SuperKEKB Lattice and Dynamic Aperture

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KEKB Machine Advisory Committee
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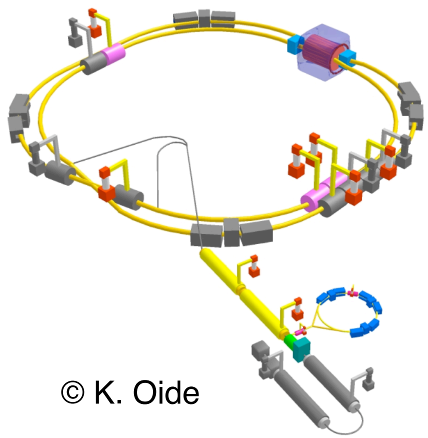


Introduction

- Concept of lattice design in Super KEKB is the same as the KEKB lattice.
- Non-interleaved sextupole scheme is successfully working in KEKB.
  - Chromaticity correction with reducing nonlinearities
  - Sextupole bumps are used for optics corrections.
- Lattice of interaction region(IR) is different from KEKB.
  - Very small beta function at IP (β_x^*/β_y^* = 20 cm /3 mm)
  - Finite crossing angle is 30 mrad.
- Half of wigglers are replaced with RF cavities in LER.
  - Damping time becomes longer. (43 msec→~56 msec)
- We need to check lattice performance of SuperKEKB.
  - Tracking simulations includes machine errors and optics correction
  - Dynamic aperture (injection, lifetime)

Machine parameters of SuperKEKB

	Symbol	LER	HER	Unit
Luminosity	L	2.5×10^{35}		$cm^{-2}s^{-1}$
Energy	E	3.5	8.0	GeV
Beam current	I	9.4	4.1	A
No. bunches	n_B	5018		
Emittance	ε_x	24		nm
Beta at IP	β_x^*	20		cm
	β_y^*	3		mm
Bunch length	σ_z	3		mm
Momentum compaction	α_p	3×10^{-4}		
RF voltage	V_c	14	23	MV
Betatron tune	ν_x	45.506	44.515	
	ν_y	43.545	41.580	
Synchrotron tune	ν_s	0.031	0.019	
Beam-Beam	ξ_y	0.14		
Crossing angle	θ	30→0 (crab crossing)		mrad

Lattice Parameters and Beam-Beam Effect

	Symbol	bare lattice	with beam-beam	unit
Beam current (LER/HER)	I	9.4/4.1		A
Beam energy (LER/HER)	E	3.5/8.0		GeV
Emittance	ε_x	24	77	nm
Horizontal beta at IP	β_x^*	20	4.5	cm
Vertical beta at IP	β_y^*	3	2.3	mm
Horizontal beam size	σ_x^*	69	59	μm
Vertical beam size	σ_y^*	0.7	1.4	μm
Beam size ratio	$r = \sigma_y^*/\sigma_x^*$	1	2.4	%
Crossing angle	θ_x	0	0	mrad
Luminosity reduction	R_L	0.86	0.81	
ξ_x reduction	$R_{\xi x}$	0.99	0.97	
ξ_y reduction	$R_{\xi y}$	1.11	1.17	
Reduction ratio	$R_L/R_{\xi y}$	0.78	0.70	
Horizontal beam-beam (estimated with S-S simulation)	ξ_x	0.08	0.05	
Vertical beam-beam (estimated with S-S simulation)	ξ_y	0.14	0.12	
Luminosity	L	2.5×10^{35}		$cm^{-2}s^{-1}$

Non-Interleaved 2.5π Sextupole Scheme (NISS)

- Emittance and momentum compaction factor can be adjusted independently.
  - 7 families of quadrupole in a cell. (4 for -I, 2 for emittance and momentum compaction factor, 1 for phase advance)
- Sextupole pair is connected by -I'.

$$-I' = \begin{pmatrix} -1 & 0 & 0 & 0 \\ m_{21} & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & m_{43} & -1 \end{pmatrix}$$

  - Chromaticity can be corrected with canceling nonlinearities in each sextupole pair.

-I' transformation with sextupole pair

$$\begin{pmatrix} x_{\beta 1} + \eta_{x1}\delta \\ x'_{\beta 1} + \eta'_{x1}\delta \\ y_{\beta 1} \\ y'_{\beta 1} \end{pmatrix} \xrightarrow{NISS} \begin{pmatrix} -x_{\beta 1} + \eta_{x1}\delta \\ m_{21}x_{\beta 1} - x'_{\beta 1} - \eta'_{x1}\delta + \frac{K_2^{(1)} - K_2^{(2)}}{2}\left(x_{\beta 1}^2 - y_{\beta 1}^2\right) + \left(K_2^{(1)} + K_2^{(2)}\right)\eta_{x1}\delta x_{\beta 1} \\ -y_{\beta 1} \\ m_{43}y_{\beta 1} - y'_{\beta 1} - \left(K_2^{(1)} - K_2^{(2)}\right)x_{\beta 1}y_{\beta 1} - \left(K_2^{(1)} + K_2^{(2)}\right)\eta_{x1}\delta y_{\beta 1} \end{pmatrix}$$

$K_2^{(1)} = K_2^{(2)}$

  - Large dynamic aperture is expected.

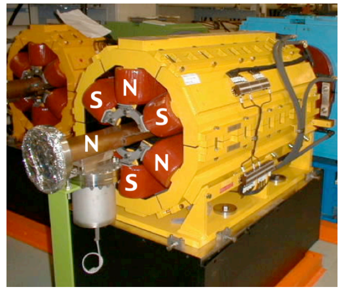
Non-Interleaved 2.5π Sextupole Scheme (NISS)

- Lattice errors can be corrected by sextupole displacement.
  - Horizontal displacement of sextupole generates quadrupole element and vertical displacement generates xy-coupling.

$$
\begin{cases}
\Delta x' = -\frac{K_2}{2}\left(x^2 - y^2\right) - \left(K_2 \Delta x_{\text{sext}}\right)x - \left(K_2 \Delta y_{\text{sext}}\right)y \\
\Delta y' = K_2 xy \qquad + \left(K_2 \Delta x_{\text{sext}}\right)y + \left(K_2 \Delta y_{\text{sext}}\right)x
\end{cases}
$$

Quad. element — Skew element

Δx_{sext} : Horizontal displacement
Δy_{sext} : Vertical displacement



  - Sextupole magnet has a mover which can transversely move the magnet.

- Orthogonal knobs:

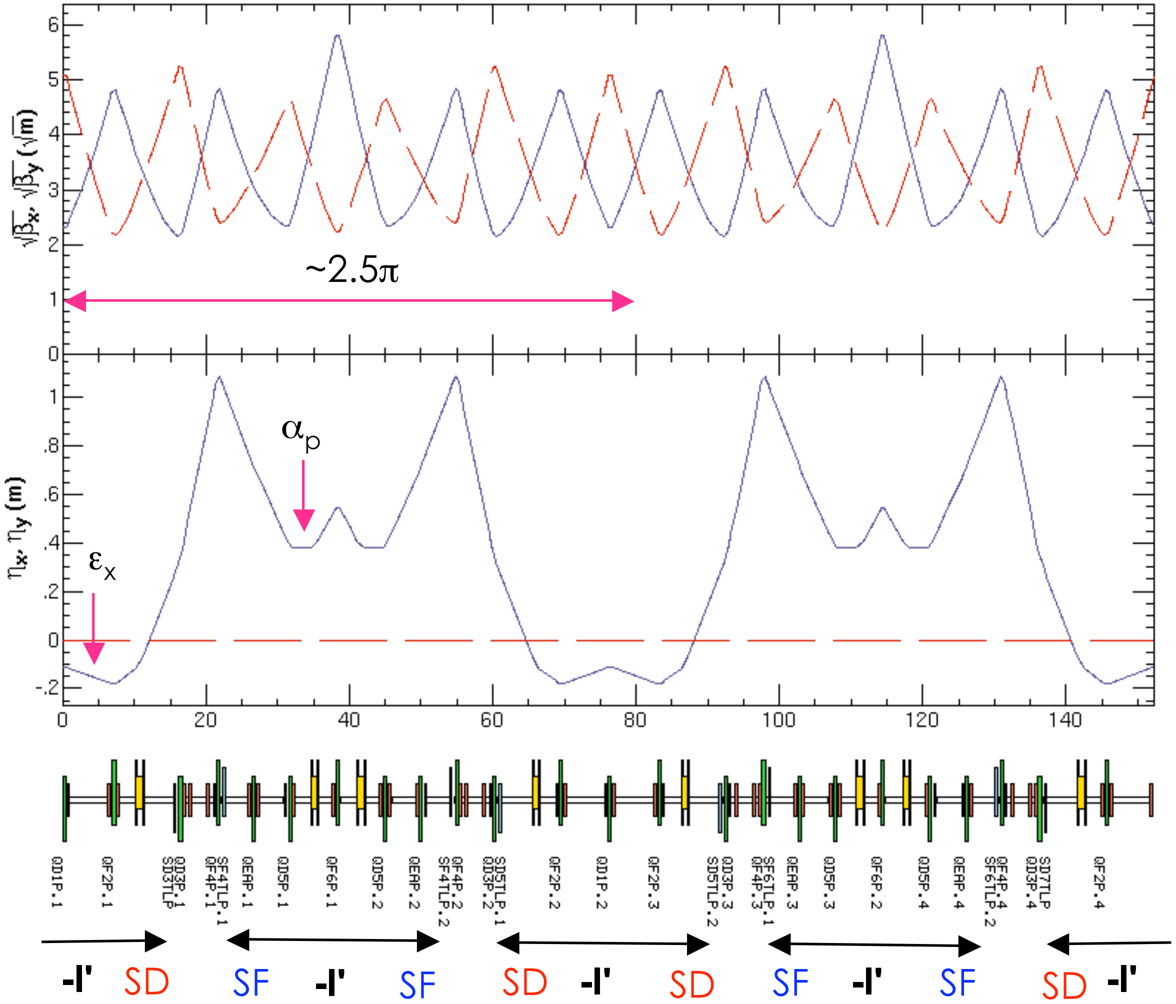
displacement	same direction	opposite direction	
Δx_{sext}	β-function	η_x	SF
	localized dispersion	localized β-beat	
Δy_{sext}	xy-coupling	η_y	SD
	localized dispersion-coupling	localized xy-coupling	

NISS Arc Lattice

LER

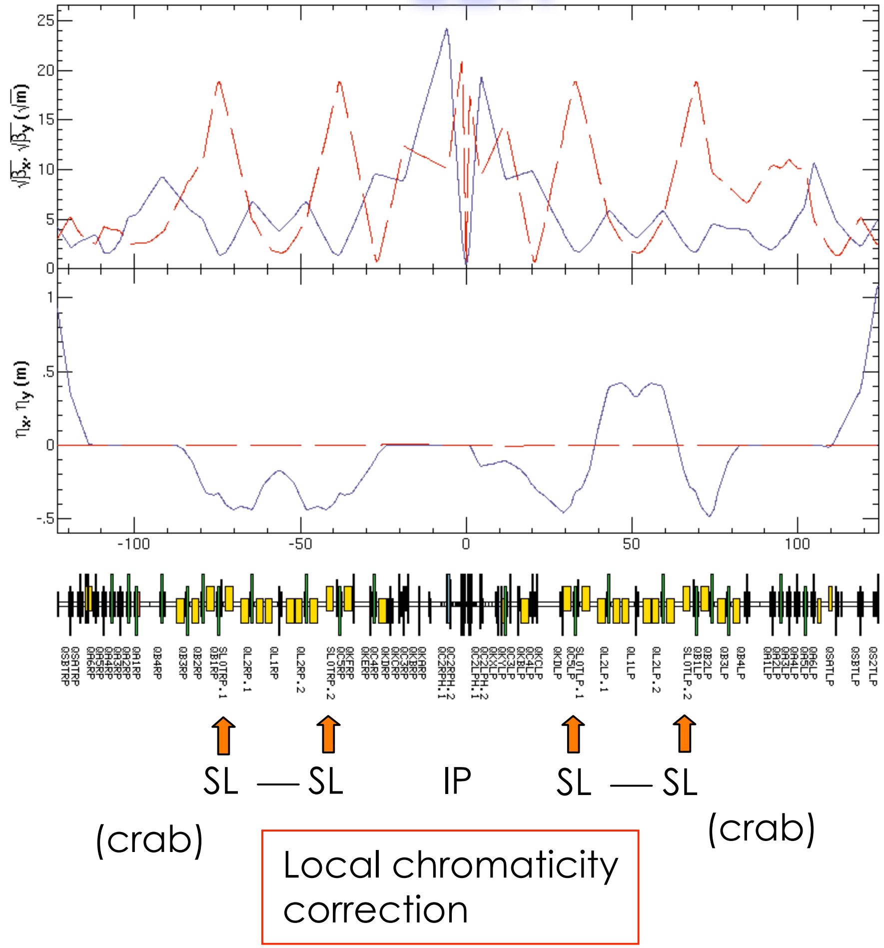
$\alpha_p = 4.27\text{x}10^{-4}$
$\varepsilon_x = 24$ nm

Flexibility:
10 nm < ε_x < 36 nm
$-4\text{x}10^{-4} < \alpha_p < +4\text{x}10^{-4}$

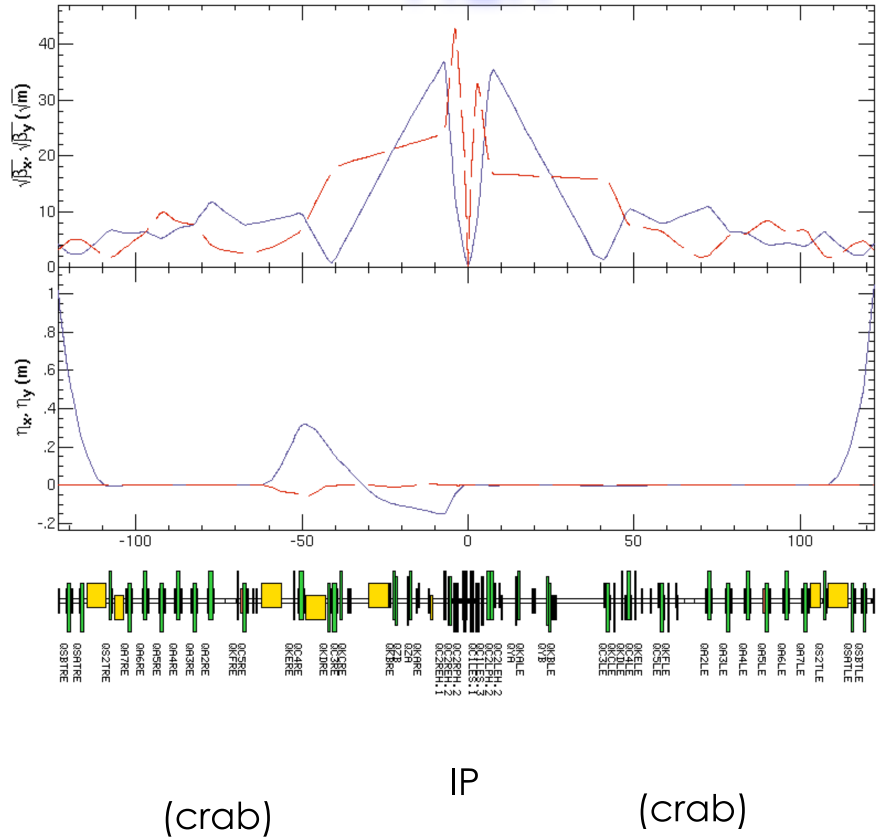


Interaction Region

LER



HER



Computer Simulations

- SAD: SAD is a computer program complex for accelerator design. It has been developed in KEK and used at KEKB. (http://acc-physics.kek.jp/SAD/sad.html)
- Machine errors:
  - The errors are assumed to be Gaussian distribution with a cut-off of 3σ.
  - LER is considered to estimate tolerance of machine errors.

	alignment error		rotation error	gradient error
	Δx (μm)	Δy (μm)	$\Delta\theta$ (mrad)	$\Delta k/k$
Bend	100	100	0.1	10^{-4}
Quadrupole	100	100	0.1	10^{-4}
Sextupole	100	100	0.1	10^{-4}
Steering	100	100	0.1	10^{-3}

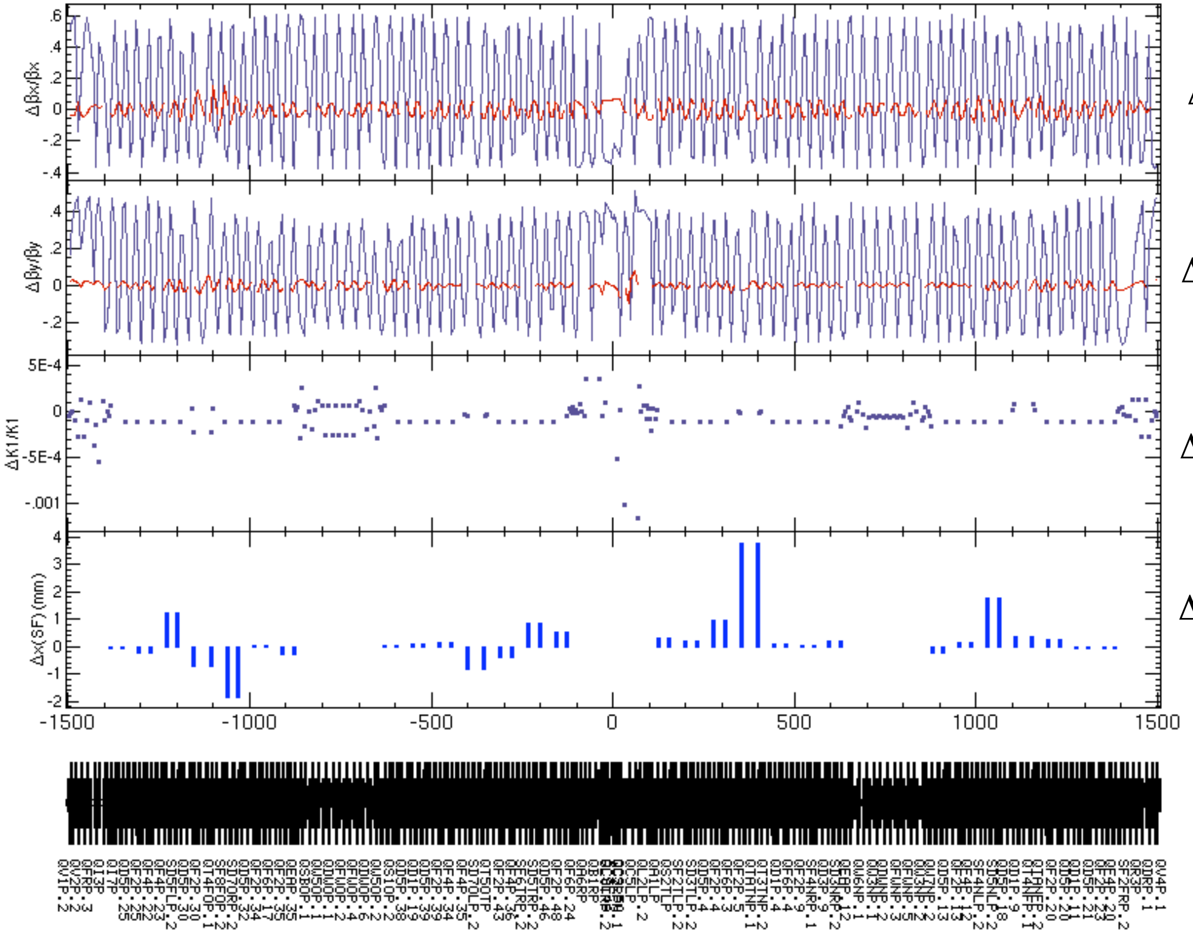
- Lattice errors are corrected by sextupole movers, skew quadrupoles and field gradient of quadrupoles.

Beta Correction

Blue: before
Red: after correction

correction of field gradient (fudge factor)

sextupole(SF) mover (horizontal)

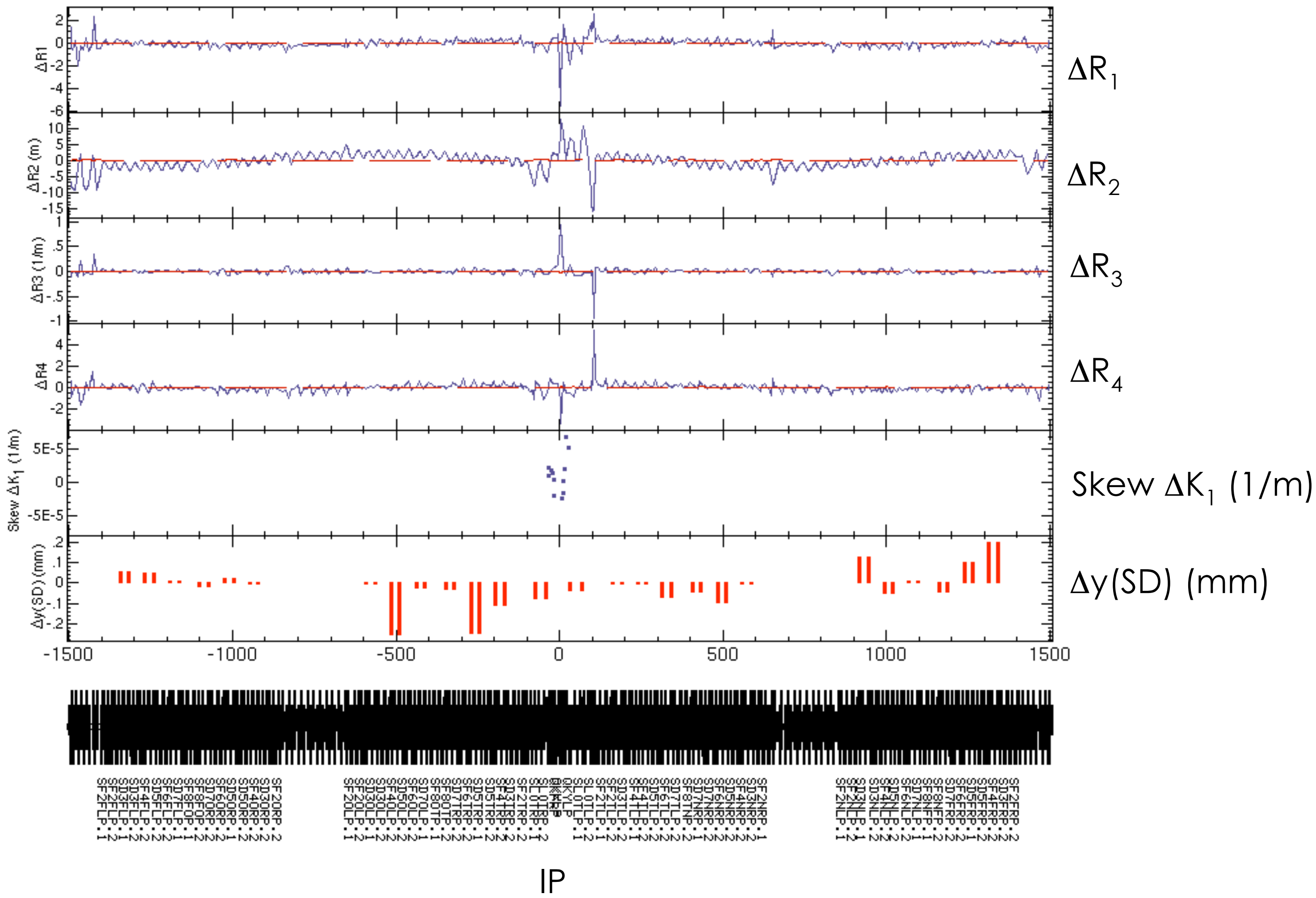


xy-coupling Correction

Blue: before
Red: after correction

skew quad. correction

sextupole(SD) mover (vertical)

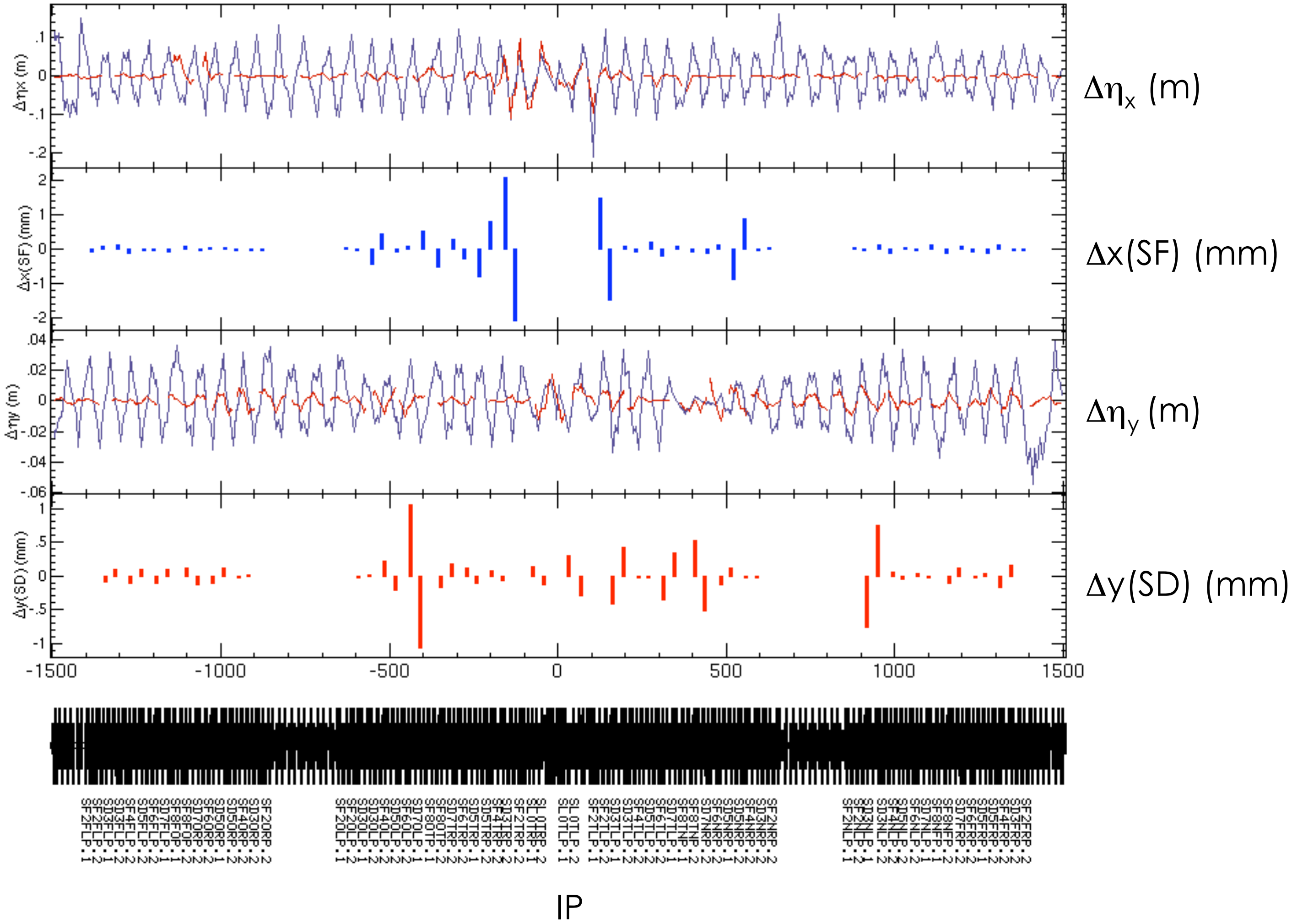


Dispersion Correction

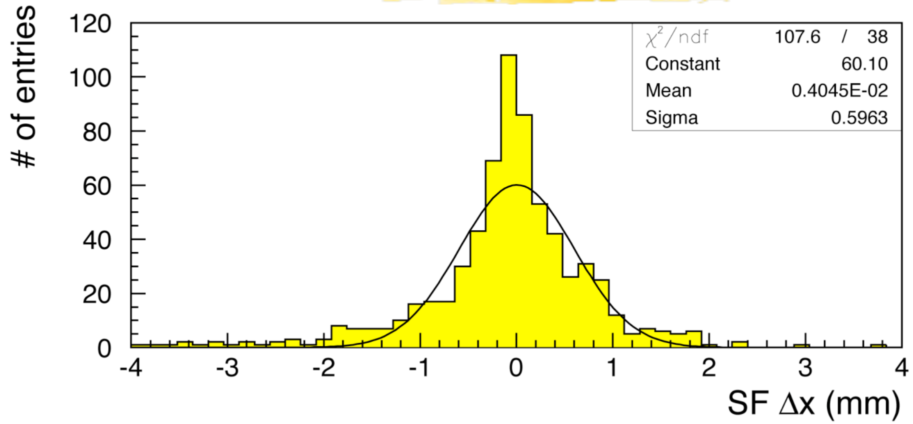
Blue: before
Red: after correction

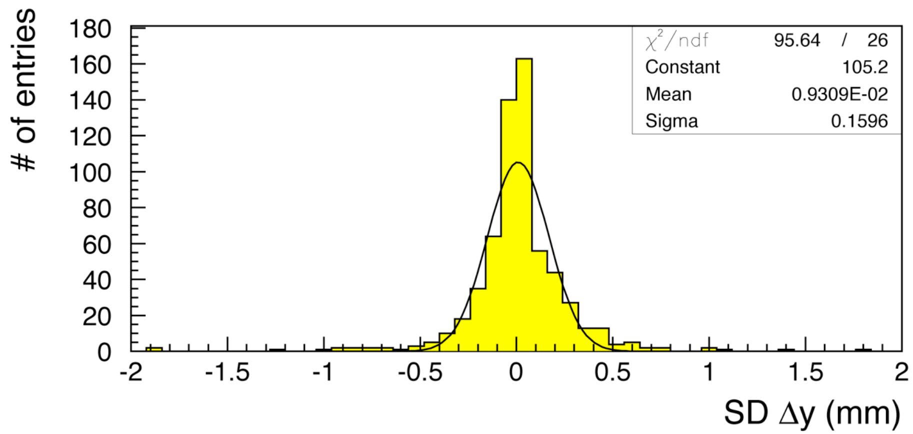
sextupole(SF) mover (horizontal)

sextupole(SD) mover (vertical)



Sextupole Mover



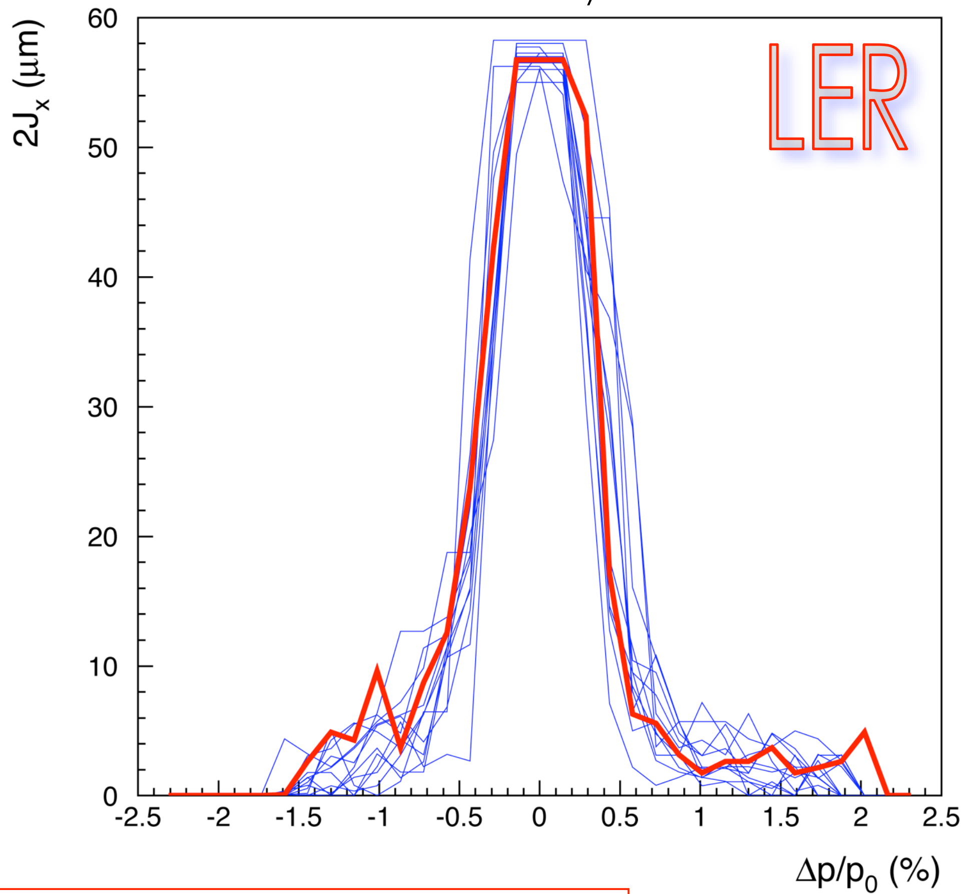


Mover displacement used for optics correction

- Maximum stroke of ±3 mm is necessary for sextupole movers to correct optics.
- Sextupole local bumps are not available for SuperKEKB to keep synchrotron light path in the ante-chamber.

Dynamic Aperture in LER

Stored beam $J_y/J_x = 2\ \%$



red: no machine error
blue: machine error + optics correction
(12 lines indicate different seed numbers.)

Touschek lifetime : 75 min

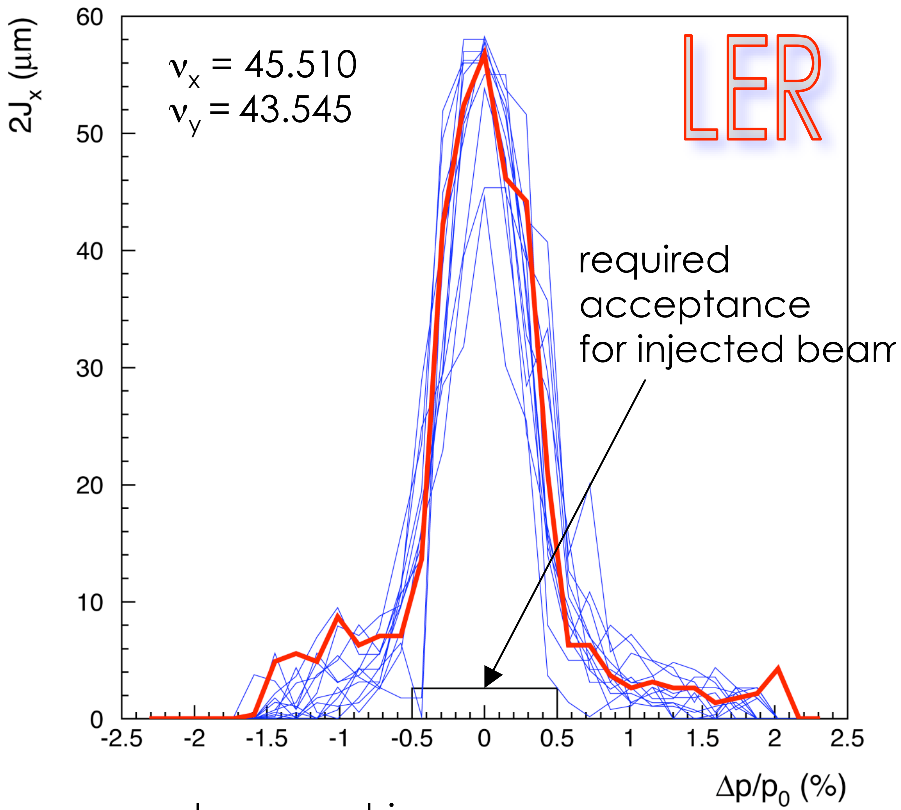
Required Acceptance for Injected Beam

	LER 3.5 GeV			HER 8 GeV		
	e^+	e^+	e^-	e^+	e^+	e^-
Damping Ring	NO	YES	-	NO	YES	-
A_x(μm)	7.5	1.8	2.6	4.5	1.5	1.9
A_y(μm)	1.2	0.056	0.18	0.52	0.025	0.08
A_y/A_x (%)	16	3	7	12	2	4
			Energy Switch	Energy Switch	Energy Switch	

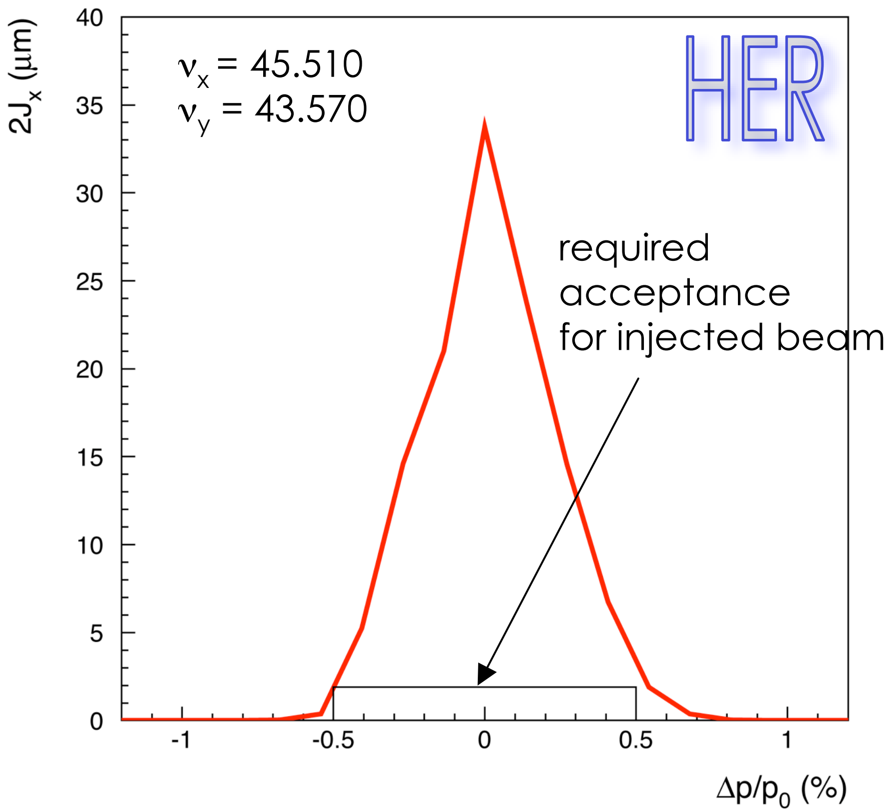
e^+ damping ring is assumed in SuperKEKB.

Dynamic Aperture for Injected Beam

Injected beam $J_y/J_x = 7\ \%$



Injected beam $J_y/J_x = 4\ \%$



red: no machine error
blue: machine error + optics correction
(12 lines indicate different seed numbers.)

Dynamic aperture satisfies injected beam.

Tracking Simulation with Beam-Beam Effect

- Beam-beam kick is given by Bassetti-Erskine formula.
  - $x' \to x' + \Delta x'$, $y' \to y' + \Delta y'$ at I.P

$$\Delta x' = -\frac{N_{-} r_e}{\gamma_+} F_x(x, y, \sigma_x^*, \sigma_y^*)$$

$$\Delta y' = -\frac{N_{-} r_e}{\gamma_+} F_y(x, y, \sigma_x^*, \sigma_y^*)$$

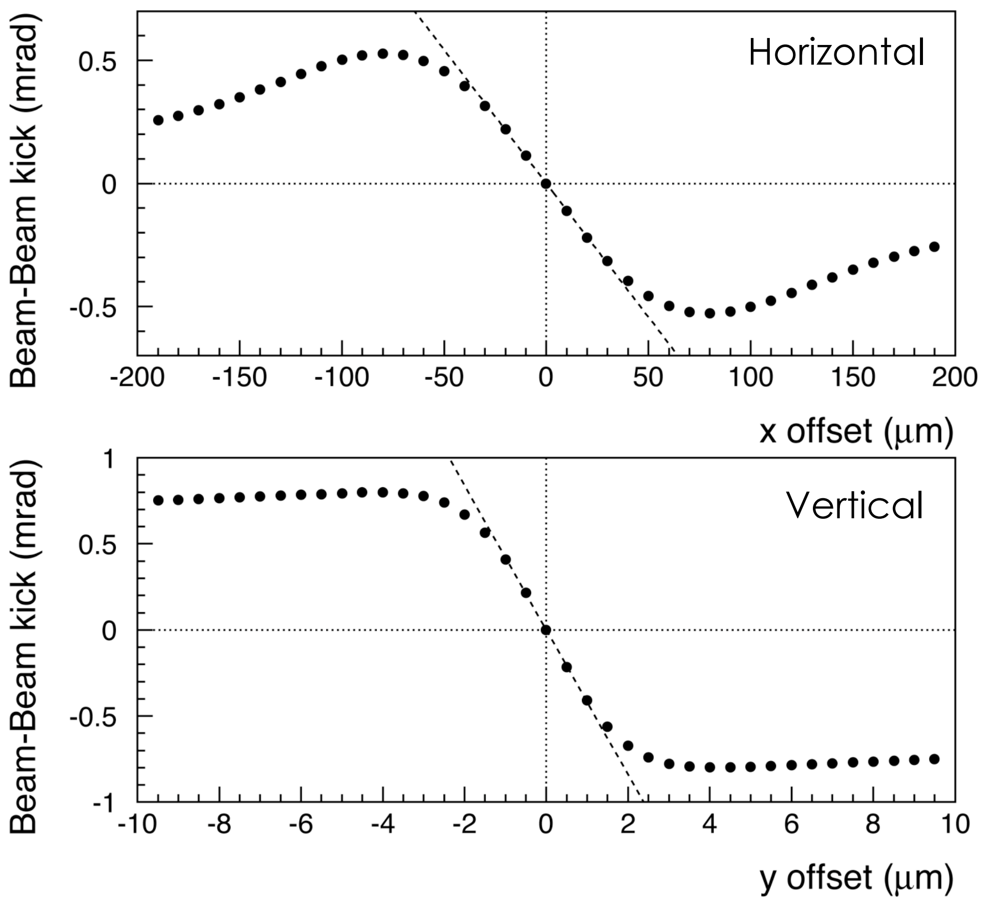
LER (e^+)

$$F_x(x,y,\sigma_x^*,\sigma_y^*) - iF_y(x,y,\sigma_x^*,\sigma_y^*) = -i\sqrt{\frac{2\pi}{\sigma_x^{*2} - \sigma_y^{*2}}}$$

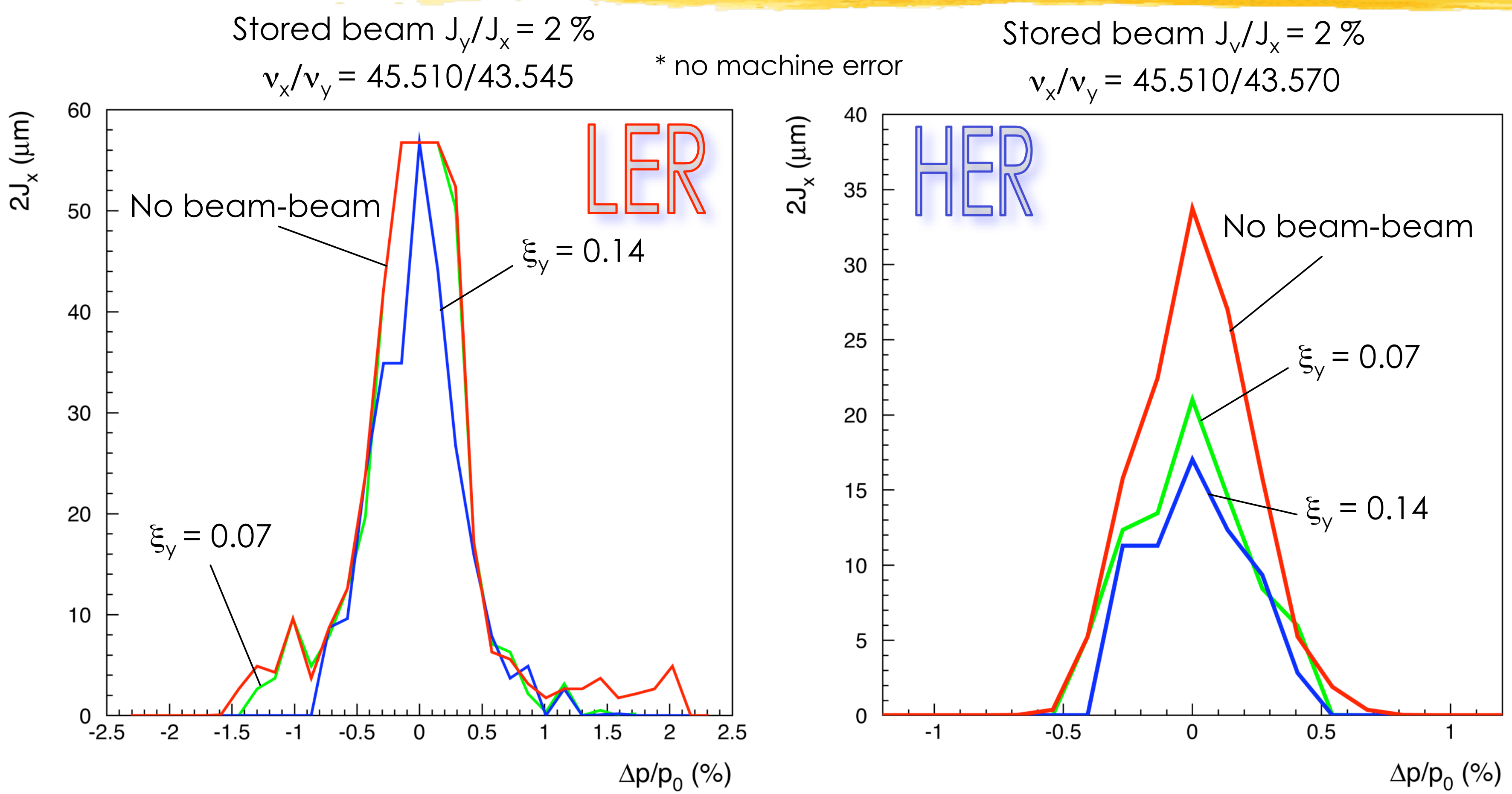
$$\times\left\{ w\left(\frac{x+iy}{\sqrt{2(\sigma_x^{*2}-\sigma_y^{*2})}}\right) - \exp\left(-\frac{x^2}{\sigma_x^{*2}} - \frac{y^2}{\sigma_y^{*2}}\right) w\left(\frac{\frac{\sigma_y^{*2}}{\sigma_x^{*2}}x + i\frac{\sigma_x^{*2}}{\sigma_y^{*2}}y}{\sqrt{2(\sigma_x^{*2}-\sigma_y^{*2})}}\right)\right\}$$

- Tracking simulation is "Weak-Strong".

Demonstration of beam-beam kick with tracking



Dynamic Aperture with Beam-Beam Effect



- Case $\xi_y = 0.14$, dynamic aperture shrinks in large momentum deviation for LER.
- Transverse aperture decreases in HER due to beam-beam effect.
- Touschek lifetime with beam-beam(ξ_y= 0.14): 50 min in LER / 180 min in HER

Lifetime

Item	LER	HER
Quantum lifetime	very long	
Vacuum lifetime	~10 hours	
Luminosity lifetime	170 min	70 min
Touschek lifetime for single beam (J_y/J_x=2%)	75 min	320 min
Touschek lifetime with beam-beam (J_y/J_x=2%)	50 min	180 min
Total (collision lifetime)	40 min	50 min

To keep CIM, 40 nC·Hz/pulse injection for LER, 14 nC·Hz/pulse for HER are needed at least.

Summary

- Non-interleaved sextupole scheme(NISS) is applied to SuperKEKB lattice.
- Tolerance of machine errors and optics correction
  - Sextupole mover is important to make optics correction.
- Dynamic aperture satisfies the requirement of injected beam in both rings.
- Dynamic aperture with beam-beam effect
  - Momentum aperture decreases in LER, transverse aperture decreases in HER.
  - Lifetime(beam-beam) : 50 min (LER) / 180 min (HER)
- Sextupole optimization still needs improvement.
  - Local chromaticity correction in HER

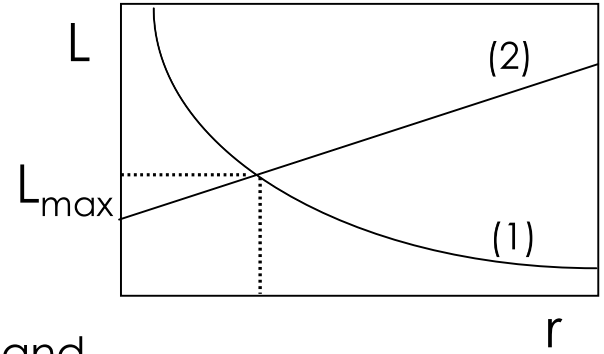
Appendix

Luminosity Formula

- Luminosity expressed by Beam-Beam parameters ($\gamma_{e+}N_{e+} = \gamma_{e-}N_{e-}$)

$$\begin{cases} L \le \dfrac{\gamma_{e\pm}}{2er_e}(1+r)\left(\dfrac{I_{e\pm}\xi_x}{r\beta_x^*}\right) & (1) \\ L \le \dfrac{\gamma_{e\pm}}{2er_e}(1+r)\left(\dfrac{I_{e\pm}\xi_y}{\beta_y^*}\right) & (2) \end{cases}$$

$$r \equiv \frac{\sigma_y^*}{\sigma_x^*}$$



- When $\xi_x/r\beta_x^* = \xi_y/\beta_y^*$, luminosity is maximum and

$$L = \frac{\gamma_{e\pm}}{2er_e}(1+r)\left(\frac{I_{e\pm}\xi_y}{\beta_y^*}\right)$$

Luminosity expression used in machine design

- Flat beam: r ~ O(1%)

$$L \propto \frac{I_{e\pm}\xi_y}{\beta_y^*}$$

Geometrical Reductions to Luminosity

- Geometrical reduction to luminosity: R_L

$$L \rightarrow L = \frac{N_{e+} N_{e-} f}{4\pi\sigma_x^* \sigma_y^*} R_L \qquad R_L = \frac{a}{\sqrt{\pi}} e^b K_0(b)$$

modified Bessel

$$a = \frac{\beta_y^*}{\sigma_z}$$

$$b = \frac{a^2}{2}\left[1 + \left(\frac{\sigma_z}{\sigma_x^*} \tan\frac{\theta_x}{2}\right)^2\right]$$

- Geometrical reduction to beam-beam parameter: $R_{\xi y}$

$$\xi_{y,e\pm} \rightarrow \xi_{y,e\pm} = \frac{r_e N_{e\mp} \beta_y^*}{2\pi\gamma_{e\pm}\sigma_y^*(\sigma_x^* + \sigma_y^*)} R_{\xi y} \qquad R_{\xi y} = \int dz' \rho(z') \sqrt{1 + \left(\frac{S}{\beta_y^*}\right)^2} f_y\left(z' \tan\frac{\theta}{2}, \sigma_x^*, \sigma_y^*\right)$$

Montague's function

- Luminosity expression used in machine design: $R_L/R_{\xi y}$

$$L \rightarrow L = \frac{\gamma_{e\pm}}{2er_e}(1+r)\left(\frac{I_{e\pm}\xi_y}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi y}}\right)$$

Beam-Beam simulation using Supercomputer

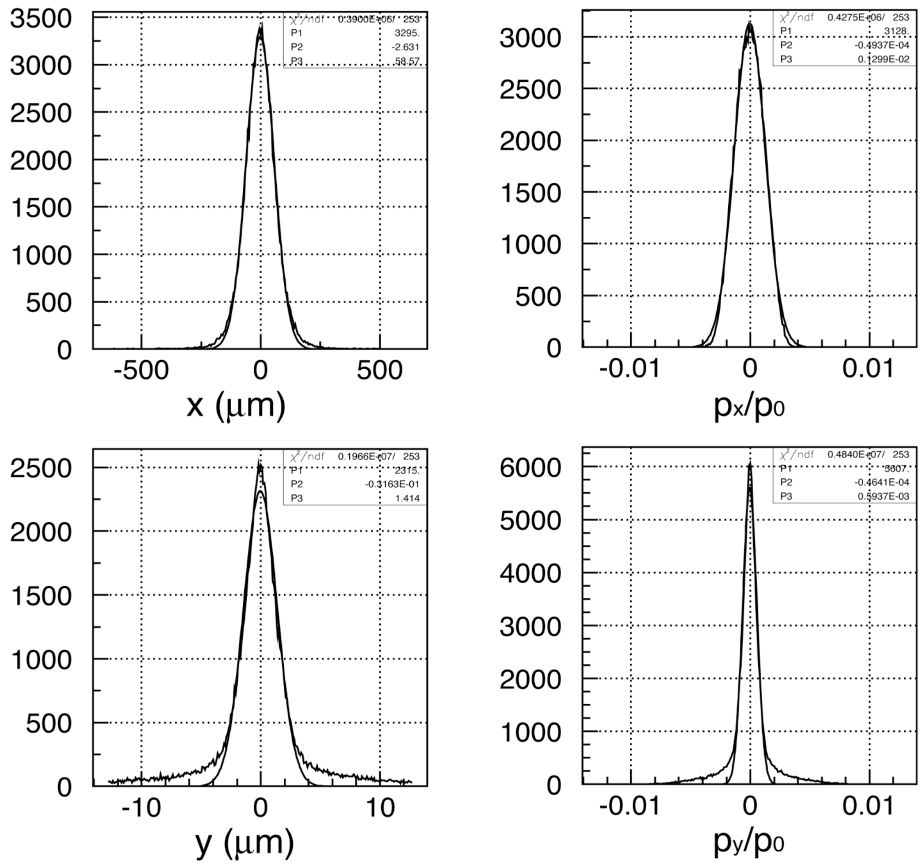
Positron beam

σ_x = 59 mm

$\sigma_{px/p0}$ = 1.3x10^{-3}

σ_y = 1.4 mm

$\sigma_{py/p0}$ = 0.59x10^{-3}



initial condition

Beam-Beam effect

β_x^* = 20 cm / β_y^* = 3 mm
ε_x = 24 nm / ε_y = 0.18 nm

Dynamic effects →

β_x^* = 4.5 cm / β_y^* = 2.3 mm
ε_x = 77 nm / ε_y = 0.83 nm