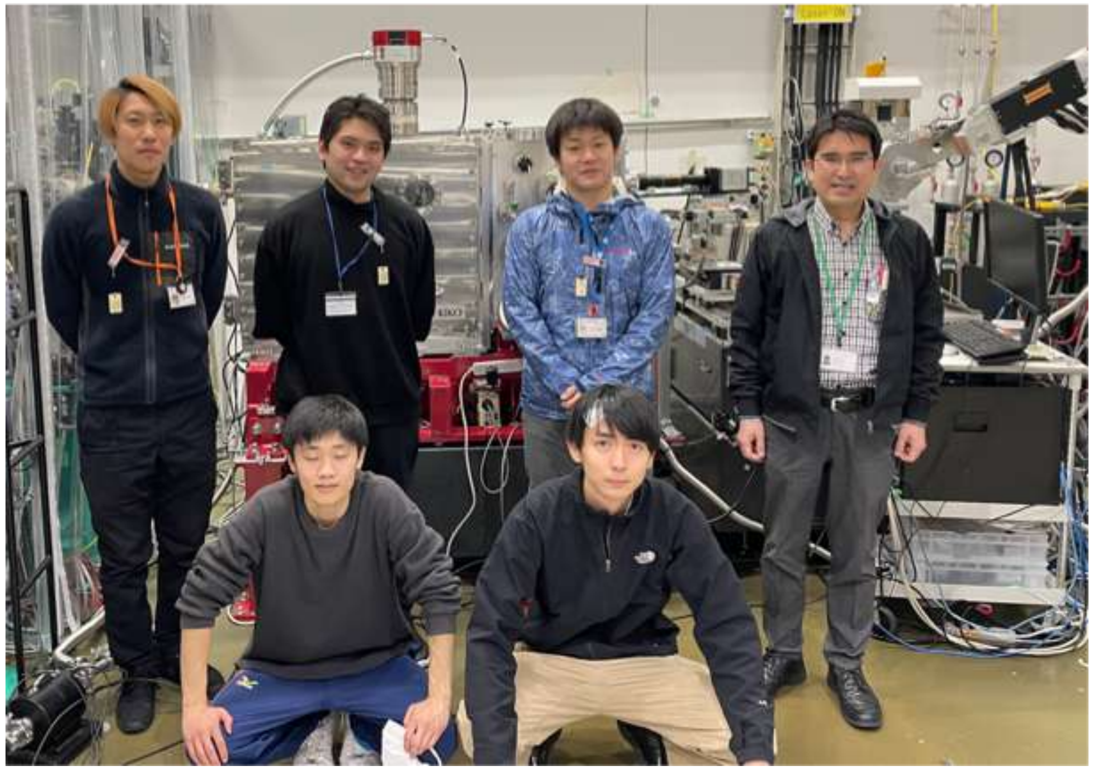
7x7 nm focusing system has been developed.

In solid sample case, 2-μm depth-of-focus is sufficient for practical use.

We believe that the sub-10 XFEL will open up unique & new science

On behalf of the XFEL sub-10nm developing teams (Osaka U., JASRI, RIKEN)





Contact: yamada@spring8.or.jp