Beam-beam simulations for SuperKEKB

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1st meeting of beam-beam workgroup, Aug. 24, 2021, KEK

Kind reminding

- This talk gives an overview of beam-beam simulations I did in the past years in collaboration with K. Ohmi and other members of KEKB/SuperKEKB team. The main purpose is to share the lessons I learned and I hope the talk is informative to the ITF-BB workgroup as well to the ITF team.
- The “nano-beam scheme” adopted at SuperKEKB design does not include crab waist because of its strong impact on dynamic aperture and beam lifetime. Therefore, most of my old work on beam-beam simulations was done without crab waist.
- The beam-beam effects on optics design/optimization were reviewed by H. Koiso in the ITF kick-off meeting (See Ref.[1]).
- The beam-beam effects at SuperKEKB were reviewed by K. Ohmi in this meeting.

[1] H. Koiso, Talk presented at the International Task Force Meeting for SuperKEKB Upgrade, Jul. 28, 2021 https://kds.kek.jp/event/38899/contributions/193478/attachments/145910/181459/BeamBeam-CrabWaist-DA_koiso.pdf.

Types of simulations for beam-beam effects [2]

- Weak-strong model + simple one-turn map: BBWS code
  - The weak beam is represented by N macro-particles (statistical errors ~ $1/\sqrt{N}$). The strong beam has a rigid charge distribution with its EM fields expressed by Bassetti-Erskine formula.
  - The simple one-turn map contains lattice transformation (Tunes, alpha functions, beat functions, X-Y couplings, dispersions, etc.), chromatic perturbation, synchrotron radiation damping, quantum excitation, crab waist, etc.

$$M = M_{rad} \circ M_{chr} \circ M_{bb} \circ M_{cw} \circ M_0$$

$$M_0 = R \cdot M_{lin} \cdot R^{-1}$$

- Weak-strong model + full lattice: SAD code
  - The BBWS code was implemented into SAD as a type of BEAMBEAM element, where beam-beam maps is called in particle tracking.
  - Tracking using SAD: 1) Symplectic maps for elements of BEND, QUAD, MULT, CAVI, etc. 2) Element-by-element SR damping/excitation; 3) Distributed weak-strong space-charge; 4) MAP element for arbitrary perturbation maps (such as crab waist, wake fields, artificial SR damping/excitation, etc.); …

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- Strong-strong model + simple one-turn map: BBSS code
  - Both beam are represented by N macro-particles
  - The one-turn map is the same as weak-strong code. Beamstrahlung model is also available. Choices of numerical techniques: PIC, Gaussian fitting for each slice, …
  - For SuperKEKB, it is hard to include lattice.

[2] K. Ohmi, Talk presented at the 2019 SAD workshop, https://conference-indico.kek.jp/event/75/contributions/1473/attachments/979/1037/Beam-beam-code-Ohmi.pdf.

Types of simulations for beam-beam effects [2]

- Weak-strong model + simple one-turn map: BBWS code
  - Pros: Fast simulation of luminosity and beam-beam effects. Not require much computing resources. Used for tune survey, fast luminosity calculation, etc..
  - Cons: Strong beam frozen. Crab waist of strong beam not implemented. Not sensitive to coherent beam-beam head-tail (BBHT) instability (BBHTI).
- Weak-strong model + full lattice: SAD code
  - Pros: Relatively fast to allow tracking with lattice. Interplay of beam-beam and lattice nonlinearity. Space-charge modeling possible. Localized geometric wakes possible.
  - Cons: Same as BBWS code. Tune survey possible but relatively slow.
- Strong-strong model + simple one-turn map: BBSS code
  - Pros: Allow dynamic evolution of 3D distribution of two beams. Detect BBHTI.
  - Cons: Tracking quite slow. Not feasible for tune survey. No effective method of parallelization.

[2] K. Ohmi, Talk to the 2019 SAD workshop, https://conference-indico.kek.jp/event/75/contributions/1473/attachments/979/1037/Beam-beam-code-Ohmi.pdf.

Beam-beam simulations with chromatic effects for KEKB

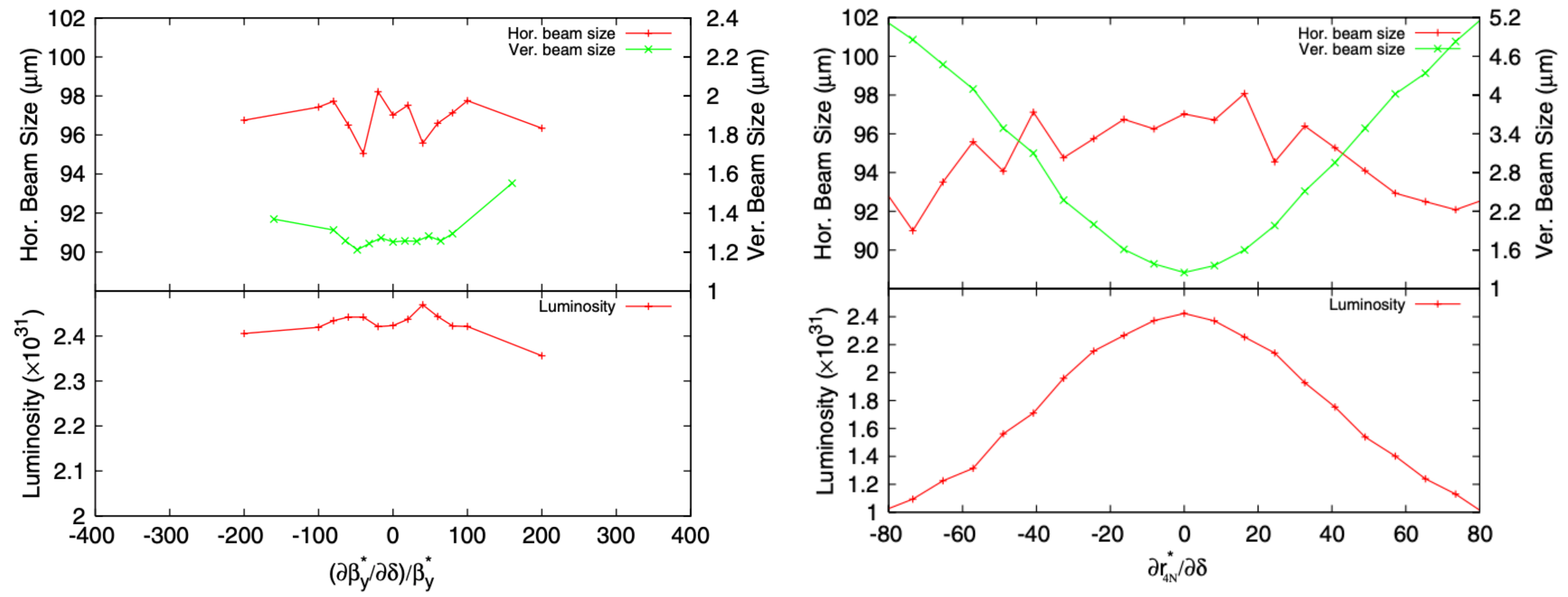
- Model of chromatic effects [3,4]
  - Twiss parameters expressed in Taylor series.
  - Chromaticities of Twiss parameters are estimated using lattice with error seeds and also measured with beams.
  - Symplectic maps for chromatic effects reconstructed and implemented into BBWS and BBSS.
- Simulations
  - BBWS: Fast survey of chromatic alpha/beta functions, and couplings. Tune survey of chromatic effects.
  - BBSS: Simulation of luminosity performance.
  - Findings: Chromatic couplings at IP causes remarkable luminosity loss at KEKB.
- Beam tunings with chromatic knobs qualitatively agreed with beam-beam simulations, contributing to luminosity boost at KEKB.
- The tools were then applied to investigate the chromatic effects on luminosity at SuperKEKB.

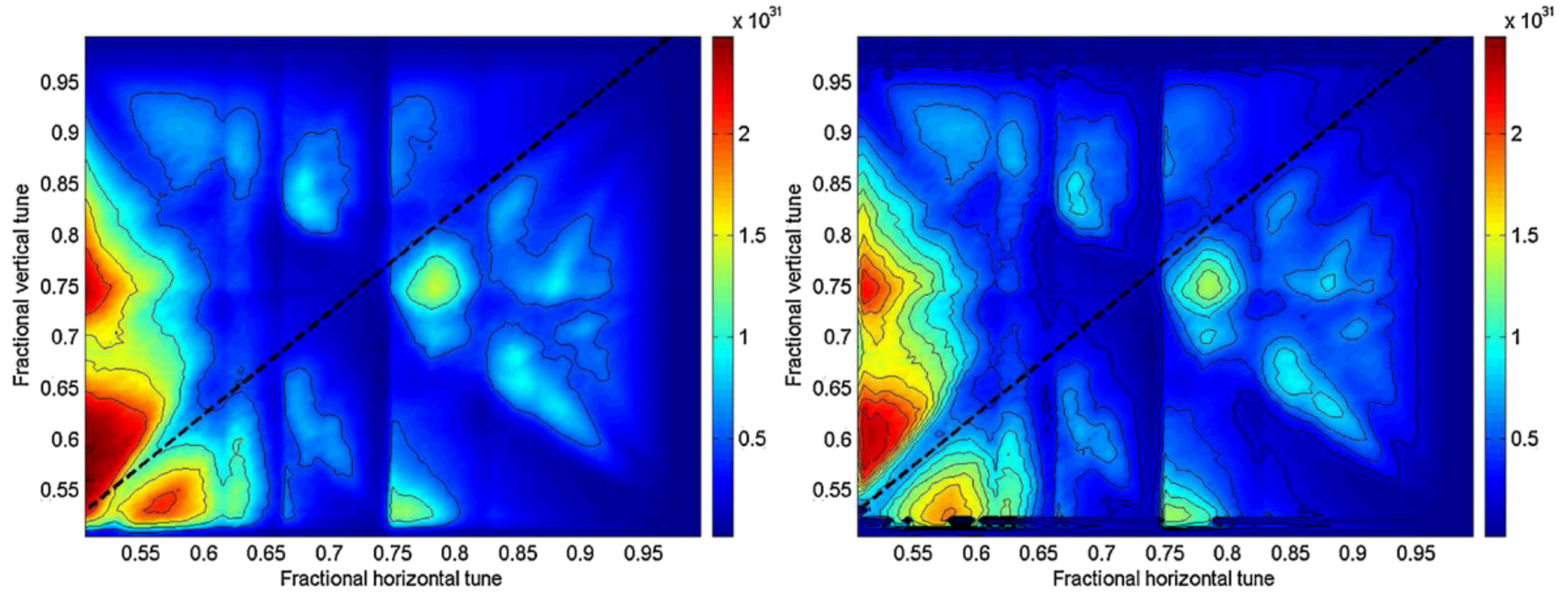
$$\alpha_u(\delta) = \sum_{i=0}^{\infty} \alpha_{ui}\delta^i \qquad \beta_u(\delta) = \sum_{i=0}^{\infty} \beta_{ui}\delta^i$$

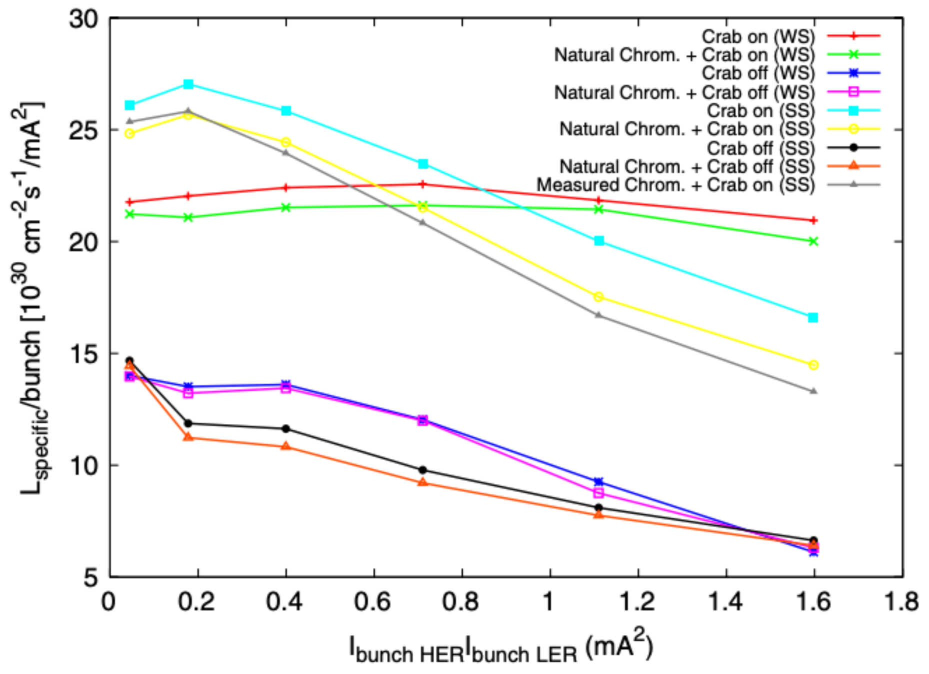
$$\nu_u(\delta) = \sum_{i=0}^{\infty} \nu_{ui}\delta^i \qquad r_j(\delta) = \sum_{i=0}^{\infty} r_{ji}\delta^i$$

$$u = x, y \quad \text{and} \quad j = 1, 2, 3, 4,$$

$$H_I(x, p_x, y, p_y, \delta) = \sum_{n=1}^{\infty}(a_n x^2 + b_n x p_x + c_n p_x^2 + e_n x p_y + f_n p_x y + g_n p_x p_y + u_n y^2 + v_n y p_y + w_n p_y^2)\delta^n$$







[3] D. Zhou et al., "Simulations of beam-beam effect in the presence of general chromaticity", Phys. Rev. ST Accel. Beams 13, 021001 (2010).

[4] Y. Seimiya et al., "Symplectic Expression for Chromatic Aberrations", Prog. Theor. Phys. (2012) 127 (6): 1099-1119.

Beam-beam simulations for SuperKEKB

$$r_i(\delta) = r_{i0} + r_{i1}\delta \quad i = 1, 2, 3, 4$$

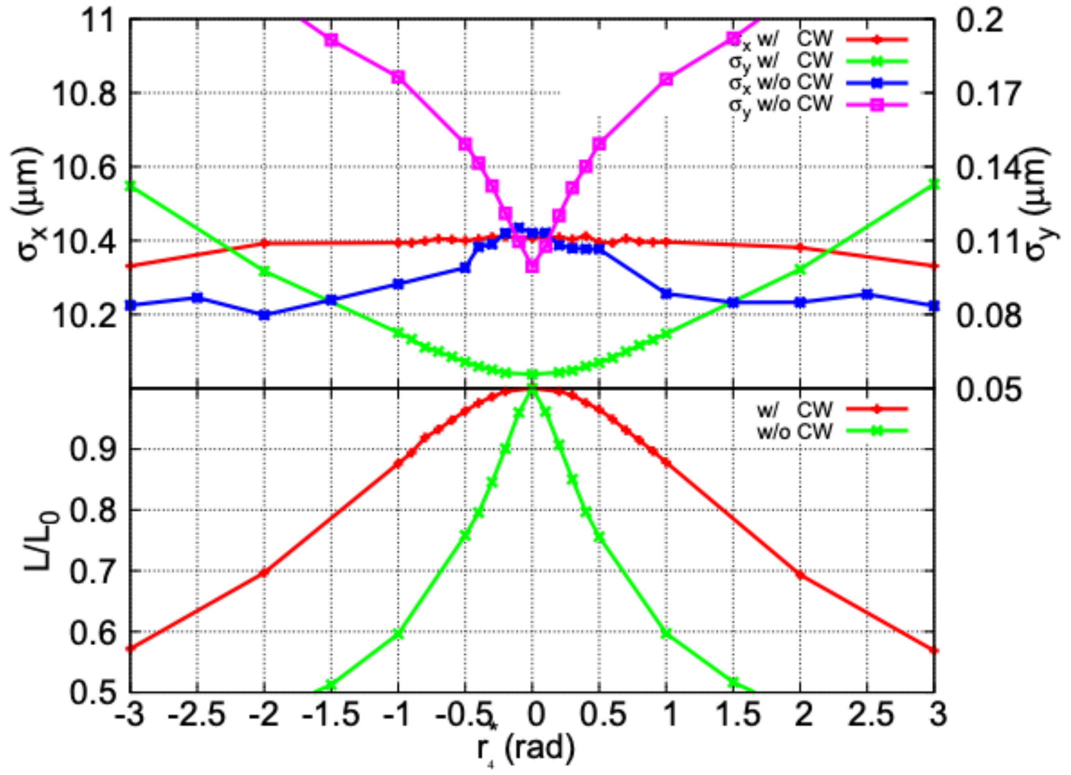
- BBWS simulations: Tolerances on linear and chromatic couplings
  - Non-zero linear and chromatic couplings at IP will directly cause luminosity loss. With small emittances and beta functions at IP, luminosity of SuperKEKB will be very sensitive to these parameters.
  - Weak-strong simulations were done to define the tolerances.
  - Chromatic couplings were estimated using design lattice with error seeds.
- Findings [5]
  - Crab waist is effective in suppressing vertical blowup.
  - Crab waist is effective in increasing tolerances on linear and chromatic couplings.
  - Control of machine errors and reliable IP tuning knobs are necessary to minimize the luminosity degradation.

Table 1: Main parameters of the SuperKEKB use for beam-beam simulations.

Parameter	e^+	e^-
$E\,(GeV)$	4.0	7.0
C (m)	3016	3016
$N\,(10^{10})$	9.04	6.53
$\beta_x^*\,(mm)$	32	25
$\beta_y^*\,(mm)$	0.27	0.42
$\epsilon_x\,(nm)$	3.2	1.7
$\epsilon_y\,(pm)$	12.8	8.16
$\sigma_z\,(mm)$	6	5
$\sigma_\delta\,(10^{-4})$	8.34	8.34
ν_x	45.523	44.570
ν_y	43.548	41.590
ν_z	0.015	0.015

Table 2: Average and variance of the chromatic X-Y couplings calculated from 1000 seeds of errors at the SuperKEKB LER.

Parameter	Average	Variance
$r_{11}\,(rad)$	-0.23	0.21
$r_{21}\,(m)$	0.060	0.013
$r_{31}\,(m^{-1})$	-290	230
$r_{41}\,(rad)$	37	23



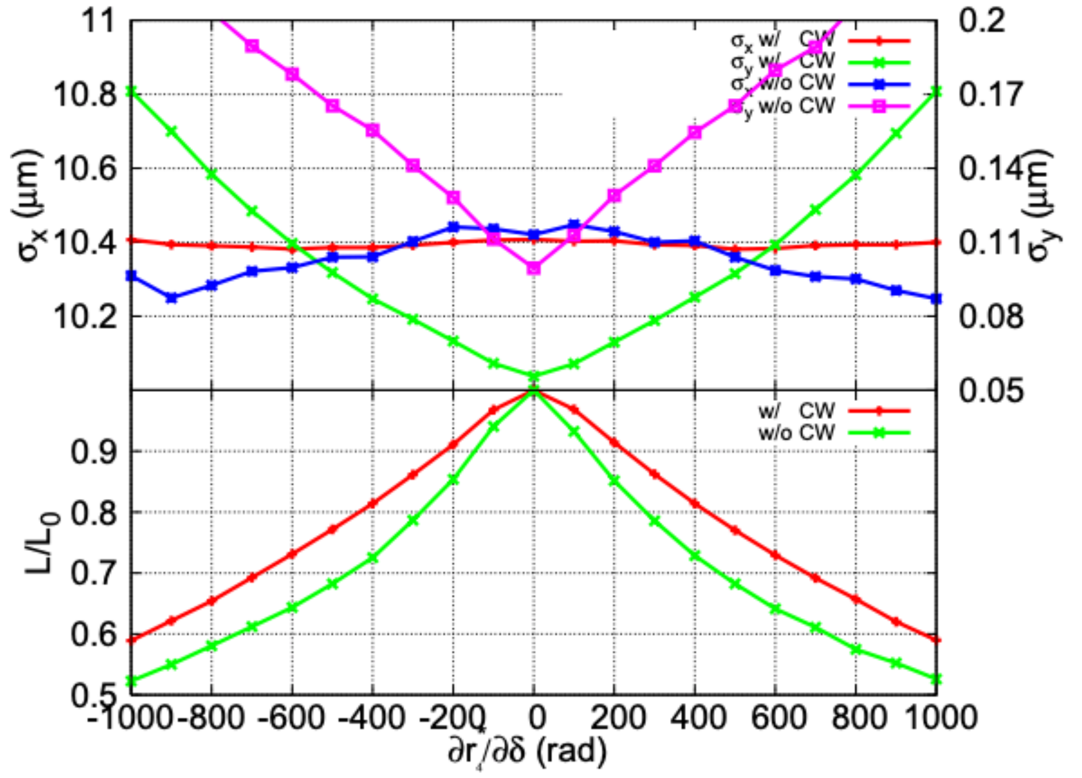


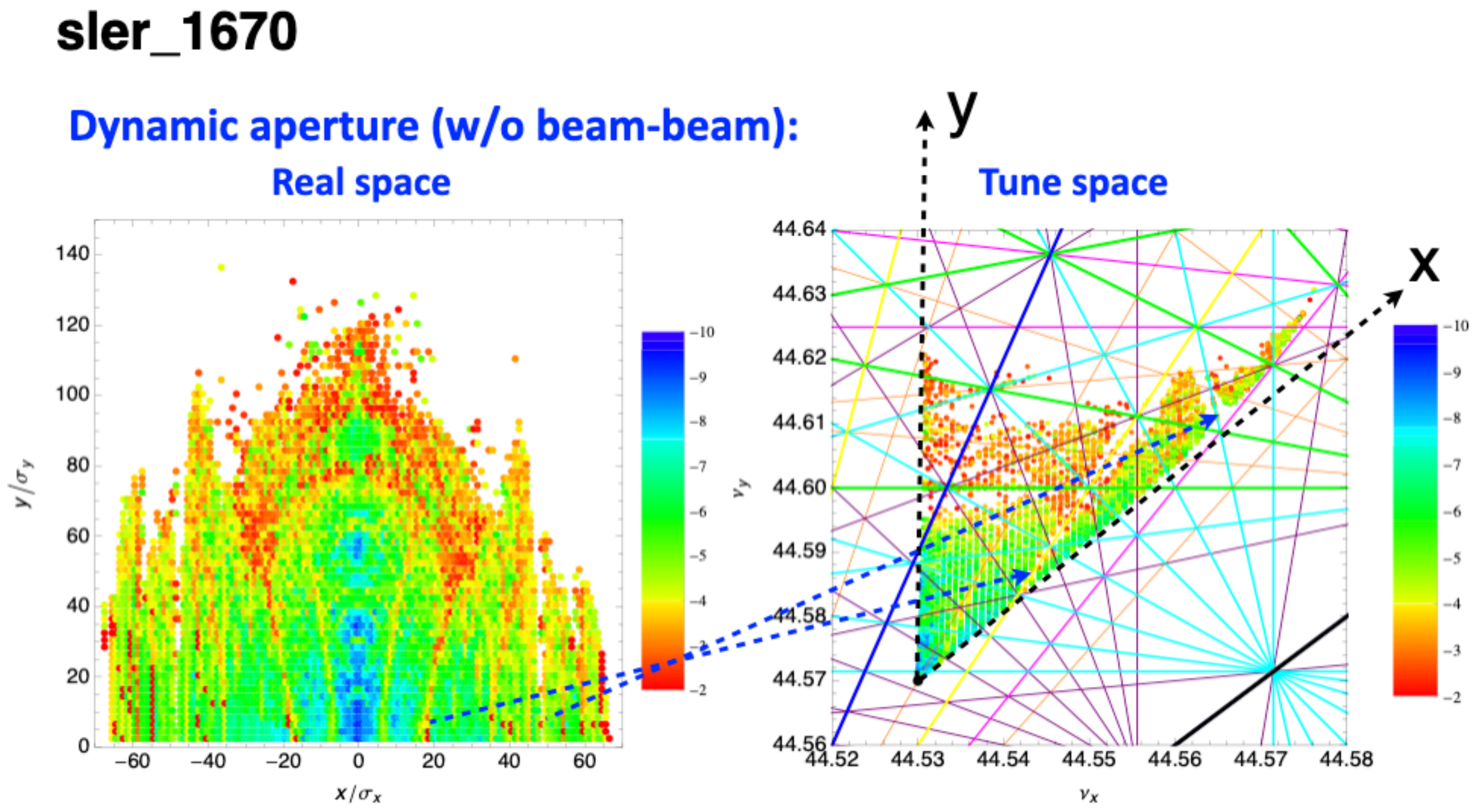
Table 3: Tolerances for the linear and chromatic X-Y couplings at the IP of the SuperKEKB LER, assuming a rate of 20% luminosity degradation.

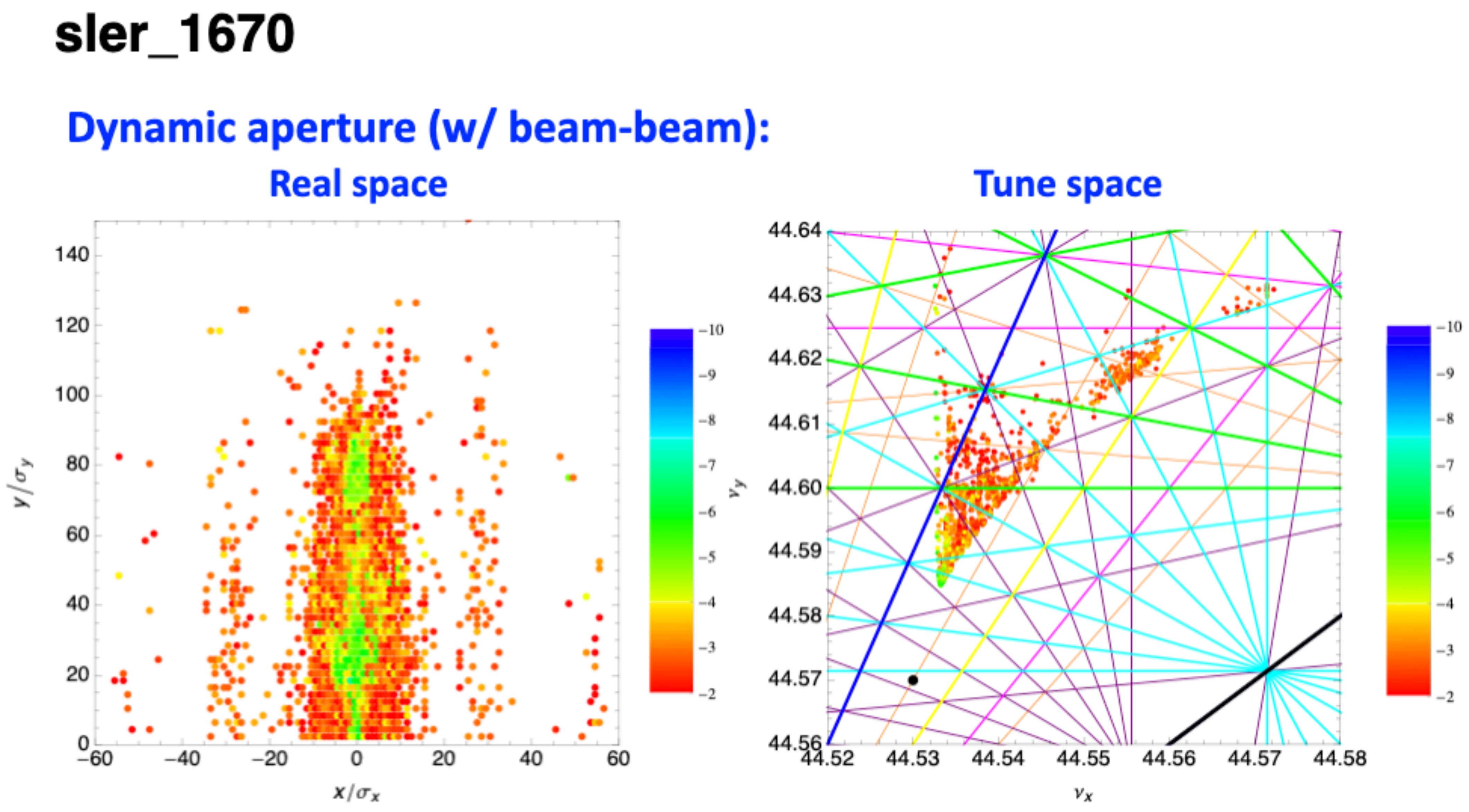
Parameter	w/ crab waist	w/o crab waist
$r_1^*\,(mrad)$	±5.3	±3.5
$r_2^*\,(mm)$	±0.18	±0.13
$r_3^*\,(m^{-1})$	±55	±15
$r_4^*\,(rad)$	±1.4	±0.4
$r_{11}\,(rad)$	±2.3	±2.0
$r_{21}\,(m)$	±0.09	±0.07
$r_{31}\,(m^{-1})$	±11000	±9400
$r_{41}\,(rad)$	±430	±280

[5] D. Zhou et al., Effects of Linear and Chromatic X-Y Couplings in the SuperKEKB, in Proceedings of IPAC'10, Kyoto, Japan.

Beam-beam simulations for SuperKEKB

- Interplay of beam-beam and lattice nonlinearity without crab waist
  - FMA was done in July of 2012 to investigate beam-beam effects on dynamic aperture [6].
  - FMA was done with ideal lattice (with DA optimization and no machine errors).
  - Particles were tracked to 1024 turns with BEAMBEAM element at IP.
- Findings [6]
  - With nominal beam-beam tune shift of ~0.09, the beam-beam interaction could strongly reduce dynamic aperture (DA).
  - Reduction of DA is more serious in LER than in HER.
  - This raised a concern of luminosity loss due to lattice nonlinearity.





[6] D. Zhou, First results of FMA for SuperKEKB, Talk presented at the SuperKEKB optics meeting, KEK, Jul. 17, 2012.

Beam-beam simulations for SuperKEKB

- Interplay of beam-beam and lattice nonlinearity
  - Simulations of luminosity were done using SAD.
  - Simulations were updated with new lattice designs when they were available.
  - KEKB was also checked.
- Findings [7]
  - Interplay of beam-beam and lattice nonlinearity might cause significant loss of luminosity at SuperKEKB (~25% loss with design lattice of LER without machine errors). This was a big surprise when reported later in the SuperKEKB ARC meeting [8].
  - The loss rate depends on lattice designs (IR model, tunes, etc.).
  - Simulations with KEKB LER lattice showed ~6% loss of luminosity. KEKB HER lattice did not show luminosity loss.

SuperKEKB machine parameters Used for simulations

	LER[1]	HER[1]	Bare lattice LER[2]	Bare lattice HER[3]	Unit
ε_x	3.2[4]	4.6[4]	1.858	4.47	nm
ε_y	8.64[5]	11.5[5]	0.758	1.54	pm
σ_z	6[6]	5[6]	4.81	4.9	mm
σ_δ	8.08	6.37	7.73	6.3	$\times 10^{-4}$

1) Design, Y. Ohnishi et al., Prog. Theor. Exp. Phys. 2012;
2) sler_1682; 3) sher_5753;
4) Intra-beam scattering; 5) X-Y coupling, beam-beam, errors, etc.;
6) Collective effects.

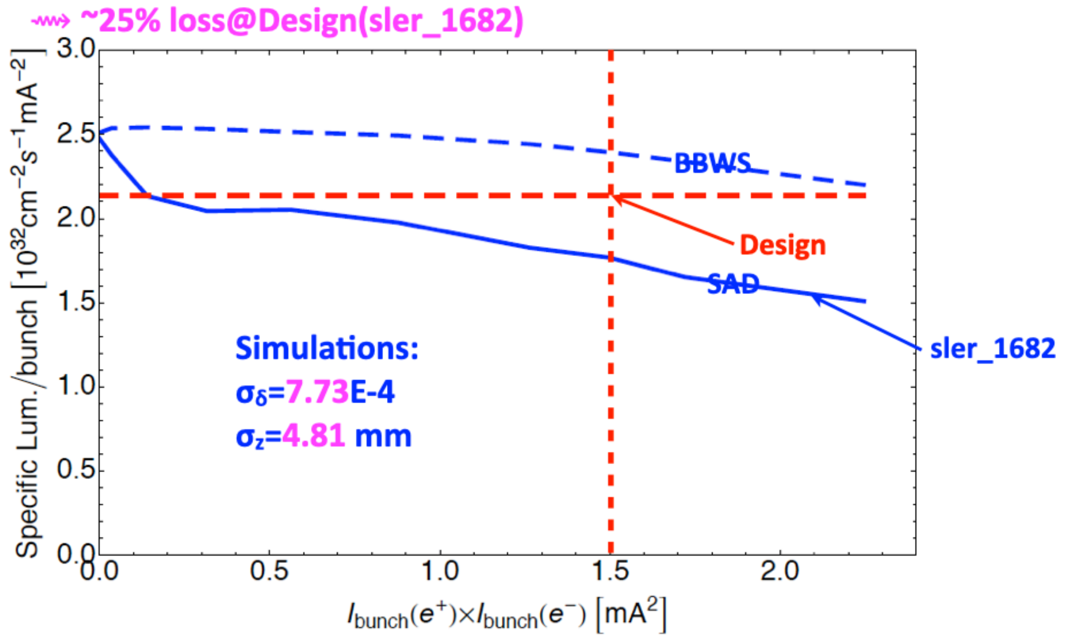
KEKB machine parameter

	LER[1]	HER[1]	Bare lattice LER[2]	Bare lattice HER[2]	Unit
ε_x	19.25	24.19	19.25	24.19	nm
ε_y	192.5	241.9	1.716	8.646	pm
σ_z	4.68[3]	5.20[3]	4.68	5.2	mm
σ_δ	7.27	6.67	7.27	6.67	$\times 10^{-4}$

1) Used for simulations;
2) provided by Y. Ohnishi, lattice used on Jun. 17, 2009;
3) No collective effects.

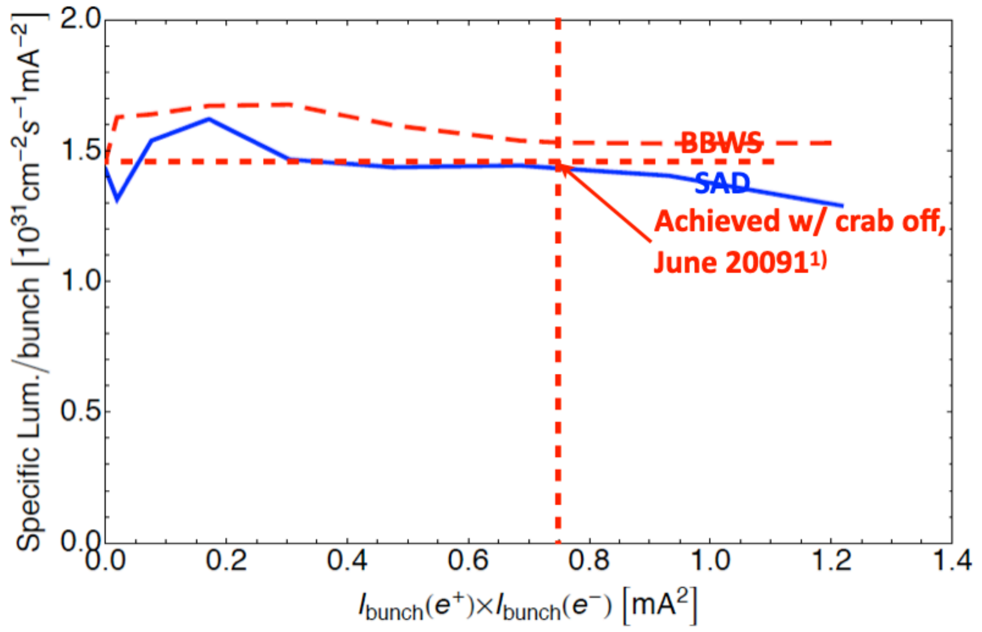
Simulation results - SuperKEKB LER

Specific luminosity: use σ_z of bare lattice (σ_δ under-estimated ⇝ momentum-dependent nonlinearities undercounted)
⇝ ~25% loss@Design(sler_1682)



KEKB: LER: Simulation results w/o crab cavities

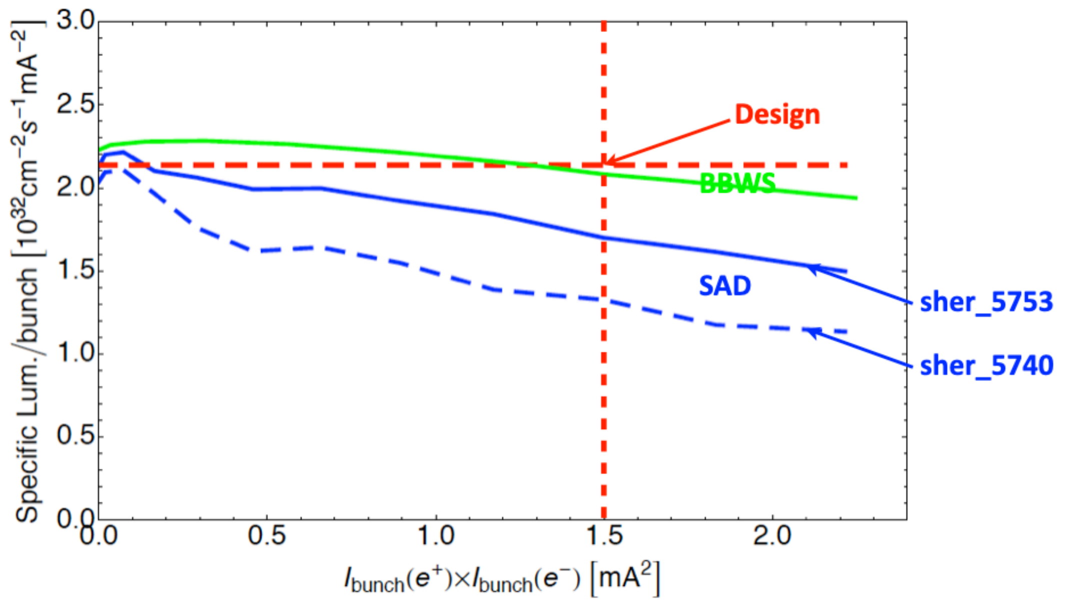
Specific luminosity: use σ_z of bare lattice(Jun.17, 2009)
⇝ ~6% loss@Beam currents on Jun.17, 2009



1) Y. Funakoshi et al., Prog. Theor. Exp. Phys. 2012.

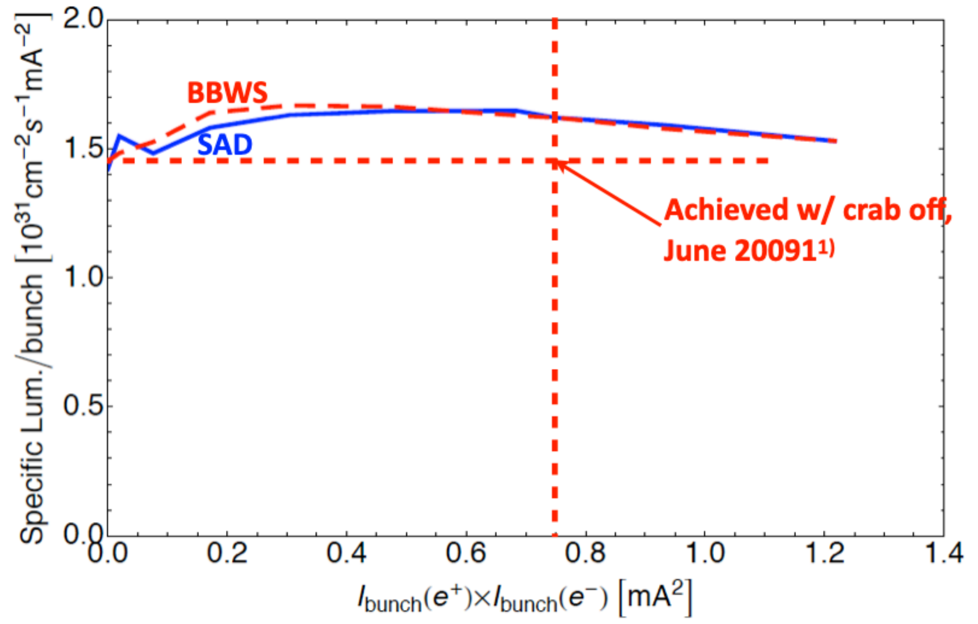
Simulation results - SuperKEKB HER

Specific luminosity: use σ_z of design ⇝ ~20% loss@Design(sher_5753)
luminosity loss is mainly due to blow-up in ε_y



KEKB: HER: Simulation results w/o crab cavities

Specific luminosity: use σ_z of bare lattice(Jun.17, 2009)
⇝ almost no loss@Beam currents on Jun.17, 2009



1) Y. Funakoshi et al., Prog. Theor. Exp. Phys. 2012.

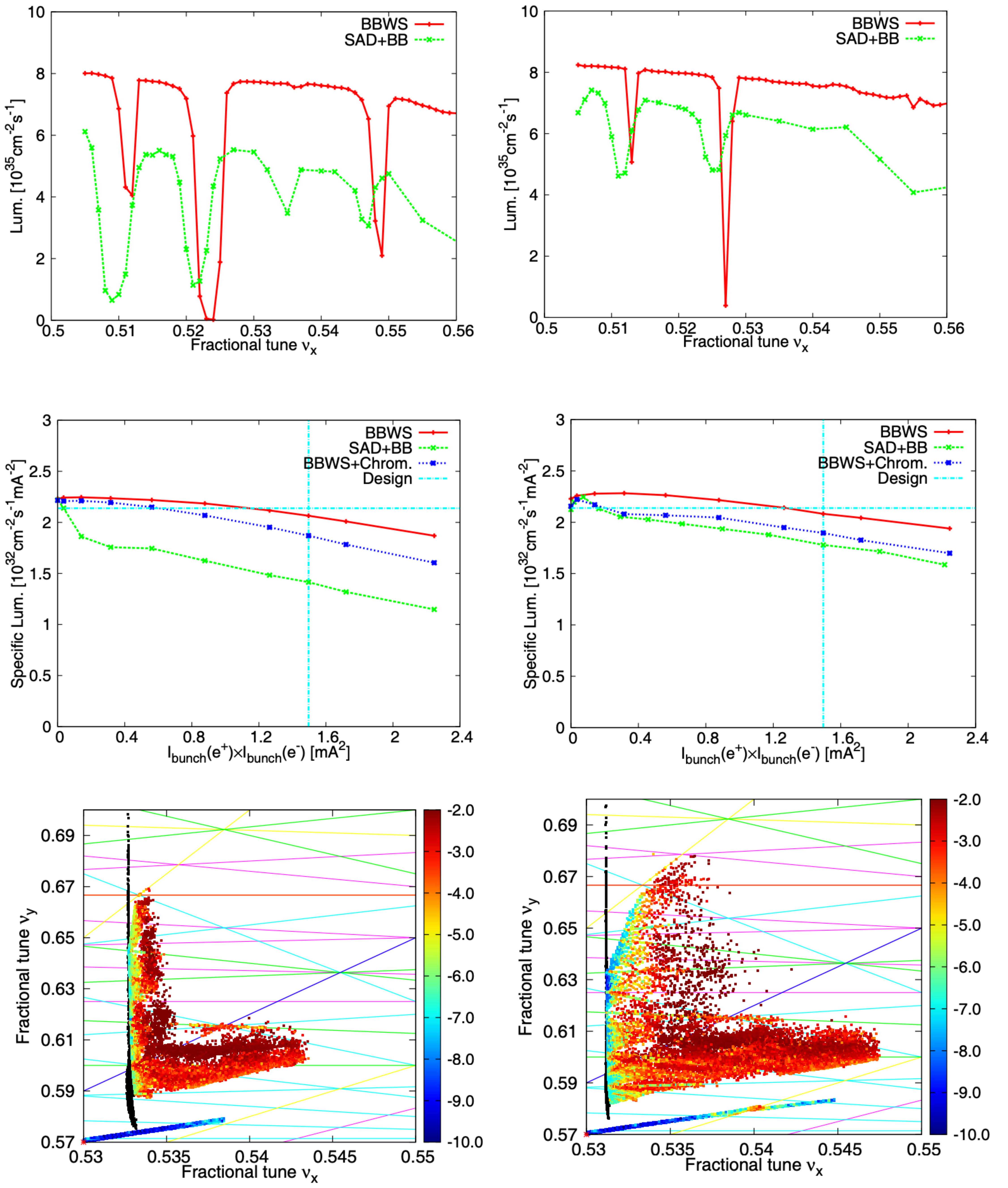
[7] D. Zhou, Crosstalk between beam-beam interaction and lattice nonlinearities in the SuperKEKB, Talk presented at the SuperKEKB optics meeting, KEK, Jan. 17, 2013.
[8] D. Zhou, Beam Dynamics Issues in SuperKEKB, Talk presented at the 18th KEKB Accelerator Review Committee, KEK, Mar. 4-6, 2013.

Beam-beam simulations for SuperKEKB

- Findings [9]
  - In addition to direct loss of luminosity, the synchro-beta resonances $2(\nu_x - k\nu_s) = N$ become wider with lattice, limiting choice of working point.
  - The chromatic terms were extracted from lattice and used in BBWS simulations. Their contribution to luminosity loss was small (this is reasonable because, with experiences of KEKB, the chromatic terms were minimized in lattice designs of SuperKEKB) compared with other unknown sources.
  - Consider tune spread of particles in the physical area of $10\sigma_x \times 10\sigma_y$, beam-beam stretches the tune footprint in vertical direction.

Table 1: Main Parameters of the SuperKEKB use for Beam-beam Simulations

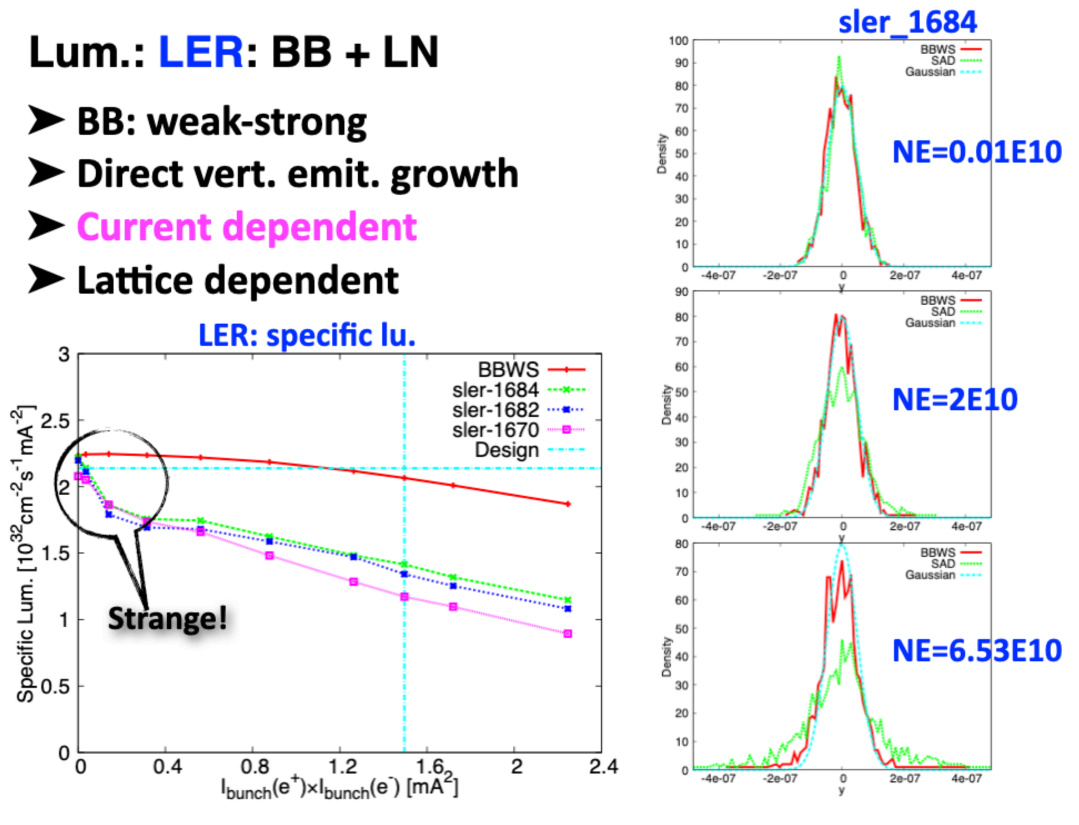
Parameter	LER(e^+)	HER(e^-)
E (GeV)	4.0	7.007
C (m)	3016	3016
N (10^{10})	9.04	6.53
β_x^* (mm)	32	25
β_y^* (μm)	0.27	0.3
ϵ_x (nm)	3.2	4.6
ϵ_y (pm)	8.64	11.5
σ_z (mm)	6	5
σ_δ (10^{-4})	8.08	6.37
ν_x	44.53	45.53
ν_y	46.57	43.57
ν_z	0.0247	0.028

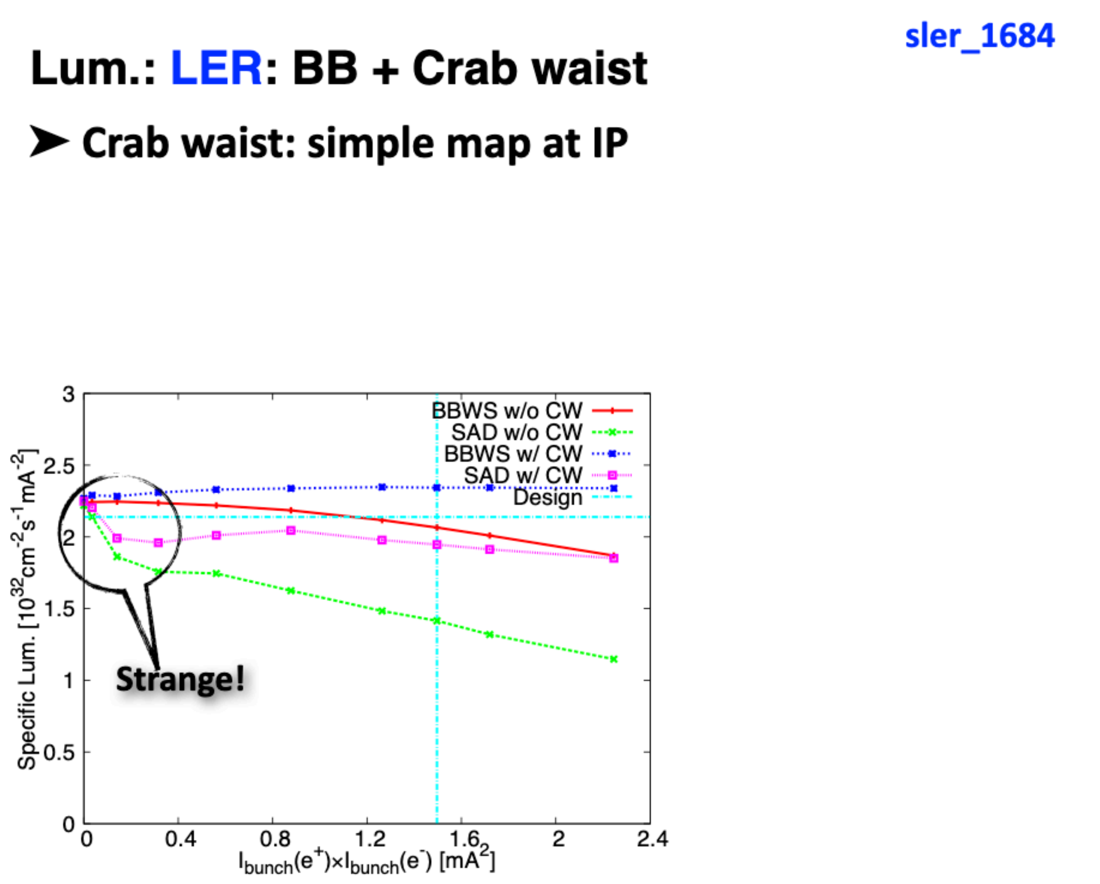


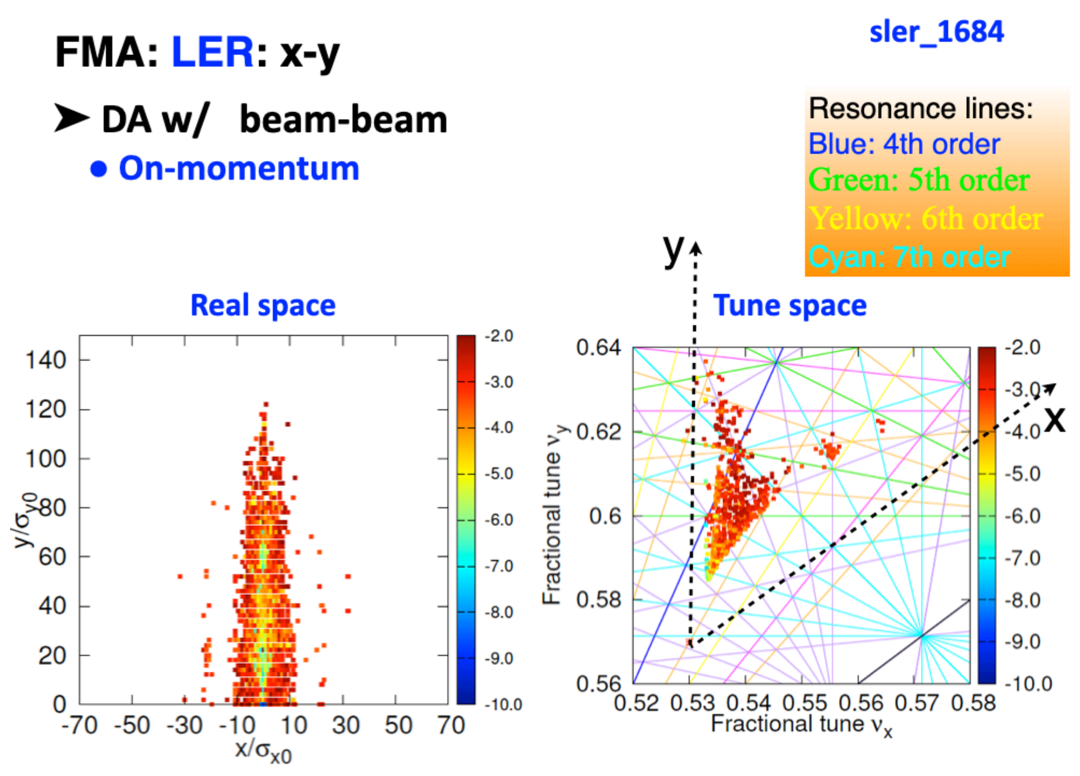
[9] D. Zhou et al., Crosstalk Between Beam-beam Interaction and Lattice Nonlinearities in the SuperKEKB, in Proceedings of IPAC'13, Shanghai, China.

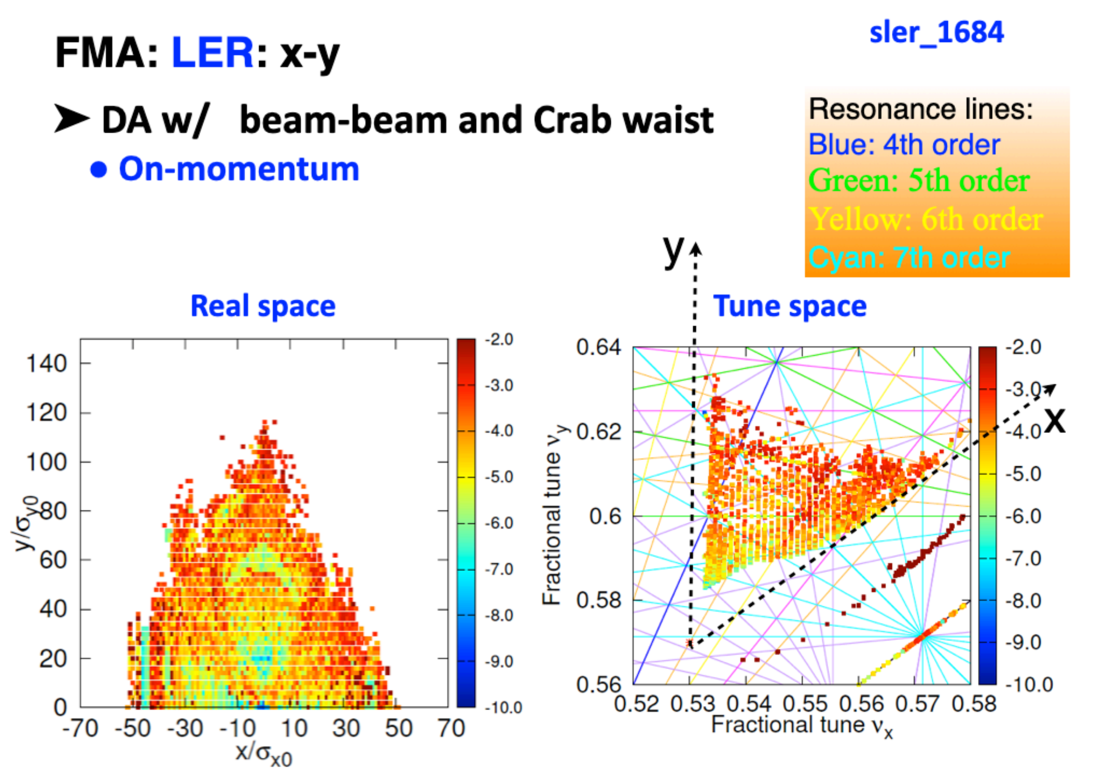
Beam-beam simulations for SuperKEKB

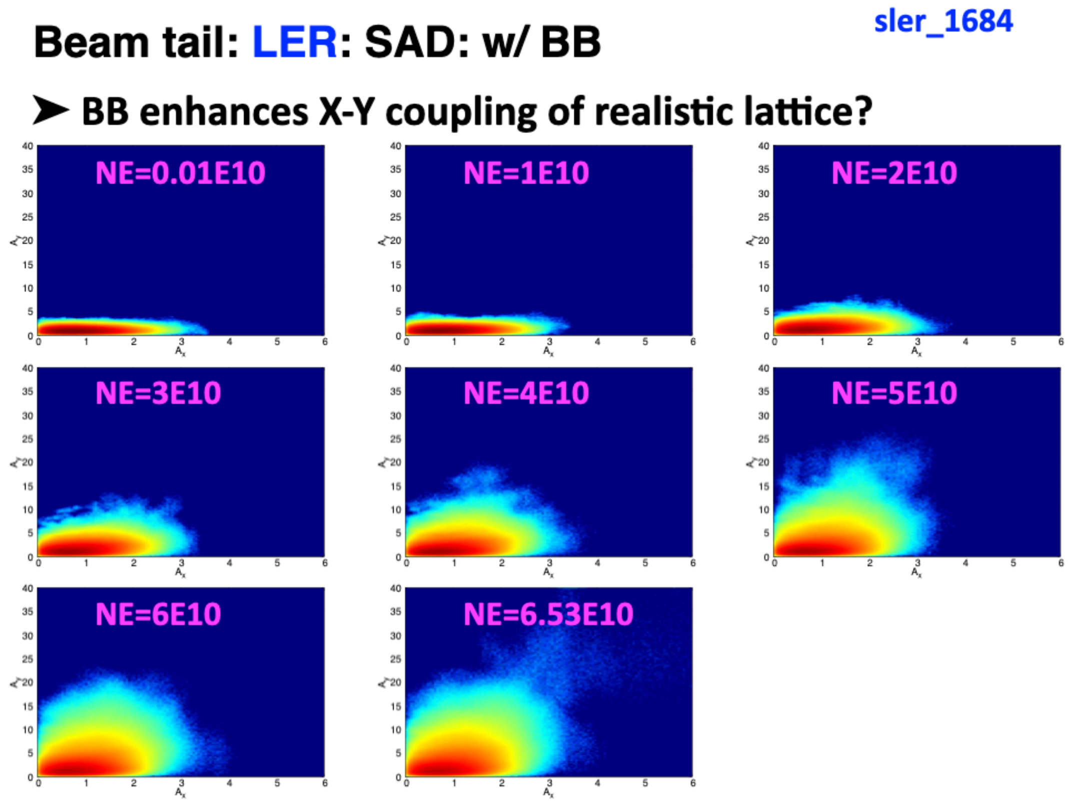
- Findings [10]
  - The fast drop of specific luminosity at low bunch currents was hard to understand.
  - Simple map of crab waist (perfect crab waist) was used in SAD simulations.
  - Perfect crab waist is effective in recovering luminosity at high bunch currents, but not effective at low bunch currents.
  - Perfect crab waist is also effective in recovering DA with beam-beam and in suppressing beam halo.
  - But even perfect crab waist cannot work well in the presence of lattice nonlinearity.

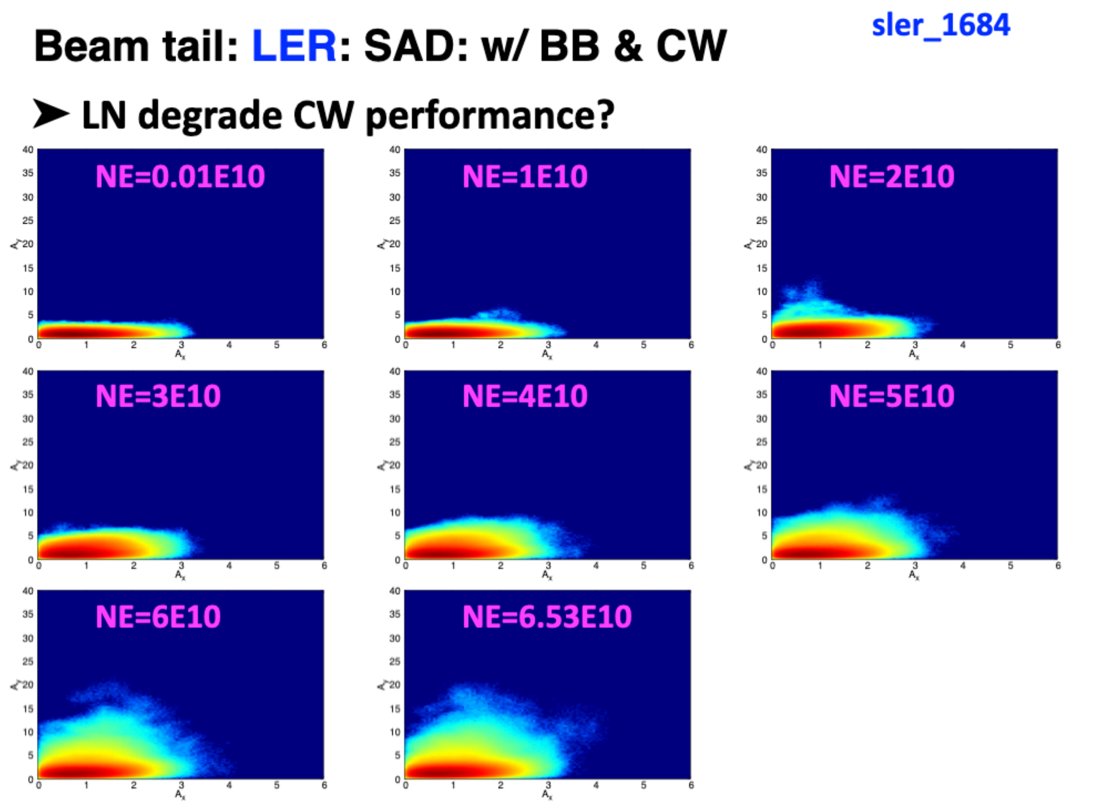












[10] D. Zhou, Beam-beam effects at SuperKEKB, Talk presented at the SuperKEKB optics meeting, KEK, Oct. 08, 2013.

Beam-beam simulations for SuperKEKB

- Findings [11,12]
  - The power of crab waist was demonstrated in tune survey via BBWS simulations.
  - Then space charge (SC) will play an important role (suggested by M. Zobov). This is ONLY true if vertical emittance of $\epsilon_y \approx 10$ pm is achieved.
  - SAD simulations with weak-strong model of SC were tried and showed strong effects. The results were questionable since the used SC model was not self-consistent.
  - SC effects is a topic to be investigated, requiring self-consistent simulations.

SC: Case of SuperKEKB LER

➤ **Linear tune shift**

- **Same order for SC and BB**
- **But with opposite signs**

$$\Delta\nu_i = -\frac{1}{4\pi}\frac{2r_e}{\beta^2\gamma^3}\int_0^C \frac{\lambda\beta_i}{\sigma_i(\sigma_x+\sigma_y)}ds$$

$$i = x, y \qquad \lambda(s) = N/\sqrt{2\pi}\sigma_z(s)$$

$$\sigma_x^2 = \epsilon_x\beta_x + \langle\delta^2\rangle D^2$$

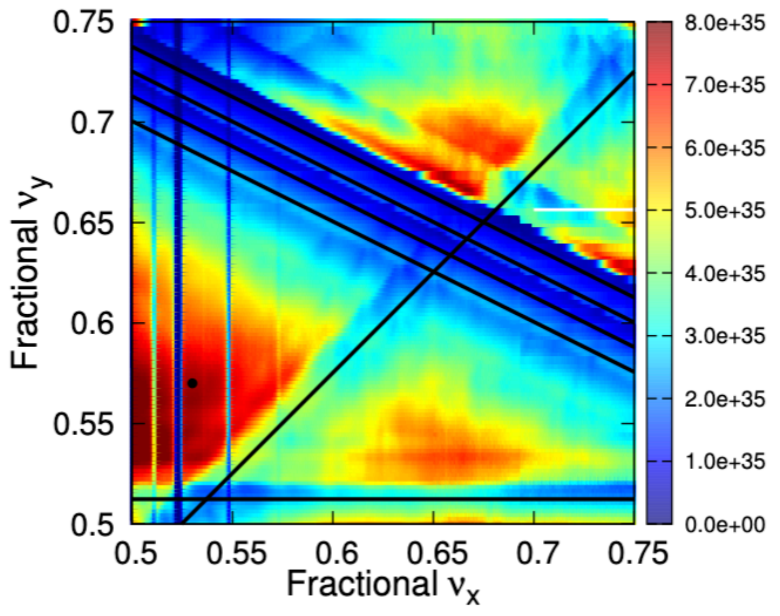
	SuperKEKB[1]		KEKB[4]	
	LER[2]	HER[3]	LER	HER
ϵ_x (nm)	3.2	4.6	18	24
ϵ_y (pm)	8.64	11.5	180	240
ξ_x	0.0028	0.0012	0.127	0.102
ξ_y	0.0881	0.0807	0.129	0.09
$\Delta\nu_x$	-0.0027	-0.0004	-0.0005	-3E-05
$\Delta\nu_y$	-0.0943	-0.0121	-0.0072	-0.0004

[1]Main parameters from Y. Ohnishi et al., Prog. Theor. Exp. Phys. 2012;
[2]sler_1682; [3]sher_5753; [4]Lattice used on Jun.17, 2009.

BB and luminosity

➤ **SuperKEKB LER w/o crab waist**

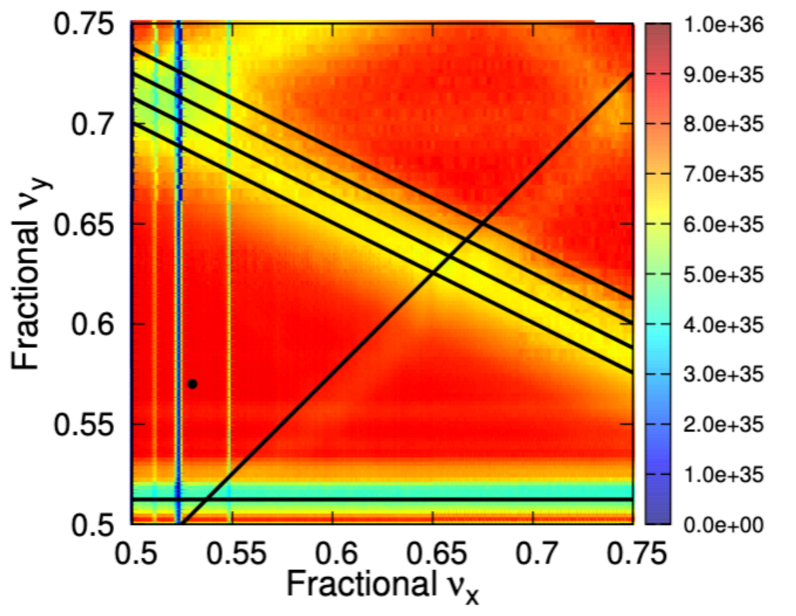
- **Lum. tune scan by BBWS**



BB and luminosity

➤ **SuperKEKB LER w/ crab waist**

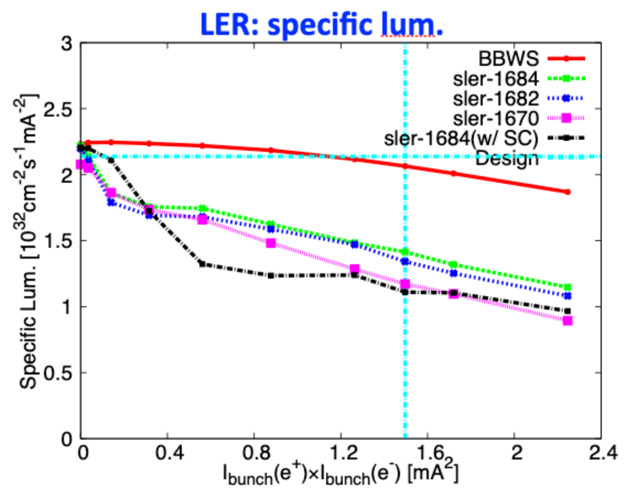
- **Lum. tune scan by BBWS**

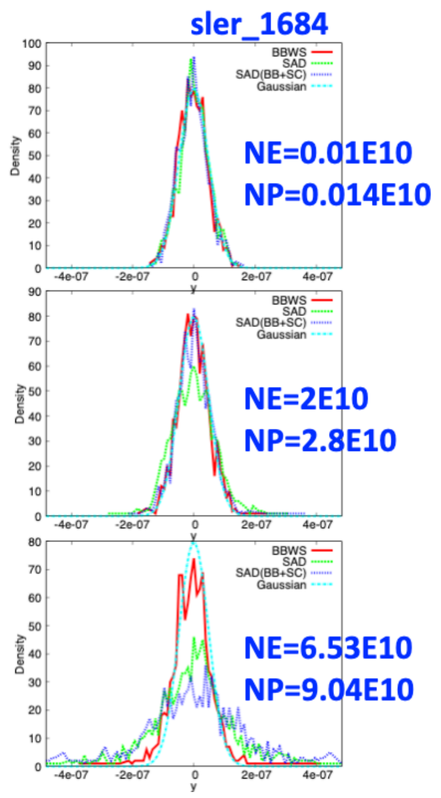


SC: Case of SuperKEKB LER

➤ **SC causes lum. degradation**

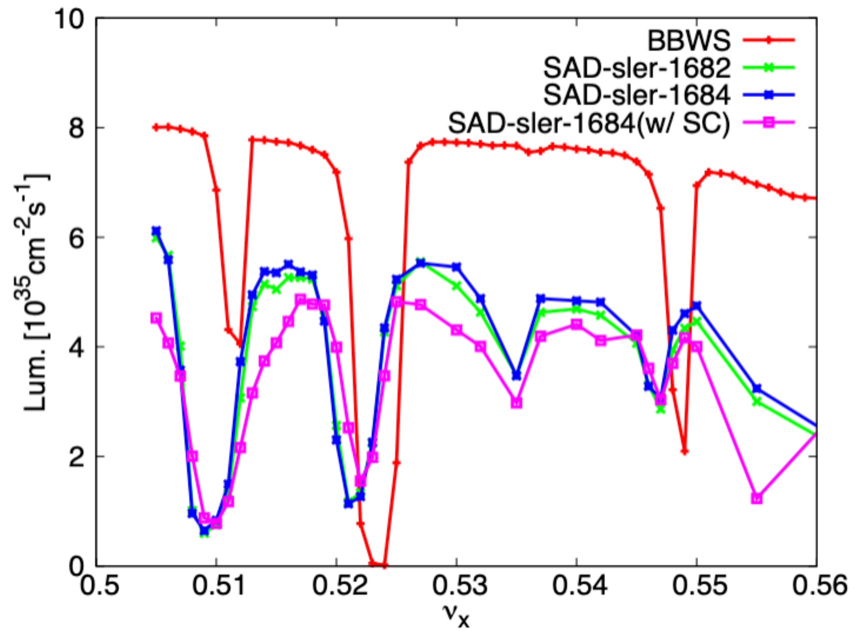
➤ **BB + SC: compensate at low currents?**





SC: Case of SuperKEKB LER

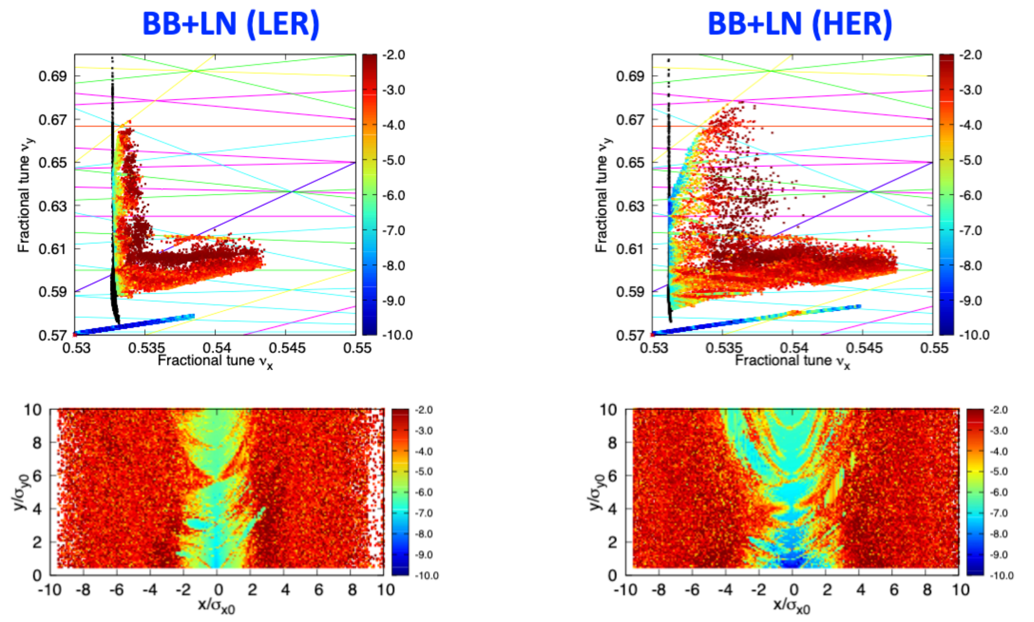
➤ **Hor. tune scan**



Interplay: Baseline lattice: BB+LN

➤ **FMA with beam distribution: $10\sigma_x \times 10\sigma_y$**

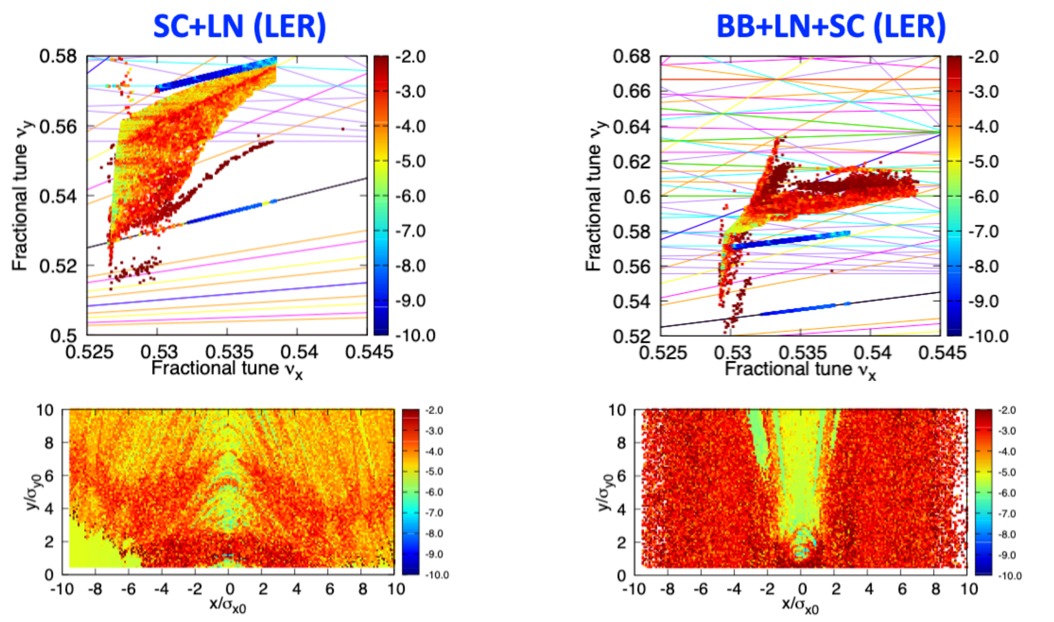
- **Footprint in the tune space extended**



Interplay: Baseline lattice: BB+LN+SC

➤ **FMA with beam distribution: $10\sigma_x \times 10\sigma_y$**

- **Footprint in the tune space strongly distorted**



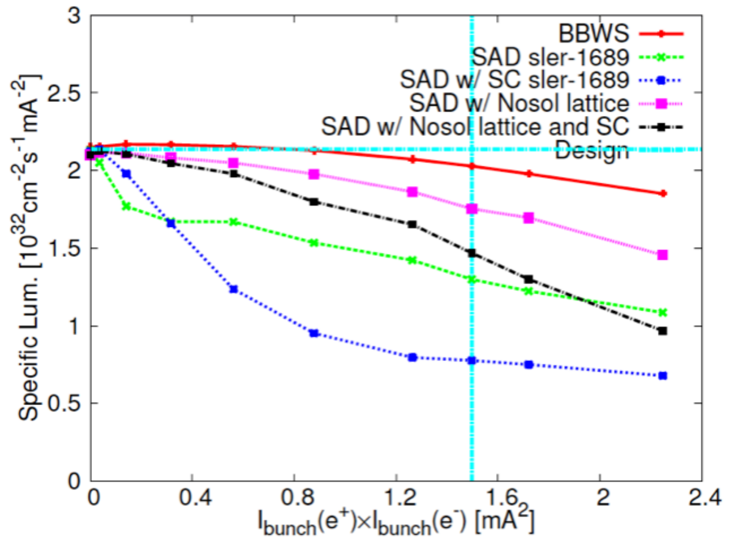
[11] D. Zhou, Beam-beam, lattice nonlinearity and space charge at SuperKEKB, Talk presented at the ICFA Mini-Workshop on Commissioning of SuperKEKB and e+e– Colliders, KEK, Nov. 11-13, 2013.
[12] D. Zhou, Interplay of beam-beam, lattice nonlinearity and space charge effects in the SuperKEKB collider, in Proceedings of IPAC'15, May 3-8, 2015; Talk.

Beam-beam simulations for SuperKEKB

- Findings [13,14]
  - Investigations were carried out to understand the sources of luminosity in beam-beam simulations with lattice.
  - H. Sugimoto made an LER lattice with IR simplified (no solenoids, no offsets of QCS magnets). Luminosity loss with the simplified lattice was found to be weaker.
  - It was concluded that the nonlinear IR should be the source of luminosity loss [14].
  - Detuned lattices (larger $\beta^*_{x,y}$ with respect to the final design) were prepared for the early commissioning. Beam-beam simulations using SAD did not show obvious loss of luminosity.
  - It was concluded that in the early phase of SuperKEKB commissioning, lattice nonlinearity and space charge should not be show-stopper. Unfortunately, this was a misleading conclusion.

Lum. calculation: LER: Simplified IR

➤ Simplified lattice by H. Sugimoto
➤ sler_simple001.sad: no solenoid but preserve main optics parameters
➤ No significant lim. degradation at low current
➤ Solenoid is the main source of lattice nonlinearity?



LER

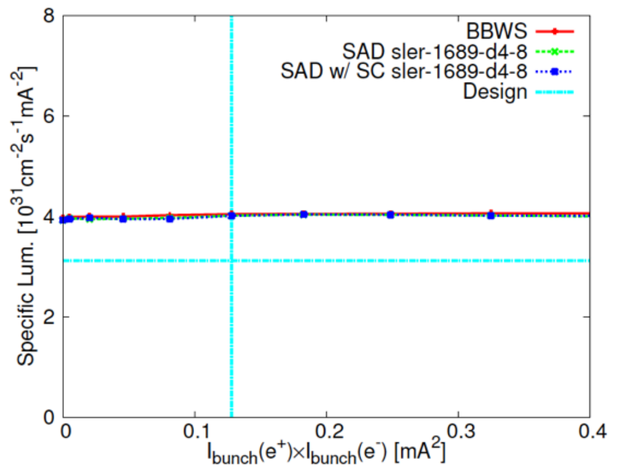
β_x at IP	128	mm
β_y at IP	2.16	mm
I_b	1	A
n_b	2500	
ε_x	1.75	nm
$\varepsilon_y/\varepsilon_x$	2	%

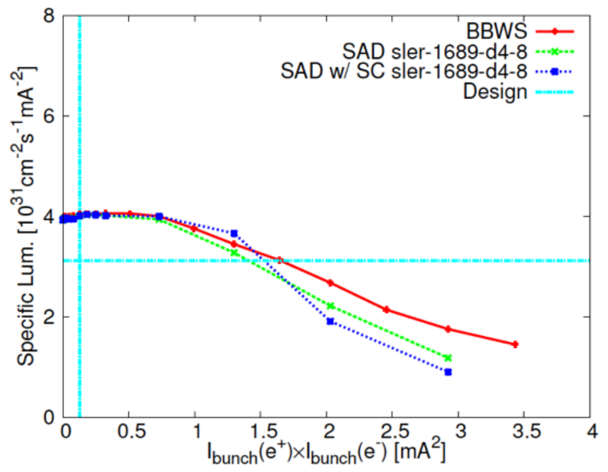
HER

β_x at IP	100	mm
β_y at IP	2.40	mm
I_b	0.8	A
n_b	2500	
ε_x	4.5	nm
$\varepsilon_y/\varepsilon_x$	2	%

Lum. calculation: Detuned lattice

➤ Assume: ε_x=1.75nm, coupling = 2%
➤ Space-charge is not important
➤ Lattice nonlinearity is not very important
➤ L=1×10^{34}cm^{-2}s^{-1} is promising
➤ L=10×10^{34}cm^{-2}s^{-1} is possible by increasing beam currents?

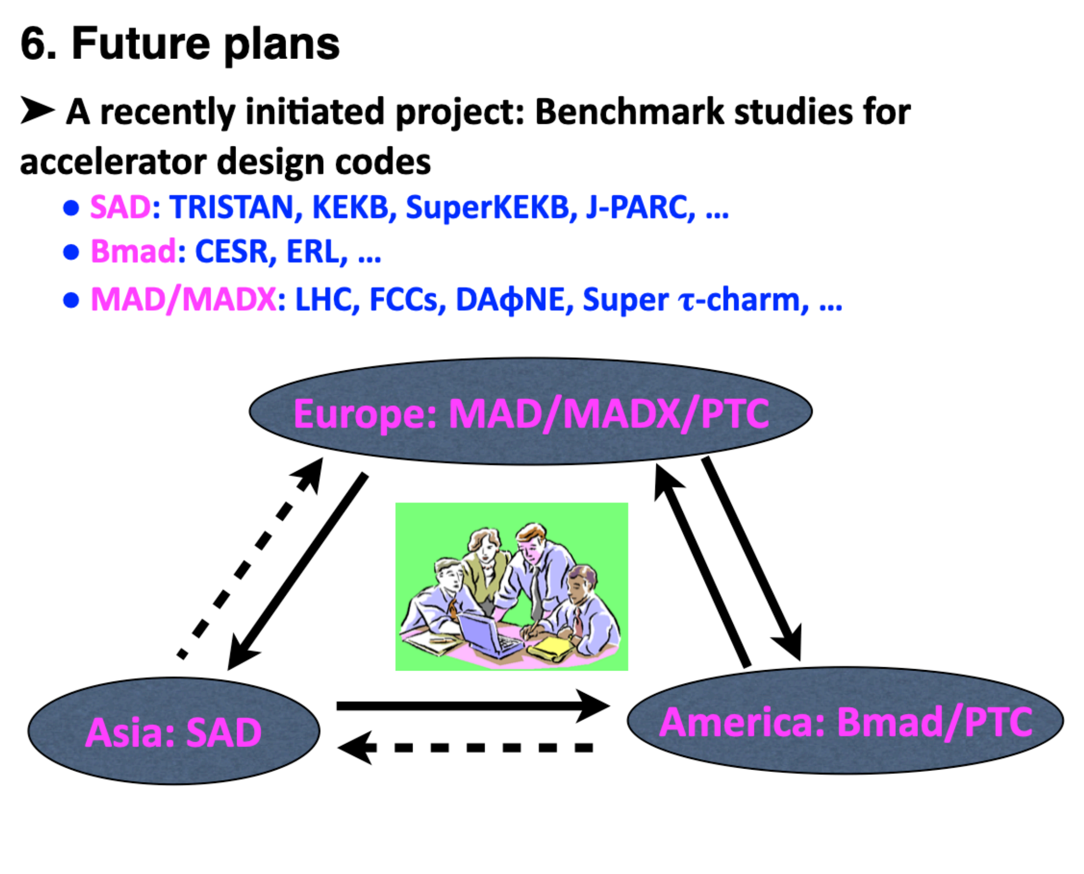


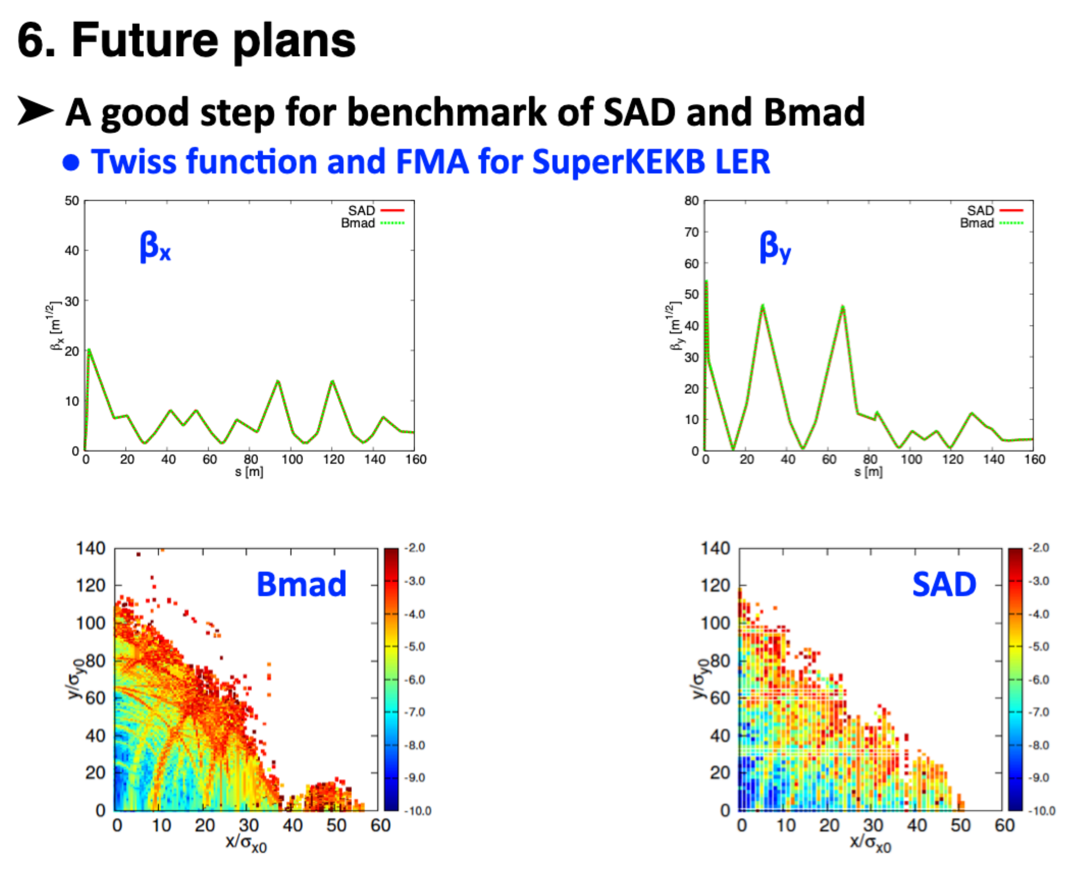


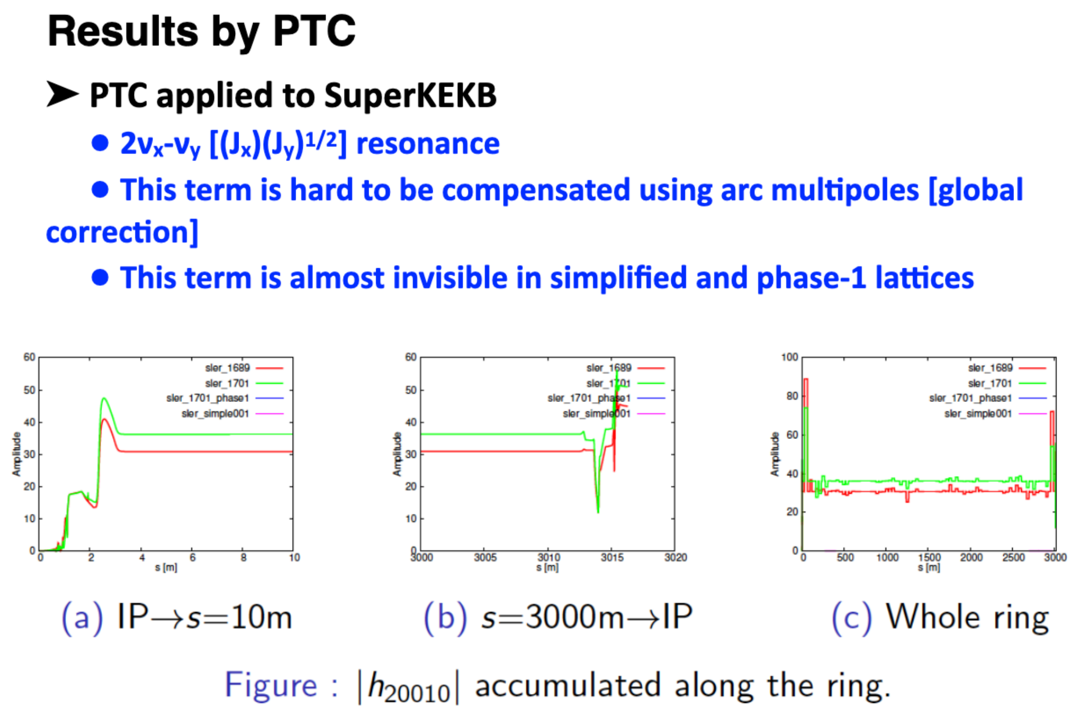
[13] D. Zhou, Luminosity calculations and analysis of lattice nonlinearity for SuperKEKB, Talk presented at the SuperKEKB optics meeting, KEK, Apr. 17, 2014.
[14] D. Zhou, Ideas on beam dynamics issues in SuperKEKB and benchmark of SAD and PTC, Talk presented at the SuperKEKB mini optics meeting, KEK, Aug. 20, 2015.

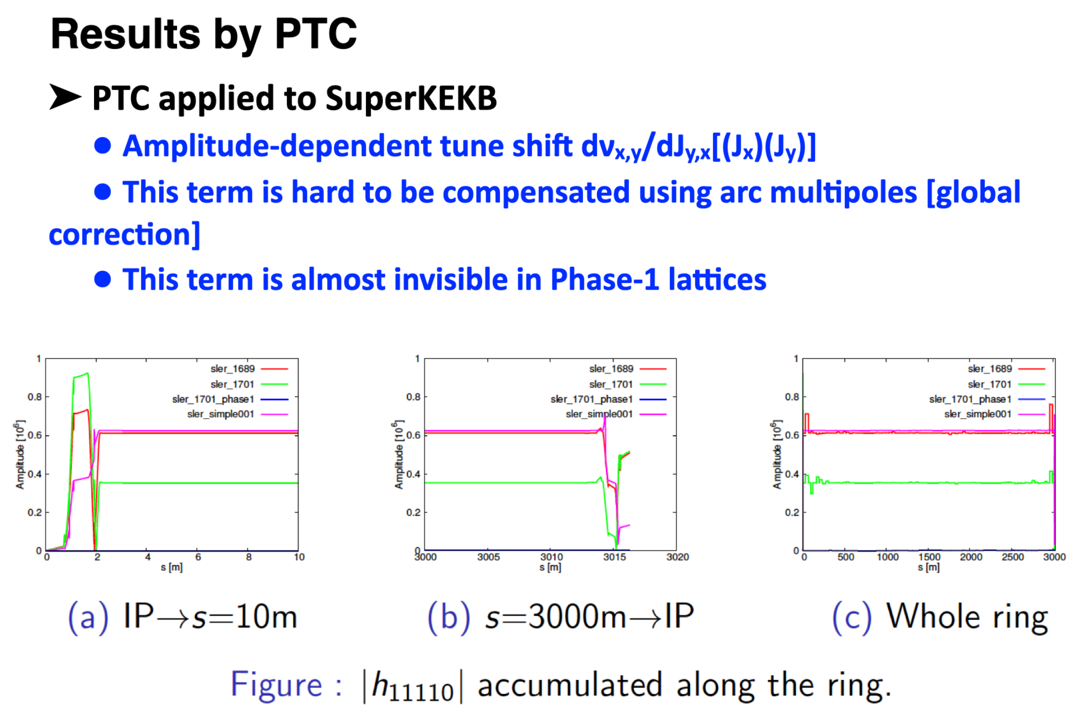
Beam-beam simulations for SuperKEKB

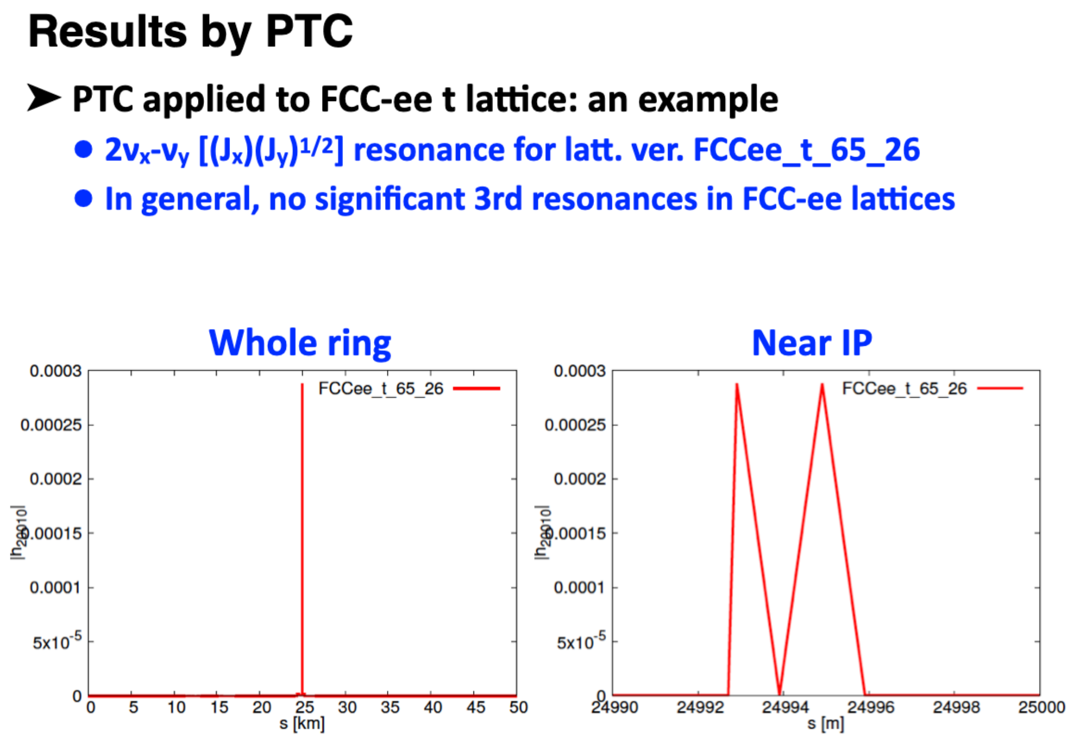
- Findings [12,15,16]
  - To better understand the IR nonlinearity, we initiated a project of lattice translation between accelerator codes (such as PTC, Bmad, etc.) [15]. Actually this project was quite successful, creating profits to studies of other subjects and even to subjects in other accelerator projects.
  - With help of E. Forest, I used PTC to calculate the nonlinear resonant driving terms (RDTs) of SuperKEKB lattice [16]. The s-dependence of RDTs clearly showed the overlapping region of detector solenoids and QCS magnets generates is the source. Some 3rd RDTs are hard to be suppressed in lattice design/optimization. For comparison, FCC-ee design (by K. Oide) had a very clean IR.

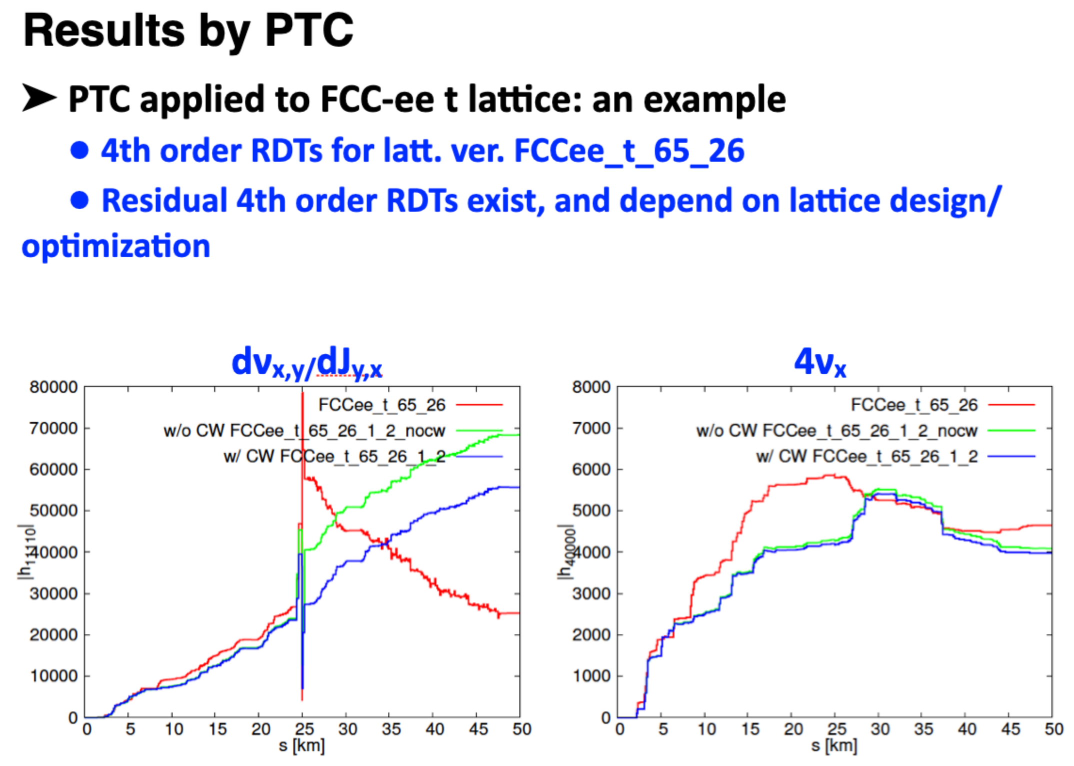












[15] D. Zhou et al., Lattice translation between accelerator simulation codes for SuperKEKB, in Proceedings of IPAC'16, Busan, Korea, May. 08-13, 2016.
[16] D. Zhou, Calculation of resonance driving terms for the SuperKEKB using PTC, Talk presented at the SuperKEKB mini optics meeting, KEK, May. 26, 2016.

Beam-beam simulations for SuperKEKB

- Findings [17]
  - K. Ohmi and K. Hirosawa developed a simpler method to calculated the nonlinear terms. Good agreements were found with PTC results.
  - Then perturbation maps were made via MAP element in SAD to simulate luminosity loss. Finally, the term of $p_x^2 p_y$ was found to be important. Its sources were also well understood. Other chromatic terms can also be important in addition to chromatic couplings.
  - **Finally we arrived at a clear picture for the luminosity loss in beam-beam simulations (weak-strong model plus design lattice): The sources are beam-beam resonances and nonlinearity of the IR. But, the remedy is far from apparent (see Ref.[1] for further information).**

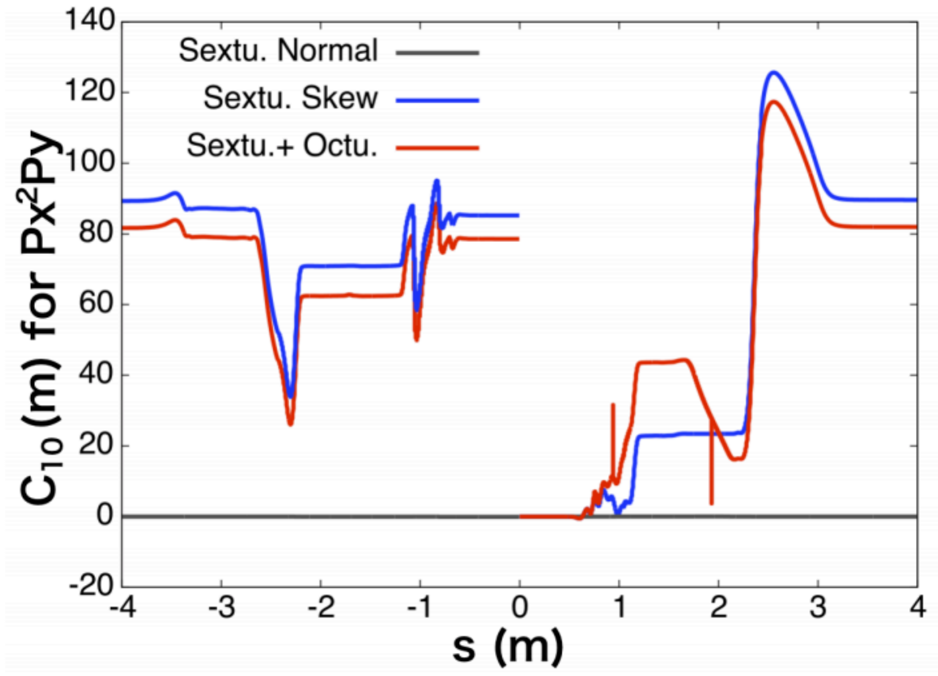


Figure 4: Coefficient of $P_X^2 P_Y$ caused by skew sextupole (SK_2) and octupole ($K_3 + SK_3$) fields.

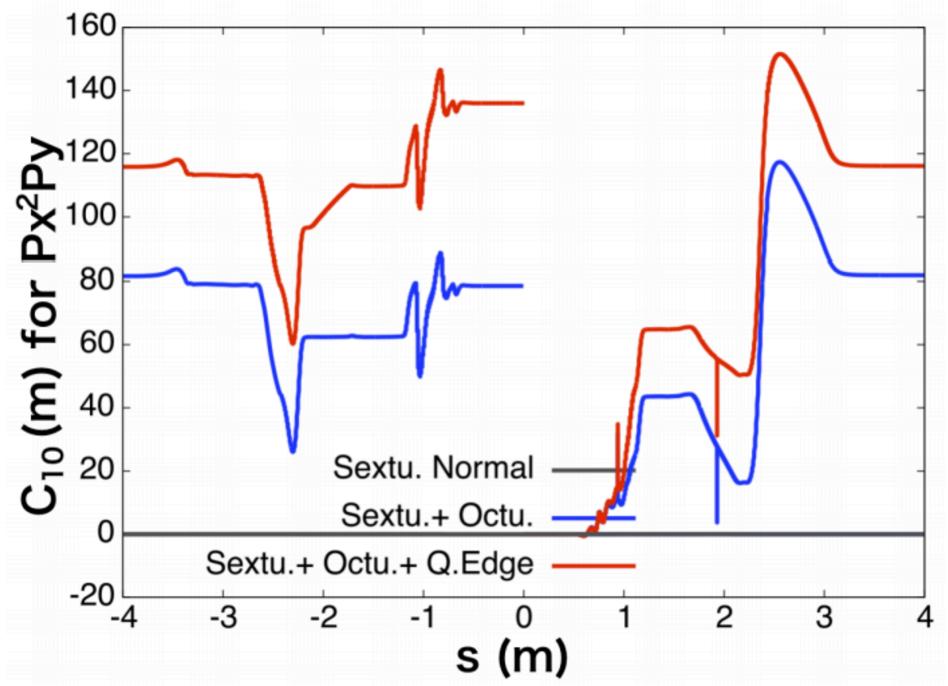


Figure 5: Coefficient of $P_X^2 P_Y$ for sextupole and octupole ($SK_2 + K_3 + SK_3$) and quadrupole hard-edge fringe ($SK_2 + K_3 + SK_3 + Q.edge$) fields.

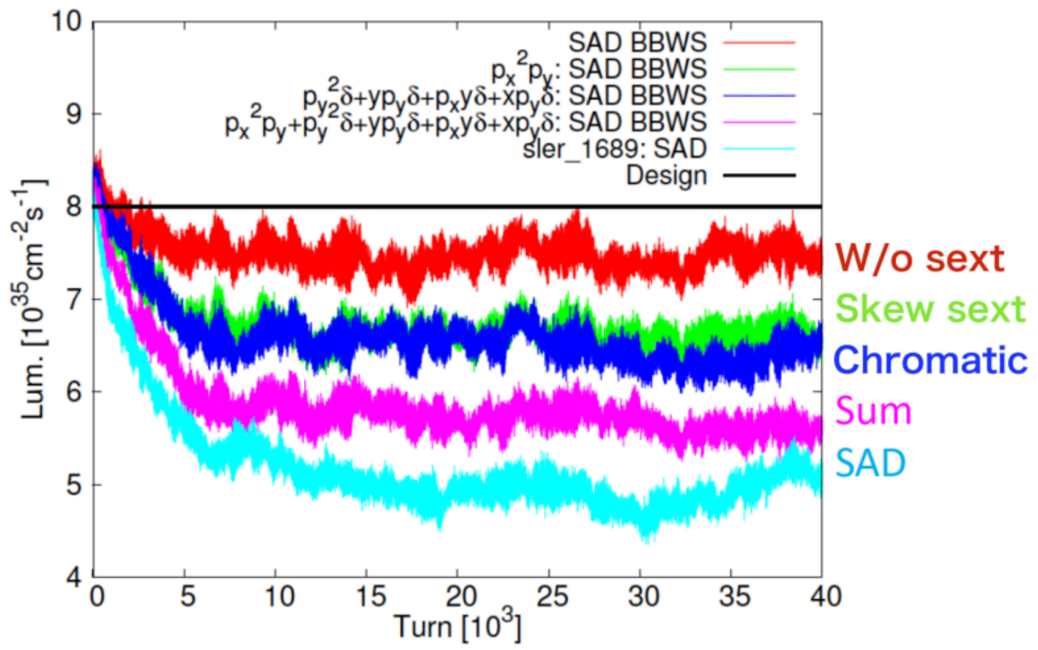
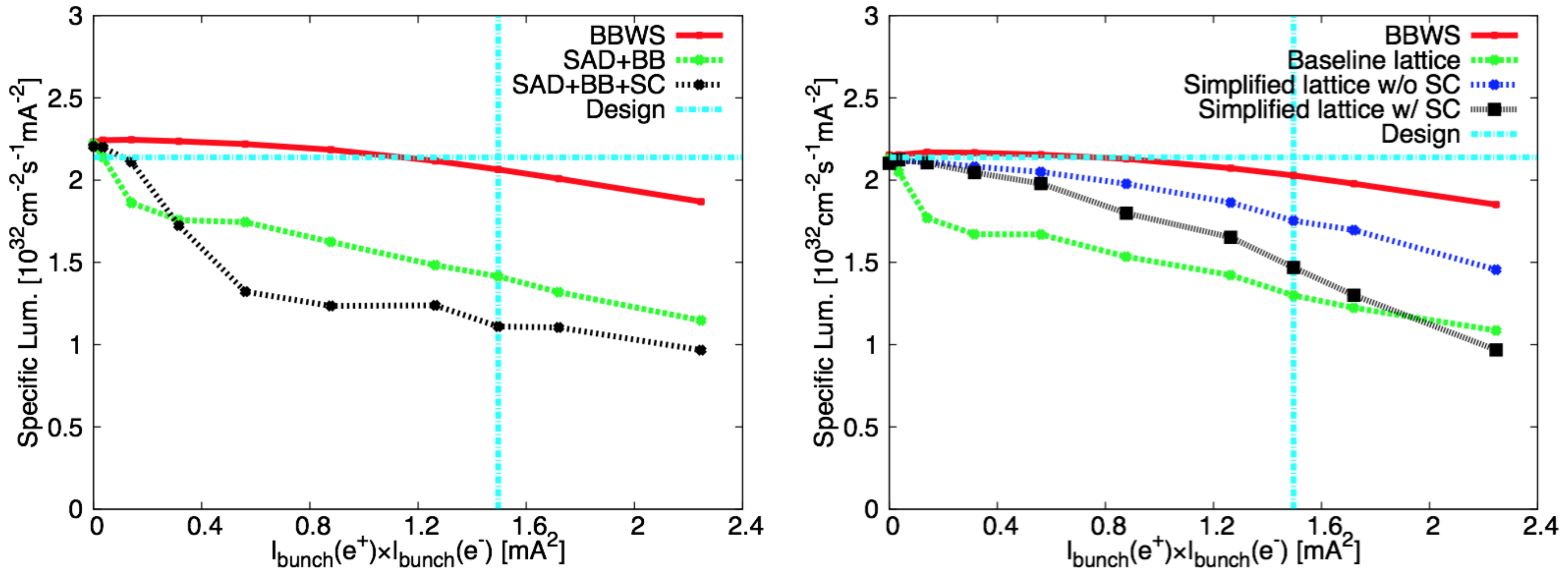


Figure 6: Luminosities for sextupole term (: $P_X^2 P_Y$), chromatic twiss, and SAD.



[17] K. Hirosawa et al., The influence of higher order multipoles of IR magnets on luminosity for SuperKEKB, in Proceedings of IPAC'18, Vancouver, BC, Canada, 2018.

Beam-beam simulations for SuperKEKB

- Phase-2 commissioning
  - The Phase-2 commissioning started in March 2018 with Belle-2 detector. Lots of challenges were encountered. Beam-beam simulations were done to help understand the observed beam phenomena.
  - Observations: Peak luminosity lower than predictions of simulations; Easy blowup of one beam; Small area in tune space for good luminosity; Unexpected high Belle-2 background; No or small gain of luminosity via squeezing $\beta^*_{x,y}$; Hard to approach to the design working point (.53, .57); …
  - Tune scan using BBWS showed that the beam-beam resonances of $\pm\nu_x + 4\nu_y + \alpha = N$ (they appear without crab waist) can be important [18].

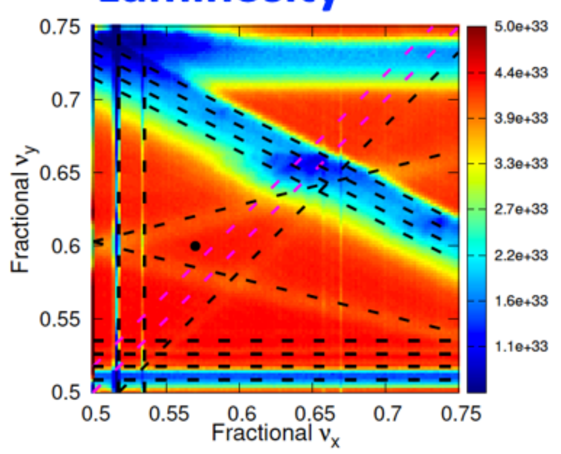
Machine parameters of Phase-2 for beam-beam simulations

	200/6		200/4		100/4		100/2	
	HER	LER	HER	LER	HER	LER	HER	LER
E (GeV)	7.007	4	7.007	4	7.007	4	7.007	4
I_b (mA)	285	340	285	340	285	340	285	340
# bunch	789		789		789		789	
ε_x (nm)	4.7	2.0	4.7	2.0	4.5	1.9	4.5	1.9
ε_y (pm)	47	20	47	20	45	19	45	19
ε_z (μm)	3.7	4.5	3.7	4.5	3.4	3.5	3.4	3.6
β_x (mm)	200	200	200	200	100	100	100	100
β_y (mm)	6	6	4	4	4	4	2	2
σ_z (mm)	5.8	5.9	5.8	5.9	5.3	4.6	5.3	4.7
vx	45.57	44.57	45.57	44.57	45.57	44.57	45.57	44.57
vy	43.60	46.60	43.60	46.60	43.60	46.60	43.60	46.60
vs	0.0234	0.0176	0.0234	0.0176	0.0258	0.0223	0.0258	0.0225

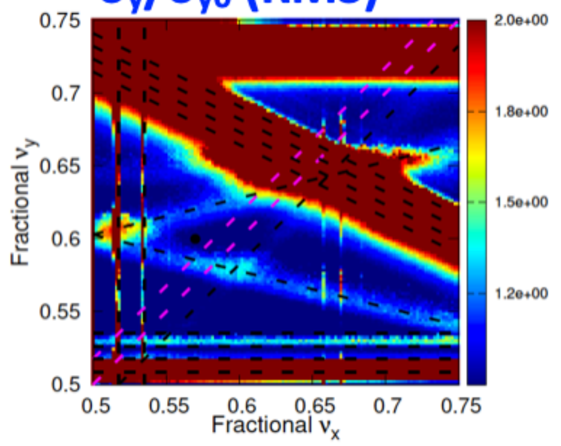
BBWS simulation

- Optics: HER 200/4 mm and LER 200/4 mm
  - Weak beam: LER:

Luminosity



σ_y/σ_{y0} (RMS)



Geometric luminosity:
L=4.2x10^{33}cm^{-2}s^{-1}

Beam-beam resonances:

$$\nu_x - k\nu_s = N, \quad k = 1,2$$
$$2\nu_y - j\nu_s = N, \quad j = 1,2,3,4$$
$$\nu_x + 2\nu_y + k\nu_s = N, \quad k = 1,2,3,4$$
$$\pm\nu_x + 4\nu_y + k\nu_s = N$$

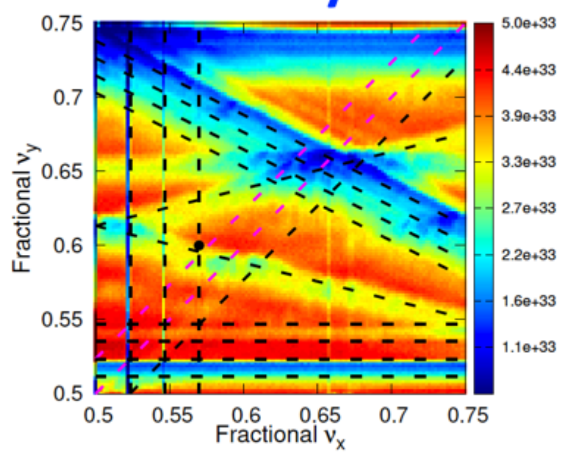
Lattice resonances:

$$\nu_x - \nu_y + k\nu_s = N, \quad k = -1,0,1$$

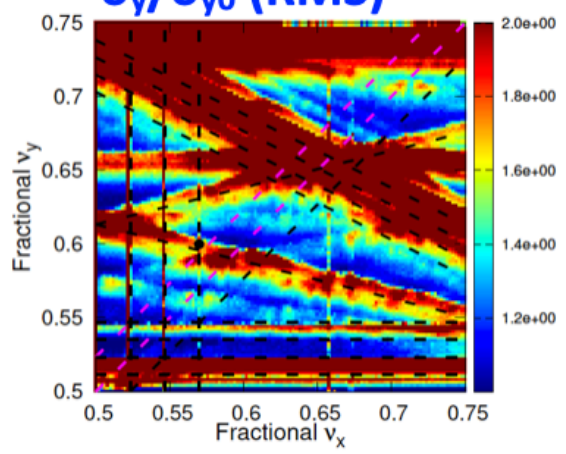
BBWS simulation

- Optics: HER 200/4 mm and LER 200/4 mm
  - Weak beam: HER: plots with normalization

Luminosity



σ_y/σ_{y0} (RMS)



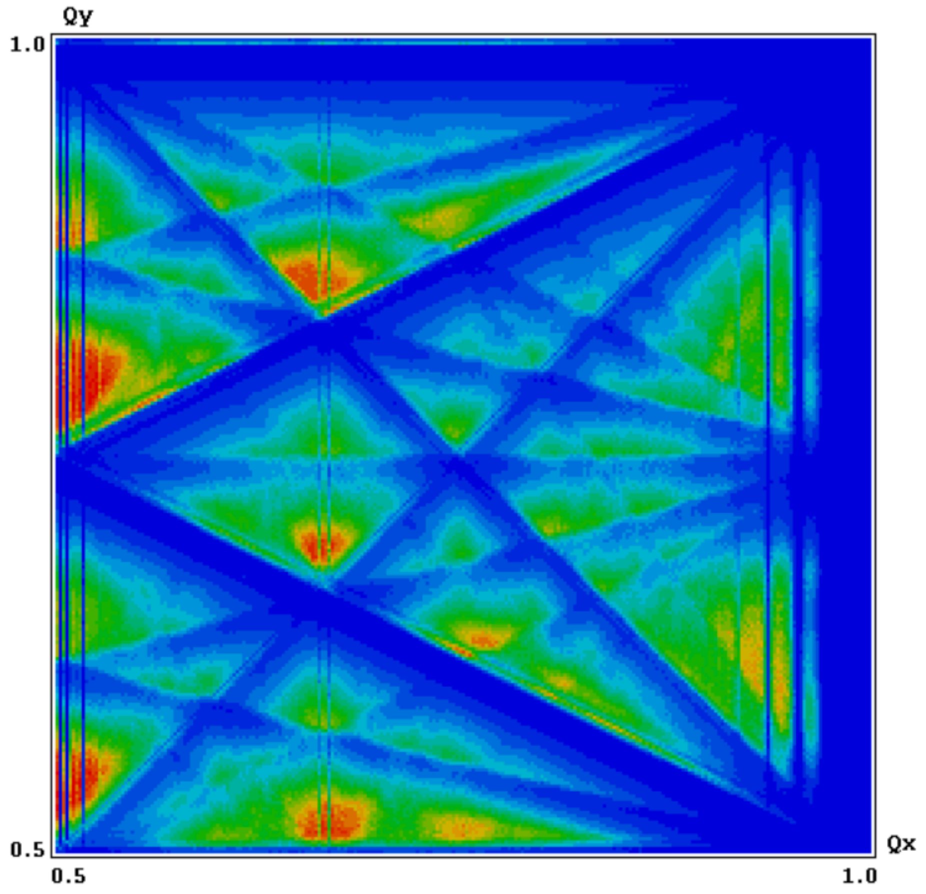
Geometric luminosity:
L=4.2x10^{33}cm^{-2}s^{-1}

[18] D. Zhou , Weak-strong beam-beam simulations for SuperKEKB Phase-2, Talk presented at the SuperKEKB beam-beam performance meeting, KEK, Jun. 14, 2018.

Beam-beam simulations for SuperKEKB

- Phase-2 commissioning
  - In Phase-2, the working point was optimized in a triangle area between beam-beam resonances $\pm\nu_x + 4\nu_y + \alpha = N$ and lattice resonance $\nu_x - \nu_y + \nu_s = N$.
  - In beam commissioning, squeezing $\beta^*_{x,y}$ did not change the situation much. The beam-beam resonances looked to be a strong constraint.
  - The BBWS simulations of beam-beam resonances were consistent with D. Shatilov's simulations using Lifetrac (informed by Y. Zhang from IHEP) [18].

D. Shatilov's simulations using beam parameters similar to SuperKEKB design



$\beta_y = \sigma_z / \phi$

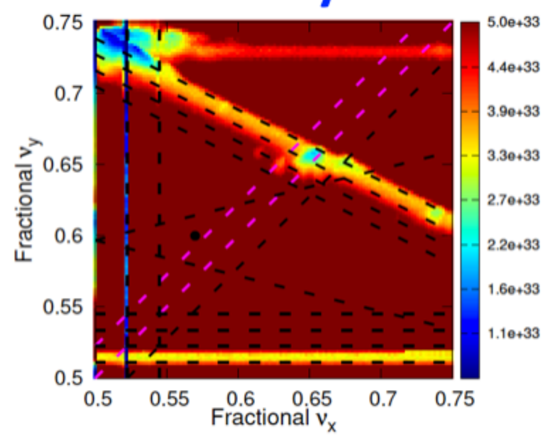
This plot approximately corresponds to the scheme currently adopted for SuperKEKB

BBWS simulation

➤ **Optics: HER 100/2 mm and LER 100/2 mm**

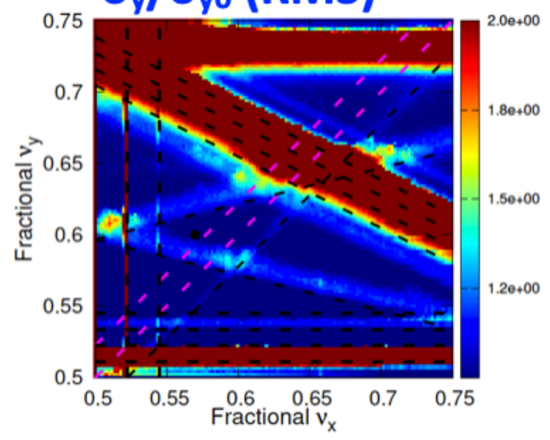
- **Weak beam: LER:**

Luminosity



Geometric luminosity:
L=7.1x10^{33}cm^{-2}s^{-1}

σ_y/σ_{y0} (RMS)

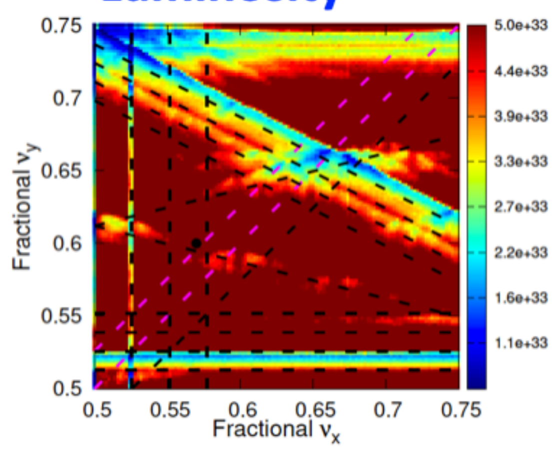


BBWS simulation

➤ **Optics: HER 100/2 mm and LER 100/2 mm**

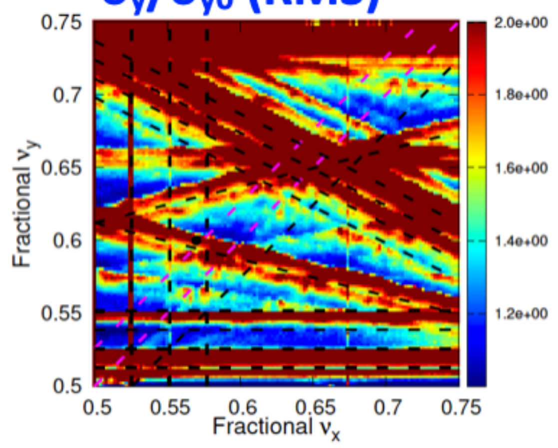
- **Weak beam: HER: plots with normalization**

Luminosity



Geometric luminosity:
L=7.1x10^{33}cm^{-2}s^{-1}

σ_y/σ_{y0} (RMS)



[18] D. Zhou , Weak-strong beam-beam simulations for SuperKEKB Phase-2, Talk presented at the SuperKEKB beam-beam performance meeting, KEK, Jun. 14, 2018.

Beam-beam simulations for SuperKEKB

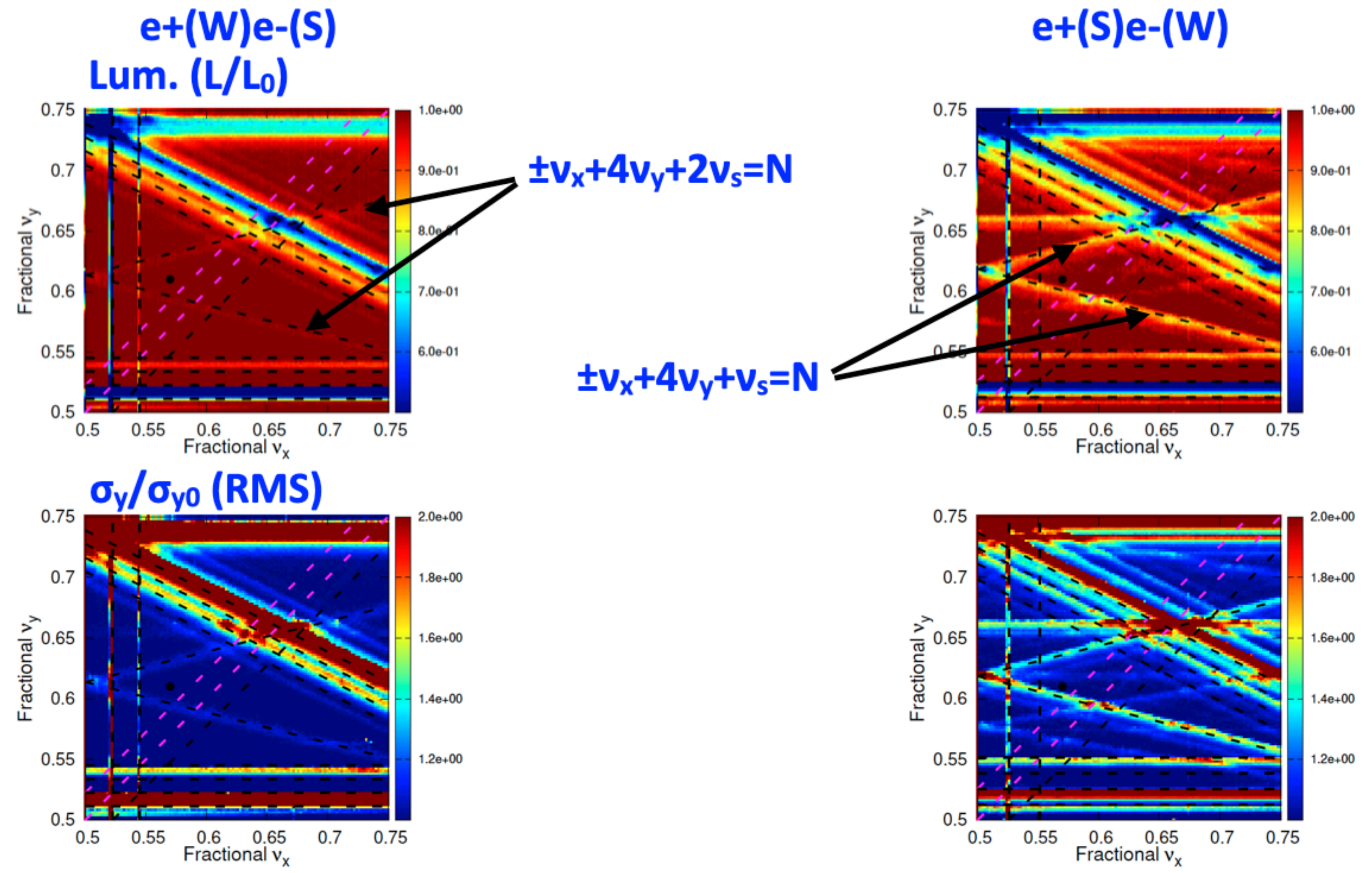
- Preparation of Phase-3 commissioning
  - Before Phase-3 commissioning started, beam-beam simulations were done with “roadmap” parameter sets defined. The working point of (.57, .61) was assumed.
  - The beam-beam resonances were always of concern from viewpoint of BBWS simulations.
  - The nonzero α in $\pm\nu_x + 4\nu_y + \alpha = N$ was mysterious. It seemed to be related to ν_s but not confirmed.

“Roadmap” parameter sets for Phase-3

	1		1ex		2		2ex		3		3'		3ex	
	HER	LER	HER	LER	HER	LER	HER	LER	HER	LER	HER	LER	HER	LER
I_b (A)	1.0	1.2	1.0	1.4	1.0	1.4	1.2	1.7	1.3	1.8	1.15	1.6	1.4	2.0
# bunch	1576		1576		1576		1576		1576		1576		1576	
ε_x (nm)	4.6	2.0	4.6	2.0	4.6	2.0	4.6	2.0	4.6	2.0	4.6	2.0	4.6	2.0
ε_y (pm)	368	160	230	150	138	140	128.8	130	138	140	101.2	100	101.2	100
β_x (mm)	100	100	100	100	100	100	100	100	100	100	100	100	100	100
β_y (mm)	3	3	3	3	2	2	2	2	1.4	1.4	1.25	1.25	1.2	1.2
σ_z (mm)	6	6	6	6	6	6	6	6	6	6	6	6	6	6
ν_x	45.57	44.57	45.57	44.57	45.57	44.57	45.57	44.57	45.57	44.57	45.57	44.57	45.57	44.57
ν_y	43.61	46.61	43.61	46.61	43.61	46.61	43.61	46.61	43.61	46.61	43.61	46.61	43.61	46.61
ν_s	0.0258	0.0225	0.0258	0.0225	0.0258	0.0225	0.0258	0.0225	0.0258	0.0225	0.0258	0.0225	0.0258	0.0225
ξ_y(Geom.)	0.0272	0.0262	0.0328	0.0331	0.0278	0.0351	0.0351	0.0436	0.0302	0.0387	0.0301	0.0397	0.0369	0.0453
$\mathcal{L}$(Geom.)	1.06E+34		1.46E+34		2.08E+34		3.14E+34		4.11E+34		4.00E+34		6.20E+34	
$\mathcal{L}$(BBSS)	1.00E+34		1.30E+34		1.74E+34		2.16E+34		2.52E+34		2.55E+34		3.21E+34	

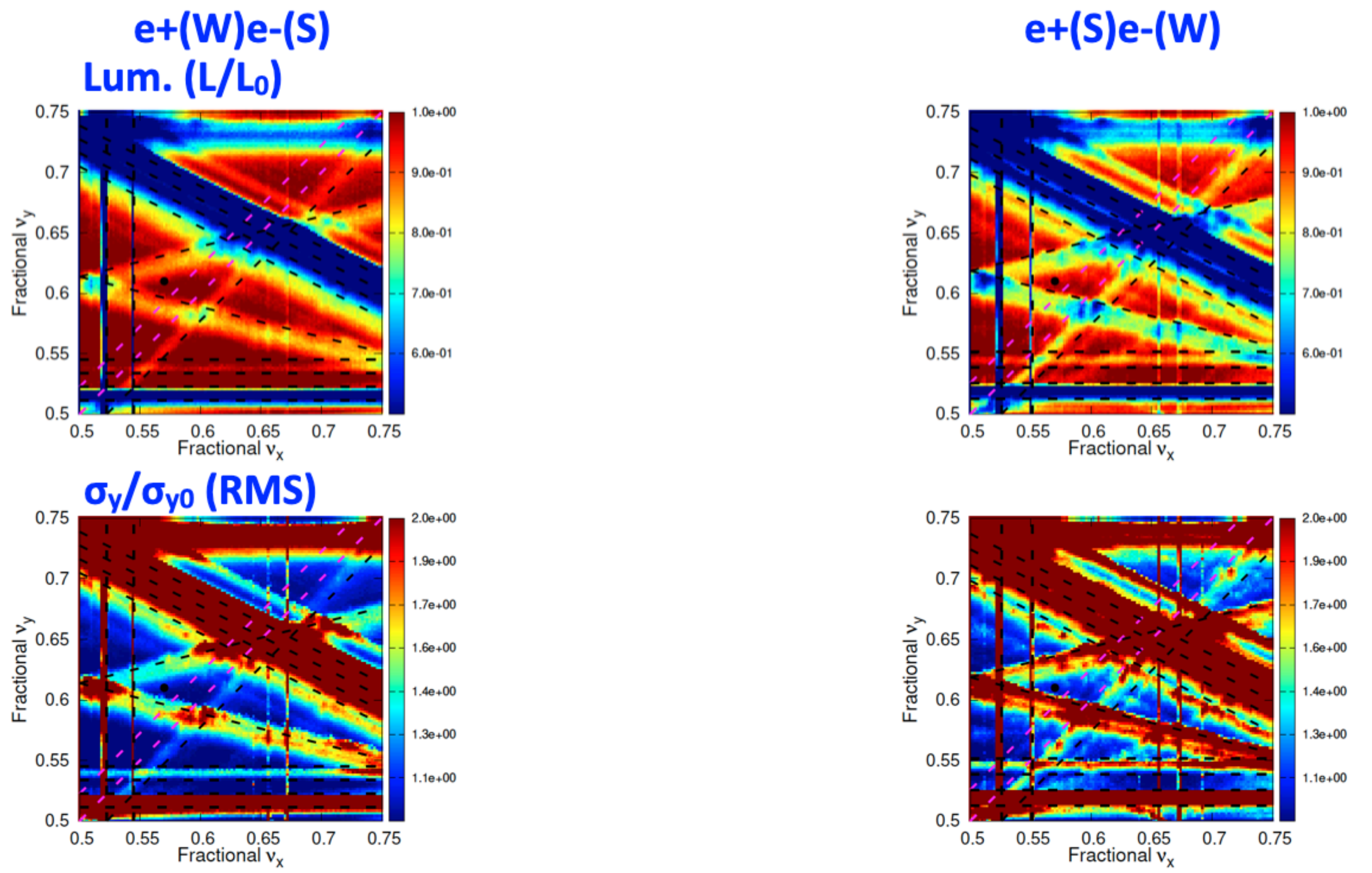
BBWS simulation: Tune scan

- ➤ Parameter set (1)



BBWS simulation: Tune scan

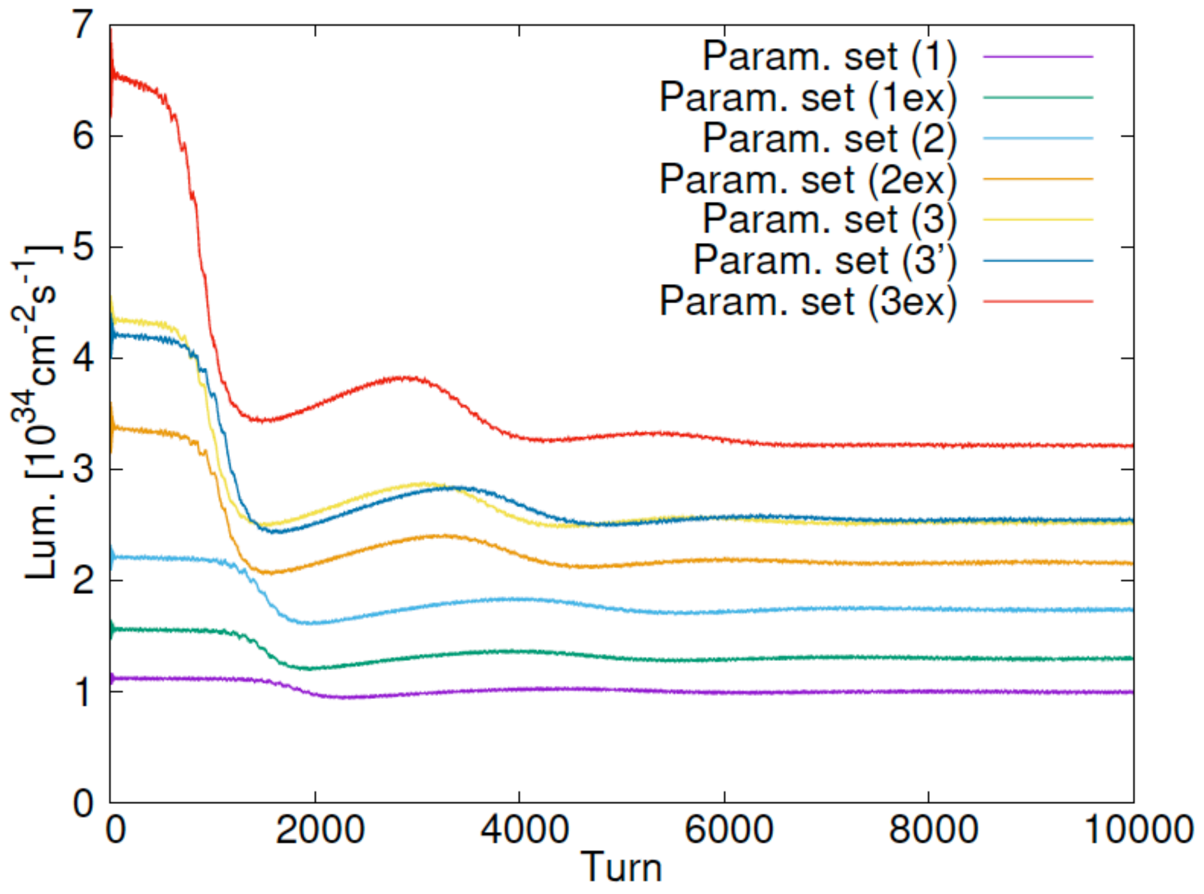
- ➤ Parameter set (3ex)

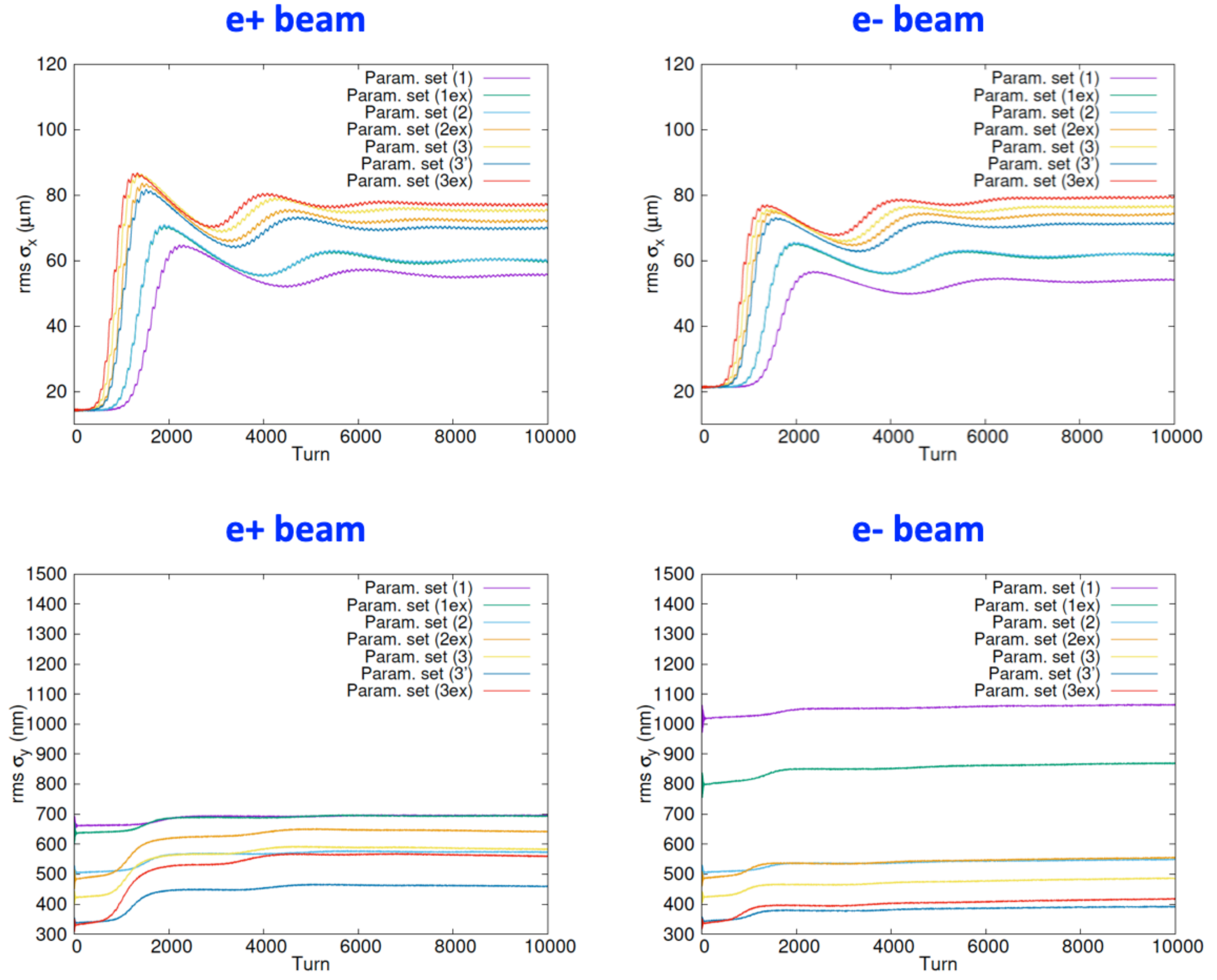


[19] D. Zhou, Beam-beam simulations for SuperKEKB Phase-3, Talk presented at the SuperKEKB optics meeting, KEK, Dec. 13, 2018.

Beam-beam simulations for SuperKEKB

- Preparation of Phase-3 commissioning
  - Meanwhile I started to run strong-beam beam-beam simulations using BBSS. Turned out that for all the “roadmap” parameter sets, the coherent BBHTI (it was discovered by K. Ohmi in 2016 [20,21]) occurs [19].
  - The BBHTI is hard to appear in BBWS simulations. Strong-strong simulations are necessary to detect BBHTI. But BBSS simulations are time-consuming and require lots of CPUs.
  - The BBHTI was believed to be avoidable provided that working point was properly chosen. BBHTI looked to be invisible or weak in beam commissioning, supporting this belief.





“Roadmap” parameter sets for Phase-3 [22]

	1		1ex		2		2ex		3		3’		3ex	
	HER	LER	HER	LER	HER	LER	HER	LER	HER	LER	HER	LER	HER	LER
I_b (A)	1.0	1.2	1.0	1.4	1.0	1.4	1.2	1.7	1.3	1.8	1.15	1.6	1.4	2.0
# bunch	1576		1576		1576		1576		1576		1576		1576	
ε_x (nm)	4.6	2.0	4.6	2.0	4.6	2.0	4.6	2.0	4.6	2.0	4.6	2.0	4.6	2.0
ε_y (pm)	368	160	230	150	138	140	128.8	130	138	140	101.2	100	101.2	100
β_x (mm)	100	100	100	100	100	100	100	100	100	100	100	100	100	100
β_y (mm)	3	3	3	3	2	2	2	2	1.4	1.4	1.25	1.25	1.2	1.2
σ_z (mm)	6	6	6	6	6	6	6	6	6	6	6	6	6	6
ν_x	45.57	44.57	45.57	44.57	45.57	44.57	45.57	44.57	45.57	44.57	45.57	44.57	45.57	44.57
ν_y	43.61	46.61	43.61	46.61	43.61	46.61	43.61	46.61	43.61	46.61	43.61	46.61	43.61	46.61
ν_s	0.0258	0.0225	0.0258	0.0225	0.0258	0.0225	0.0258	0.0225	0.0258	0.0225	0.0258	0.0225	0.0258	0.0225
ξ_y(Geom.)	0.0272	0.0262	0.0328	0.0331	0.0278	0.0351	0.0351	0.0436	0.0302	0.0387	0.0301	0.0397	0.0369	0.0453
$\mathcal{L}$(Geom.)	1.06E+34		1.46E+34		2.08E+34		3.14E+34		4.11E+34		4.00E+34		6.20E+34	
$\mathcal{L}$(BBSS)	1.00E+34		1.30E+34		1.74E+34		2.16E+34		2.52E+34		2.55E+34		3.21E+34	

[19] D. Zhou, Beam-beam simulations for SuperKEKB Phase-3, Talk presented at the SuperKEKB optics meeting, KEK, Dec. 13, 2018.

[20] K. Ohmi et al., Coherent Beam-Beam Instability in Collisions with a Large Crossing Angle, Phys. Rev. Lett. **119**, 134801 (2017).

[21] N. Kuroo et al., Cross-wake force and correlated head-tail instability in beam-beam collisions with a large crossing angle, Phys. Rev. Accel. Beams 21, 031002 (2018).

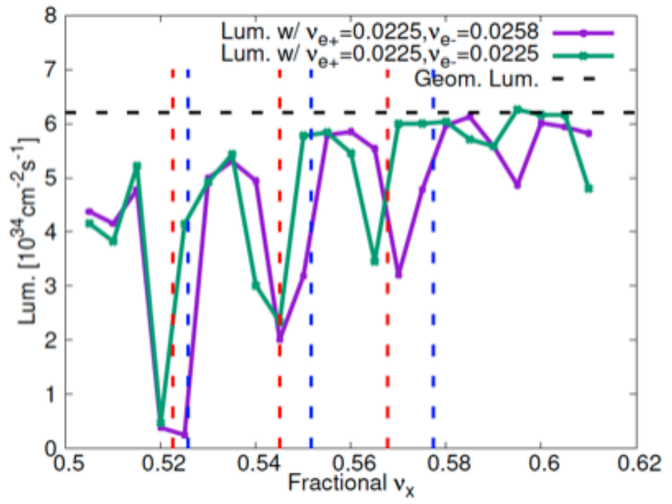
Beam-beam simulations for SuperKEKB

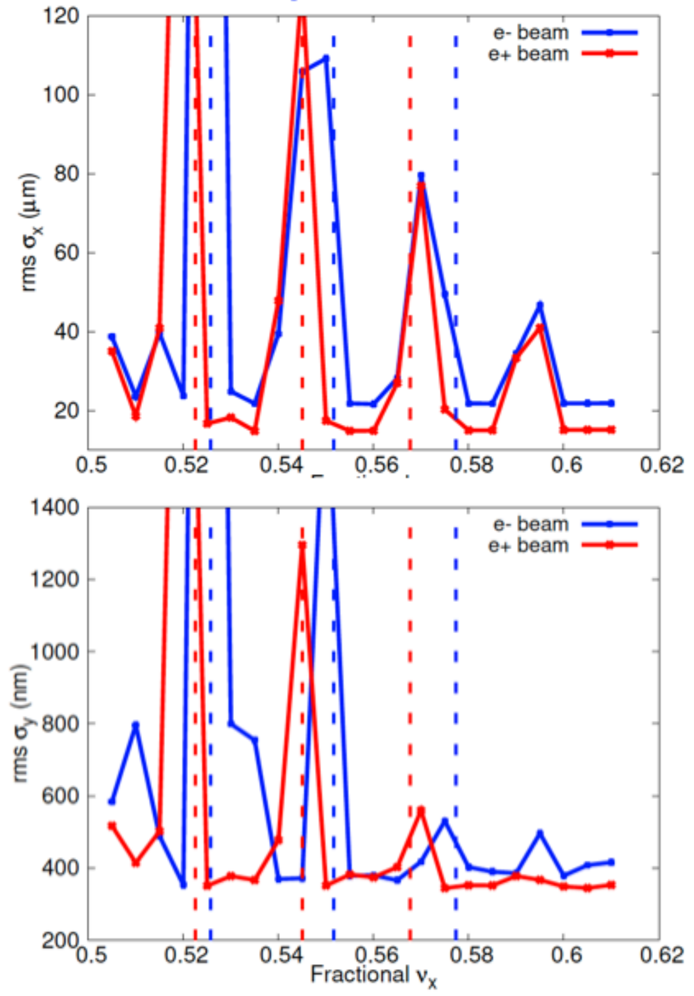
- Preparation of Phase-3 commissioning
  - To avoid BBHTI, it is preferred to have same fractional $\nu_{x,y,s}$ for the two colliding beams [22]. But it is hard to be satisfied in realistic beam commissioning.
  - The BBHTI is serious around synchro-beta resonances of $\nu_x - k\nu_s = N/2$, therefore unequal ν_s of the two beams will set narrower choices of ν_x [22].
  - The BBWS and BBSS simulations have consistency when BBHTI is not important.

BBSS simulation

➤ **All parameter set (3ex): ν_y=*.61**

- **Scan of ν_x (same fractional part for LER and HER)**



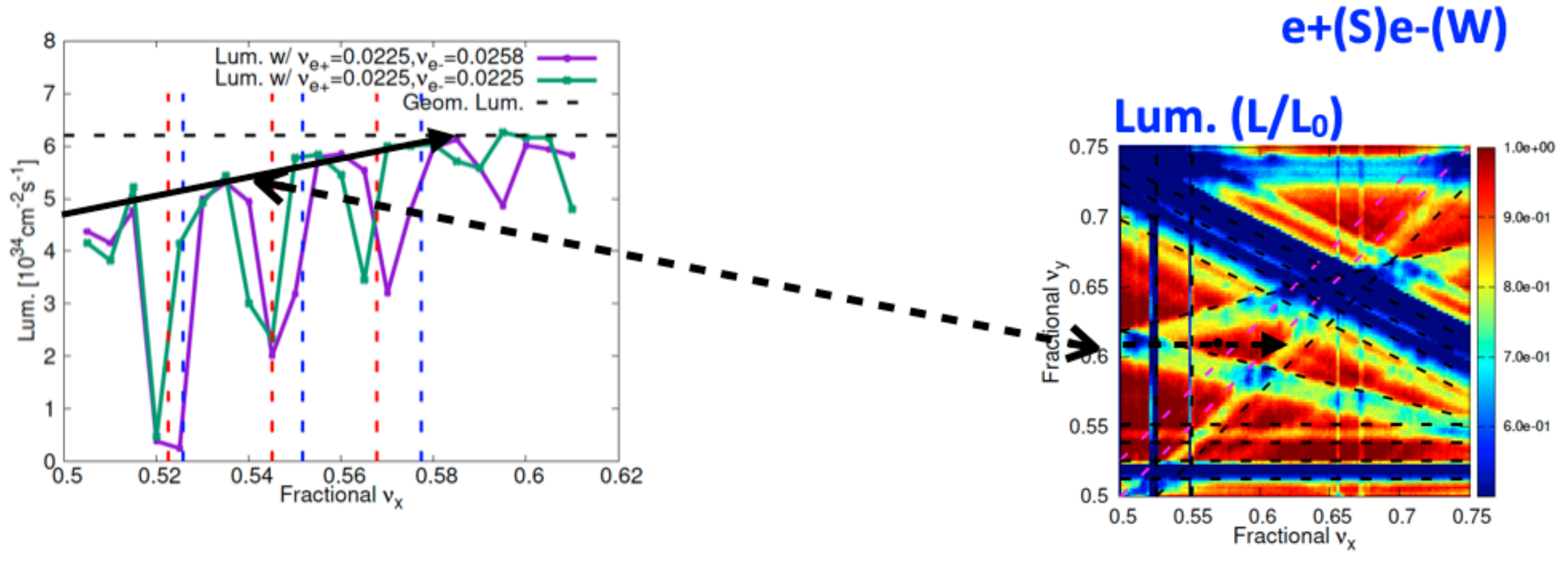


Beam sizes for ν_{s+}=.0225, ν_{s-}=.0258

BBSS simulation

➤ **All parameter set (3ex): ν_y=*.61**

- **Synchro-beta resonances are wider in BBSS simulation than in those in BBWS**
- **The luminosity slope (black arrow) can be explained in BBWS sim.**



"Roadmap" parameter sets for Phase-3 [22]

	1		1ex		2		2ex		3		3'		3ex	
	HER	LER	HER	LER	HER	LER	HER	LER	HER	LER	HER	LER	HER	LER
I_b (A)	1.0	1.2	1.0	1.4	1.0	1.4	1.2	1.7	1.3	1.8	1.15	1.6	1.4	2.0
# bunch	1576		1576		1576		1576		1576		1576		1576	
ε_x (nm)	4.6	2.0	4.6	2.0	4.6	2.0	4.6	2.0	4.6	2.0	4.6	2.0	4.6	2.0
ε_y (pm)	368	160	230	150	138	140	128.8	130	138	140	101.2	100	101.2	100
β_x (mm)	100	100	100	100	100	100	100	100	100	100	100	100	100	100
β_y (mm)	3	3	3	3	2	2	2	2	1.4	1.4	1.25	1.25	1.2	1.2
σ_z (mm)	6	6	6	6	6	6	6	6	6	6	6	6	6	6
ν_x	45.57	44.57	45.57	44.57	45.57	44.57	45.57	44.57	45.57	44.57	45.57	44.57	45.57	44.57
ν_y	43.61	46.61	43.61	46.61	43.61	46.61	43.61	46.61	43.61	46.61	43.61	46.61	43.61	46.61
ν_s	0.0258	0.0225	0.0258	0.0225	0.0258	0.0225	0.0258	0.0225	0.0258	0.0225	0.0258	0.0225	0.0258	0.0225
ξ_y(Geom.)	0.0272	0.0262	0.0328	0.0331	0.0278	0.0351	0.0351	0.0436	0.0302	0.0387	0.0301	0.0397	0.0369	0.0453
$\mathcal{L}$(Geom.)	1.06E+34		1.46E+34		2.08E+34		3.14E+34		4.11E+34		4.00E+34		6.20E+34	
$\mathcal{L}$(BBSS)	1.00E+34		1.30E+34		1.74E+34		2.16E+34		2.52E+34		2.55E+34		3.21E+34	

[22] D. Zhou, Beam-beam simulations for SuperKEKB Phase-3, Talk presented at the SuperKEKB optics meeting, KEK, Mar. 07, 2019.

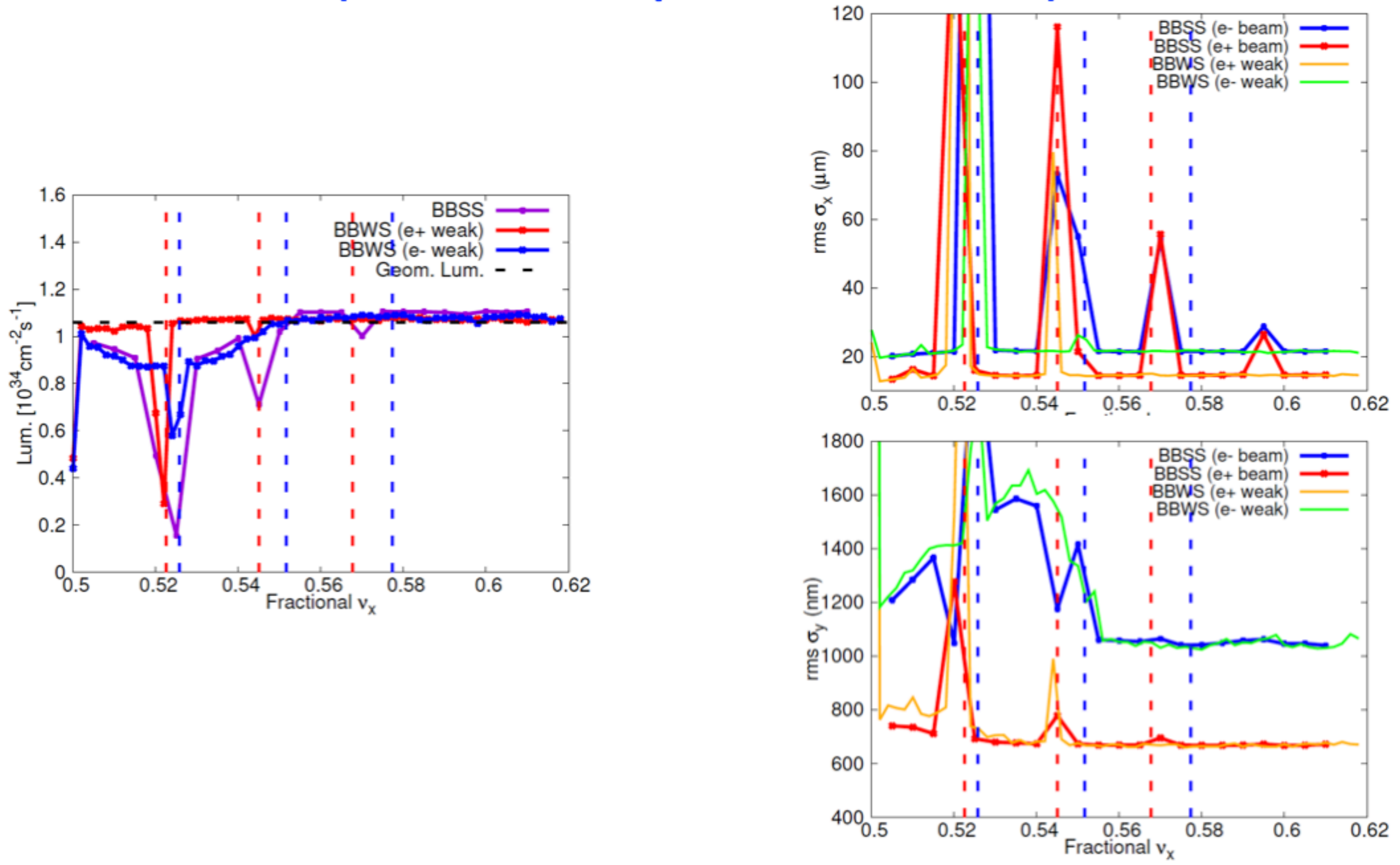
Beam-beam simulations for SuperKEKB

- Preparation of Phase-3 commissioning
  - The beam-beam resonances seen in BBWS simulations also appear in BBSS simulations. The main difference is from BBHTI [23].

BBSS simulation

➤ **Parameter set (1): ν_y=*.61**

- **Scan of ν_x (same fractional part for LER and HER)**



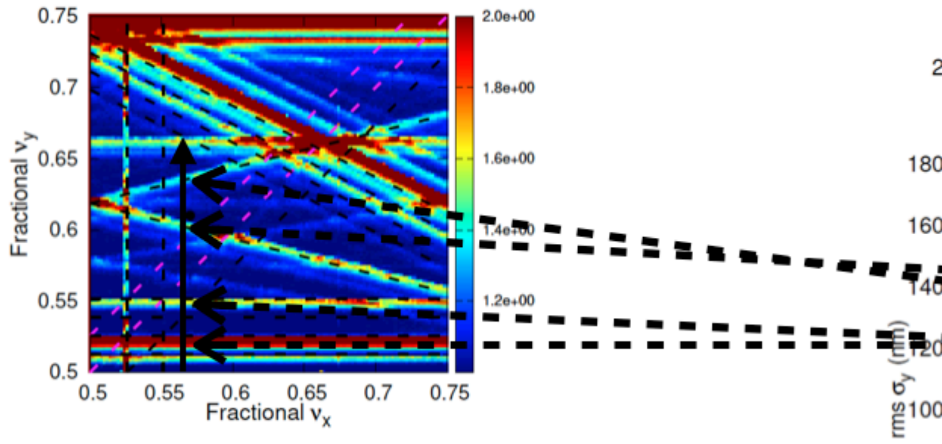
BBSS simulation

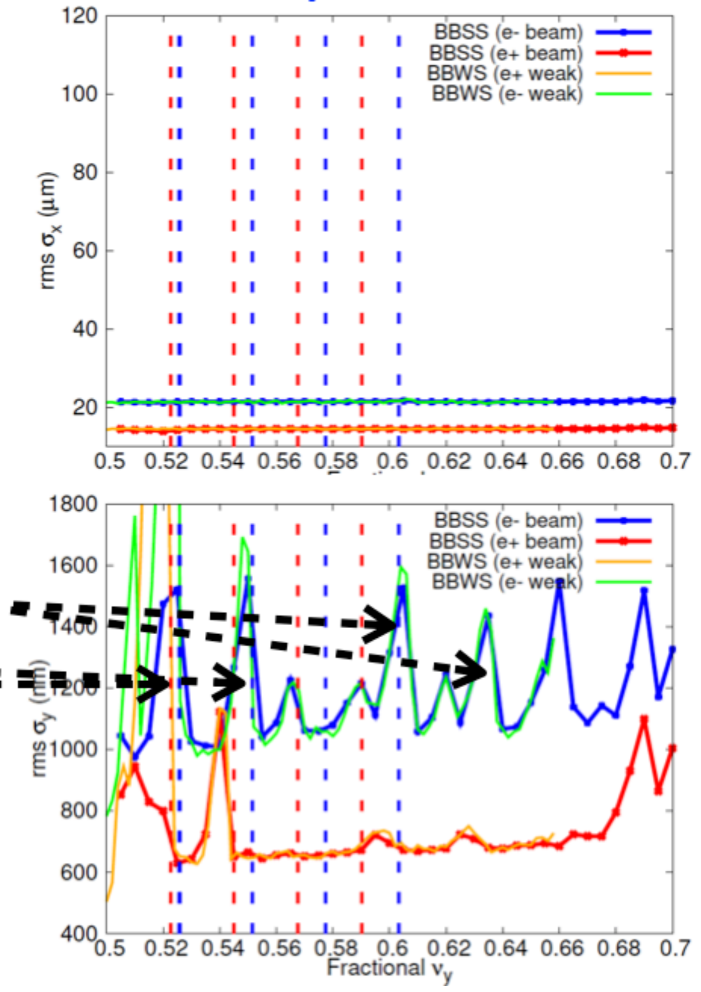
➤ **Parameter set (1): ν_x=*.56**

- **Scan of ν_y (same fractional part for LER and HER)**
- **Beam very unstable for ν_y<*.53**

e+(S)e-(W)

σ_y/σ_{y0} (RMS)





➤ **Phase-2 (Last stage) and Phase-3 machine parameters (Early stage)**

	1		1(op1)		1(op2)		2019.03.30		2019.04.02		2018.07.13(11AM)	
	HER	LER	HER	LER	HER	LER	HER	LER	HER	LER	HER	LER
I_b (A)	1.0	1.2	1.0	1.2	1.0	1.2	0.21	0.26	0.17	0.22	0.158	177
# bunch	1576		1576		1576		789		789		395	
ε_x (nm)	4.6	2.0	4.6	2.0	4.6	2.0	4.728	1.731	4.537	1.641	4.6	2.0
ε_y (pm)	368	160	160	160	160	160	122.5	40	53.33	13.33	42.4	43.2
β_x (mm)	100	100	100	230	80	80	200	200	100	200	100	200
β_y (mm)	3	3	3	3	3	3	4	4	3	3	3	3
σ_z (mm)	6	6	6	6	6	6	6	6	6	6	6	6
σ_y (nm)	1051	693	693	693	693	693	700	400	400	200	357	360
ν_x	45.57	44.57	45.57	44.57	45.57	44.57	45.564	44.571	45.5439	44.5568	45.542	44.559
ν_y	43.61	46.61	43.61	46.61	43.61	46.61	43.603	46.610	43.6082	46.618	43.6072	46.603
ν_s	0.0258	0.0225	0.0258	0.0225	0.0258	0.0225	0.0256	0.0219	0.02576	0.02205	0.0258	0.0225
ξ_y(Geom.)	0.0272	0.0262	0.0272	0.0397	0.0272	0.0397	0.0272	0.0220	0.0345	0.0233	0.0309	0.0486
$\mathcal{L}$(Geom.)	1.06E+34		1.36E+34		1.37E+34		1.50E+33		1.85E+33		2.46E+33	
$\mathcal{L}$(BBSS)	1.00E+34		9.30E+33		1.34E+34		1.25E+33		1.39E+33		2.43E+33	

"Roadmap" and operation parameter sets [23]

[23] D. Zhou, Recent results of beam-beam simulations for SuperKEKB, Talk presented at the 2nd SuperKEKB beam dynamics workgroup meeting, KEK, Apr. 16, 2019.

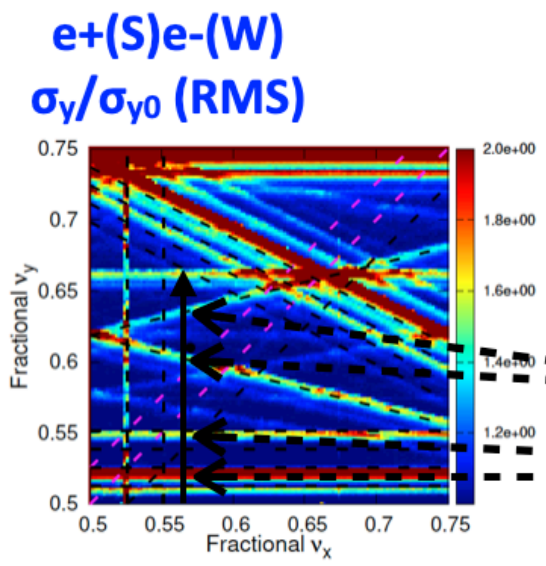
Beam-beam simulations for SuperKEKB

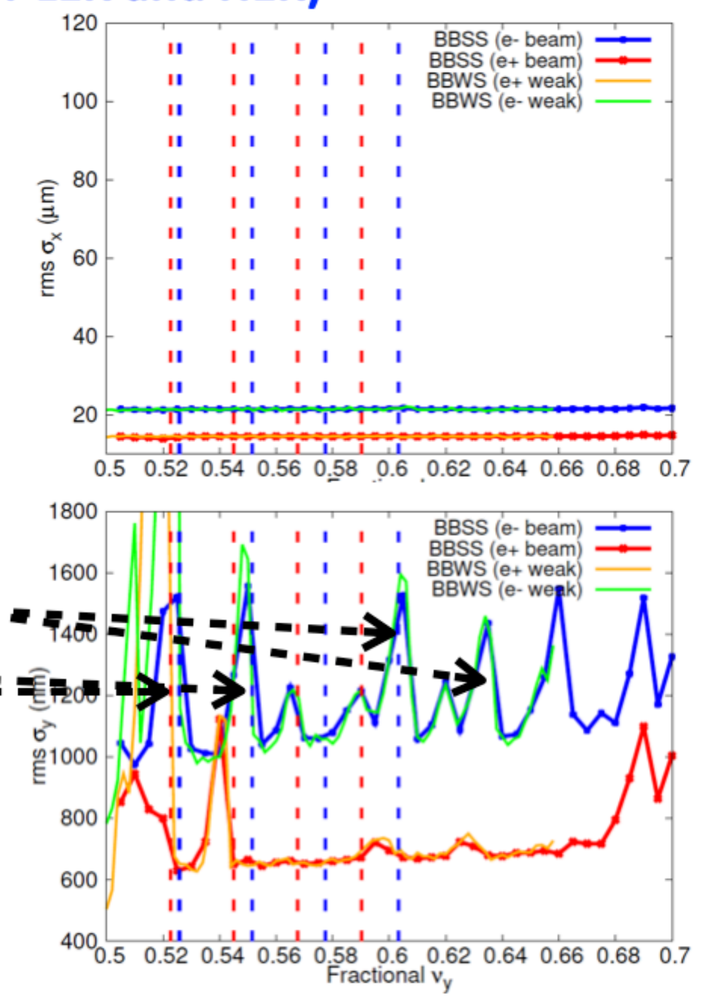
- Phase-3 commissioning
  - The beam-beam resonances seen in BBWS simulations also appear in BBSS simulations. The main difference is from BBHTI [23].
  - I also started to take parameter sets observed in the control room for simulations.
  - It was found that in simulations unequal ν_x of the two beams is worse than equal ν_x [24].

BBSS simulation

➤ **Parameter set (1): ν_x=*.56**

- **Scan of ν_y (same fractional part for LER and HER)**
- **Beam very unstable for ν_y<*.53**





➤ **Phase-3 (Early stage) machine parameters**

- **A few examples of parameter sets observed in the control room**

Operation parameter sets [24]

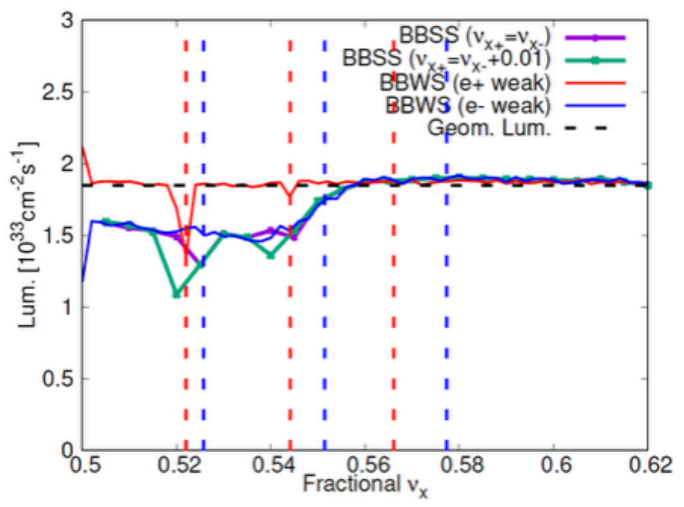
	2019.03.30		2019.04.02		2019.06.20*		2019.07.01	
	HER	LER	HER	LER	HER	LER	HER	LER
I_b (A)	0.21	0.26	0.17	0.22	0.5	0.5	0.8	0.8
# bunch	789		789		1576		1576	
ε_x (nm)	4.728	1.731	4.537	1.641	4.537	1.64	4.49	1.93
ε_y (pm)**	122.5	40	53.33	13.33	7.5	18	16.2	6.05
β_x (mm)	200	200	100	200	100	200	80	80
β_y (mm)	4	4	3	3	3	3	2	2
σ_z (mm)	6	6	6	6	5.5	5	5.5	5.2
σ_y (nm)	700	400	400	200	150	230	180	110
ν_x	45.564	44.571	45.5439	44.5568	45.5439	44.559	45.53	44.542
ν_y	43.603	46.610	43.6082	46.618	43.6082	46.618	43.583	46.605
ν_s	0.0256	0.0219	0.02576	0.02205	0.02718	0.023	0.02717	0.02349
ξ_y(Geom.)	0.0272	0.0220	0.0345	0.0233	0.041	0.1	0.088	0.089
$\mathcal{L}$(Geom.)	1.50E+33		1.85E+33		1.16E+34		3.78E+34	

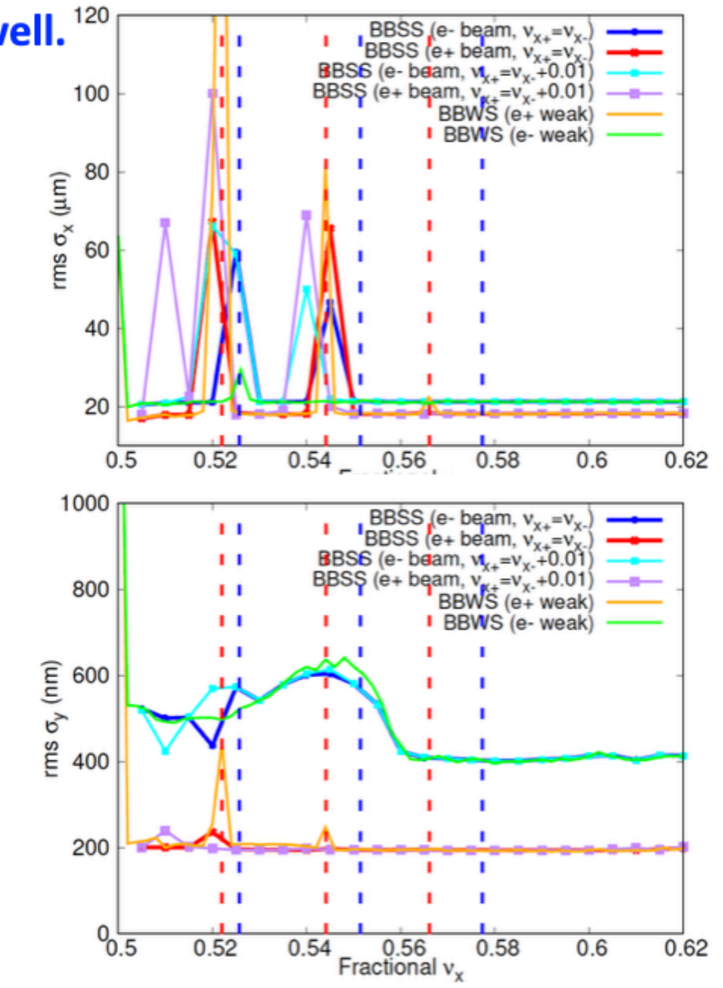
*Vert. emittances of e- and e+ were exchanged by mistake **Single beam emittance estimated from XRM data

BBSS simulation

➤ **Parameter set (2019.04.02)**

- **Scan of ν_x: Comparison of strong-strong and weak-strong simulations)**
- **Away from resonances, BBWS works well.**





[23] D. Zhou, Recent results of beam-beam simulations for SuperKEKB, Talk presented at the 2nd SuperKEKB beam dynamics workgroup meeting, KEK, Apr. 16, 2019.

[24] D. Zhou, Simulations of beam-beam effects, Talk presented at the 1st SuperKEKB Beam Dynamics Mini-Workshop, KEK, Jul. 17, 2019.

Beam-beam simulations for SuperKEKB

- Phase-3 commissioning
  - The tolerances of luminosity and beam-size blowup on closed orbit and linear IP aberrations were also simulated using BBWS [24].
  - It was found that small vertical emittances will make the luminosity and vertical beam sizes to be very sensitive to vertical orbit offset and vertical crossing angle [24].

Tolerances of IP aberrations

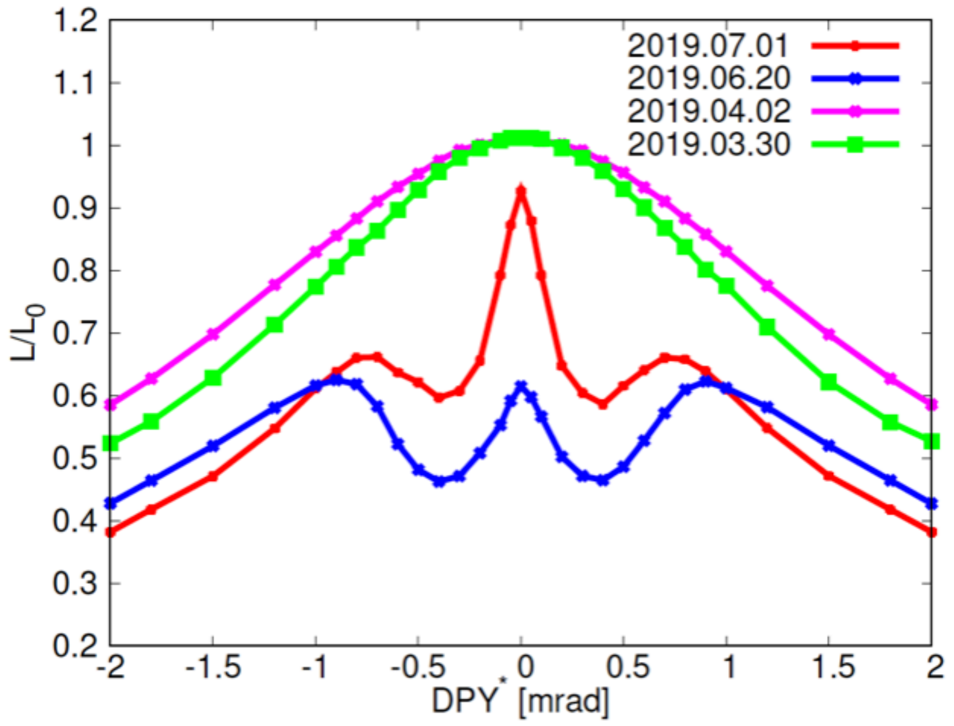
➤ **Various IP aberrations: the case of e+ beam**

- **DPY* (vert. crossing angle)**

  ** Luminosity becomes very sensitive to DPY* at very small vertical emittance. This is due to increase of projected vertical emittance

  ** Luminosity drops faster around DPY*=0 because of additional blowup due to nonzero v-angle

  ** With strong beam-beam blowup, the dependence can be "Tri Peaks"



Operation parameter sets [24]

➤ **Phase-3 (Early stage) machine parameters**

- **A few examples of parameter sets observed in the control room**

	2019.03.30		2019.04.02		2019.06.20*		2019.07.01	
	HER	LER	HER	LER	HER	LER	HER	LER
I_b (A)	0.21	0.26	0.17	0.22	0.5	0.5	0.8	0.8
# bunch	789		789		1576		1576	
ε_x (nm)	4.728	1.731	4.537	1.641	4.537	1.64	4.49	1.93
ε_y (pm)**	122.5	40	53.33	13.33	7.5	18	16.2	6.05
β_x (mm)	200	200	100	200	100	200	80	80
β_y (mm)	4	4	3	3	3	3	2	2
σ_z (mm)	6	6	6	6	5.5	5	5.5	5.2
σ_y (nm)	700	400	400	200	150	230	180	110
ν_x	45.564	44.571	45.5439	44.5568	45.5439	44.559	45.53	44.542
ν_y	43.603	46.610	43.6082	46.618	43.6082	46.618	43.583	46.605
ν_s	0.0256	0.0219	0.02576	0.02205	0.02718	0.023	0.02717	0.02349
ξ_y(Geom.)	0.0272	0.0220	0.0345	0.0233	0.041	0.1	0.088	0.089
$\mathcal{L}$(Geom.)	1.50E+33		1.85E+33		1.16E+34		3.78E+34	

*Vert. emittances of e- and e+ were exchanged by mistake   **Single beam emittance estimated from XRM data

Tolerances of IP aberrations

➤ **Various IP aberrations: the case of e+ beam**

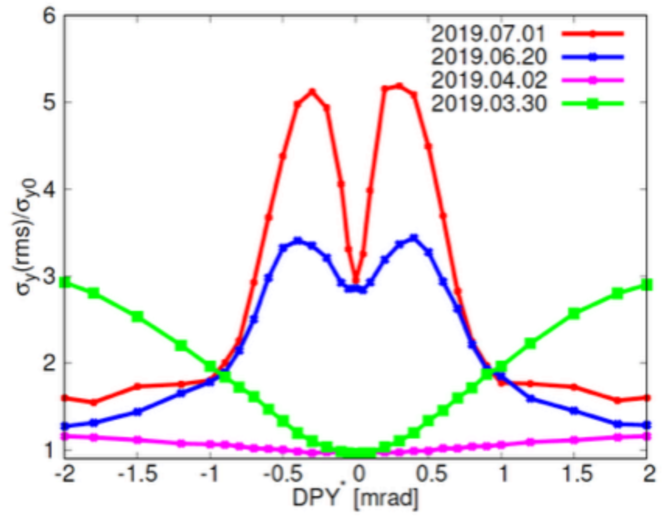
- **DPY* (vert. crossing angle)**

  ** With small blowup at DPY*=0, the dependence is "V" shape

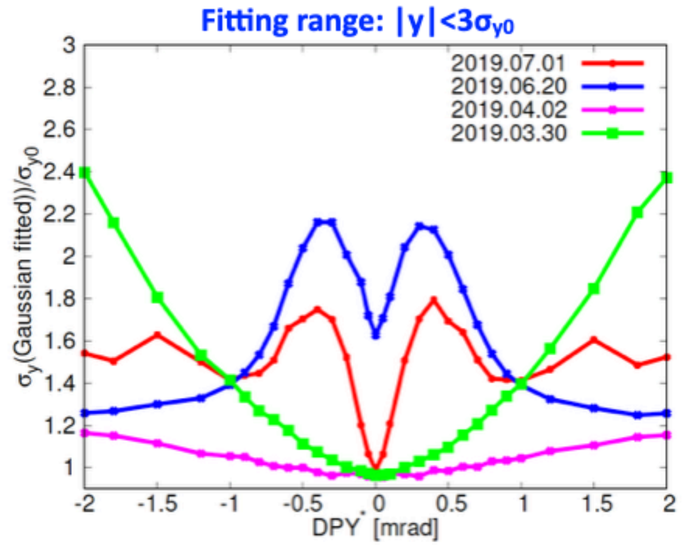
  ** With strong blowup at DPY*=0, the dependence becomes "M" shape

  ** With strong blowup at DPY*=0, the vertical beam size is sensitive to DPY* around 0

RMS vertical beam size



Gaussian fitted beam size
Fitting range: $|y|<3\sigma_{y0}$



[24] D. Zhou, Simulations of beam-beam effects, Talk presented at the 1st SuperKEKB Beam Dynamics Mini-Workshop, KEK, Jul. 17, 2019.

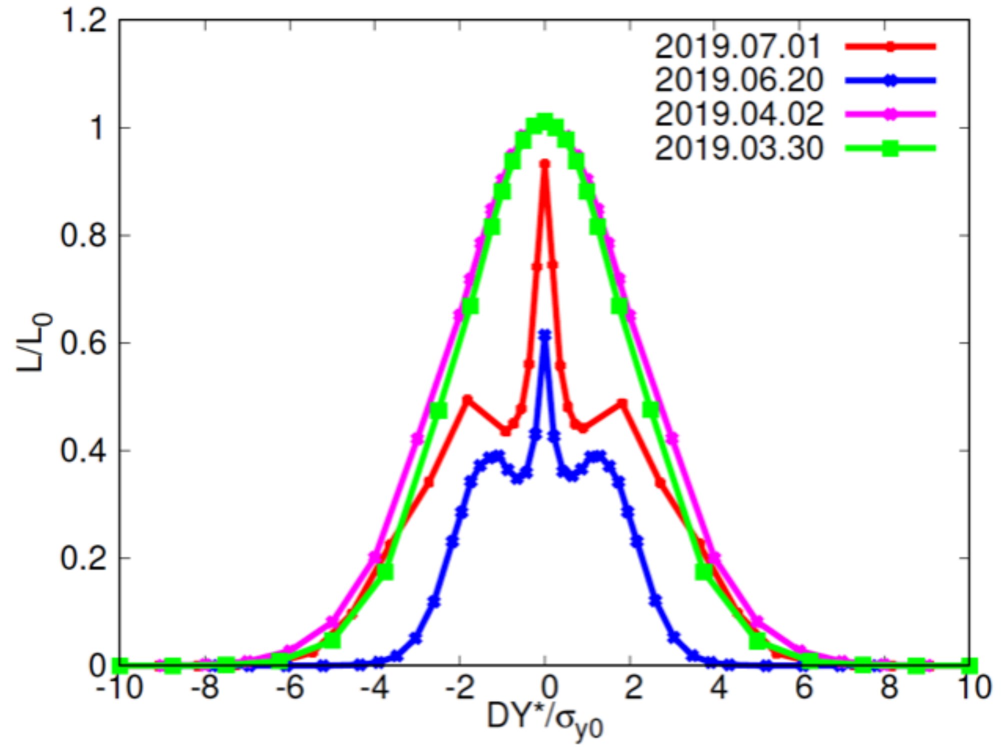
Beam-beam simulations for SuperKEKB

- Phase-3 commissioning
  - The tolerances of luminosity and beam-size blowup on closed orbit and linear IP aberrations were also simulated using BBWS [24].
  - It was found that small vertical emittances will make the luminosity and vertical beam sizes to be very sensitive to vertical orbit offset and vertical crossing angle [24].

Tolerances of IP aberrations

➤ **Various IP aberrations: the case of e+ beam**

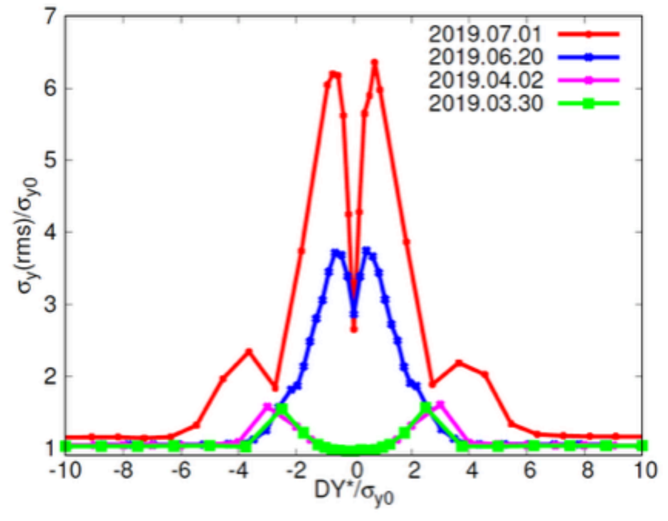
- DY* (Vertical offset)
  - ** Without beam-beam blowup, the dependence is very normal: Gaussian
  - ** With beam-beam blowup, the dependence becomes non-Gaussian
  - ** Luminosity drops faster around DY*=0 because of additional blowup due to nonzero v-angle

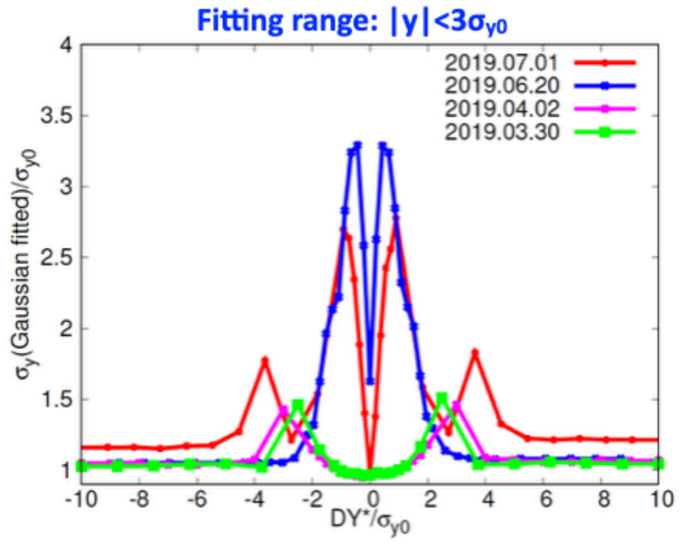


Tolerances of IP aberrations

➤ **Various IP aberrations: the case of e+ beam**

- DY* (Vertical offset)
  - ** Dependence on DY* is special: widened "M" shape
  - ** With beam-beam blowup, the behavior can become "Quadri Peaks"





Operation parameter sets [24]

➤ **Phase-3 (Early stage) machine parameters**

- A few examples of parameter sets observed in the control room

	2019.03.30		2019.04.02		2019.06.20*		2019.07.01	
	HER	LER	HER	LER	HER	LER	HER	LER
I_b (A)	0.21	0.26	0.17	0.22	0.5	0.5	0.8	0.8
# bunch	789		789		1576		1576	
ε_x (nm)	4.728	1.731	4.537	1.641	4.537	1.64	4.49	1.93
ε_y (pm)**	122.5	40	53.33	13.33	7.5	18	16.2	6.05
β_x (mm)	200	200	100	200	100	200	80	80
β_y (mm)	4	4	3	3	3	3	2	2
σ_z (mm)	6	6	6	6	5.5	5	5.5	5.2
σ_y (nm)	700	400	400	200	150	230	180	110
ν_x	45.564	44.571	45.5439	44.5568	45.5439	44.559	45.53	44.542
ν_y	43.603	46.610	43.6082	46.618	43.6082	46.618	43.583	46.605
ν_s	0.0256	0.0219	0.02576	0.02205	0.02718	0.023	0.02717	0.02349
ξ_y(Geom.)	0.0272	0.0220	0.0345	0.0233	0.041	0.1	0.088	0.089
$\mathcal{L}$(Geom.)	1.50E+33		1.85E+33		1.16E+34		3.78E+34	

*Vert. emittances of e- and e+ were exchanged by mistake   **Single beam emittance estimated from XRM data

[24] D. Zhou, Simulations of beam-beam effects, Talk presented at the 1st SuperKEKB Beam Dynamics Mini-Workshop, KEK, Jul. 17, 2019.

Beam-beam simulations for SuperKEKB

- Phase-3 commissioning
  - SAD simulations showed that the tolerances would be severe with lattice [25].

Operation parameter sets [24]

➤ **Phase 3-1 machine parameters**

- A few examples of parameter sets observed in the control room

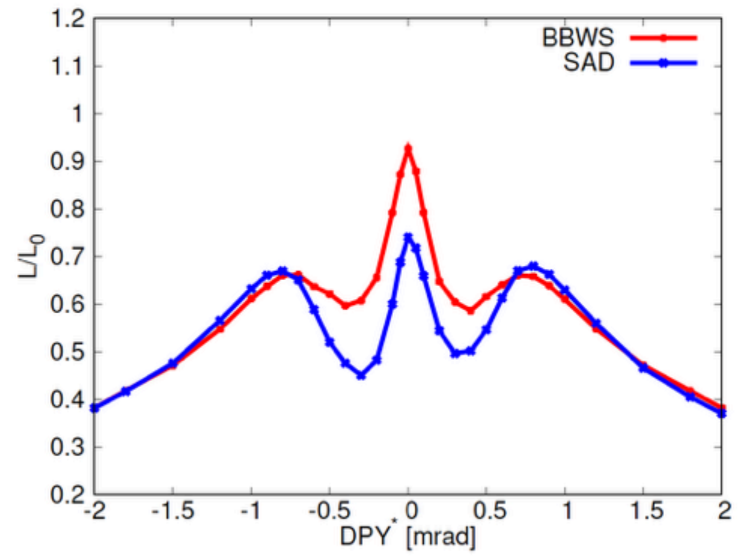
	2019.06.25		2019.07.01		2019.07.01(op1)		2019.07.01(op2)		2019.07.01(op3)	
	HER	LER	HER	LER	HER	LER	HER	LER	HER	LER
I_b (A)	0.05	0.03	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
# bunch	789		1576		1576		1576		1576	
ε_x (nm)	4.466	1.64	4.49	1.93	4.49	1.93	4.49	1.93	4.49	1.93
ε_y (pm)**	16.2	6.05	16.2	6.05	40	6.05	16.2	40	40	40
β_x (mm)	80	80	80	80	80	80	80	80	80	80
β_y (mm)	2	2	2	2	2	2	2	2	2	2
σ_z (mm)	5.05	4.66	5.5	5.2	5.5	5.2	5.5	5.2	5.5	5.2
σ_y (nm)	180	110	180	110	283	110	180	283	283	283
ν_x	45.5345	44.542	45.53	44.542	45.53	44.542	45.53	44.542	45.53	44.542
ν_y	43.5835	46.606	43.583	46.605	43.583	46.605	43.583	46.605	43.583	46.605
ν_s	0.02717	0.02349	0.02717	0.02349	0.02717	0.02349	0.02717	0.02349	0.02717	0.02349
ξ_y(Geom.)	0.0073	0.012	0.088	0.089	0.057	0.089	0.034	0.089	0.034	0.057
$\mathcal{L}$(Geom.)	1.95E+32		3.78E+34		2.63E+34		2.38E+34		1.99E+34	

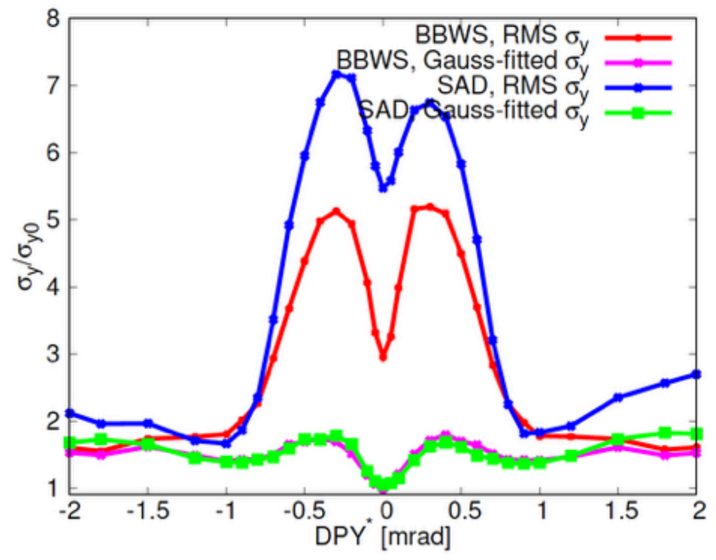
**Single beam emittance estimated from XRM data

Tolerances of IP aberrations with lattice

➤ **Various IP aberrations: the case of e+ beam**

- DPY* (vert. crossing angle) with parameter set of 2019.07.01
  - ** Luminosity becomes very sensitive to DPY* at very small vertical emittance.
  - ** Luminosity drops faster around DPY*=0 because of additional blowup due to nonzero v-angle
  - ** With lattice, large amplitude particles (beam-beam tail) pick up more nonlinear forces from the final focus system

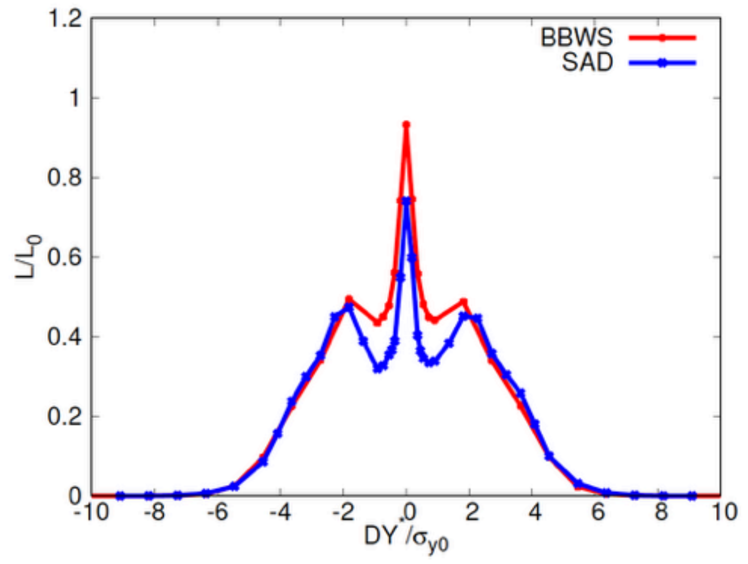


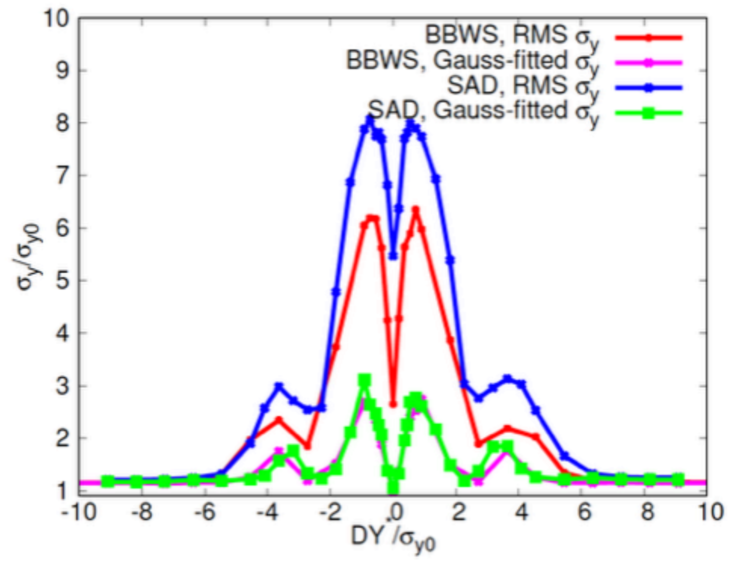


Tolerances of IP aberrations with lattice

➤ **Various IP aberrations: the case of e+ beam**

- DY* (Vertical offset) with parameter set of 2019.07.01
  - ** Luminosity drops faster around DY*=0 because of additional blowup due to nonzero v-offset
  - ** With lattice, large amplitude particles (beam-beam tail) pick up more nonlinear forces from the final focus system



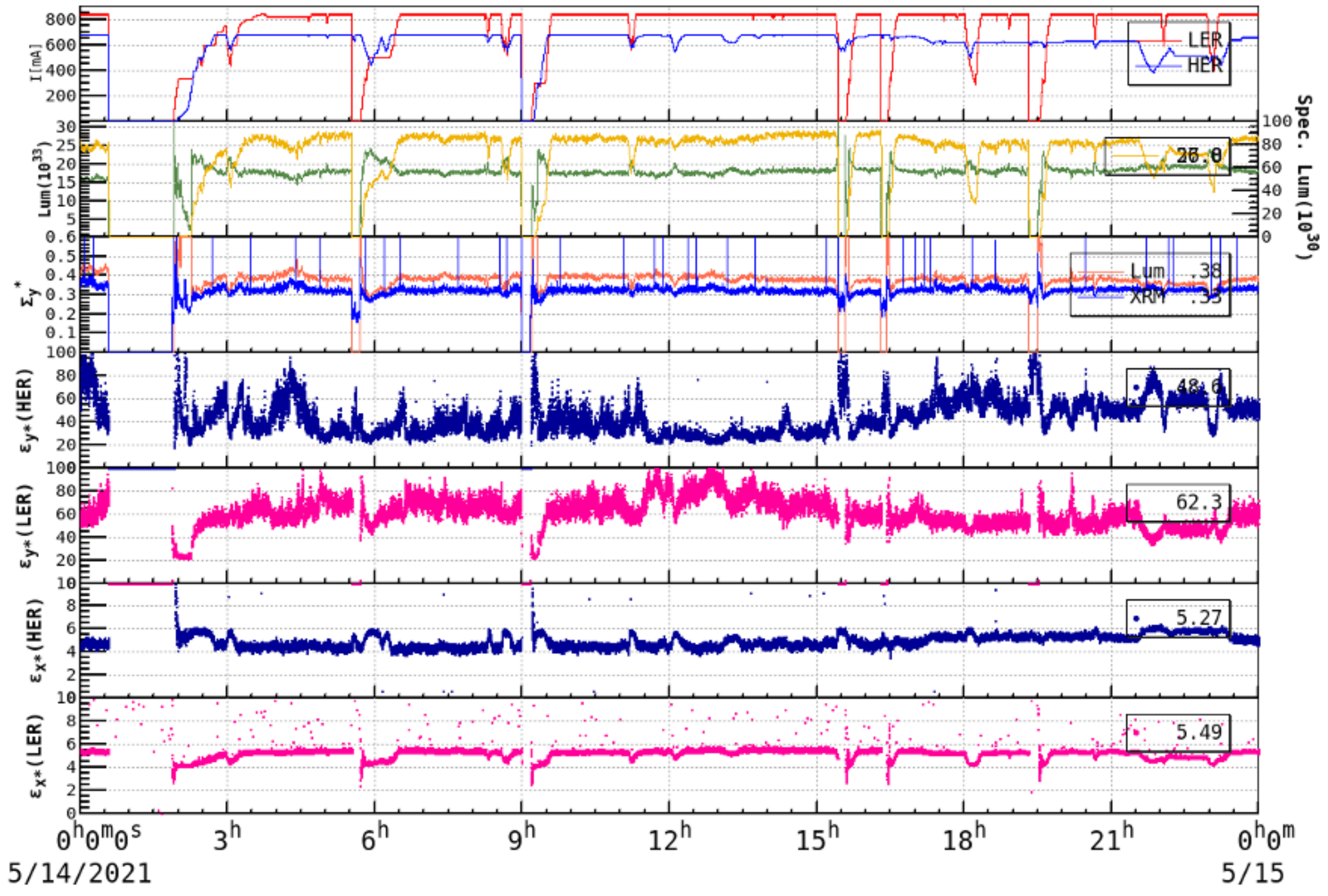


[25] D. Zhou, Simulations of beam-beam effects, Talk presented at the 2nd SuperKEKB Beam Dynamics Mini-Workshop, KEK, Sep. 20, 2019.

Beam-beam simulations for SuperKEKB

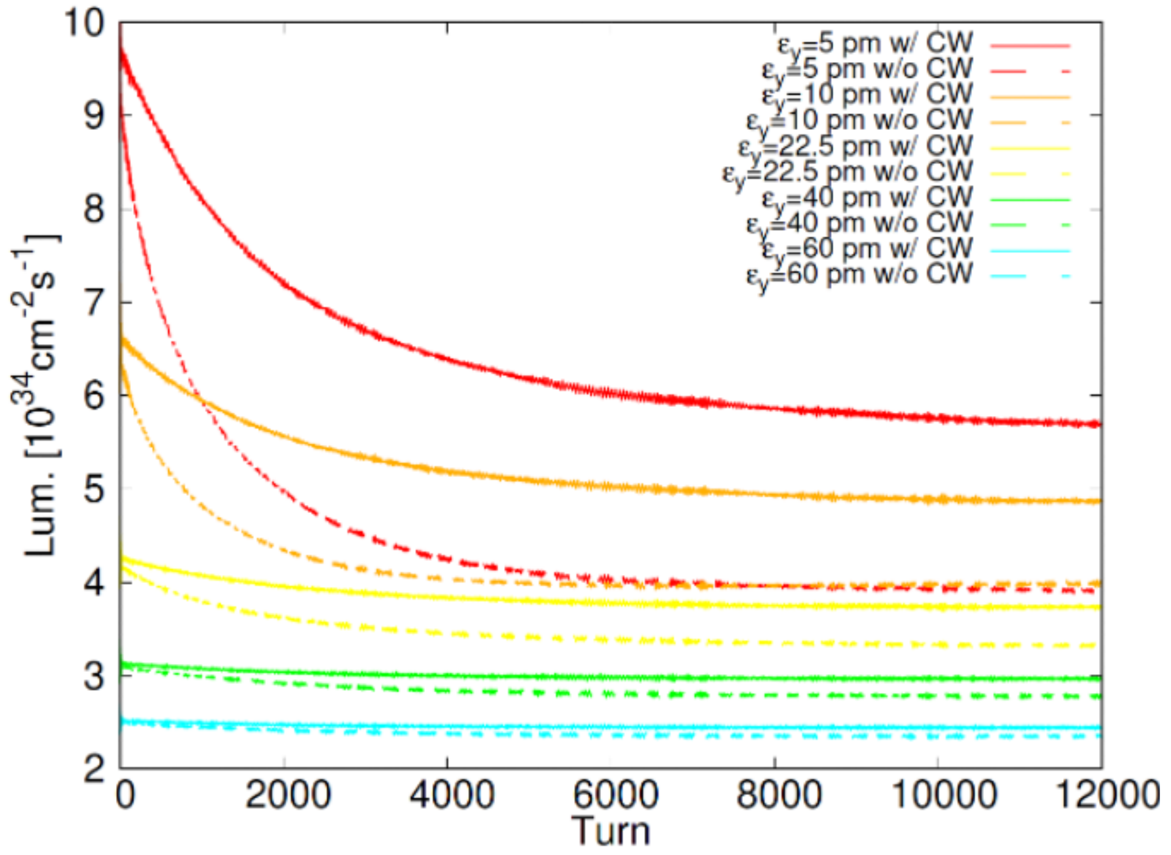
- Phase-3 commissioning with crab waist
  - Since 2020, crab waist was introduced and led to luminosity boost. Recently, I started to run beam-beam simulations with crab waist and try to compare with experimental observations.
  - With single-beam ϵ_y of 22.5 pm, BBSS simulations predict lum. of ~3.75e34 $cm^{-2}s^{-1}$ without obvious BBHTI. This is compared to the achieved luminosity of 3.0e34 $cm^{-2}s^{-1}$ in 2021ab run.
  - In BBSS simulations, the crab waist and the single-beam ϵ_y were also varied. It was found that both of these parameters are essential in determining the luminosity performance.
  - Weak blowup in ϵ_x was observed in the control room, but not well-confirmed.

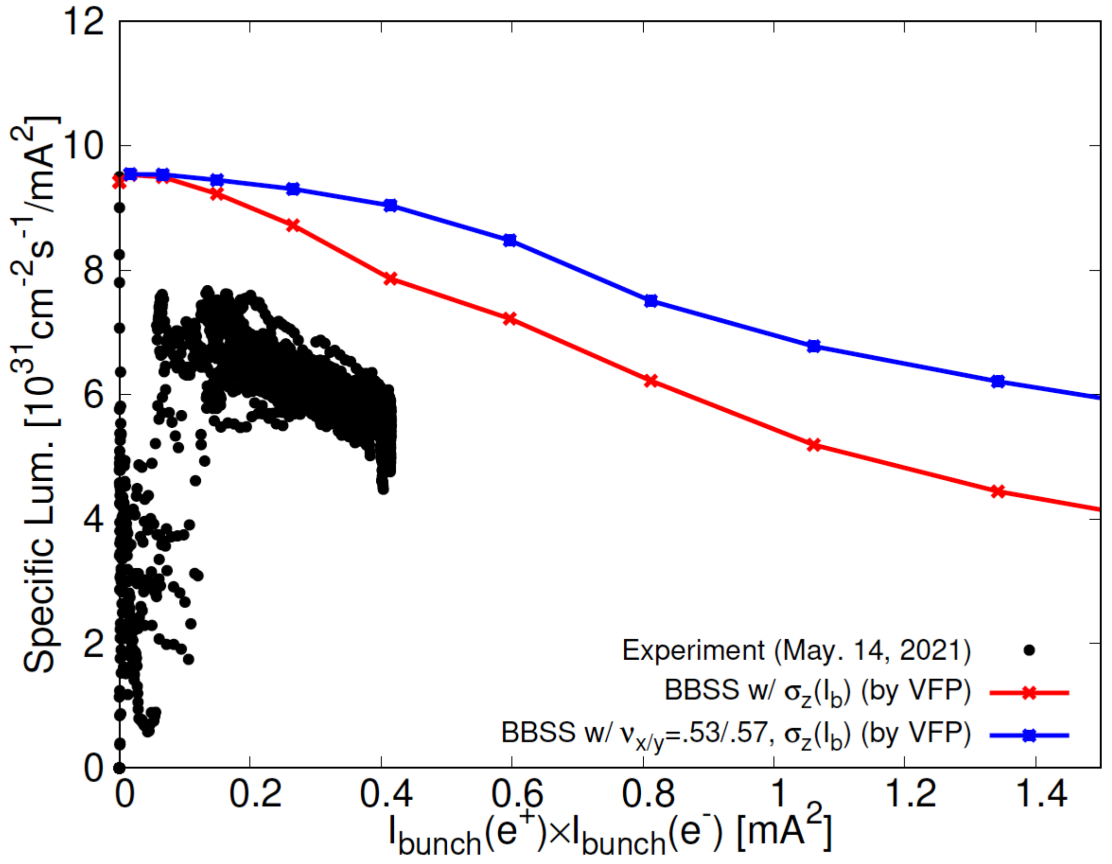
Luminosity history panel seen in SuperKEKB control room



Operation parameter set [26]

	2021.05.14		Comments
	HER	LER	
I_b (A)	0.68	0.84	
# bunch	1174		
ϵ_x (nm)	4.6	4.24	w/ IBS
ϵ_y (pm)	22.5	22.5	Estimated from XRM data
β_x (mm)	60	80	Calculated from lattice
β_y (mm)	1	1	Calculated from lattice
σ_z (mm)	6	6	w/ bunch lengthening by impedance
σ_y (μm)	0.15	0.15	Observed from XRM
ν_x	45.52989	44.5247	Measured tune of pilot bunch
ν_y	43.59055	46.57279	Measured tune of pilot bunch
ν_s	0.02719	0.02212	Calculated from lattice
Crab waist	40%	80%	Lattice design



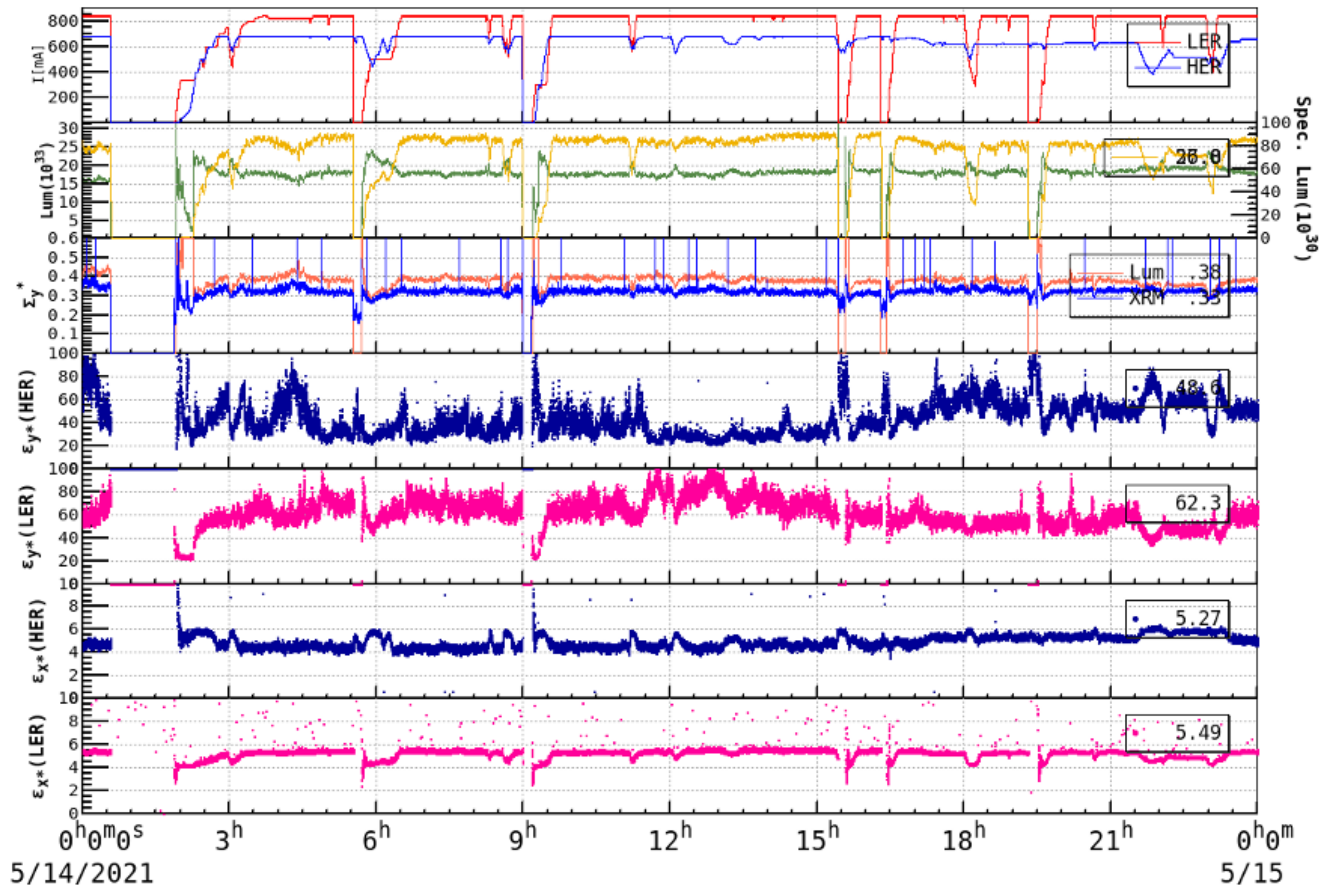


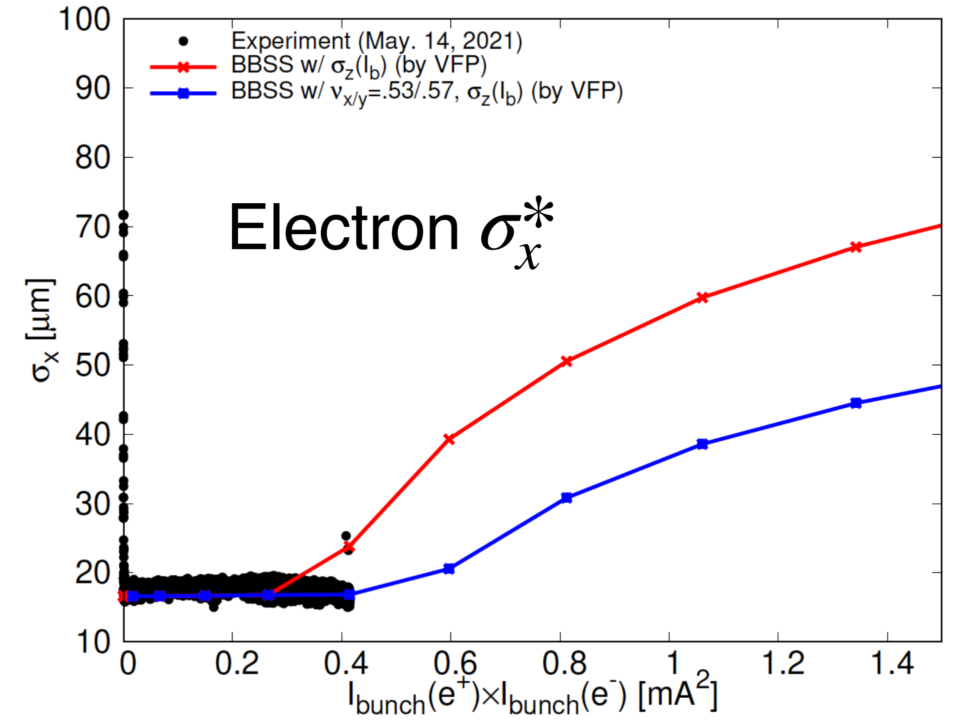
[26] D. Zhou, Beam dynamics issues: Comparisons of theories, simulations and experiments, Talk presented at the SuperKEKB 2021ab summary meeting, KEK, Jul. 29, 2021.

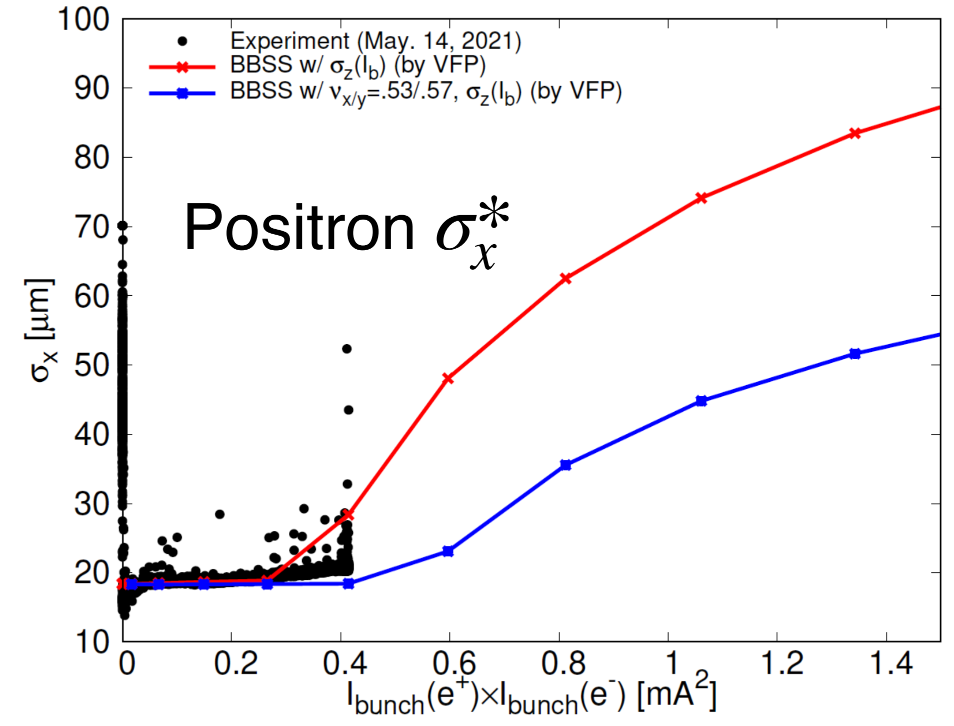
Beam-beam simulations for SuperKEKB

- Phase-3 commissioning with crab waist
  - Using beam parameter observed on May. 14, 2021, BBSS simulations were done.
  - Simulations showed that the machine seemed to operate round the BBHTI threshold: The blowup of positron σ_x^* in experimental data occurred around the simulated BBHTI threshold.
  - The observed blowup of σ_y^* of both electron and positron beams were complicated (see 24 hours' history of ϵ_y). BBSS simulations cannot reproduce the trends of σ_y^* blowup.
  - Simulations showed working point (.53,.57) is better: Higher BBHTI threshold and weaker beam-size blowup.

Luminosity history panel seen in SuperKEKB control room

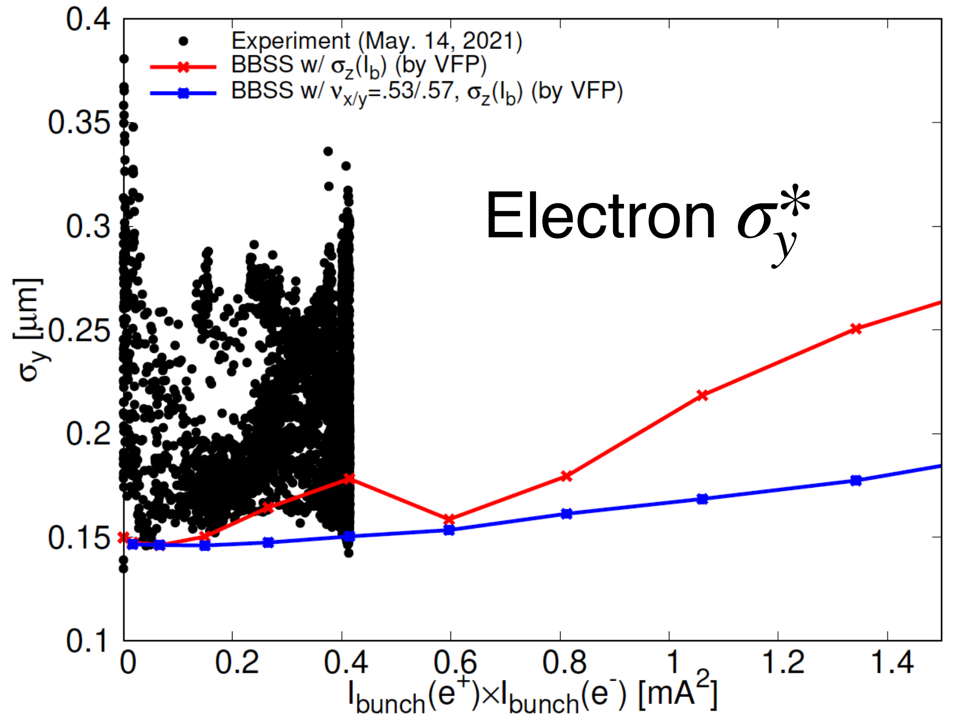


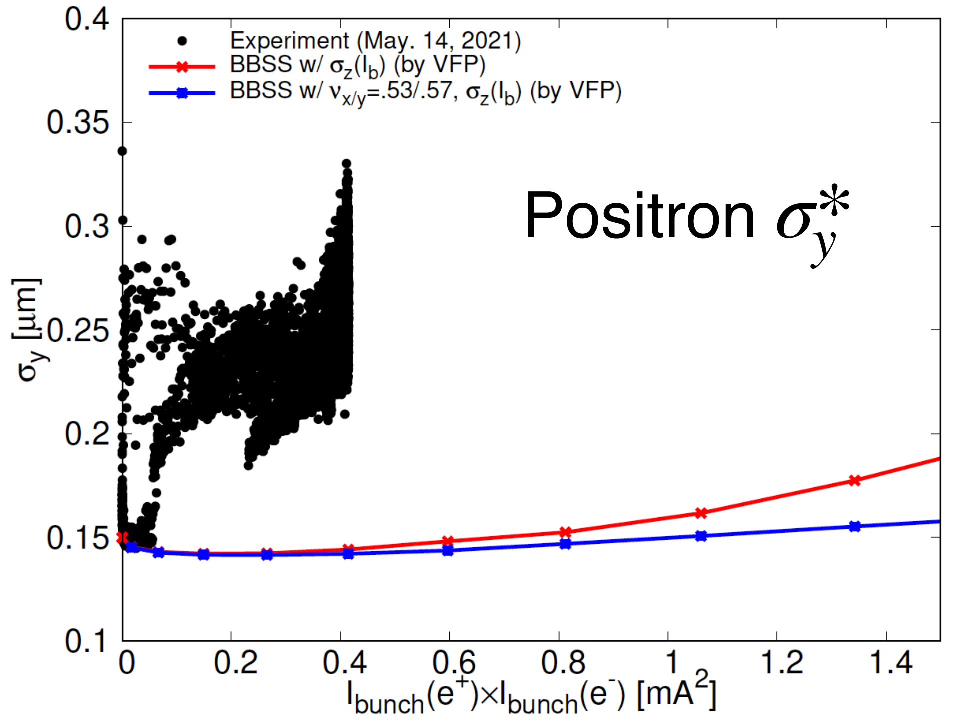




Operation parameter set [26]

	2021.05.14		Comments
	HER	LER	
I_b (A)	0.68	0.84	
# bunch	1174		
ε_x (nm)	4.6	4.24	w/ IBS
ε_y (pm)	22.5	22.5	Estimated from XRM data
β_x (mm)	60	80	Calculated from lattice
β_y (mm)	1	1	Calculated from lattice
σ_z (mm)	6	6	w/ bunch lengthening by impedance
σ_y (μm)	0.15	0.15	Observed from XRM
ν_x	45.52989	44.5247	Measured tune of pilot bunch
ν_y	43.59055	46.57279	Measured tune of pilot bunch
ν_s	0.02719	0.02212	Calculated from lattice
Crab waist	40%	80%	Lattice design





[26] D. Zhou, Beam dynamics issues: Comparisons of theories, simulations and experiments, Talk presented at the SuperKEKB 2021ab summary meeting, KEK, Jul. 29, 2021.

Beam-beam simulations for SuperKEKB

- Phase-3 commissioning with crab waist
  - On Jul. 1st, 2021, a machine study was done with high bunch-currents for collision. Strong blowup in LER σ_y^* and obvious blowup in LER σ_x^* were observed in experiment.
  - BBSS simulations were done to compare the experimental observations. With strong BBHTI and assumed bunch lengthening, the simulated slope of specific luminosity seemed to agree with experimental data.
  - Parameters such as ϵ_y, σ_z, and $\nu_{x,y}$ were varied in simulations. Turned out that the design working point (.53,.57) has weaker BBHTI, giving high luminosity. BBHTI seemed to play an important role.

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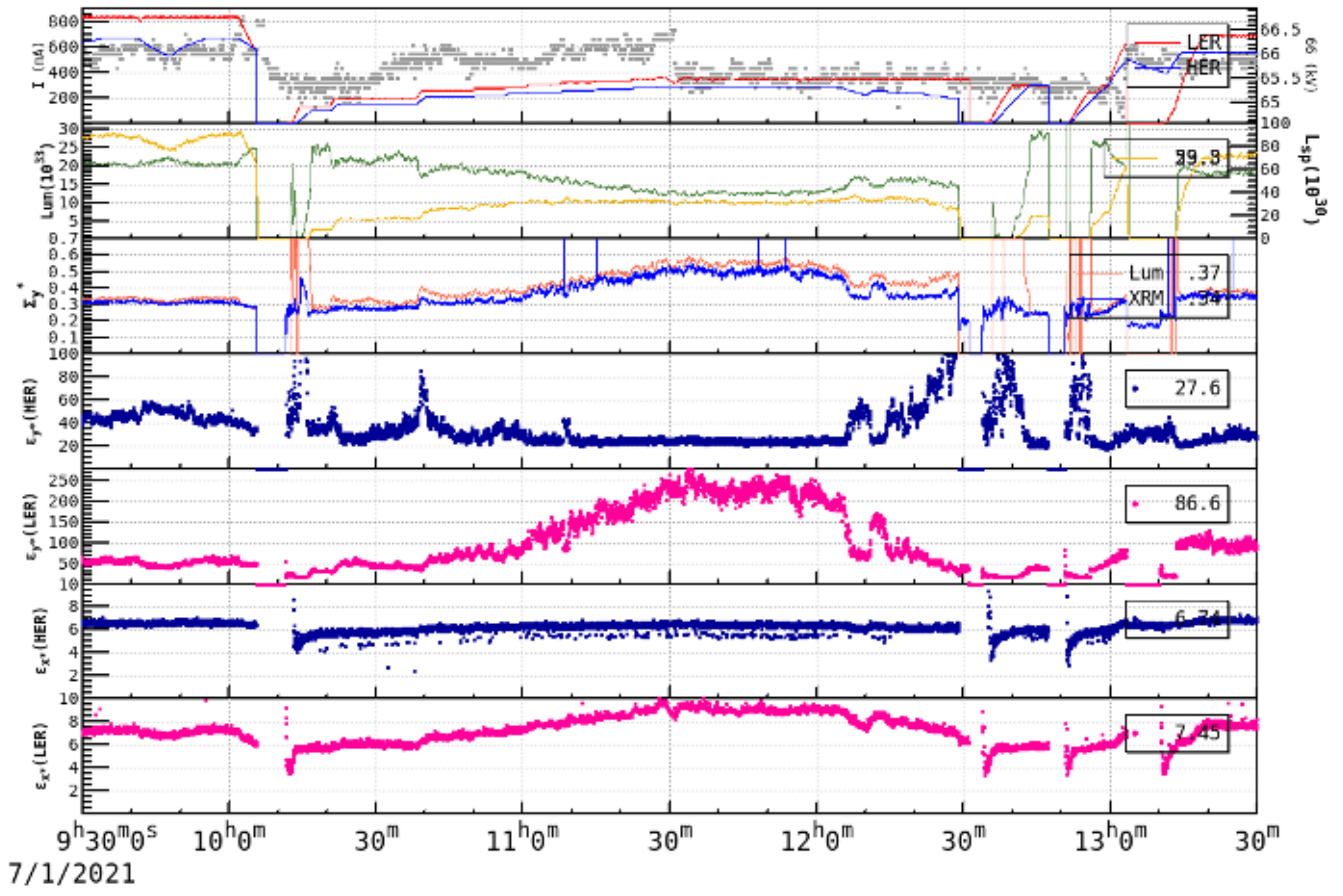
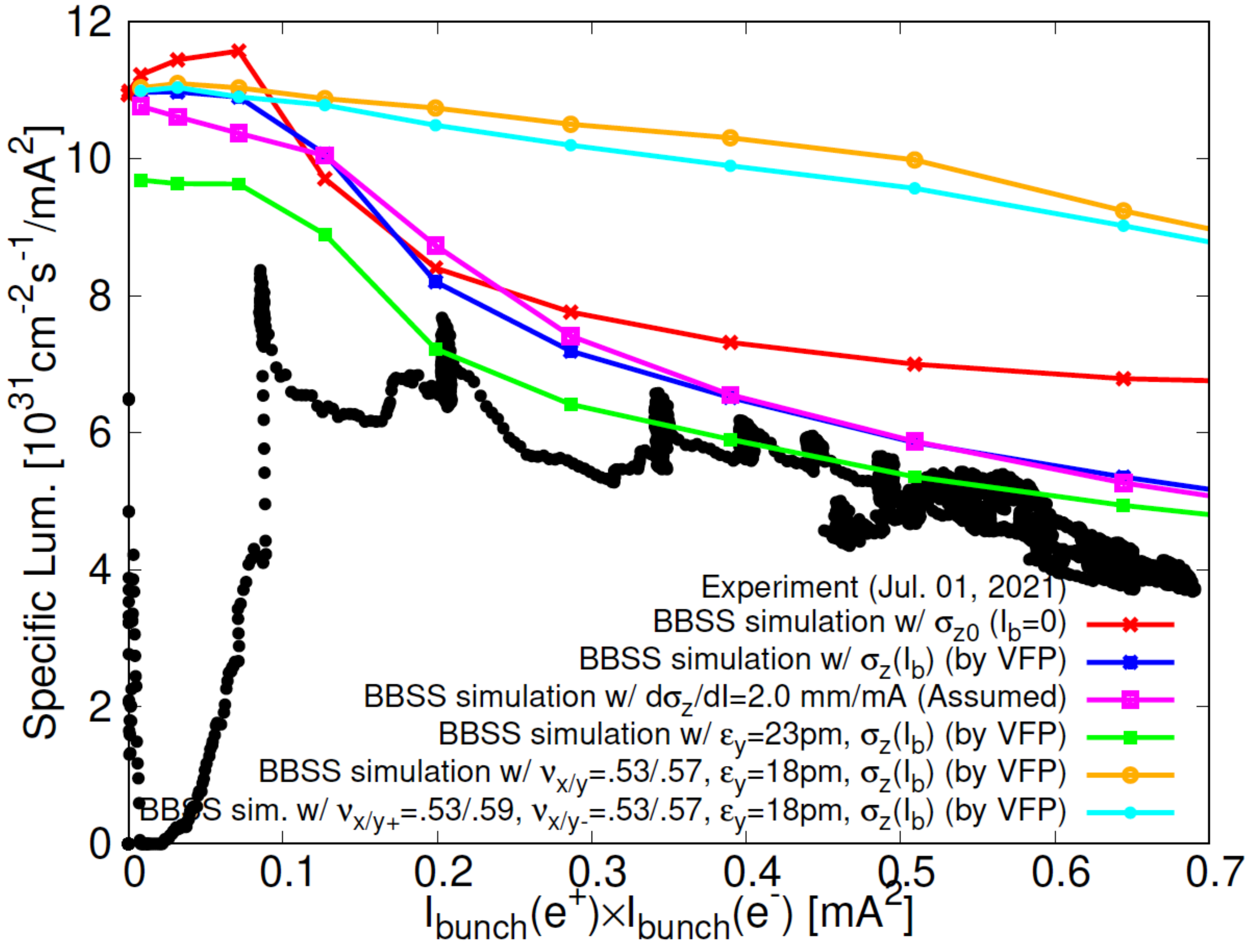


Operation parameter sets [26]

	2021.07.01		Comments
	HER	LER	
I_b (A)	Ie	1.255*Ie	
# bunch	393		
ε_x (nm)	4.6	4.0	w/ IBS
ε_y (pm)	18	18	Single beam (Estimated from XRM data)
β_x (mm)	60	80	Calculated from lattice
β_y (mm)	1	1	Calculated from lattice
σ_z (mm)	5.05	4.84	Natural bunch length (w/o MWI)
ν_x	45.532	44.525	Measured tune of pilot bunch
ν_y	43.582	46.593	Measured tune of pilot bunch
ν_s	0.0272	0.0221	Calculated from lattice
Crab waist	40%	80%	Lattice design

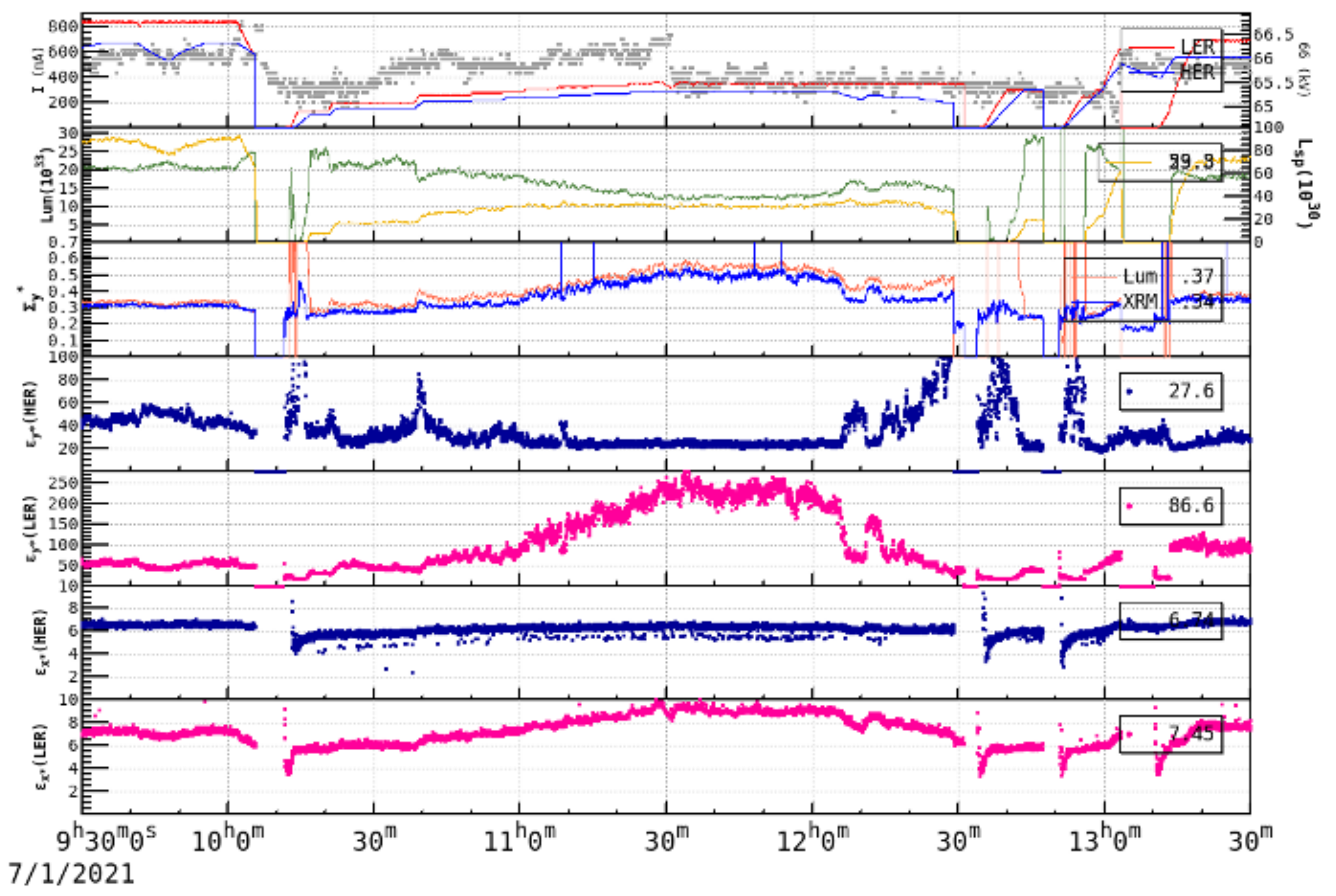


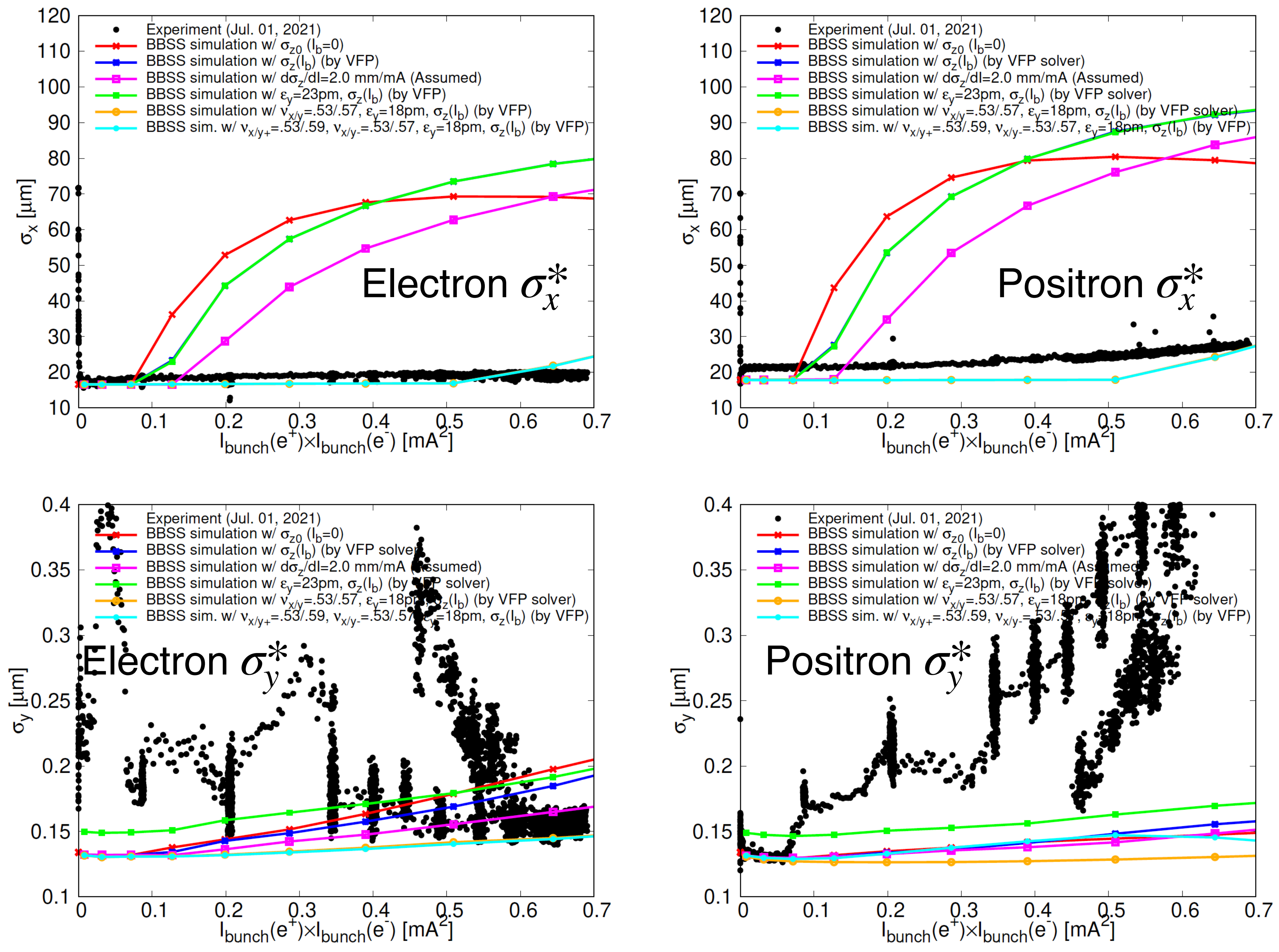
[26] D. Zhou, Beam dynamics issues: Comparisons of theories, simulations and experiments, Talk presented at the SuperKEKB 2021ab summary meeting, KEK, Jul. 29, 2021.

Beam-beam simulations for SuperKEKB

- Phase-3 commissioning with crab waist
  - BBSS simulations showed clear BBHTI threshold. The threshold is sensitive to σ_z and ν_x, not sensitive to ϵ_y and ν_y. This is consistent with BBHTI theory (K. Ohmi et al.)
  - Simulations showed that BBHTI makes vertical emittance growth more severe.
  - From simulations, careful choice of working point can relax BBHTI by increasing its threshold.
  - Experiment phenomena are quite complicated. It was hard to determine the BBHTI threshold. Blowup of σ_y^* was much different from simulations. The two beams had unbalanced blowup.

Luminosity history panel seen in SuperKEKB control room





Operation parameter sets [26]

	2021.07.01		Comments
	HER	LER	
I_b (A)	Ie	1.255*Ie	
# bunch	393		
ϵ_x (nm)	4.6	4.0	w/ IBS
ϵ_y (pm)	18	18	Single beam (Estimated from XRM data)
β_x (mm)	60	80	Calculated from lattice
β_y (mm)	1	1	Calculated from lattice
σ_z (mm)	5.05	4.84	Natural bunch length (w/o MWI)
ν_x	45.532	44.525	Measured tune of pilot bunch
ν_y	43.582	46.593	Measured tune of pilot bunch
ν_s	0.0272	0.0221	Calculated from lattice
Crab waist	40%	80%	Lattice design

[26] D. Zhou, Beam dynamics issues: Comparisons of theories, simulations and experiments, Talk presented at the SuperKEKB 2021ab summary meeting, KEK, Jul. 29, 2021.

Summary

- Beam-beam simulations with design lattice
  - Interplay of beam-beam (w/o crab waist) and lattice nonlinearity was found to cause severe luminosity loss.
  - The IR nonlinearity was analyzed and found to be the main source of luminosity loss.
- Beam-beam simulations with Phase-2 and Phase-3 machine parameters
  - Without crab waist, beam-beam resonances set a strong limit in luminosity performance.
  - BBHTI seems to be important, but not confirmed yet. Simulations showed that careful choice of working point can relax BBHTI.
  - Both simulations and experiments showed crab waist is effective in suppressing beam blowup and boosting luminosity.

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Further information: https://research.kek.jp/people/dmzhou/