Calibration of the X-ray Monitor During the Phase I of SuperKEKB Commissioning

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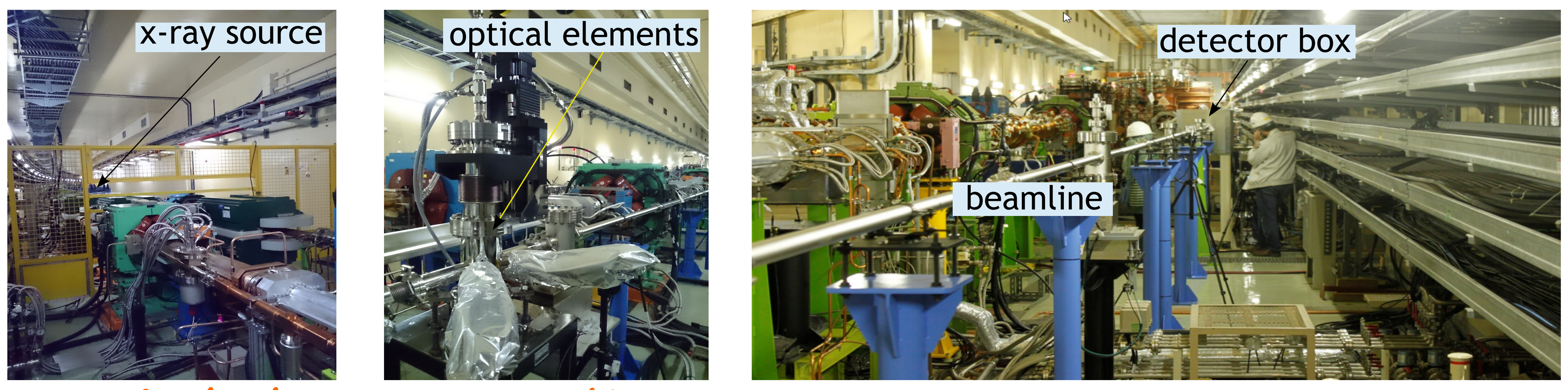
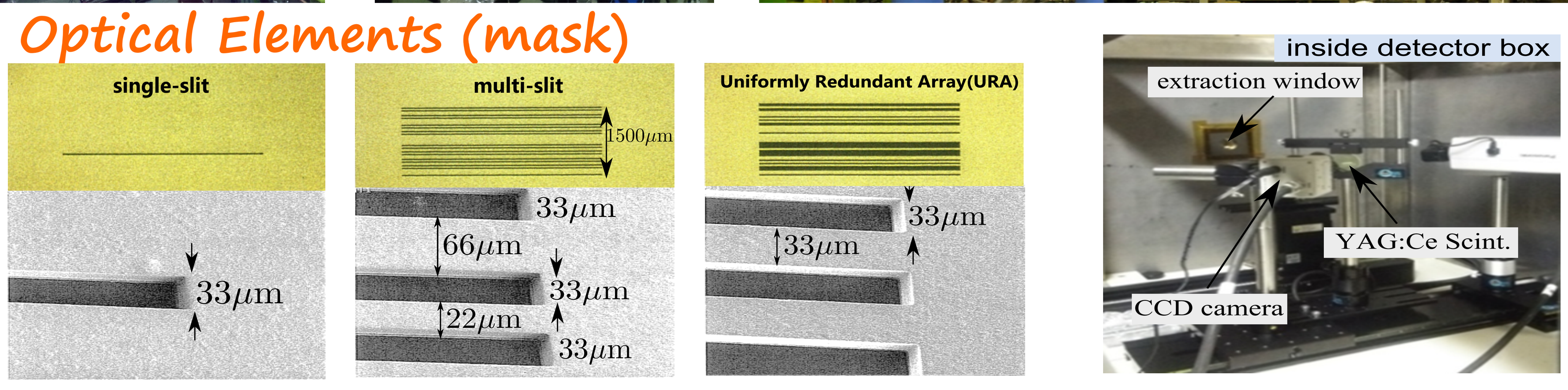
ABSTRACT

X-ray monitors (XRM) have been installed in each SuperKEKB ring, the Low Energy Ring (LER) and High Energy Ring (HER), primarily for vertical beam size measurement. Both rings have been commissioned in Phase I of SuperKEKB operation (February-June 2016), and several XRM calibration studies have been carried out. The geometrical scale factors seems to be well understood for both LER and HER. The emittance knob ratio method yielded results consistent with expectations based on the machine model optics (vertical emittance ϵ_y is $\approx 8\,\mathrm{pm}$) for the LER. For the HER, the vertical emittance ϵ_y is $\approx 41\,\mathrm{pm}$, which is $4\times$ greater than the optics model expectation. Analysis of beam size and lifetime measurements suggests unexpectedly large point response functions, particularly in the HER.

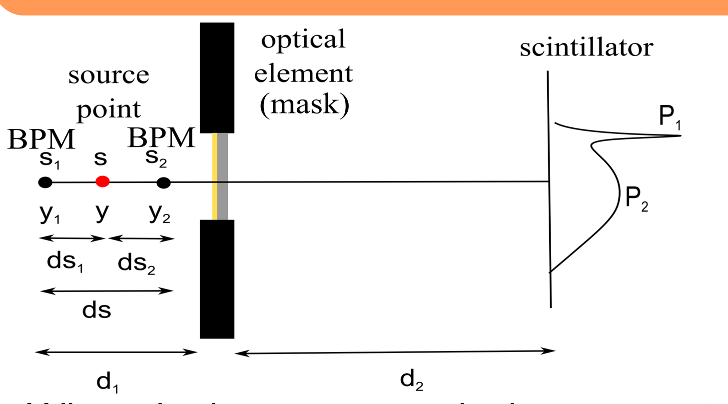
XRM HARDWARE



Optical Elements (mask)



GEOMETRICAL SCALE FACTORS CHECK



The geometrical scale factors based on beam-based measurement are measured by moving either the beam or optical elements (single slit and coded apertures), observing how the peak features (P_1)move then calculating the ratio of geometric magnification (M) and scintillator camera scale (m).

When the beam is moved, the ratio M/m is determined by fitting Eq:

$$P_1 = \Big(-\frac{M}{m}(1-\frac{ds_1}{ds})\Big)y_1 - \frac{M}{m}\frac{ds_1}{ds}y_2 + \alpha$$

where P_1 is the position (in pixels) of a peak feature from x-rays that passed through a slit onto the scintillator

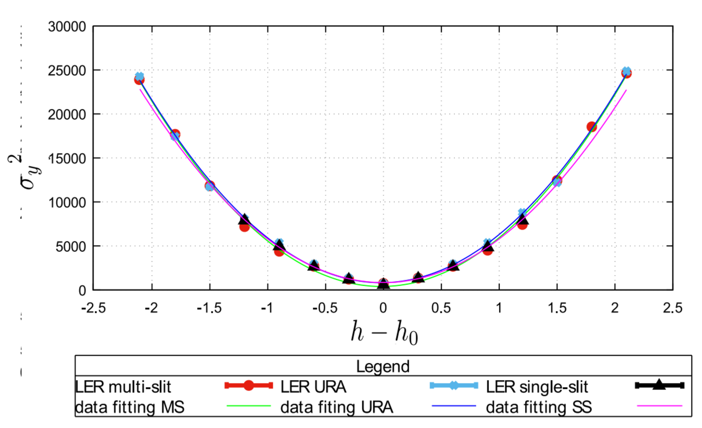
Parameters		
LER (Tape Measurement)		
M/m	(pixels/mm)	$66.2 \pm 0.2 (0.3\,\%)$
(M+1)/m	(pixels/mm)	$85.5 \pm 0.2 (0.2\,\%)$
LER (Beam-Based Measurement)		
M/m	(pixels/mm)	$69.5 \pm 0.5 (0.7\,\%)$
(M+1)/m	(pixels/mm)	$86.0 \pm 0.6 (0.65\,\%)$
HER (Tape Measurement)		
M/m	(pixels/mm)	$60.9 \pm 0.2 (0.3\,\%)$
(M+1)/m	(pixels/mm)	$80.0 \pm 0.2 (0.2\,\%)$
HER (Beam-Based Measurement)		
M/m	(pixels/mm)	$59.2 \pm 0.5 (0.9\,\%)$
(M+1)/m	(pixels/mm)	$79.3 \pm 0.1 (0.13\,\%)$

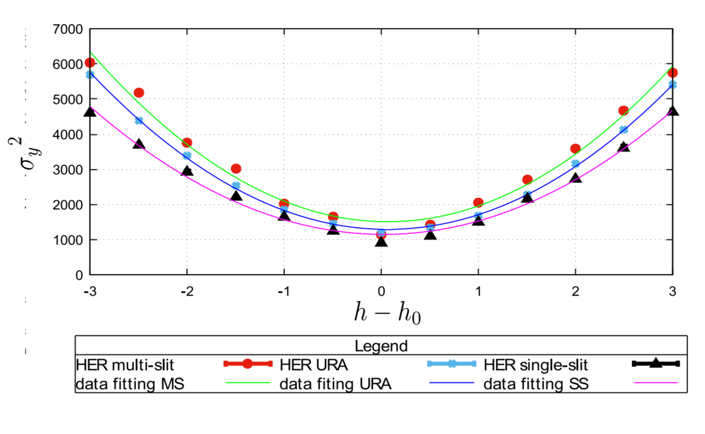
The parameter α represents the offset between beam and detector coordinate systems. When the mask is moved, the ratio $(M+1)/m$ is determined by fitting Eq:

$$P_1 = \frac{M+1}{m}y_{mask} + \alpha$$

Geometric magnification factors agree well between tape measurements and beam-based measurements at both lines.

EMITTANCE CONTROL KNOB





Mask	σ_{y0} μm	Cal. factor (c)
LER		
single-slit	$28.34 \pm 1.12 (3.9\,\%)$	$1.03 \pm 0.01 (1.0\,\%)$
multi-slit	$19.08 \pm 4.27 (22.4\,\%)$	$1.07 \pm 0.01 (0.9\,\%)$
URA	$27.38 \pm 2.79 (10.2\,\%)$	$1.06 \pm 0.01 (0.9\,\%)$
HER		
single-slit	$30.86 \pm 1.11\ (3.6\,\%)$	$1.09 \pm 0.02 (1.8\,\%)$
multi-slit	$31.09 \pm 1.54 (4.9\,\%)$	$1.25 \pm 0.03 (2.4\,\%)$
URA	$29.88 \pm 0.47 (1.6\,\%)$	$1.20 \pm 0.01 (0.8\,\%)$

The emittance control knob ratio method measures the overall scaling factor between the reported beam size measurements and the true beam size. The variation of the vertical beam size by changing the bump height can be represented as:

$$(\sigma_y^{meas})^2 = (c\sigma_{y0})^2 + (cA)^2(h-h_0)^2$$

with correlation between beam size σ_y, emittance ϵ_y and beta function β as:

$$\sigma_y = \sqrt{\epsilon_y \beta}$$

where σ_{y0} and σ_y^{meas} are the true vertical beam size and the beam size measured by the XRM. The parameters h and h_0 are the bump height and its offset, c is the calibration (scaling) factor and A is a linear coefficient where $A^2 = \Delta\epsilon_y \times \beta_y$, and $\Delta\epsilon_y$ is the expected change in emittance for a unit change in bump height.

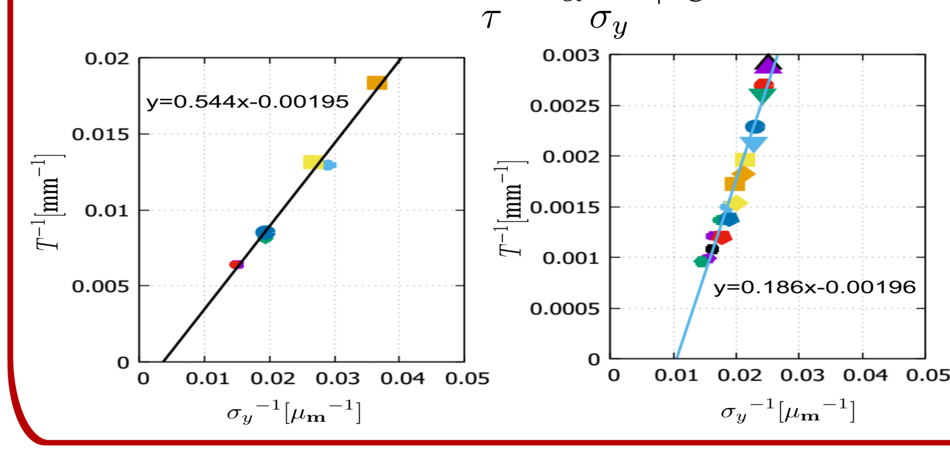
The value for the LER is close to the design value ($\approx$ 10 pm), but is much higher than design for the HER. To investigate this discrepancy, a study of smearing factors (point spread functions) was made using beam lifetime data.

LIFETIME STUDIES

The beam lifetime was also recorded during the emittance control knob studies. A bunch of charged particles (electrons/positrons) in a ring decay due to a variety of mechanisms: quantum lifetime, Coulomb scattering, Bremsstrahlung and the Touschek effect. None of these mechanisms is related to the beam size except for the Touschek effect. The Touschek lifetime is related to the beam size as shown in Eq:

$$\frac{1}{\tau} = \frac{1}{\tau_{tk}} + \frac{1}{\tau_{qu}} + \frac{1}{\tau_{cs}} + \frac{1}{\tau_{bs}}, \qquad \frac{1}{\tau} = \frac{r_e^2 cQ}{8\pi e \sigma_y \sigma_x \sigma_z}\frac{\lambda^3}{\gamma^2}D(\epsilon) + C$$

where τ is the total lifetime, τ_{tk} is the Touschek lifetime, $D(\epsilon)$ is the Touschek lifetime function (approximately constant for small ϵ), τ_{qu}, τ_{cs} and τ_{bs} are the quantum, coulomb and bremsstrahlung scattering lifetimes, respectively (written as a constant parameter C). In this analysis, we only change the σ_y and the other parameters are constant, giving the simplified equation shown in Eq: $\frac{1}{\tau} = \alpha\frac{1}{\sigma_y} + C$



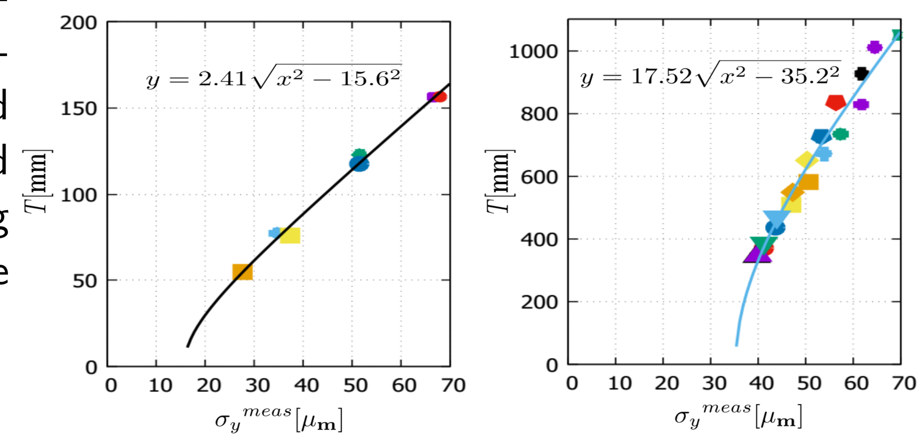
The non-positive value of C indicates that the lifetime is heavily dominated by the Touschek lifetime, and further suggests the presence of a positive asymptote in the beam size.

Smearing Factors

If a beam of initial size σ_{y0} is convolved with a Gaussian smearing function of size σ_s to make a measured beam size σ_y^{meas}, then the measured beam size can be represented by adding the real beam size and the smearing size in quadrature as shown in Eq:

$$\sigma_y^{meas} = \sqrt{(\sigma_{y0})^2 + (\sigma_s)^2}$$

$$\sigma_{y0} = \sqrt{(\sigma_y^{meas})^2 - (\sigma_s)^2}$$



If we consider just the Toushek effect then the correlation between τ and σ_y^{meas} becomes:

$$\tau = \alpha\sigma_{y0} = \alpha\sqrt{(\sigma_y^{meas})^2 - (\sigma_s)^2}$$

Parameter	LER	HER
Smearing size (σ_s)	12.1 ± 2.1 μm	32.8 ± 0.4 μm
Minimum vertical beam size (σ_{y0})	23.5 ± 0.3 μm	17.8 ± 0.8 μm
Minimum vertical emittance (ϵ_y)	$\approx 8\,\mathrm{pm}$	$\approx 41\,\mathrm{pm}$

The smearing function for the HER is much larger than that for the LER. Also, even after accounting for this smearing function, the HER emittance is about 4 times larger than the design value.

SYSTEMATIC RESOLUTION

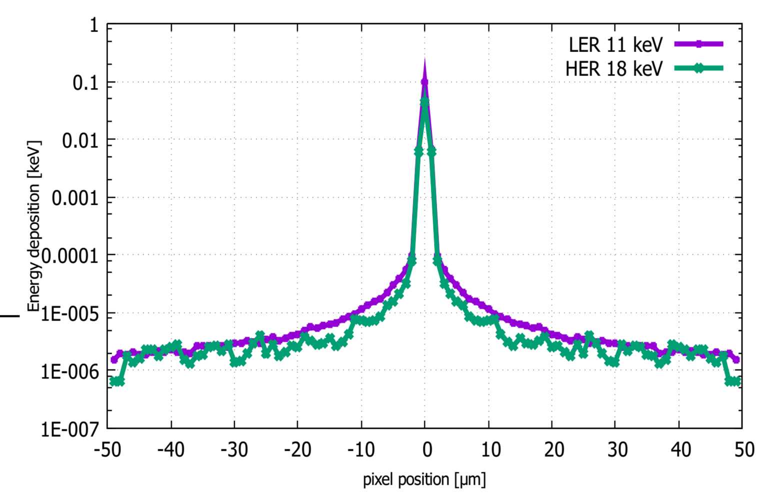
Based on the above discussion, there are smearing factors for both rings that need to be understood. Regarding the detector, there are some parameters that will affect the spatial resolution: defect of focus, diffraction effect and spherical aberration. If R_f is the spatial resolution, dz is the depth of the scintillator 141μm), NA is the numerical aperture of the camera (0.03132), M is the magnification of the XRM (3.2) and λ is the wavelength of visible light from scintillator ($550\,\mathrm{nm}$).

$$R_f = \frac{dzNA}{M} + \frac{\lambda}{MNA} + \frac{dz(NA)^2}{M}$$

The effects contribute ≈ 5 μm of smearing as expressed at the source point

EGS5 code was used to determine the effect of scattering anywhere in the beam line or detector on the point spread function of the imaging system.

The EGS5 calculation result shows that the scattered background falls off by an order of magnitude within 1 μm. Altogether, contributions for sources of point spread in the XRM of ≈ 6 μm as expressed at the source point.



This is insufficient to account for the observed smearing according to the lifetime studies. Other possible sources of smearing or resolution loss might be beam tilt or motion, camera misfocus or some source of scattering not simulated by EGS5, such as impurities or inhomogeneities in the Be filters.

CONCLUSION

The geometrical magnification factors seem to be well understood for both LER and HER. The overall performance is reasonable for the LER, and yielded results consistent with expectations based on the optics estimation with $\approx 8\,\mathrm{pm}$ of vertical emittance (ϵ_y). For the HER, the vertical emittance ϵ_y is $\approx 41\,\mathrm{pm}$ which is $4\times$ higher than the optics estimation. In addition, some smearing is observed, not all of which is fully accounted for yet. For our future plan, we plan to study possible sources of smearing either at the x-ray source point or in the beamline.

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2. E. Mulyani, and J.W. Flanagan, *"Design of Coded Aperture Optical Elements for SuperKEKB X-ray Beam Size Monitors"*, in Proc. of IBIC2015, Melbourne, paper TUPB025, pp. 377-380.
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5. *The EGS5 Code System*, http://rcwww.kek.jp/research/egs egs5 manual slac730-130308.pdf.