Introduction to SuperKEKB

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Request to this talk

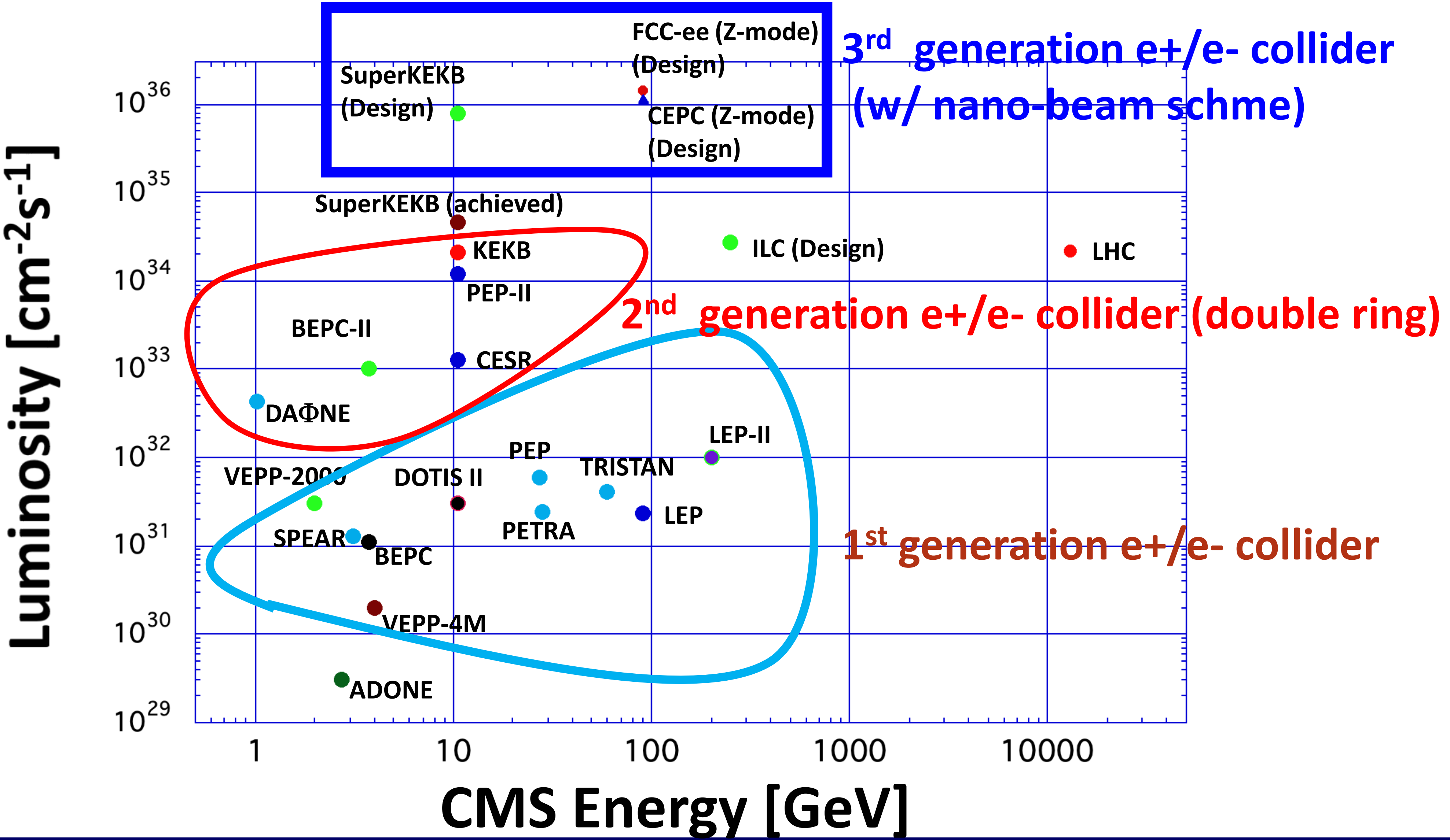
- Requests
  - Introduction to SuperKEKB, including explanation about some important optical parameters, nano-beam scheme, and so on.
- Contents
  - Luminosity formula
  - Nano-beam scheme
    - Large Piwinski angle collision
    - Crab waist scheme
  - Some important optics parameters
    - Emittance
    - X-Y coupling
    - Chromatic coupling
    - Dynamic aperture

Luminosity formula (1)

$$L = \frac{N_- N_+}{2\pi\sqrt{\sigma_{x-}^2 + \sigma_{x+}^2}\sqrt{\sigma_{y-}^2 + \sigma_{y+}^2}} n_b f_{rev} R$$

- $N_{-,+}$: Number of paricles in a bunch (e-,e+)
- n_b : number of bunches -> drastically increased in double rings
- f_{rev} : revolution frequency
- R : Geometrical Loss factor

Luminosity Comparison



3rd generation e+/e- collider
(w/ nano-beam schme)

2nd generation e+/e- collider (double ring)

1st generation e+/e- collider

Luminosity formula (2)

Small for the flat beam

$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{y\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi\pm}}\right)$$

(Take ether of + or -)

Not far from unity

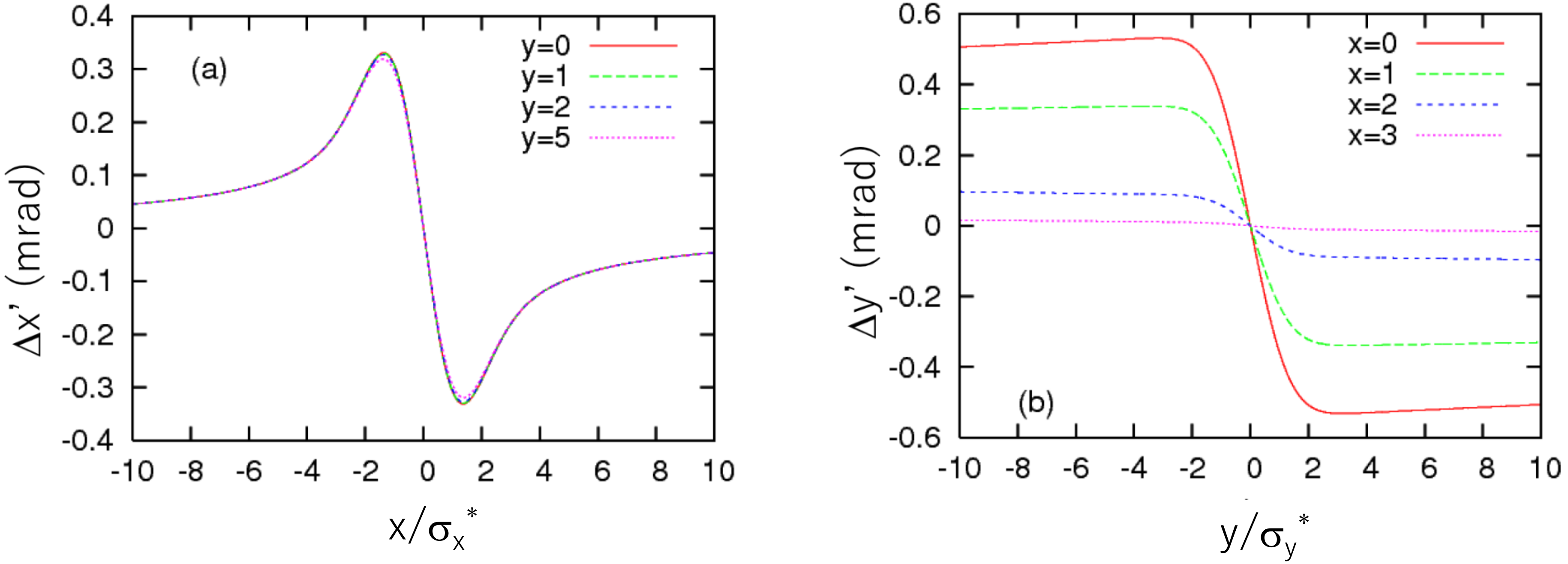
In the energy region where the beam-beam interaction is important, this formula is commonly used.
This formula is derived with an assumption that the beam sizes at IP (σ_x^*, σ_y^*) are equal between two beams.

- γ: Lorentz foctor
- σ_x^*, σ_y^* : horizontan and vertical beam sizes
- I : Total beam current
- β_y^*: vertical beta function at IP
- ξ_y : vertical beam-beam parameter
- R_ξ : Geometrical Loss factor for beam-beam parameter

Luminosity is mainly determined by those three parameters.

Beam-beam parameters

- Beam-beam force



・Very nonlinear force

-> Linear part (near bunch center) gives focusing force like quadrupoles

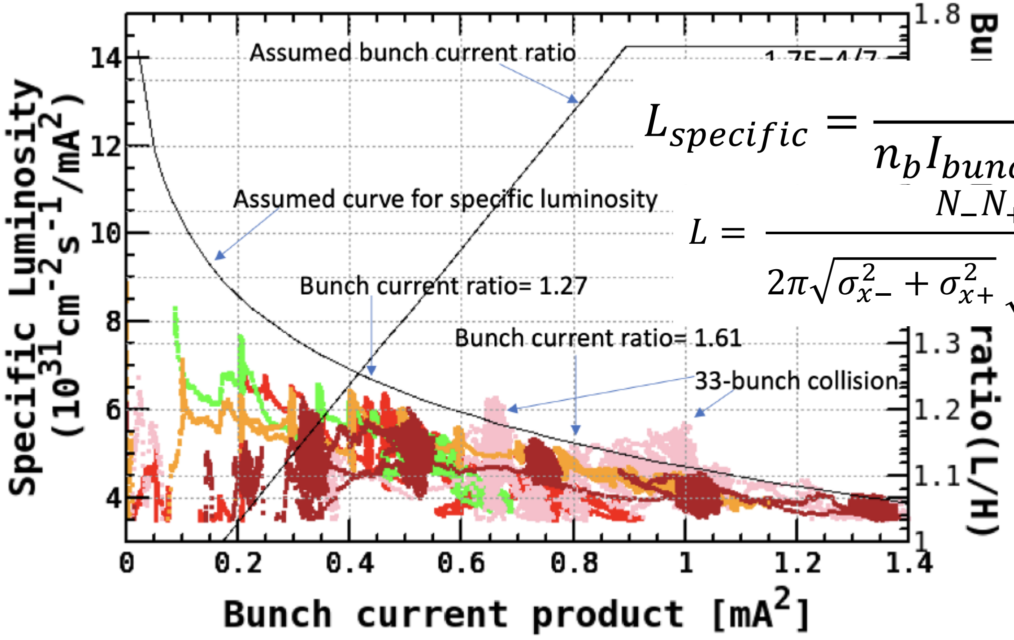
$$\Delta x' = -\frac{2Nr_e}{\gamma}\frac{x}{\sigma_x^*\left(\sigma_x^* + \sigma_y^*\right)} \qquad \Delta y' = -\frac{2Nr_e}{\gamma}\frac{x}{\sigma_y^*\left(\sigma_x^* + \sigma_y^*\right)}$$

⇨ Tune shift

Beam-beam parameter

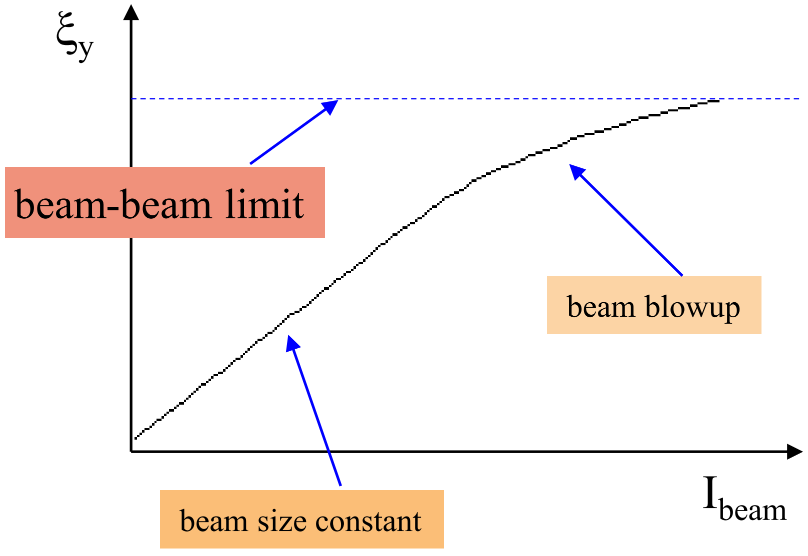
- Beam-beam parameter (or beam-beam tune shift)

$$\xi_{x\pm} = \frac{r_e}{2\pi\gamma_\pm} \frac{\beta^*_{x\pm} N_\mp}{\sigma^*_{x\mp}\left(\sigma^*_{x\mp} + \sigma^*_{y\mp}\right)} \qquad \xi_{y\pm} = \frac{r_e}{2\pi\gamma_\pm} \frac{\beta^*_{y\pm} N_\mp}{\sigma^*_{y\mp}\left(\sigma^*_{x\mp} + \sigma^*_{y\mp}\right)}$$



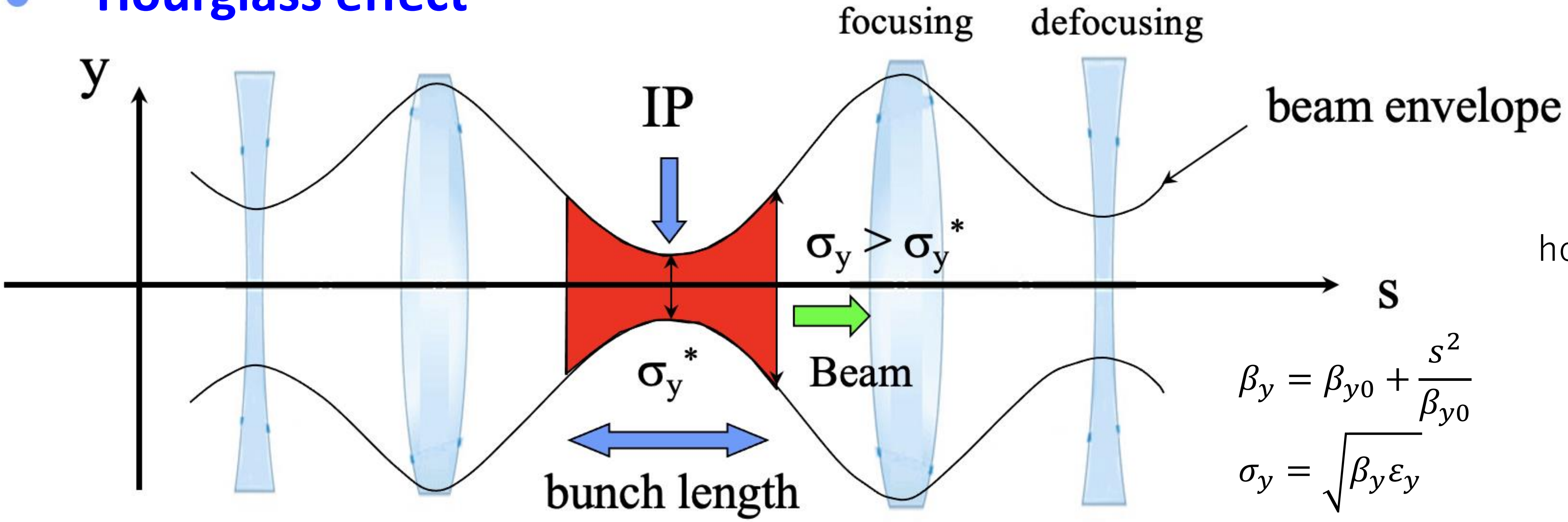
$$L_{specific} = \frac{L}{n_b I_{bunch,+} I_{bunch,-}}$$

$$L = \frac{N\_N_+}{2\pi\sqrt{\sigma^2_{x-} + \sigma^2_{x+}}\sqrt{\sigma^2_{y-} + \sigma^2_{y+}}} n_b f_{rev} R$$



Luminosity limitation due to hourglass effect

- **Hourglass effect**



$$\beta_y = \beta_{y0} + \frac{s^2}{\beta_{y0}}$$

$$\sigma_y = \sqrt{\beta_y \varepsilon_y}$$

hourglass

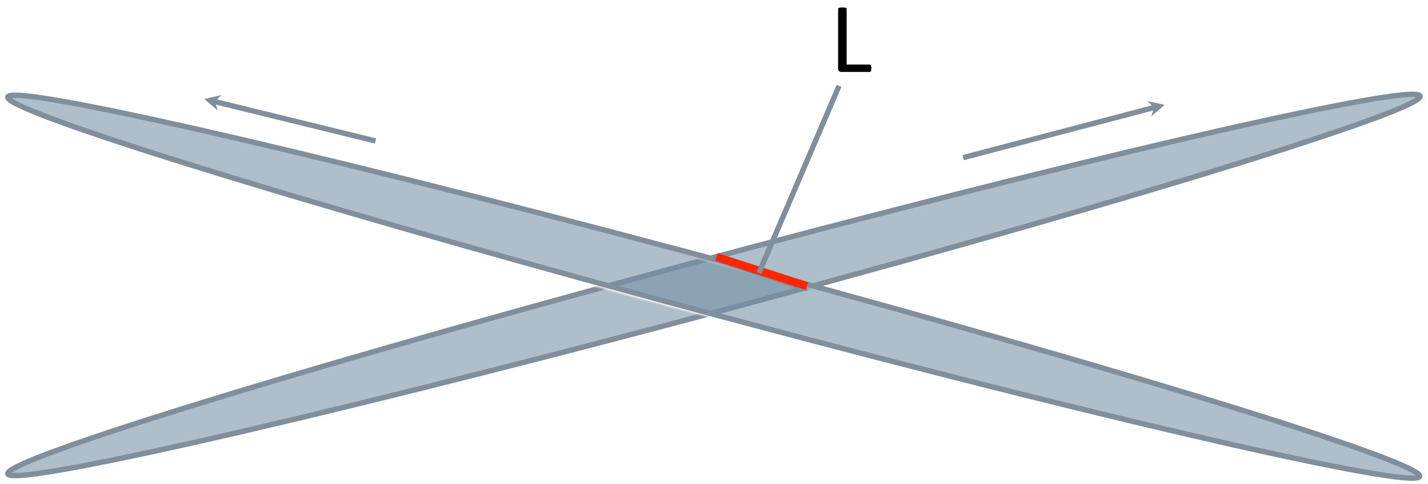
- **Luminosity does not increase by squeezing βy* down to less than ~ σ_z (bunch length). [ex. KEK $\sigma_{z:}$ ~ 6mm, βy* : 5.9mm)**
  - **Beam size increase in the range of bunch length (geometrical degradation).**
  - **Effects of beam-beam interaction is stronger at larger βy position (-> additional beam-beam blowup).**

Head-on collision and Nanobeam collision

- Head-on collision

hourglass condition: $\beta_y^* >\sim \sigma_z$

- NanoBeam collision



hourglass condition: $\beta_y^* >\sim L = \sigma_z^{\text{effective}}$

Nanobeam collision scheme

P. Raimondi

- Luminosity

$$L = \frac{1}{2\sqrt{2}\pi}\frac{N_e N_p}{\sigma_z \sin\phi_c \sqrt{\sigma_{ye}^2+\sigma_{yp}^2}} f_{col} R_L$$

- Piwinski-angle (ϕ_p)

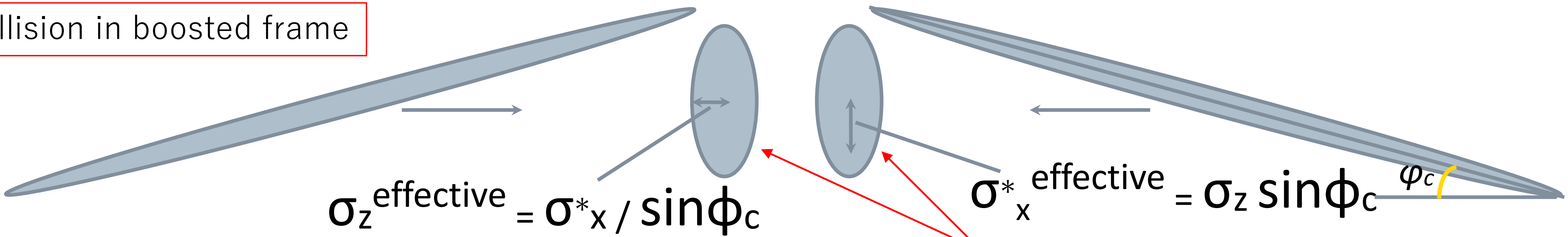
$$\phi_p = \frac{\sigma_z}{\sigma_x^*}\tan\phi_c = \frac{\sigma_z}{\sigma_z^{effective}}$$

Luminosity enhancement factor

- Beam-beam parameter

$$\xi_{yp} = \frac{r_e}{2\pi\gamma_p}\frac{\beta_{yp}N_e}{\sigma_z \sin\phi_c \sigma_{ye}} R_{\xi yp} \qquad \xi_{ye} = \frac{r_e}{2\pi\gamma_e}\frac{\beta_{ye}N_p}{\sigma_z \sin\phi_c \sigma_{yp}} R_{\xi ye}$$

Collision in boosted frame



Machine Parameters

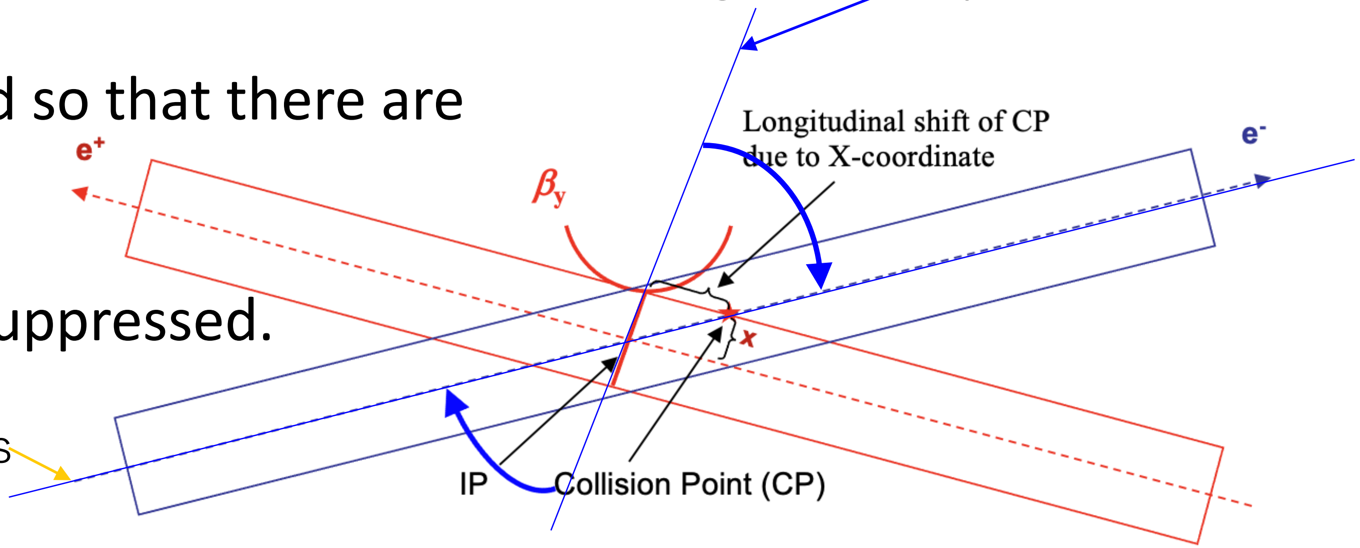
	KEKB (LER, achieved)	SuperKEKB (LER, design)	SuperKEKB (LER, achieved)
Crossing angle	±11 mrad	±41.5 mrad	±41.5 mrad
β_x^*	1.2 m	32 mm	80 mm
β_y^*	5.9 mm	0.27 mm	1 mm (0.8 mm)
ε_x	18 nm	3.2 nm	4.0 nm
ε_y	169 pm	8.64 pm	50 pm
$\varepsilon_y/\varepsilon_x$	0.94 %	0.27 %	1.25 %
σ_x^*	147 μm	10.1 μm	17.9 μm
σ_x^*effective	-	249 μm	249 μm
σ_y^*	~1 μm	48 nm	223 nm
σ_z^*	~7 mm	6 mm	~6 mm
σ_z^* effective	-	0.24 mm	0.43 mm
ϕ_{Piwinski}	0.524	24.7	13.9

Nano-beam scheme
= Large Piwinski angle collision

Crab waist scheme

P. Raimondi

- Collision point with the center of the other beam for a partice with a horizontal offset
  - Due to large crossing angle, a parcle with horizontal offset collide with the center of the other beam at a location offset from the waist (minimum of β_y).
  - The vertical beam-beam kick depends on the horizontal offset.
    -> X-Y coupling resonances driven by the beam-beam interaction -> beam-beam blowup
- Crab waist scheme
  - Waist points of one beam are shifted so that there are aligned along the center of the other beam.
  - The X-Y coupling resonaces can be suppressed.

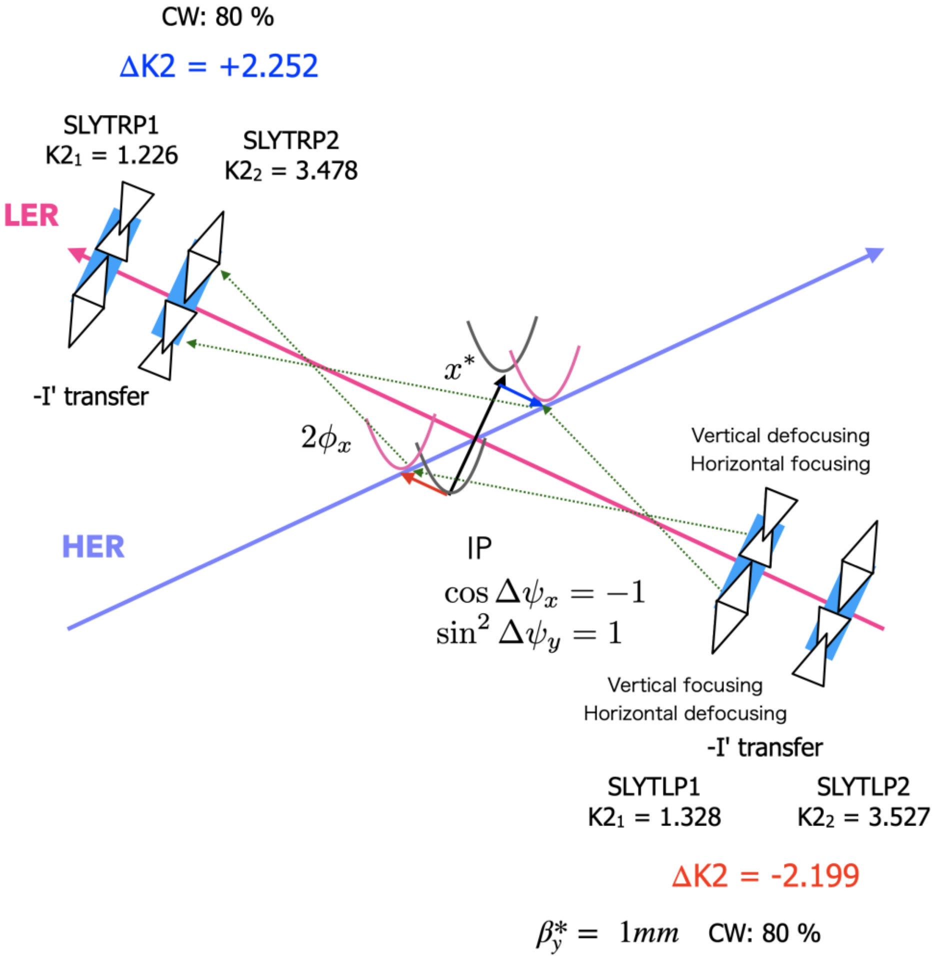


Original waist points of e+

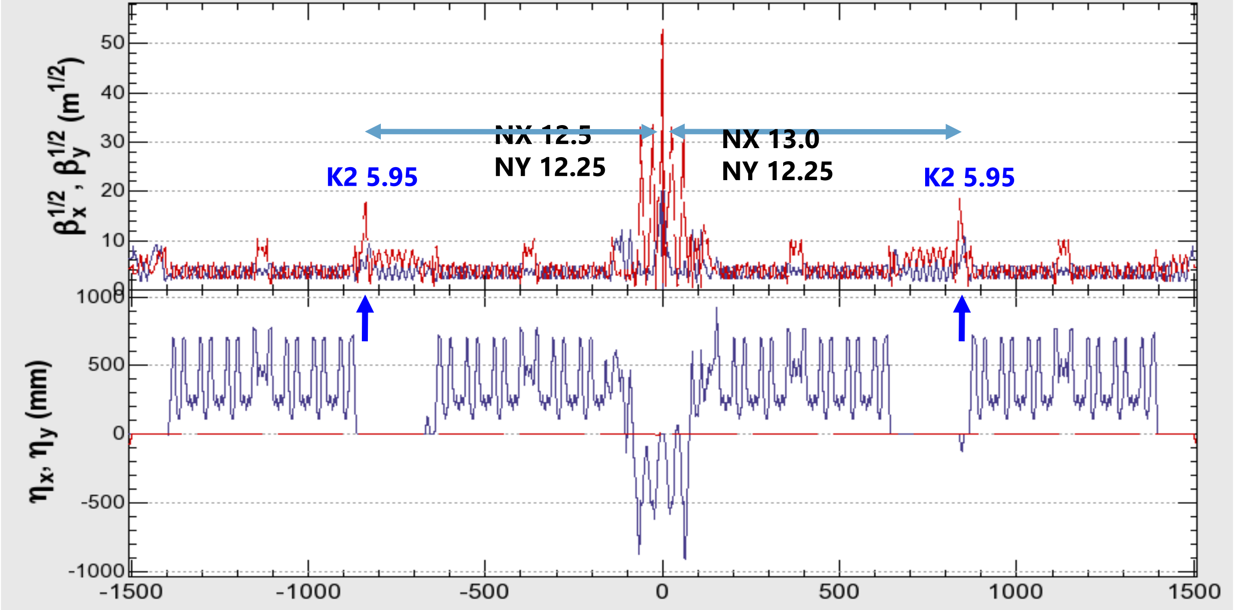
Shifted waist points

How to realize crab waist scheme

Present scheme at SuperKEKB



Backup plan at SuperKEKB design stage

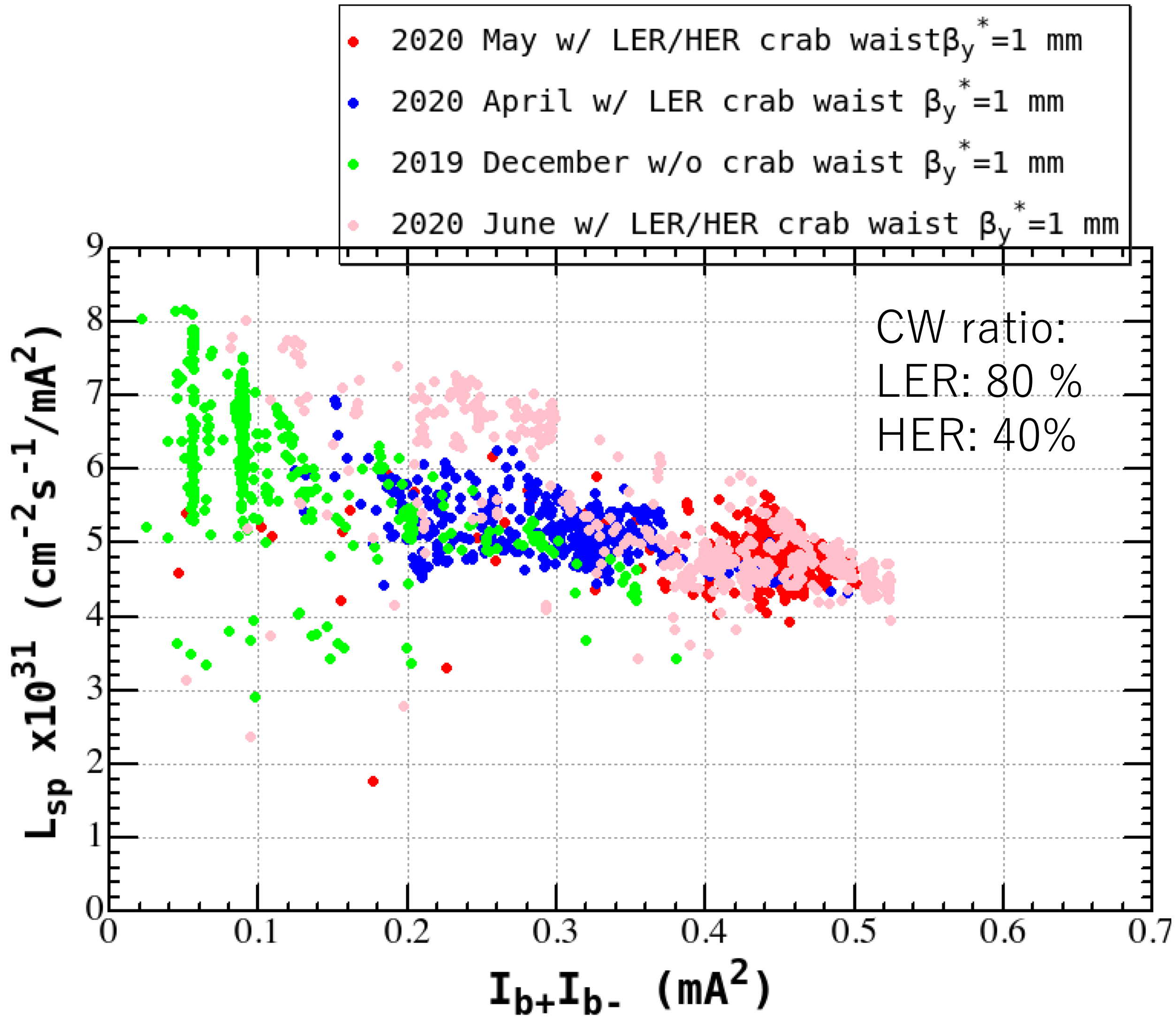


--Crab waist scheme is realized by unisg a pair of sextupole magents which have appropriate betatron phase relations with IP.

--At the design stage, crab waist scheme was considered to be a backup plan.

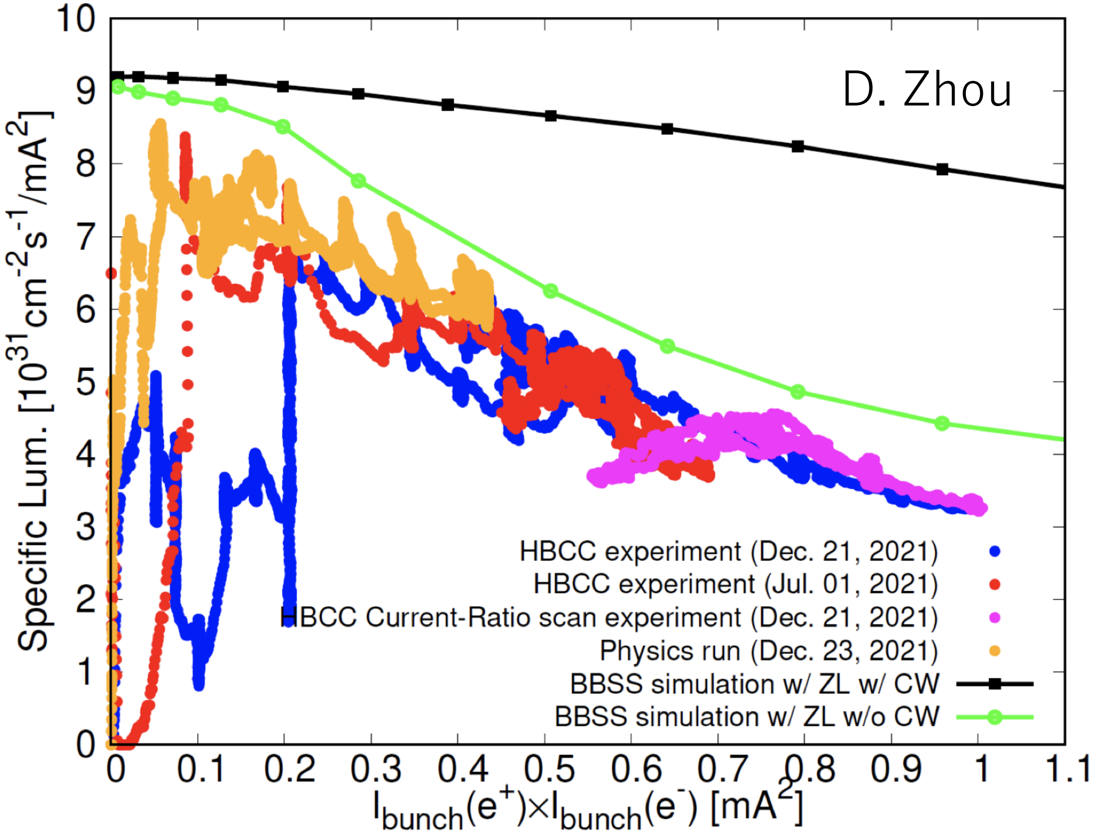
--Problem, which was thought to be serious, was a short beam lifetime due to narrow dynamic aperture.

Specific luminosity w/ and w/o crab waist



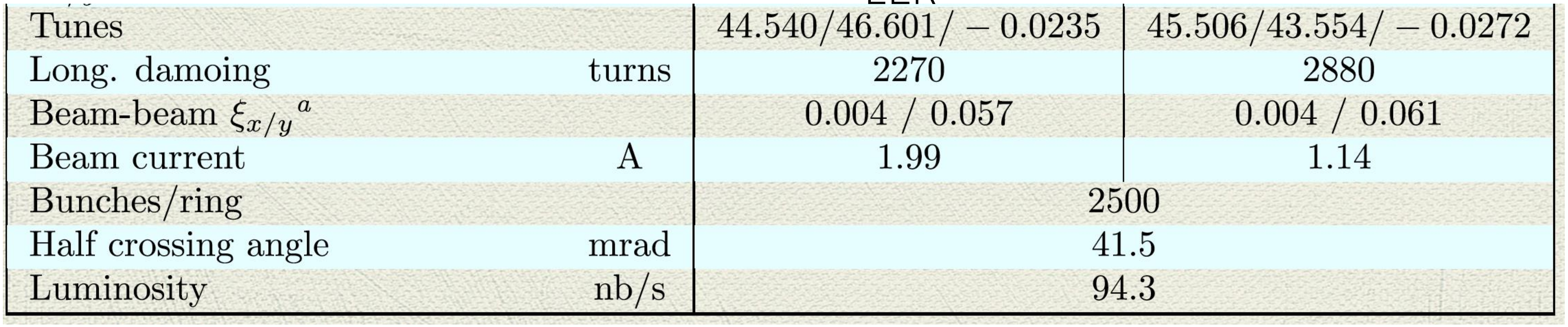
CW ratio:
LER: 80 %
HER: 40%

Strong-Strong Beam-Beam simulation

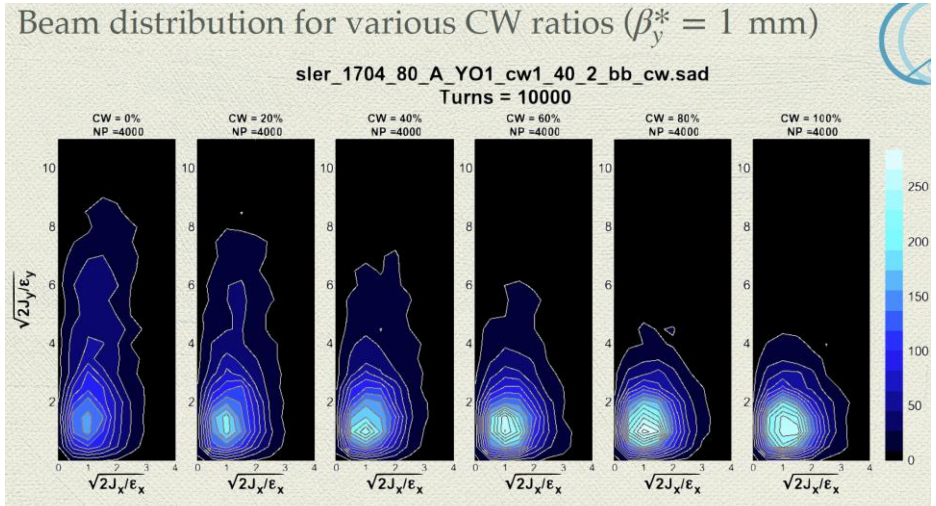


Strong-weak simulation on crab waist

K. Oide

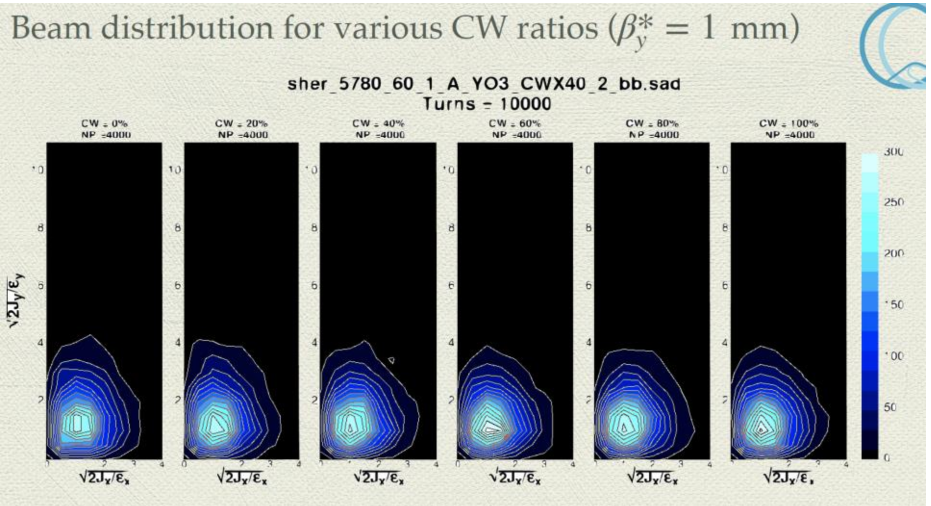


		LER	HER
Tunes		44.540/46.601/ − 0.0235	45.506/43.554/ − 0.0272
Long. damoing	turns	2270	2880
Beam-beam $\xi_{x/y}{}^{a}$		0.004 / 0.057	0.004 / 0.061
Beam current	A	1.99	1.14
Bunches/ring		2500	
Half crossing angle	mrad	41.5	
Luminosity	nb/s	94.3	



Beam distribution for various CW ratios ($\beta_y^* = 1$ mm)

LER



Beam distribution for various CW ratios ($\beta_y^* = 1$ mm)

HER

Summary of operation with crab waist scheme

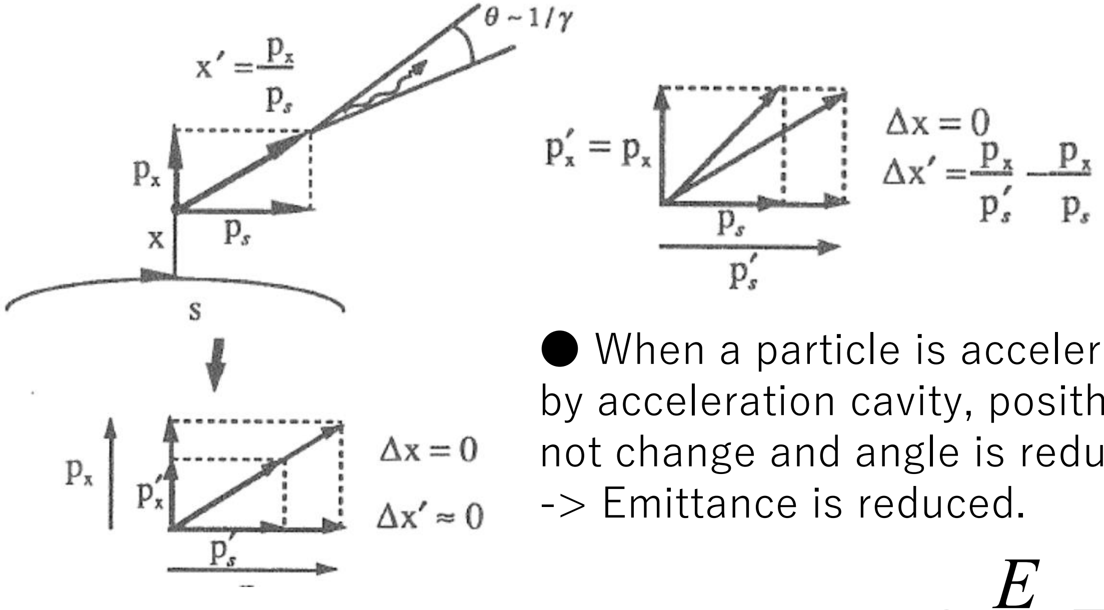
- Benefits of use of crab waist scheme
  - Suppression of beam-beam blowup
    - Specific luminosity was improved.
  - Increase of the bunch currents of both beams
    - W/o crab waist, beam injections was limited due to beam blowup.
- Beam lifetime issue
  - Dynamic aperture shrinks w/ crab waist and the lifetime decrease w/ crab waist was expected.
    - But in βy^*= 1mm case, no lifetime decrease was observed in LER and HER, since the collimator physical aperture is already very narrow.
      - On July 1st 2021, the lifetime of LER increased with wider collimators and so lifetime seems to be determined by physical aperture.
    - In case of lower βy^*, the lifetime w/ crab waist will be an issue.

Emittance

- Horizontal emittance
  - Determined by the balance between radiation damping and radiation excitation.
  - KEKB and SuperKEKB rings have a wide range of tunability of emittance and momentum compaction factor.

Radiation damping

- Radiation Damping of betatron oscillation



● When a particle is accelerated by acceleration cavity, posith does not change and angle is reduced.
-> Emittance is reduced.

●Both position and angle do not change by emitting SR.

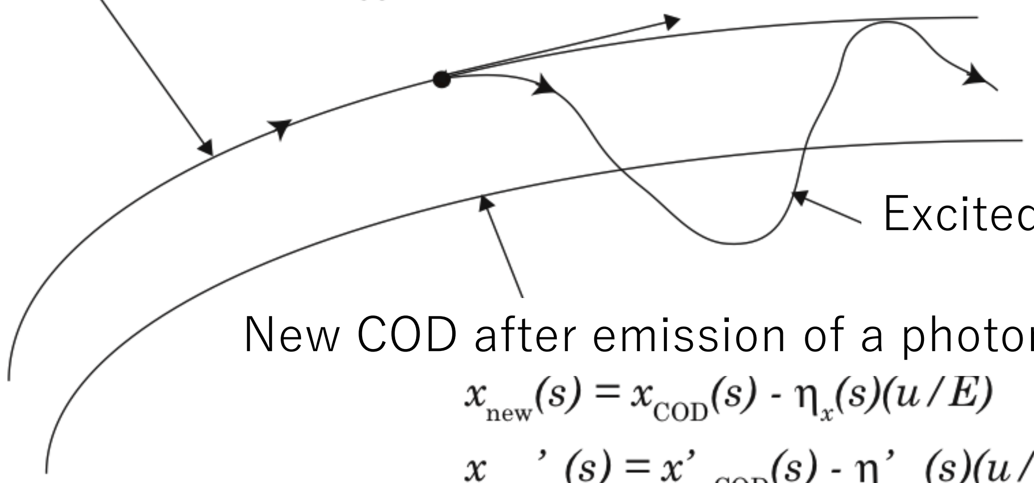
$$t_b = 2\frac{E}{U_0}T$$

Revolusion time

Energy loss / turn

Radiation damping time of betatron oscillation

Quantum excitation



$$x(s) = x_{\mathrm{COD}}(s)$$

Original COD

$$x'(s) = x'_{\mathrm{COD}}(s)$$

Emit a photon with energy of u

Excited betatron

New COD after emission of a photon

$$x_{\mathrm{new}}(s) = x_{\mathrm{COD}}(s) - \eta_x(s)(u/E)$$

$$x_{\mathrm{new}}'(s) = x'_{\mathrm{COD}}(s) - \eta'_x(s)(u/E)$$

$$\Delta x_\beta = \eta_x \frac{u}{E}$$

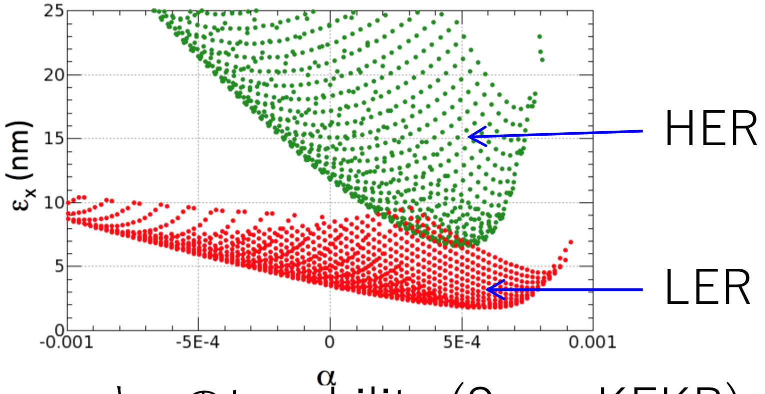
$$\Delta x'_\beta = \eta'_x \frac{u}{E}$$

When a photon is emitted at a place where dispersion is non-zero, a betatron oscillation is excited. Quantum excitation becomes weaker with smaller dispersion.

2.5 π cell lattice

- Tunability of horizontal emittance and momentum compaction (α)

●With 2.5π lattice , ε_x and αをcan be tuned in a wide range



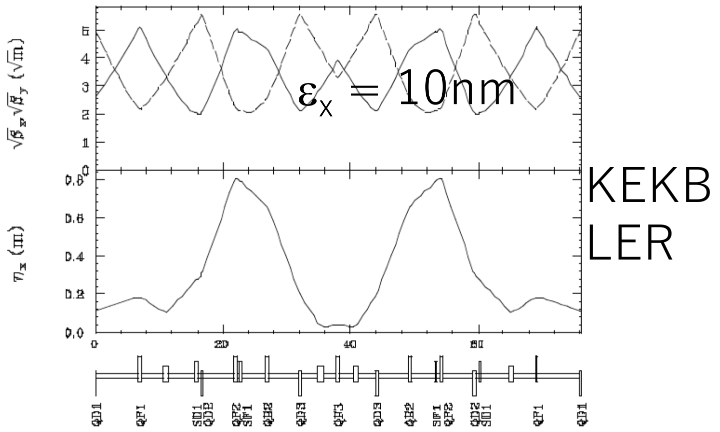
ε_xとαのtunability (SuperKEKB)

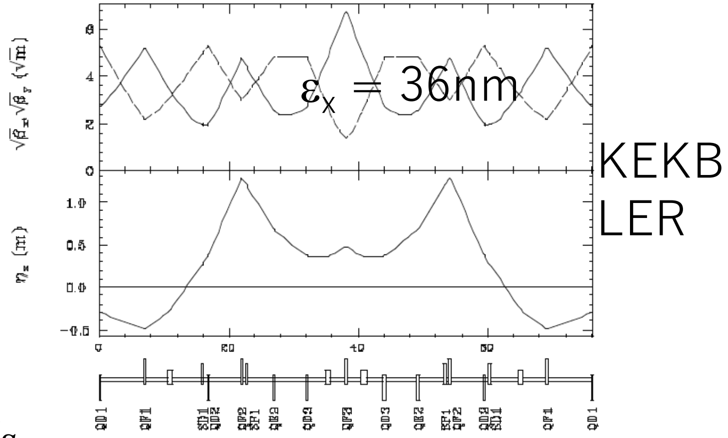
●SuperKEKB: lower ε_x is realized.

● KEKB(LER): ε_x 18nm, L=0.9m -> 4m
SuperKEKB: ε_x 3.2nm -> 4nm (with longer bends)

● Low α-> shorter bunch length
In KEKB, lower βy* than PEP-II was possible with lower α.

$$a = \frac{1}{C}\oint\frac{h}{r}ds$$





Vertical emittance

- Vertical emittance (single beam, zero current)

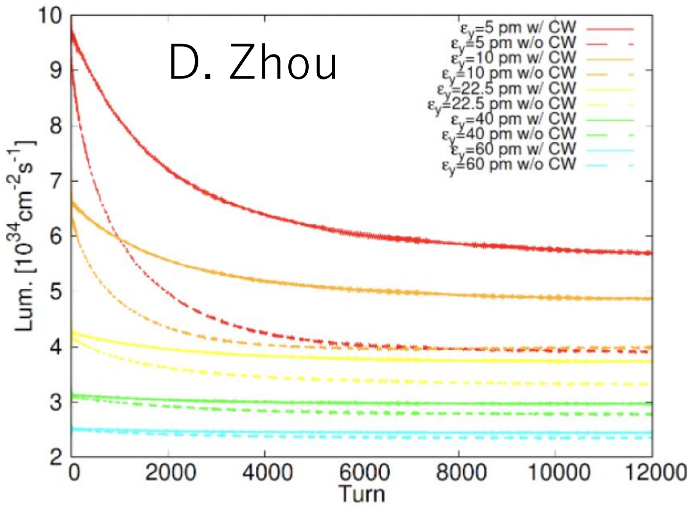
$$e_y = ke_x + A\left(h_y^{rms}\right)^2 + e_y^{OA}$$

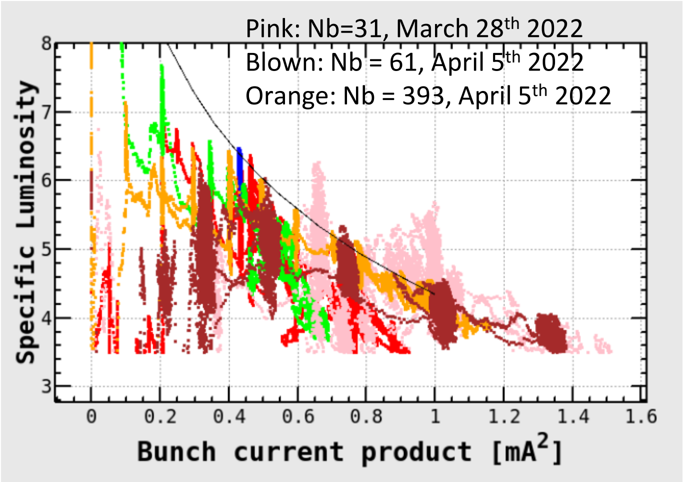
coupling dispersion opening angle

  - x-y coupling
    - Machine errors (such as mis-alignment of Q or SX mganets.)
      - The coupling correction can reduce residual coupling value.
  - Vertical dispersion
    - Machine errors (such as mis-alignment of Q or SX mganets.)
      - The dispersion correction can reduce residual dispersions.
    - Vertical dispersion in design
      - Fringe field of detector solenoid, vertical bending magnets -> (small, εy ~ 0.33 pm, LER)
  - Opening angle of radiation
    - Usually negligible (or ultimate limit of vertical emittance)
- Others
  - Synchro-beta emittance (a.k.a anomalous emittance)
  - Beam-beam blowup (large)
  - Instablility (TMCI, Electron clouds)

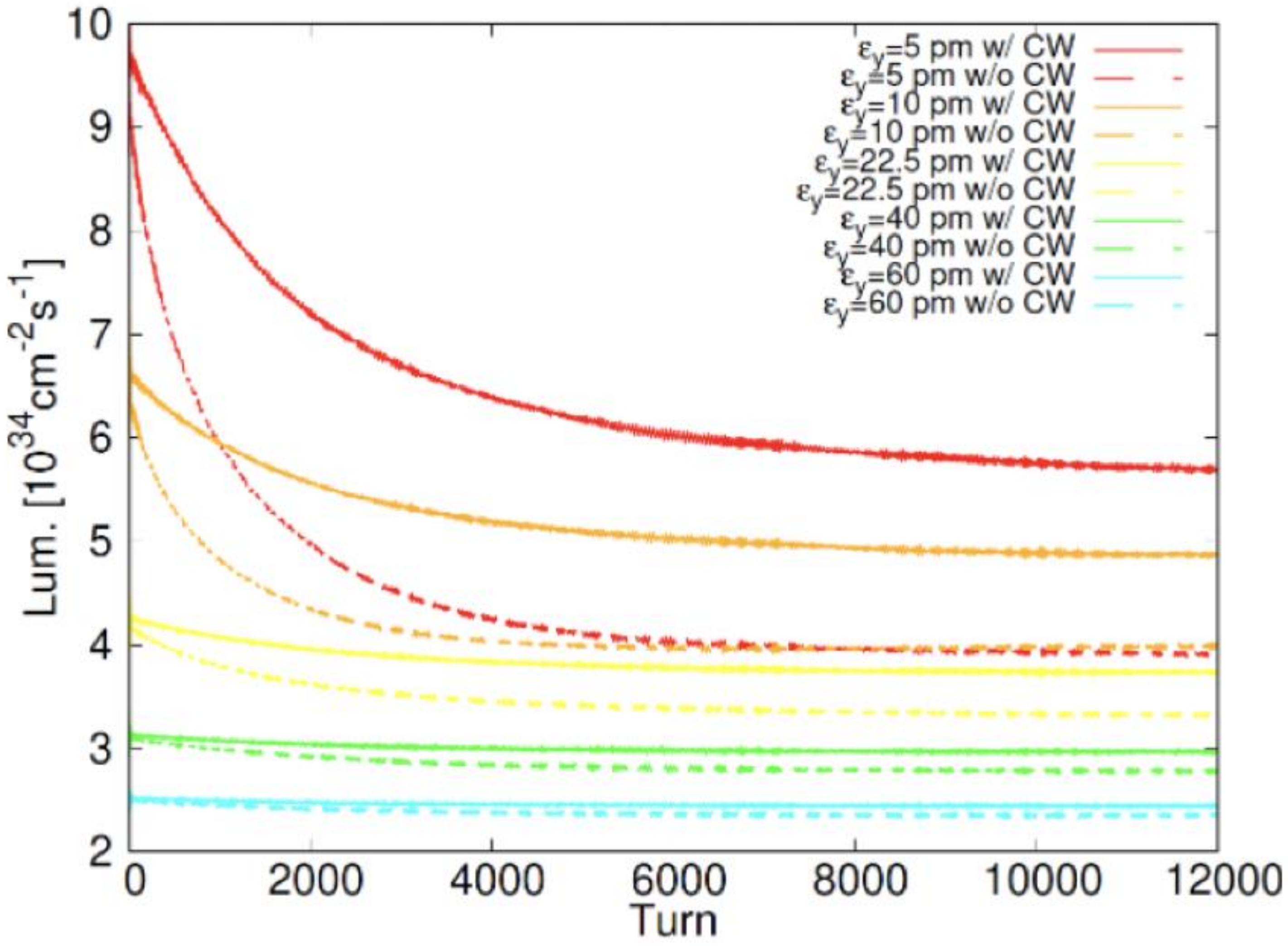
Luminosity vs single beam vertical emittance

- Ways to better beam-beam performance
  - Beam-beam simulations predict better beam-beam performance with
    - Smaller vertical emittance in single beam (matter of optics corrections)
    - Higher crab waist ratio in HER (strength)
  - Identification of causes of discrepancy between simulations and experiments
  - Better working points
- Beam-beam parameters
  - Achieved values in physics runs: : ξy(LER) =0.0407 , ξy(HER) = 0.0279
  - Achieved values in high bunch collision study: ξy(LER) =0.0565 , ξy(HER) = 0.0434
  - By increasing bunch currents in physics run, higher ξy and then a higher luminosity is expected.


D. Zhou

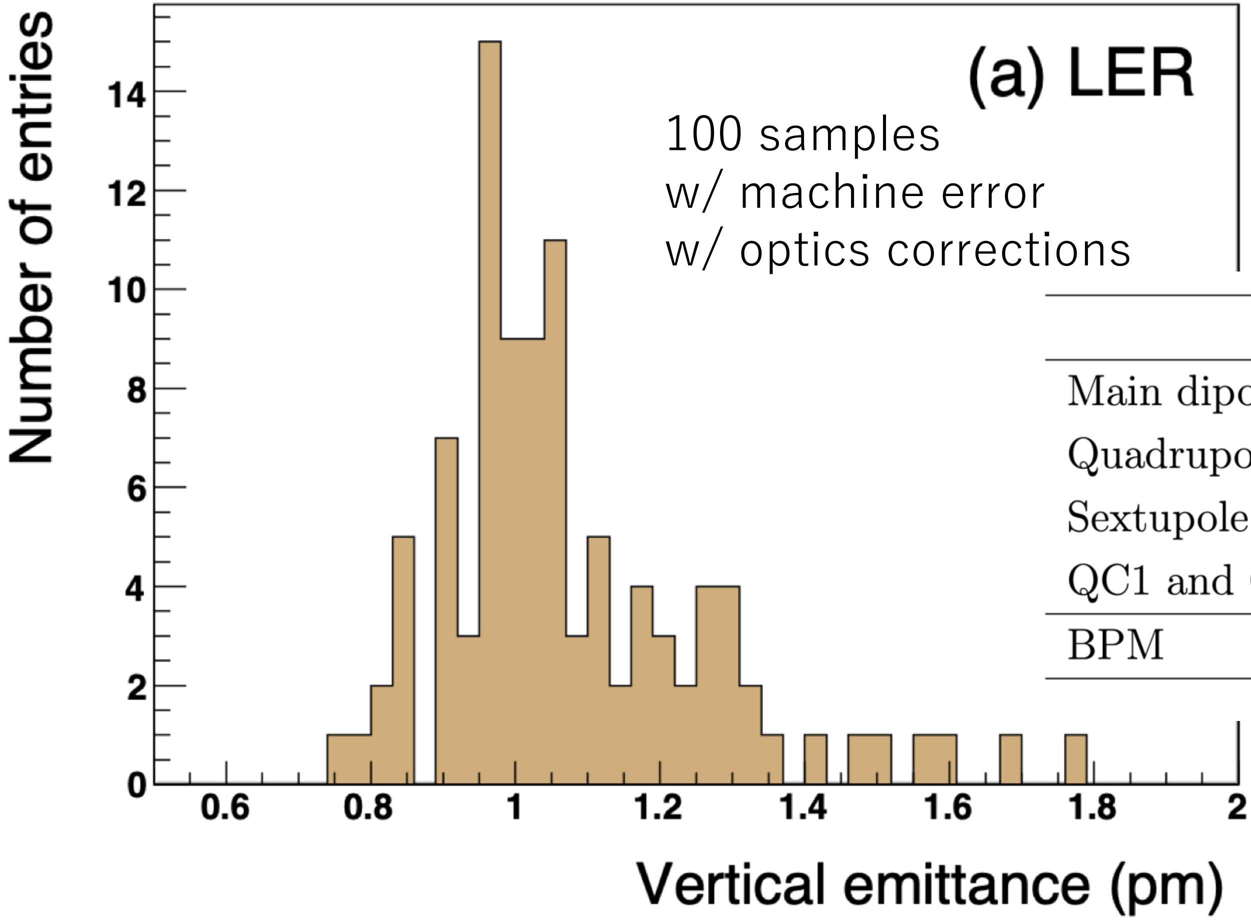

Pink: Nb=31, March 28th 2022
Blown: Nb = 61, April 5th 2022
Orange: Nb = 393, April 5th 2022

Luminosity vs single beam vertical emittance



Vertical emittance

Design Report $\varepsilon_y < 2$ pm



100 samples
w/ machine error
w/ optics corrections

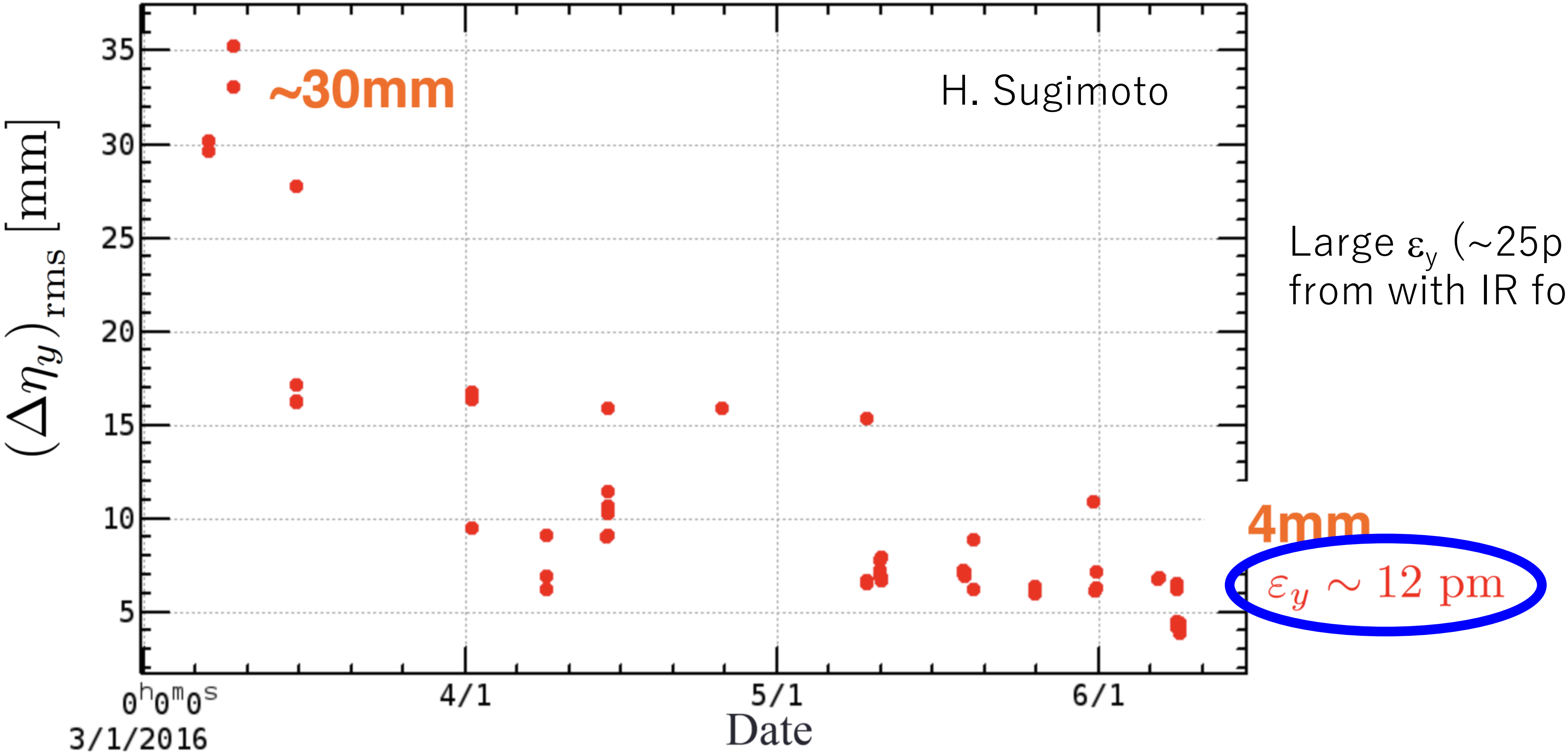
	Δx_{rms} (μm)	Δy_{rms} (μm)	θ_{rms} (mrad)	$(\Delta K/K)_{rms}$
Main dipole	-	-	0.1	3.5×10^{-4}
Quadrupole	100	100	0.1	7×10^{-4}
Sextupole	100	100	-	1.3×10^{-3}
QC1 and QC2	100	100	-	-
BPM	75	75	1	-

Real machine

ε_y=~25 pm (LER, single beam, Phase 3)

ε_y in Phase 1

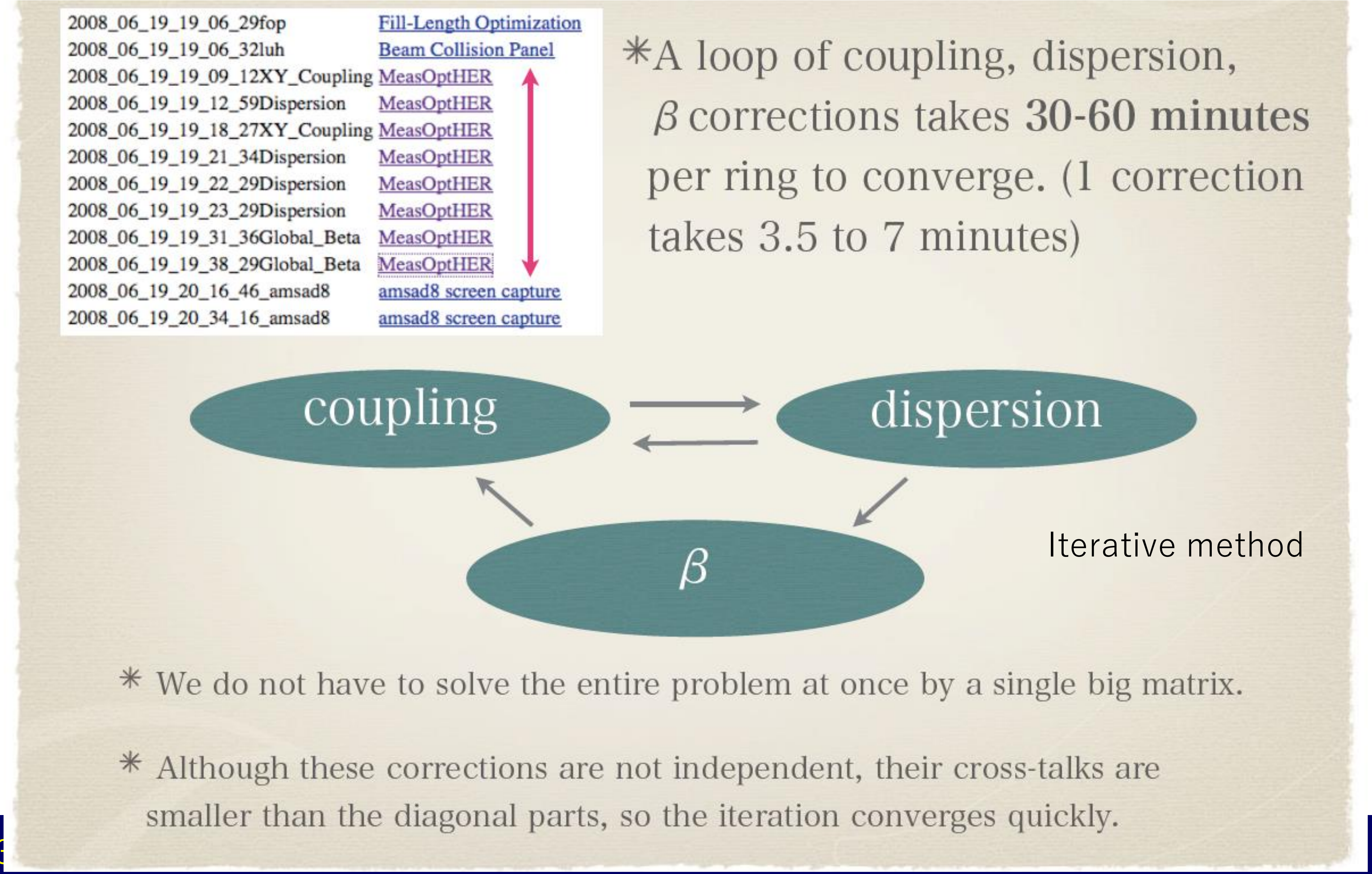
History of residual vertical dispersion (LER)



Large ε_y (~25pm) in Phase 3 may come from with IR for some unknown reason.

- Optics correction and hardware calibration are iteratively repeated.

Method of optics correction (KEKB, SuperKEKB)



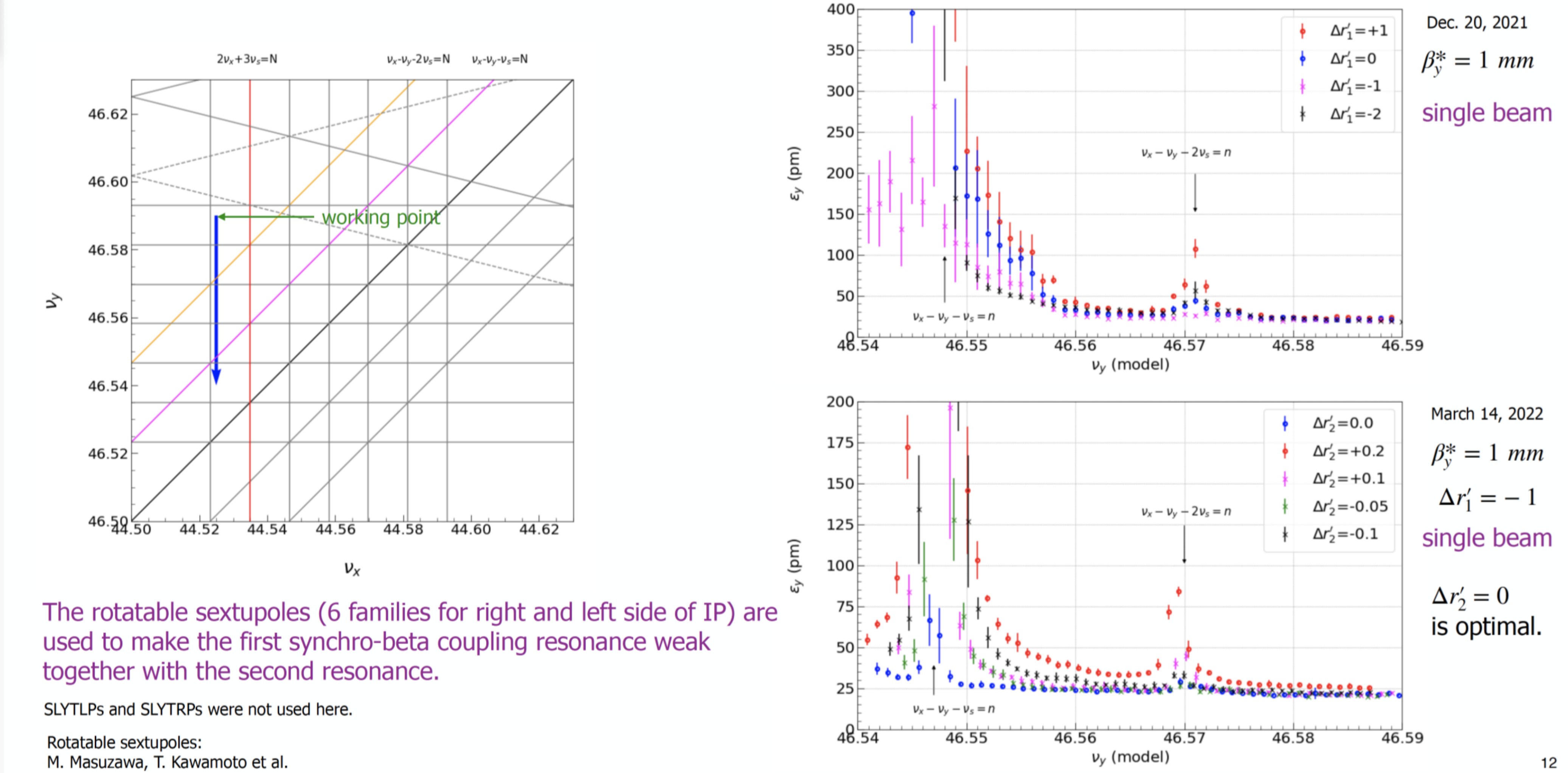
2008_06_19_19_06_29fop	Fill-Length Optimization
2008_06_19_19_06_32luh	Beam Collision Panel
2008_06_19_19_09_12XY_Coupling	MeasOptHER
2008_06_19_19_12_59Dispersion	MeasOptHER
2008_06_19_19_18_27XY_Coupling	MeasOptHER
2008_06_19_19_21_34Dispersion	MeasOptHER
2008_06_19_19_22_29Dispersion	MeasOptHER
2008_06_19_19_23_29Dispersion	MeasOptHER
2008_06_19_19_31_36Global_Beta	MeasOptHER
2008_06_19_19_38_29Global_Beta	MeasOptHER
2008_06_19_20_16_46_amsad8	amsad8 screen capture
2008_06_19_20_34_16_amsad8	amsad8 screen capture

- A loop of coupling, dispersion, β corrections takes **30-60 minutes** per ring to converge. (1 correction takes 3.5 to 7 minutes)

Iterative method

- We do not have to solve the entire problem at once by a single big matrix.
- Although these corrections are not independent, their cross-talks are smaller than the diagonal parts, so the iteration converges quickly.

Chromatic coupling correction in LER



Dec. 20, 2021

$\beta_y^* = 1\ mm$

single beam

March 14, 2022

$\beta_y^* = 1\ mm$

$\Delta r_1' = -1$

single beam

$\Delta r_2' = 0$
is optimal.

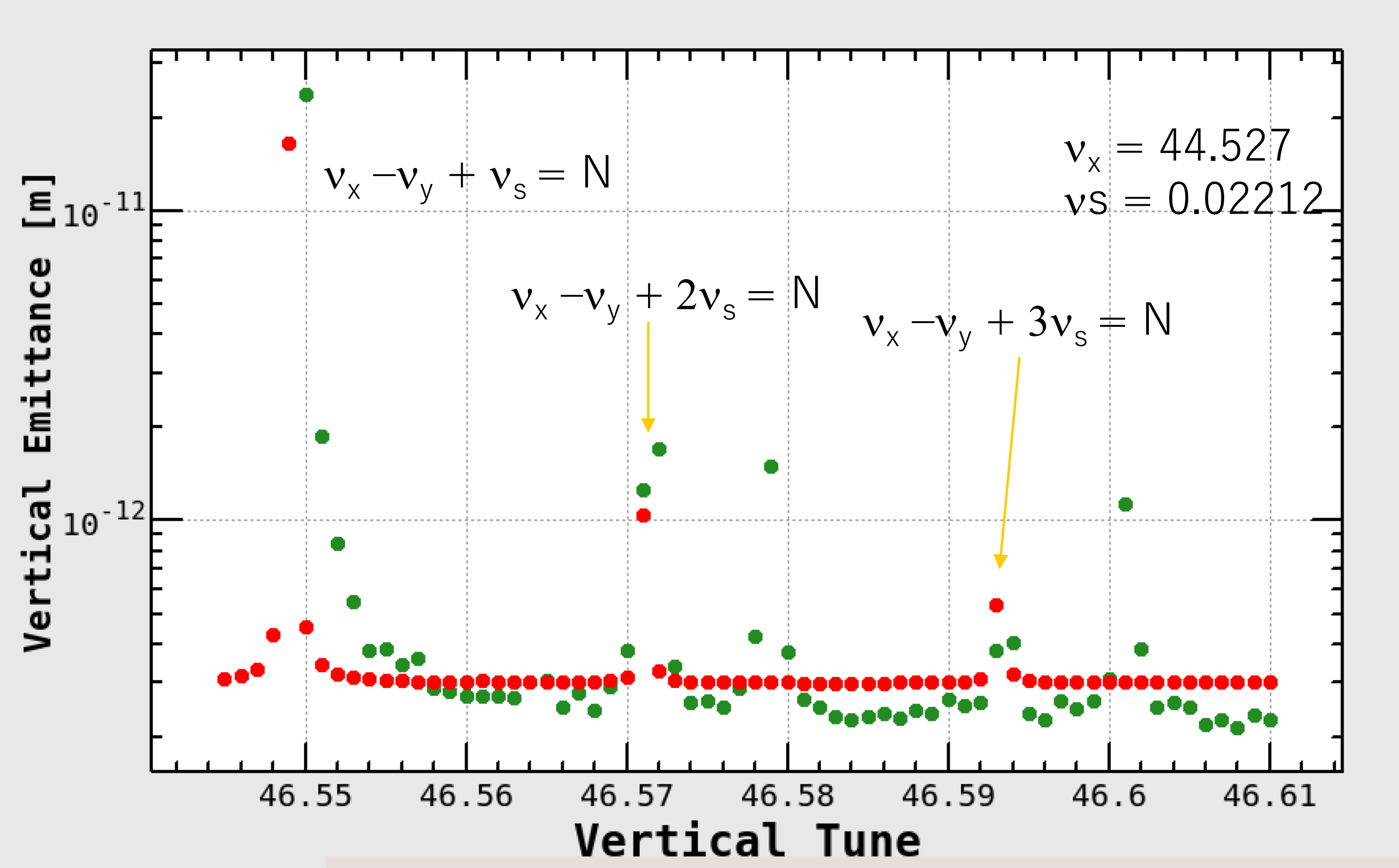
The rotatable sextupoles (6 families for right and left side of IP) are used to make the first synchro-beta coupling resonance weak together with the second resonance.

SLYTLPs and SLYTRPs were not used here.

Rotatable sextupoles:
M. Masuzawa, T. Kawamoto et al.

Synchro-beam emittance depends on chromatic X-Y coupling and be corrected by using skew-sextupoles. Large chromatic X-Y coupling at IP could degrade the luminosity.

Synchro-beta emittance (LER) βy* = 1mm



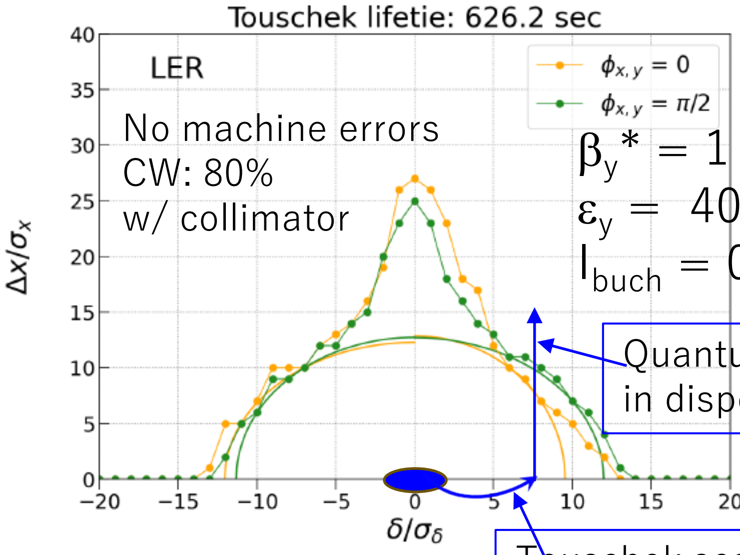
Red: synchro-beta emittance command (main-trunk)
Green: particle tracking 1000 particles, 20,000 turns Rad, Fluc:ON
No machine errors

Dynamic aperture

- Dynamic aperture
  - Stable region in (x,x’,y,y’,ΔE/E,τ) phase space
  - <-> physical aperture (usually determined by the collimator aperture)
  - In general, dynamic aperture shrinks with lower βy*.
  - By optimizing settings of sextupole magnets, dynamic aperture can be improved.
- Beam lifetime
  - In SuperKEKB, Touschek lifetime is dominant. (others: beam-gas Coulomb scattering, radiative BhaBha scattering)
  - Touschek lifetime is usually determined by the dynamic (or physical) aperture in horizontal-energy direction.
- Beam injection efficiency
  - In SuperKEKB, the injection efficiency is limited by the dynamic (or physical) aperture mainly in the horizontal direction.

Dynamic aperture simulation by SAD

Y. Ohnishi

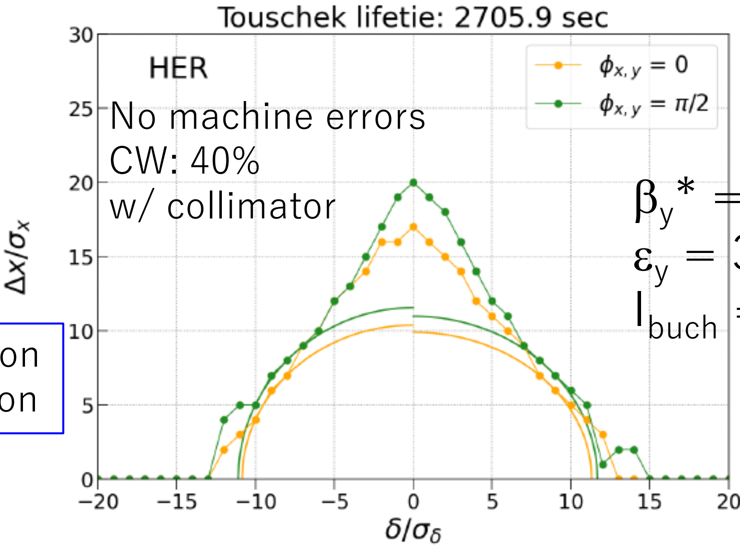


No machine errors
CW: 80%
w/ collimator

$\beta_y^* = 1$ mm
$\varepsilon_y = 40$ pm
$I_{buch} = 0.62$ mA

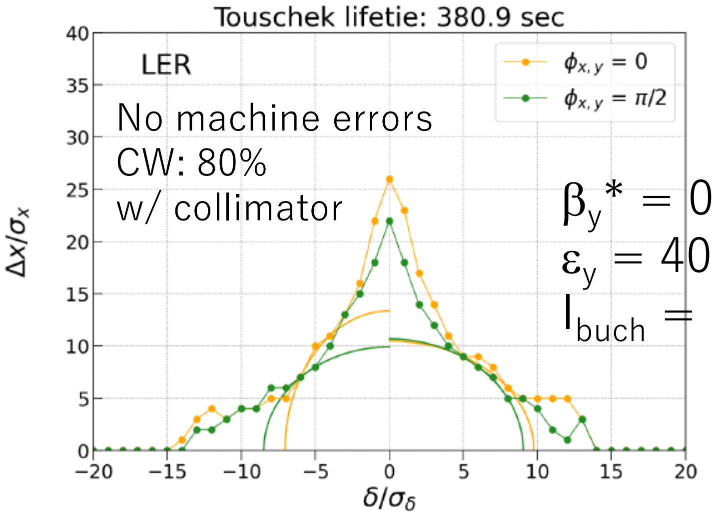
Quantum excitation
in dispersive region

Touschek scattering



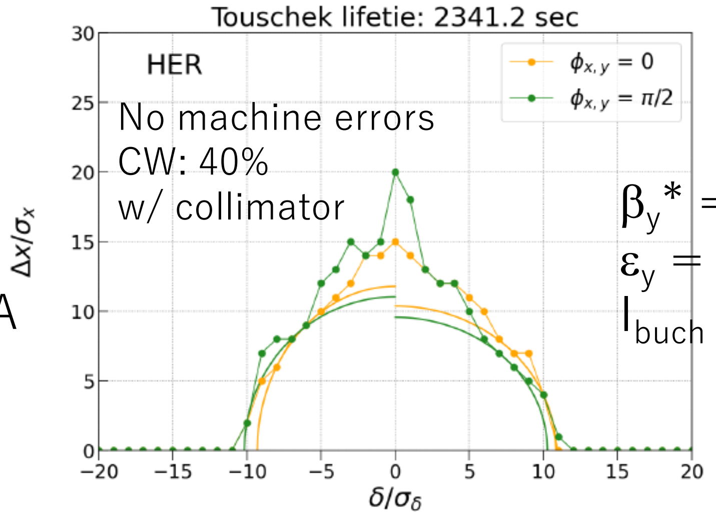
No machine errors
CW: 40%
w/ collimator

$\beta_y^* = 1$ mm
$\varepsilon_y = 35$ pm
$I_{buch} = 0.5$ mA



No machine errors
CW: 80%
w/ collimator

$\beta_y^* = 0.8$ mm
$\varepsilon_y = 40$pm
$I_{buch} = 0.62$mA

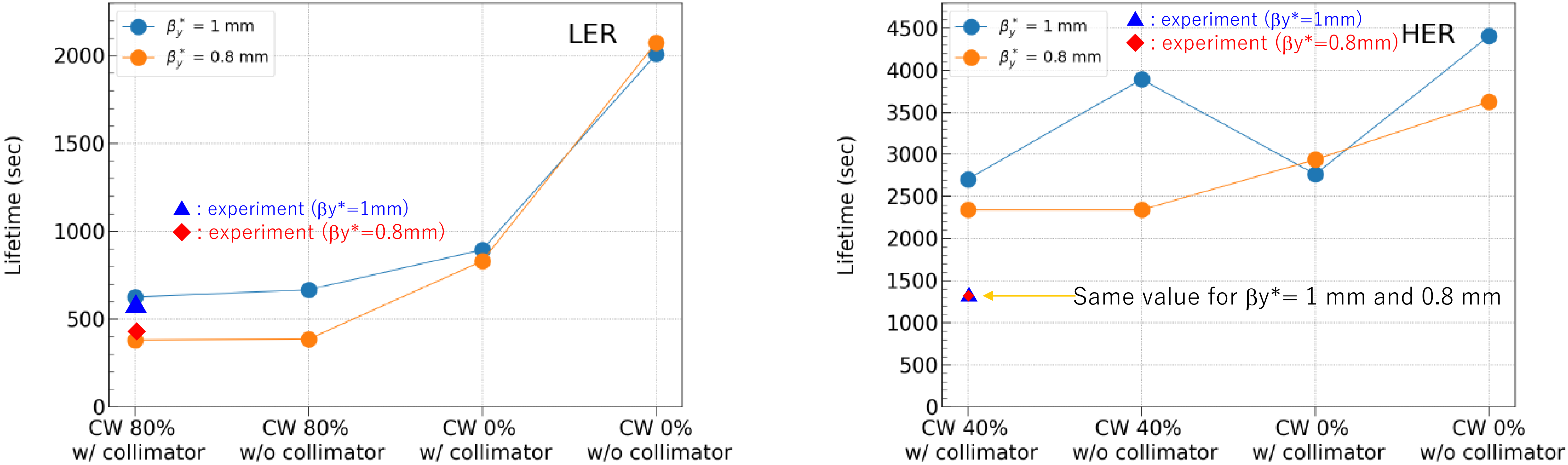


No machine errors
CW: 40%
w/ collimator

$\beta_y^* = 0.8$ mm
$\varepsilon_y = 35$ pm
$I_{buch} = 0.5$mA

Touschek beam lifetime (simulation & experiment)

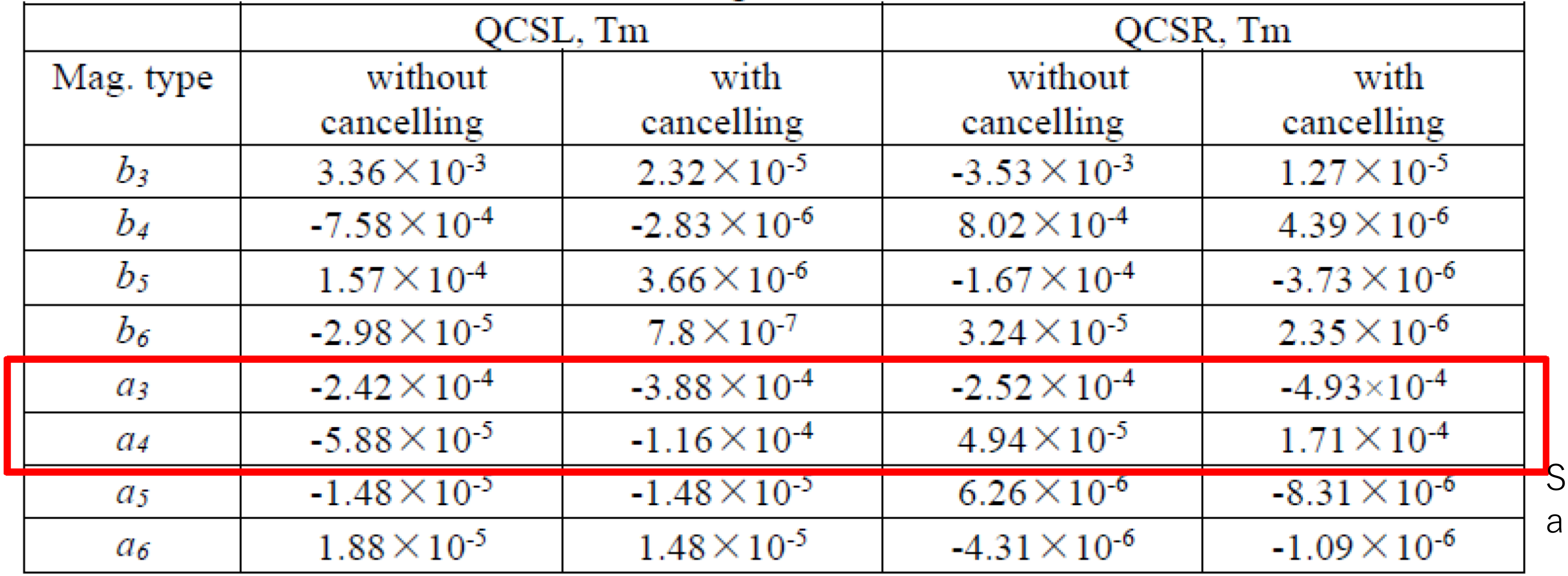
Y. Ohnishi



- LER lifetimes measured are consistent with simulations. HER lifetimes measured are ~ half of simulation.
- LER (CW:80%, βy*:1mm): Physical aperture is slightly narrower than the dynamic aperture.
- LER (CW:80%, βy*:0.8mm): Dynamic aperture is narrower than physical aperture.
- LER (CW:40%, βy*:1mm): Physical aperture is narrower than the dynamic aperture.
- LER (CW:40%, βy*:0.8mm): Dynamic aperture is narrower than physical aperture.

Error of cancel coils for QC1P leakage field

Table 24: Measured integral leak fields at R_{ref}=10 mm



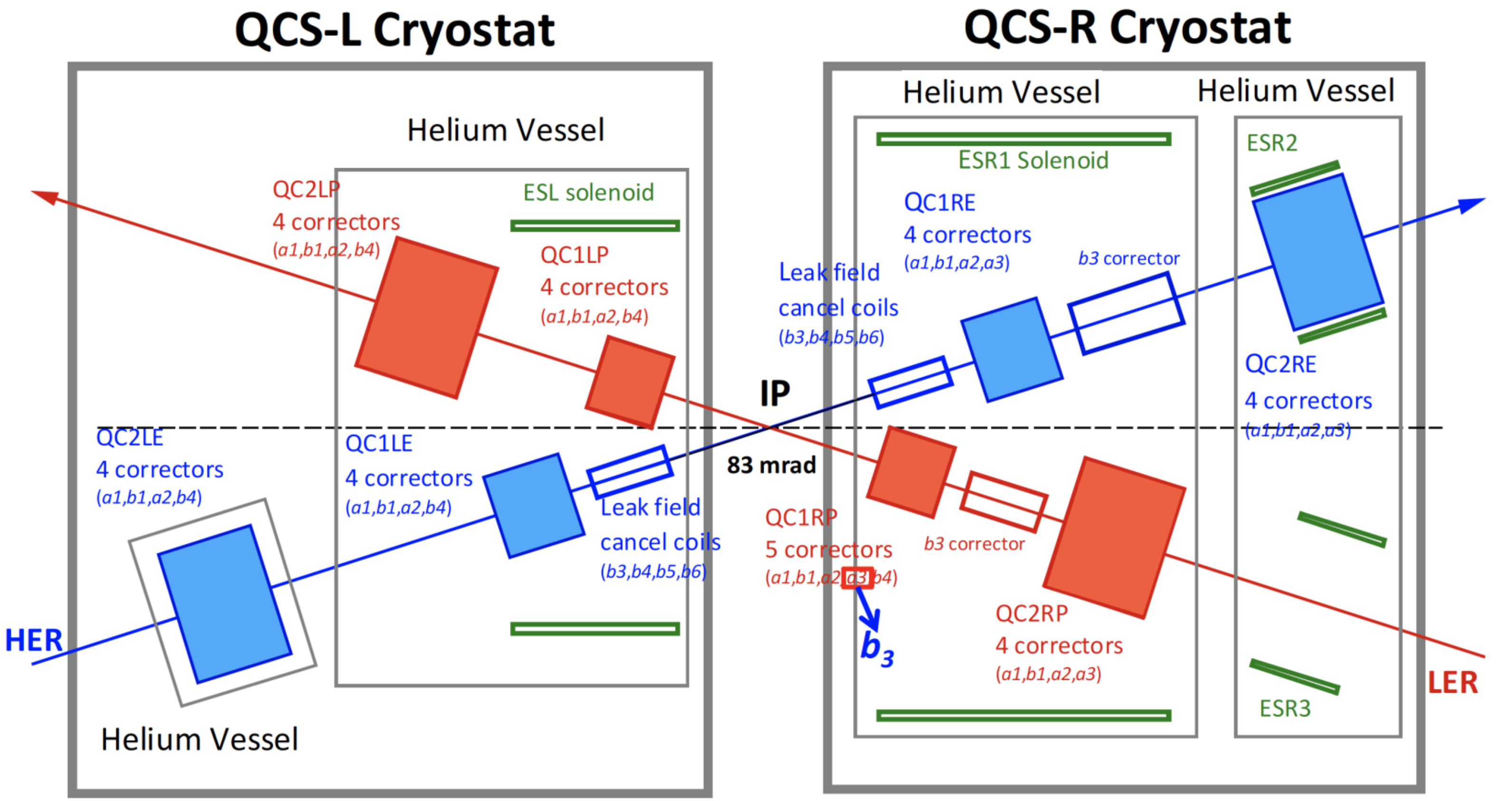
	QCSL, Tm		QCSR, Tm	
Mag. type	without cancelling	with cancelling	without cancelling	with cancelling
b_3	3.36×10^{-3}	2.32×10^{-5}	-3.53×10^{-3}	1.27×10^{-5}
b_4	-7.58×10^{-4}	-2.83×10^{-6}	8.02×10^{-4}	4.39×10^{-6}
b_5	1.57×10^{-4}	3.66×10^{-6}	-1.67×10^{-4}	-3.73×10^{-6}
b_6	-2.98×10^{-5}	7.8×10^{-7}	3.24×10^{-5}	2.35×10^{-6}
a_3	-2.42×10^{-4}	-3.88×10^{-4}	-2.52×10^{-4}	-4.93×10^{-4}
a_4	-5.88×10^{-5}	-1.16×10^{-4}	4.94×10^{-5}	1.71×10^{-4}
a_5	-1.48×10^{-5}	-1.48×10^{-5}	6.26×10^{-6}	-8.31×10^{-6}
a_6	1.88×10^{-5}	1.48×10^{-5}	-4.31×10^{-6}	-1.09×10^{-6}

Skew components are increased.

Almost no effect to beam lifetime.
Beam injection efficiency may be affected

b3(b4) and a3(b4) coils are excited by the same power supply.

QCS correction coils



4 SC main quadrupole magnets: 1 collared magnet, 3 yoked magnets
16 SC correctors: a1, b1, a2, b4
4 SC leak field cancel magnets: b3, b4, b5, b6
1 compensation solenoid

4 SC main quadrupole magnets: 1 collared magnet, 3 yoked magnets
19 SC correctors: a1, b1, a2, a3, b3, b4
4 SC leak field cancel magnets: b3, b4, b5, b6
3 compensation solenoid

HER injection with error of cancel coil

N. Iida

Simulation

Reflecting this effect, all injected particles no longer entered in the DA as shown in (d).

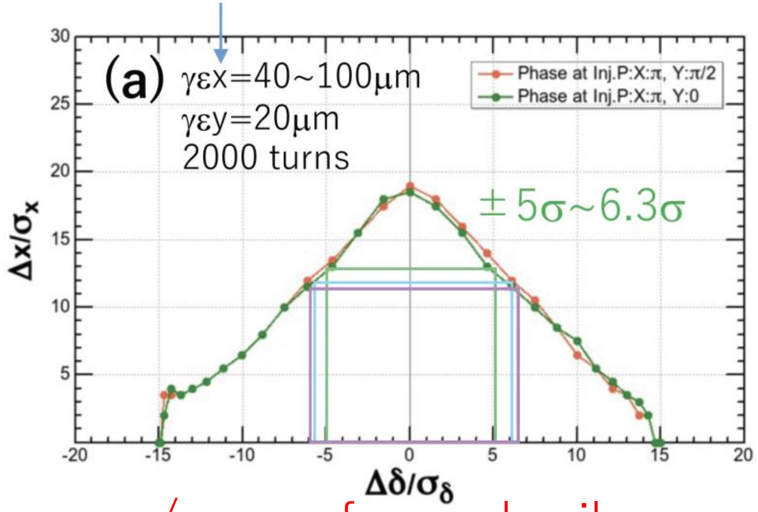
However, by widening the aperture near the injection point and by an improvement of the magnetic field of the septum magnet in LS1, it was found that the situation recovers to some extent as shown in (c).

In the future

Tracking simulation of HER injection under the conditions below to obtain the injection efficiency.

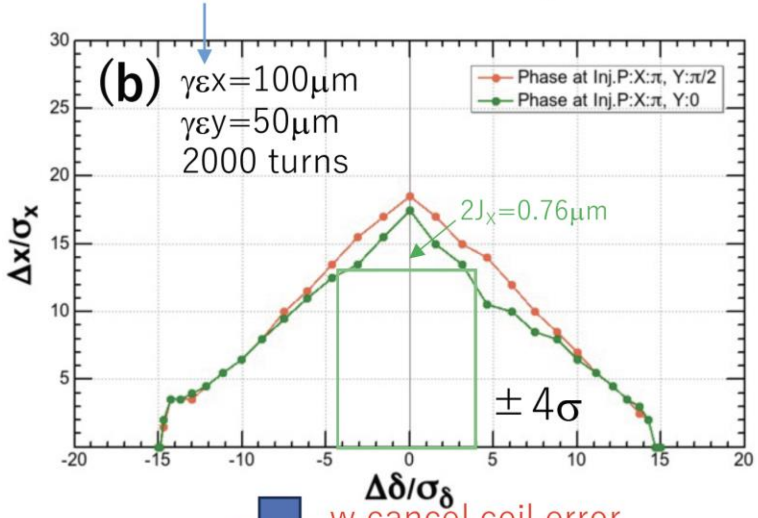
w/o error of cancel coils

Designed vertical emittance of injected beam

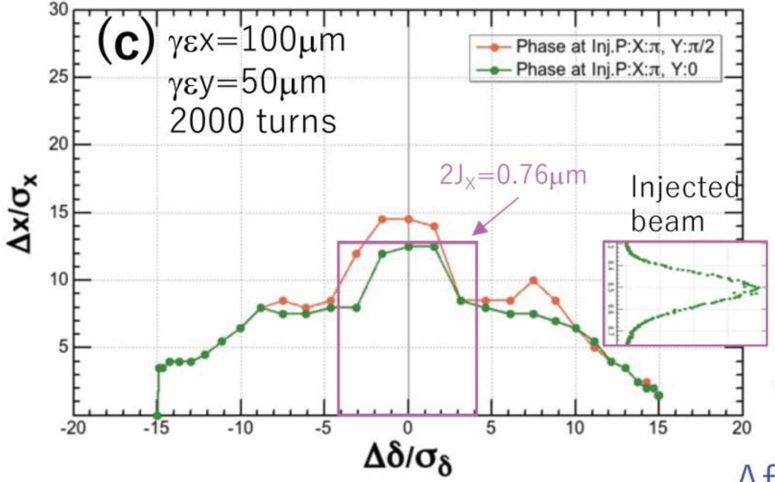


w/o error of cancel coils

Measured best emittance of injected beam

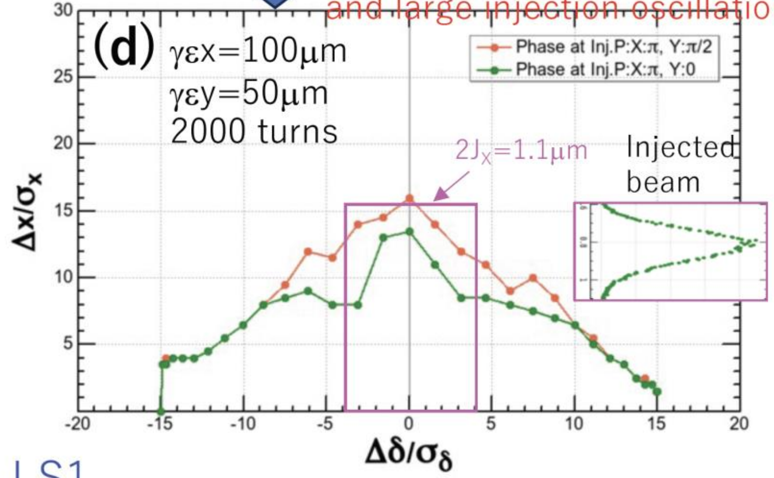


w/ error of cancel coils



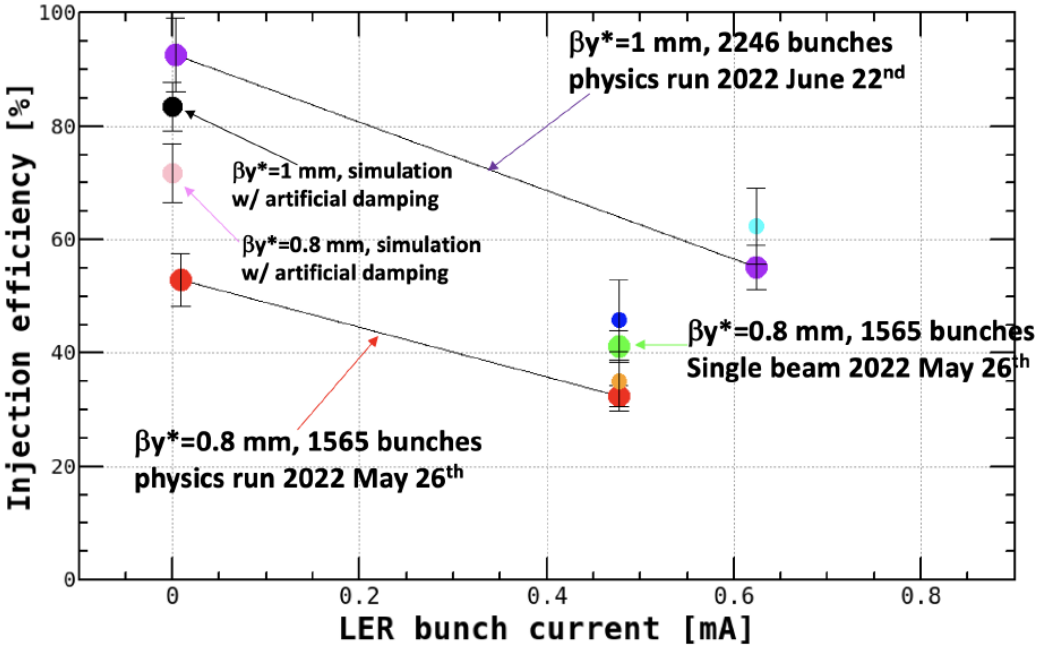
w cancel coil error

~~and large injection oscillation~~



After LS1

Injection efficiency (simulation and experiments)



LER

Figure 5. Injection efficiency as a function of the bunch current in LER. Both cases of β_y^* at 0.8 mm and 1 mm are shown. There is strong beam current dependence. Here, we plot the dependence as the bunch current dependence. The data in cyan, blue, and orange are obtained by the simulations. The data in back and pink are obtained by the simulation with artificial extra damping to the oscillation of the center-of-gravity of the injecting bunch with a damping time of 100 turns which is intended to simulate the effect of the bunch-by-bunch feedback system.

Comparison of machine parameters

IPAC2020
K. Shibata

IPAC2022
at present

	KEKB achieved		SuperKEKB 2020 May 1st		SuperKEKB 2022 June 8th		SuperKEKB design	
	LER	HER	LER	HER	LER	HER	LER	HER
I_{beam} [A]	1.637	1.188	0.438	0.517	1.321	1.099	3.6	2.6
# of bunches	1585		783		2249		2500	
I_{bunch} [mA]	1.033	0.7495	0.5593	0.6603	0.5873	0.4887	1.440	1.040
βy^* [mm]	5.9	5.9	1.0	1.0	1.0	1.0	0.27	0.30
ξy	0.129	0.090	0.0236	0.0219	0.0407 (0.0565)[a]	0.0279 (0.0434)[a]	0.0881	0.0807
Luminosity [$10^{34}cm^{-2}s^{-1}$]	2.11		1.57		4.65		80	
Integrated Luminosity [ab^{-1}]	1.04		0.03		0.40		50	

doubled

a) High bunch current collision study

Fin.

Thank you for your attention.

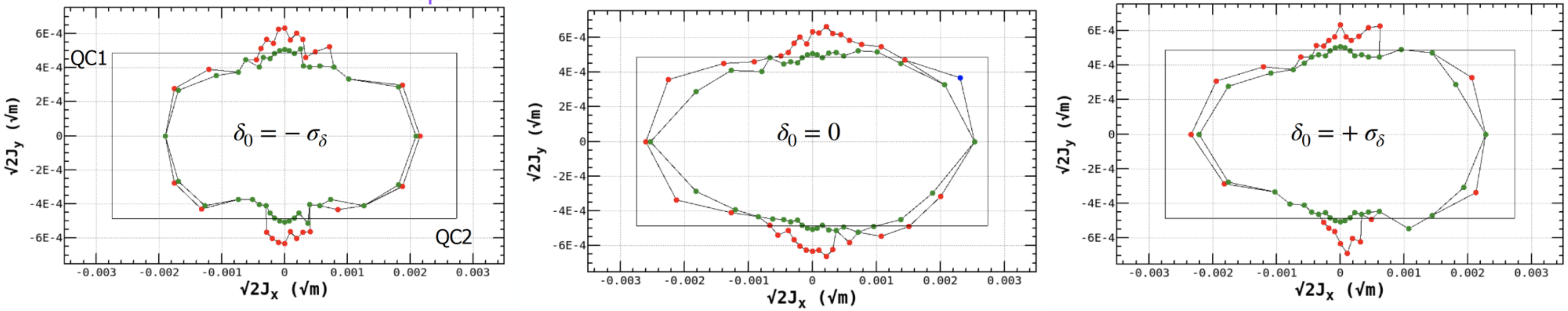
Transverse aperture (LER)

$\phi_{x0} = 0,\ \phi_{y0} = 0$ ☐ is determined by the physical aperture of QC1 and QC2

LER

CW 80 %

collimator: full open



Y. Ohnishi

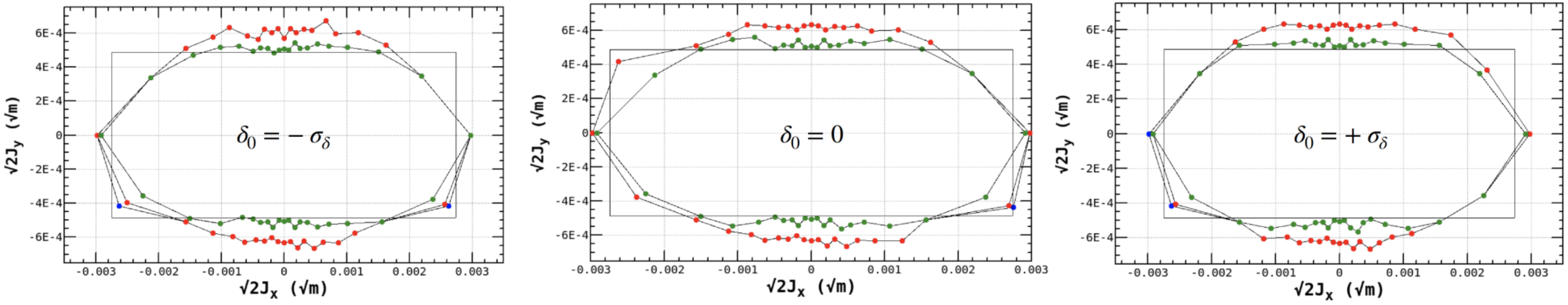
AQC1: AY =20.0 mm
AQC1: AY =18.0 mm
AQC1: AY =13.5 mm

Tested three different vertical apertures for QC1

Horizontal dynamic aperture is reduced by the crab waist scheme.

If the vertical physical aperture of QC1P is increased to 17 mm, the stable region is extended.
(Above 17 mm is limited by the dynamic aperture.)

CW 0 %



Beam lifetime estimation (at the design stage)

	KEKB (design)		KEKB (operation)		SuperKEKB	
	LER	HER	LER	HER	LER	HER
Radiative Bhabha	21.3h	9.0h	6.6h	4.5h	28min.	20min.
Beam-gas	45h[a)]	45h[a)]			24.5min.[b)]	46min. [b)]
Touschek	10h	-			10min.	10min.
Total	5.9h	7.4h	~133min.	~200min.	6min.	6min.
Beam current	2.6A	1.1A	1.6A	1.1A	3.6A	2.6A
Loss Rate	0.12mA/s	0.04mA/s	0.23mA/s	0.11mA/s	10mA/s	7.2mA/s

4nC@25Hz 2.9nC@25Hz

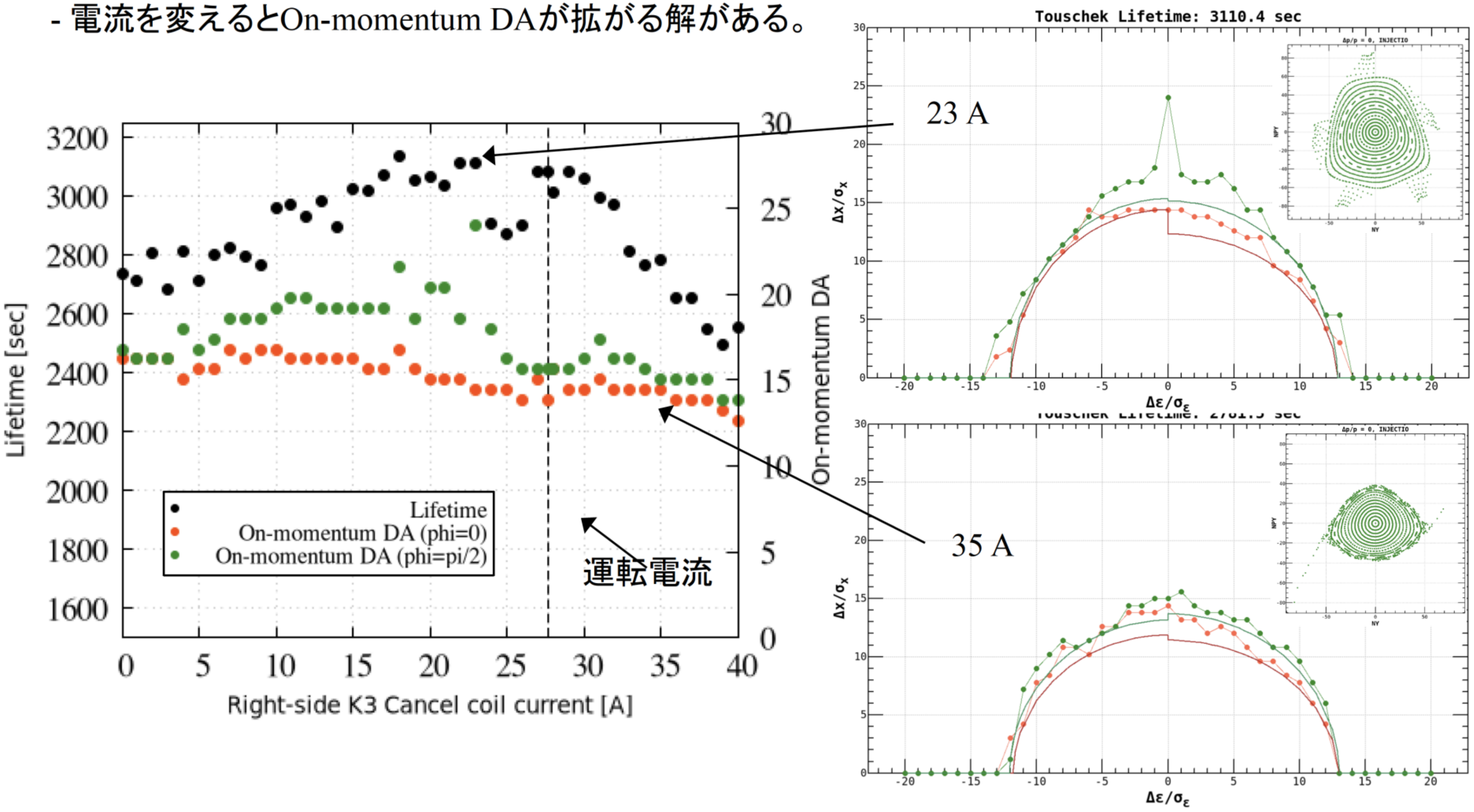
a) Bremsstrahlung

b) Coulomb scattering, sensitive to collimator setting

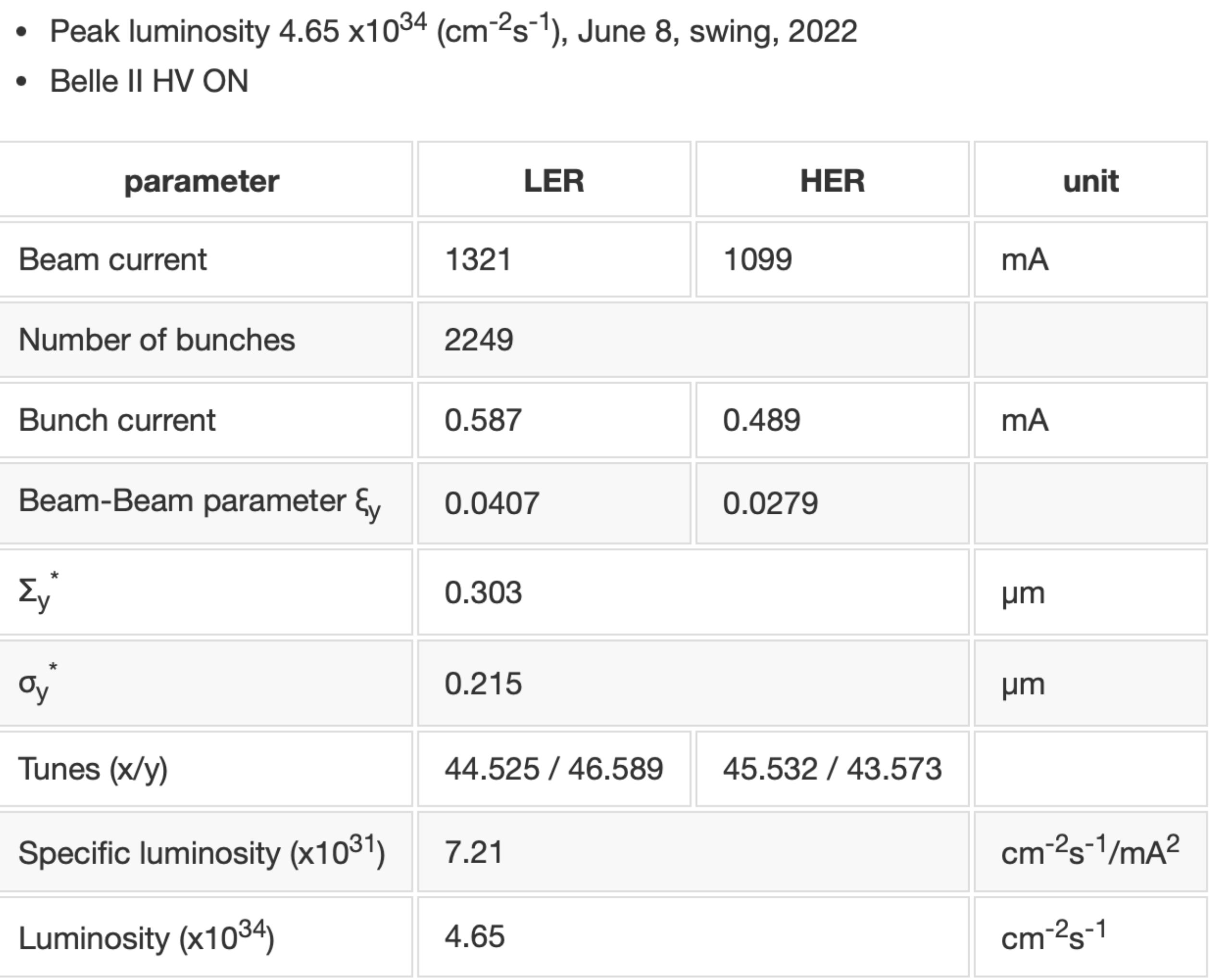
As for loss rate, beam loss accompanied with the beam injection should be added.

R側のB4(K3)コイル電流とDA

- B4コイルの電流を変えるとK3とSK3が変わる。
- R側のB4(K3)キャンセルコイルの電流を変えるとDAはどうなるか？
  -> DAとしては運転電流付近が最適。
- 電流を変えるとOn-momentum DAが拡がる解がある。



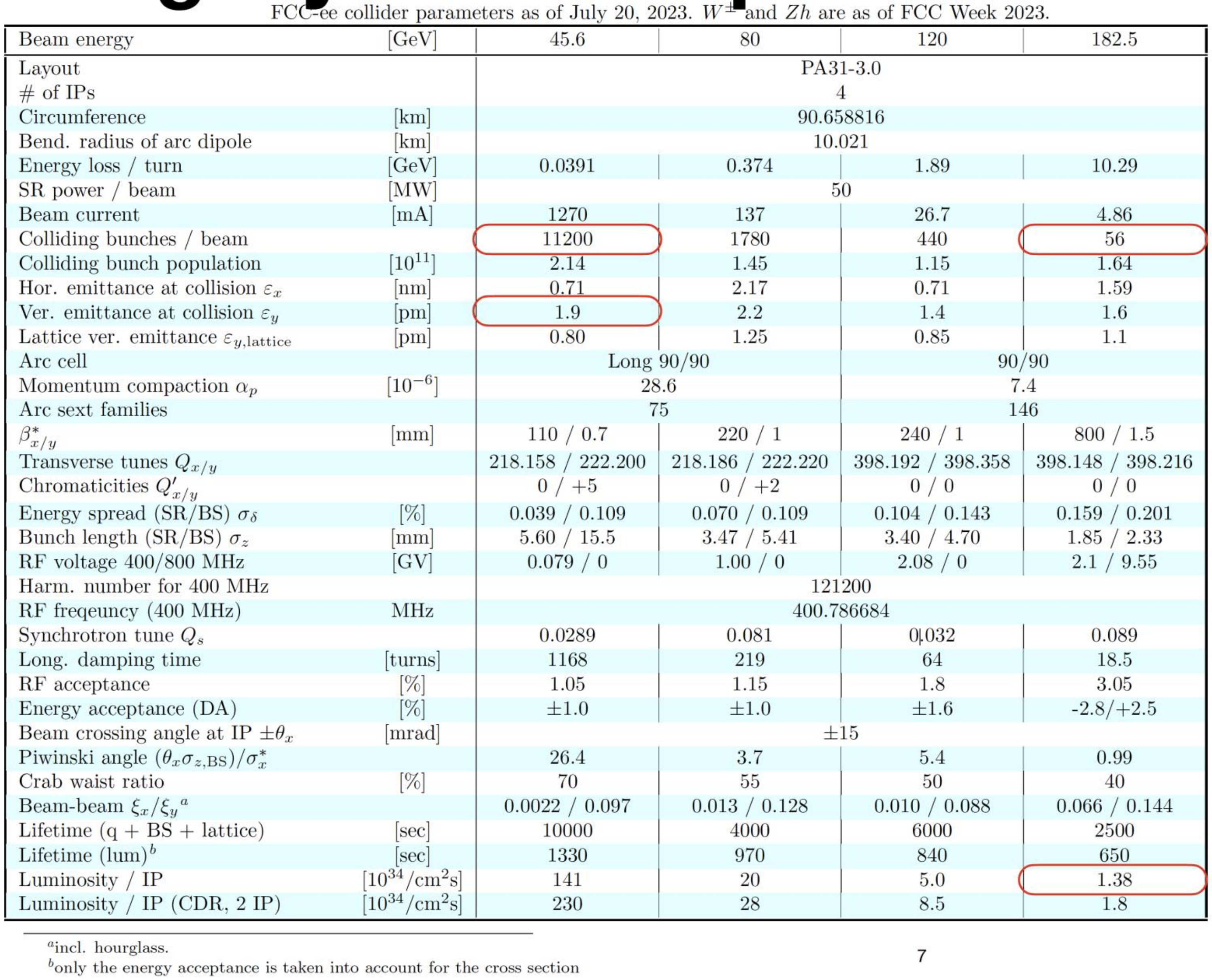
Machine parameters at highest luminosity



- Peak luminosity 4.65 x10^{34} ($cm^{-2}s^{-1}$), June 8, swing, 2022
- Belle II HV ON

parameter	LER	HER	unit
Beam current	1321	1099	mA
Number of bunches	2249		
Bunch current	0.587	0.489	mA
Beam-Beam parameter ξ_y	0.0407	0.0279	
Σ_y^*	0.303		μm
σ_y^*	0.215		μm
Tunes (x/y)	44.525 / 46.589	45.532 / 43.573	
Specific luminosity (x10^{31})	7.21		$cm^{-2}s^{-1}/mA^2$
Luminosity (x10^{34})	4.65		$cm^{-2}s^{-1}$

Slightly modified parameter set



FCC-ee collider parameters as of July 20, 2023. $W^{\pm}$ and Zh are as of FCC Week 2023.

Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-3.0			
# of IPs		4			
Circumference	[km]	90.658816			
Bend. radius of arc dipole	[km]	10.021			
Energy loss / turn	[GeV]	0.0391	0.374	1.89	10.29
SR power / beam	[MW]	50			
Beam current	[mA]	1270	137	26.7	4.86
Colliding bunches / beam		11200	1780	440	56
Colliding bunch population	[10^{11}]	2.14	1.45	1.15	1.64
Hor. emittance at collision ε_x	[nm]	0.71	2.17	0.71	1.59
Ver. emittance at collision ε_y	[pm]	1.9	2.2	1.4	1.6
Lattice ver. emittance $\varepsilon_{y,\mathrm{lattice}}$	[pm]	0.80	1.25	0.85	1.1
Arc cell		Long 90/90		90/90	
Momentum compaction α_p	[10^{-6}]	28.6		7.4	
Arc sext families		75		146	
$\beta^*_{x/y}$	[mm]	110 / 0.7	220 / 1	240 / 1	800 / 1.5
Transverse tunes $Q_{x/y}$		218.158 / 222.200	218.186 / 222.220	398.192 / 398.358	398.148 / 398.216
Chromaticities $Q'_{x/y}$		0 / +5	0 / +2	0 / 0	0 / 0
Energy spread (SR/BS) σ_δ	[%]	0.039 / 0.109	0.070 / 0.109	0.104 / 0.143	0.159 / 0.201
Bunch length (SR/BS) σ_z	[mm]	5.60 / 15.5	3.47 / 5.41	3.40 / 4.70	1.85 / 2.33
RF voltage 400/800 MHz	[GV]	0.079 / 0	1.00 / 0	2.08 / 0	2.1 / 9.55
Harm. number for 400 MHz		121200			
RF freqeuncy (400 MHz)	MHz	400.786684			
Synchrotron tune Q_s		0.0289	0.081	0.032	0.089
Long. damping time	[turns]	1168	219	64	18.5
RF acceptance	[%]	1.05	1.15	1.8	3.05
Energy acceptance (DA)	[%]	±1.0	±1.0	±1.6	-2.8/+2.5
Beam crossing angle at IP $\pm\theta_x$	[mrad]	±15			
Piwinski angle $(\theta_x \sigma_{z,\mathrm{BS}})/\sigma^*_x$		26.4	3.7	5.4	0.99
Crab waist ratio	[%]	70	55	50	40
Beam-beam ξ_x/ξ_y[a]		0.0022 / 0.097	0.013 / 0.128	0.010 / 0.088	0.066 / 0.144
Lifetime (q + BS + lattice)	[sec]	10000	4000	6000	2500
Lifetime (lum)[b]	[sec]	1330	970	840	650
Luminosity / IP	[10^{34}/cm^{2}s]	141	20	5.0	1.38
Luminosity / IP (CDR, 2 IP)	[10^{34}/cm^{2}s]	230	28	8.5	1.8

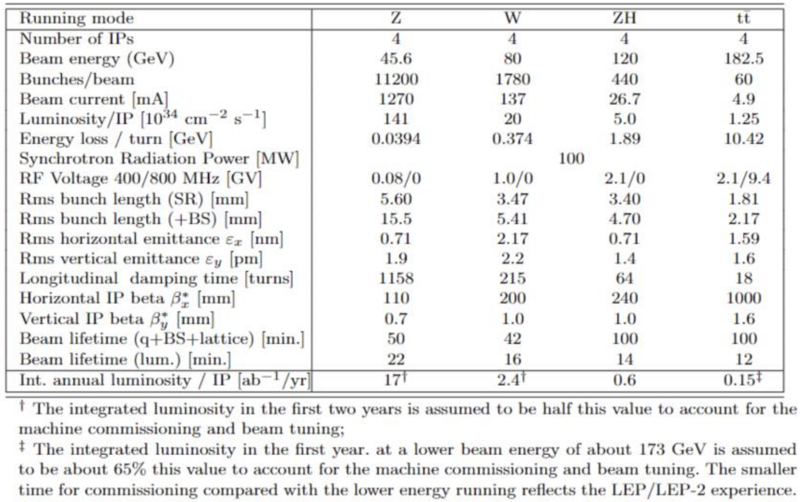
---

[a] incl. hourglass.

[b] only the energy acceptance is taken into account for the cross section

7

- Small modifications have been made @$Z/t\bar{t}$, according to the changes described above.
- Not yet looked at $W^{\pm}, Zh$.
- Still not far from the official ones (below) for the mid-term review.



Running mode	Z	W	ZH	$t\bar{t}$
Number of IPs	4	4	4	4
Beam energy (GeV)	45.6	80	120	182.5
Bunches/beam	11200	1780	440	60
Beam current [mA]	1270	137	26.7	4.9
Luminosity/IP [10^{34} cm^{-2} s^{-1}]	141	20	5.0	1.25
Energy loss / turn [GeV]	0.0394	0.374	1.89	10.42
Synchrotron Radiation Power [MW]	100			
RF Voltage 400/800 MHz [GV]	0.08/0	1.0/0	2.1/0	2.1/9.4
Rms bunch length (SR) [mm]	5.60	3.47	3.40	1.81
Rms bunch length (+BS) [mm]	15.5	5.41	4.70	2.17
Rms horizontal emittance ε_x [nm]	0.71	2.17	0.71	1.59
Rms vertical emittance ε_y [pm]	1.9	2.2	1.4	1.6
Longitudinal damping time [turns]	1158	215	64	18
Horizontal IP beta β^*_x [mm]	110	200	240	1000
Vertical IP beta β^*_y [mm]	0.7	1.0	1.0	1.6
Beam lifetime (q+BS+lattice) [min.]	50	42	100	100
Beam lifetime (lum.) [min.]	22	16	14	12
Int. annual luminosity / IP [ab^{-1}/yr]	17†	2.4†	0.6	0.15‡

† The integrated luminosity in the first two years is assumed to be half this value to account for the machine commissioning and beam tuning;

‡ The integrated luminosity in the first year. at a lower beam energy of about 173 GeV is assumed to be about 65% this value to account for the machine commissioning and beam tuning. The smaller time for commissioning compared with the lower energy running reflects the LEP/LEP-2 experience.

F. Zimmermann

July 21, 2023, K. Oide

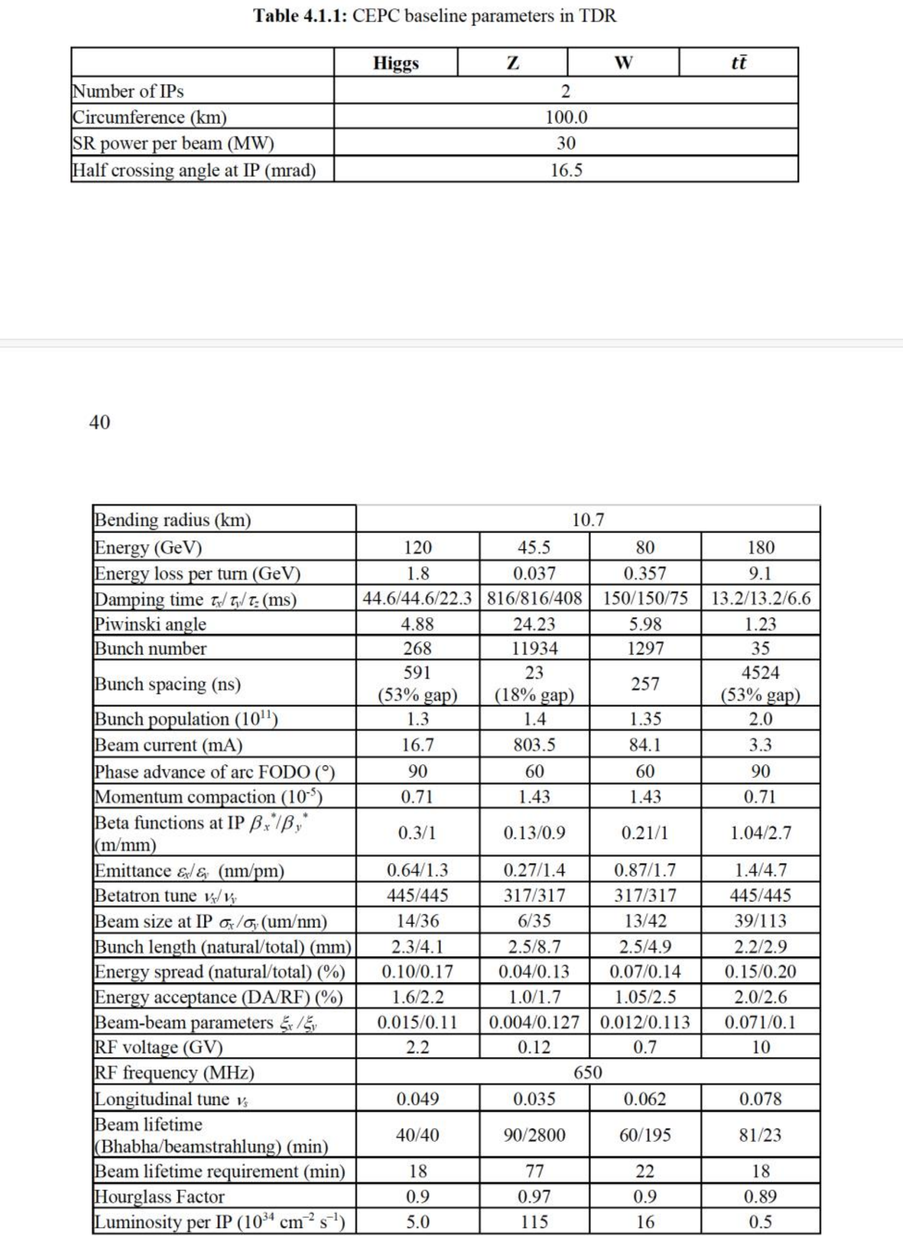
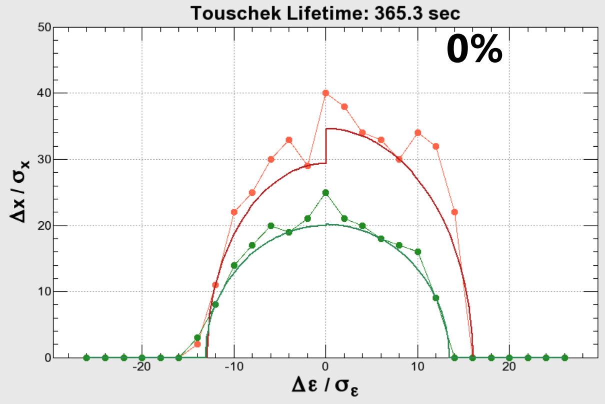


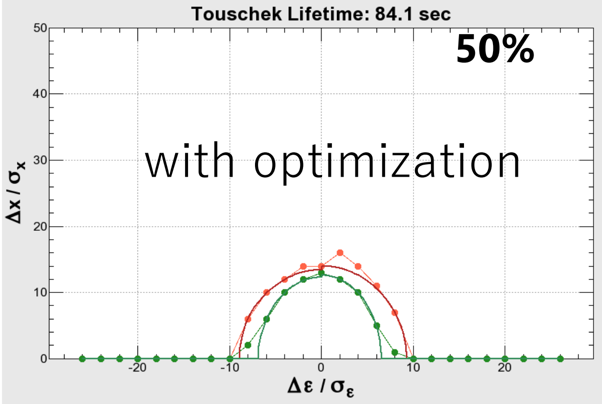
Table 4.1.1: CEPC baseline parameters in TDR

	Higgs	Z	W	$t\bar{t}$
Number of IPs	2			
Circumference (km)	100.0			
SR power per beam (MW)	30			
Half crossing angle at IP (mrad)	16.5			
Bending radius (km)	10.7			
Energy (GeV)	120	45.5	80	180
Energy loss per turn (GeV)	1.8	0.037	0.357	9.1
Damping time $\tau_x/\tau_y/\tau_z$ (ms)	44.6/44.6/22.3	816/816/408	150/150/75	13.2/13.2/6.6
Piwinski angle	4.88	24.23	5.98	1.23
Bunch number	268	11934	1297	35
Bunch spacing (ns)	591 (53% gap)	23 (18% gap)	257	4524 (53% gap)
Bunch population (10^{11})	1.3	1.4	1.35	2.0
Beam current (mA)	16.7	803.5	84.1	3.3
Phase advance of arc FODO (°)	90	60	60	90
Momentum compaction (10^{-5})	0.71	1.43	1.43	0.71
Beta functions at IP β_x^*/β_y^* (m/mm)	0.3/1	0.13/0.9	0.21/1	1.04/2.7
Emittance $\varepsilon_x/\varepsilon_y$ (nm/pm)	0.64/1.3	0.27/1.4	0.87/1.7	1.4/4.7
Betatron tune ν_x/ν_y	445/445	317/317	317/317	445/445
Beam size at IP σ_x/σ_y (um/nm)	14/36	6/35	13/42	39/113
Bunch length (natural/total) (mm)	2.3/4.1	2.5/8.7	2.5/4.9	2.2/2.9
Energy spread (natural/total) (%)	0.10/0.17	0.04/0.13	0.07/0.14	0.15/0.20
Energy acceptance (DA/RF) (%)	1.6/2.2	1.0/1.7	1.05/2.5	2.0/2.6
Beam-beam parameters ξ_x/ξ_y	0.015/0.11	0.004/0.127	0.012/0.113	0.071/0.1
RF voltage (GV)	2.2	0.12	0.7	10
RF frequency (MHz)	650			
Longitudinal tune ν_s	0.049	0.035	0.062	0.078
Beam lifetime (Bhabha/beamstrahlung) (min)	40/40	90/2800	60/195	81/23
Beam lifetime requirement (min)	18	77	22	18
Hourglass Factor	0.9	0.97	0.9	0.89
Luminosity per IP (10^{34} cm^{-2} s^{-1})	5.0	115	16	0.5

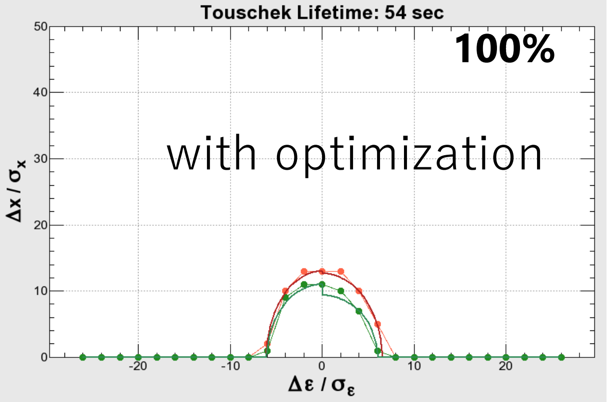
Dynamic aperture with sextupoles for crab waist (LER)



a11: 12.9433 b11: 29.3525 a12: 16.0000 b12: 34.6410 (519.074 sec)
a21: 13.0990 b21: 19.9531 a22: 13.4164 b22: 20.1246 (281.845 sec)

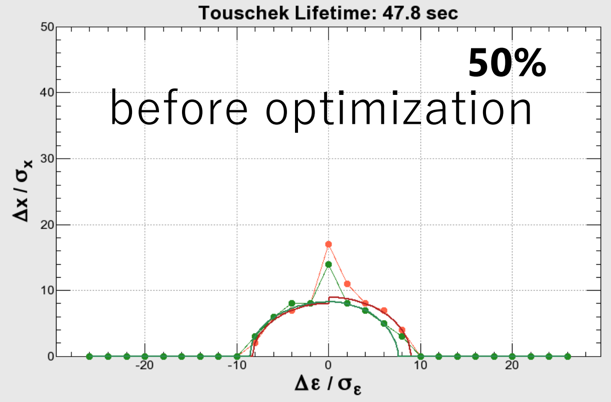


a11: 8.9443 b11: 13.4164 a12: 9.2376 b12: 14.0000 (110.878 sec)
a21: 6.8739 b21: 12.2963 a22: 6.5363 b22: 12.6046 (67.8016 sec)

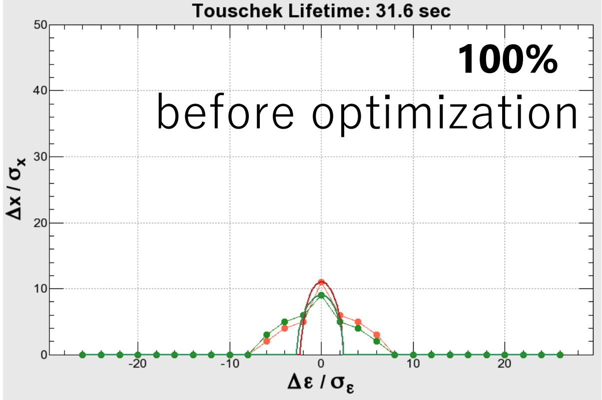


a11: 6.0723 b11: 13.0000 a12: 6.5320 b12: 12.6491 (63.7355 sec)
a21: 6.0249 b21: 11.0000 a22: 6.0346 b22: 9.3488 (46.9154 sec)

$\beta_y^* = 0.27\text{mm}$



a11: 8.2624 b11: 8.0000 a12: 8.9443 b12: 8.9443 (49.8753 sec)
a21: 8.5918 b21: 8.2260 a22: 7.5388 b22: 8.2583 (45.9688 sec)



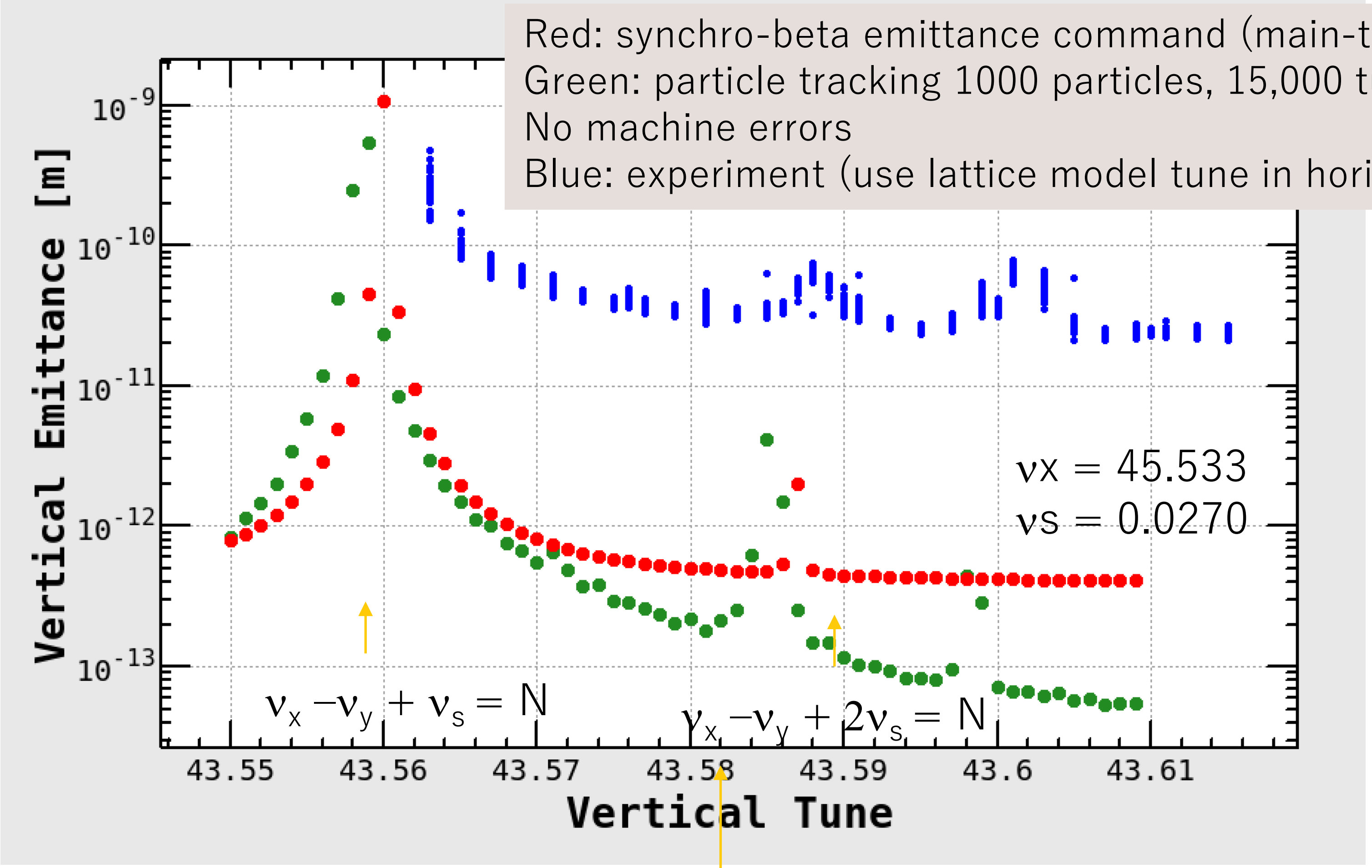
a11: 2.2454 b11: 11.0000 a12: 2.3862 b12: 11.0000 (34.4833 sec)
a21: 2.6833 b21: 9.0000 a22: 2.4054 b22: 9.0000 (29.1834 sec)

At the design stage, crab waist scheme was thought to be unusable due to dynamic aperture decrese.

H. Koiso

Synchro-beta emittance (HER)

$\beta y^* = 1\text{mm}$



Red: synchro-beta emittance command (main-trunk)
Green: particle tracking 1000 particles, 15,000 turns Rad, Fluc:ON
No machine errors
Blue: experiment (use lattice model tune in horizontal axis)

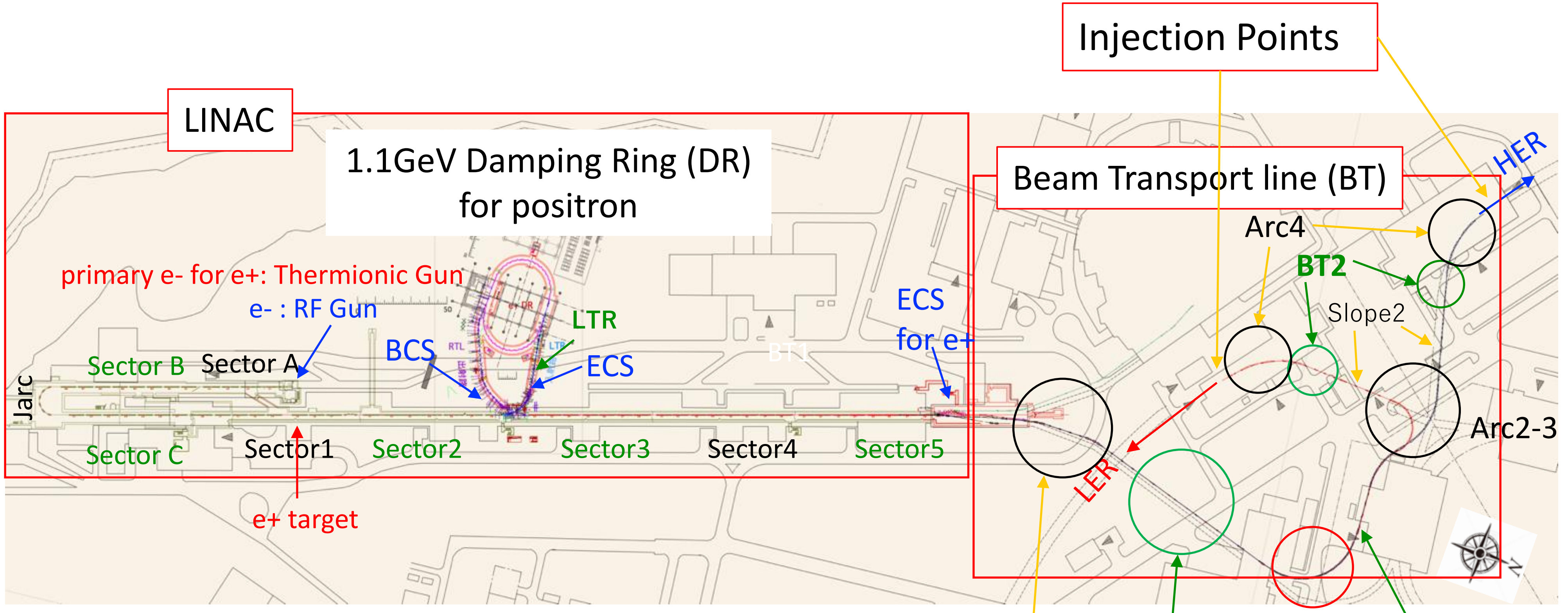
Oct. 2021

Present working point

Layout of LINAC, BT, Injection to MR

e+ beam is injected into the LER via DR:
The injection BG is not almost affected by the beam condition at upstream of the DR.

e- beam directly injects into HER:
The injeciton BG is directly affected by the condition of RF-gun, LINAC, and BT.

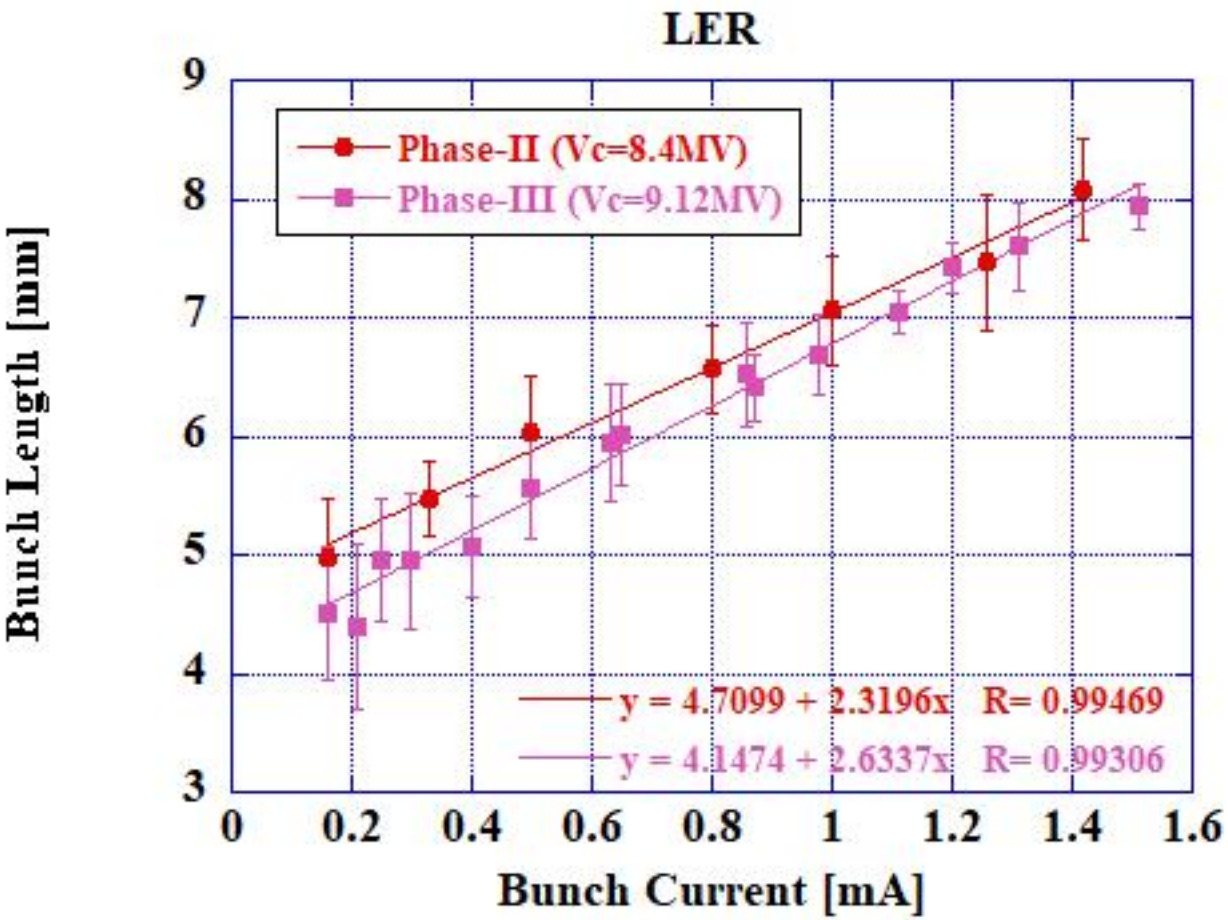


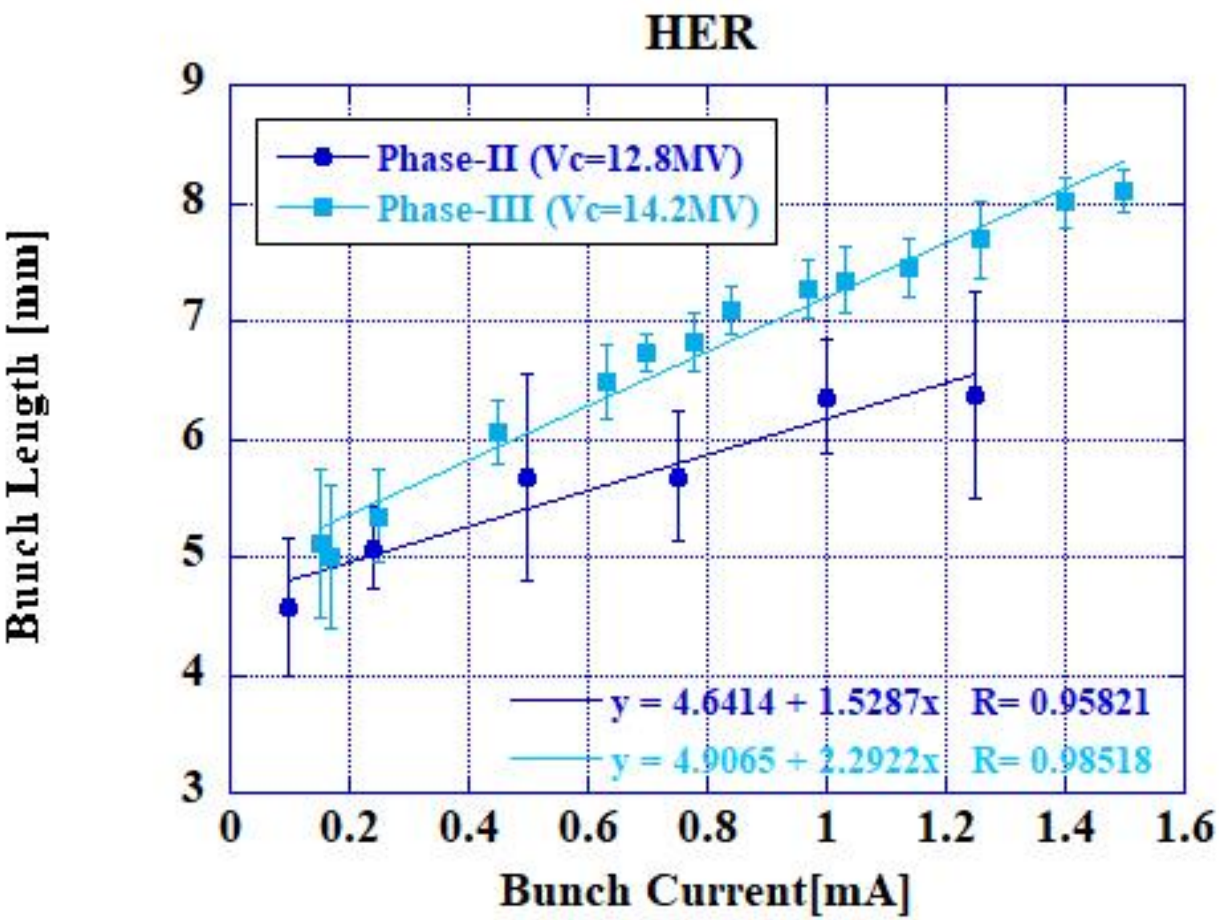
BT1 and BT2: Wire scanners(WSs), MSE.10:OTR

BCS: Bunch Compression System (for e+)

ECS: Energy Compression System (for e+)

Bunch length (measurement by streak camera)





Definition of R matrix

$$T^{-1} = \begin{pmatrix} \mu I & -SR^T S \\ -R & \mu I \end{pmatrix}$$

1. Definition in the SAD code

$$\begin{pmatrix} u \\ p_u \\ v \\ p_v \end{pmatrix} = T \begin{pmatrix} x \\ p_x \\ y \\ p_y \end{pmatrix}$$

$$T(s) = \begin{pmatrix} \mu I & SR^t S \\ \boxed{R} & \mu I \end{pmatrix} = \begin{pmatrix} \mu & 0 & -R4 & R2 \\ 0 & \mu & R3 & -R1 \\ R1 & R2 & \mu & 0 \\ R3 & R4 & 0 & \mu \end{pmatrix}$$

Usual coordinate

R matrix

$$S = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

Normal (uncoupled) coordinate

$$\mu^2 + \det R = 1$$

Luminosity improvement [1/4] Crab waist

- Introduction of crab waist at SuperKEKB
  - Motivations
    - The beam-beam performance was poor in spite of all of knob tunings for improving it.
  - Method
    - FCC-ee type scheme: use of imbalance sextupoles in the vertical local chromaticity correction section.
  - Time table
    - 2020 March 16th : LER crab waist (40%)
    - 2020 March 24th : LER crab waist (60%)
    - 2020 April 24th : HER crab waist (40%)
    - 2030 June 1st : LER crab waist (80%)

Injection efficiency (simulation and experiments)

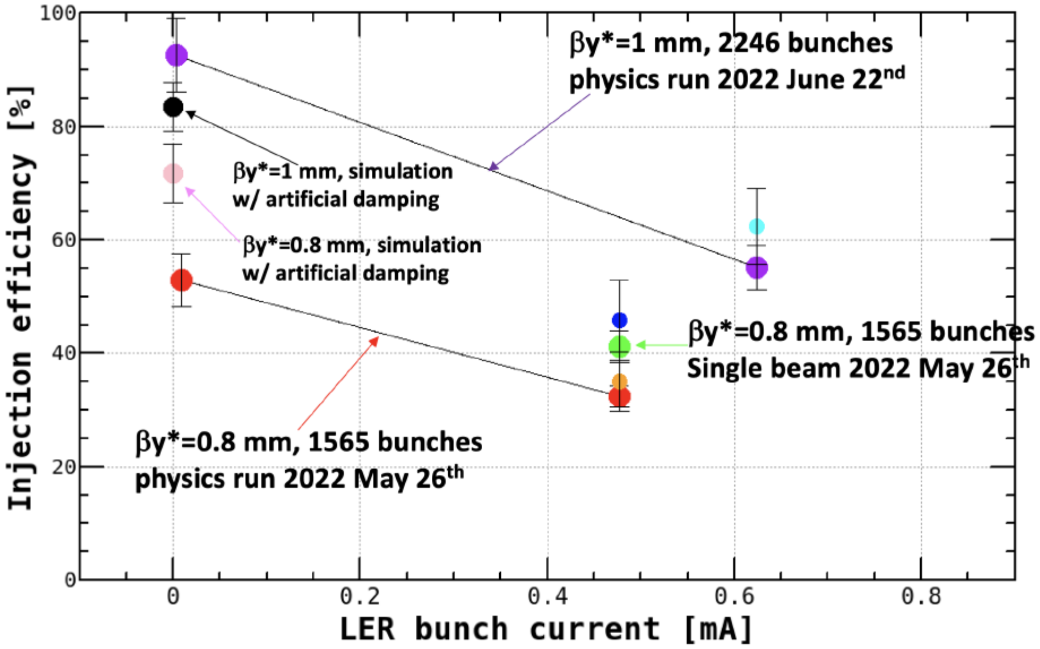


Figure 5. Injection efficiency as a function of the bunch current in LER. Both cases of β_y^* at 0.8 mm and 1 mm are shown. There is strong beam current dependence. Here, we plot the dependence as the bunch current dependence. The data in cyan, blue, and orange are obtained by the simulations. The data in back and pink are obtained by the simulation with artificial extra damping to the oscillation of the center-of-gravity of the injecting bunch with a damping time of 100 turns which is intended to simulate the effect of the bunch-by-bunch feedback system.

Beam Lifetime

Time	Ibeam[mA]	Ibunch [mA]	nb	Tau [min]	emity [pm]	emitx [nm]	sig_z [mm]
2021/12/20/8:56	227.3	0.5784	393	8.35	22.3	3.1	5.67
2021/12/20/10:01	225.1	0.1643	1370	21.8	21.1	2.9	4.58

- Lifetime model

$$\tau_{Touschek} = C_T \frac{n_b}{I_{beam}} \sqrt{\varepsilon_x \varepsilon_y} \sigma_z$$

$$\tau_{Vacuum} = C_V \frac{1}{I_{beam}}$$

$C_T = C_T$(physical aperture, dynamic aperture)

$C_V = C_V$(dP/dI, physical aperture, dynamic aperture)

$\xcancel{\frac{\tau_{Touschek}}{\tau_{Vacuum}}} \propto n_b$

$$\frac{1}{\tau_{Total}} = \frac{1}{\tau_{Touschek}} + \frac{1}{\tau_{Vacuum}}$$

$C_T = 1.973*10^{11}$ [sec A /m^3]

$C_V = 7622$ [sec A]

- Result of analysis

Time	Ibeam [mA]	nb	Tau [min]	sig_z [mm]	Touschek [min.]	Vacuum [min.]	sig_z [mm]	Touschek [min.]	Vacuum [min.]
2021/12/20/ 8:56	227.3	393	8.35	5.67	8.48	558.9	4.58	9.46	70.9
2021/12/20/ 10:01	225.1	1370	21.8	4.58	22.7	564.3	4.58	31.3	71.6