Beam-beam related issues at SuperKEKB

Y. Funakoshi, K. Ohmi, Y. Ohnishi, H. Sugimoto, Y. Yamamoto, D. Zhou

2024.10.07

B2GM

Contents

- Beam-Beam force
- Crab waist
- Specific luminosity and beam-beam parameters
- Beam injection
- Effect of bunch-by-bunch feedback system
- Tune survey
- Beam-beam simulations

Beam-beam force

Terminology

- Bunch current
  - Total beam current / number of bunches
- Specific luminosity
  - Peak luminosity / number of bunches/ LER bunch current / HER bunch current
- Beam-beam parameter (beam-beam tune shift)
  - To be explained in the following slides

Beam-beam force (2 dimensions)

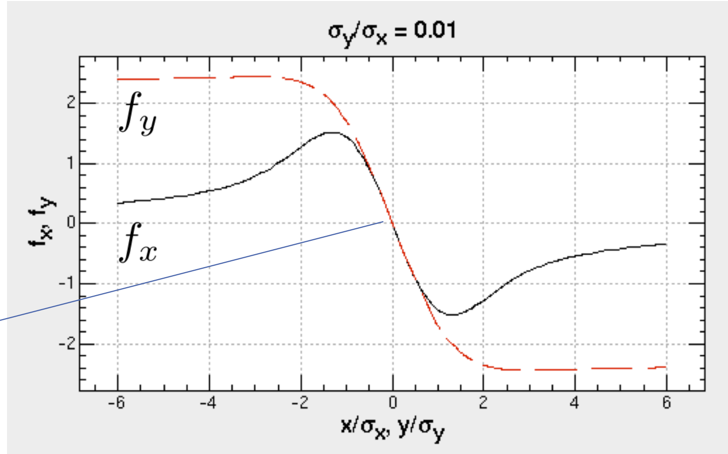
- When the beam is Gaussian:

Bassetti-Erskine formula

$$f_y + i f_x = -\frac{N r_e}{\gamma}\sqrt{\frac{2\pi}{\sigma_x^2-\sigma_y^2}}\left[w\left(\frac{x+iy}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right) - \exp\left(-\frac{x^2}{2\sigma_x^2}-\frac{y^2}{2\sigma_y^2}\right) w\left(\frac{\frac{\sigma_y}{\sigma_x}x + i\frac{\sigma_x}{\sigma_y}y}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right)\right]$$

$$w(z) \equiv \exp(-z^2)\left\{1-\mathrm{erf}(-iz)\right\}$$

(w: complex error function)



Q-force (focusing force) near zero-offset

↓

Q-force is represented by K-value.

$$r_e = \frac{e^2}{4\pi\varepsilon_0 mc^2}$$

↓

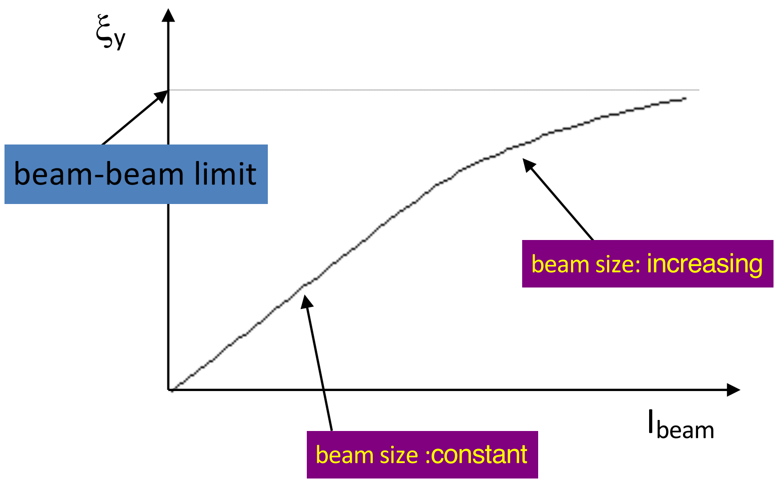
Q-force makes tune shift: $\Delta\nu_{x,y} = K_{x,y}\beta_{x,y}/(4\pi)$ ⟹ Beam-beam tune shift (or beam-beam parameter): $\xi_{x,y}$

Beam-beam parameters

- Beam-beam parameter (tune shift)

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

$$\xi_{y\pm} = \frac{r_e}{2\pi\gamma_\pm} \frac{\beta^*_{y\pm} N_\mp}{\sigma^*_{x,eff\mp}\sigma^*_{y\mp}}$$ Nano-beam scheme



- Effective $\sigma^*_{x,eff}$ in nano-beam scheme

$$\sigma^*_{x,eff\pm} = \sigma_{z\pm} Sin\phi$$

- Beam-beam parameters may saturate at some value due to vertical beam size blowup (beam-beam limit).
- Beam-beam parameters are global parameters across different colliders.
- Its maximum value is an indicator of the beam-beam performance of each collider.
- Maximum beam-beam parameters can be increased by beam tuning.

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}.

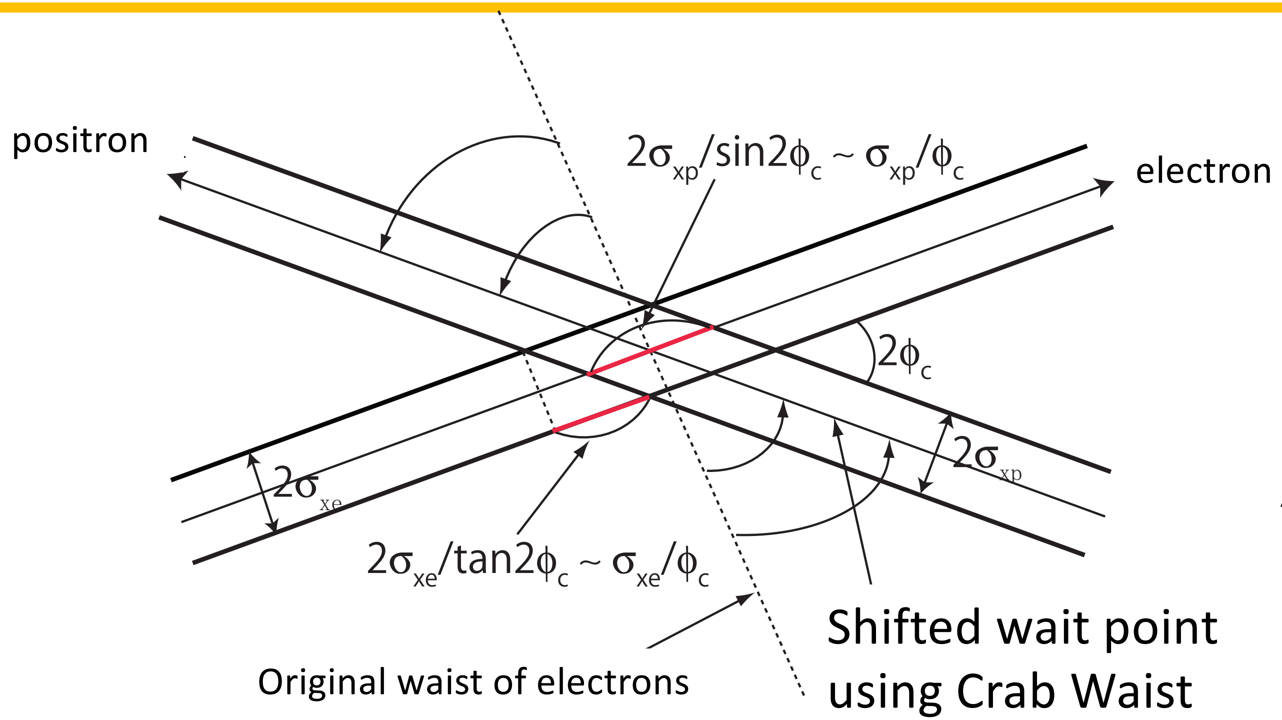
  - Another way for calculation

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

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

What is Crab Waist?



$$L_{\text{cross}} \cong \frac{\sigma^*_{xp}}{\phi_c}$$

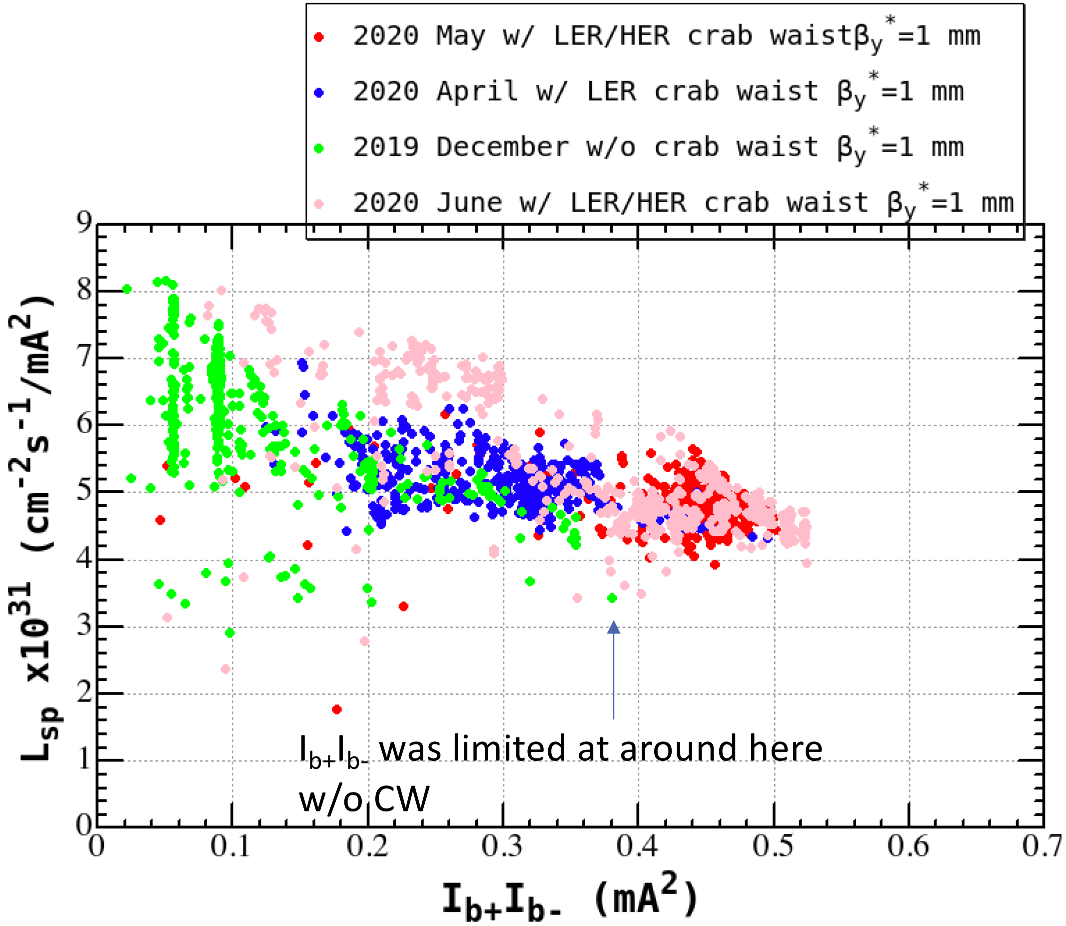
$$\Delta s_{\text{waist}} \cong \frac{\sigma^*_{xe}}{\phi_c}$$

As a result of large crossing angle、 a particle with horizontal offset collides with the center of the other beam where the β_y is larger than its minimum point (waist). -> another kind of hourglass effect
``Crab Waist" is to compensate this effect.

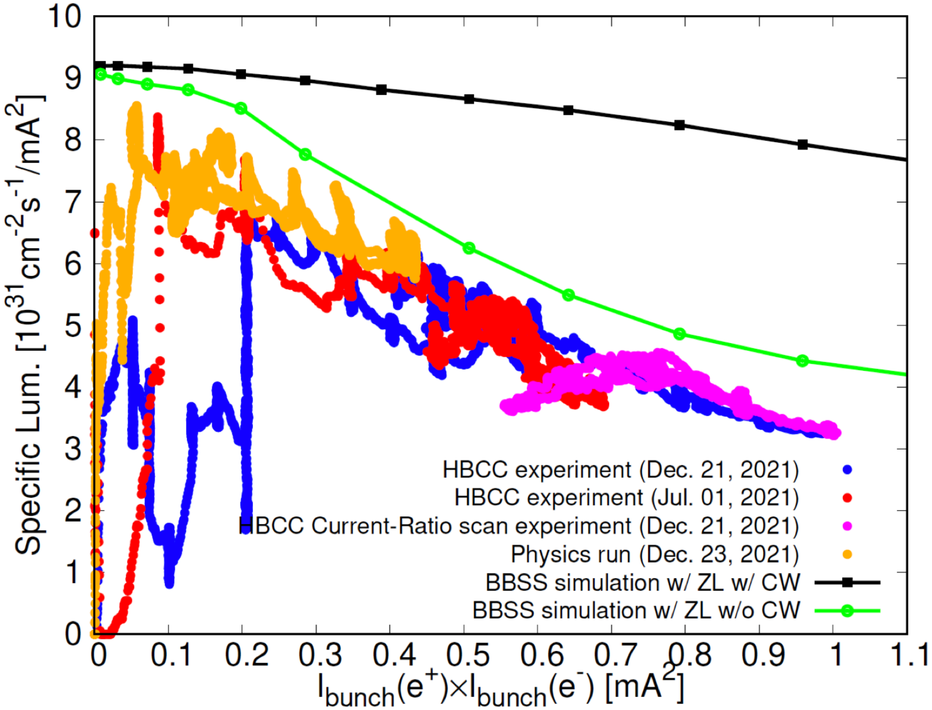
Crab waist scheme

- 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%)
    - 2030 June 1st : LER crab waist (80%)

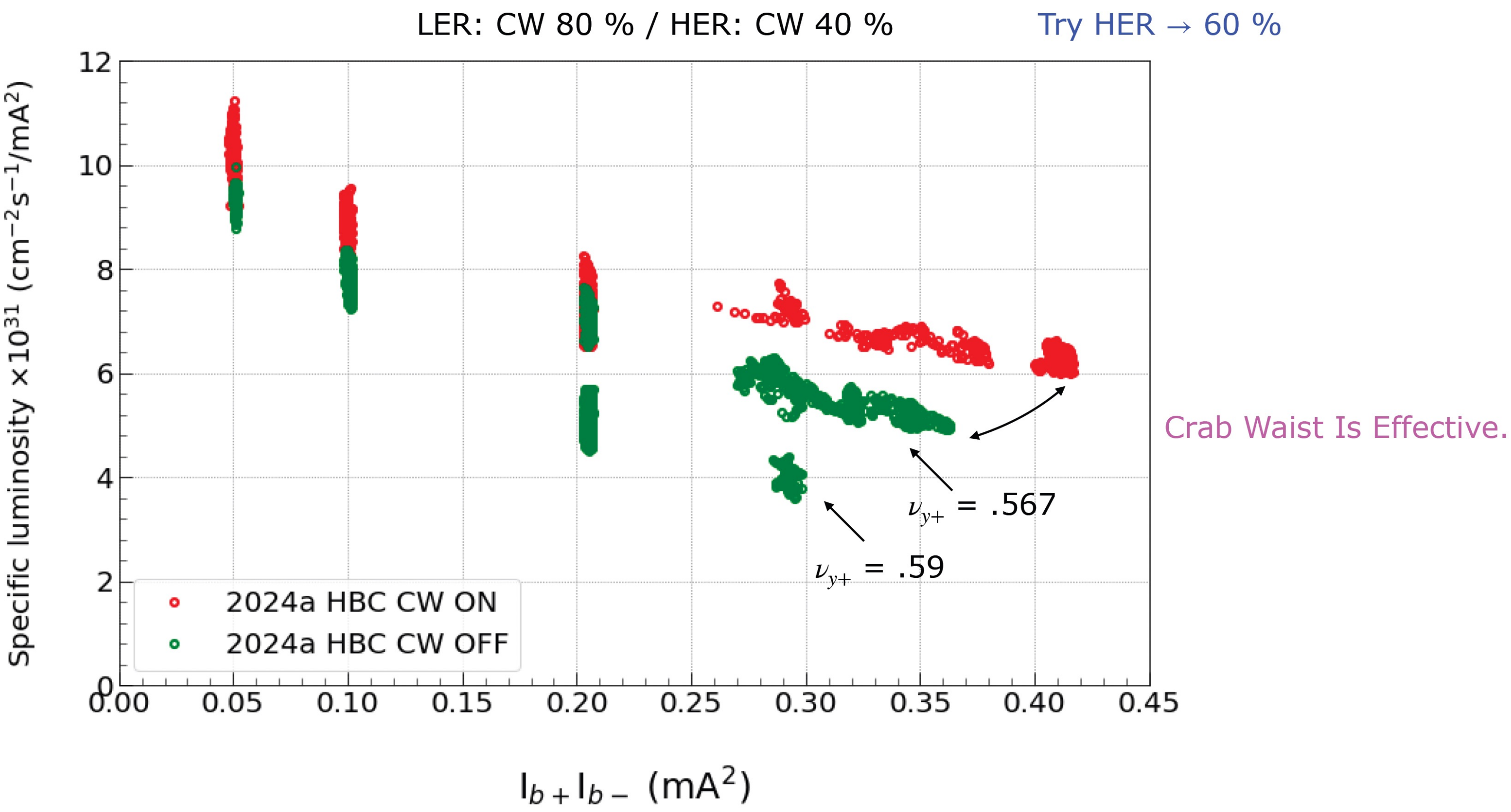
Specific luminosity w/ and w/o crab waist



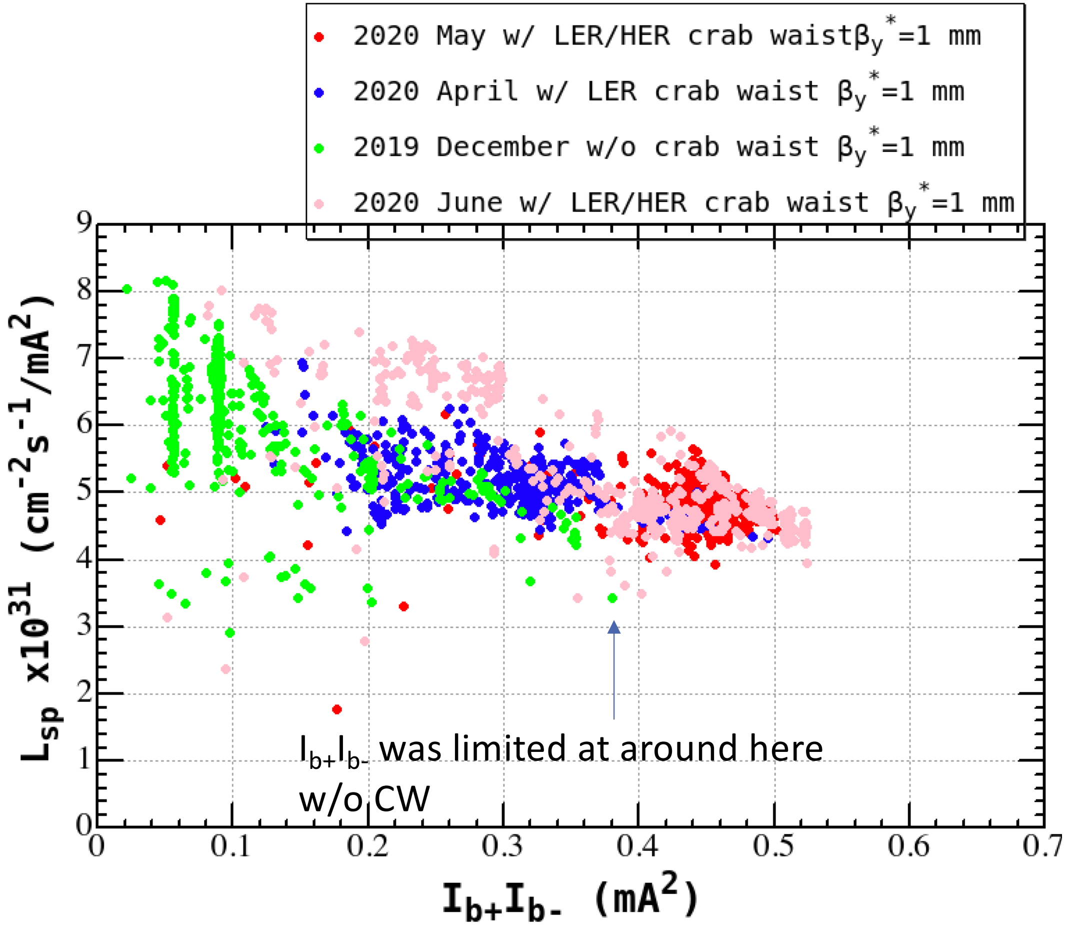
Strong-Strong Beam-Beam simulation (D. Zhou)

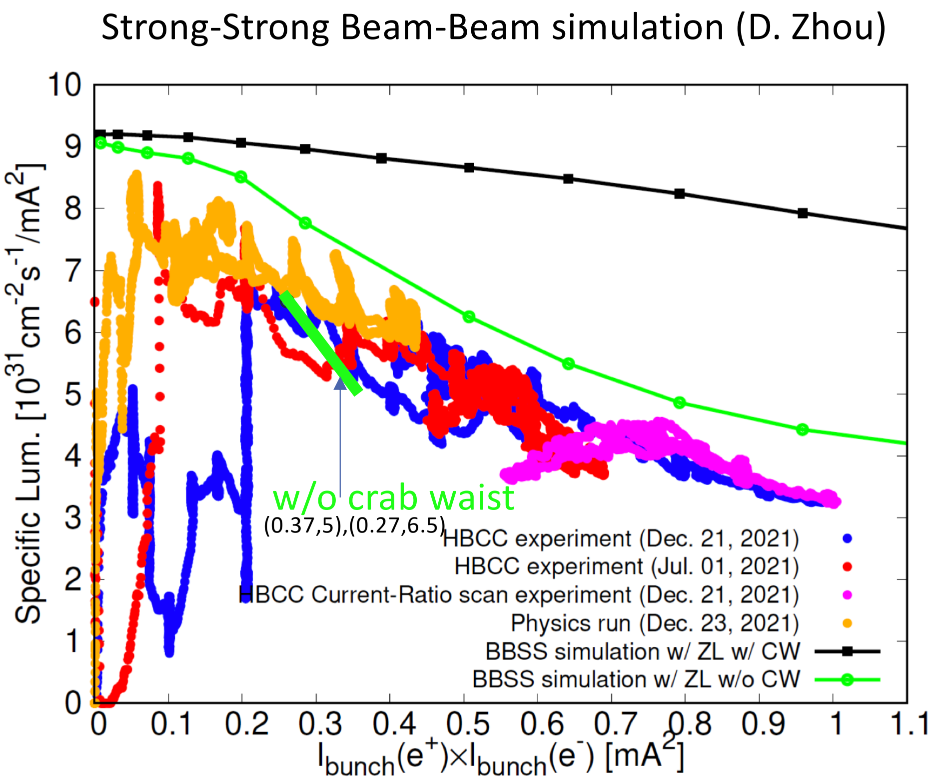


Crab waist ON and OFF (2024)



Specific luminosity w/ and w/o crab waist



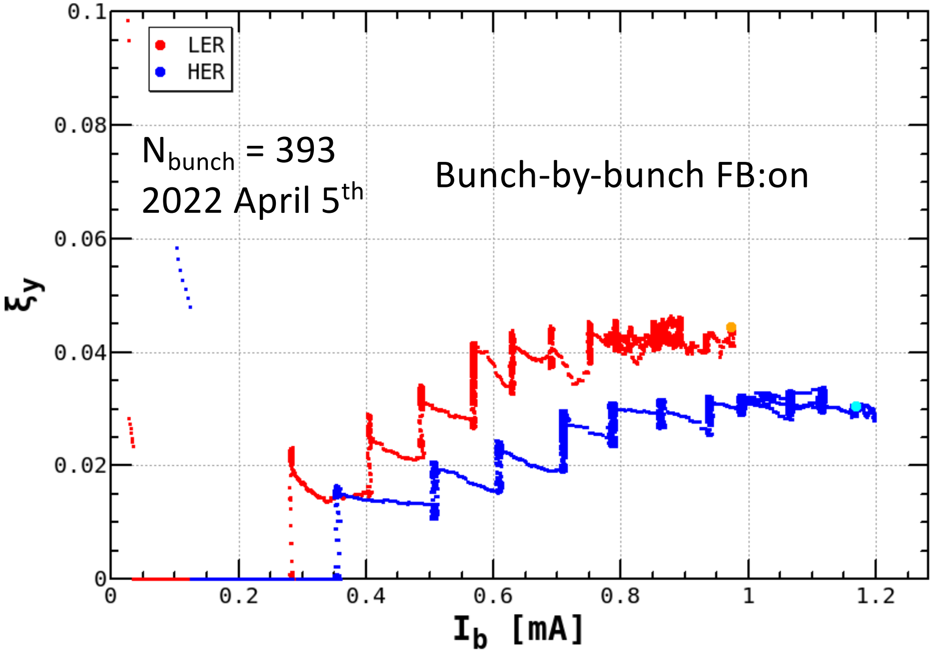


Summary of crab waist scheme

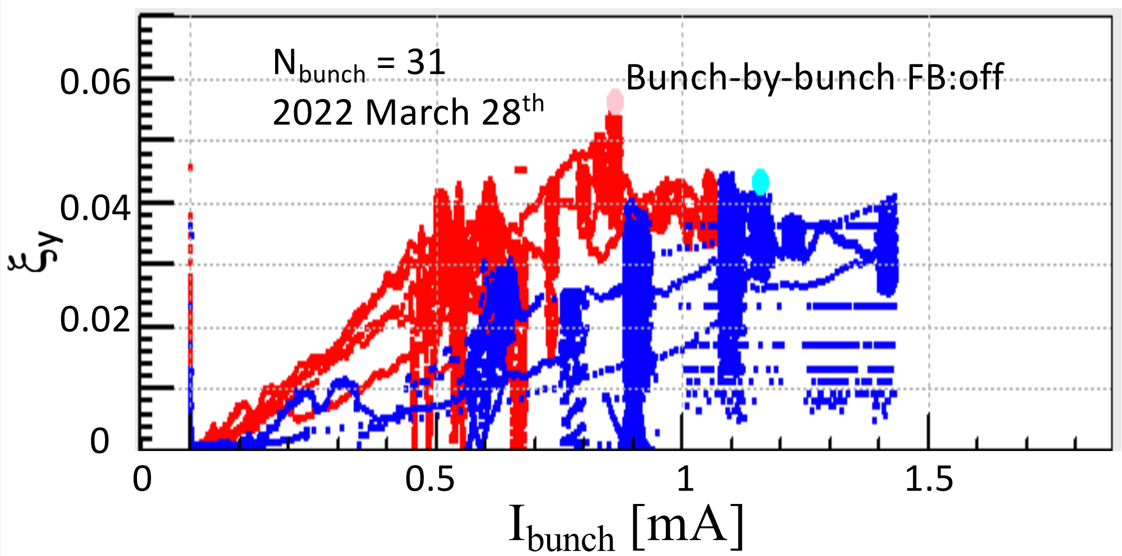
- Benefits of use of crab waist scheme
  - Suppression of beam-beam blowup
    - Specific luminosity was improved. The gain of the luminosity with CW is about 30 % at $0.35 mA^2$.
  - Increase of the bunch currents of both beams
    - W/o crab waist, beam injections was limited due to bad injection efficiency.
- 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, maybe since the collimator physical aperture is already very narrow.
    - In case of lower βy^*, the lifetime w/ crab waist will be an issue.

Specific luminosity and beam-beam parameters

Beam-beam parameters

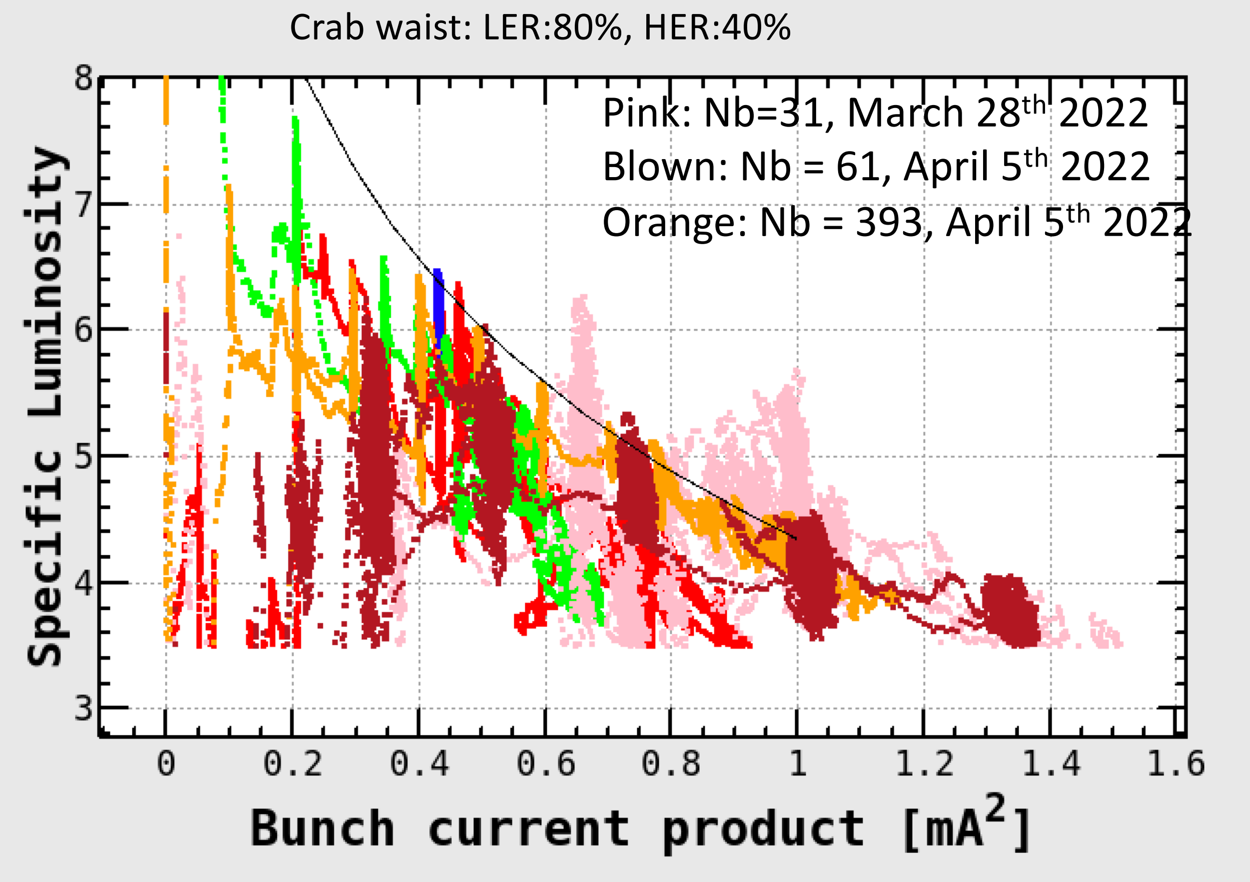


Vertical beam-beam parameter (ξ_y) of HER is saturated around 0.03.

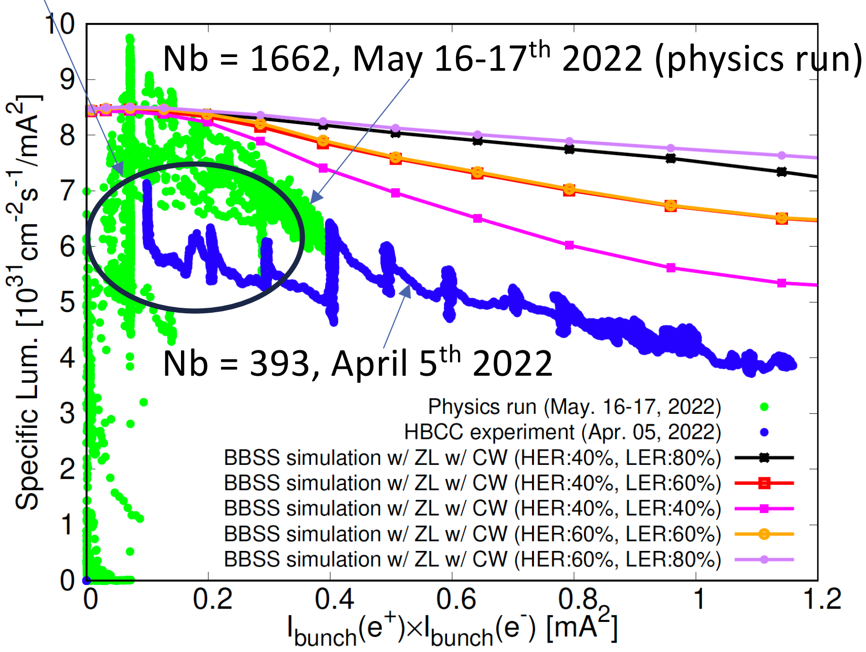


With smaller number of bunches (31 bunches), which allowed us to switch FB off, ξ_y of HER reached ~0.043. This is the highest value achieved ever at SuperKEKB.

Specific luminosity

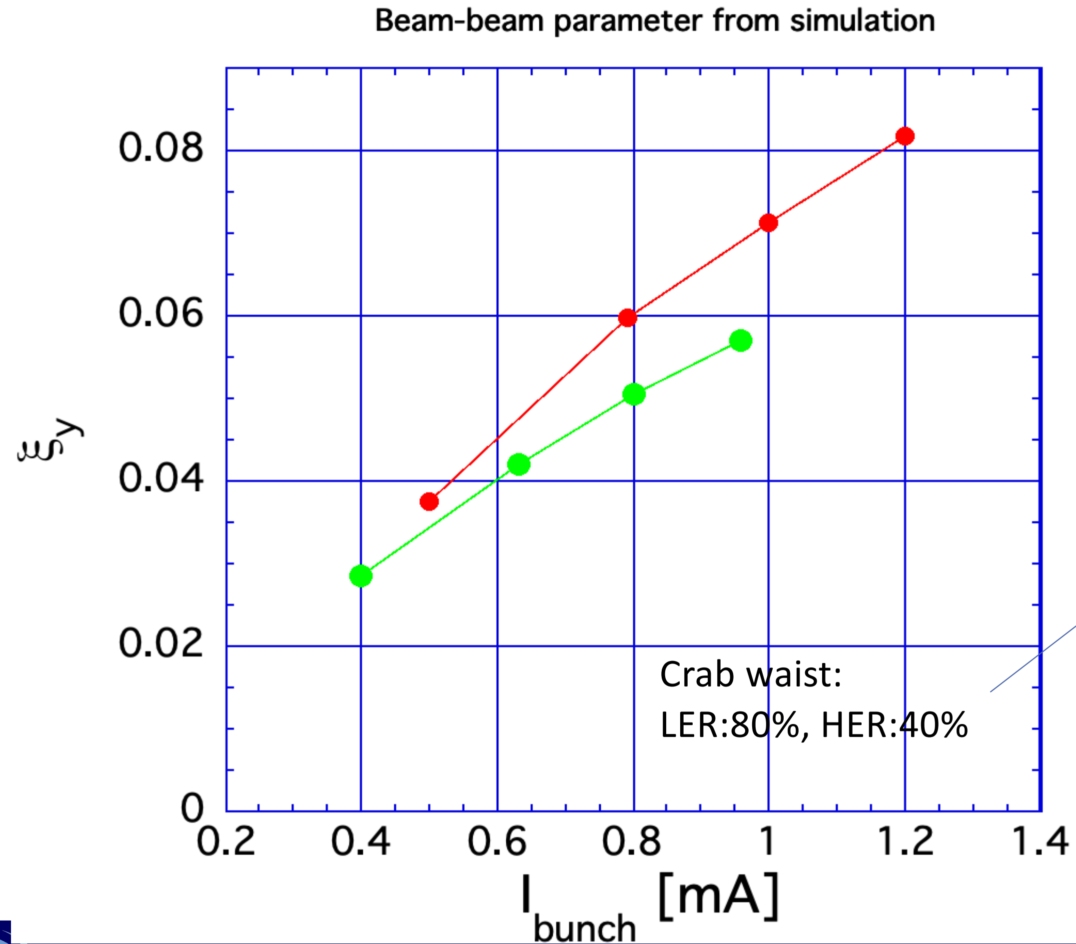


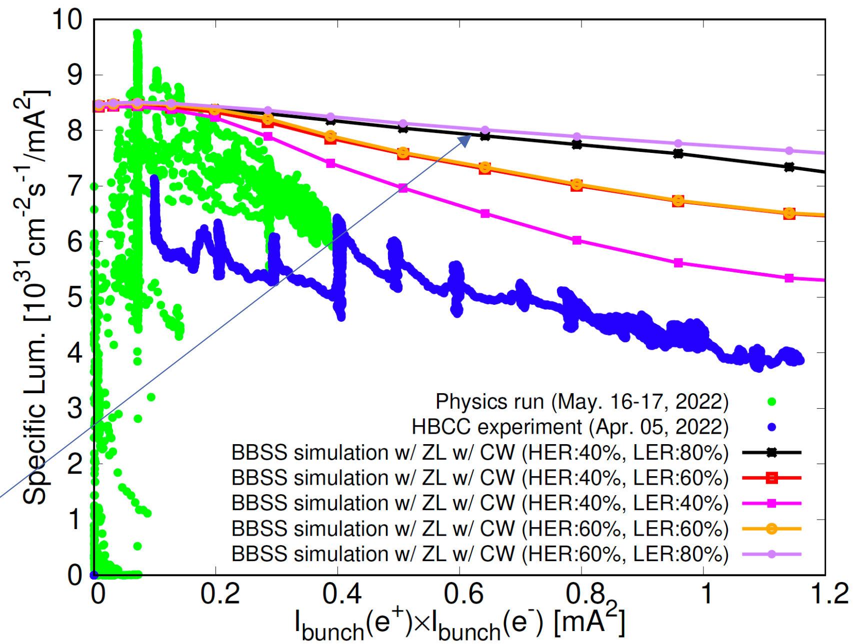
Machine tuning was not enough for April 5th study.



There is a big discrepancy between simulation and experiment. This issue is very serious.

Beam-Beam Parameter calculation from simulation



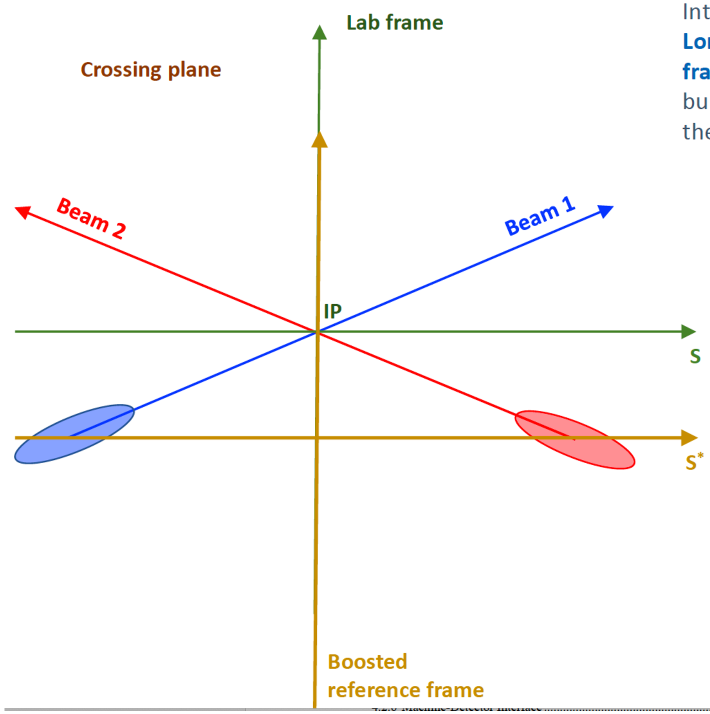


Summary of Specific luminosity and beam-beam parameters

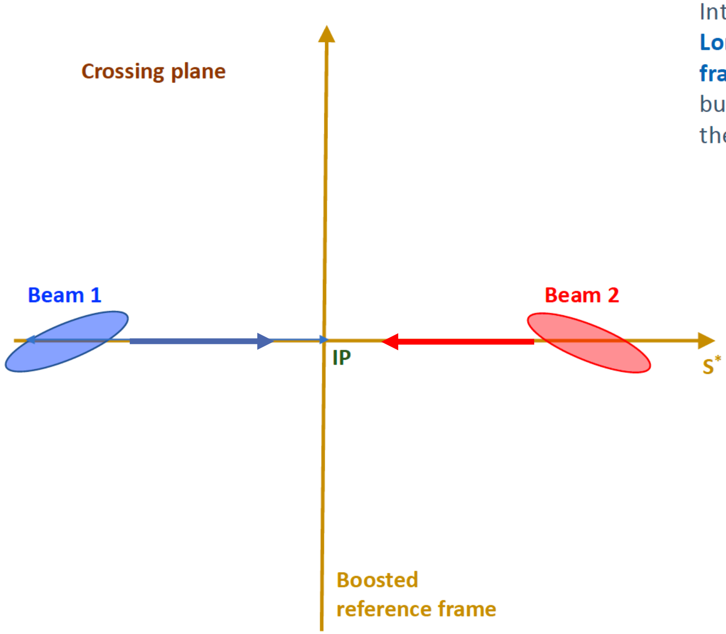
- The achieved specific luminosity at a higher bunch current product (~> 1 mA2) is about a half of the strong-strong simulation (w/ longitudinal wake).
  - To identify the cause for this is very important for SuperKEKB.
- In high bunch current collision (HBCC) experiment ,vertical beam-beam parameters (ξ_y) of HER and LER seems to be saturated at around 0.03 and 0.045, respectively.
- With FB off, the specific luminosity was improved and the Vertical beam-beam parameters (ξ_y) of HER and LER obtained were 0.0434 and 0.0565, respectively.

Simulations on beam-beam effects

Boosted frame



Interaction is computed in a **Lorentz-boosted reference frame** in which the two bunches are moving along the same direction



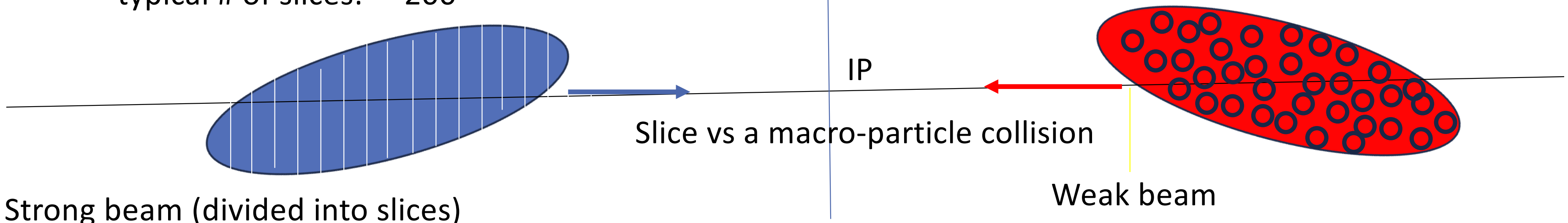
Interaction is computed in a **Lorentz-boosted reference frame** in which the two bunches are moving along the same direction

G. Iadarola

Strong-weak and strong-strong simulations

- Strong-weak simulation

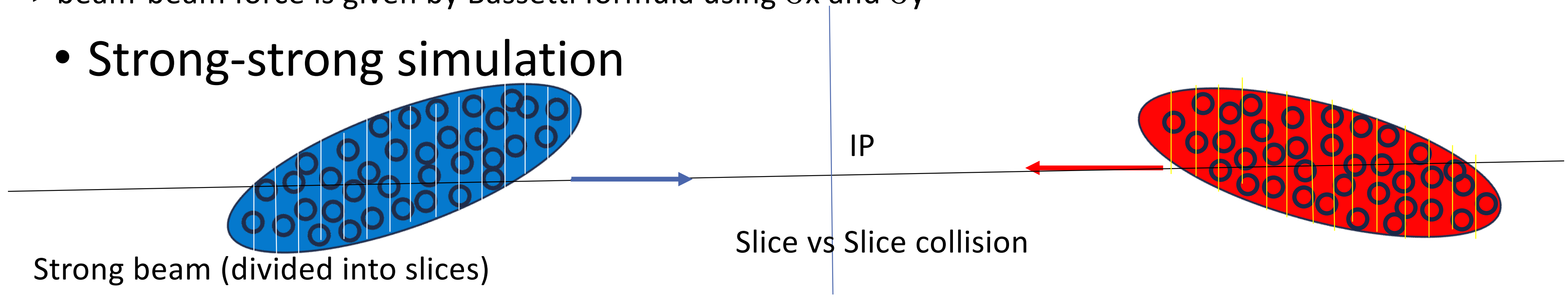
typical # of slices: ~ 200



Strong beam (divided into slices)
Each slice has rigid gaussian shape
-> beam-beam force is given by Bassetti formula using σx and σy

Weak beam
represented by macro particles
(typical # of macro particles: 100 ~ 10^6)

- Strong-strong simulation



Strong beam (divided into slices)
Each slice represented by macro particles
Beam-beam force is given by Bassetti formula by doing gaussian fit after each slice-slice collision (soft gaussian method) or by solving 2D Poisson equation using particle density distribution deposited on the grid cells (X-Y plane) (PIC method)

Parameters of recent strong-strong simulation (K. Ohmi) using BBSS

BBSS input

```
&HERING
  circumfh=3016.26, emxh=4.6e-9, emyh=25.e-12, emzh=2.95e-6,
   dmpxh=1.736E-4, dmpyh=1.736E-4, dmpzh=3.47E-4,
   twissh=0., 0.06, 45.532, 0., 0.0009, 43.573, 0., 8.54, 0.027   &END
 &LERING
   circumfl=3016.24, emxl=4.e-9, emyl=25.e-12, emzl=3.47e-6,
   dmpxl=2.203E-4, dmpyl=2.202E-4, dmpzl=4.403E-4,
   twissl=0., 0.08, 44.525, 0., 0.0009, 46.589, 0., 7.2, 0.023, &END
 &ebeam    emass=510999.06, rne=5.e10, Ee=7.0e9  &end
 &pbeam    pmass=510999.06, rnp=6.25e10, Ep=4.e9 &end
 &ip    xangle=0.0415,
   cwl=0.,0.,0.,0.,0.,0.,   0.,0.,0.,0.,0.,0.,   0.,0.,9.64,0.,0.,0.
   cwh=0.,0.,0.,0.,0.,0.,  0.,0.,0.,0.,0.,0.,   0.,0.,7.23,0.,0.,0.
 &end
```

```
&wake_h
     Zwrangeh=0.0384, nizh=512,
     fWkh='W2021c_HER.dat‘ &end
&wake_l
     Zwrangel=0.0384, nizl=512,
     fWkl=‘W2021c_LER.dat‘   &end
&meshsize
  dx=4.E-6,dy=0.04E-6,   &end
&model
   ne=1200000, np=1200000, nturn=5000,
   nslice=120, itmon=100, col3d=3,
   gaussmodel=.true. &end
```

# of macro particles = 1.2 x 10^6

# of slice = 120, soft gaussian method

Twiss= α_x,β_x,ν_x , α_y,β_y,ν_y , α_z,β_z,ν_z ,

emz=$\sigma_z\ \sigma_\delta$ twiss(8)= $\beta_z = \sigma_z/\sigma_\delta$

Tools

Tool	Weak-strong 6D	Quasi-strong-strong 6D	Strong-strong 6D SG	Strong-strong 6D PIC	Beamstrahlung	Bhabha-scattering	Transverse wakefields	Longitudinal wakefields	Linear tracking	Lattice tracking	Open source	Runs on GPU	
GUINEA-PIG [2]	Available	Not available	Not available	Available	Available	Available	Not available	Not available	Not available	Not available	Available	Not available	Linear colliders
COMBI [3]	Available	Available	Available	Available	Not available	Not available	Available	Not available	Available	Not available	Available	Not available	CERN LHC
BBWS [4]	Available	Not available	Not available	Not available	Available	Not available	Available	Available	Available	Available	Not available	Not available	KEK Ohmi
BBSS [5]	Not available	Not available	Available	Available	Available	Not available	Available	Available	Available	Not available	Not available	Not available	KEK Ohmi
SCTR [6]	Not available	Not available	Available	Available	Available	Not available	Available	Available	Available	Available	Not available	Available	KEK Ohmi
IBB [7]	Not available	Not available	Available	Not available	Available	Not available	Available	Available	Available	Not available	Not available	Not available	IHEP
LIFETRAC [8]	Available	Available	Not available	Not available	Available	Not available	Not available	Not available	Available	Available	Not available	Not available	BINP
BeamBeam3D [9]	Available	Not available	Available	Available	Available	Not available	Available	Not available	Available	Not available	Available	Not available	LBL
Xsuite [10]	Available	Available	Available	Not available	Available	Available	Available	Available	Available	Available	Available	Available	CERN

Available | Not available

[2] D. Schulte https://cds.cern.ch/record/331845/files/shulte.pdf

[3] T. Pieloni, W. Herr https://accelconf.web.cern.ch/p05/PAPERS/TPAT078.PDF

[4] K. Ohmi https://indico.cern.ch/event/438918/contributions/1085290/attachments/1147002/_1644777/BenchBBcodes.pdf

[5] K. Ohmi https://oraweb.cern.ch/pls/hhh/code_website.disp_code?code_name=BBSS

[6] K. Ohmi https://indico.cern.ch/event/1398060/contributions/5876155/attachments/2831376/4947208/Beam-beamFCCee_ohmi.pdf

[7] Y. Zhang https://journals.aps.org/prab/pdf/10.1103/PhysRevAccelBeams.23.104402

[8] D. Shatilov http://cds.cern.ch/record/1120233/files/p65.pdf

[9] J. Qiang https://amac.lbl.gov/~jiqiang/BeamBeam3D/

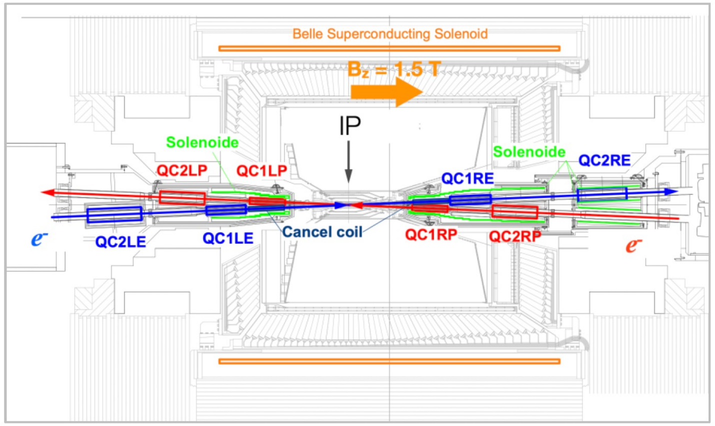
[10] Xsuite 10.18429/JACoW-HB2023-TUA2I1

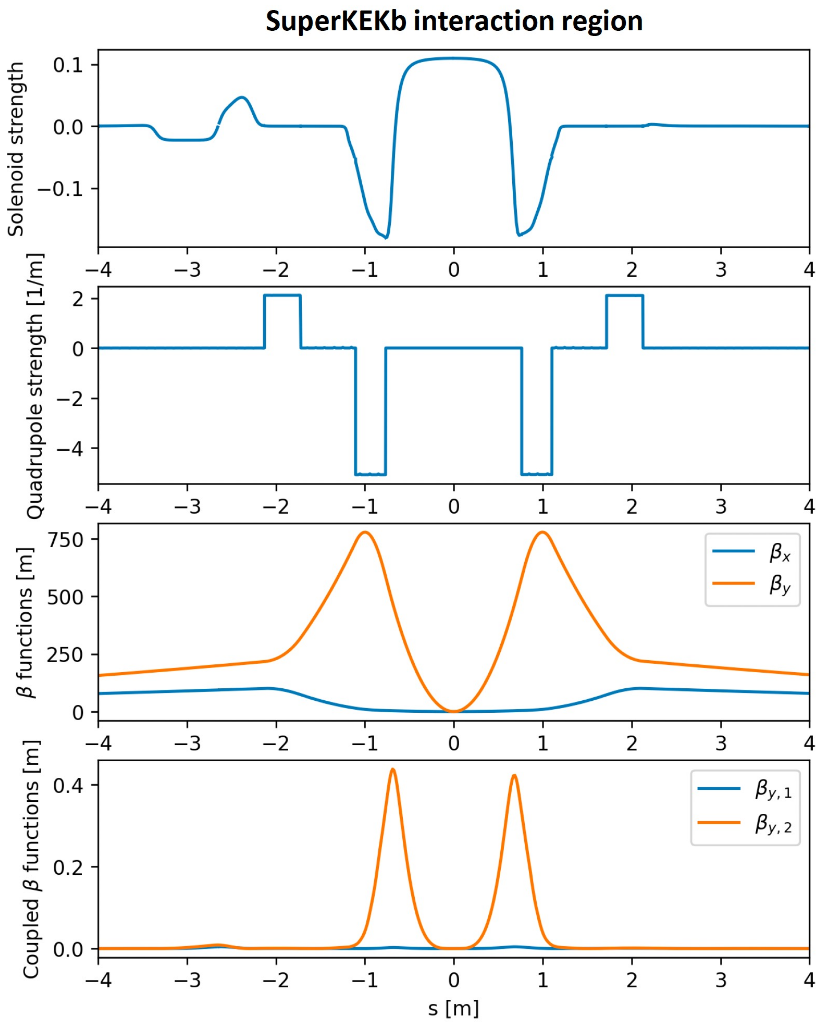
Solenoids and overlapping elements

Recent developments allow modelling of **experimental solenoids** of lepton colliders also in the presence of **overlapping multipole fields**

- Tested on **FCC-ee** and **SuperKEKb** models

Plan:
SAD Lattice -> Xsuite
Beam-beam simulation of SuperKEKB using Xsuite (J. P. Salvesen).





Many thanks to G. Broggi, J. P. Salvesen, KEK experts

International Collaboration in SuperKEKB

- **International Working Group** (new organization introduced at the last ARC)
  - Beam Tuning and Operation
  - Sudden Beam Loss (SBL)
  - **Beam-Beam Interaction and Collective Effects**
  - Beam Instrumentation
  - Future Upgrade
- One possible avenue for cooperation with US national labs/universities is **Beam-Beam Interactions.**
  - Strong-strong beam-beam simulations **with the full lattice**, using the BMAD package.
  - US DOE HPC (high-performance computing) machines are available for HEP for these simulations.
  - The proposal could involve junior acc. physicists, supervised by senior scientists, Yunhai Cai (SLAC), David Sagan (Cornell), Mark Palmer (BNL)
- US accelerator leaders, Tor Raubenheimer, Sergei Nagaitsev, and Mark Palmer, are highly supportive
- **The DOE has requested a clear plan** for a possible US contribution to SuperKEKB

On validity of beam-beam codes used in SuperKEKB

D. Zhou

- Beam-beam codes used in SuperKEKB
  - In-house codes at KEK: BBWS/BBSS/STCR (developed by K. Ohmi) and SAD (maintained by K. Oide et al.)
    - BBWS: weak-strong model + perturbation maps
    - BBSS: strong-strong model (soft-Gaussian and PIC options) + perturbation maps
    - STCR: strong-strong model + full lattices + space charge
    - SAD: weak-strong model (BBWS integrated into SAD) + full lattices + space charge
  - External third-party codes
    - IBB (Y. Zhang, IHEP): strong-strong model (soft-Gaussian and PIC options) + perturbation maps
    - APES-T (Z. Li and Y. Zhang, IHEP): strong-strong model + full lattices
    - Xsuite (P. Kicsiny, CERN): weak-strong and strong-strong models
  - Findings/Achievements
    - Overall, all codes consistently capture the key beam-beam physics in SuperKEKB, including coherent X-Z instability, combined effects of beam-beam and impedances, synchrobetatron resonances, and the effects of machine aberrations.
    - External codes have been improved through benchmarking and collaborative studies with KEK researchers, as well as through their applications to SuperKEKB. These activities have also provided valuable training for young accelerator physicists, particularly from China and Europe.
- Other successful benchmarks/collaborations
  - BBSS benchmarked with BeamBeam3D (J. Qiang)
  - BBSS benchmarked with Lifetrac (D. Shatilov)
  - BBSS benchmarked with Y. Cai's code for KEKB (PRST-AB 12, 061002) and high-current SuperKEKB (SLAC-PUB-11188)

Comparison between Ohmi and Y. Cai's

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **12**, 061002 (2009)

Potential-well distortion, microwave instability, and their effects with colliding beams at KEKB

Yunhai Cai
SLAC National Accelerator Laboratory, Stanford University, Menlo Park, California 94025, USA

J. Flanagan, H. Fukuma, Y. Funakoshi, T. Ieiri, K. Ohmi, K. Oide, and Y. Suetsugu
KEK, Oho, Tsukuba, Ibaraki 305-0801, Japan

Jamal Rorie
University of Hawaii at Manoa, Honolulu, Hawaii 96822, USA
(Received 25 February 2009; published 30 June 2009)

2009 KEKB case

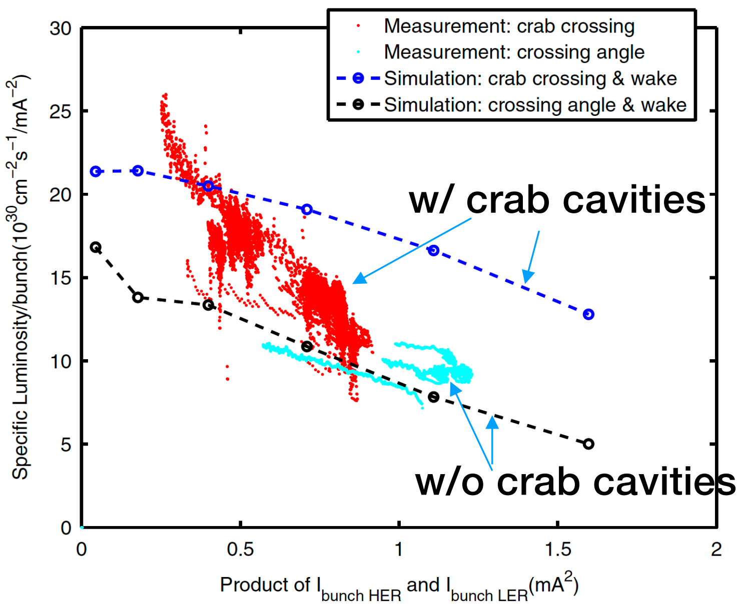
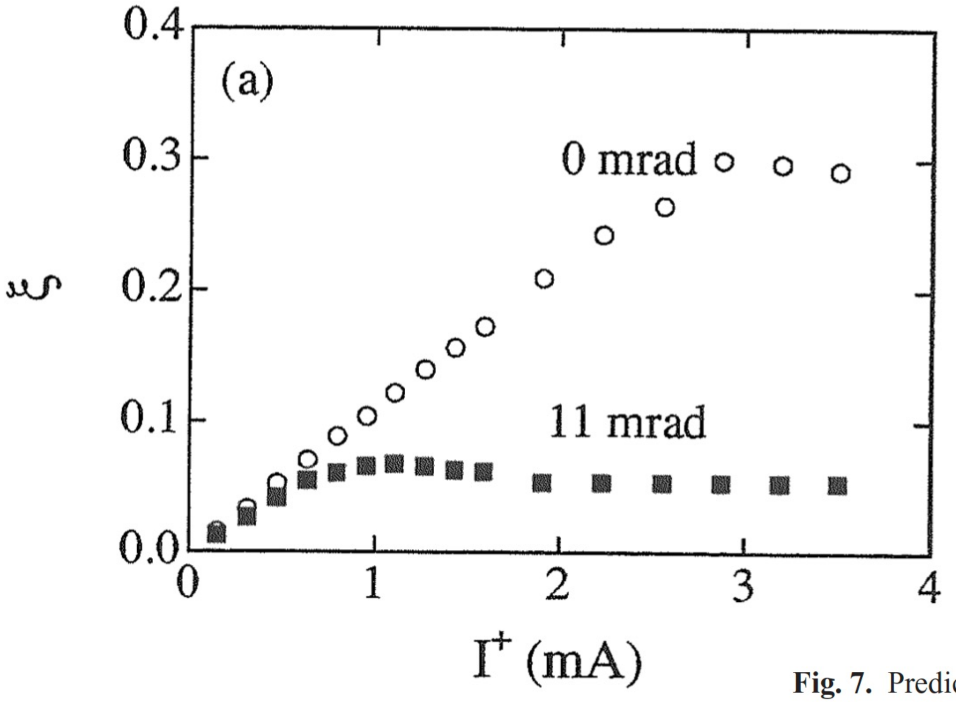


FIG. 9. (Color) Comparison of measured and simulated specific luminosity as a function of the product of bunch currents with/without crab cavities.

- In the Yunhai Cai's simulation, it was confirmed that the luminosity would be doubled by using the crab cavities which was predicted by Ohmi's simulation.
- No explicit statement is given in this paper. But the simulated specific luminosity by Cai's simulation was consistent with Ohmi's simulation.
- Before installing the crab cavities, the simulated luminosity was consistent with the experiments.

Beam-beam parameters in KEKB

Strong-weak simulation (BBWS) (Ohmi)



Strong-weak simulation (BBSS) (Ohmi)

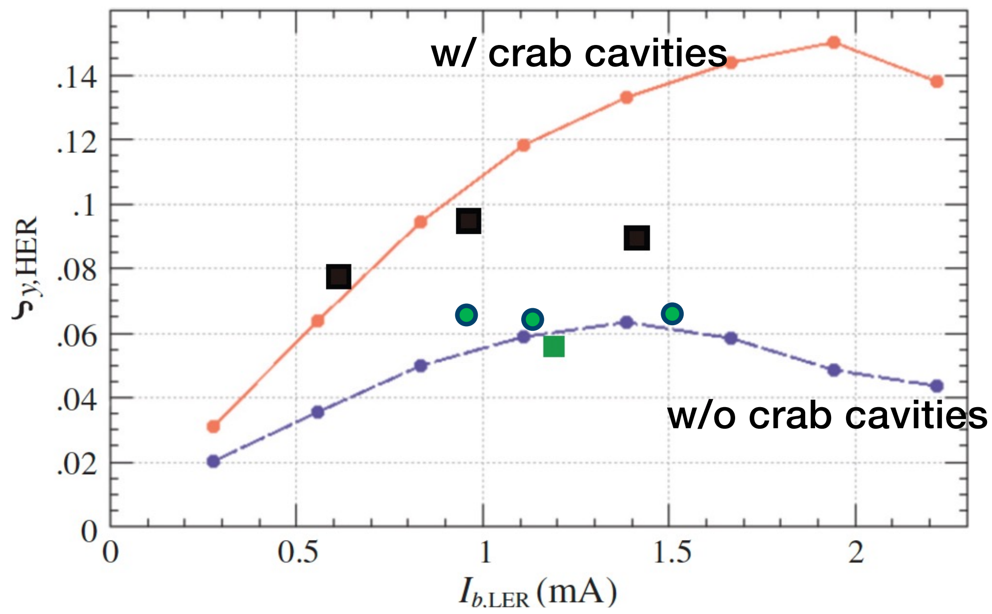


Fig. 7. Predicted beam–beam parameters by the strong–strong beam–beam simulations with a crossing angle of 22 mrad (purple) and the head-on collision (crab crossing) (red). Some experimental data are also shown with squares. The black and green squares denote data with and without the crab cavities, respectively.

Before introducing crab cavities, the predicted beam-beam parameter by simulation was actually achieved in experiment.

Comparison between Ohmi and Y. Cai's

Jul, 2004

SLAC-PUB-11188

A MULTI-BUNCH, THREE-DIMENSIONAL, STRONG-STRONG BEAM-BEAM SIMULATION CODE FOR PARALLEL COMPUTERS

A. Kabel, Y. Cai
Stanford Linear Accelerator Center, Stanford, CA 94309, USA*

Table 1: Benchmark Parameters. For PEP, a bunch spacing of 1.26 m is used

Symbol	PEP-II		Super KEKB		Units
	LER	HER	LER	HER	
E_0	3.1	9.0	3.5	8.0	GeV
N	7.15	4.41	12.6	5.5	10^{10}
β_x^*	0.50	0.27	0.30	0.30	m
β_y^*	10.5	11.1	3.0	3.0	mm
σ_z	10.5	11.6	3.0	3.0	mm
σ_δ	0.65	0.61	0.7	0.7	10^{-3}
ε_x	22.0	59.0	24.0	24.0	nm
ε_y	1.40	2.33	0.18	0.18	nm
ν_x	0.5162	0.5203	0.508	0.508	
ν_y	0.5639	0.6223	0.550	0.550	
ν_s	0.0270	0.0495	0.02	0.02	
$\tau_{x,y}$	9800	5030	4000	4000	Turns
τ_s	4800	2573	2000	2000	Turns

Parameters for high beam current option of SuperKEKB

BENCHMARKING

We have checked two typical cases: One is a single-bunch luminosity simulation for Super-KEKB with parameters as given by table 1. The other is a simulation of PEP-II, including the two nearest parasitic crossings, taken into account with a longitudinal resolution of 1, and for a bunch train of 4 bunches. It was not possible to do a multi-bunch simulation with sufficient resolution due to a bug in the HDF5 implementation at NERSC occuring for high number of processors. We could, however, check the code for consistency in this case. The results for Super-KEKB luminosity and rms y beam radius are given in figures 2, 1 and show good agreement with [6].

REFERENCES

[1] R. W. Hockney and J. W. Eastwood, *Computer Simulation Using Particles*. Bristol and Philadelphia, 1988.

[2] M. Frigo and S. G. Johnson, FFTW 2.15 User's Manual, `http://www.fftw.org/fftw2_doc/`

[3] F. Baker for the HDF5 project, HDF5 User's Guide, `http://hdf.ncsa.uiuc.edu/HDF5/doc/UG/`

[4] K. Ohmi, Phys. Rev. E**62**, 7287 (2000)

[5] K. Ohmi, in *Proceedings of the 2003 IEEE Particle Accelerator Conference*

[6] K. Ohmi, M. Tawada, Y. Cai, S. Kamada, K. Oide, and J. Qiang, PRL **92** (2004), 214801-1–4

Message from Ohmi'san

- Yunhai Cai has only worked on KEKB and PEPII, so I think he will have a hard time with the large Piwinski angle.
- J. Qiang (LBNL) seems to have done some work with the EIC collider. He often compares it with IBB by Y. Zhang (IHEP).
- CERN is starting to work on it little by little.
- In any case, we cannot use a code that does not reproduce the theoretically clear coherent instability.
- The series of work being done with IHEP is theoretically established, so we cannot use the code until we have confirmed that it produces the same phenomenon.
- If you want to do a simulation that takes lattices into account, the only option is the GPU code I created, BBSCL (SCTR-bb). Running various things with this takes too much time for the IR, so I would like to simplify it first.

Ohmi-san's references

- K. Ohmi, N. Kuroo, K. Oide, D. Zhou, F. Zimmermann, Phys. Rev. Lett. 119, 134801 (2017).
- N. Kuroo, K. Ohmi, K. Oide, D. Zhou, F. Zimmermann, Phys. Rev. Accel. Beams 21, 031002 (2018).
- Y. Zhang, N. Wang, C Lin, D. Wang, C. Yu, K. Ohmi, M. Zobov, Phys. Rev. Accel. Beams 23, 104402 (2020).
- Y. Zhang, N. Wang, K. Ohmi, D. Zhou, T. Ishibashi, C. Lin, Phys. Rev. Accel. Beams 26, 064401 (2023).
- K. Ohmi, Y. Zhang, C. Lin, Phys. Rev. Accel. Beams 26, 111001 (2023).
- C. Lin, K. Ohmi, and Y. Zhang, Phys. Rev. Accel. Beams 25, 011001 (2022).
- D. Zhou, K. Ohmi, Y. Funakoshi, Y. Ohnishi, Y. Zhang, Phys. Rev. Accel. Beams 26, 071001 (2023).

My opinions

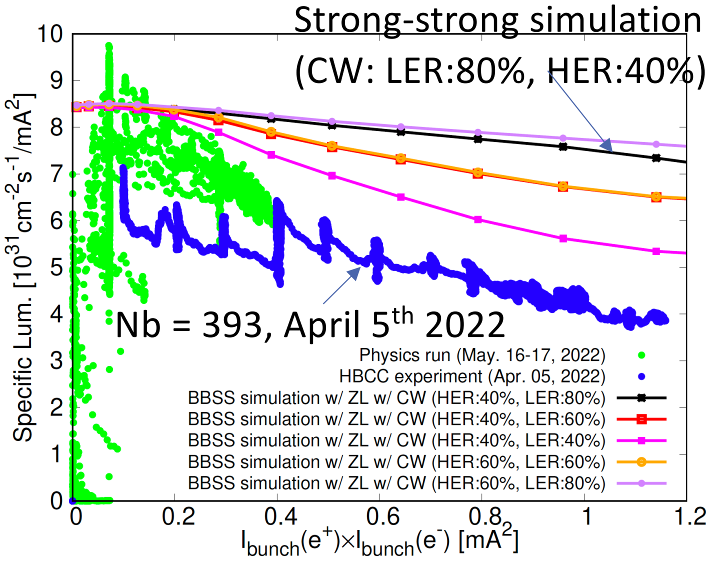
- The KEKB beam-beam study team (K. Ohmi and D. Zhou) is one of the front runners in the world accelerator community on the beam-beam issues.
  - The beam-beam simulation codes developed at KEK (BBSS, BBWS, SCTR) are considered to be well-established standards that have helped improve other codes (e.g. IBB, APES-T, Xsuite, BeamBeam3D) through benchmarking and collaborative research.
  - Pioneering feature
    - Strong-strong simulation with full lattice (SCTR and APES-T) and with space charge effects
    - Speeding up simulation time by running on GPU
  - Discovery of coherent instability
    - X-Z instability in a large Piwinski angle collision (FCC-ee, CEPC, SuperKEKB)
    - TMCI-like instability
- The KEKB beam-beam code (BBSS) has been well benchmarked by other codes.
  - Y. Cai's code, IBB, BeamBeam3D, LIFETRAC…
- I think that the beam-beam code at KEK is reliable. But there is large discrepancy between simulations and experiments. In my opinion, the discrepancy is due to some unknown (possibly multiple) physical effects which are not included in the present simulations and it is important to identify such effects.
- Collaboration with US and CERN researchers
  - We will welcome collaborators from other laboratories.
  - I don't think that mere benchmarking study is fruitful.
  - Researchers who will study SuperKEKB problems through persistent, long-term efforts visiting at KEK are particularly helpful.

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*. Unexpectedly large nonlinearity, Imperfect crab waist scheme
  - Other effects: Beam-beam + lattice nonlinearity, Beam-beam + impedance, Beam-beam + space charge
  - Effects of FB system (noise)
  - BBSS simulation with PIC gives ~5% lower values than simulation with Gaussian fitting model at $_{Ib+}I_{b-}$ = 0.8mA^2 (D, Zhou).
  - Belle II – accelerator mis-alignment? (K. Oide)

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



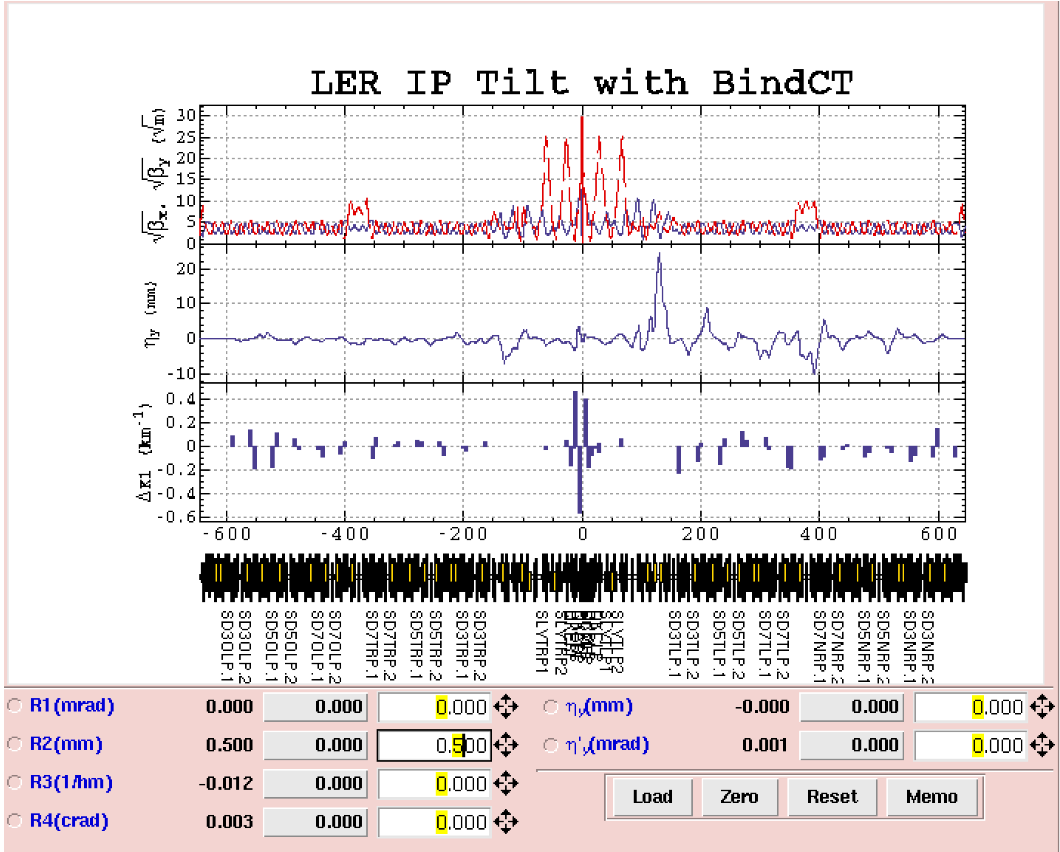
Luminosity tuning (compensation of machine errors)

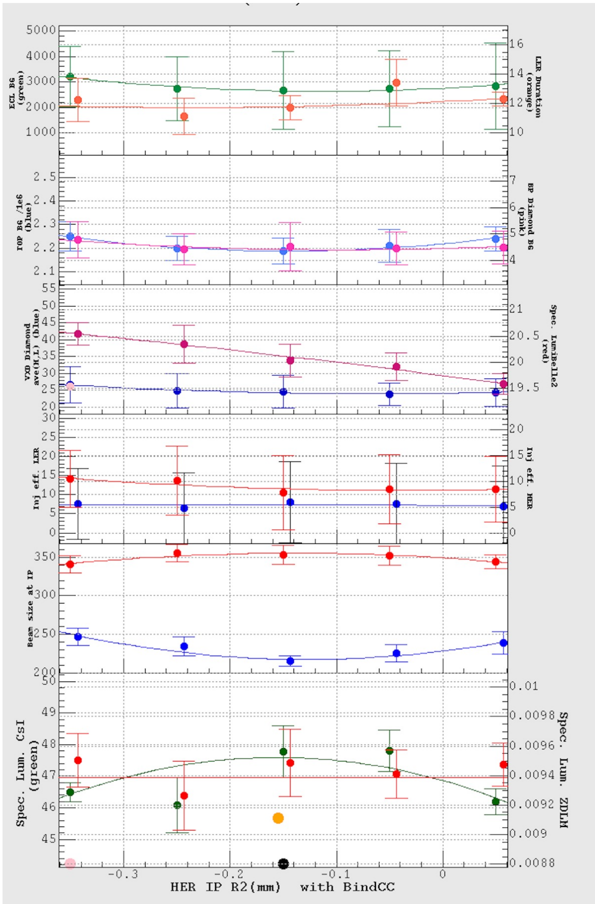
- Machine tuning routinely done even during physics run on machine parameters. In spite of those efforts, the achieved specific luminosity is very low compared with simulation so far.

Tuning parameters	Observables	Typical frequency
Beam offset at IP (orbit feedback)	beam-beam kick (BPMs)	FB 32kHz
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

Very important for luminosity → x-y coupling and dispersion at IP

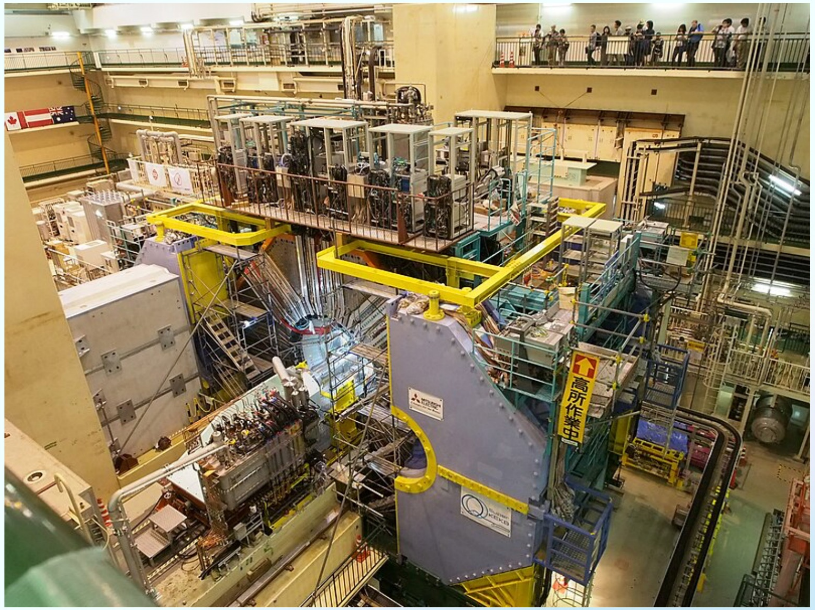
Tuning knob on X-Y coupling at IP





Alignment of the detector (a speculation) — SuperKEKB

- All accelerator components of SuperKEKB have been well aligned with accuracy better than $\sigma \lesssim 100\,\mu\mathrm{m}$.
- However, the orbit around the interaction region looks strange:
  - Unexpected shining of the inner detector by SR observed.
  - Strange steering of the orbit is required to ensure the collision and avoid the SR shining.
- A speculation is that the alignment of the Belle-II detector might have large errors, in positions and angles, relative to nearby accelerator components.
  - It may explain the low beam-beam parameter (0.03) achieved so far.
- If it is true, re-alignment of accelerator components is necessary, by smoothly redefine the ring layout in this straight from the IP to the arc.
  - It is very difficult to move the detector itself (1400 tons) with a good accuracy.



https://en.wikipedia.org/wiki/Belle_II_experiment

K. Oide @ BB24 workshop

Some simulations by Koiso-san are underway.

Beam-Beam study group

- Beam-beam study group was established in July 2024 in SuperKEKB accelerator group.
- Motivations
  - D. Zhou (beam-beam expert) has left from SuperKEKB and Ohmi-san (beam-beam expert) is now in China. And so we had to create a group to study beam-beam related issues.
- Member
  - K. Ohmi, Y. Yamamoto (new comer), Y. Ohnishi, H. Sugimoto, S. Uno, Y. Funakoshi
- Task list
  - Simulations
    - Tune survey on injection efficiency (Strong-Weak: BBWS+SAD): ongoing (urgent)
    - Bunch current dependence of specific luminosity with βy^* = 0.9mm (Strong-Strong: BBSS) just started
    - Tune survey with BBSS code with Wx,y,z wake (impedance). Just started.
    - Strong-Strong simulations with machine errors
    - (Study on machine errors)
    - Strong-strong simulations with full SAD lattice (SCTR)
  - Beam study
    - Effect of bunch-by-bunch FB
    - Study on machine errors
      - Amplitude dependent tune shift
      - Skew-sextupole at QC1

Fin.

Thank you for your attention.

Spare slides

Coherent Beam-Beam Instability in Collisions with a Large Crossing Angle

K. Ohmi,[1,*] N. Kuroo,[1,3] K. Oide,[1,2] D. Zhou,[1,2] and F. Zimmermann[2]
[1]*KEK, 1-1 Oho, Tsukuba 305-0801, Japan*
[2]*CERN, 1211 Geneva 23, Switzerland*
[3]*University of Tsukuba, Tsukuba, 305-8577, Japan*
(Received 14 March 2017; published 26 September 2017)

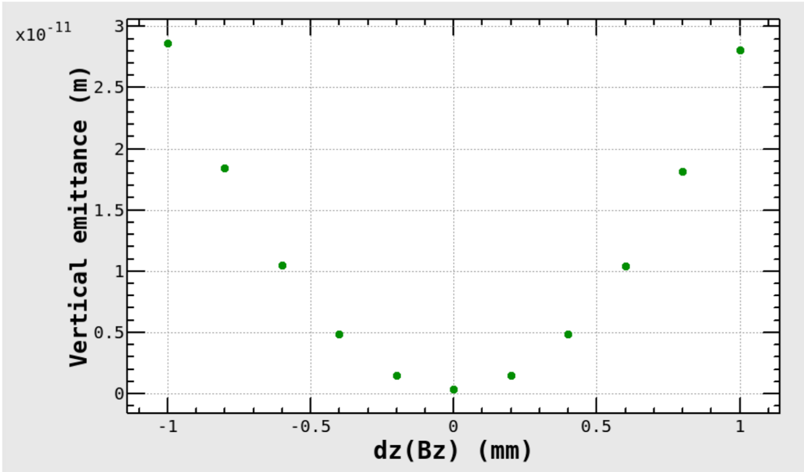
In recent years the "crab-waist collision" scheme [P. Raimondi, *Proceedings of 2nd SuperB Workshop, Frascati, 2006*.; M. Zobov *et al.*, Phys. Rev. Lett. **104**, 174801 (2010)] has become popular for circular e^+ e^- colliders. The designs of several future colliders are based on this scheme. So far the beam-beam effects for collisions under a large crossing angle with or without crab waist were mostly studied using weak-strong simulations. We present here strong-strong simulations showing a novel strong coherent head-tail instability, which can limit the performance of proposed future colliders. We explain the underlying instability mechanism starting from the "cross-wake force" induced by the beam-beam interaction. Using this beam-beam wake, the beam-beam head tail modes are studied by an eigenmode analysis. The instability may affect all collider designs based on the crab-waist scheme. We suggest an experimental verification at SuperKEKB during its commissioning phase II.

DOI: 10.1103/PhysRevLett.119.134801

ソレノイド分布の誤差の影響

H. Koiso

- LER 2024-06-11_15:03:52.882_MeasOpt について調べた。
- -140 cm から+180 cm の範囲のB_Z分布 (変化の大きい領域)を進行方向に 1mm 並行移動すると、~28 pm の垂直エミッタンスが発生する。
- 1 mm のずれで R1* 0.0037。 R2*の発生量は小さい。
- 軌道のずれも小さい。

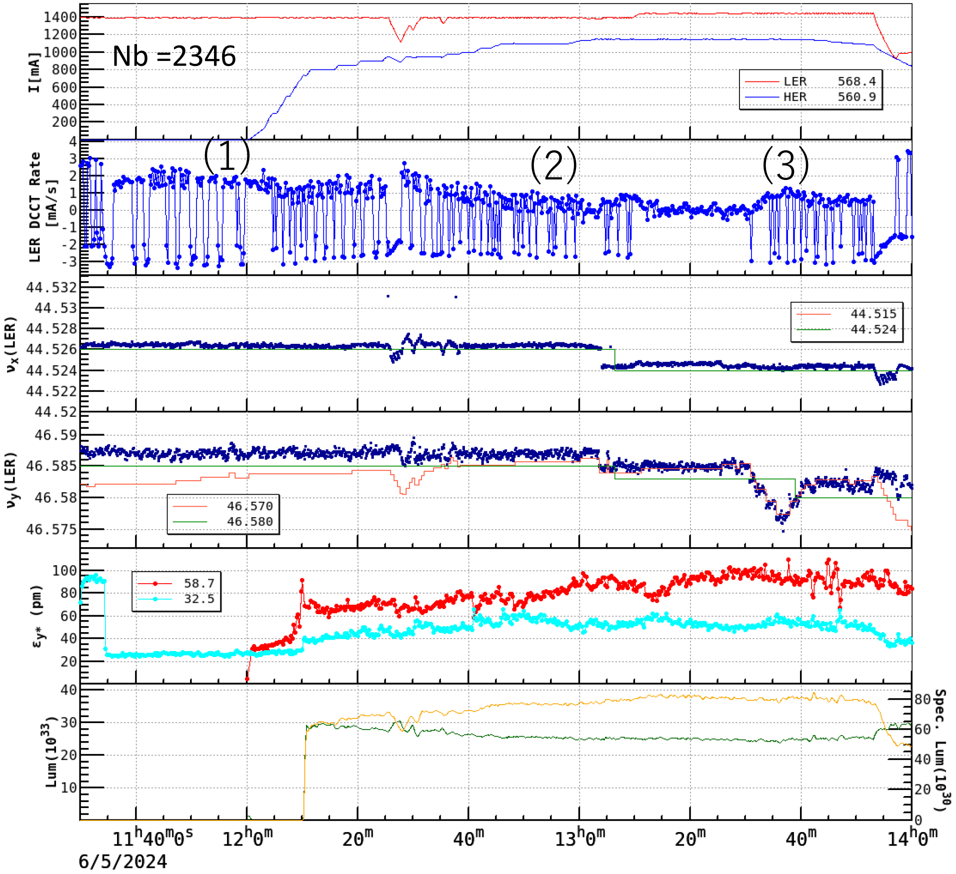


AX	BX	NX	EX	EPX	Element	R1	R2	R3	R4	AY	BY	NY	EY	EPY	DetR	#	
1.81E-4	.07897	21.1177	-1.0E-6	-1.1E-7	IP.1	.0037	-2.E-6	-.0035	.8360	.00164	.00100	22.0023	-2.8E-8	4.75E-7	.0031	3773	+1 mm
-1.2E-5	.07898	21.1177	1.07E-6	-1.5E-8	IP.1	-.0037	4.8E-6	.0320	-.8475	-.00157	9.97E-4	22.0024	1.84E-8	-5.5E-7	.0031	3773	-1 mm

AX	BX	NX	EX	EPX	Element	DX	DPX	DY	DPY	AY	BY	NY	EY	EPY	DetR	#	
1.81E-4	.07897	21.1177	-1.0E-6	-1.1E-7	IP.1	3.E-17	-2E-16	3.E-17	-1E-14	.00164	.00100	22.0023	-2.8E-8	4.75E-7	.0031	3773	+1 mm
-1.2E-5	.07898	21.1177	1.07E-6	-1.5E-8	IP.1	4.E-17	-2E-16	1.E-17	-1E-14	-.00157	9.97E-4	22.0024	1.84E-8	-5.5E-7	.0031	3773	-1 mm

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.

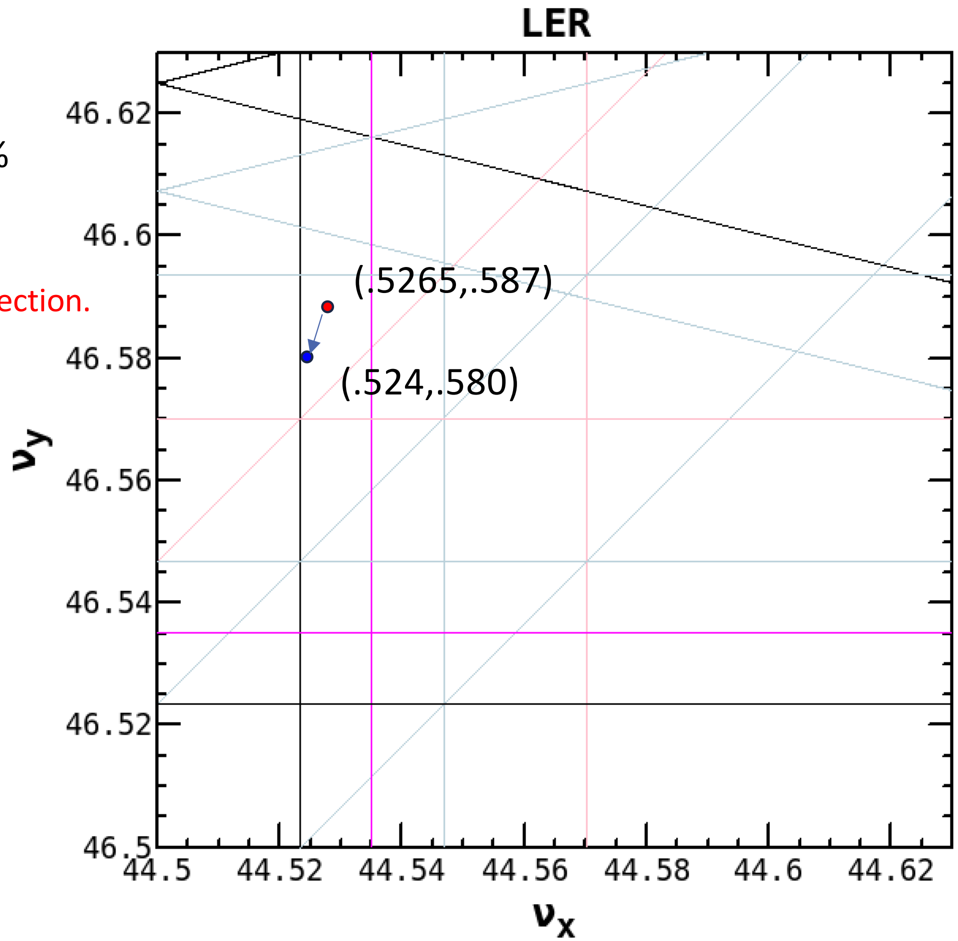
	Ibeam (LER)	Ibeam (HER)	IncRate (L)	Life (L)	InjEff (L)
(1)	1395 mA	0 mA	1.68mA/s	7.3 min.	77.4%
(2)	1395mA	1100mA	0.42mA/s	8.9 min.	48.0%
(3)	1444mA	1100mA	1.02mA/s	8.0 min.	64.8%

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

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

Summary of beam injection

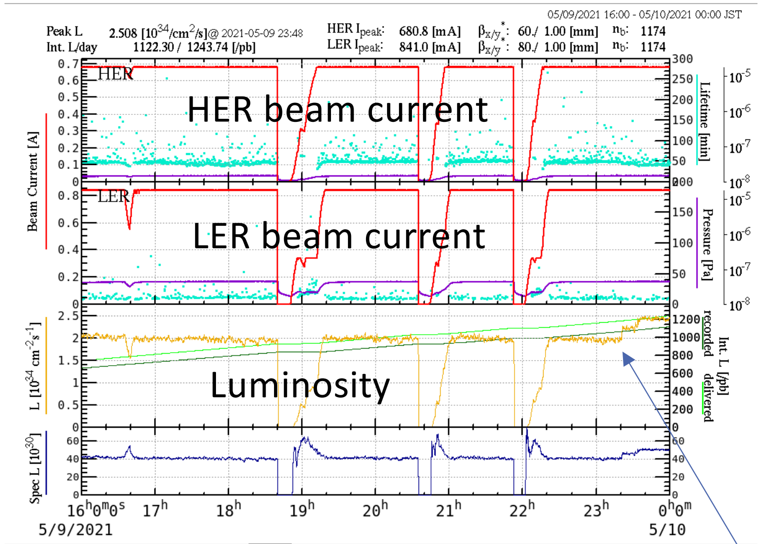
- Injection scheme of SuperKEKB
  - Usual betatron (horizontal) injection with stacking mode
  - With crab waist, the beam injection was improved.
- Even with crab waist LER injection efficiency was decreased by ~30% with beam-beam effects.
  - At the present SuperKEKB, the beam injection limits the 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 the next 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

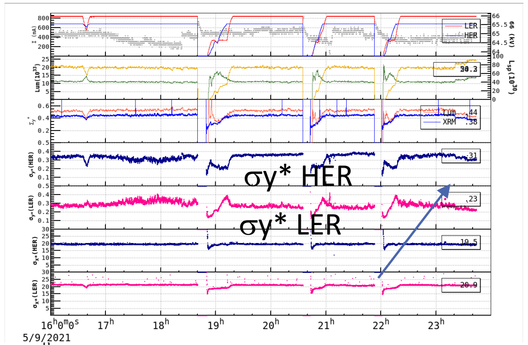


Effect of bunch-by-bunch feedback system

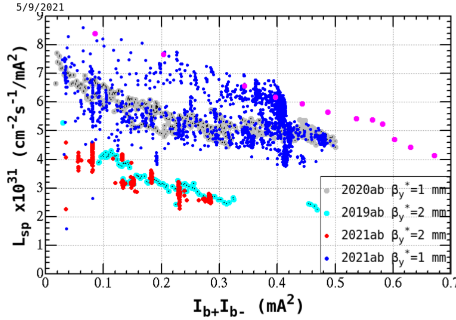
Bunch-by-bunch feedback gain

- 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



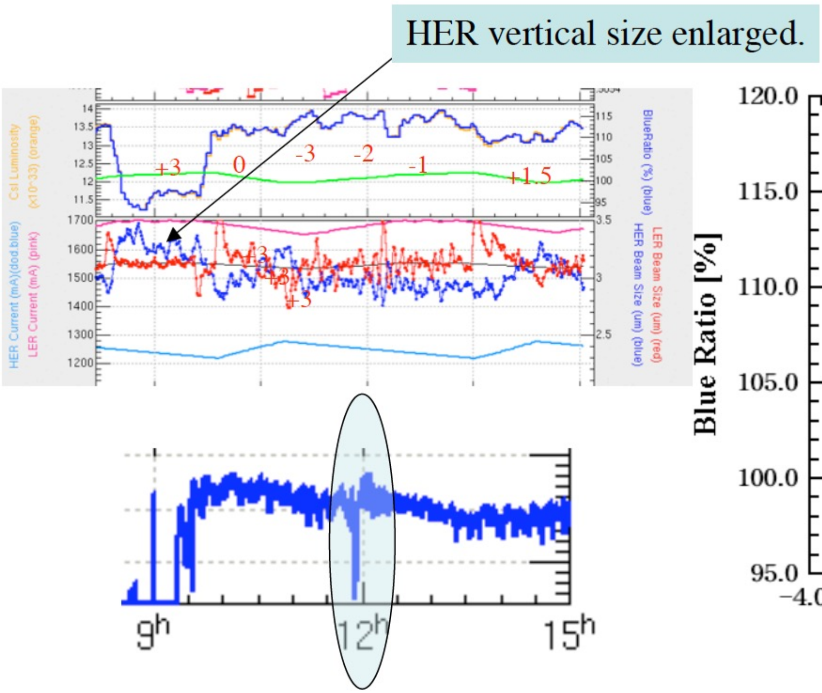
Specific luminosity

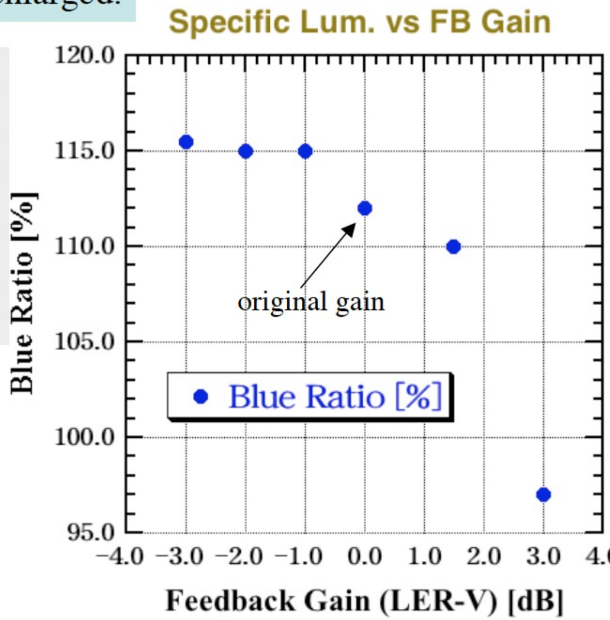
The luminosity increased by lowering HER vertical FB gain by 4dB + 4dB.

The increase in the luminosity was ~25%.

KEKB case

Specific Luminosity vs FB Gain

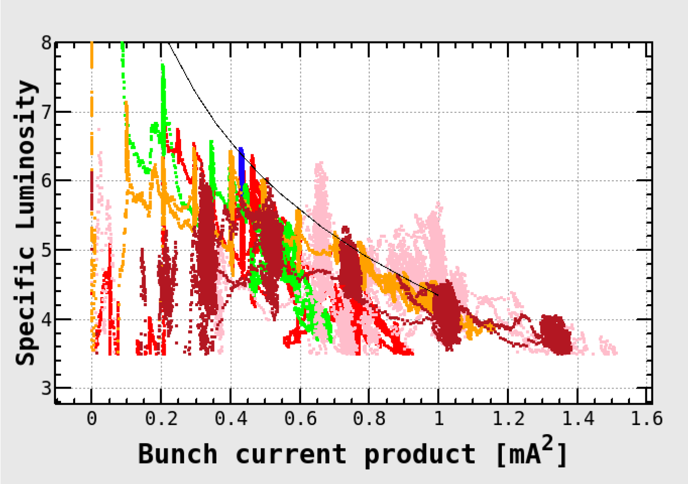




FB gain of the LER vertical affects the specific luminosity.
The other gains (LER H, HER H/V) bring no effects.

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 the next run, we will try to confirm this effect.

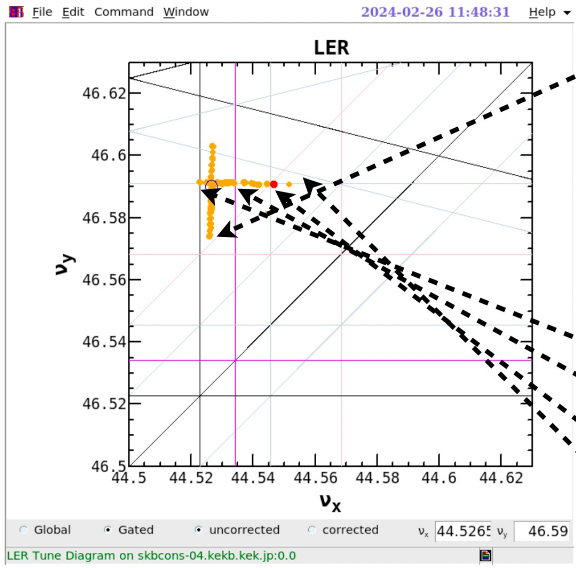


Tune survey

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:

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

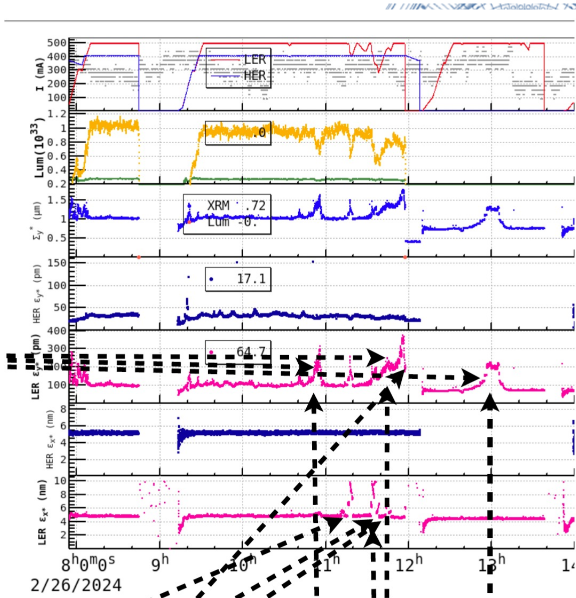
Beam-beam resonances:

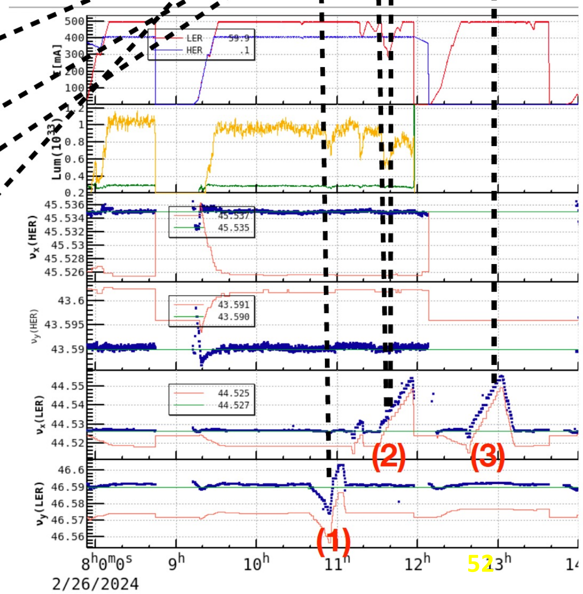
$\nu_x - \nu_s = N/2$

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

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

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





D. Zhou

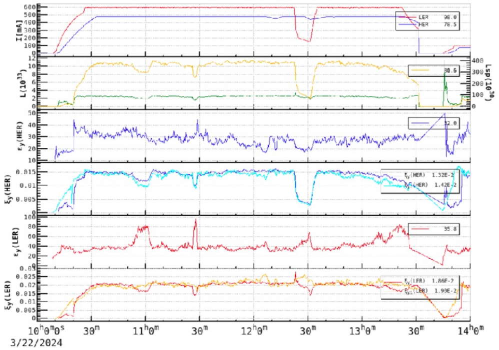
$\nu_x - 1.5\nu_s = N/2$ was strong in this experiment (not strong in 2022b run).

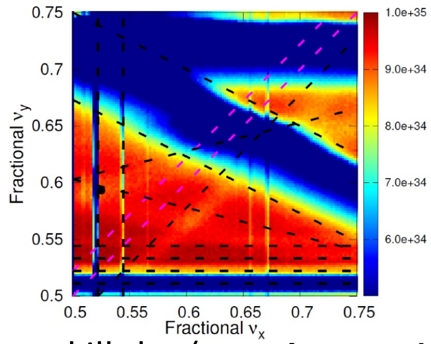
It can be linear IP aberrations that make the deviate from 3D Gaussian (symmetric).

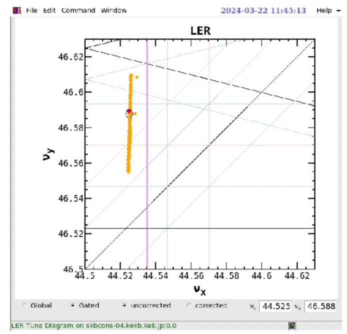
Recent beam-beam machine studies

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

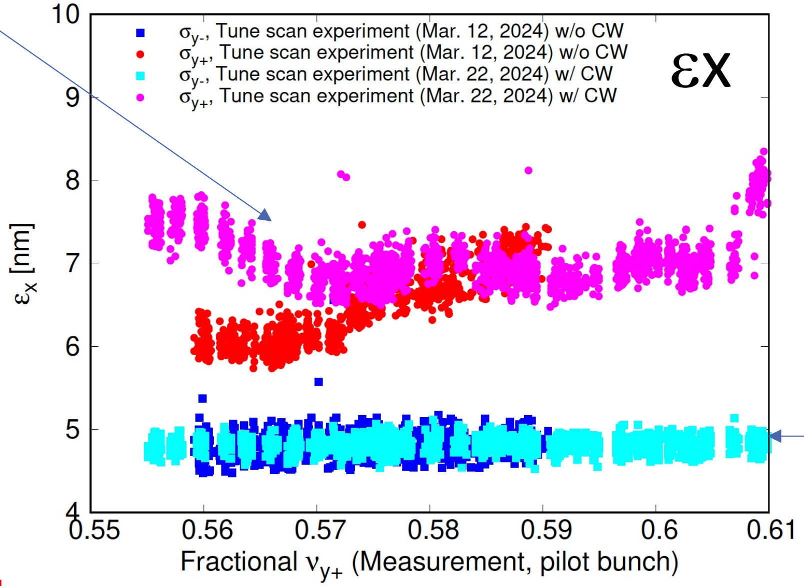




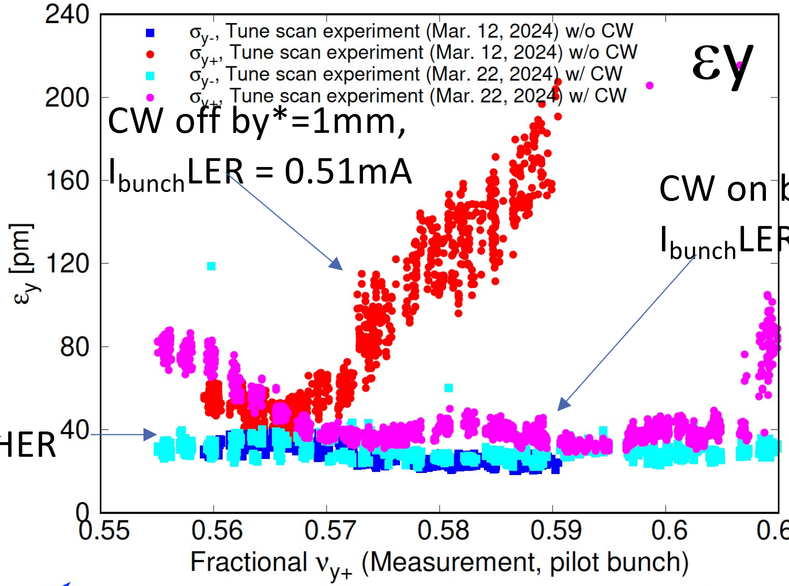


Horizontal emittance growth is observed in LER.

Crab waist (CW) seems to kill the ($\nu x + 4\nu y + \alpha$=N) resonance.



HER



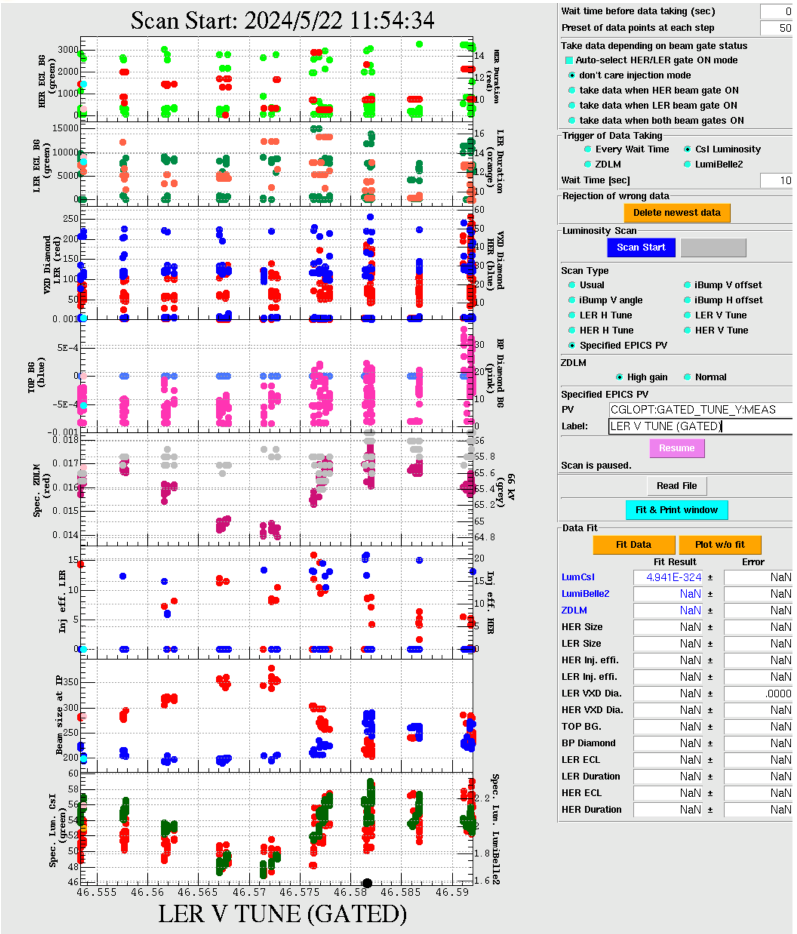
CW off by*=1mm, I_{bunch}LER = 0.51mA

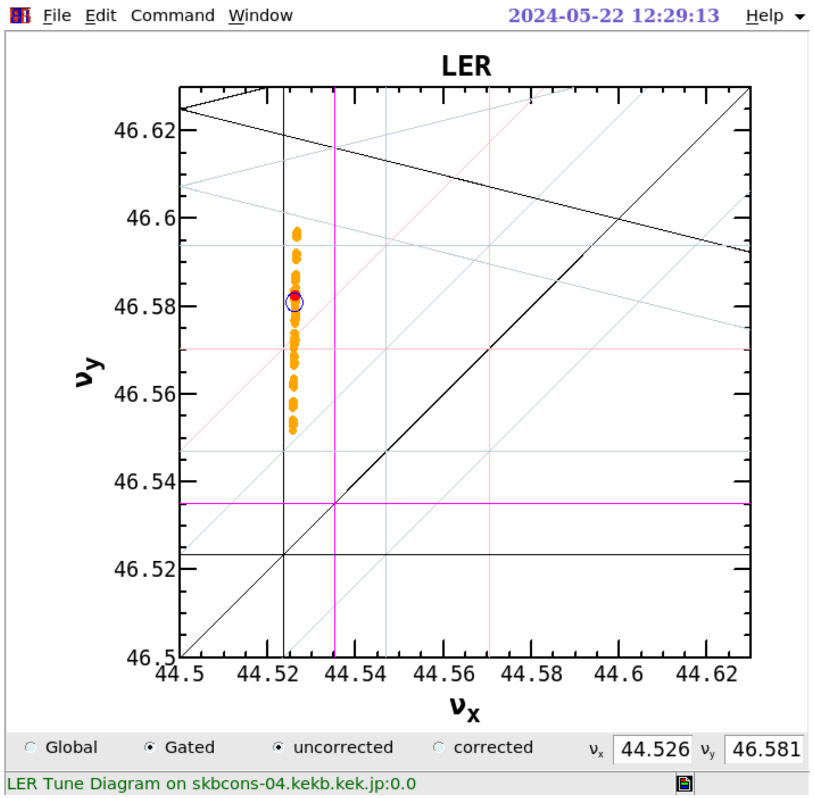
CW on by*=1mm, I_{bunch}LER = 0.26mA

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

D. Zhou

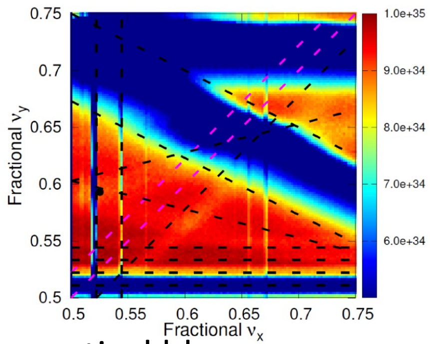
Vertical tune scan in LER on May 22nd 2024

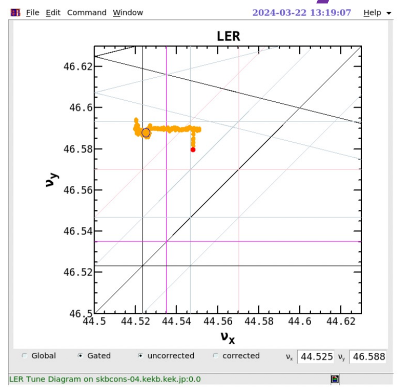




Recent beam-beam machine studies LER Horizontal tune survey

- 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

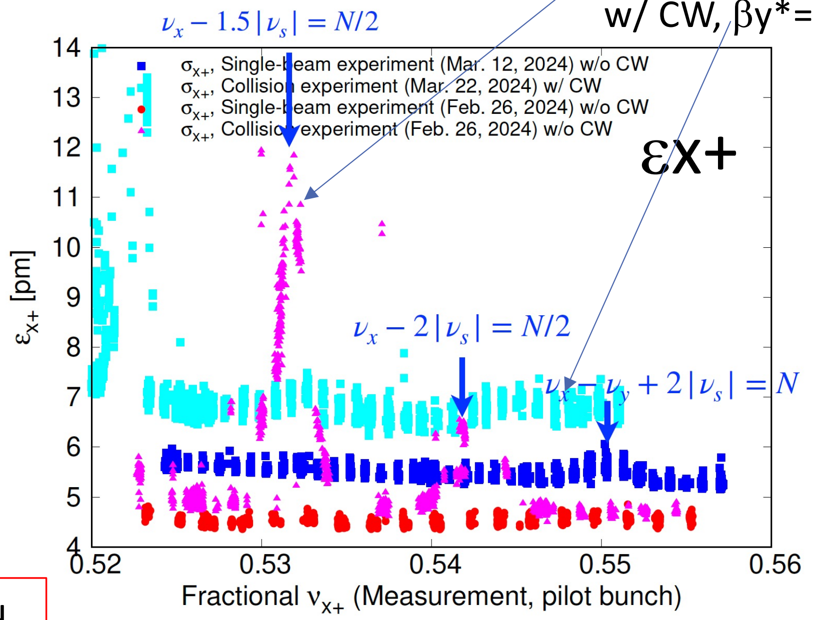


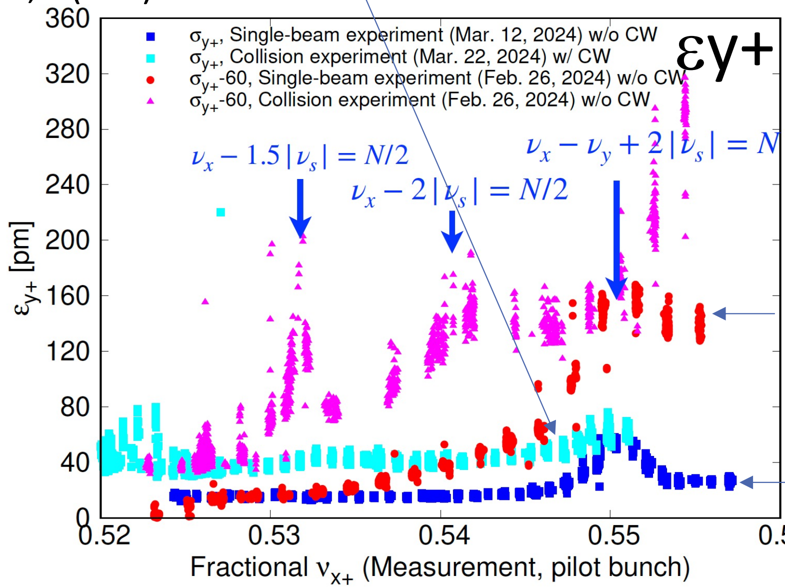


The working point νx+-44.548 seems worse than νx+=44.525 due to vertical blowup.

w/o CW, βy*=8mm,Ib(LER)=0.32mA

w/ CW, βy*=1mm,Ib(LER)=0.26mA





single, βy*=8mm, Ib(LER)=0.32mA

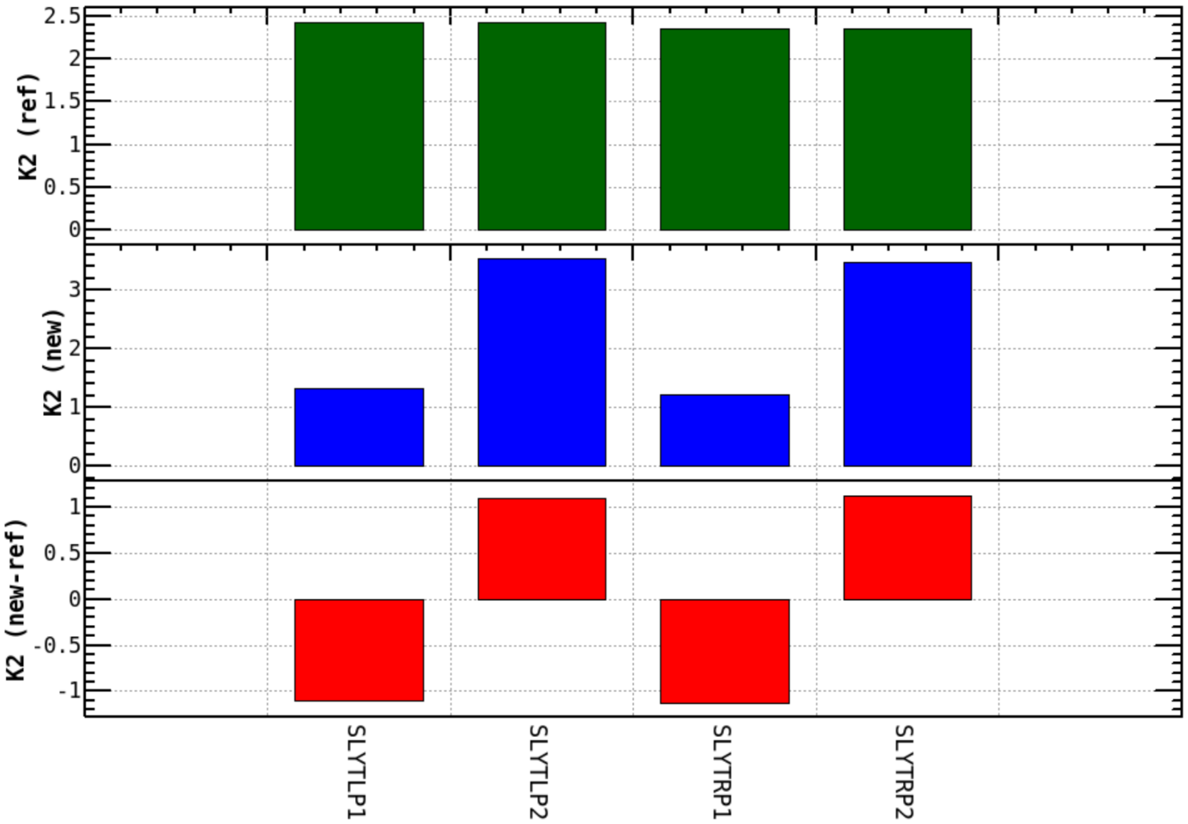
single, βy*=1mm, Ib(LER)=0.51mA

Summary of tune survey

- Crab waist (CW) seems to kill the ($\nu x + 4\nu y + \alpha = N$) resonance as is expected.
- The working point νx+-44.548 seems worse than νx+=44.525 due to vertical blowup, although simulation showed νx+-44.548 is good to suppress the horizontal blowup,
  - We need to try again after chromatic coupling correction.
- 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 so far.
- 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.

Crab waist sextupoles

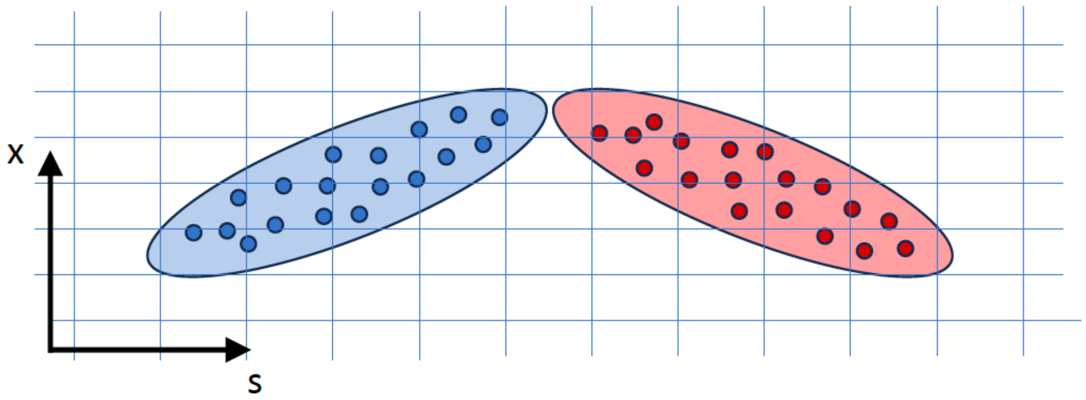
LER: Crab waist ratio = 80%



Strong-strong simulations – Particle In Cell

The beam-beam forces are computed on a **cartesian 3D Grid** using a **discrete time step**. At each step:

- The particles charge **is deposited on the grid cells**
- The scalar potential ϕ is computed by solving for each slice a **2D Poisson equations** (FFT method, Integrated Green Function[1])
- Force on individual particles is computed by **interpolation** (both transverse kicks and energy change are applied)
- **Particles are propagated** for a single time step

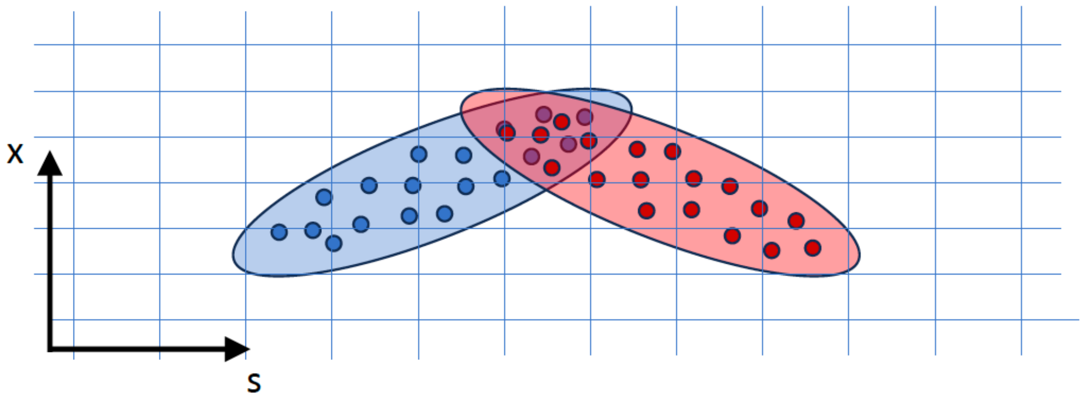


[1] From J. Qiang et al., "A parallel particle-in-cell model for beam–beam interaction in high energy ring colliders", Journal of Computational Physics 198 (2004) 278–294

Strong-strong simulations – Particle In Cell

The beam-beam forces are computed on a **cartesian 3D Grid** using a **discrete time step**. At each step:

- The particles charge **is deposited on the grid cells**
- The scalar potential ϕ is computed by solving for each slice a **2D Poisson equations** (FFT method, Integrated Green Function[1])
- Force on individual particles is computed by **interpolation** (both transverse kicks and energy change are applied)
- **Particles are propagated** for a single time step

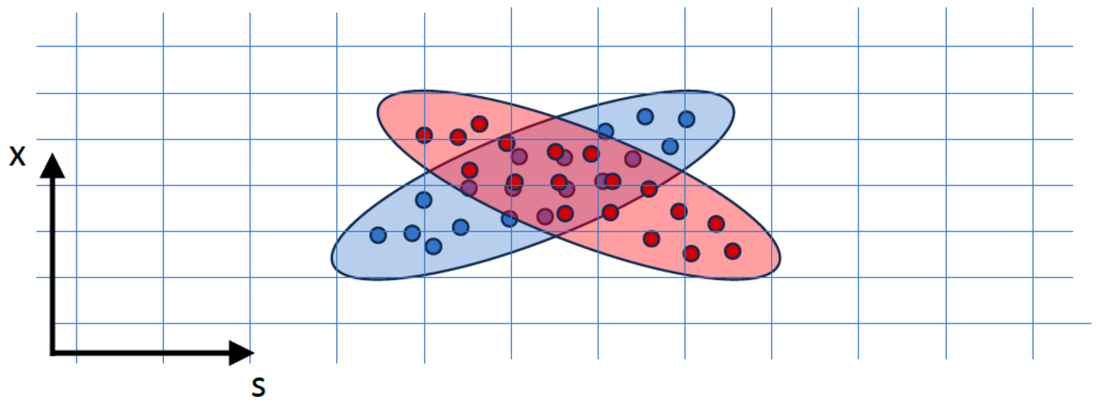


[1] *From J. Qiang et al., "A parallel particle-in-cell model for beam–beam interaction in high energy ring colliders", Journal of Computational Physics 198 (2004) 278–294*

Strong-strong simulations – Particle In Cell

The beam-beam forces are computed on a **cartesian 3D Grid** using a **discrete time step**. At each step:

- The particles charge **is deposited on the grid cells**
- The scalar potential ϕ is computed by solving for each slice a **2D Poisson equations** (FFT method, Integrated Green Function[1])
- Force on individual particles is computed by **interpolation** (both transverse kicks and energy change are applied)
- **Particles are propagated** for a single time step

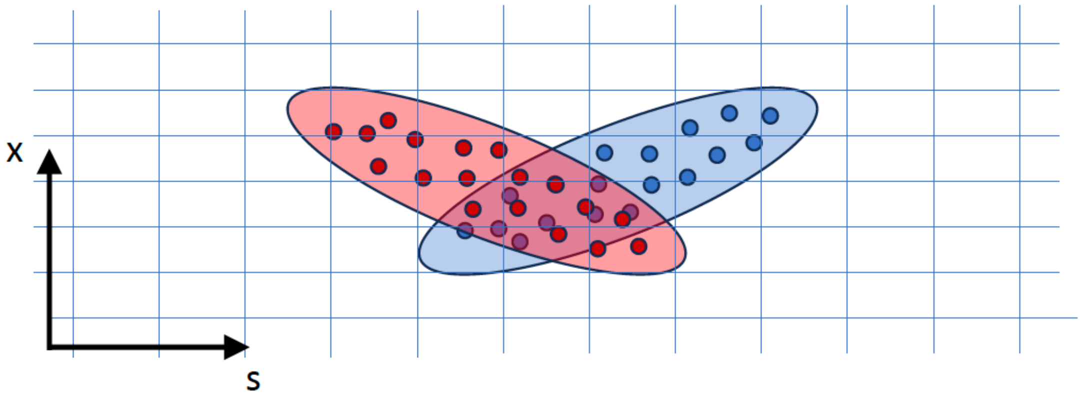


[1] *From J. Qiang et al., "A parallel particle-in-cell model for beam–beam interaction in high energy ring colliders", Journal of Computational Physics 198 (2004) 278–294*

Strong-strong simulations – Particle In Cell

The beam-beam forces are computed on a **cartesian 3D Grid** using a **discrete time step**. At each step:

- The particles charge **is deposited on the grid cells**
- The scalar potential ϕ is computed by solving for each slice a **2D Poisson equations** (FFT method, Integrated Green Function[(1)])
- Force on individual particles is computed by **interpolation** (both transverse kicks and energy change are applied)
- **Particles are propagated** for a single time step

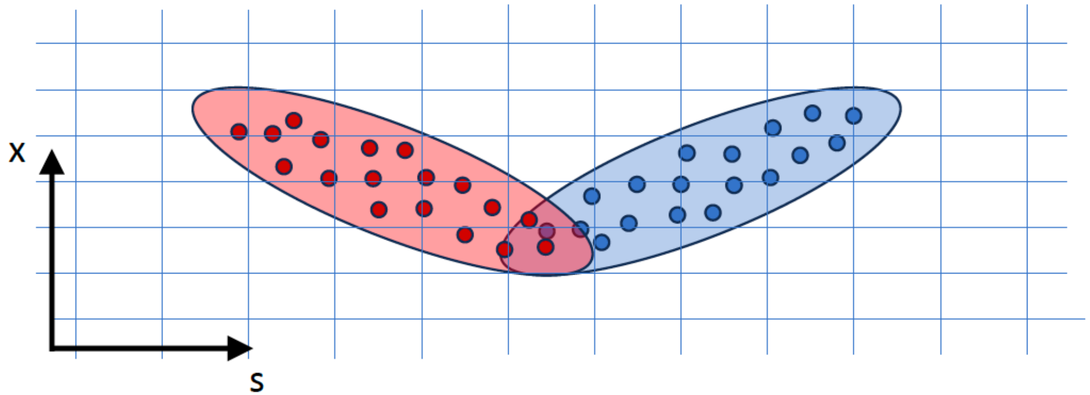


[(1)] *From J. Qiang et al., "A parallel particle-in-cell model for beam–beam interaction in high energy ring colliders", Journal of Computational Physics 198 (2004) 278–294*

Strong-strong simulations – Particle In Cell

The beam-beam forces are computed on a **cartesian 3D Grid** using a **discrete time step**. At each step:

- The particles charge **is deposited on the grid cells**
- The scalar potential ϕ is computed by solving for each slice a **2D Poisson equations** (FFT method, Integrated Green Function[1])
- Force on individual particles is computed by **interpolation** (both transverse kicks and energy change are applied)
- **Particles are propagated** for a single time step

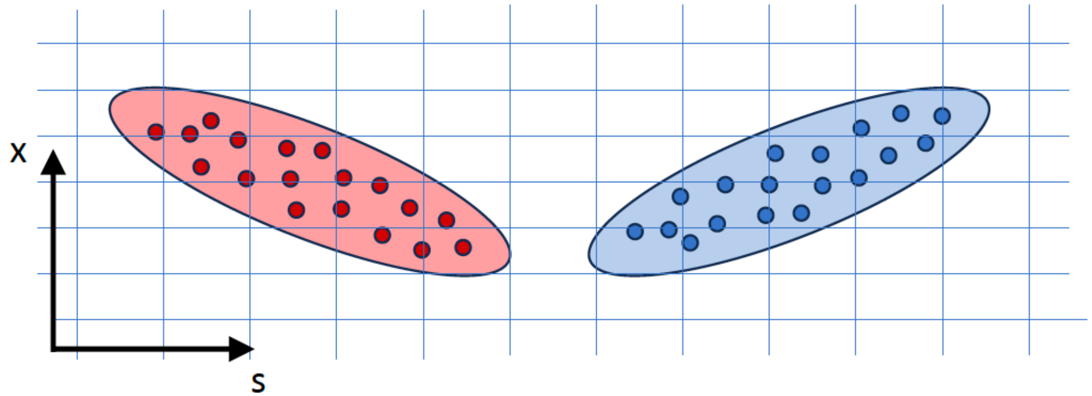


[1] From J. Qiang et al., "A parallel particle-in-cell model for beam–beam interaction in high energy ring colliders", Journal of Computational Physics 198 (2004) 278–294

Strong-strong simulations – Particle In Cell

The beam-beam forces are computed on a **cartesian 3D Grid** using a **discrete time step**. At each step:

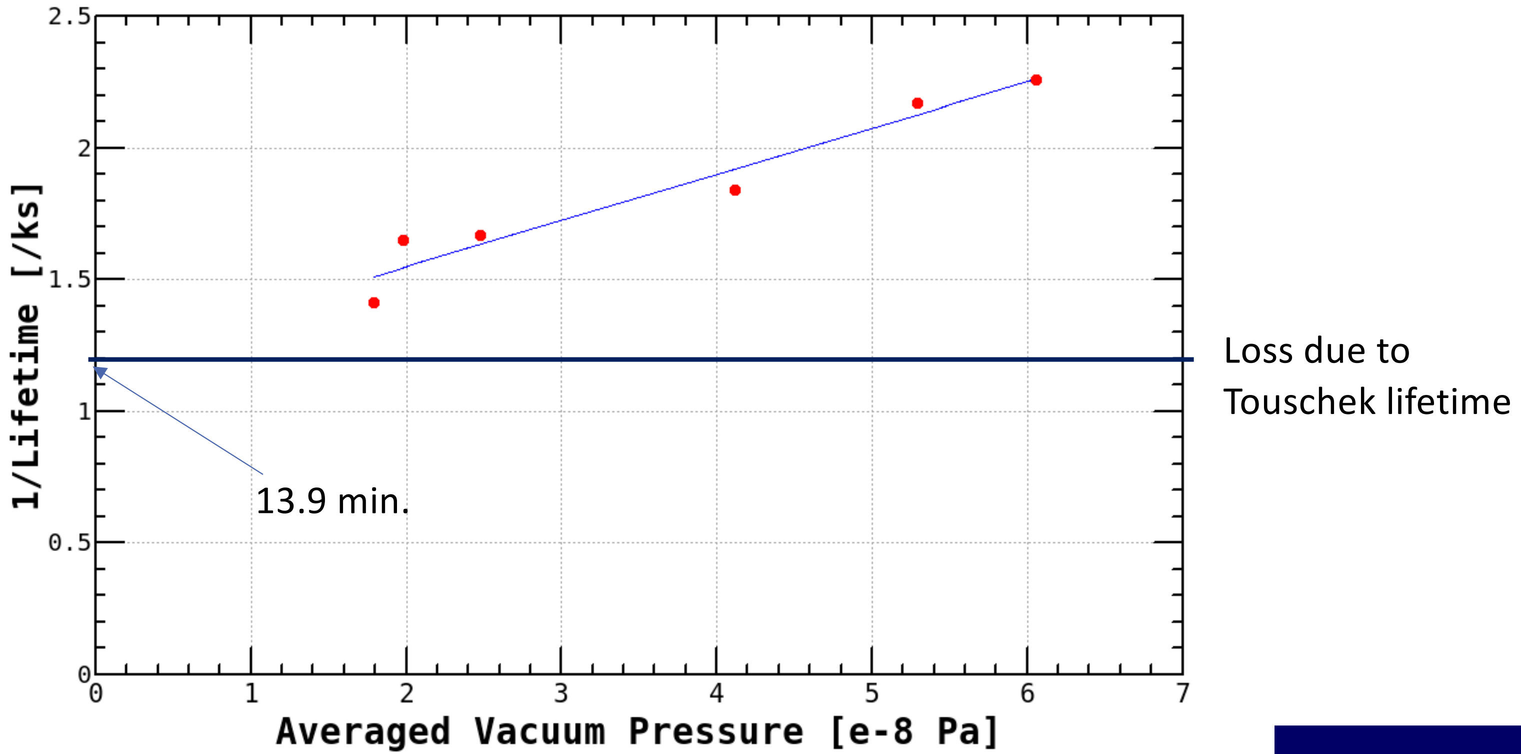
- The particles charge **is deposited on the grid cells**
- The scalar potential ϕ is computed by solving for each slice a **2D Poisson equations** (FFT method, Integrated Green Function[1])
- Force on individual particles is computed by **interpolation** (both transverse kicks and energy change are applied)
- **Particles are propagated** for a single time step



[1] *From J. Qiang et al., "A parallel particle-in-cell model for beam–beam interaction in high energy ring colliders", Journal of Computational Physics 198 (2004) 278–294*

Inverse of beam lifetime as function averaged vacuum pressure

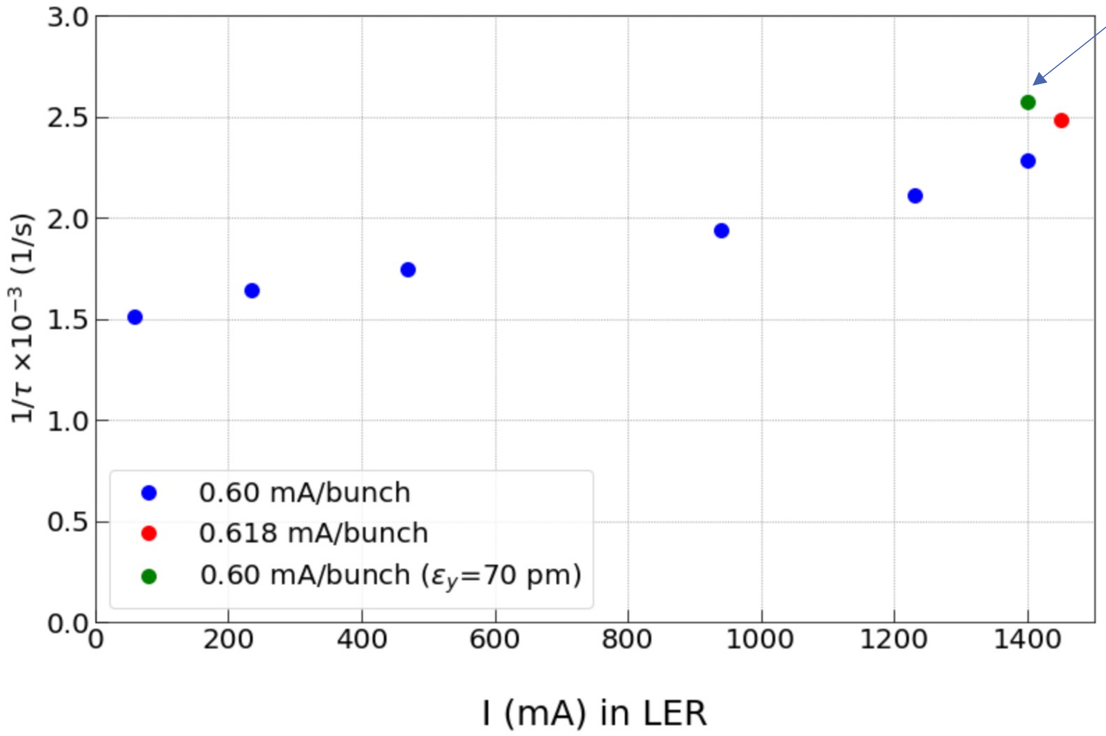
```
ChiSquare =  .03118  Goodness  =  .40601
ccc1 = 1.19754 +/-  .13169              ccc2 =  .17563 +/-  .03310

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

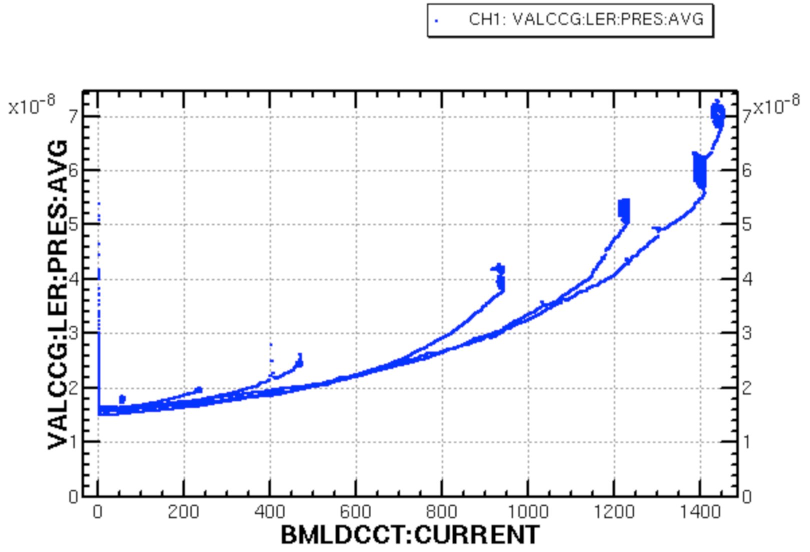


Beam lifetime as function of total beam current with keeping the bunch current

- 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.

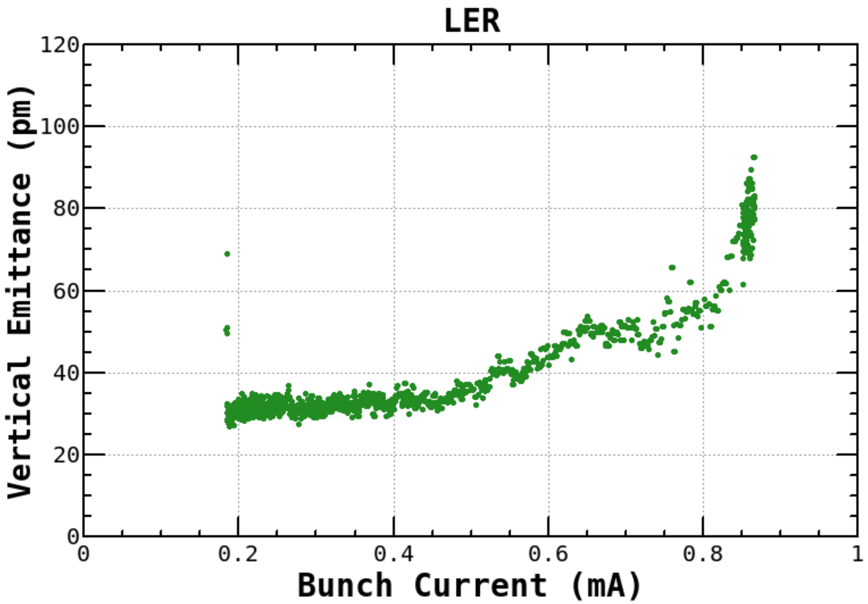
Beam lifetime decreased with larger vertical emittance.
Emittance was changed by using YaECK.

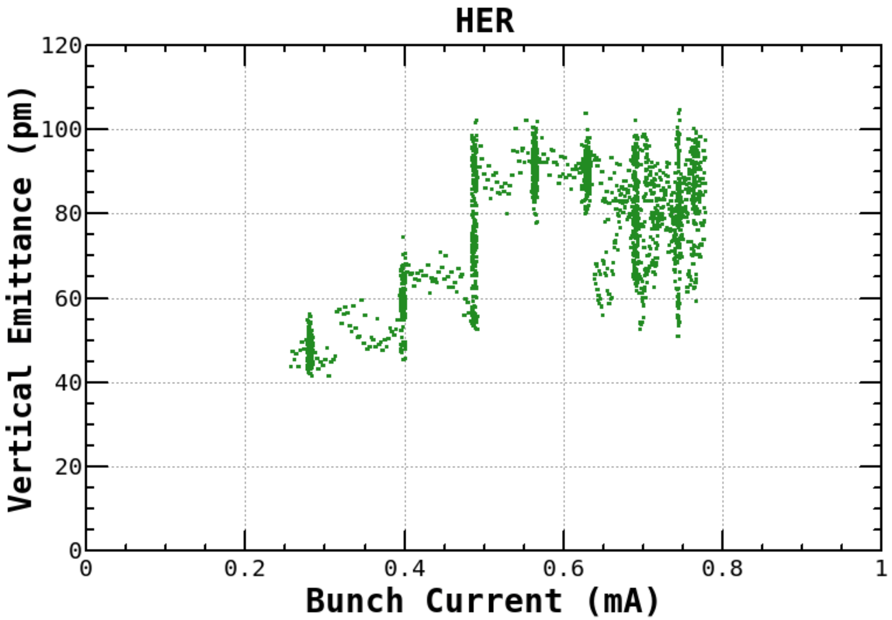




Beam sizes (single beam) on June 27th 2024

2024 June 27th βy^* = 0.9mm

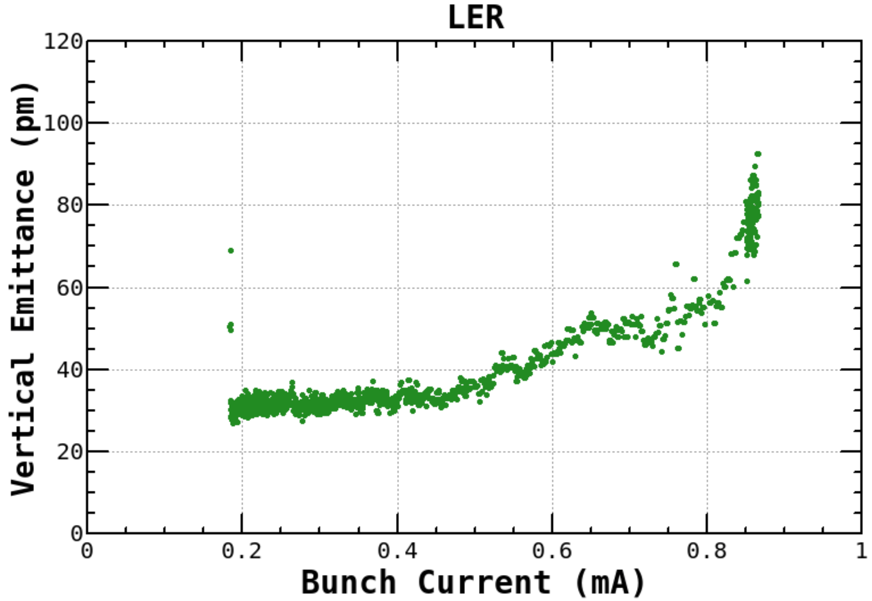




The single beam blowup must be suppressed for a higher luminosity.

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

2024 June 27th βy^* = 0.9mm



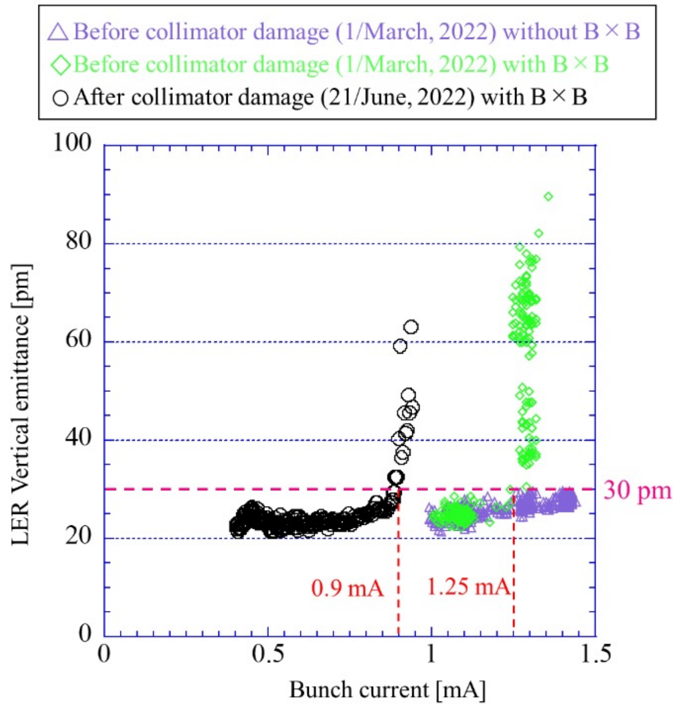
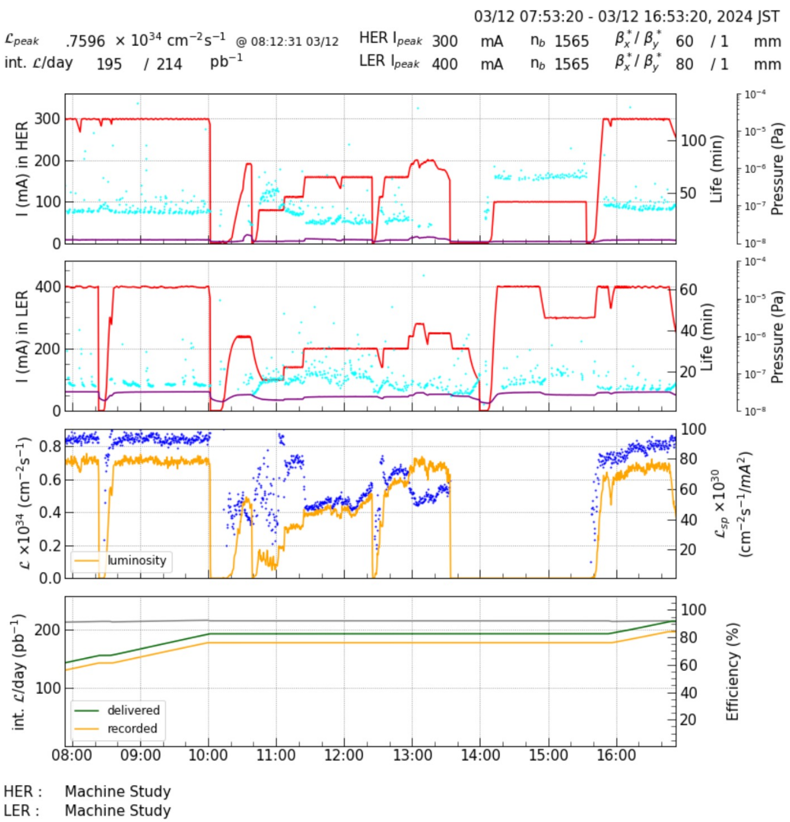


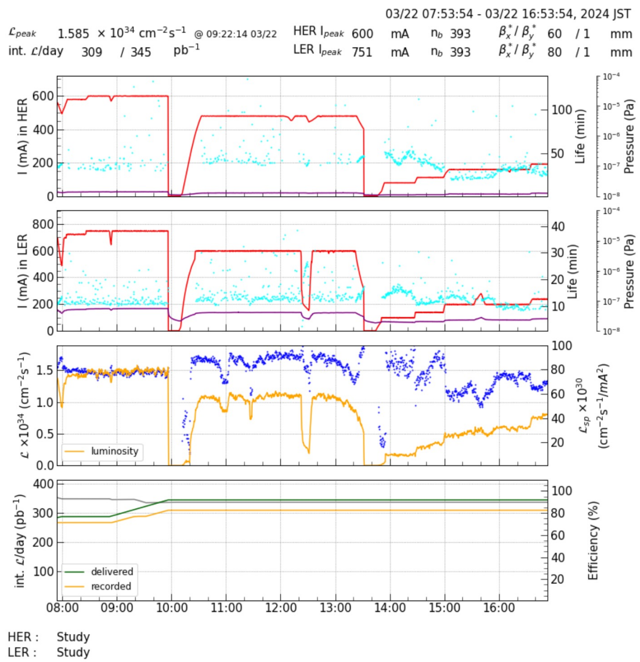
FIG. 10. The vertical beam emittance versus bunch current with $\beta_y^* =$ 1 mm, before (green diamonds) and after (black circles) the event of collimator jaw damage with BxB feedback on. The data of purple triangles show the measurement with BxB feedback off.

Beam-Beam Study

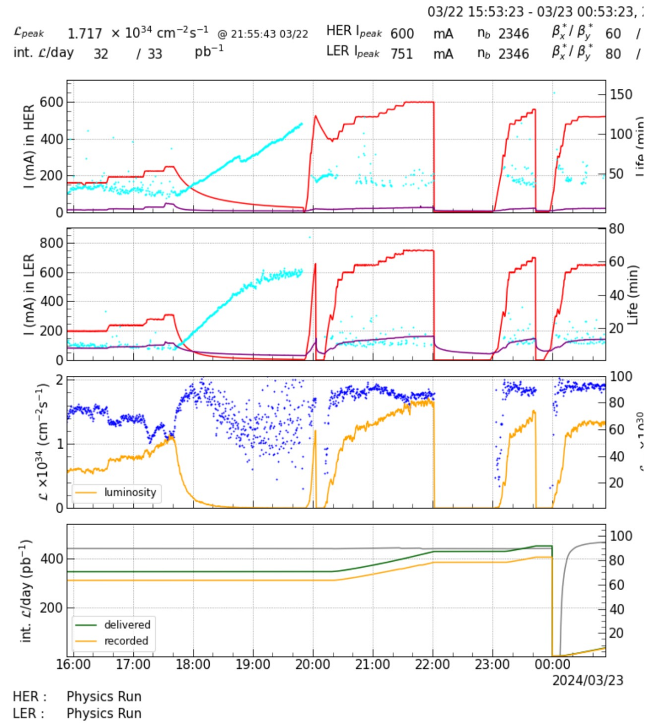
Shift summary



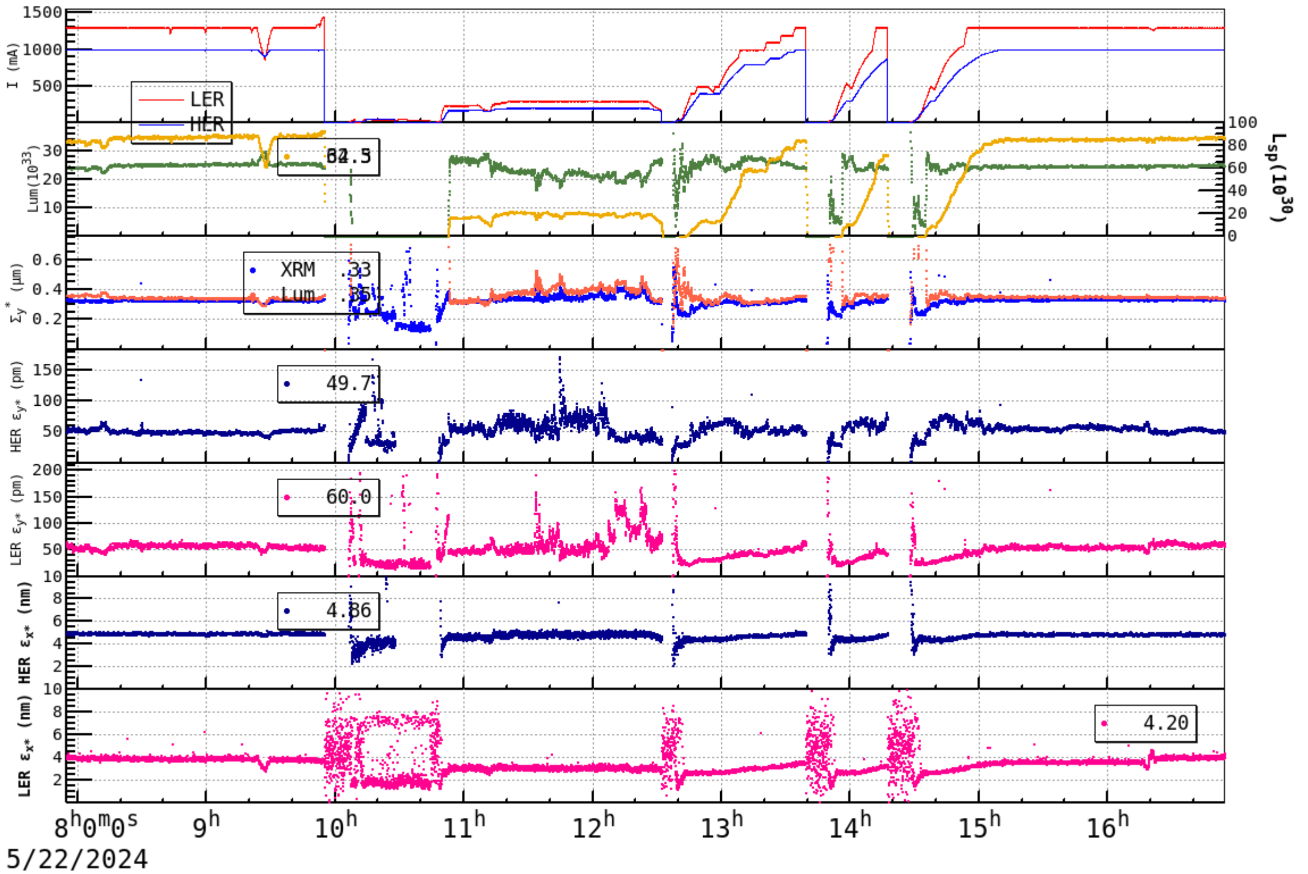
Shift summary



Shift summary



Collision with 393 bunches May 22nd 2024



Specific luminosity at KEKB

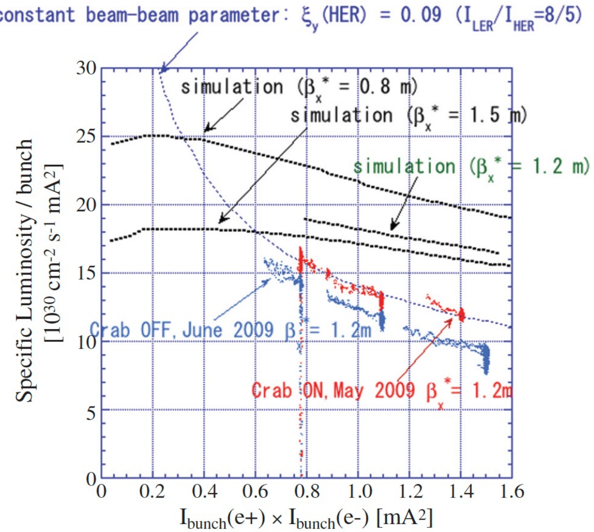


Fig. 8. Comparison of the specific luminosity per bunch with and without crab cavities as a function of the bunch current product of the two beams. The specific luminosity is defined as the luminosity divided by the bunch current product of the two beams and also divided by the number of bunches. Three different lines from the beam–beam simulations are also shown, corresponding to different values of the IP horizontal beta function, β_x^*. The simulations predicted that a smaller β_x^* (smaller σ_x^*) would give a higher luminosity. Also shown in the figure is a line corresponding to a constant vertical beam–beam parameter of 0.09 for the HER, assuming the bunch current ratio between the LER and the HER is 8/5. As seen in the figure, the data with crab cavities are aligned on this line. This means that the HER vertical beam–beam parameter, ξ_y(HER), is saturated at around 0.09.

Machine performance of SuperKEKB

IPAC2020 IPAC2022

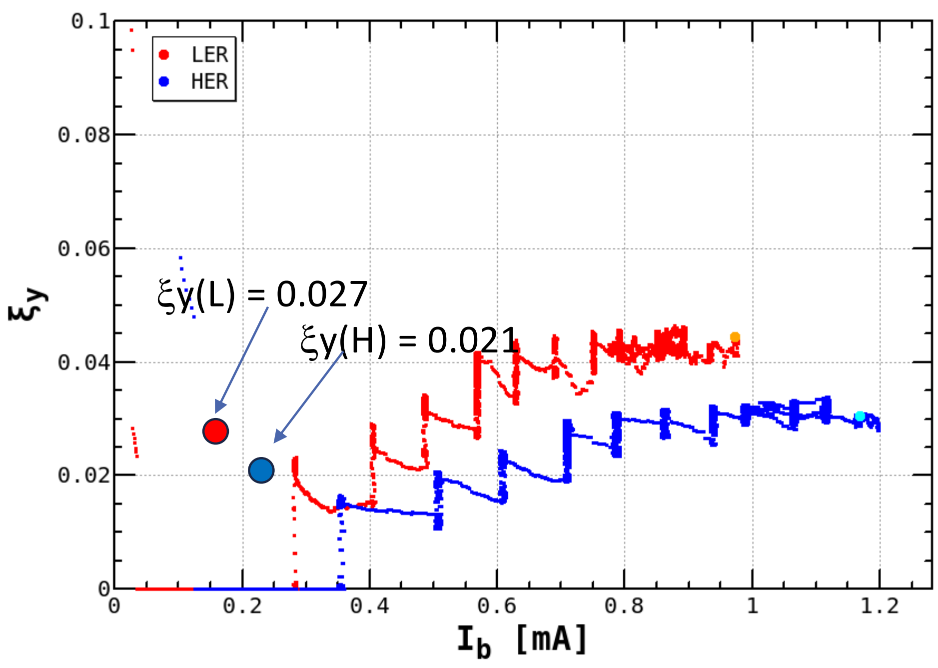
	KEKB achieved		SuperKEKB 2020 May 1st		SuperKEKB 2022 June 8th		SuperKEKB design	
	LER	HER	LER	HER	LER	HER	LER	HER
I_{beam} [A]	1.637	1.188	0.438	0.517	1.321	1.099	3.6	2.6
# of bunches	1585		783		2249		2500	
I_{bunch} [mA]	1.033	0.7495	0.5593	0.6603	0.5873	0.4887	1.440	1.040
βy* [mm]	5.9	5.9	1.0	1.0	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

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

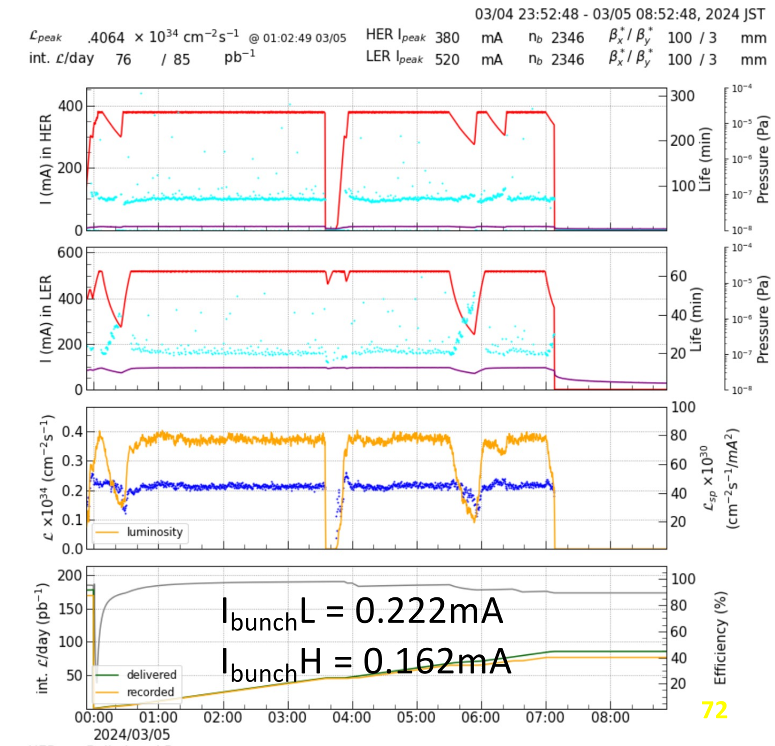
Beam-beam parameter with βy*=3 mm



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

Energy (10.583 GeV)	LER (4.002 GeV) / DR (1.1 GeV)	HER (7.010 GeV)
Beam Current	520.2 mA / 3.5 mA	380.9 mA
Beta at IP	100 mm / 3 mm	100 mm / 3 mm
Crab Waist Ratio	3.231892e-14 %	4.06515e-13 %
Number of bunches	2346	2346
Single Abort	2	3
Both Abort	0	

Shift summary



List for future investigation

- Experiment
  - Confirmation of beam-beam performance w/ FB off.
  - Tune scan with chromatic coupling correction and with higher bunch current product
  - Tune survey from view points of be injection efficiency
  - Nonlinear optics corrections
- Simulations
  - Simulation on beam injection with beam-beam interaction (tune survey).
  - Beam-beam simulation with full lattices
  - More beam-beam simulation with impedance
  - Beam-beam simulation with space charge
- Parameter optimization
  - Squeeze βx^* of LER (80 mm -> 60 mm) is to be done in the next run for better injection and for suppression of horizontal beam blowup (this will also reduce ΔK_2 for SLY (CW SX).