X-ray Based Undulator Commissioning in SACLA

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Undulator Commissioning in XFELs

- In XFELs, a long undulator composed of many segments is usually installed.
- To achieve lasing, all segments should work “coherently” and behave as a single undulator.
- What to align or tune?
  - Steering magnet (trajectory straightness)
  - Undulator gap and height (K value)
  - Phase shifter gap (phase matching)
  - Undulator taper (wake field compensation)

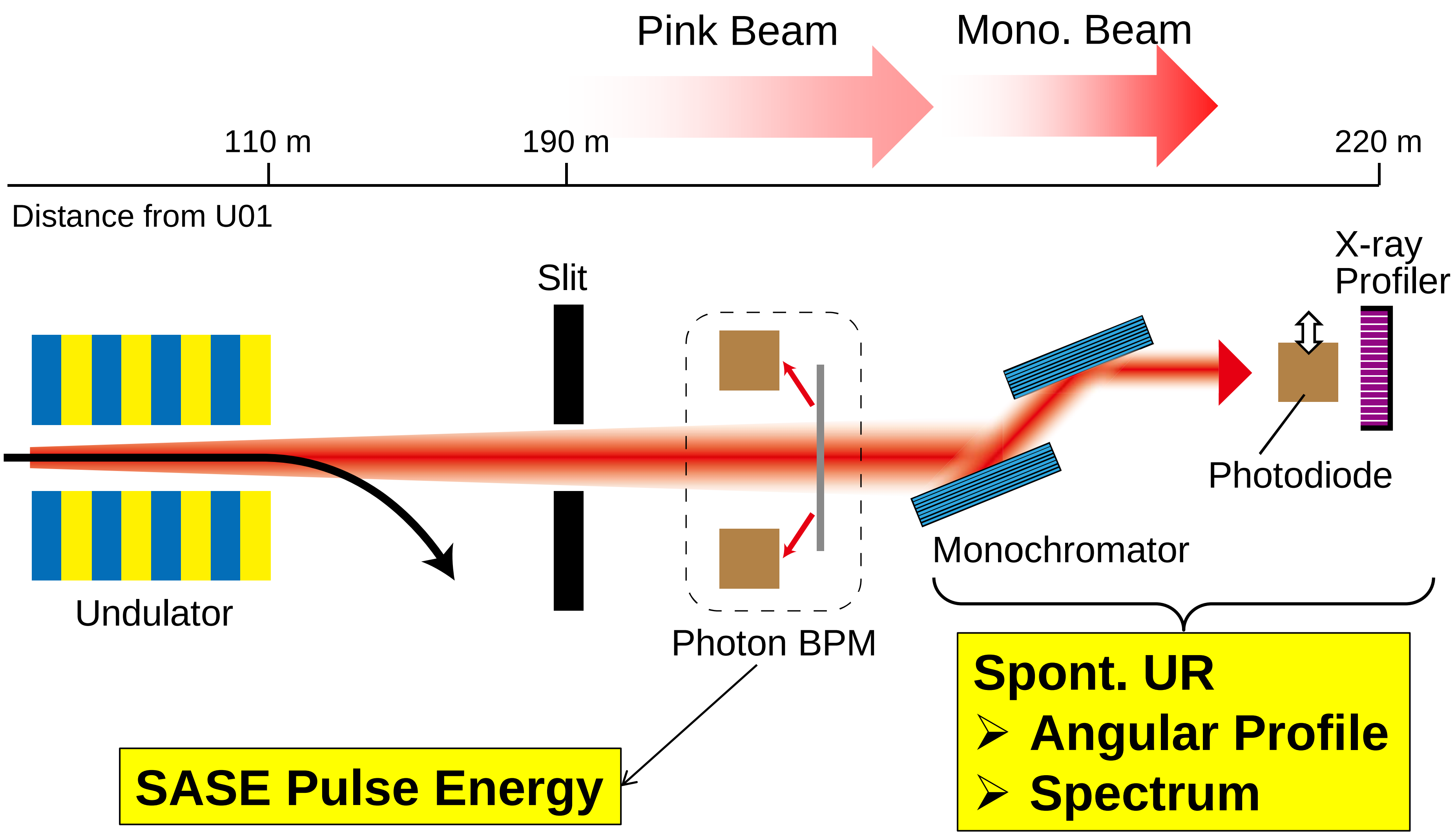
Error Sources &Tolerances

Commissioning Target		Tolerance	Tuning Method	
			Rad. Type	Item
Trajectory	BPM	2.2 μm	-	-
	Injection Angle	0.5 μrad	Mono. SR	Angular Profile
K Value	Gap	1.9 μm	Mono. SR	Spectrum
	Height	60 μm		
	Total	5×10^{-4}	-	-
Phase Matching (Phase Slippage)		30°	SASE	Intensity
			Mono. SR	Spectrum
Undulator Taper (Wake Compensation)		1.6×10^{-4} /segment	SASE	Intensity

“X-ray” Based Commissioning

- Alignment or tuning of devices related undulator operation by characterization of radiation
- Spontaneous
  - Available at any time & under any conditions
  - Should be monochromatized
- SASE
  - Lasing condition should be satisfied
  - Enhancement of SASE intensity is the top priority

Photon Diagnostics System at SACLA



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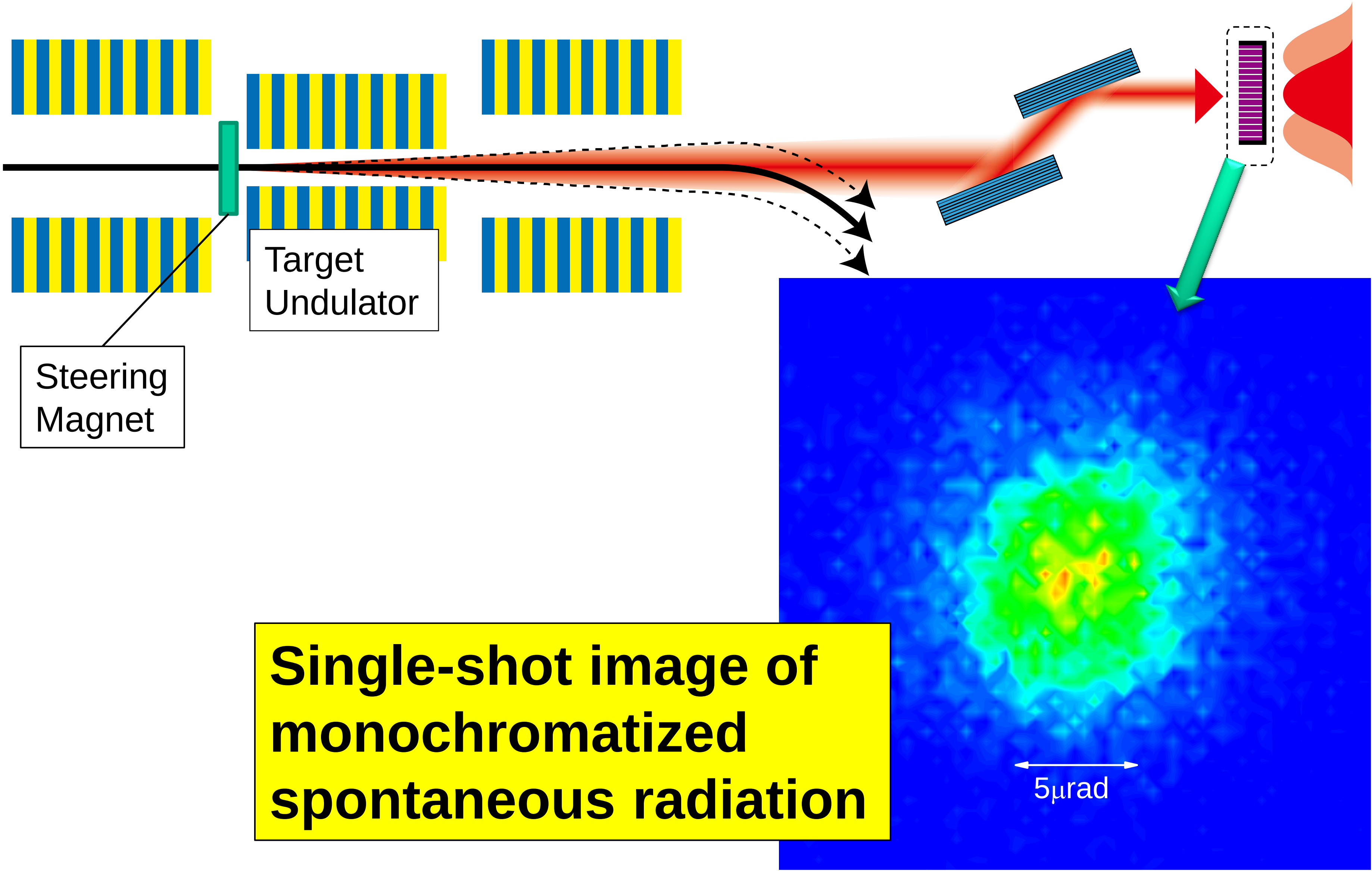
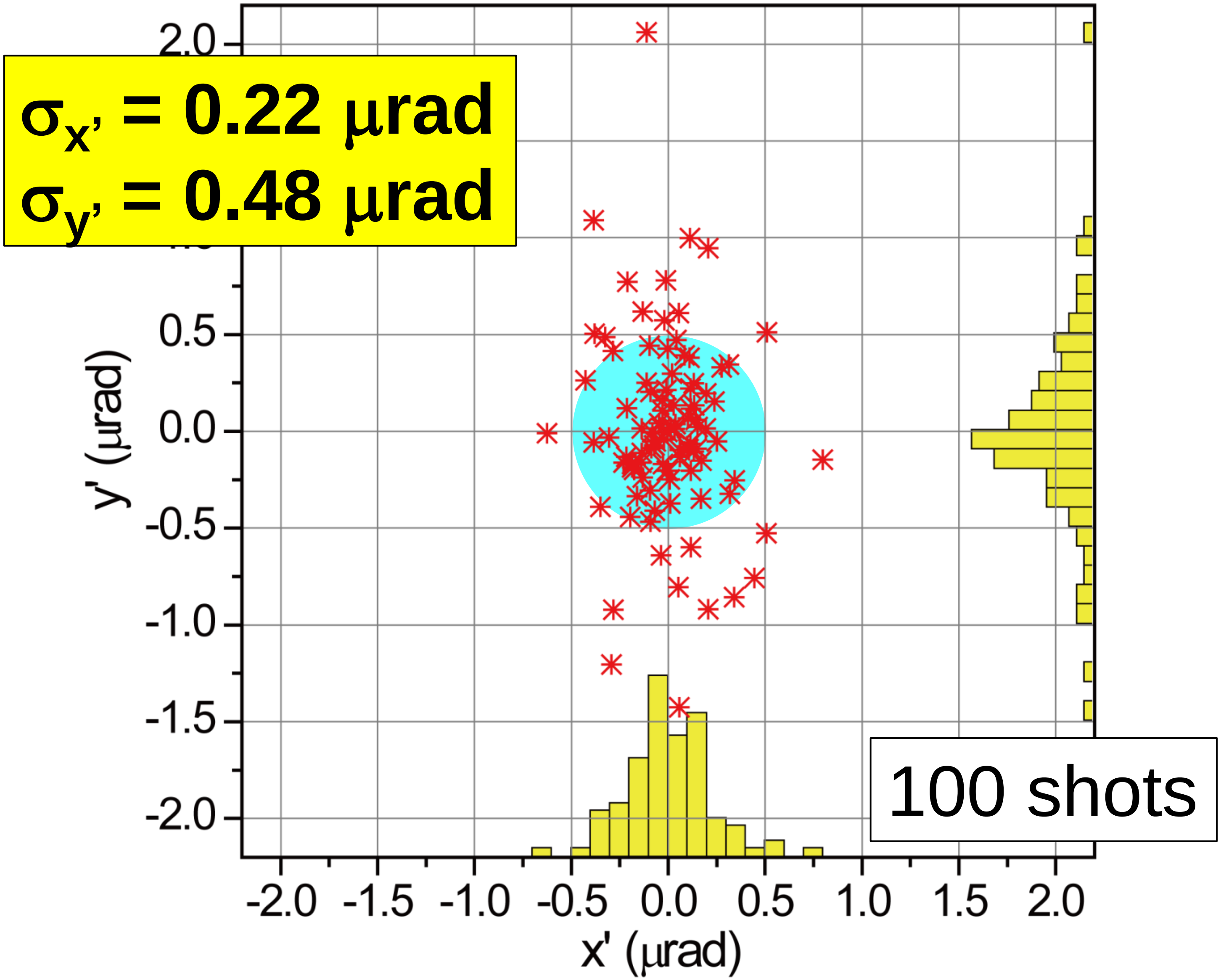
Estimation of Injection Angle



Single-shot image of monochromatized spontaneous radiation

Mono. SR Beam Pointing Stability

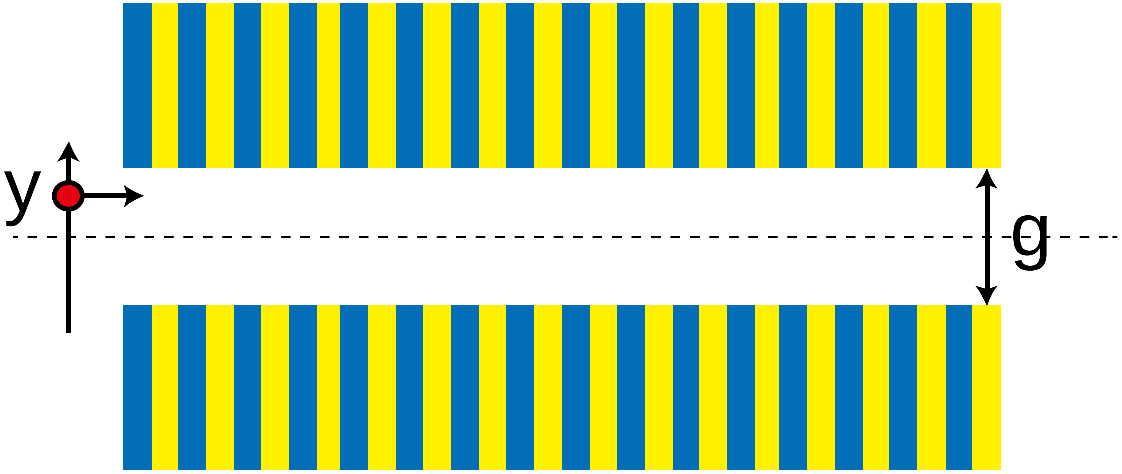


Commissioning Target		Tolerance	Tuning Method	
			Rad. Type	Item
Trajectory	BPM	2.2 μm	-	-
	Injection Angle	0.5 μrad	Mono. SR	Angular Profile
K Value	**Gap**	**1.9 μm**	**Mono. SR**	**Spectrum**
	Height	**60 μm**		
	Total	**5×10^{-4}**	**-**	**-**
Phase Matching (Phase Slippage)		30º	SASE	Intensity
			Mono. SR	Spectrum
Undulator Taper (Wake Compensation)		1.6×10^{-4} /segment	SASE	Intensity

Undulator K-value Tuning

- The undulator K value depends on the magnet gap and vertical position

$$K(g,y) = K_0 e^{-\pi g/\lambda_u} \cosh(2\pi y/\lambda_u)$$



Both the undulator gap and height should be aligned for precise K value tuning!

K-value Determination by Spectrum

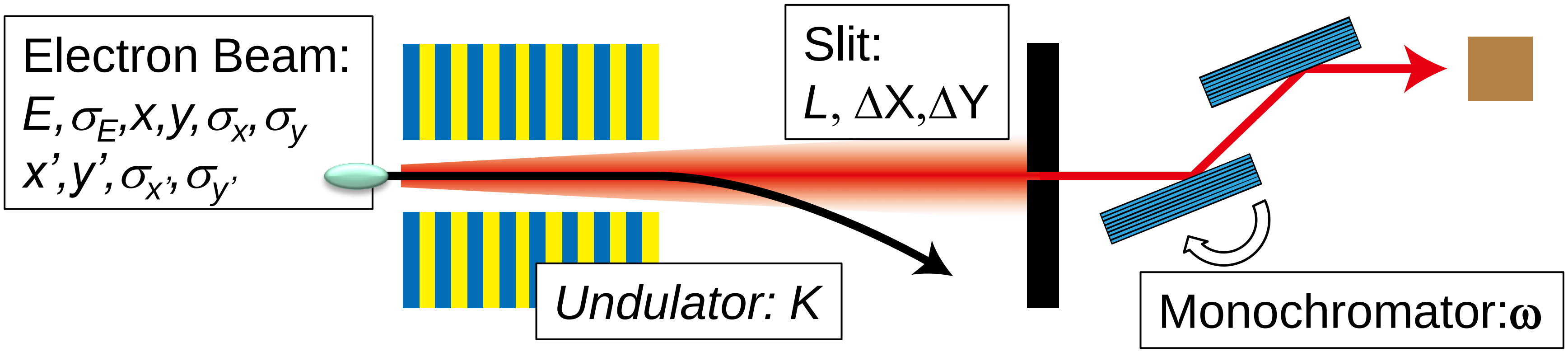
- UR is quasi-monochromatic at the fundamental energy of ω_{1st}

$$\omega_{1st} = \frac{4\pi c\gamma^2}{\lambda_u(1 + K^2/2 + \gamma^2\theta^2)}$$

- For better resolution, the angular acceptance ($\Delta\theta$) should be small to reduce the spectral bandwidth.
- From the practical point of view, it is better to apply $\Delta\theta$ larger than the UR angular spread.

Condition of Spectrum Measurement

UR spectrum depends on many parameters



Narrow Slit

Wide Slit

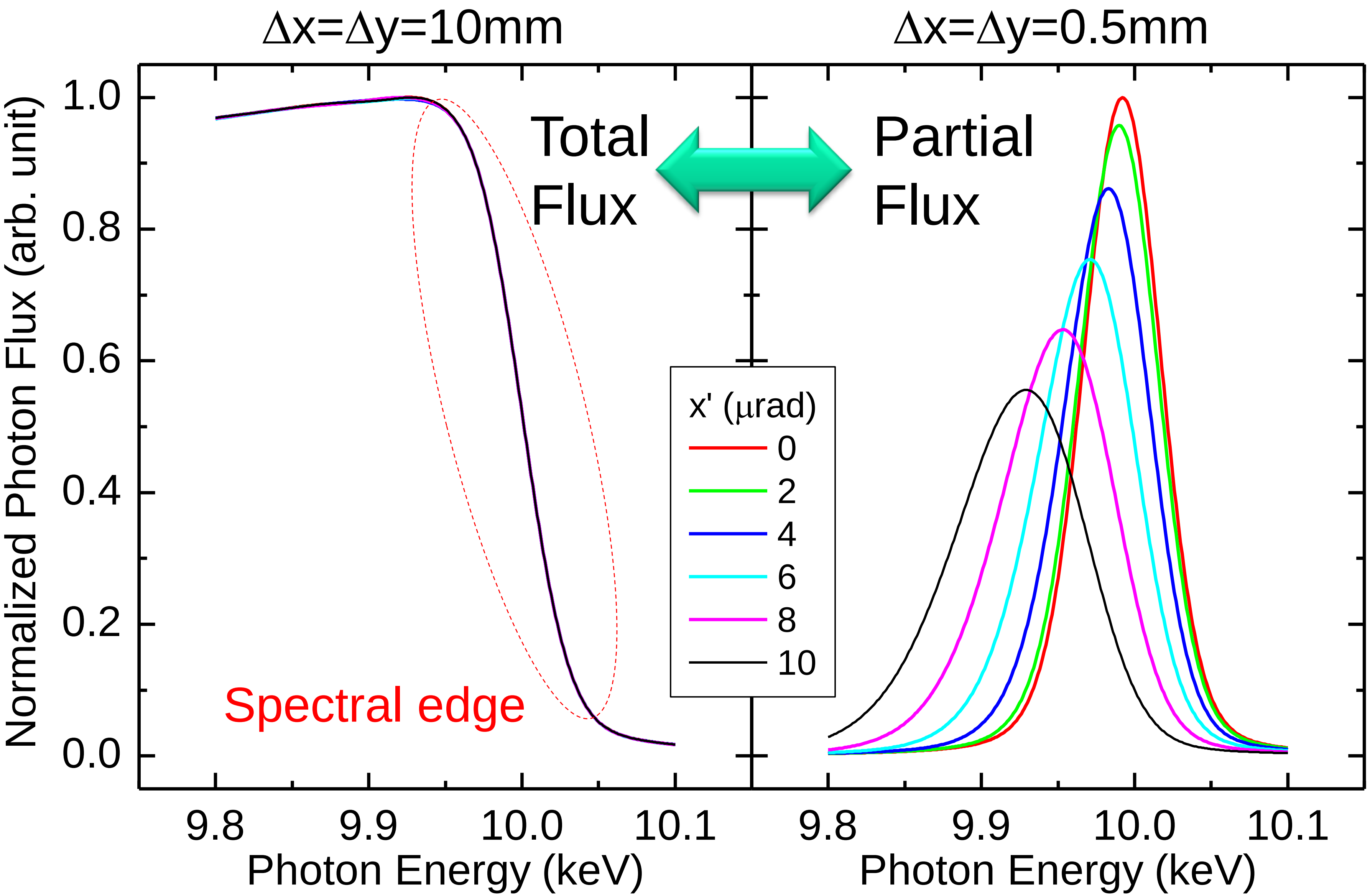
"Partial Flux"
Sharp spectrum, but sensitive to condition

$$f(\omega, K, E, \sigma_E, L, \Delta X, \Delta Y, x, y, \sigma_{x,y}, x', y', \sigma_{x',y'})$$

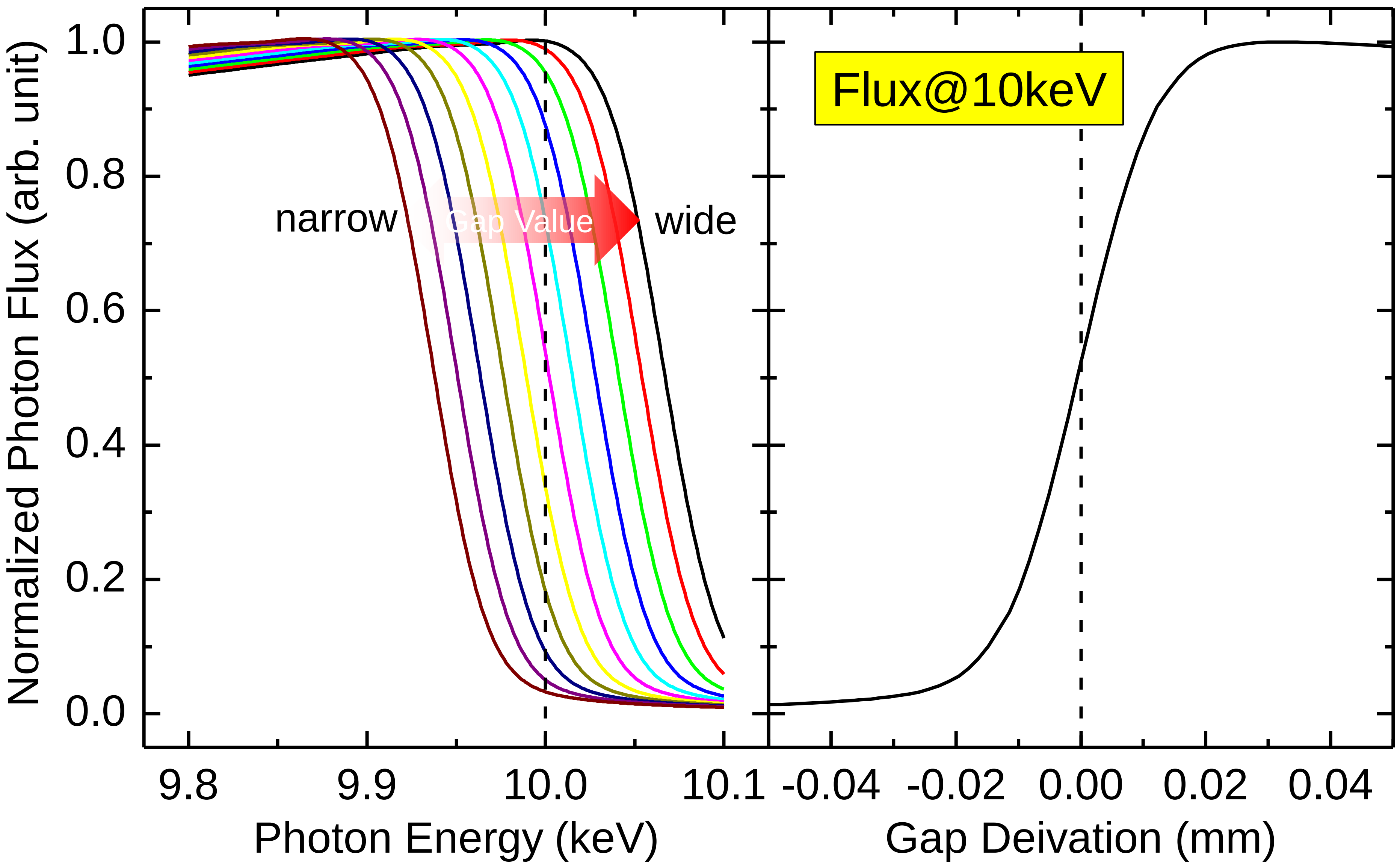
"Total Flux"
Wide spectrum, but insensitive to condition

$$F(\omega, K, E, \sigma_E)$$

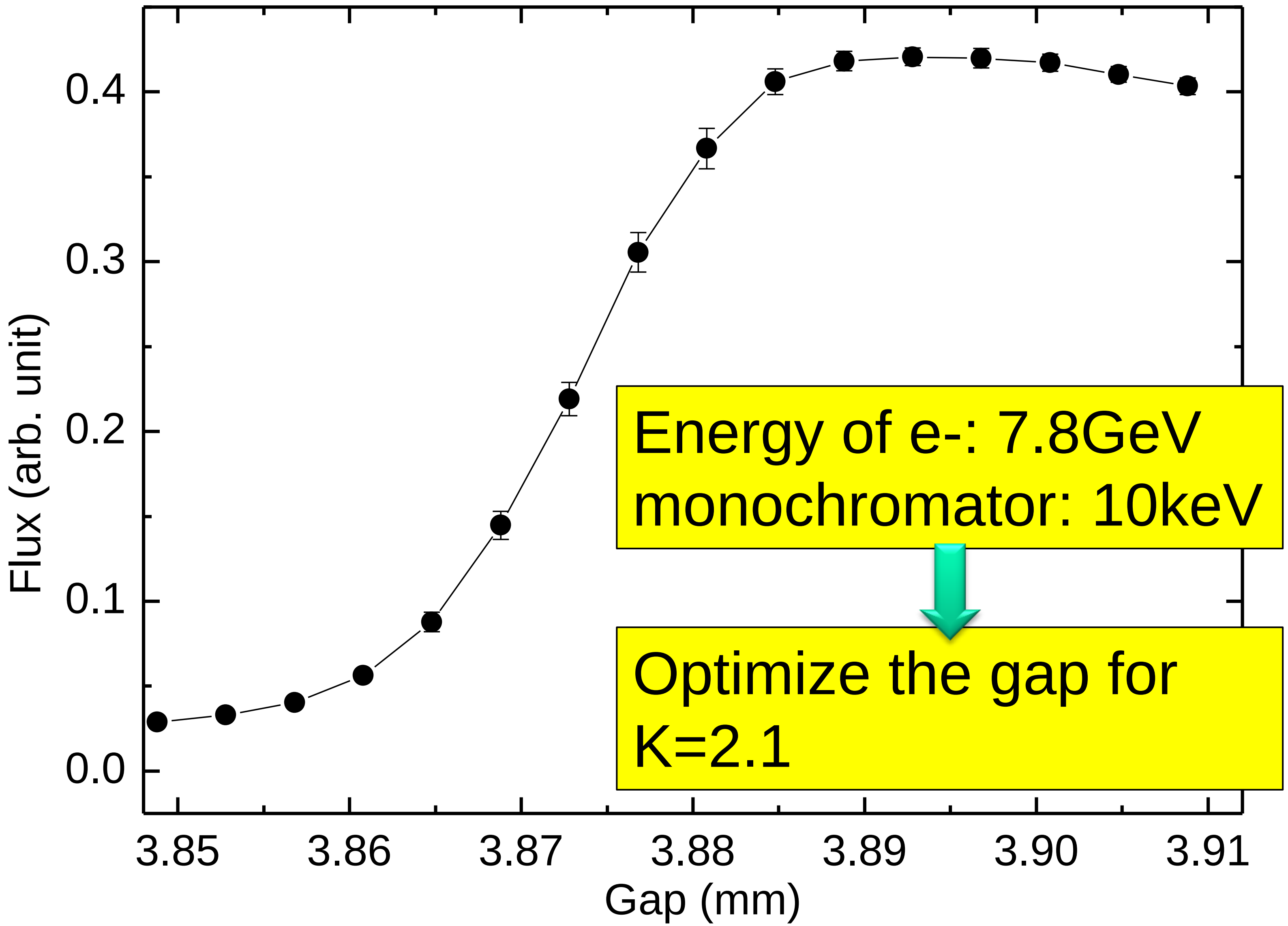
Example of UR Spectra



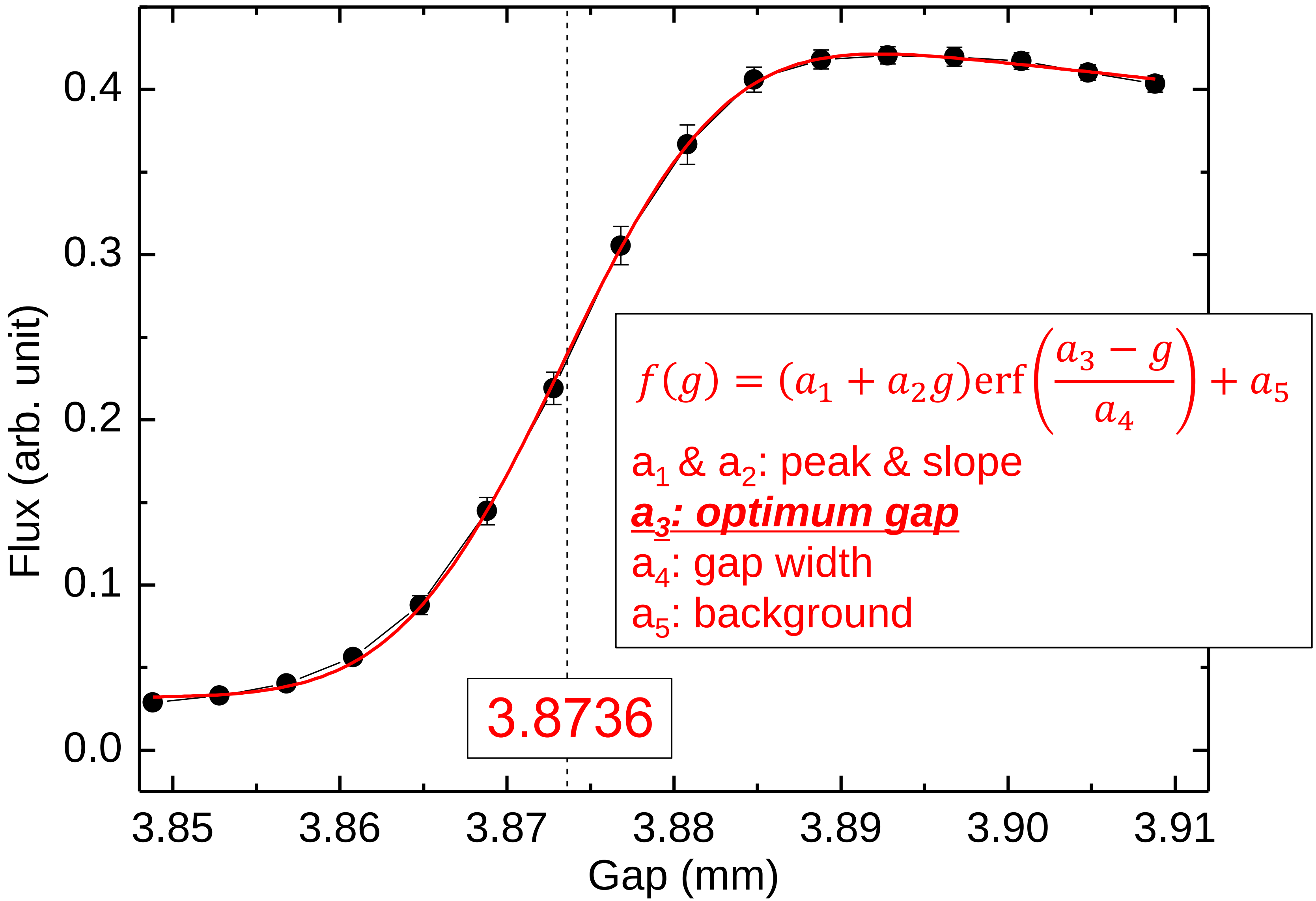
Gap Tuning


Normalized Photon Flux (arb. unit)
1.0
0.8
0.6
0.4
0.2
0.0
narrow
Gap Value
wide
9.8
9.9
10.0
10.1
Photon Energy (keV)
Flux@10keV
-0.04
-0.02
0.00
0.02
0.04
Gap Deivation (mm)

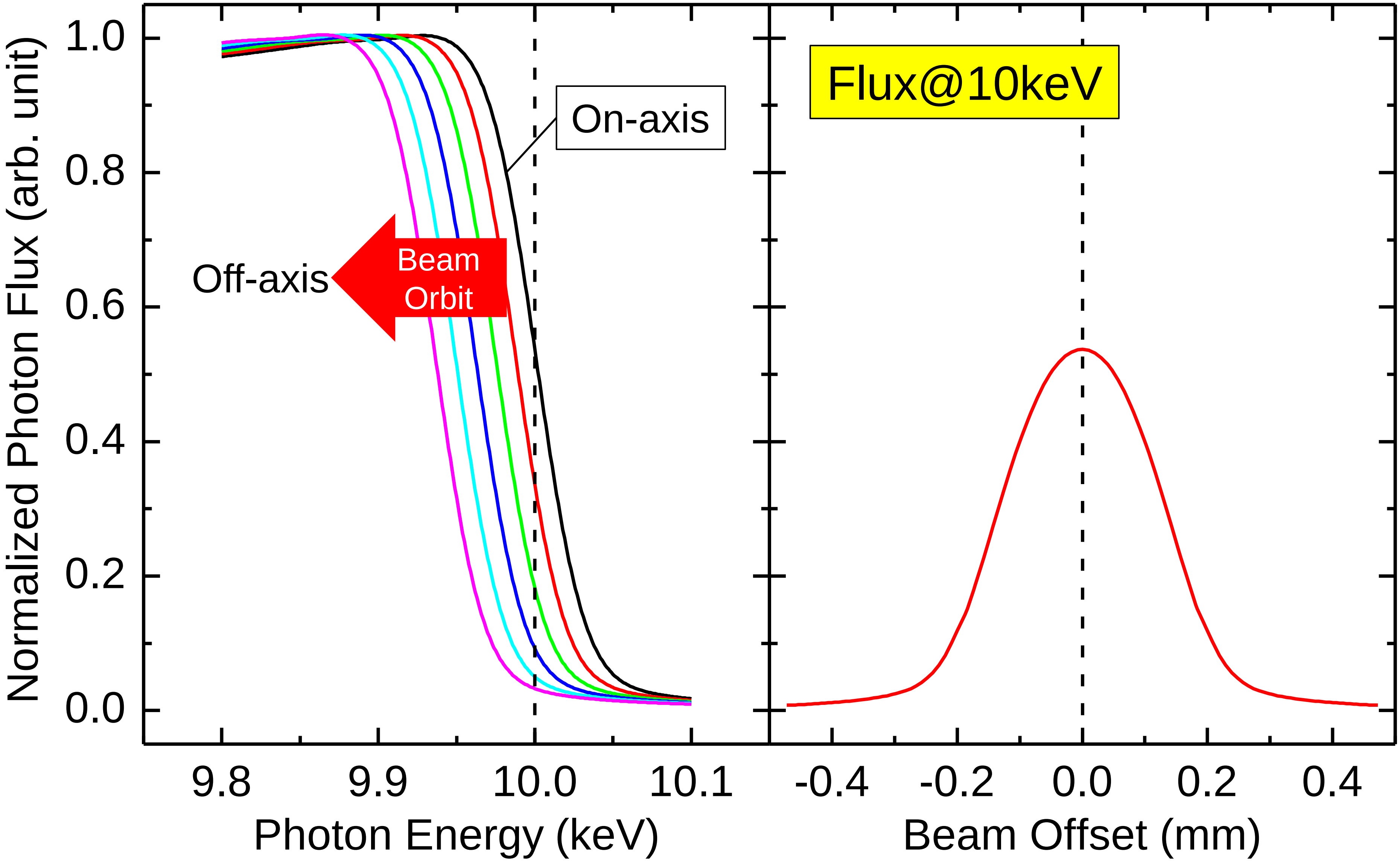
Example of Tuning



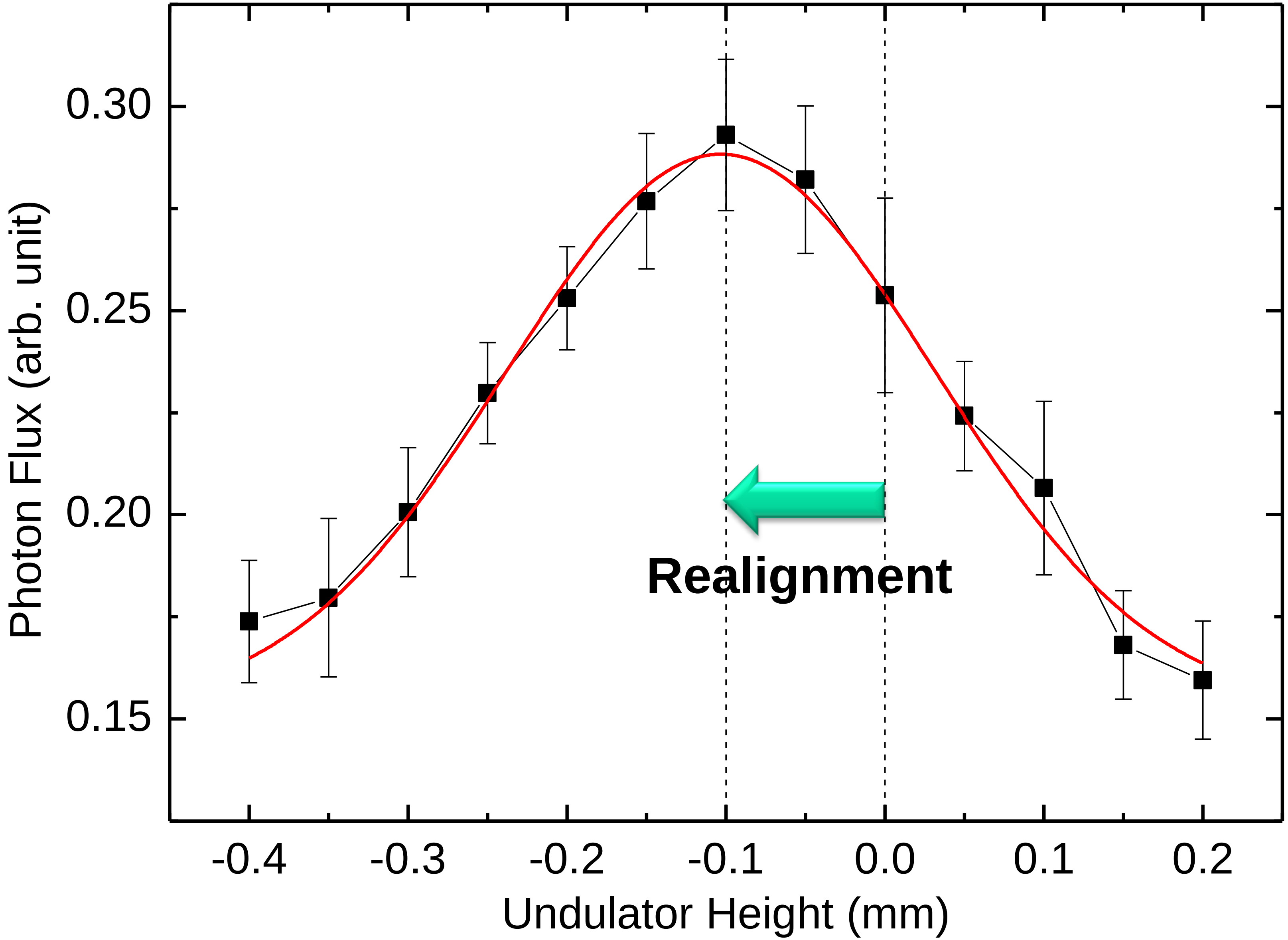
Fitting Function for the Optimum Gap



Height Alignment

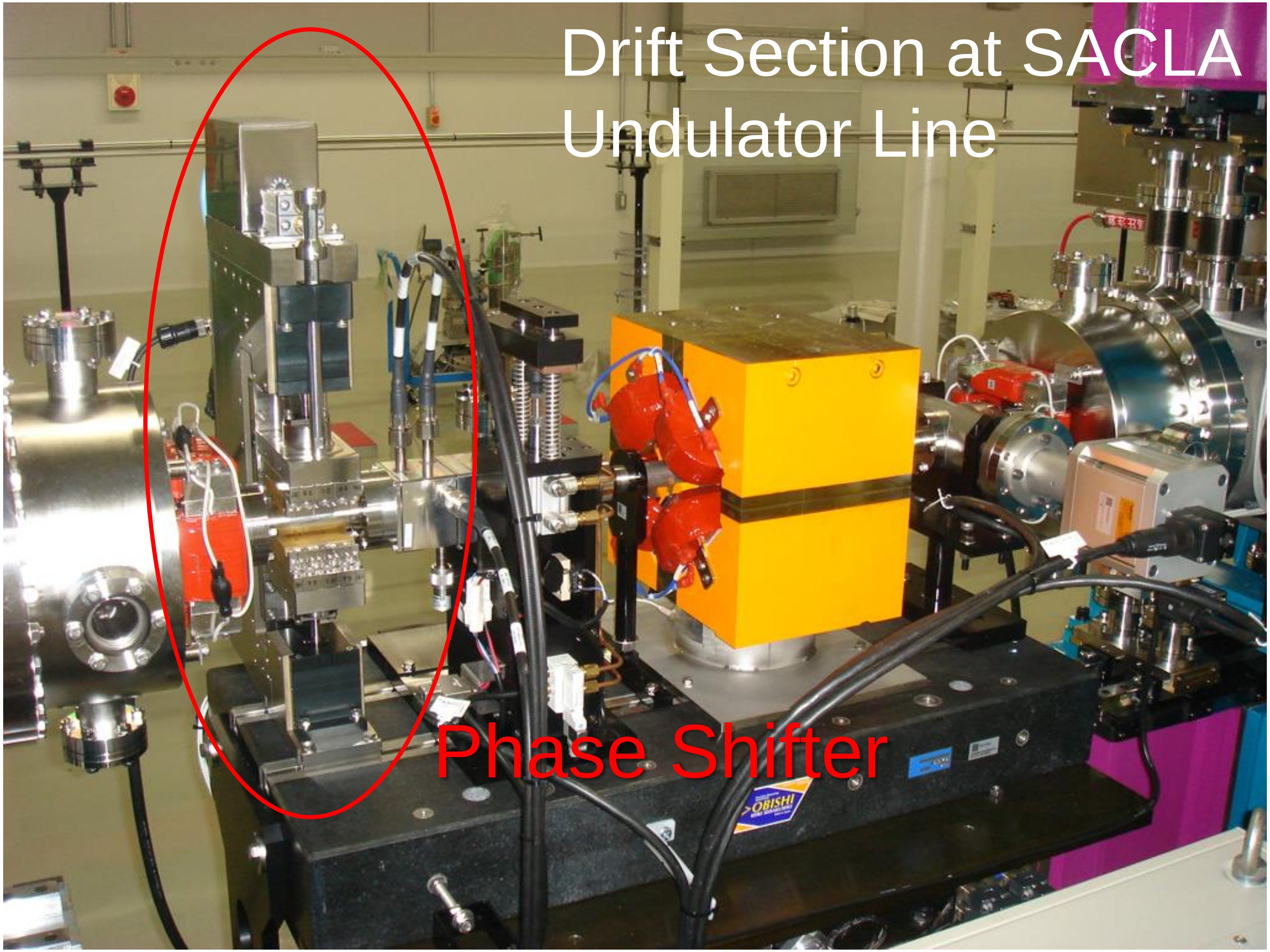


Example of Alignment



Commissioning Target		Tolerance	Tuning Method	
			Rad. Type	Item
Trajectory	BPM	2.2 μm	-	-
	Injection Angle	0.5 μrad	Mono. SR	Angular Profile
K Value	Gap	1.9 μm	Mono. SR	Spectrum
	Height	60 μm		
	Total	5×10^{-4}	-	-
Phase Matching (Phase Slippage)		**30º**	**SASE**	**Intensity**
			Mono. SR	**Spectrum**
Undulator Taper (Wake Compensation)		1.6×10^{-4} /segment	SASE	Intensity

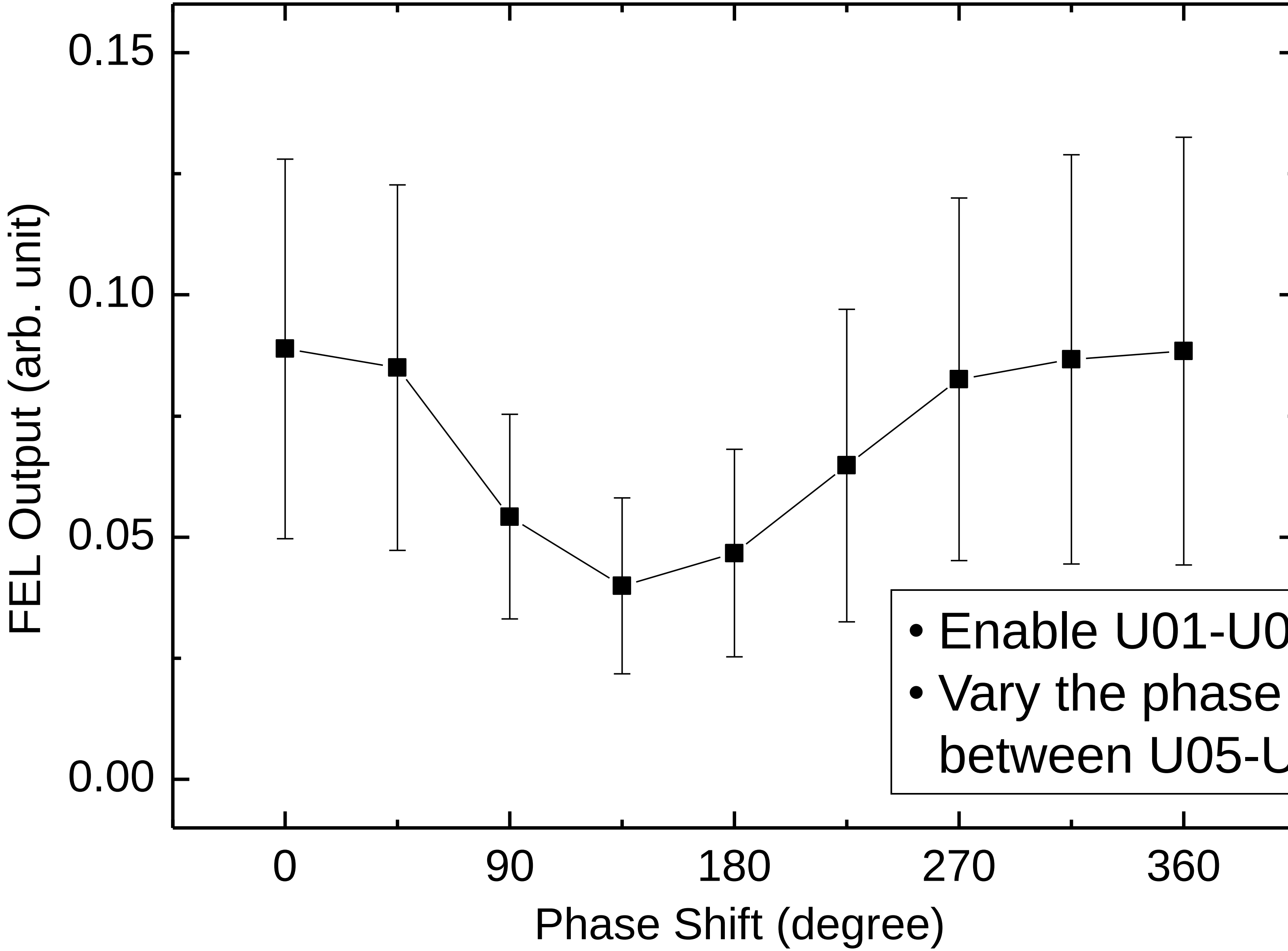
Phase Shifter



Phase Shifter

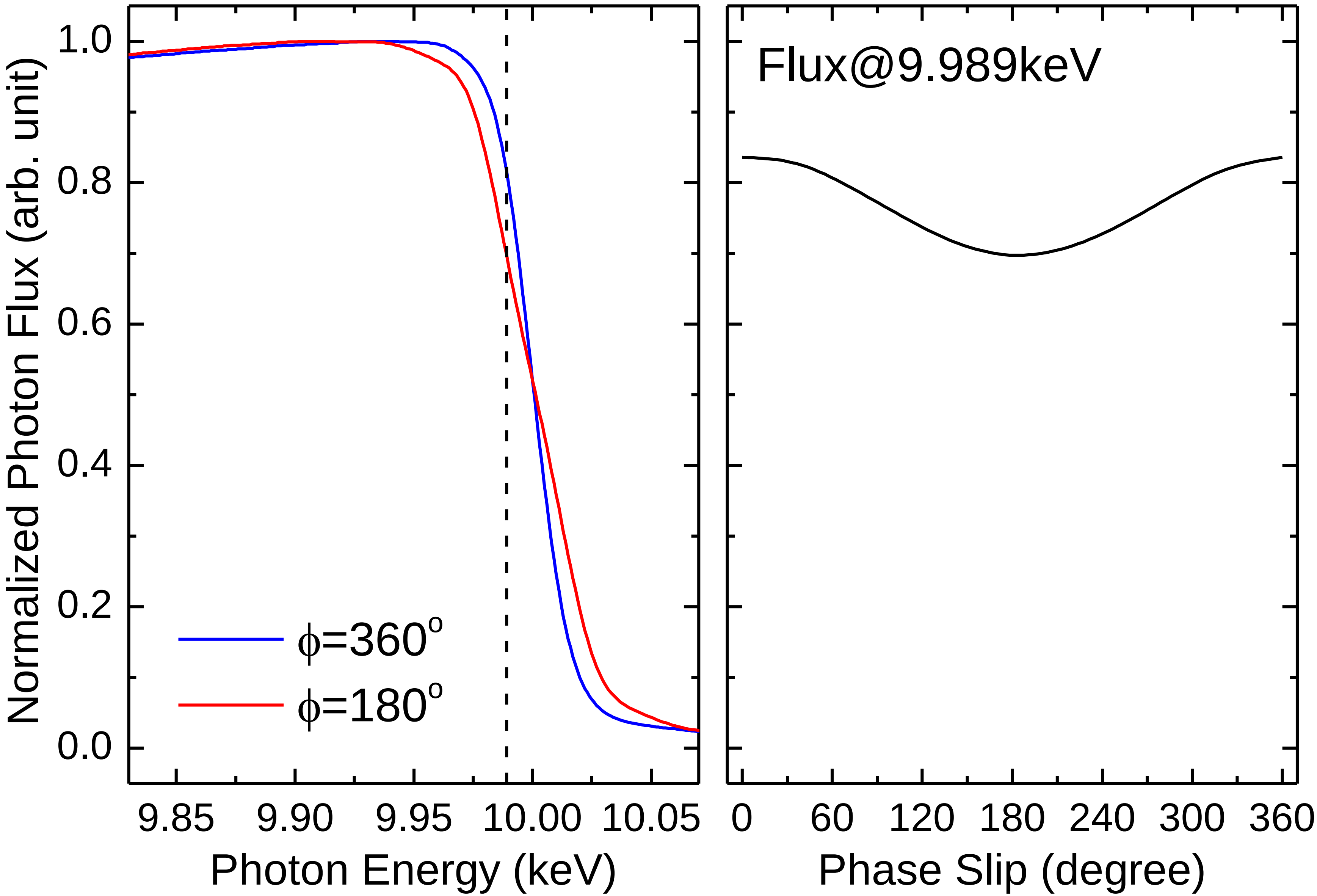
- How to satisfy the matching condition?
  - SASE: optimize the laser intensity
  - Spontaneous: ??

SASE Intensity vs. Phase

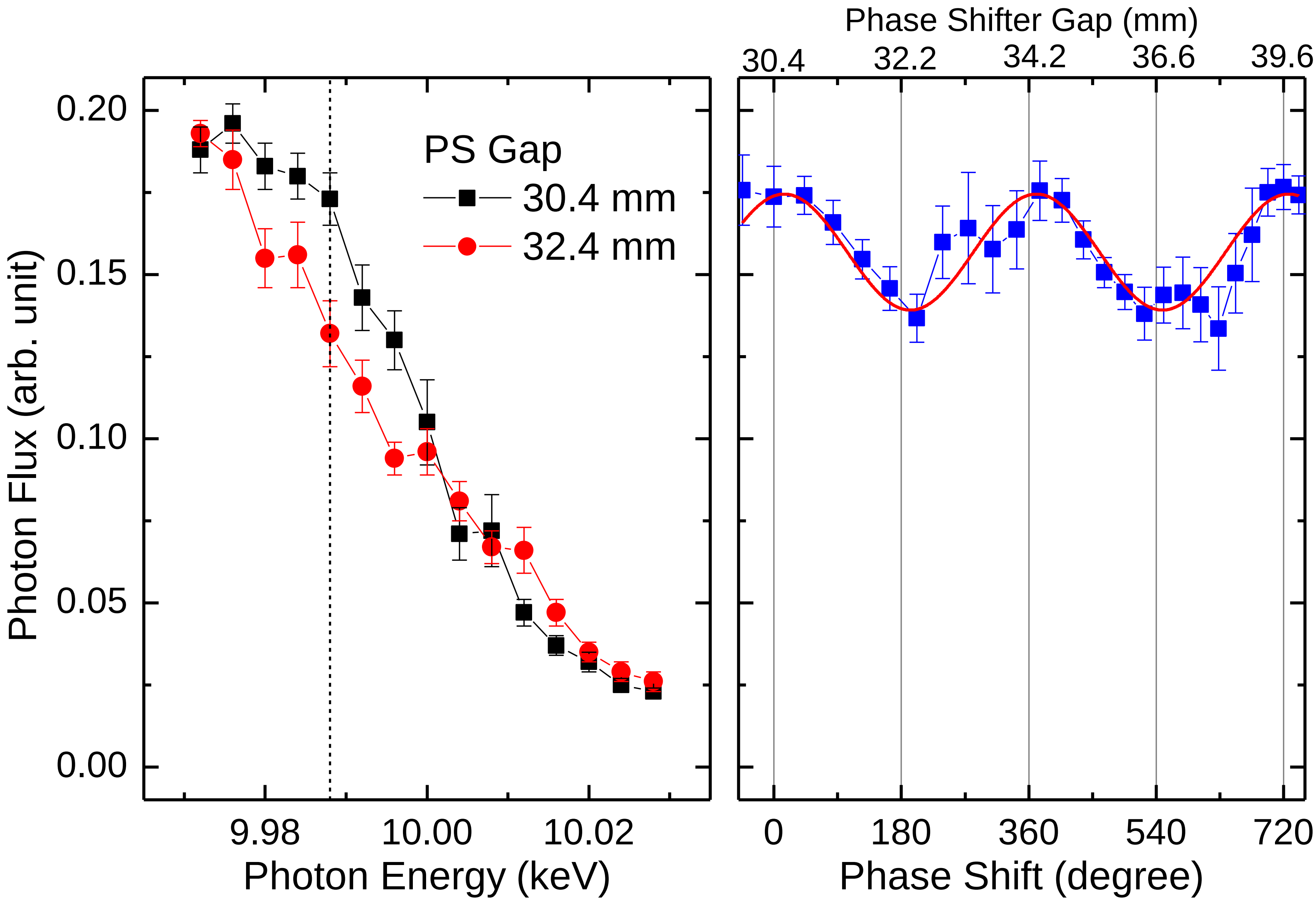


- Enable U01-U06
- Vary the phase between U05-U06

SR Spectrum vs. Phase



Example of Phase Matching



Commissioning Target		Tolerance	Tuning Method	
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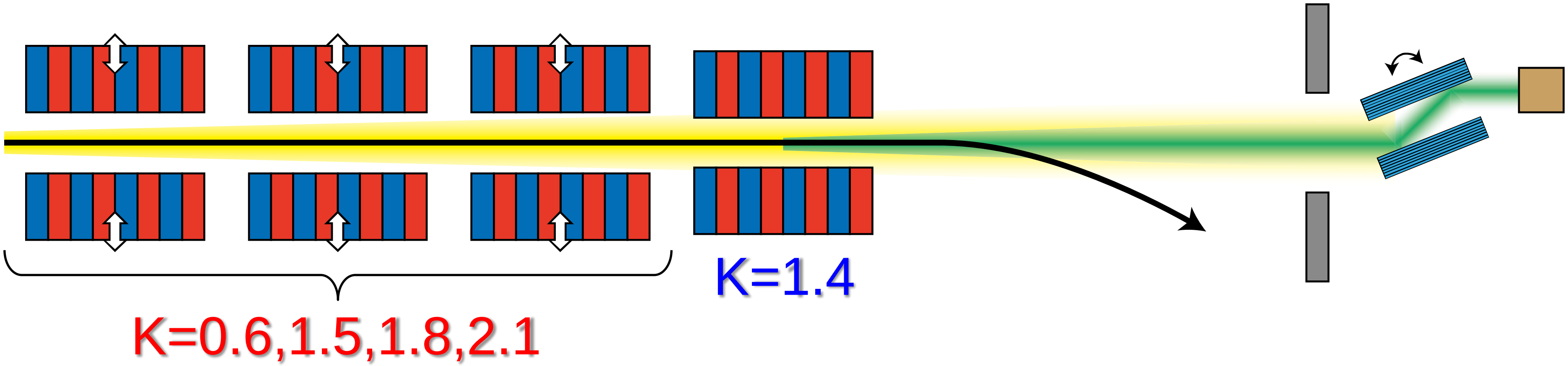
Trajectory	BPM	2.2 μm	-	-
	Injection Angle	0.5 μrad	Mono. SR	Angular Profile
K Value	Gap	1.9 μm	Mono. SR	Spectrum
	Height	60 μm		
	Total	$5x10^{-4}$	-	-
Phase Matching (Phase Slippage)		30^o	SASE	Intensity
			Mono. SR	Spectrum
Undulator Taper (Wake Compensation)		**$1.6x10^{-4}$ /segment**	**SASE**	**Intensity**

Undulator Taper

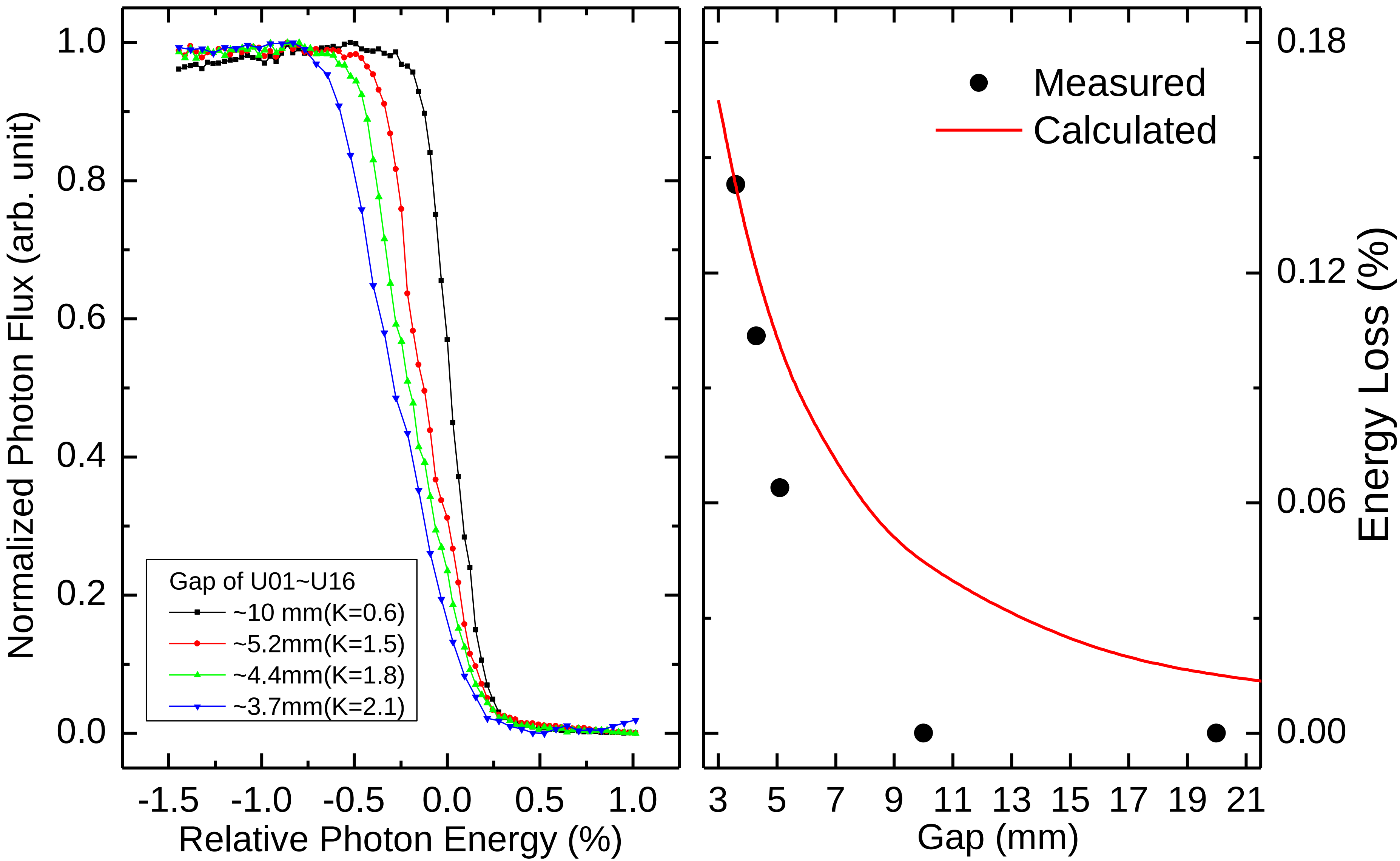
- The wakefield induced in the undulator results in an energy loss, which can be compensated by undulator tapering.
- The optimum taper is easily determined to maximize the FEL gain.
- Even so, it is important to roughly estimate the optimum taper before trying to achieve lasing, especially in SACLA.

Wake Estimation by UR Spectrum

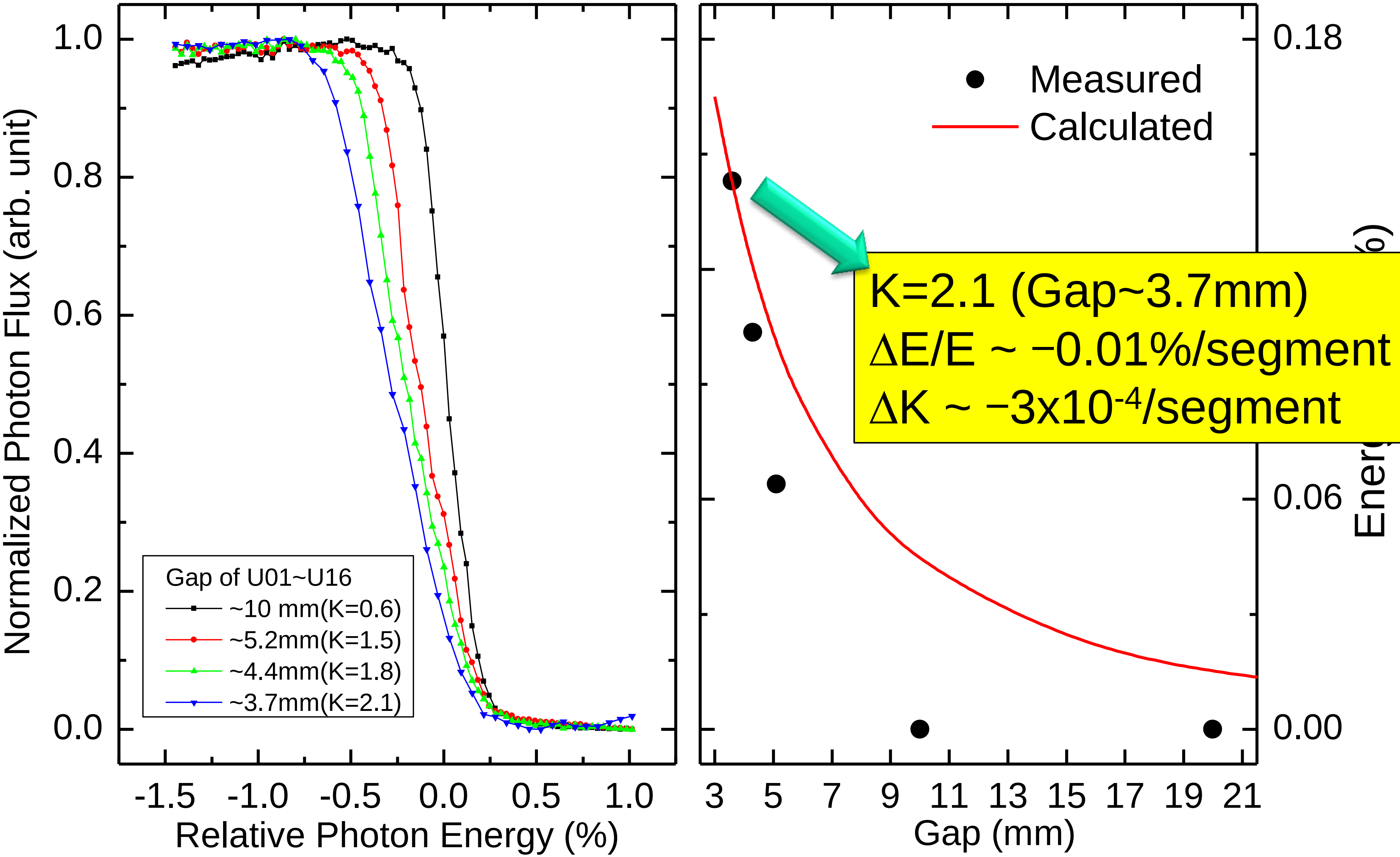


- The gap of the last undulator is set differently on purpose.
- Spectrum of SR emitted from the last undulator is measured for different wakefield conditions.

Example of Wake Estimation

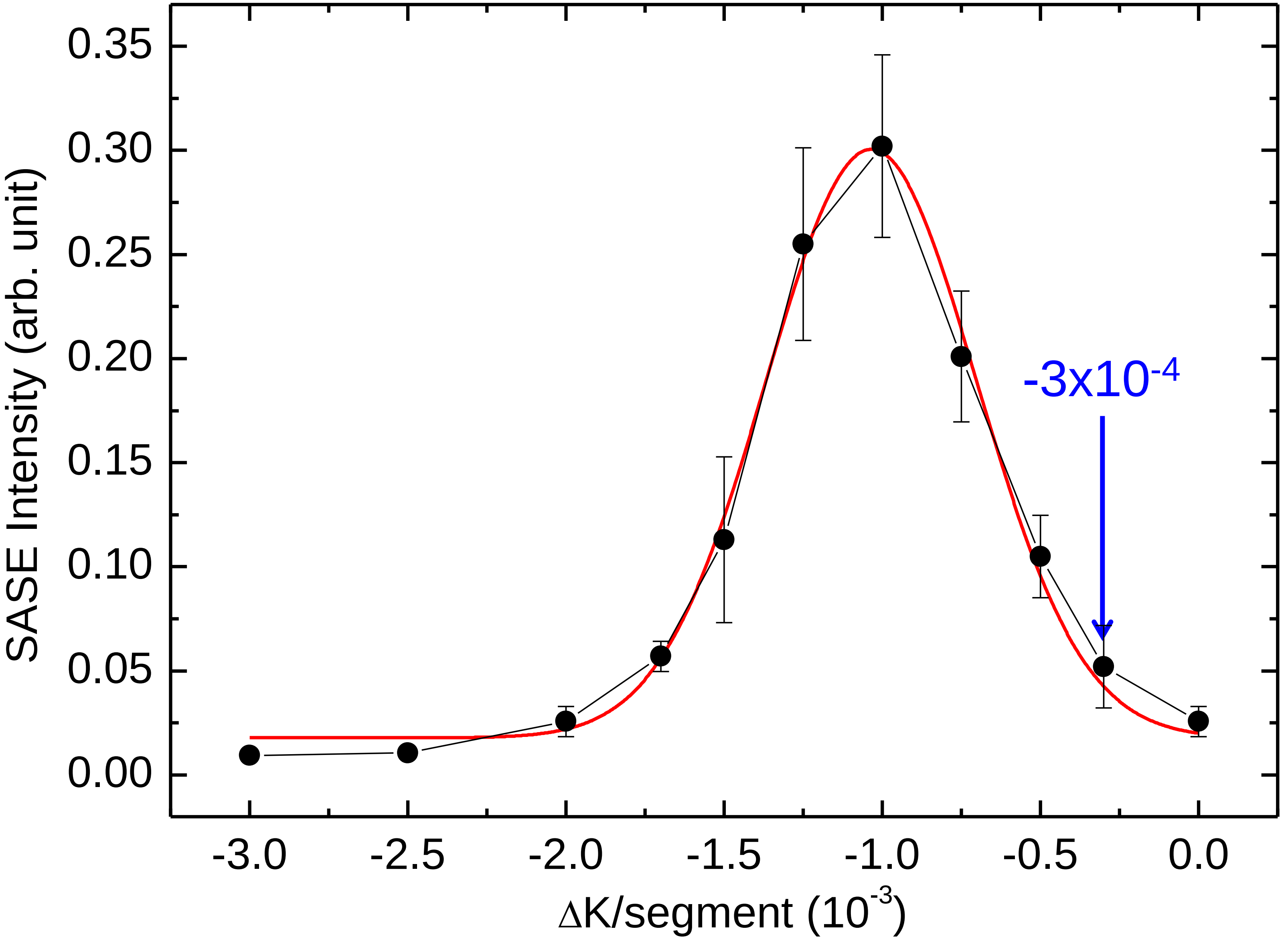


Example of Wake Estimation



K=2.1 (Gap~3.7mm)
ΔE/E ~ −0.01%/segment
ΔK ~ -3×10^{-4}/segment

Taper Optimization by SASE Intensity



Contents

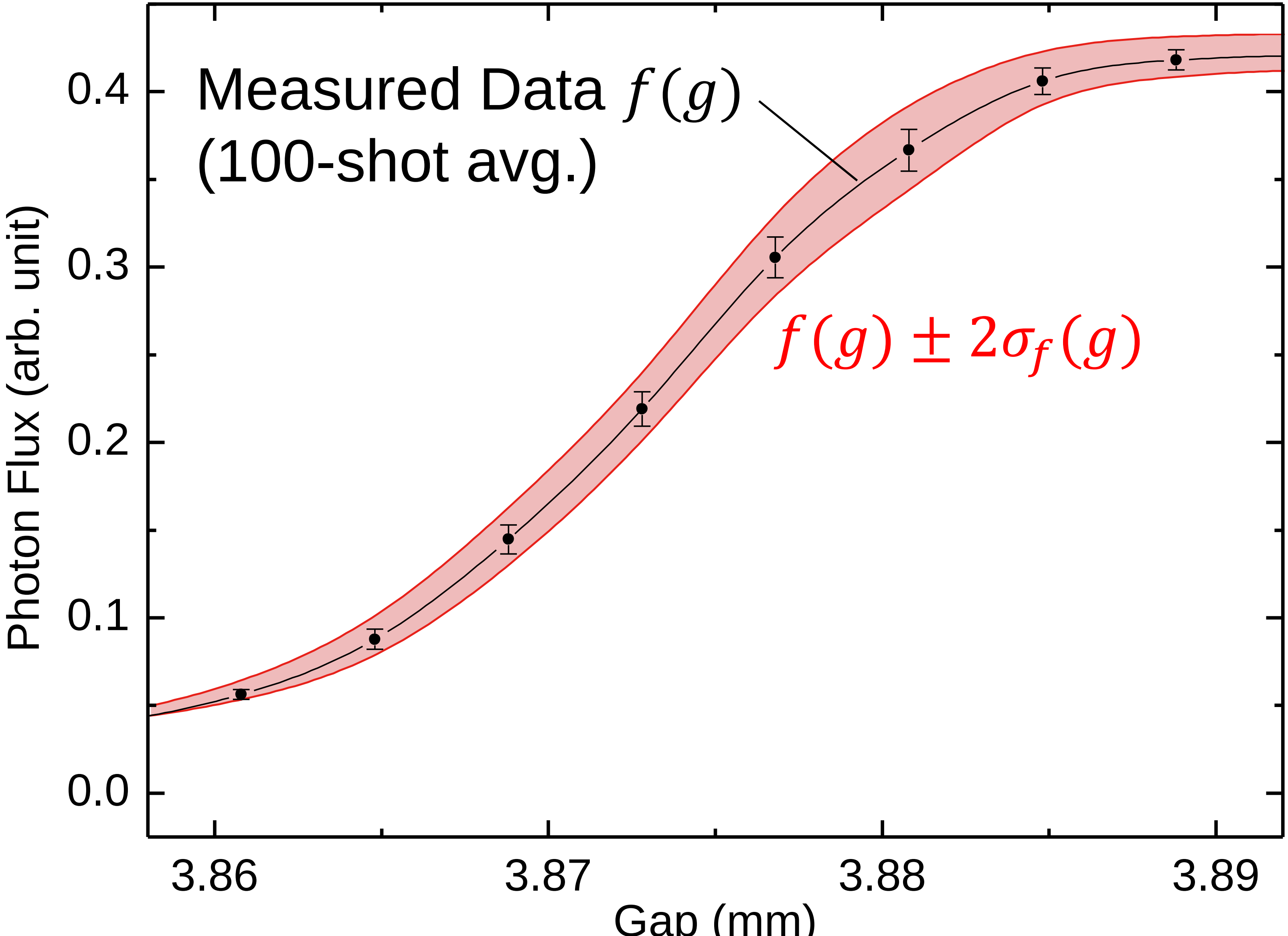
Evaluation of Alignment Accuracy

- How is the alignment accuracy achieved in our scheme?
  - Trajectory alignment: pointing stability
  - Others: reliability of fitting functions

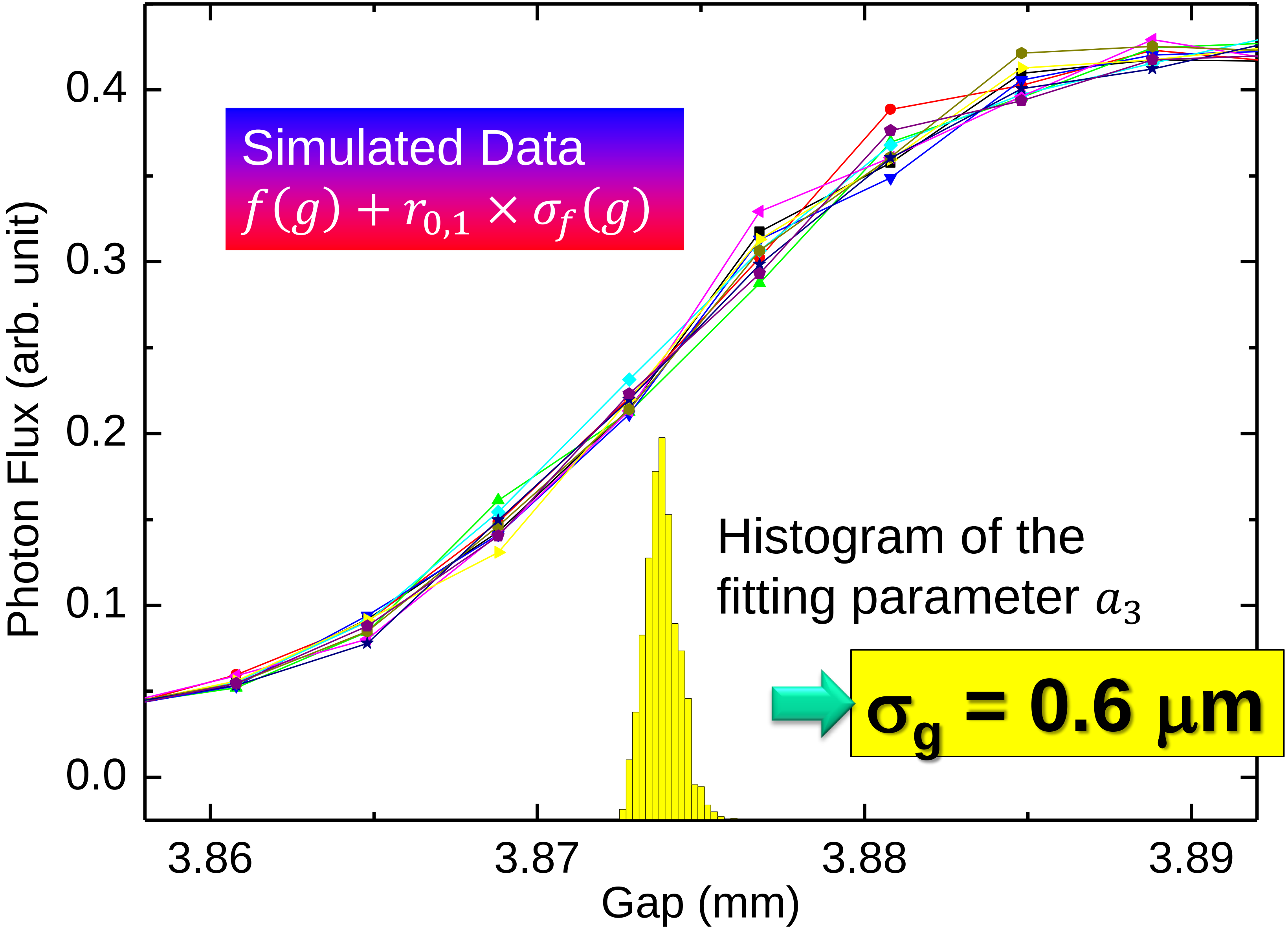
↓

Simulate the fluctuation of fitting parameters based on the statistics of the actual measurement

Example: K-value Tuning



Example: K-value Tuning



Achieved Accuracy

Commissioning Target		Accuracy	
		Required	Achieved
Trajectory		2.2 μm = 0.5 μrad	0.22 μrad (x) 0.48 μrad (y)
K Value	Total	5×10^{-4}	2×10^{-4}
	Gap	1.9 μm	0.6 μm
	Height	60 μm	10 μm
Phase		30°	15° (SR) 120° (SASE)*
Taper (ΔK/segment)		1.6×10^{-4}	4×10^{-5}

* @exponential growth region

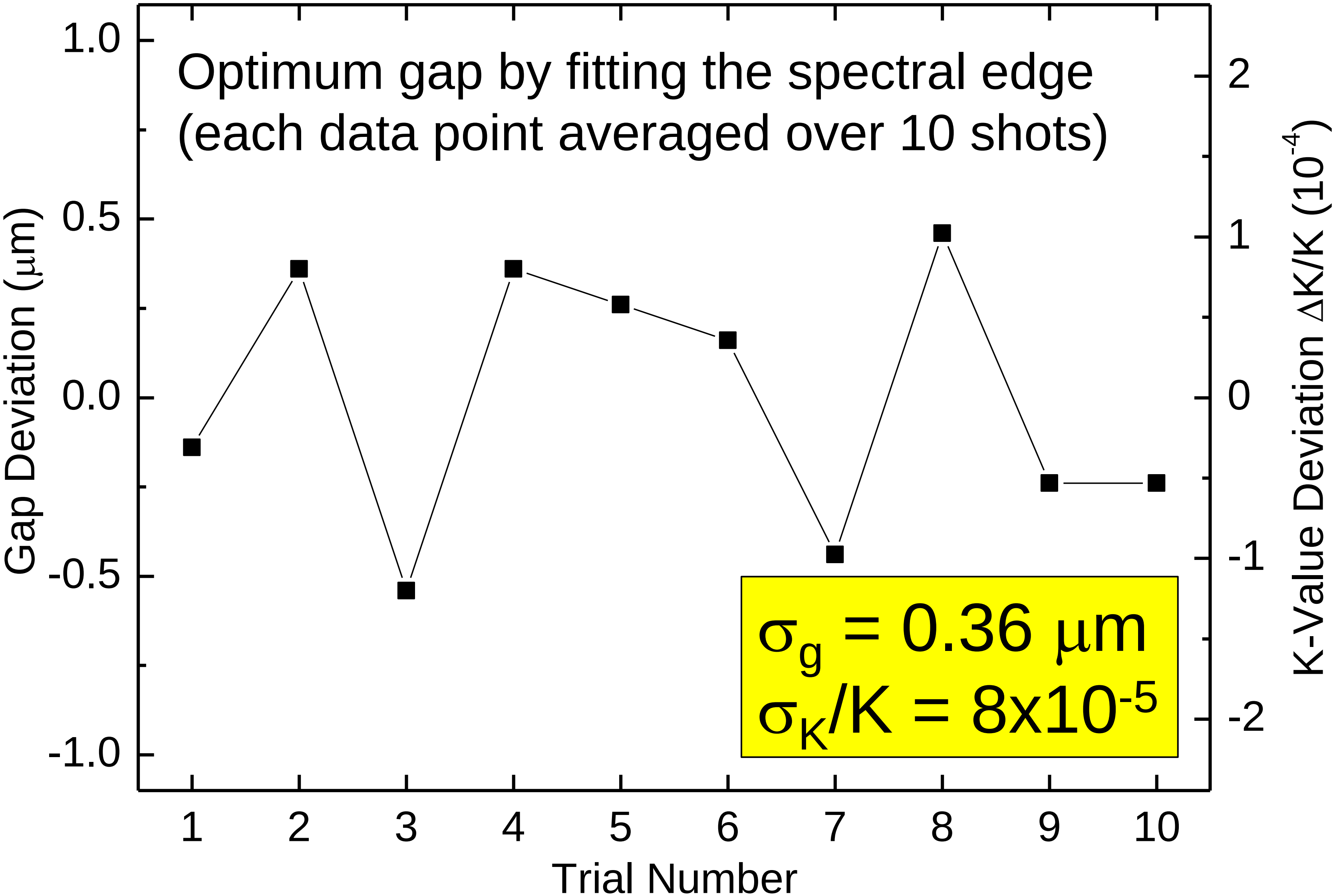
Achieved Accuracy

Commissioning Target		Accuracy	
		Required	Achieved
Trajectory		2.2 μm [illegible] 0.5 μrad	0.22 μrad (x) 0.48 μrad (y)
K V[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]
	Height	60 μm	10 μm
Phase		30^{o}	15^{o} (SR) 120^{o} (SASE)*
Taper (ΔK/segment)		1.6x10^{-4}	4x10^{-5}

Increasing the averaging number of shots improves the accuracy!!

* @exponential growth region

Improvement by 10 Shot Averaging



Summary

- Undulator commissioning by means of x-ray characterization has been successfully carried out in SACLA, which is now routinely in operation to offer the best performance to users.
- Among all the alignment items, the trajectory correction is done most frequently, e.g., every two or three weeks.

Thank you for your attention!

Alignment Tolerance

How to specify the alignment tolerance of respective components?

1) Create a number of error models with the target component being aligned with some tolerance (others perfect)
2) Perform simulations to calculate the gain reduction due to misalignment
3) Repeat the above processes for different alignment accuracies
4) Define the tolerance so that 90% of the ideal SASE intensity is obtained

Angular Profile of Mono. SR

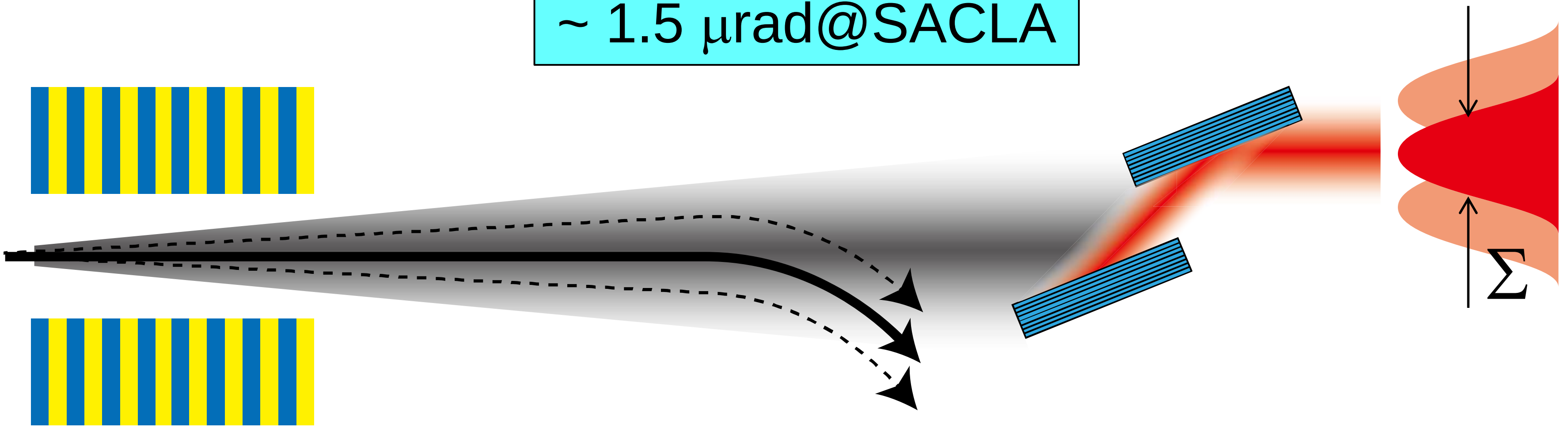
- After monochromatization, the angular spread of SR is given by

$$\sqrt{{\sigma_{r'}}^2 + {\sigma_{b'}}^2} = \Sigma$$

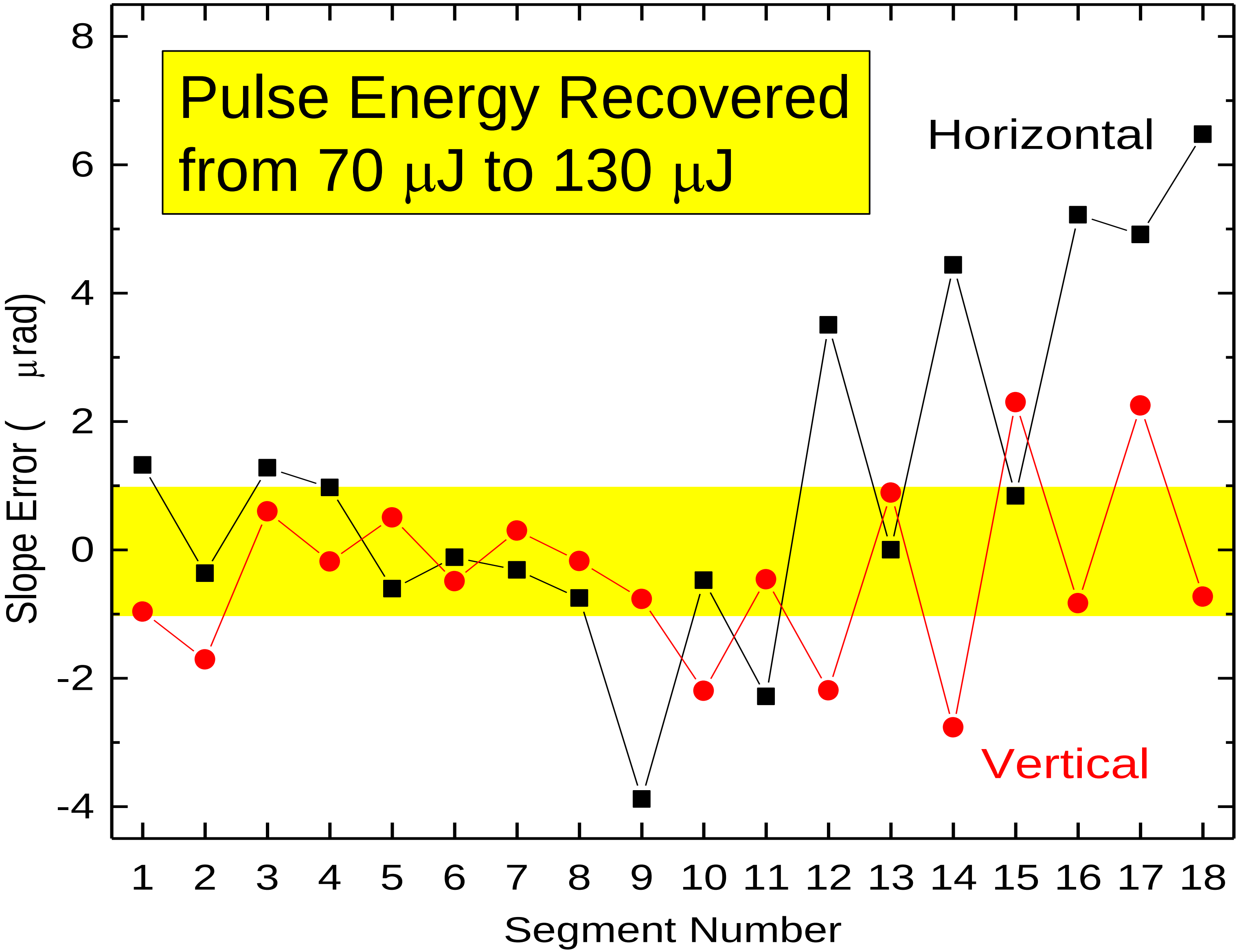
UR natural spread
~ 3.5 μrad@10keV

e- beam spread
~ 1.5 μrad@SACLA

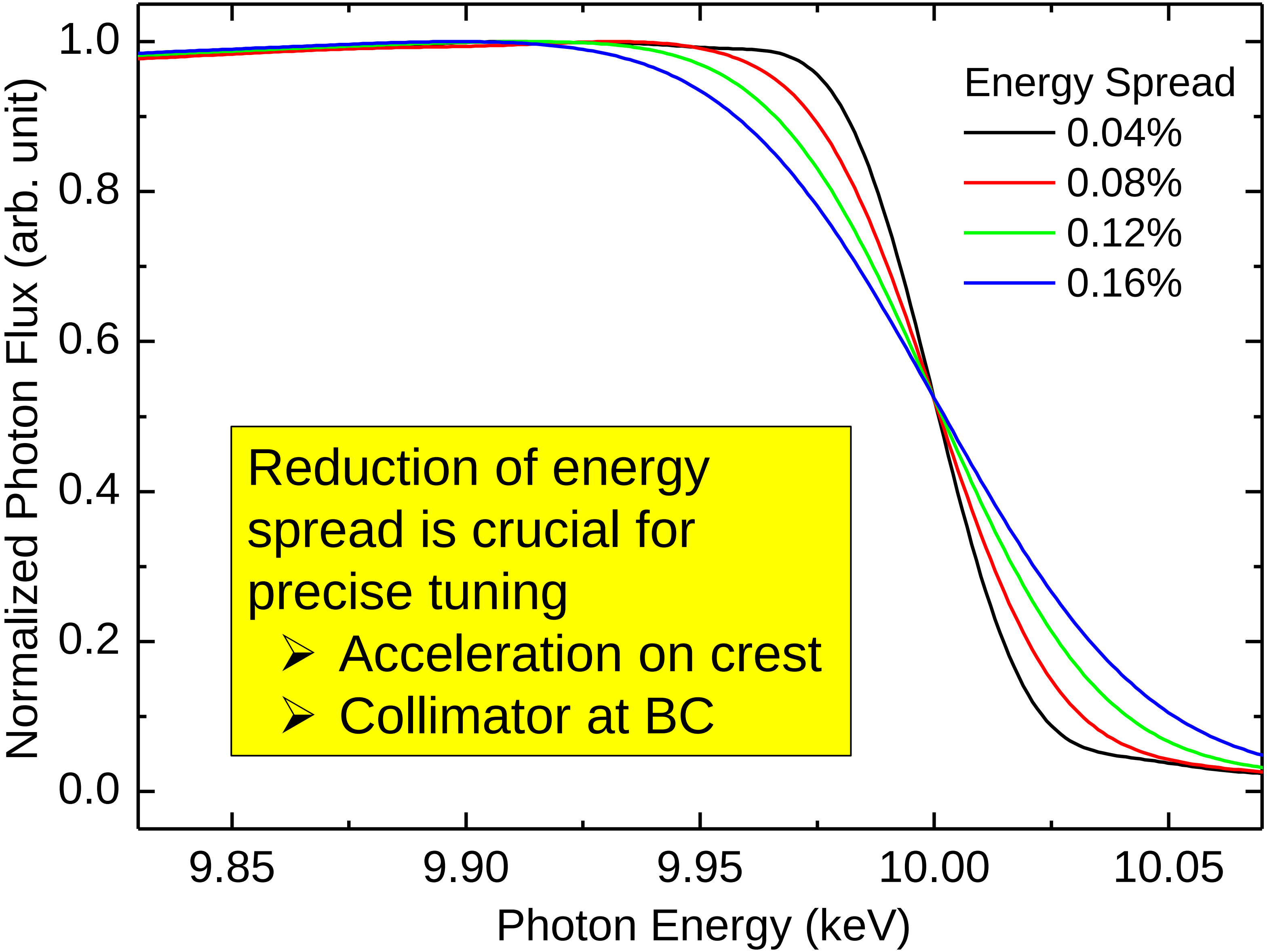
photon beam spread
~ 3.8 μrad@SACLA



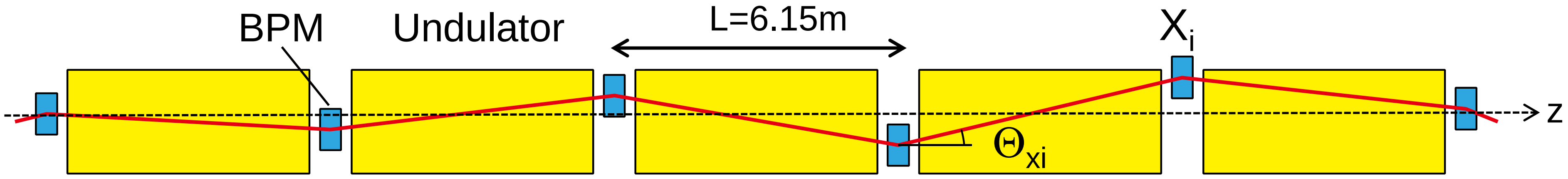
Example of Correction



Energy-Spread Effects



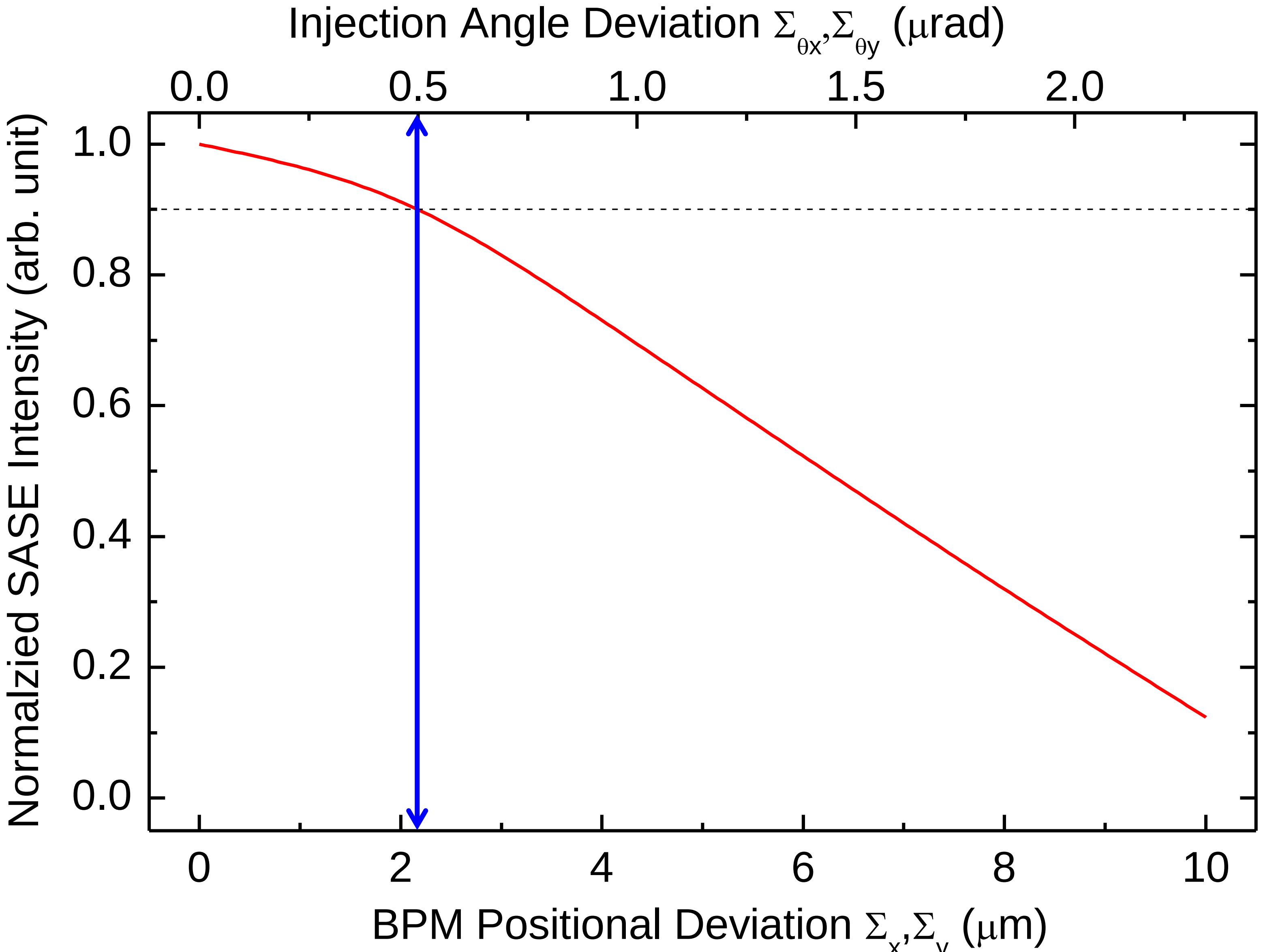
Example: Trajectory Alignment



- Trajectory error at the i-th segment is described in two forms:
  - BPM alignment error X_i, Y_i
  - Injection angle error Θ_{xi}, Θ_{yi}
- Both errors follow the Gauss random number

$$\Sigma_{\Theta X} = \frac{\sqrt{2}\Sigma_X}{L}, \Sigma_{\Theta Y} = \frac{\sqrt{2}\Sigma_Y}{L}$$

Tolerance: Trajectory Alignment



Example: K-value Tuning