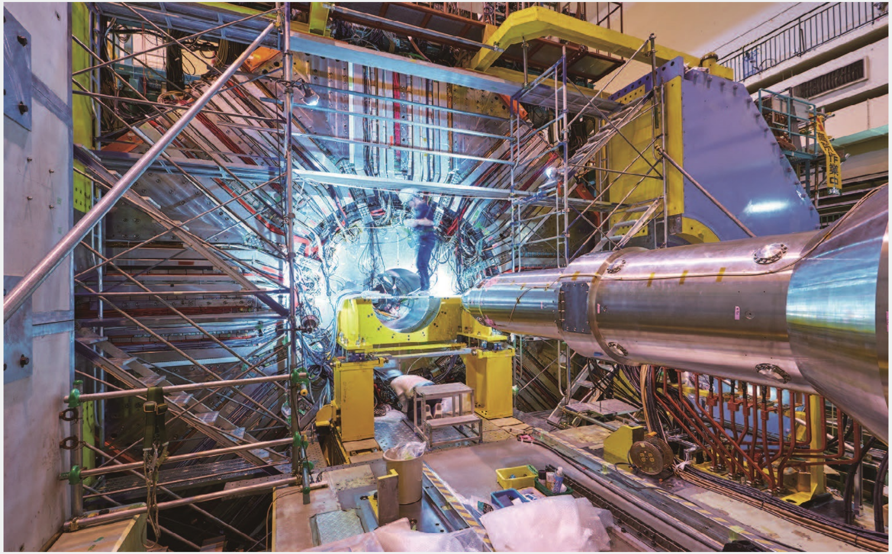
SuperKEKB Accelerator

- Status and Lessons -



Hiroshi Sugimoto

On Behalf of SuperKEKB commissioning group

Super KEKB

Belle II

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

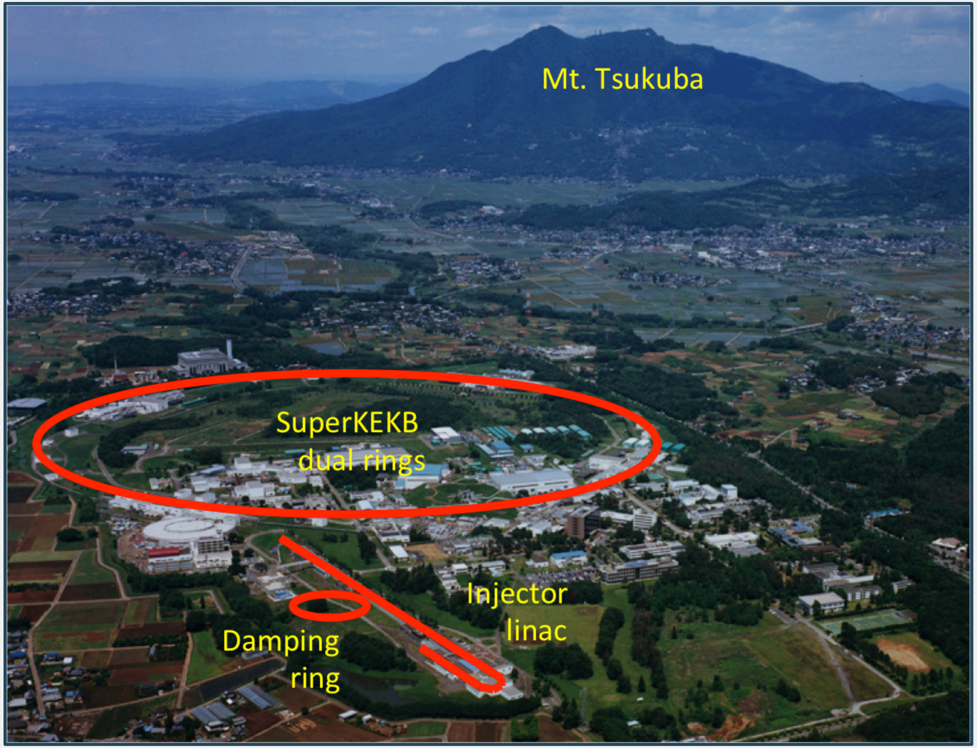
Workshop on future Super c-tau factories 2021
Nov 15th-17th, 2021

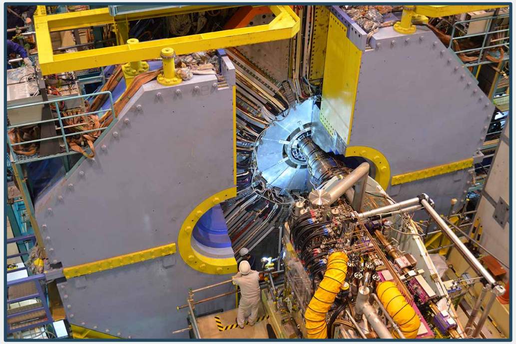
Contents

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

SuperKEKB Accelerator

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

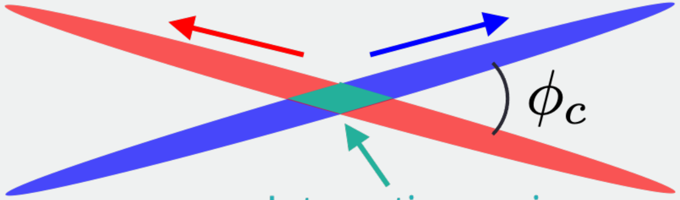




Collision Scheme - Nano Beam Scheme -

- 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

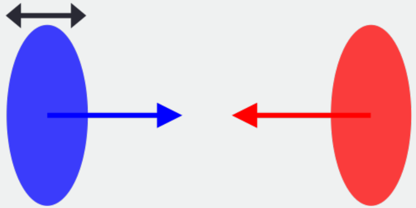
Top view



$=$

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

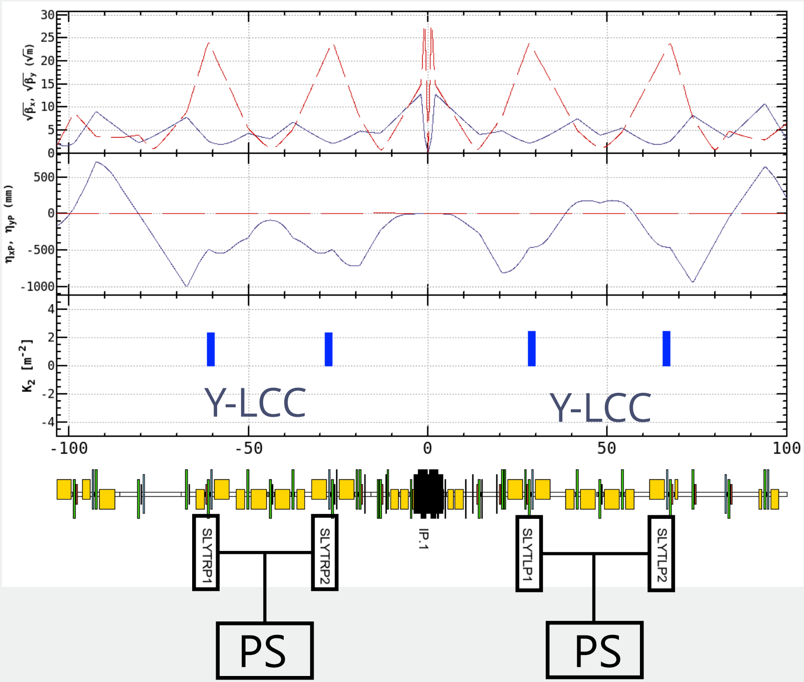
$$\beta_y^* = 0.3 \text{ mm}$$

Crab Waist Scheme with FCC-ee Style

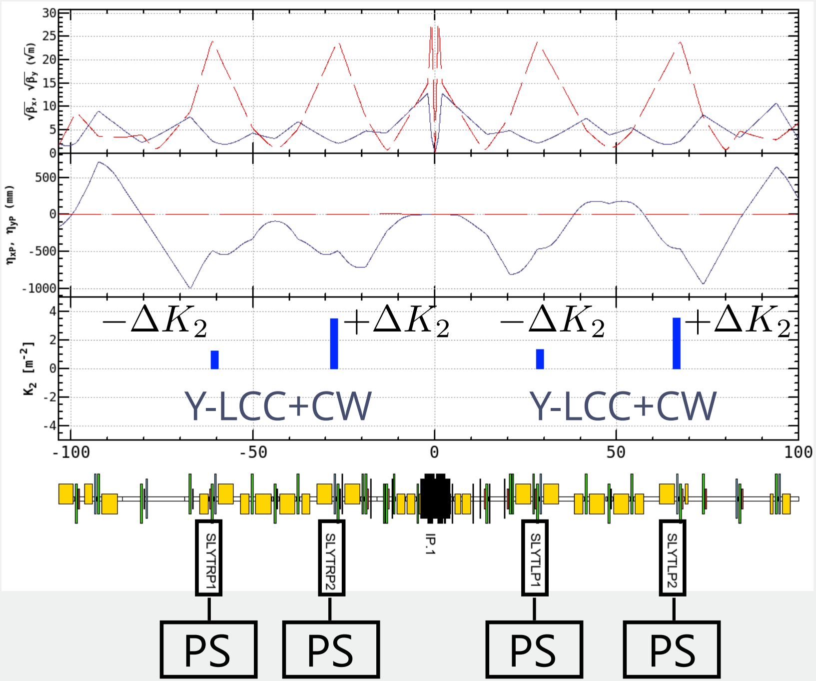
Oide, K., et al., 2016,
Phys. Rev. Accel. Beams 19, 111005.

- 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.

Y-LCC W/O CW



Y-LCC W/ CW

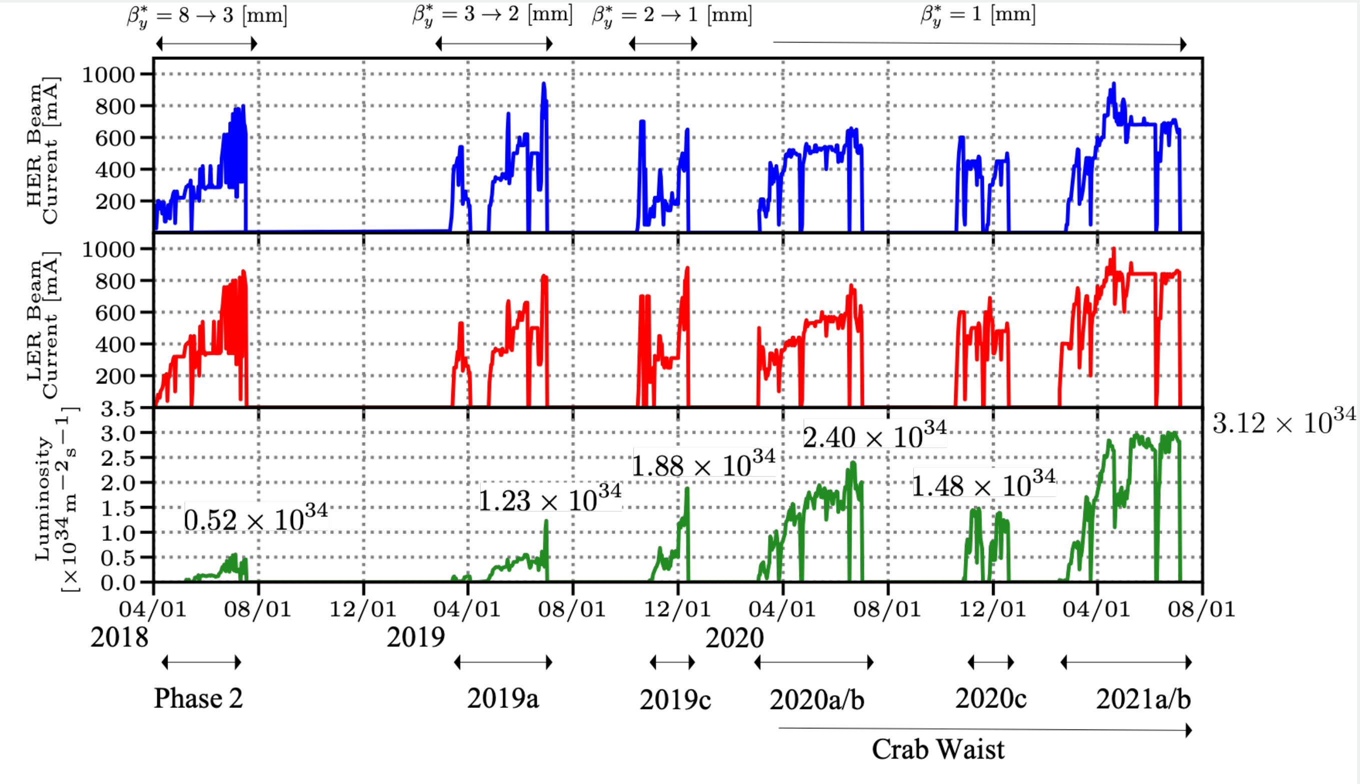


Operation Summary

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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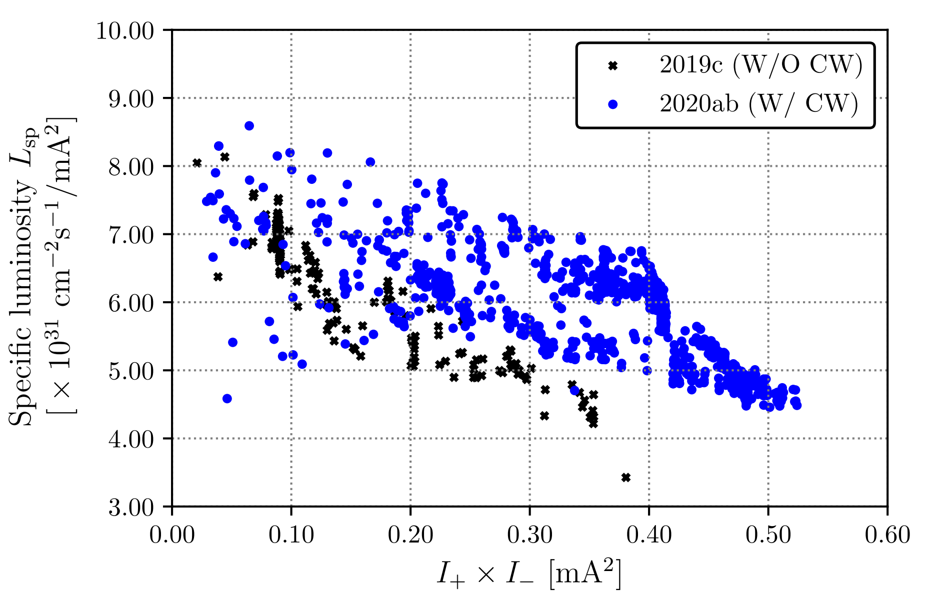
Specific Luminosity and Bunch Current

- CW enables collision operation at high-bunch-current region.
- Currently, bunch intensity in LER is limited by transverse-mode-coupling instability (TMCI) due to impedance of narrow beam collimators.
- We are now trying to increase luminosity by increasing number of bunches

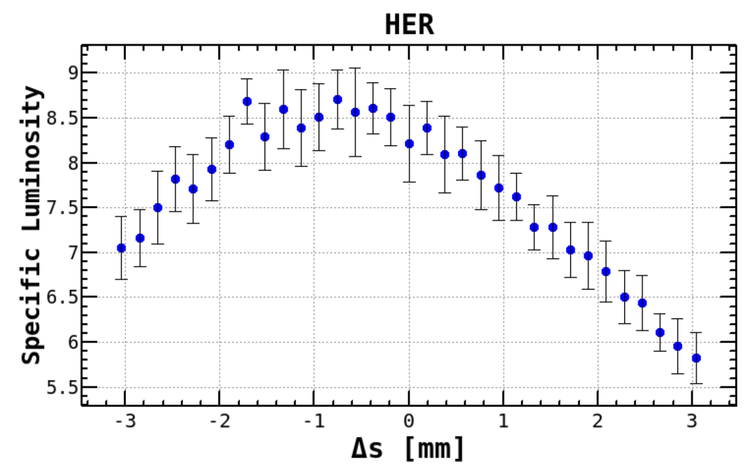


Luminosity Tuning

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

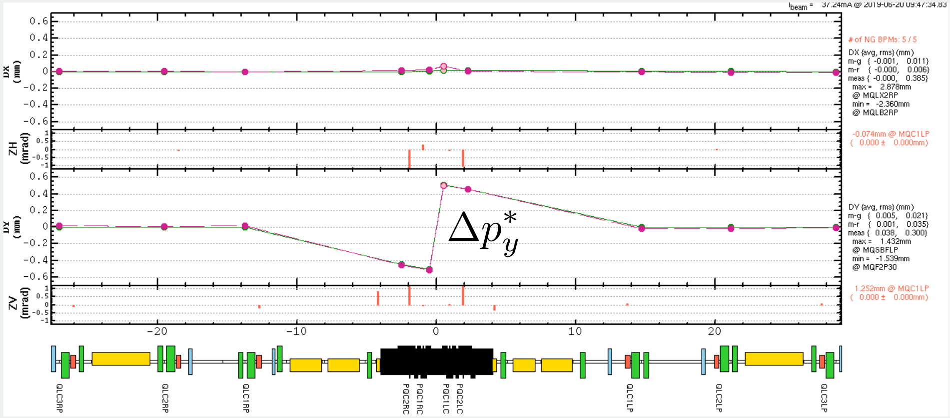


- Some of them are routinely changed to keep the performance during physics run.
- Some important parameters is shown in the following slides.

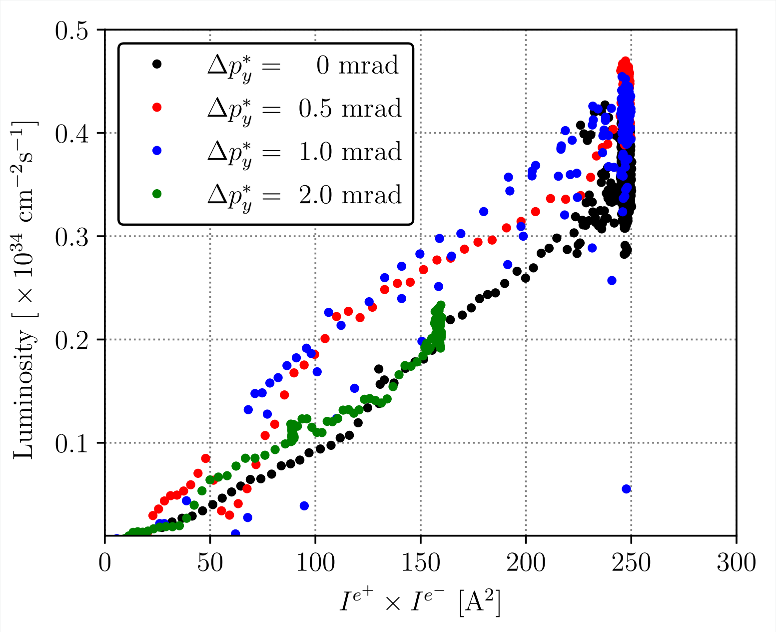
Vertical Crossing Angle

- 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

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

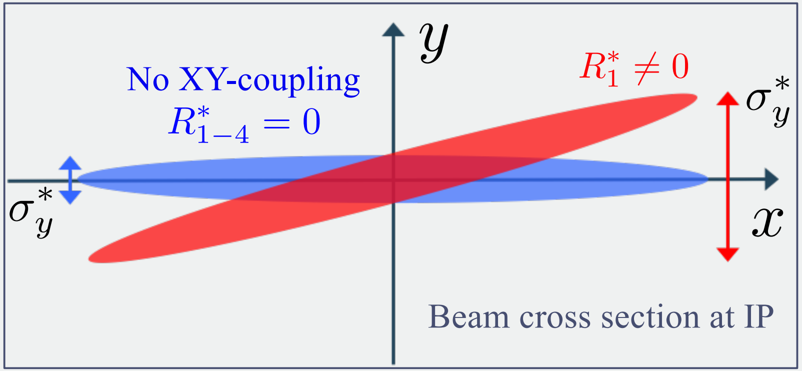
- $R_{1\text{-}4}$ parameters characterize Betatron(XY)-coupling as,

Decoupled coordinate   Coupled coordinate

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

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

Dispersion



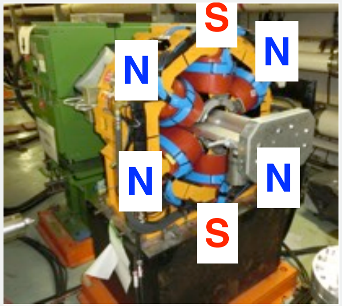
- Δs represents vertical waist shift.

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

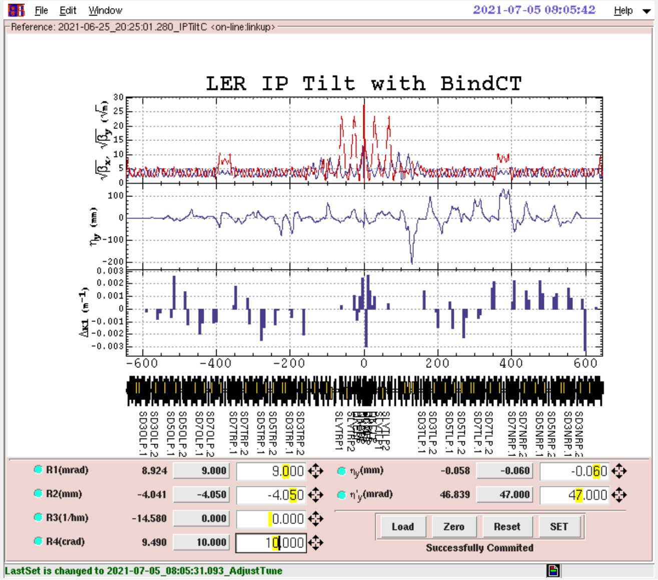
- Tuning of these parameters mainly relies on luminosity or beam size monitors.

Luminosity Scan with XY-Coupling Knobs

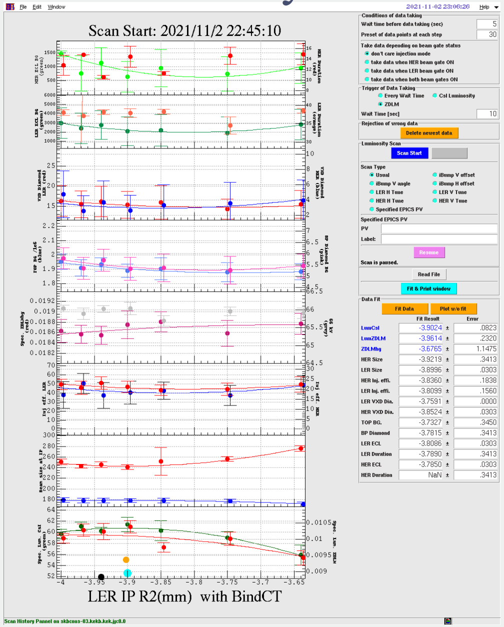
- $R_{1\text{-}4}$ parameters and vertical dispersion are controlled by skew quadrupole coils of sextupole magnets.
- These parameters are routinely adjusted by observing machine performance.



Knob Setting Panel

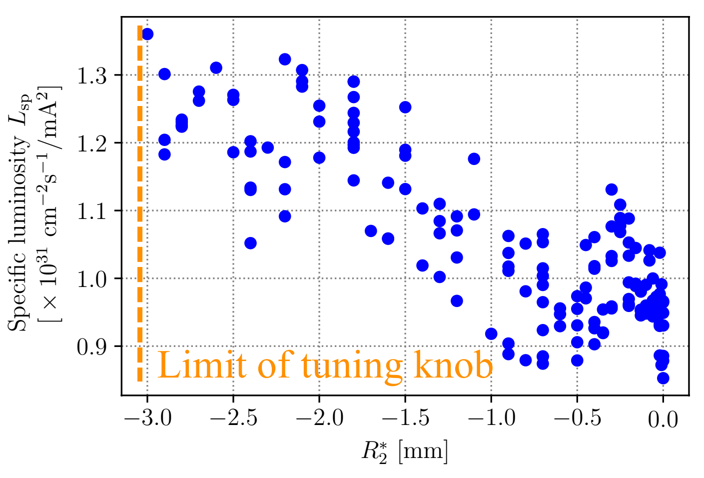


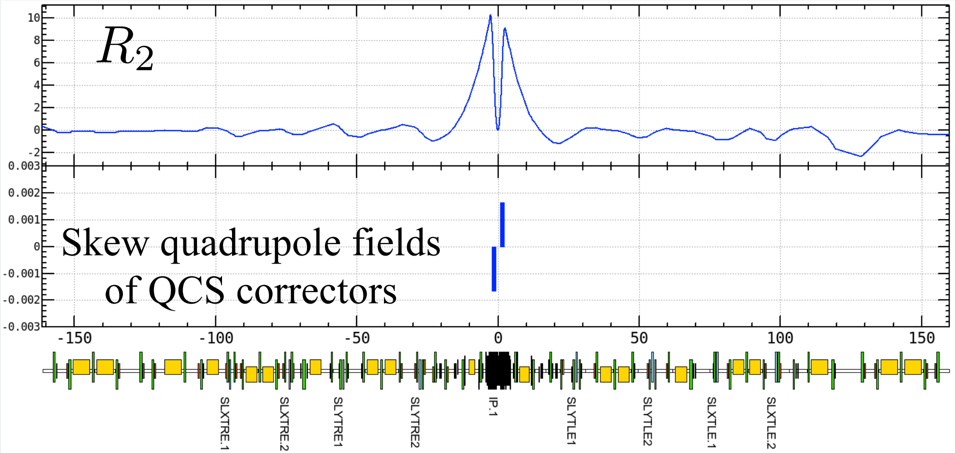
Scan History Panel



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.

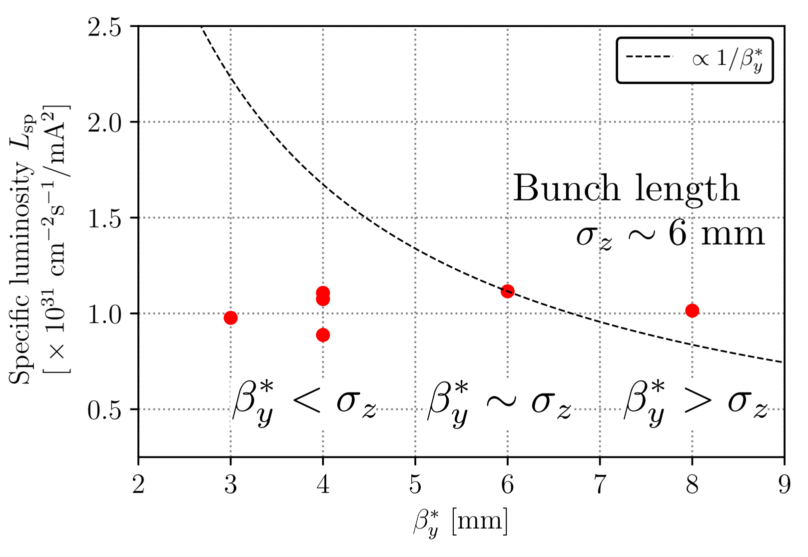




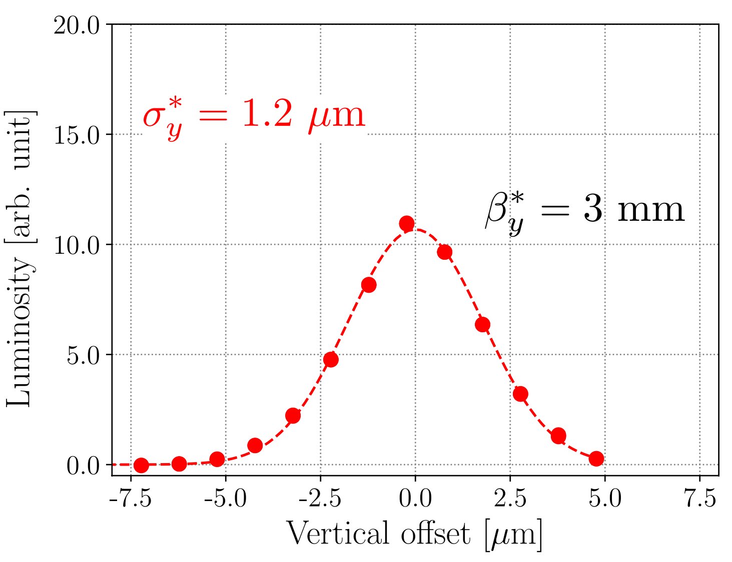
XY-coupling Correction and Beta-Squeezing

- 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*



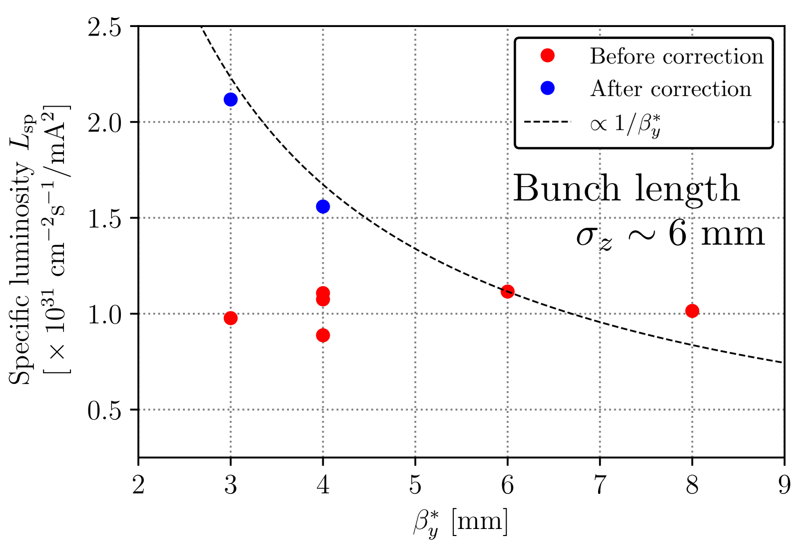
Vertical beam size obtained with vertical offset scan



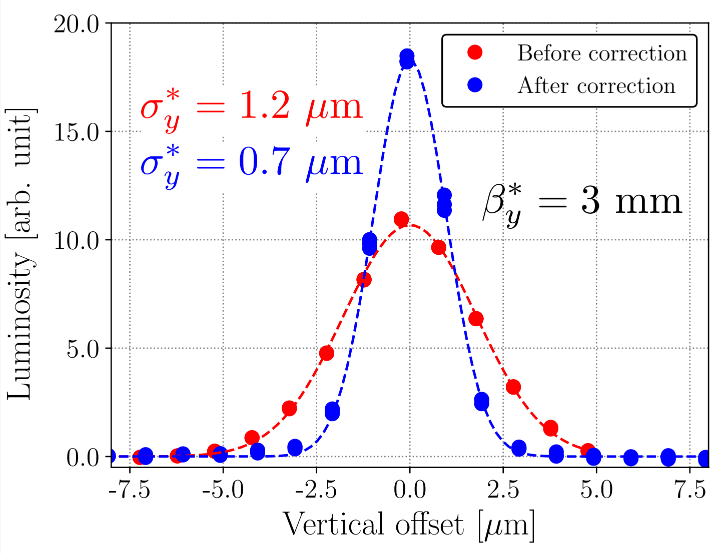
XY-coupling Correction and Beta-Squeezing

- 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.

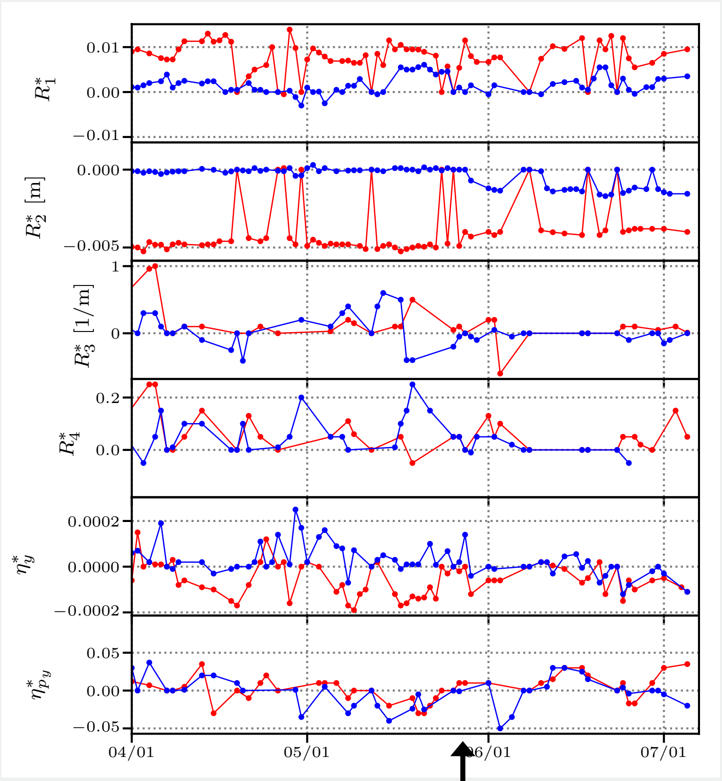
Specific luminosity and by* with low bunch current



Vertical beam size obtained with vertical offset scan



History of Knob Values



LER

HER

QCS corrector strength was changed.

- R_1 and R_2 are effective to luminosity performance.

- Vertical dispersion is also effective for beam size control.

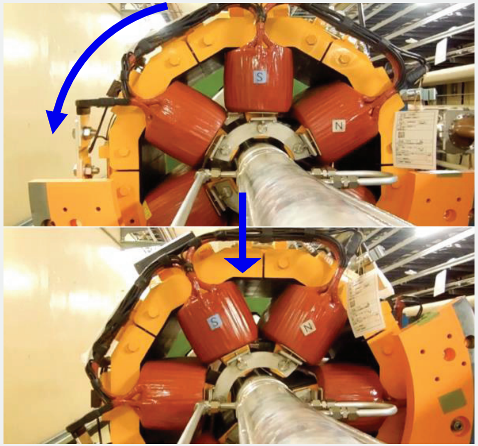
- The optimum R_1 and R_2 values are almost constant if QCS skew quadrupole correctors are fixed.

- 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.

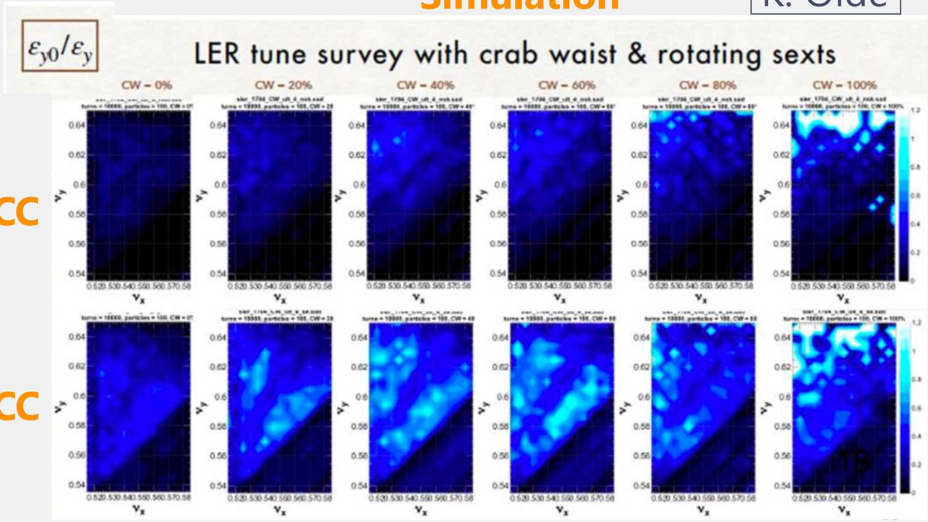
Simulation K. Oide



M. Masuzawa

W/O Ch-XYCC

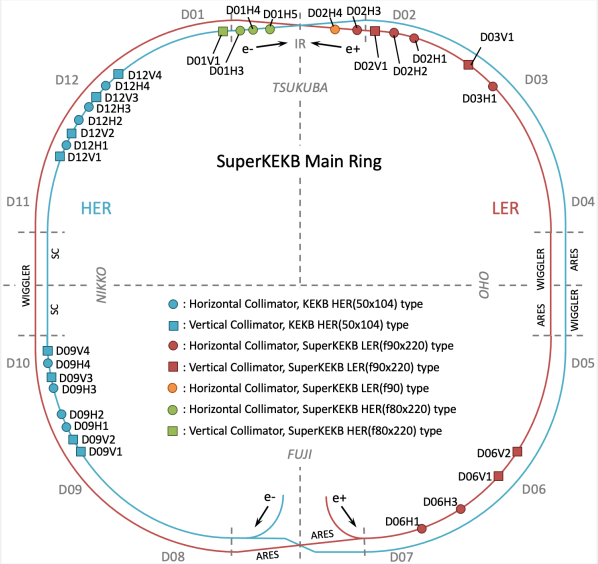
W/ Ch-XYCC



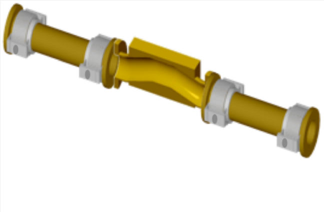
Issues

Transverse Mode Coupling Instability - TMCI -

- Reduction of beam background (BG) to particle physics detectors is the one of most important item because of short beam lifetime and extremely large beta function in the interaction region(IR)
- Currently, bunch intensity in LER is limited by TMCI due to impedance of narrow beam collimators.

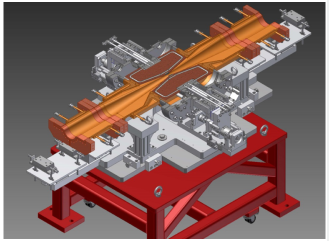


T. Ishibashi



KEKB type

[Y. Suetsugu et al., NIM A 513, 465 (2003)]



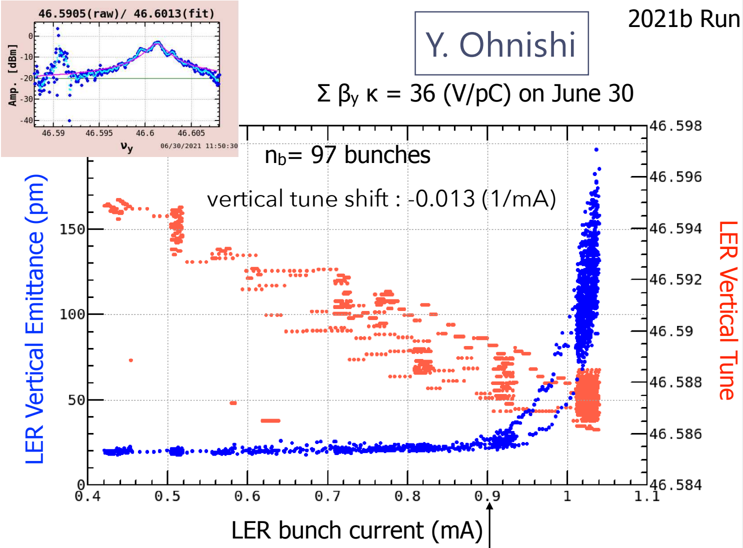
SuperKEKB type

[T. Ishibashi et al., PRAB 23, 053501 (2020)]

Y. Ohnishi

2021b Run

$\Sigma\, \beta_y\, \kappa$ = 36 (V/pC) on June 30



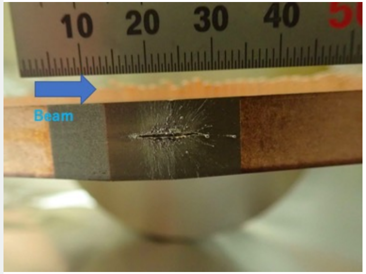
$$I_{th} = \frac{2\pi f_s(E/e)}{\sum_i \beta_{yi}\kappa_i}$$ = 1.6 mA > 0.9 mA (measured)

The measured threshold is much lower than expected.

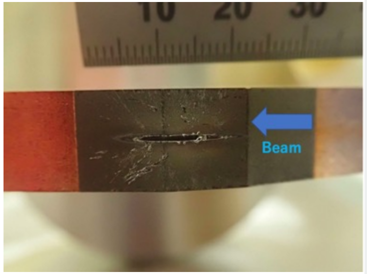
Abnormal Beam Loss and Collimator Damage

- The catastrophic beam loss events not in coincidence with injection is a very worrisome.
- These events occur very rapidly (in a few turns) making it very difficult to abort the stored beam in time to prevent damage to the detector and to machine equipment such as collimators.
- These also induces quench of QCS and reduces operation time.

T. Ishibashi, S.Terui

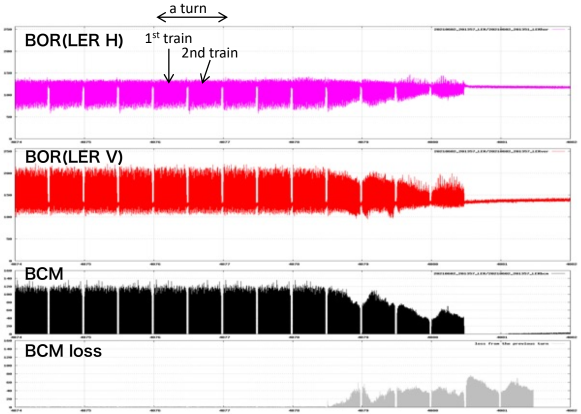


D02V1 bottom side (38 μSv/h)

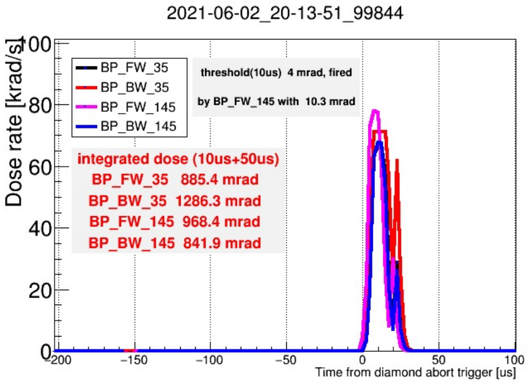


D02V1 top side (95 μSv/h)

- Sudden beam loss happened within 2-turn before the beam abort.
- Dose on VXD diamond sensors of Belle II were extremely high and the signal saturated (usual beam loss abort: ~50 mRad or less).
- The cause of the huge beam loss is unknown so far. One of the candidates is the interaction between the beam and a dust in the beam pipe.
    - Results of simulations indicate that the beam loses at not the vertical collimators but the horizontal collimators mainly [Y. Funakoshi].



Bunch oscillation recorder (BOR) and bunch current monitor (BCM),
BOR signal is proportional to (bunch displacement)×(bunch intensity).



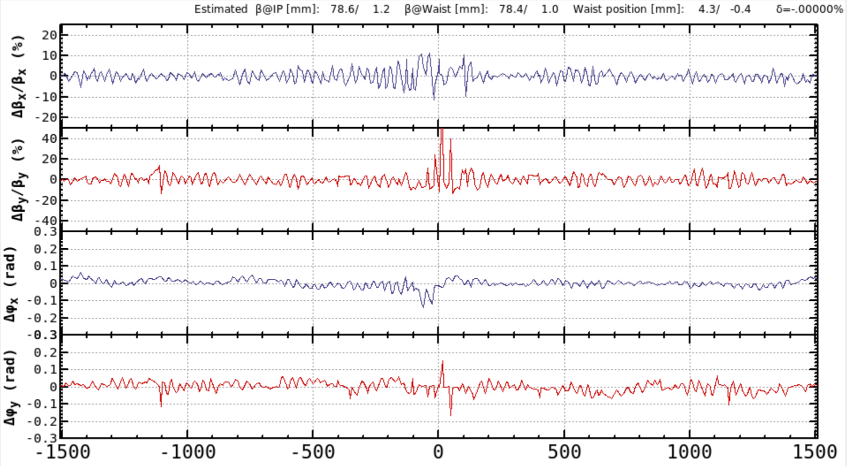
Dose in VXD diamond sensors of Belle II

9

Machine Stability

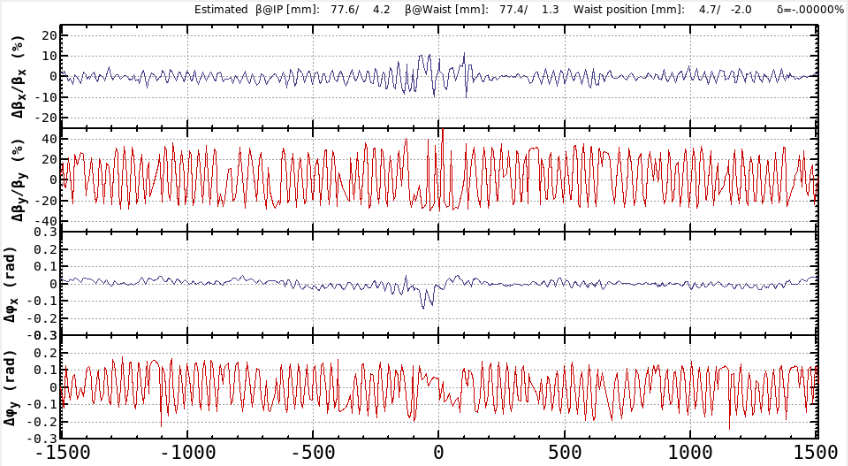
- We sometime observe unexpected behavior of machine after maintenance day or a series of physics runs.
- Example: Optics distortion in LER

Just after optics correction



IP

After a few days



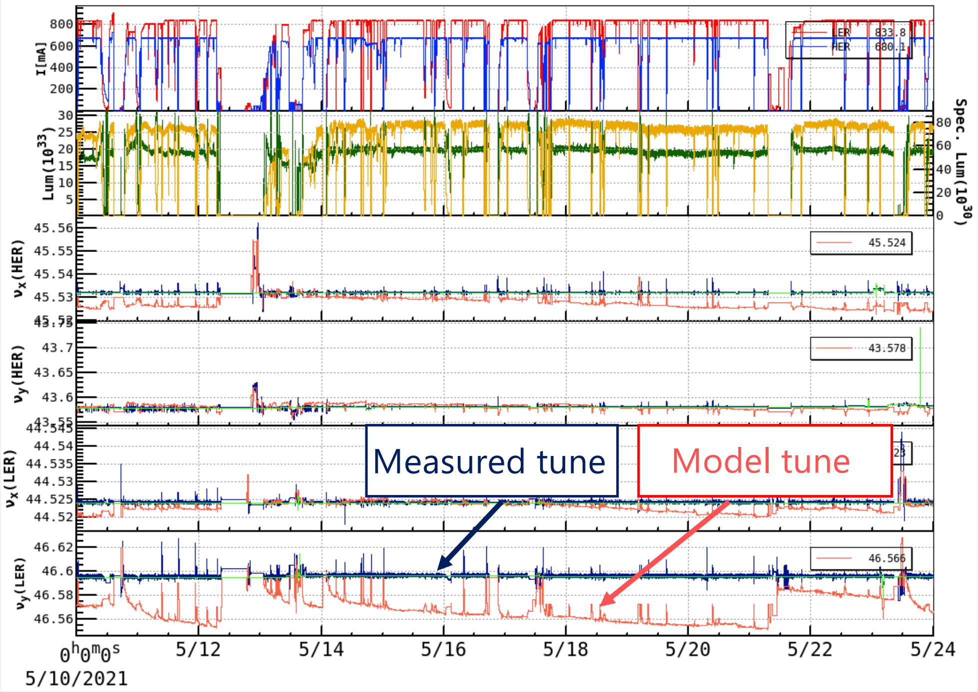
IP

- We observe luminosity reduction due to the beta-beating.

Source of Optics Degradation - Example -

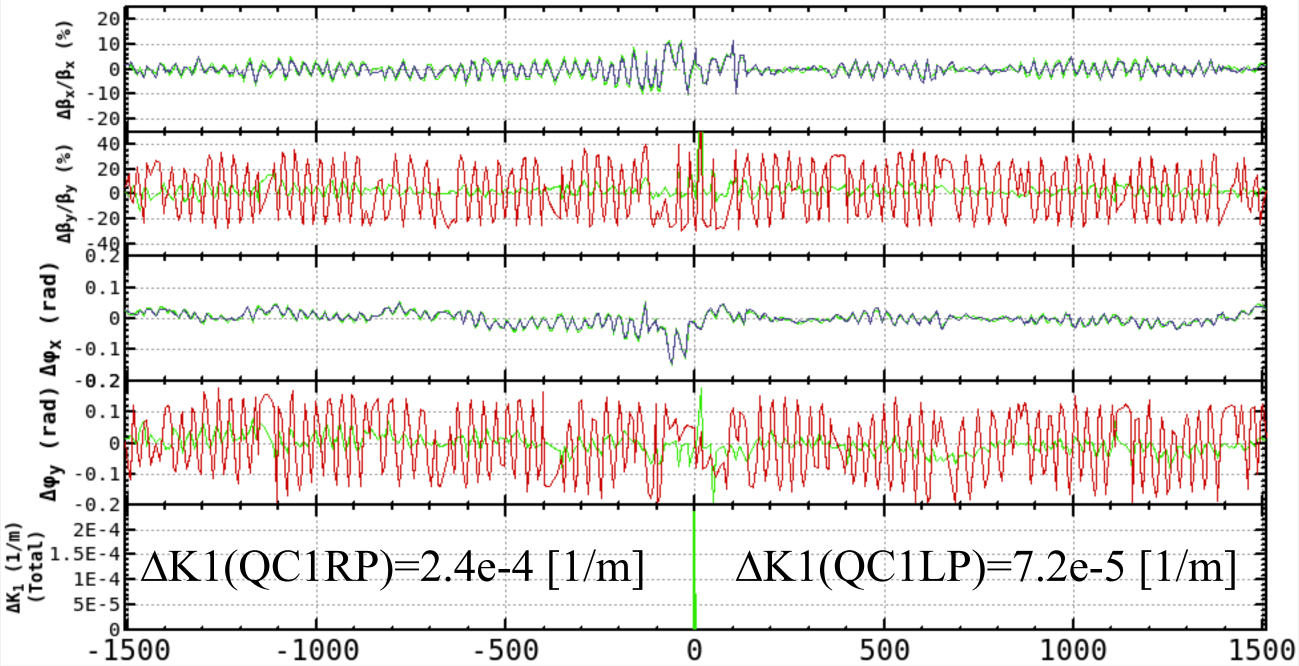
- We have a slow tune feedback system, which keep measured tune a constant by changing the model lattice tune.

- Discrepancy between the model and measured tunes gradually increased just after optics correction.



Machine Stability - Analysis -

- QC1s field error of ~10^{-2} % explains the observed distortion well.



Expected beat-beating after correction with QC1s

IP

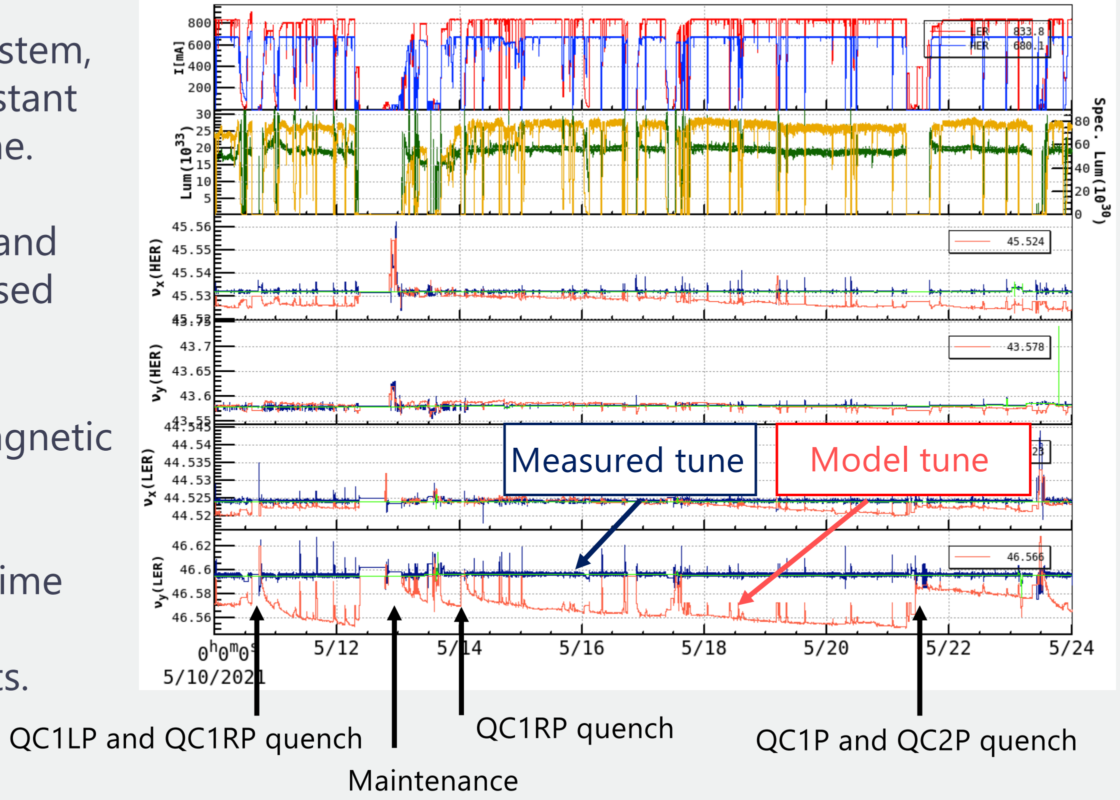
Source of Optics Degradation - Example -

- We have a slow tune feedback system, which keep measured tune a constant by changing the model lattice tune.

- Discrepancy between the model and measured tunes gradually increased just after optics correction.

- We suspect of drifting of QCS magnetic field after its startup.

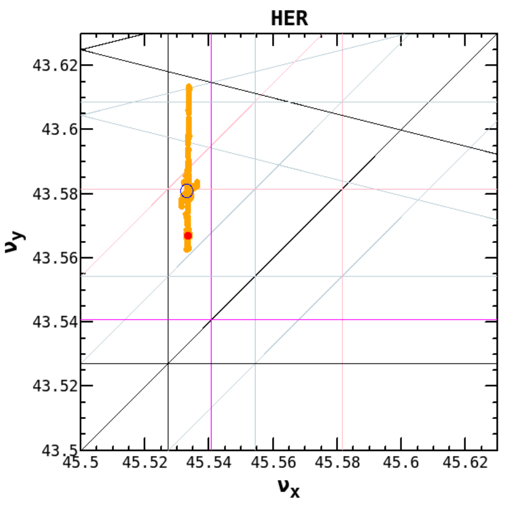
- QCS group plan to measure the time evolution of magnetic field with the R&D QC1P and QC1E magnets.

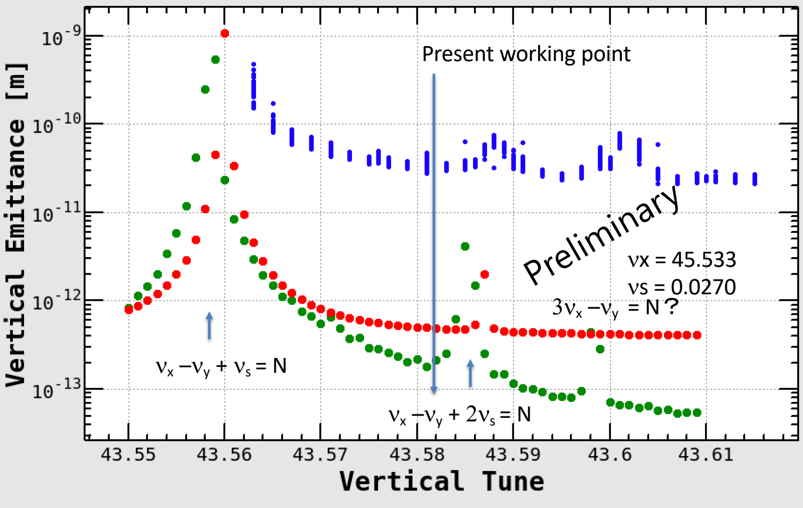


Blowup of HER Single Beam

- We observe vertical beam size blowup in HER depending on the Betatron tunes.
- The operating point is carefully chosen considering not only luminosity, but also injection performance, detector background so on.
- Some Synchro-beta resonance lines are studied to understand the real machine.
- Their location are qualitatively consistent with the that of numerical calculation
- More detailed study (bunch current dependency, etc.) are on going.

Study on beam size blowup (single beam, low bunch current)





Measurement

Model calculation

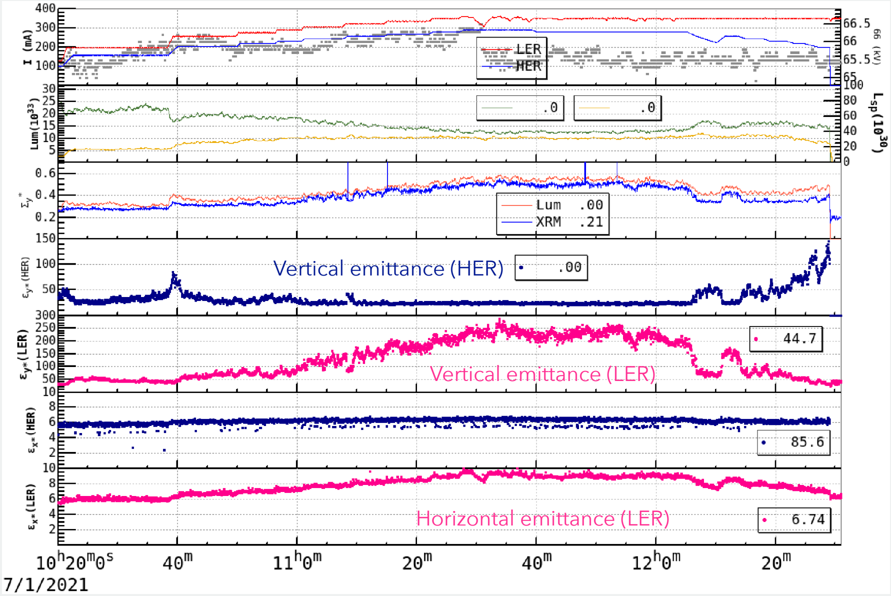
Tracking simulation

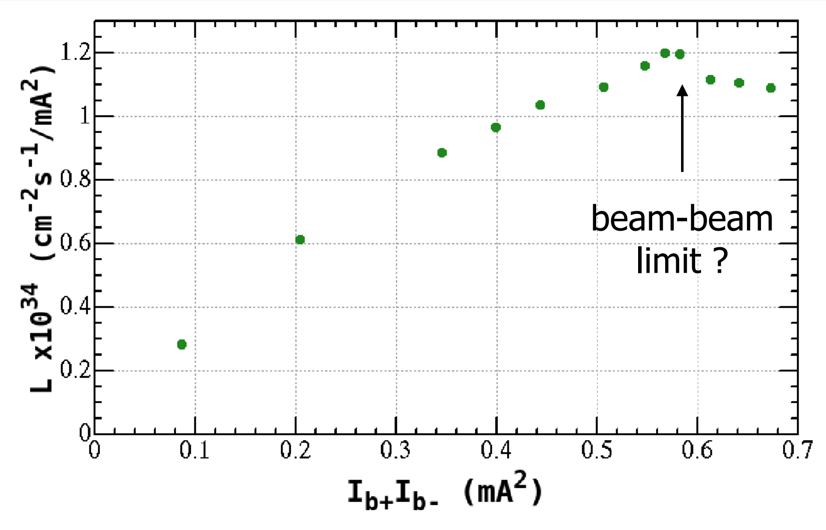
Y. Funakoshi

High Bunch Current Study

Y. Ohnishi

- Small number of bunches (nb=393)
- The LER vertical emittance is increased from 40 pm to 250 pm.
- Specific luminosity is then saturated high bunch current (beam-beam limit?)
- Estimated maximum beam-beam parameters are ~0.04 for LER and ~0.04 for HER





Summary

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

- Luminosity tuning and difficulties
    - Luminosity can be improved by beta-squeezing while avoiding hour-glass effect
    - Effect of linear orbital and optical parameters on luminosity was well studied.
    - Beam-beam parameters is about 0.03, which is much smaller than expected.
    - Beam-beam blowup is studied by both simulation and experiments but, its mechanism is still not clear.
    - TMCI-like instabilities limit bunch current.
    - Abnormal beam loss events are worrisome in high beam current operation.
    - The stability and reproducibility of the machine is troublesome in machine tuning.
    - Aging accelerator components prevents smooth machine tuning and physics runs.
    - etc.

Thank you for your kind attention.