Beam-beam related experimental results at SuperKEKB

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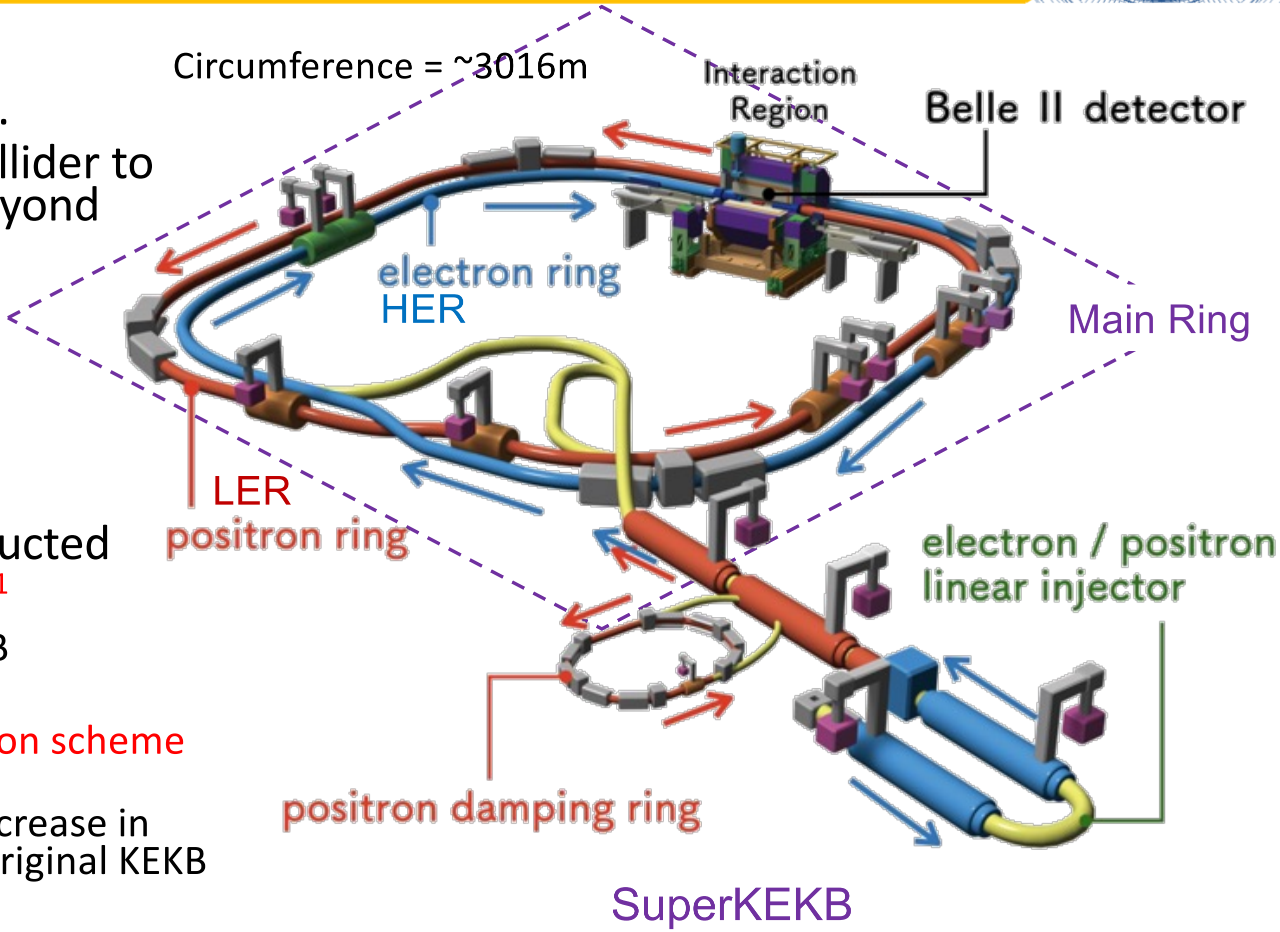
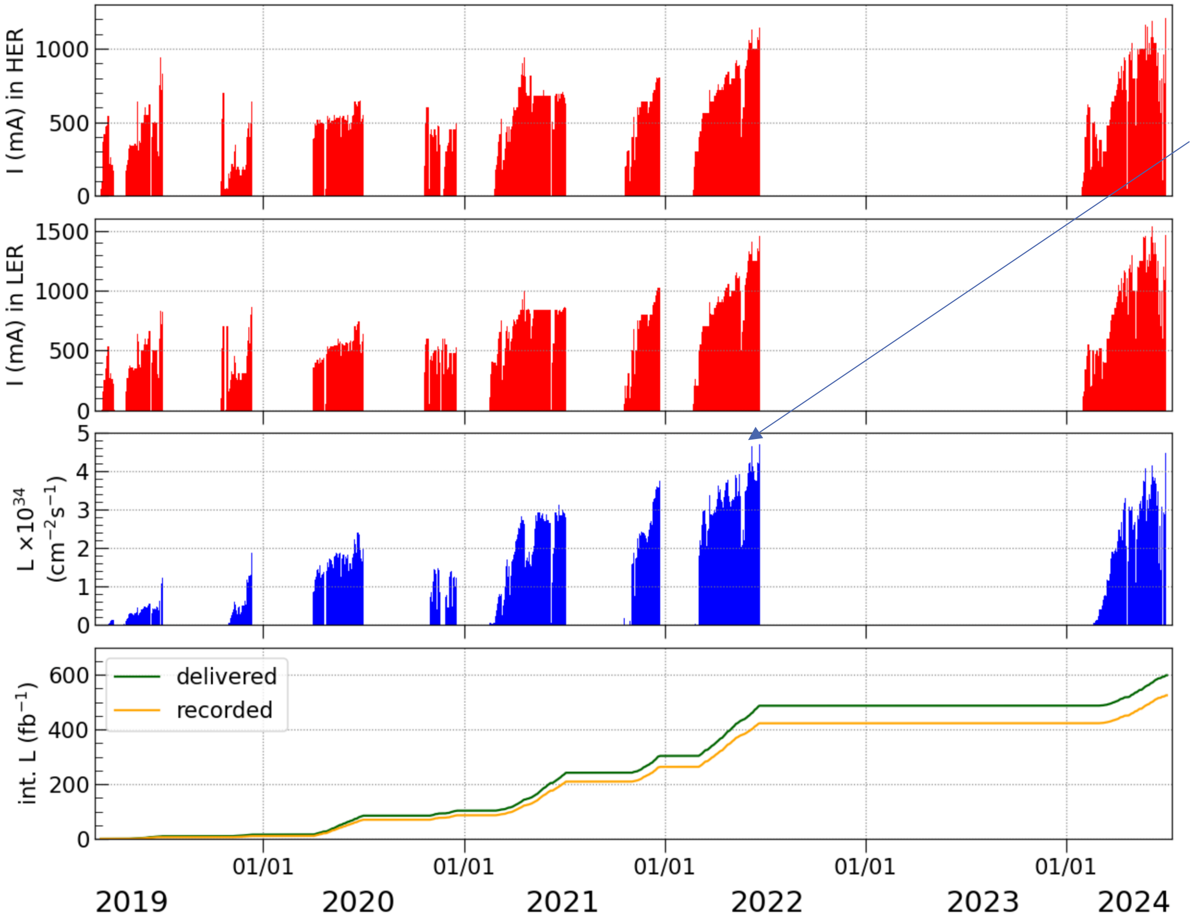
SuperKEKB

- SuperKEKB;
  - An upgrade of KEKB B-factory (KEKB).
  - High-luminosity electron-positron collider to seek out new physics new physics beyond standard model
  - Main ring (MR) is composed of
    - Low Energy Ring (LER);
      - 4.0 GeV Positron, 3.6 A
    - High Energy Ring (HER);
      - 7.0 GeV electron, 2.6 A
  - Positron damping ring: newly constructed
  - Design Luminosity : 8.0×10^{35} $cm^{-2}\cdot s^{-1}$
    - ✓ 40 times maximum luminosity of KEKB
    - ✓ Twice beam current of KEKB (×2)
    - ✓ Squeezing βy^* with nano-beam collision scheme (×20)
    - ✓ Over a period of 10 years, a 50-fold increase in integrated luminosity relative to the original KEKB is expected.



History of beam operation



Highest peak luminosity at SuperKEKB with Belle-II detector ON.
4.65×10^{34} cm^{-2}s^{-1} <-World Record

Machine performance of SuperKEKB

	KEKB achieved		SuperKEKB 2020 May 1st (IPAC2020)		SuperKEKB 2022 June 8th (IPAC2022)		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

Beam operation after Long Shutdown 1 (LS1) (2024 Feb. ~ June), we couldn't make a new luminosity record.

Contents

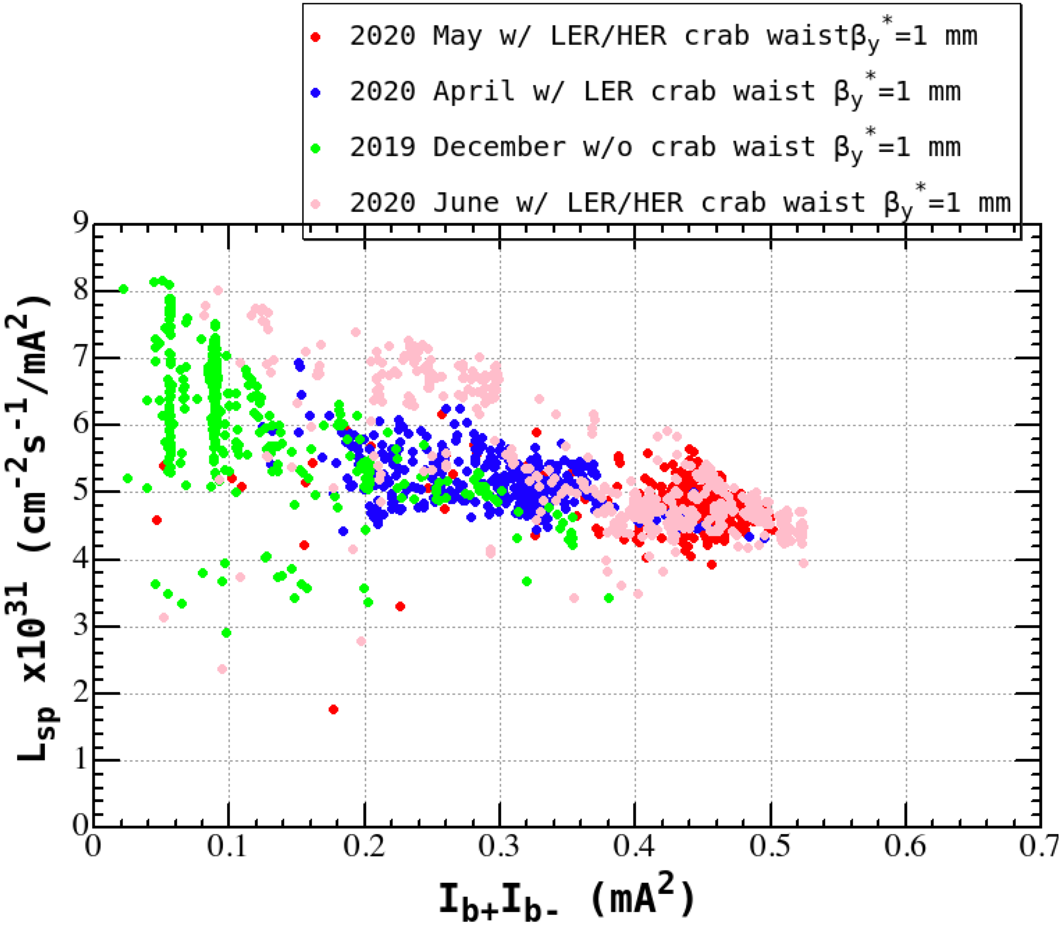
- Crab waist
- Specific luminosity and beam-beam parameters
- Beam injection
- Effect of bunch-by-bunch feedback system
- Tune survey <- skip
- Luminosity tuning <- covered by D. Zhou's talk

Crab waist

Crab waist scheme

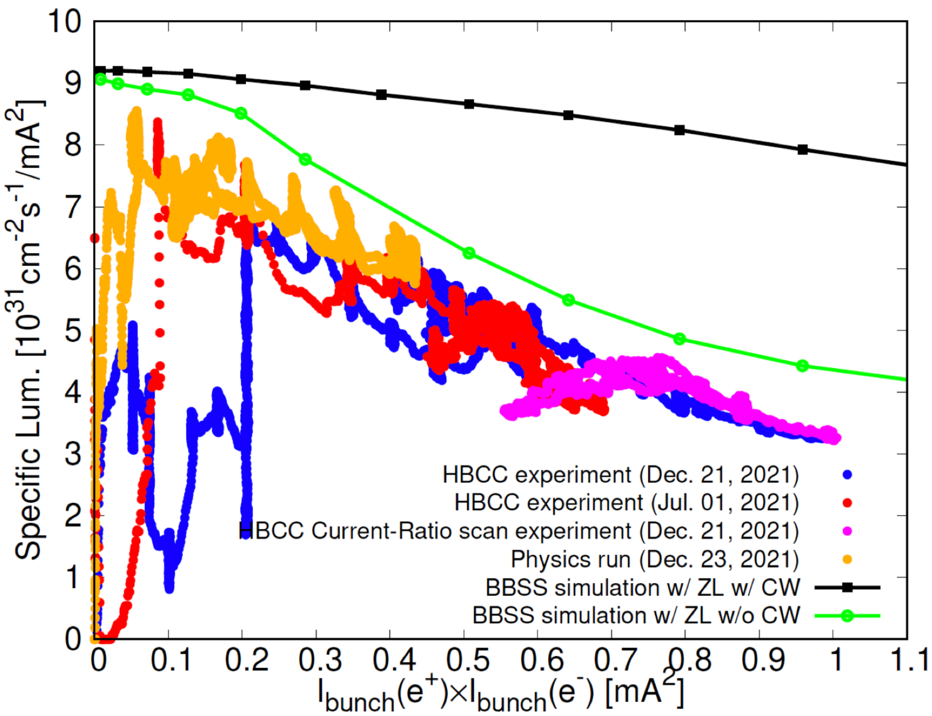
- Introduction of crab waist at SuperKEKB
  - Motivations
    - The beam-beam performance was poor in spite of all of knob tunings for improving it.
  - Method
    - FCC-ee type scheme: use of imbalance sextupoles in the vertical local chromaticity correction section.
  - Time table
    - 2020 March 16th : LER crab waist (40%)
    - 2020 March 24th : LER crab waist (60%)
    - 2020 April 24th : HER crab waist (40%)
    - 2020 June 1st : LER crab waist (80%)
    - 2024 June 5th : HER crab waist (60%)

Specific luminosity w/ and w/o crab waist



$L_{sp} = L_{total}/N_{bunch}/I_{bunch+}/I_{bunch-}$

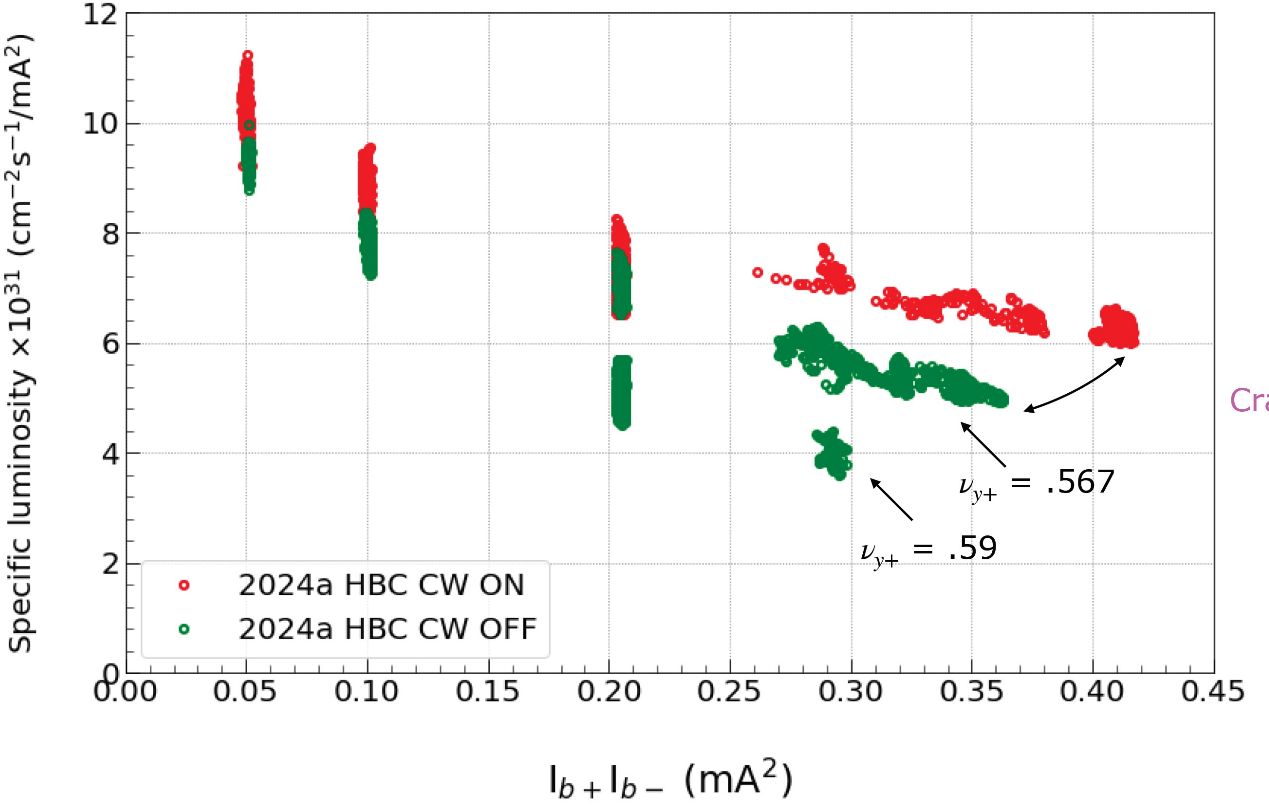
Strong-Strong Beam-Beam simulation (D. Zhou)



Crab waist ON and OFF (2024)

LER: CW 80 % / HER: CW 40 %

Try HER → 60 %



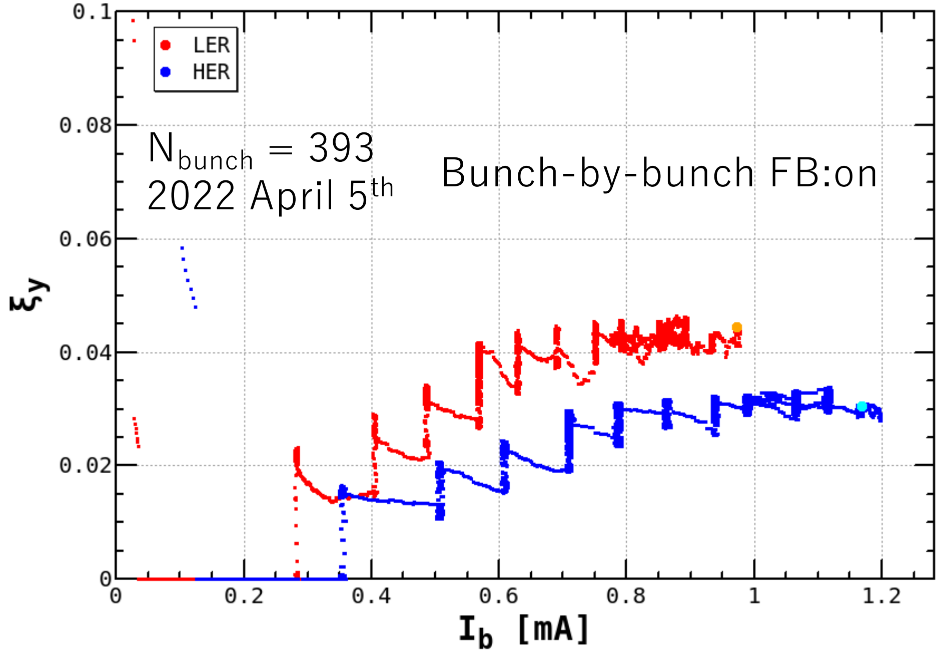
Crab Waist Is Effective.

Summary of crab waist scheme

- Benefits of use of crab waist scheme
  - Suppression of beam-beam blowup
    - Specific luminosity was improved by ~15%.
  - Increase of the bunch currents of both beams
    - W/o crab waist, beam injections was limited due to poor injection efficiency.
- 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.

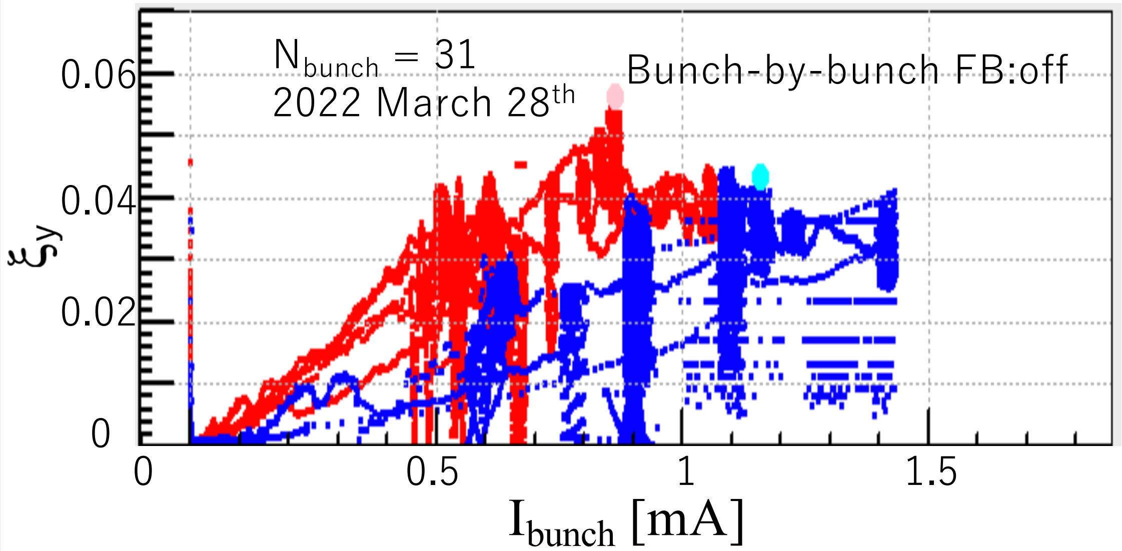
Specific luminosity and beam-beam parameters

Beam-beam parameters



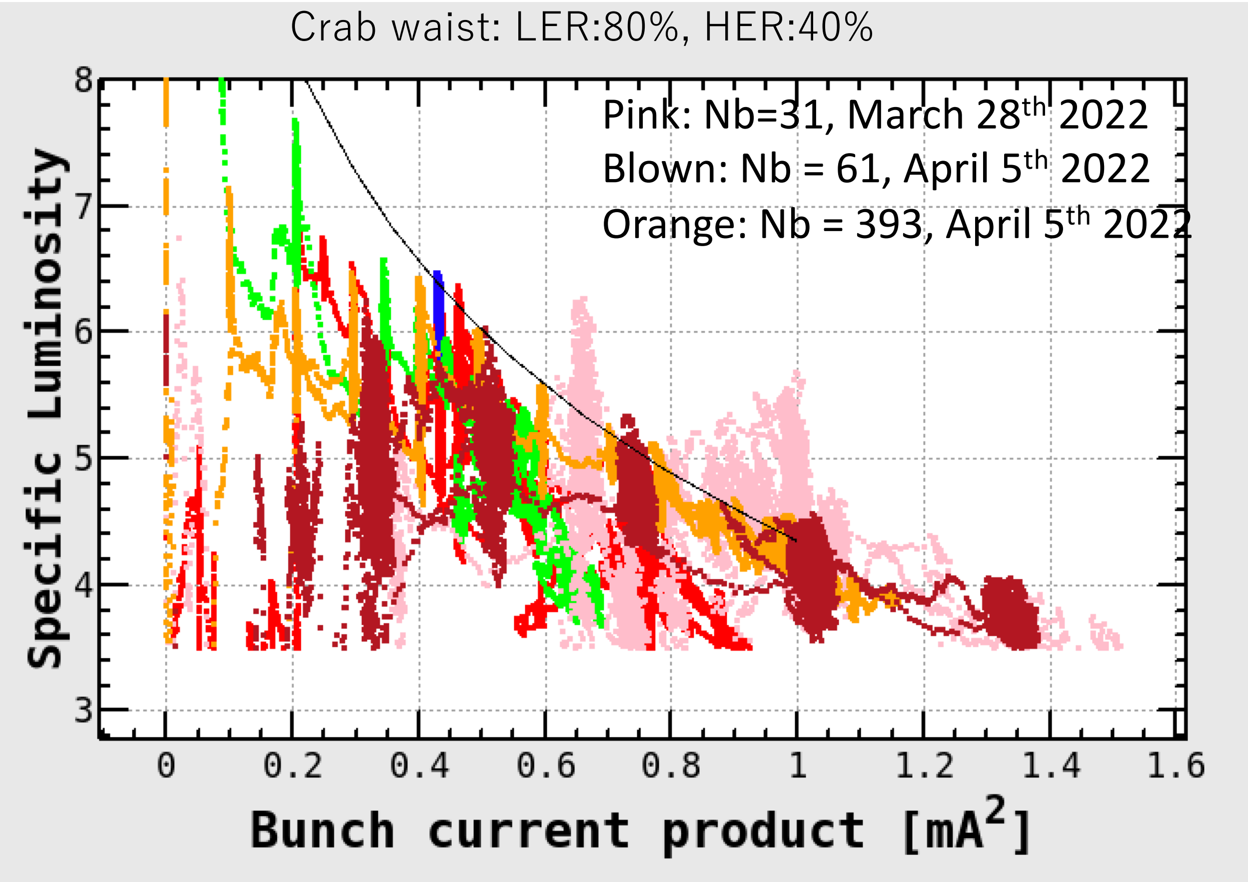
Bunch current of opposite beam

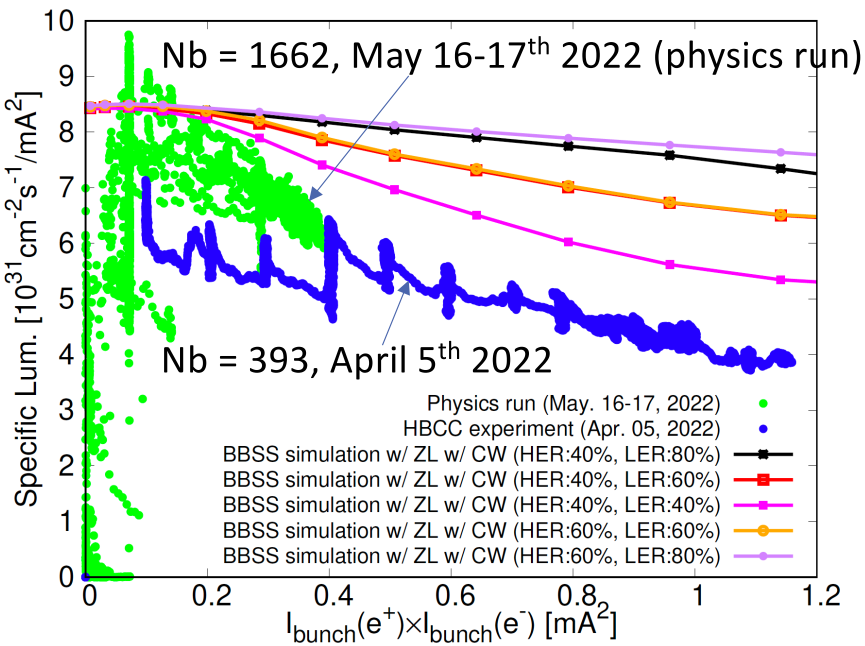
Vertical beam-beam parameter (ξ_y) of HER is saturated around 0.03.



With smaller number of bunches (31 bunches), which allowed us to switch FB off, ξ_y of HER reached ~0.043. This is the highest value achieved ever at SuperKEKB.

Specific luminosity





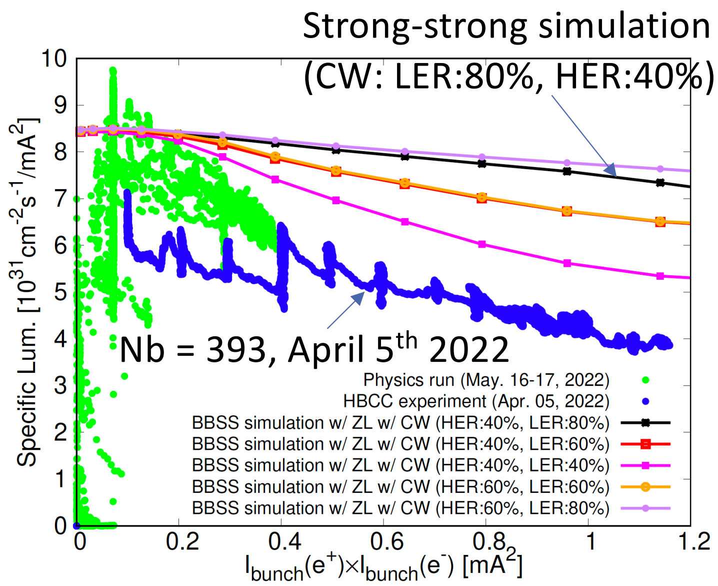
There is a big discrepancy between simulation and experiment !!!

What is the cause of discrepancy btw simulation and experiment?

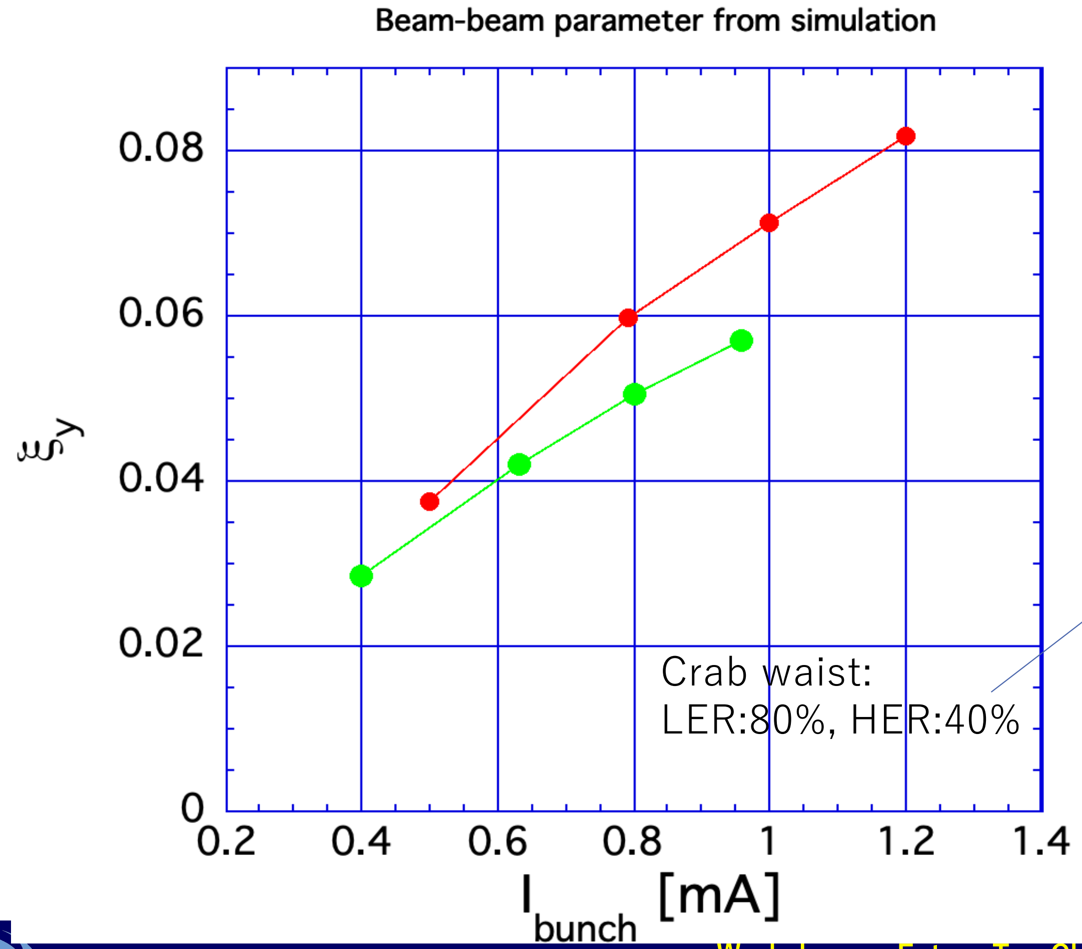
- Observed luminosity performance is much lower than simulations with BBSS (Beam-Beam Strong-Strong). This has been and will be challenges for us.
- Candidates of causes
  - Machine imperfections: Non-zero coupling and dispersions at IP, beam-current dependent optics distortion due to orbit change at QCS* and SLY* etc. Imperfect crab waist scheme
  - Beam-beam + lattice nonlinearity, Beam-beam + impedance, Beam-beam + space charge
  - BBSS simulation with PIC gives ~5% lower values than simulation with soft Gaussian model at $I_{b+}I_{b-}$ = 0.8mA^2.
  - Effects of FB system

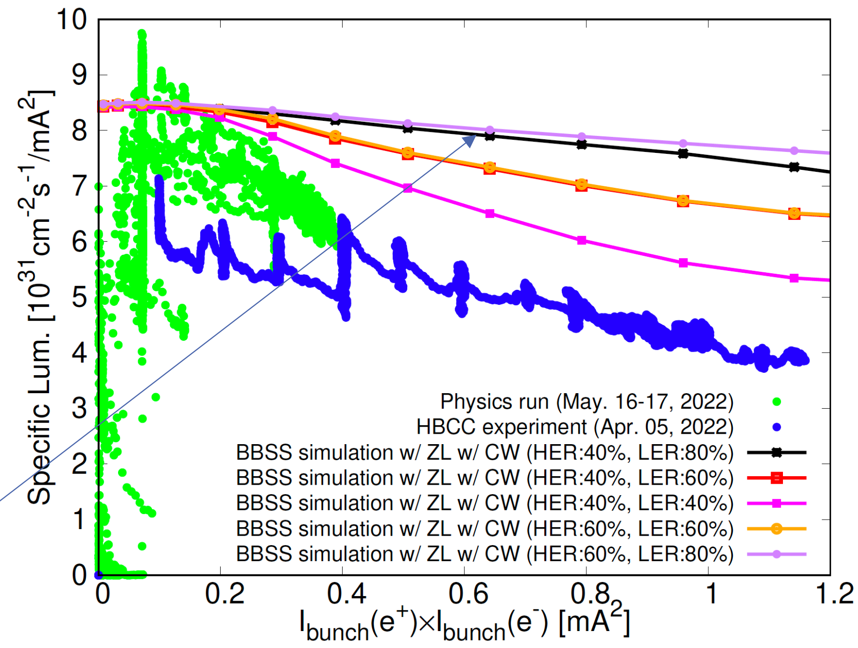
Operation parameter set for BBSS simulation

	2022.04.05		Comments
	HER	LER	
I_{bunch} (mA)	Ie	1.25*Ie	
# bunch	393		Assumed value
ε_x (nm)	4.6	4.0	w/ IBS
ε_y (pm)	35	30	Estimated from XRM data
β_x (mm)	60	80	Calculated from lattice
β_y (mm)	1	1	Calculated from lattice
σ_{z0} (mm)	5.05	4.60	Natural bunch length (w/o MWI)
ν_x	45.532	44.524	Measured tune of pilot bunch
ν_y	43.572	46.589	Measured tune of pilot bunch
ν_s	0.0272	0.0233	Calculated from lattice
Crab waist	40%	80%	Lattice design



Beam-Beam Parameter calculation from simulation



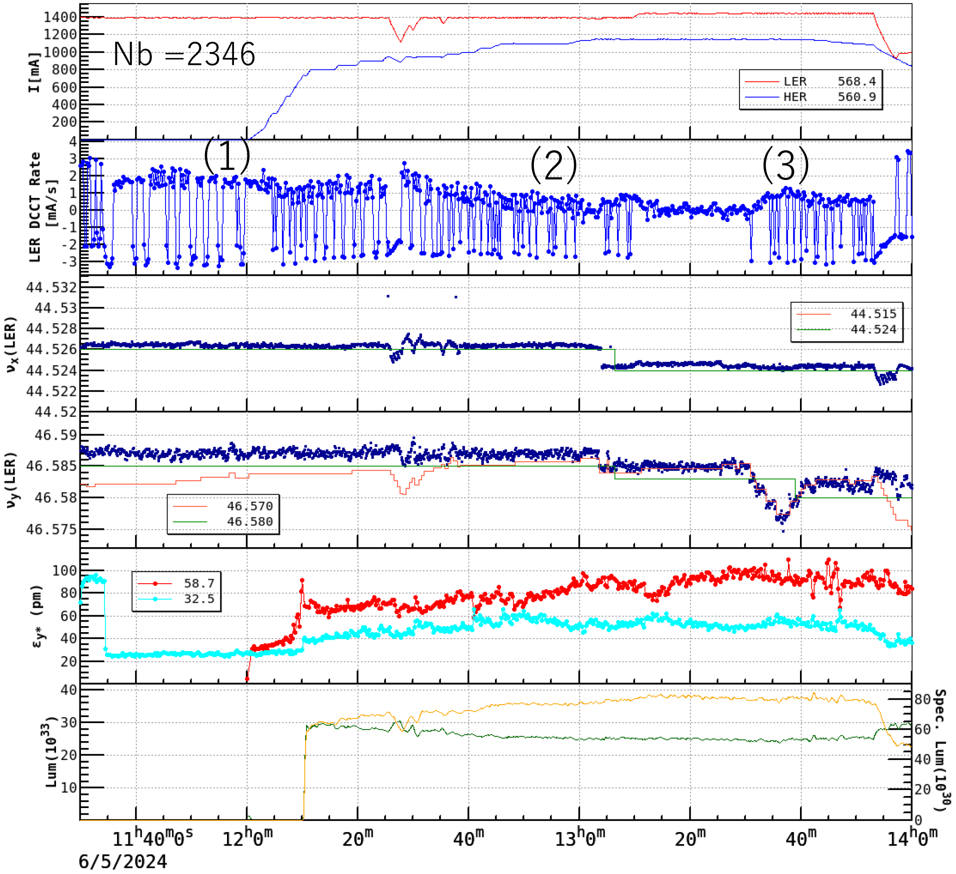


Summary of Specific luminosity and beam-beam parameters

- The achieved specific luminosity at a higher bunch current product (~> 1 mA^2) is about a half of the strong-strong simulation (w/ longitudinal wake).
- Vertical beam-beam parameters (ξ_y) of HER and LER seems to be saturated around 0.03 and 0.04, respectively.
- With FB off, the specific luminosity was improved and the vertical beam-beam parameters (ξ_y) of HER and LER reached 0.0434 and 0.0565, respectively.

Beam injection

Experiment on beam injection of LER



(June 5th 2024)

w/ beam-beam

- Beam lifetime increases w/ beam-beam blowup.
- Injection efficiency get worse seriously
  → By optimizing working points, the injection efficiency is improved.

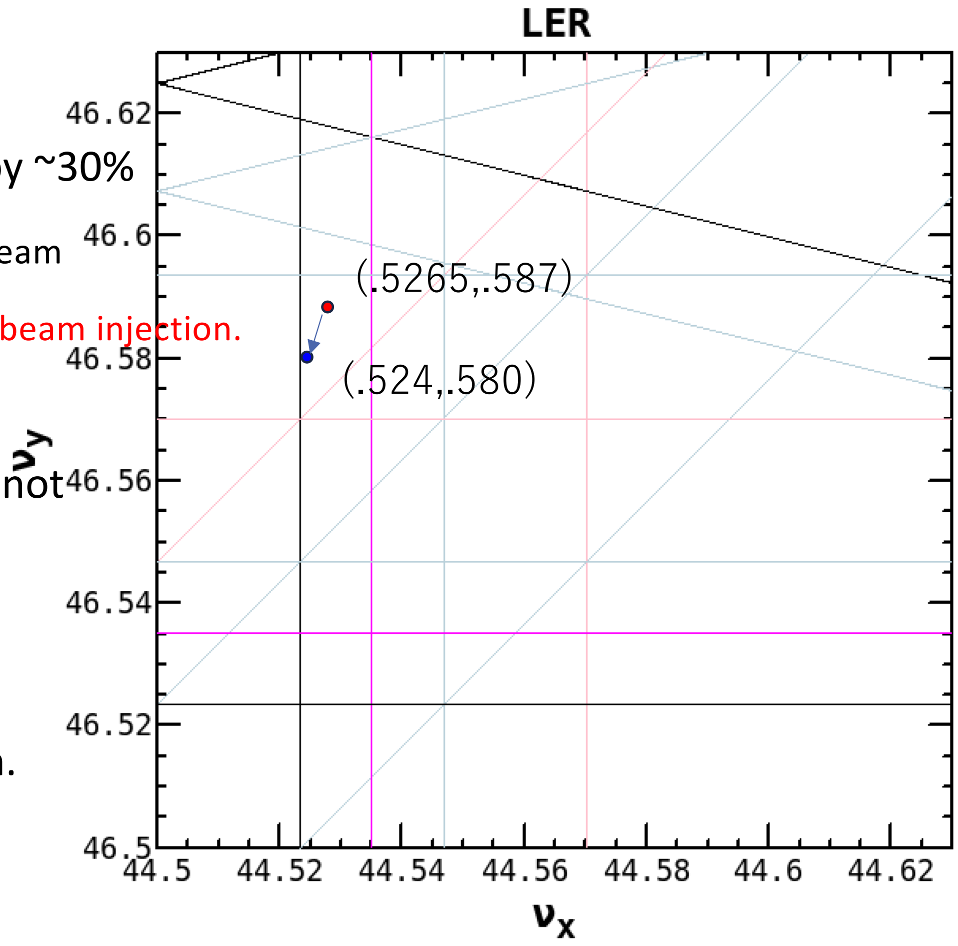
	Ibeam (LER)	Ibeam (HER)	IncRate (L)	Life (L)	InjEff (L)
(1)	1395 mA	0 mA	1.68mA/s	7.3 min.	77.4%
(2)	1395mA	1100mA	0.42mA/s	8.9 min.	48.0%
(3)	1444mA	1100mA	1.02mA/s	8.0 min.	64.8%

$$Beam\ Lifetime[s] = \frac{DCCT\ Beam\ current\ [mA]}{DCCT\ decreasing\ rate\ (Loss\ rate)[\frac{mA}{s}]}$$

$$Injection\ Efficiency[\%] = \frac{DCCT\ increasing\ rate\ \left[\frac{mA}{s}\right] + DCCT\ decreasing\ rate\ \left[\frac{mA}{s}\right]}{BT\ end\ charge\ [nC]\times Revolution\ freq.[Hz]\times 1000\times InjRepRate[Hz]}\times 100$$

Summary of beam injection

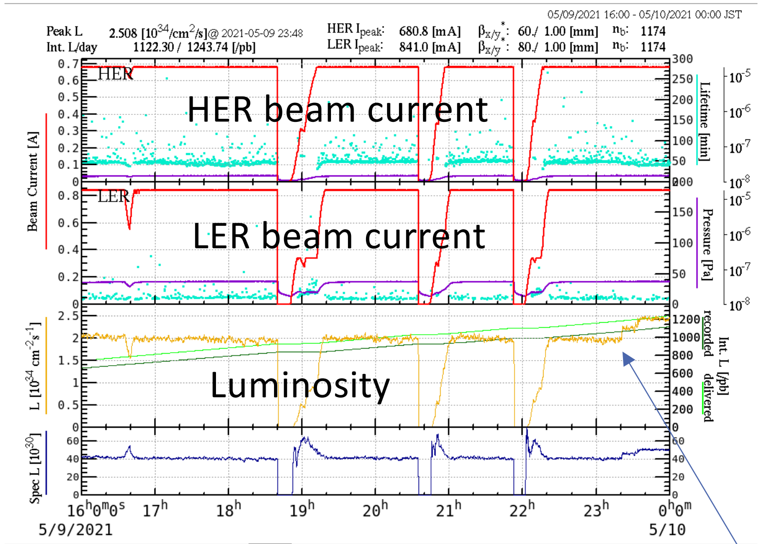
- Injection scheme of SuperKEKB
  - Usual betatron (horizontal) injection with stacking mode
  - With crab waist, the beam injection was improved.
- Even with crab waist LER injection efficiency was decreased by ~30% with beam-beam effects.
  - At the present SuperKEKB, the beam injection limits the storable beam currents and then luminosity.
  - The maximum LER beam current (and luminosity) is limited by the beam injection.
- By changing working point, the injection efficiency was recovered by ~ 15%.
- With this change in tunes, the beam sizes and luminosity did not change so much. The beam lifetime did not change so much either.
- A simulation on the injection w/ beam-beam is going on.
  - Strong-weak with SAD lattice
    - tune survey, w/ impedance
- In this run, several measures for better injection will be taken.
  - Reduce horizontal injection oscillation amplitude by increasing βx at injection point (~100m -> 160m)
  - Reduce βx^* at the IP (80mm -> 60mm: LER)
  - Try synchrotron injection in HER

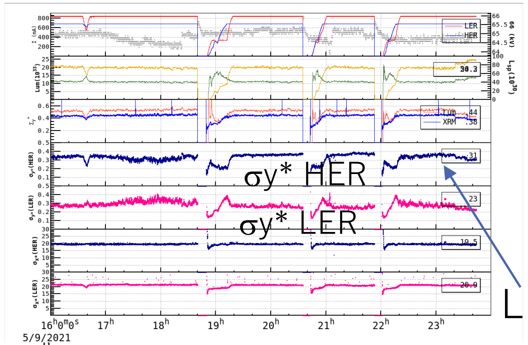


Effect of bunch-by-bunch feedback system

Bunch-by-bunch feedback gain

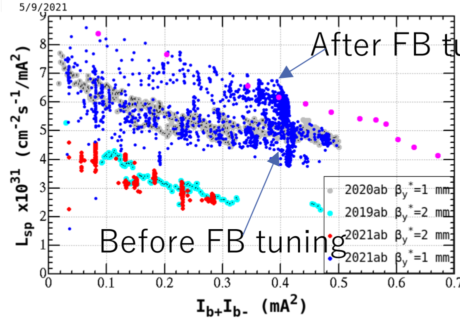
- In May 2021, the luminosity increased by lowering gain of the bunch-by-bunch feedback system in HER.
- Noise mixed in FB system seemed to affect the luminosity.
  - The noise was caused by a troubled module. Since the noise frequency was near the betatron tune, its effect was large.





Beam sizes

Luminosity up



Specific luminosity

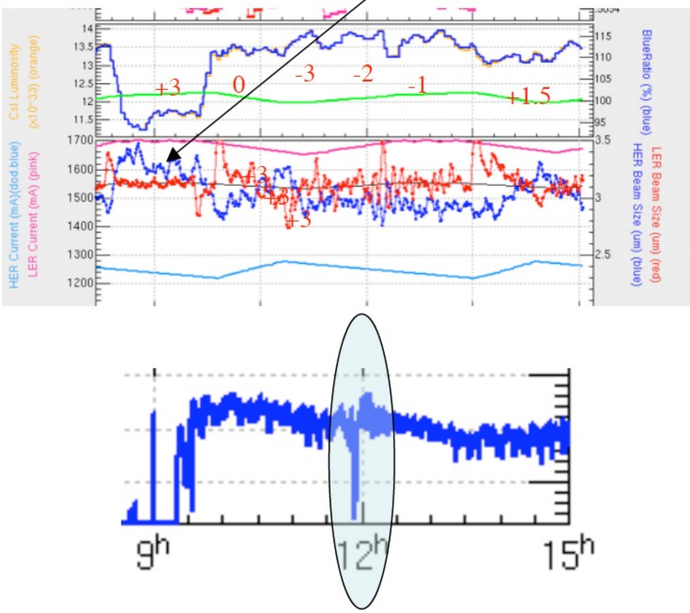
The luminosity increased (~25%) by lowering HER vertical FB gain by 4dB + 4dB.

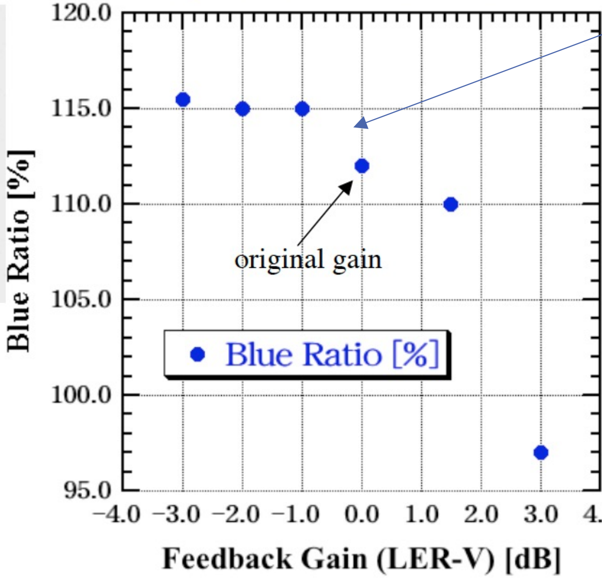
The increase in the luminosity was ~25%.

KEKB case

Specific Luminosity vs FB Gain

HER vertical size enlarged.



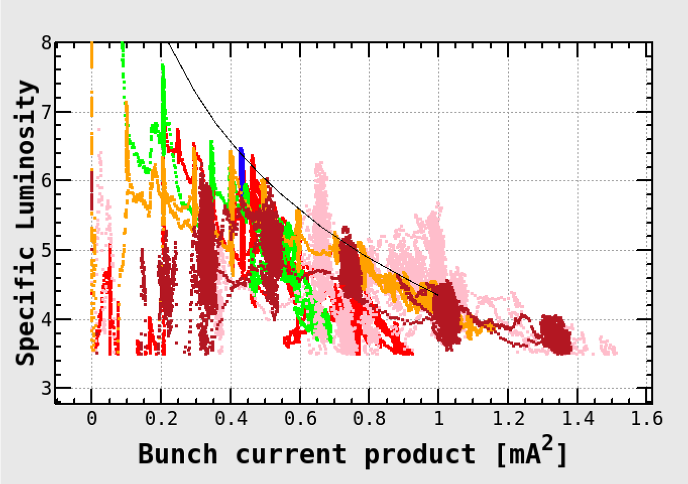


Luminosity gain is ~3%.

FB gain of the LER vertical affects the specific luminosity.
The other gains (LER H, HER H/V) bring no effects.

Summary of effects of FB system

- In some situation, the luminosity is increased by reducing the gain of the bunch-by-bunch feedback (FB).
- With FB off, the specific luminosity was increased by ~20 % at the bunch current product of ~ 1 mA^2 once in March 2022.
  - In this run, we will try to confirm this effect.



Summary

- To do list
  - Large discrepancy between strong-strong simulation and experiment
    - We have to study the following candidates.
      - Machine imperfections: Non-zero coupling and dispersions at IP, beam-current dependent optics distortion due to orbit change at QCS* and SLY* etc. Imperfect crab waist scheme
      - Beam-beam + lattice nonlinearity, Beam-beam + impedance, Beam-beam + space charge
      - BBSS simulation with PIC gives ~5% lower values than simulation with soft Gaussian model at $I_{b+}I_{b-}$ = 0.8mA^2.
      - Effects of FB system
  - Beam injection with beam-beam effects
    - Reduce amplitude of injection oscillation by enlarging βx at the injection point.
    - Reduce βx^* at the collision point
    - More tune survey

Fin.

Thank you for your attention.

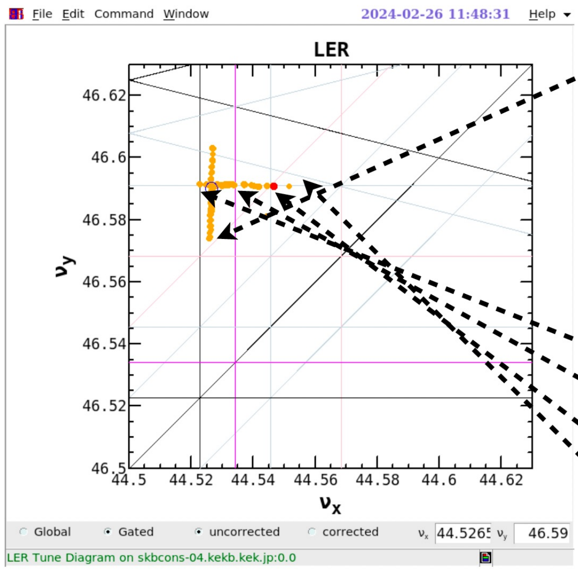
Spare slides

Tune survey

Resonance lines

Findings

* Most of the physics of beam-beam, lattice nonlinearities and their interplay can be attributed to “resonances”.
* The complexity lies in the fact that $\nu_{x,y,s}(I_b)$ are current dependent.
* With collision, one beam’s tunes depend on the other beam’s currents: $\nu_{x\pm,y\pm,s\pm}(I_{b\pm}, I_{b\mp})$



Lattice resonances:

$\nu_x - \nu_y + 2\nu_s = N$

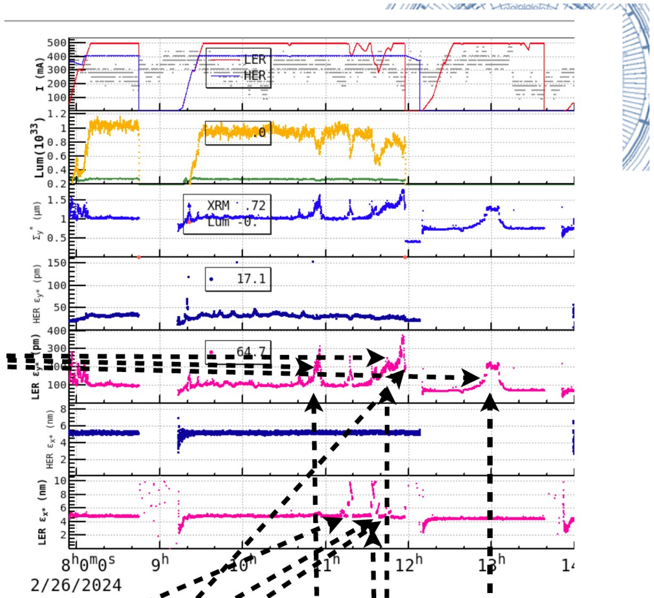
Beam-beam resonances:

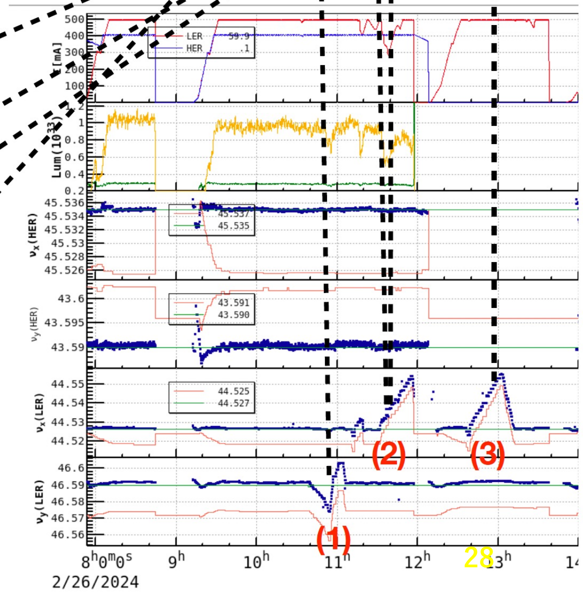
$\nu_x - \nu_s = N/2$

$\nu_x - 1.5\nu_s = N/2$

$\nu_x - 2\nu_s = N/2$

$\nu_x + 4\nu_y + \alpha = N$





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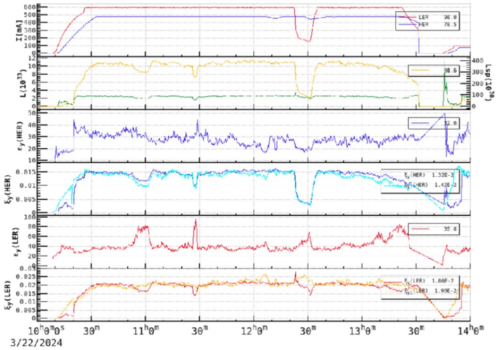
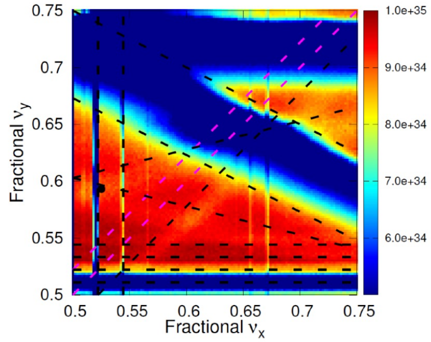
$\nu_x - 1.5\nu_s = N/2$ was strong in this experiment (not strong in 2022b run).

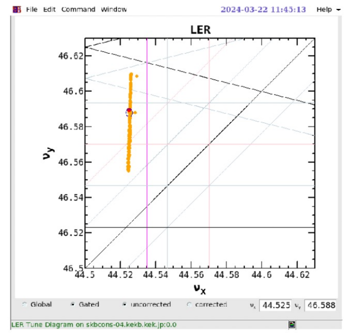
It can be linear IP aberrations that make the deviate from 3D Gaussian (symmetric).

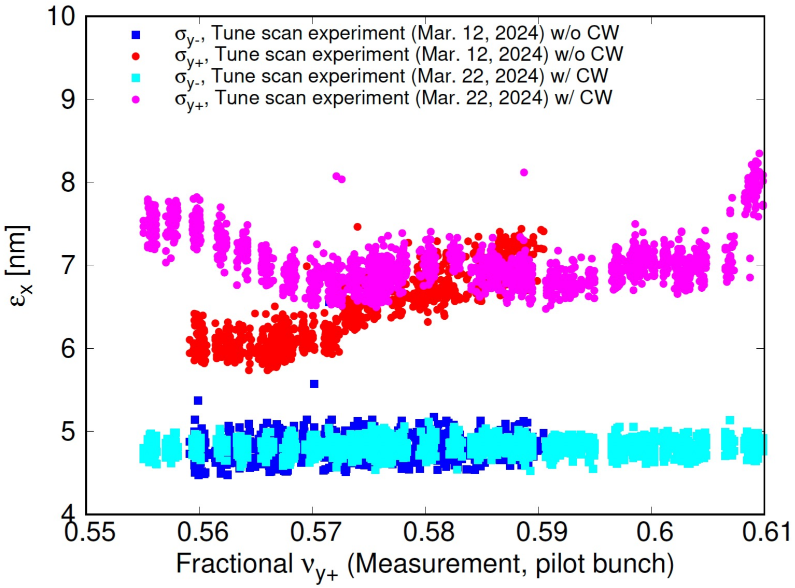
Recent beam-beam machine studies

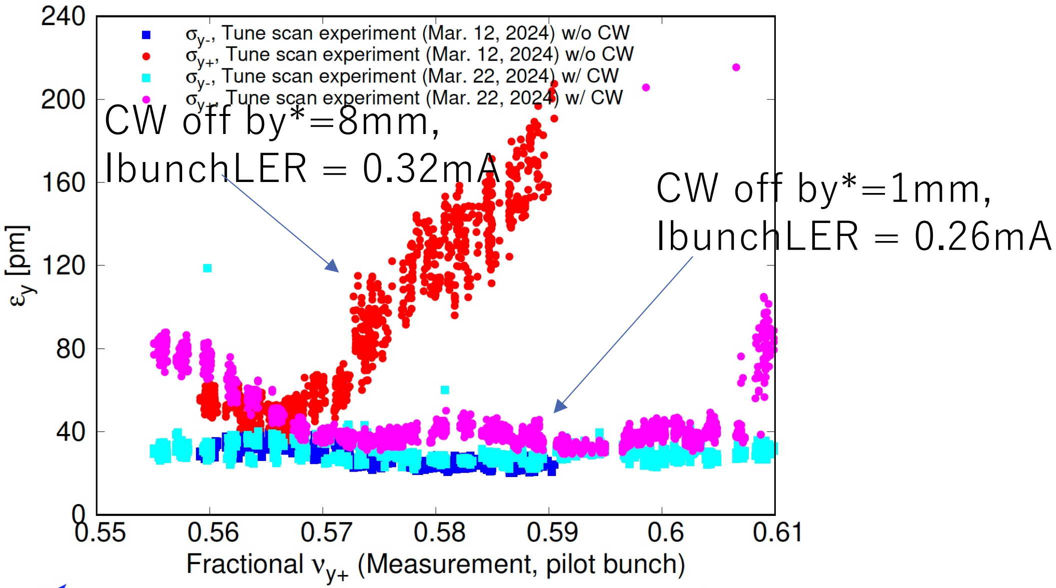
LER vertical tune survey

- LER vertical tune scan compared
  - β_y^*=1 mm, w/o CW, 2024.03.12
  - β_y^*=1 mm, w/ CW, 2024.03.22







Escaping from resonance $\nu_x + 4(\nu_y + \xi_y) = N$

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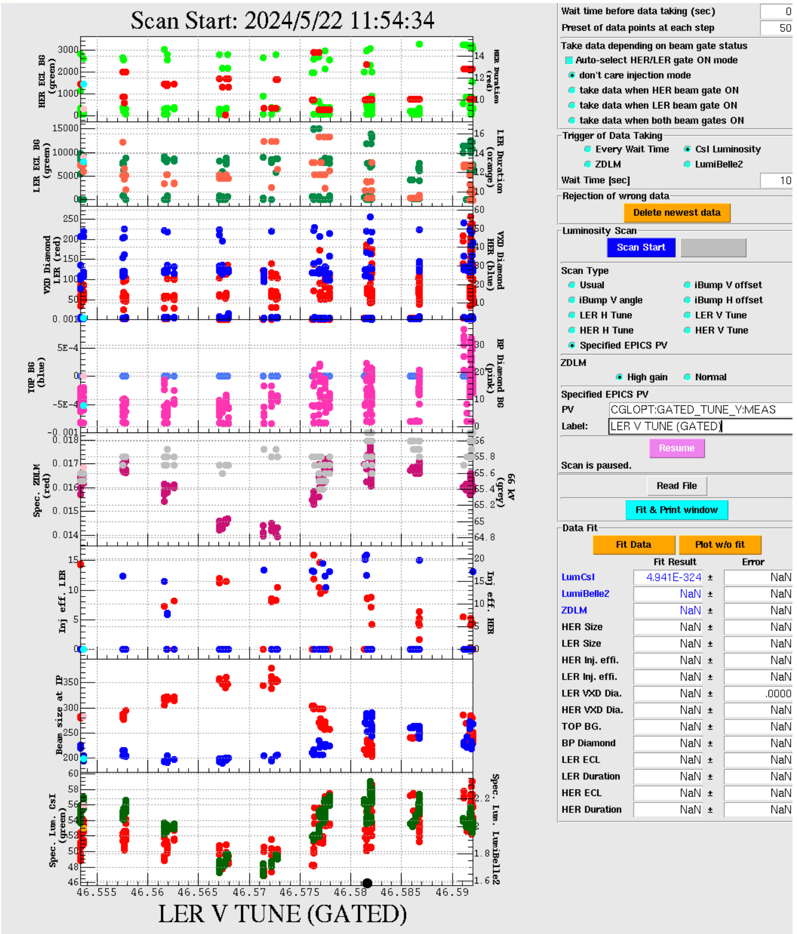
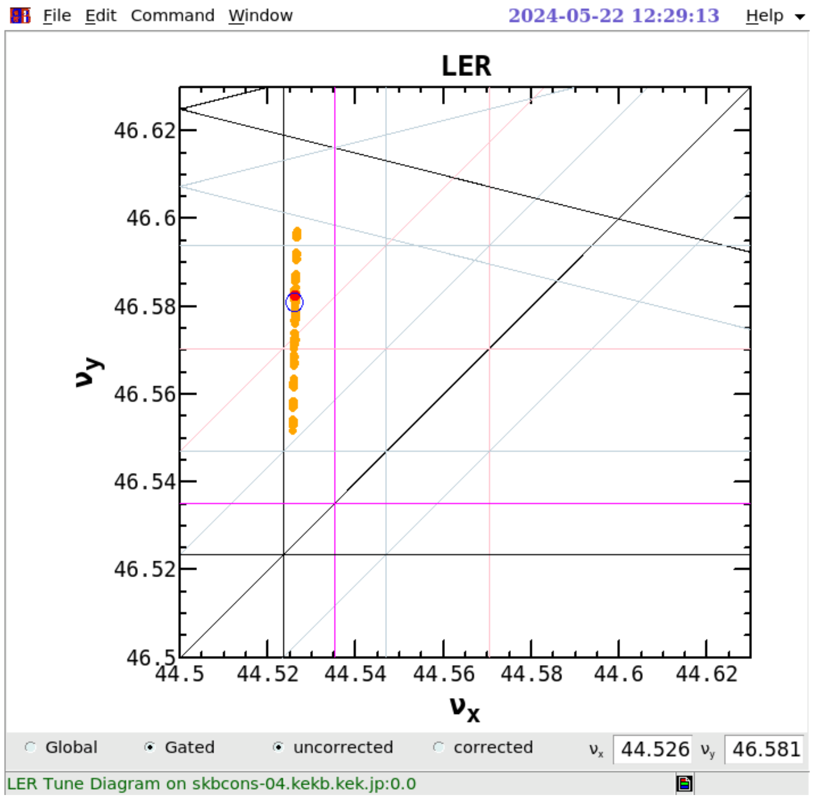
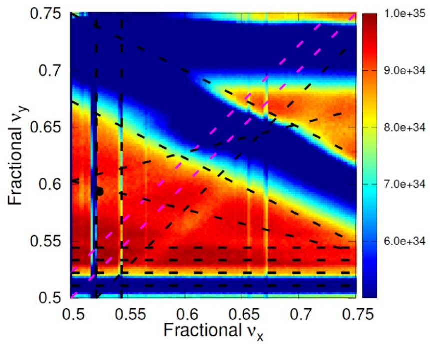
Vertical tune scan in LER on May 22nd 2024

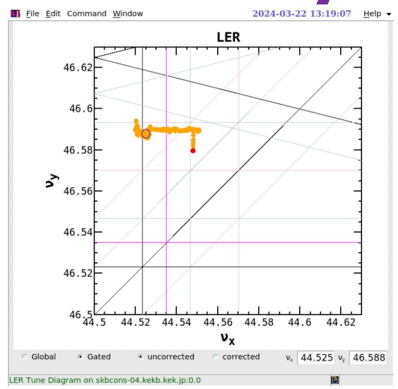


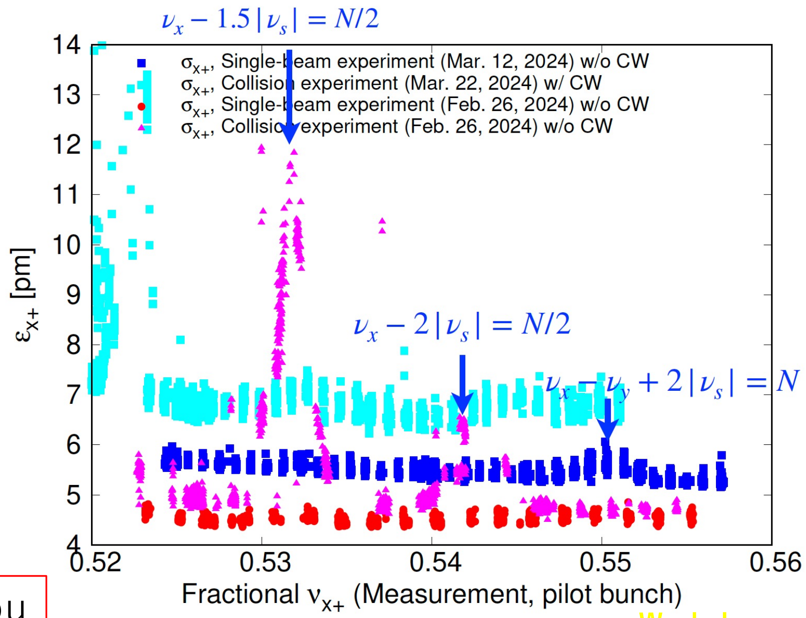


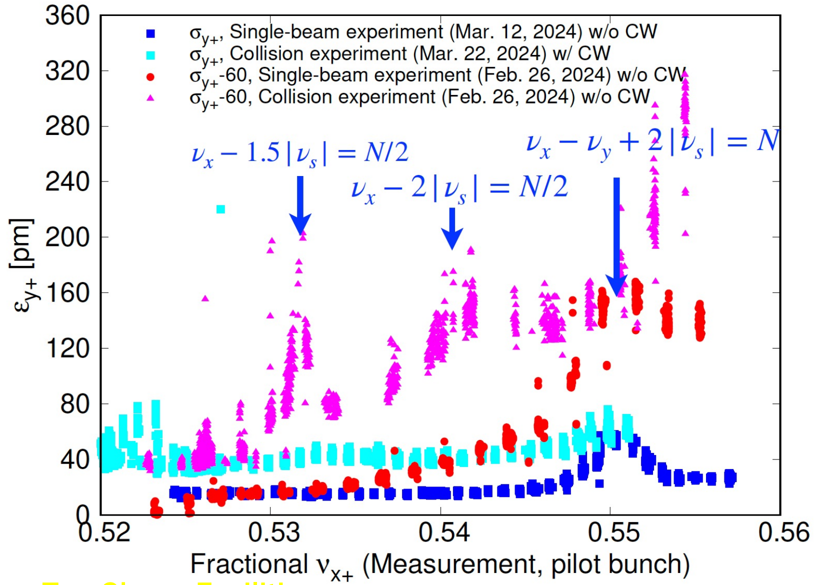
Recent beam-beam machine studies **LER Horizontal tune survey**

- LER horizontal tune scan compared
  - β_y^*=8 mm, w/o CW, 2024.02.26
  - β_y^*=1 mm, w/o CW, 2024.03.12
  - β_y^*=1 mm, w/ CW, 2024.03.22

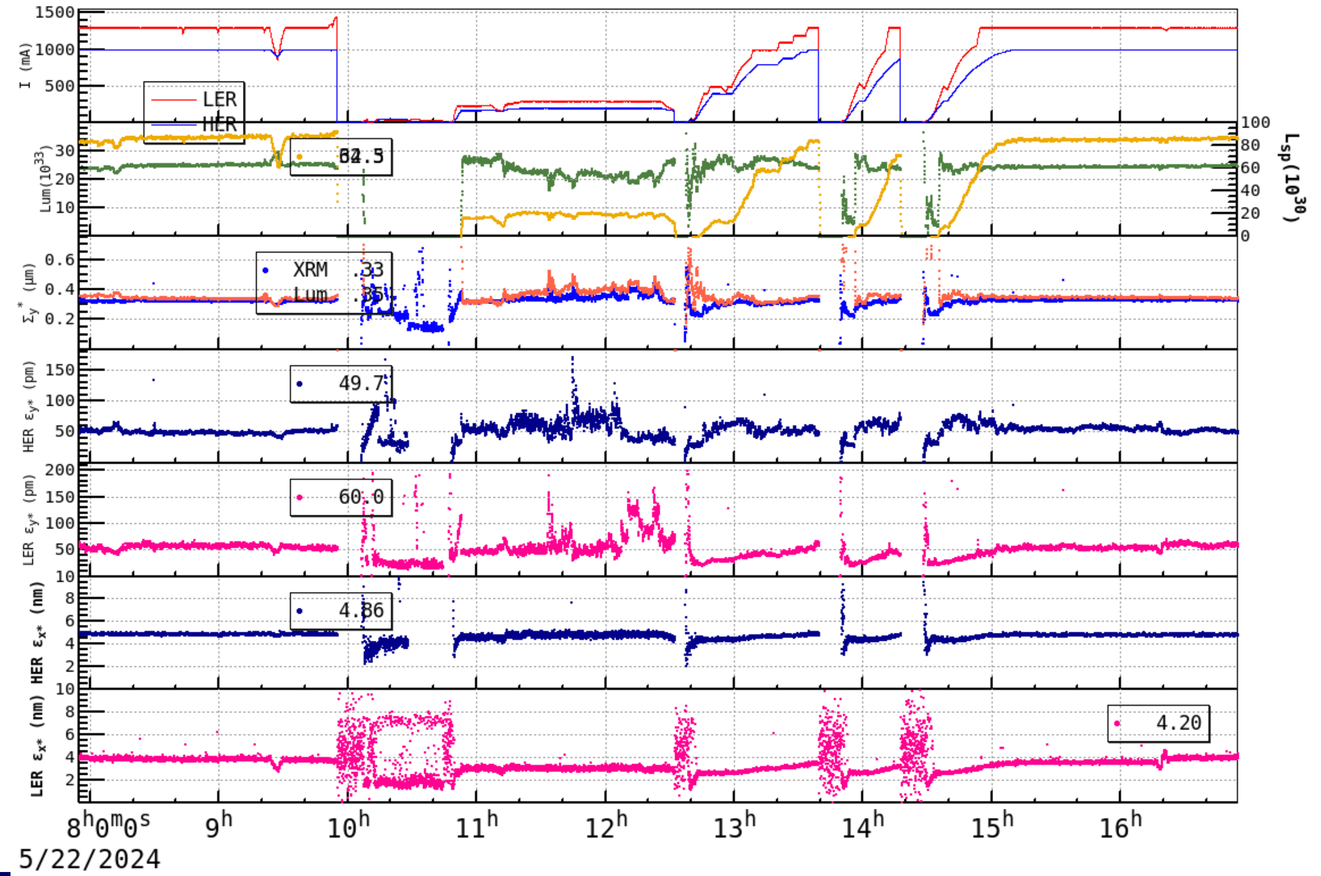








Collision with 393 bunches May 22nd 2024



Summary of tune survey

- The present working points of (ν_x,ν_y) = (.523, .580) (LER) and (.531, .575)(HER) at the end of 2024b run are near to the design value of (ν_x,ν_y) = (.530, .570) .
- To search for better working points for LER, which give a higher luminosity, a relatively wide-range (horizontal and vertical) tune survey was done. However, a better working point was not found.
- In the tune scan, the beam-beam and lattice resonance lines were clearly seen.
- At the present SuperKEKB, one of the most serious problem is that the total beam current of LER (and HER) (and the luminosity) is limited by the balance between beam injection and beam lifetime. Beam-beam effects affect beam injection efficiency and their effects depend on betatron tune. We need more tune survey in both simulations and experiment.

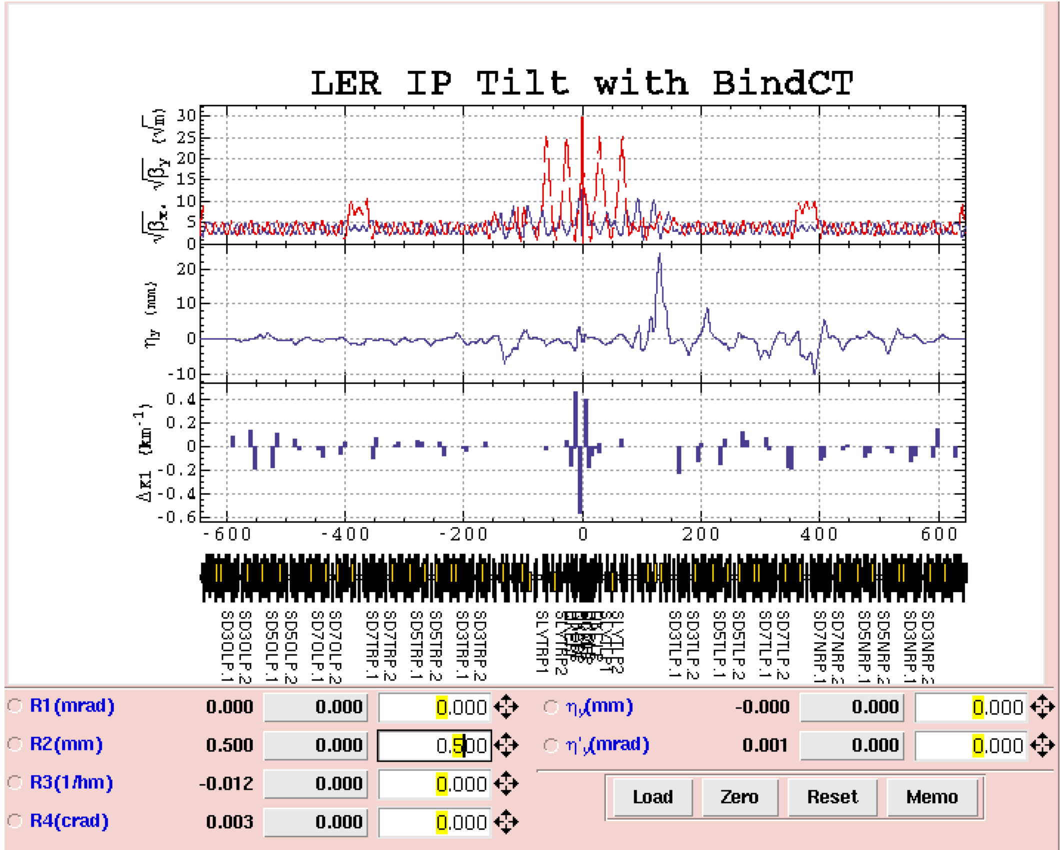
Luminosity tuning

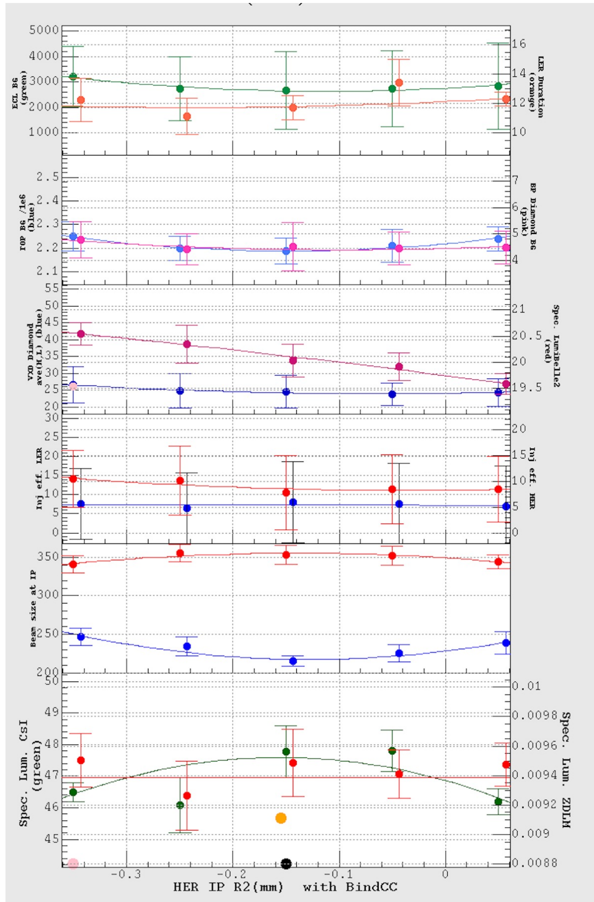
Luminosity tuning

- Machine tuning routinely done even during physics run on machine parameters

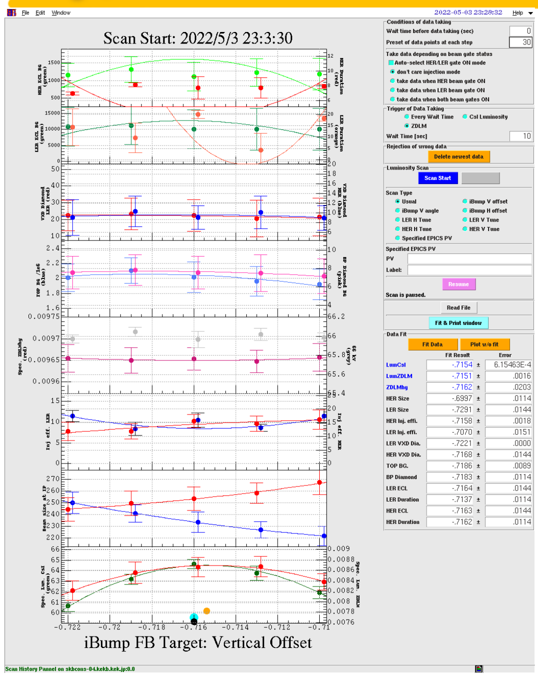
Tuning parameters	Observables	Typical frequency
Beam offset at IP (orbit feedback)	Beam-beam kick (BPMs)	FB
Target of orbit feedback at IP (offset)	vertical size at SRM, luminosity	~1/2 day
Global closed orbit	BPMs	~ 20 s
Betatron tunes	tunes of non-colliding bunches	FB ~ 20 s
Relative RF phase	center of gravity of the vertex	~ 10 min
Global coupling, dispersion, beta-beat	orbit response to kicks, RF freq.	~ 14 days
Vertical waist position	vertical size at SRM, luminosity	~ 14 days
x-y coupling and dispersion at IP	vertical size at SRM, luminosity	~ 1/2 day
Chromaticity of x-y coupling at IP	vertical size at SRM, luminosity	~ 14 days

Tuning knob on X-Y coupling at IP

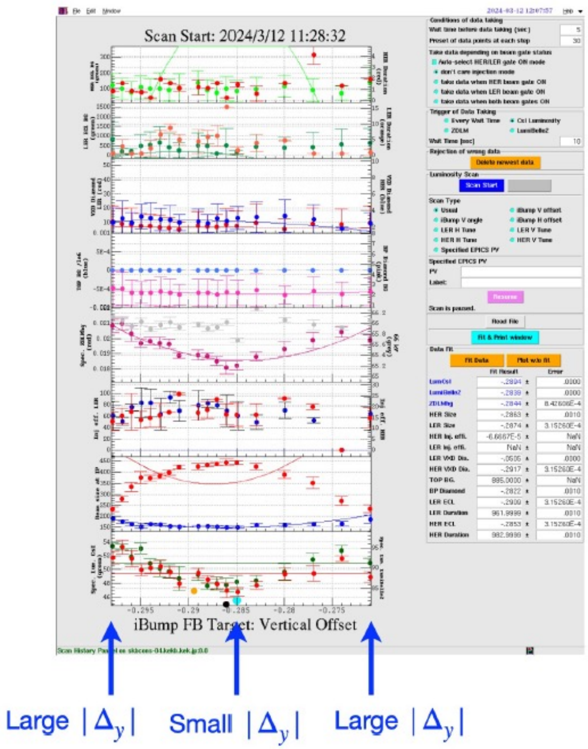




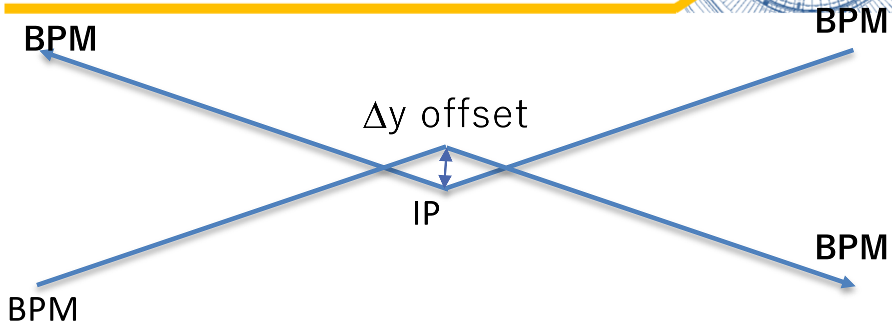
IP orbit feedback



Typical result of scan of target value of IP vertical orbit feedback.



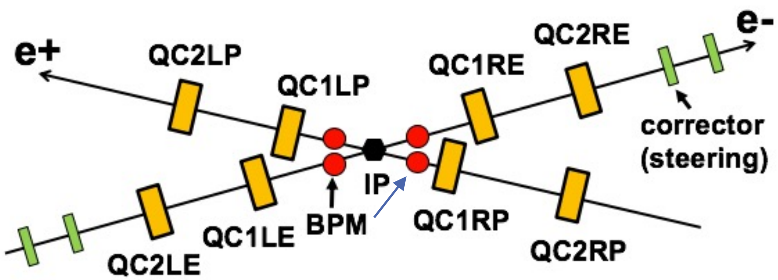
Scan of target value of IP orbit feedback in wider range (machine study)



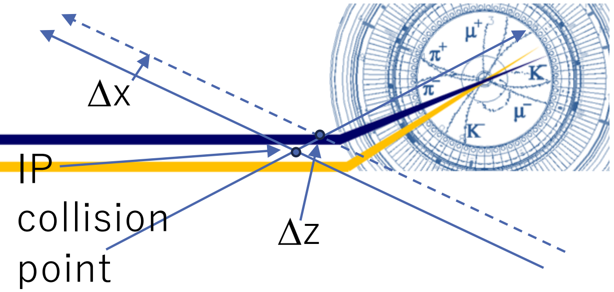
The orbit kinks due to beam-beam deflection with finite orbit offset is detected with BPM's near IP.

➔ The IP orbit feedback is created by relying on the beam-beam kick.

- Feedback repetition ~32kHz



Collision point (vertex position)



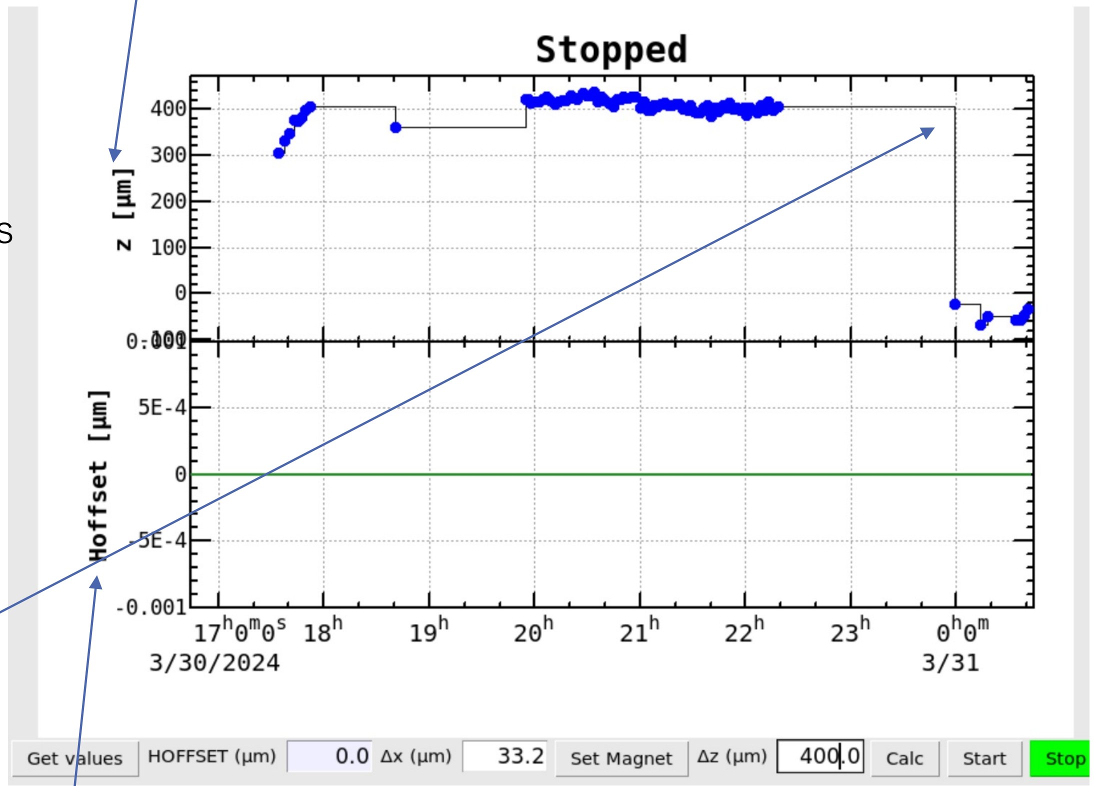
Beam collision point is controlled by horizontal orbit bump at IP.

The collision point is detected from the vertex point measured by Belle-II detector.

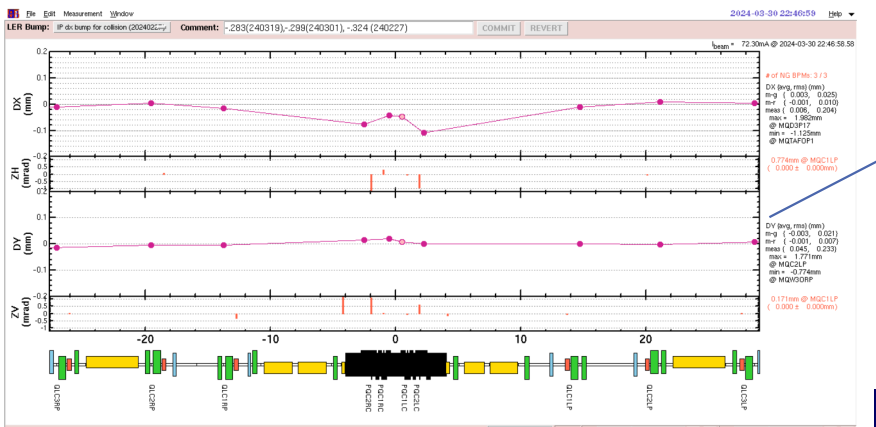
In this case, a horizontal bump at IP (below) was created in LER to adjust the collision point.

We also utilize a feedback to keep the collision point at around the optimum position.

Collision point (vertex point)



Horizontal bump height for feedback in HER



Calculation of beam-beam parameters

- **Definition**

$$\xi_{y\pm} = \frac{r_e}{2\pi\gamma_\pm}\frac{\beta^*_{y\pm}N_\mp}{(\sigma_{z\mp}\phi)\sigma^*_{y\mp}}$$

- **Incoherent beam-beam parameters ($\xi_{yi}(LER), \xi_{yi}(HER)$)**

$\sigma^*_{y\mp}$: from X-ray monitor, $\sigma_{z\mp}$: nominal bunch length (LER: 4.6 mm, HER: 5.1 mm)

- **Beam-beam parameters from luminosity($\xi_y(LER), \xi_y(HER)$)**
  - Assume beam sizes at IP are equal for both beams

$$L = \frac{1}{4\pi}\frac{N_+N_-}{\sigma_z\phi\sigma^*_y}N_b f_{rev} \Rightarrow \frac{N_-}{\sigma_z\phi\sigma^*_y} = L\frac{4\pi}{N_+N_b f_{rev}} = L\frac{4\pi e}{I_{beam+}} \Rightarrow \xi_{y+} = \frac{r_e}{\gamma_+}L\frac{2\beta^*_{y+}e}{I_{beam+}}$$

If the difference in σ_y* of the two beams are large, ξ_y from this calculation becomes much different from ξ_{yi}.

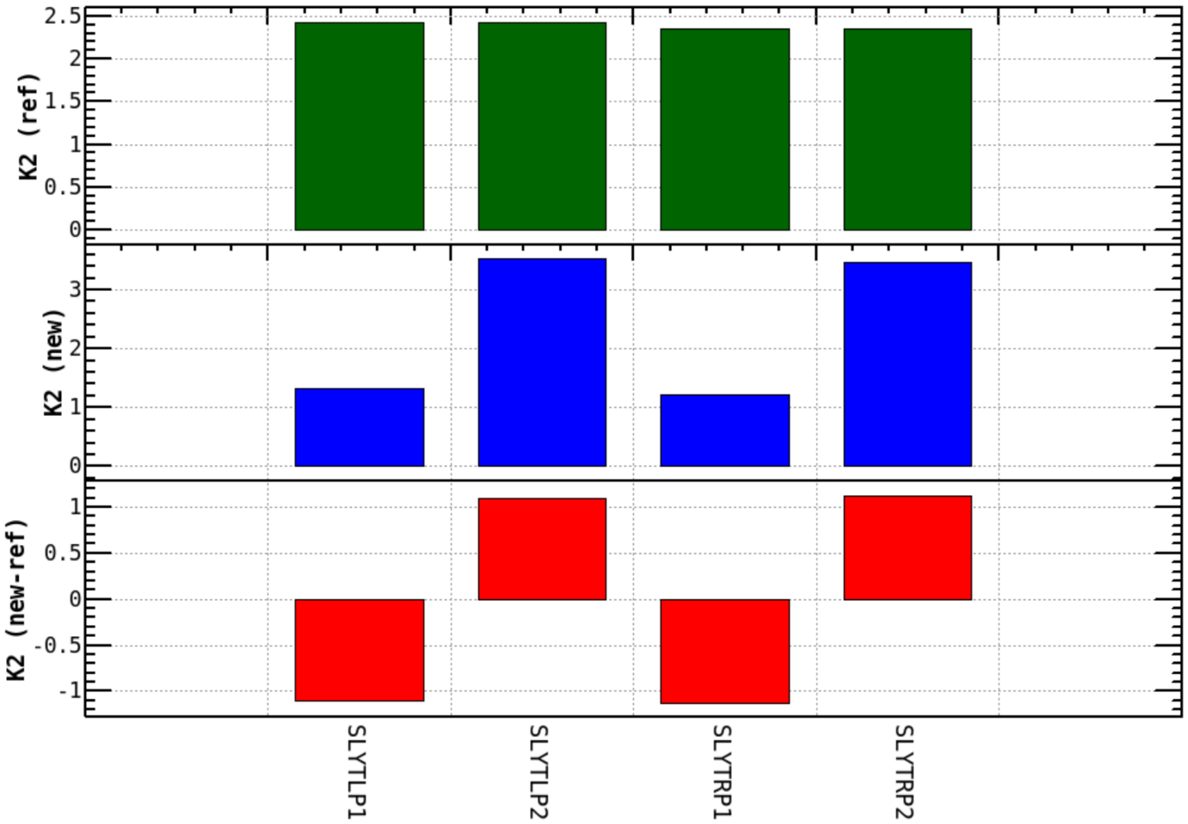
  - Another way for calculation

$$L = \frac{1}{2\pi}\frac{N_+N_-}{\sqrt{(\sigma_{z+}\phi)^2 + (\sigma_{z-}\phi)^2}\sqrt{\sigma^2_{y+} + \sigma^2_{y-}}}N_b f_{rev}$$

By using r=($\sigma_{y+}^*/\sigma_{y-}^*$) from X-ray monitor, σ_{y+}^* and σ_{y-}^* can be calculated from luminosity.
-> beam-beam parameters

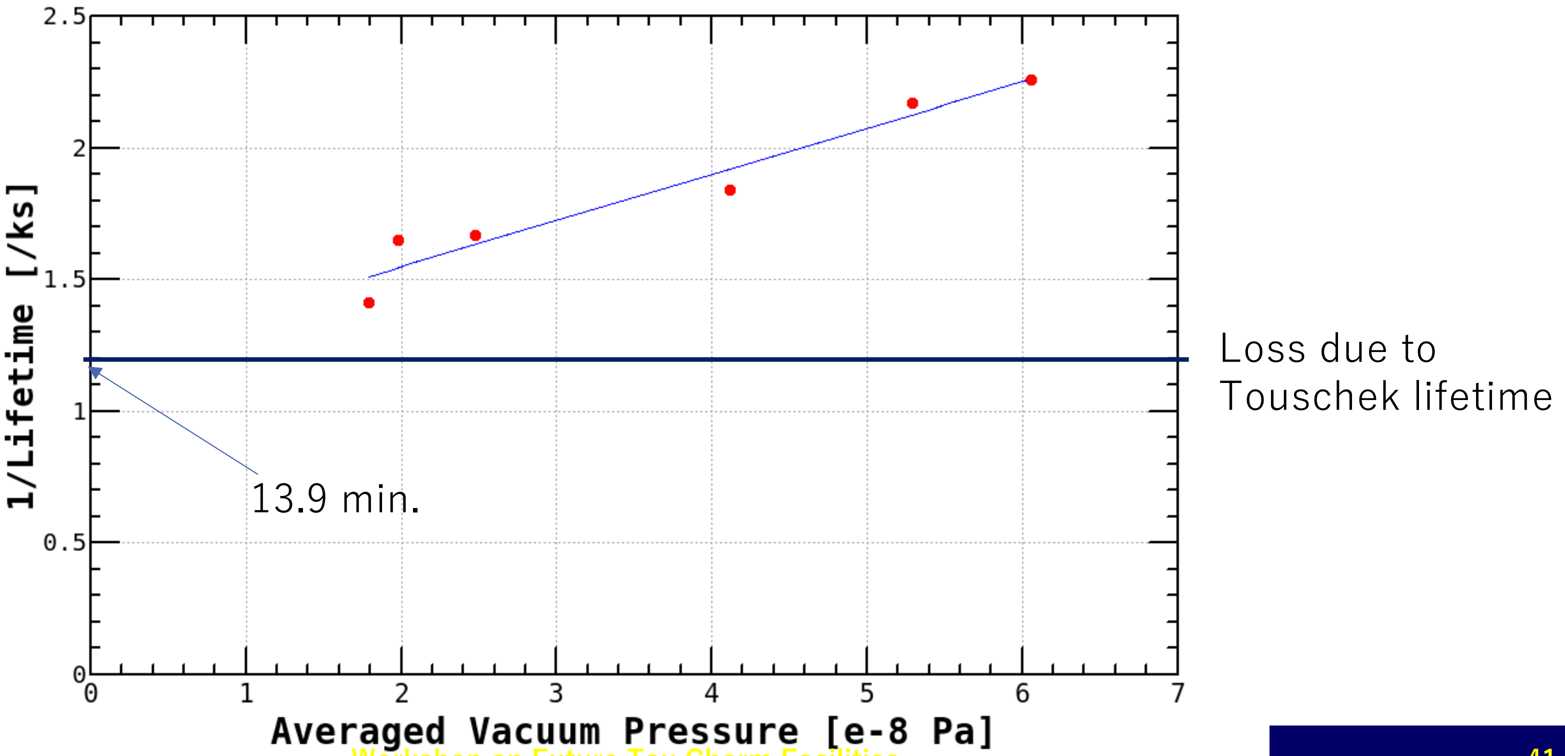
Crab waist sextupoles

LER: Crab waist ratio = 80%



Inverse of beam lifetime as function averaged vacuum pressure

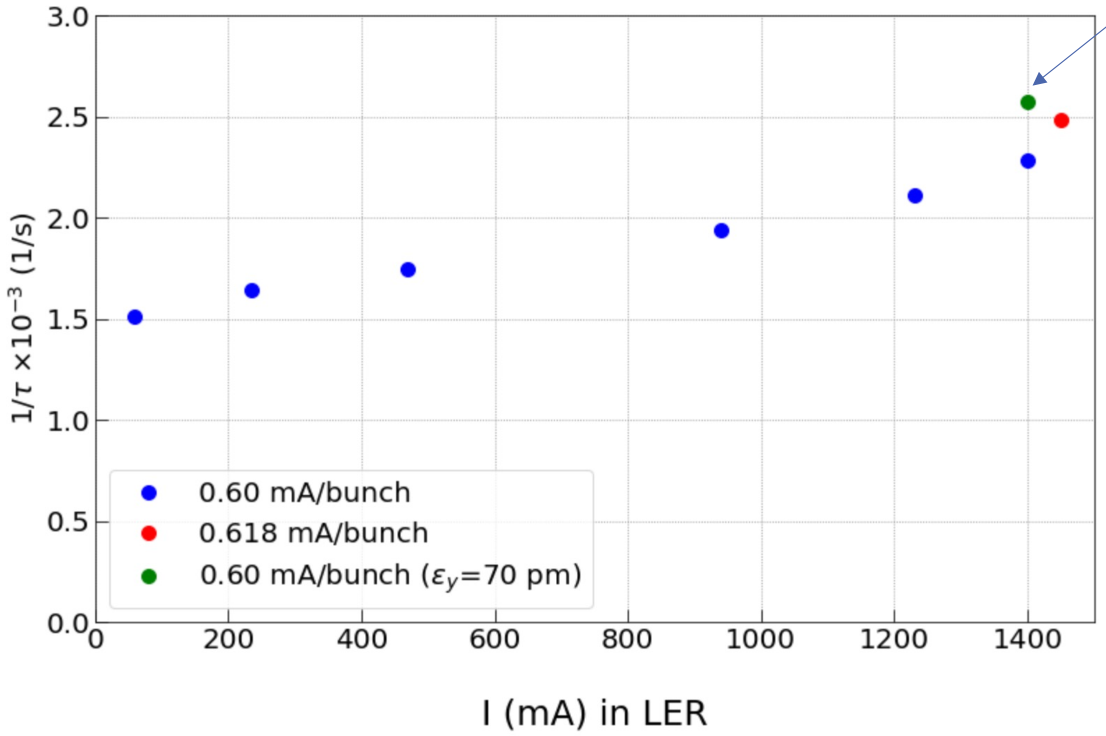
```
ChiSquare =  .03118  Goodness  =  .40601
ccc1 = 1.19754 +/-  .13169              ccc2 =  .17563 +/-  .03310

   Function = (ccc1+(ccc2 x))
```

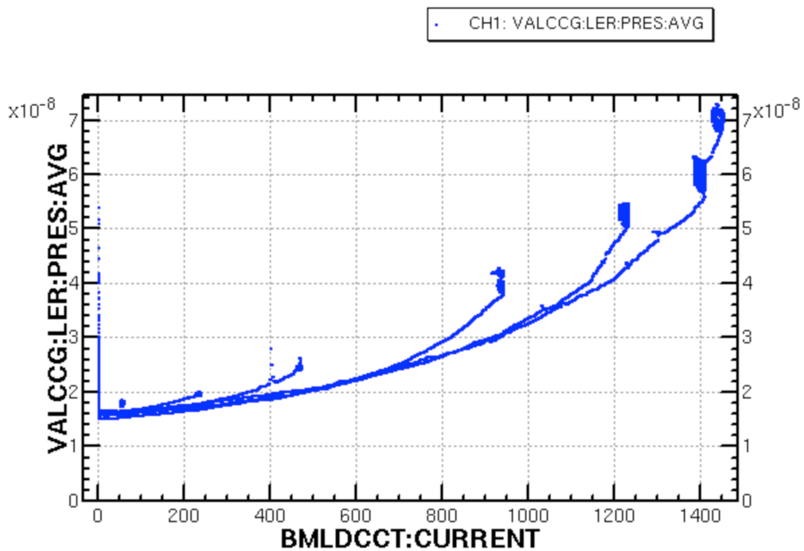


Beam lifetime as function of total beam current with keeping the bunch current

- LER lifetime study
  - Number of bunches is increased by keeping the bunch current to be 0.6 mA.
  - measure the lifetime with 97, 393, 783, 1565, 2053, and 2346 bunches.

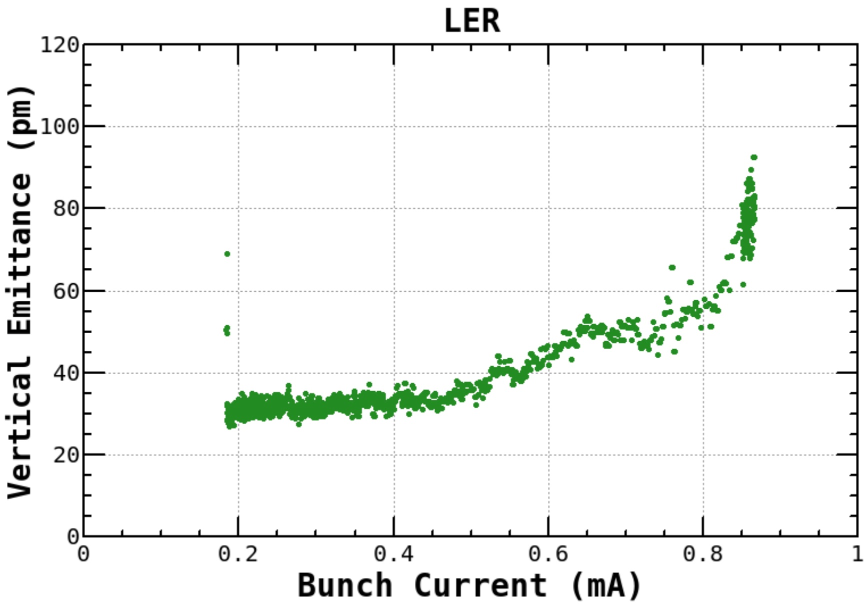
Beam lifetime decreased with larger vertical emittance.
Emittance was changed by using YaECK.

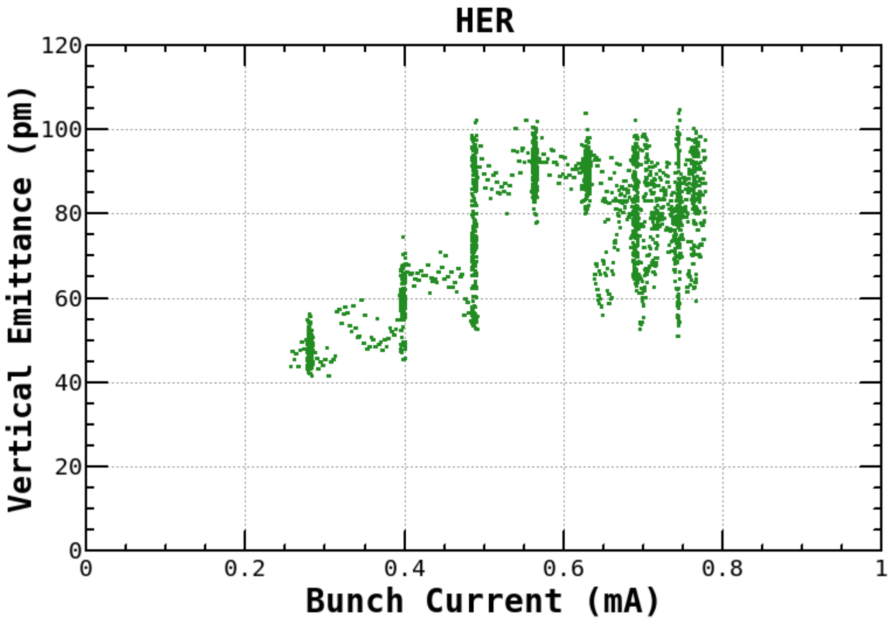




Beam sizes (single beam) on June 27th 2024

2024 June 27th $\beta y^* = 0.9$mm

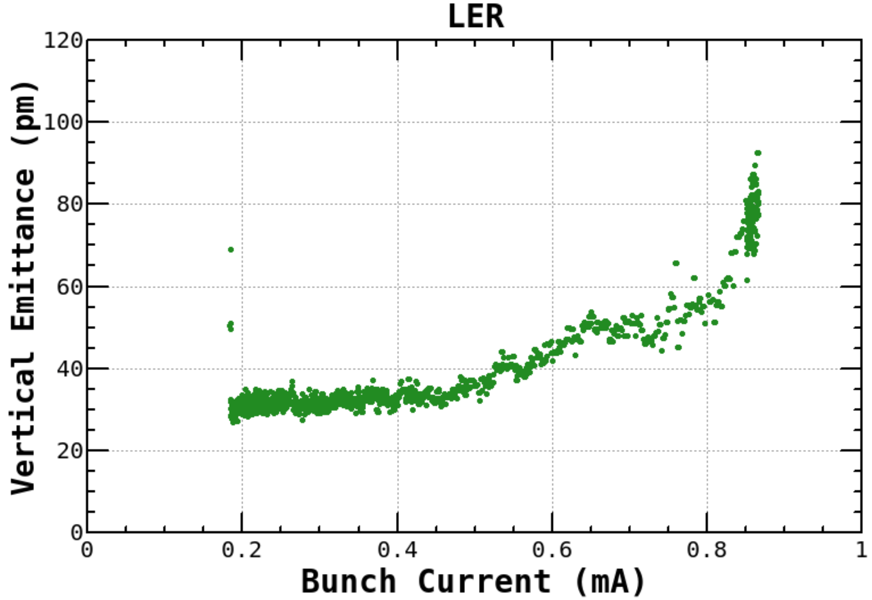




The single beam blowup must be suppressed for a higher luminosity.

Comparison of LER single beam emittance (before and after LS1)

2024 June 27th $\beta y^* = 0.9$mm



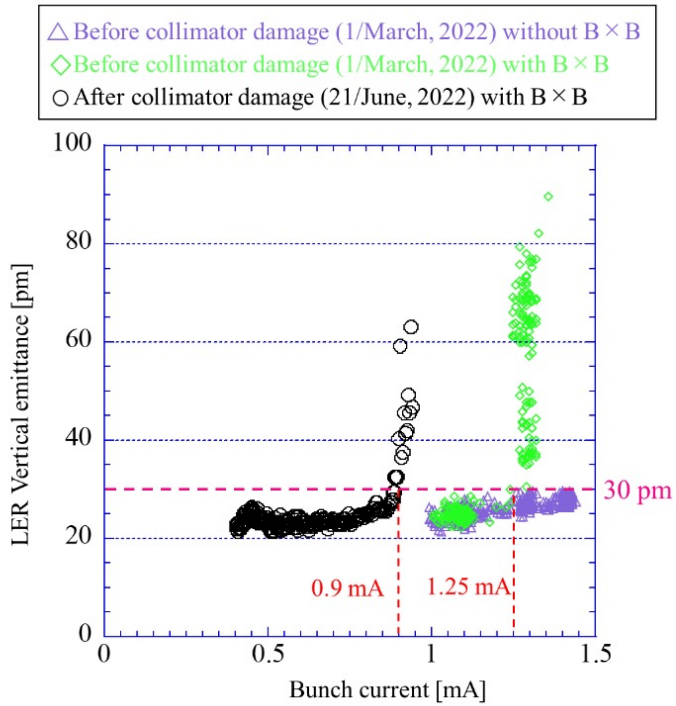
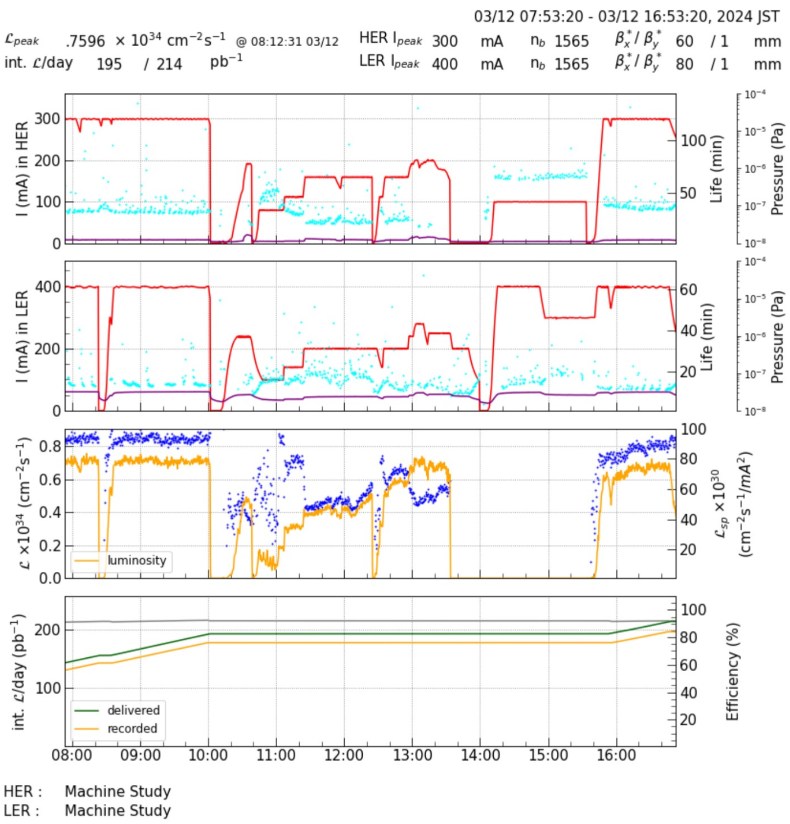


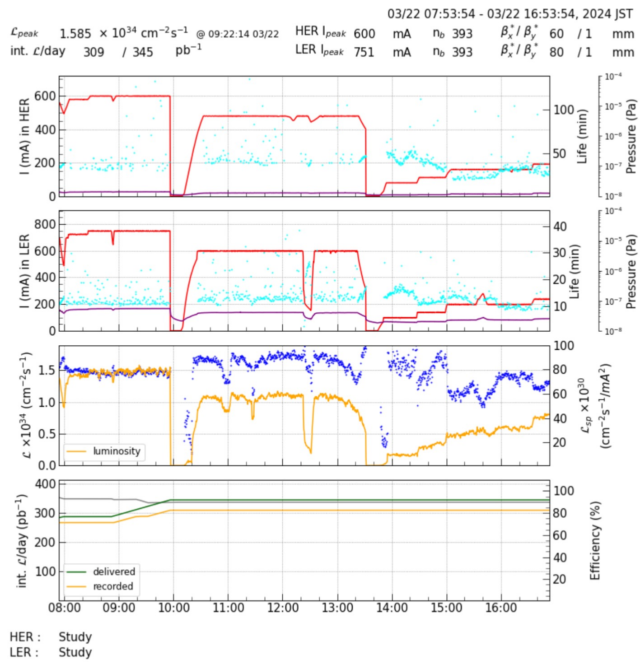
FIG. 10. The vertical beam emittance versus bunch current with $\beta_y^* =$ 1 mm, before (green diamonds) and after (black circles) the event of collimator jaw damage with BxB feedback on. The data of purple triangles show the measurement with BxB feedback off.

Beam-Beam Study

Shift summary



Shift summary



Shift summary