Optics Issues

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18th KEKB Review
KEK, March 3-5, 2014

R1: The committee recommends concentrating on developing very detailed and robust procedures for *correcting the closed orbit and linear optics distortions caused by realistic field errors*, especially in difficult places like the local chromaticity correction section.

For the IR optics, an algorithm should be developed for the control-room operational usage, *aimed at improving the beam lifetime (and the dynamic aperture) by numerous nonlinear corrections*, in addition to the blind downhill-simplex optimization.

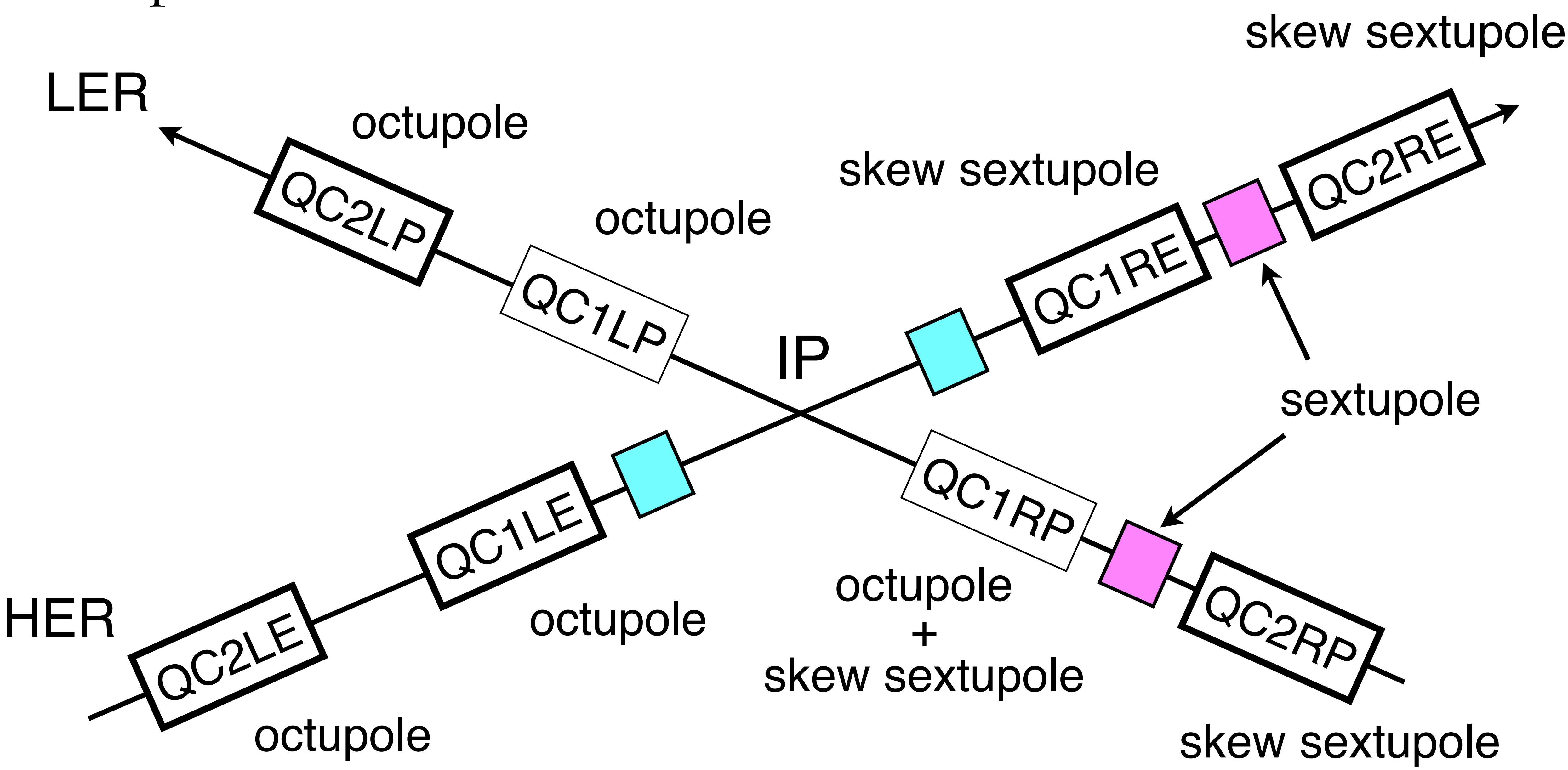
R2: The Optics Group should continue to merge the IR and ring lattices with the intent *to study optimized luminosity tuning with full IR fields, full error tolerances, all correctors*, and the needed small vertical emittances.

Contents

- IR design (Final focus system, corrector coils)
- Optics correction and Dynamic aperture
- Dynamic aperture with Beam-Beam effect (new issue)

IR design: Final focus system

- IR design has been fixed. Especially, additional sextupole and skew sextupole correctors to correct error fields induced by a coil displacement in the radial direction.



Ideal lattice is OK ....

How to adjust these nonlinear correctors ?

Optics Correction and Dynamic Aperture

Machine error for optics correction

Assumption of machine error

	Δx_{rms} (μm)	Δy_{rms} (μm)	$\Delta\theta_{rms}$ (μrad)	$(\Delta K/K)_{rms}$
Dipole	0	0	100	3.5×10^{-4}
Quadrupole	100	100	100	7×10^{-4}
Sextupole	100	100	0	1.3×10^{-3}
QCS	100	100	0	0
BPM*	75	75	1000	-

*BPM jitter error of 2 μm (rms) is included for an averaged mode.

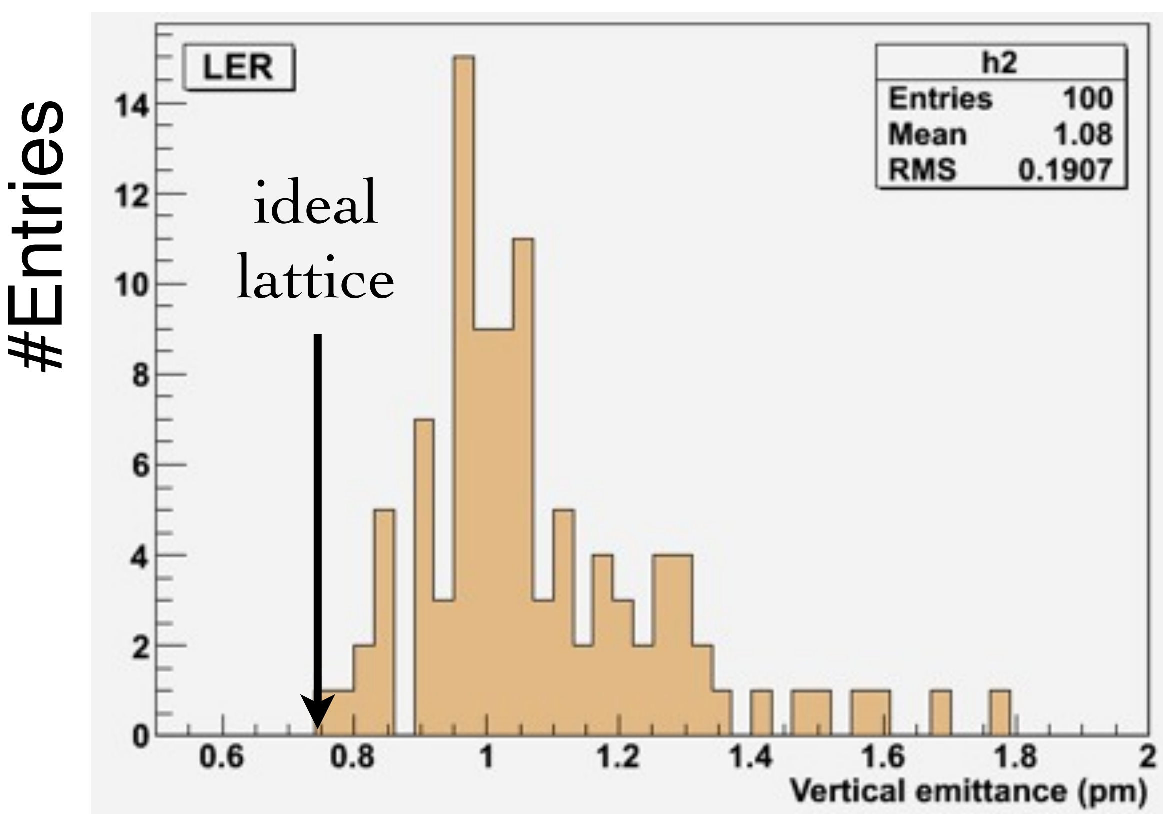
Misalignment is based on the measurement at KEKB. (realistic error)

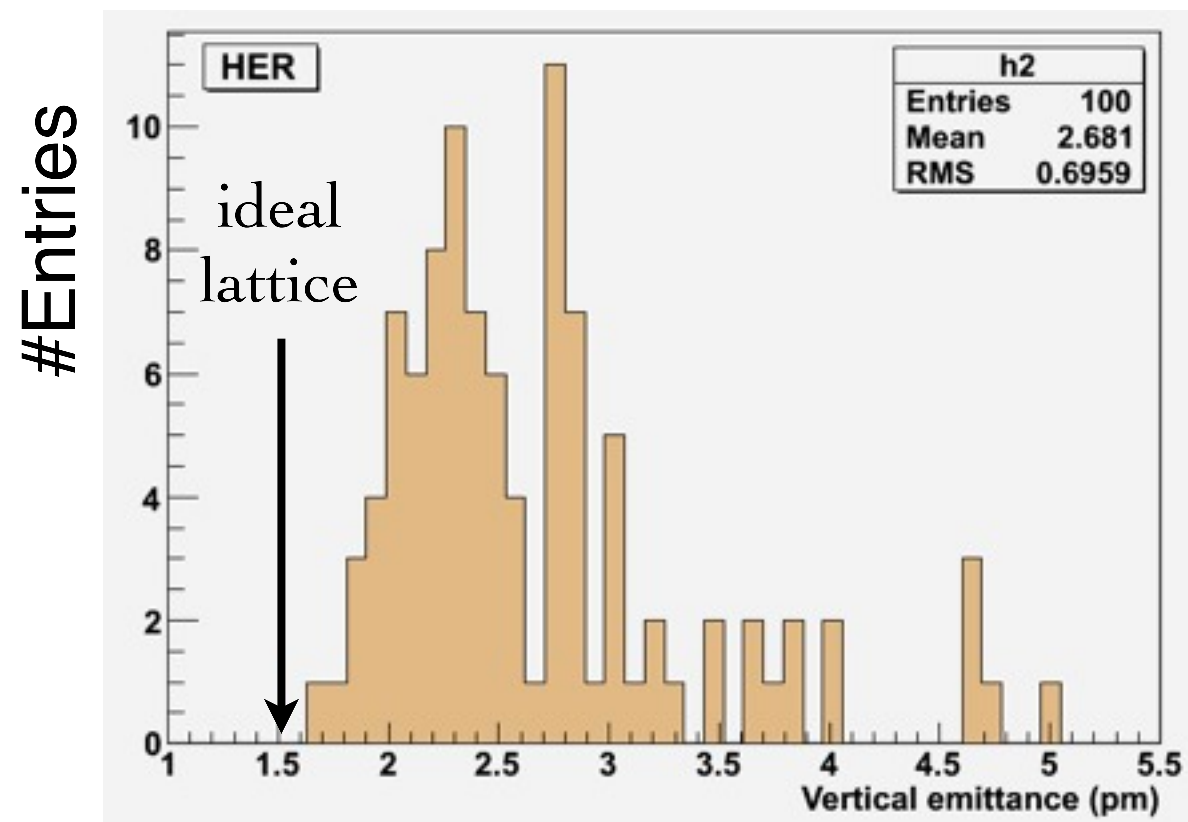
We evaluate the beam quality after corrections of these machine error on the computer simulation.

Vertical emittance after optics correction

- Optics correction is based on the measurement of orbit response. (quaint technique)
- Machine error is corrected by using dipole, quadrupole, and skew quadrupole correctors.
- Closed orbit distortion, X-Y coupling, dispersions, and beta functions are corrected.

#samples: 100 (different seed numbers)





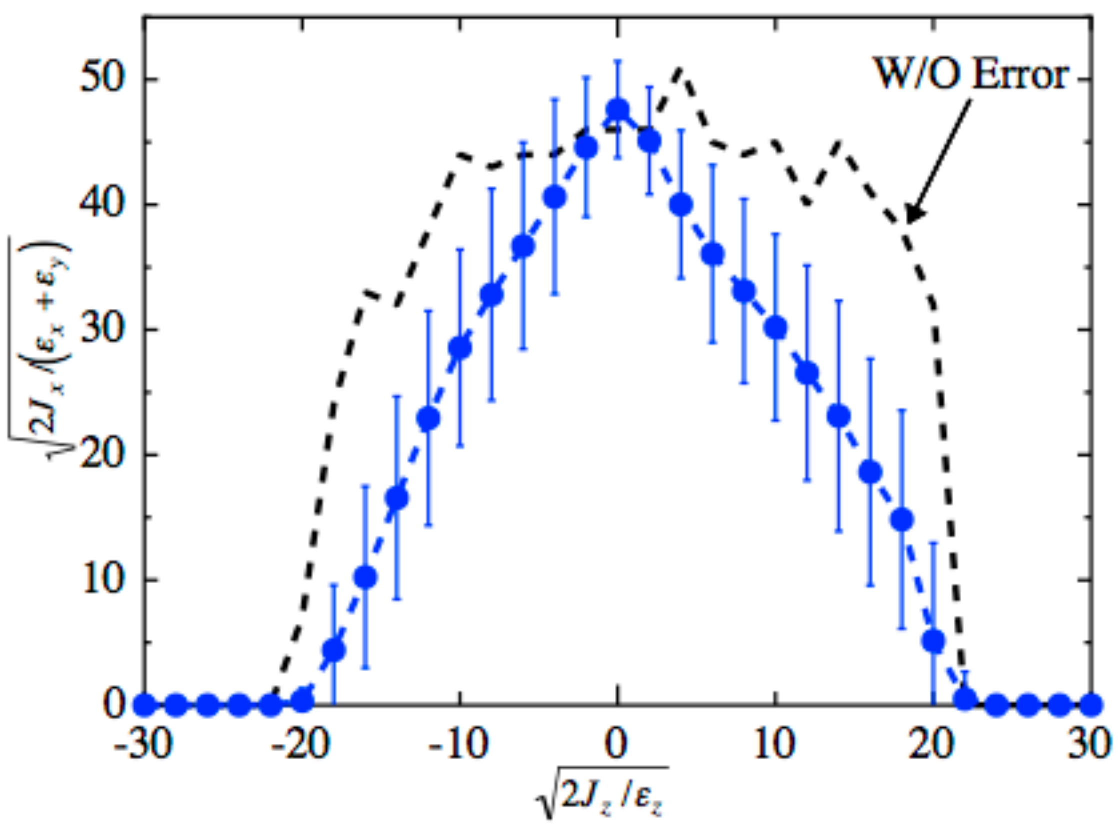
The vertical emittance can be corrected down to a few pm, which satisfy the luminosity performance.

H. Sugimoto

Dynamic aperture after correcting the machine error

LER

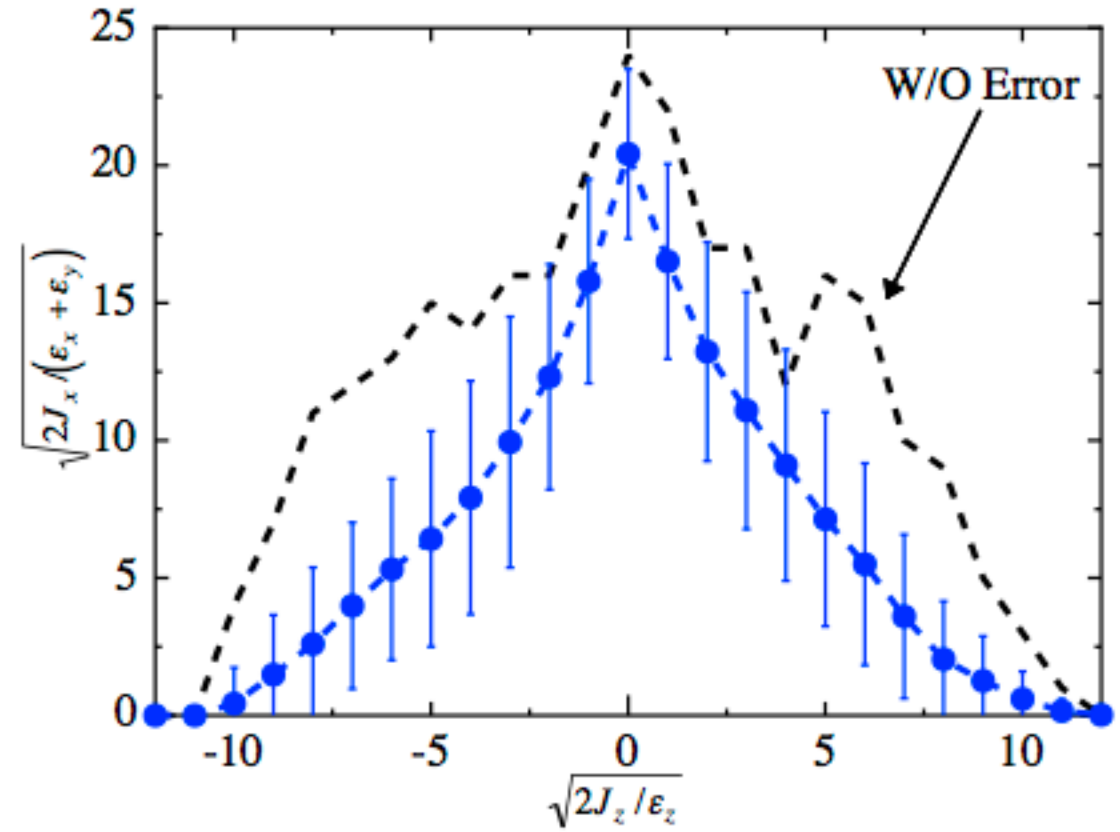
transverse aperture



momentum aperture

HER

transverse aperture



momentum aperture

blue plots: averaged value of 100 samples
bars: standard deviation
dashed line: ideal lattice

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Correction of nonlinear optics

- Even though COD, X-Y coupling, dispersions, and beta functions are corrected, dynamic aperture can not be recovered by these corrections perfectly.
- In order to recover the dynamic aperture, sextupole, skew sextupole, and octupole optimizations are necessary.
- So, how to adjust these nonlinear correctors ?
- We have 135 one-pass BPMs for each ring. Information from one-pass BPMs with rf-frequency shift gives us **chromatic phase-advance** and **chromatic X-Y coupling**. Sextupole and skew sextupoles can be optimized by using these measurement in principle.

Derivation of phase advance

- Beam position is measured by one-pass BPM.

$$x_1(n) = \sqrt{2J\beta_1}\cos\psi(n)$$
$$x_2(n) = \sqrt{2J\beta_2}\cos\{\psi(n)+\psi_{21}\}$$

$\psi(n) = 2\pi\nu n + \phi_0$

n: turn number

- Averaged values of x_1, x_2 and x_1x_2:

$$< x_1(n)^2 > = J\beta_1$$
$$< x_2(n)^2 > = J\beta_2$$
$$< x_1(n)x_2(n) > = J\sqrt{\beta_1\beta_2}\cos\psi_{21}$$

- Phase advance between two BPMs:

$$\psi_{21} = \cos^{-1}\frac{< x_1(n)x_2(n) >}{\sqrt{< x_1(n)^2 >< x_2(n)^2 >}}$$

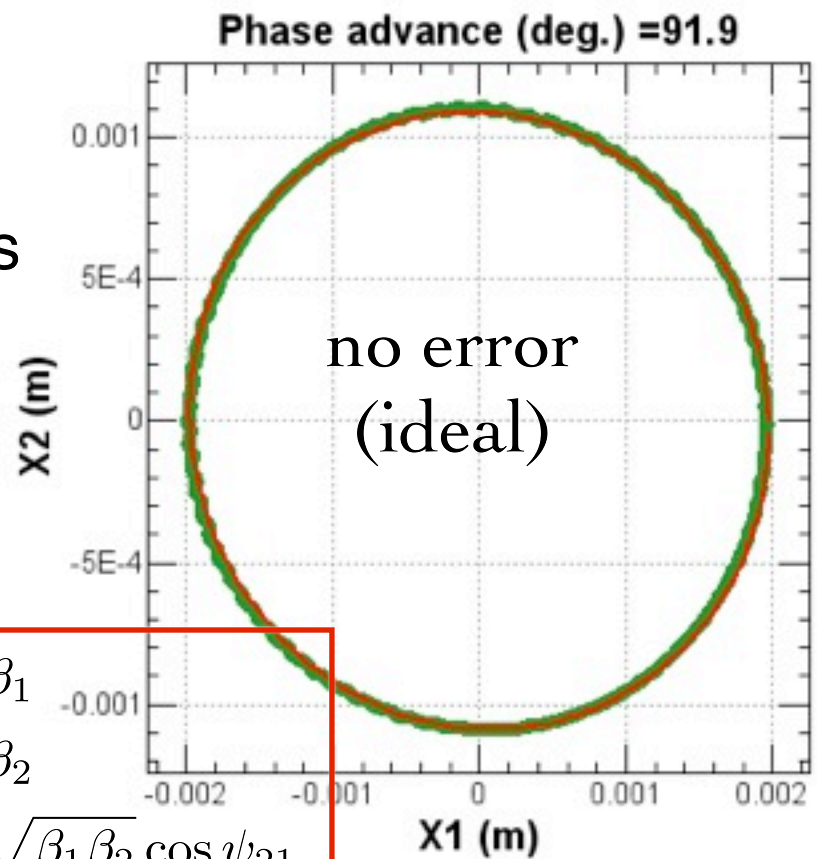
two-hold ambiguity:

$\psi_{21} \quad or \quad 2\pi - \psi_{21}$

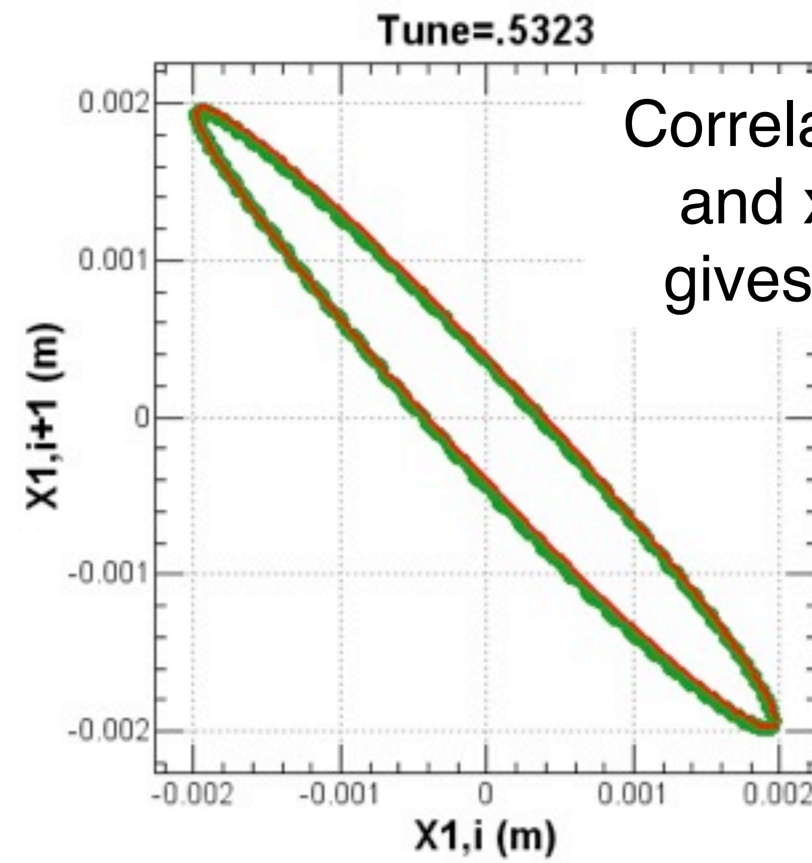
Measurement of phase advance

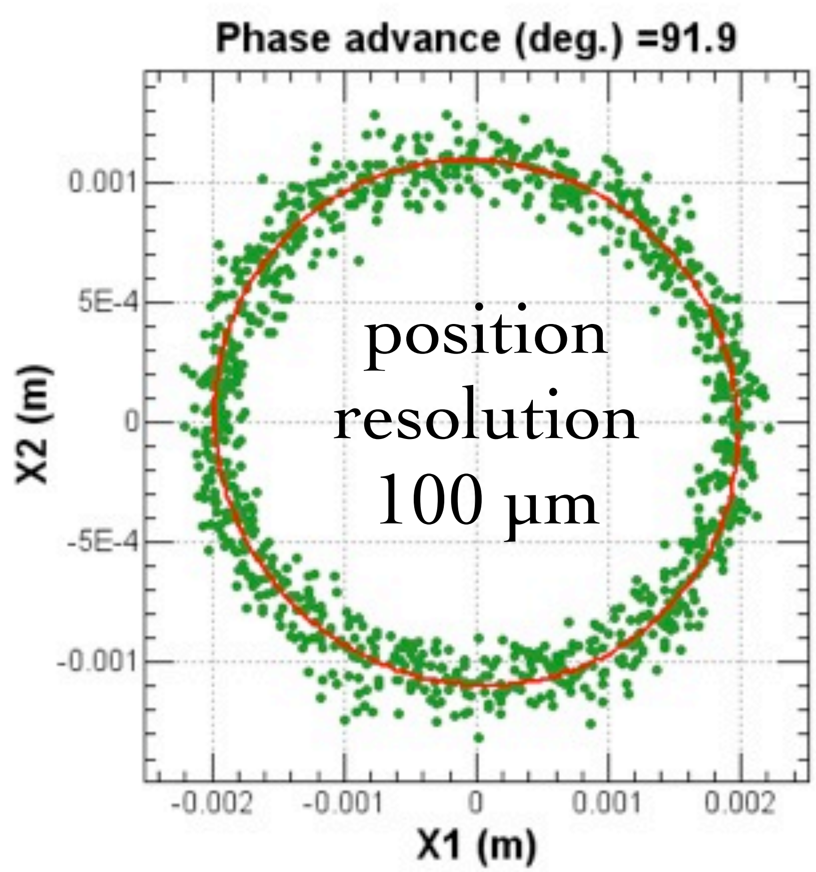
Correlation between neighbor BPMs

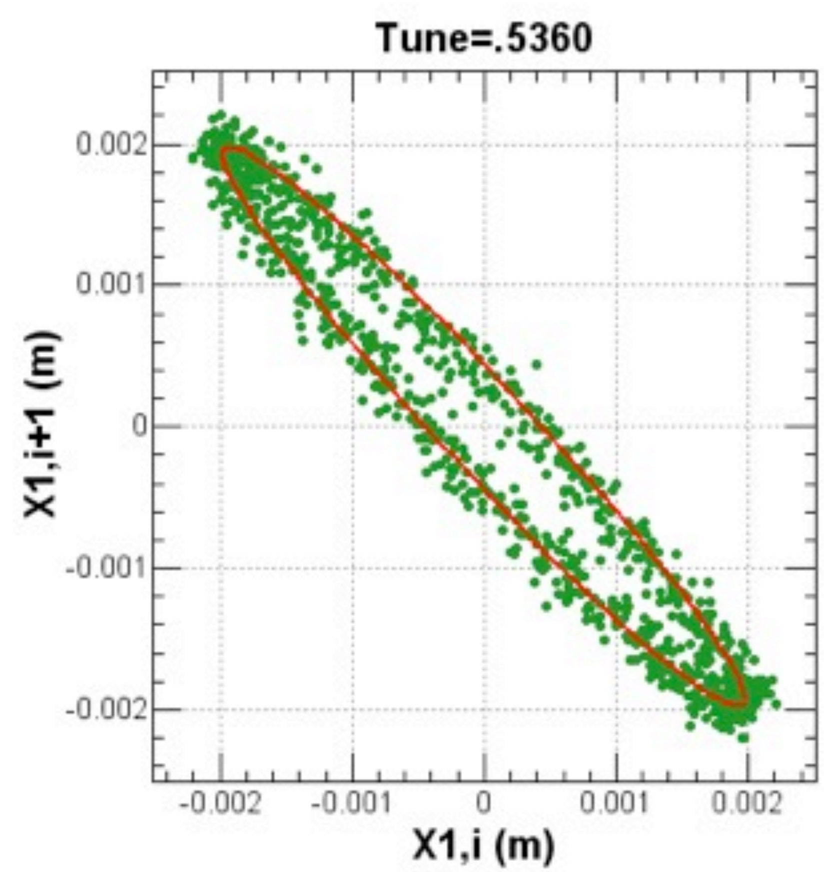
$$< x_1(n)^2 > = J\beta_1$$
$$< x_2(n)^2 > = J\beta_2$$
$$< x_1(n)x_2(n) > = J\sqrt{\beta_1\beta_2}\cos\psi_{21}$$



Correlation between x(i) and x(i+1) at a BPM gives a betatron tune

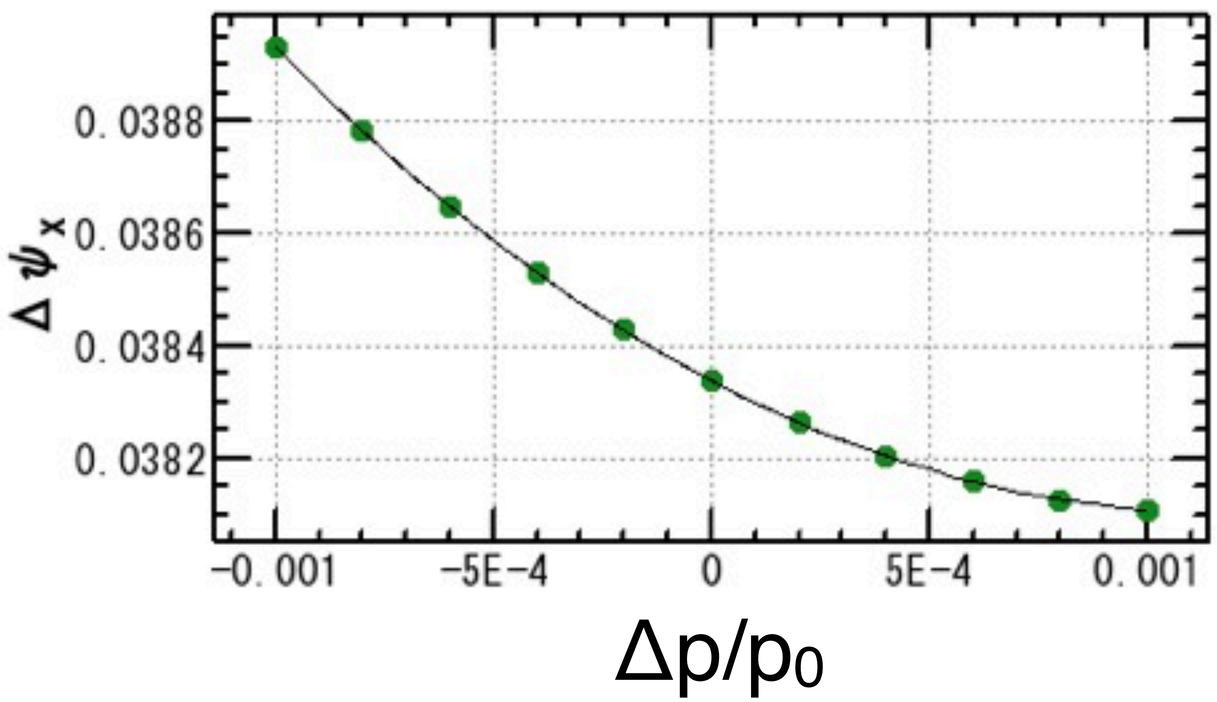


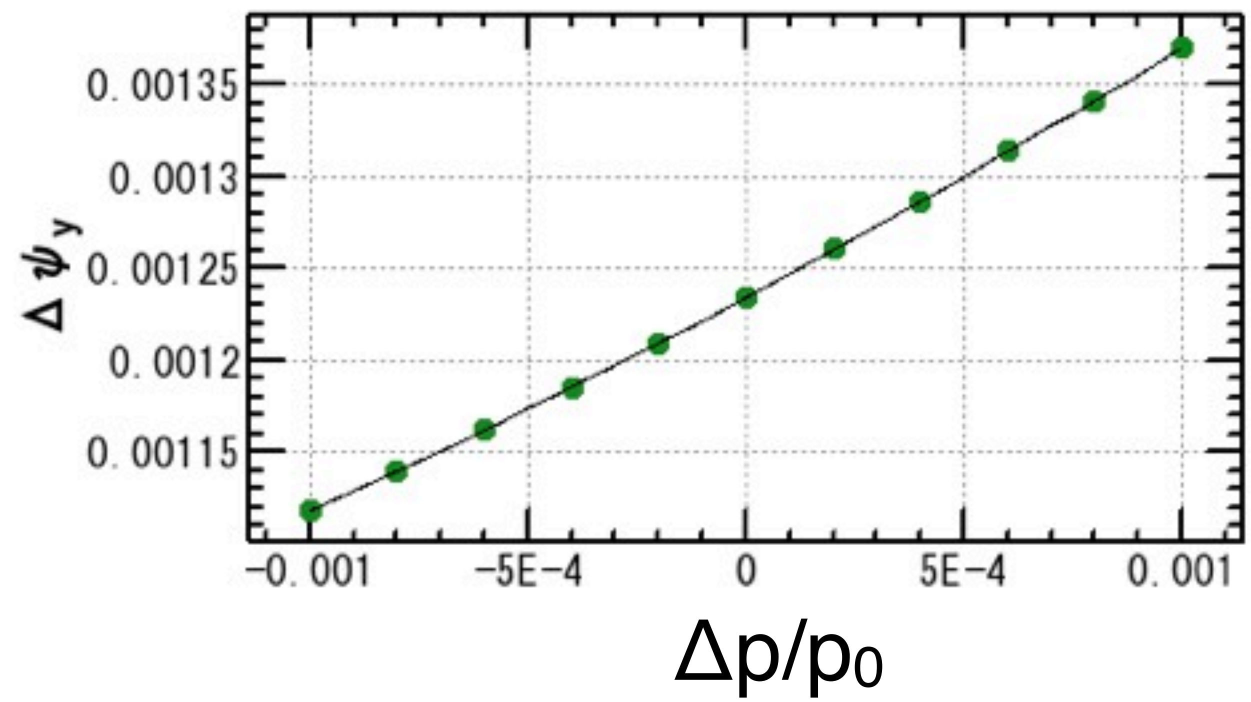




Measurement of chromatic phase-advance

- Example: one-pass BPM at QC1LP and QC2LP
- Measurement of chromatic phase-advance with rf-frequency shift (-0.1<δ<+0.1 %)





$$\frac{\partial \Delta \psi_x}{\partial \delta} = -0.407$$

$$\frac{\partial \Delta \psi_y}{\partial \delta} = 0.127$$

Chromatic phase-advance

- In case that QC1LP has sextupole error filed of B3/B2 = 0.1 %
- Deviation of chromatic phase-advance between neighbor one-pass BPMs

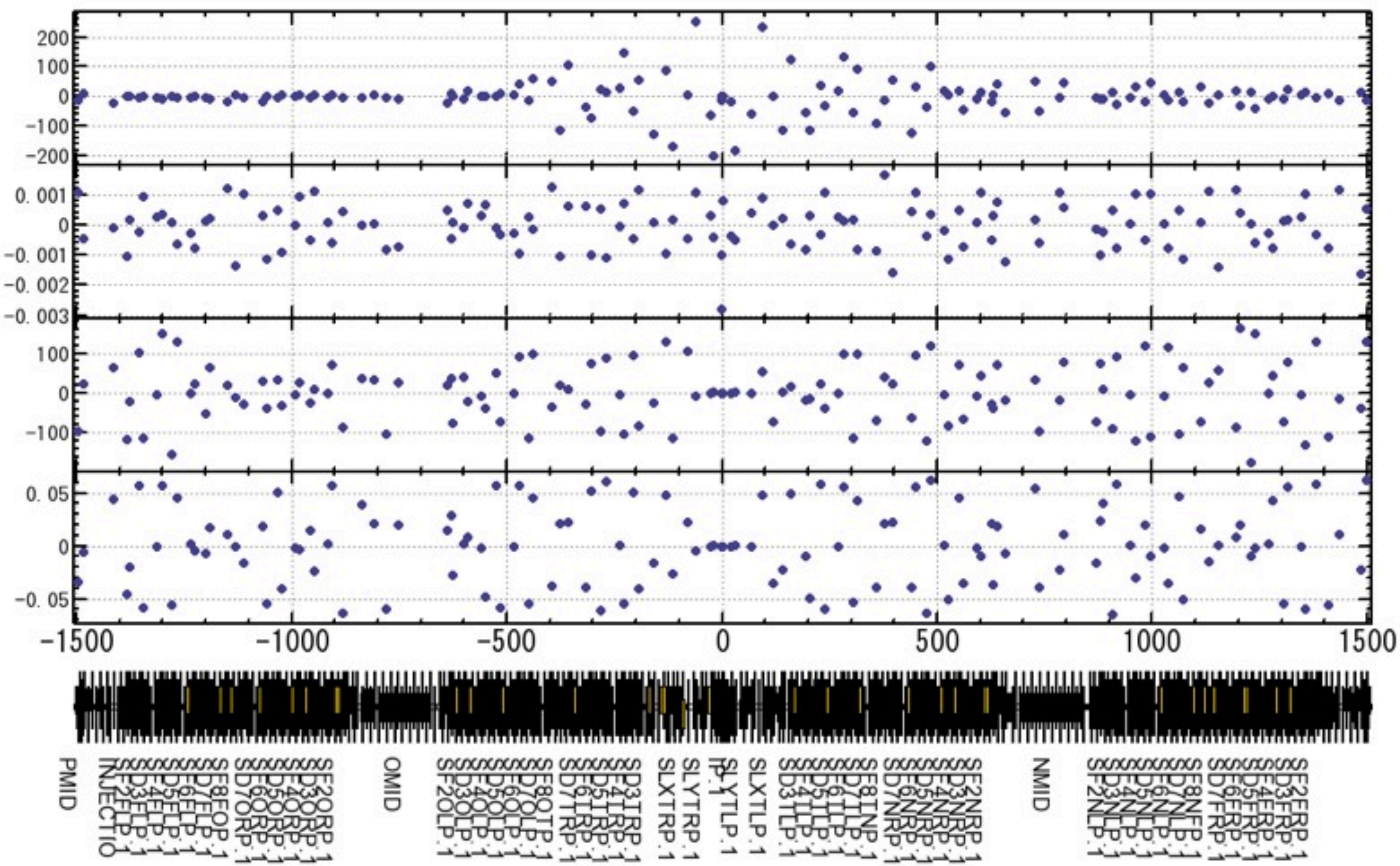
LER

$$\left(\frac{\partial \Delta\psi_x}{\partial \delta}\right)_{design}$$

$$\Delta\left(\frac{\partial \Delta\psi_x}{\partial \delta}\right)$$

$$\left(\frac{\partial \Delta\psi_y}{\partial \delta}\right)_{design}$$

$$\Delta\left(\frac{\partial \Delta\psi_y}{\partial \delta}\right)$$



IP

Derivation of X-Y coupling

physical coordinate

$$\begin{pmatrix} x \\ p_x \\ y \\ p_y \end{pmatrix} = \begin{pmatrix} \mu & 0 & r_4 & -r_2 \\ 0 & \mu & -r_3 & r_1 \\ -r_1 & -r_2 & \mu & 0 \\ -r_3 & -r_4 & 0 & \mu \end{pmatrix} \begin{pmatrix} u \\ p_u \\ v \\ p_v \end{pmatrix}$$

normal coordinate

$$\mu^2 + (r_1 r_4 - r_2 r_3) = 1$$

$$< x^2 > = \mu^2 < u^2 > + r_4^2 < v^2 > -2 r_2 r_4 < v p_v > + r_2^2 < p_v^2 > \simeq \mu^2 < u^2 >$$

$$< x p_x > = \mu^2 < u p_u > - r_1 r_2 < p_v^2 > + (r_1 r_4 + r_2 r_3) < v p_v > - r_3 r_4 < v^2 > \simeq \mu^2 < u p_u >$$

$$< p_x^2 > = \mu^2 < p_u^2 > + r_3^2 < v^2 > -2 r_1 r_3 < v p_v > + r_1^2 < p_v^2 > \simeq \mu^2 < p_u^2 >$$

We can solve the equations

$$\begin{pmatrix} < xy > \\ < x p_x > \\ < x p_y > \\ < p_x p_y > \end{pmatrix} = -\frac{1}{\mu} \Sigma \begin{pmatrix} r_1 \\ r_2 \\ r_3 \\ r_4 \end{pmatrix}$$

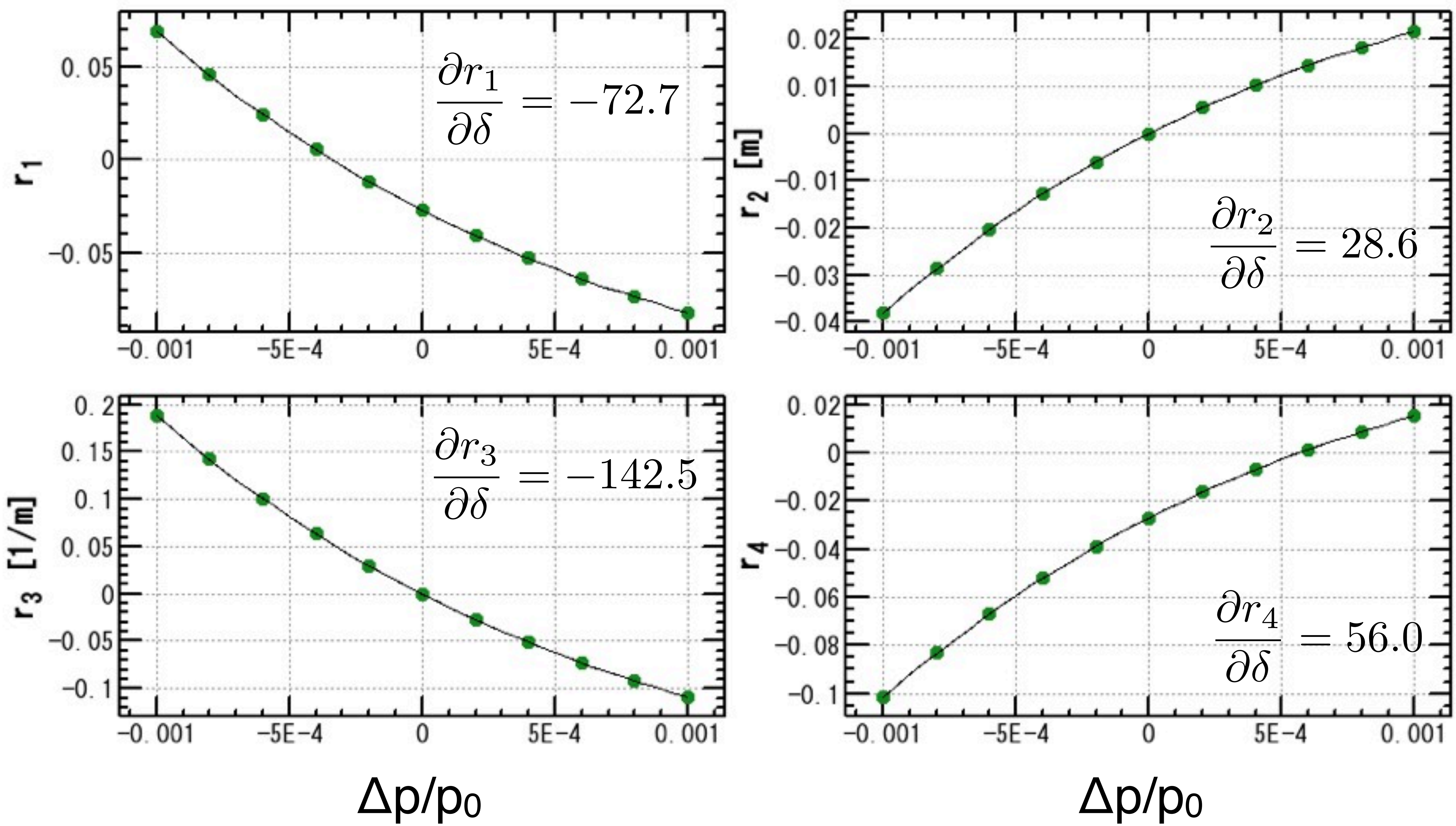
Need to estimate p_x and p_y using two BPMs

where

$$\Sigma = \begin{pmatrix} < x^2 > & < x p_x > + < y p_y > & 0 & - < y^2 > \\ < x p_x > - < y p_y > & < p_x^2 > & < y^2 > & 0 \\ 0 & < p_y^2 > & < x^2 > & < x p_x > - < y p_y > \\ < p_y^2 > & 0 & < x p_x > + < y p_y > & < p_x^2 > \end{pmatrix}$$

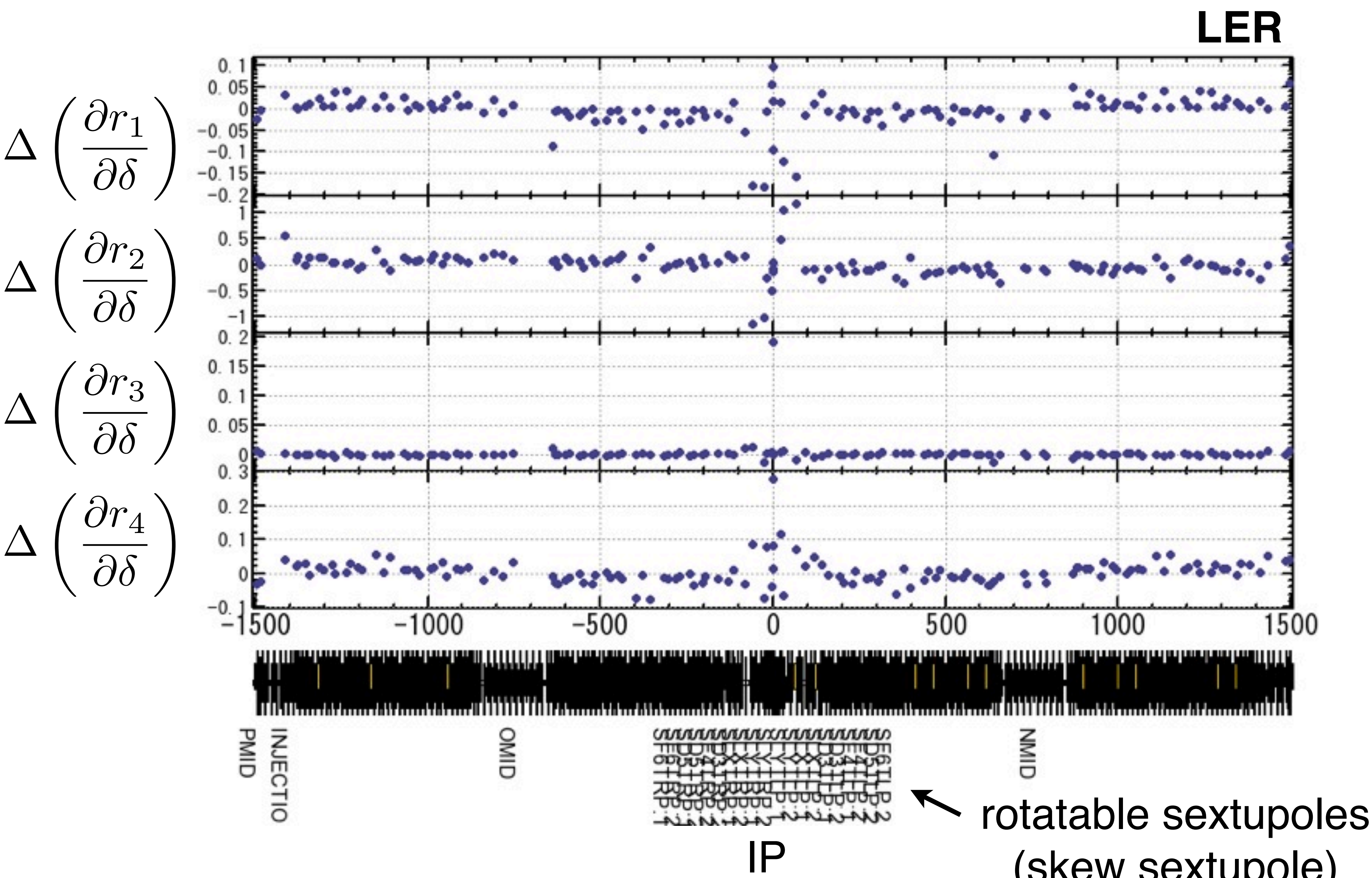
Measurement of chromatic X-Y coupling

- Example: one-pass BPM at QC1LP
- Measurement of X-Y coupling with rf-frequency shift ($-0.1<\delta<+0.1$ %)



Chromatic X-Y coupling

- In case that QC1LP has skew error filed of A3/B2 = 0.1 %
- Deviation of chromatic X-Y coupling at one-pass BPMs



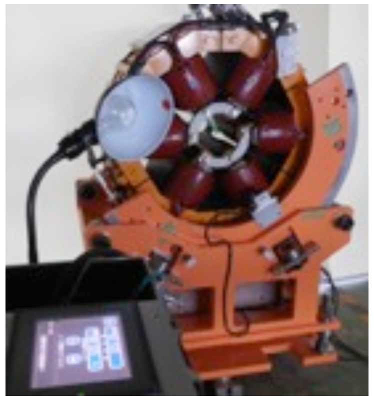
Correction of chromatic effects (1/2)

- If we can detect any deviation of chromatic phase-advance from the ideal lattice, we can correct them by using the sextupole corrector between QC1R and QC2R and normal sxtupoles(54 families).
- If we can detect any deviation of chromatic X-Y coupling from the ideal lattice, we can correct them by using the skew sextupole correctors at QC1/QC2 and 12 families of rotatable sextupoles(LER only) or 10 families of skew sextupoles in HER.
- We need to check sensitivity of the measurement and whether dynamic aperture can be recovered or not.
- These measurements and corrections are used for making an initial condition.
- Adiabatic tuning is still necessary during beam operation(day-by-day tuning). Downhill-simplex method and/or new algorithm are necessary.

Correction of chromatic effects (2/2)

- The orbit does not pass along a center at a sextupole magnet in general.
- If we change field strength of a sextupole, quadrupole and skew quadrupole fields are induced as a side effect.
- In order to preserve the optics before the change, quadrupole correctors neighbor of the sextupole and a skew quadrupole-like corrector at the sextupole should be adjusted properly.
- In the case of a rotatable sextupole, the situation becomes more complicated. Additional variables are a rotation angle and K-value to control a normal and skew element.
- Under developing a realistic procedure for the control-room operational usage.

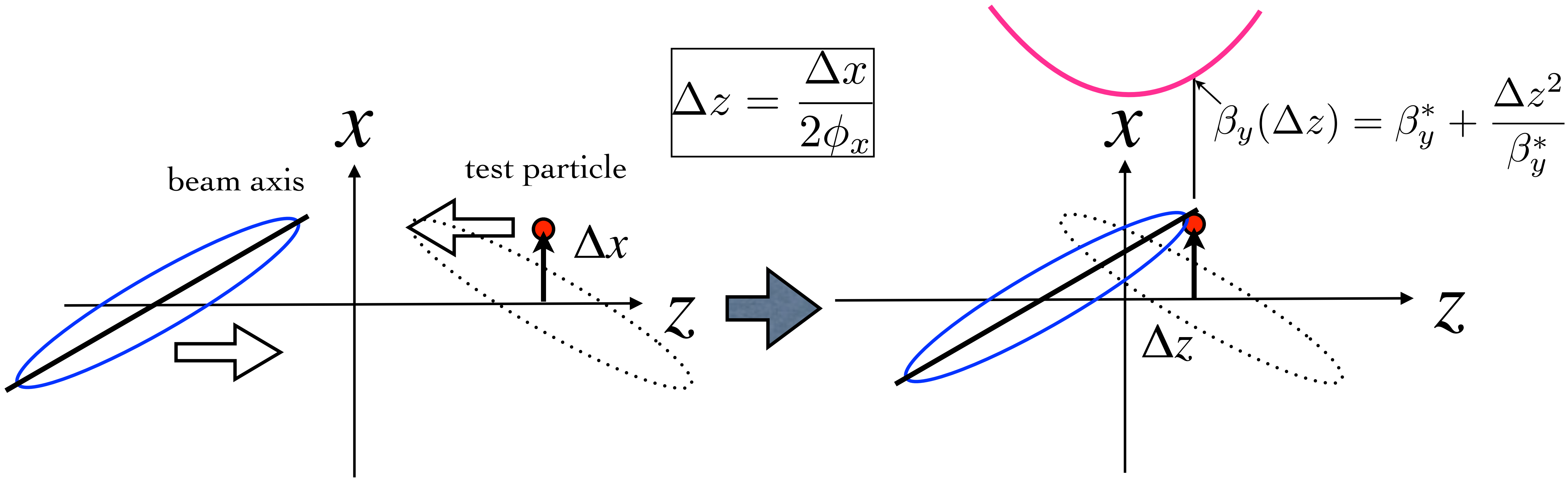
R1: The committee recommends concentrating on developing very detailed and robust procedures for correcting the closed orbit and linear optics distortions caused by realistic field errors, ... still the relevant statement now



Dynamic Aperture with Beam-Beam Effect

Beam-beam effect for large horizontal orbit

- The horizontal orbit(deviation from beam axis) is translated into the longitudinal displacement in the nano-beam scheme.



$$\Delta x = 30\sigma_{x0} \rightarrow \Delta z = 3.6\ mm$$

high vertical beta → $\beta_y(\Delta z) = 48\ mm >> \beta_y^* = 0.27\ mm$

$$\Delta y \propto \theta_y^{bb}\sqrt{\beta_y(\Delta z)}$$ ~factor of 180

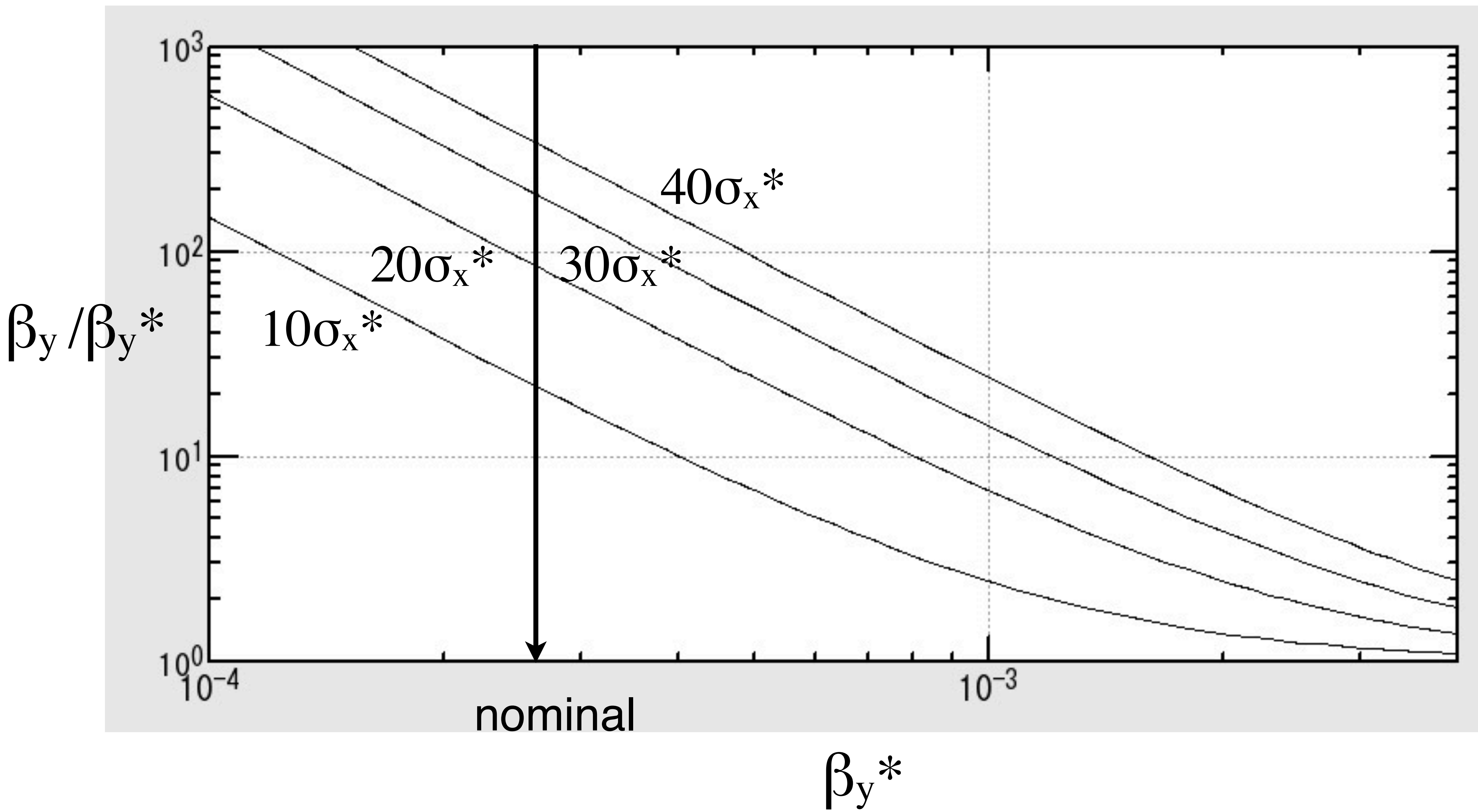
- Particles with a large horizontal orbit are kicked by beam-beam at high vertical beta region if there is a vertical orbit. Consequently, the vertical betatron oscillation increases due to the vertical beam-beam kick. The transverse aperture decreased, which implies small dynamic aperture.

Beta function at colliding point

Enhancement factor

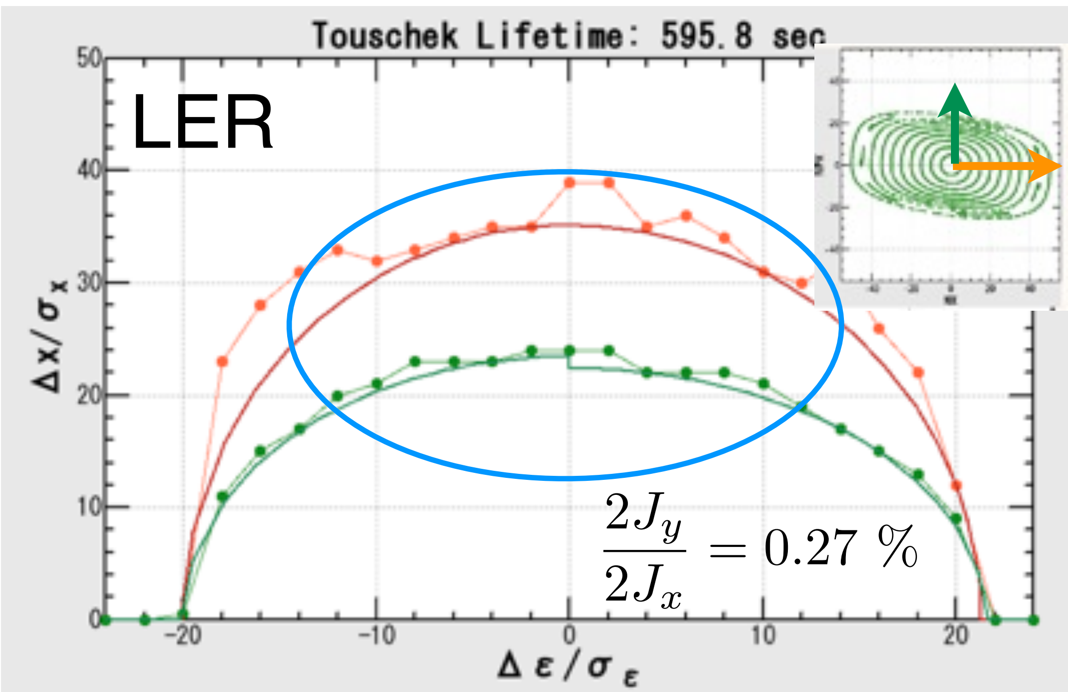
$$\frac{\beta_y(\Delta z)}{\beta_y^*} = 1 + \left(\frac{\Delta x}{2\phi_x \beta_y^*}\right)^2$$

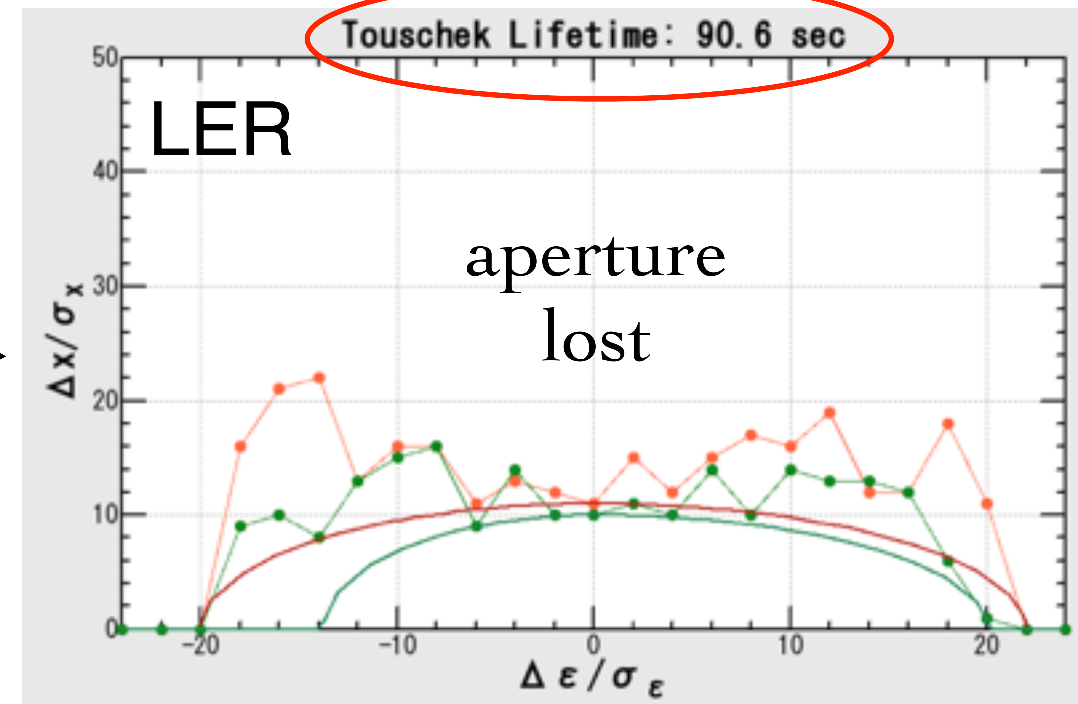
$\sigma_x^* = 10\ \mu m$



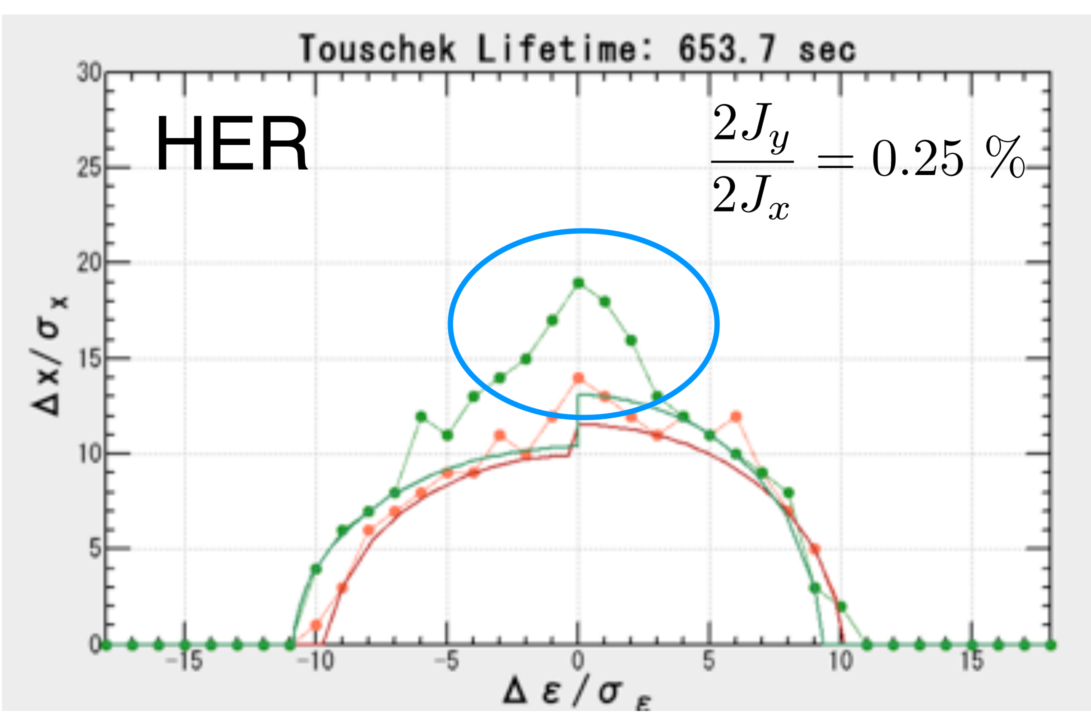
Difficulty in the Nano-Beam scheme

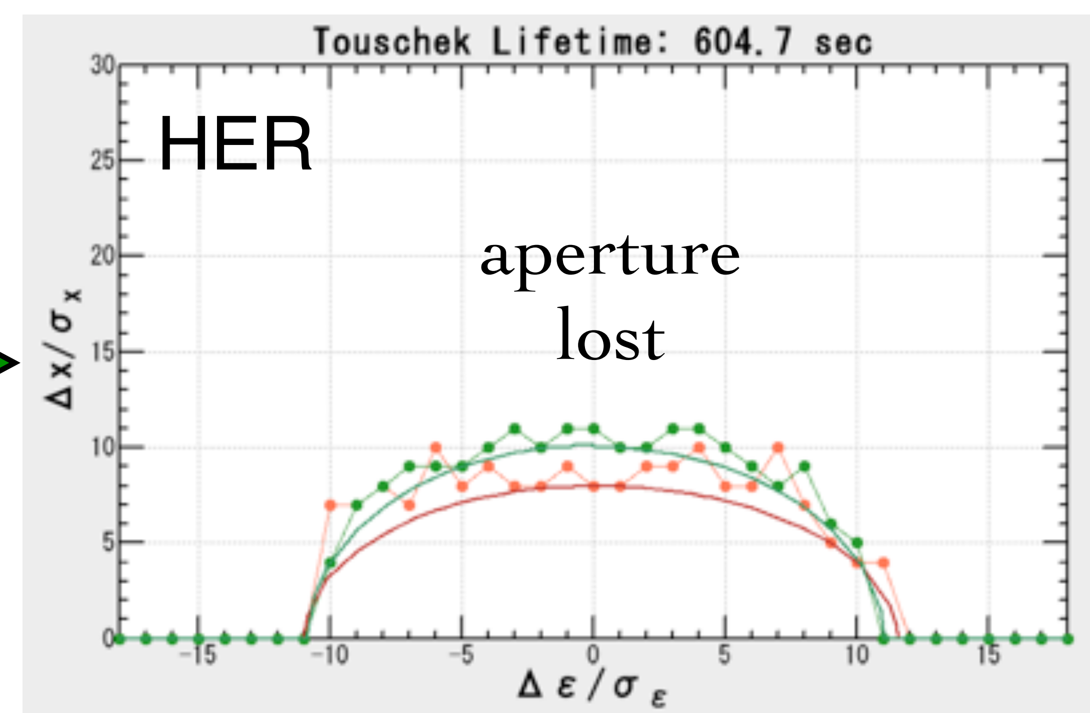
w/o beam-beam | **with beam-beam (W-S)**





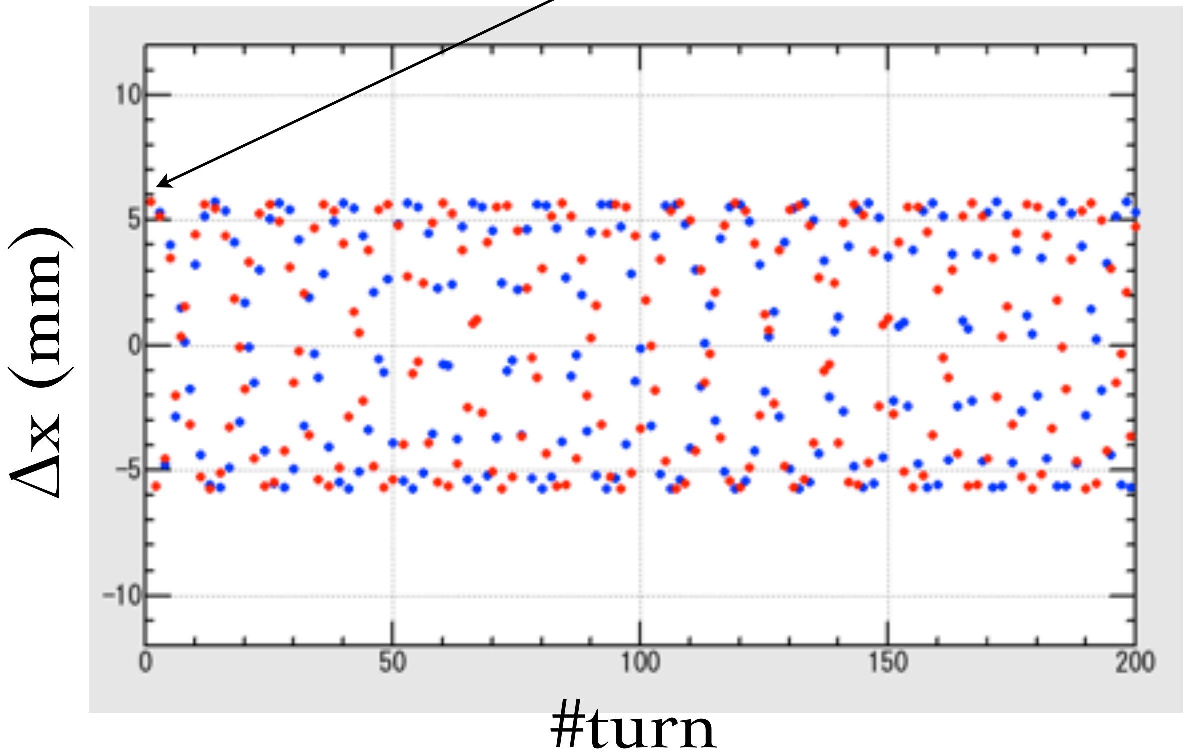
Transverse aperture is reduced significantly.





Tracking simulation for single particle

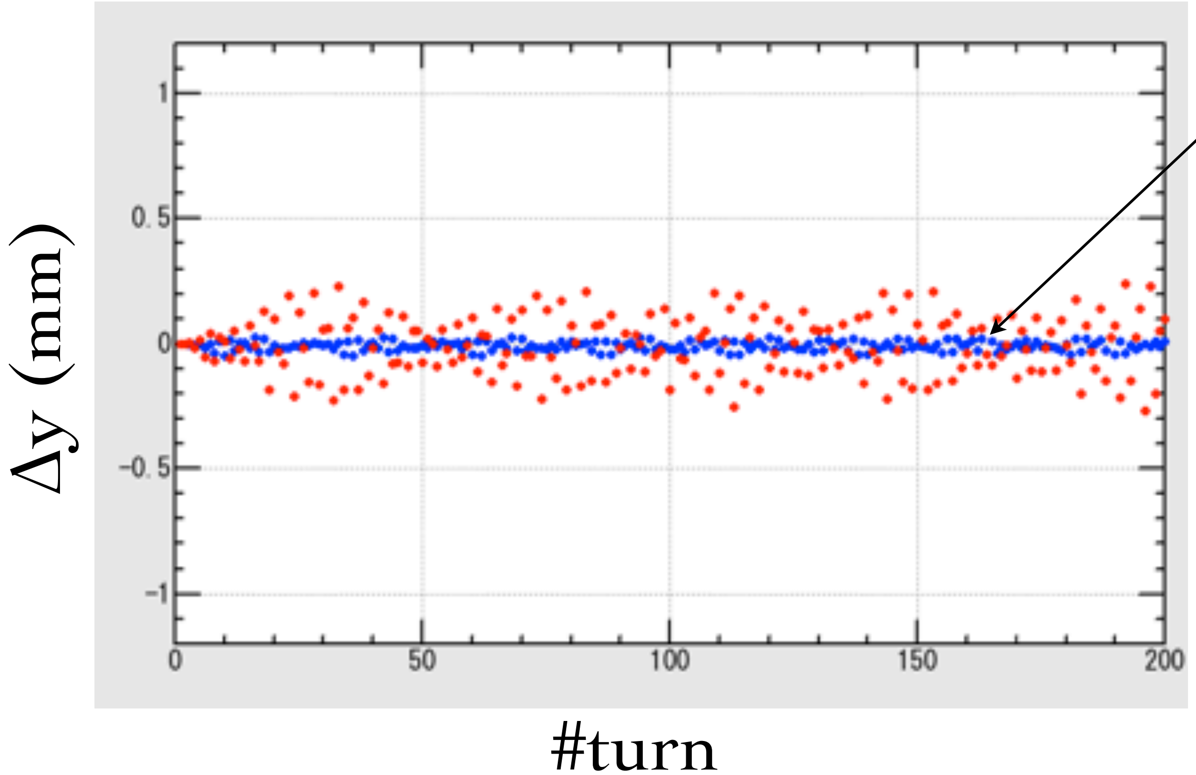
Initial orbit is **10 sigmas** in the horizontal direction and **0** for the vertical direction



blue: no beam-beam

red: with beam-beam

Horizontal betatron oscillation is stable for both case.

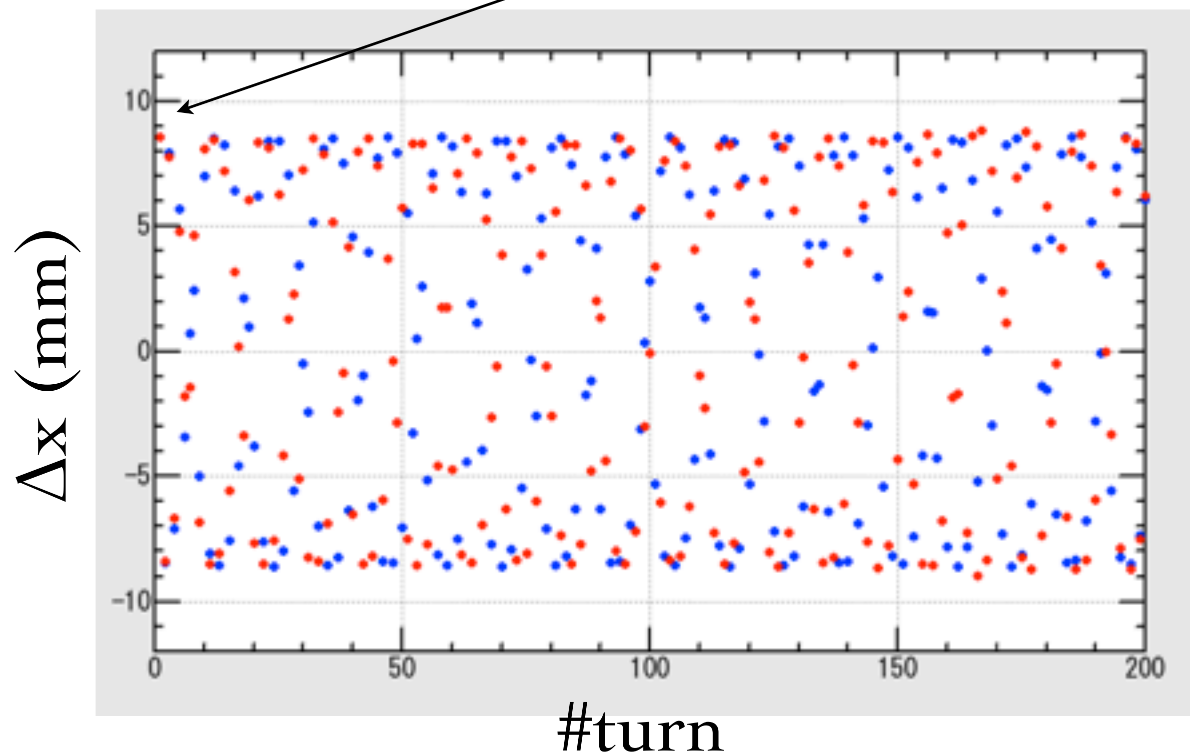


The vertical oscillation exists for the case w/o beam-beam, since there is a X-Y coupling.

Vertical betatron oscillation is stable for beam-beam effect.
The amplitude is slightly large.

Tracking simulation: beam-beam effect

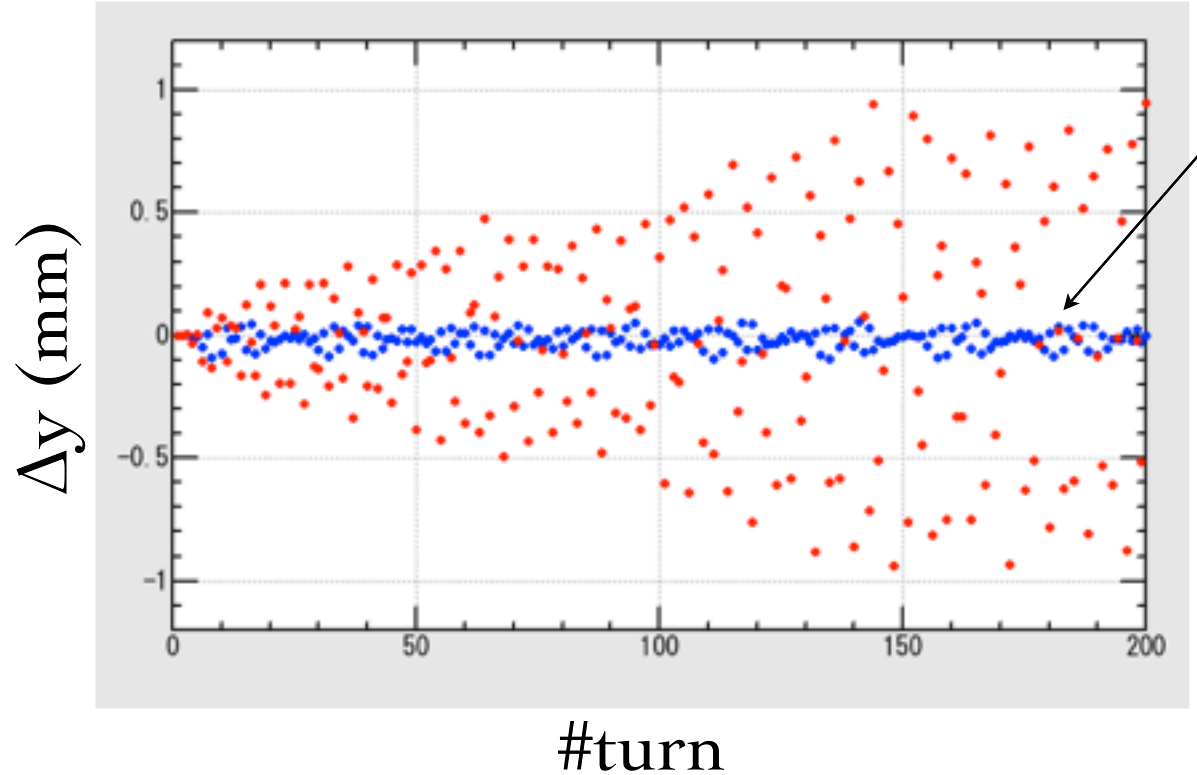
Initial orbit is **15 sigmas** in the horizontal direction and **0** for the vertical direction



blue: no beam-beam

red: with beam-beam

Horizontal betatron oscillation is stable for both case.

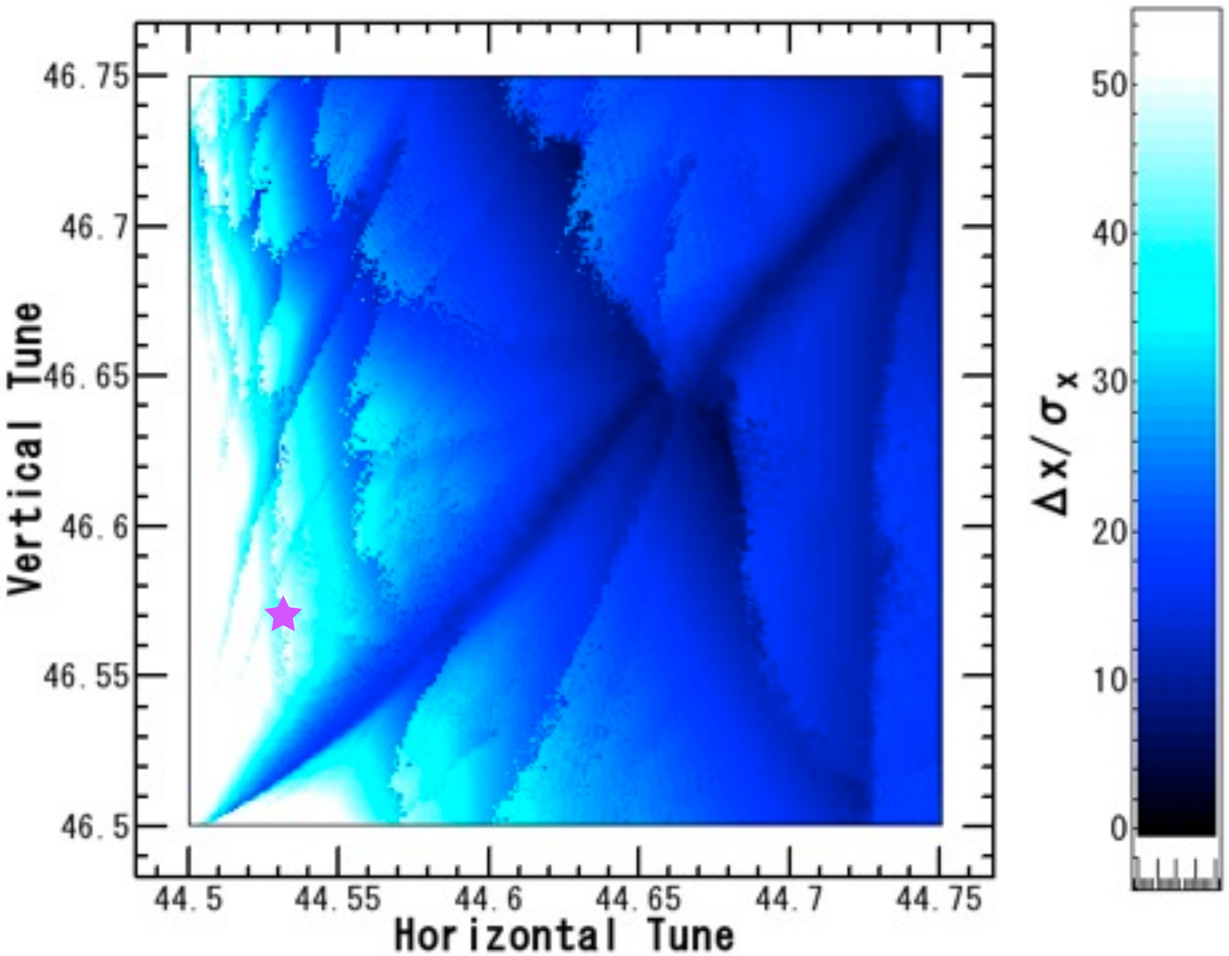


The vertical oscillation exists for the case w/o beam-beam, since there is a X-Y coupling.

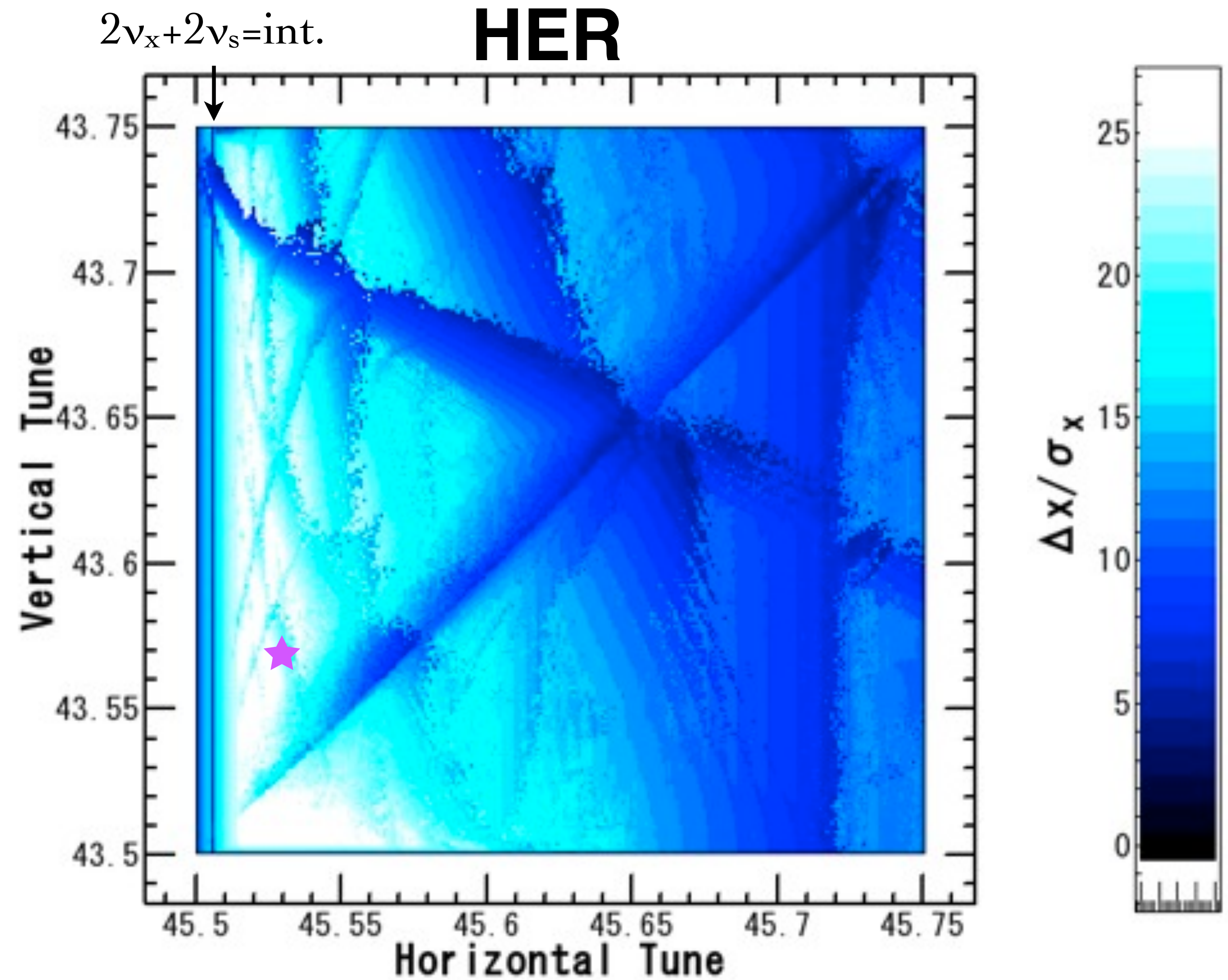
Vertical betatron oscillation is unstable for beam-beam effect.

Tune survey: No beam-beam effect

LER



HER



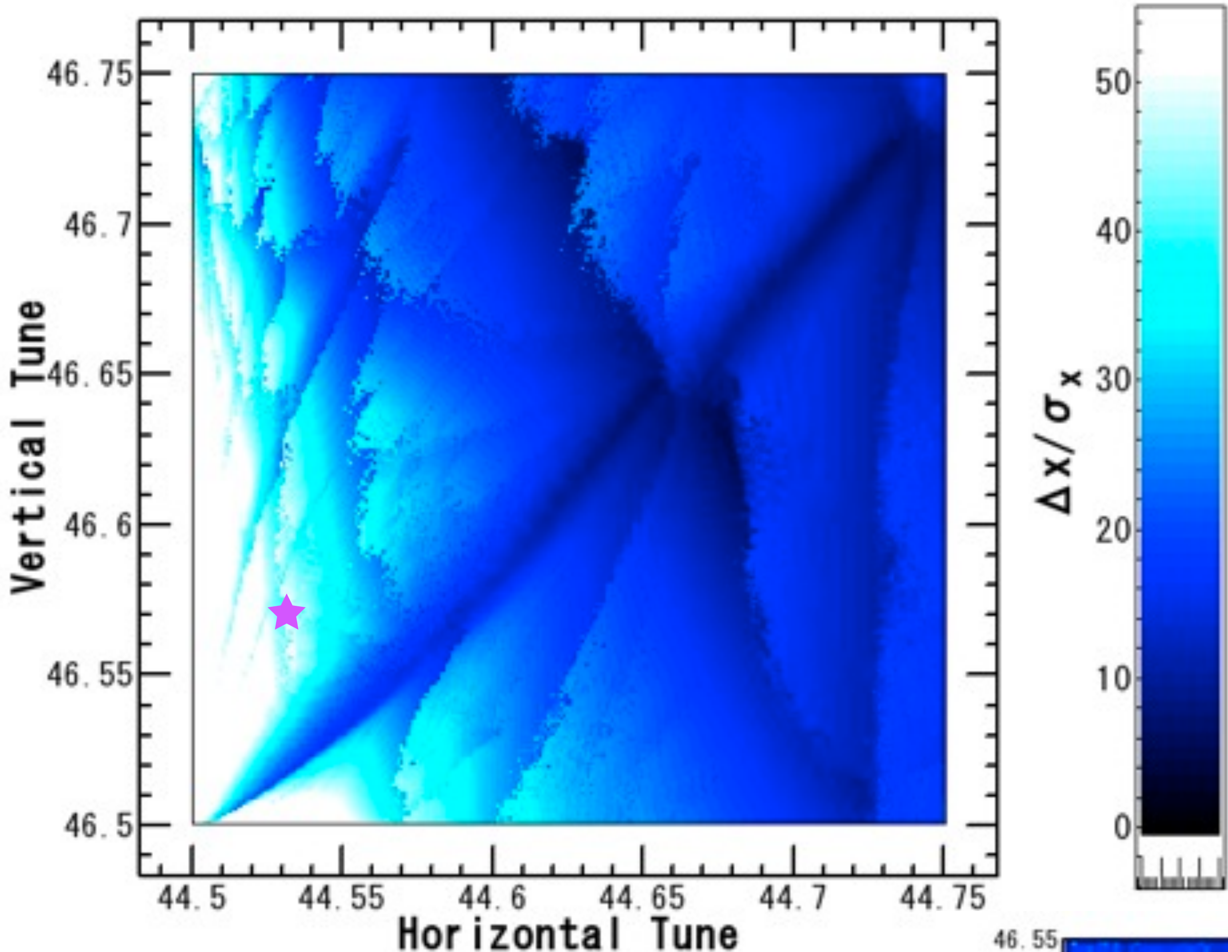
★$(\nu_x, \nu_y)=(44.53, 46.57)$

★$(\nu_x, \nu_y)=(45.53, 43.57)$

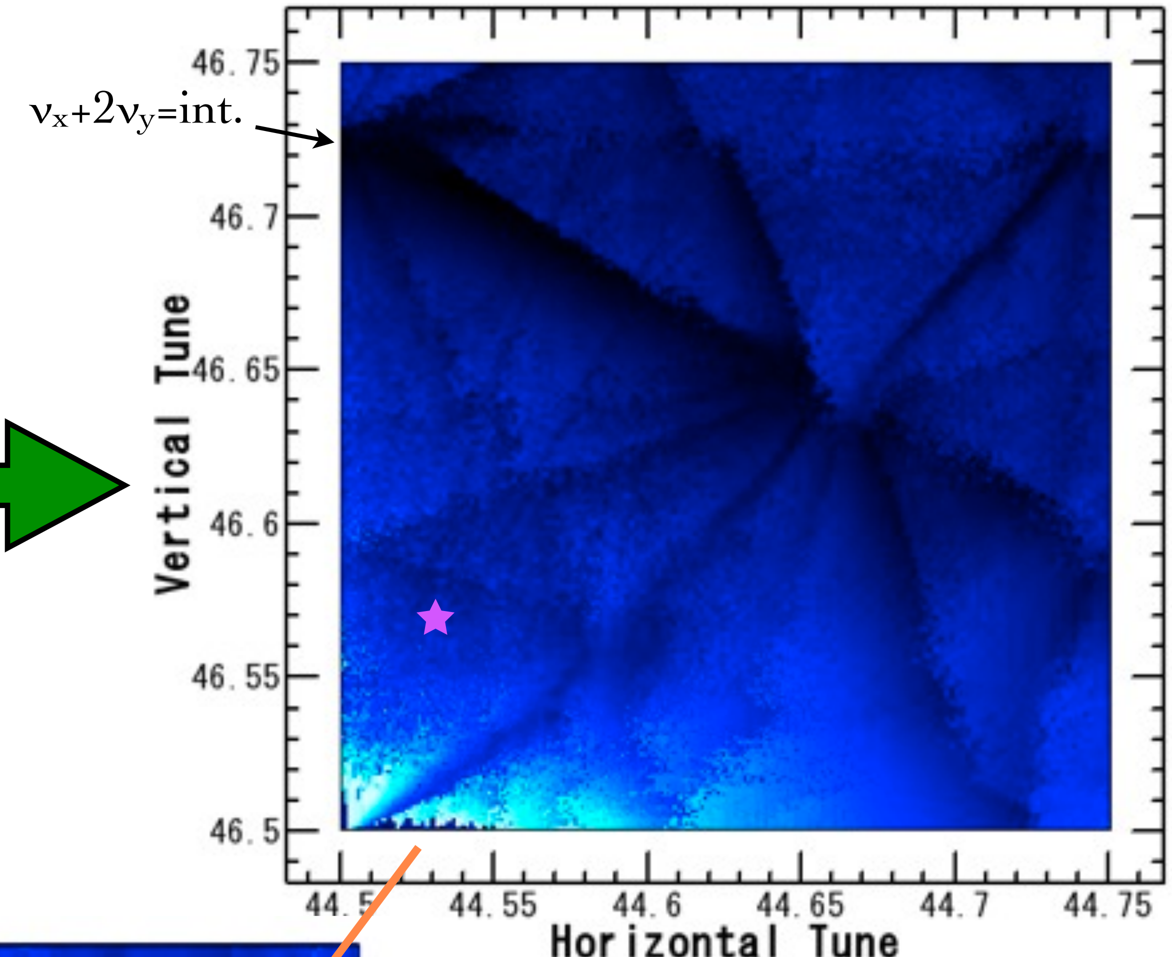
Single-beam operation (no beam-beam effect)
Lighter color indicates larger dynamic aperture (**only for on-momentum**).
Nominal working point is .53 for the horizontal and .57 for the vertical direction.

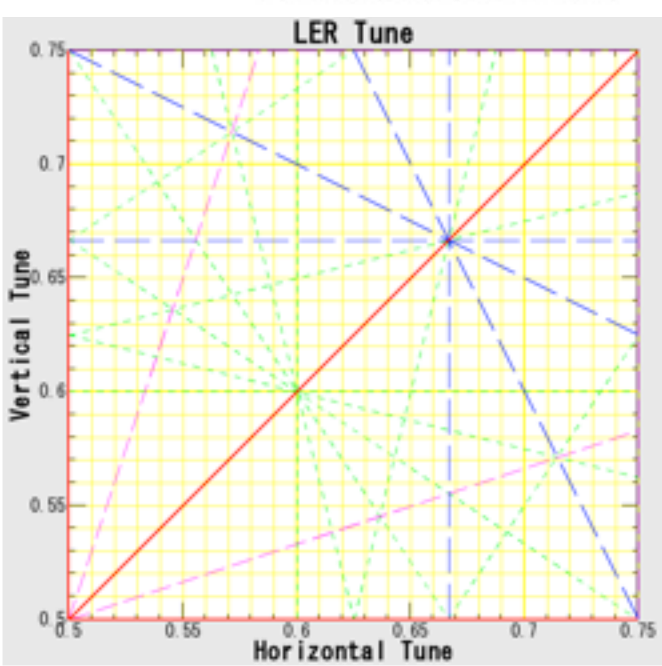
LER tune survey: Beam-beam effect

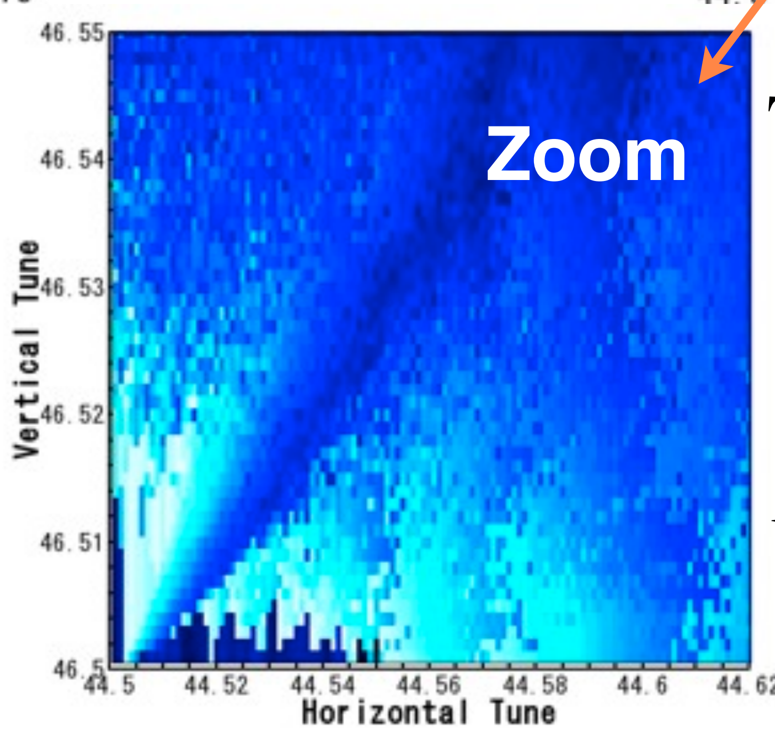
LER: w/o beam-beam



LER: with beam-beam





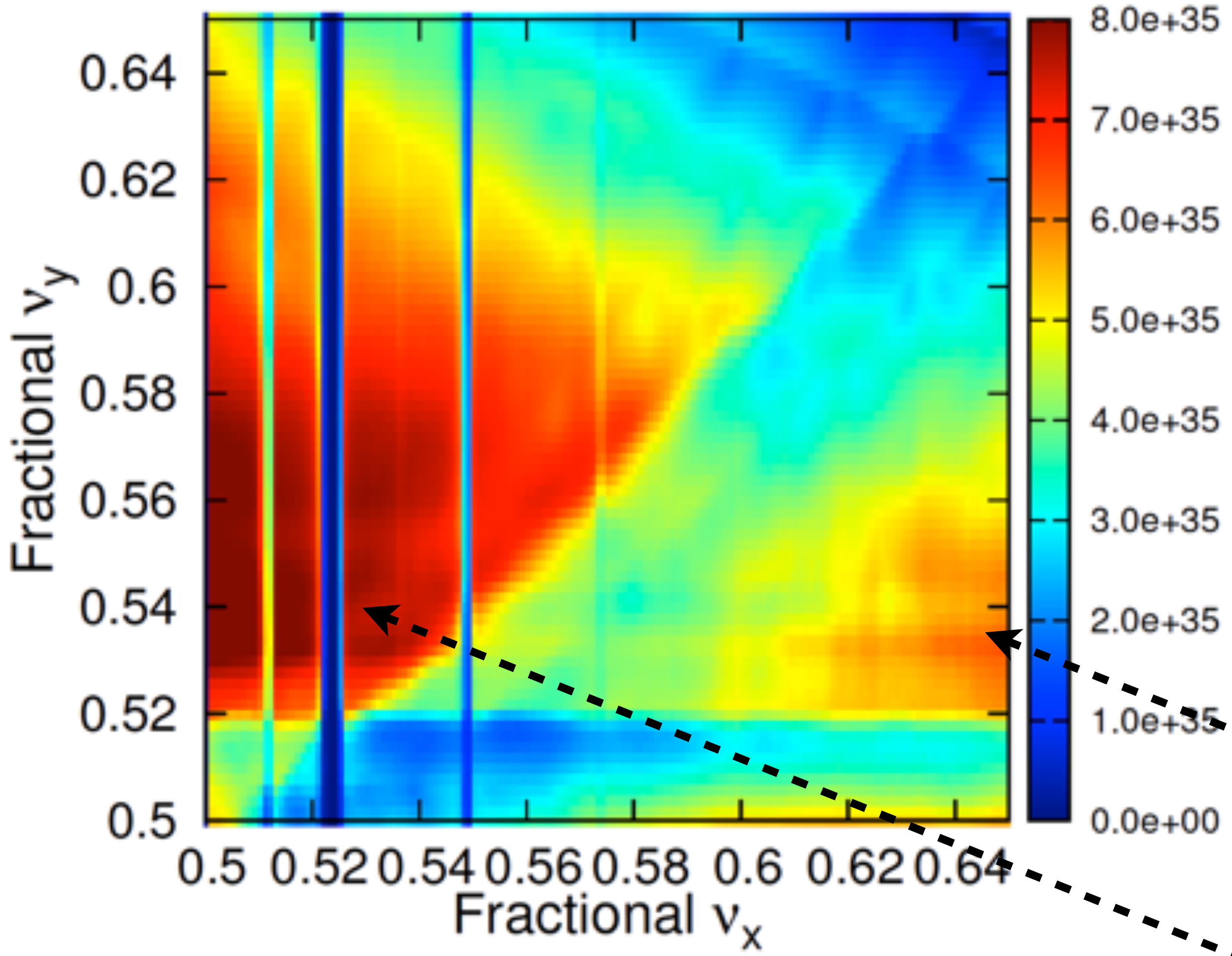


There is a good region near half integer resonance for the vertical tune.

Chromaticity correction becomes very difficult near half integer.

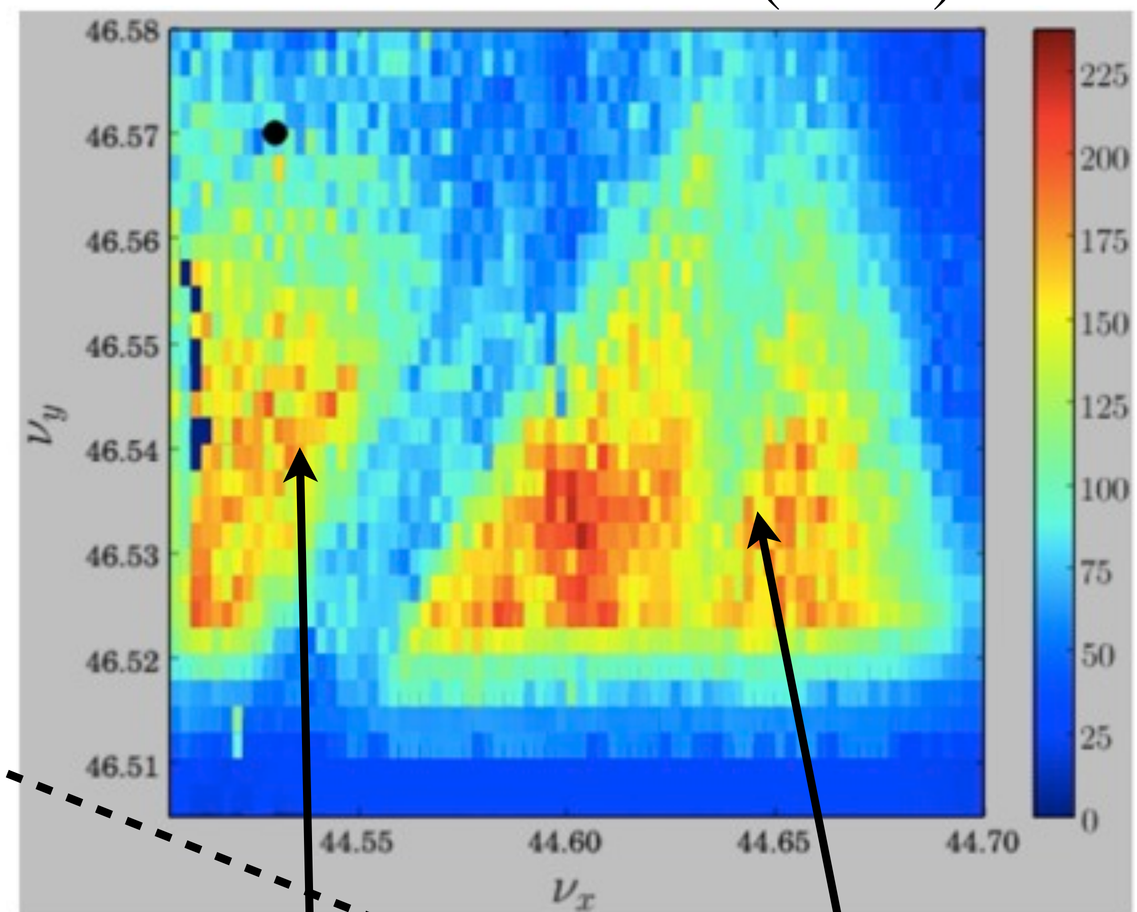
Better working point for Touschek lifetime ?

Luminosity (W-S model)



D. Zhou **w/o lattice nonlinear**

Touschek lifetime (LER)



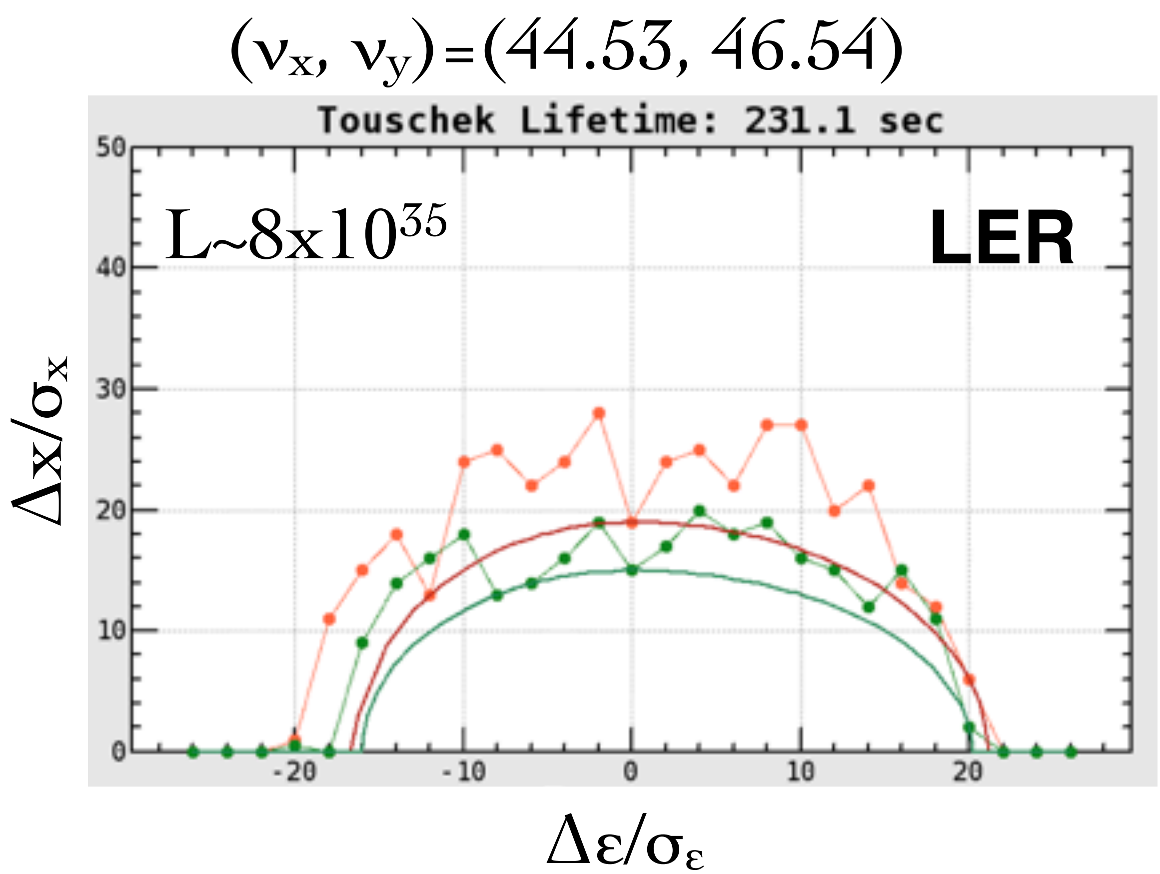
H. Sugimoto

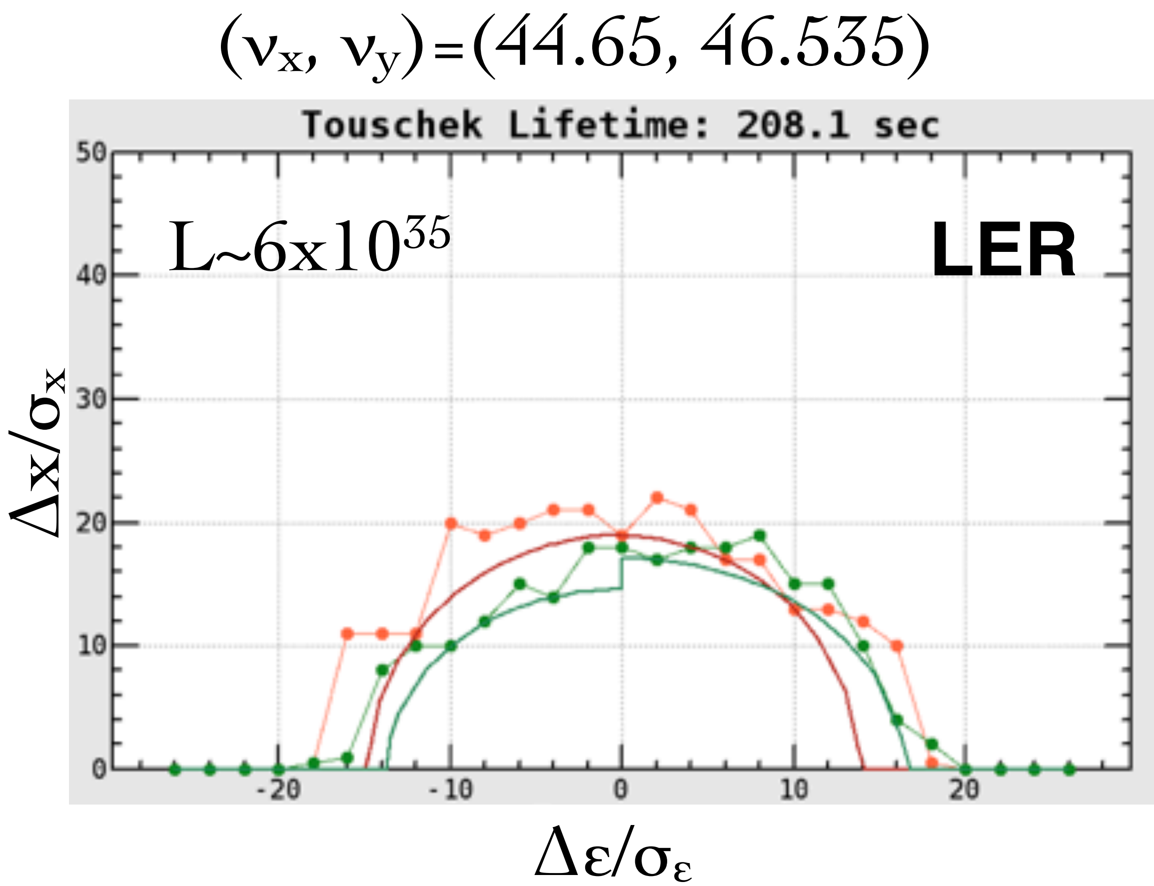
Candidates are (44.53,46.54) and (44.65,46.535)

L~8x10^{35} L~6x10^{35}

Optimization of DA with beam-beam effect

H. Sugimoto





Optimization is done by sextupoles, skew sextupoles, and octupoles.
Touschek lifetime is improved up to 230 sec. Still short lifetime.

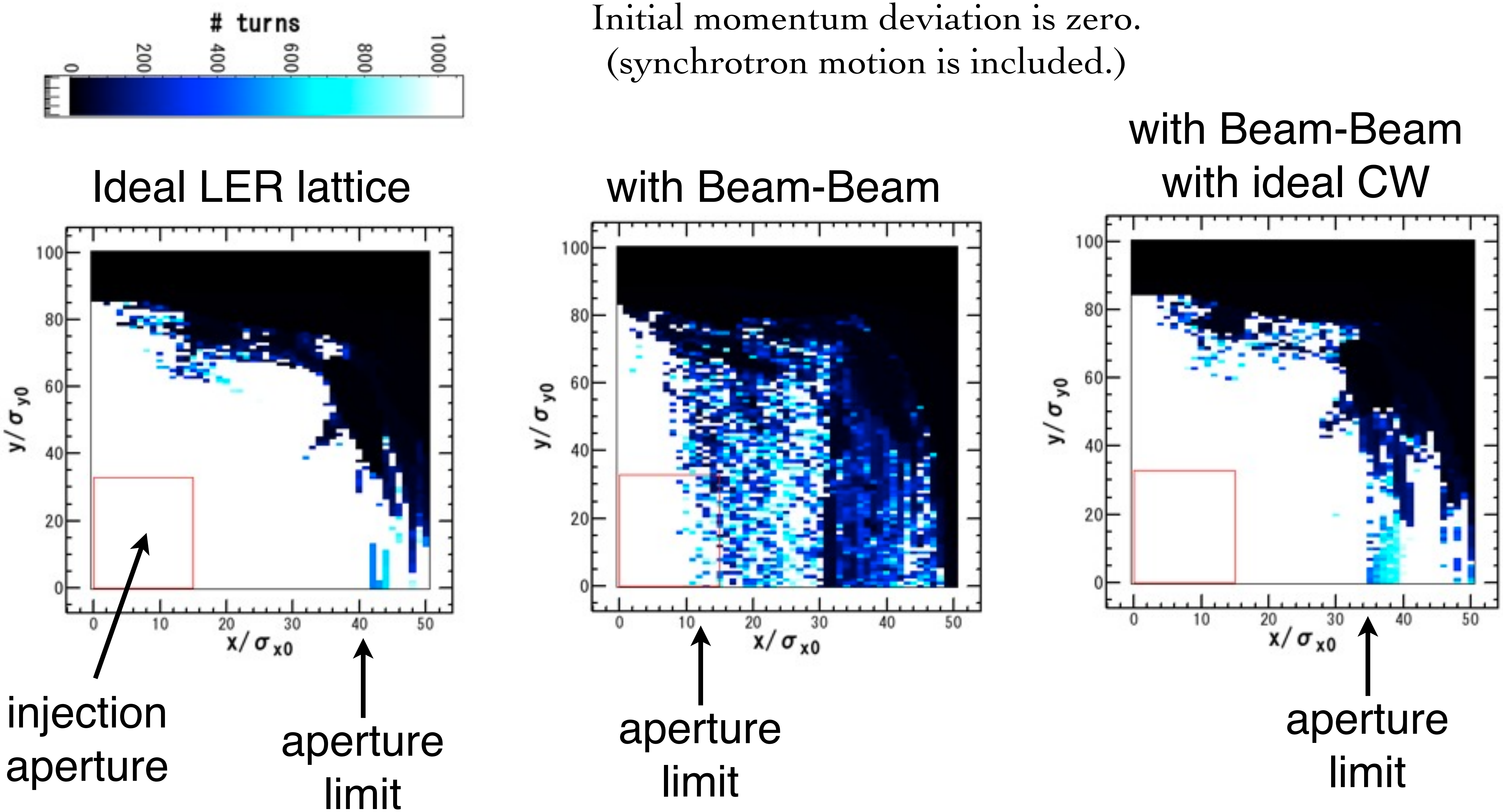
Crab-waist scheme to mitigate DA reduction with Beam-Beam effect ?

- Ideal crab-waist has a potential to mitigate this effect. (only solution)
- But a real crab-waist consists of sextupoles has a serious issue.

Dynamic aperture with beam-beam and ideal CW

Stability of an initial amplitude in the horizontal and vertical plane.

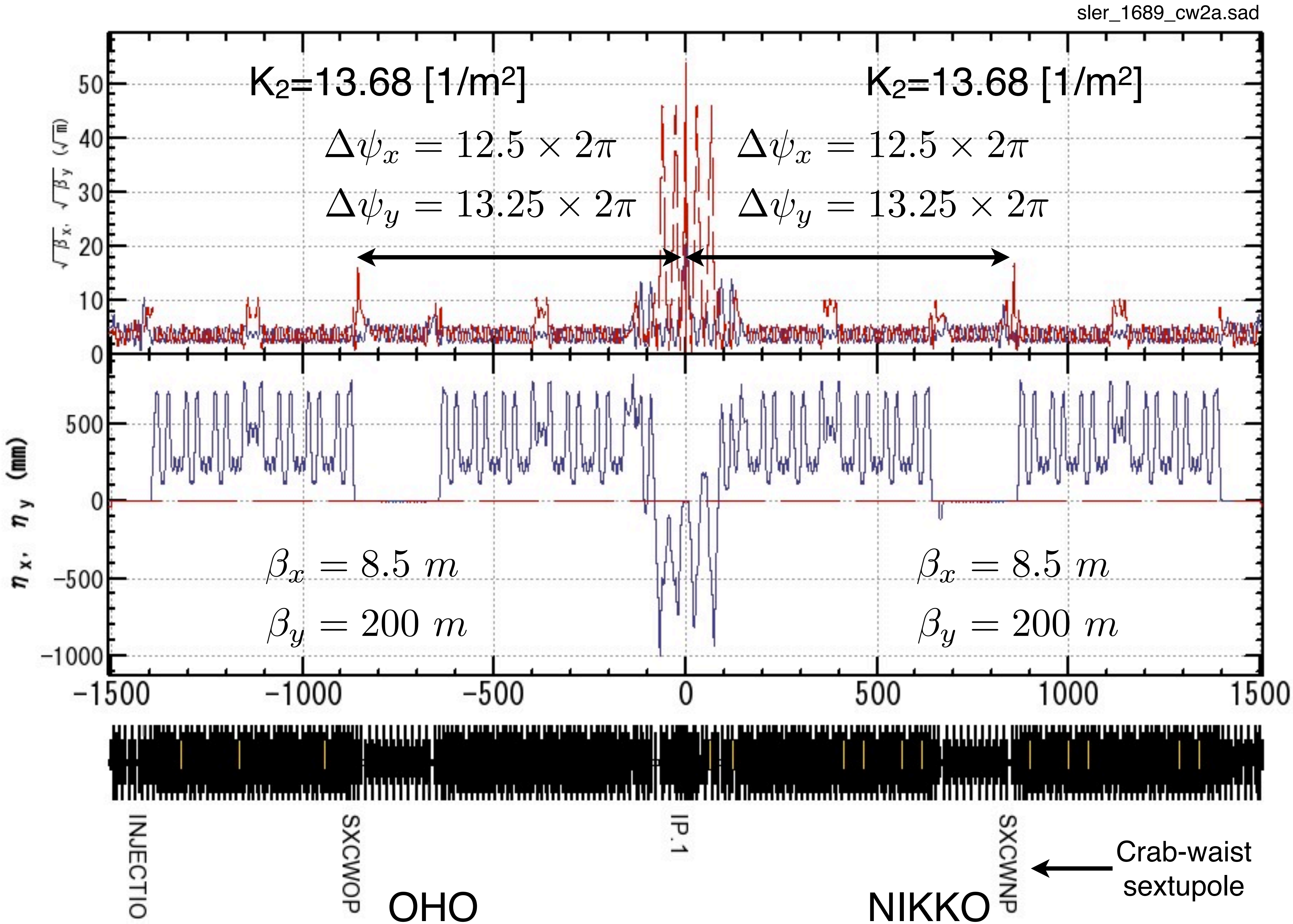
Initial momentum deviation is zero.
(synchrotron motion is included.)



Ideal crab-waist is a map of $f_{BB} \rightarrow f_{CW}(+\lambda) f_{BB} f_{CW}(-\lambda)$ $\quad \lambda = \dfrac{1}{\tan 2\phi_x}$

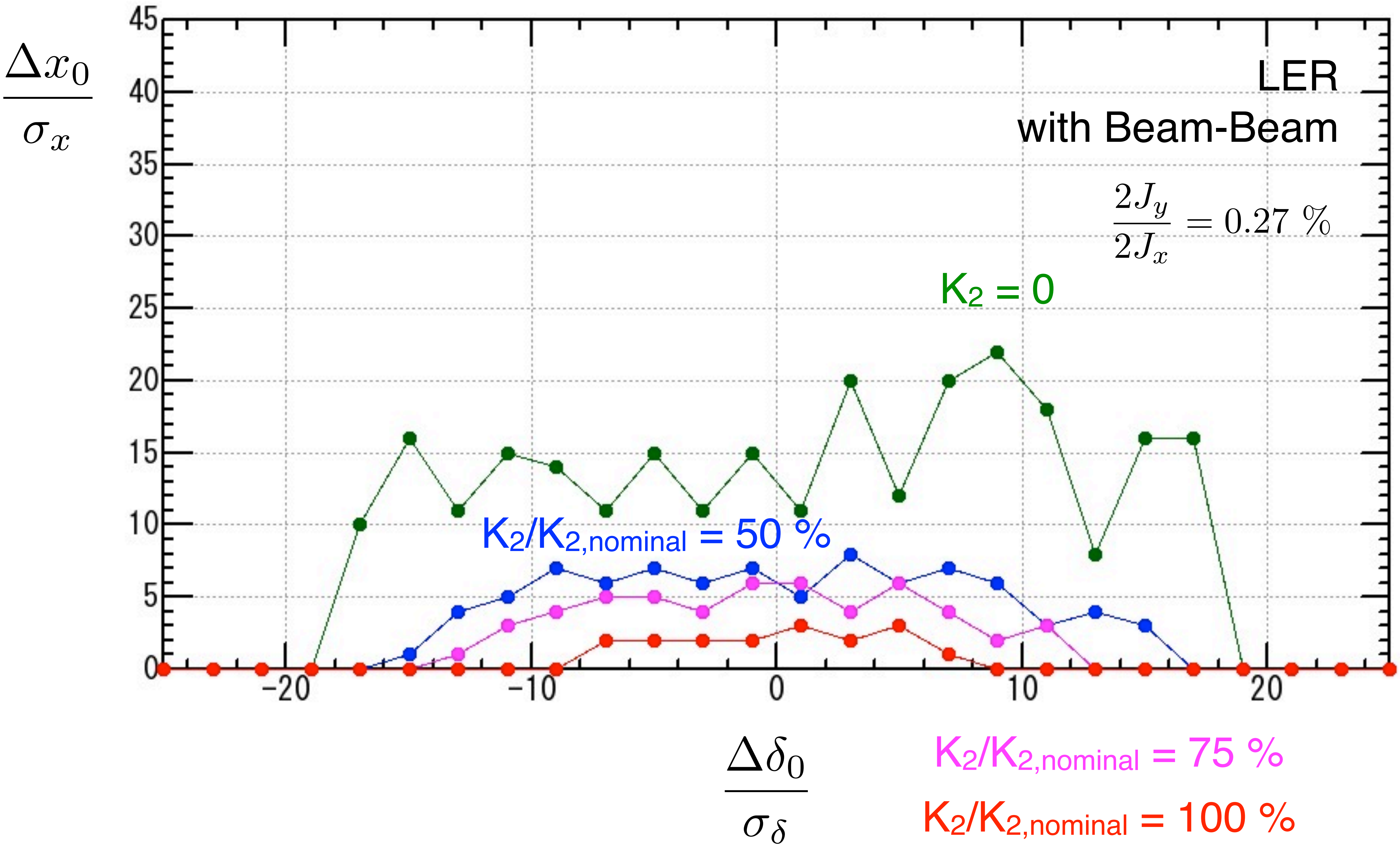
$$f_{CW}(\lambda) : p_x \rightarrow p_x + \frac{\lambda}{2} p_y^2, \;\; y \rightarrow y - \lambda x p_y$$

Crab-waist optics in LER



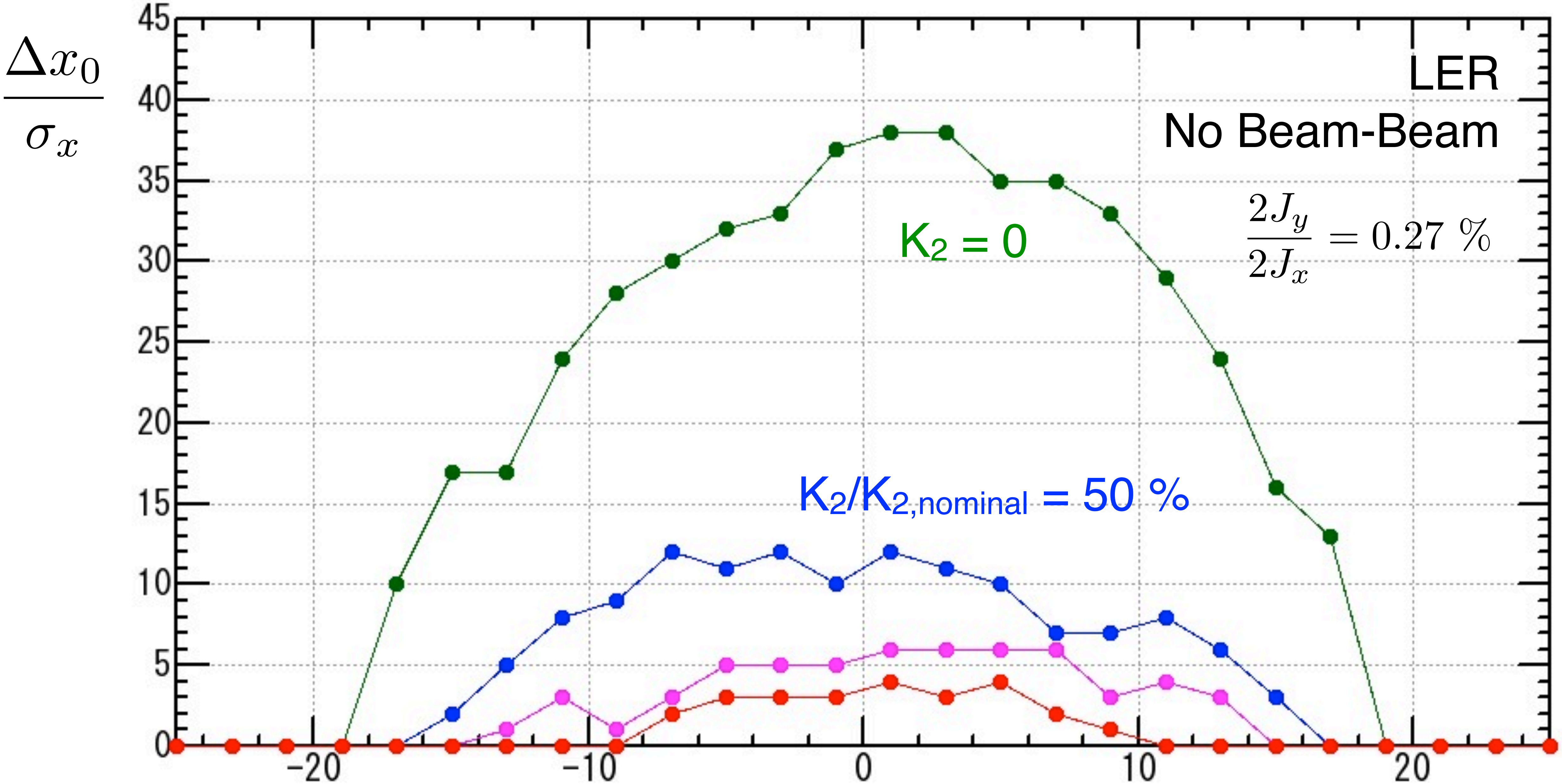
Dynamic aperture in realistic crab-waist

Crab-waist sextupole reduces dynamic aperture under the influence of beam-beam effect.



Dynamic aperture in realistic crab-waist

Crab-waist sextupole reduces dynamic aperture
without beam-beam effect significantly.



$$H_{SX} = -9871x^{*3} + 6x^{*}p_y^{*2}$$

The x^3 term does not affect DA.

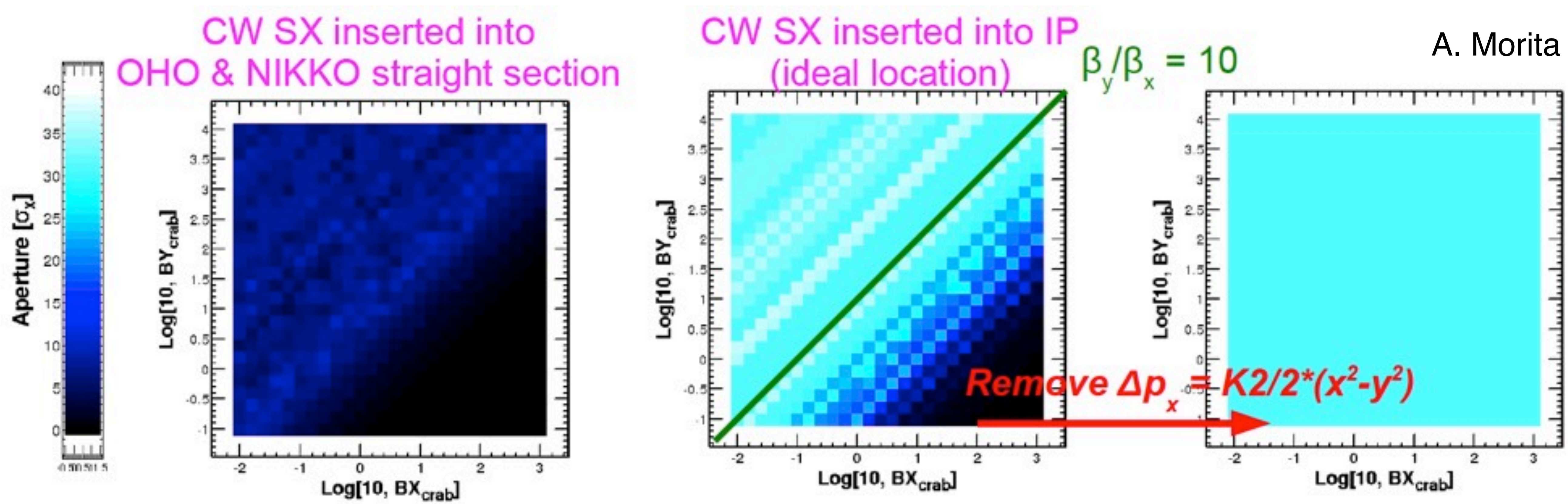
$\frac{\Delta\delta_0}{\sigma_\delta}$

$K_2/K_{2,nominal} = 75\ \%$

$K_2/K_{2,nominal} = 100\ \%$

Simple IR and crab waist (1/2)

- Simple IR: No solenoid, B_1=0, A_1=0, A_2=0, no offset and rotation of QC1/2, Bn and An (n>3) are non-zero



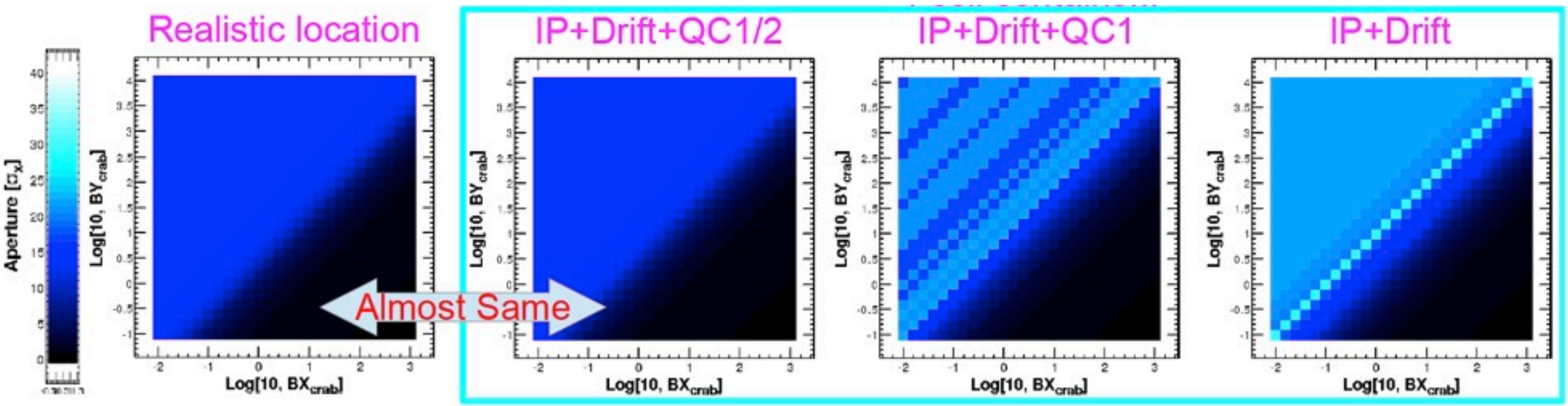
- Dynamic aperture depends on the location of CW sextupole, realistic location does not work. There are QC1 and QC2 between IP and CW sextupole.

- Ratio of βy to βx at CW sextupole should be larger than 10.

Simple IR and crab waist (2/2)

- Simple IR: No solenoid, B_1=0, A_1=0, A_2=0, no offset and rotation of QC1/2, no multipoles, QCs have B_2 only.

A. Morita



CW sextupole in NIKKO and OHO | QC1 and QC2 between CW I-cell | QC1 only between CW I-cell | No QCs between CW I-cell

- Dynamic aperture still depends on the location of CW sextupole, even though QCs are the simple **simple quadrupoles**.
- Nonlinear maxwellian fringe of QCs and kinematic term at drift space between CW I-cell reduce the dynamic aperture significantly.

Summary

- We checked the performance of optics corrections with a realistic machine error. correction of COD , X-Y coupling, dispersions, beta functions.
- The vertical emittance can be recovered to be almost that of the ideal lattice.
- However, dynamic aperture can not be recovered by the *traditional* optics corrections.
- New technique is necessary to fix the dynamic aperture issue.
- Dynamic aperture with beam-beam is still the serious issue.
- Crab-waist is a possible cure, but nonlinear Maxwellian fringe and kinematic term between CW sextupole and IP reduce the dynamic aperture. No solution so far.

$$x_2 = x_1 + \frac{p_{x1}}{p_{s1}} l \quad p_s = \sqrt{p_t^2/c^2 - m^2c^2 - p_x^2 - p_y^2}$$

The longest journey begins with a single step.

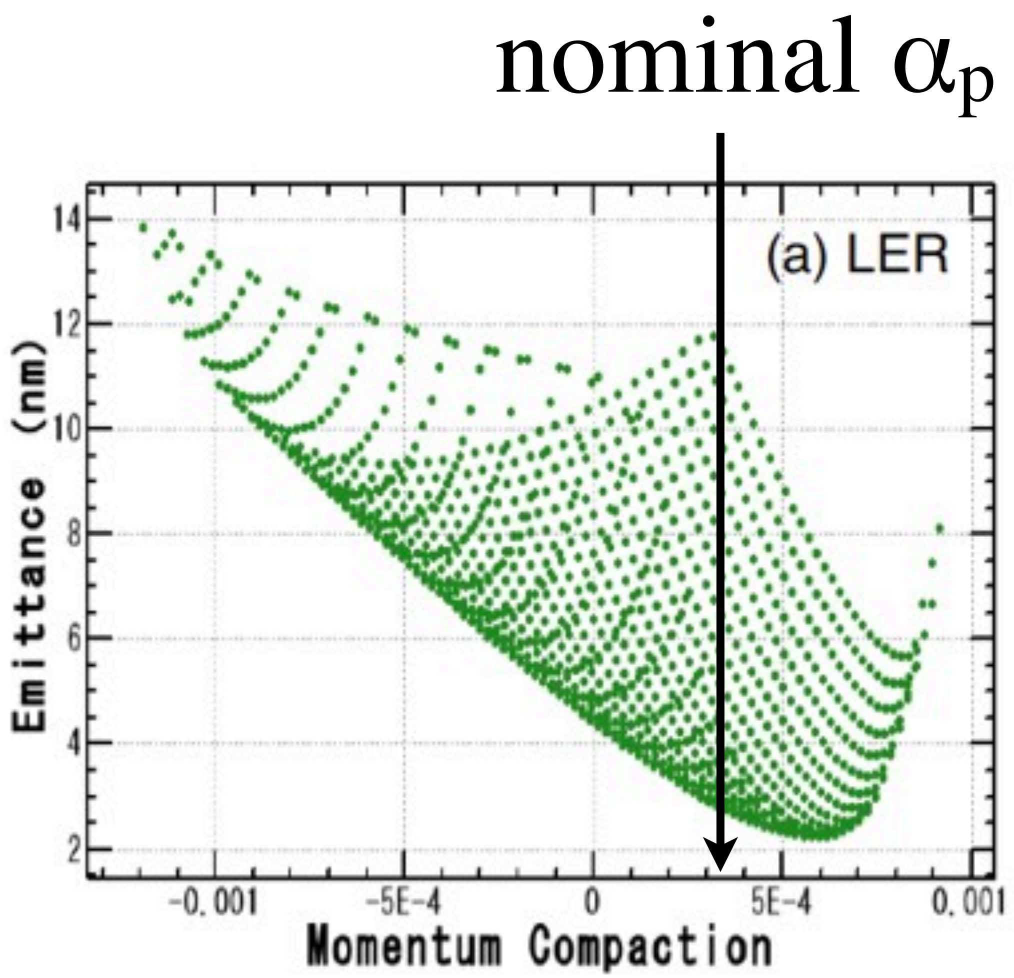
千里の道も一歩から。

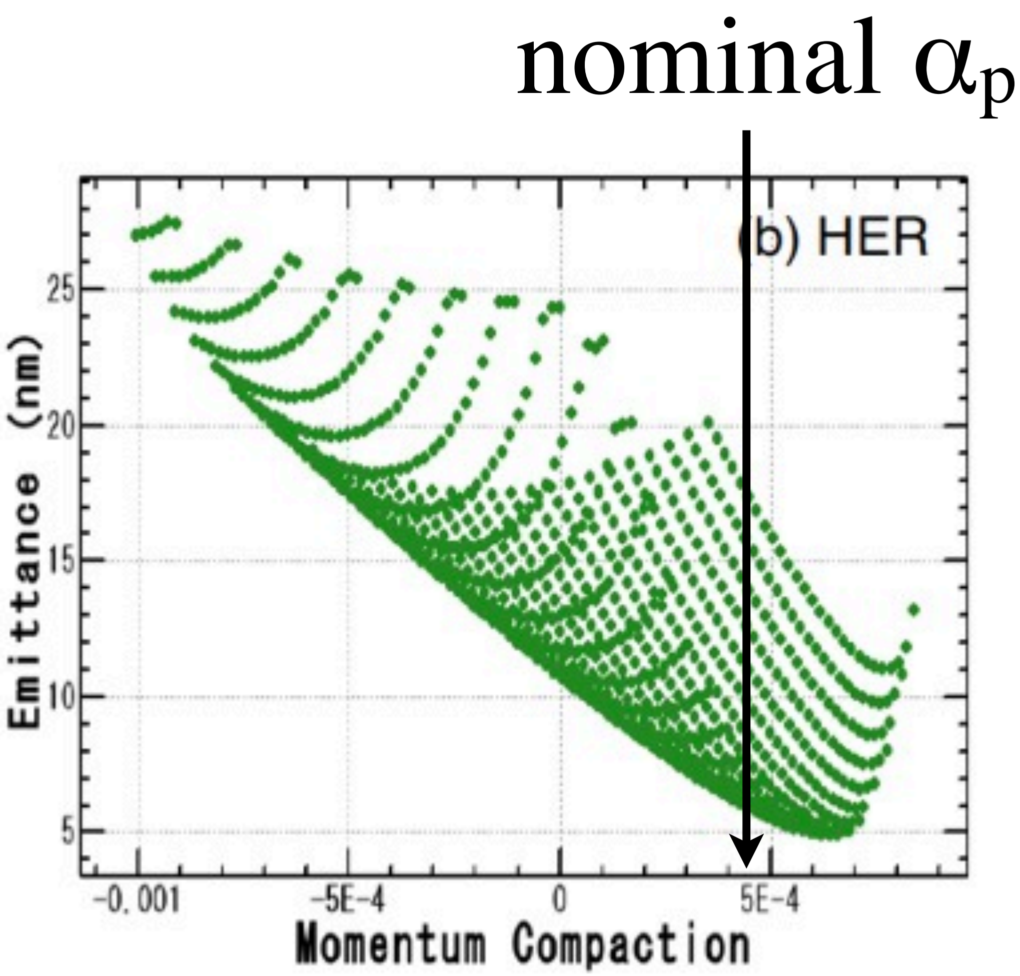
Commissioning and Lattice Preparation

phase	sub-phase	IR status	lattice, commissioning	I_b (mA)
Phase 1	Phase 1.1	No QCS No Belle II	wiggler off, device check, optics tuning, vacuum scrub.	< 30-100
	Phase 1.2		wiggler on, circumference, optics tuning	< 30
	Phase 1.3		high emittance for **vacuum scrubbing** (LER)	500-1000
	Phase 1.4		**optics tuning (low emittance)**	< 30
Phase 2	Phase 2.1	QCS Belle II w/o VXD	vertical beta* = 80 mm, optics and injection tuning	< 30
	:		:	:
	Phase 2.x		vertical beta* = 2.2 mm, **optics and luminosity tuning**	1000/800
Phase 3	Phase 3.1	QCS Belle II with VXD (Physics Run)	vertical beta* = 2.2 mm, optics and luminosity tuning	1000/800
	:		:	:
	Phase 3.x		**ultimate beta***, optics and luminosity tuning	3600/2600

Emittance change in arc

- Emittance of arc cell can be changed by field strength of quadrupols.
- Range is from 2 to 12 nm in LER and from 5 to 17 nm in HER, respectively.



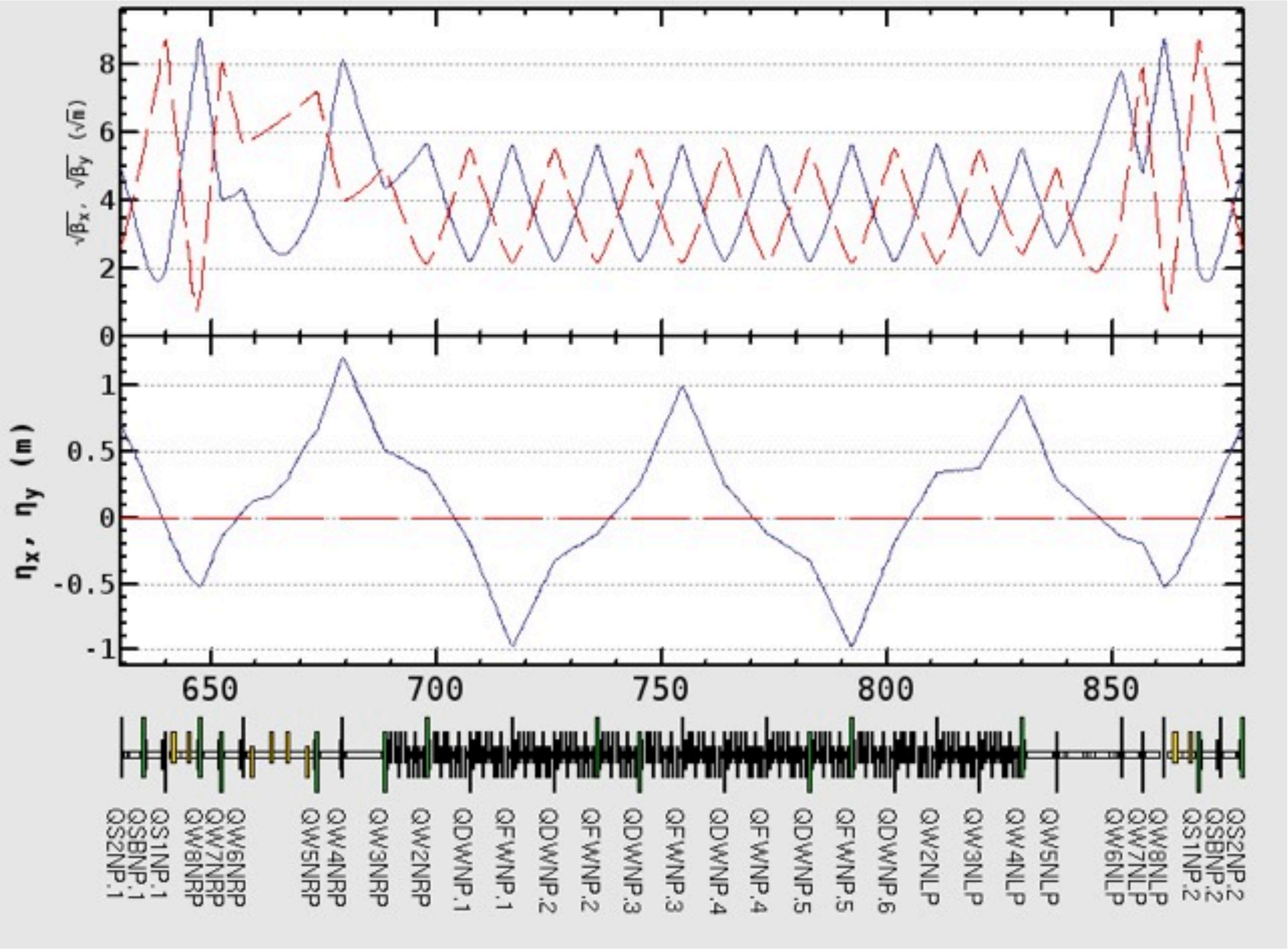


LER: Emittance change in wiggler section

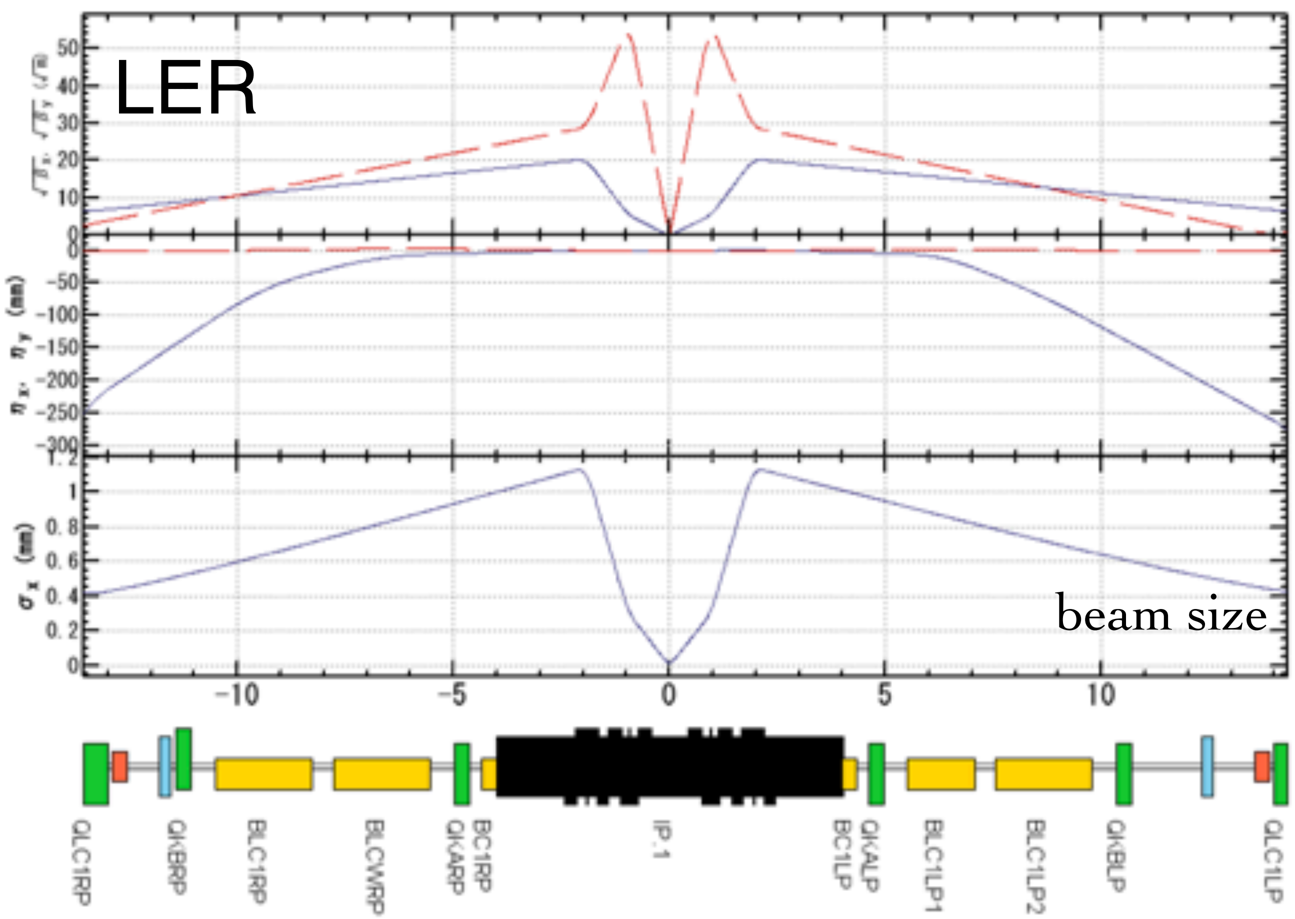
- Emittance can be adjusted by optics in Nikko section(No cavity).
- Only adjust field strength of the quadrupole magnets
- Emittance becomes 20* nm in case of 1 m dispersion at midpoint the straight section.

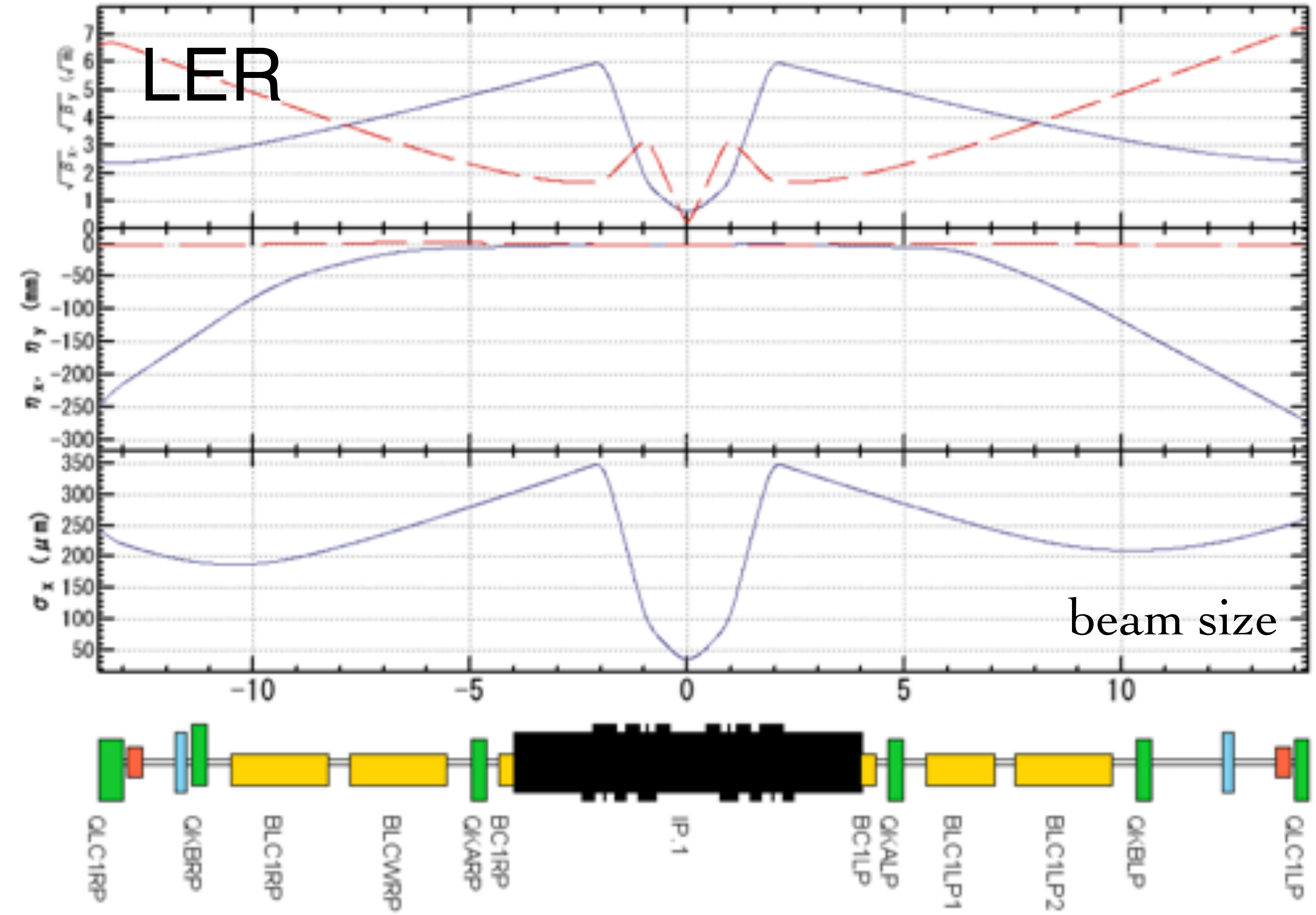
LER: Nikko

* without intra-beam scattering



Phase 3.x $\beta_x^* = 32\ mm$ $\beta_y^* = 0.27\ mm$ → Phase 2.1 $\beta_x^* = 400\ mm$ $\beta_y^* = 80\ mm$





Phase 3.x	Phase 2.1
σ_x = 1100 μm at QC2	σ_x = 350 μm at QC2
r_b = 35 mm at QC2	r_b = 35 mm at QC2
r_b/σ_x = 31 (linear calc.)	r_b/σ_x = 100 (linear calc.)

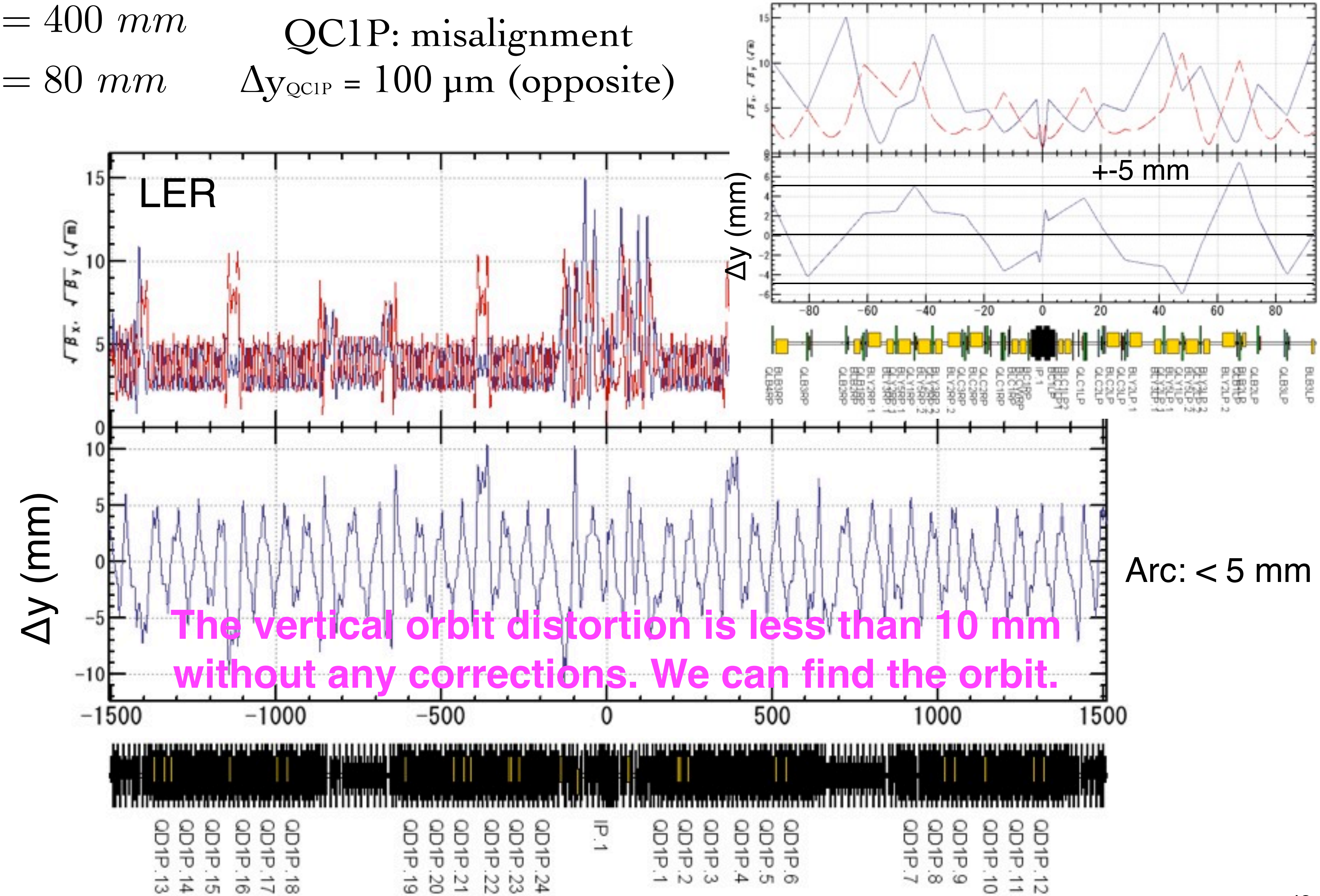
KEKB $\beta_x^* = 590\ mm$ $\beta_y^* = 5.9\ mm$

$\beta_x^* = 400\ mm$

$\beta_y^* = 80\ mm$

QC1P: misalignment

Δy_{QC1P} = 100 μm (opposite)



The vertical orbit distortion is less than 10 mm without any corrections. We can find the orbit.

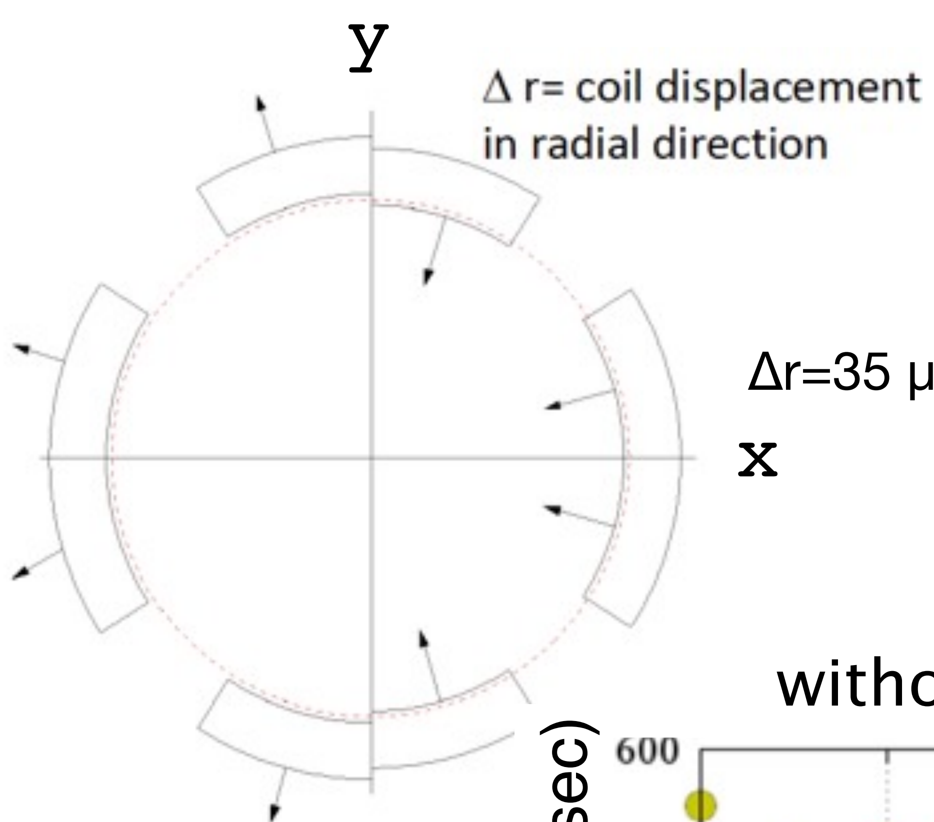
Machine parameters with QCS

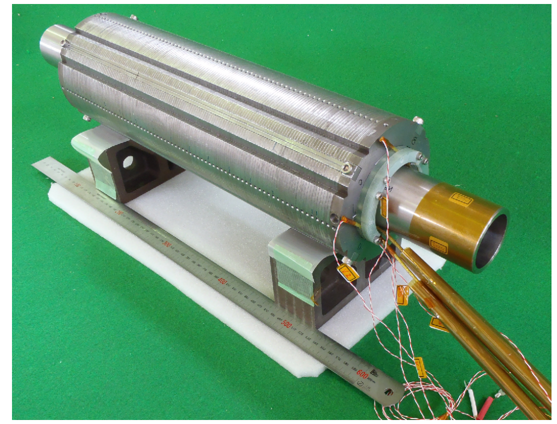
Parameters	symbol	Phase 2.x (Pilot run)		Phase 3.x (Ultimate)		unit
		LER	HER	LER	HER	
Energy	E	4	7.007	4	7.007	GeV
#Bunches	n_b	2500		2500		
Emittance	ε_x	2.2	5.2	3.2	4.6	nm
Coupling	$\varepsilon_y/\varepsilon_x$	2	2	0.27	0.28	%
Hor. beta at IP	β_x^*	128	100	32	25	mm
Ver. beta at IP	β_y^*	2.16	2.4	0.27	0.30	mm
Bunch current	I_b	1.0	0.8	3.6	2.6	A
Beam-beam	ξ_y	0.0240	0.0257	0.088	0.081	
Hor. beam size	σ_x^*	16.8	22.8	10	11	μm
Ver. beam size	σ_y^*	308	500	48	62	nm
Luminosity	L	1×10^{34}		8×10^{35}		$cm^{-2}s^{-1}$

Y. Funakoshi

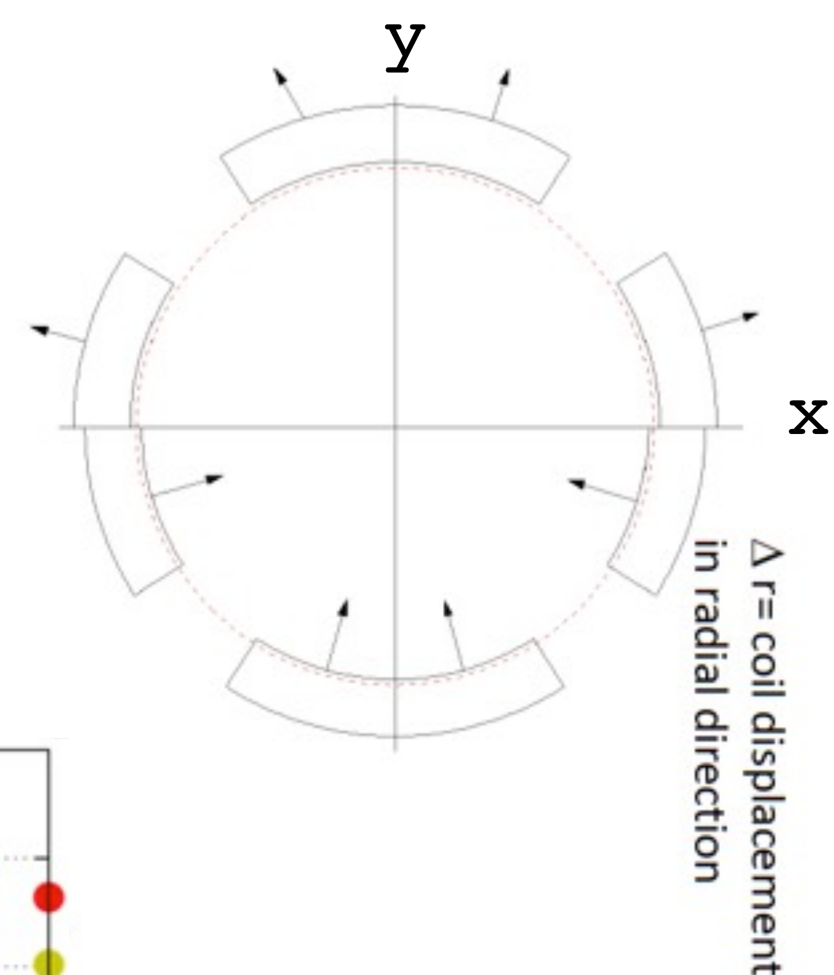
Misalignment of quadrupole coils in QC1 and QC2

Sextupole field





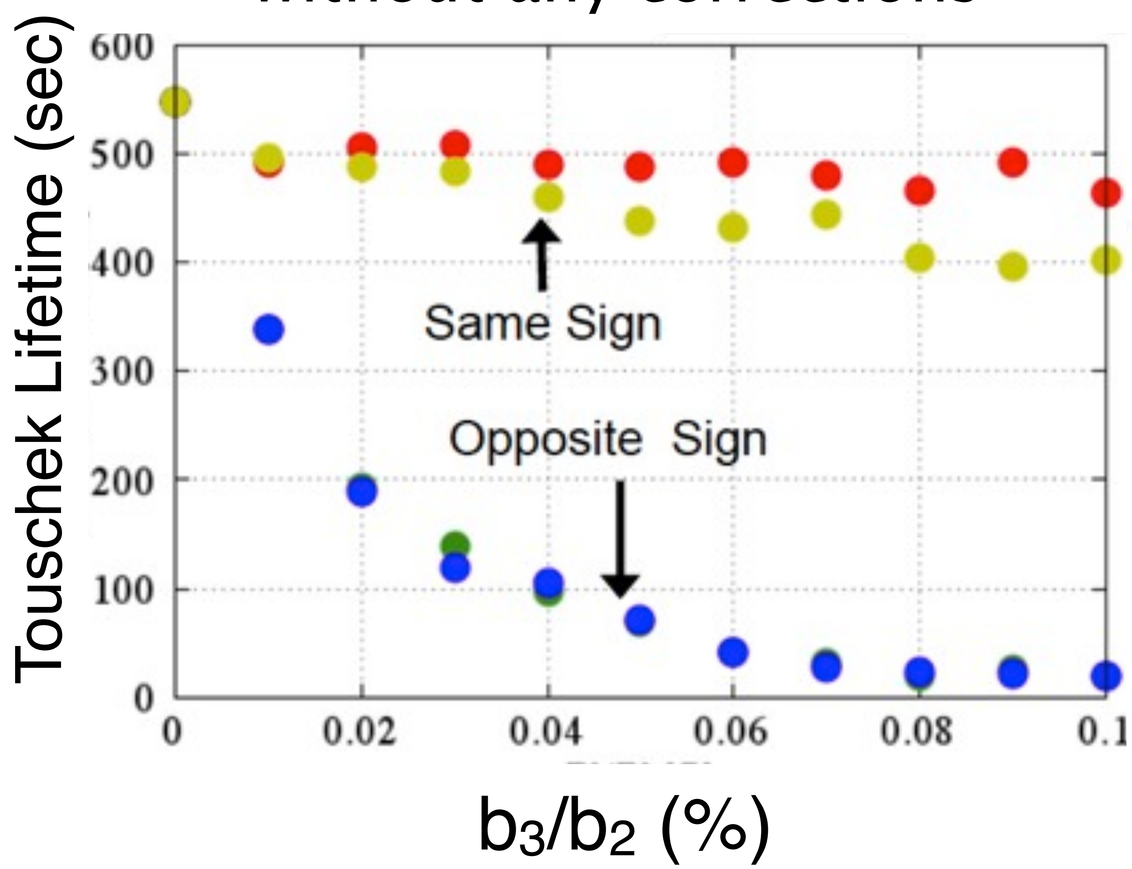
Skew sextupole field

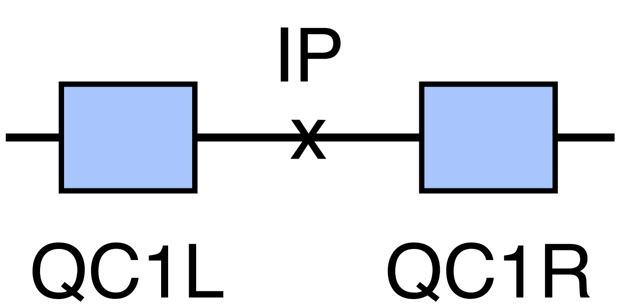


Δr=35 μm induces 0.1 % of B_3/B_2.

B_3 ~7 Gauss

without any corrections



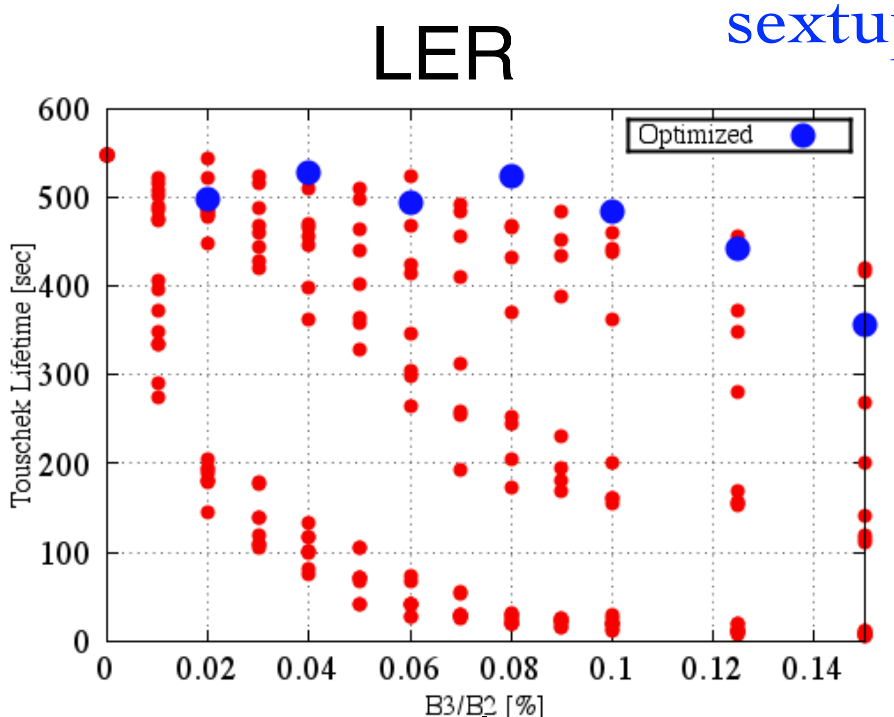


	sign of error field	
+		+
-		-
+		-
-		+

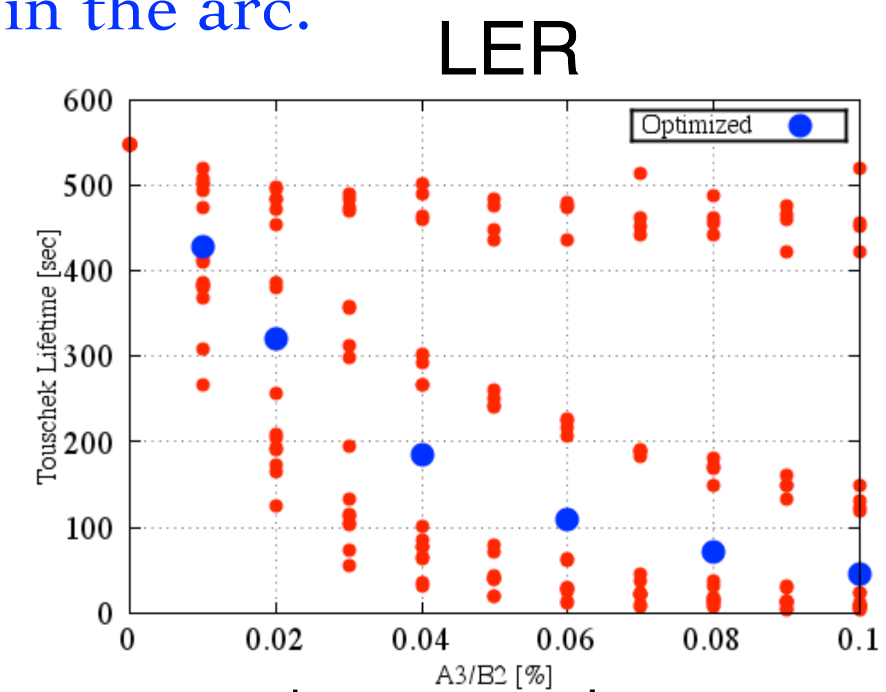
Sextupole error field: normal and skew

Touschek lifetime for 16 combinations of field error in 4 QCs

Dynamic aperture is optimized by using normal sextupoles(108) and skew sextupoles(24) in the arc.

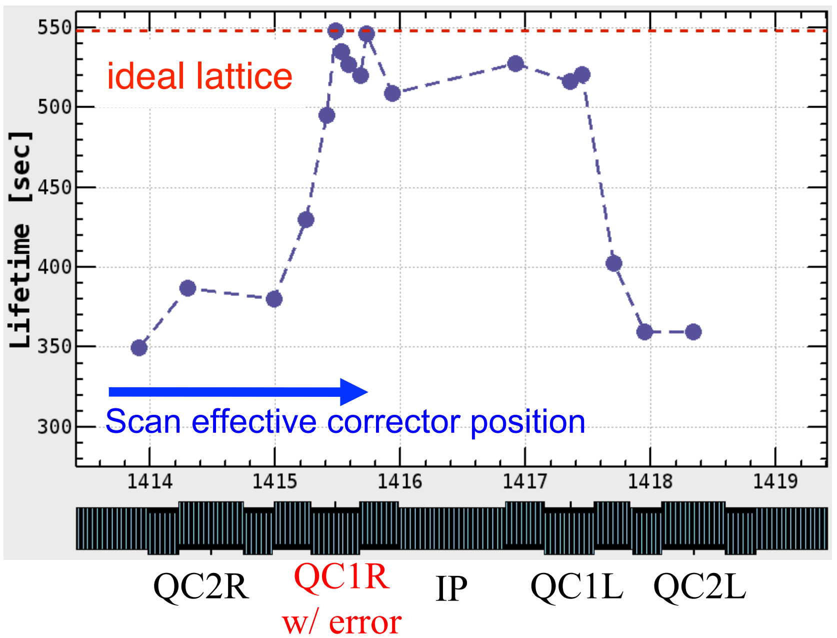


sextupole error



skew sextupole error

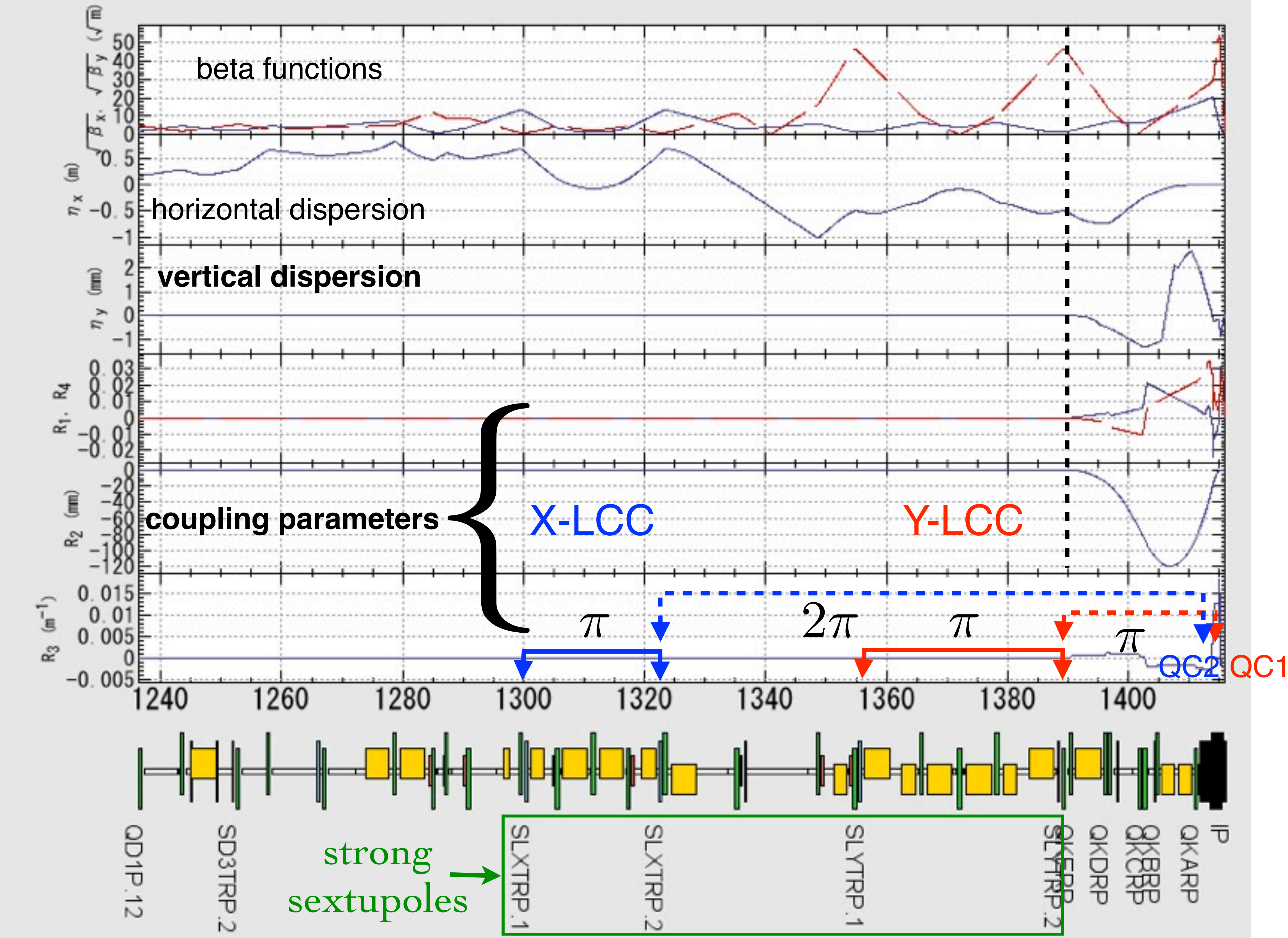
Sextupole error can be recovered by using normal sextupoles(in the arc), however, skew sextupoles error can not be corrected for enough level.



Position dependence of the skew corrector coil is stronger than that of normal.

Skew sextupole corrector must be installed in the vicinity of the error source.

X-LCC corrects QC2 chromaticity and Y-LCC corrects QC1 chromaticity locally.



IR optics in HER

X-LCC corrects QC2 chromaticity and Y-LCC corrects QC1 chromaticity locally.