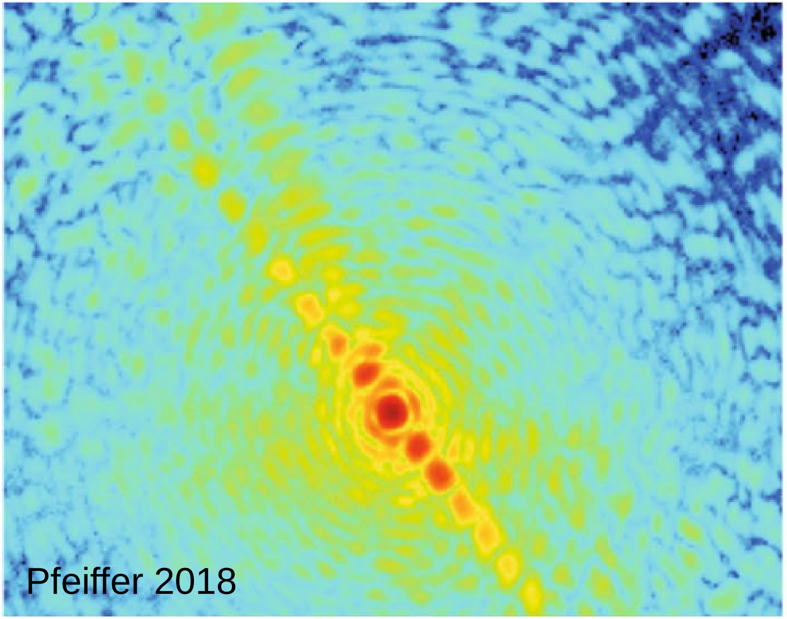
Generation and use of coherent X-ray beams at future SKIF storage ring



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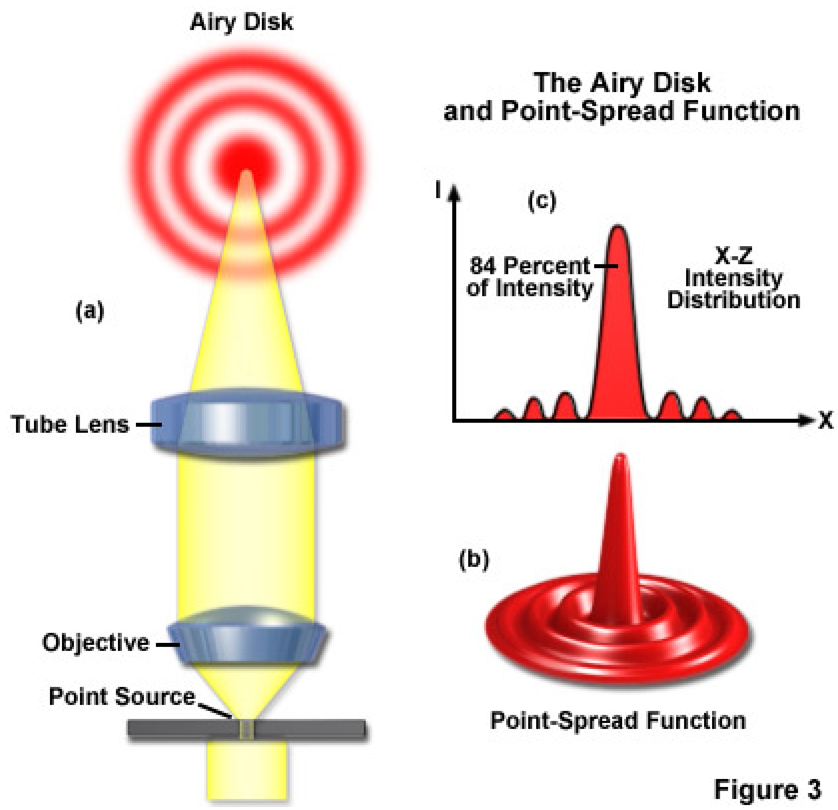
SFR-2020

Generation and use of coherent X-ray beams at future SKIF storage ring

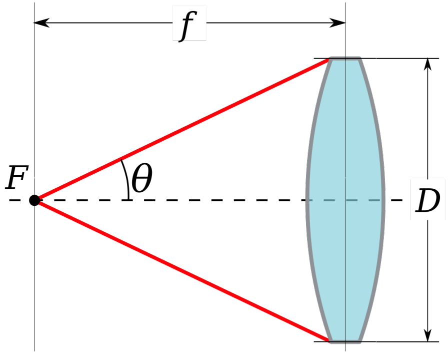
- **Why** do we need coherent X-ray beams:
  lensless 3D-imaging of nanostructures
- **How many** coherent photons do we need:
  optimization of coherent flux at 4^{th} generation storage rings
- Coherent imaging at future SKIF storage ring

Why do we need coherent X-ray beams?

Is nm-resolution X-ray microscopy possible: Abbe diffraction limit



$$\boxed{\begin{aligned}\Delta &= 0.61\frac{\lambda}{N.A.}\\ &= 0.61\frac{\lambda}{n\sin\theta}\end{aligned}}$$



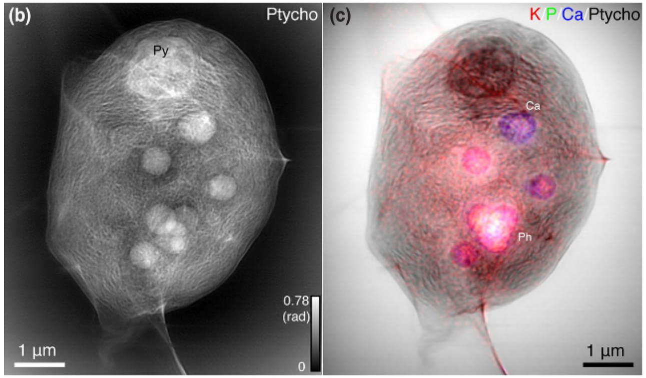
Resolution in microscopy is limited by
wavelength
AND
lens numerical aperture ($n\sin\theta$)

VIS: λ ~ 500 nm, *N.A.* ~ 1 (Δ ~ 250 nm)
X-RAY: λ ~ 0.1 nm, *N.A.* ~ 0.001 (Δ ~ 50 nm)

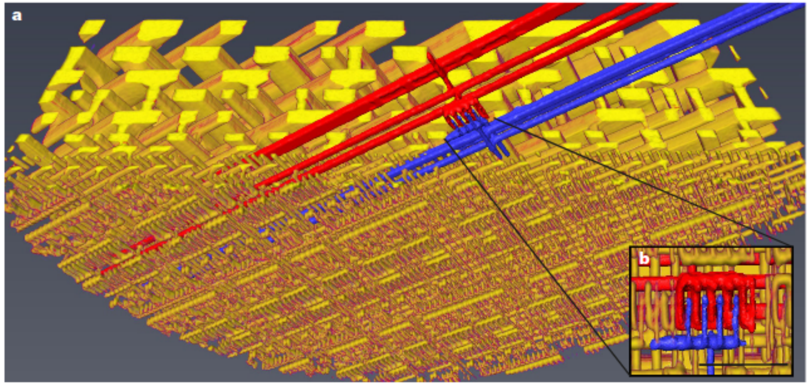
From ZEISS

Fortunately, we have EM.
Unfortunately:

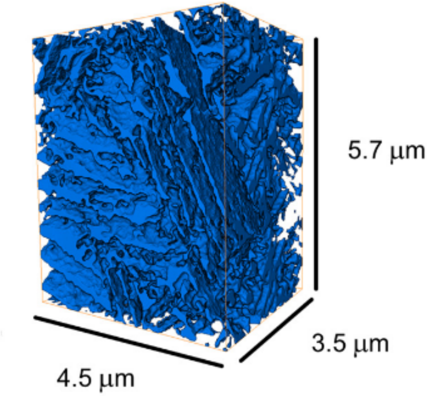
- Cellular structures (incl. *in vivo*)
- 3D nanostructures in integrated circuits
- 3D nanostructures in aerospace alloys
- 3D nanostructures in energy storage devices
- *Non-destructive?*



Algae cell – Deng *et al.* 2017

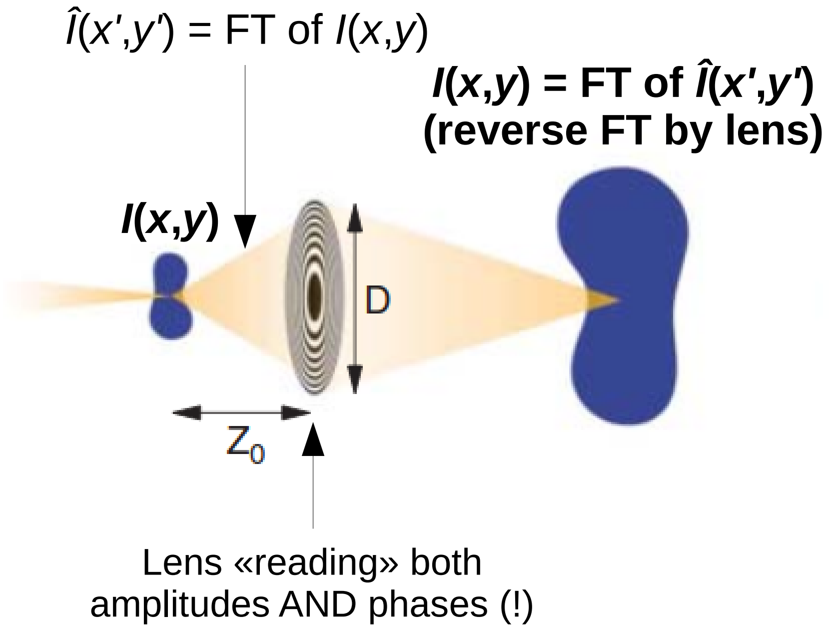


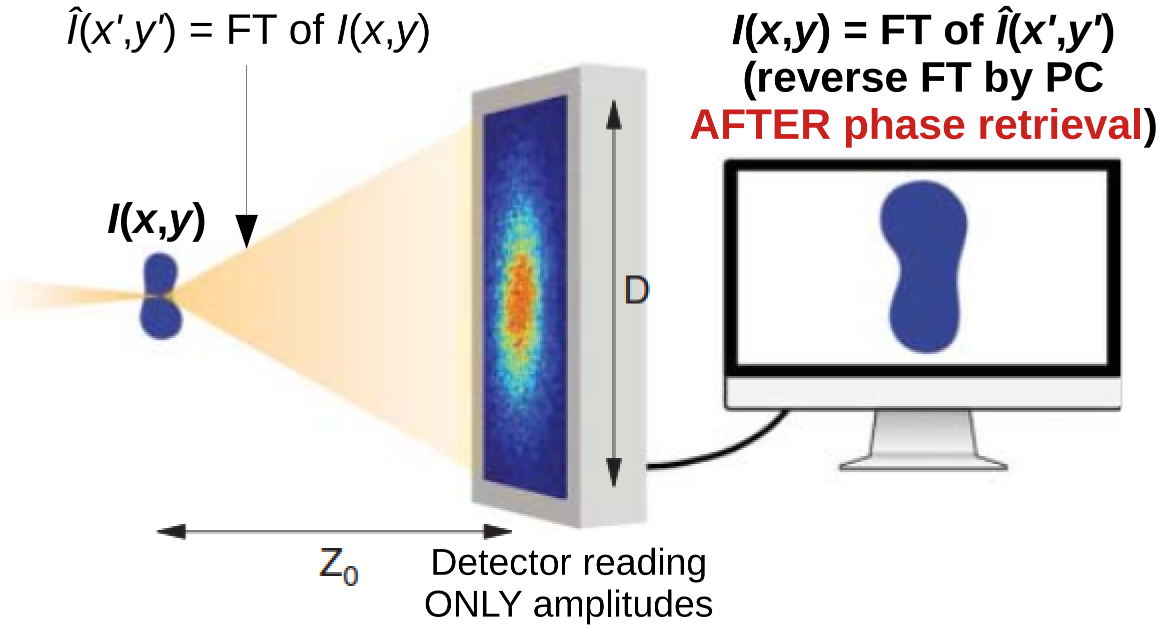
Intel chip – Holler et al. 2017



Aerospace alloy – Barriobero-Vila et al. 2017

Do we really need *a bad* lens: lensless CXDI beyond Abbe limit



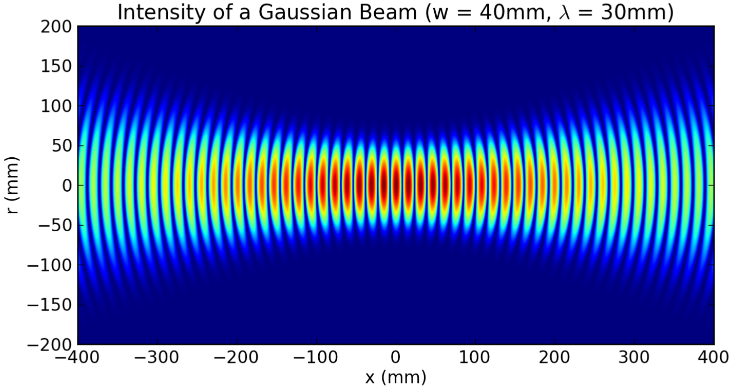


- DOES NOT require coherent illumination
  - Resolution limited by lens N.A.

- **DOES require coherent illumination**
- **Resolution limited by detector size**

From Willmott 2019

Towards coherent illumination: evaluating X-ray beam coherence



Diffraction-limited Gaussian beam (TEM_{00} mode)

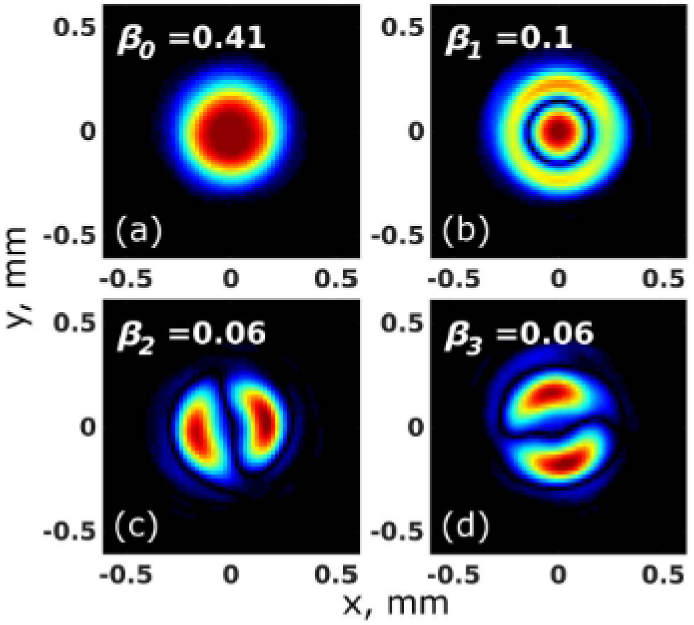
$$\sigma \cdot \sigma' = \frac{\lambda}{4\pi} = \varepsilon_{coh}$$

Gaussian Schell-model beam (partially coherent)

$$\Sigma \cdot \Sigma' = \frac{1}{f_{coh}} \cdot \varepsilon_{coh}$$

PETRA IV, 12 keV:

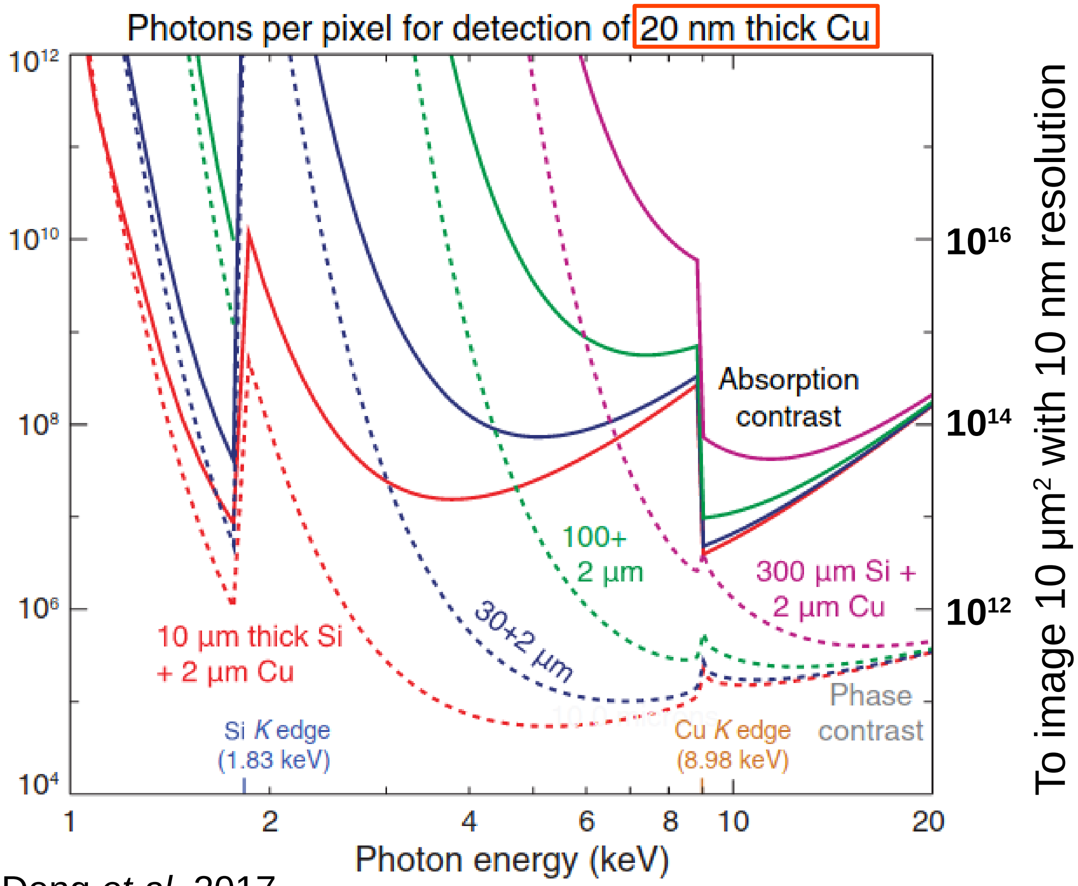
CMD into HG + LG modes



Khubbutdinov *et al.* 2019

How many coherent photons do we need?

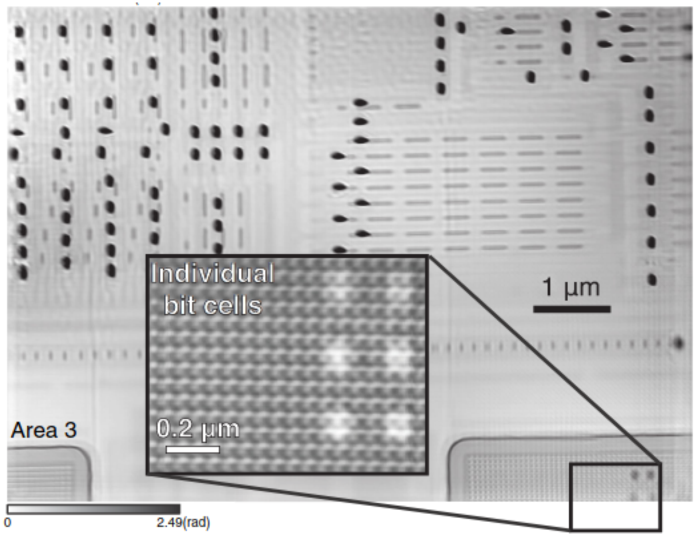
High-energy CXDI at 3rd generation storage rings



Deng *et al.* 2017

Coherent flux at ~20 keV
(ESRF ID16A before upgrade):
~10^{10} ph/s/**1%**: ~10^{2} s)

1 nm resolution: ~10^{6} s (11 days)



Hynix DRAM – Deng *et al.* 2017

How many coherent photons do we need?

At least two orders of magnitude more!

Maximizing coherent fraction of photon flux:

$$f_{coh} = \frac{\varepsilon_{coh}}{\Sigma_x \Sigma'_x} \cdot \frac{\varepsilon_{coh}}{\Sigma_y \Sigma'_y}$$

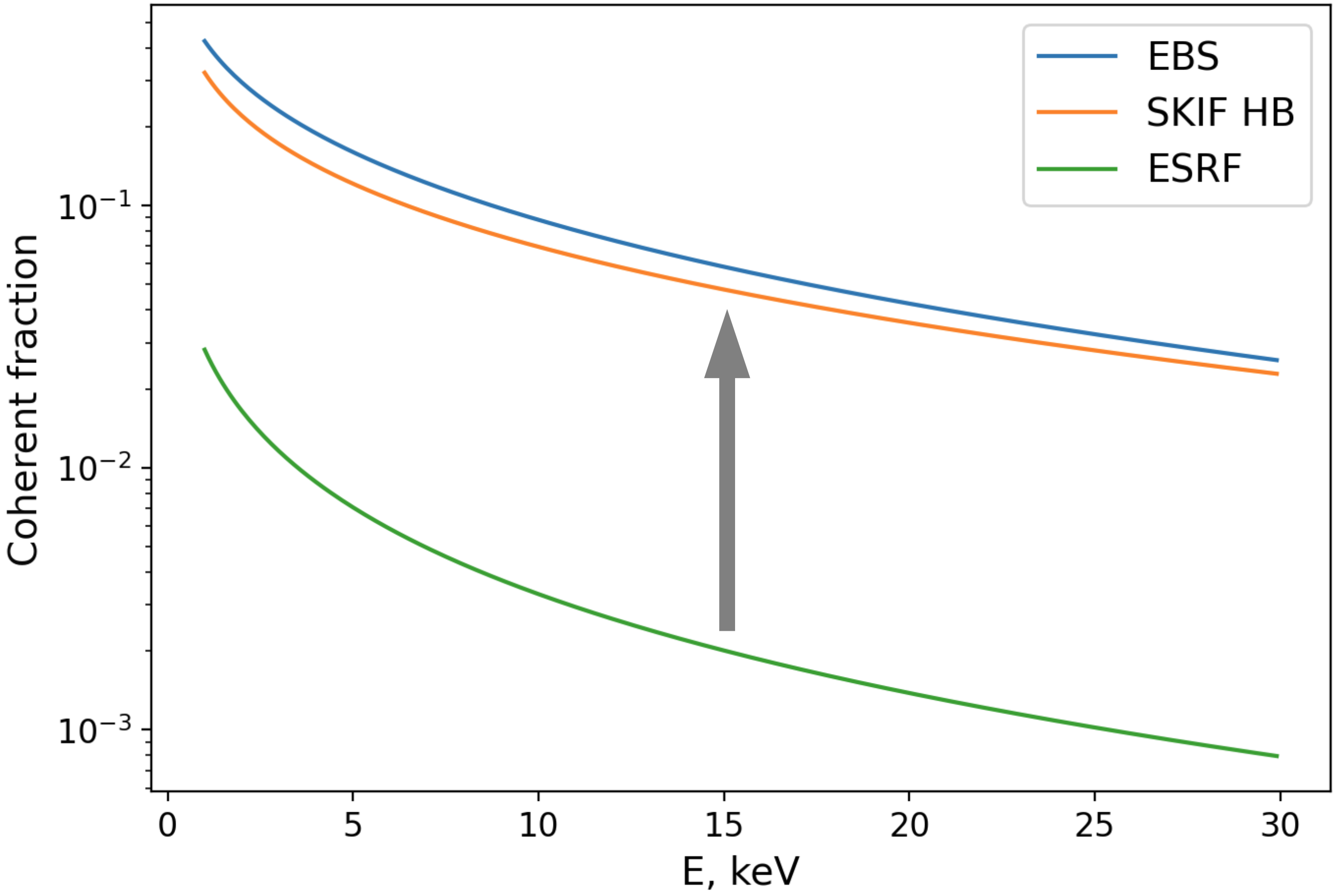
$$= \frac{\varepsilon_{coh}^2}{\sqrt{\varepsilon_{e,x}\beta_{e,x} + \varepsilon_{coh}\beta_p}\sqrt{\frac{\varepsilon_{e,x}}{\beta_{e,x}} + \frac{\varepsilon_{coh}}{\beta_p}}\sqrt{\varepsilon_{e,y}\beta_{e,y} + \varepsilon_{coh}\beta_p}\sqrt{\frac{\varepsilon_{e,y}}{\beta_{e,y}} + \frac{\varepsilon_{coh}}{\beta_p}}},$$

where ε_e corresponds to electron beam emittance,
and β is waist size over divergence ratio:

- β_e given by magnetic lattice for electron beam
- $\beta_p = L / \pi$ for single electron undulator emission at resonance

Due to non-Gaussian character of undulator emission, *projected* r.m.s. values of source size and divergence are limited by $\varepsilon_{coh} \approx \lambda / 2\pi$ rather than $\lambda / 4\pi$

Coherent fraction at 4th generation storage ring



EBS:
ε = **110** / 5 pm·rad
β = 6.9 / 2.6 m
L = 3.2 m

SKIF HB:
ε = **69** / 7 pm·rad
β = 15.7 / 2.3 m
L = 2.3 m

ESRF:
ε = 4000 / 5 pm·rad
β = 37.6 / 3.0 m
L = 3.2 m

Maximizing coherent fraction of photon flux:

$$f_{coh} = \frac{\varepsilon_{coh}}{\Sigma_x \Sigma'_x} \cdot \frac{\varepsilon_{coh}}{\Sigma_y \Sigma'_y}$$

$$= \frac{\varepsilon_{coh}^2}{\sqrt{\varepsilon_{e,x}\beta_{e,x} + \varepsilon_{coh}\beta_p}\sqrt{\frac{\varepsilon_{e,x}}{\beta_{e,x}} + \frac{\varepsilon_{coh}}{\beta_p}}\sqrt{\varepsilon_{e,y}\beta_{e,y} + \varepsilon_{coh}\beta_p}\sqrt{\frac{\varepsilon_{e,y}}{\beta_{e,y}} + \frac{\varepsilon_{coh}}{\beta_p}}},$$

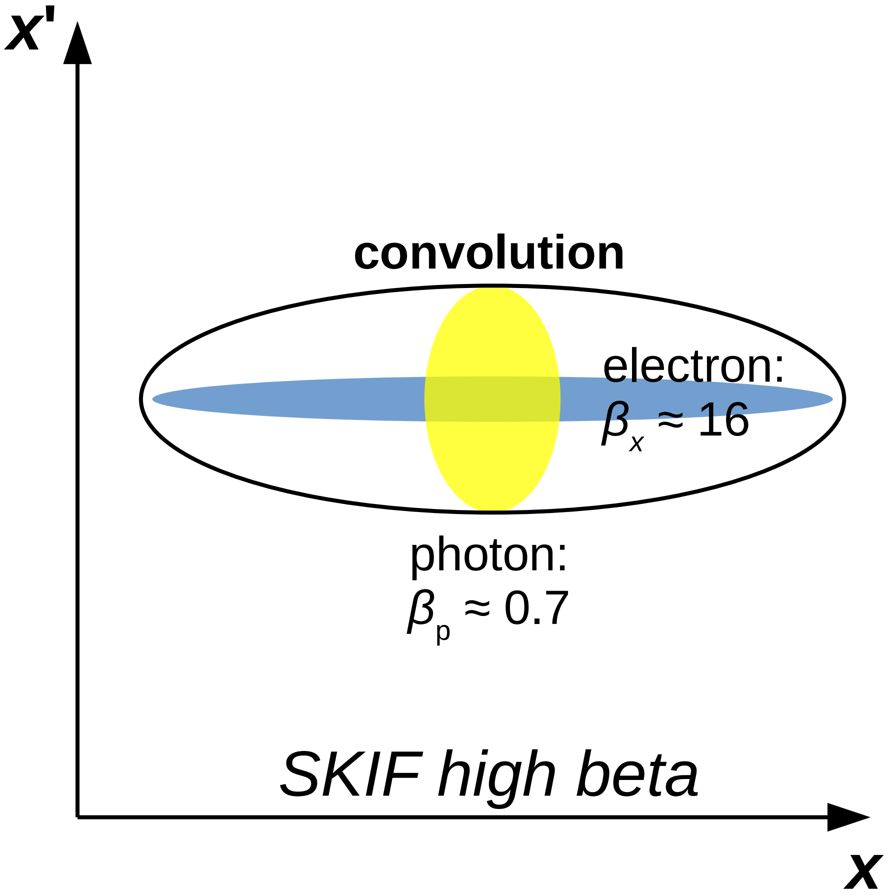
$$(1)\min \varepsilon_{e,x} \cdot \varepsilon_{e,y} = \varepsilon_{e,x}^2 \cdot \kappa$$

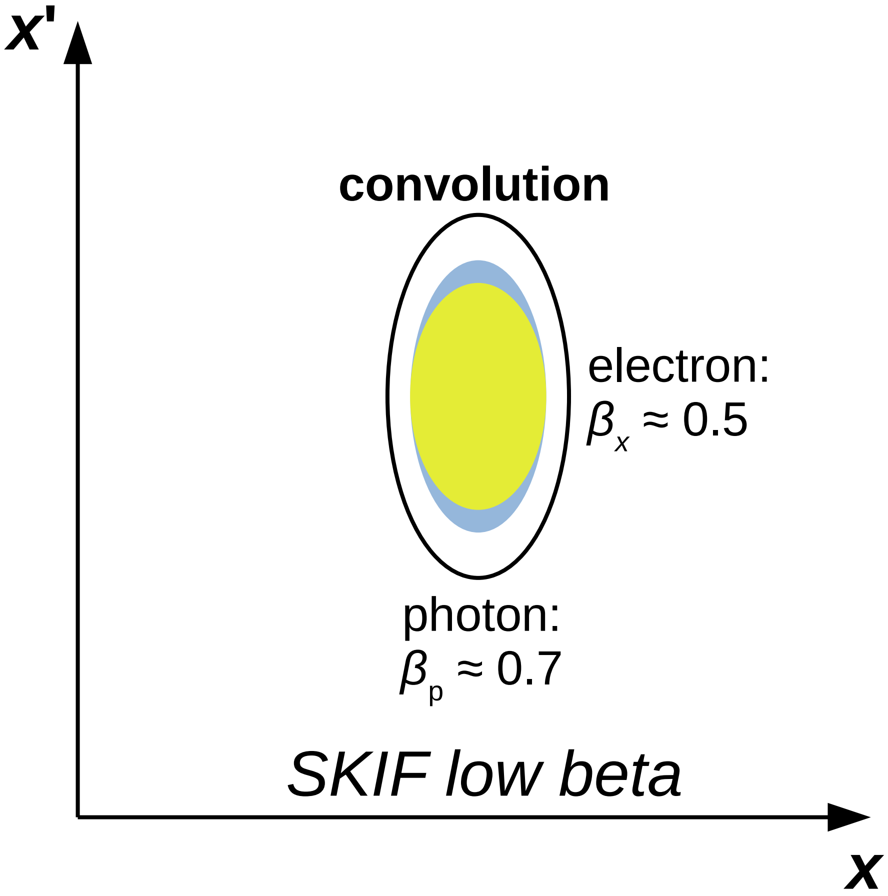
(minimization of electron beam emittance)

$$(2)\beta_e = \beta_p = L/\pi$$

(matching of electron and photon phase space ellipses)

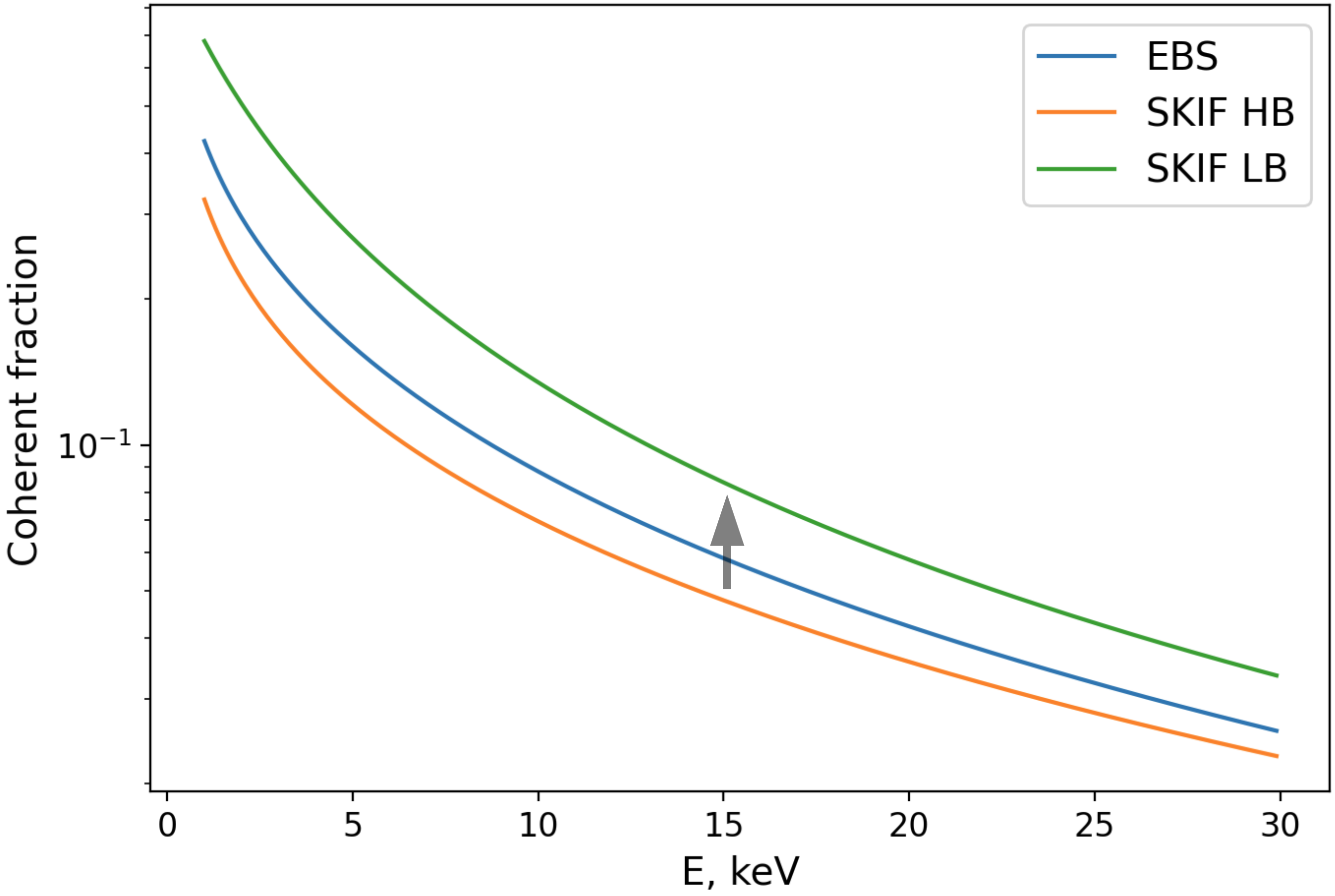
Matching of phase space ellipses





~3 keV (4 Å) photons example

Coherent fraction at 4th generation storage ring



EBS:
ε = 110 / 5 pm·rad
β = 6.9 / 2.6 m
L = 3.2 m

SKIF HB:
ε = 69 / 7 pm·rad
β = 15.7 / 2.3 m
L = 2.3 m

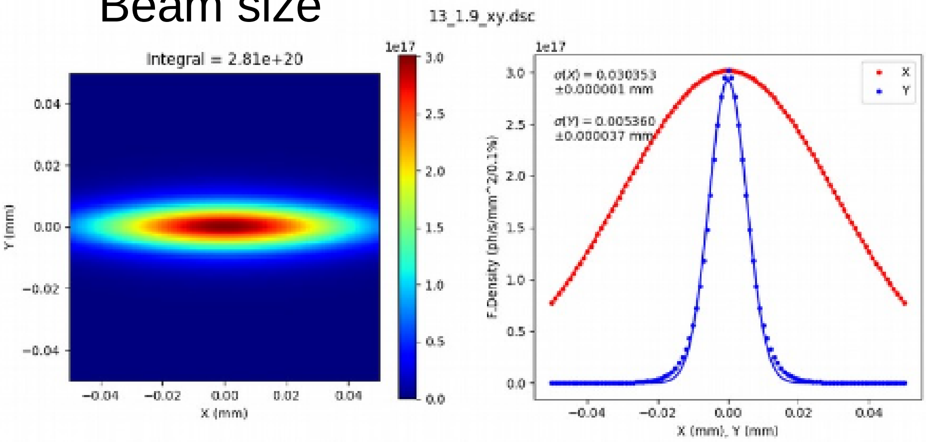
SKIF LB:
ε = 69 / 7 pm·rad
β = **0.5** / 3.0 m
L = 2.3 m

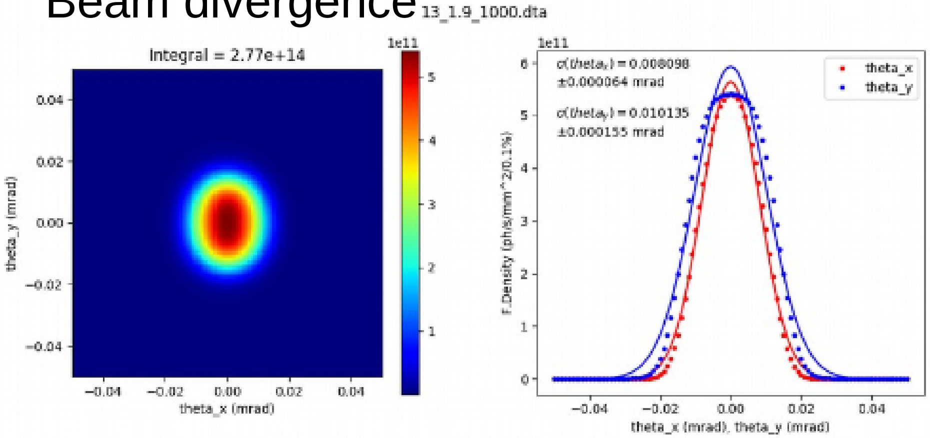
How beam will look like?

7th harmonic of SKIF SCU15.6 at 14.4 keV

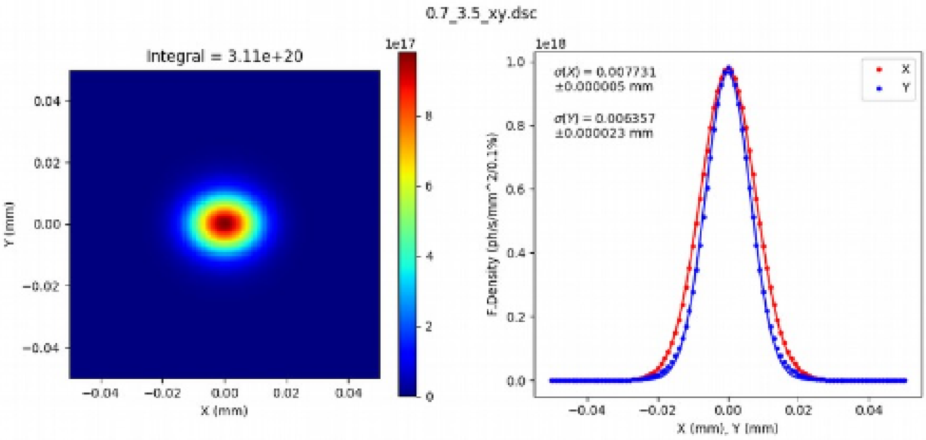
Beam size

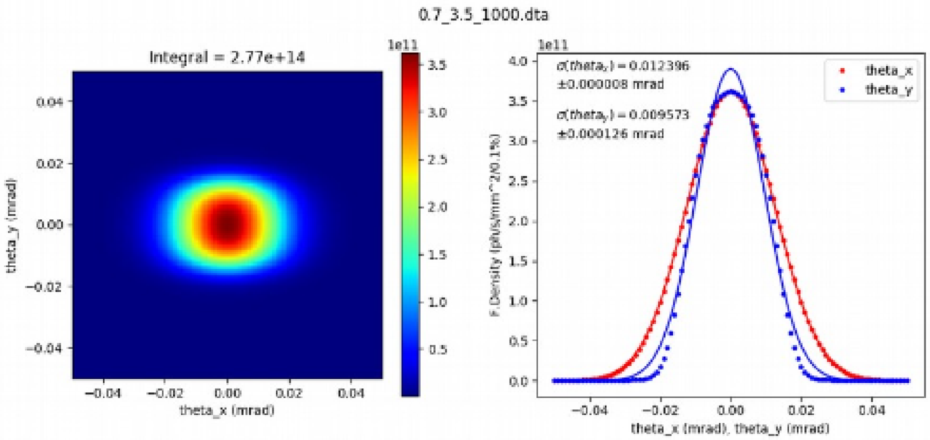
Beam divergence





High beta





Low beta

Maximizing coherent fraction of photon flux:

$$f_{coh} = \frac{\varepsilon_{coh}}{\Sigma_x \Sigma'_x} \cdot \frac{\varepsilon_{coh}}{\Sigma_y \Sigma'_y}$$

$$= \frac{\varepsilon_{coh}^2}{\sqrt{\varepsilon_{e,x}\beta_{e,x} + \varepsilon_{coh}\beta_p}\sqrt{\frac{\varepsilon_{e,x}}{\beta_{e,x}} + \frac{\varepsilon_{coh}}{\beta_p}}\sqrt{\varepsilon_{e,y}\beta_{e,y} + \varepsilon_{coh}\beta_p}\sqrt{\frac{\varepsilon_{e,y}}{\beta_{e,y}} + \frac{\varepsilon_{coh}}{\beta_p}}},$$

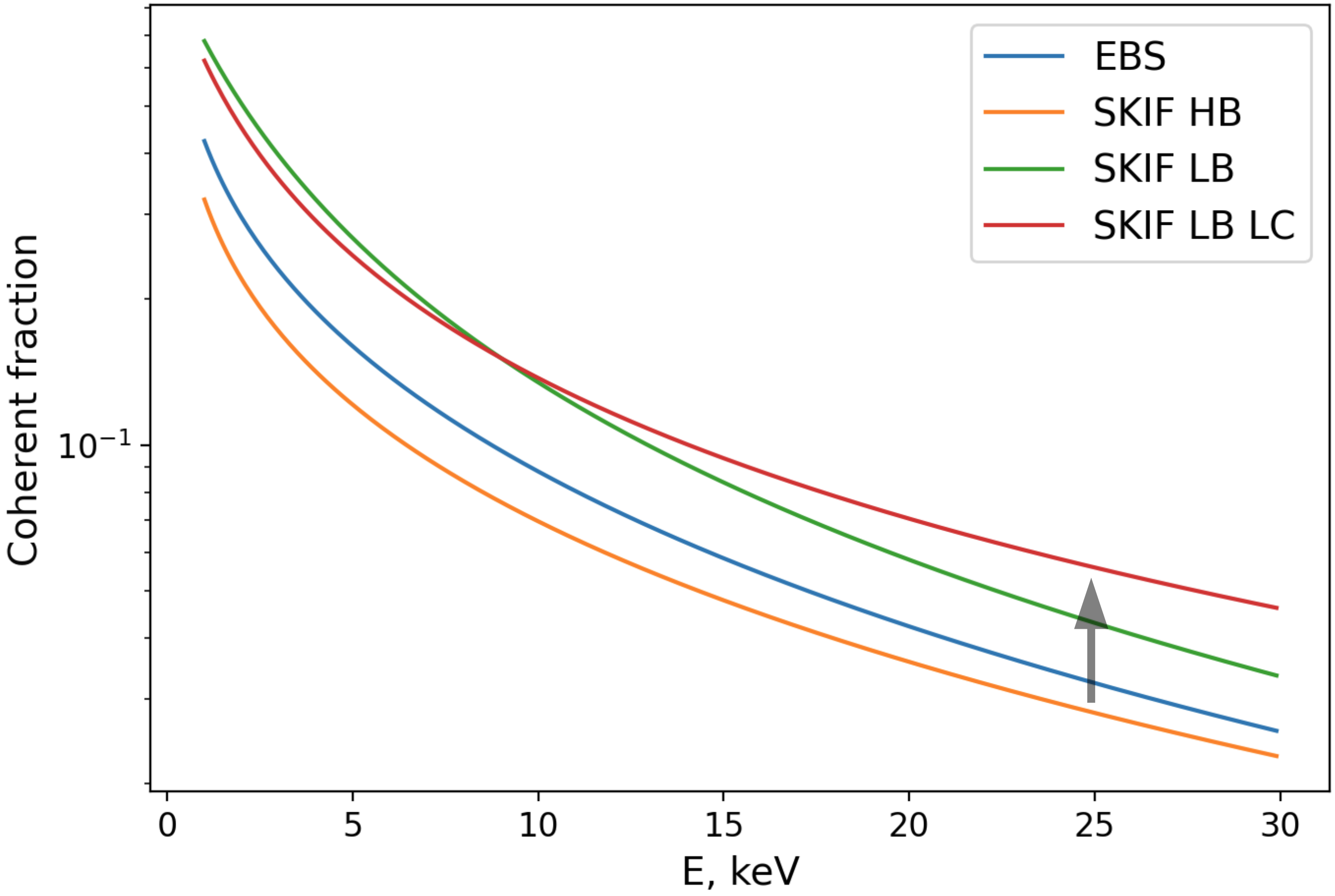
$$(1)\ \min \varepsilon_{e,x} \cdot \varepsilon_{e,y} = \varepsilon_{e,x}^2 \cdot \kappa$$

(minimization of electron beam emittance)

$$(2)\ \beta_e = \beta_p = L/\pi$$

(matching of electron and photon phase space ellipses)

Coherent fraction at 4th generation storage ring

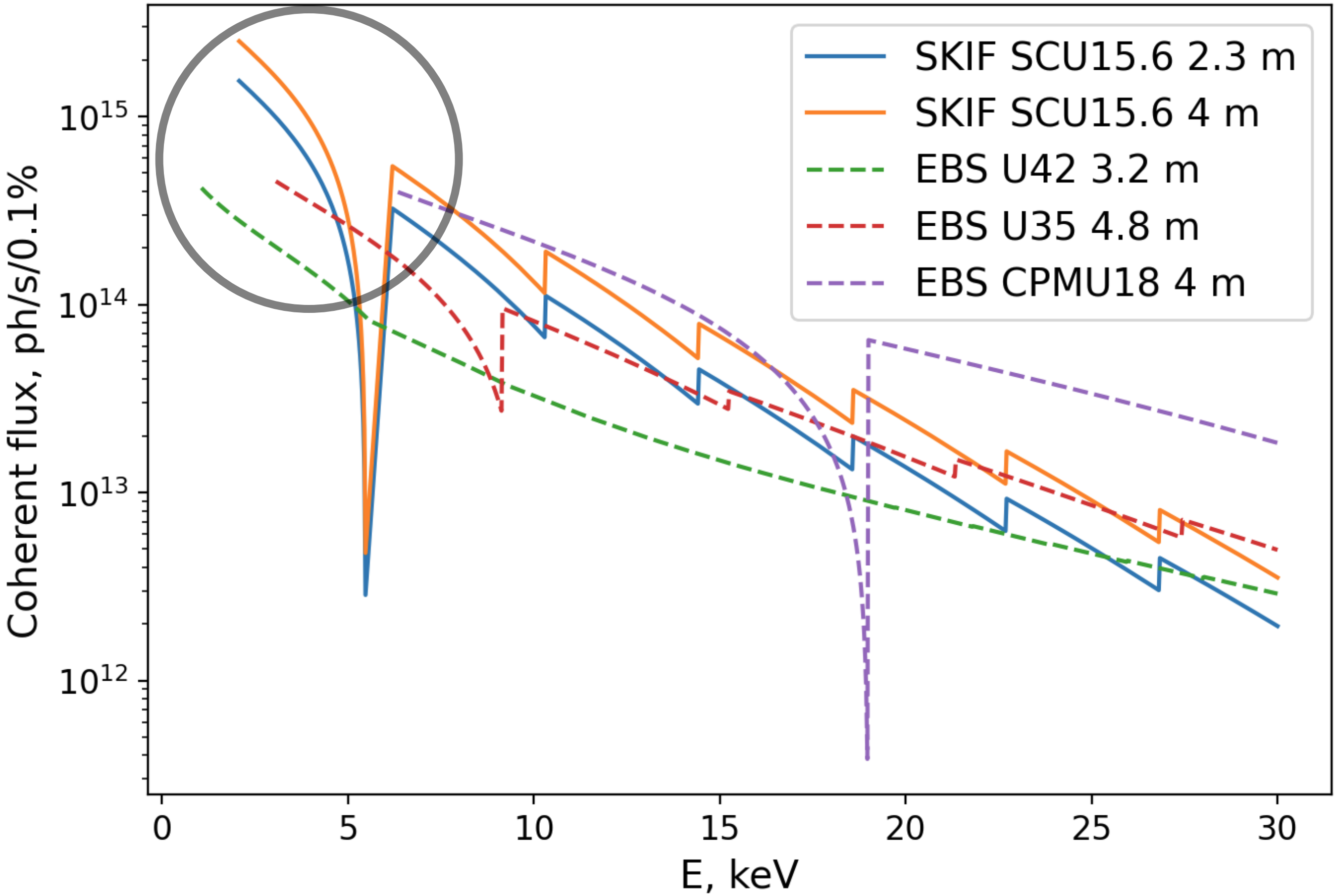


SKIF HB:
ε = 69 / 7 pm·rad
β = 15.7 / 2.3 m
L = 2.3 m

SKIF LB:
ε = 69 / 7 pm·rad
β = 0.5 / 3.0 m
L = 2.3 m

SKIF LB LC:
ε = 115 / **0.6** pm·rad
β = 0.5 / 3.0 m
L = 2.3 m

From coherent fraction to *coherent flux*



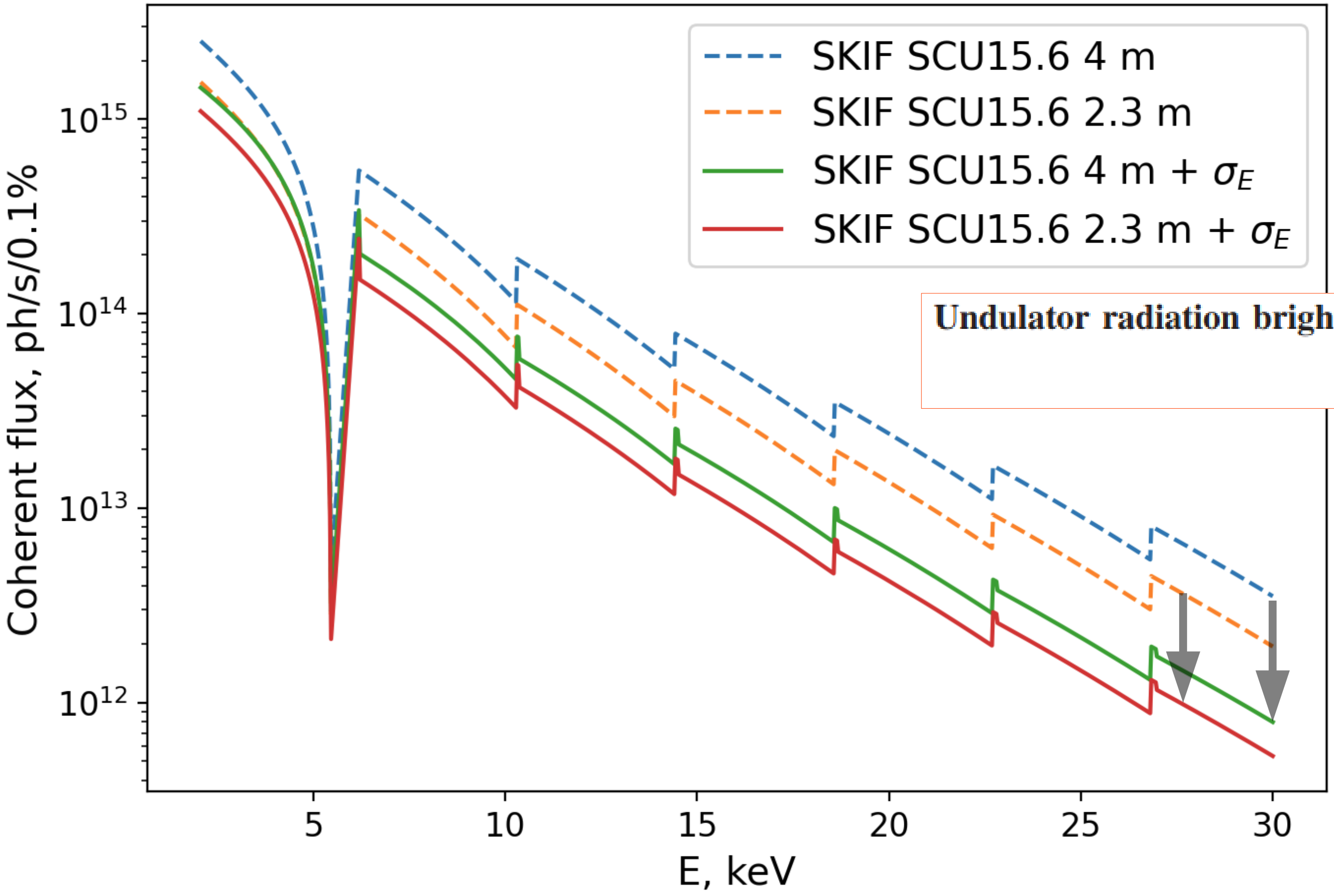
$$F_{coh} = f_{coh} \cdot F = \frac{\varepsilon_{coh}^2}{\Sigma_x \Sigma'_x \cdot \Sigma_y \Sigma'_y} \cdot F$$

$$= \lambda^2 \cdot \frac{F}{4\pi^2 \Sigma_x \Sigma'_x \cdot \Sigma_y \Sigma'_y} = \lambda^2 \cdot B$$

- Up to ~8 keV, low-energy storage rings have *intrinsically* higher coherent flux

- Between 5-20 keV SKIF SCU and EBS CPMU will provide the same coherent flux

Electron energy spread and photon coherence



At SKIF
$\sigma_E \approx 0.14\%$

Undulator radiation brightness and coherence near the diffraction limit

Richard P. Walker

Universal function for the brilliance of undulator radiation considering the energy spread effect

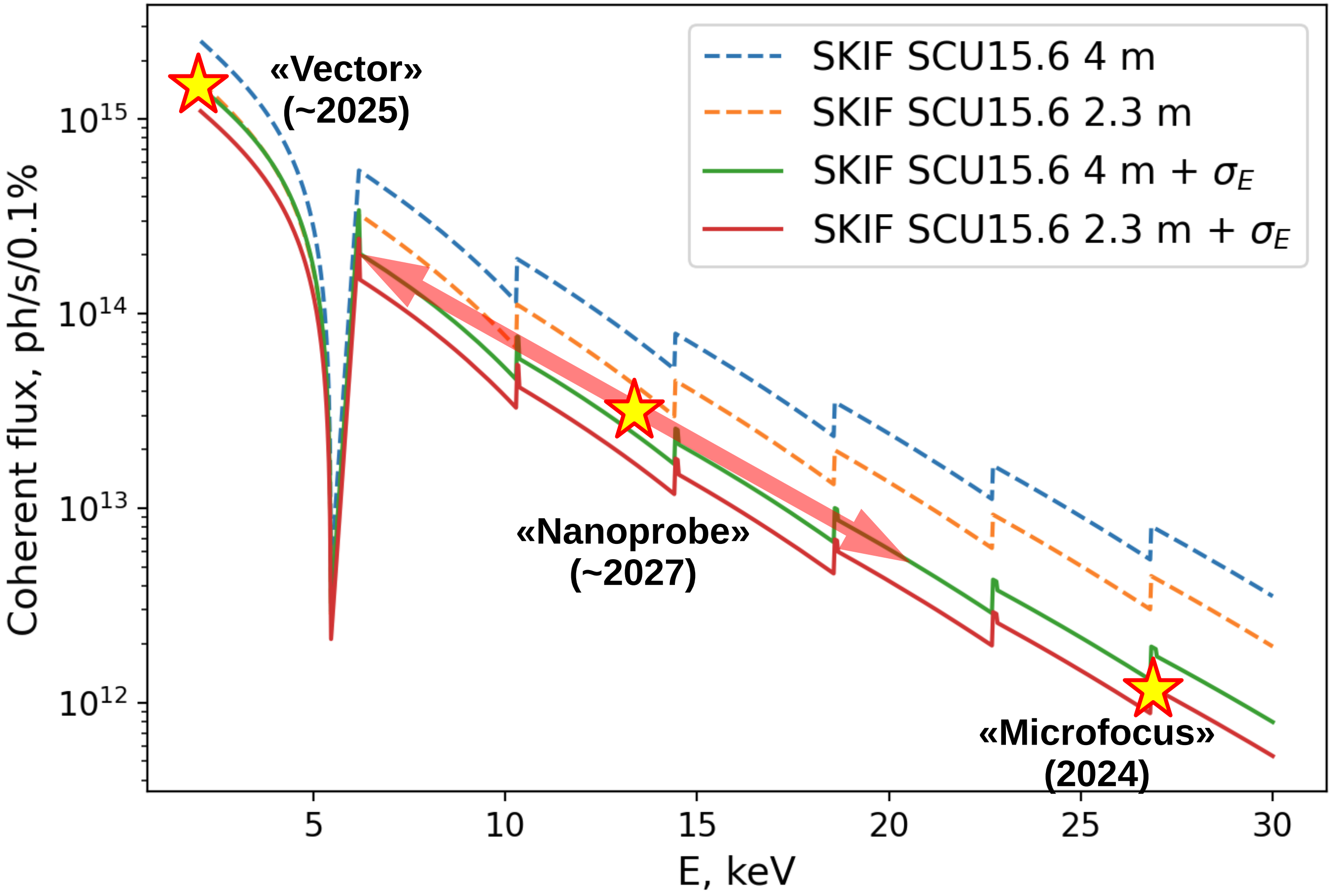
Takashi Tanaka* and Hideo Kitamura

Coherence properties of the high-energy fourth-generation X-ray synchrotron sources

R. Khubbutdinov,[a,b] A. P. Menushenkov[b] and I. A. Vartanyants[a,b]*

Coherent imaging at future SKIF storage ring

Coherent diffraction imaging beamlines at SKIF



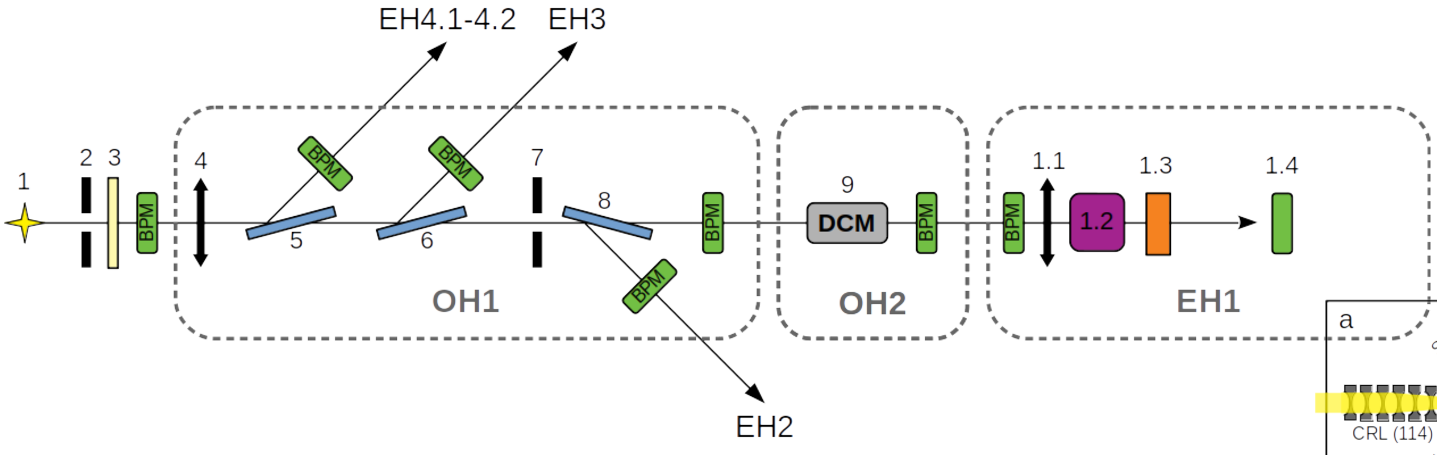
«Microfocus»:
High-energy (27 keV) direct coherent focusing end-station (CRL focusing with relaxed ~600 nm spot)

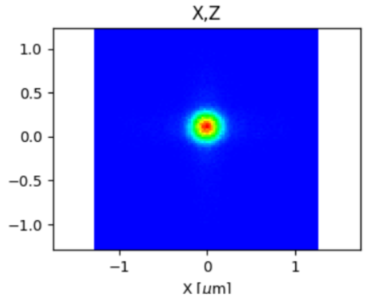
«Vector»:
Extreme flux in tender x-ray; sub-μm direct coherent focusing with KB for single-particle CXDI

«Nanoprobe»:
150-m secondary source beamline for **nm-sized beams** (MLL focusing)

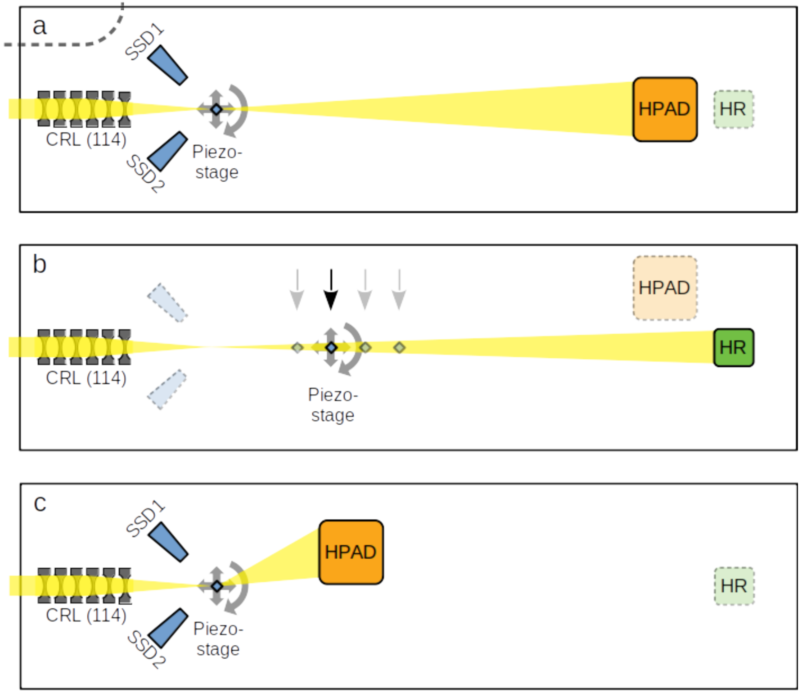
+*Bragg CXDI, XPCS, AXCCA…*

High-energy CXDI section of “Microfocus” beamline

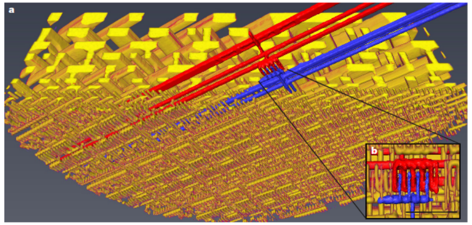




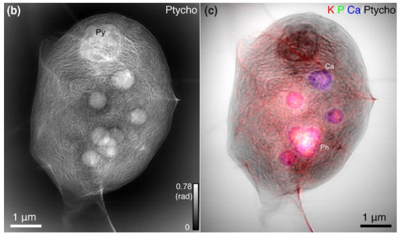
- Direct coherent focusing at ~70 m from the source: spatial filtering by 0.1-mm aperture + CRL ($f \approx 0.5$ m)
- Diffraction limited 600-nm spot: relaxed requirements to positioning during ptychographic scans
- ‘Pink beam’ option (DMM)
- HPAD + sub-μ resolution CCD camera, XRF detectors



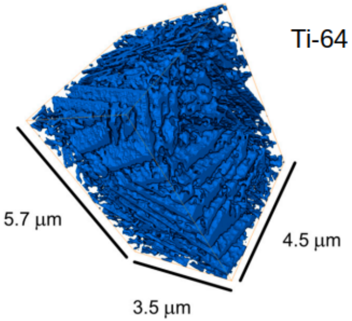
Coherent imaging of complex and hierarchic nanostructures



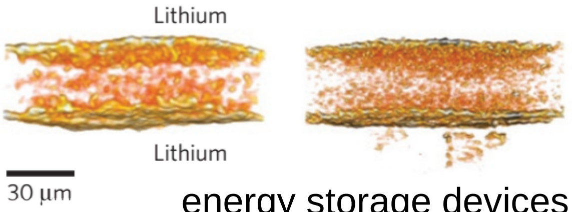
nanoelectronics



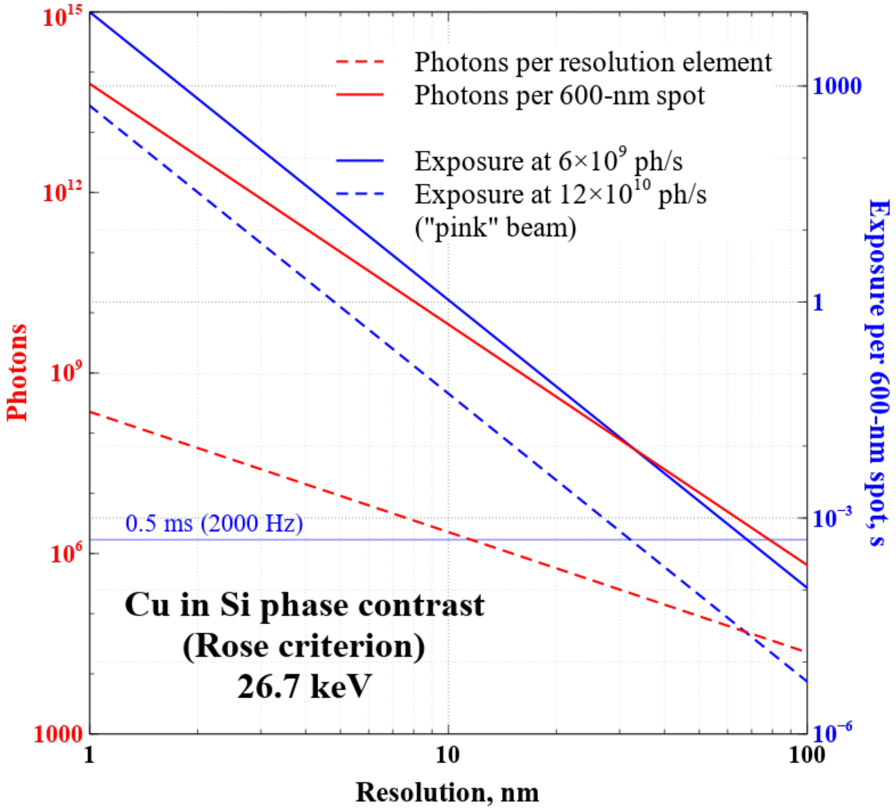
in vivo cells
(low radiation damage)



aerospace alloys



energy storage devices
(Harry *et al.* 2014)

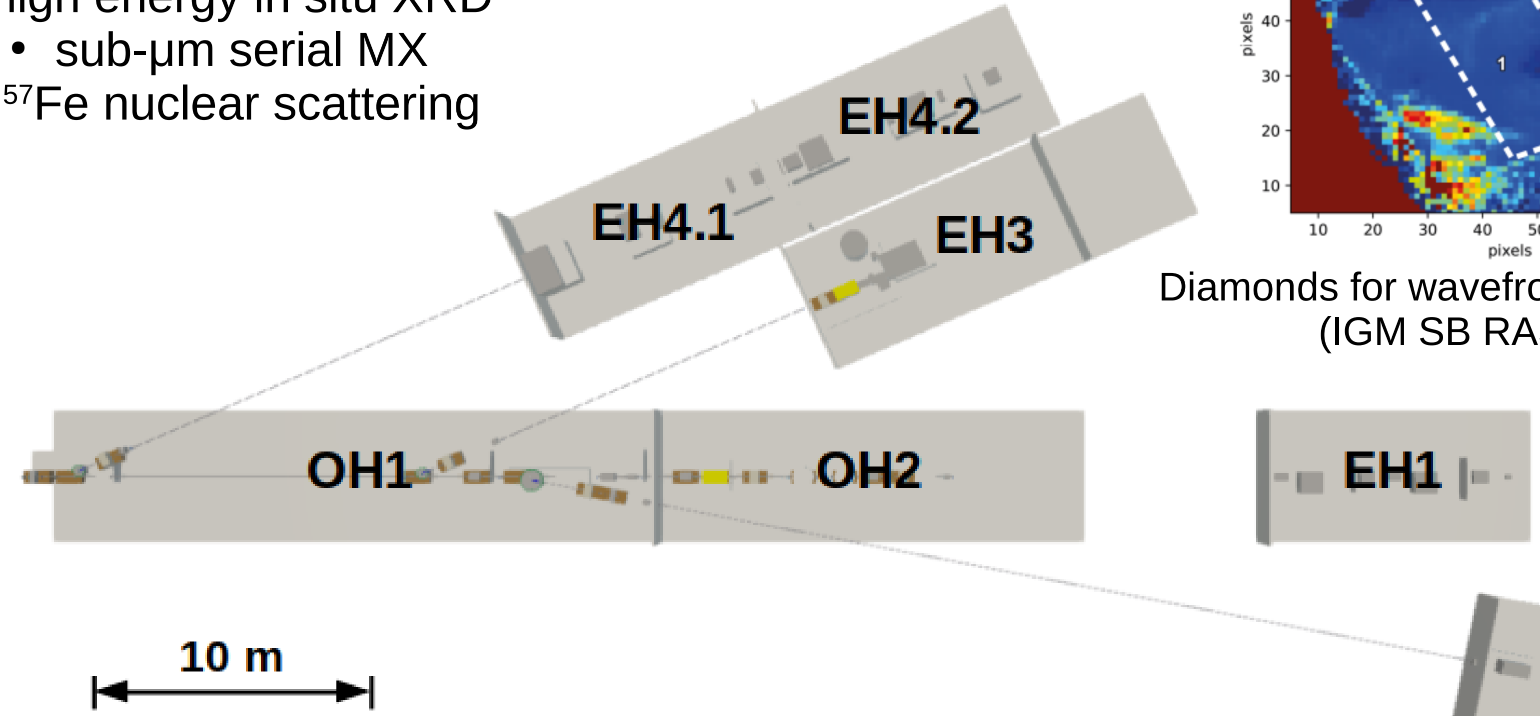


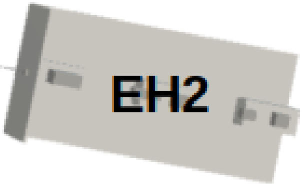
- High-energy CXDI and ptychography **up to 1-nm-resolution**
- Holotomography with 150-nm-resolution
- XRD and XRF nanotomography with 200-nm-resolution

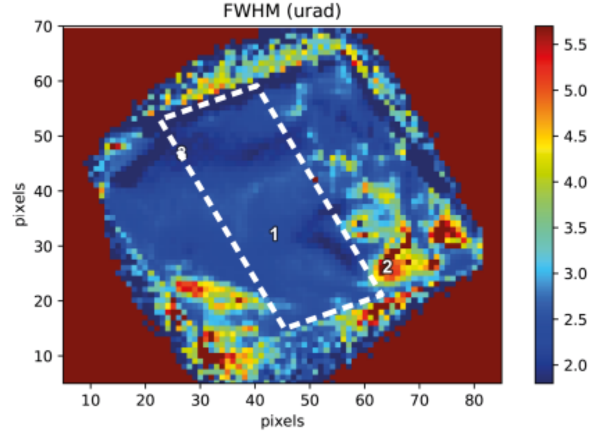
Beam multiplexing concept

Side end-stations with fixed-energy techniques:

- high energy in situ XRD
- sub-μm serial MX
- ^{57}Fe nuclear scattering







Diamonds for wavefront-preserving optics
(IGM SB RAS + IKBFU)

Thank you for your attention!