Luminosity Tuning at SuperKEKB

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On Behalf of SuperKEKB commissioning group

KEK Unravelling the mysteries of matter, life and the universe.

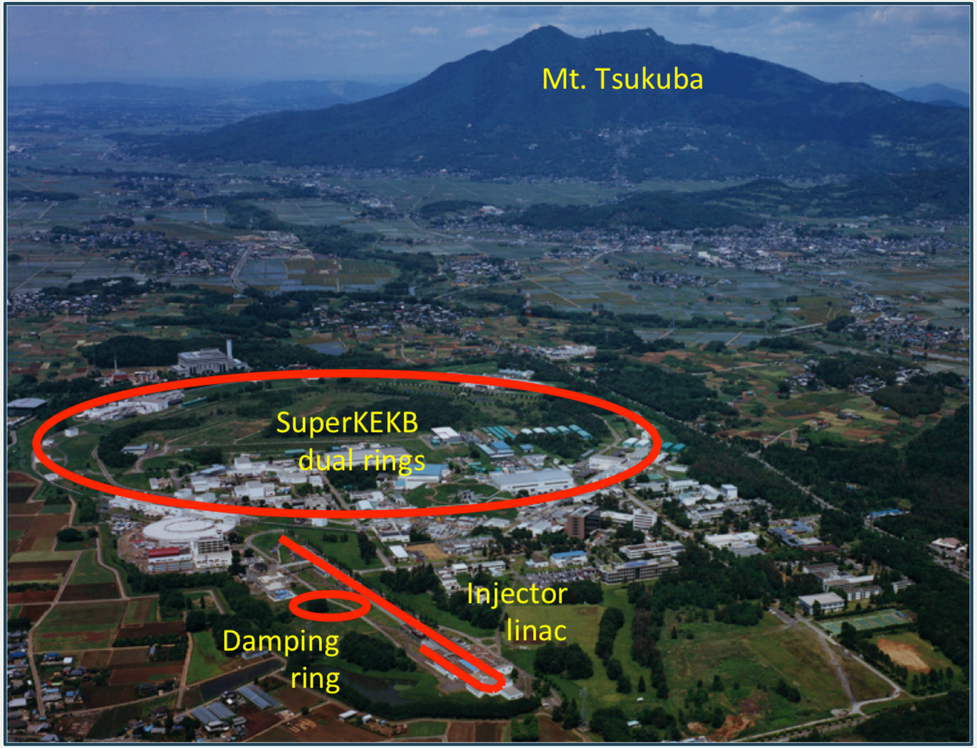
The 2021 International Workshop on CEPC
Nov 8th-12th, 2021

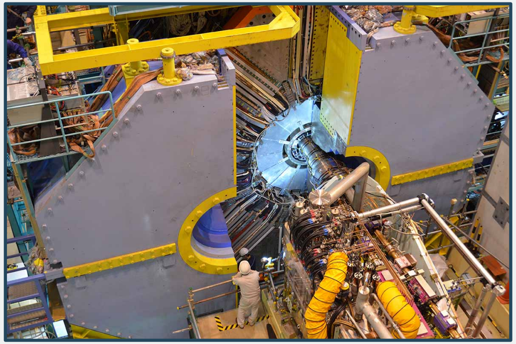
Contents

- **Brief Introduction and Overview of Operation**
- **Luminosity Tuning**

SuperKEKB Accelerator

- Electron(7GeV) – positron(4GeV) double-ring collider
- Successor project of KEKB B factory

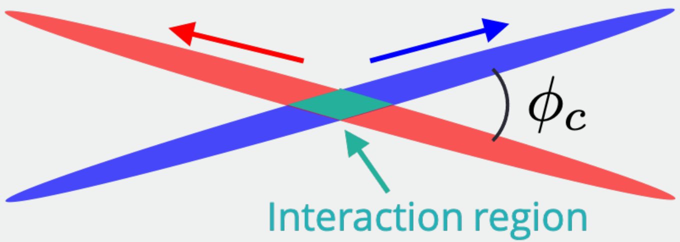




Collision Scheme - Nano Beam Scheme -

- Collision with a large crossing angle in the horizontal plane.
- Realize narrow overlap region to realize small by* while avoiding hourglass effect.
- It is equivalent to head-on collision with small bunch length

Top view



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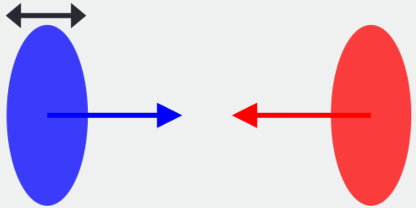
Seeing from a different coordinate system

$$\sigma_z^{\text{effective}} = \sigma_x^* / \sin(\phi_c/2)$$



$$\phi_c = 83 \text{ mrad}$$
$$\sigma_x^* = 10 \ \mu\text{m} \longrightarrow \sigma_z^{\text{effective}} = 0.24 \text{ mm}$$
$$\sigma_z = 6 \text{ mm}$$

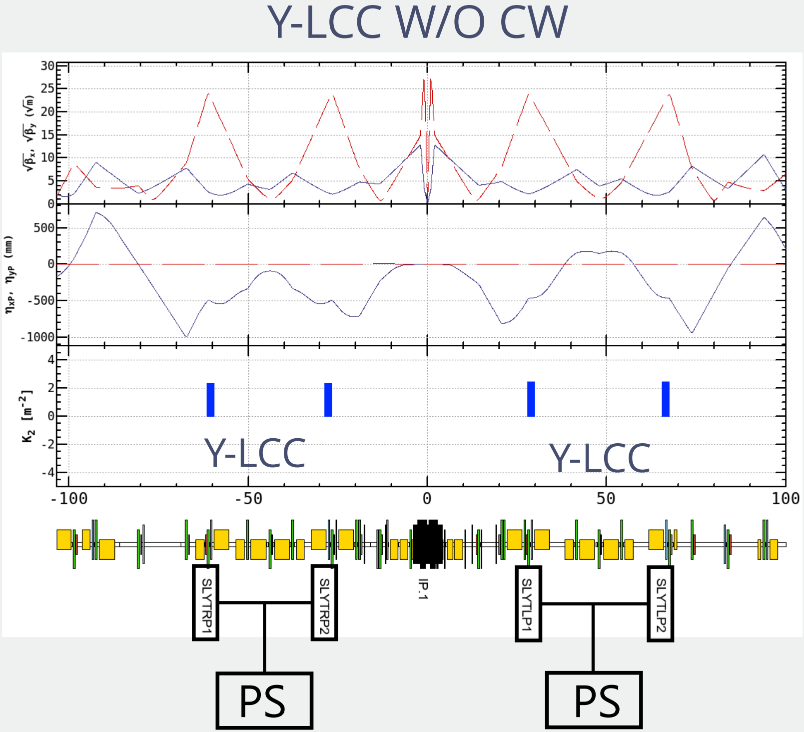
Ort target is

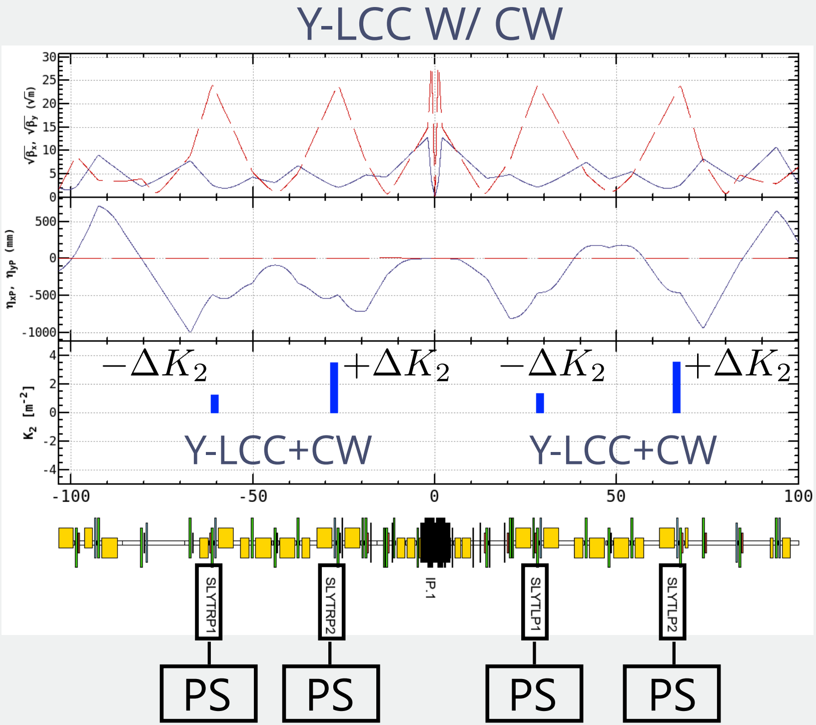
$$\beta_y^* = 0.3 \text{ mm}$$

Crab Waist Scheme with FCC-ee Style

Oide, K., et al., 2016, Phys. Rev. Accel. Beams 19, 111005.

- Vertical local chromaticity correction (Y-LCC) consists of 2 pairs of sextupole magnets.
- Crab waist scheme introduced by applying different strength of sextupole field to these magnets.



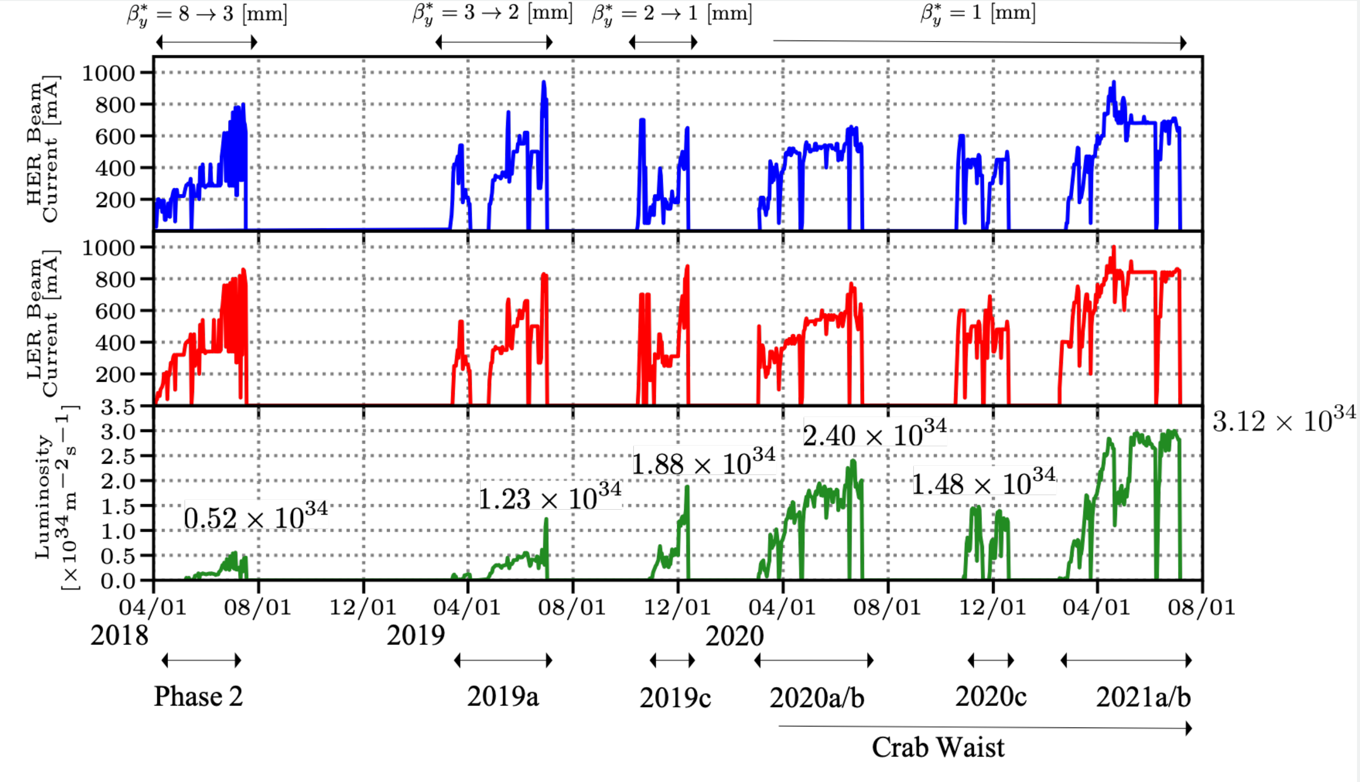


Operation Summary

Peak luminosity $L = 3.12 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

HER
= Electron ring

LER
= Positron ring



Machine Parameters

Y. Ohnishi

	2020b : June 21, 2020		2021b : June 22, 2021		Unit
Ring	LER	HER	LER	HER	
Emittance	4.0	4.6	4.0	4.6	nm
Beam Current	712	607	790	687	mA
Number of bunches	978		1174		
Bunch current	0.728	0.621	0.673	0.585	mA
Lifetime	760	1270	540	1320	sec
Horizontal size σ_x*	17.9	16.6	17.9	16.6	μm
Vertical cap sigma Σ_y*	0.403		0.324		μm*1
Vertical size σ_y*	0.285		0.229		μm*2
Betatron tunes ν_x / ν_y	45.523 / 43.581	44.531 / 41.577	44.524 / 46.596	45.532 / 43.581	
β_x* / β_y*	80 / 1.0	60 / 1.0	80 / 1.0	60 / 1.0	mm
Piwinski angle	10.7	12.7	10.7	12.7	
Crab Waist Ratio	80	40	80	40	%
Beam-Beam parameter ξ_y	0.039	0.026	0.046	0.030	
Specific luminosity	5.43×10^{31}		6.76×10^{31}		$cm^{-2}s^{-1}/mA^2$
Luminosity	2.40×10^{34}		3.12×10^{34}		$cm^{-2}s^{-1}$

*1) estimated by luminosity with assuming design bunch length
*2) divide *1 by √2

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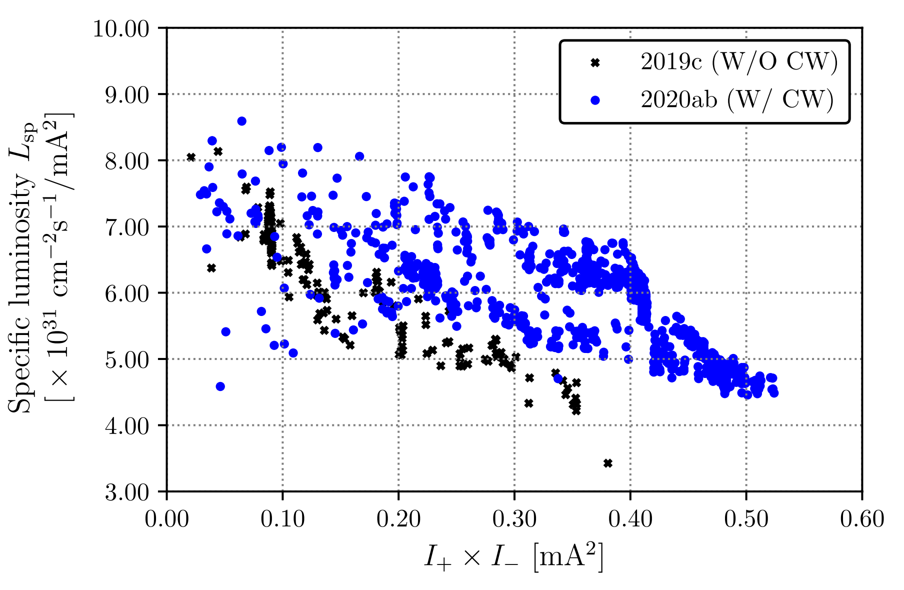
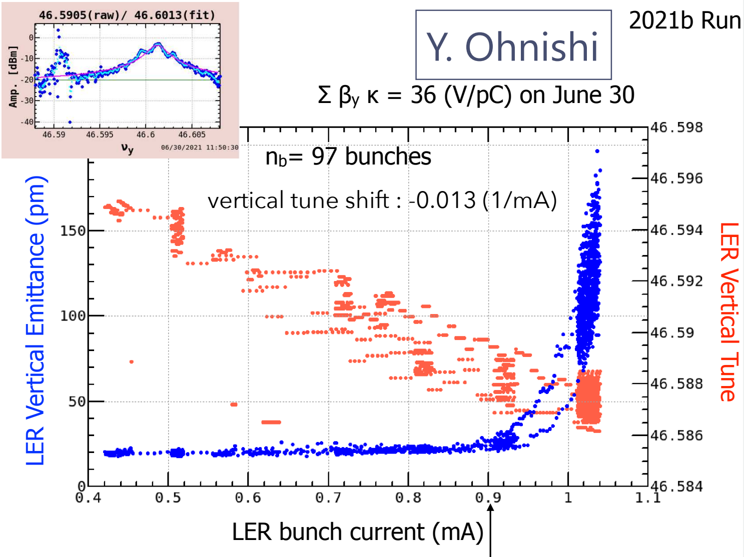
Specific Luminosity and Bunch Current

- CW enables collision operation at high-bunch-current region.
- CW also reduces beam background as predicted by numerical simulations.
- Currently, bunch intensity in LER is limited by transverse-mode-coupling instability (TMCI) due to impedance of narrow beam collimators.





$$I_{th} = \frac{2\pi f_s (E/e)}{\sum_i \beta_{yi}\kappa_i}$$ = 1.6 mA > 0.9 mA (measured)

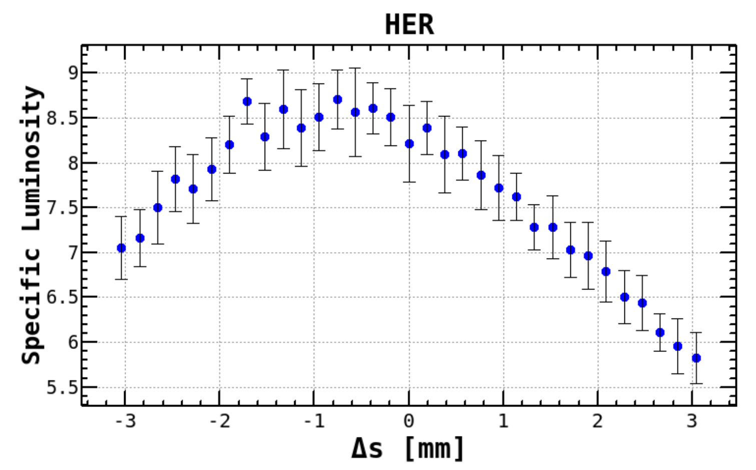
The measured threshold is much lower than expected.

Luminosity Tuning

Overview

- Many trials were performed to improve machine performance.
  - Vertical offset at IP
  - Vertical crossing angle
  - Waist position
  - Betarton-coupling at IP
  - Chromatic Betarton-coupling at IP
  - Vertical dispersion at IP
  - Bunch by bunch feedback
  - Betatron tunes
  - Collimator aperture
  - etc.

Example: Luminosity scan with vertical waist position

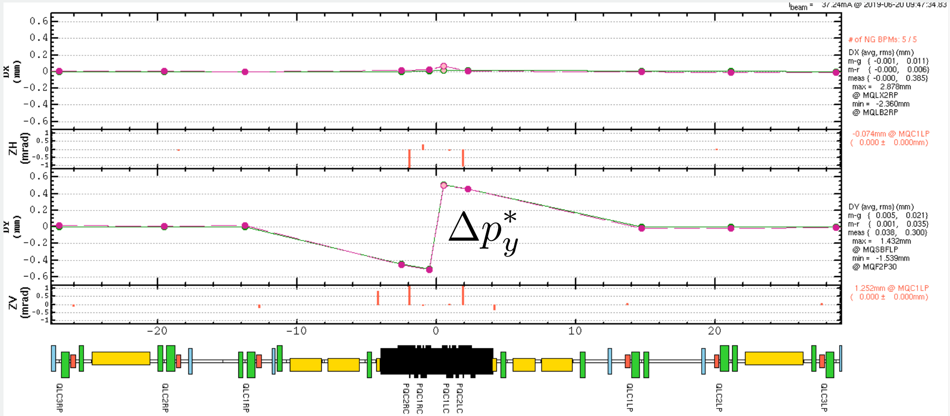


- Some of them are routinely changed to keep the performance during physics run.
- Some important parameters is shown in the following slides.

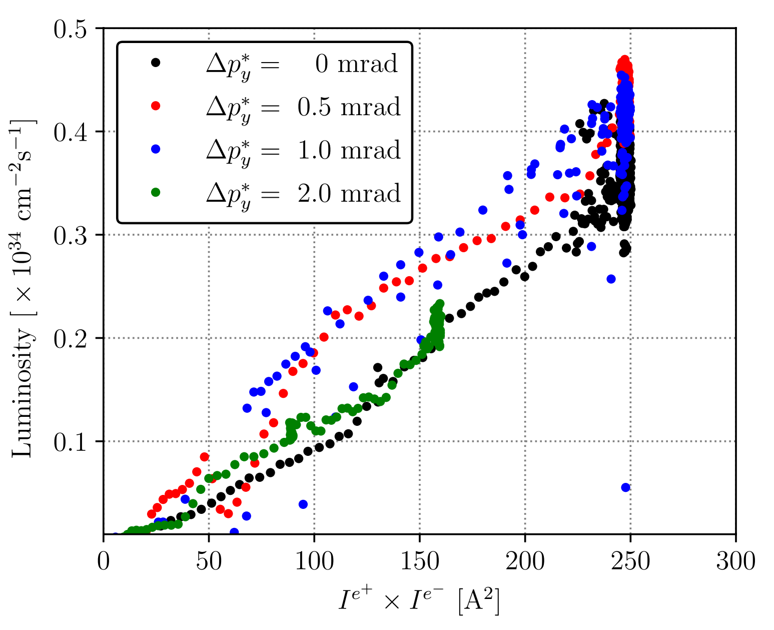
Vertical Crossing Angle

- Importance of vertical angle was recognized June 20, 2019. (by*=3mm)
- We applied vertical orbit bump to control vertical crossing angle at IP in LER.
- After the optimization specific luminosity was improved by ~20%.
- It also reduces beam background.

Vertical orbit bump at IP in LER



IP



Vertical Beam Size at IP

$$\sigma_y^{*2} = \mu^2 \varepsilon_y \left(\beta_y^* + \Delta s^2/\beta_y\right) + \left(\eta_y^* \sigma_\delta\right)^2 + \varepsilon_x \left(R_2^* + R_4^* \Delta s\right)^2 / \beta_x^* + \varepsilon_x \beta_x^* \left(R_1^* + R_3^* \Delta s\right)^2$$

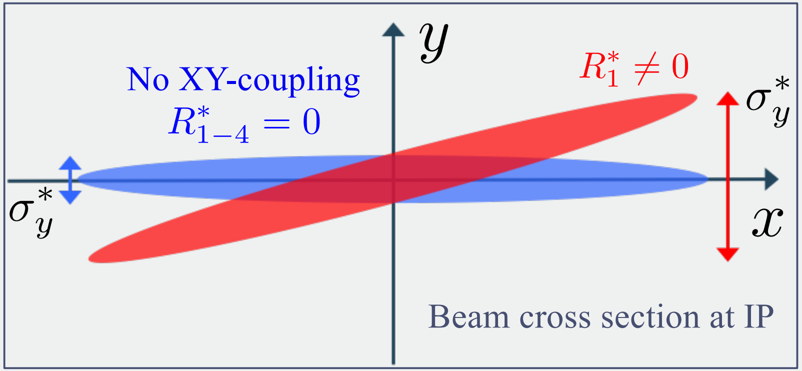
- $R_{1\text{-}4}$ parameters characterize Betatron(XY)-coupling as,

Decoupled coordinate Coupled coordinate

$$\begin{pmatrix} X \\ P_X \\ Y \\ P_Y \end{pmatrix} = \begin{pmatrix} \mu & 0 & -R_4 & R_2 \\ 0 & \mu & R_3 & -R_1 \\ R_1 & R_2 & \mu & 0 \\ R_3 & R_4 & 0 & \mu \end{pmatrix} \left\{ \begin{pmatrix} x \\ p_x \\ y \\ p_y \end{pmatrix} + \begin{pmatrix} \eta_x \\ \eta_{p_x} \\ \eta_y \\ \eta_{p_y} \end{pmatrix} \delta \right\}$$

Dispersion

$$\mu^2 \equiv 1 + R_2 R_3 - R_1 R_4$$



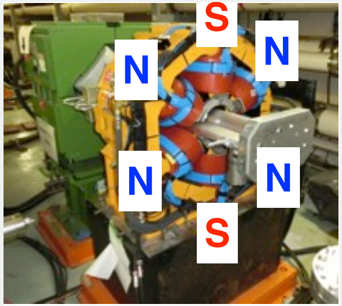
- Δs represents vertical waist shift.

- Exact values of $R_{1\text{-}4}$ and Δs can not be well determined by beam measurement.

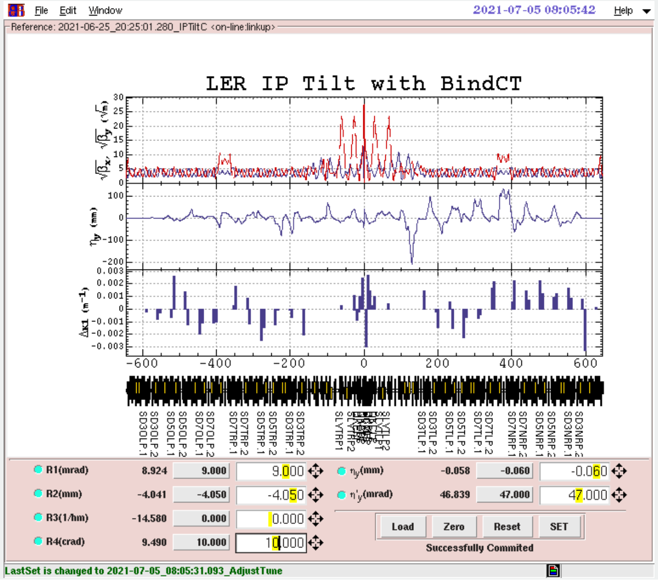
- Tuning of these parameters mainly relies on luminosity or beam size monitors.

Luminosity Scan with XY-Coupling Knobs

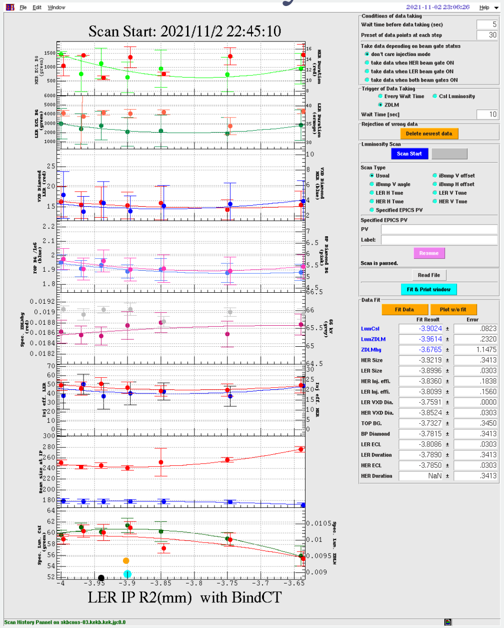
- $R_{1\text{-}4}$ parameters and vertical dispersion are controlled by skew quadrupole coils of sextupole magnets.
- These parameters are routinely adjusted by observing machine performance.



Knob Setting Panel

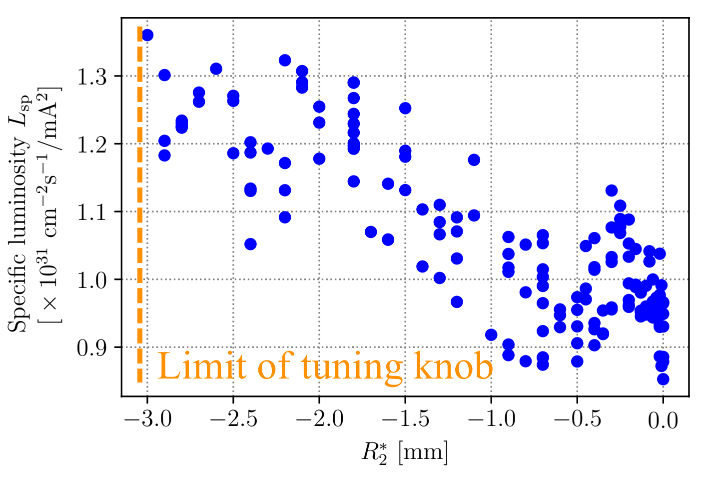


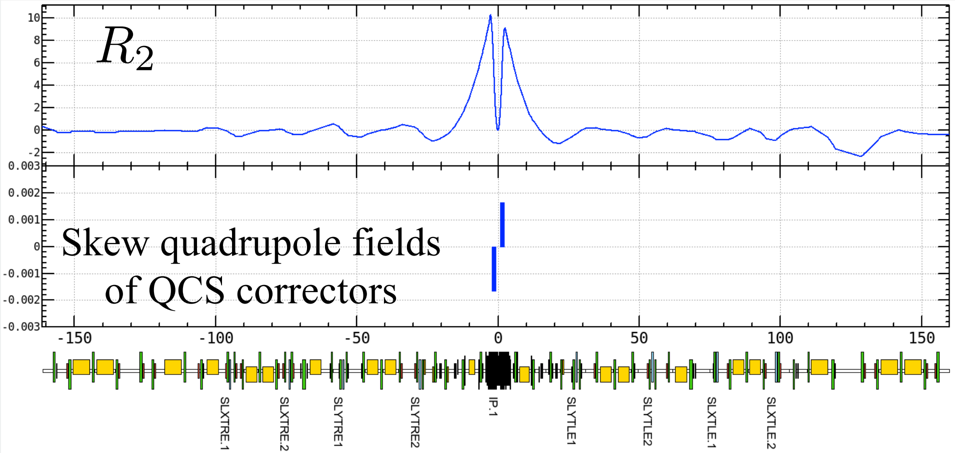
Scan History Panel



XY-coupling Correction with QCS Skew Quadrupole Coils

- In the early stage of luminosity tuning, the R_2 knob hits hardware limit of the correctors.
- We suspected that there is large XY-coupling error localized in the vicinity of IP.
- Global optics correction can not seem to detect this localized error.
- We changed R_2 at IP with skew quadrupole correctors of final focusing quadrupoles (QCS).
- Asymmetrical excitation of left- and right- sides of QCS correctors is applied so that degradation of global optics can be correctable by global optics correction.

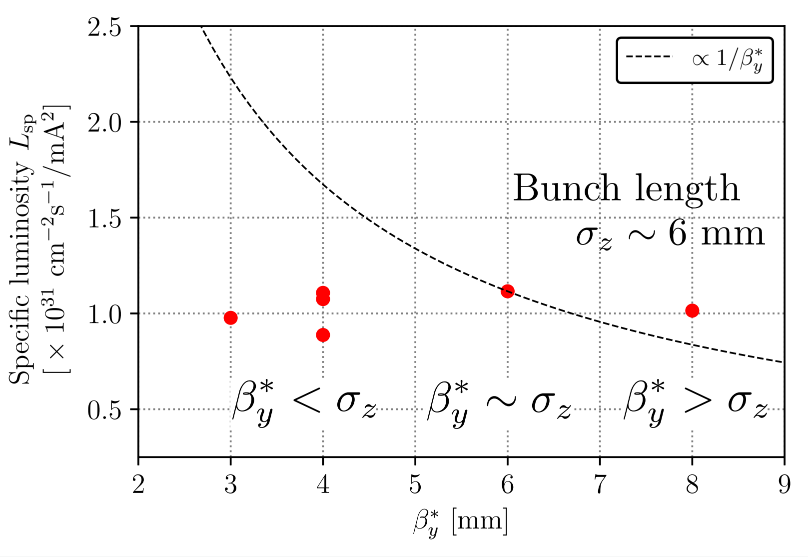




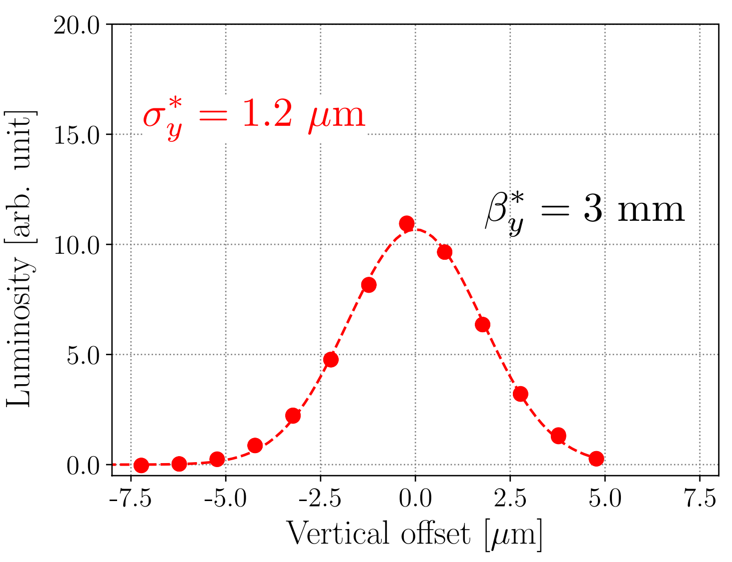
XY-coupling Correction and Beta-Squeezing

- Before XY-coupling correction at IP, specific luminosity was not improved by beta-squeezing.
- Specific luminosity is basically inversely proportional to by* if nano-beam scheme can truly avoids the hourglass effect.

Specific luminosity and by*



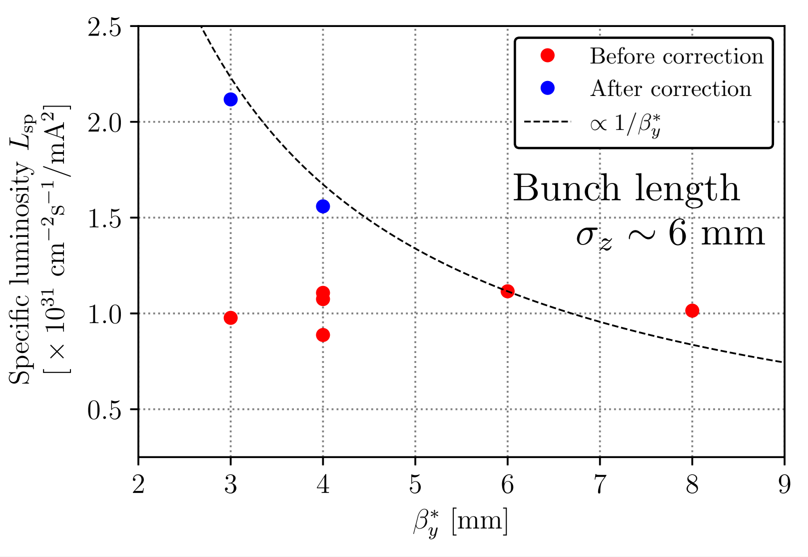
Vertical beam size obtained with vertical offset scan



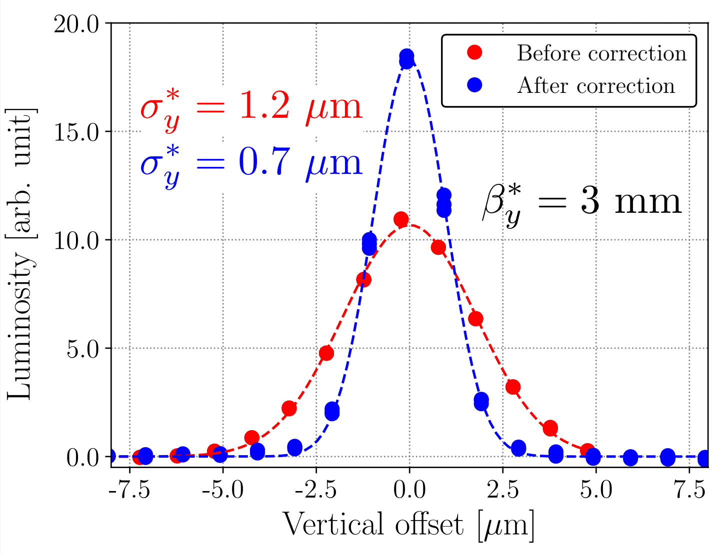
XY-coupling Correction and Beta-Squeezing

- Specific luminosity was improved and inversely proportional to by* after correction of localized error in the interaction region (IR) such as a waist shift, local XY coupling at the IP and so on.

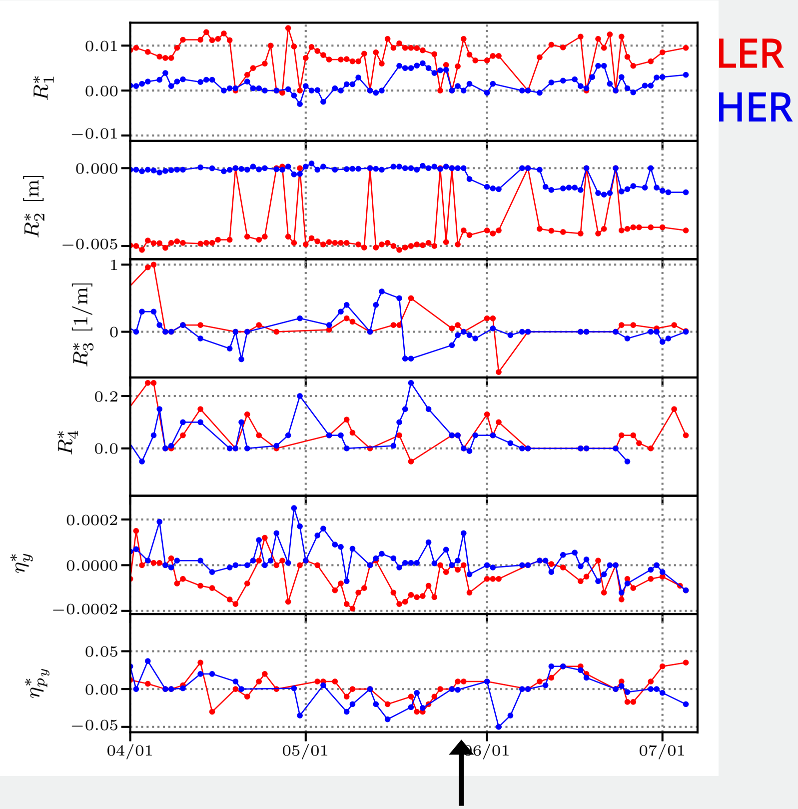
Specific luminosity and by*



Vertical beam size obtained with vertical offset scan



History of Knob Values



QCS corrector strength was changed.

- R_1 and R_2 are effective to luminosity performance.

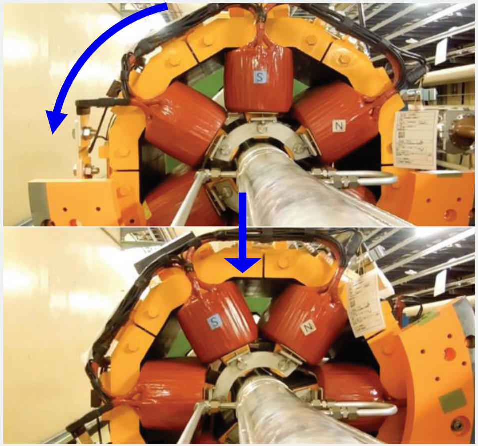
- Vertical dispersion is also effective for beam size control.

- The optimum R_1 and R_2 values are almost constant if QCS skew quadrupole correctors are fixed.

- R_3 and R_4 are not so effective to luminosity performance, but these parameters affect beam background.

Chromatic XY-Coupling Correction (Ch-XYCC)

- Numerical simulations indicate Ch-XYCC will effectively suppress beam blow up.
- We tried Ch-XYCC in two different ways,
  (a) Rotatable sextupole magnets (We can change their angles remotely)
  (b) Adjusting skew quadrpole coils of sextupole magnets during luminosity run.
- Effect on luminosity performance is still not clear.



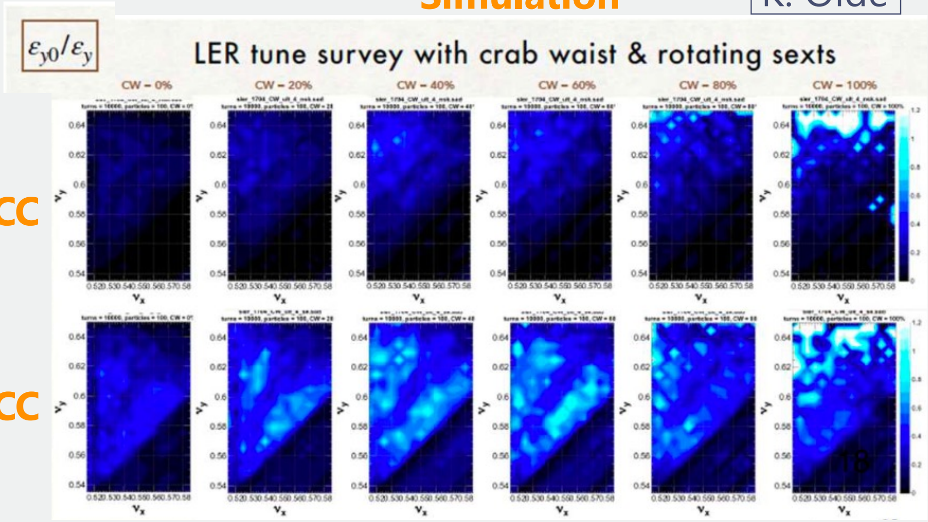
M. Masuzawa

Simulation

K. Oide

W/O Ch-XYCC

W/ Ch-XYCC



Difficulty in Further Tuning

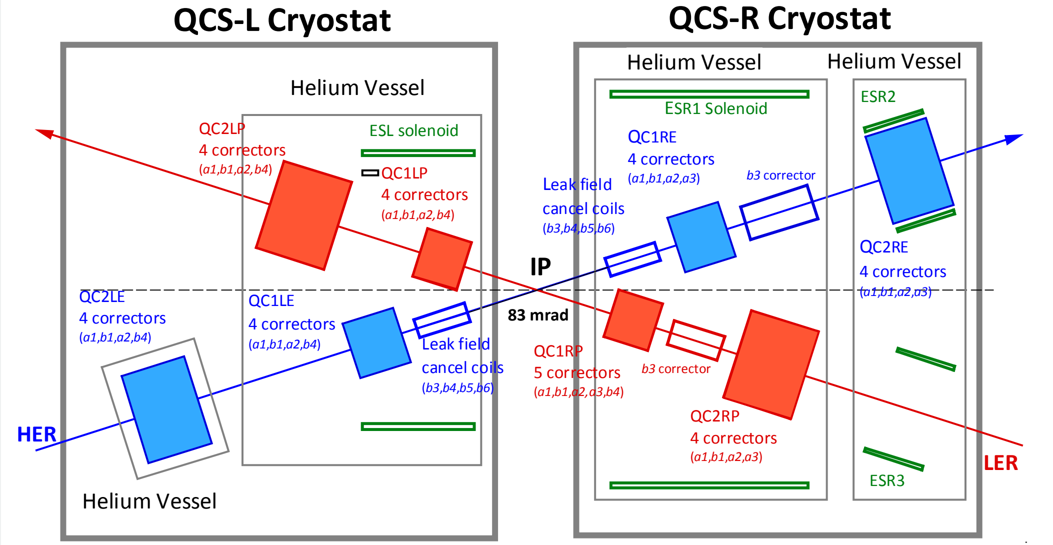
- Improvement from linear orbital and optical parameters looks saturated.
  (Or we may be trapped by local maximum?)

- IR has many tuning knobs for non-linear parameters, but its generally affects linear parameters and we do not have a clear path for the optimization.

- Changing theses parameters evolves additional machine tuning and reduces integrated luminosity.

- Even keeping the present machine performance is not so easy.

- The stability and reproducibility is a practically urgent issue.



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

N Ohuchi

Summary

- Owing to trial and error on many machine tuning, SuperKEKB shows that luminosity can be improved by beta-squeezing while avoiding hour-glass effect .

- The highest peak luminosity so far is 3.12×10^{34} $cm^{-2}s^{-1}$ (June 2021).

- Effect of linear orbital and optical parameters on luminosity was well studied through the past machine tuning.

- Beam-beam parameters is about 0.03, which is much smaller than expected.

- The stability and reproducibility is a practically urgent issue.

Thank you for your kind attention.