Recent Progress in X-ray Emittance Diagnostics at SPring-8

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Outline

Introduction

X-ray Pinhole Camera

X-ray Fresnel Diffractometry Monitor (XFD)

Conclusions

Introduction

Light Source Facilities are Competing to

Achieve Lower Emittance and Emittance Coupling Ratio for Higher Brilliance.

Serious and Elaborate Efforts are being Paid for

Upgrade Plans of Existing Rings or New Plans of Low Emittance Rings.

X-ray Synchrotron Radiation (SR) is

Key Diagnostic Probe for Non-Destructive Beam Emittance Measurement.

Both Direct Imaging and Interferometric Technique

can Resolve the Micrometer-order Transverse Beam Size.

Emittance is Obtained from the Measured Size

with Other Knowledge (Betatron and Dispersion Functions, Energy Spread).

Introduction

Two Alternative Targets of X-ray Emittance Diagnostics at Light Source Rings

Dipole Magnet Source and Insertion Device Source (Undulator)

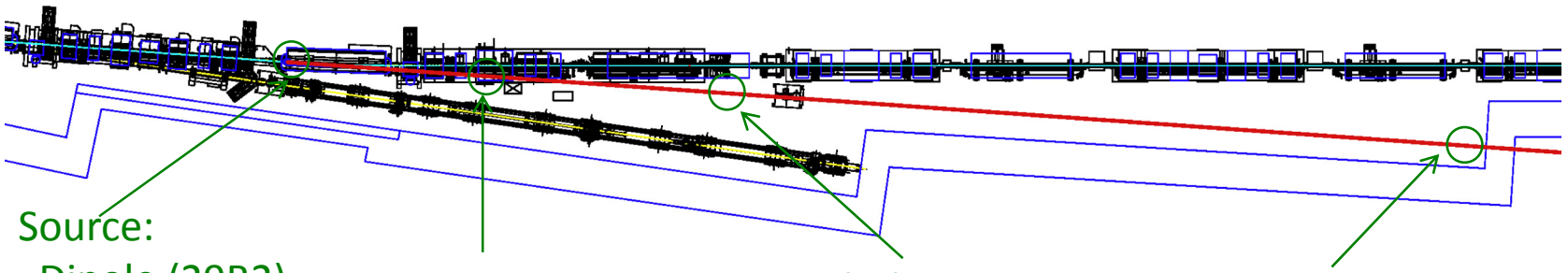
It Seems from the View Point of Machine Operation that
Emittance Diagnostics of Dipole Source is Necessary and Sufficient
for Tuning the Beam of the Accelerator

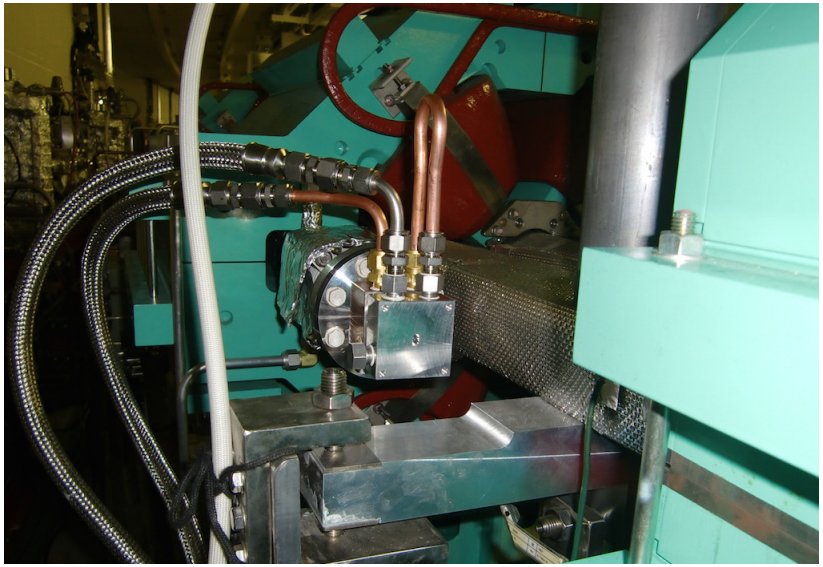
Nonetheless,
Diagnostics of Undulator Source Emittance Cannot be Avoided
Because the Undulator is Just the Source of Light Delivered to Experimental Users

Two X-ray Instruments for Emittance Diagnostics Recently Implemented at SPring-8
Dipole Source: X-ray pinhole camera
Undulator source: X-ray Fresnel Diffractometry monitor (XFD)

X-ray Pinhole Camera @ SPring-8

Layout

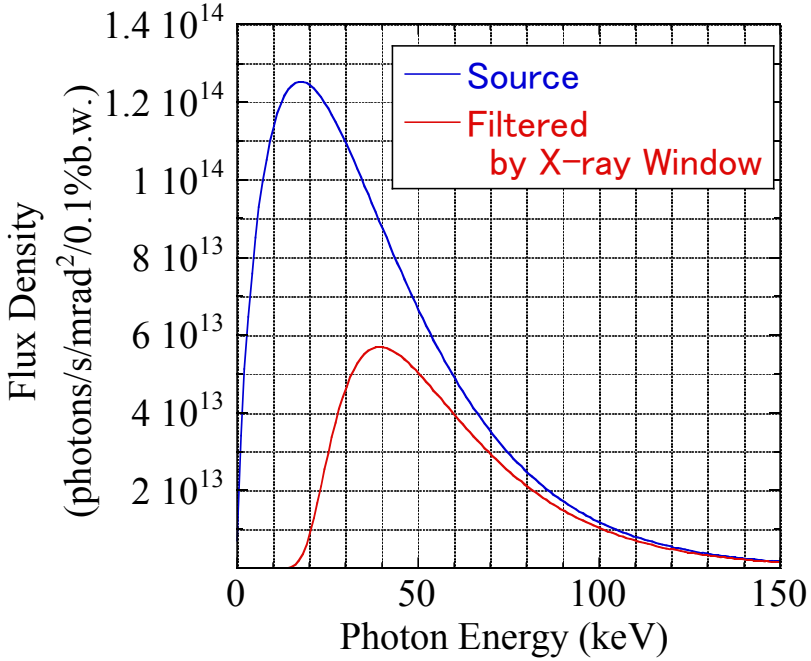




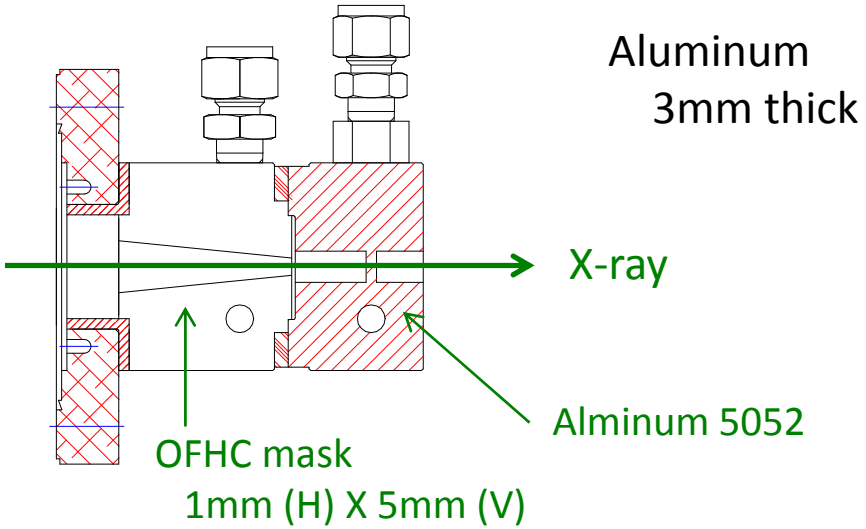
X-ray Pinhole Camera @ SPring-8

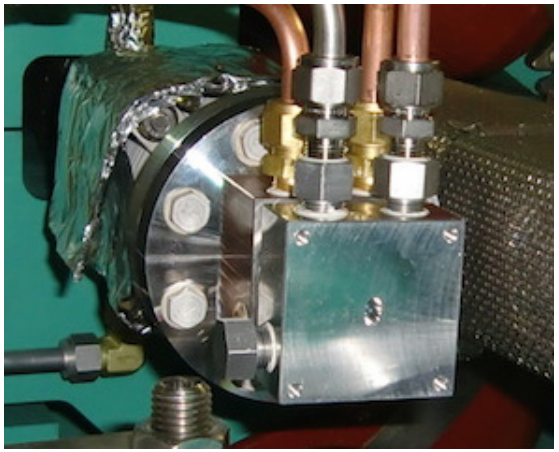
Source: Dipole (29B2)

B = 0.5 T Ec = 21.1 keV



X-ray Window @ 6.2 m

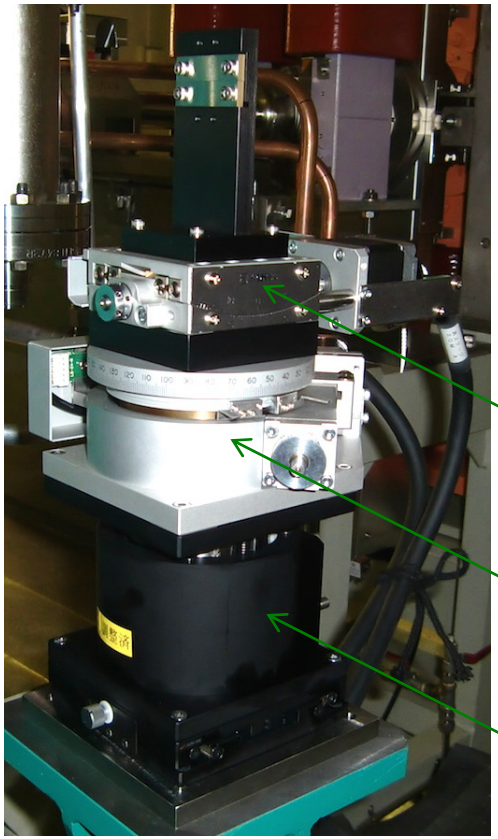


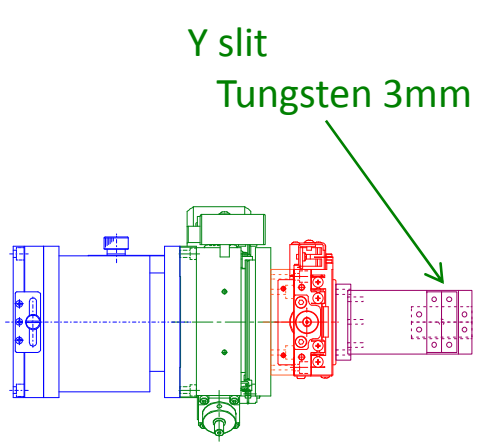


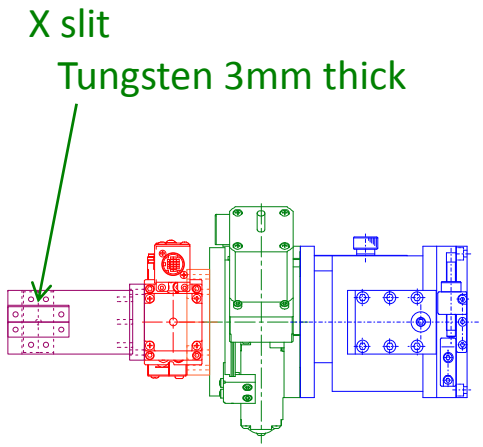
X-ray Pinhole Camera @ SPring-8

Pinhole Assembly @ 11.4 m

Aperture: 20 μm x 20μm



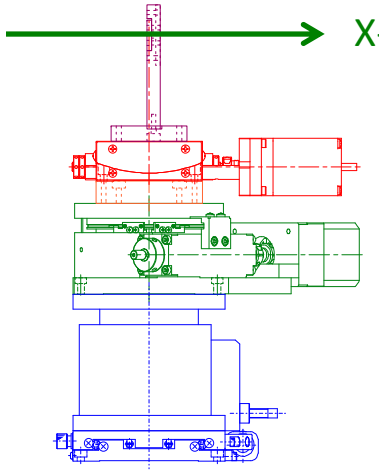




gonio stage

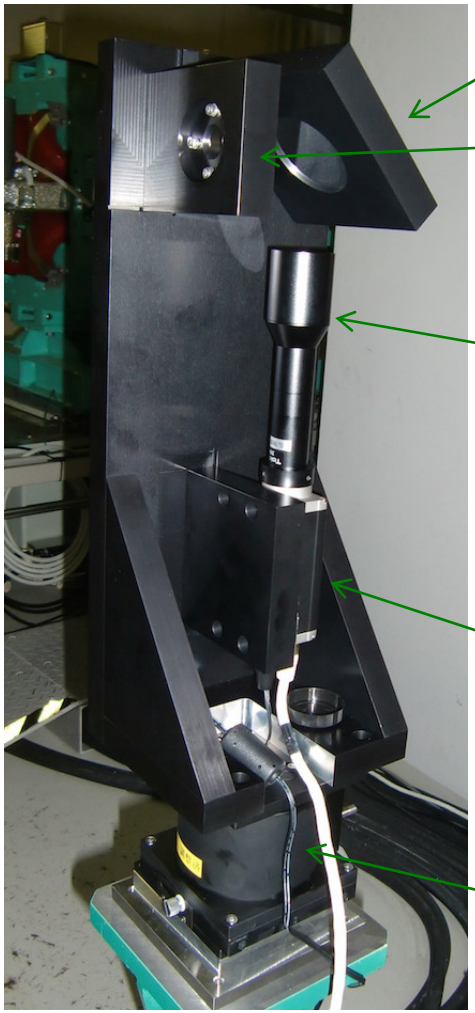
rotary stage

manual XZ stage



X-ray Pinhole Camera @ SPring-8

Scintillator & Camera Assembly@ 34.3m



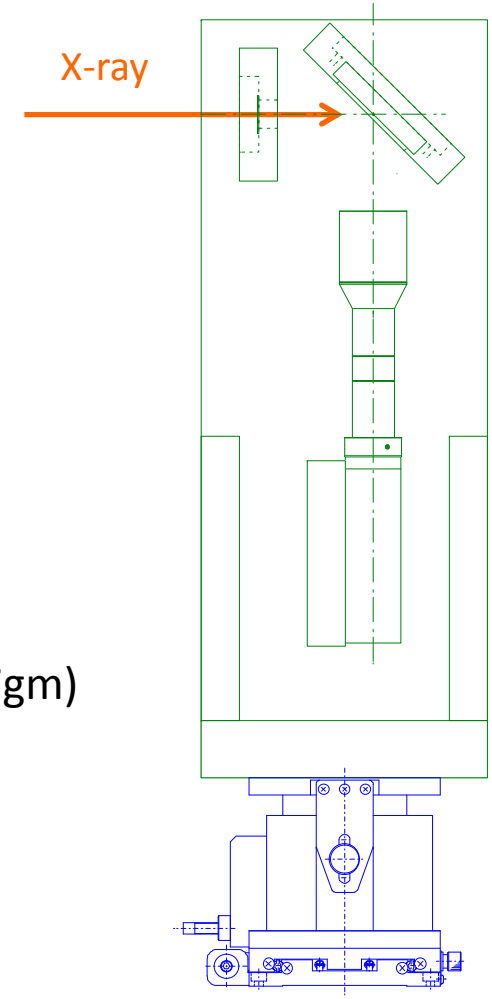
Mirror

Scintillator
$CdWO_4$ (CWO)
0.5mm thick

Lens
object-space
telecentric
x2 magnification
W. D. = 111 mm

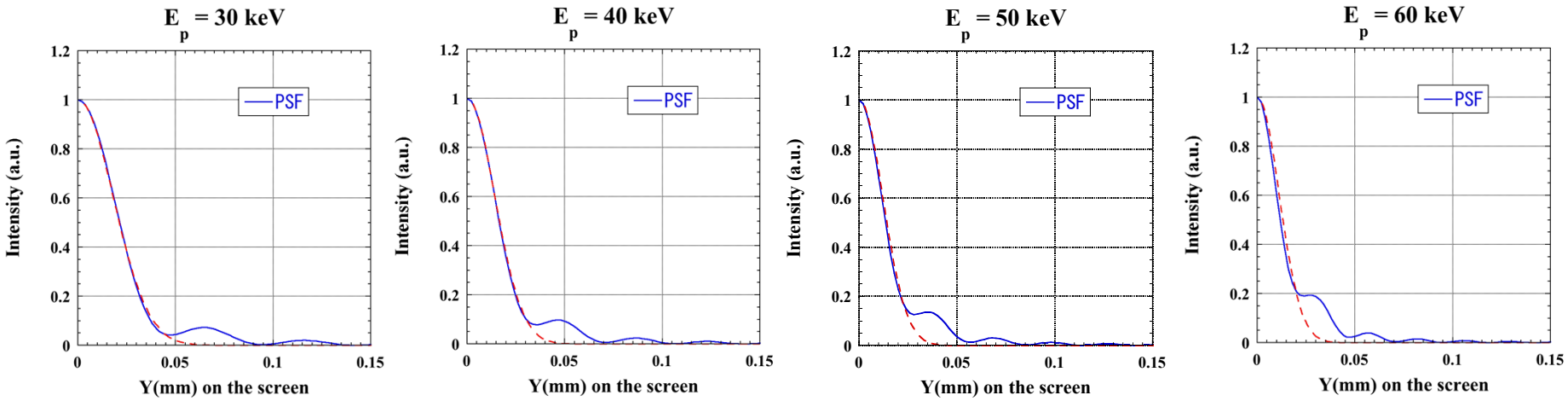
CCD Camera (Basler piA2400-17gm)
GigE interface
2448 x 2050 pixels
3.45 µm x 3.45 µm pixel size

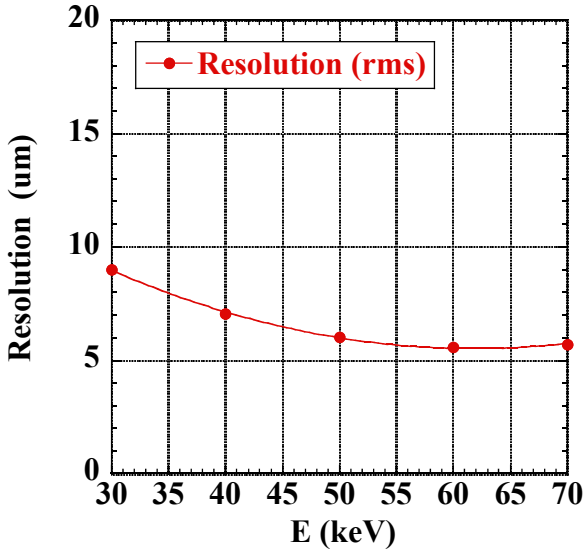
manual XZ stage



X-ray Pinhole Camera @ SPring-8

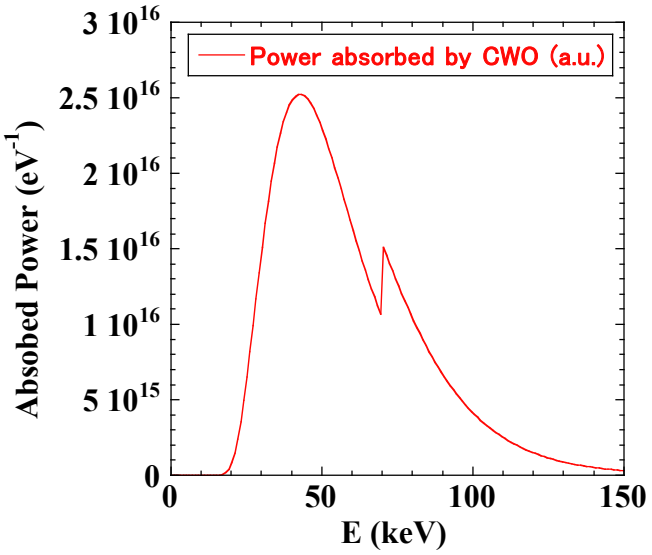
Resolution of Pinhole (PSF calculation based on Wave Optics)





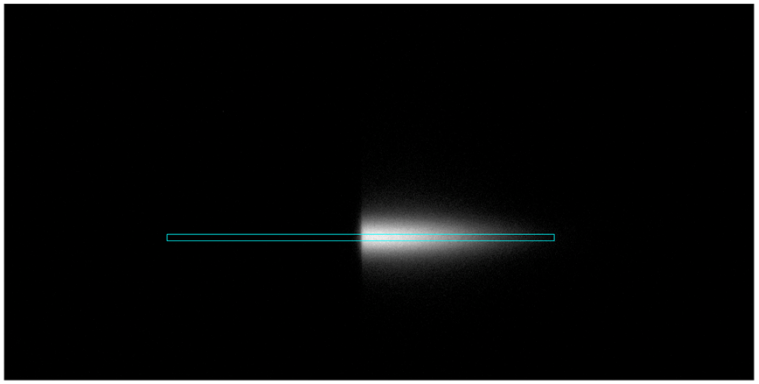
Pinhole Resolution (rms)

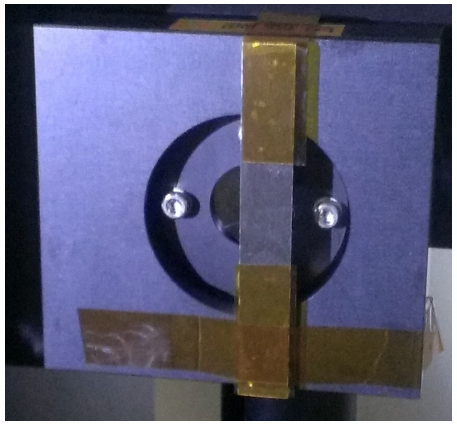
σ_{diff} = 6.9 μm
@ 42 kev

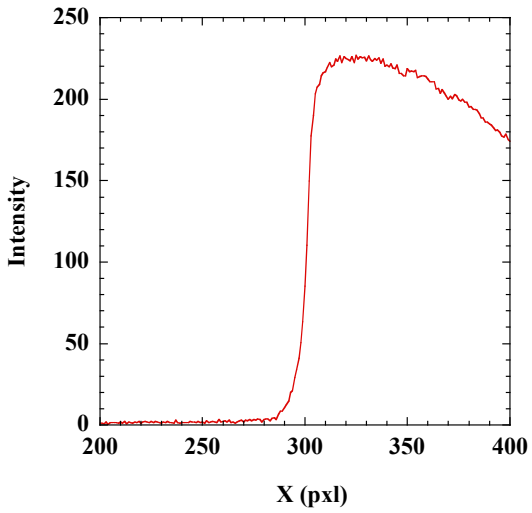


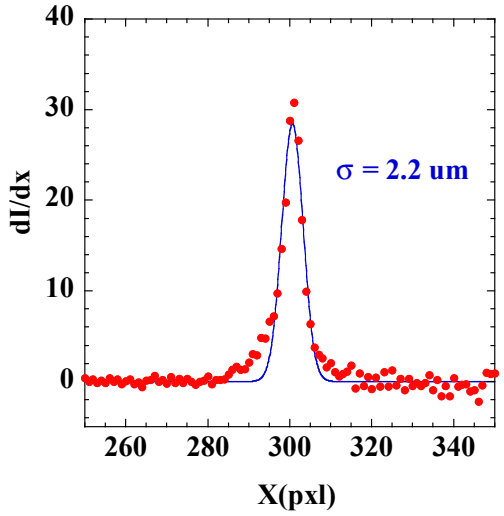
X-ray Pinhole Camera @ SPring-8

Scintillator & Camera Assembly Resolution Calibration









sharpness of edge of W bar placed in front of scintillator measured

Resolution (rms) of Scintillator & Camera Assembly

σ_{CAM} = 2.2 μm

X-ray Pinhole Camera @ SPring-8

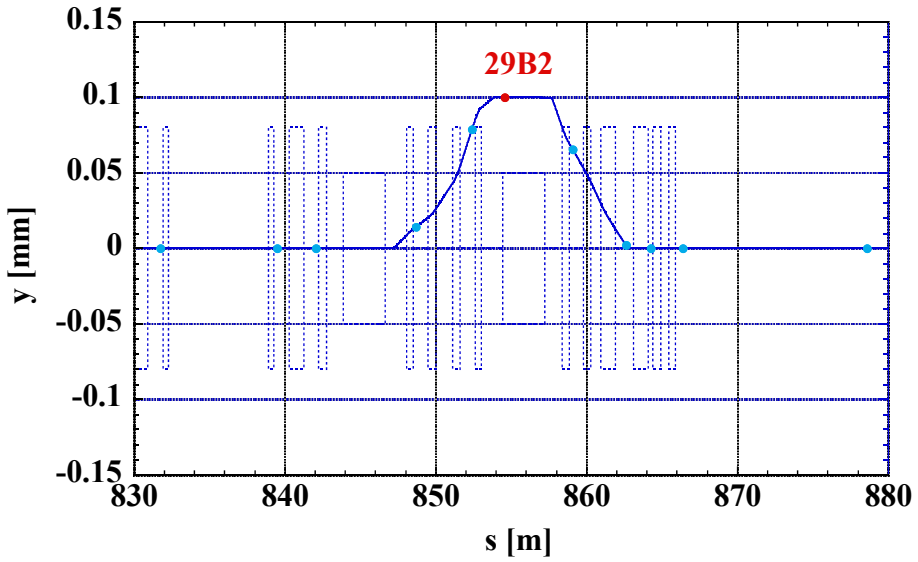
Total Spatial Resolution σ_{XPC} (rms)

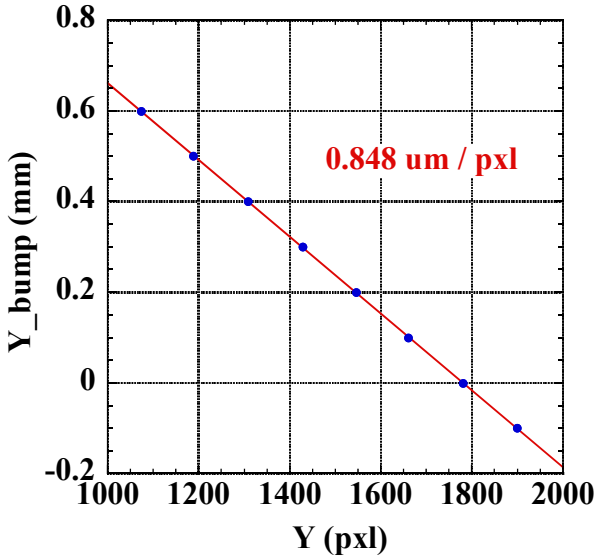
$$\sigma_{XPC} = \sqrt{\sigma_{diff}^{\ 2} + \sigma_{CAM}^{\ 2}} \quad = 7.2\ \mu m$$

Pinhole σ_{diff} = 6.9 μm
Scintillator & Camera σ_{CAM} = 2.2 μm

Scale of Camera Pixel to Beam Coordinate

measured by introducing vertical bump orbits



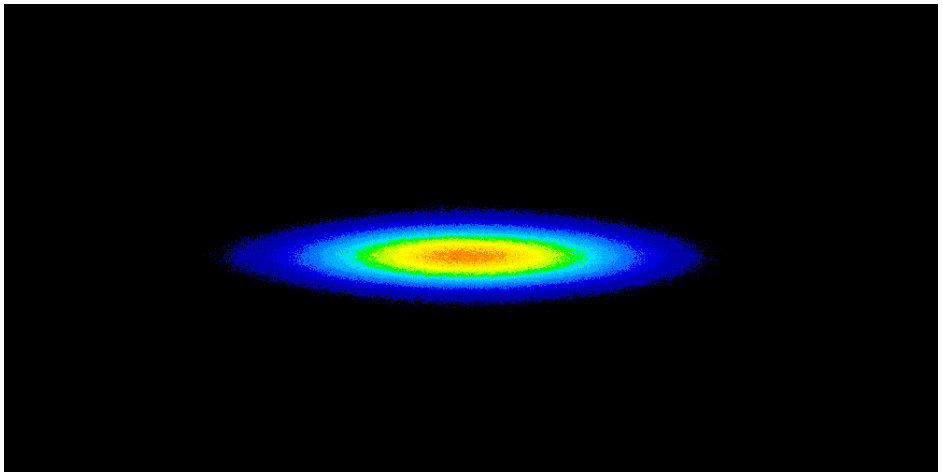


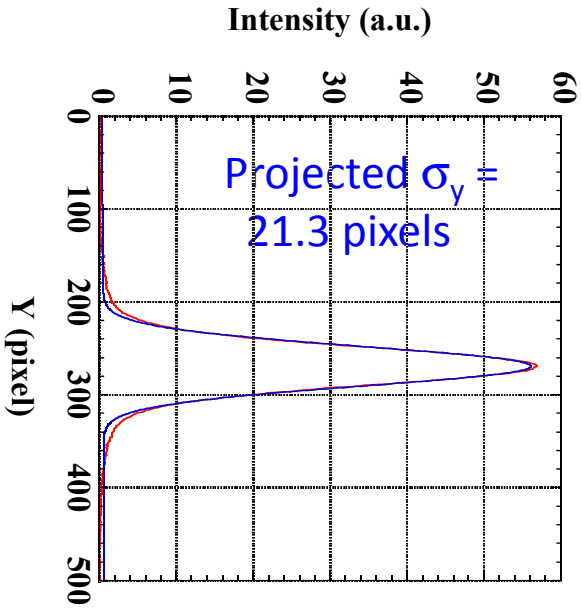
consistent with
designed value 0.8625 μm/pixel

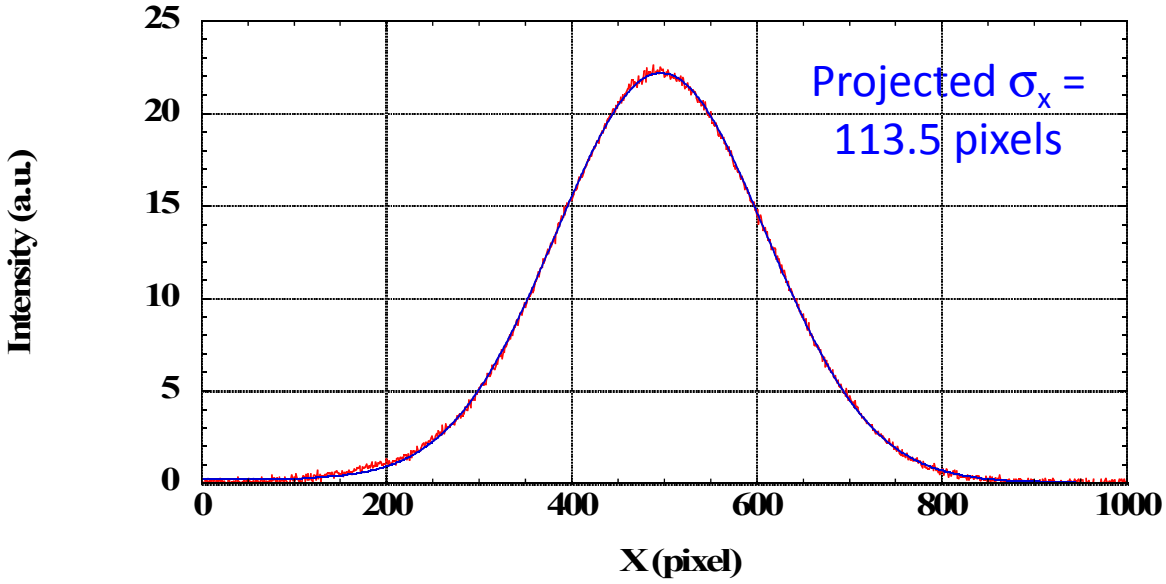
X-ray Pinhole Camera @ SPring-8

Example of data

I = 100 mA, exposure time 1 ms







Projected profiles (horizontal and vertical) consistent with Gaussian profiles

Projected Beam Size

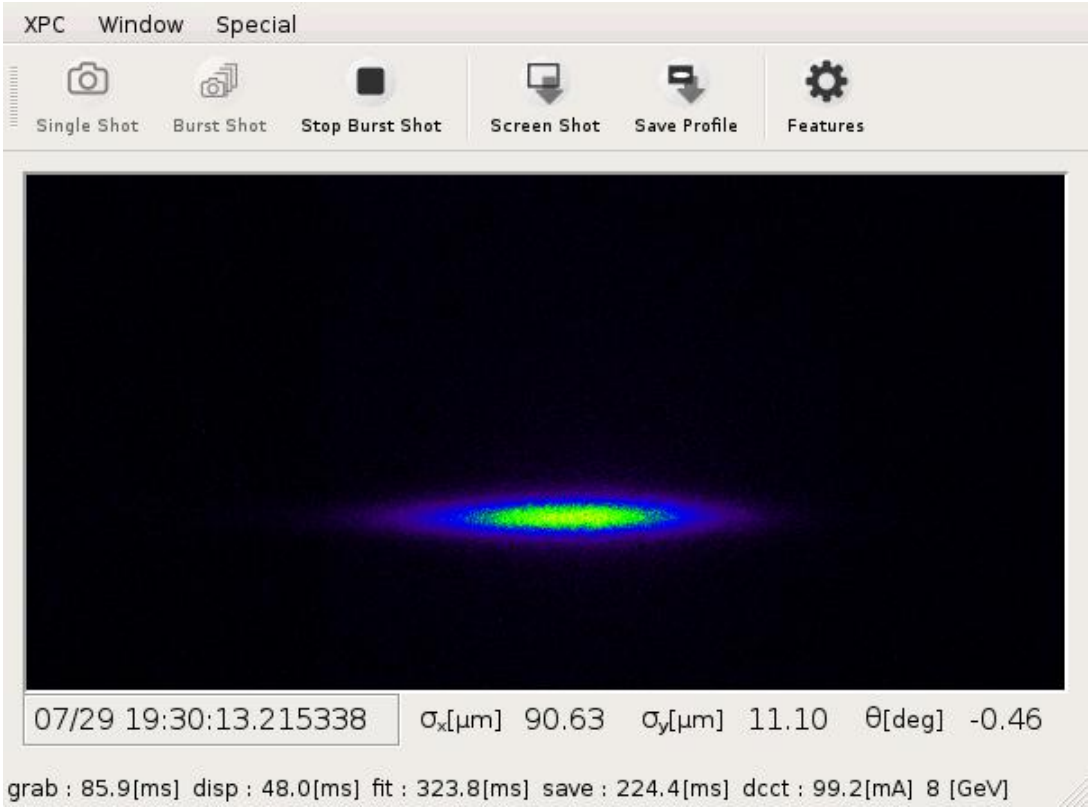
σ_x = 96.0 µm

σ_y = 16.6 µm

(resolution subtracted)

X-ray Pinhole Camera @ SPring-8

Control Room Display



Live Beam Image View
~ 15 fps

Parameters of Beam Profile
beam size σ_x and σ_y
beam tilt angle θ
Continuously Logged
to SPring-8 Control Database

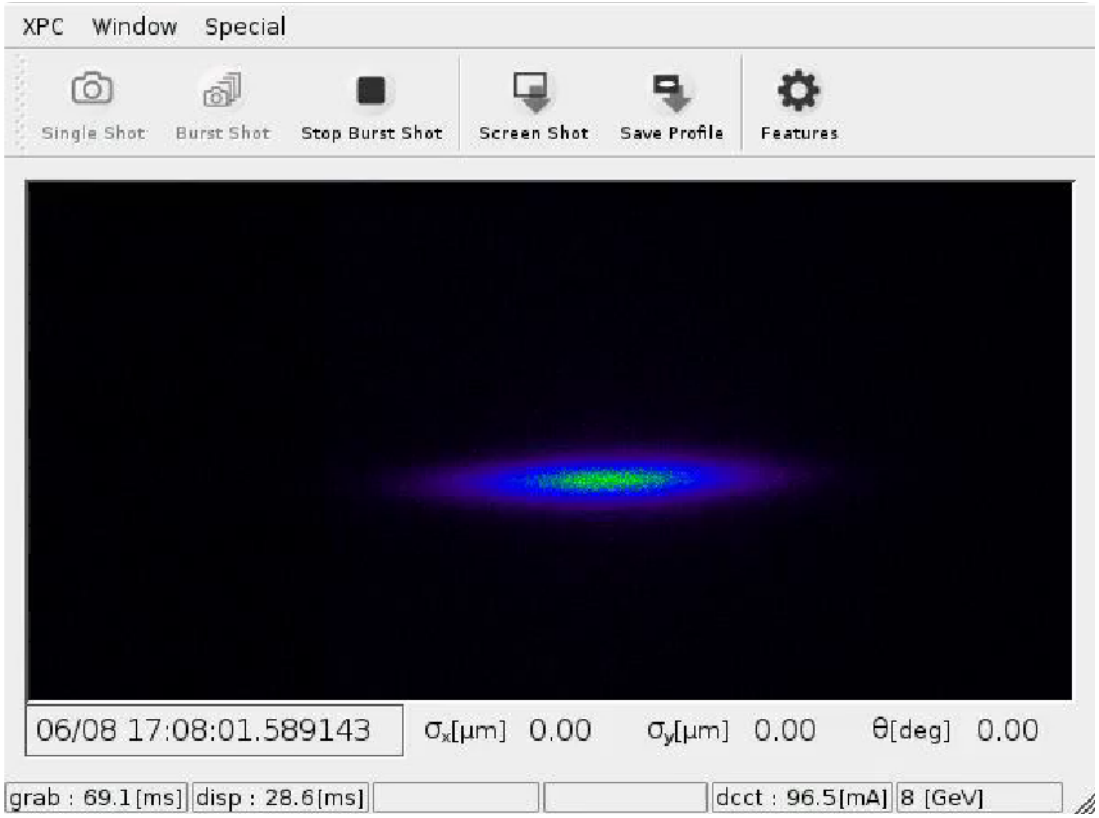
By Periodical Image Analysis
(1s cycle time)

2D Gaussian Profile is
Fitted to Beam Image Data

ε_y = 7.5 pm.rad
(coupling 0.3%)

X-ray Pinhole Camera @ SPring-8

Control Room Display



Live Beam Image View
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By Periodical Image Analysis
(1s cycle time)

2D Gaussian Profile is
Fitted to Beam Image Data

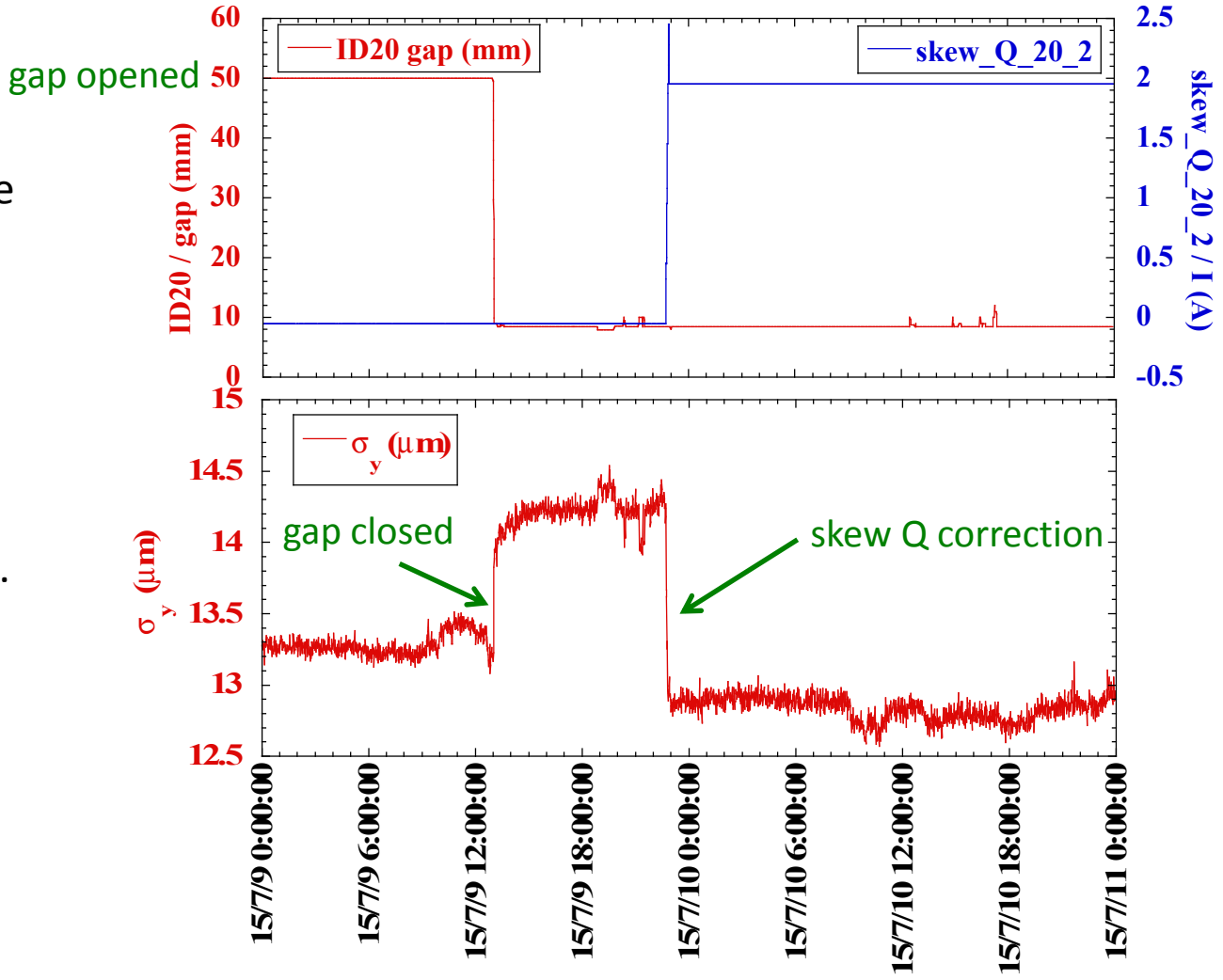
ε_y = 7.5 pm.rad
(coupling 0.3%)

X-ray Pinhole Camera @ SPring-8

Diagnostics for User Operation: Betatron Coupling induced by ID20

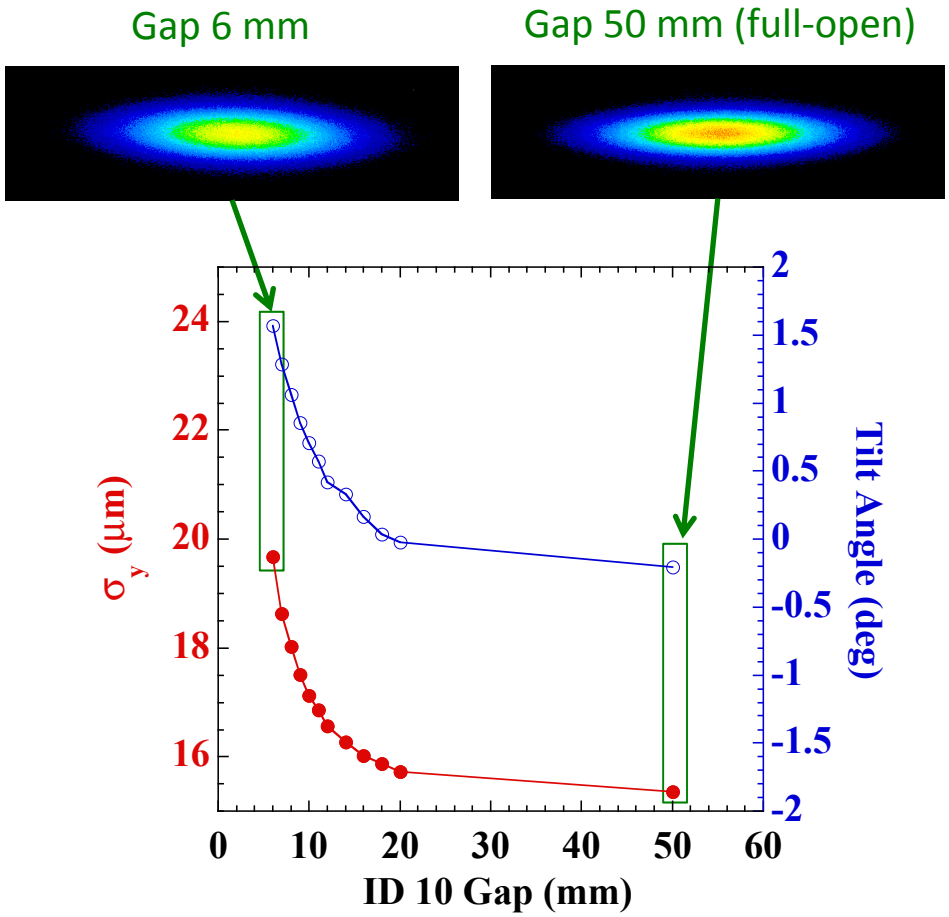
ID error fields excite betatron coupling in user operation.

Betatron coupling is corrected by tuning skew Q parameters.

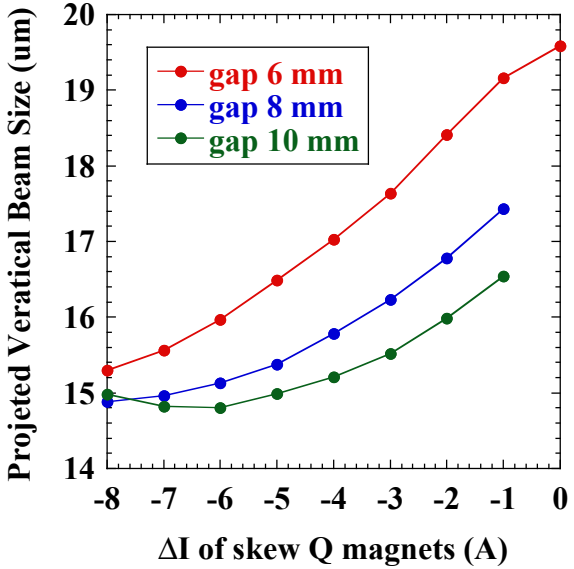


X-ray Pinhole Camera @ SPring-8

Diagnostics for Machine Tuning: Betatron Coupling induced by ID10



Search for
Correcting skew Q parameters



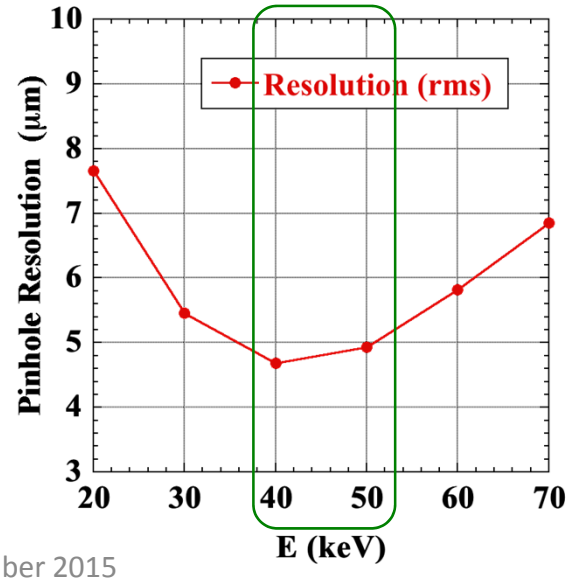
* radiation induced-demagnetization of ID10 suspected, and B field readjusted in March 2015

X-ray Pinhole Camera @ SPring-8

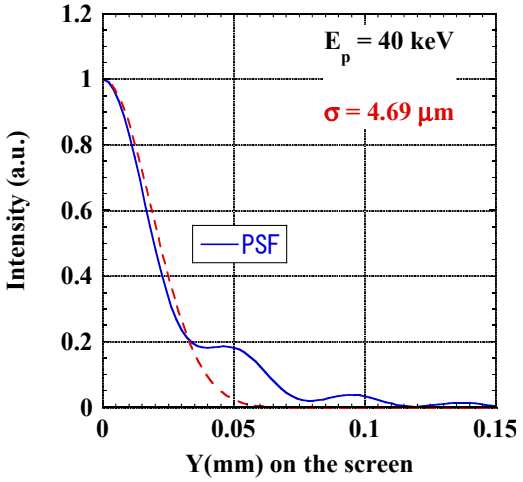
Preliminary Plan for SPring-8 Upgrade (SPring-8-II)

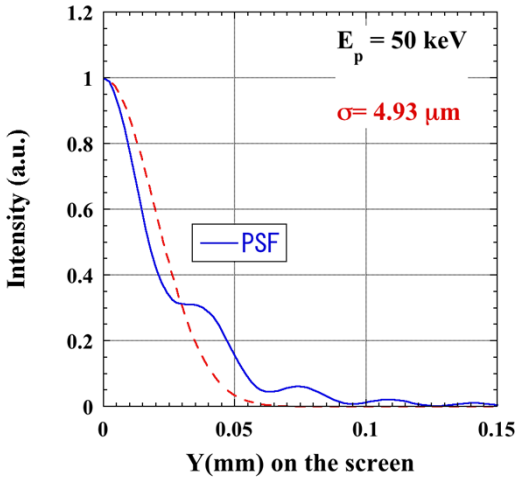
Source: Dipole Magnet
Layout (distance from source)
Pinhole: 6.5m, Scintillator: 32m

Pinhole
Magnification : x 3.9
Size : 20 μm x 20 μm



Point Spread Function (Wave Optics Calculation)





Pinhole Resolution (rms) better than 5 μm feasible for 40 – 50 keV X-rays

Resolution of Present Scintillator Assembly scales to 1.1 μm

X-ray Pinhole Camera @ SPring-8

Summary

Specifications of the SPring-8 X-ray Pinhole Camera		
Light Source	Bending Magnent (29B2)	
Pinhole	Distance from Source (m)	11.4
	Aperture Size (μm)	20 x 20
Scintillator	Distance from Source (m)	34.3
	Material	$CdWO_4$
Camera	Number of Pixels	2448 x 2050
	Pixel Size (μm)	3.45 x 3.45
Magnification Factor	x 4 (Pinhole: x 2, Lens: x 2)	
Resolution (rms) (μm)	7.2 (Pinhole: 6.9, Scintillator & Camera: 2.2)	

Live Beam Image View @ Control Room ~ 15 fps

Parameters of Beam Profile Continuously Logged to SPring-8 Control DB

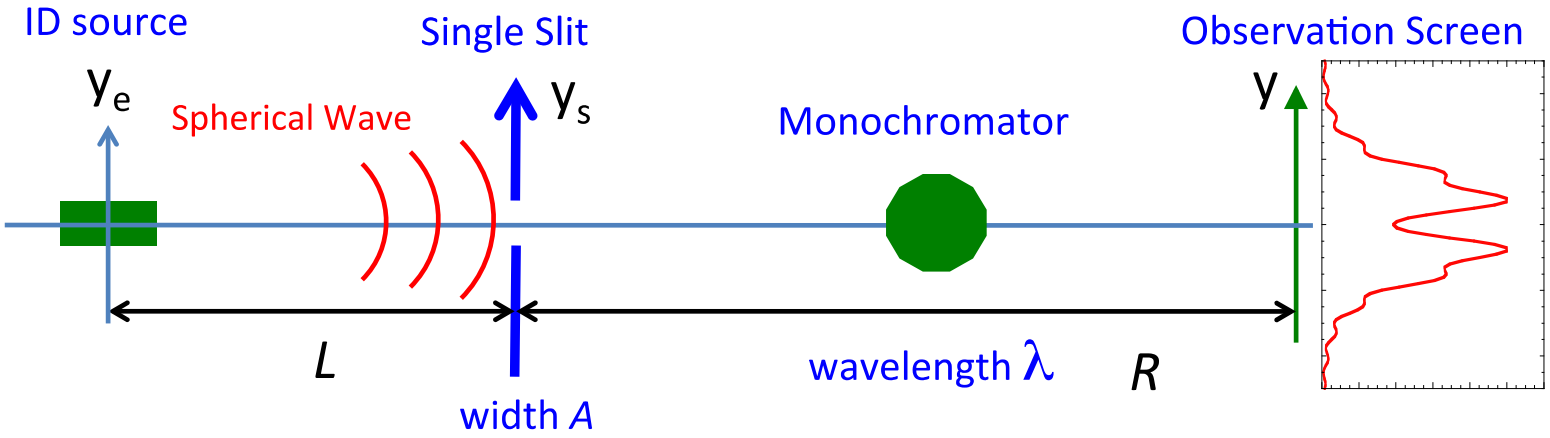
Indispensable for Beam Tuning and User Operation

Resolution (rms) Better than 5 μm Feasible for Upgrade Plan of SPring-8

X-ray Fresnel Diffractometry Monitor (XFD)

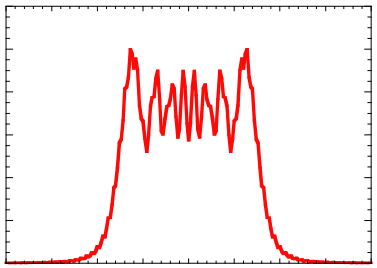
Principle

M. Masaki et al., IBIC2014 TUCZB1 (2014).
M. Masaki et al., Phys. Rev. ST Accel. Beams 18, 042802 (2015).

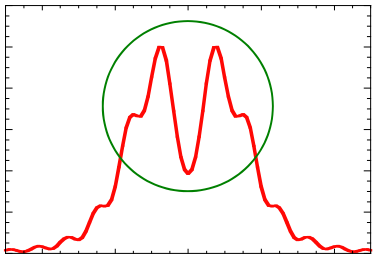


Diffraction patterns depending on a width A of the slit

Fresnel Diffraction
wide slit ($A^2 > R\lambda$)



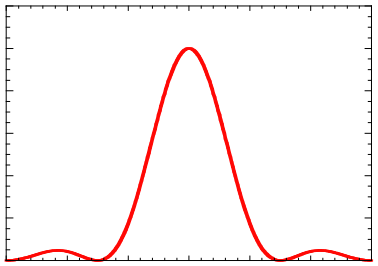
Double-Lobed
Fresnel Diffraction



optimum slit width
for the deepest dip

$$A \approx \sqrt{7\lambda \frac{LR}{L+R}}$$

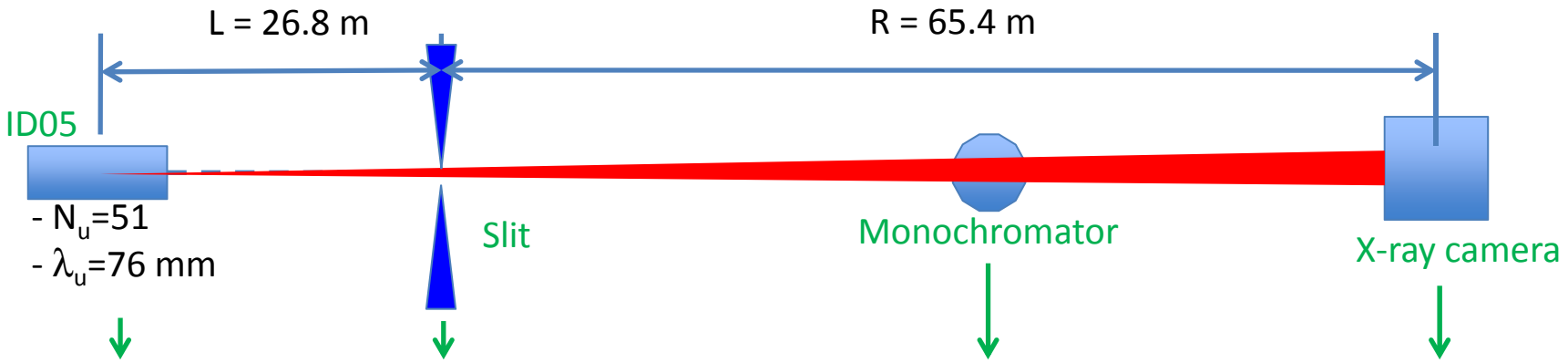
Fraunhofer Diffraction
narrow slit ($A^2 << R\lambda$)

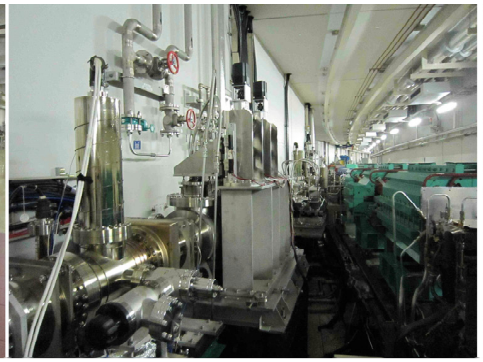


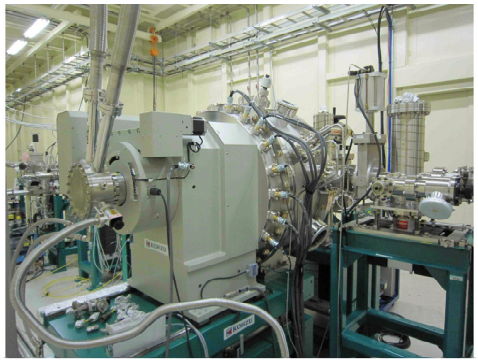
The depth of a median dip correlates with a light source size.

XFD @ SPring-8

Setup for Initial Experiments







optimum slit width A
for the deepest dip

$$A \approx \sqrt{7\lambda \frac{LR}{L+R}}$$

- P43 Screen
- lenses
- CCD camera

min. exp. time: 1ms

resolution σ_{res}: 6.8 μm

XFD @ SPring-8

Initial Results

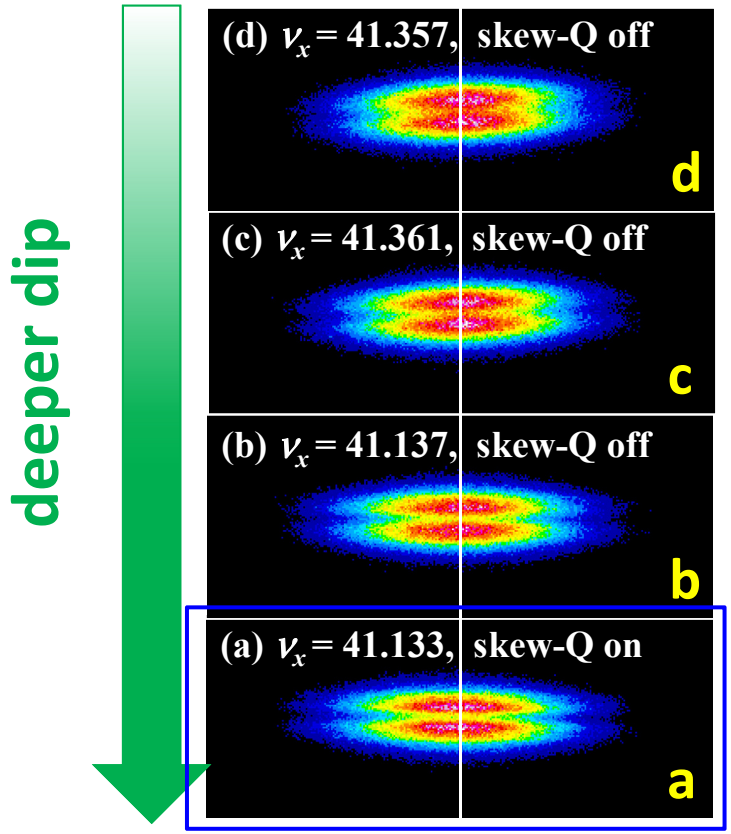
M. Masaki et al., IBIC2014 TUCZB1 (2014).
M. Masaki et al., Phys. Rev. ST Accel. Beams 18, 042802 (2015).

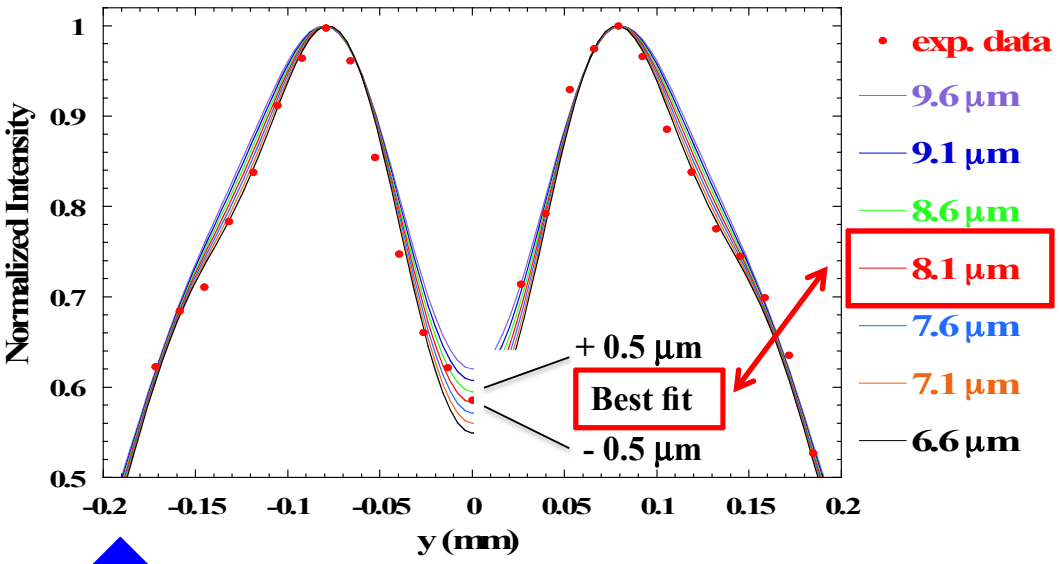
X-ray energy 7.2 keV

slit width ΔY = 150 μm

Fitted function:

$$f(y) = C \int_{-\infty}^{\infty} \underbrace{I(y, y_e)}_{\text{PSF}} \exp\left[-\frac{(y_e - y_0)^2}{2(\underbrace{\sigma_{y,e}^2}_{\text{Source Size}} + \underbrace{\sigma_{res}^2}_{\text{Camera Resolution}})} \right] dy_e$$



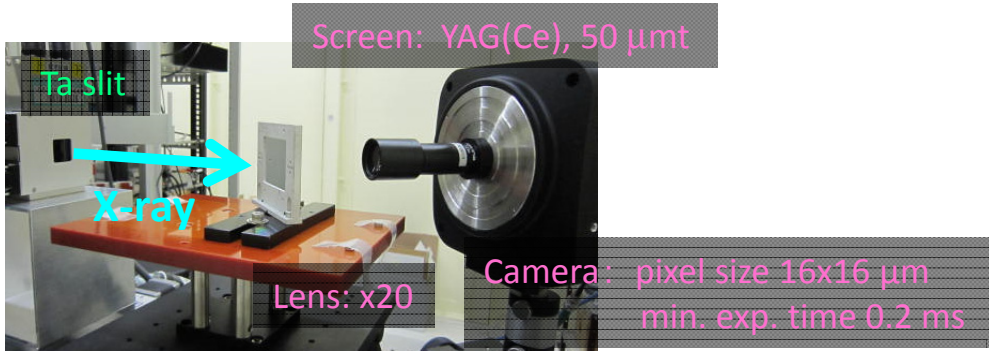


Undulator source size smaller than 10 μm successfully resolved

XFD @ SPring-8

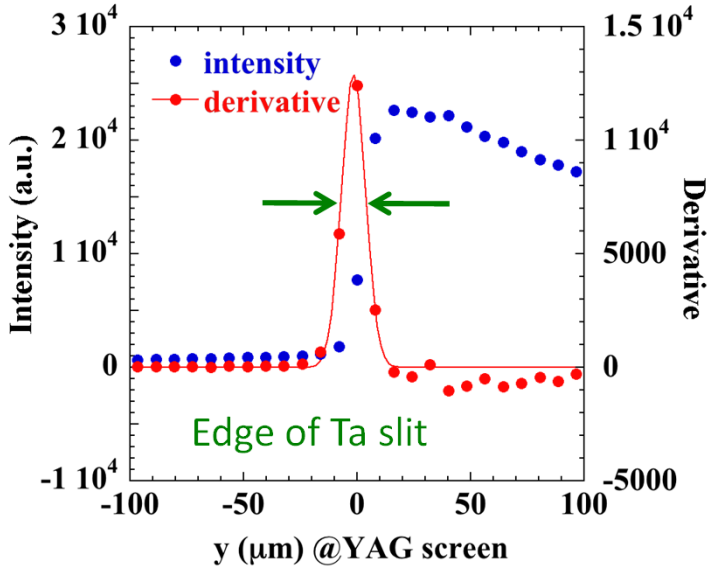
Recent Progress

New X-ray Imaging Setup

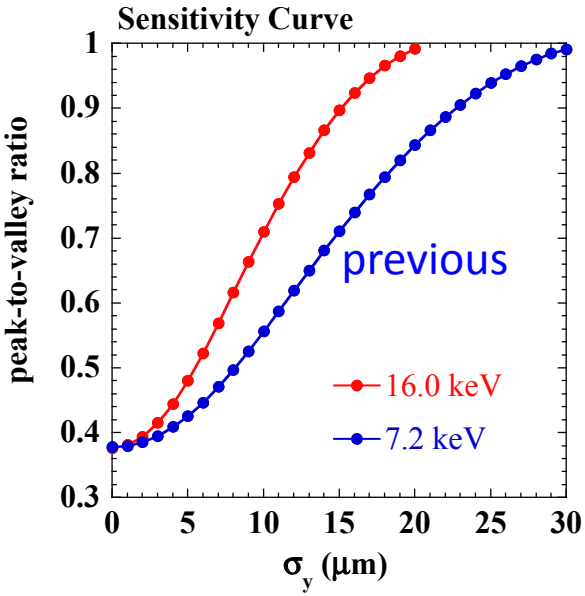


Imaging Resolution (rms) @ Source Point:

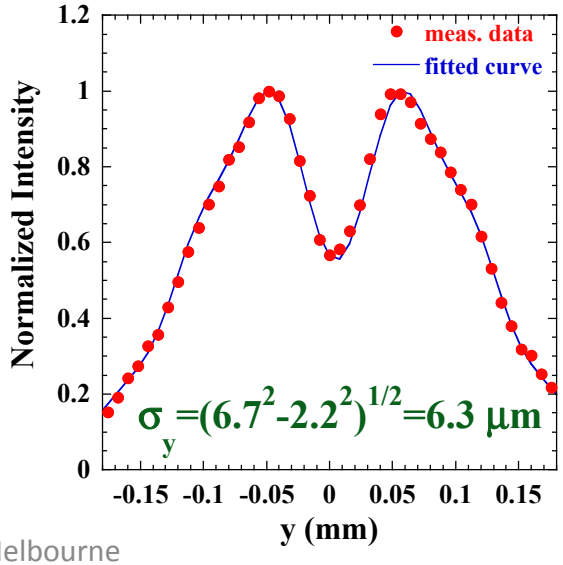
2.2 μm <- 6.8 μm (previous)



Increased Observing Energy: 16 keV



Result



exp. time
0.5 ms

source size
6.3 μm (rms)

ε_y = 7.9 pm.rad
(coupling 0.3%)

XFD

Summary

Diagnostic technique for light source rings
to measure small beam size at ID (undulator) source point

Able to resolve beam size smaller 5 μm

Requires only
slit, monochromator, and imaging device (X-ray camera)

Has potential universal availability to ID beamlines of the
diffraction limited storage rings (DLSRs)

Conclusions

SPring-8 X-ray Pinhole Camera

Resolution (rms) ~ 7 μm

Live Beam Image View @ Control Room ~ 15 fps

Beam Parameters Logged to Control DB by Periodical (1s cycle) Image Analysis

Indispensable for Beam Tuning and User Operation of SPring-8

X-ray Fresnel Diffraction (XFD) Monitor

Diagnostic Technique for Light Source Rings
to Measure Small Beam Size at ID (Undulator) Source Point

Requires Only
Slit, Monochromator, and Imaging Device (X-ray Camera)

Able to Resolve Beam Size smaller 5 μm

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Thank you for your attention !