Single-shot resolution of x-ray monitor using coded aperture imaging

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Outline

- Introduction
  - Measurement principles
  - Target machines
- Single-shot resolution estimation
- Comparison with measurements at CesrTA
- Resolution estimates at ATF2
- Resolution estimates at SuperKEKB
- Summary

Introduction: Measurement principles

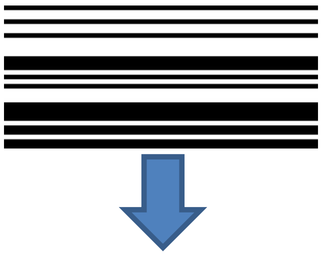
R.H. Dicke, Astrophys. Journ., 153, L101, (1968).

- Coded Aperture Imaging:
  - Technique developed by x-ray astronomers using a mask to modulate incoming light. Resulting image must be deconvolved through mask response (including diffraction and spectral width) to reconstruct object.
  - Open aperture of 50% gives high flux throughput for bunch-by-bunch measurements. Heat-sensitive and flux-limiting monochromator not needed.
    - We need such a wide aperture, wide spectrum technique for shot-by-shot (single bunch, single turn) measurements.

E.E. Fenimore and T.M. Cannon, Appl. Optics, V17, No. 3, p. 337 (1978).

- URA (Uniformly Redundant Array) mask
  - Pseudo-random pattern gives relatively flat spatial frequency response.
  - In noiseless, geometric limit, detector image can in principle be inverted directly to give source profile
  - Unfortunately, we don't operate in that limit.
  - Need something like recursive or template fitting.
    - In this talk will discuss latter approach.

What the detector sees



•Source SR wavefront amplitudes:

$$\begin{bmatrix} A_\sigma \\ A_\pi \end{bmatrix} = \frac{\sqrt{3}}{2\pi}\gamma\frac{\omega}{\omega_c}\left(1+X^2\right)(-i)\begin{bmatrix} K_{2/3}(\eta) \\ \frac{iX}{\sqrt{1+X^2}}K_{1/3}(\eta) \end{bmatrix},$$

where

$$X = \gamma\psi,$$

$$\eta = \frac{1}{2}\frac{\omega}{\omega_c}\left(1+X^2\right)^{3/2},$$

K.J. Kim, AIP Conf. Proc. 184 (1989).

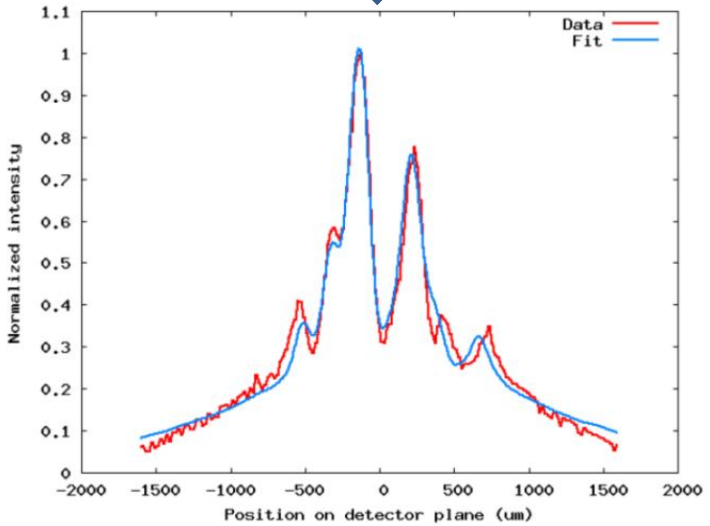
J.D. Jackson, "Classical Electrodynamics," (Second Edition),John Wiley & Sons, New York (1975).

•Kirchhoff integral over mask

(+ detector response)

→ Detected pattern:

$$A_{\sigma,\pi}\left(Detector\right) = \frac{iA_{\sigma,\pi}\left(Source\right)}{\lambda} \times \int_{mask} \frac{t\left(y_m\right)}{r_1 r_2} e^{i\frac{2\pi}{\lambda}\left(r_1+r_2\right)} \left(\frac{\cos\theta_1 + \cos\theta_2}{2}\right) dy_m$$



Measured slow-scan detector image (red) at CesrTA, used to validate simulation (blue)

- $t(y_m)$ is complex transmission of mask element at y_m.
- Sum intensities of each polarization and wavelength component.
- Sum weighted set of detector images from point sources.
  - The source beam is considered to be a vertical distribution of point sources.
  - Can also be applied to sources with non-zero angular dispersion and longitudinal extent, for more accurate simulation of emittance and source-depth effects.
  - For machines under consideration here these effects are small, so for computational speed we restrict ourselves to 1-D vertical distributions.

Why URA mask?

- Advantage over simple pinhole/slit:
  - Greater open aperture for single-shot measurements
  - Somewhat better resolution
    - Get some peak-valley ratios that help at smaller beam sizes.
    - Make use of more of the detector
- What about a simple equal-spaced array of pinholes/slits?
  - Flatter frequency response
    - Better chance of reconstructing shape
    - Unique position determination (non-repeating pattern)
  - On the other hand, an equal-spaced array can offer tuned resolution over a narrower range of sizes
    - Array may be suitable for a very stable machine, such as a light source.
- For instability studies (e-cloud, e.g.) or other machine studies, or for a luminosity machine which is always running at the limit of stability, a URA mask promises better performance over a range of bunch conditions.

Single-shot resolution estimation

- Want to know, what is chance that a beam of a certain size is misfit as one of a different size?
- Tend to be photon statistics limited. (Thus coded aperture.)
- So:
  - Calculate simulated detector images for beams of different sizes
  - "Fit" images pairwise against each other:
    - One image represents true beam size, one the measured beam size
    - Calculate χ^2/ν residuals differences between images:

N = # pixels/channels
n = # fit parameters (=1, normalization)
S_i = expected number of photons in channel *i*

$$\frac{\chi^2}{\upsilon} = \frac{1}{N-n-1}\sum_{i=1}^{N}\frac{[s_i' - s_i]^2}{\sigma_i^2},$$

    - Weighting function for channel i:

$$\sigma_i = \sqrt{s_i}\,.$$

  - Value of χ^2/ν that corresponds to a confidence interval of 68% is chosen to represent the 1-s confidence interval

Introduction: Target machines

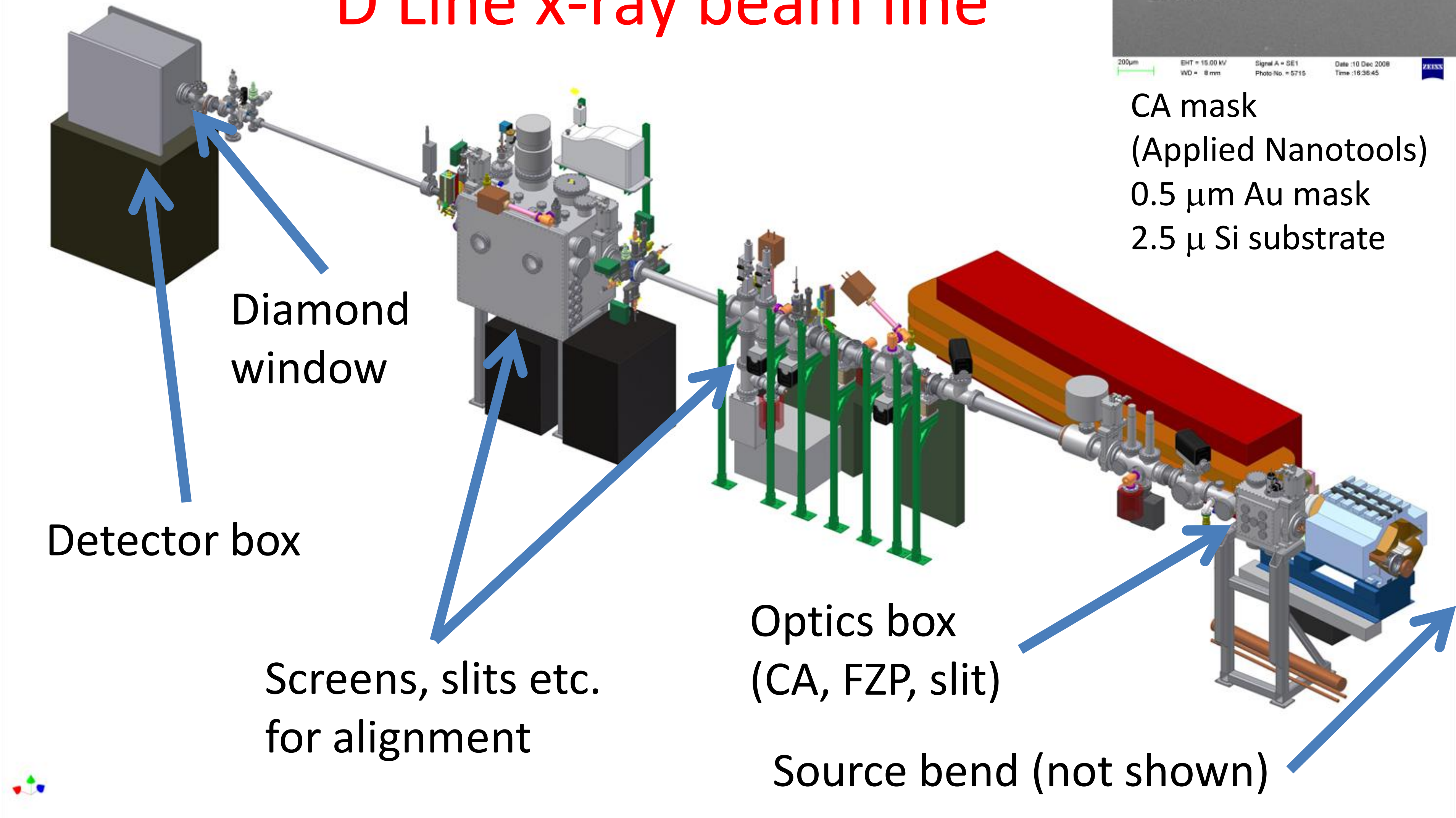
X-ray Source Parameters:

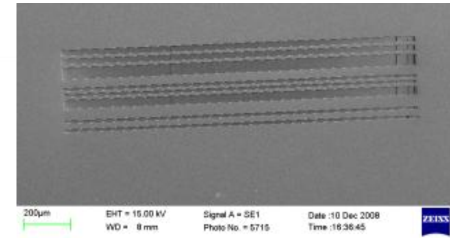
Parameter	**CesrTA (low-energy)**	**ATF2**	**SuperKEKB** LER / HER
ε_y (pm-rad) (min)	<20	~30	~10
σ_y (μm) (min.)	~10	~4	~10
Beam Energy (GeV)	2.085	1.3	4 / 7
Bending radius (m)	31.65	4.3	31.74 / 106
Critical Energy (keV)	0.63	1.1	4.4 / 7.1

Machines:

- CesrTA
  - ILC damping ring and low-emittance ring test machine, with focus on low emittance tuning and electron-cloud studies.
- ATF2
  - ILC final focus test extraction line from ATF.
- SuperKEKB
  - Super B factory: e+ e- two-ring energy-asymmetric collider for new physics searches.

Comparison with data: CesrTA

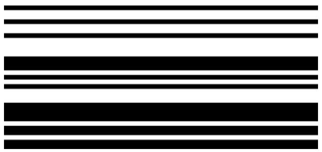


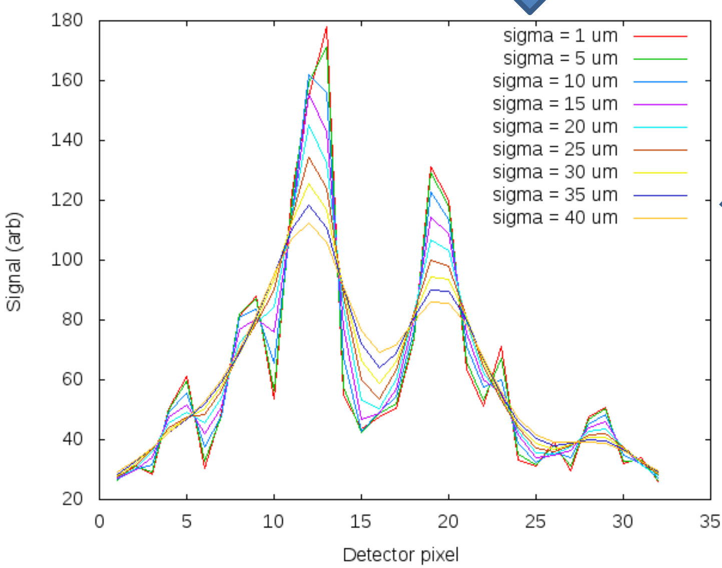


CA mask
(Applied Nanotools)
0.5 μm Au mask
2.5 μ Si substrate

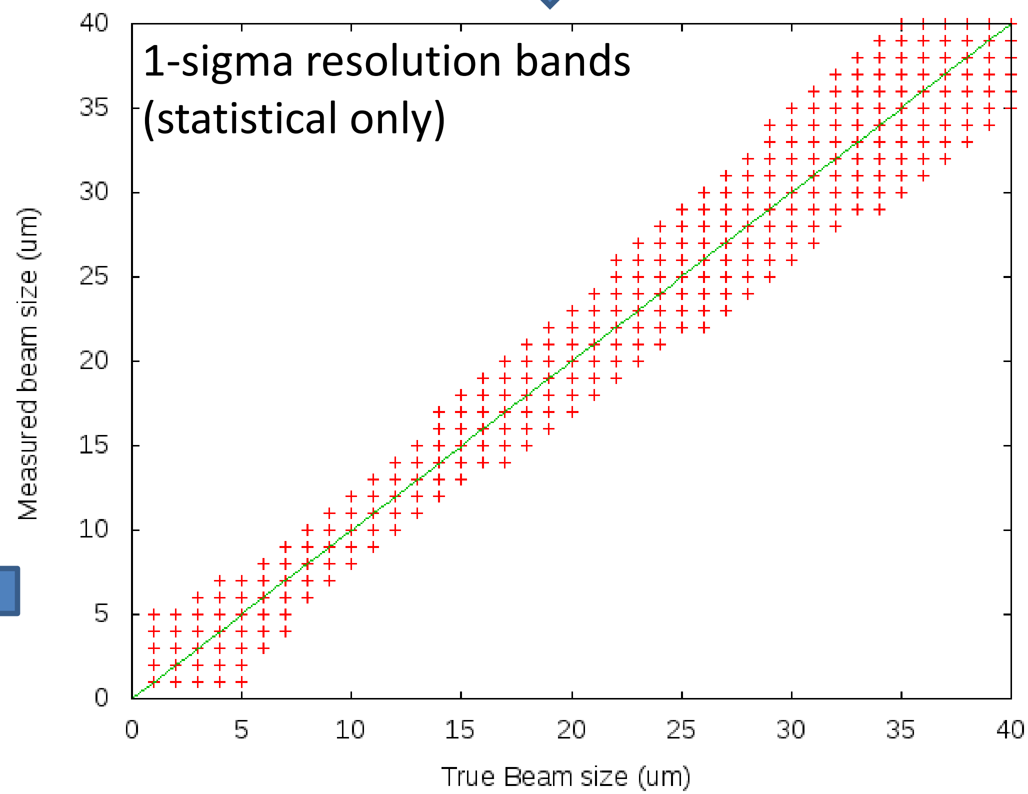
10 μm, 31-element CA mask @ D Line 2 GeV

Generate detector images for various beam sizes:





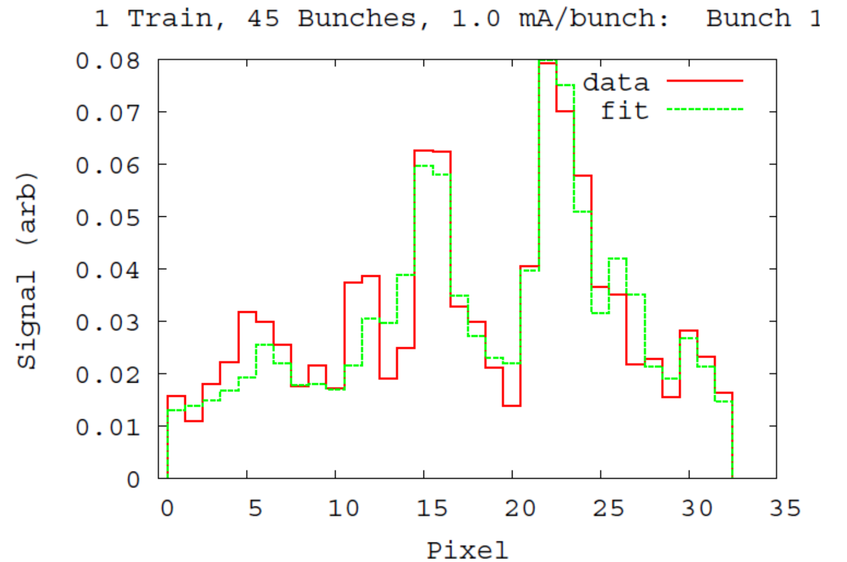
Cross-fit between beam sizes.
Plot 1-sigma statistical confidence regions,
Assuming 200 photons/pixel average
(=> 0.56 mA at 2 GeV):



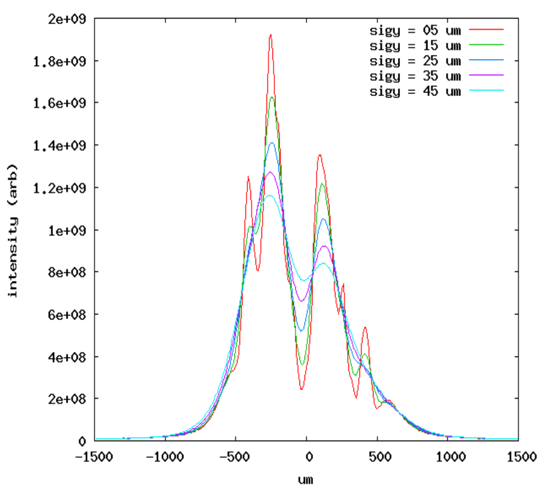
Statistical single-shot resolution at 10 μm beam size = +/- ~2 μm
(Assuming ideal detector.)

Data Analysis

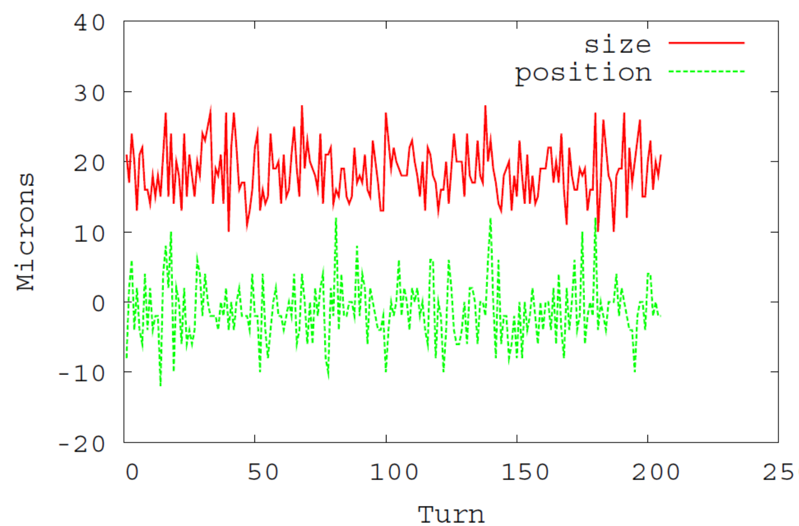
- 1) Simulate point response functions (PRFs) from various source positions to detector, taking into account beam spectrum, attenuations and phase shifts of mask and beamline materials, and detector response.
- 2) Add PRFs, weighted to possible proposed beam distributions.
- 3) Find best fit to detector data.



Example of single-shot data (single-bunch, single-turn)



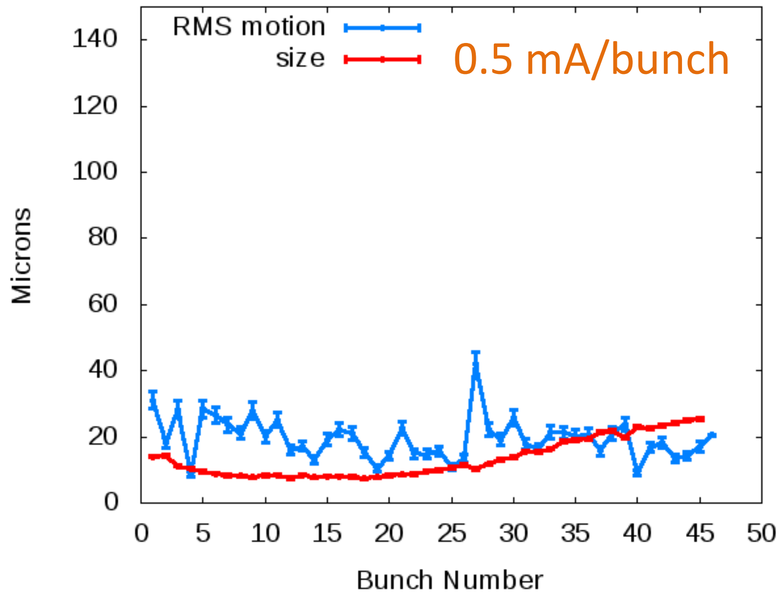
Simulated detector image for various beam sizes at CesrTA

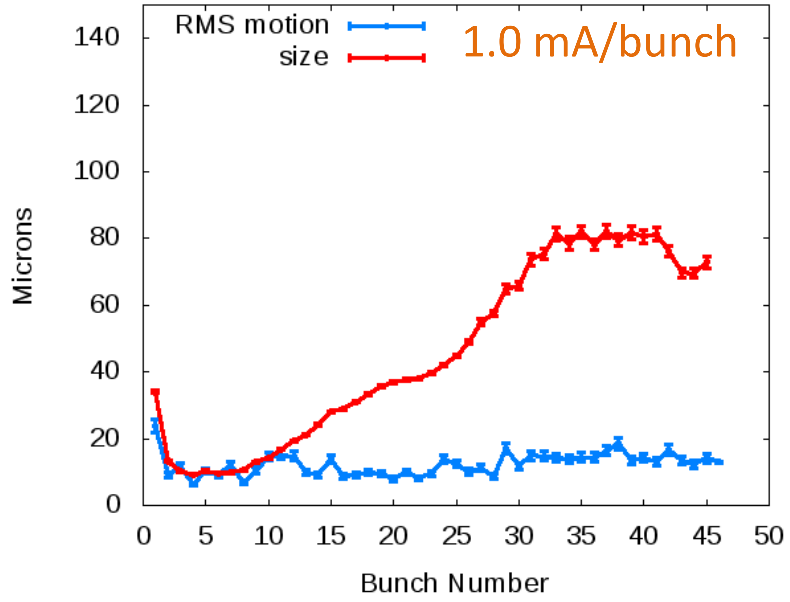


Example of turn-by-turn data (one bunch out of train)

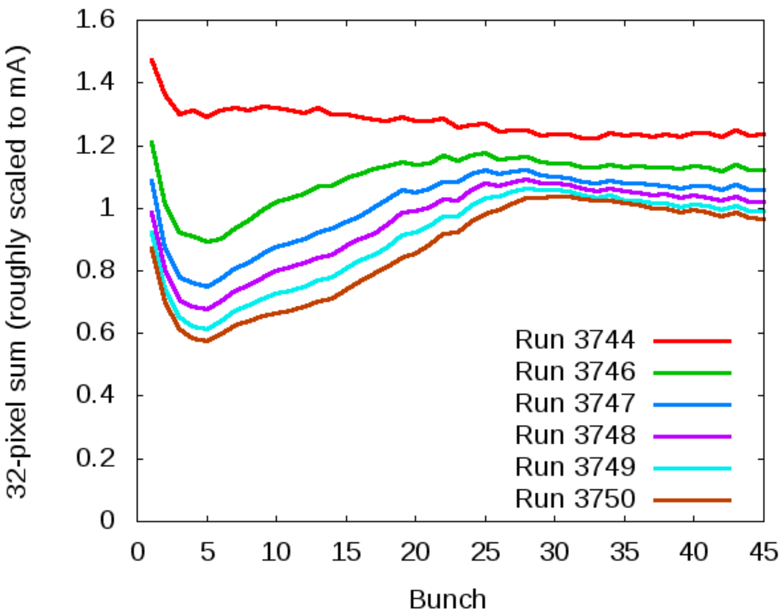
Electron-cloud study data

- Study of effect of electron clouds on beam size.
- As cloud density increases along train, size of bunch increases due to presence of clouds.
- We can use this range of sizes to compare with resolution estimates.
  - Compare spread of sizes at each bunch with calculated resolution confidence intervals





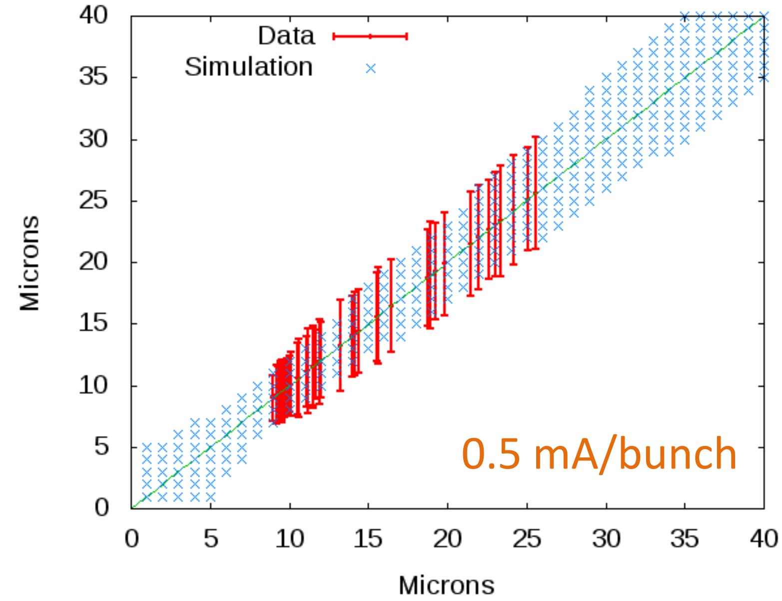
X-ray signal heights (“X-ray Bunch Current Monitor”)

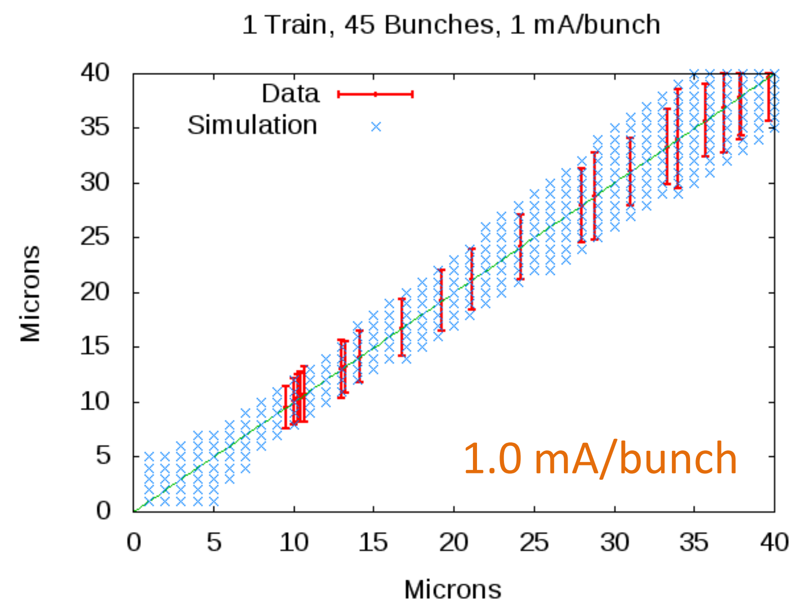


- Bunch currents along train for successive runs (~5 minutes apart)
- Initially 1.3 mA/bunch
- Lifetime pattern resembles measured sizes.
  - Minimum at ~ bunch 4
  - Maximum at ~bunch 30
  - First bunch blow-up
    - Residual cloud
    - Feedback tuning
      - Still under study

Resolution data vs simulation: CA

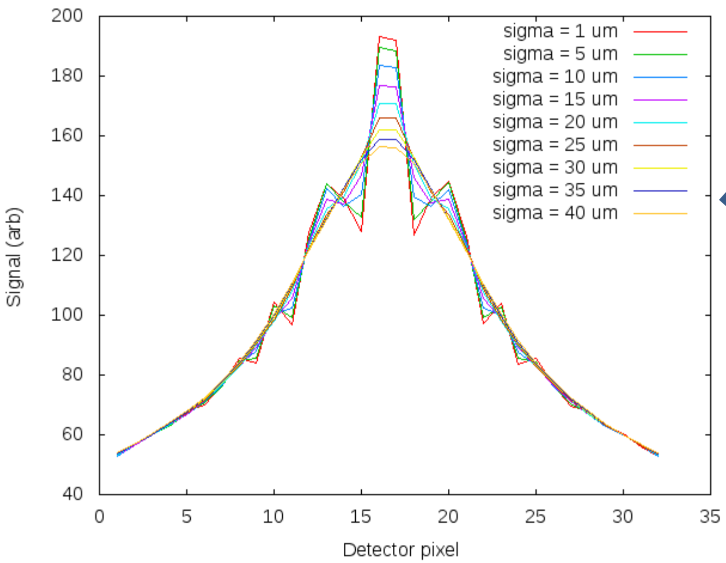
- Using May 10 2010 E-Cloud study data as data source.
- Simulation statistical confidence bands assume
  - Perfect, noiseless detector
  - 200 photons/pixel/shot on average
    - =>0.56 mA/bunch
- Shot-by-shot spread in data is between that at 0.5 mA and 1.0 mA in the data
  - Not using a perfect, noiseless detector.
- Seems reasonable agreement



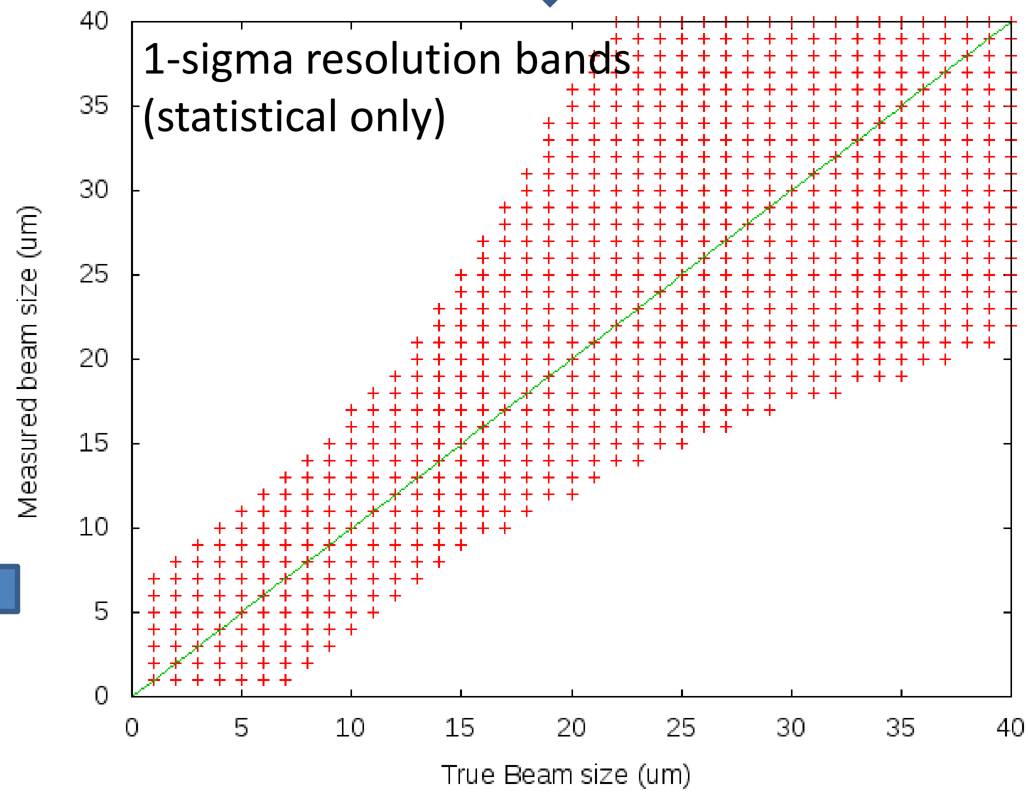


Fresnel Zone Plate@ D Line 2 GeV

Operated without monochromator



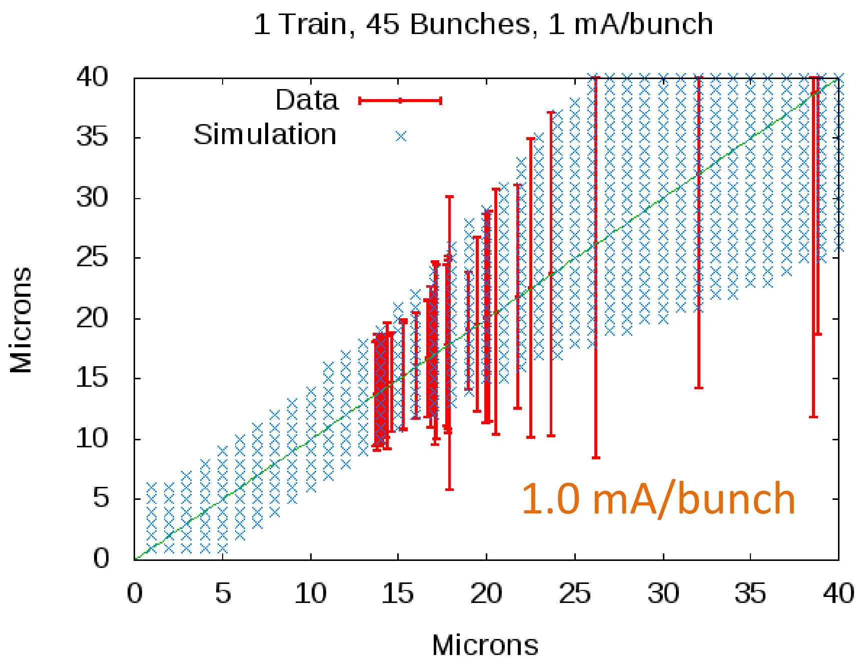
Cross-fit between beam sizes.
Plot 1-sigma statistical confidence regions,
Assuming 200 photons/pixel average
(=> 0.56 mA at 2 GeV):



Statistical single-shot resolution at 10 μm beam size = +/- ~6.5 μm
(Assuming ideal detector.)

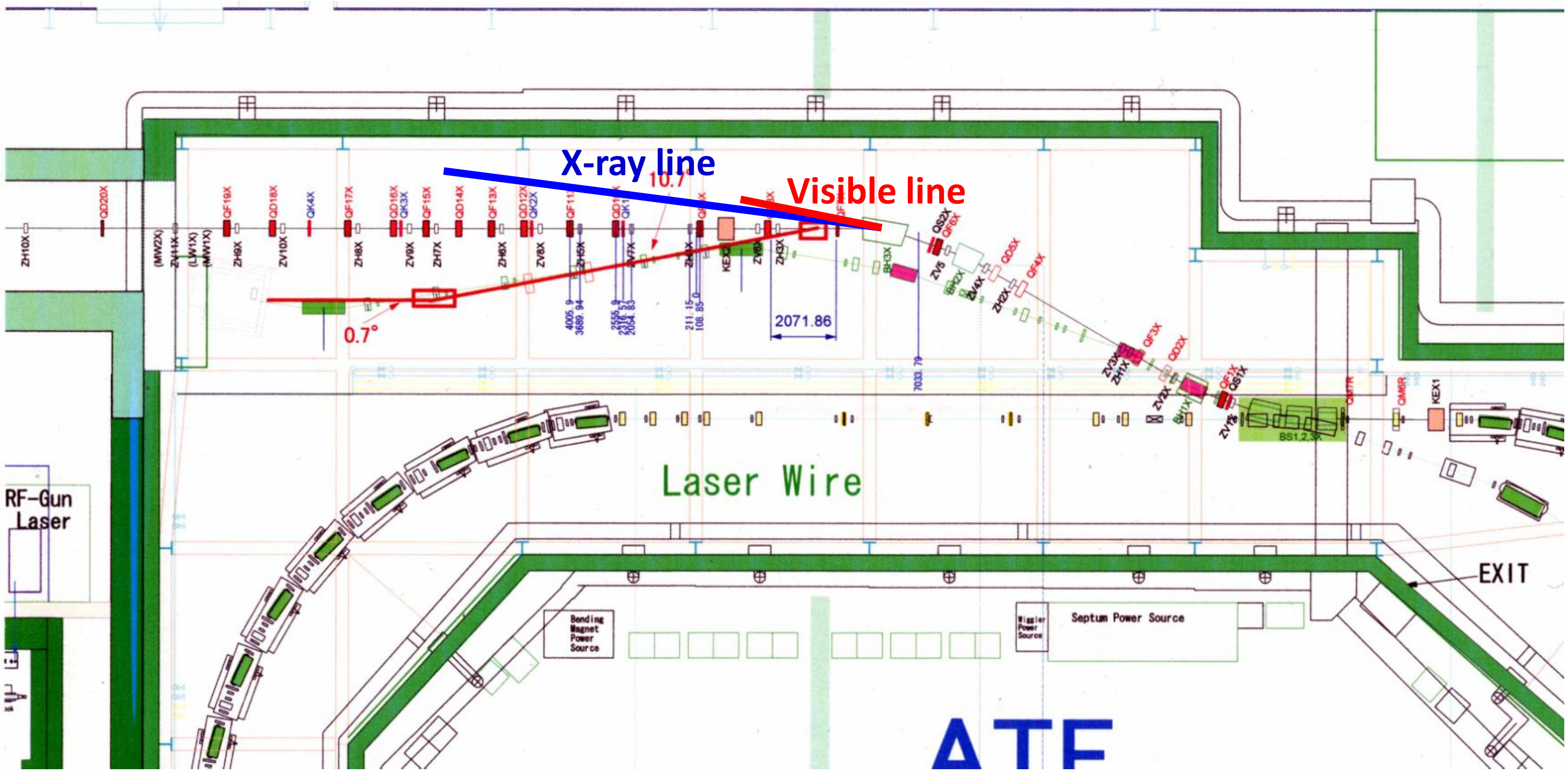
Resolution data vs simulation: FZP

- Using May 10 2010 E-Cloud study data as data source.
- Simulation statistical confidence bands assume
  - Perfect, noiseless detector
  - 200 photons/pixel/shot on average
    - =>0.56 mA/bunch
- Not so good agreement above ~18 um:
  - Actual spread larger than simulation.
  - Due to band of low misfits?



Resolution estimates at ATF2

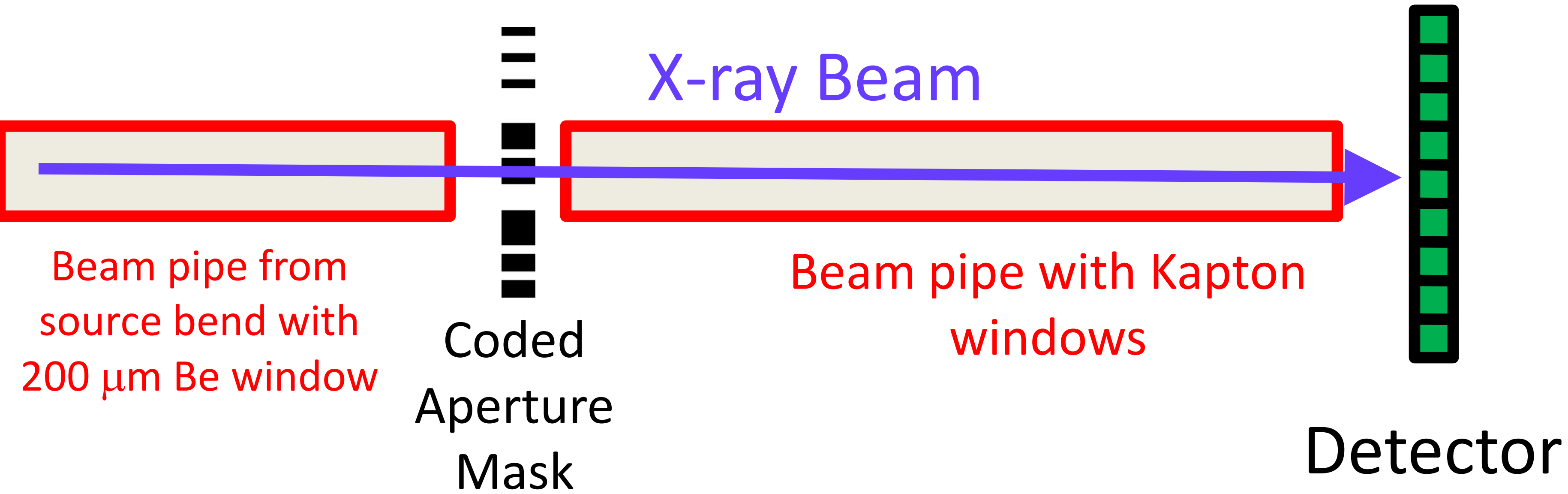
Source of SR: BH3X



T. Mitsuhashi

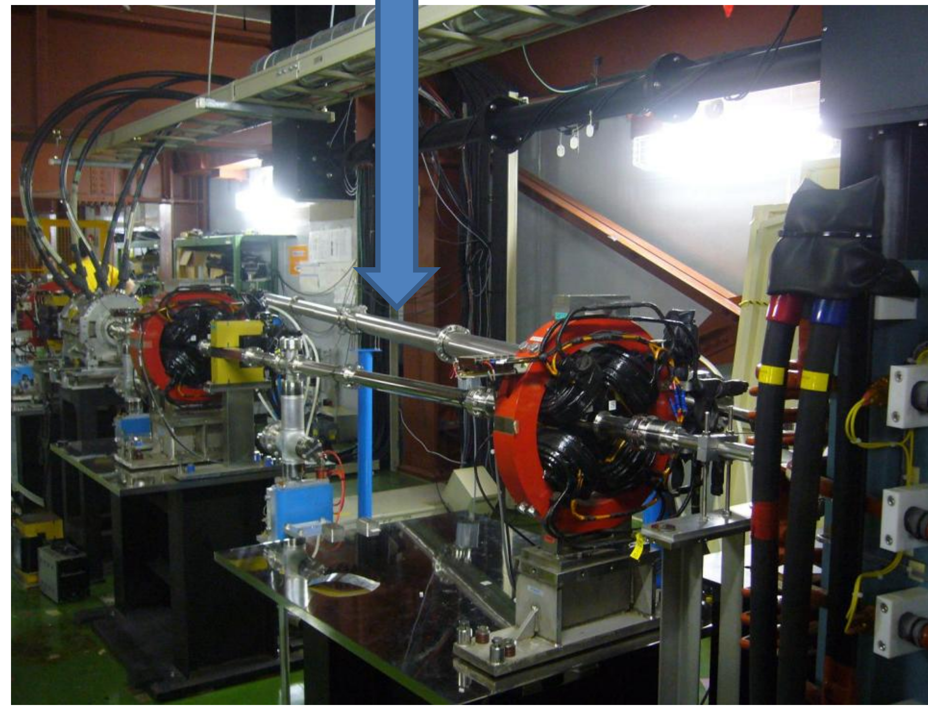
ATF2 Beamline

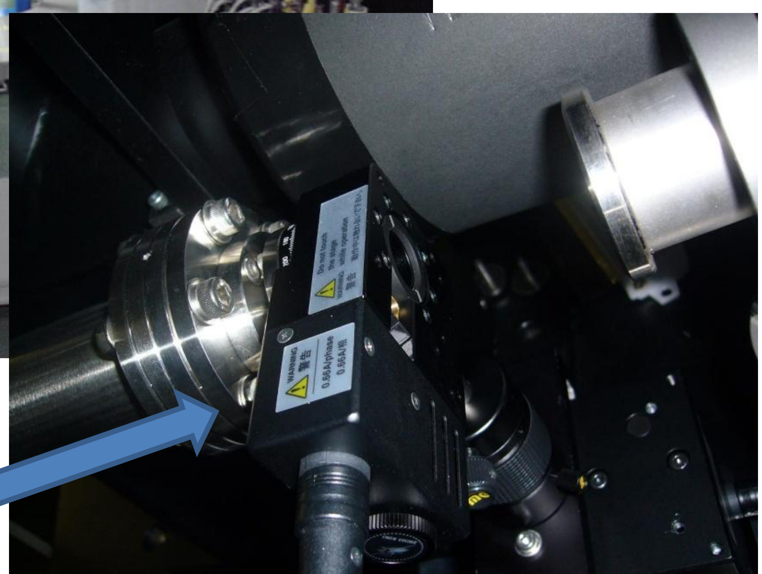
- Extract x-rays from BH3X bend
  - Energy 1.3 Gev, bending radius 4.3 m
  - Critical energy: 1.12 keV
  - 1.5 m from source to CA mask, 9 m from mask to detector
  - Mask:
    - 10 μm 31-element (same as CesrTA)
    - 5 μm 47-element (4 um Ta on ~2 um Ru/SiN/SiC membrane (NTT-AT))
  - Detector: 64-pixel Fermionics InGaAs array
  - Predicted flux at detector: ~250 photons/nC/bunch/50-um pixel



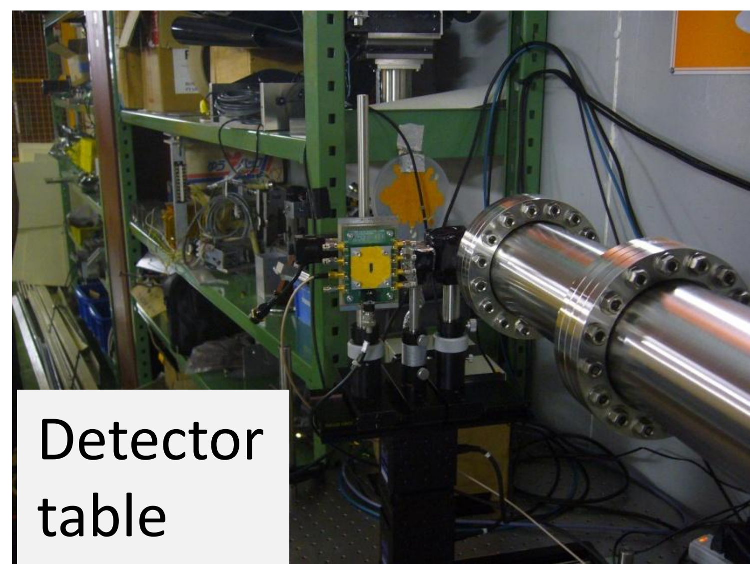
ATF2 x-ray beamline

Under construction





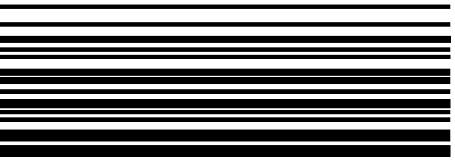
Rotating mask holder

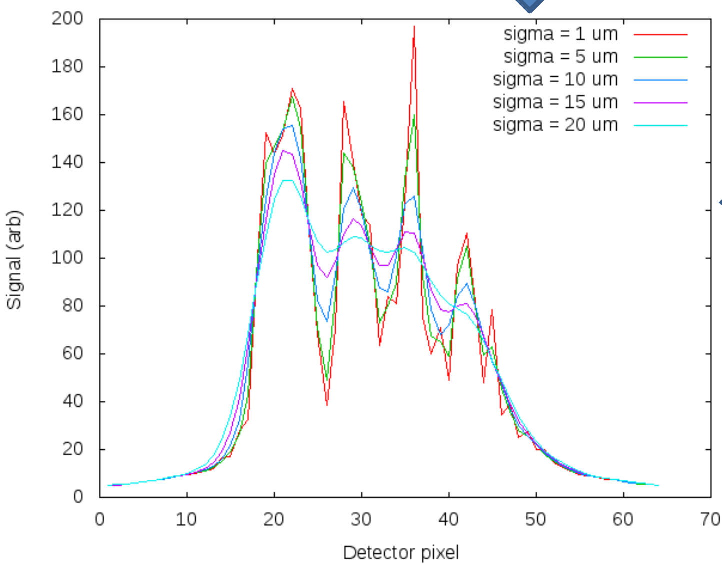


Detector table

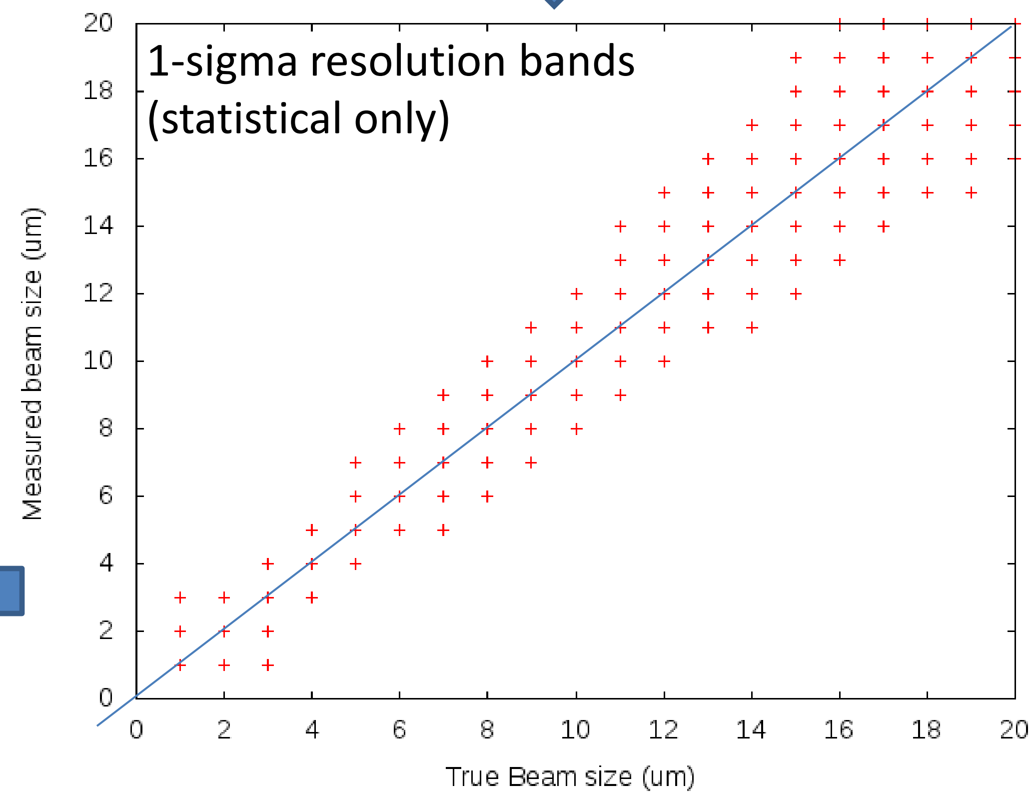
47-element, 5 μm/element URA mask @ ATF2

Generate detector images for various beam sizes:





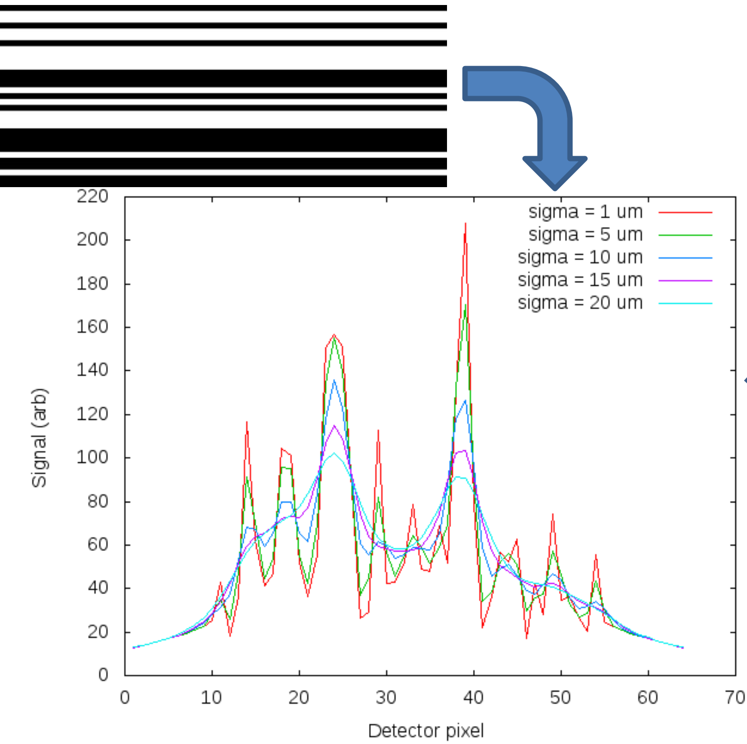
Cross-fit between beam sizes.
Plot 1-sigma statistical confidence regions,
Assuming 200 photons/pixel (average):



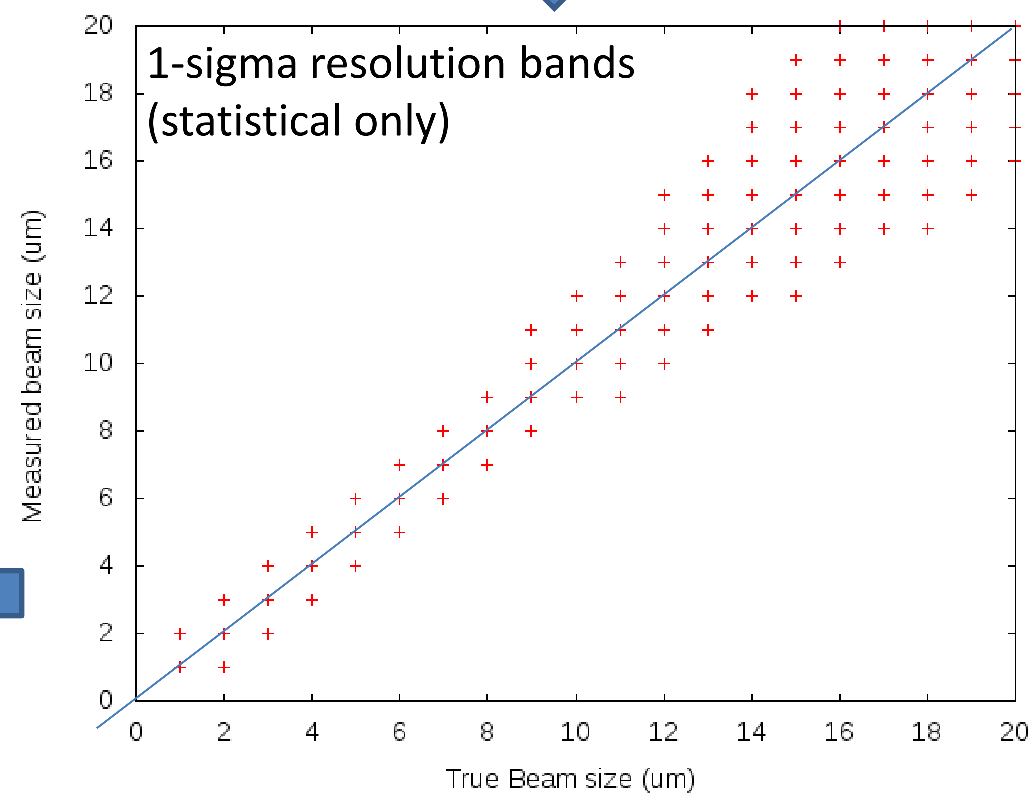
Statistical single-shot resolution at 4 μm beam size = +/- ~1 μm
(Assuming ideal detector.)

31-element, 10 μm/element URA mask @ ATF2

Generate detector images for various beam sizes:

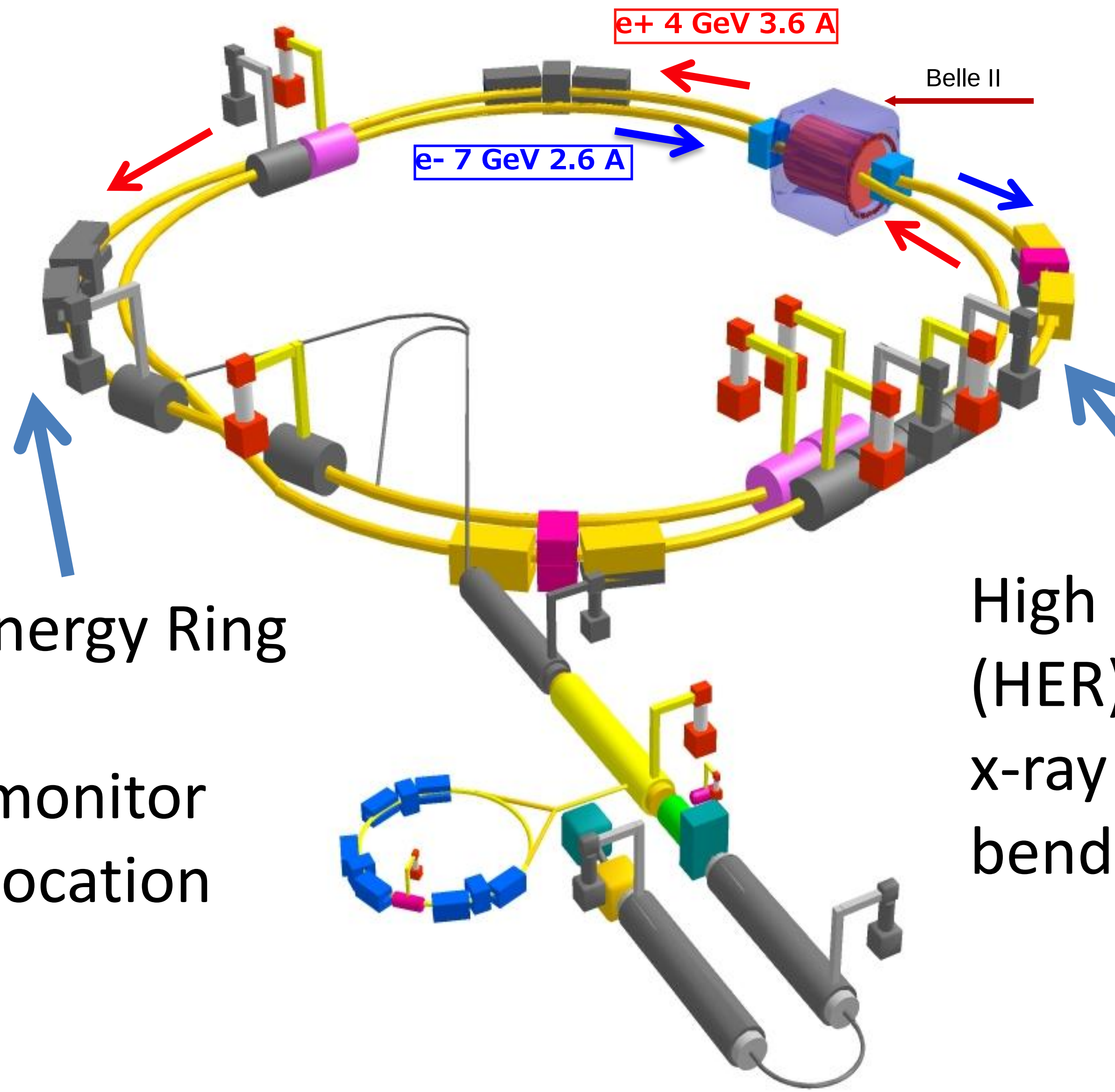


Cross-fit between beam sizes.
Plot 1-sigma statistical confidence regions,
Assuming 200 photons/pixel (average):



Statistical single-shot resolution at 4 μm beam size = +/- ~1 μm
(Assuming ideal detector.)

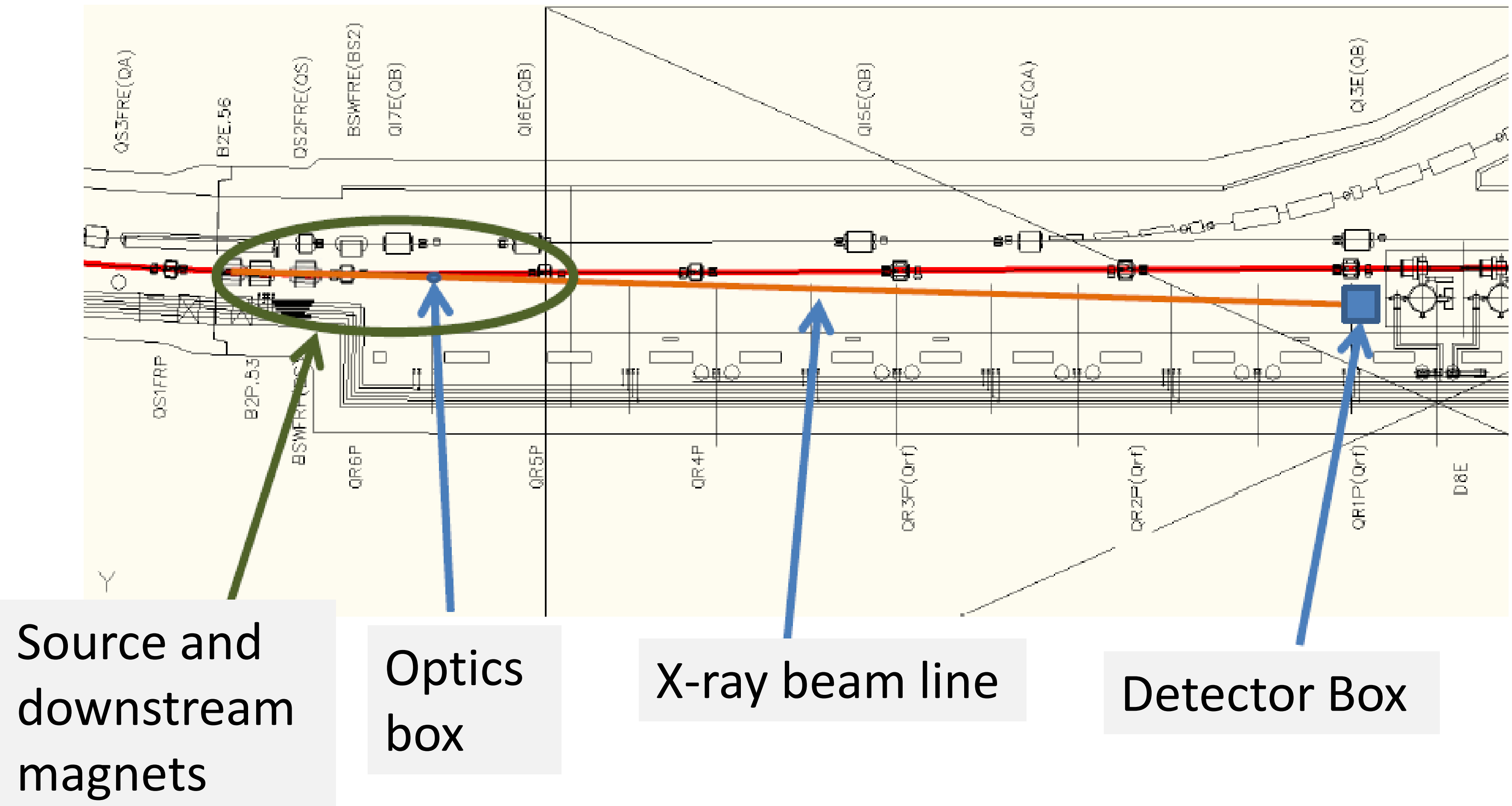
Resolution estimates: SuperKEKB



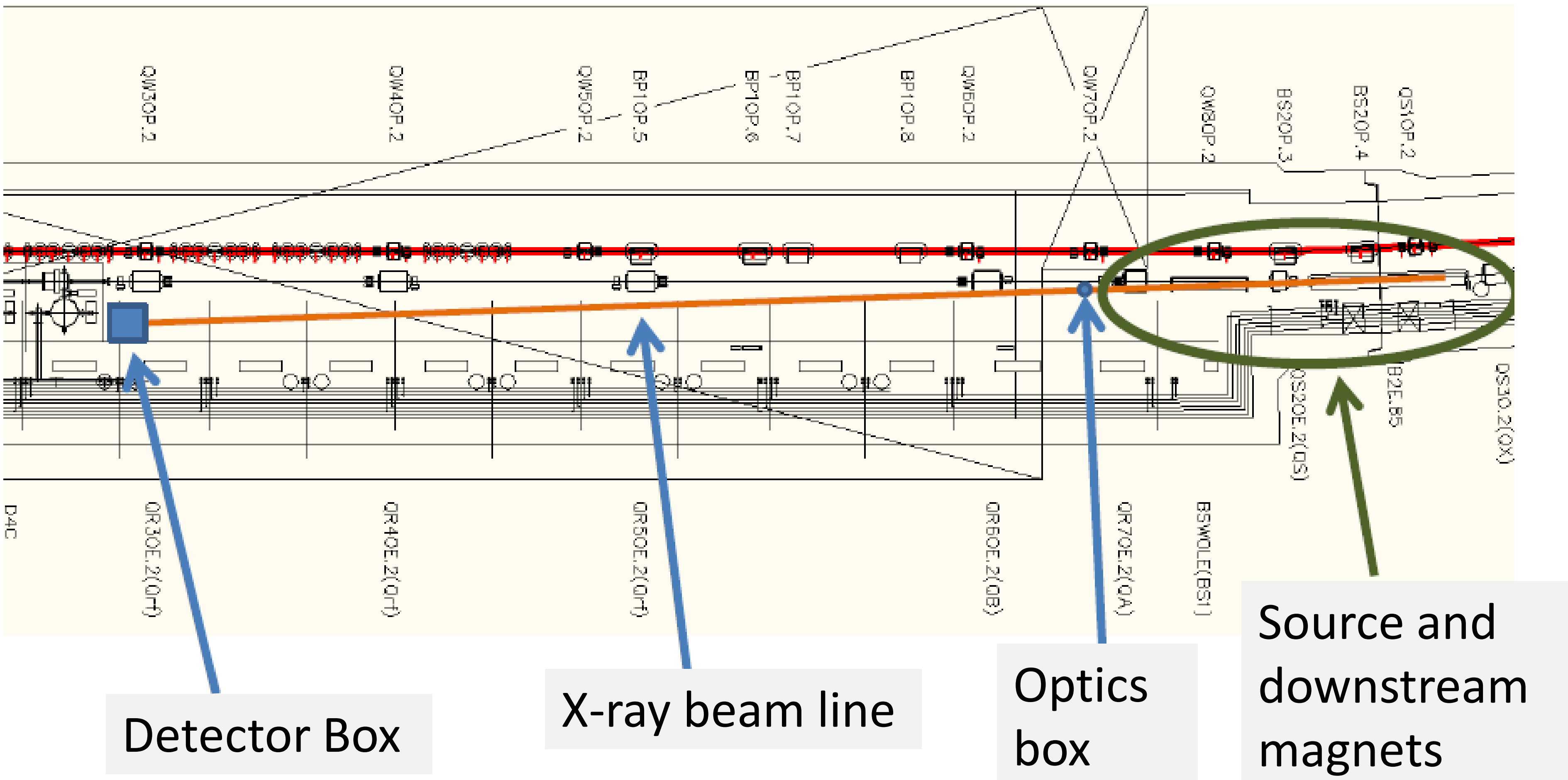
Low Energy Ring (LER)
x-ray monitor bend location

High Energy Ring (HER)
x-ray monitor bend location

LER X-ray beam line



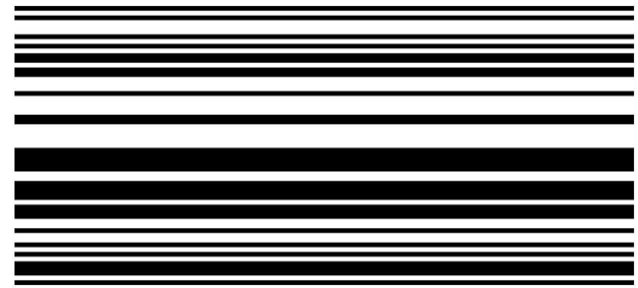
SuperKEKB HER X-ray beam



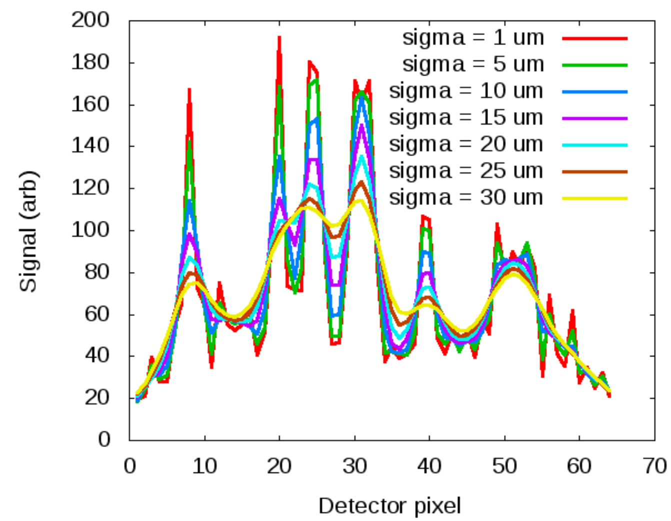
SuperKEKB x-ray monitor

Xray Source Bend Par.	S-LER (BS2FRP.1)	S-HER (BS2E.82)	Units
ε_x	3.20E-09	4.30E-09	m
κ	0.27%	0.24%	
ε_y	8.64E-12	1.03E-11	m
β_y	50.0	11.5	m
σ_y	20.8	10.9	μm
Beam Energy	4	7	GeV
Effective length	0.89	5.9	m
Bend angle	28.0	55.7	mrad
ρ	31.7	105.9	m
Critical Energy	4.4	7.1	keV

- Mask:
  - 59-element, 10 μm/element URA
  - High-power design
    - 10 μm Au mask
    - 625 μm Si substrate
    - Test at CesrTA
  - Other patterns, materials under study
- Detector:
  - 64-channel, 50 μm pitch



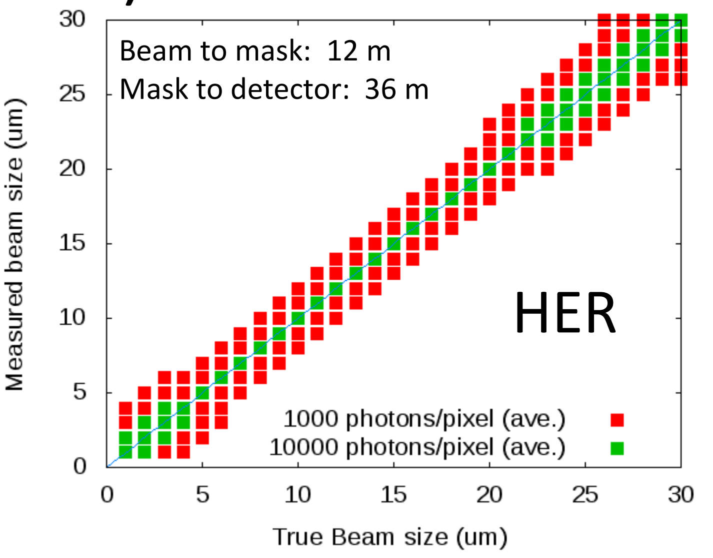
Uniformly Redundant Array (URA) for x-ray imaging to be used at SuperKEKB

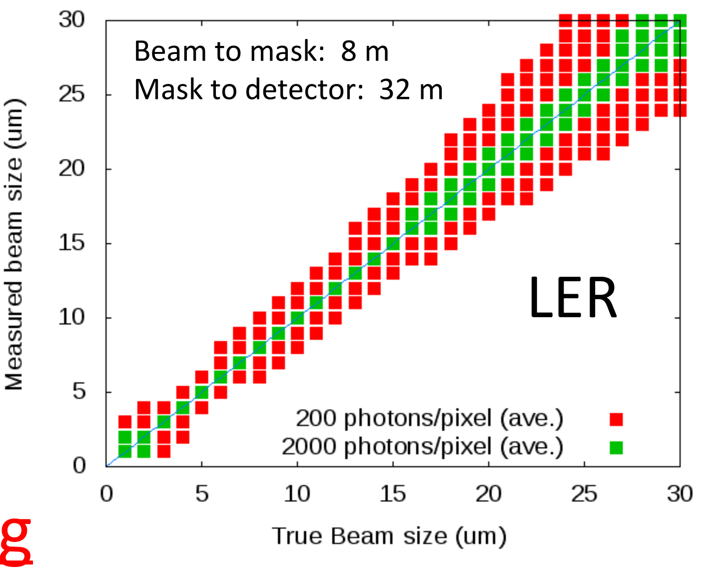


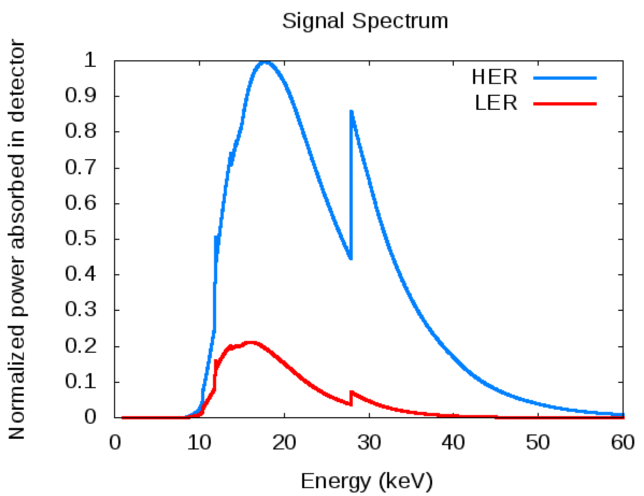
Simulated detector response for various beam sizes at SuperKEKB LER

SuperKEKB Estimated single-shot resolutions (SuperKEKB full current)

- Red points: using 64-pixel detector of same type as at CesrTA
- Green points: using detector with improved photon detection efficiency at higher x-ray energies (not yet developed)







Detected spectrum (Fermionics detector)

Looks promising

Future plans

- Studies continuing at CesrTA
- Studies at ATF2 beamline (from Fall 2011)
- Construction of SuperKEKB beam lines
- Other topics to be pursued:
  - Absolute calibration checks at CesrTA (June 2011)
  - Reconstruction methods for best recovering full profile information
  - Development of detector and read-out systems for SuperKEKB, with improved photon detection efficiency at the higher energy photons that will be generated there.

Summary

- Estimates of the size-dependent statistical resolution of a coded aperture mask have been compared with data.
- The measured confidence intervals are, as expected, a bit larger than would be explained purely by photon statistics, but the spreads seem to be in reasonable agreement with the calculated resolutions as a function of beam size.
- The same estimation procedure has been applied to the ATF2 and SuperKEKB.
  - Looks promising