Novel Emittance Diagnostics for Diffraction Limited Light Sources based on X-ray Fresnel Diffractometry

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Presentation Outline

- Introduction
- Principle of X-ray Fresnel Diffractometry (XFD)
- Simulation for Ultra-low Emittance Diagnostics using XFD
- Proof-of-Principle Experiment at SPring-8
- Future Prospects of XFD

  - Expansion to Two Dimensions

  - Achievable Resolution of XFD

- Summary

Introduction

Significance of Emittance Diagnostics in Synchrotron Light Sources

- maximizing brilliance and transverse coherence which are major light performances.

Diagnostic techniques established for bending magnet sources

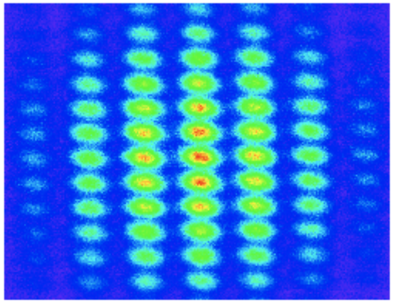
Visible light

- π-polarization imaging
- interferometric techniques

2D-interferometer @SPring-8

2D beam profiling including beam tilt angle

M. Masaki et.al, J. Synchrotron Rad. 10, p.295 (2003)

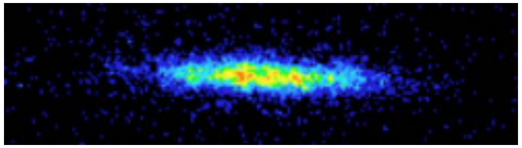


X-ray

- pinhole camera
- imaging method

X-ray Beam Imager using a FZP @SPring-8

S. Takano et.al, NIM. Phys. Res. A, 556, p.357 (2006)



Introduction (Cont.)

Emittance Diagnostics for ID sources are essential !!

to maximize brilliance and transverse coherence at photon beamlines for user experiments.

through the machine tuning to correct local lattice distortions, local XY betatron coupling, etc.

For a Diffraction Limited Storage Ring (DLSR) with ultra-low emittance,

- **Local corrections will be even more important.**
- **Diagnostics for ID sources will be crucial.**

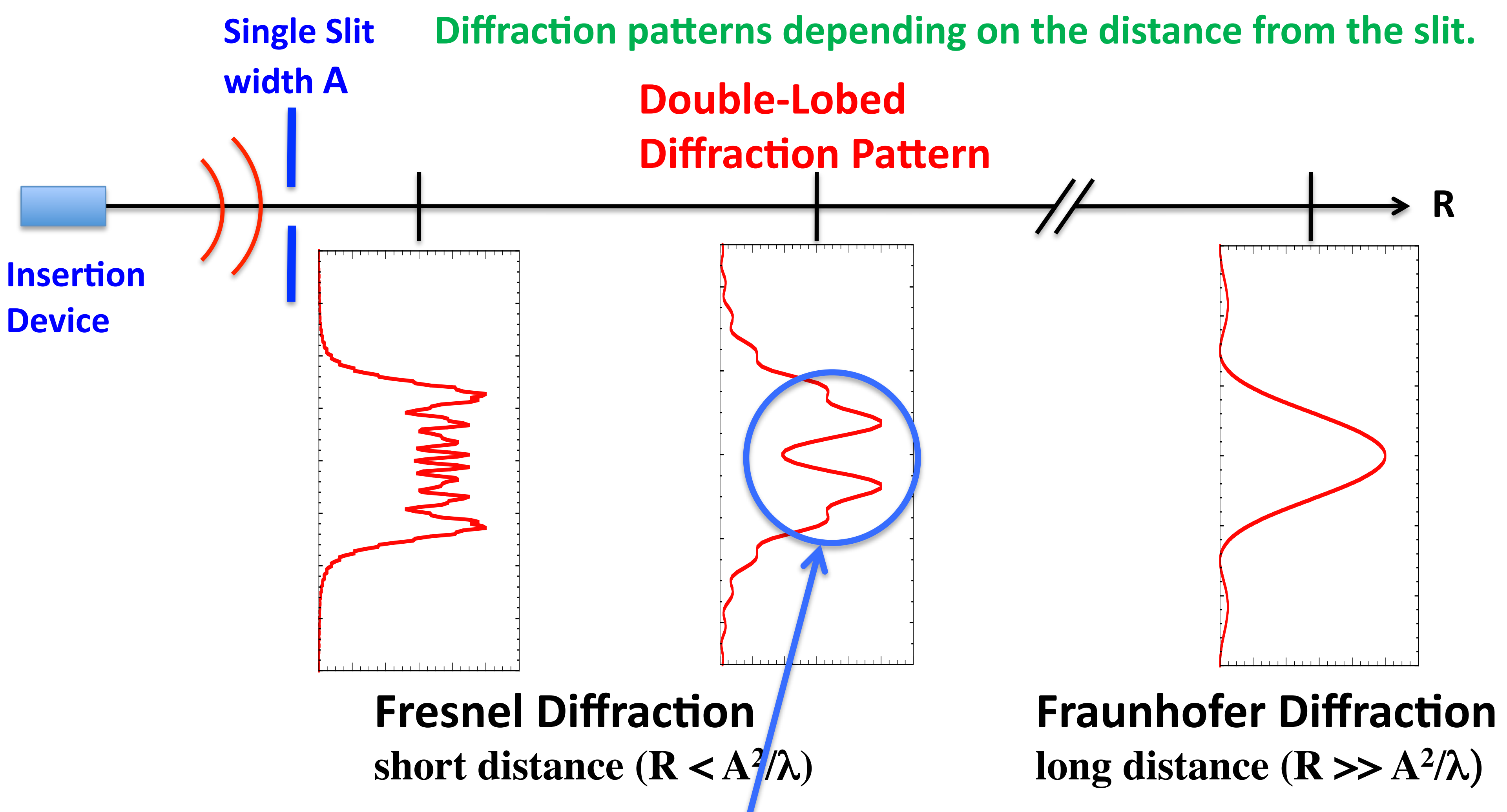
Newly developed X-ray Fresnel Diffractometry (XFD)

- **Resolving a micron-order ID source size with high sensitivity.**

  At ID source points with small vertical betatron functions of several meters, vertical beam size < 10 μm (r.m.s.)

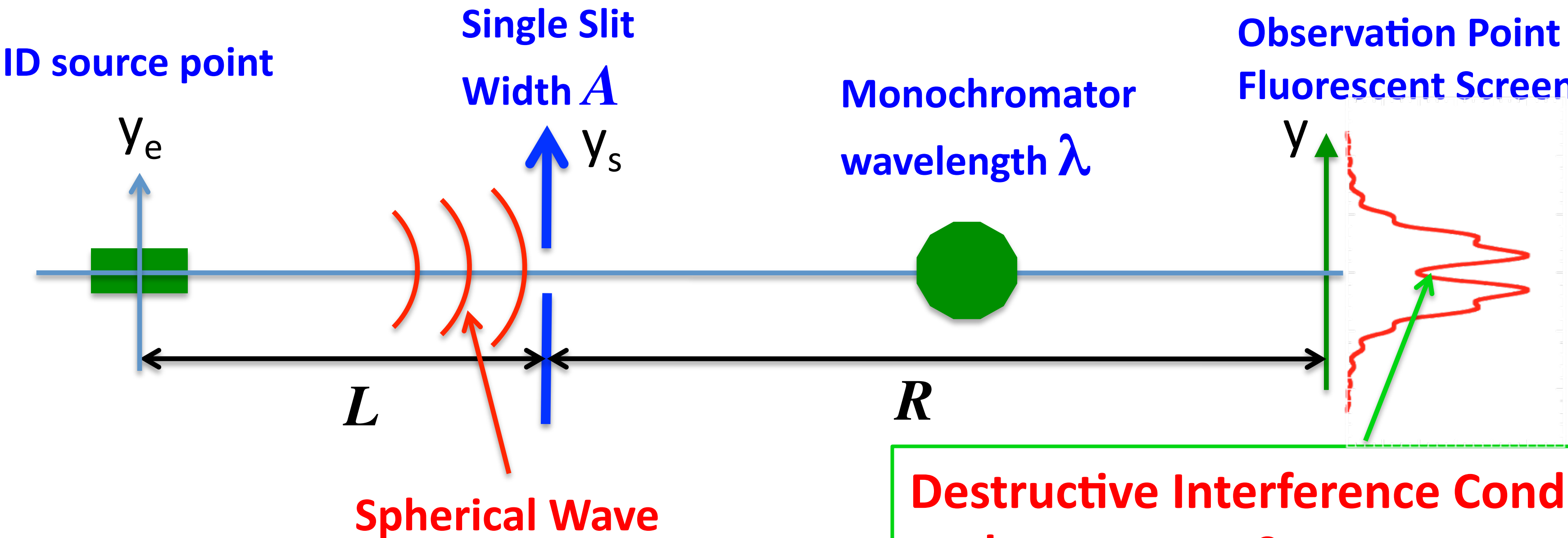
- **Available at typical beamlines with a 4-jaw slit and a monochromator.**

X-ray Fresnel Diffractometry (XFD)



The depth of a median dip correlates with a light source size.
The dip becomes shallow with growth in the source size.

X-ray Fresnel Diffractometry (XFD)



Destructive Interference Condition at the center y=0

The best slit width to get the deepest median dip $A \approx \sqrt{7\lambda \frac{LR}{L+R}}$

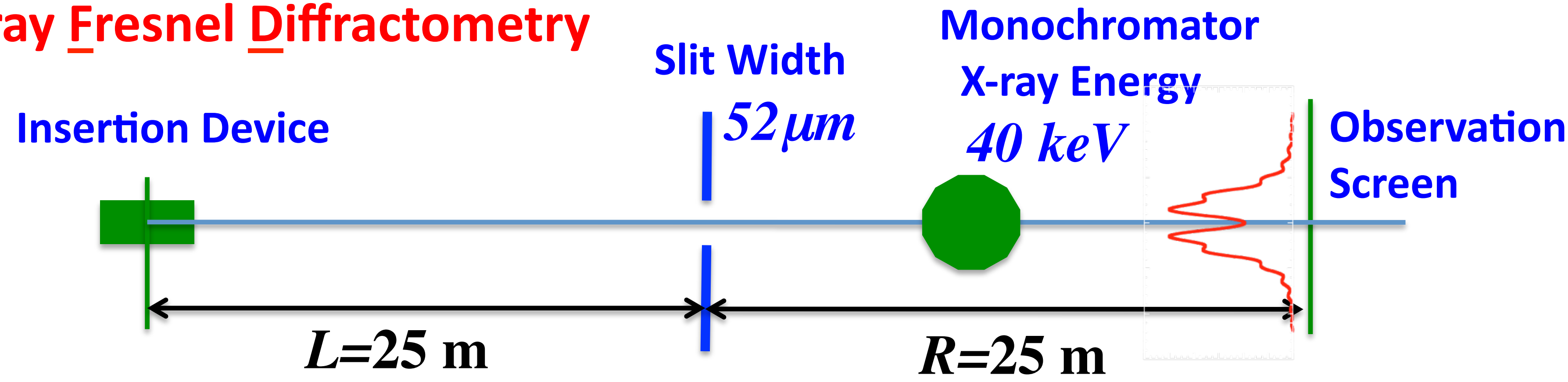
Requirement for light source

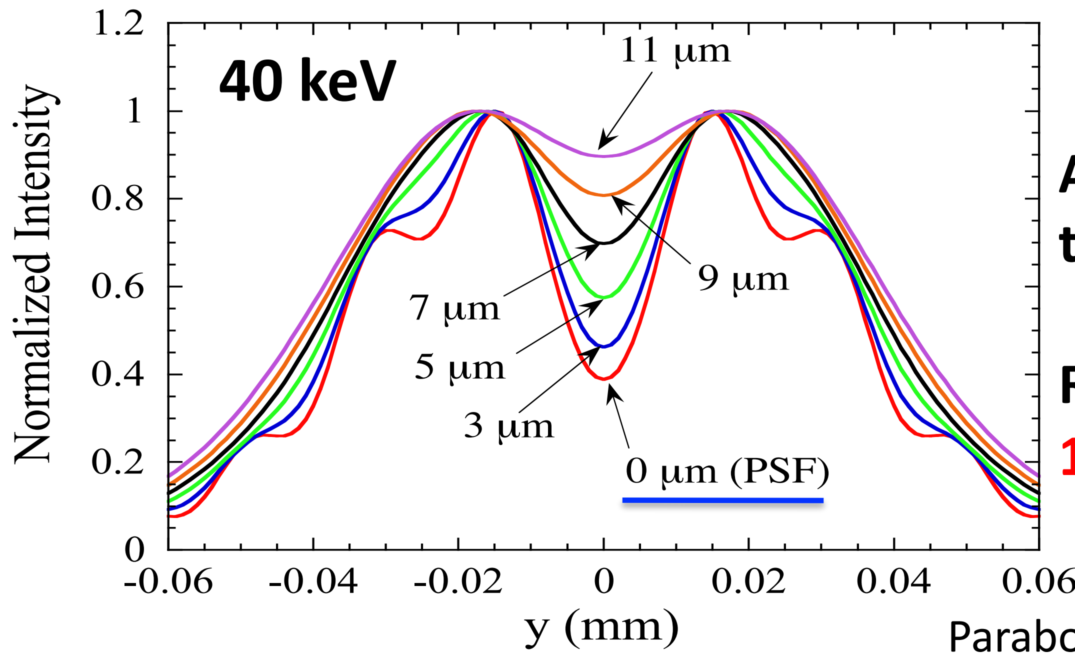
The radiation should be a spherical wave with a flux distribution wider than the slit width.

Most types of undulators and wigglers satisfy this requirement !!

Simulation of ID Source Size Measurement for DLSR

X-ray Fresnel Diffractometry





As the source size gets larger, the dip becomes less deeper.

Resolving source sizes of less than 10 μm with a resolution of 1 μm.

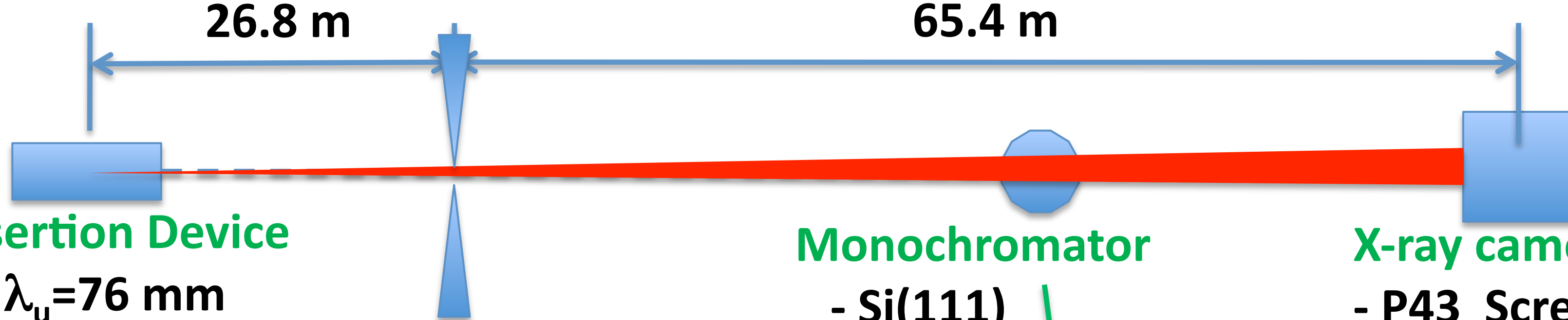
Parabolic Approximation of Spherical Phase

Point Spread Function (PSF)

$$I(y,y_e) \propto \left| \int_{-A/2}^{A/2} \sqrt{I_s(y_s - y_e)} \exp\left[i\frac{\pi}{\lambda}\left\{\frac{1}{L}+\frac{1}{R}\right\}\left\{(y_s - y_e) - \frac{L(y-y_e)}{L+R}\right\}^2\right] dy_s \right|^2$$

Proof-of-Principle Experiment

Vertical ID Source Size Measurement at SPring-8 Diagnostics Beamline (BL05SS)



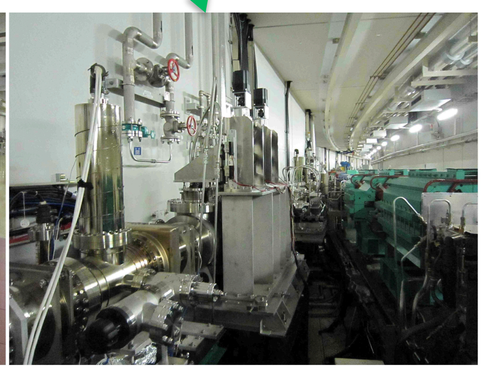
Insertion Device
- λ_u=76 mm
- N_u=51
- L_u = 3.876 m

Single Slit

Monochromator
- Si(111)

X-ray camera
- P43 Screen
- lenses
- CCD camera

exposure time 1ms



Proof-of-Principle Experiment (Cont.)

X-ray energy

7.2 keV @ 1st harmonic with deflection parameter K=0.46

Slit Width

Vertical : $\Delta Y = 150\ \mu m$ from the formula $A \approx \sqrt{7\lambda \frac{LR}{L+R}}$

Horizontal : $\Delta X = 200\ \mu m$

Experimentally adjusted to give the deepest median dip.

To minimize the contributions of the off-axis radiations coming from large horizontal emittance which can cause the contrast degradation of the PSF.

Resolution of the X-ray camera

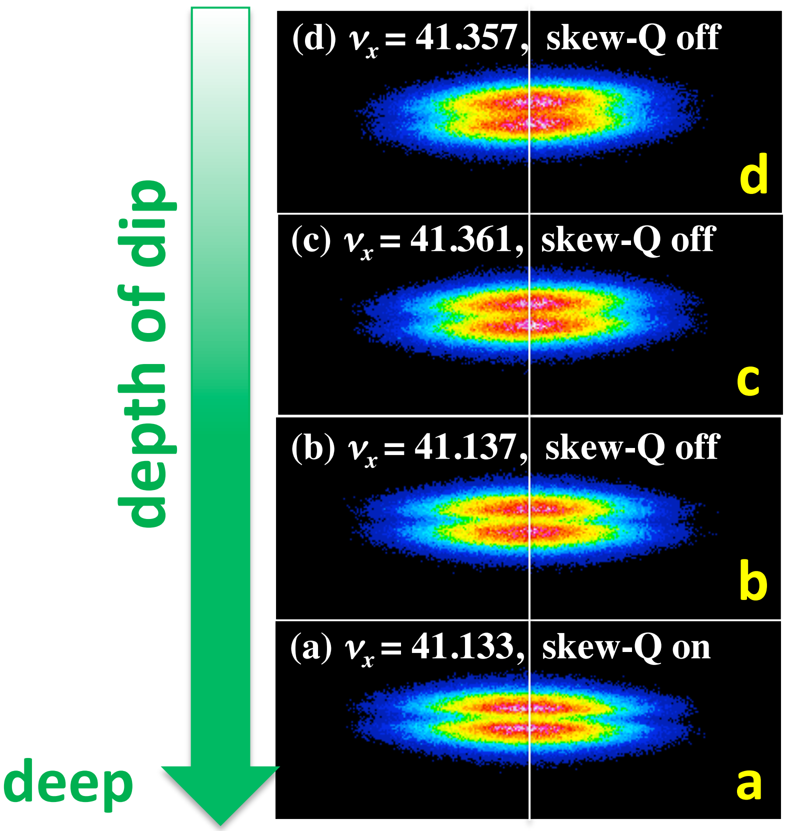
Calibrated by sharpness of observed edge of a stainless steel wire placed in front of the device.

-> $\sigma_{res} = 6.8\ \mu m$ (r.m.s.) in scale at the ID05 source point

Proof-of-Principle Experiment (Cont.)

Observed Diffraction Patterns for Different Vertical Emittances

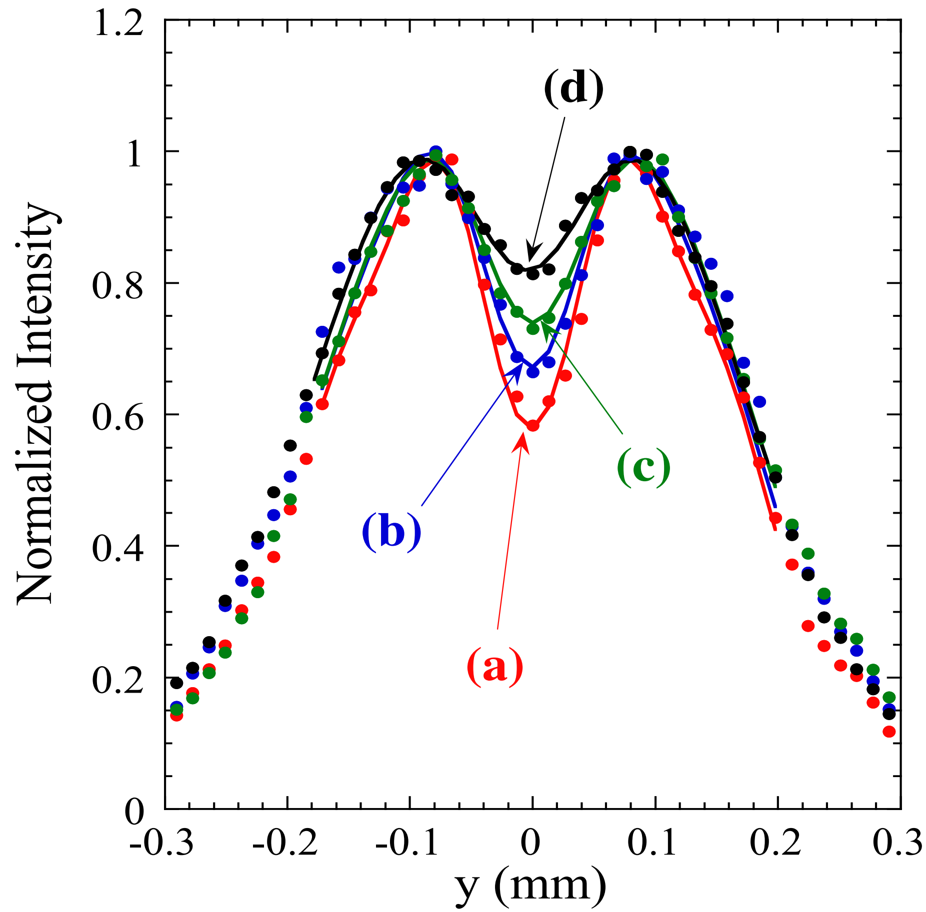
- Changing horizontal tune for betatron coupling control.
- Turning skew quadrupole magnets on and off.



Double-Lobed Structure

Vertical : Clear

Horizontal: Smeared out



Vertical line-projected profiles

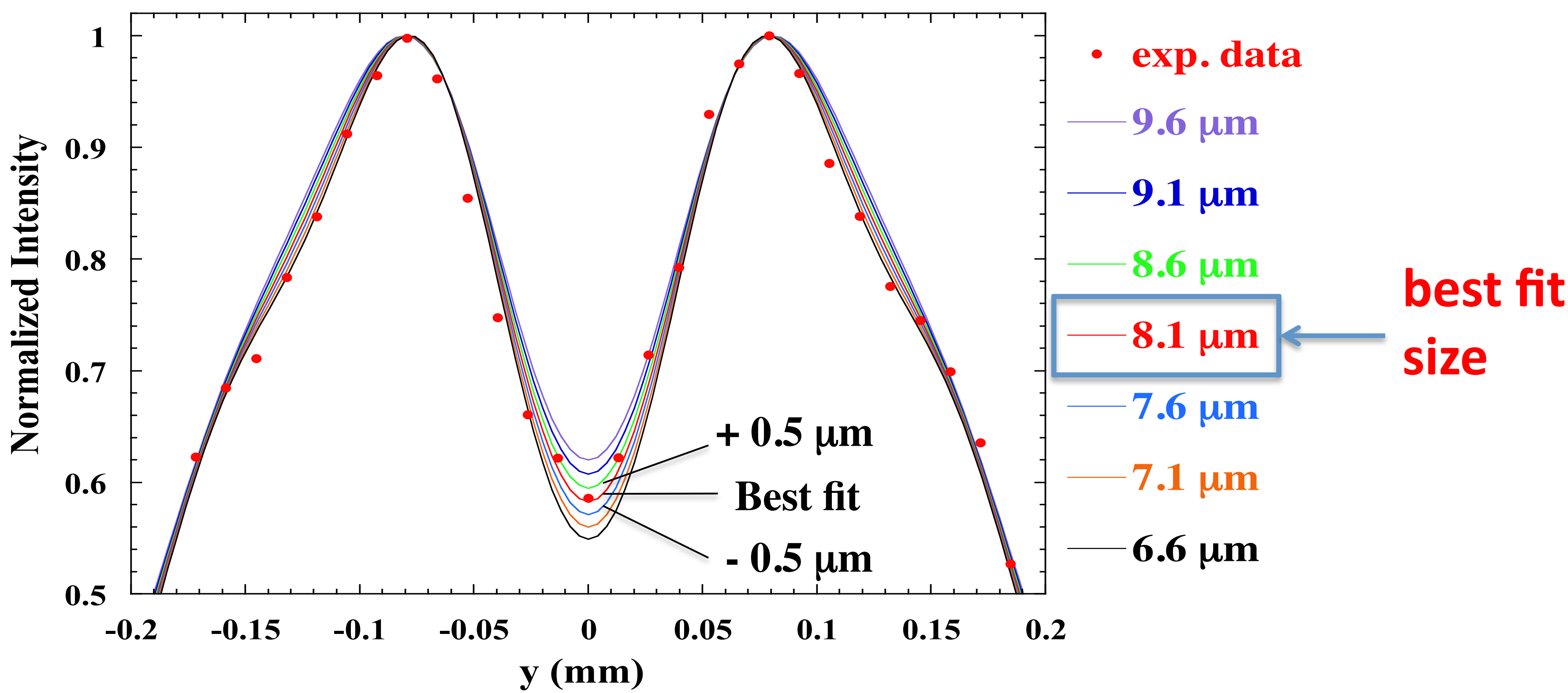
Proof-of-Principle Experiment (Cont.)

Fitted function: $$f(y) = C\int_{-\infty}^{\infty} \underline{I(y, y_e)} \exp\left[-\frac{(y_e - y_0)^2}{2(\underline{\sigma_{y,e}^2} + \sigma_{res}^2)}\right] dy_e$$

PSF

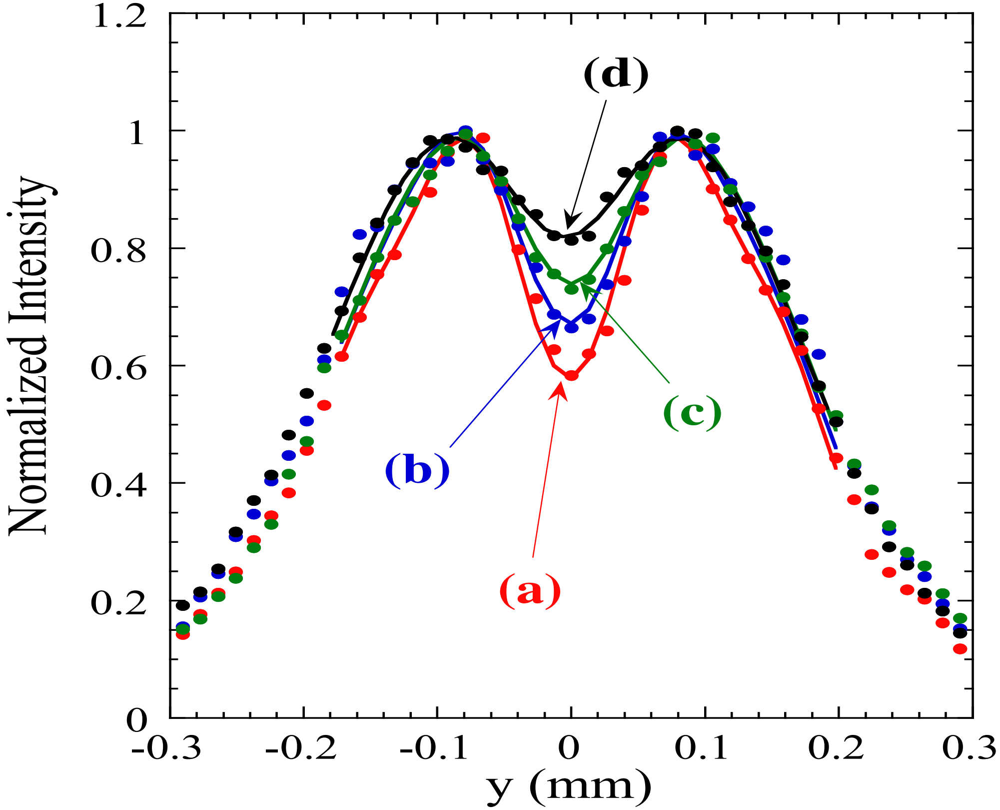
Source Size

Analysis for exp. data with the deepest dip



Proof-of-Principle Experiment (Cont.)

Fitted function: $$f(y) = C\int_{-\infty}^{\infty} I(y, y_e)\exp\left[-\frac{(y_e - y_0)^2}{2(\sigma_{y,e}^2 + \sigma_{res}^2)}\right]dy_e$$



Best Fitted Size (r.m.s.)

(d) 17.7 μm

(c) 14.5 μm

(b) 11.7 μm

(a) 8.1 μm

(1) The light source size smaller than 10 μm was successfully resolved.

(2) The resolution was in the order of sub-microns (~ 0.5 μm).

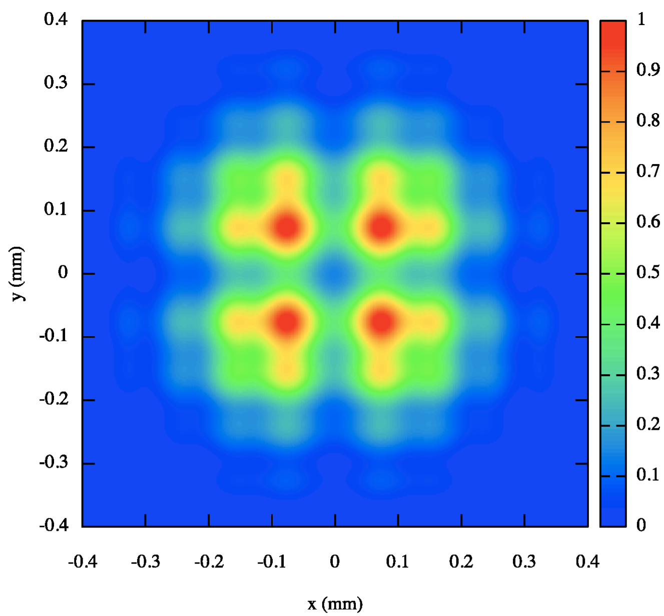
Two-Dimensional Measurement for Future Light Sources

Square Slit: 150 μm x 150 μm

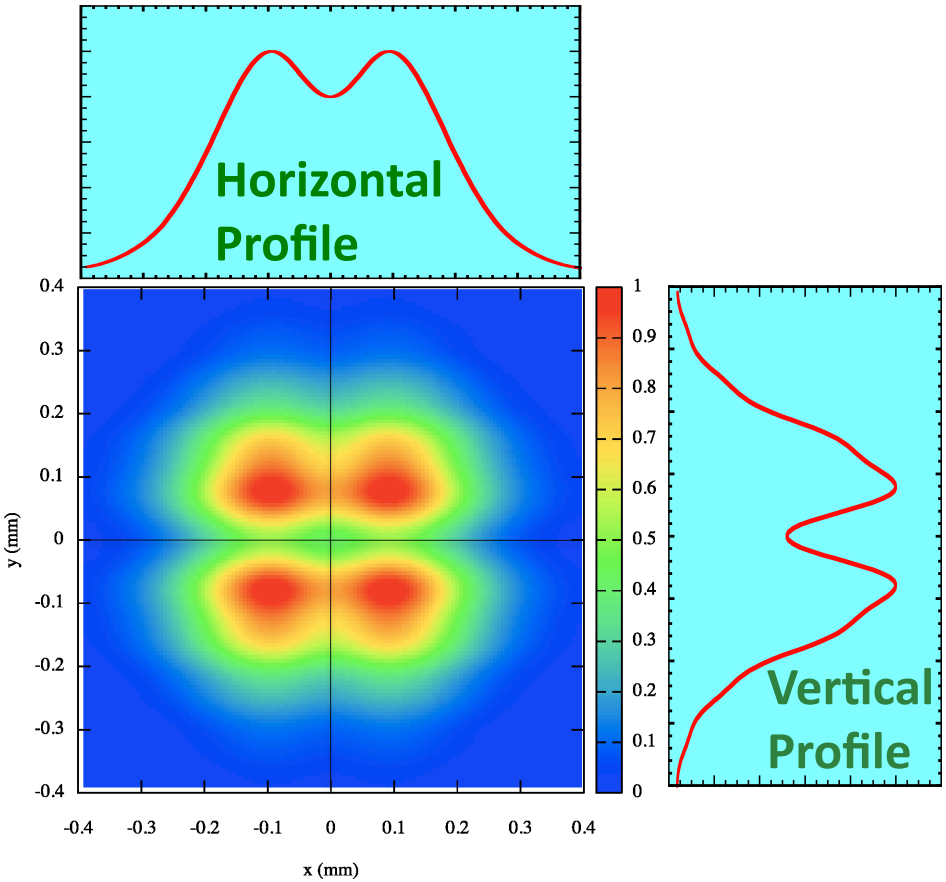
X-ray energy 7.2 keV, L=26.8 m, R=65.4 m

Numerical Calculation

2D Point Spread Function:
Diffraction Pattern
for Point Source



Diffraction Pattern for source size of
$\sigma_x = 20$ μm, $\sigma_y = 10$ μm

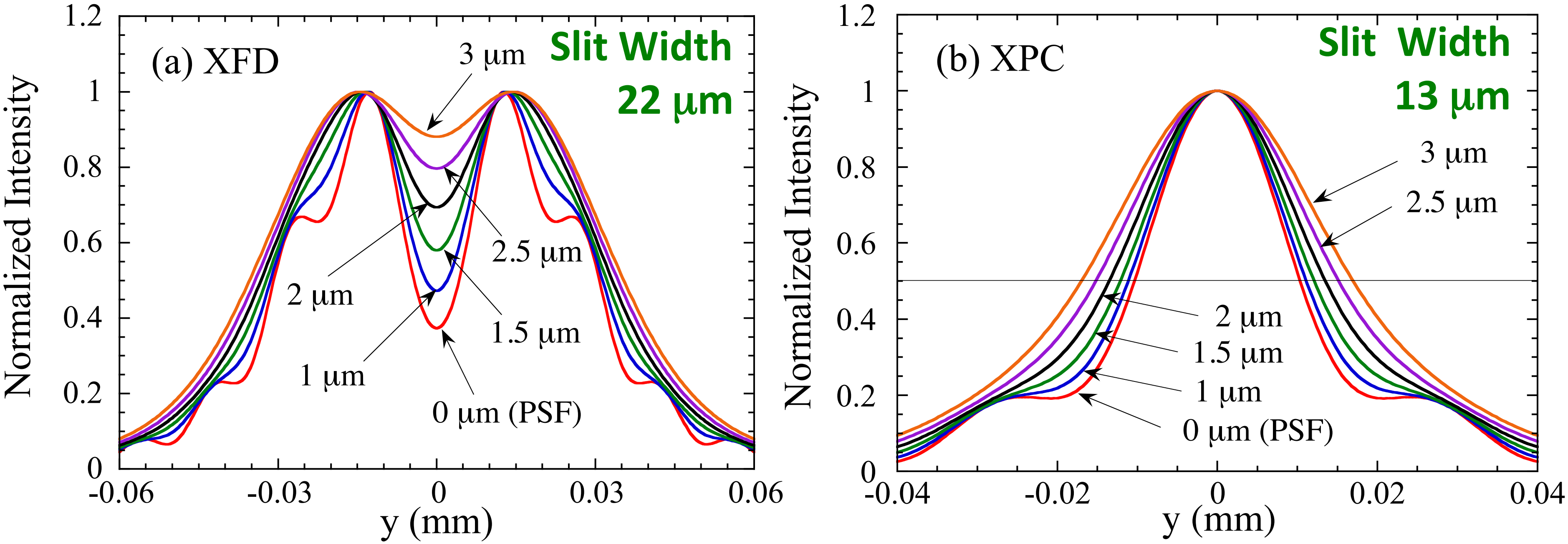


Simultaneous Horizontal and Vertical Measurements Available

Achievable Resolution of XFD

The slit placed close to the source point can improve the resolution.
Comparison between the XFD and the X-ray pinhole camera (XPC).

Source to Aperture (Slit / Pinhole)	3 m
Aperture to Observation Point	9 m
X-ray Energy	40 keV



The XFD has

(1) higher sensitivity to changes in micron-order beam sizes than the XPC.

(2) potential to resolve beam sizes of even smaller than 1 μm (r.m.s.).

Summary

(1) We have proposed a new emittance diagnostic technique, X-ray Fresnel Diffractometry (XFD) to measure micron-order beam size at ID source point.

(2) Experimental Study at SPring-8 has shown that the XFD is sensitive to micron–order change in the beam size and the light source size of less than 10 μm (r.m.s.) was successfully resolved.

(3) XFD with an optimized setting has the potential to resolve sub-micron beam sizes.

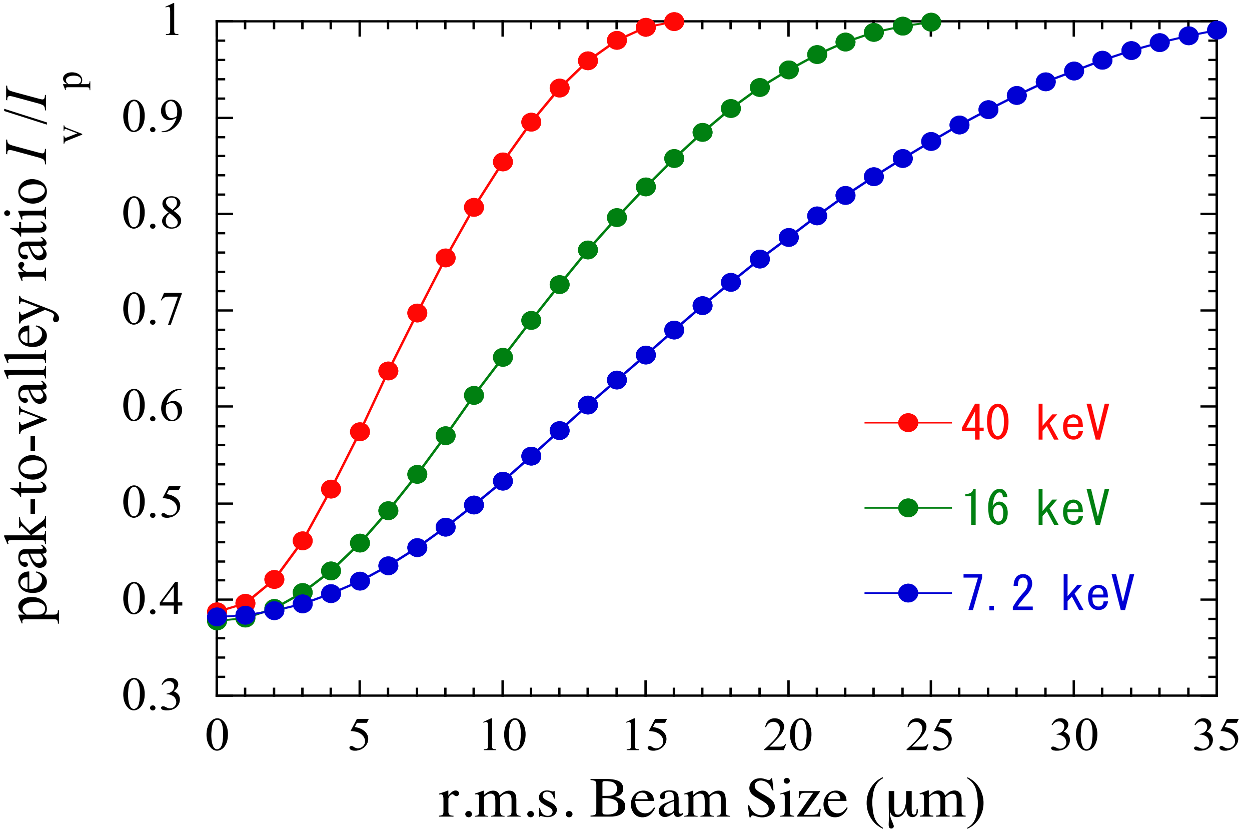
(4) This new method is a promising emittance diagnostic technique to maximize the performance of ring-based next-generation light sources.

Thank you for your attention.

Back Up

Sensitivity Curves

PV-ratio v.s. Source size

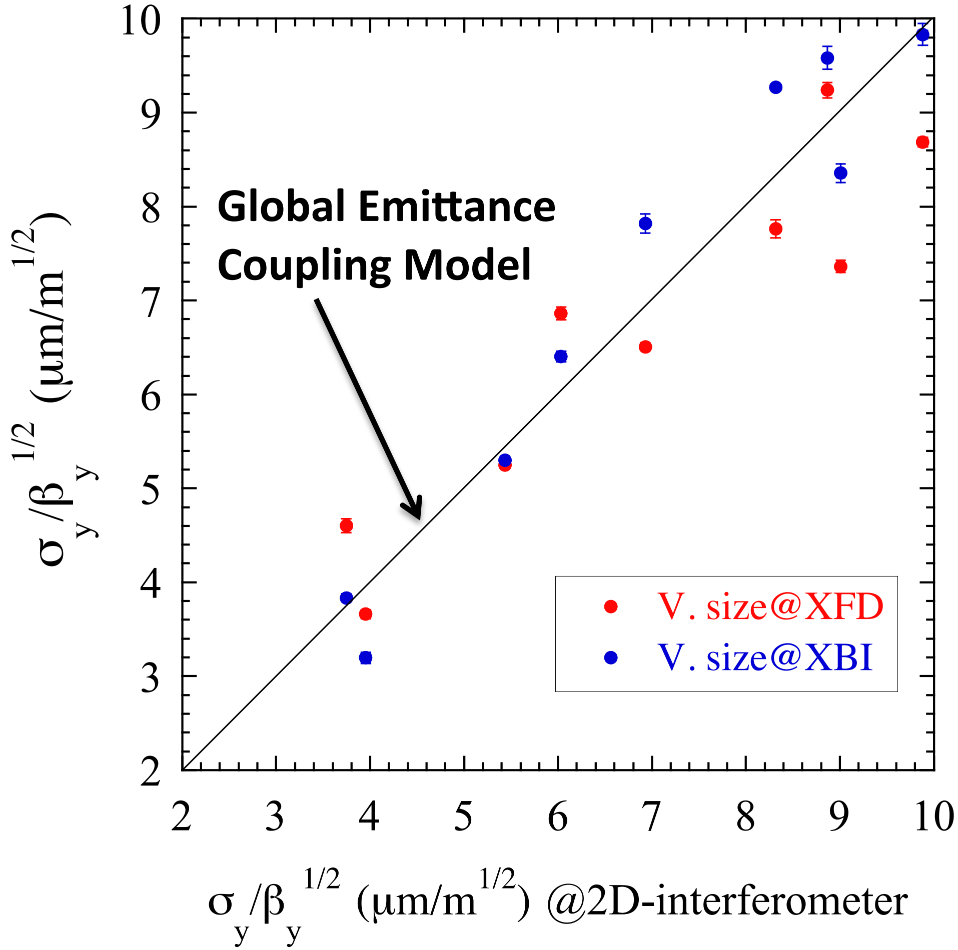


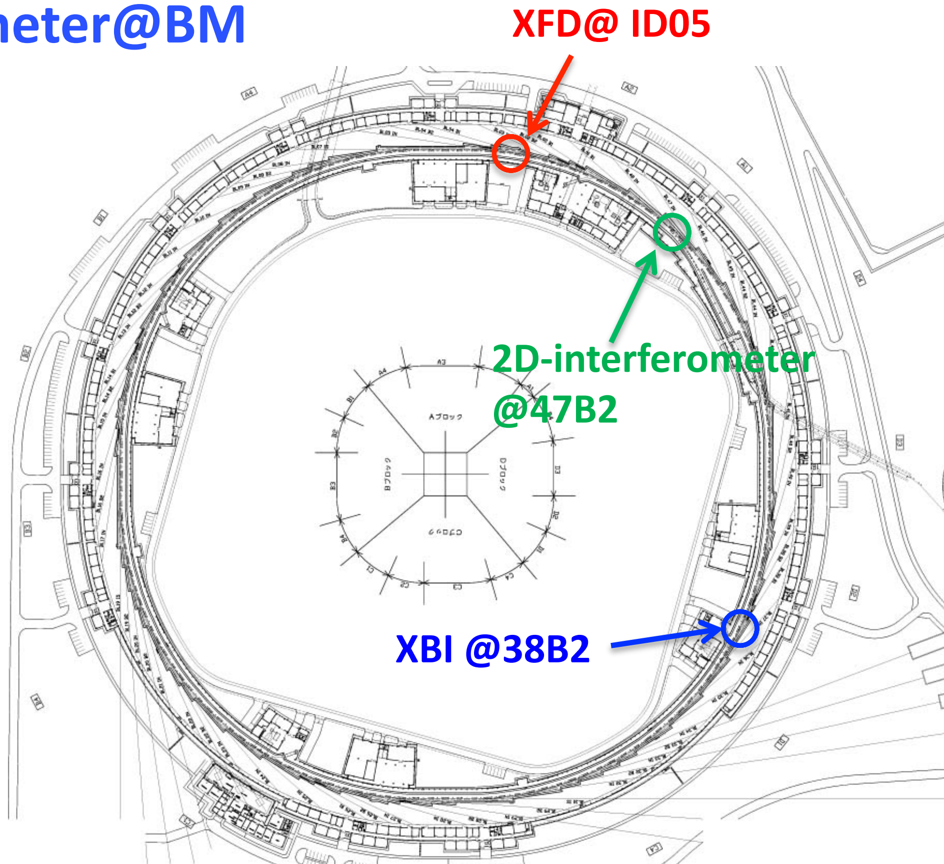
The observing X-ray energy can be selected by a beamline monochromator depending on the range of the measuring source sizes.

Comparison with other measurements

Comparison between three measurements

XFD@ID; XBI@BM; 2D-interferometer@BM





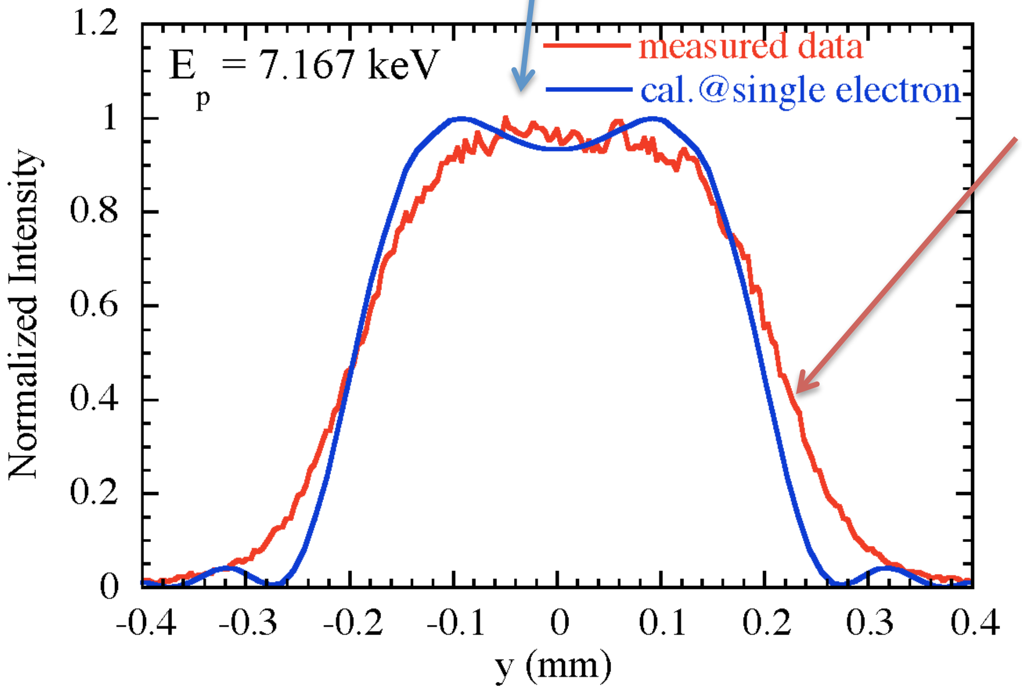
Beam size monitors at three separate source points of the storage ring.

The correlation among three measurements has a trend along the black linear line.
However, the scatters of data around the black line are larger than the error bars.
An influence of the local betatron coupling resulting in the position-dependent coupling ratio.

Vertical flux distribution at the slit to calculate PSF

Vertical Point Spread Function

$$I(y, y_e) \propto \left| \int_{-A/2}^{A/2} \sqrt{I_s(y_s - y_e)} \exp\left[i\frac{\pi}{\lambda}\left\{\frac{1}{L} + \frac{1}{R}\right\}\left\{(y_s - y_e) - \frac{L(y - y_e)}{L + R}\right\}^2 \right] dy_s \right|^2$$



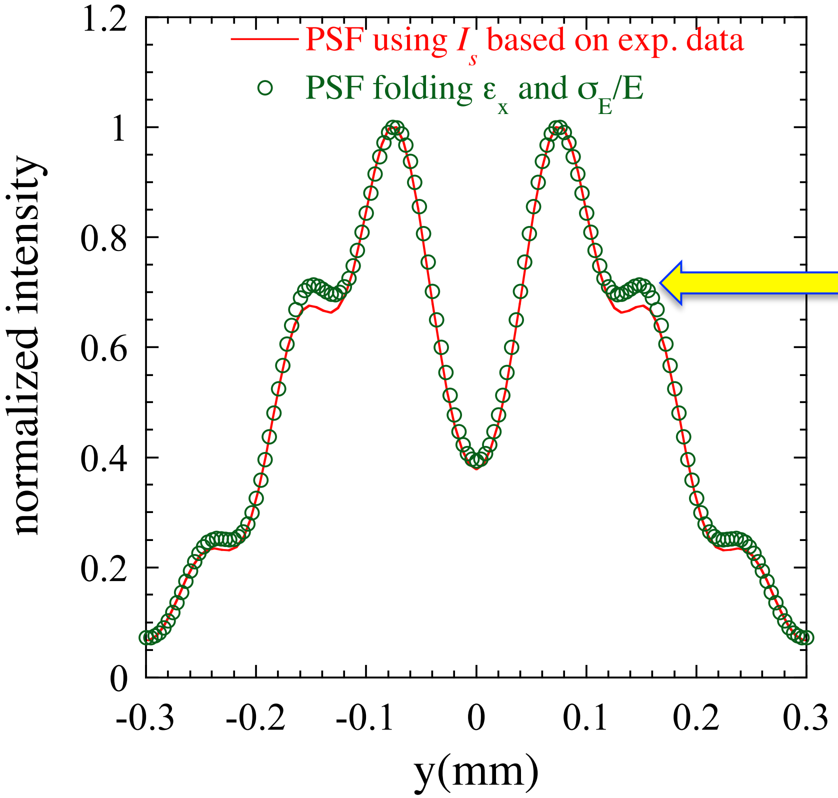
Measured vertical flux distribution with the full-opened slit, including contributions of the off-axis and off-resonant radiations, effectively.

- **off-axis radiation coming from horizontal emittance**
- **off-resonant radiation coming from energy spread**

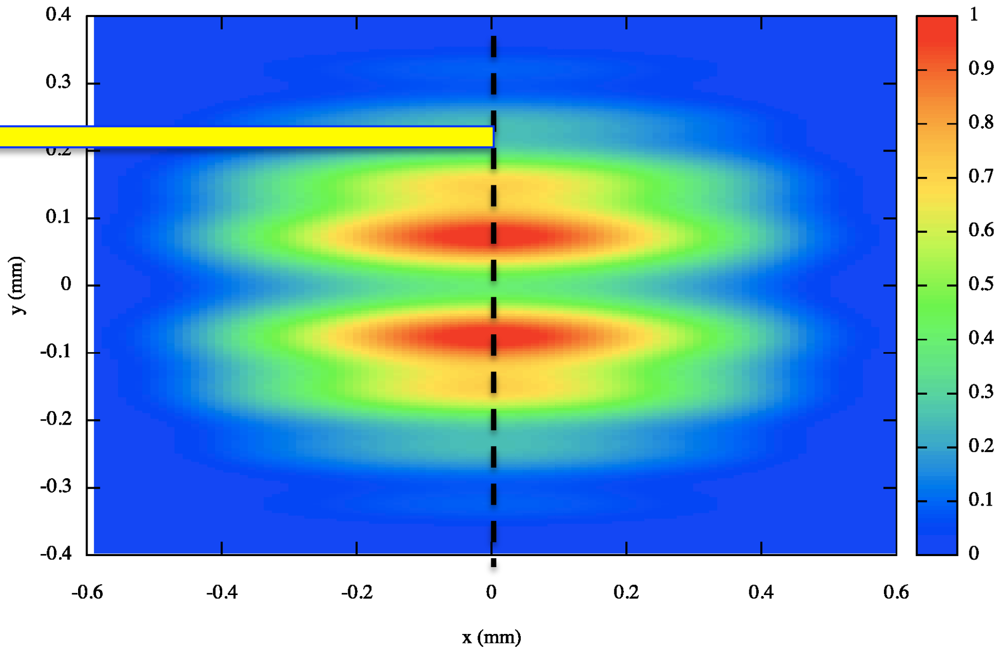
Validity of the PSF calculation using the Measured flux dist.

(1) 1D-calculation using a measured vertical flux distribution (Red line)

(2) Convolution with the Horizontal emittance and Energy spread (Green circles)
→ Integrate contributions of the off-axis and off-resonant radiations



2D distribution convoluted by
Horizontal emittance ε_x=2.4nm.rad,
Energy spread σ_E/E=0.109%



Both the PSFs make little difference.

Vertical cross section at x=0

2D images of PSF

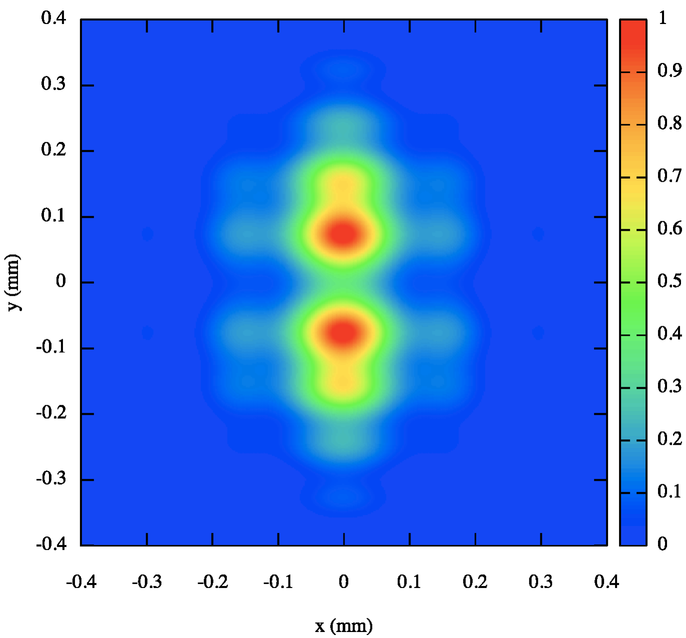
X-ray energy 7.2 keV, *L*=26.8 m, *R*=65.4 m

Rectangular slit width :

Vertical ΔY = 0.15 mm

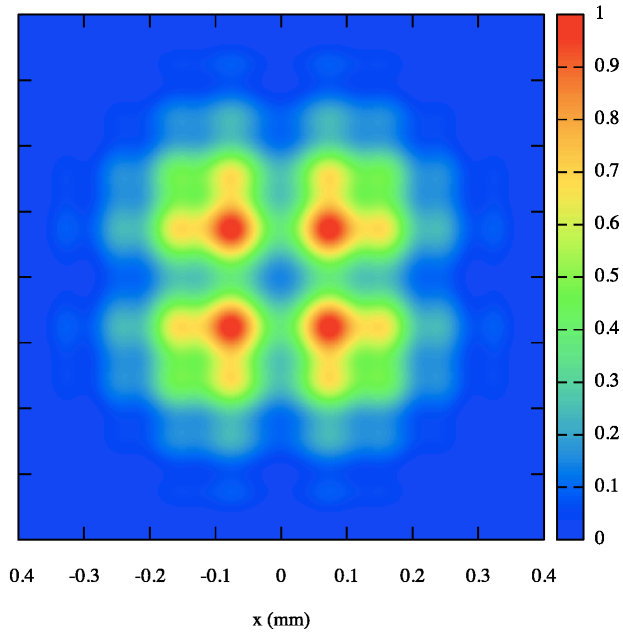
Horizontal ΔX three different values

ΔX=0.09 mm



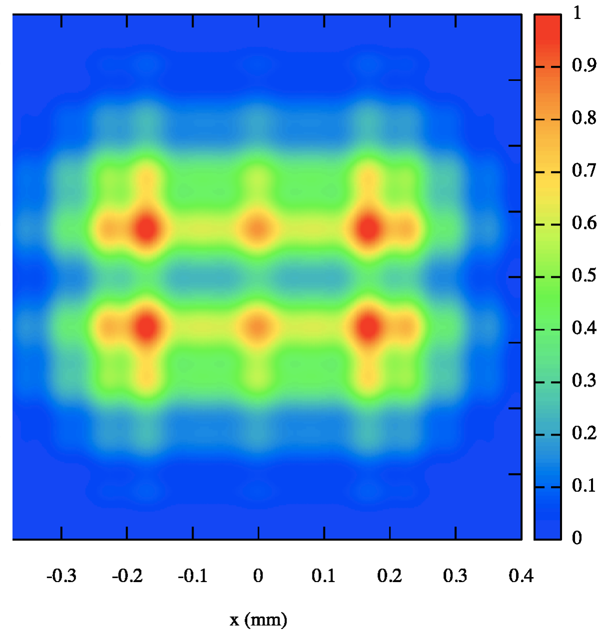
for 1D-measurement (Vertical)

ΔX=0.15 mm



for 2D-measurement

ΔX=0.2 mm



for 1D-measurement (Vertical)

Dark → Bright