Status of Optics Design

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17th B2GM

KEK, February 5, 2014

Contents

- Lattice parameters
- Dynamic aperture under influence of beam-beam effect
- Lattice preparation for each phase
- Phase 1 lattice
- Phase 2 and Phase 3 lattice
- Summary

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

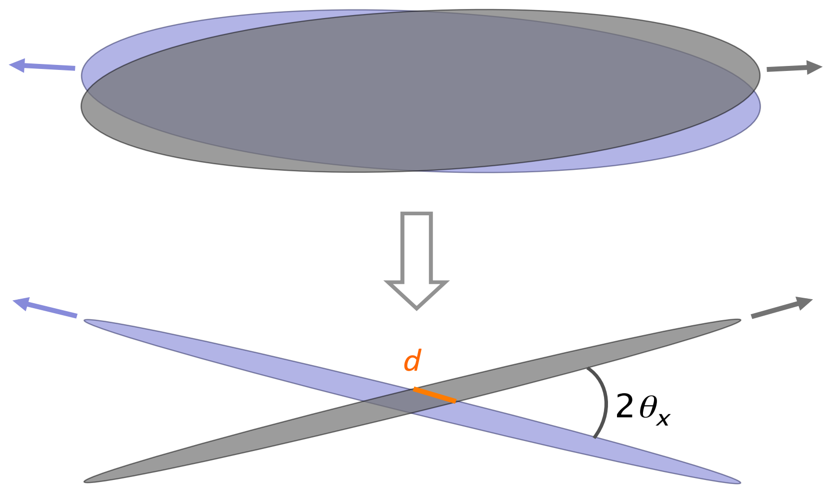
Very small vertical emittance is necessary.

	Symbol	LER	HER	Unit
Horizontal Emittance(1)	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(2)	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(1)	σ_z	6	5	mm
Full crossing angle	$2\phi_x$	83		mrad

(1) Intra-beam scattering is included.
(2) Machine error, beam-beam effect, etc. are included.

Nano-Beam Scheme

Small ϕ_{Piw}
KEKB : ~ 1
θ_x=11 mrad
No crab crossing



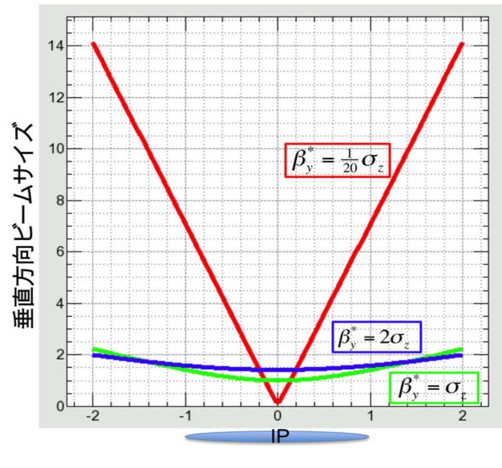
Large ϕ_{Piw}
SuperKEKB : ~ 20
θ_x=41.5 mrad

θ_x: half crossing angle

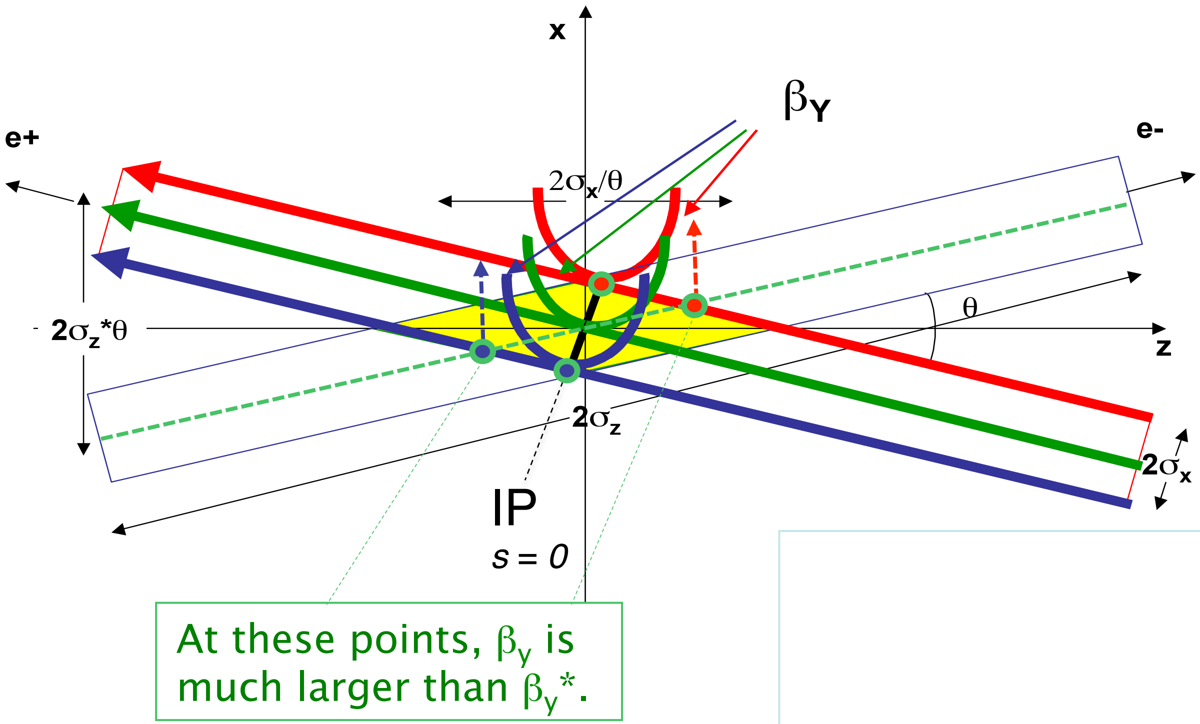
Piwinski angle

$$\phi_{Piw} = \frac{\theta_x \sigma_z}{\sigma^*_x}$$

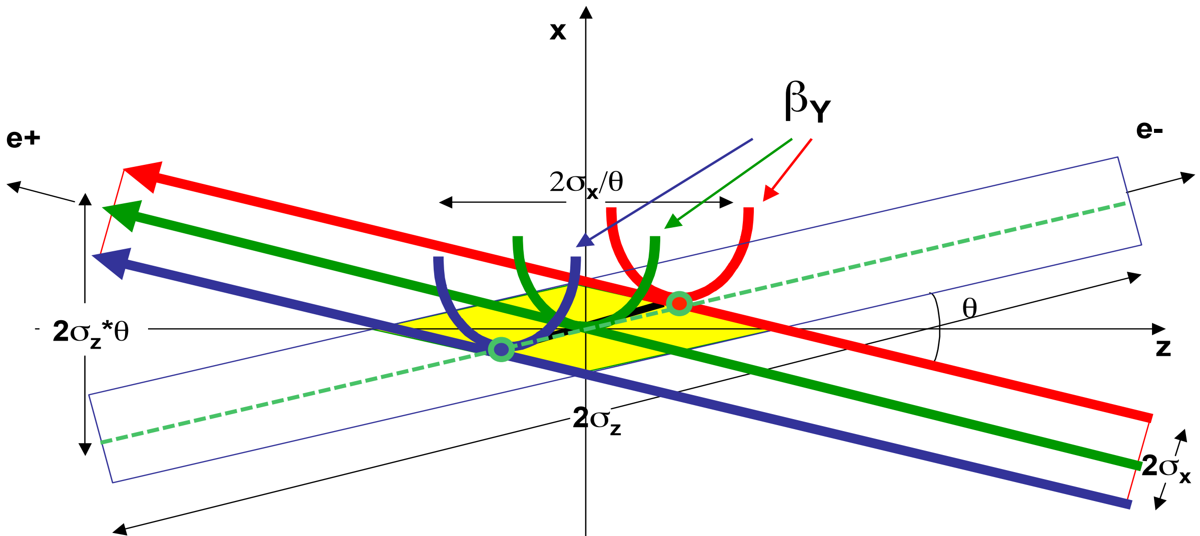
$$d = \frac{\sigma^*_x}{\theta_x} = \frac{\sigma_z}{\phi_{Piw}}$$



Schematic View of colliding bunches



No Crab Waist
SuperKEKB

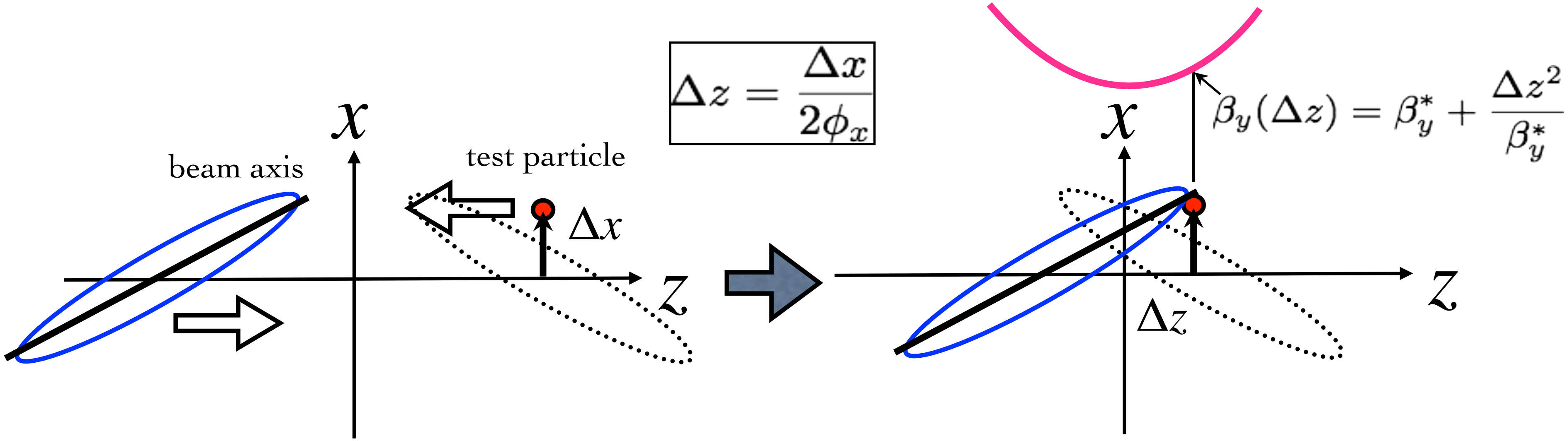


Crab Waist
Waist points are aligned along the center line of the counter-rotating beam.

M. Zovob et al., http://arxiv.org/pdf/0802.2667.pdf

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

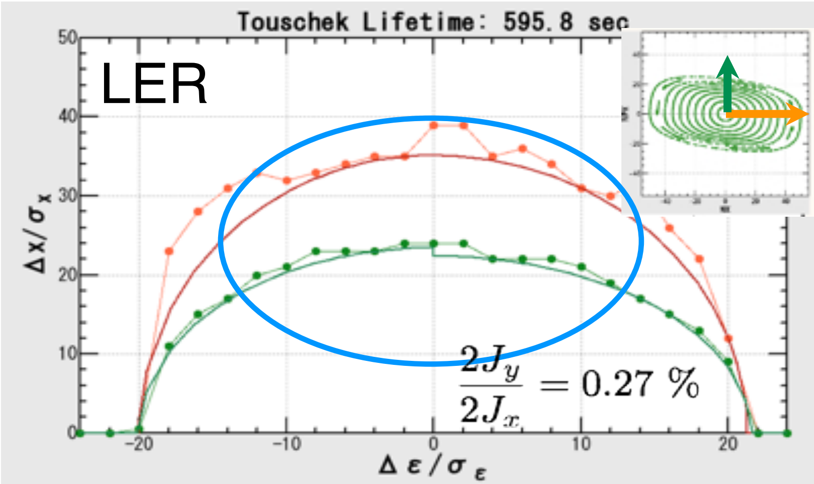
$$\Delta y \propto \theta_y^{bb} \sqrt{\beta_y(\Delta z)}$$

~factor of 180

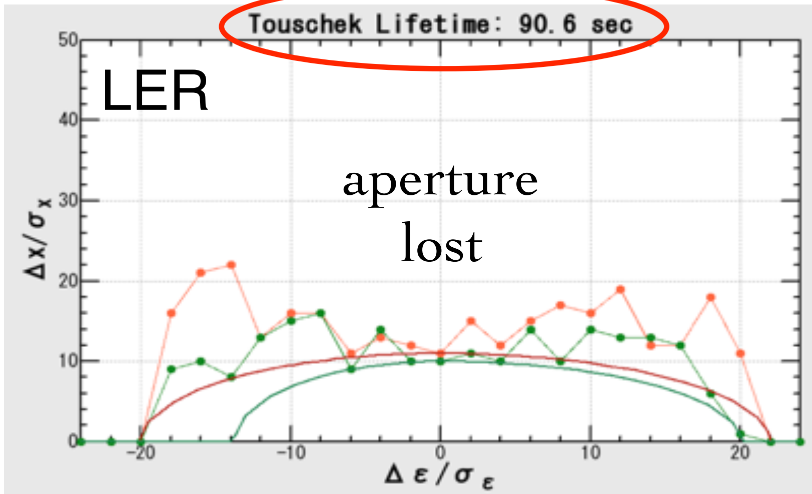
- Particles with a large horizontal orbit are kicked by the beam-beam force at high vertical beta region. Consequently, the vertical betatron oscillation increases due to the vertical beam-beam kick. The transverse aperture decreased, which implies small dynamic aperture.

Difficulty in the Nano-Beam scheme

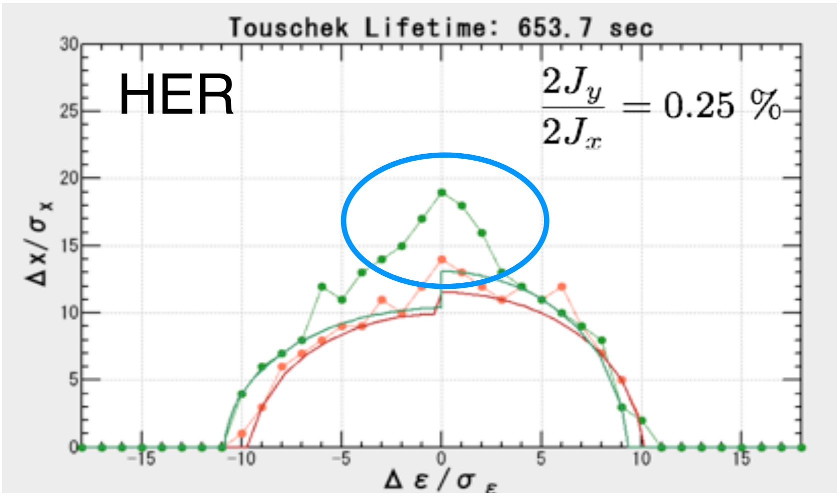
w/o beam-beam

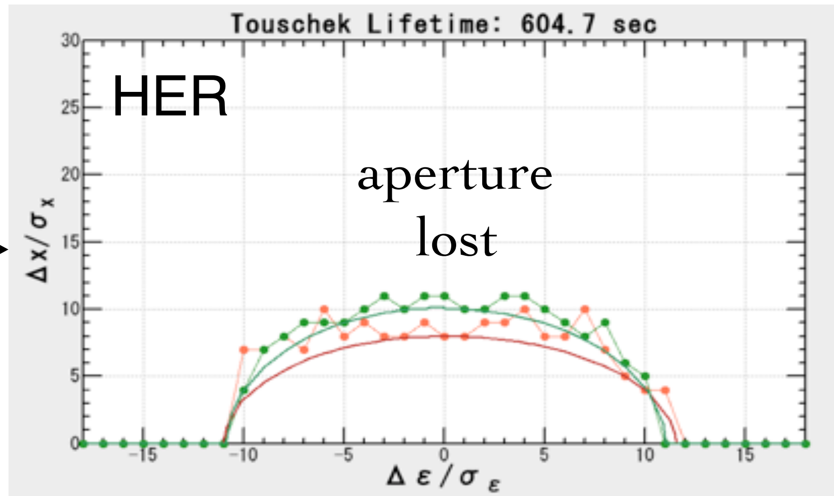


with beam-beam

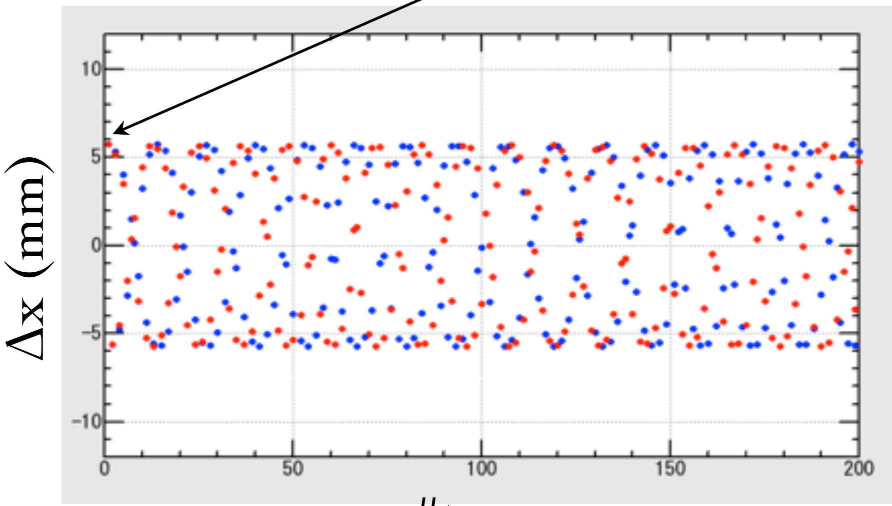


Transverse aperture is reduced significantly.





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

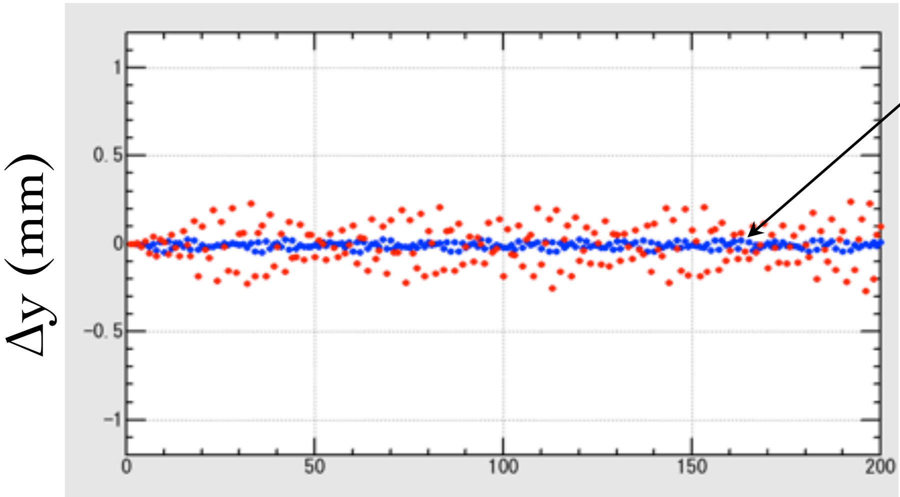


#turn

blue: no beam-beam

red: with beam-beam

Horizontal betatron oscillation is stable for both case.



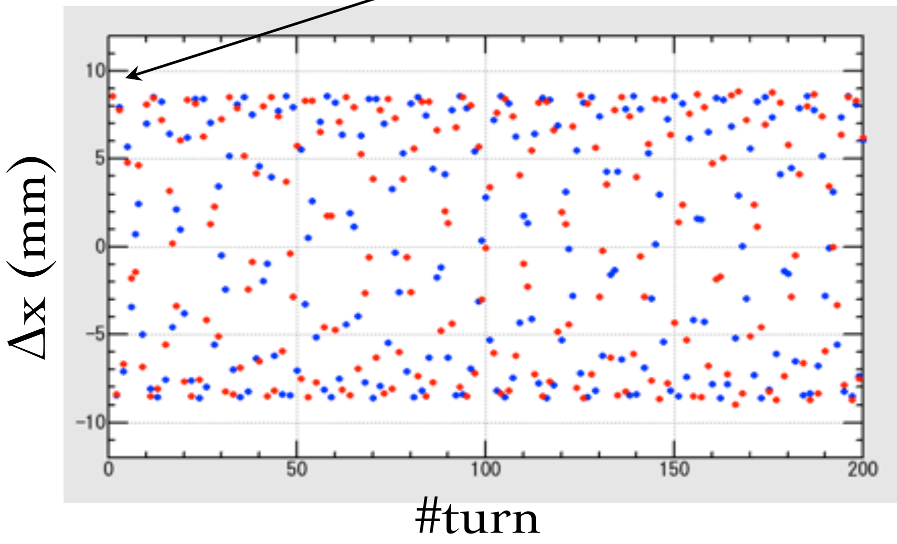
#turn

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.

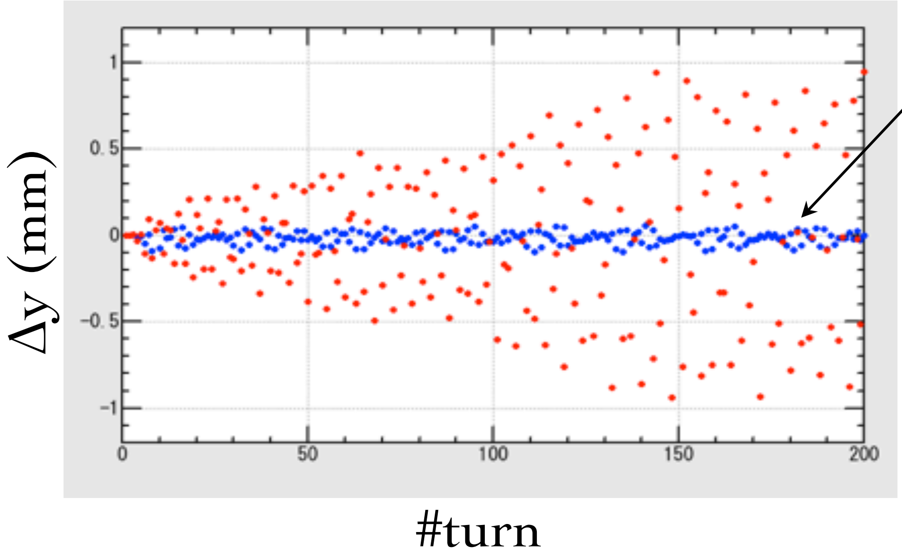
Tracking simulation: beam-beam effect

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.

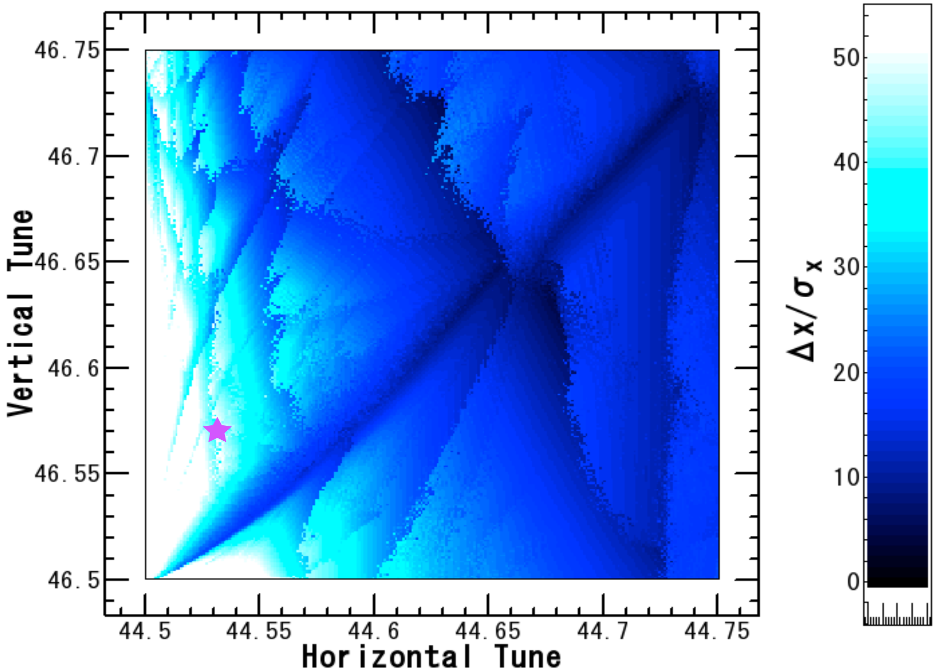
Vertical betatron oscillation is unstable for beam-beam effect.

Working point is bad ?

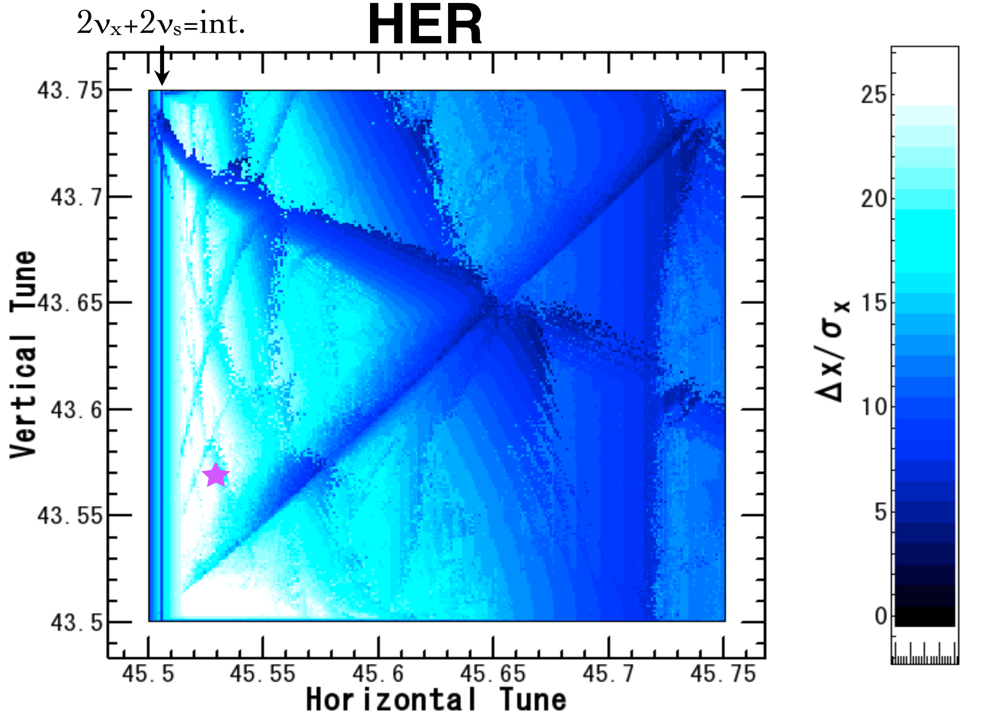
Might be resonance line ?
Check betatron tunes.

Tune survey: No beam-beam effect

LER



HER



★(ν_x, ν_y)=(44.53, 46.57)

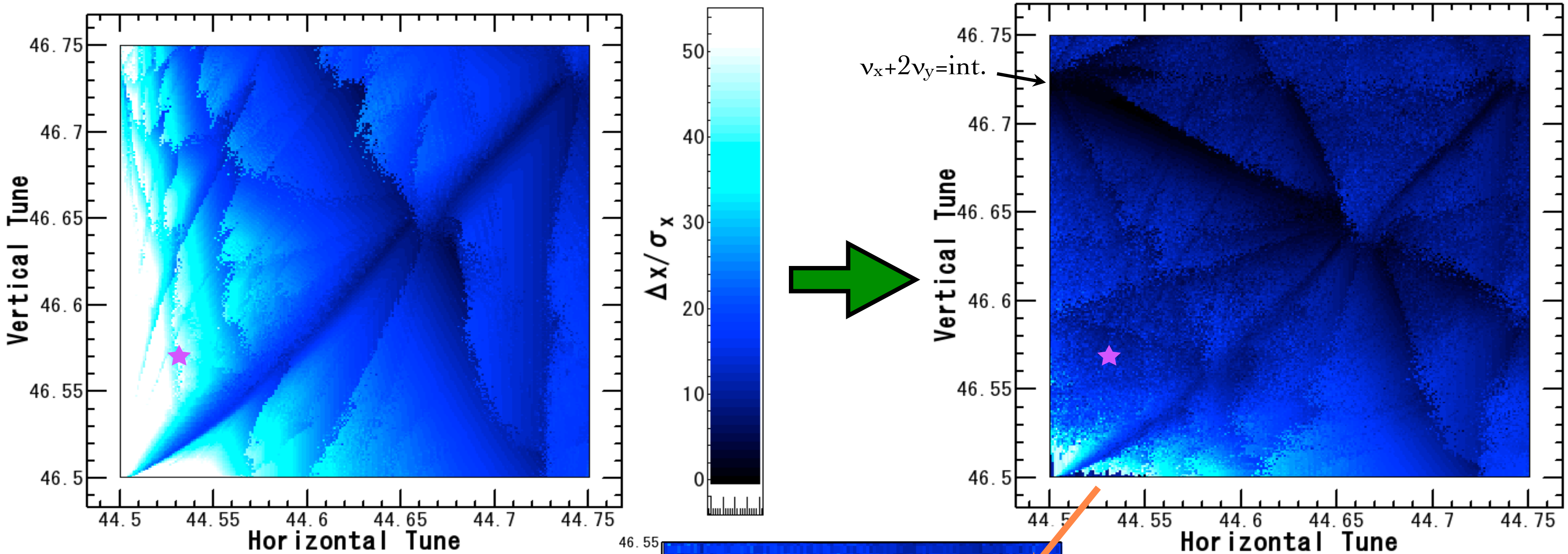
★(ν_x, ν_y)=(45.53, 43.57)

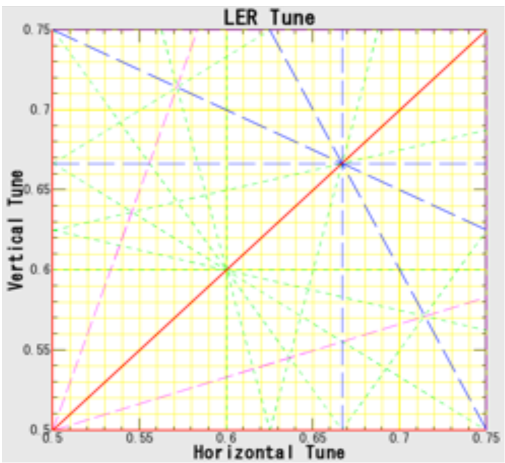
Single-beam operation (no beam-beam effect)
Lighter color indicates larger dynamic aperture (**only for on-momentum**).
Nominal working point is .53 for the horizontal and .57 for the vertical direction.

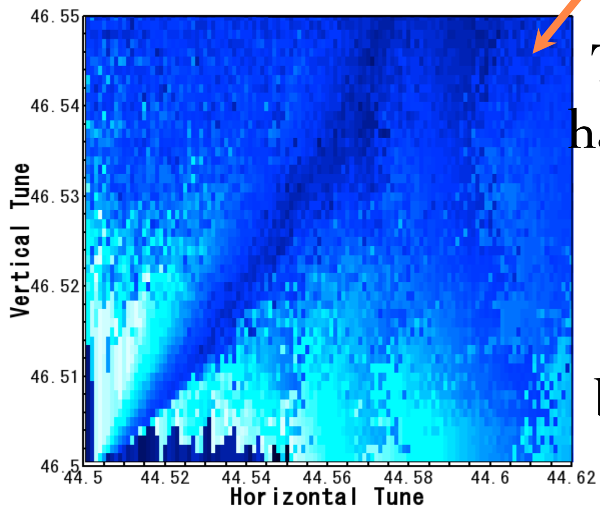
LER tune survey: Beam-beam effect

LER: w/o beam-beam

LER: with beam-beam





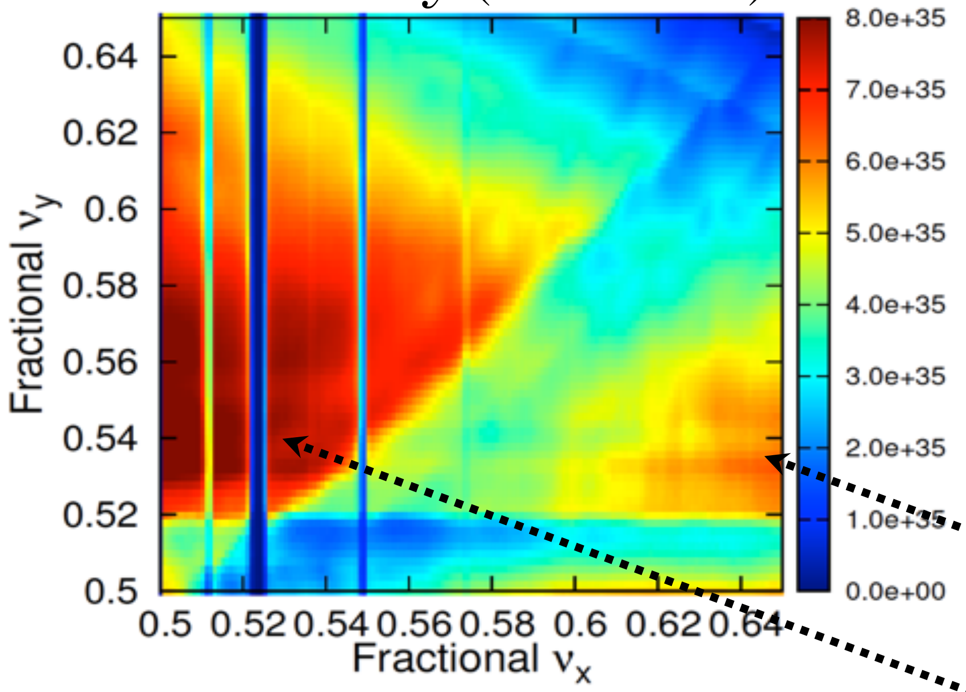


There is a good region near half integer resonance for the vertical tune.

Chromaticity correction becomes very difficult near half integer.

Better working point for Touschek lifetime ?

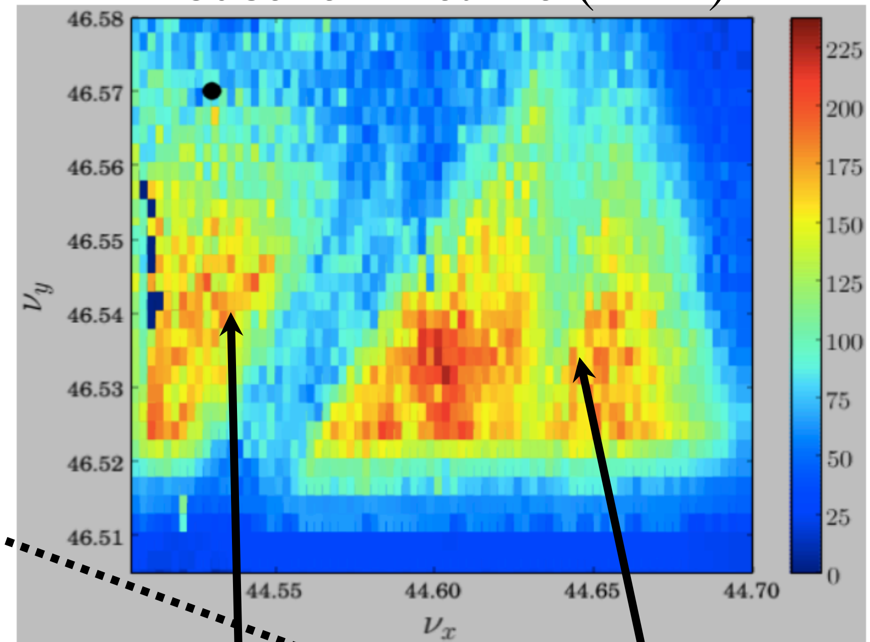
Luminosity (W-S model)



D. Zhou

w/o lattice nonlinear

Touschek lifetime (LER)



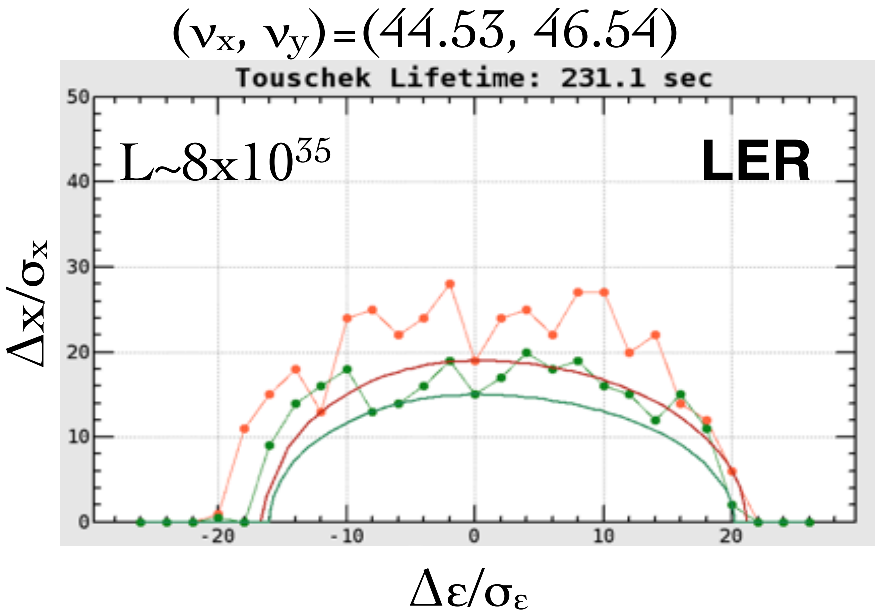
H. Sugimoto

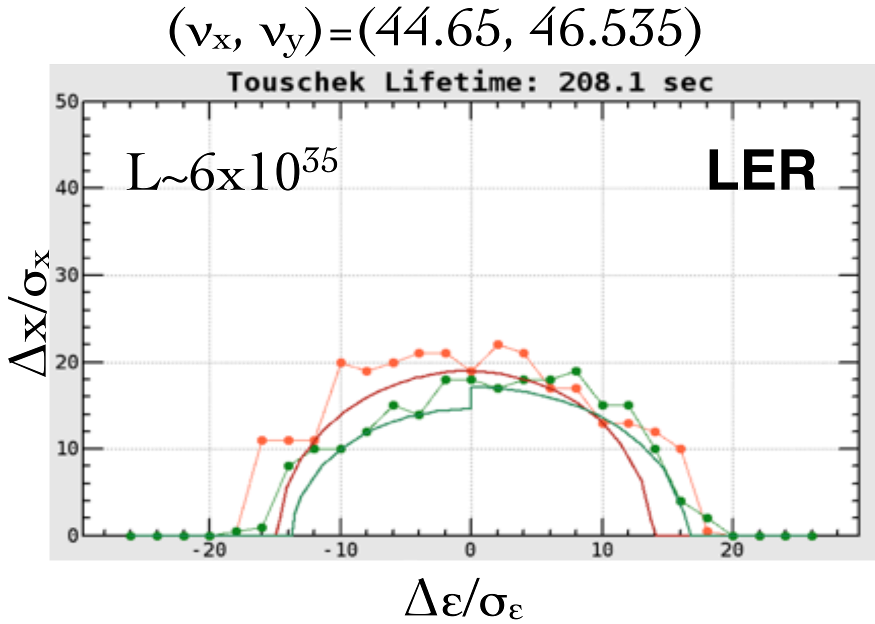
Candidates are (44.53,46.54) and (44.65,46.535)

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

Optimization of dynamic aperture

H. Sugimoto

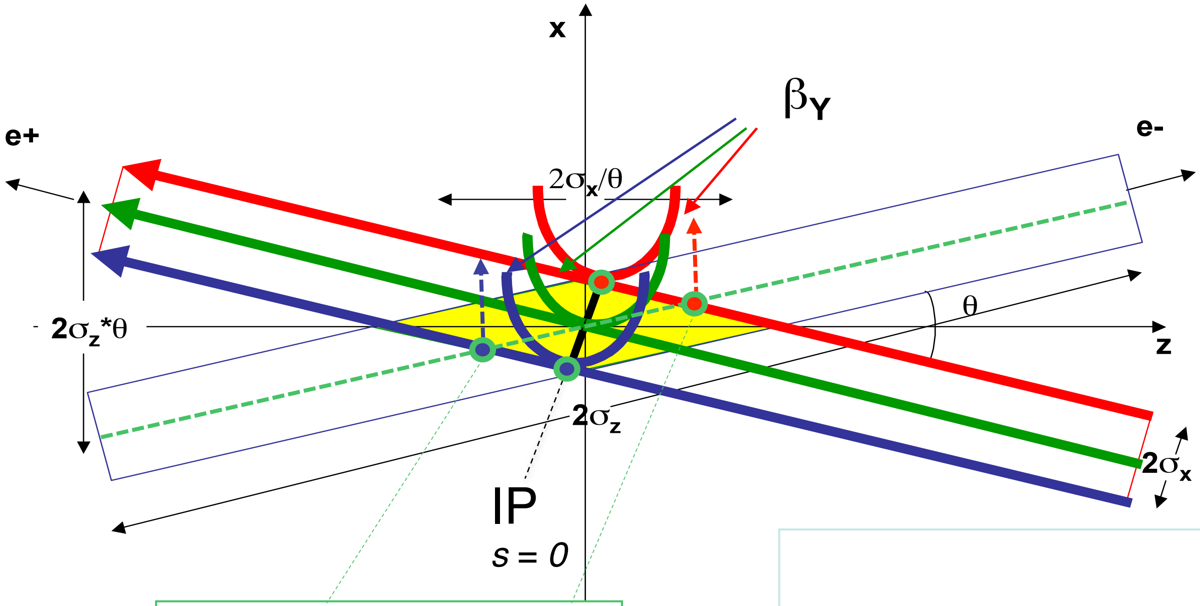




Optimization is done by sextupoles, skew sextupoles, and octupoles.
Touschek lifetime is improved up to 230 sec. Still short lifetime.

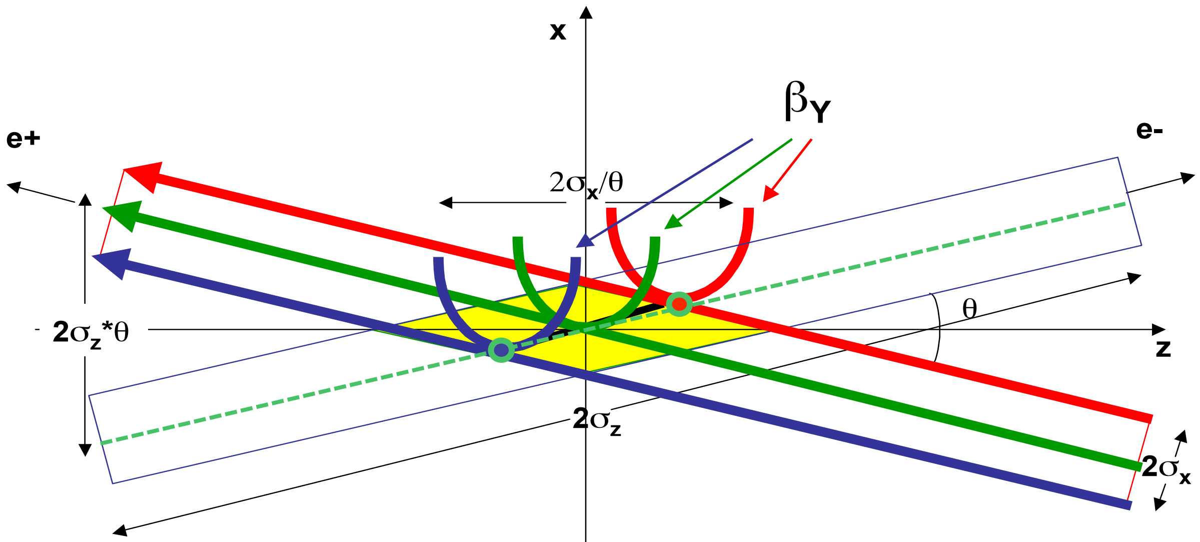
- Ideal crab-waist has a potential to mitigate this effect. (only solution)
- But a real crab-waist consists of sextupoles has a serious issue.
- Nonlinear terms between crab-waist sextupoles and Final Focus reduce the dynamic aperture. No cure for this, so far. We have to develop a new technique.

Schematic View of colliding bunches



At these points, β_y is much larger than β_y*.

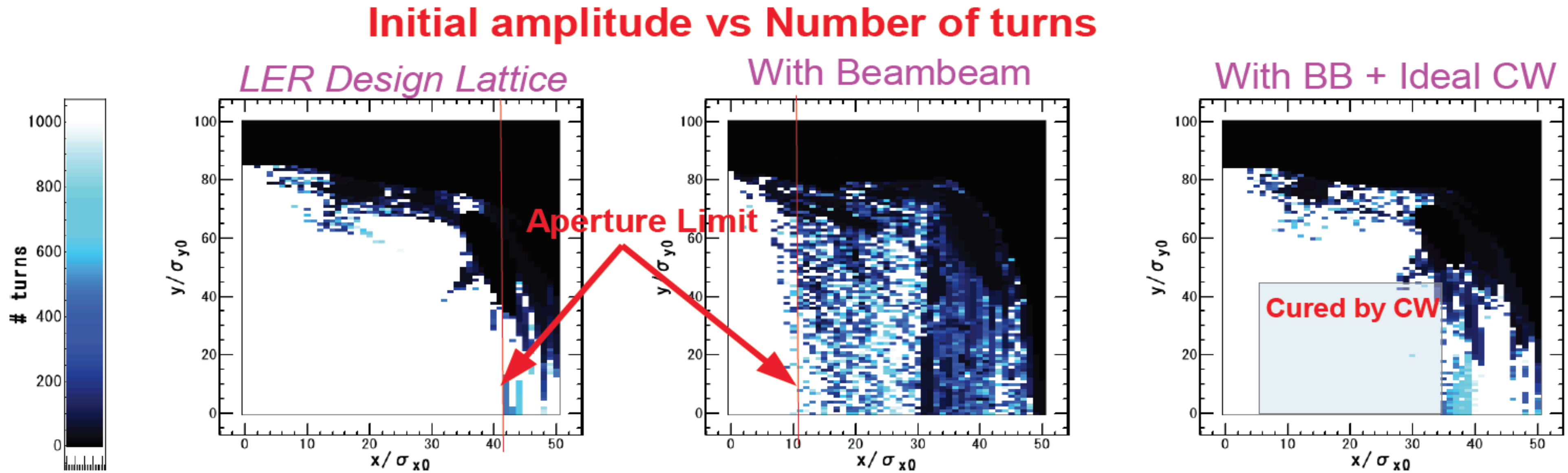
No Crab Waist
SuperKEKB



Crab Waist
Waist points are aligned along the center line of the counter-rotating beam.

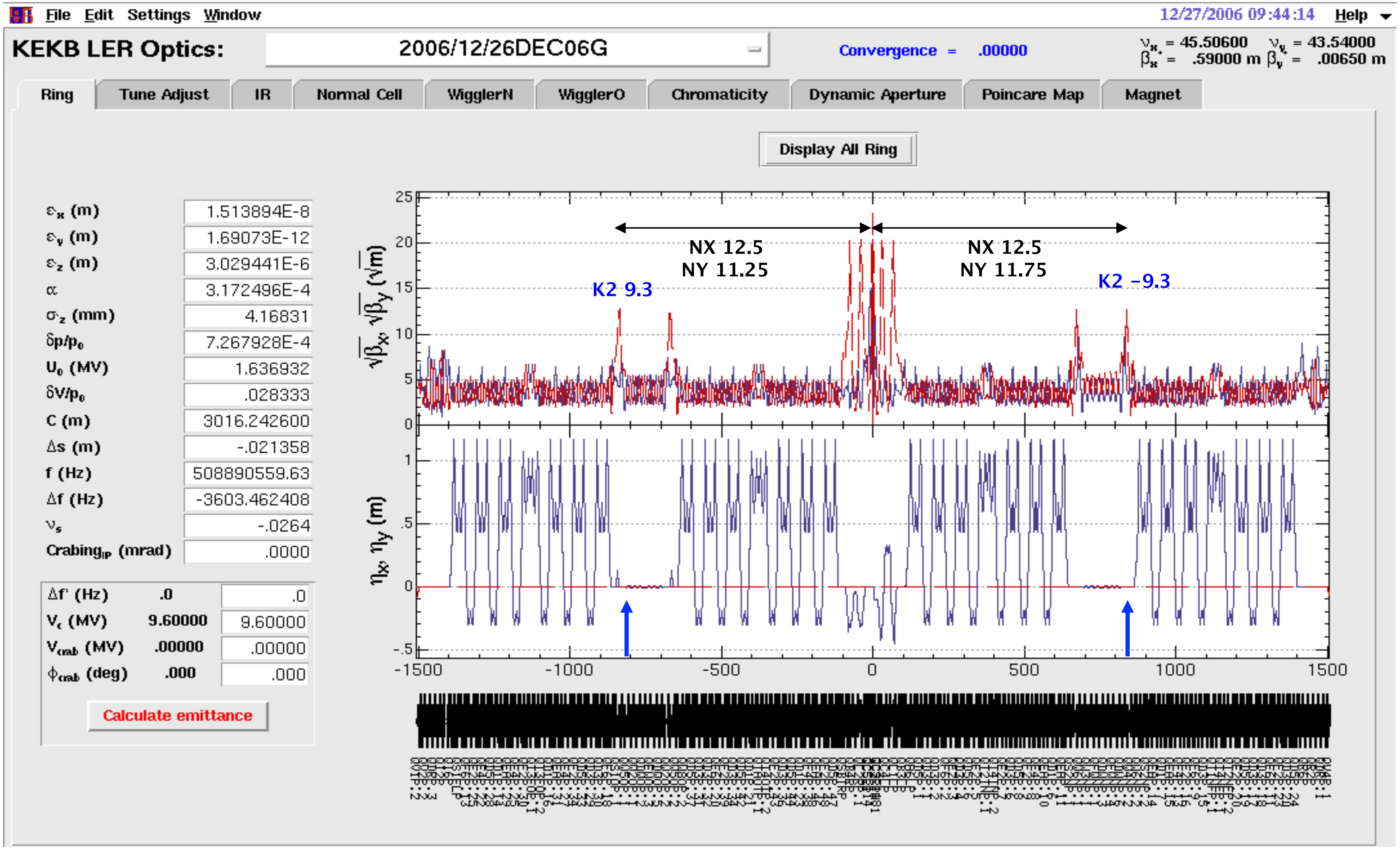
M. Zovob et al., http://arxiv.org/pdf/0802.2667.pdf

DA cured by Ideal Crab Waist

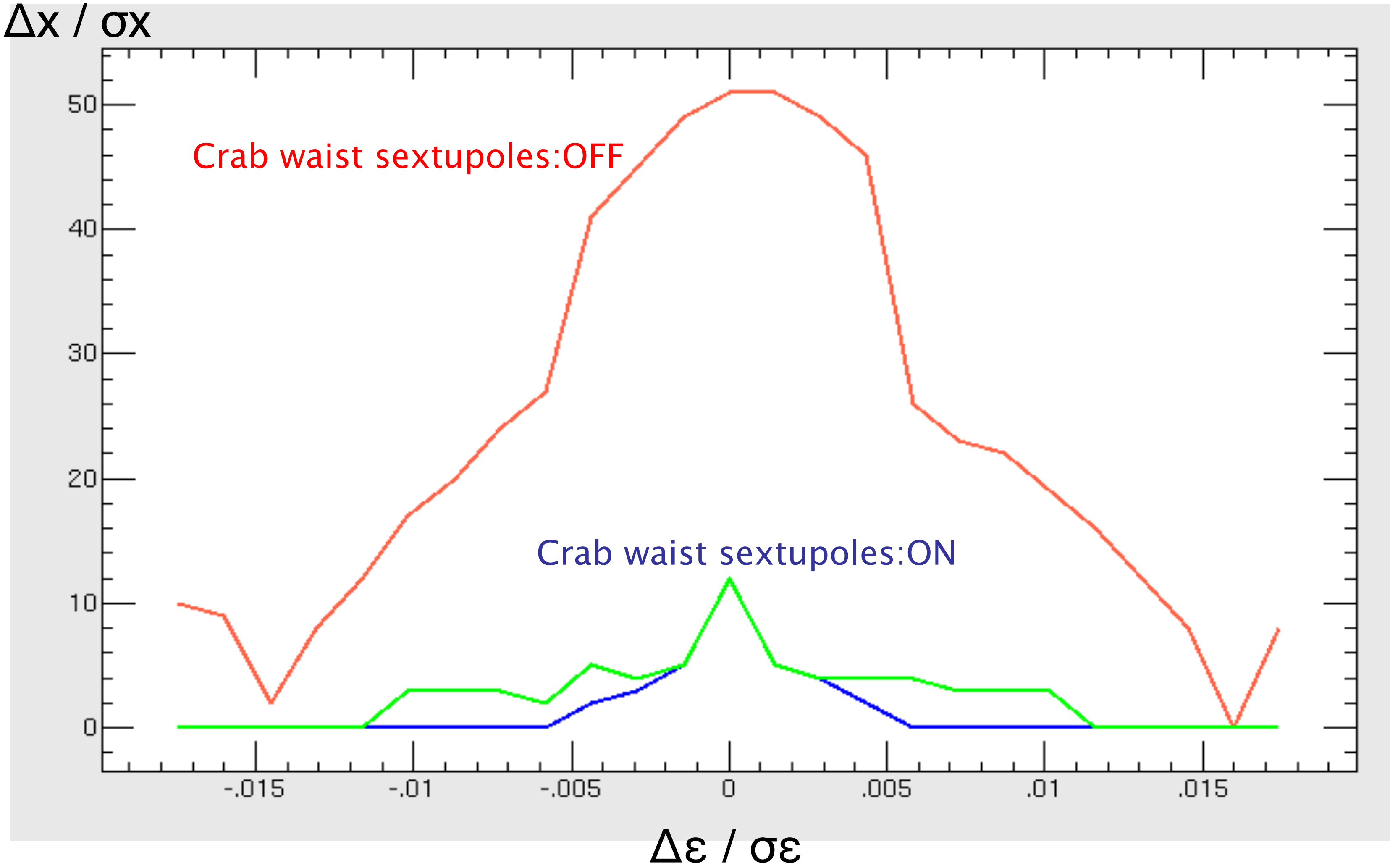


- Ideal CW replaces map f_{BB} with $f_{CW}(+\lambda)\cdot f_{BB}\cdot f_{CW}(-\lambda)$
- f_{CW} is constructed by thin sextupole between thin phase rotator pair.
- $f_{CW}(\lambda)$: $(x,x',y,y',z,\delta) \rightarrow (x,x'+\lambda/2\, y'^2,y-\lambda\, x\, y',y',z,\delta)$

KEKB Crab waist Oho-Nikko Version



KEKB Crab waist Oho-Nikko Version



Crab waist setupoles drastically decrease the dynamic aperture.

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

Phase I

- Horizontal emittance in LER can be adjusted by using the wiggler section.
  - to increase Touschek lifetime in LER for vacuum scrubbing
  - Changing the wiggler optics is much easier than the arc optics. It is applicable even though with QCS
- Horizontal emittance in HER can be adjusted by changing arc optics, if necessary
- Optics tuning without QCS is a very important stage.
  - no vertical emittance due to solenoid fringe field (simple !)
  - Vertical emittance should be less than 1 pm at Phase 1 in principle.
  - Establish ring optics except for QCS

Machine parameters with QCS

Pilot run / **Ultimate**

Parameters	symbol	Phase 2.x		Phase 3.x		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}		$cm^{-2}s^{-1}$

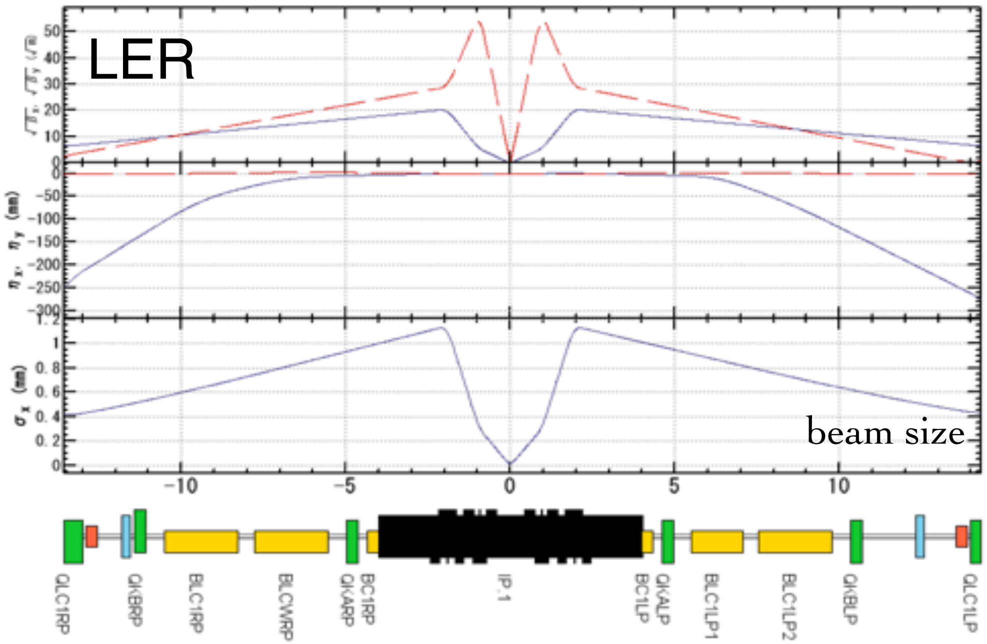
Y. Funakoshi

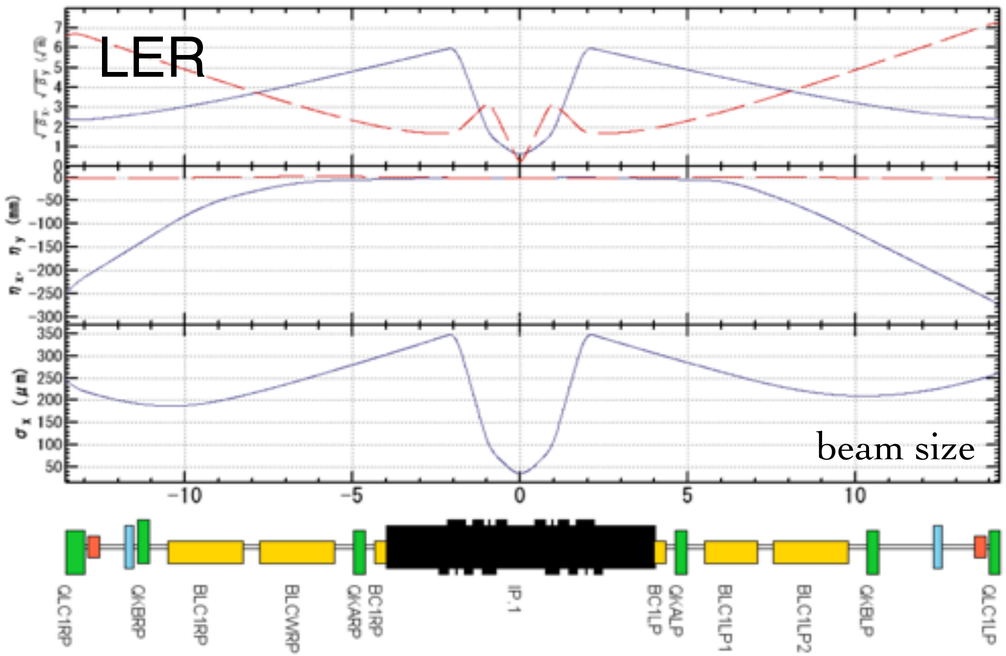
Phase 2 and Phase 3

- We can change beta function at IP successively.
- We will start very large beta at IP at Phase 2.1(virgin QCS).
  - β_y^* = 80 mm. Larger than the vertical beta of KEKB
- Target luminosity of Phase 2 is $1\text{x}10^{34}$ $\text{cm}^{-2}\text{s}^{-1}$
  - β_x^*=128 mm, β_y^*=2.16 mm, I_b = 1 A
- Phase 3 will start from the parameters of Phase 2.x.
- The beta at IP will be squeezed successively during Phase 3.
  - It depends on background, lifetime, and luminosity.

Phase 2.1 LER (1/2)

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





σ_x = 1100 μm at QC2
r_b = 35 mm at QC2
r_b/σ_x = 31 (linear calc.)

σ_x = 350 μm at QC2
r_b = 35 mm at QC2
r_b/σ_x = 100 (linear calc.)

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

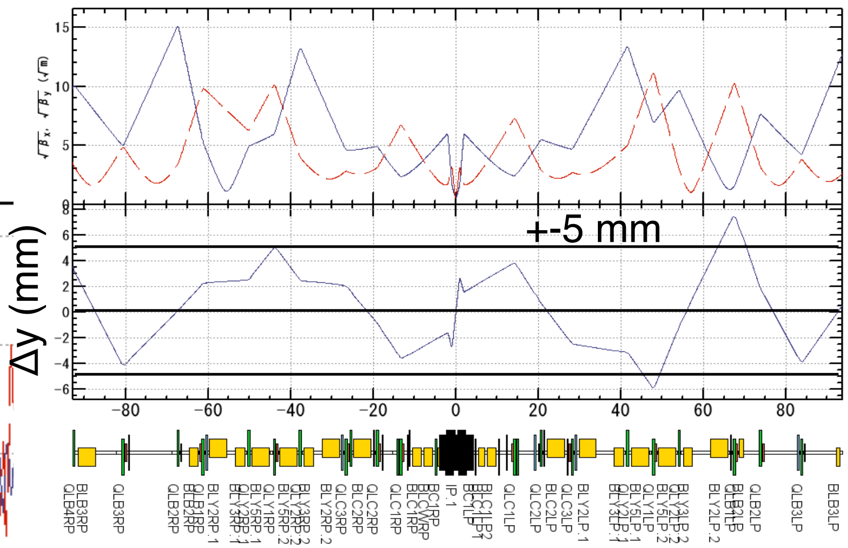
Phase 2.1 LER (2/2)

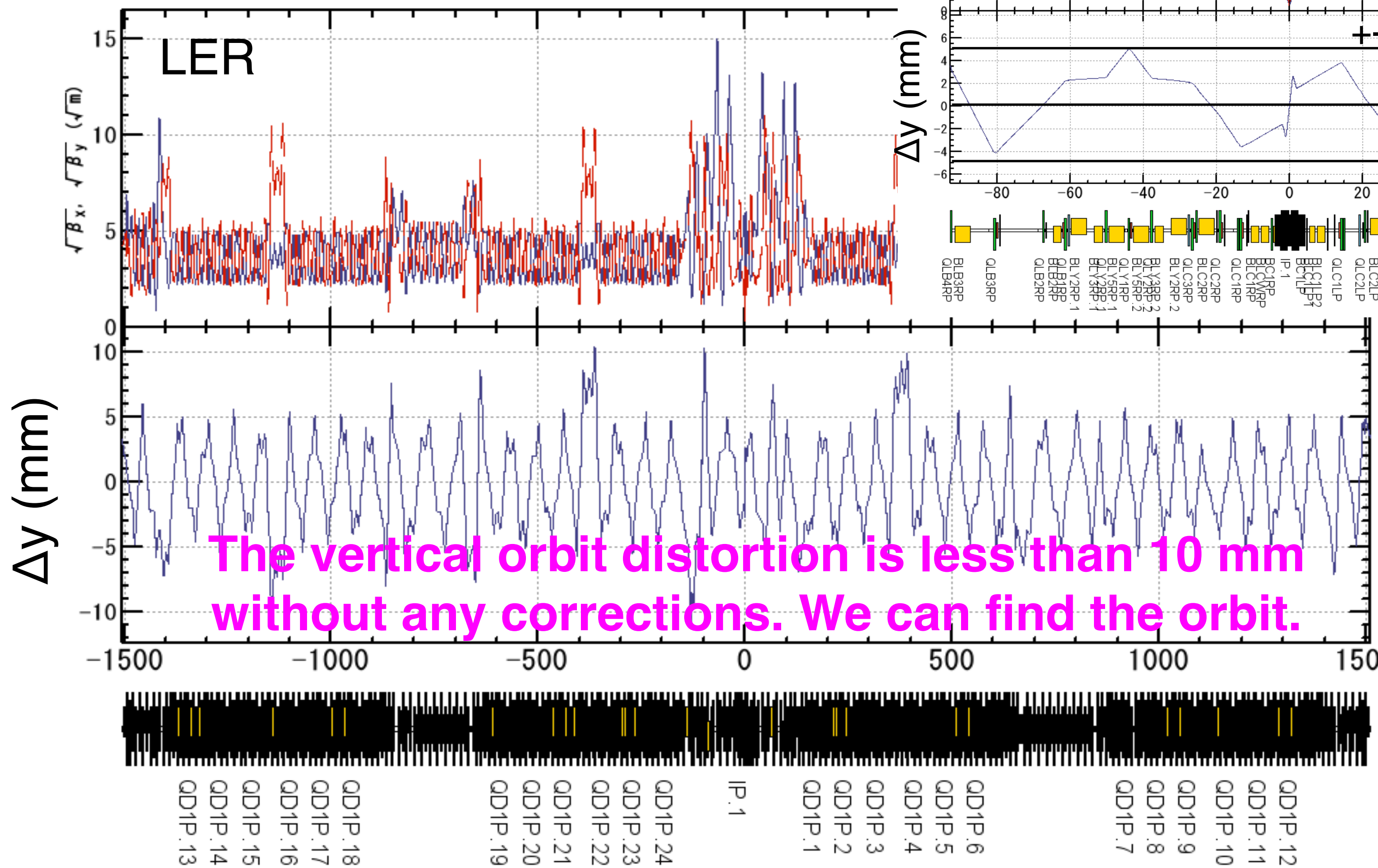
$\beta_x^* = 400\ mm$

$\beta_y^* = 80\ mm$

QC1P: misalignment

Δy_{QC1P} = 100 μm (opposite)





Arc: < 5 mm

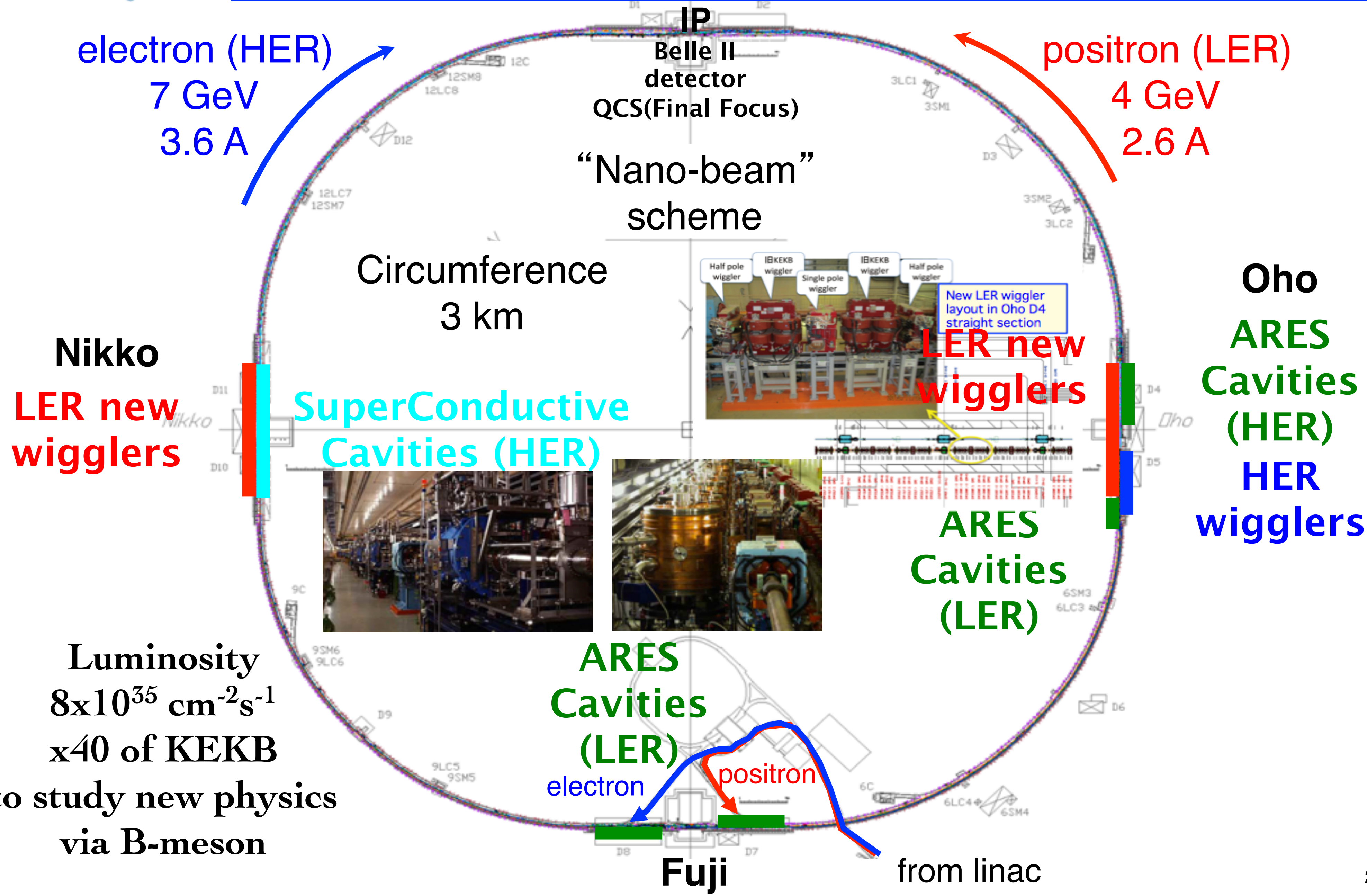
The vertical orbit distortion is less than 10 mm without any corrections. We can find the orbit.

Summary

- Dynamic aperture under influence of beam-beam effect
  - serious issue for Touschek lifetime for the ultimate parameters
- Several lattice designs have been prepared.
  - Phase 1: NoQCS(No FF)
  - Phase 2: with QCS, w/o VXD
  - Phase 3: with QCS/VXD
- We can provide a detuned lattice with adjusting beta functions at IP successively.

Appendix

Overview of SuperKEKB



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

proposed by P. Raimondi

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

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

Long "bunch length" is OK.

(effective) (6 mm x 41.5 mrad)

~ 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:

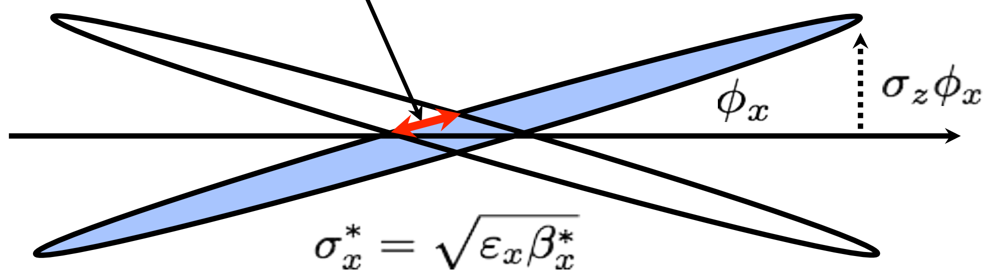
$$\beta_y^* > \tilde{\sigma}_z = \frac{\sigma_x^*}{\phi_x} \sim 250\ \mu m$$

(effective)

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

~ 0.003

Dynamic effects can be ignored.



Energy range

- We assume the requirement of the energy range is from Υ(1S) to Υ(6S), so far.
- The boost factor is the same among Υ(1S) and Υ(6S).
- We checked the magnetic field for the energy range. -> OK

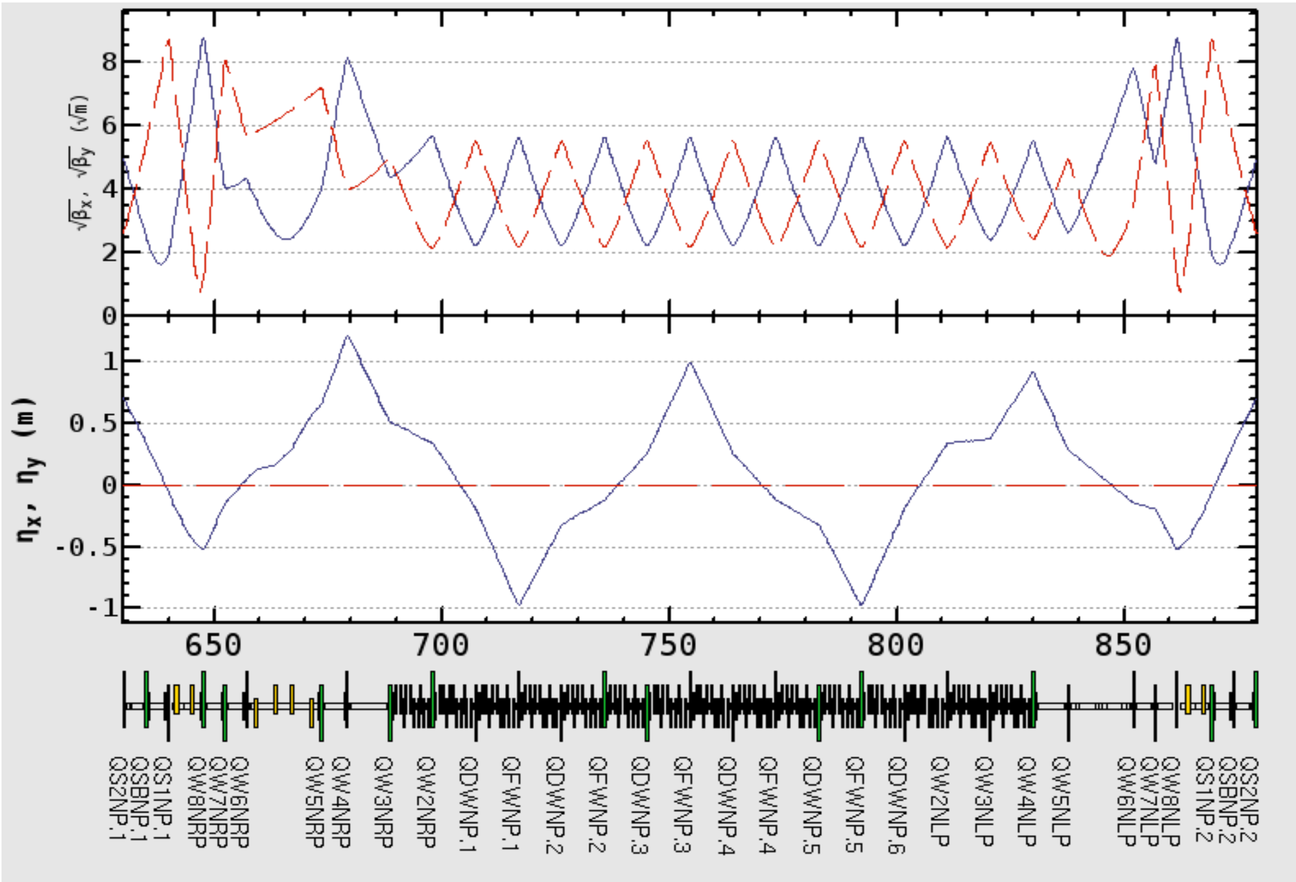
	E (GeV)	ΔE/E (%)	E_{e+} (GeV)	E_{e-} (GeV)	
Υ(1S)	9.460	-10.58	3.577	6.266	
Υ(2S)	10.023	-5.26	3.790	6.639	
Υ(3S)	10.355	-2.12	3.915	6.859	
Υ(4S)	10.579	-	4.000	7.007	nominal
Υ(5S)	10.876	+2.81	4.112	7.204	
Υ(6S)	11.019	+4.16	4.166	7.299	

LER: wiggler section

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

* without intra-beam scattering

LER: Nikko



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 is 2 μm (rms).

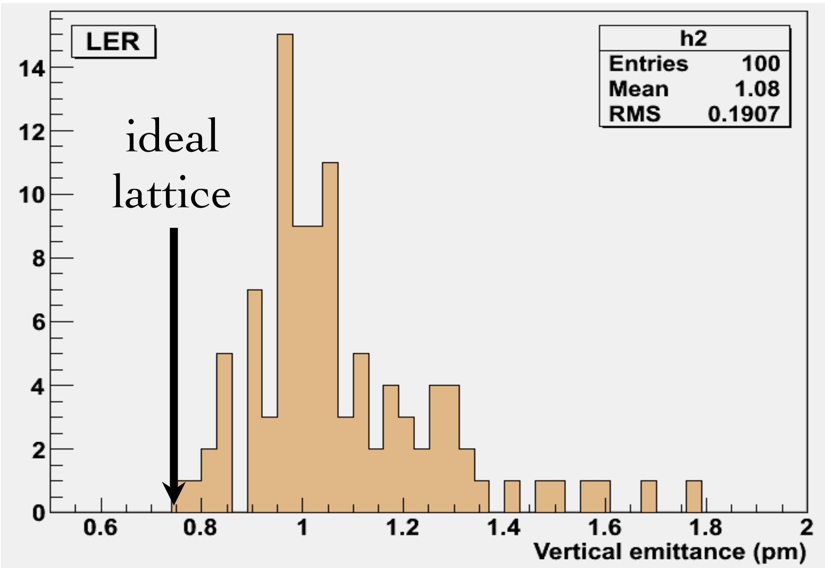
Misalignment error is based on the measurement at KEKB.

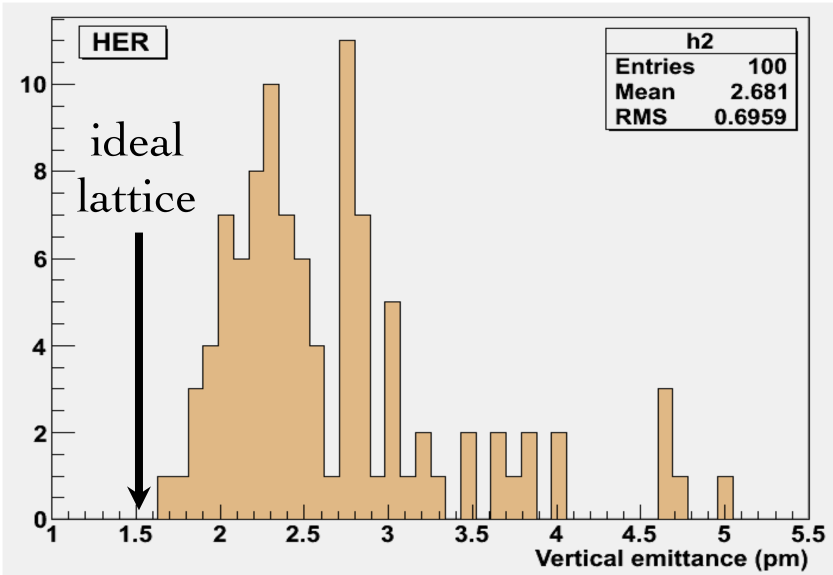
We evaluate the beam quality after with corrections of these machine error on the computer simulation.

Phase 3.x: Optics correction (2/2)

- Machine error is corrected by using dipole, quadrupole, and skew quadrupole correctors.
- Optics correction is based on the measurement of beam optics, especially orbit response.
- Correction of closed orbit distortion, X-Y coupling, dispersions, and beta functions.

#samples: 100 (different seed number)

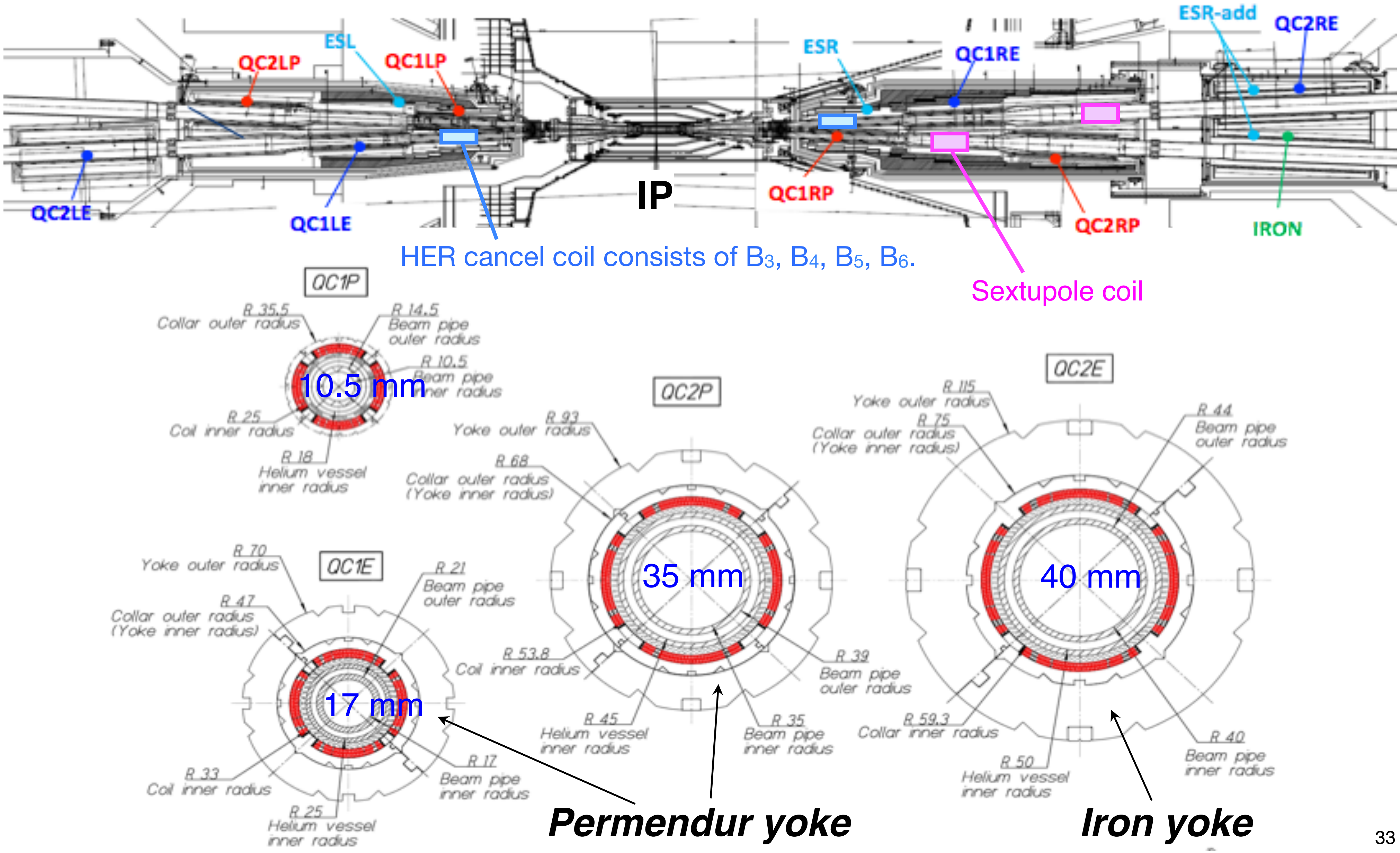




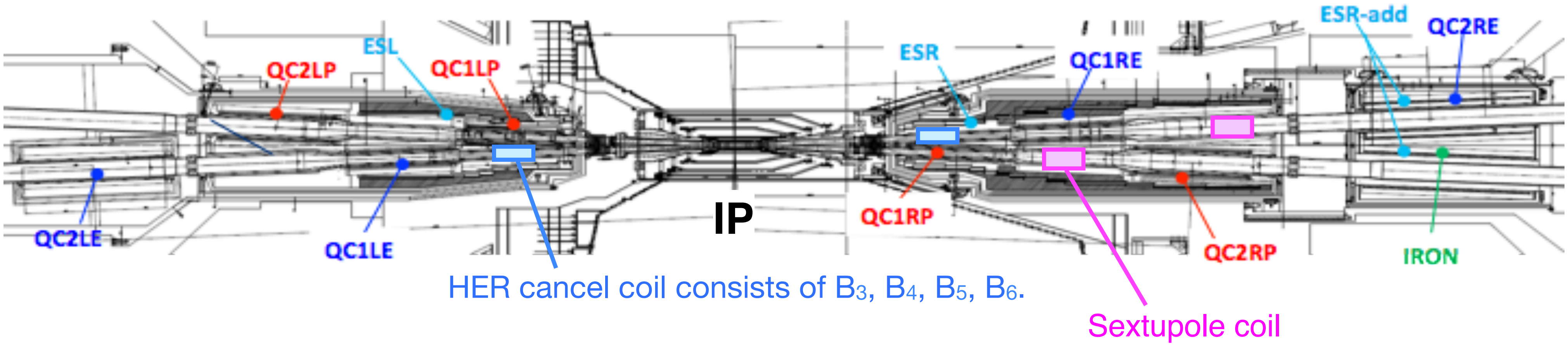
The vertical emittance can be corrected down to a few pm.

H. Sugimoto

Final focus quadrupoles



Final focus quadrupoles

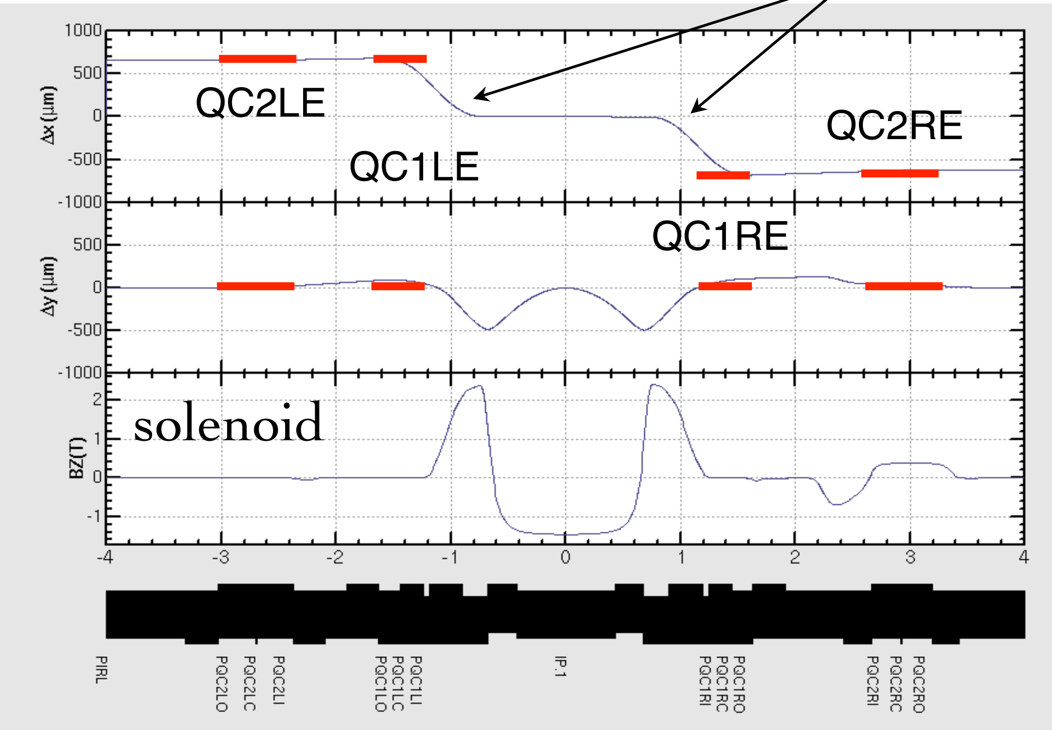


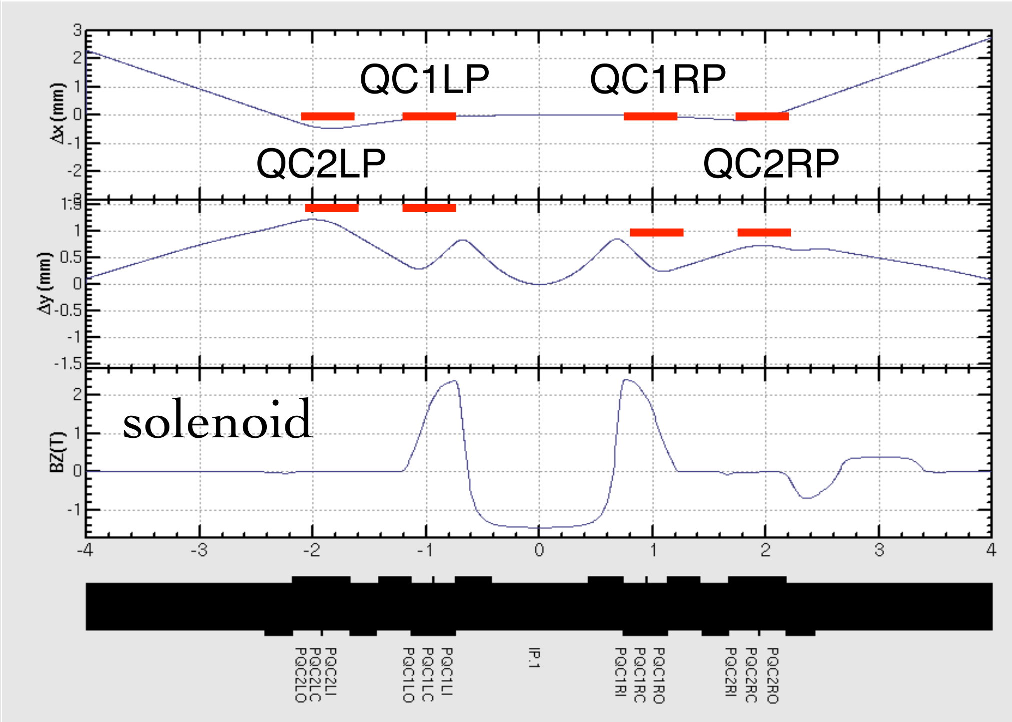
Design param.	Dipole	Skew dipole	Quad	Skew quad	Sextupole	Skew sext	Octupole
	B_1L (Tm)	A_1L (Tm)	B_2L/r_0 (T)	A_2L/r_0 (T)	B_3L/r_0^2 (T/m)	A_3L/r_0^2 (T/m)	B_4L/r_0^3 (T/m^2)
QC1LP(no shield)	0.004	-0.002	-22.96	-9.50E-05			-27.0
QC2LP	-0.0217	0.022	11.48	0.0095			48.2
QC1RP(no shield)	0.0050	-0.0086	-22.96	1.92E-05		0.0	-26.7
QC2RP	-0.0023	0.0214	11.54	-6.30E-06		0.0	
QC1RP-QC2RP					0.0		
QC1LE	0.030	0.0092	-26.94	-0.0729			8.9
QC2LE	0.000	-0.0016	15.27	0.0271			23.6
QC1RE	-0.0305	0.0053	-25.39	0.0653		0.0	
QC2RE	0.000	-0.0022	13.04	0.0559		0.0	
QC1RE-QC2RE					0.0		

QC2LP, QC2RP, QC1LE, QC1RE: permendur yoke
QC2LE, QC2RE: iron yoke

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

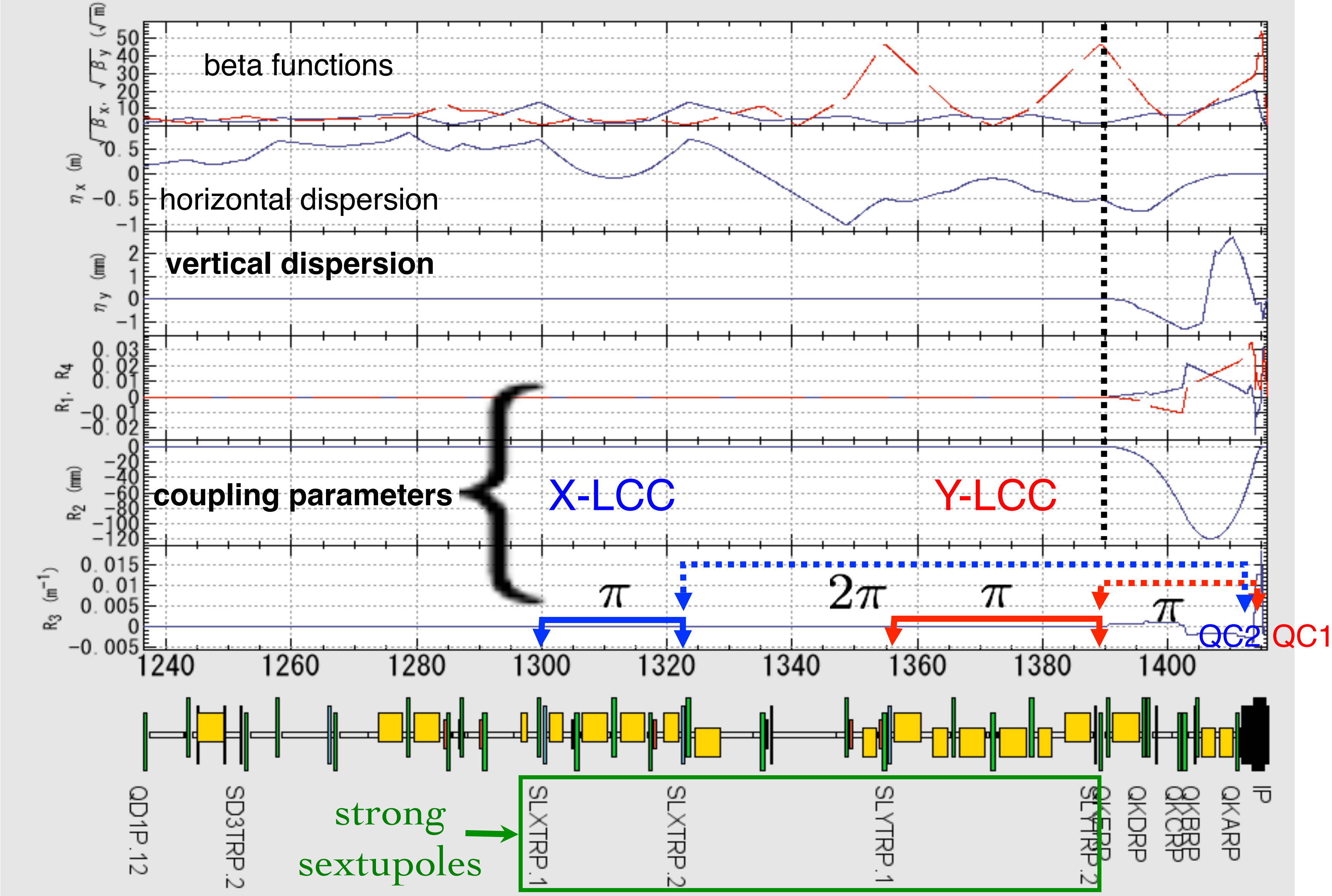
QC1/QC2 offset is adopted to control the orbit appropriately.

Slide 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 optics in LER

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



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