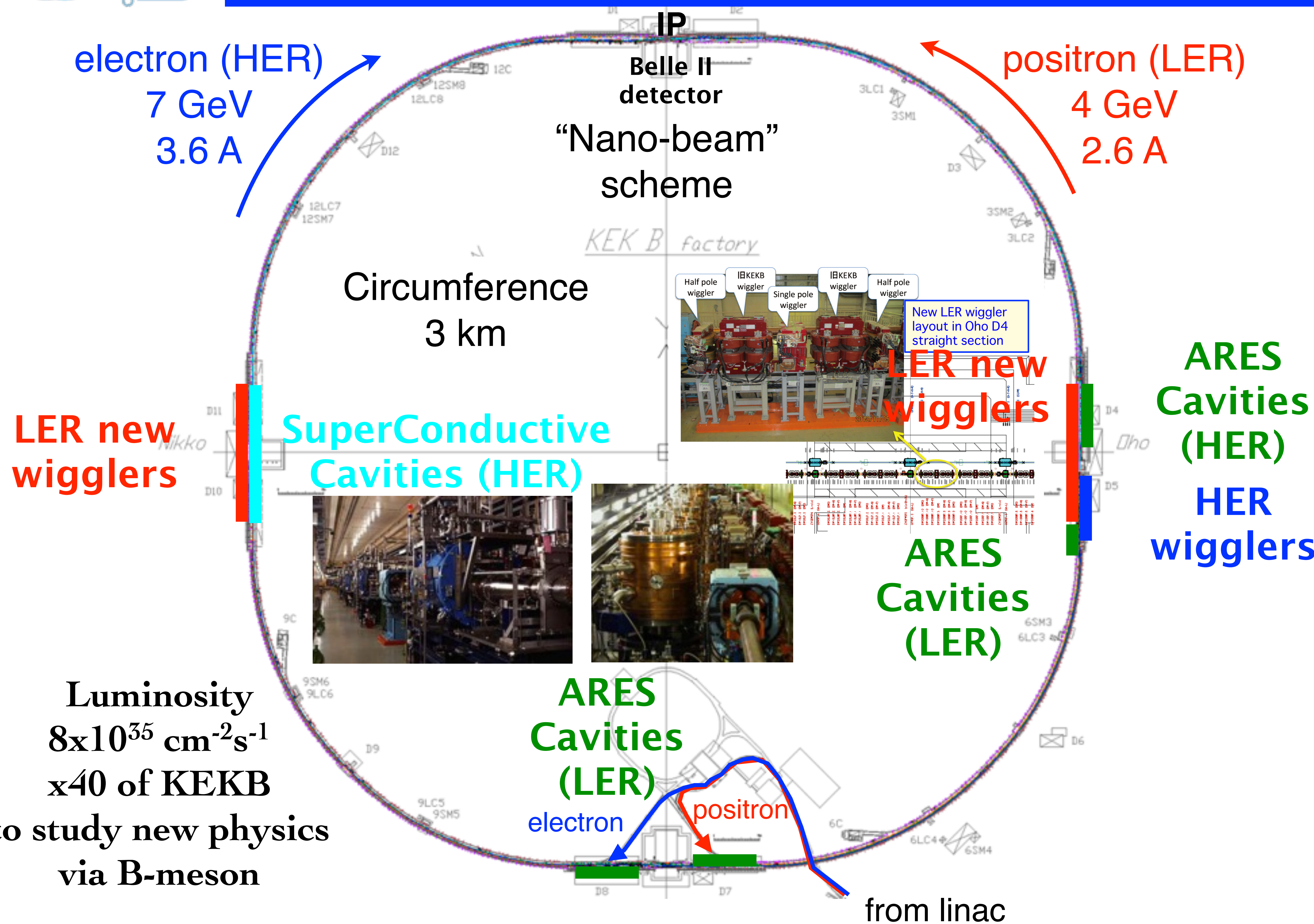
Dynamic Aperture Optimization at SuperKEKB

Y. Ohnishi

ICFA
Oct. 9-12, 2014
Beijing, China

The 55th ICFA Advanced Beam Dynamics Workshop on High Luminosity Circular e^+e^- Colliders – Higgs Factory

Overview of SuperKEKB



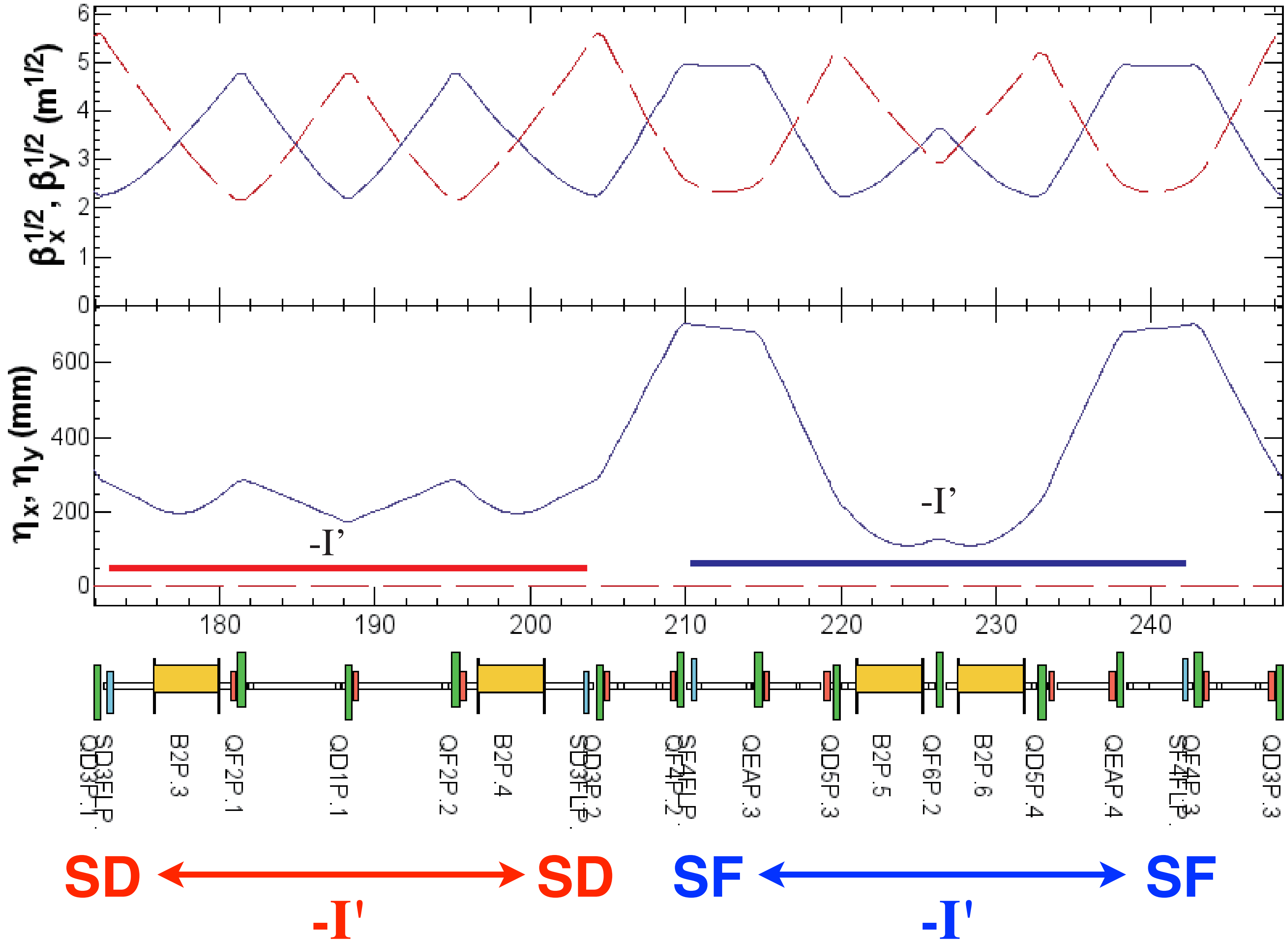
Luminosity
8×10^{35} cm^{-2}s^{-1}
x40 of KEKB
to study new physics
via B-meson

Large crossing angle and small beam size at IP in the Nano-beam scheme

Very small vertical emittance is necessary.

	Symbol	LER	HER	Unit
Horizontal Emittance	ε_x	3.2	4.6	nm
Horizontal Beta at IP	β_x^*	32	25	cm
Horizontal Beam size at IP	σ_x^*	10.1	10.7	µm
Vertical Emittance	ε_y	**8.64**	**12.9**	pm
Vertical Beta at IP	β_y^*	**270**	**300**	µm
Vertical Beam size at IP	σ_y^*	**48**	**62**	nm
Bunch length	σ_z	6	5	mm
Half crossing	ϕ_x	41.5		mrad

LER Arc Cell (Unit Cell)

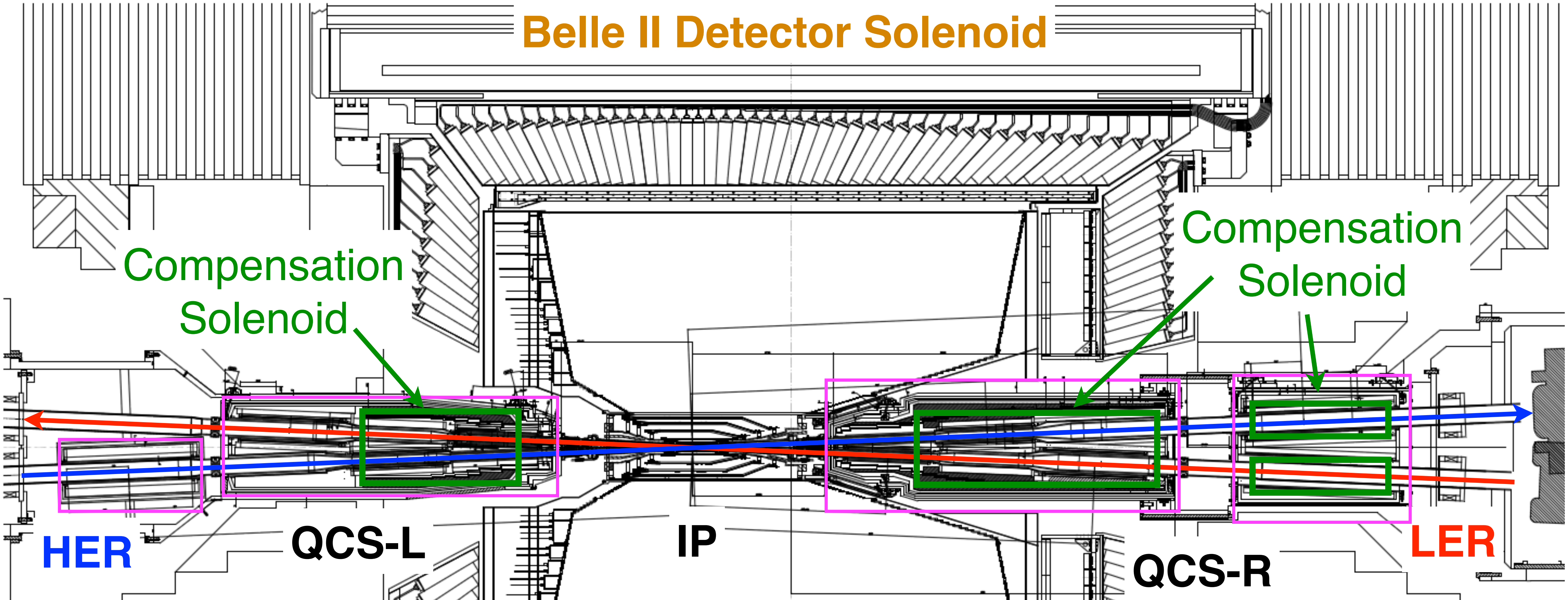


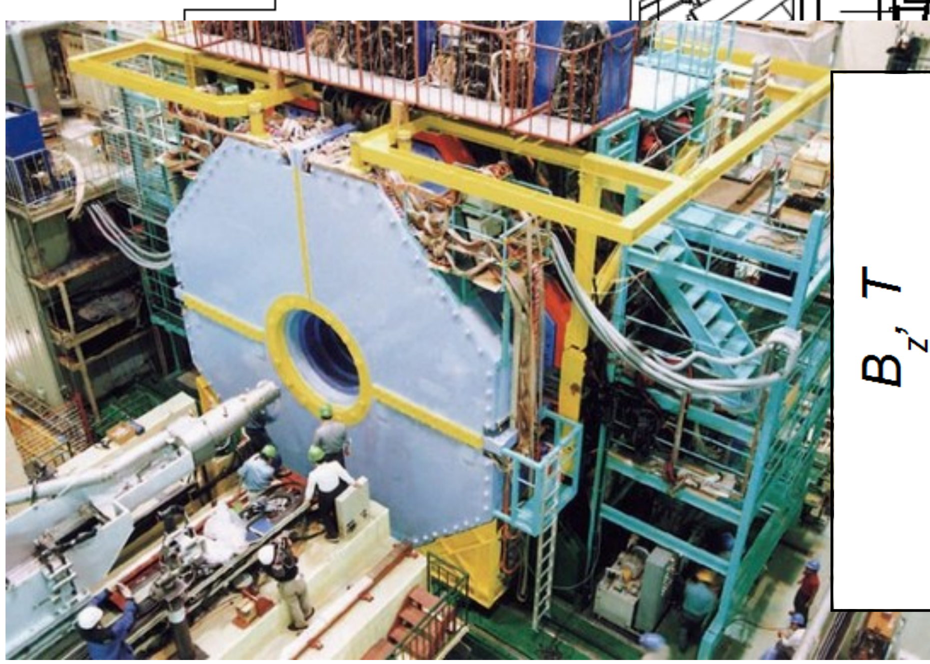
Low H function

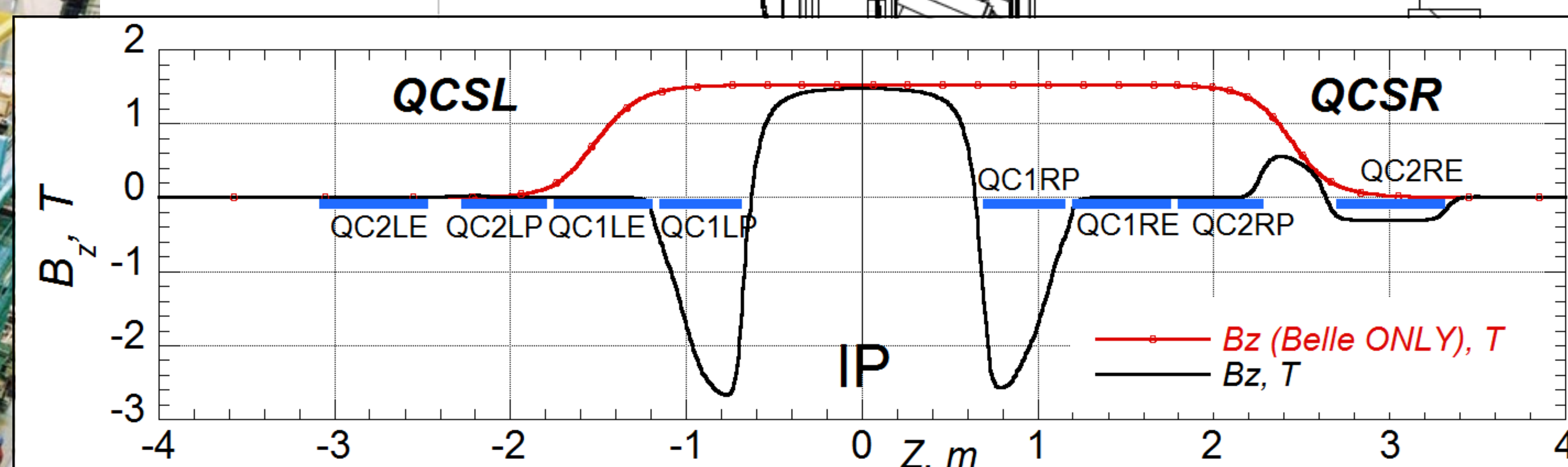
Nonlinear kick due to the sextupole is canceled by another sextupole in a pair.
Dynamic aperture can be enlarged.

Non-interleaved sextupole chromaticity correction

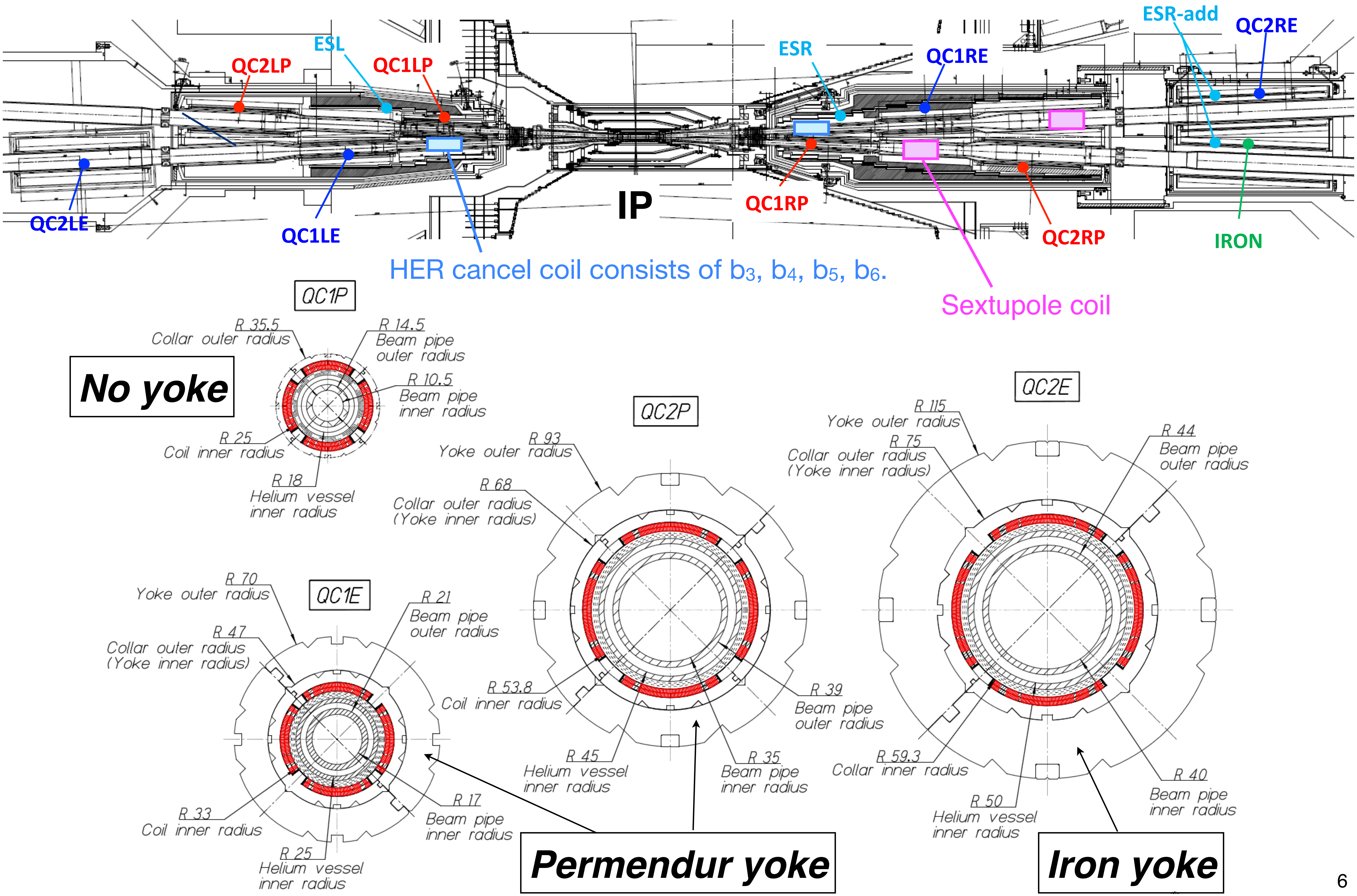
Interaction Region





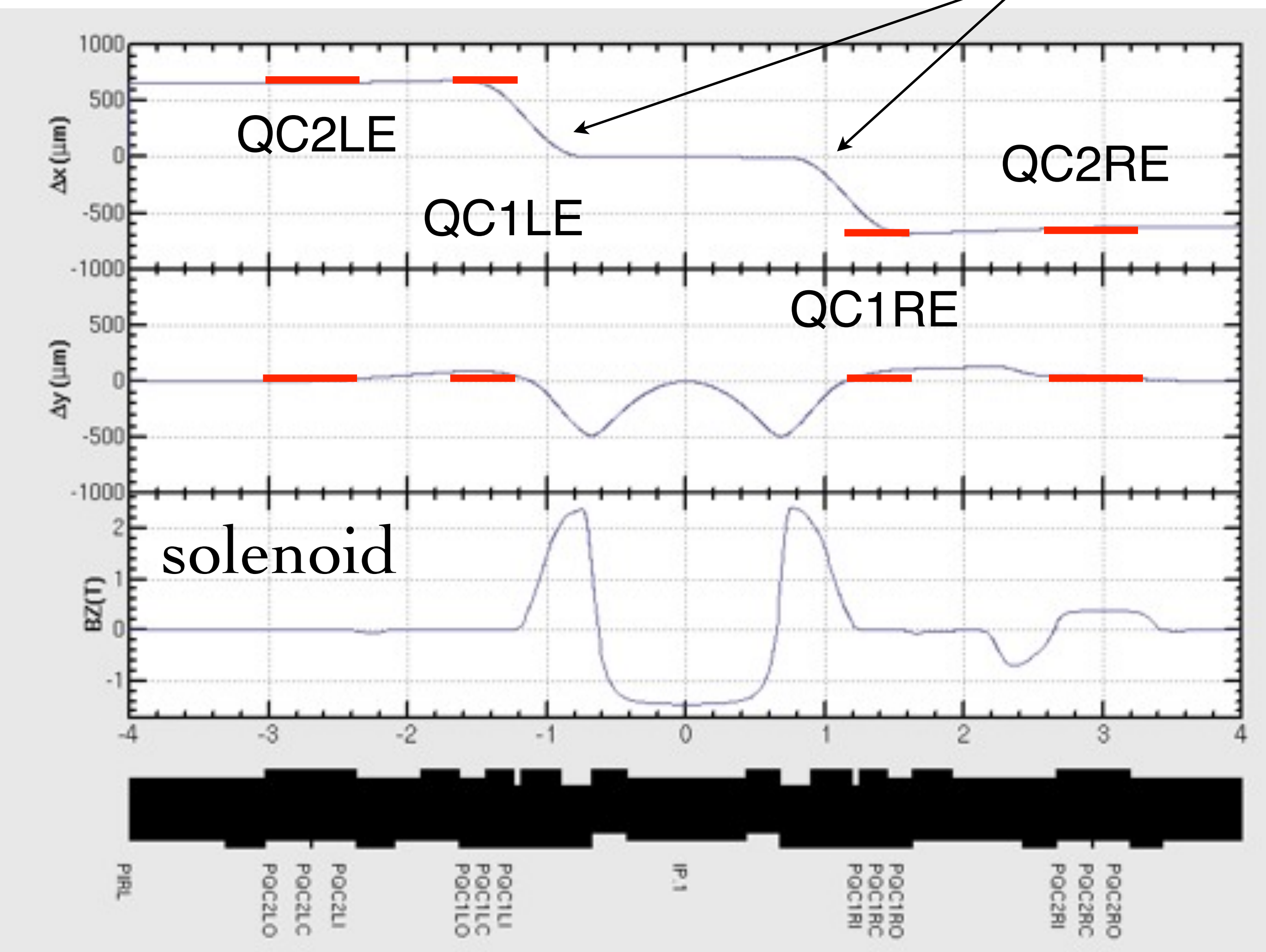


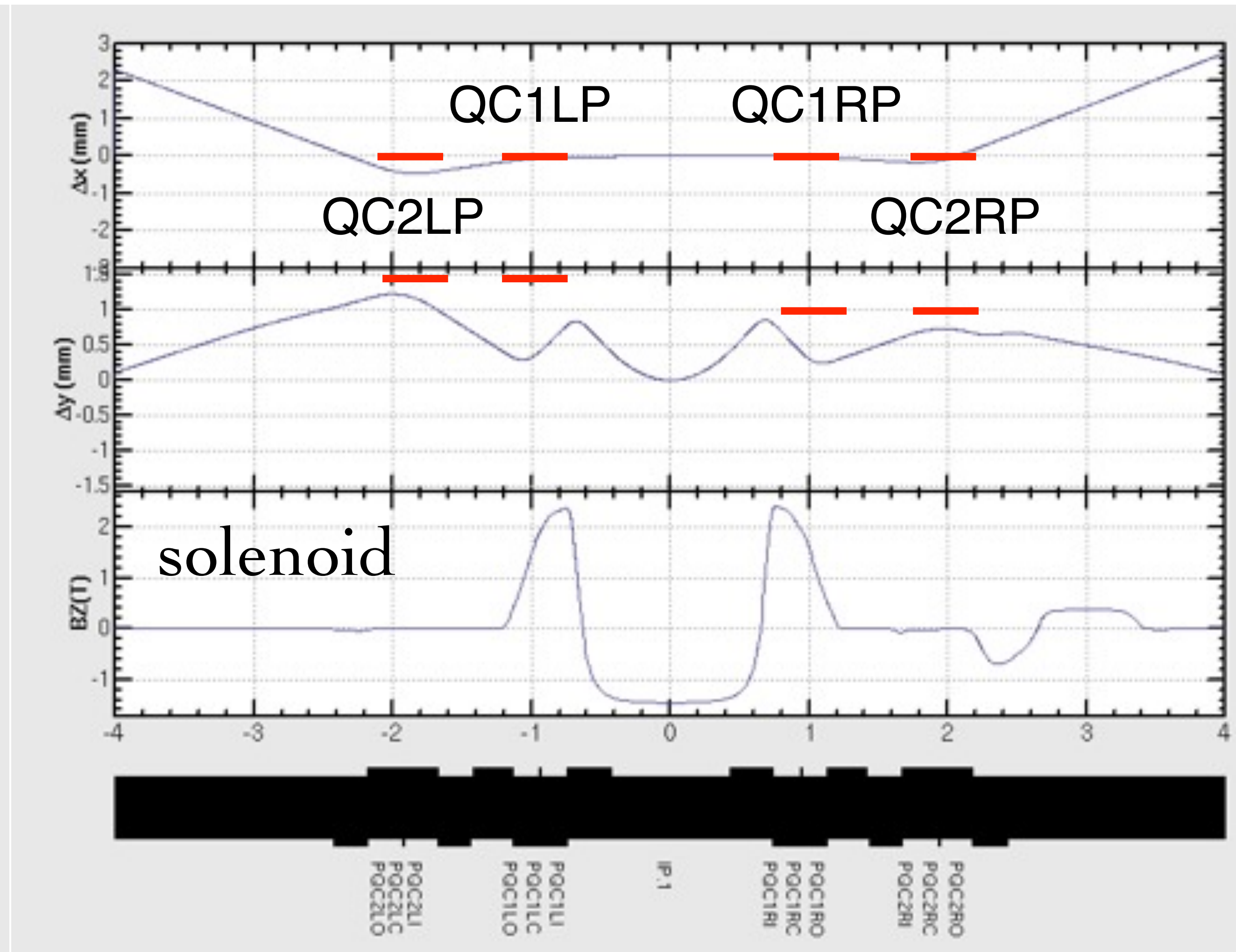
Final Focus Quadrupoles



Orbit in the vicinity of IP

HER electron → leakage field from QC1P(LER) **LER** ← positron





offset/rot.	QC2LE	QC1LE	QC1RE	QC2RE
Δx (mm)	+0.7	+0.7	-0.7	-0.7
Δθ (mrad)	0	0	0	0

offset/rot.	QC2LP	QC1LP	QC1RP	QC2RP
Δy (mm)	+1.5	+1.5	+1.0	+1.0
Δθ (mrad)	-3.725	-13.65	+7.204	-2.114

QC1/QC2 offset is adopted to control the orbit appropriately.

Slice model of 1 cm thickness is used for the optics calculation for IR.

Each slice has Maxwellian fringe and up to b_{22} and a_{22}.

IR Design Features

- The angle between Belle II Solenoid(1.5 T) and beam-axis is 41.5 mrad. Anti-solenoids are overlaid with QC1 and QC2 to compensate the Belle II solenoid field. The vertical emittance (about 1.5 pm) is generated due to the solenoid fringe field. Skew coils and/or rotation of QC1 and QC2 are used to correct the X-Y coupling and vertical dispersion between IP and the local chromaticity correction.

Many corrector coils are necessary.

- Dipole and skew dipole coils adjust a beam orbit and correct dispersions in IR.
- Skew quadrupole coils correct X-Y couplings.
- HER cancel coils correct sextupole, octupole, decapole, and dodecapole leakage field from QC1P(no iron yoke) in LER.
- Octupole coils at QC1 and QC2 enlarge a transverse aperture.

Dynamic Aperture

- Dynamic aperture is constrained by a small beta function:

$$J_y \leq \frac{\beta_y^{*2}}{(1+2|K|L^{*2}/3)L^*} A(\mu_y)$$

A(μ): universal function

K. Oide et al, Phys. Rev. E47 (1993)

SuperKEKB	β_y^* [μm]	K [m^{-2}]	L* [m]	J_y/A [μm]
LER	270	-5.1	0.76	**0.032**
HER	300	-3.1	1.22	**0.018**

<< 4.2 μm KEKB

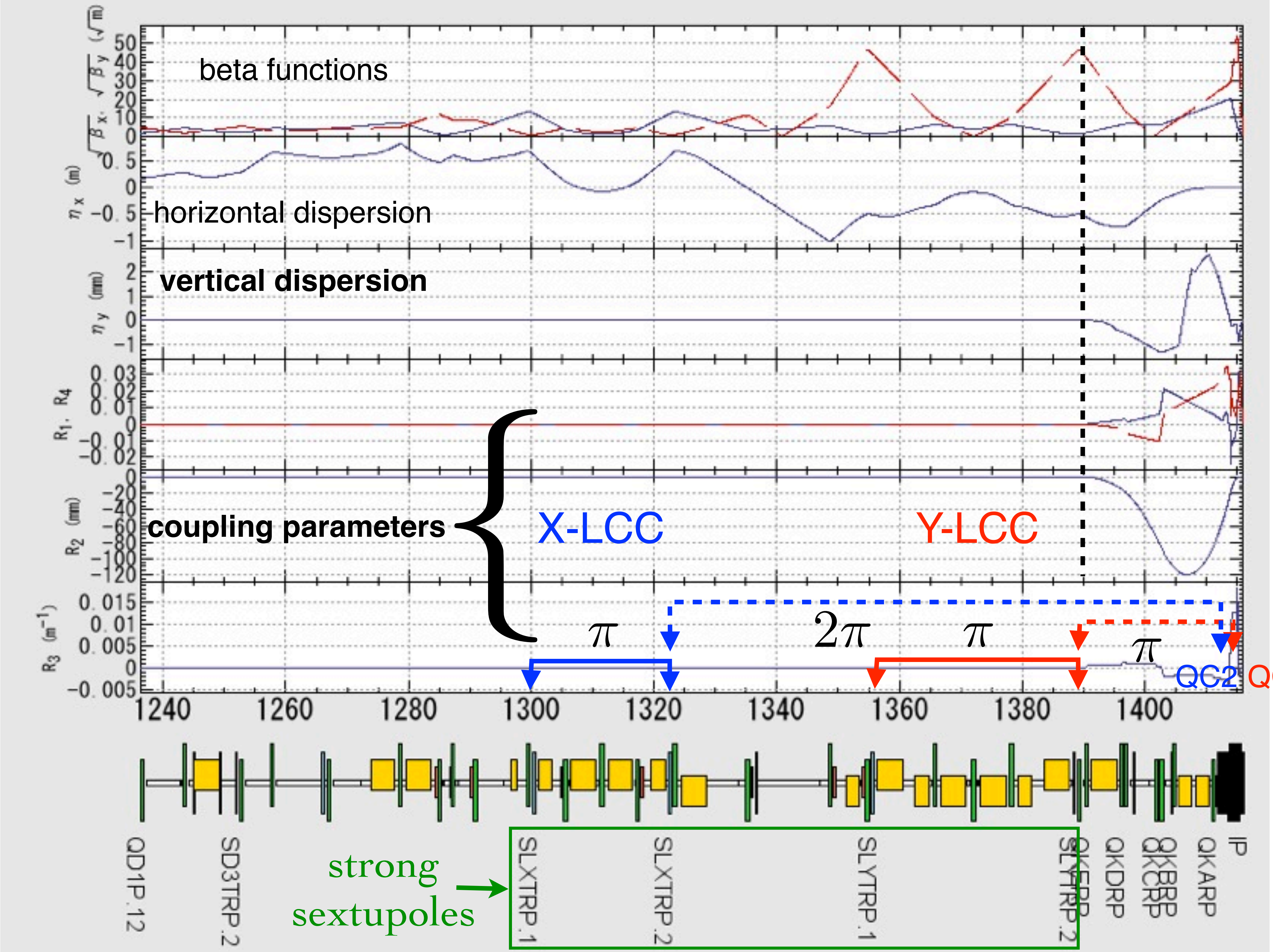
- Natural chromaticity:

	SuperKEKB		KEKB (1999~2010)	
	LER	HER	LER	HER
ξ_{x0}	**-105**	**-171**	-72	-70
ξ_{y0}	**-776**	**-1081**	-123	-124

- Approximately *80 %* of the natural chromaticity in the vertical direction is induced in the Final Focus. A "*local chromaticity correction*" is adopted to correct it.

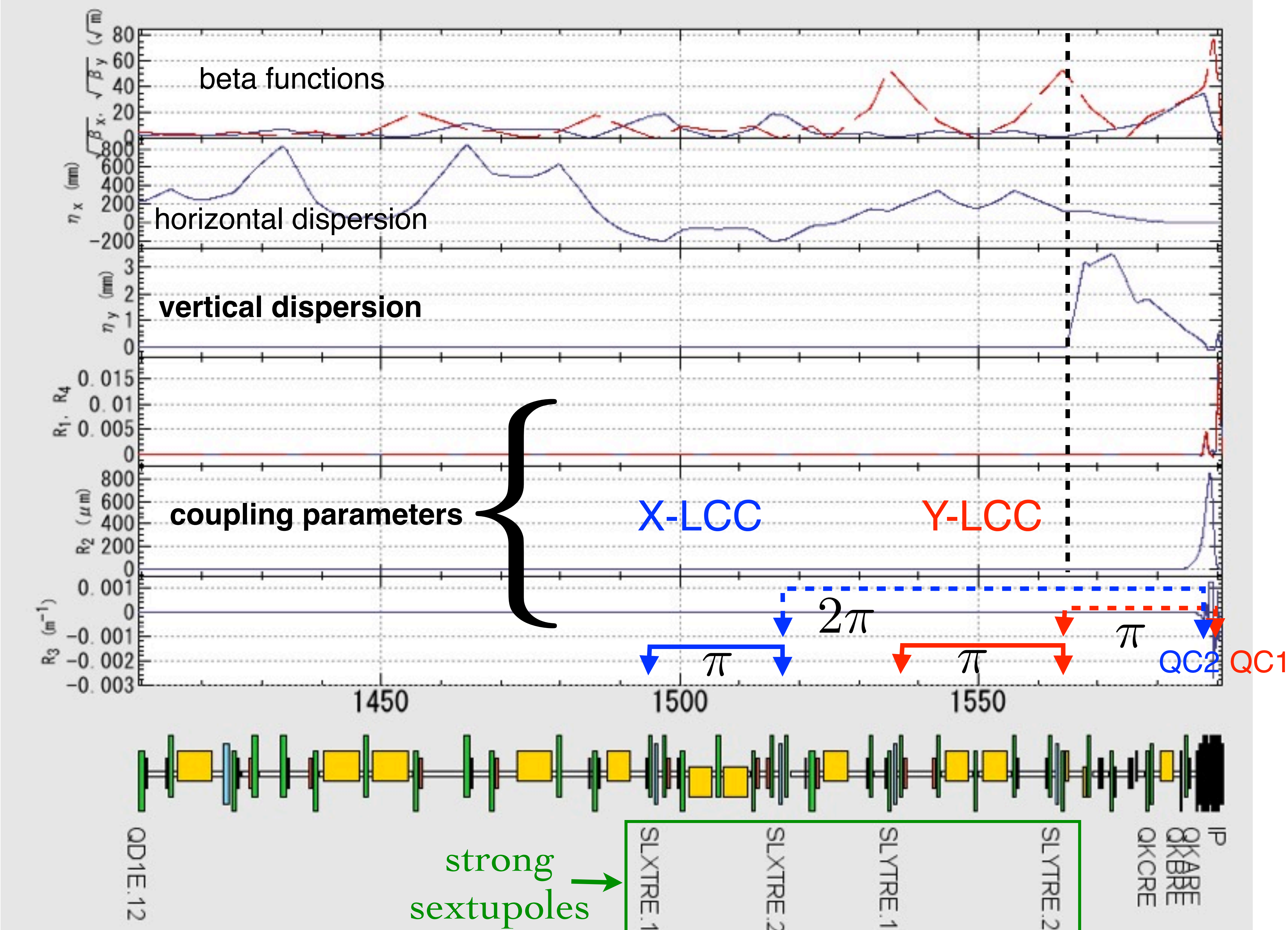
IR Optics in LER

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.

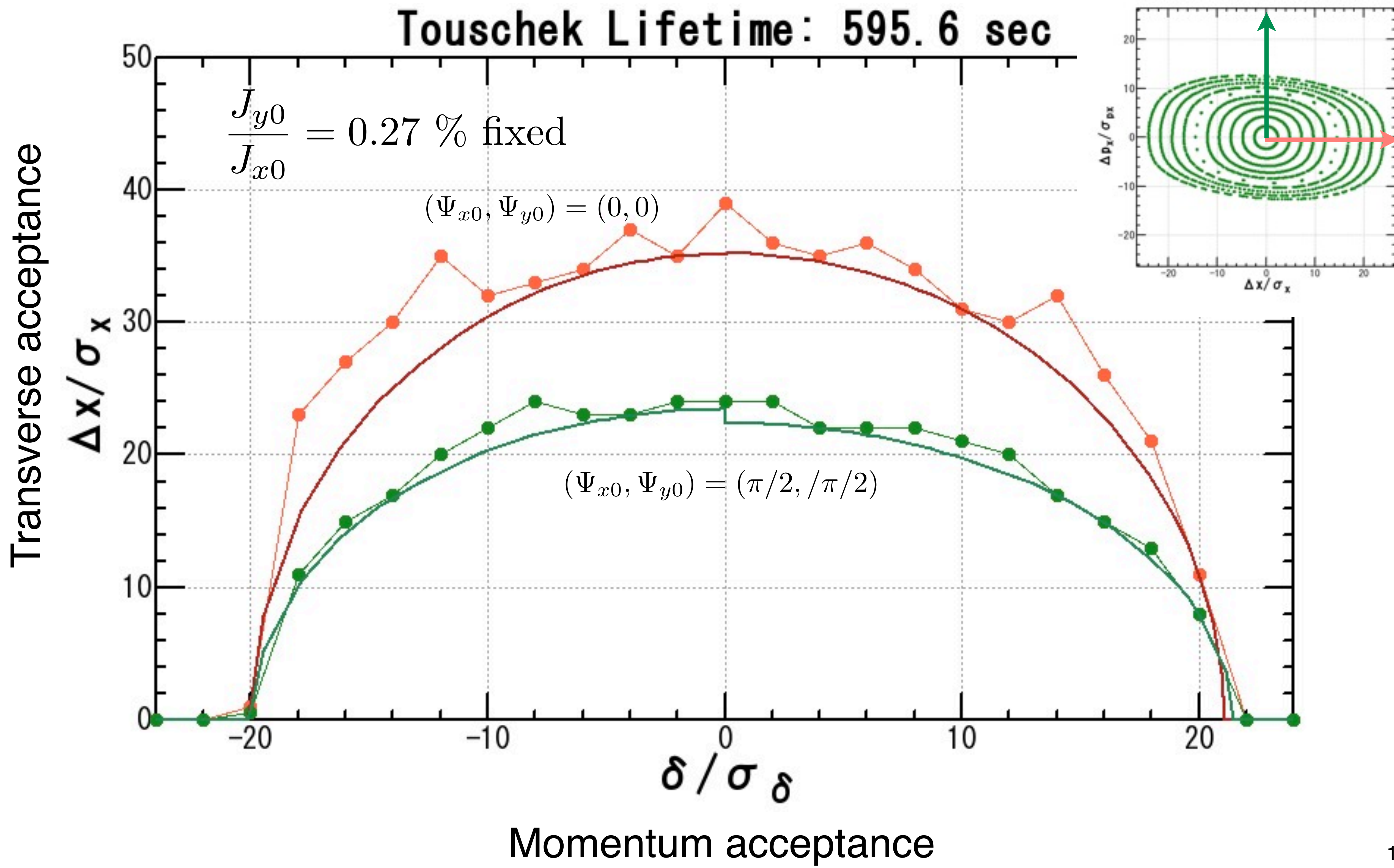


Optimization of Dynamic Aperture

- Chromaticity Correction (off-momentum matching)
  - Twiss chromaticity at IP and RF cavities as well as tunes
  - 54 sextupole magnet pairs (4 in LCC and 50 in arc)
  - Skew sextupoles (12 families in LER, 10 in HER)
  - Two octupole correctors (3 in LER)
- Downhill-simplex optimization with lifetime evaluation
  - Particle tracking(6-dimensional) to find stable phase space.
  - Touschek lifetime is obtained from area of dynamic apertures.
  - Synchrotron oscillation is included(RF cavities ON).

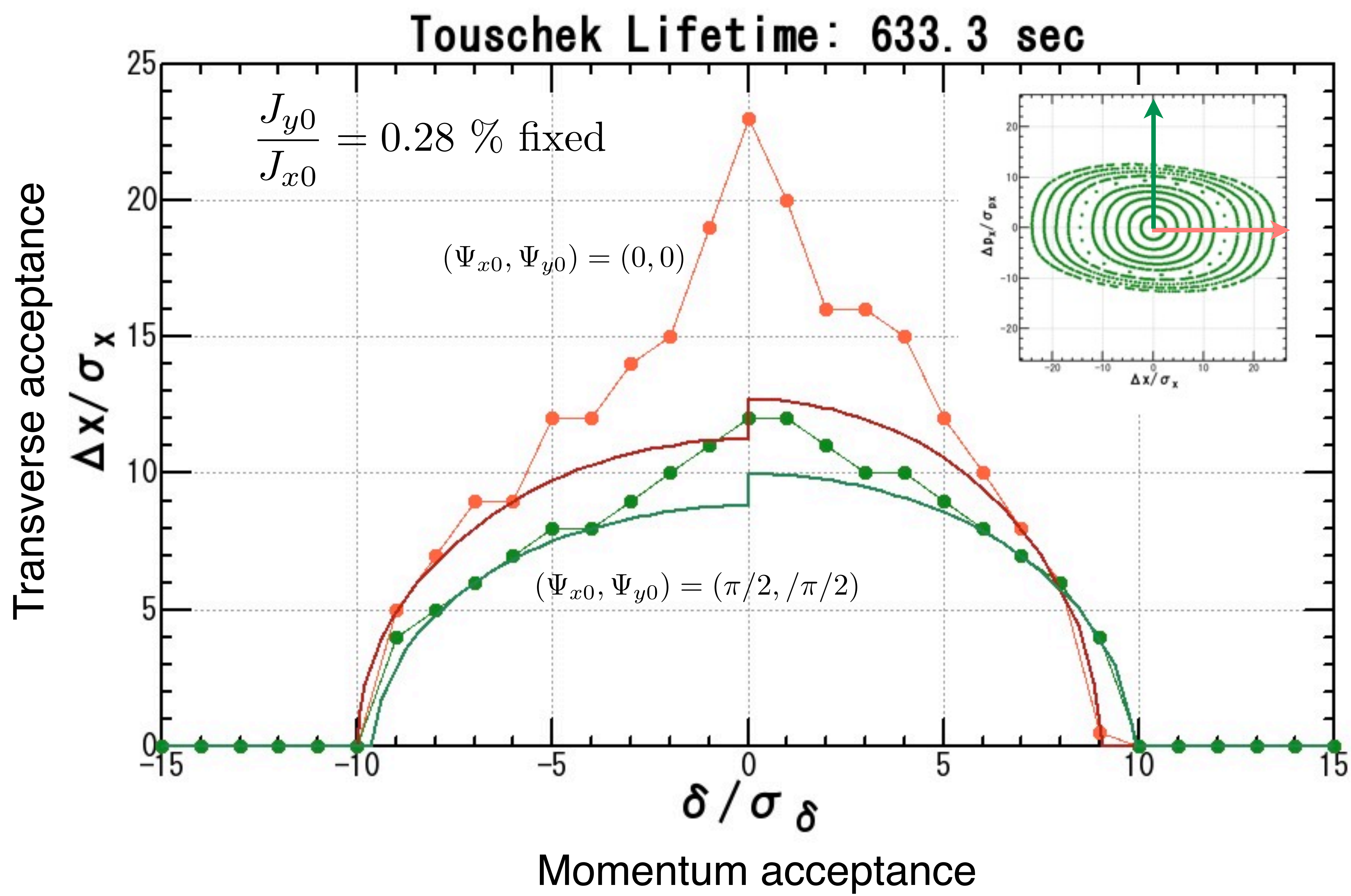
Dynamic Aperture in LER

Touschek lifetime is obtained from average of two ellipses of dynamic apertures.

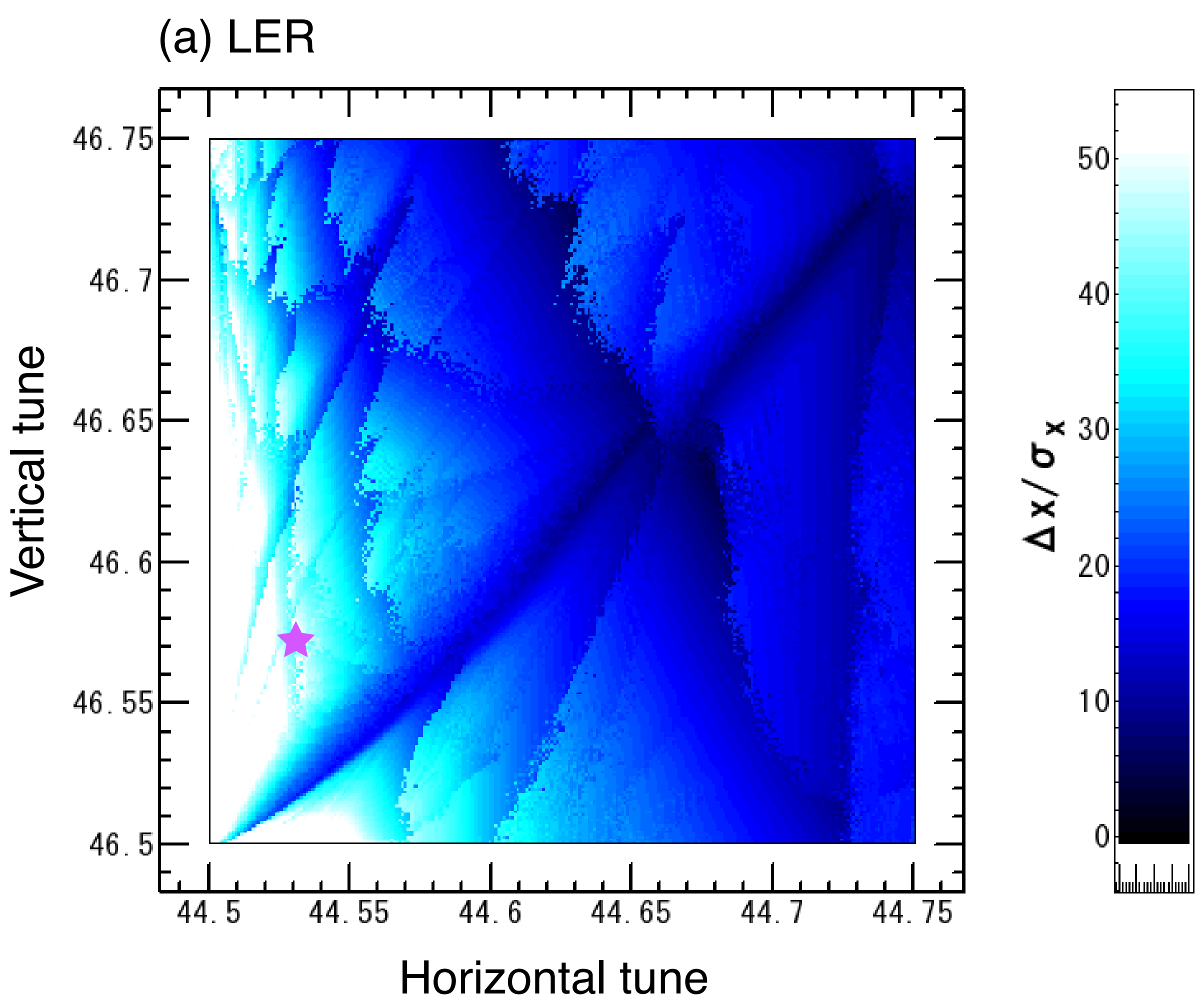


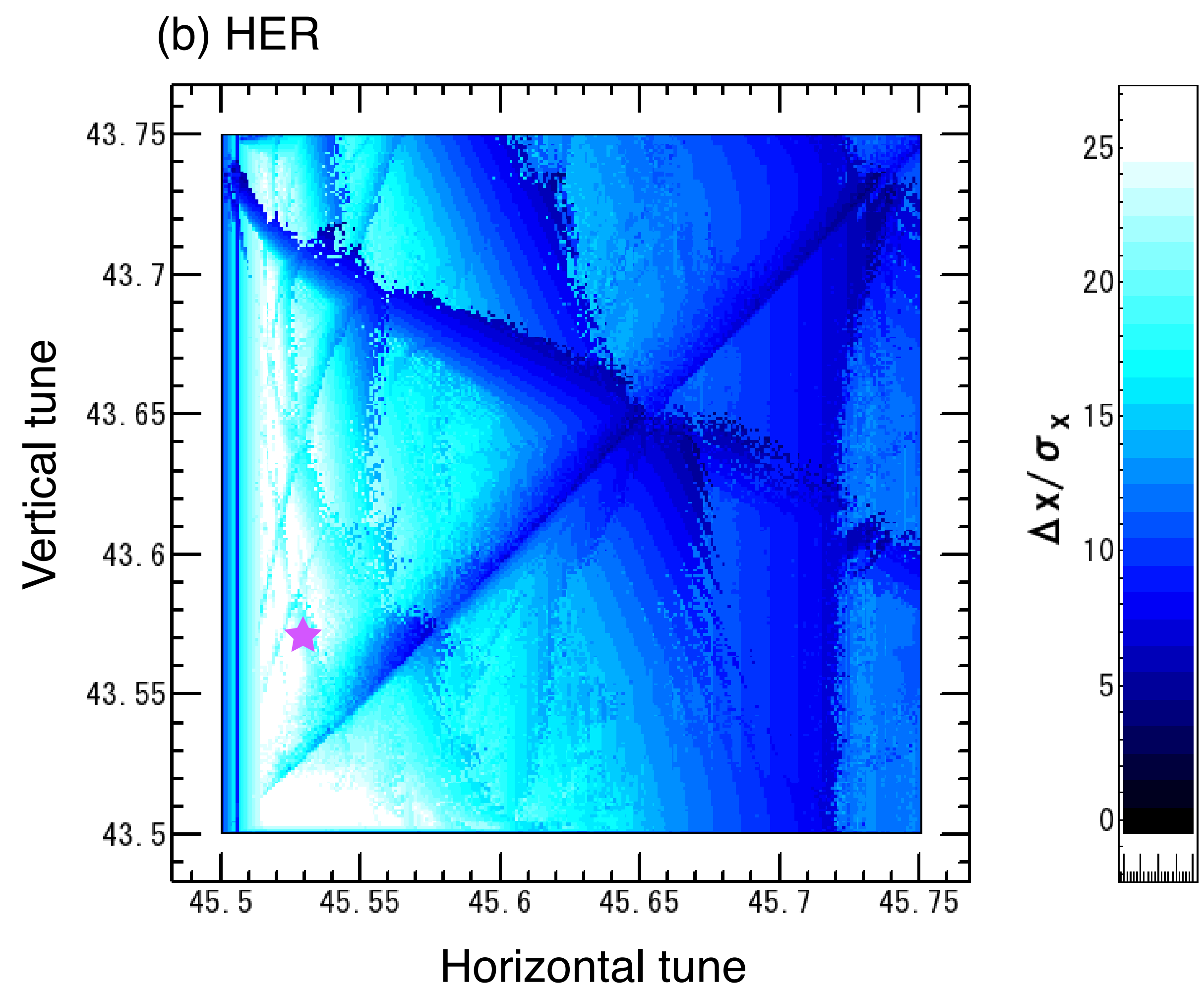
Dynamic Aperture in HER

Touschek lifetime is obtained from average of two ellipses of dynamic apertures.



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.



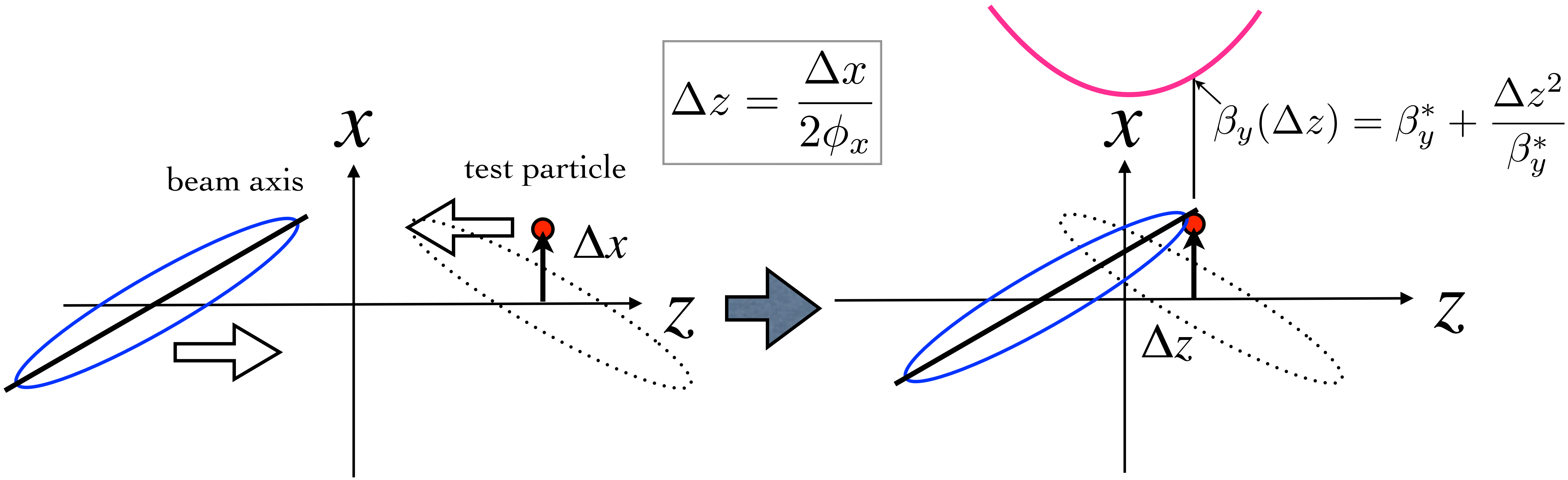


$(\nu_x, \nu_y) = (44.53, 46.57)$

$(\nu_x, \nu_y) = (45.53, 43.57)$

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.



$$\Delta z = \frac{\Delta x}{2\phi_x}$$

$$\beta_y(\Delta z) = \beta_y^* + \frac{\Delta z^2}{\beta_y^*}$$

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

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

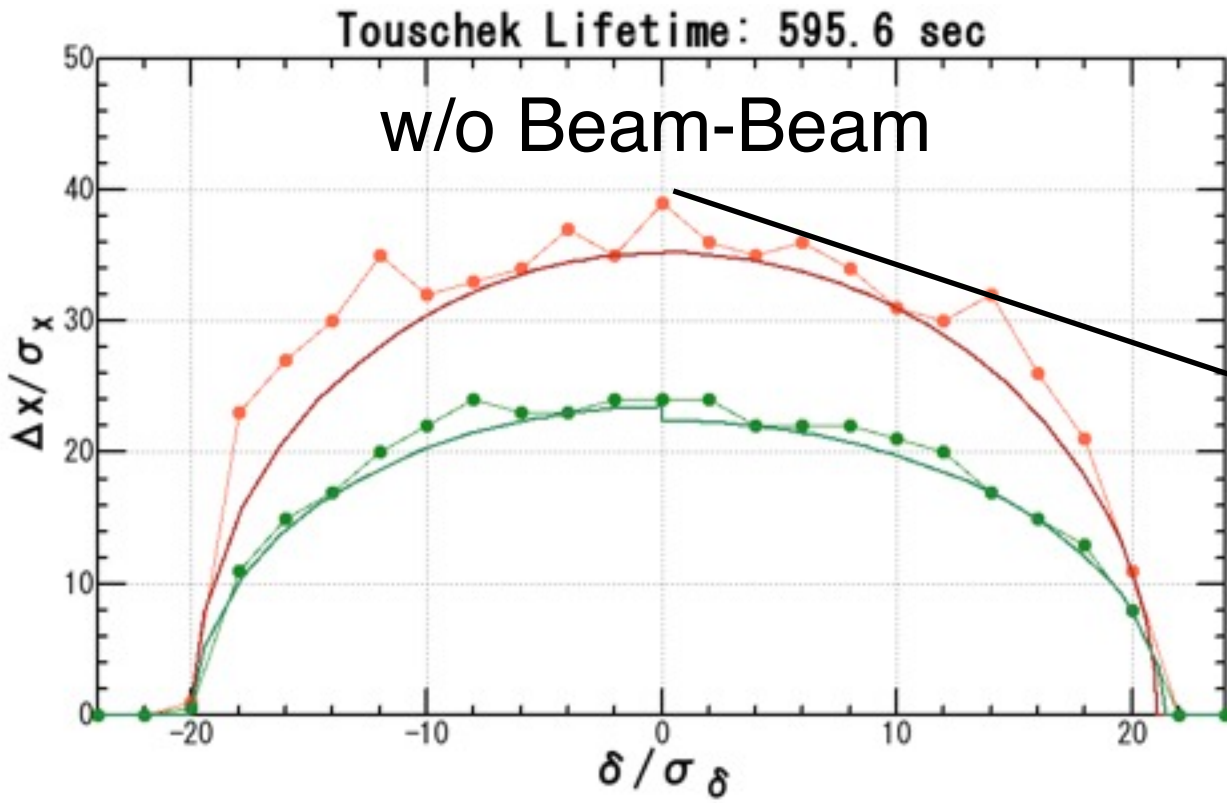
$$\Delta y \propto \theta_y^{bb} \sqrt{\beta_y(\Delta z)}$$

~factor of 180

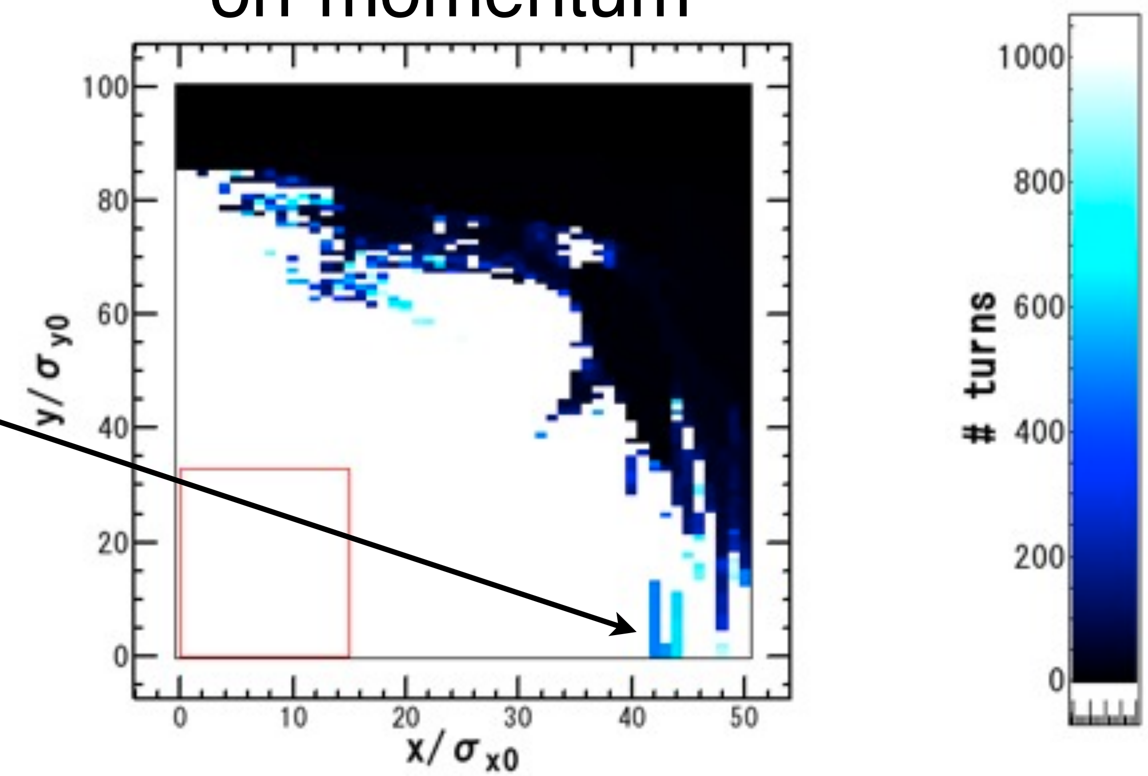
- Particles with a large horizontal orbit are kicked by beam-beam at high vertical beta region if there is a vertical orbit. Consequently, the vertical betatron oscillation increases due to the vertical beam-beam kick. The transverse aperture decreased, which implies small dynamic aperture.

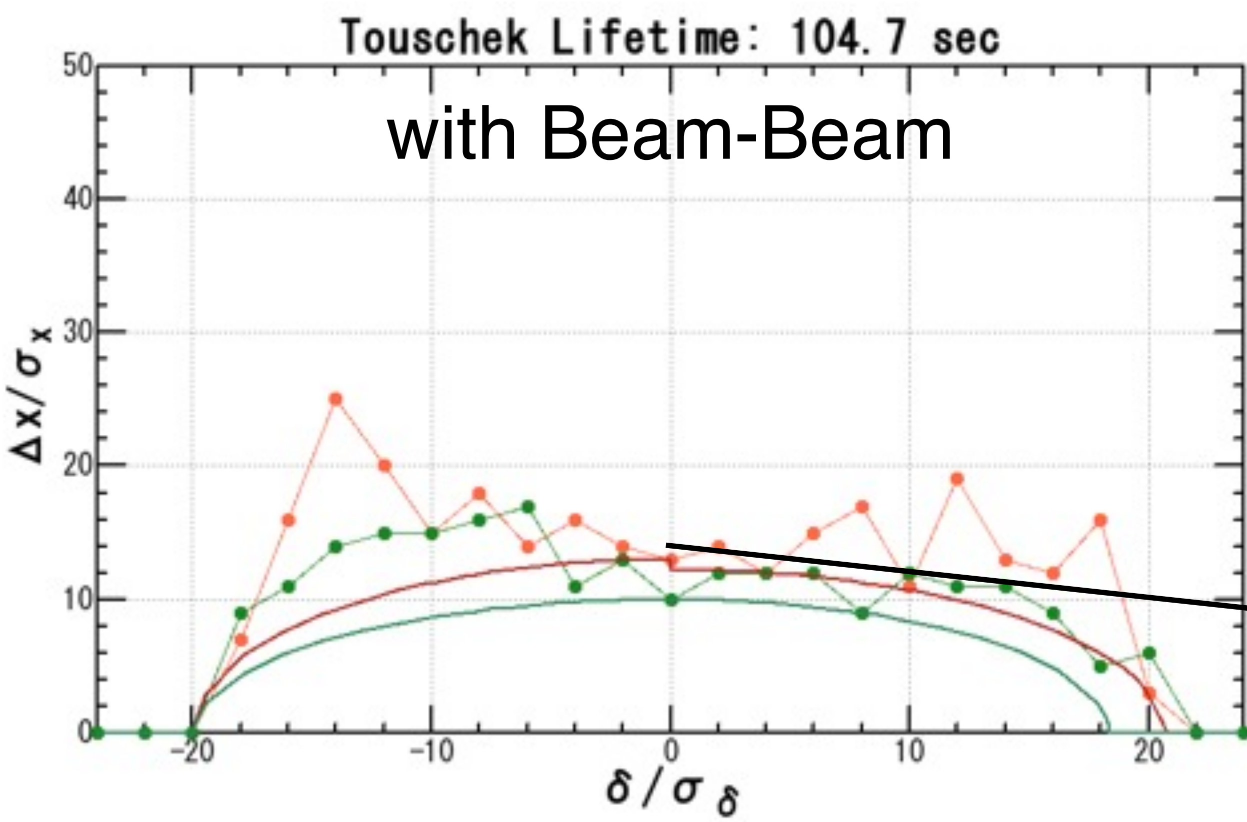
Dynamic Aperture with Beam-Beam Effect

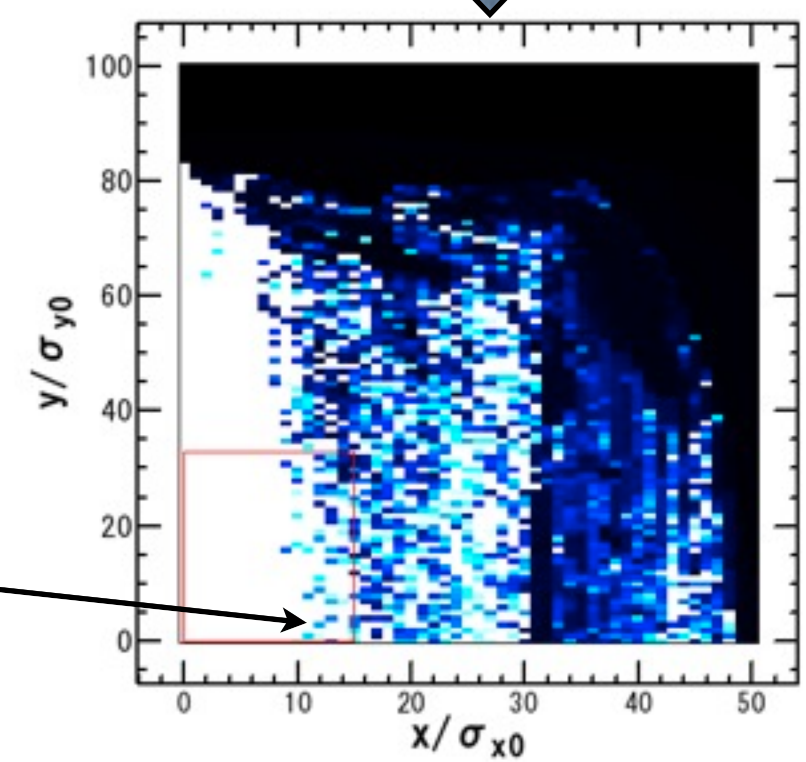
LER



on-momentum

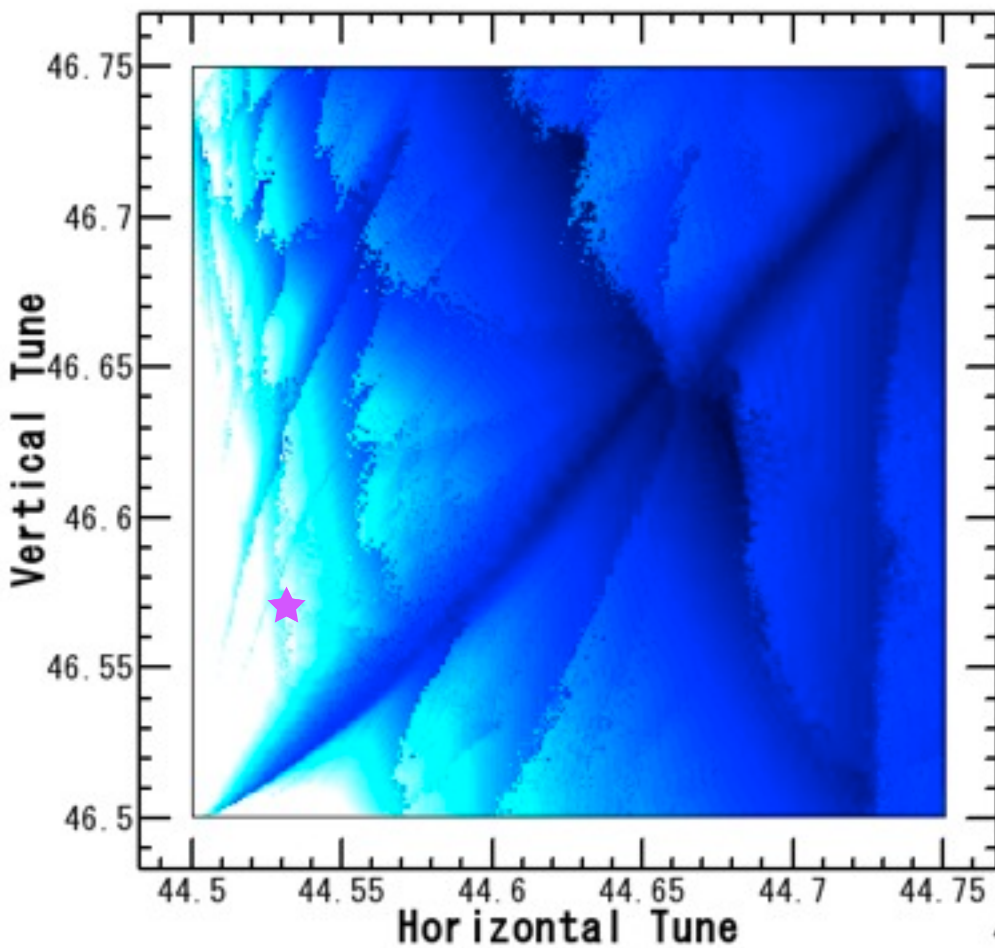


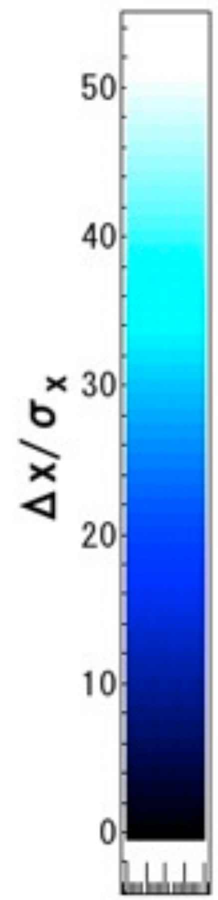




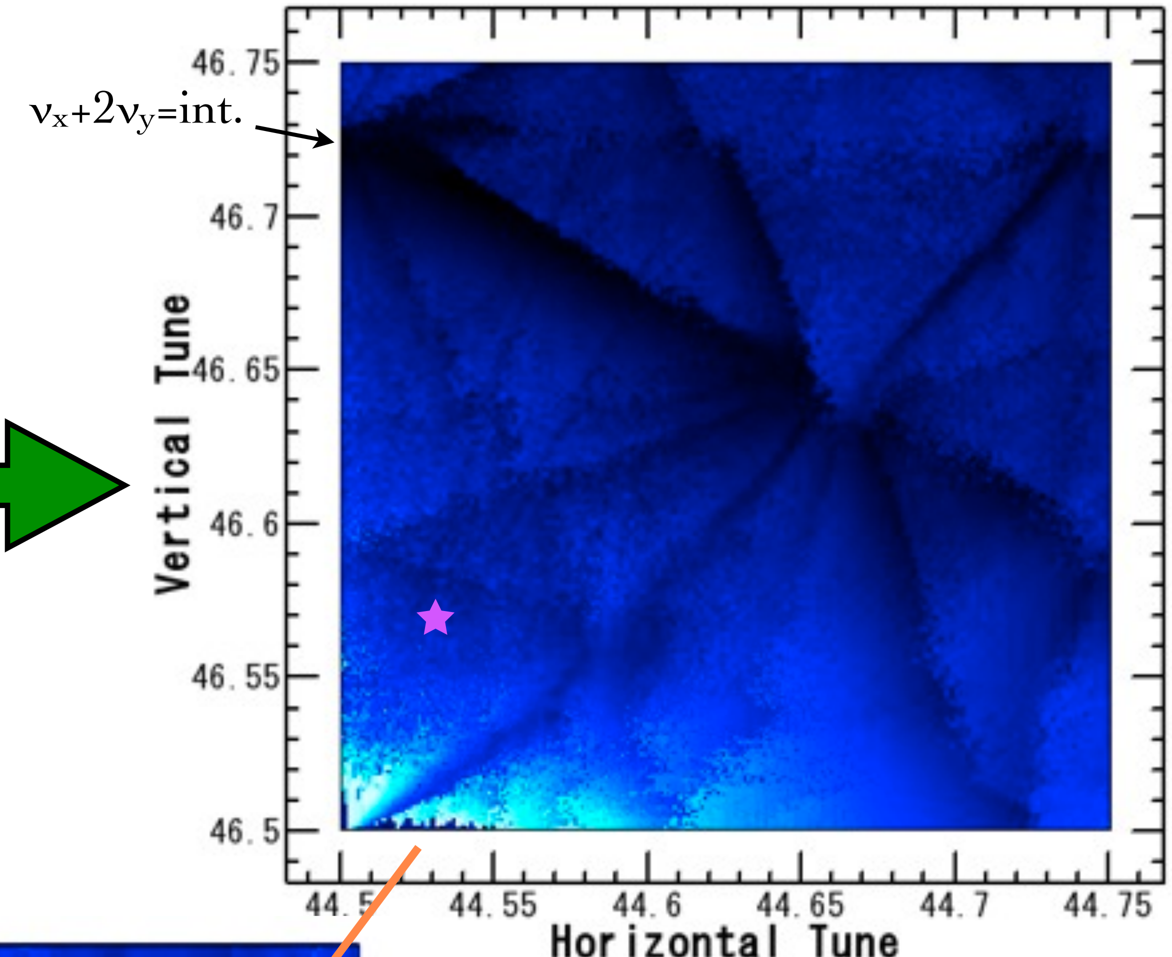
LER Tune Survey with Beam-Beam Effect

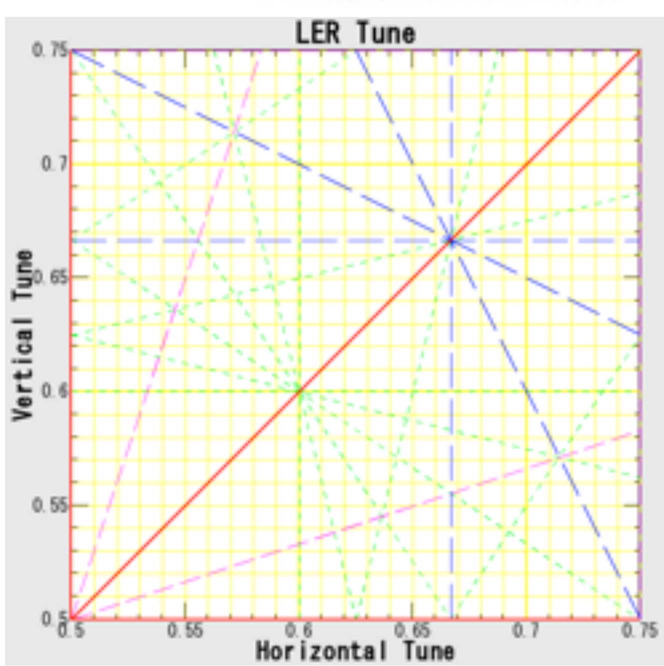
LER: w/o beam-beam

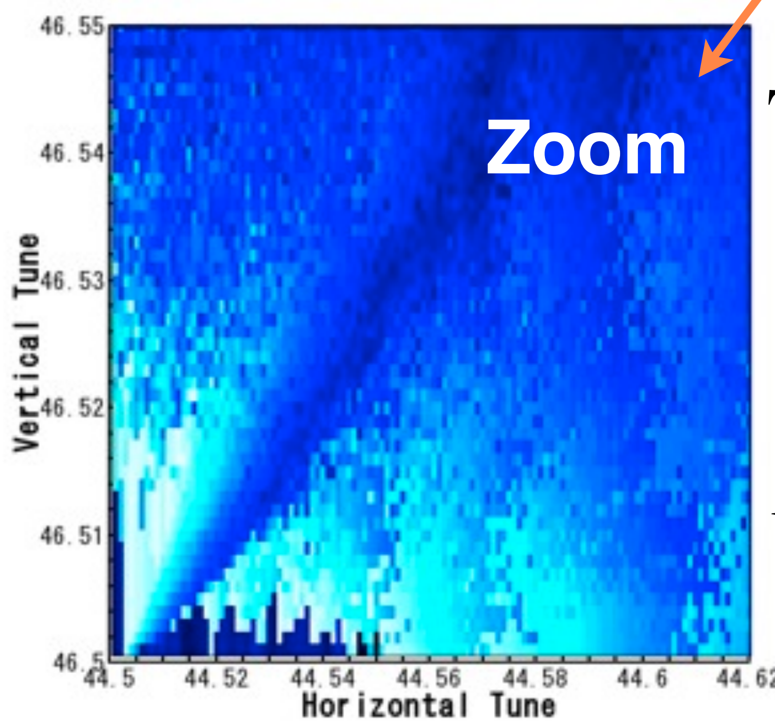




LER: with beam-beam





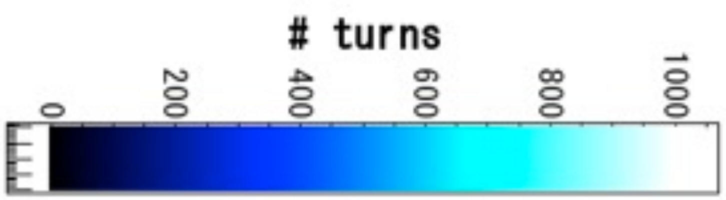


There is a good region near half integer resonance for the vertical tune.

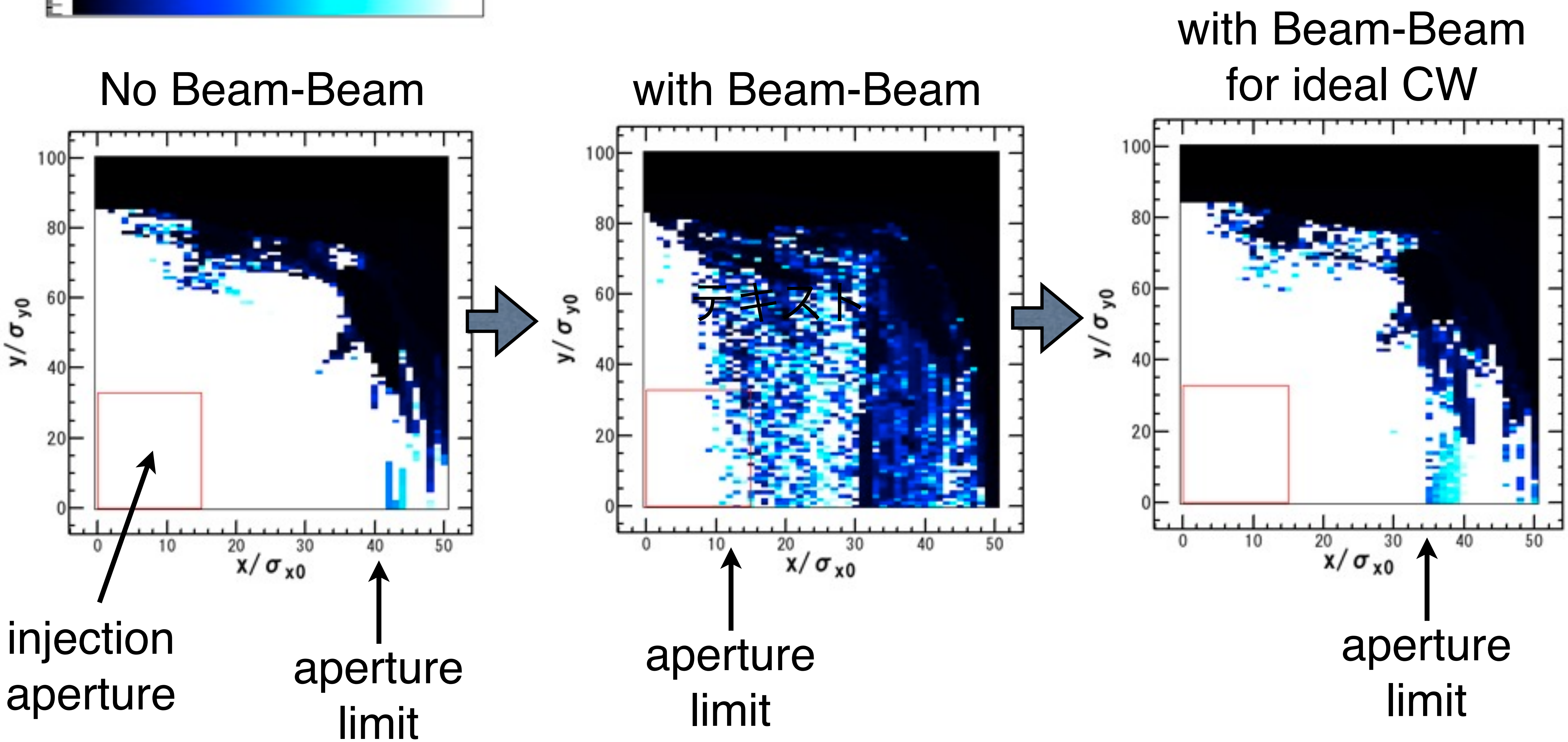
Chromaticity correction becomes very difficult near half integer.

Dynamic Aperture with Beam-Beam and Ideal CW

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



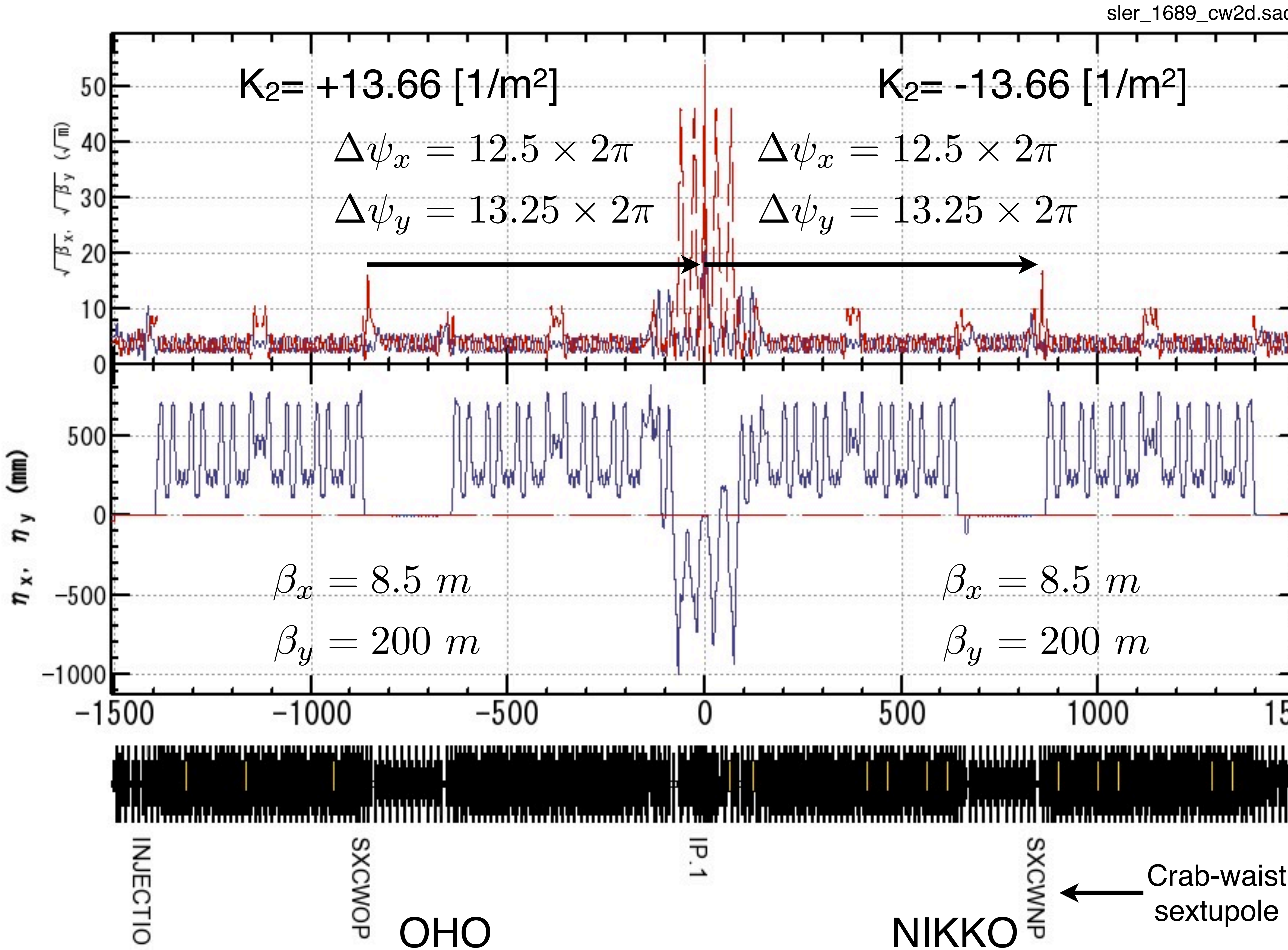
Initial momentum deviation is zero.
(synchrotron motion is included.)



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

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

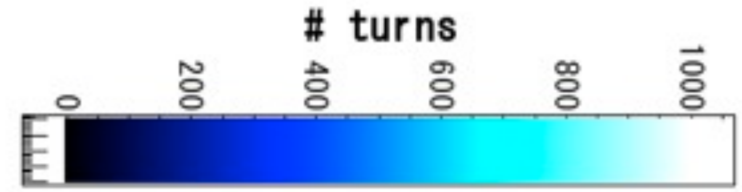
Crab-Waist Optics in LER



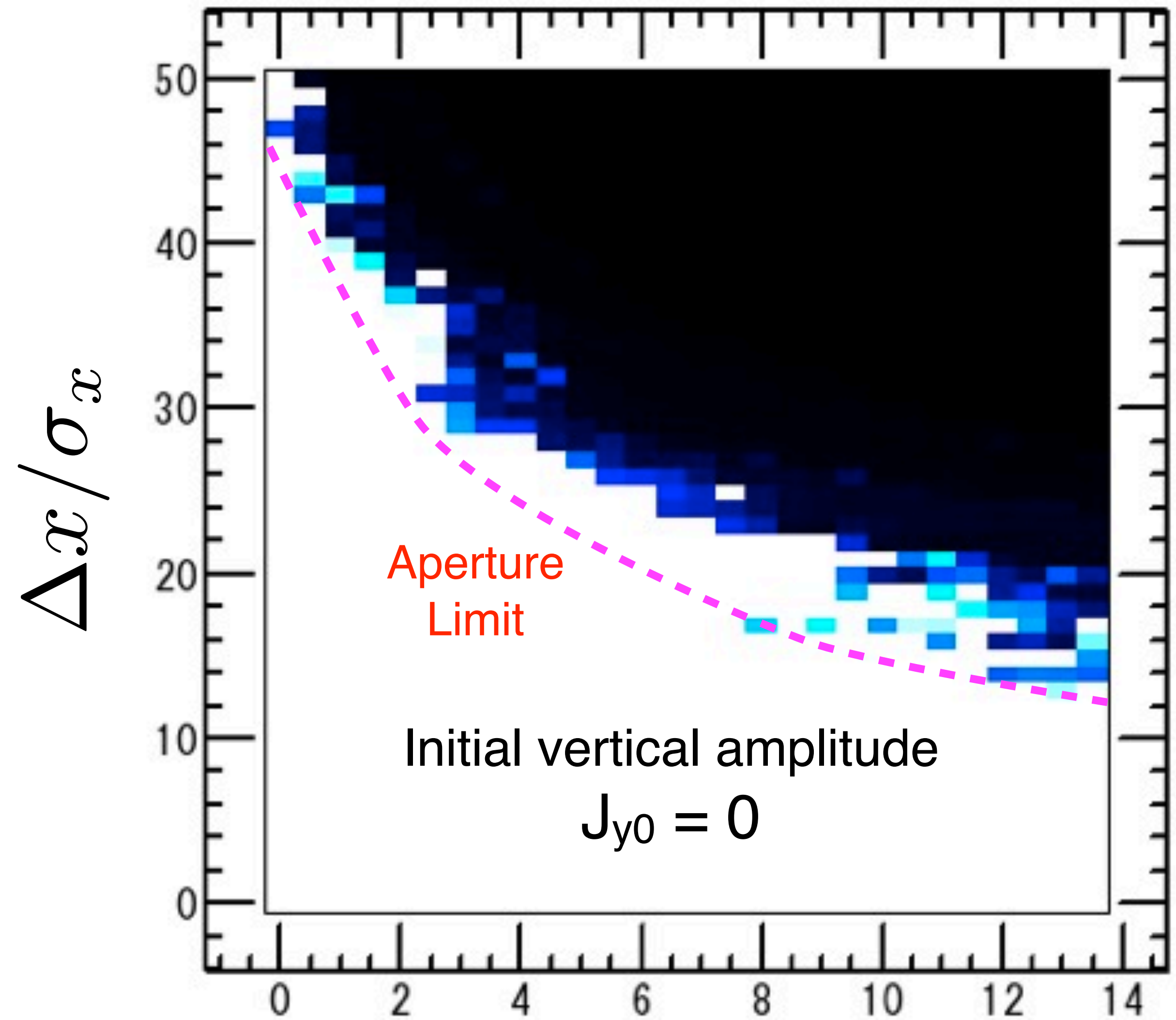
Transverse Aperture for Crab-Waist Scheme

Initial momentum deviation

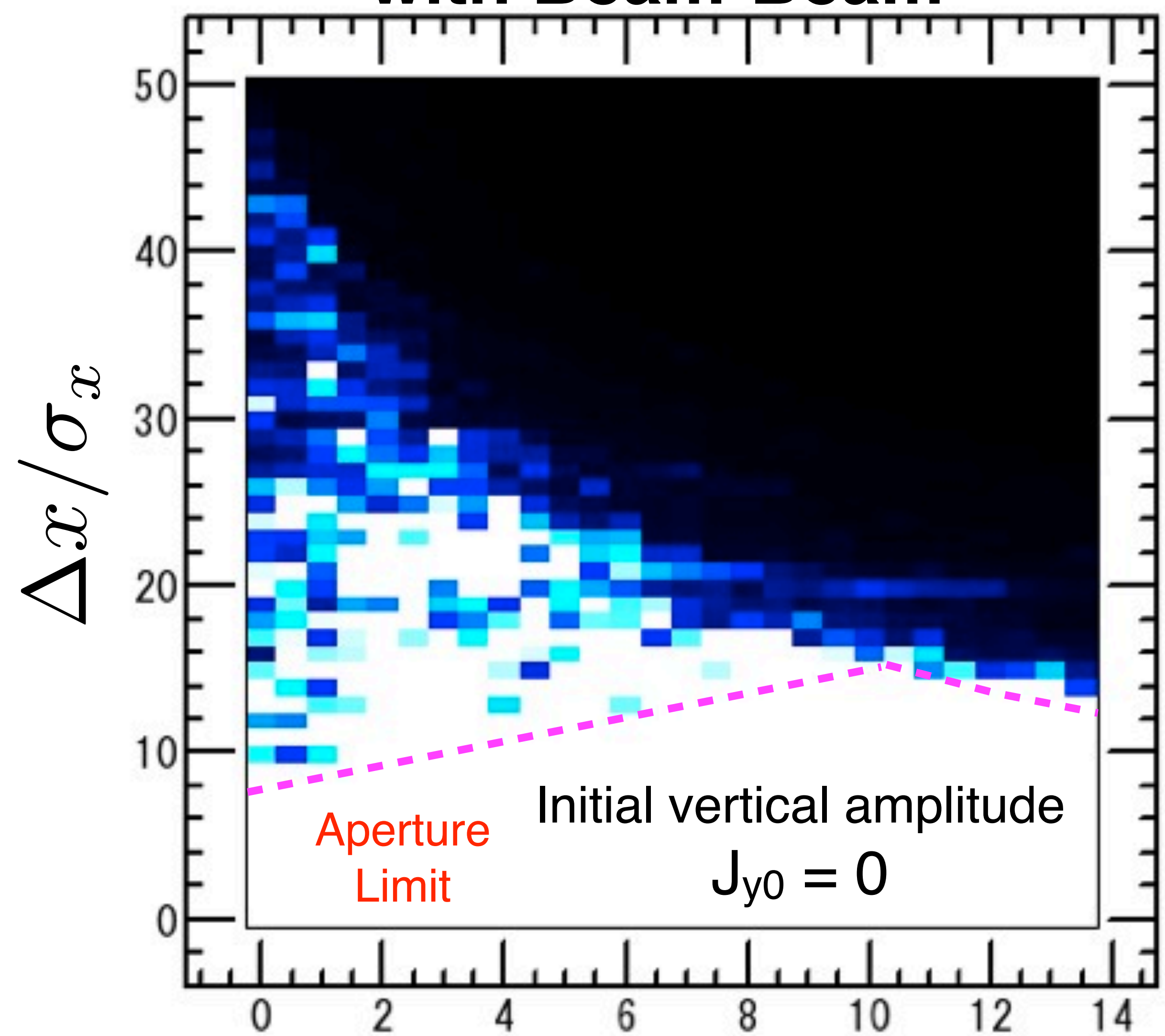
$$\delta_0 = \Delta p / p_0 = 0$$



without Beam-Beam



with Beam-Beam



$|K_2|$ [1/m^2]

Crab-Waist Sextupole OFF

Aperture is constrained by sextupole strength.

$|K_2|$ [1/m^2]

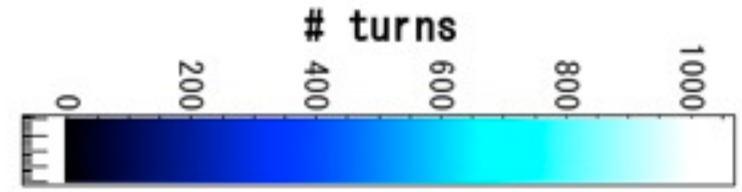
Crab-Waist Sextupole OFF

Aperture is recovered up to w/o Beam-Beam.

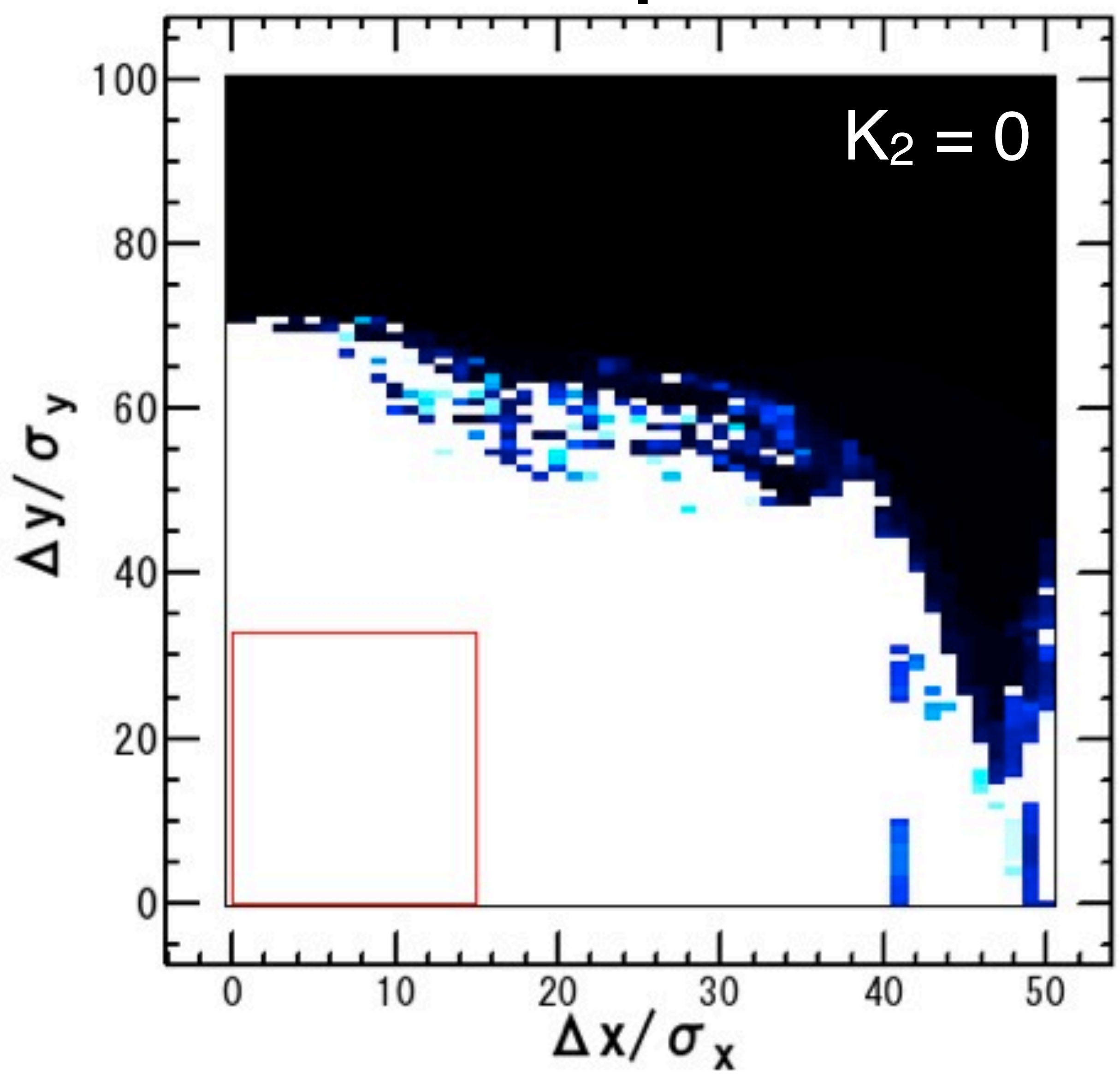
without Beam-Beam

Initial momentum deviation

$$\delta_0 = \Delta p / p_0 = 0$$

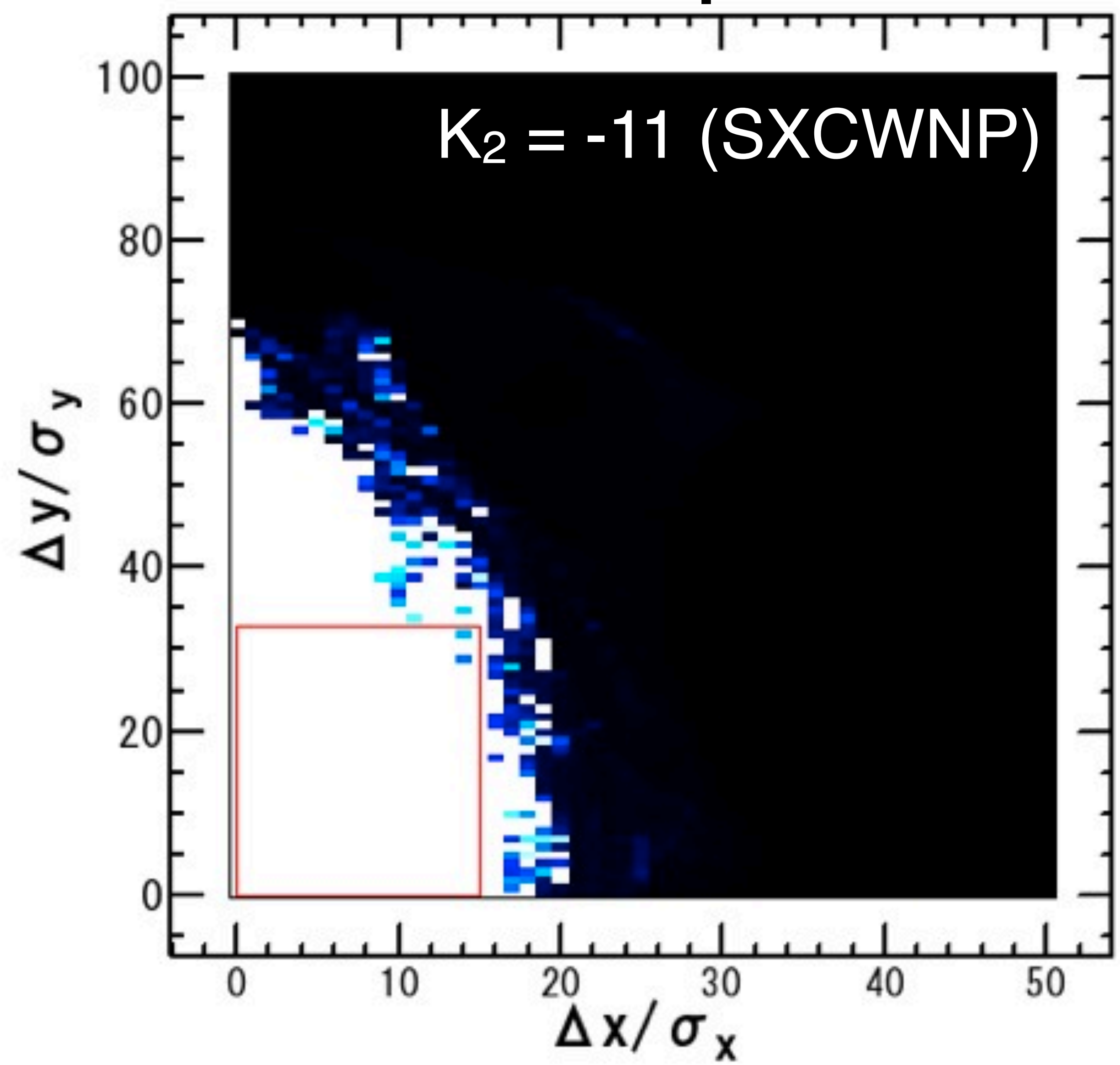


CW Sextupole OFF



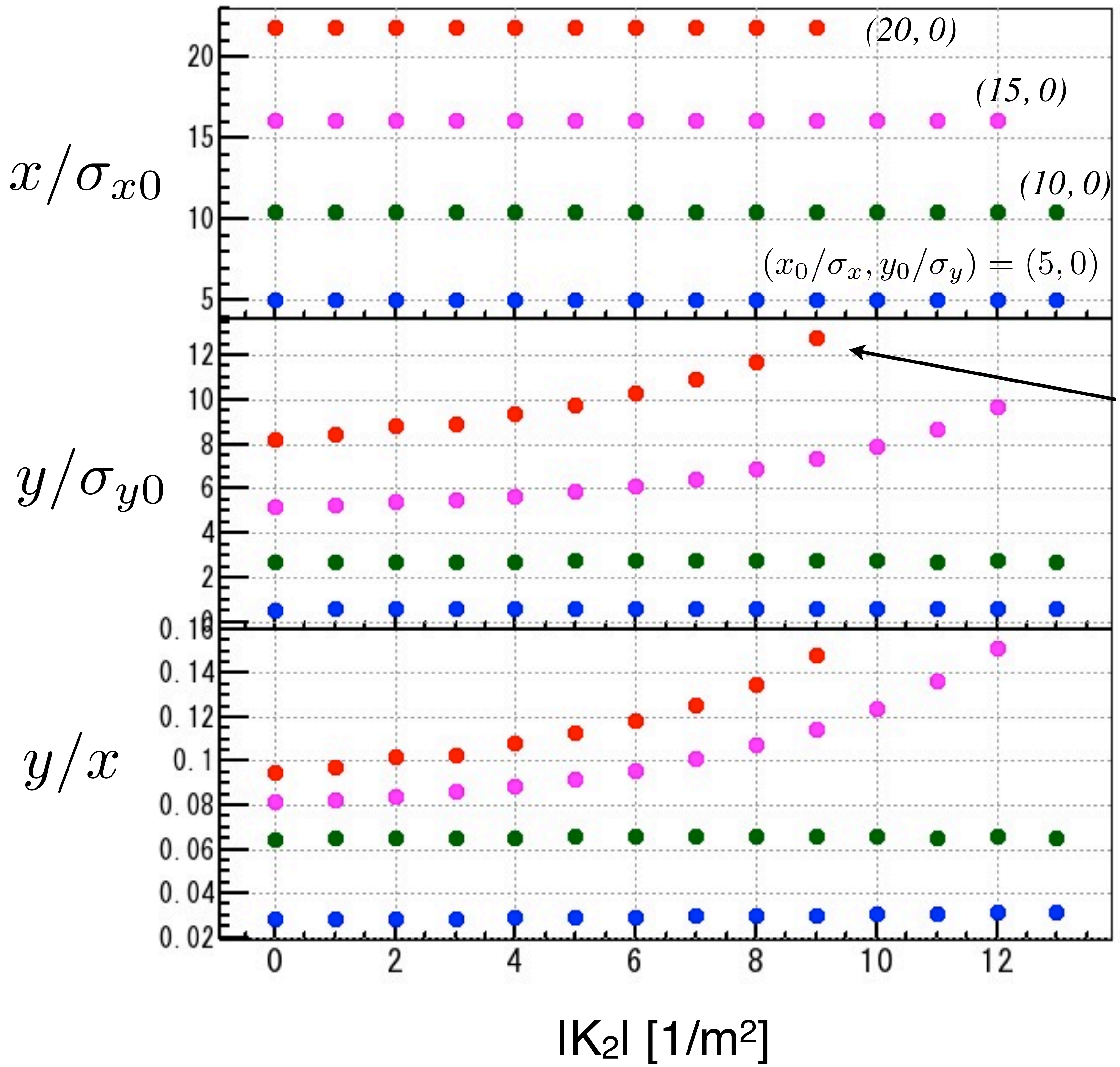
stable < 40σ_x

CW Sextupole ON



unstable > 17σ_x

Stability of Crab-Waist Scheme

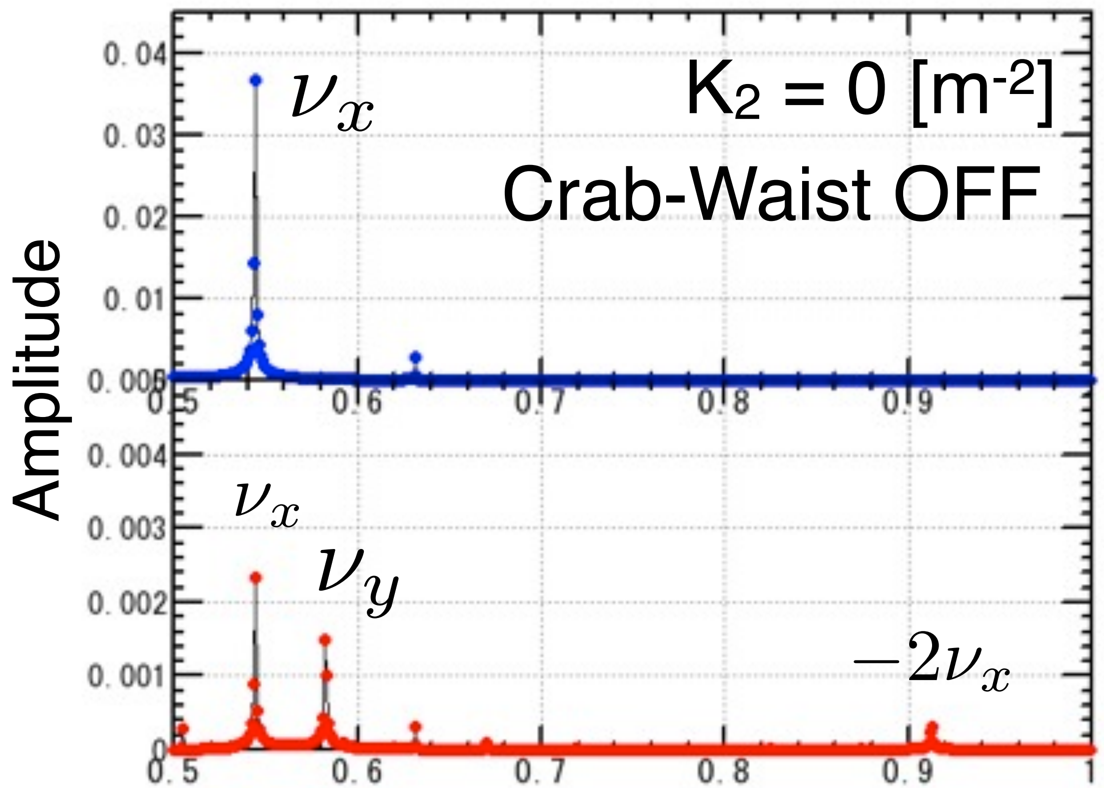


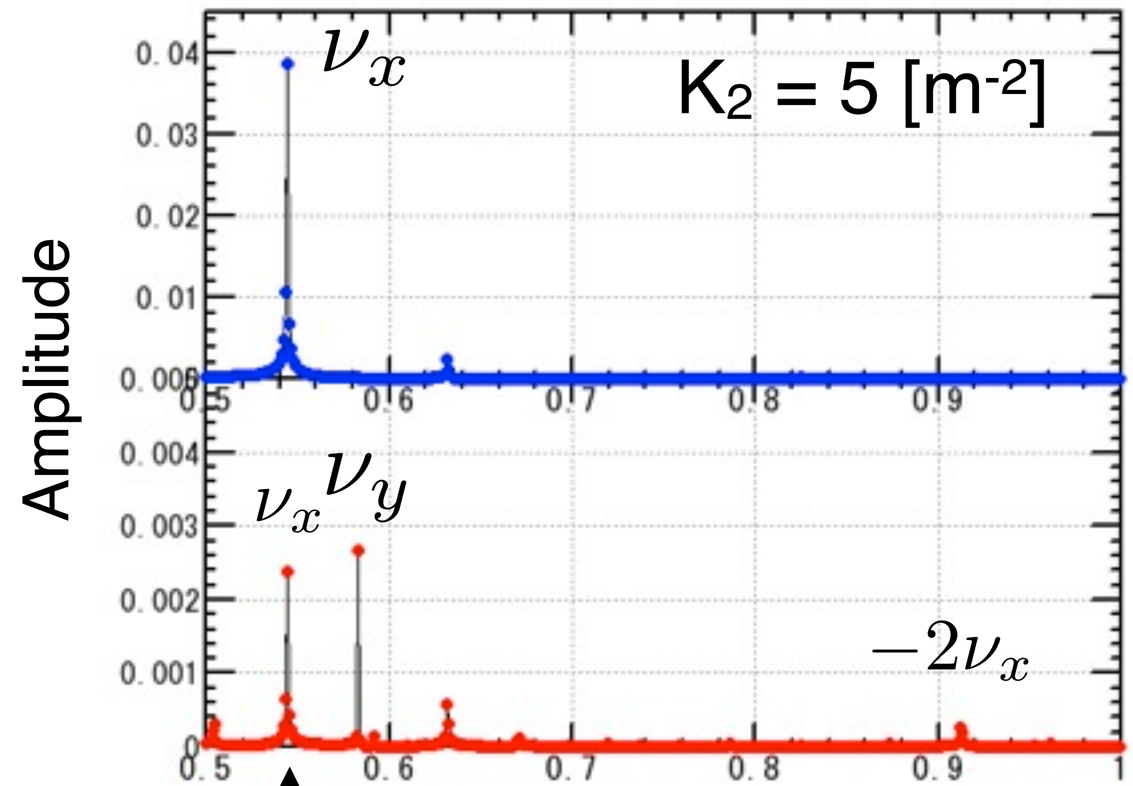
Horizontal motion is stable.

Vertical motion depends on crab-waist sextupole for large horizontal amplitude.

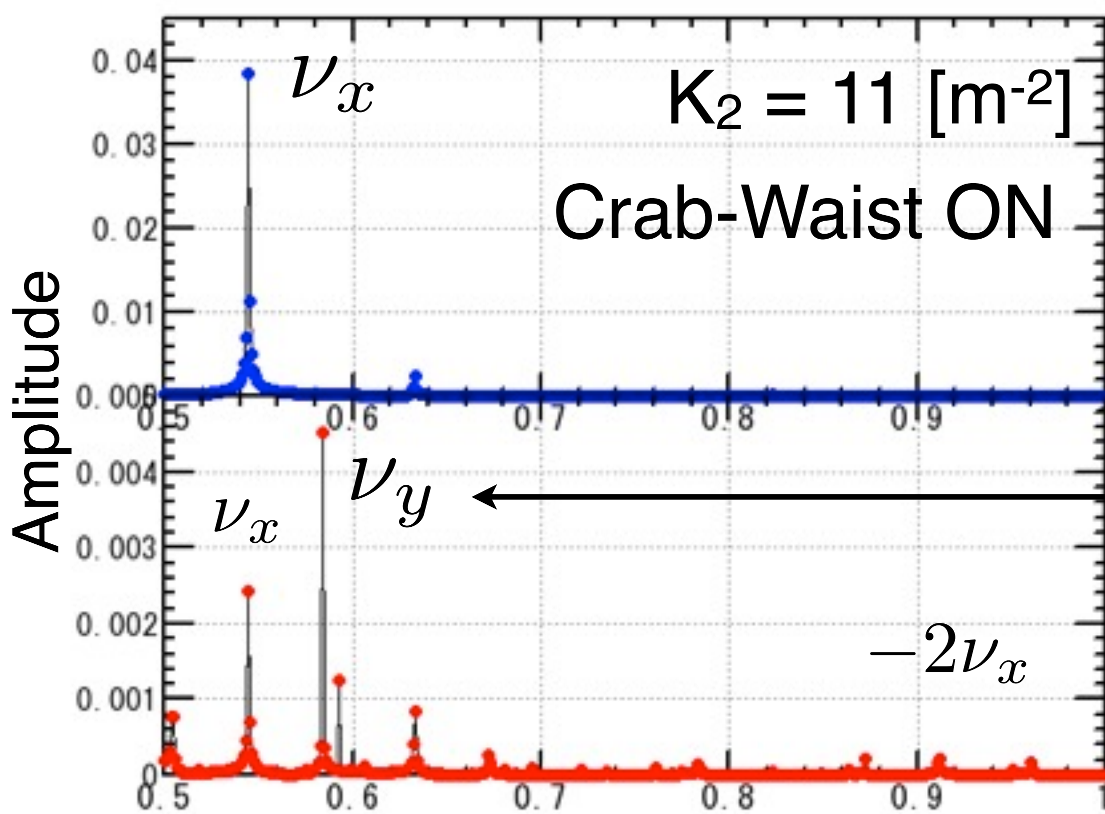
Fourier Analysis

initial amplitude: $(x_0, y_0) = (15\sigma_x, 0)$



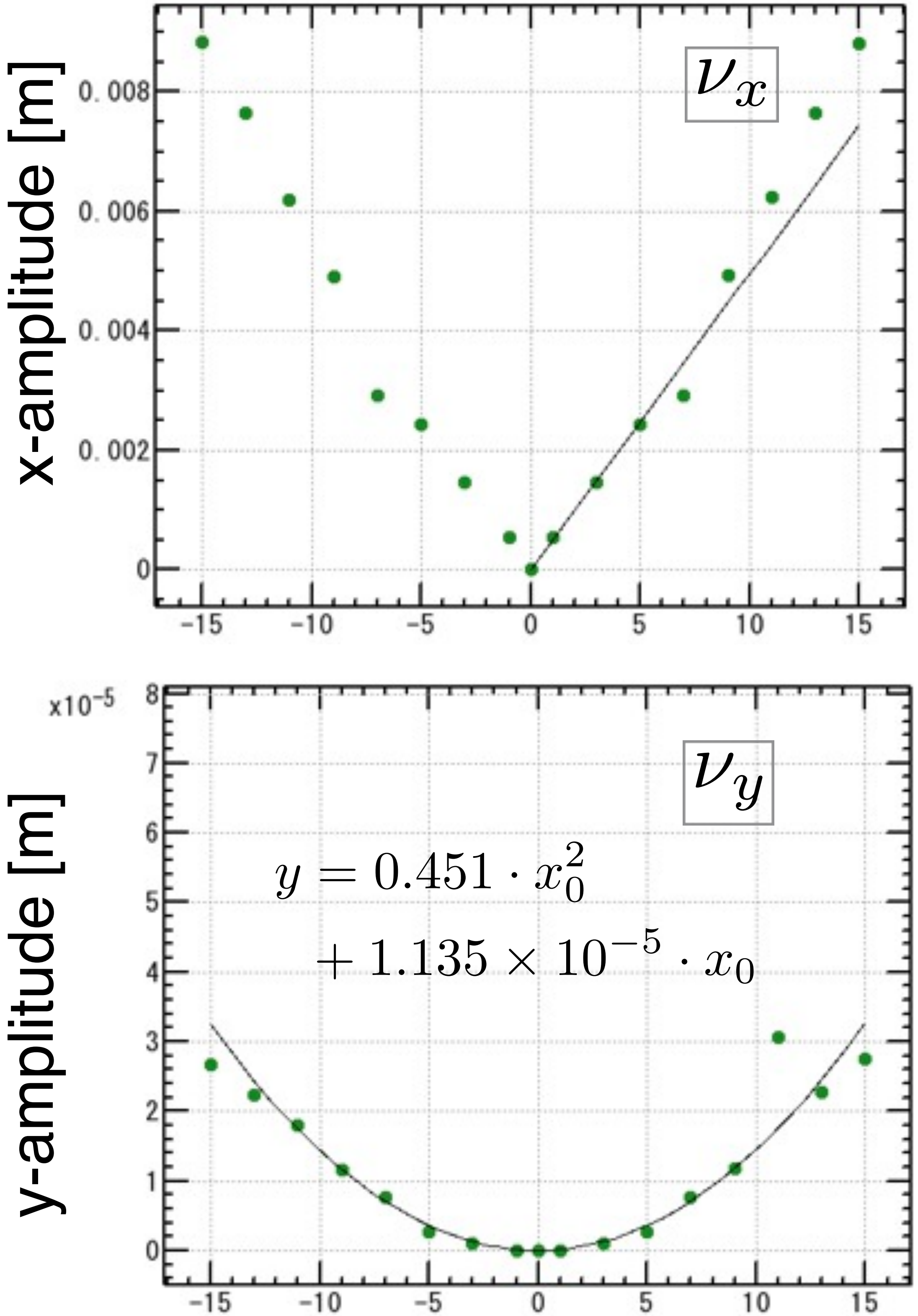


X-Y coupling (ν_x in y) is same even though increasing strength of crab-waist sextupoles.



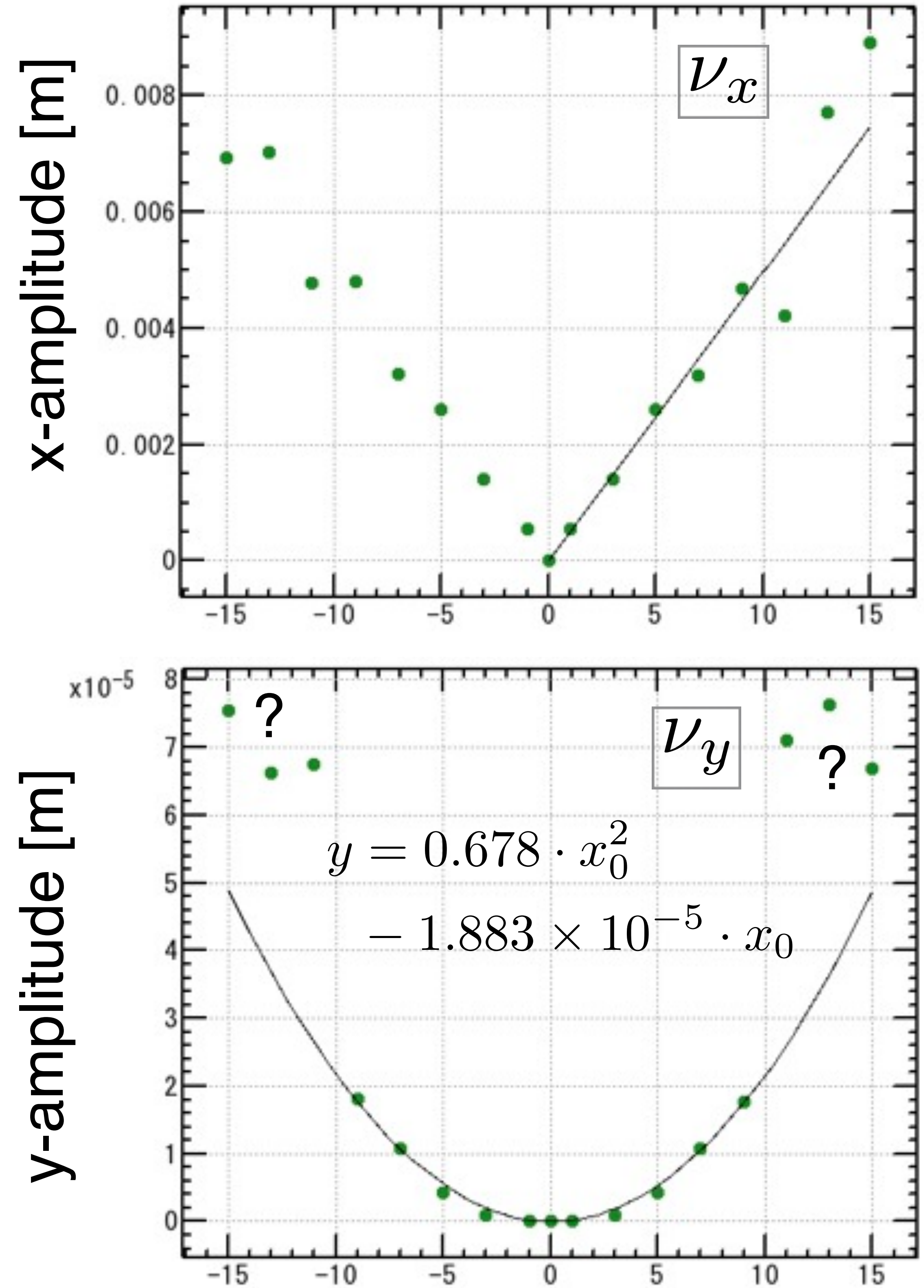
Vertical amplitude (ν_y in y) becomes larger as increasing strength of crab-waist sextupoles.

Crab-Waist OFF



x_0/σ_x stable < 40σx

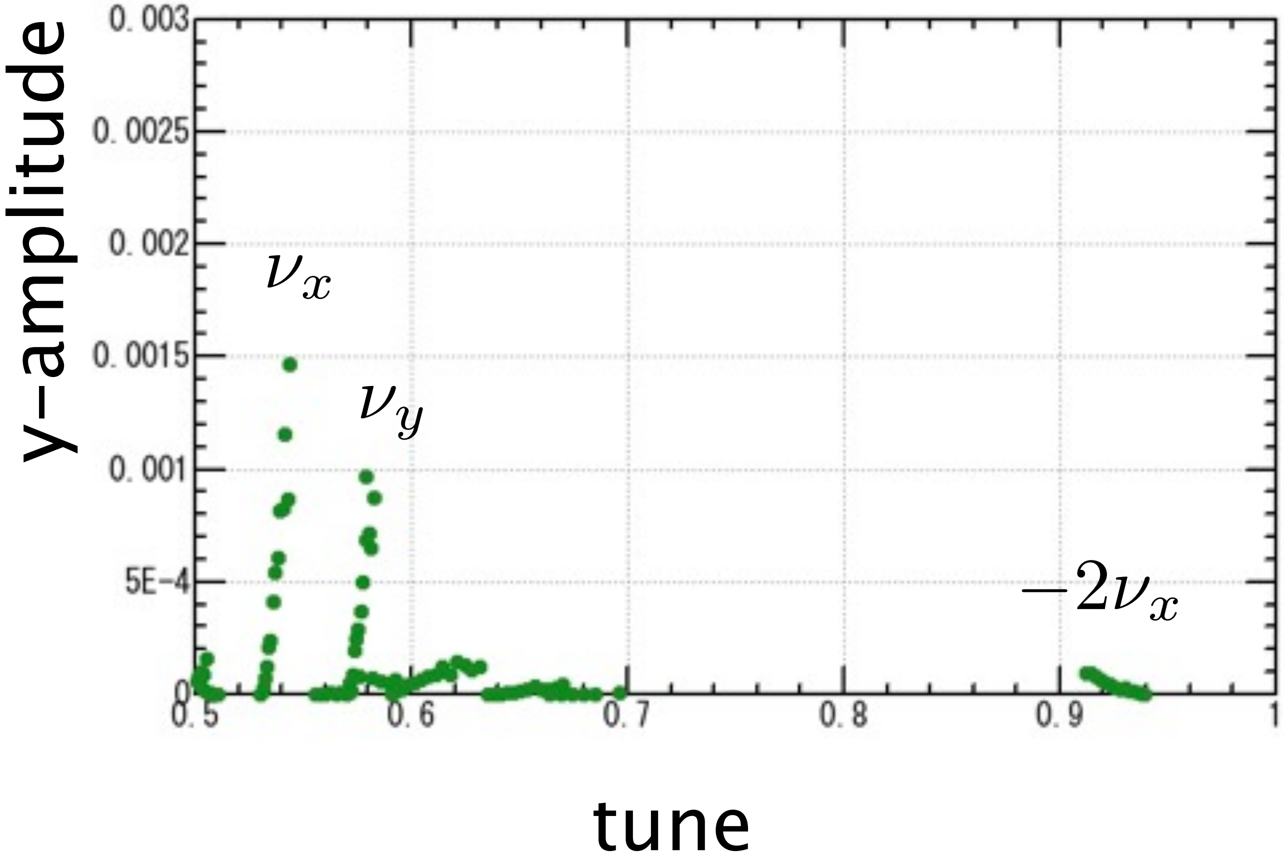
Crab-Waist ON



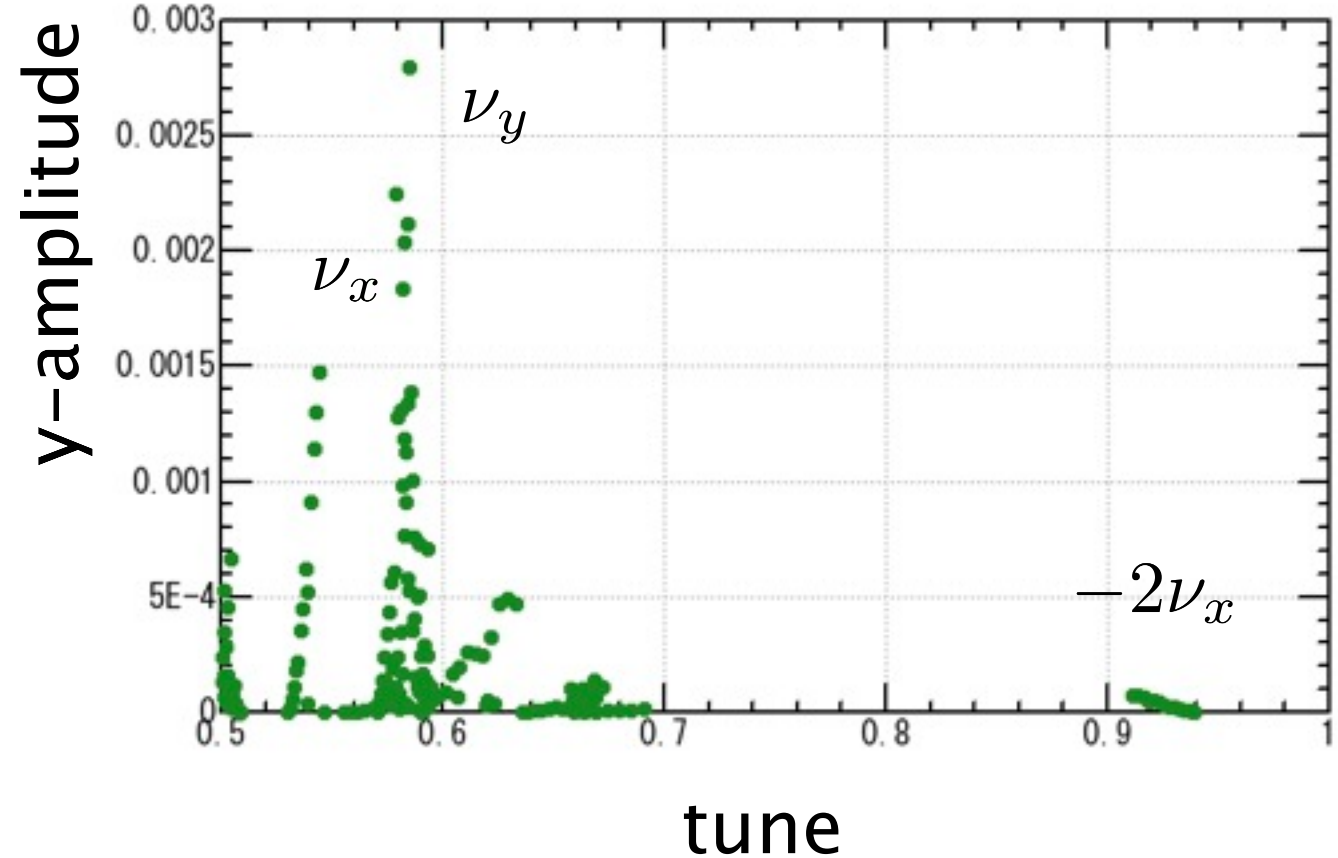
x_0/σ_x unstable > 17σx

Fourier Analysis

Crab-Waist OFF



Crab-Waist ON



Initial horizontal amplitude changes from 1 to 15 sigmas.

The frequency near the vertical tune becomes very complicated.
The amplitude becomes larger.

Summary

- Dynamic Aperture for SuperKEKB is optimized and Touschek lifetime of 600 sec has been accomplished without machine error and beam-beam interactions.
- Dynamic aperture under influence beam-beam interactions will be reduced in the nano-beam scheme. Especially, a particle with large horizontal amplitude will receive a large beam-beam kick in the vertical plane.
- Touschek lifetime of ~200 sec has been achieved by changing working point and re-optimization procedures so far.
- The crab-waist scheme is one of solutions to cure the beam-beam effect.
- The crab-waist scheme has a big issue of nonlinearities between the sextupoles. The nonlinearities comes from the FF. No way to alleviate the nonlinear kick due to the sextupoles.

Summary

Constant dripping wears away the stone.

(Constant effort will result in success.)

泰山之霤穿石

“水滴石穿”

Appendix

Nano-Beam Scheme

Luminosity formula:

$$L \propto \frac{N_+ N_-}{\sigma_z \phi_x \sqrt{\boxed{\varepsilon_y \beta_y^*}}}$$

Small β_y^*, small ε_y $\longrightarrow$ High luminosity

$$\tilde{\sigma}_x^* = \sigma_z \phi_x$$

(effective) (6 mm x 41.5 mrad)

Long "bunch length" is OK.

~ 8 x 10^{35} $cm^{-2}s^{-1}$

Beam-Beam:

$$\xi_{y\pm} \propto \frac{N_\mp}{\sigma_z \phi_x} \sqrt{\boxed{\frac{\beta_y^*}{\varepsilon_y}}}$$

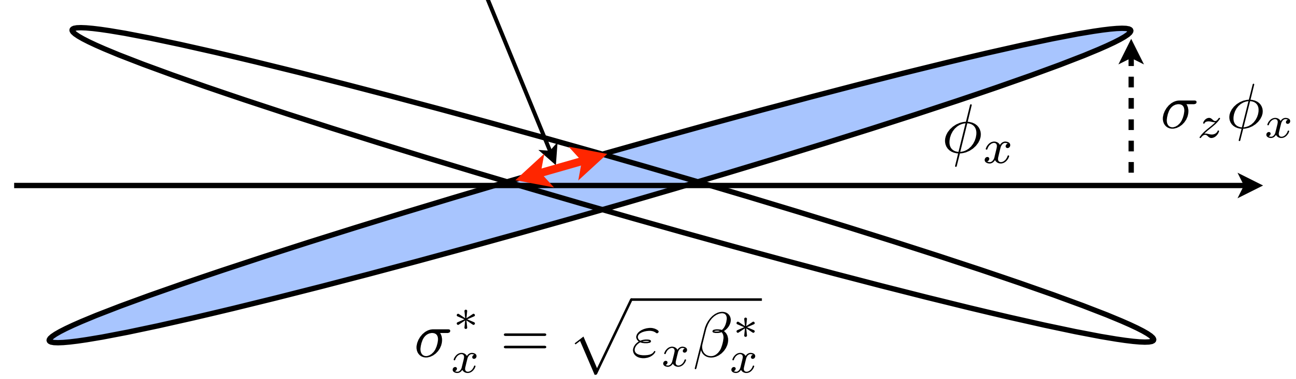
~ 0.09

To avoid too large ξ_y (dangerous), the **ratio of β_y^* to ε_y should be small.**

The hourglass condition is modified:

$$\beta_y^* > \tilde{\sigma}_z = \frac{\sigma_x^*}{\phi_x} \sim 250\ \mu m$$

(effective)



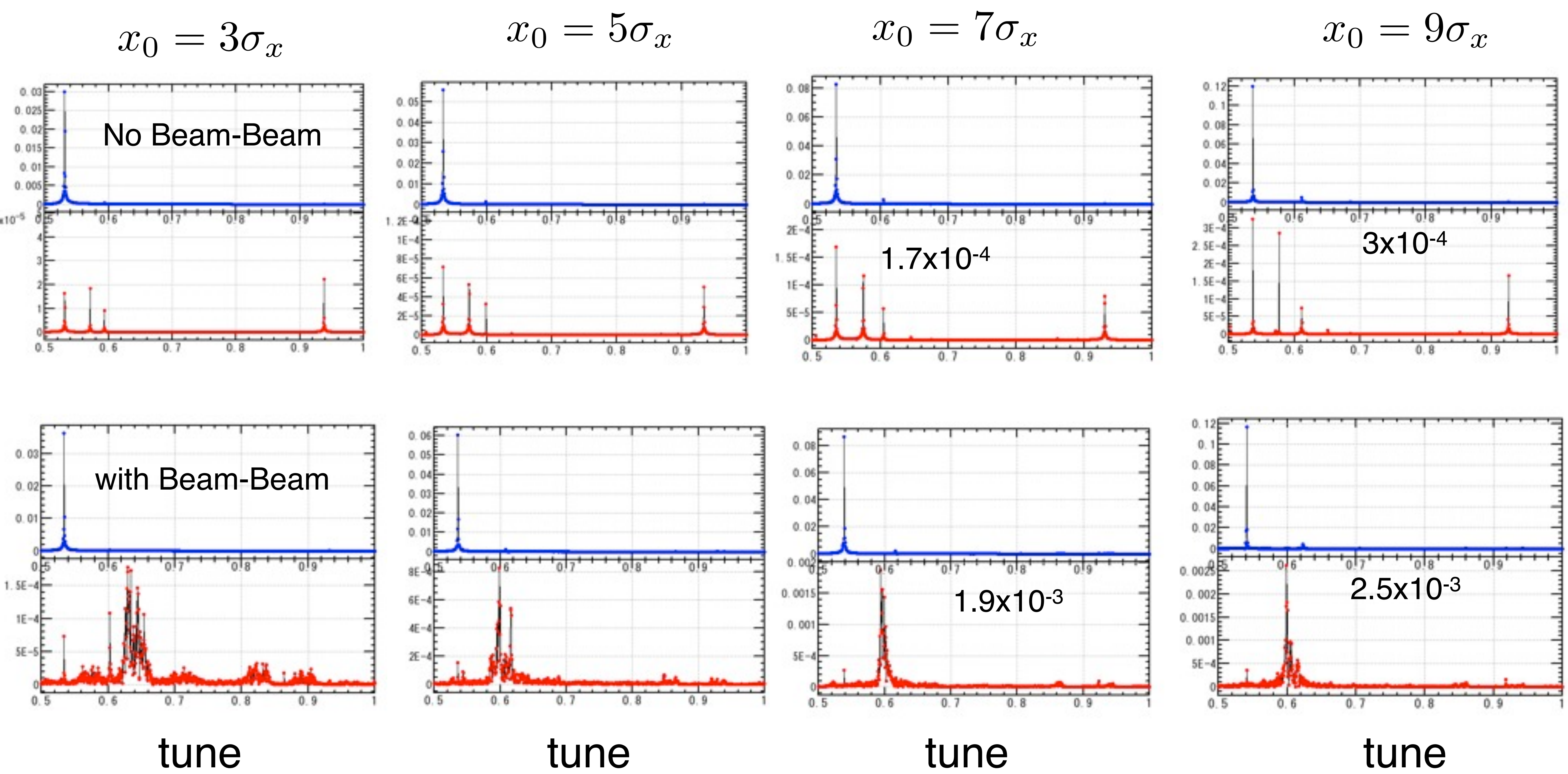
$$\xi_{x\pm} \propto \frac{N_\mp \beta_x^*}{(\sigma_z \phi_x)^2}$$

~ 0.003

Dynamic effects can be ignored.

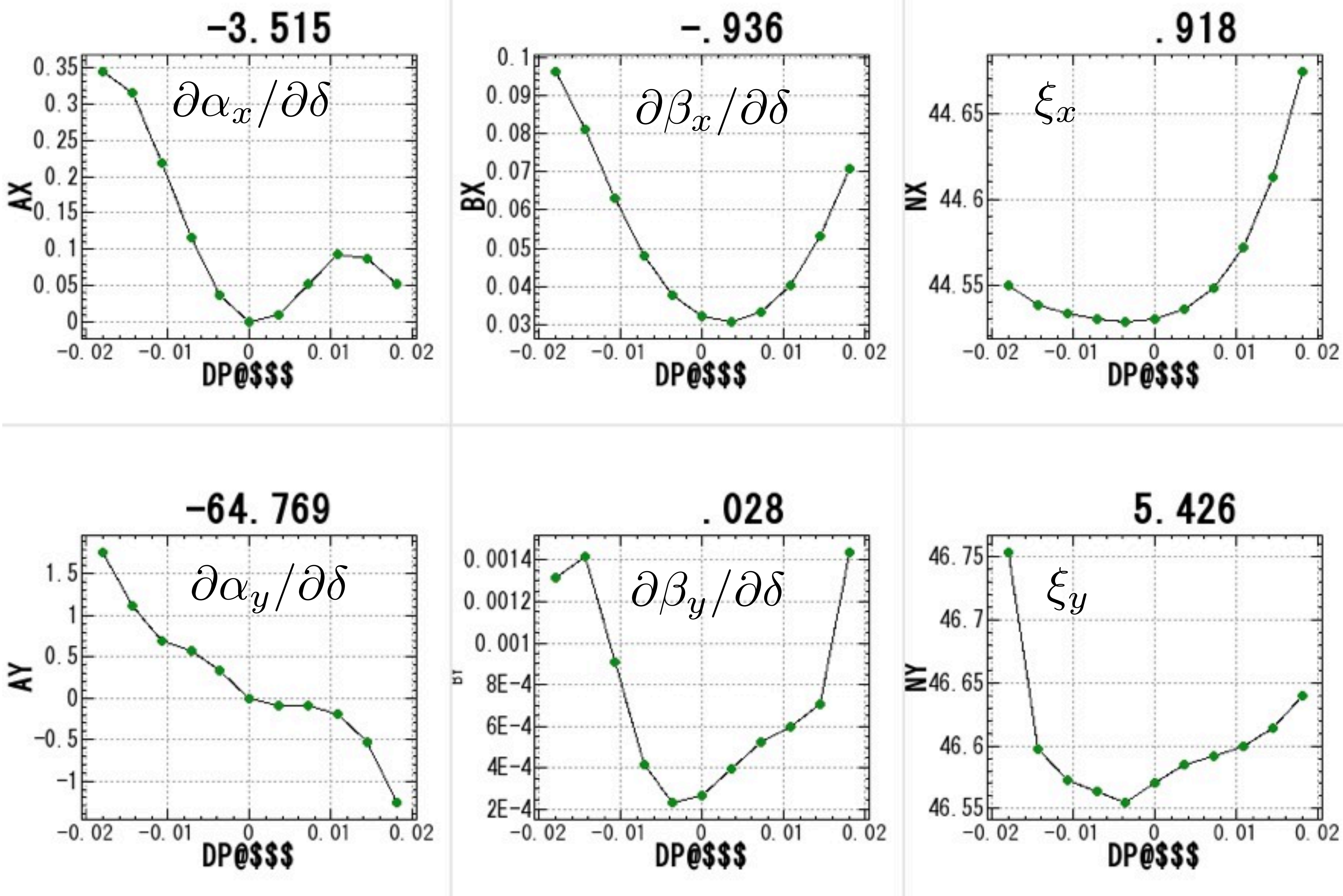
Machine Parameters

2013/July/29	LER	HER	unit	
E	4.000	7.007	GeV	
I	3.6	2.6	A	
Number of bunches	2,500			
Bunch Current	1.44	1.04	mA	
Circumference	3,016.315		m	
$\varepsilon_x/\varepsilon_y$	3.2(1.9)/8.64(2.8)	4.6(4.4)/12.9(1.5)	nm/pm	():zero current
Coupling	0.27	0.28		includes beam-beam
β_x^*/β_y^*	32/0.27	25/0.30	mm	
Crossing angle	83		mrad	
α_p	$3.18\text{x}10^{-4}$	$4.53\text{x}10^{-4}$		
σ_δ	$8.10(7.73)\text{x}10^{-4}$	$6.37(6.30)\text{x}10^{-4}$		():zero current
V_c	9.4	15.0	MV	
σ_z	6.0(5.0)	5(4.9)	mm	():zero current
ν_s	-0.0244	-0.0280		
ν_x/ν_y	44.53/46.57	45.53/43.57		
U_0	1.86	2.43	MeV	
$\tau_{x,y}/\tau_s$	43.2/21.6	58.0/29.0	msec	
ξ_x/ξ_y	0.0028/0.0881	0.0012/0.0807		
Luminosity	$8\text{x}10^{35}$		$cm^{-2}s^{-1}$	



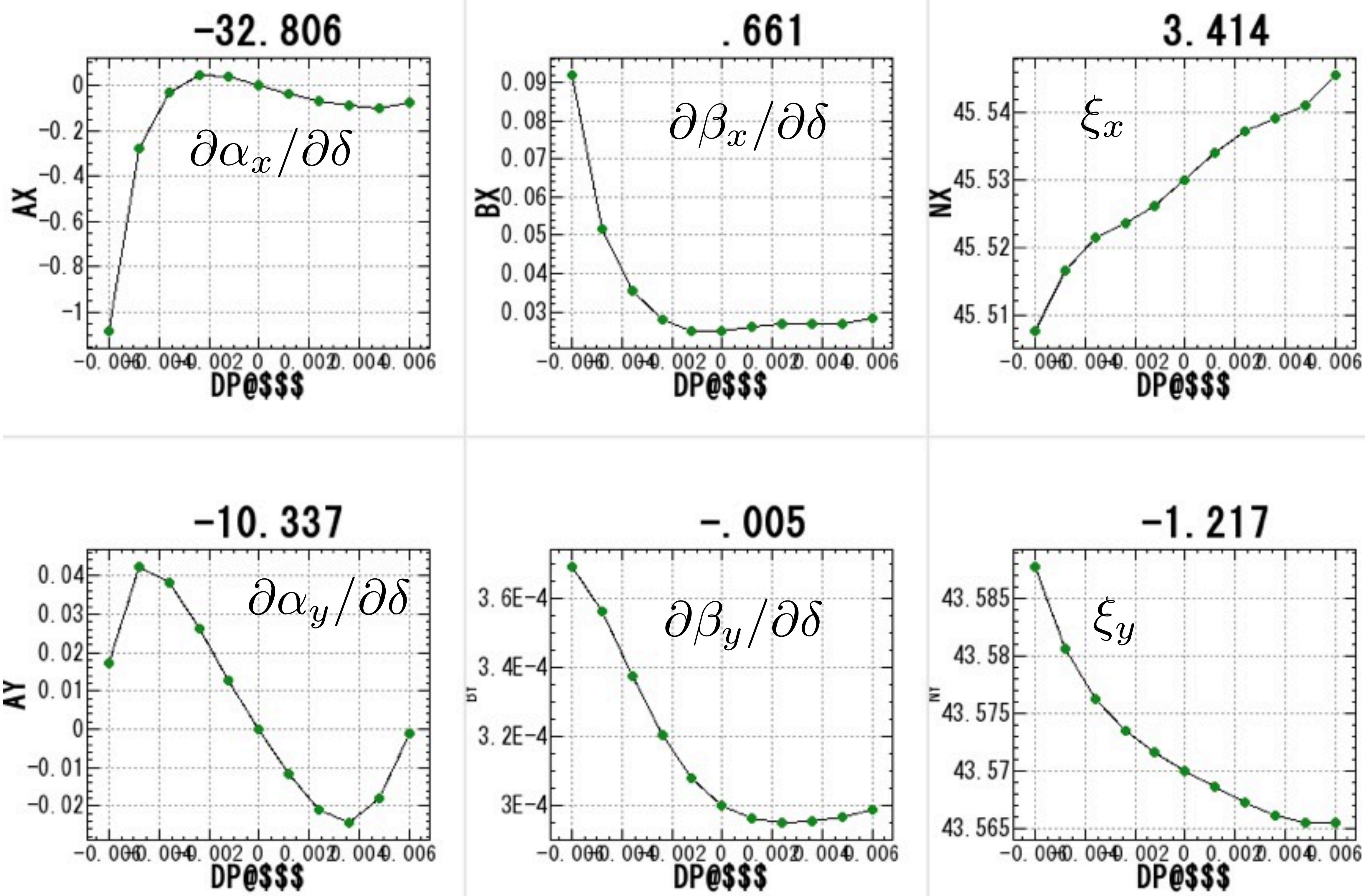
blue: horizontal
red: vertical

Twiss chromaticity at IP

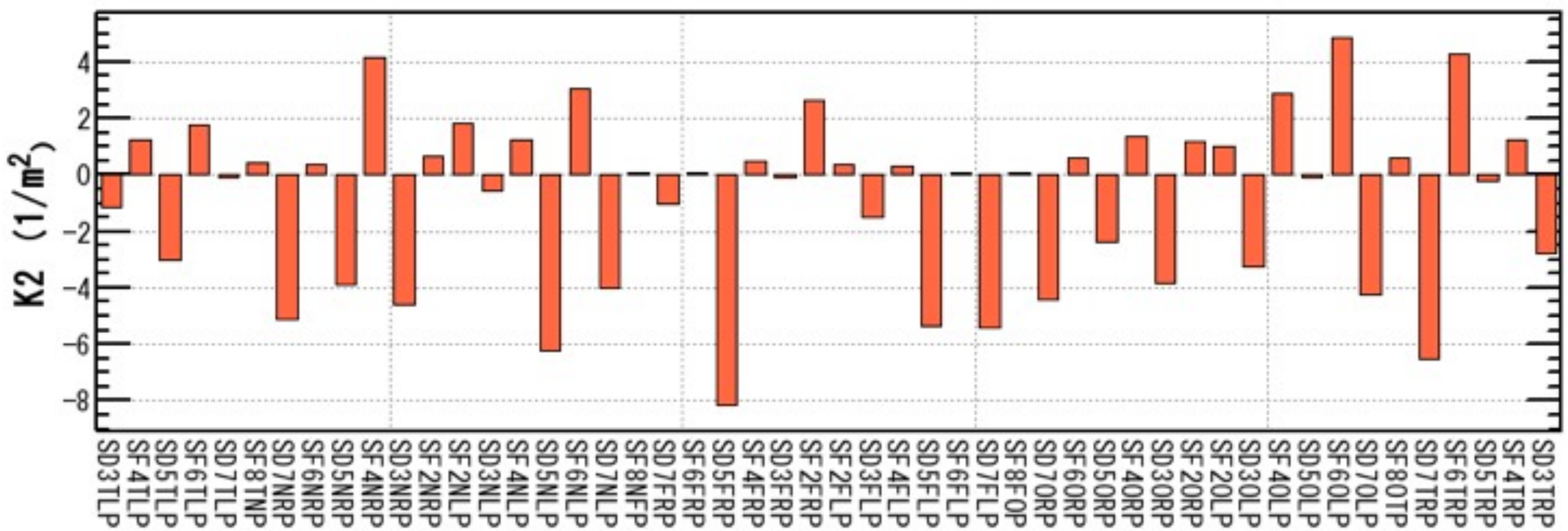


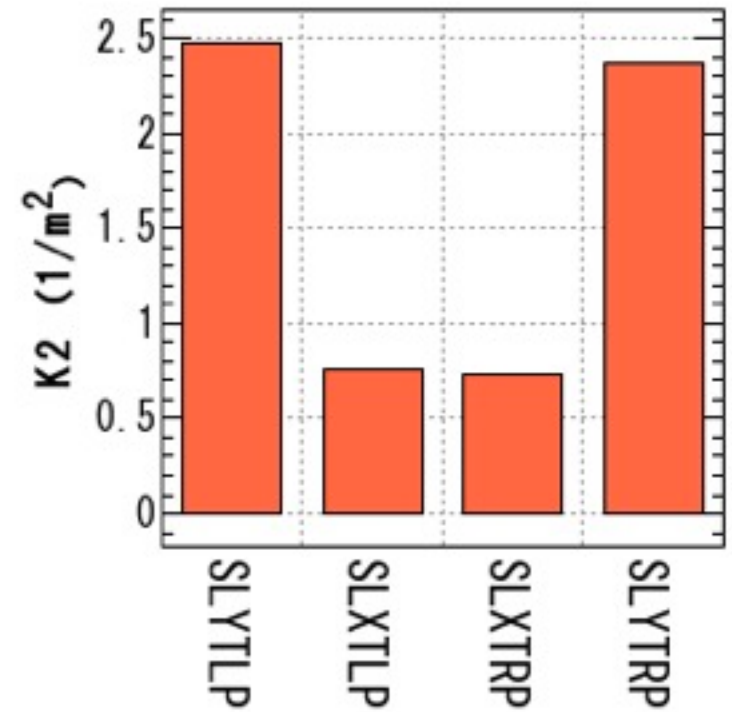
Chromaticity in HER

Twiss chromaticity at IP

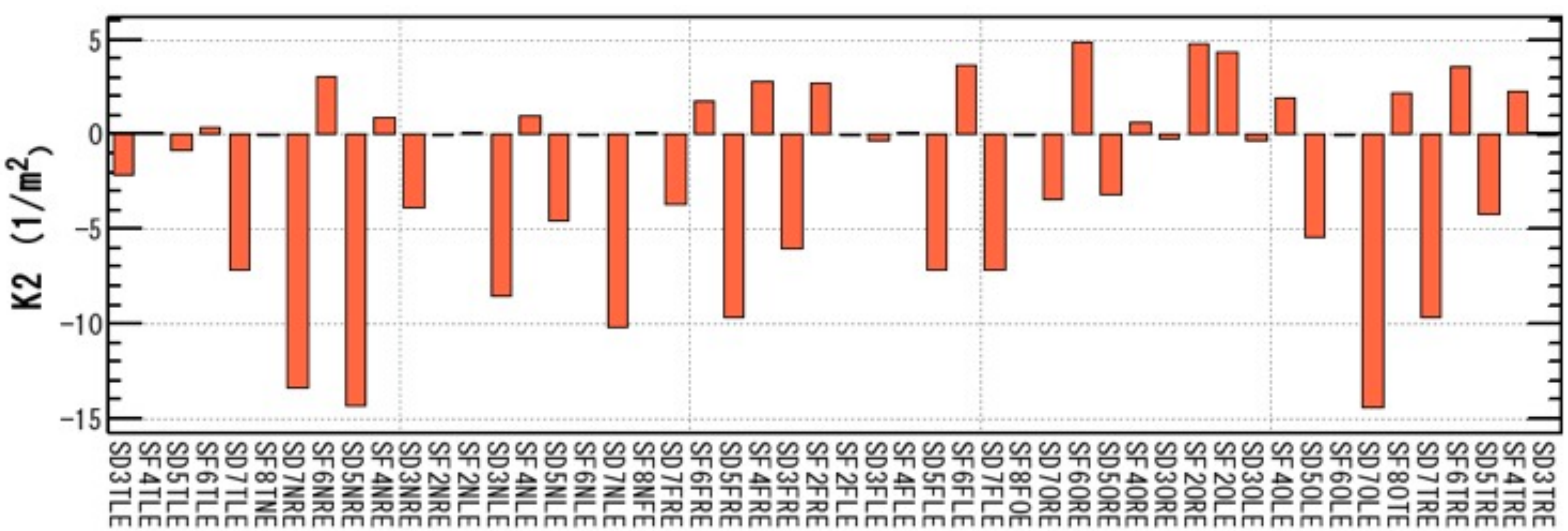


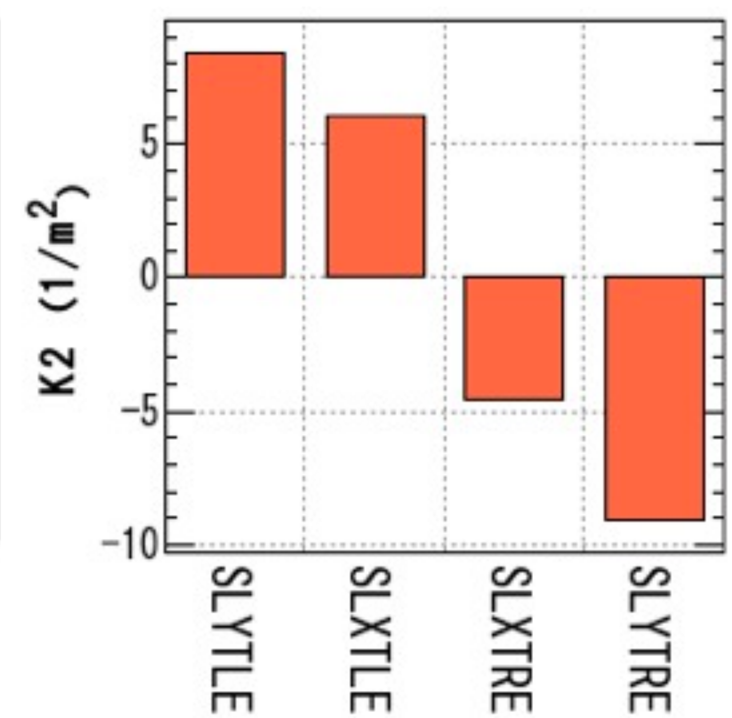
LER


K2 (1/m^2)
4
2
0
-2
-4
-6
-8
SD3TLP SF4TLP SD5TLP SF6TLP SD7TLP SF8TNP SD7NRP SF6NRP SD5NRP SF4NRP SD3NRP SF2NRP SF2NLP SD3NLP SF4NLP SD5NLP SF6NLP SD7NLP SF8NFP SD7FRP SF6FRP SD5FRP SF4FRP SD3FRP SF2FRP SF2FLP SD3FLP SF4FLP SD5FLP SF6FLP SD7FLP SF8FOP SD7ORP SF6ORP SD5ORP SF4ORP SD3ORP SF2ORP SF2OLP SD3OLP SF4OLP SD5OLP SF6OLP SD7OLP SF8OTP SD7TRP SF6TRP SD5TRP SF4TRP SD3TRP


K2 (1/m^2)
2.5
2
1.5
1
0.5
0
SLYTLP
SLXTLP
SLXTRP
SLYTRP

HER


K2 (1/m^2)
5
0
-5
-10
-15
SD3TLE SF4TLE SD5TLE SF6TLE SD7TLE SF8TNE SD7NRE SF6NRE SD5NRE SF4NRE SD3NRE SF2NRE SF2NLE SD3NLE SF4NLE SD5NLE SF6NLE SD7NLE SF8NFE SD7FRE SF6FRE SD5FRE SF4FRE SD3FRE SF2FRE SF2FLE SD3FLE SF4FLE SD5FLE SF6FLE SD7FLE SF8FOE SD7ORE SF6ORE SD5ORE SF4ORE SD3ORE SF2ORE SF2OLE SD3OLE SF4OLE SD5OLE SF6OLE SD7OLE SF8OTE SD7TRE SF6TRE SD5TRE SF4TRE SD3TRE


K2 (1/m^2)
5
0
-5
-10
SLYTLE
SLXTLE
SLXTRE
SLYTRE