Practical experience from beam-beam simulations vs reality in (Super)KEKB

Demin Zhou

Accelerator theory group, Accelerator laboratory, KEK

Acknowledgements

K. Ohmi and (Super)KEKB team

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Outline

- Brief overview of strategy for beam-beam simulations [1]
- Beam-beam simulations for KEKB
- Beam-beam simulations for SuperKEKB
- Summary and outlook

- See Ref.[1] for an overview of my work on beam-beam simulations.

[1] D. Zhou, Talk presented at the 1st meeting of SuperKEKB beam-beam workgroup, Aug. 24, KEK (https://kds.kek.jp/event/39142/).

Brief overview of strategy for beam-beam simulations

- Weak-strong model + simple one-turn map: BBWS code [2]
  - 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, beta functions, X-Y couplings, dispersions, etc.), chromatic perturbation, synchrotron radiation damping, quantum excitation, crab waist, etc.
- Weak-strong model + full lattice: SAD code
  - The BBWS code was implemented into SAD as a type of BEAMBEAM element, where beam-beam map 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.); …
- Strong-strong model + simple one-turn map: BBSS code [2]
  - 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.

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

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

```
;
BEAMBEAM   BMBMP  =(NP=3.63776D10
                  BETAX=0.06 BETAY=0.001
                  EX=0.D0 EY=0.D0
                  EMIX=4.6D-9 EMIY=40.D-12
                  SIGZ=6.D-3  DP=6.30427D-4
                  ALPHAX=0.D0 ALPHAY=0.D0
                  DX=0.E-6 DZ=0.0
                  SLICE=200.D0  XANGLE=41.5D-3
                  STURN=1000)
;
```

[2] K. Ohmi, Talk presented at the 2019 SAD workshop, https://conference-indico.kek.jp/event/75/.

Brief overview of strategy for beam-beam simulations (cont'd)

- 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.

Beam-beam simulations with chromatic effects for KEKB

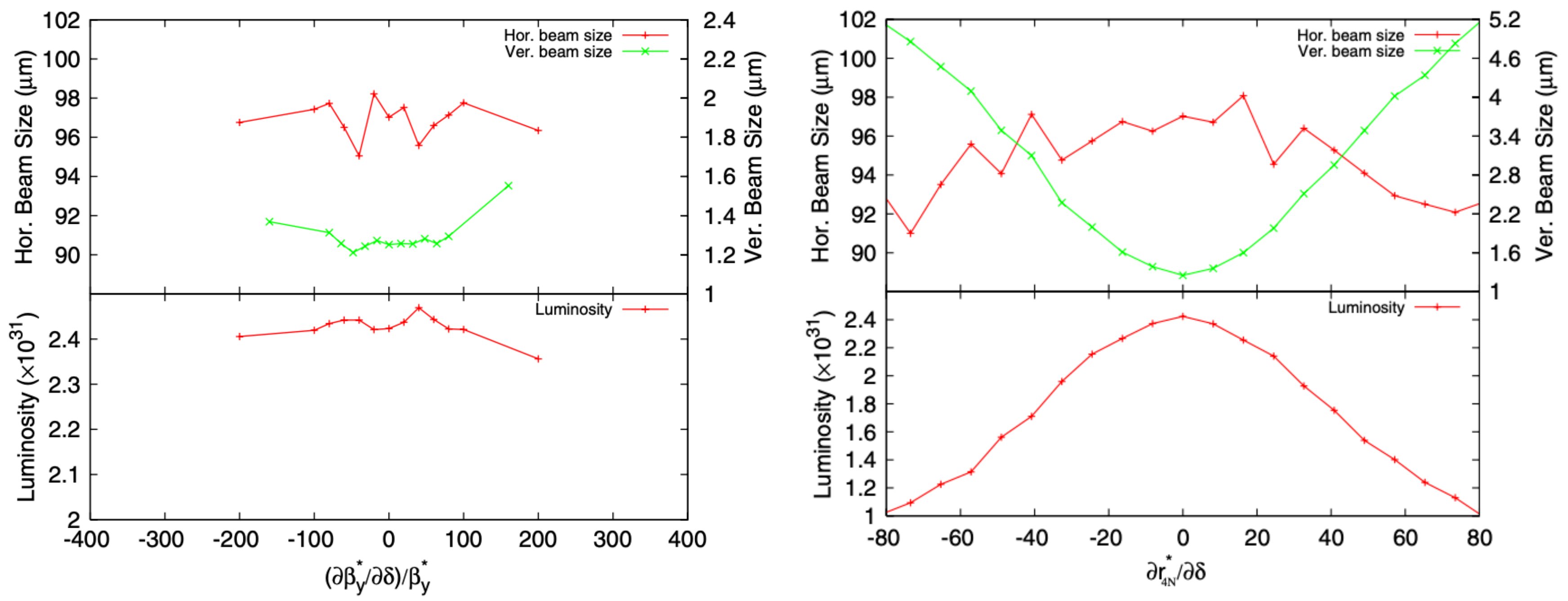
$$\alpha_u(\delta) = \sum_{i=0}^{\infty} \alpha_{ui}\delta^i \qquad \beta_u(\delta) = \sum_{i=0}^{\infty} \beta_{ui}\delta^i$$

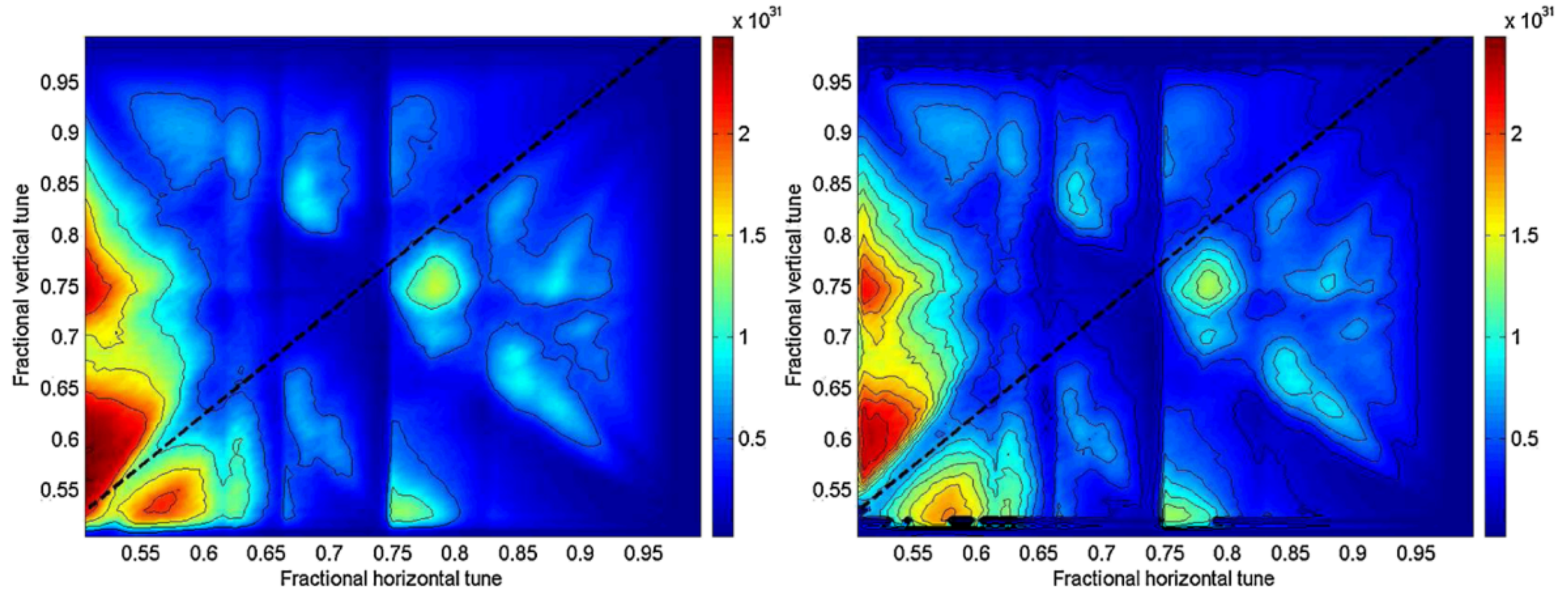
$$\nu_u(\delta) = \sum_{i=0}^{\infty} \nu_{ui}\delta^i \qquad r_j(\delta) = \sum_{i=0}^{\infty} r_{ji}\delta^i$$

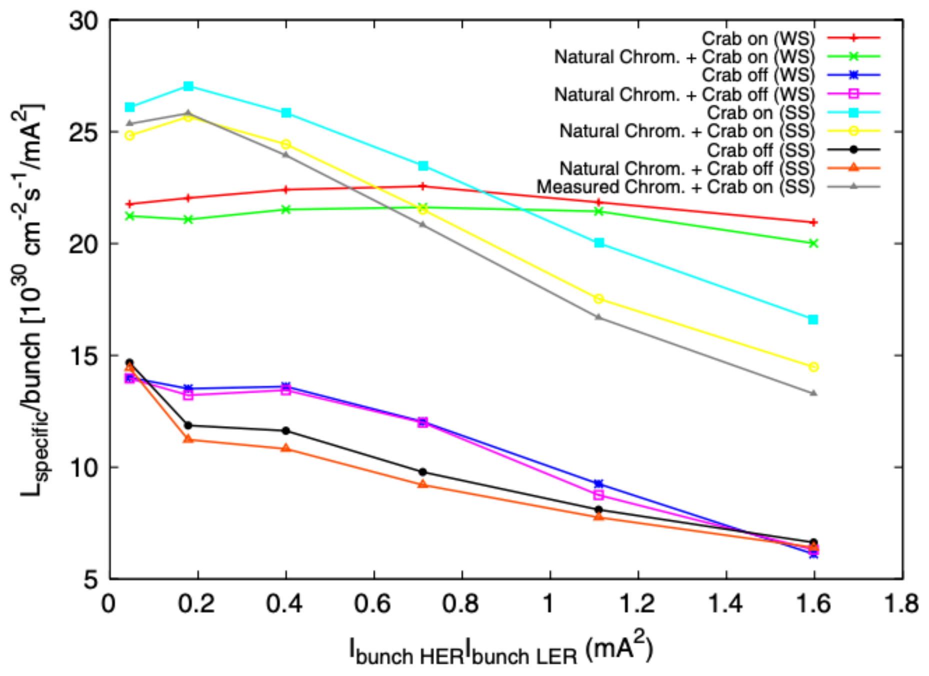
$$u = x, y \quad \text{and} \quad j = 1, 2, 3, 4,$$

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

- Model of chromatic effects [3,4]
  - Twiss parameters expressed in Taylor series.
  - Chromaticities of Twiss parameters were 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.







[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 with chromatic effects for KEKB (cont'd)

- The chromatic couplings at IP were also measured and corrected using skew sextupoles [5].
- Luminosity boost was achieved with crab cavities and skew-sextupole tunings at KEKB [6].
- The simulation tools were proved to be successful in predicting chromatic effects on luminosity.

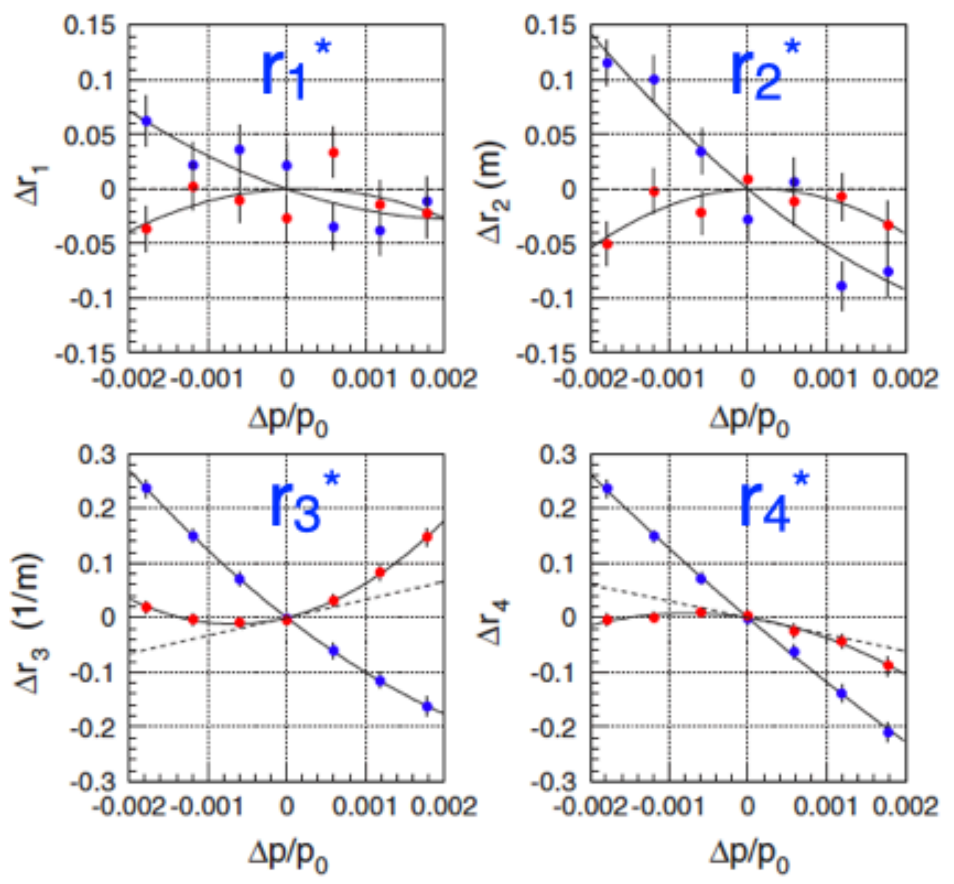
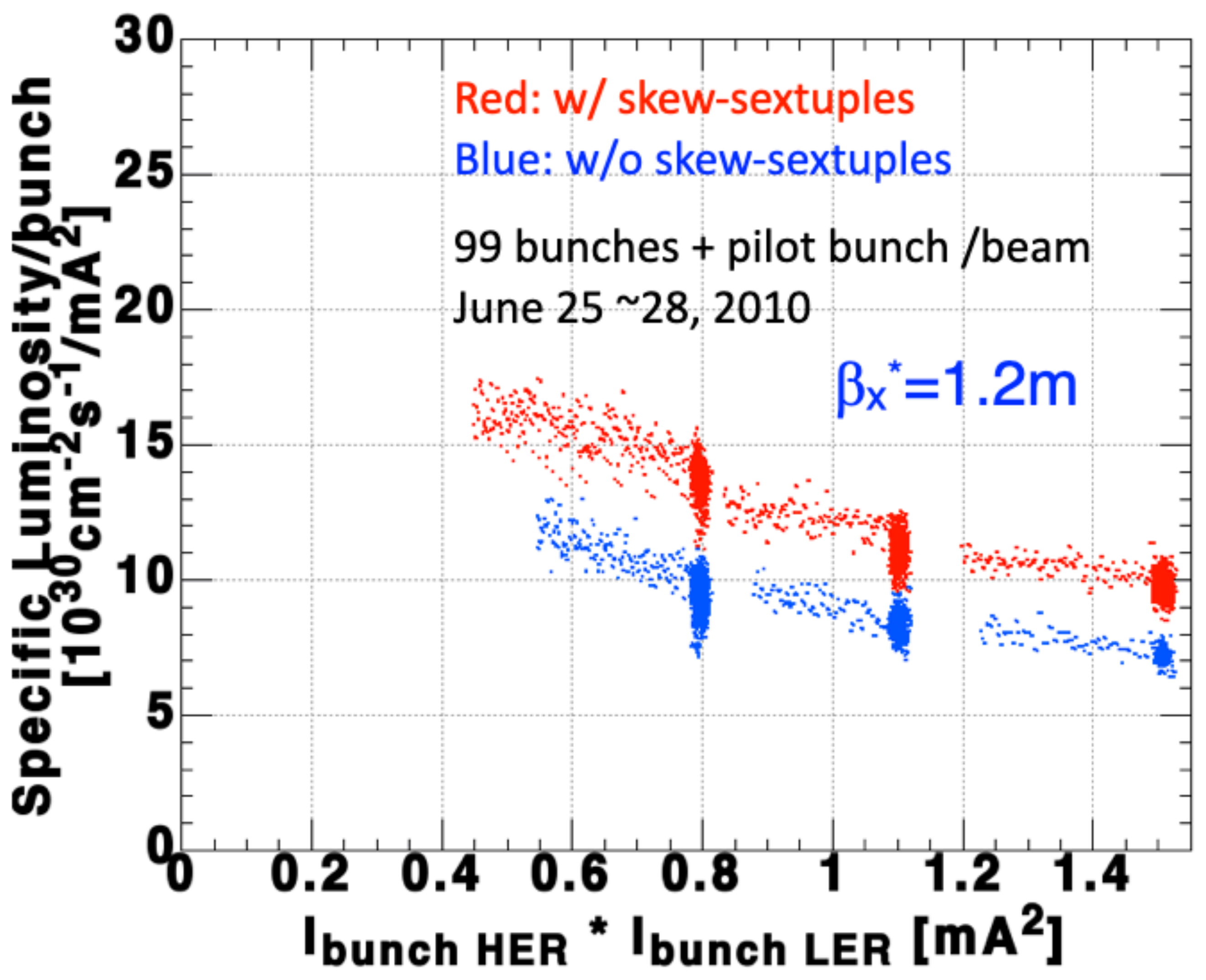


FIG. 4. (Color) Measured chromatic X-Y coupling at IP in LER. The blue plots indicate those before and the red plots indicate those after the skew sextupole correction. The dashed line indicates the natural chromatic X-Y coupling estimated using the model lattice by SAD.

Measure specific luminosity with crab cavities off



[5] Y. Ohnishi, et al., PRST-AB 12, 091002 (2009).

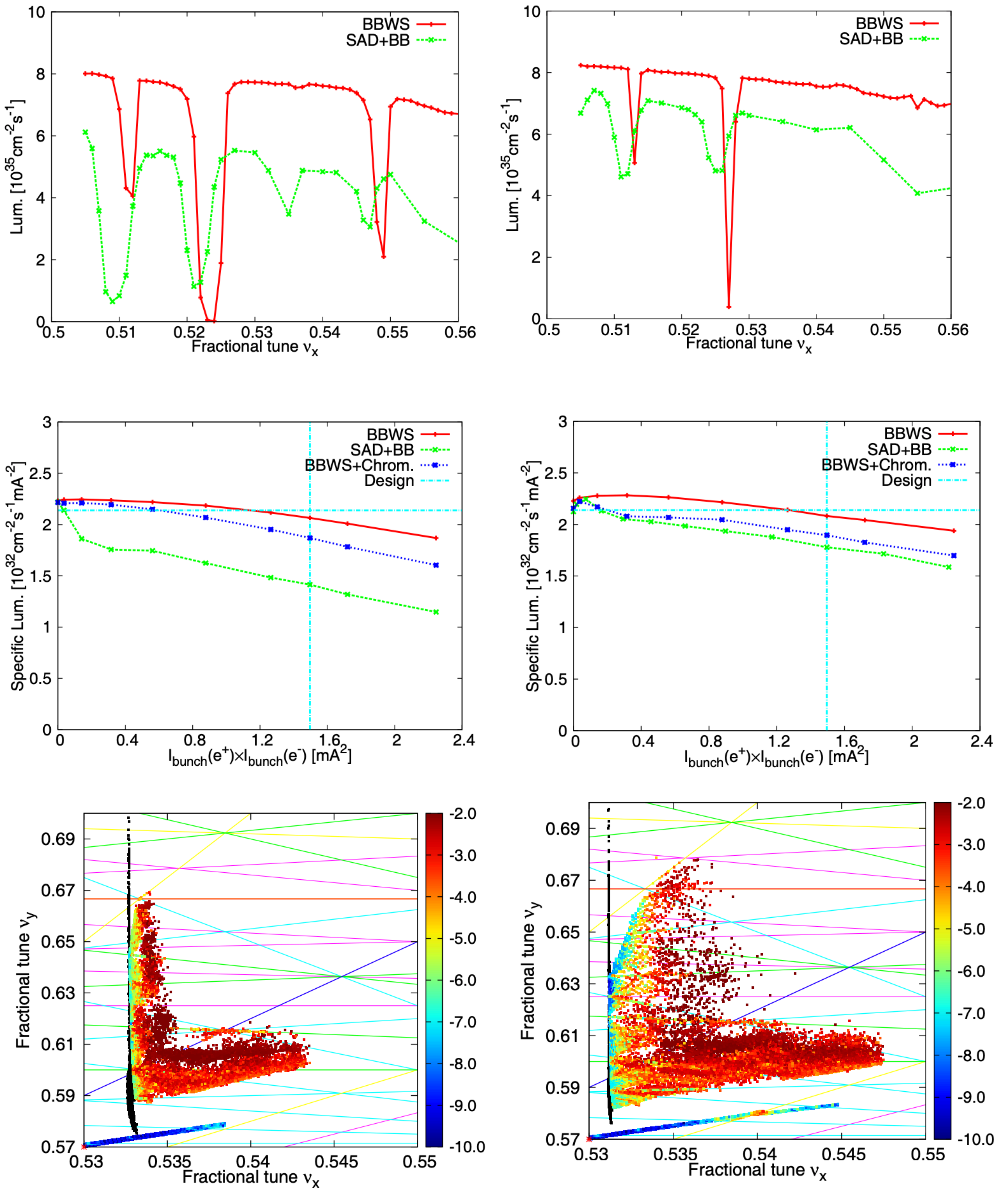
[6] Y. Funakoshi et al., WEOAMH02, IPAC'10 (2010).

Beam-beam simulations for SuperKEKB

- Interplay of beam-beam and lattice nonlinearity with final design configuration
  - Cause direct luminosity loss.
  - Strongly affect dynamic aperture and Touschek lifetime.
  - In addition to chromatic effects, other nonlinear effects are also important.

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^* (mm)	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



[7] 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 (cont'd)

- Interplay of beam-beam and lattice nonlinearity with final design configuration
  - Nonlinear analysis was done using E. Forest's PTC code and also a simple method [8].
  - Then perturbation maps were made via MAP element in SAD to simulate luminosity loss. 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.

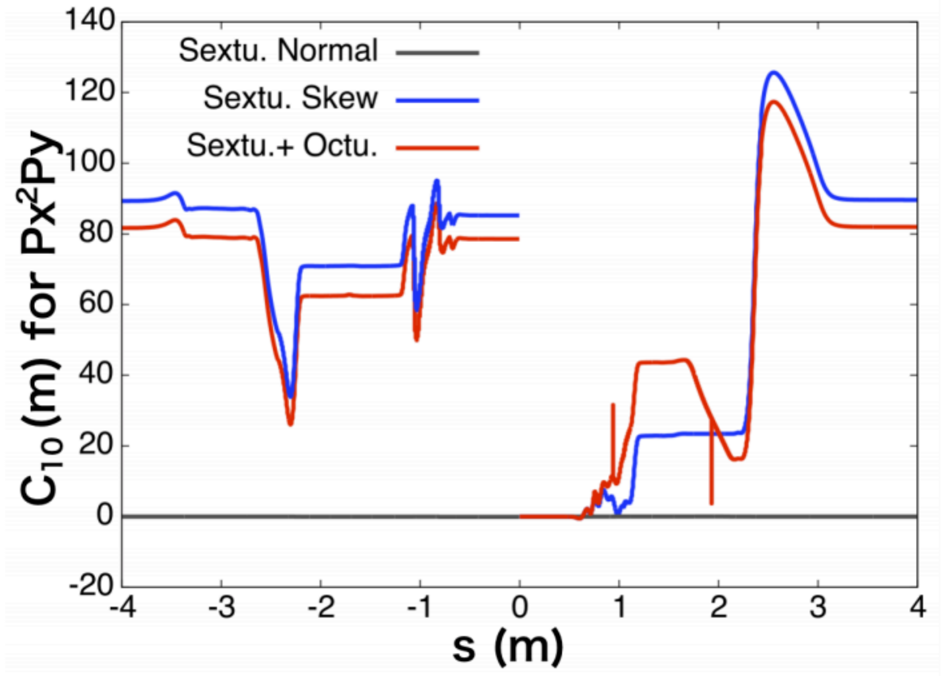


Figure 4: Coefficient of $P_X^2 P_Y$ caused by skew sextupole (SK_2) and octupole ($K_3 + SK_3$) fields.

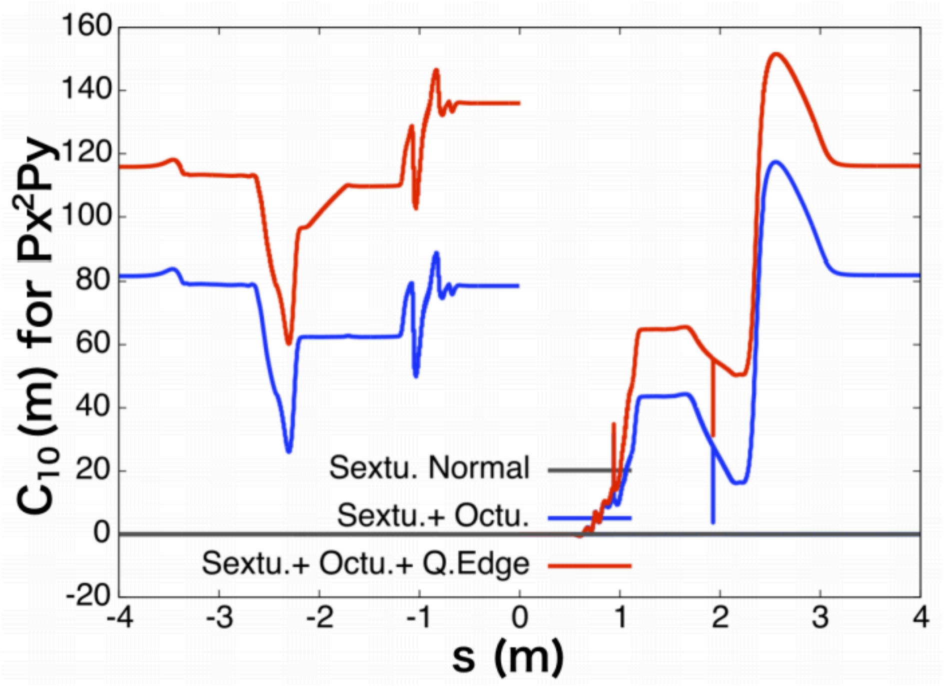


Figure 5: Coefficient of $P_X^2 P_Y$ for sextupole and octupole ($SK_2 + K_3 + SK_3$) and quadrupole hard-edge fringe ($SK_2 + K_3 + SK_3 + Q.edge$) fields.

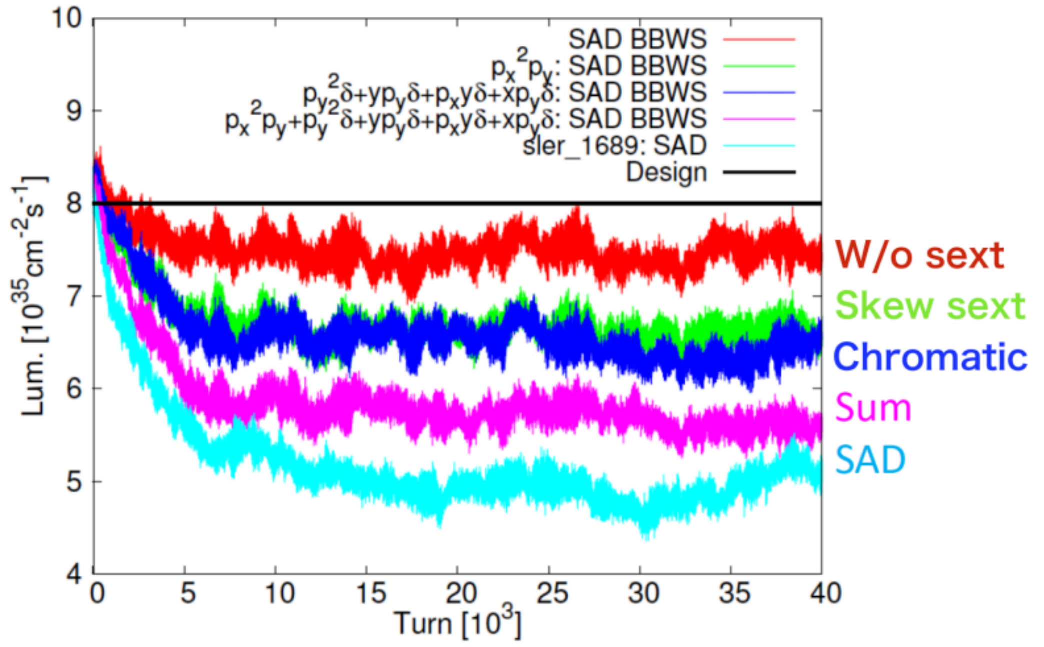
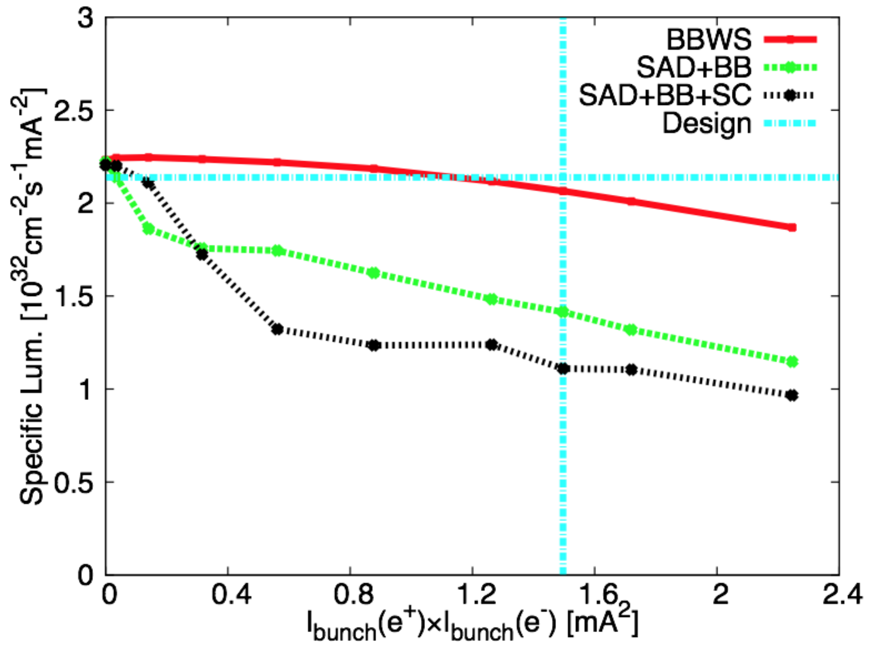
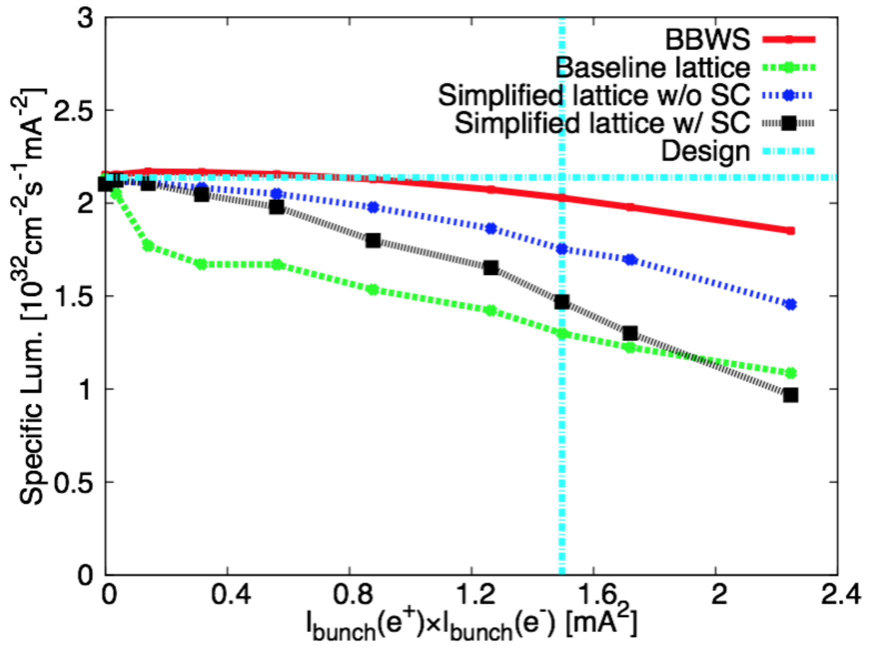


Figure 6: Luminosities for sextupole term (: $P_X^2 P_Y$), chromatic twiss, and SAD.





[8] 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 (cont'd)

- 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 [9].

Machine parameters of Phase-2 for beam-beam simulations

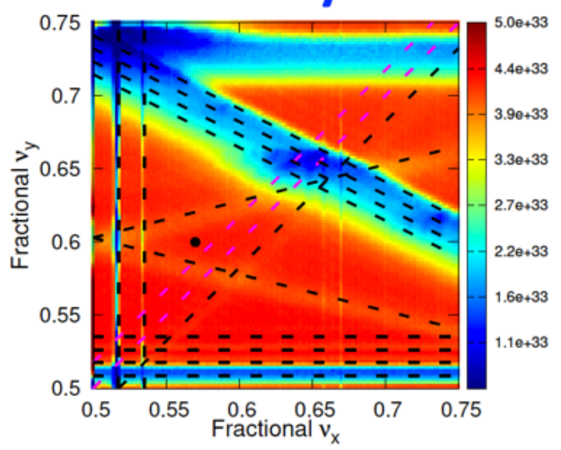
	200/6		200/4		100/4		100/2	
	HER	LER	HER	LER	HER	LER	HER	LER
E (GeV)	7.007	4	7.007	4	7.007	4	7.007	4
I_b (mA)	285	340	285	340	285	340	285	340
# bunch	789		789		789		789	
ε_x (nm)	4.7	2.0	4.7	2.0	4.5	1.9	4.5	1.9
ε_y (pm)	47	20	47	20	45	19	45	19
ε_z (μm)	3.7	4.5	3.7	4.5	3.4	3.5	3.4	3.6
β_x (mm)	200	200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

BBWS simulation

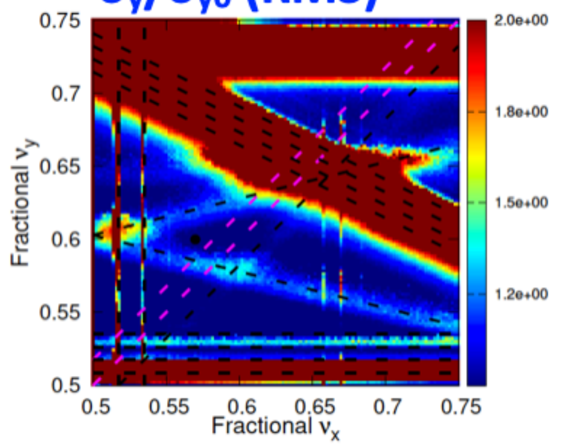
➤ Optics: HER 200/4 mm and LER 200/4 mm

- 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:

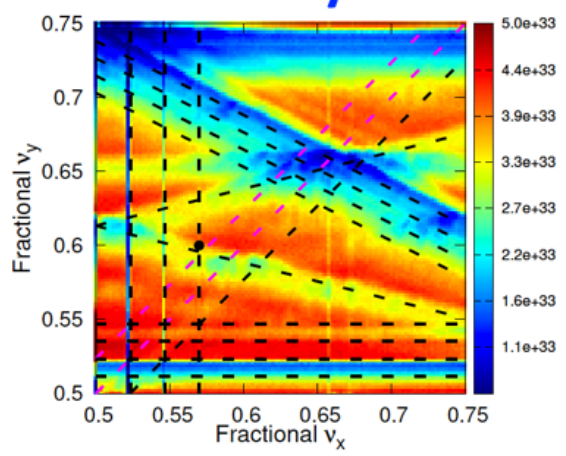
$$\nu_x - \nu_y + k\nu_s = N, \quad k = -1,0,1$$

BBWS simulation

➤ Optics: HER 200/4 mm and LER 200/4 mm

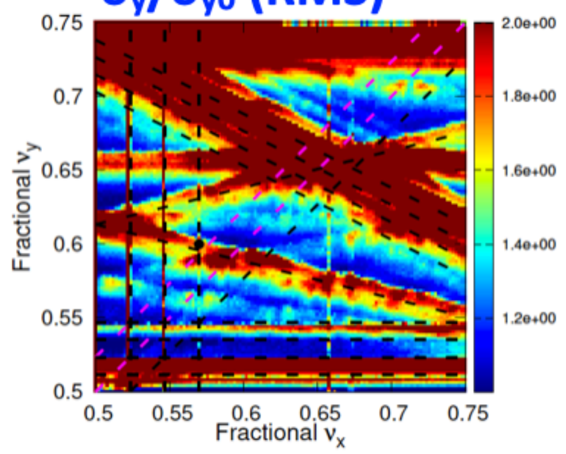
- Weak beam: HER: plots with normalization

Luminosity



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

σ_y/σ_{y0} (RMS)

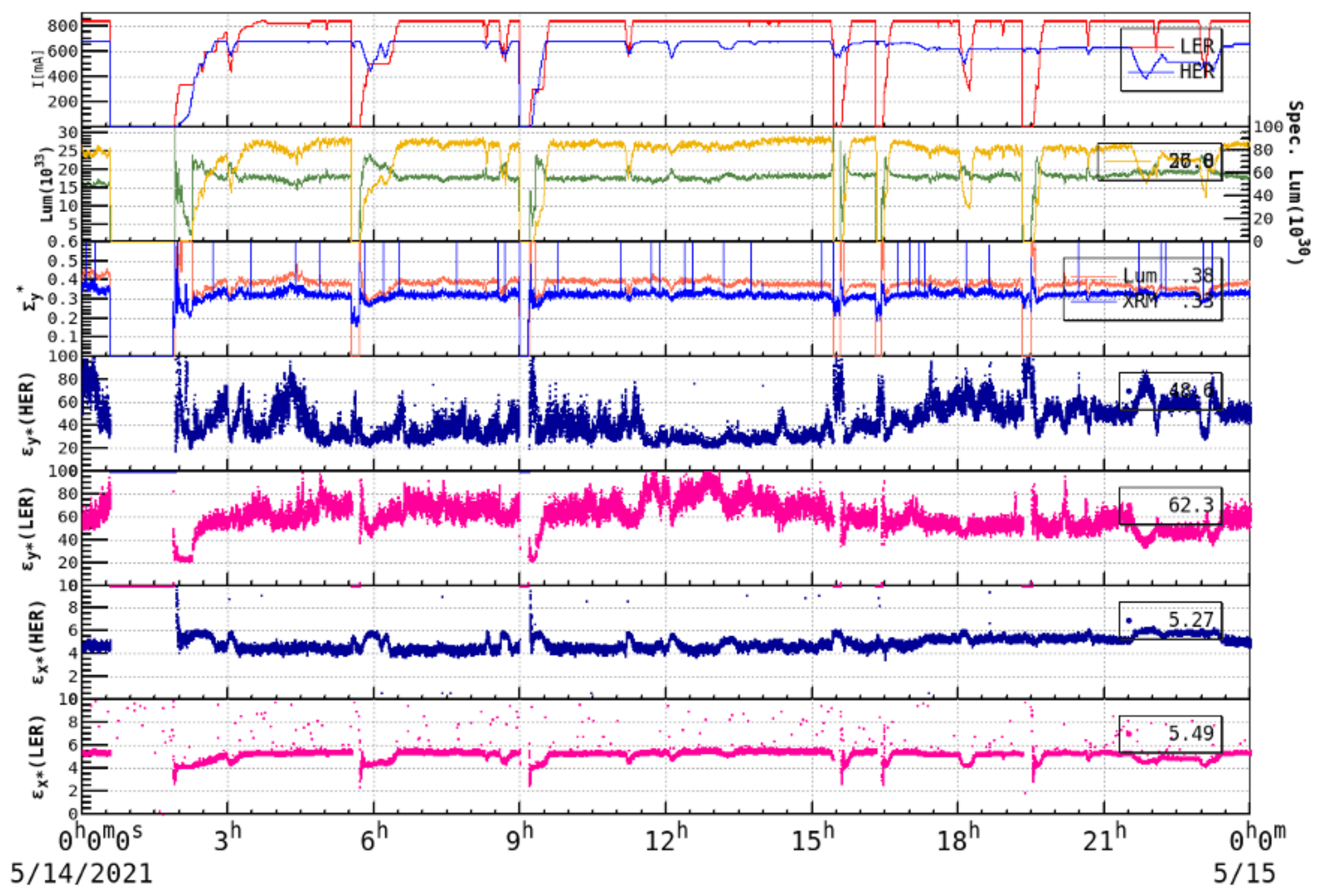


[9] D. Zhou , Weak-strong beam-beam simulations for SuperKEKB Phase-2, Talk presented at the SuperKEKB beam-beam performance meeting, KEK, Jun. 14, 2018.

Beam-beam simulations for SuperKEKB (cont'd)

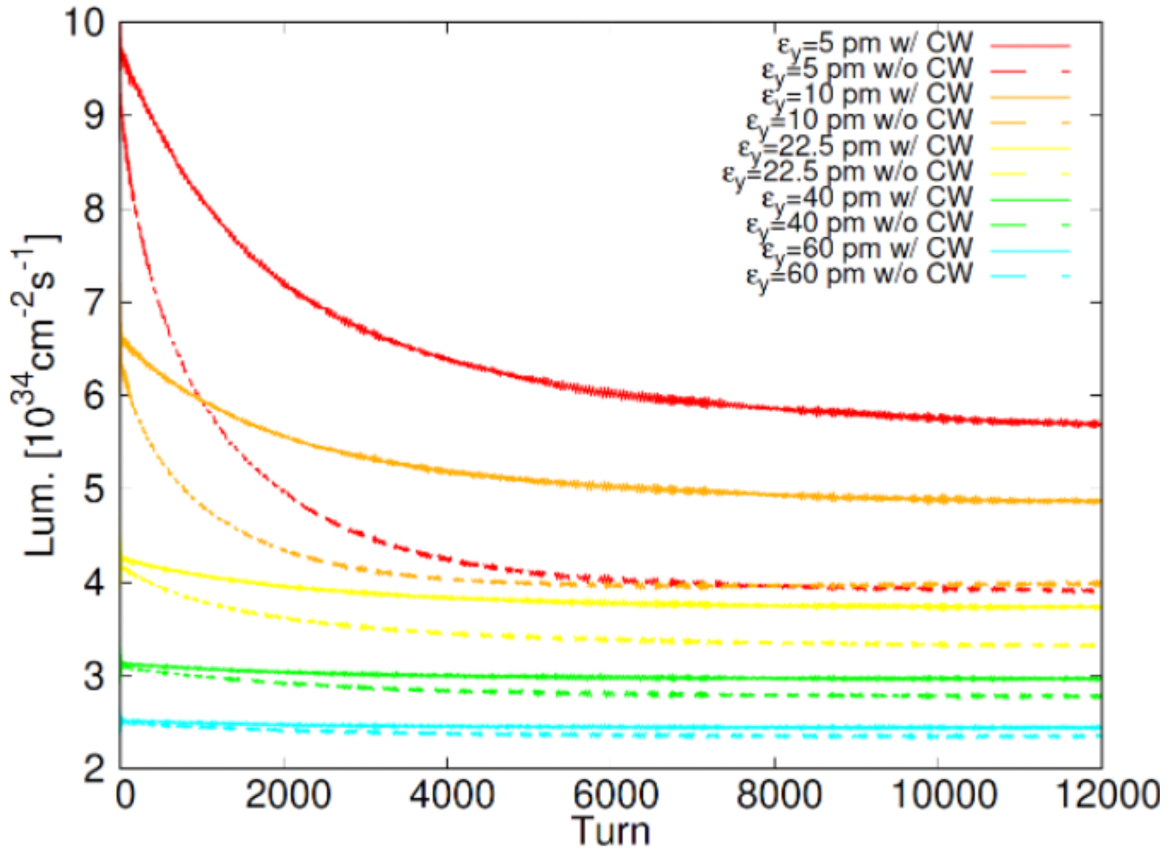
- Phase-3 commissioning with crab waist
  - Since 2020, crab waist was introduced and led to luminosity boost. Beam-beam simulations with crab waist were done to compare with experimental observations.
  - With single-beam ϵ_y of 22.5 pm, BBSS simulations predict lum. of ~3.75e34 $cm^{-2}s^{-1}$ without 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.
  - Weak blowup in ϵ_x (hint of BBHTI) was observed in the control room, but not well-confirmed.

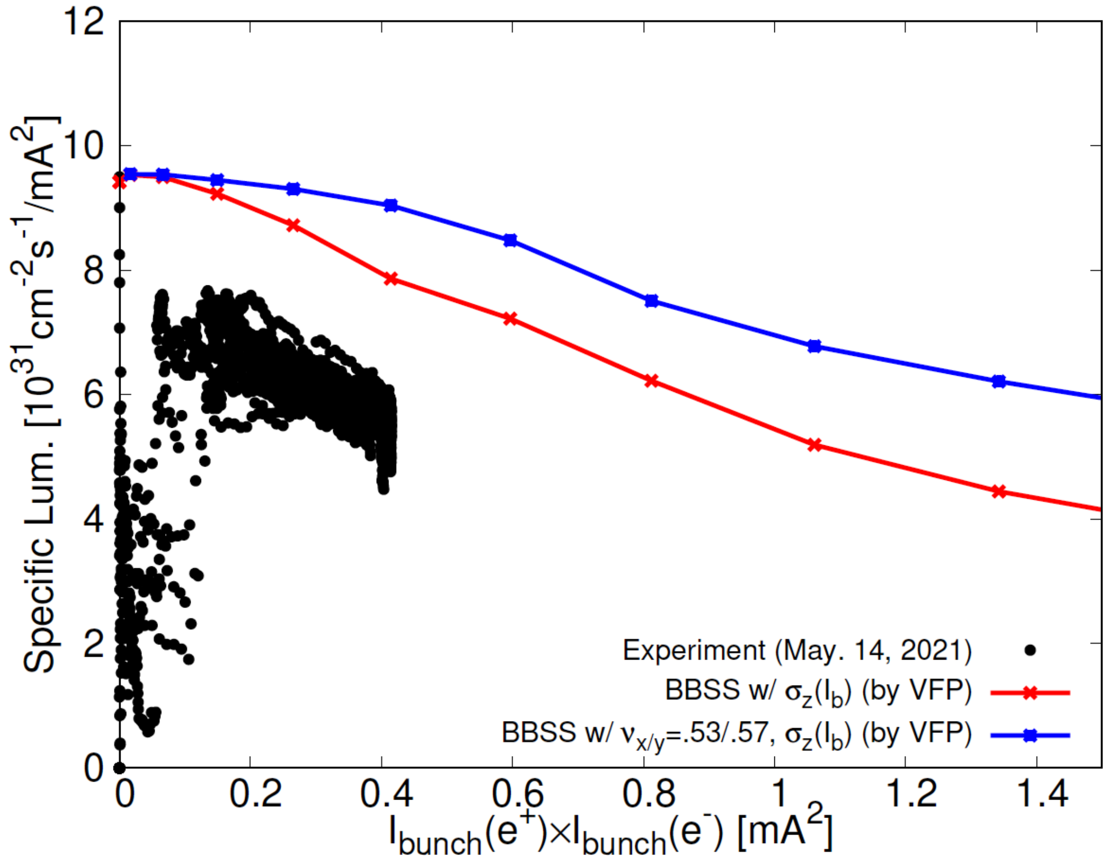
Luminosity history panel seen in SuperKEKB control room



Operation parameter set [11]

	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



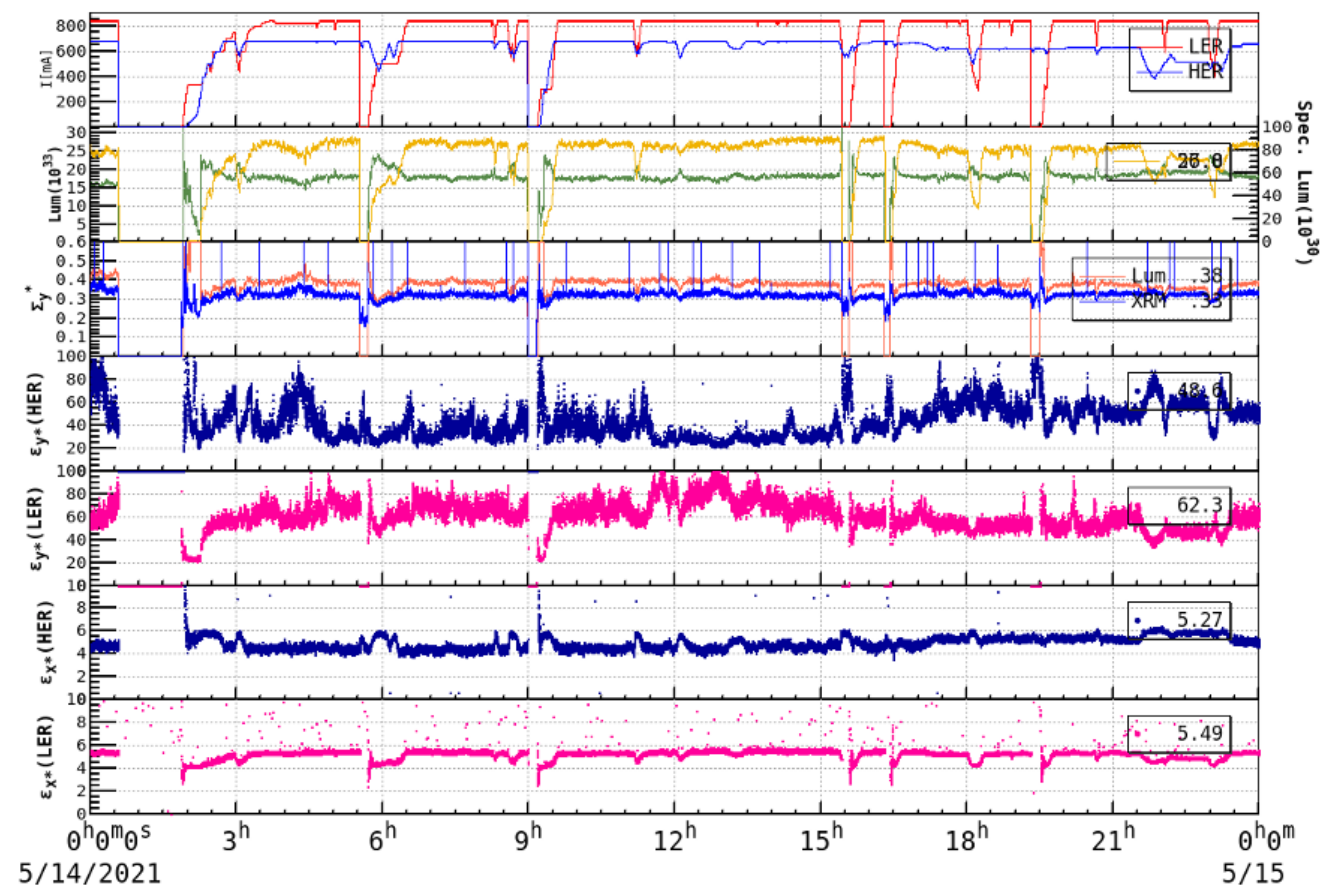


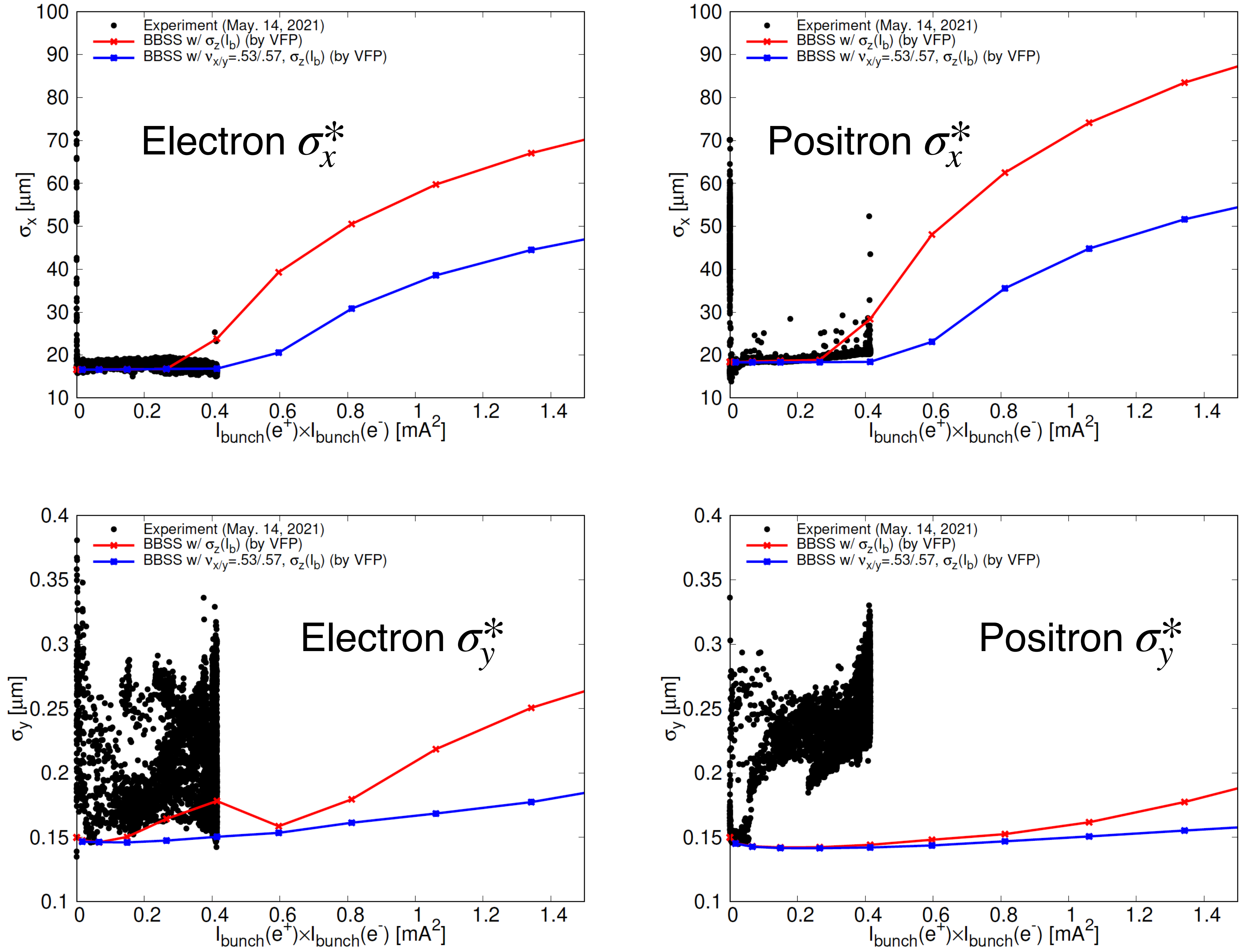
[11] D. Zhou, Beam dynamics issues: Comparisons of theories, simulations and experiments, Talk presented at the SuperKEKB 2021ab summary meeting, KEK, Jul. 29, 2021.

Beam-beam simulations for SuperKEKB (cont'd)

- 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 [11]

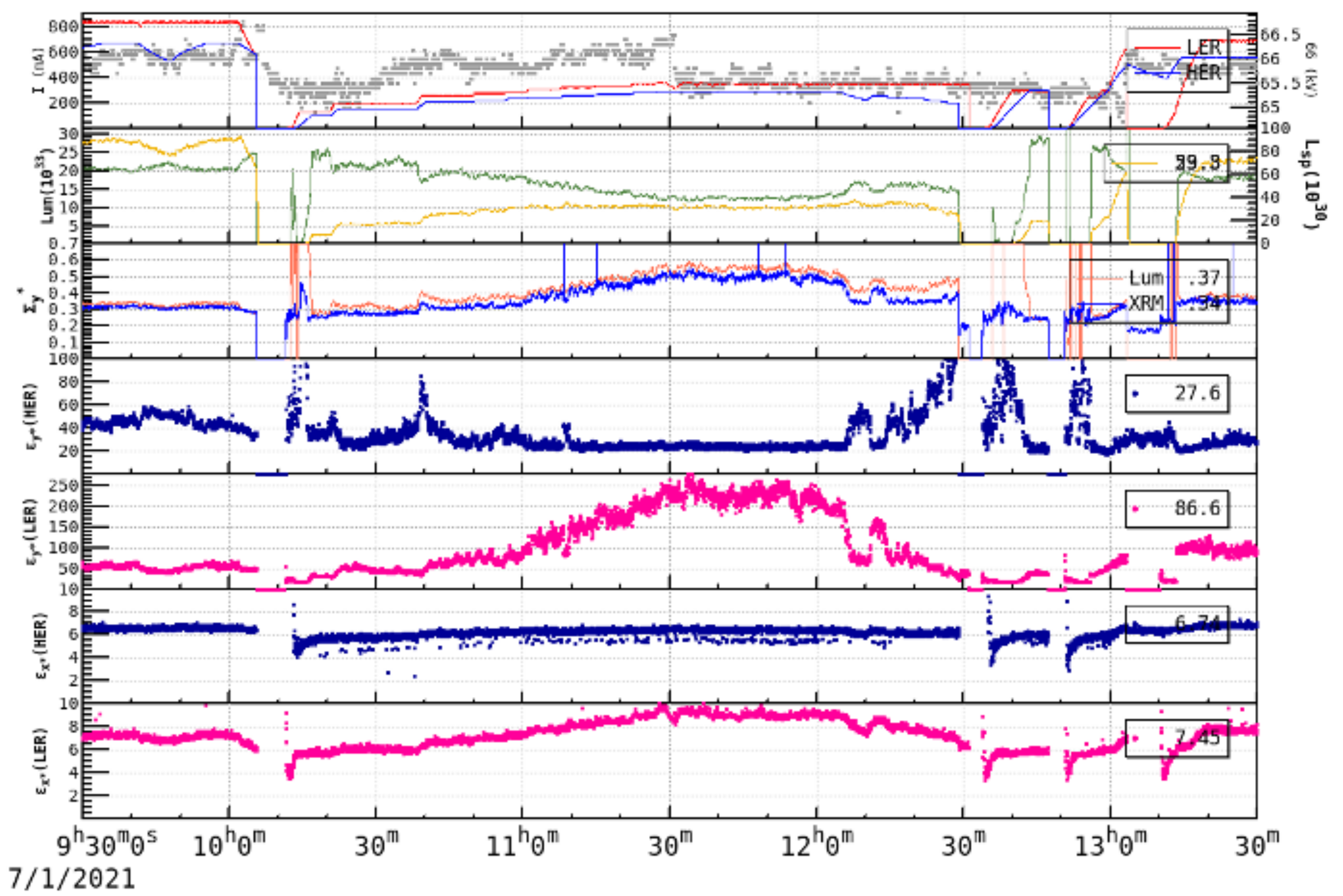
	2021.05.14		Comments
	HER	LER	
I_b (A)	0.68	0.84	
# bunch	1174		
ε_x (nm)	4.6	4.24	w/ IBS
ε_y (pm)	22.5	22.5	Estimated from XRM data
β_x (mm)	60	80	Calculated from lattice
β_y (mm)	1	1	Calculated from lattice
σ_z (mm)	6	6	w/ bunch lengthening by impedance
σ_y (μm)	0.15	0.15	Observed from XRM
ν_x	45.52989	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

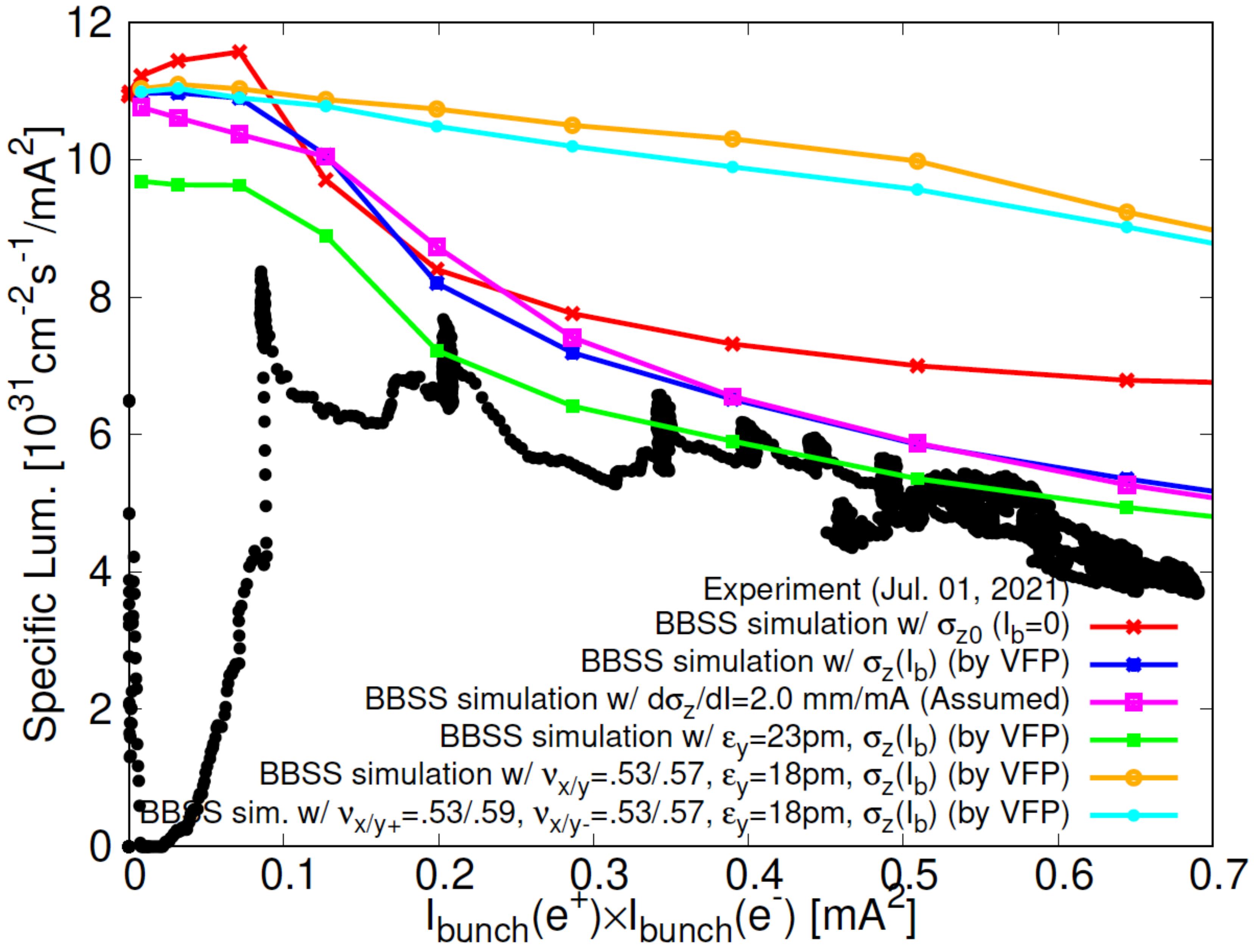
[11] D. Zhou, Beam dynamics issues: Comparisons of theories, simulations and experiments, Talk presented at the SuperKEKB 2021ab summary meeting, KEK, Jul. 29, 2021.

Beam-beam simulations for SuperKEKB (cont'd)

- 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. But this agreement was accidental (see next page).

Luminosity history panel seen in SuperKEKB control room





Operation parameter sets [11]

	2021.07.01 HER	2021.07.01 LER	Comments
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

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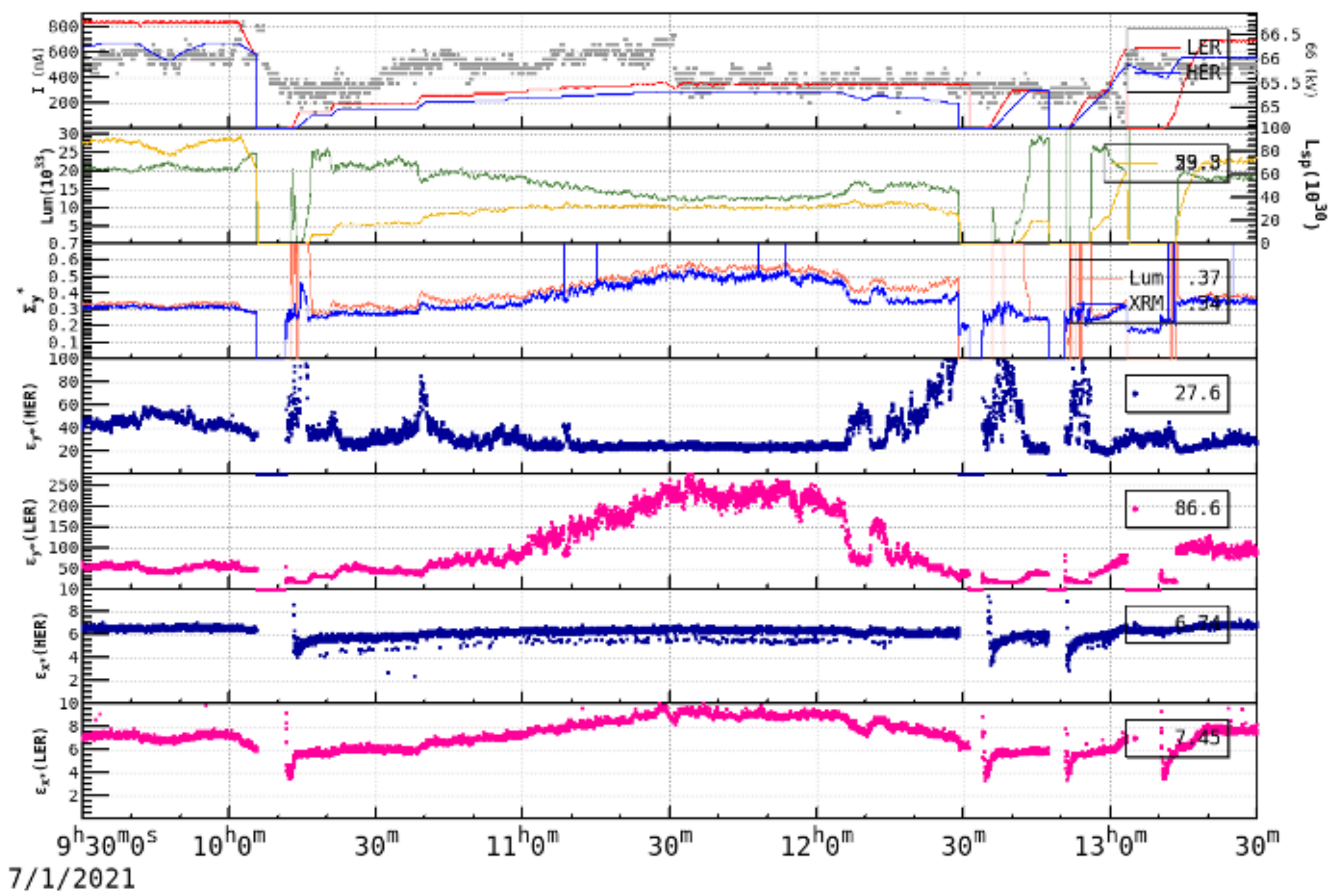
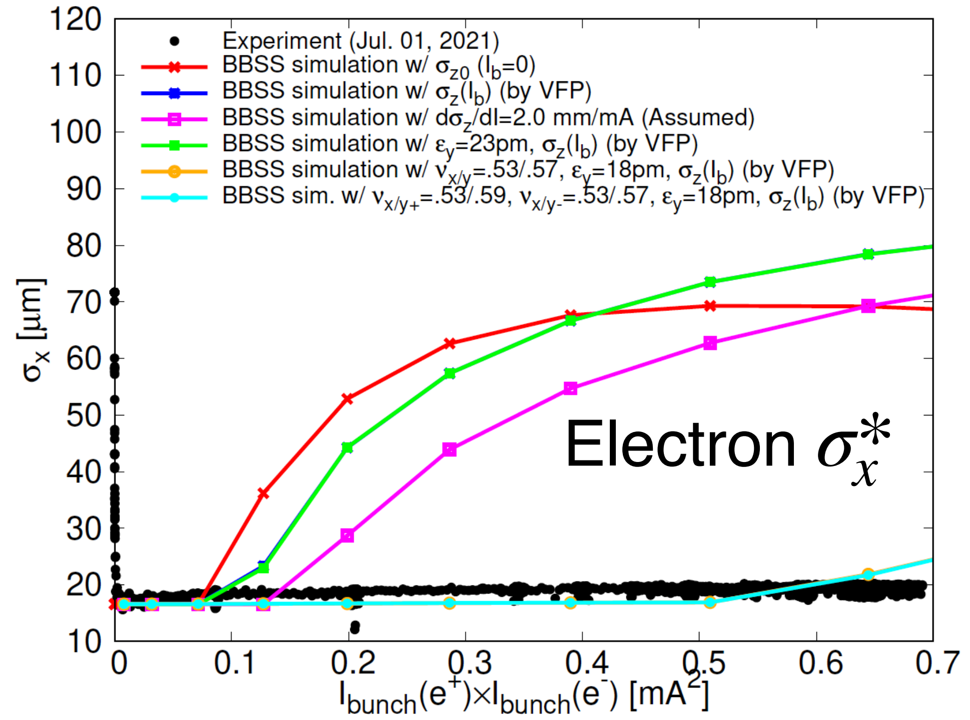
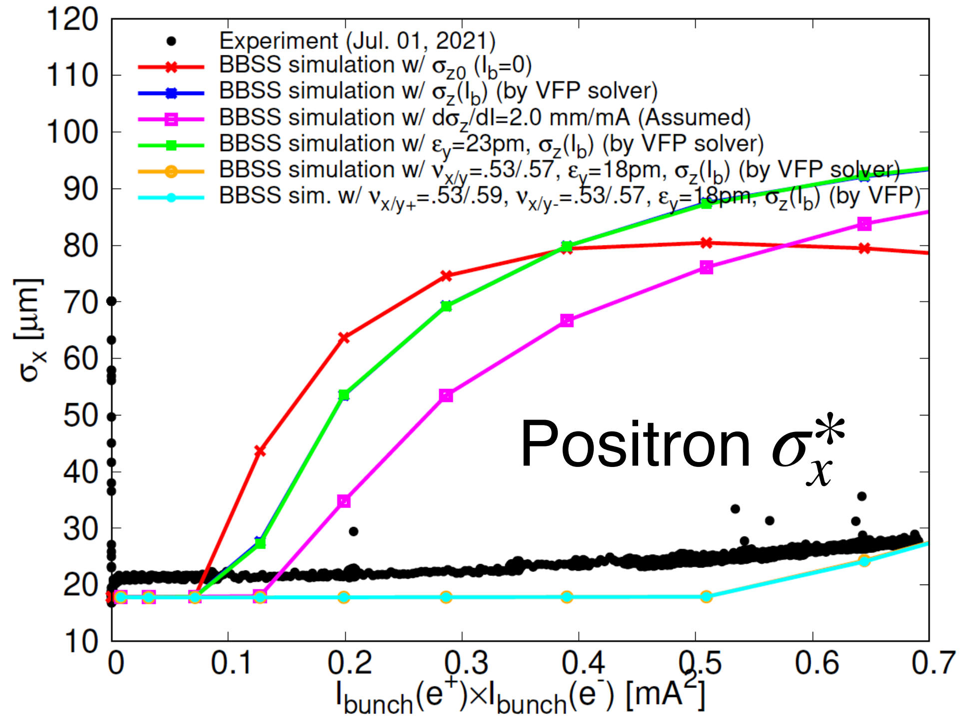
Beam-beam simulations for SuperKEKB (cont’d)

- Phase-3 commissioning with crab waist
  - BBSS simulations showed strong BBHTI, but not seen in experimental observations.
  - Experiment phenomena were 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







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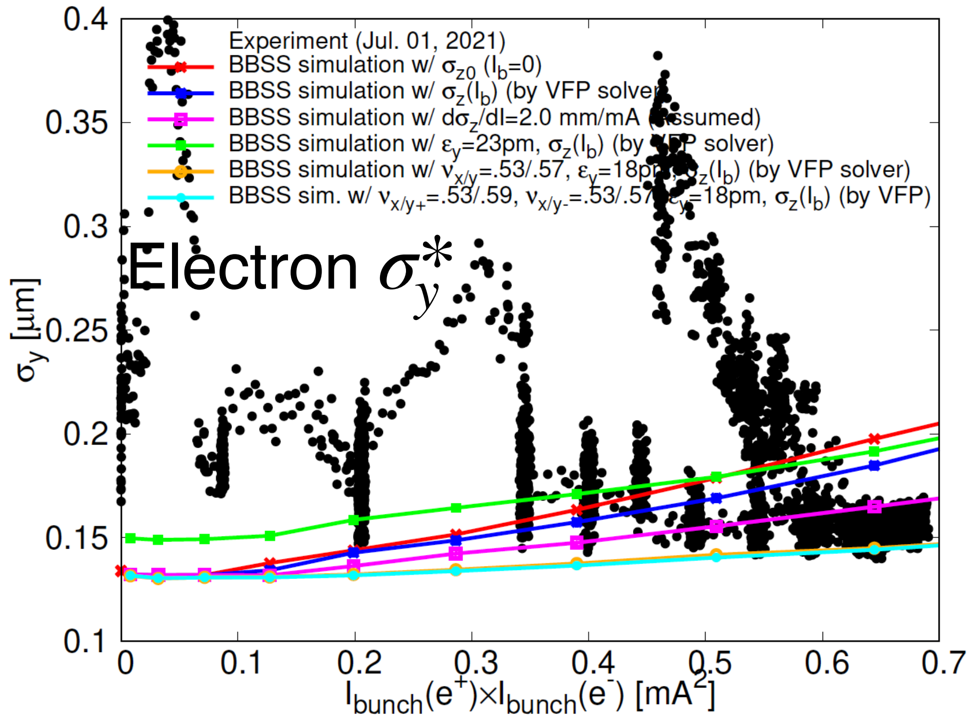

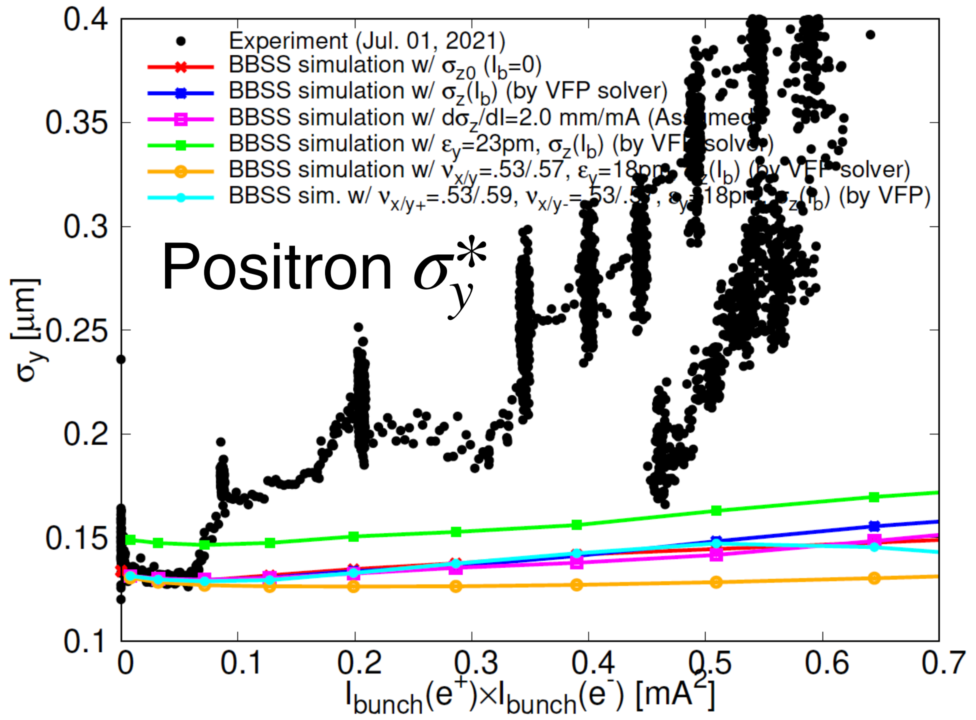

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Summary and outlook

- Beam-beam simulations for KEKB
  - Chromatic effects were found to be important.
- 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.
- Outlook
  - For SuperKEKB, strong-strong beam-beam simulations are essential in understanding the current machine performance and also in guiding the future commissioning.
  - Other beam dynamics might strongly interplay with beam-beam: machine imperfections, longitudinal and transverse wake fields, space charge, etc.
  - An important task is improving the strong-strong model to simulate the interplay of beam-beam and other beam dynamics.