Beam-beam simulations for KEKB and SuperKEKB

Demin Zhou

Accelerator theory group, Accelerator laboratory, KEK

Acknowledgements

K. Ohmi, K. Oide, D. Shatilov, M. Blaskiewicz, Y. Luo,
and KEKB/SuperKEKB team

EIC Accelerator Partnership Workshop, Oct. 27, 2021

Outline

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

Brief overview of strategy for beam-beam simulations

- Weak-strong model + simple one-turn map: BBWS code [1]
  - 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.

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

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

- Weak-strong model + full lattice: SAD code [2]
  - 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 perturbative maps (such as crab waist, wake fields, artificial SR damping/excitation, etc.); …

Beam-beam element in SAD code:

```
;
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)
;
```

- Strong-strong model + simple one-turn map: BBSS code [1]
  - Both beams 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 a full lattice in SS simulations.

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

Beam-beam simulations with chromatic effects for KEKB

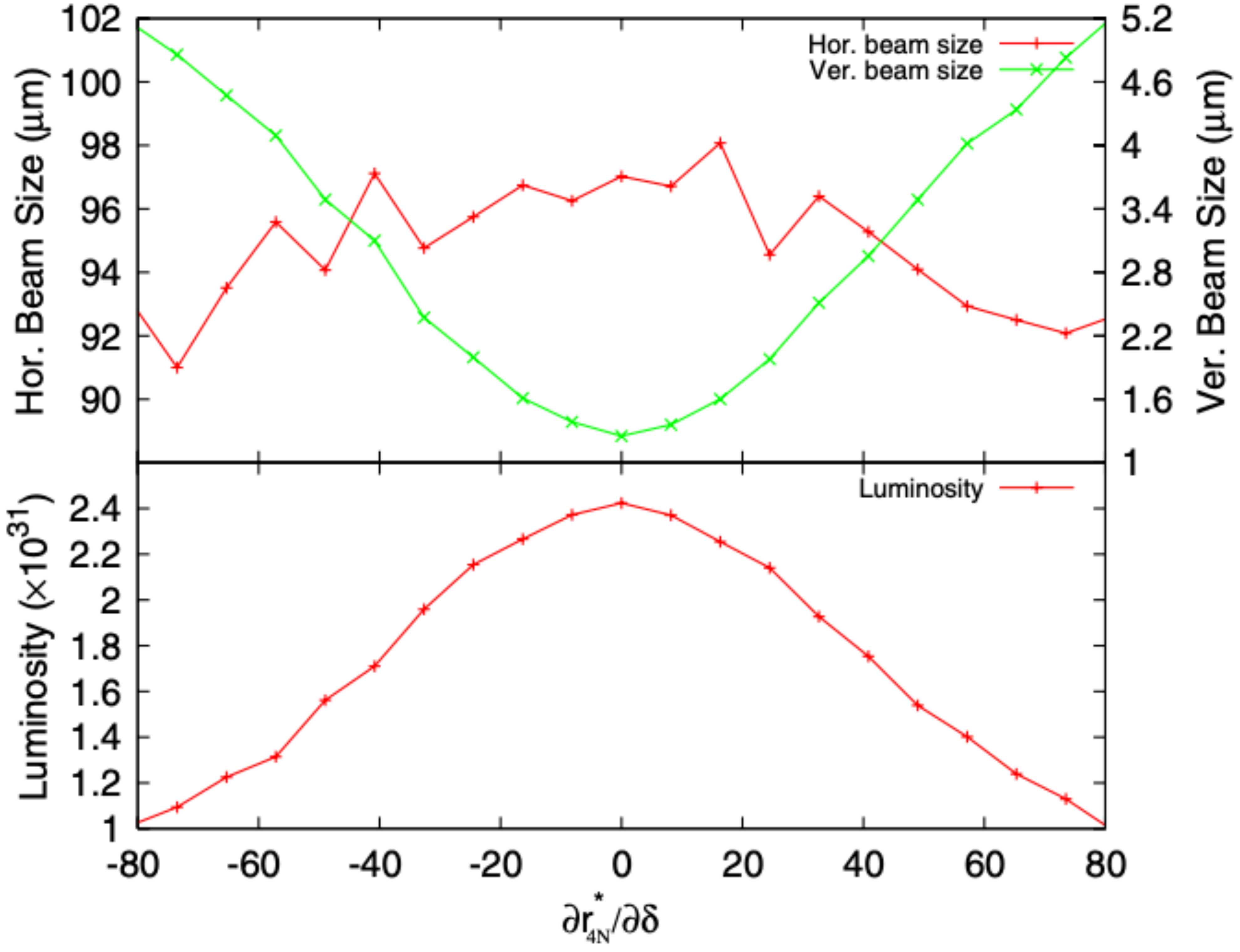
- Model of chromatic effects [3,4]
  - Twiss parameters expressed in Taylor series.
  - Chromaticities of Twiss parameters were estimated using lattice with error seeds and also measured with beams.
  - Symplectic maps for chromatic effects reconstructed and implemented into BBWS and BBSS.
- Simulations
  - BBWS: Fast scans of chromatic tunes, alpha/beta functions, dispersions, and couplings (to compare the relevant IP tuning knobs in the control room).
  - Findings: Chromatic couplings at IP causes remarkable luminosity loss at KEKB.

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

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

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

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

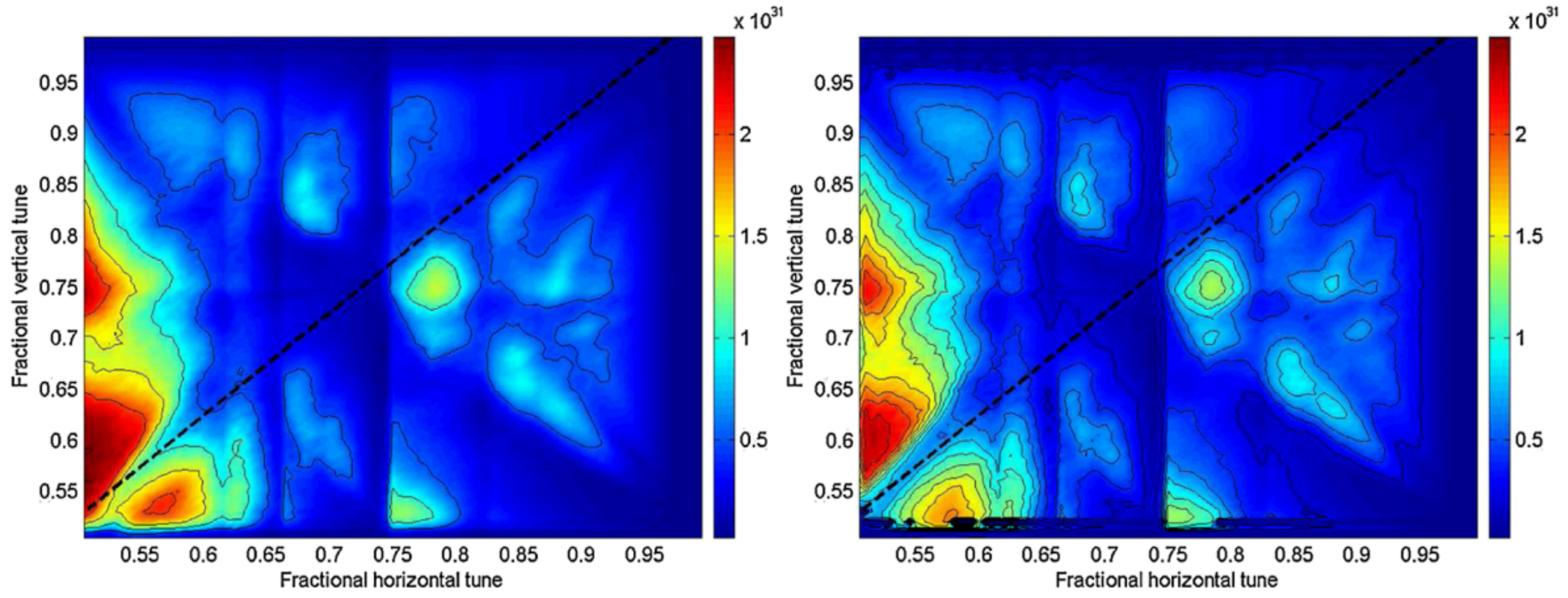


[3] D. Zhou et al., "Simulations of beam-beam effect in the presence of general chromaticity", Phys. Rev. ST Accel. Beams 13, 021001 (2010).

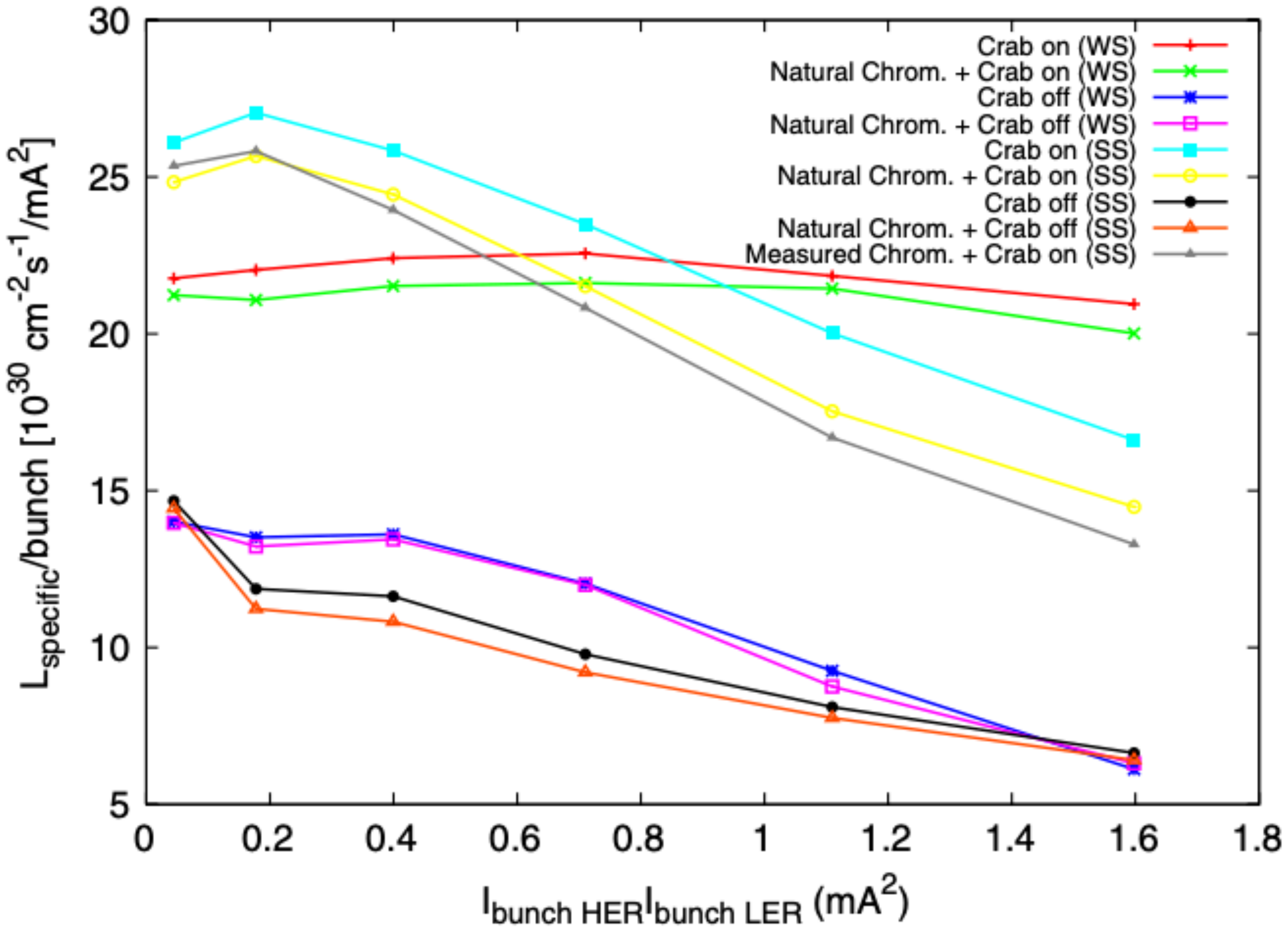
[4] Y. Seimiya et al., "Symplectic Expression for Chromatic Aberrations", Prog. Theor. Phys. (2012) 127 (6): 1099-1119.

Beam-beam simulations with chromatic effects for KEKB (cont'd)

- Simulations (cont'd)
  - BBWS: Tune survey of chromatic effects.
  - BBSS: Simulation of luminosity performance.
  - Findings: Chromatic couplings at IP causes remarkable luminosity loss at KEKB.



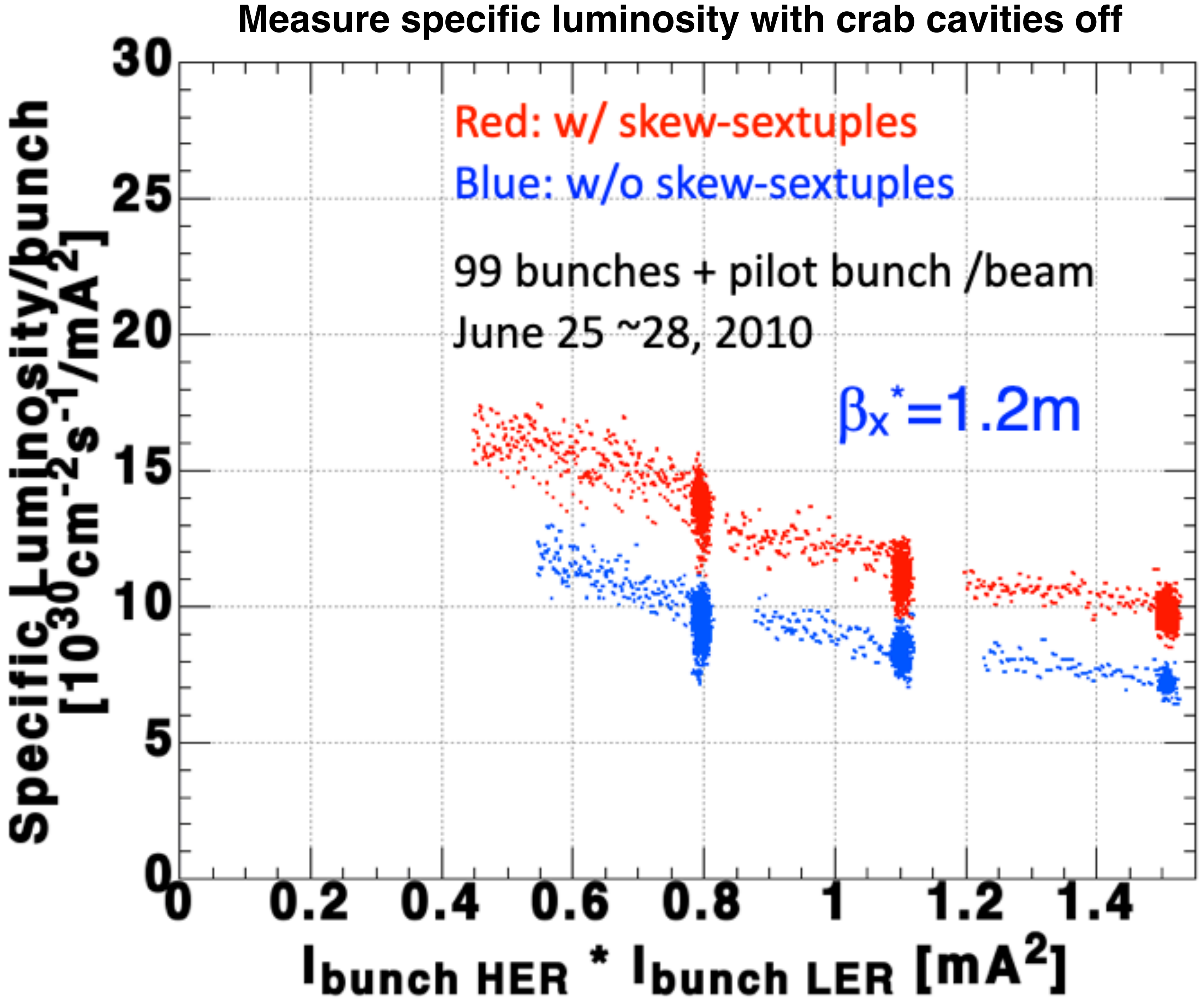
Luminosity survey w/o (left) and w/ (right) chromatic effects



WS and SS simulations w/ and w/o chromatic effects and crab cavities for KEKB

Beam-beam simulations with chromatic effects for KEKB (cont'd)

- The chromatic couplings at IP were also measured, and then 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 of KEKB.



Courtesy of Y. Funakoshi [6]

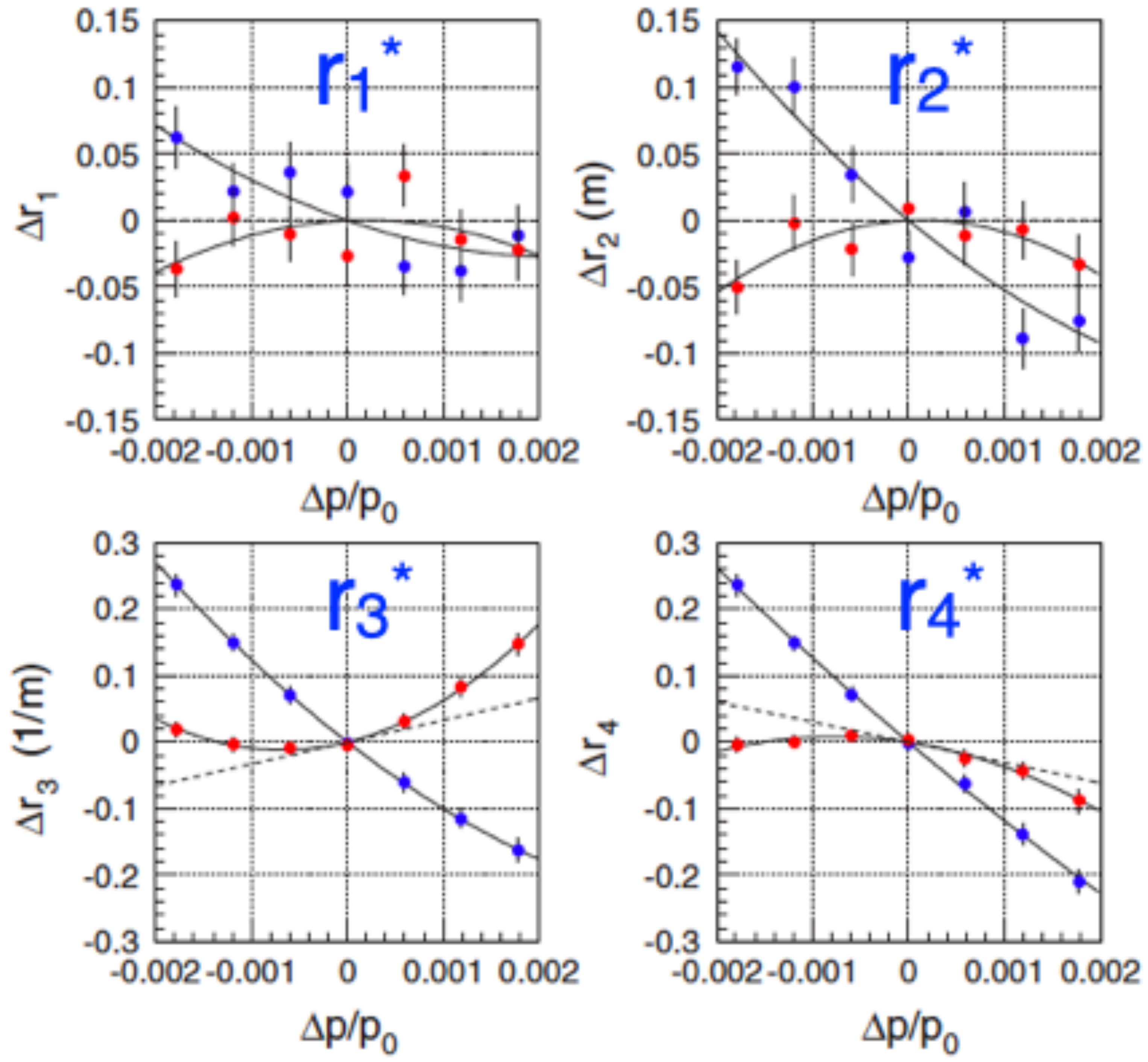


FIG. 4. (Color) Measured chromatic X-Y coupling at IP in LER. The blue plots indicate those before and the red plots indicate those after the skew sextupole correction. The dashed line indicates the natural chromatic X-Y coupling estimated using the model lattice by SAD.

Courtesy of Y. Ohnishi [5]

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

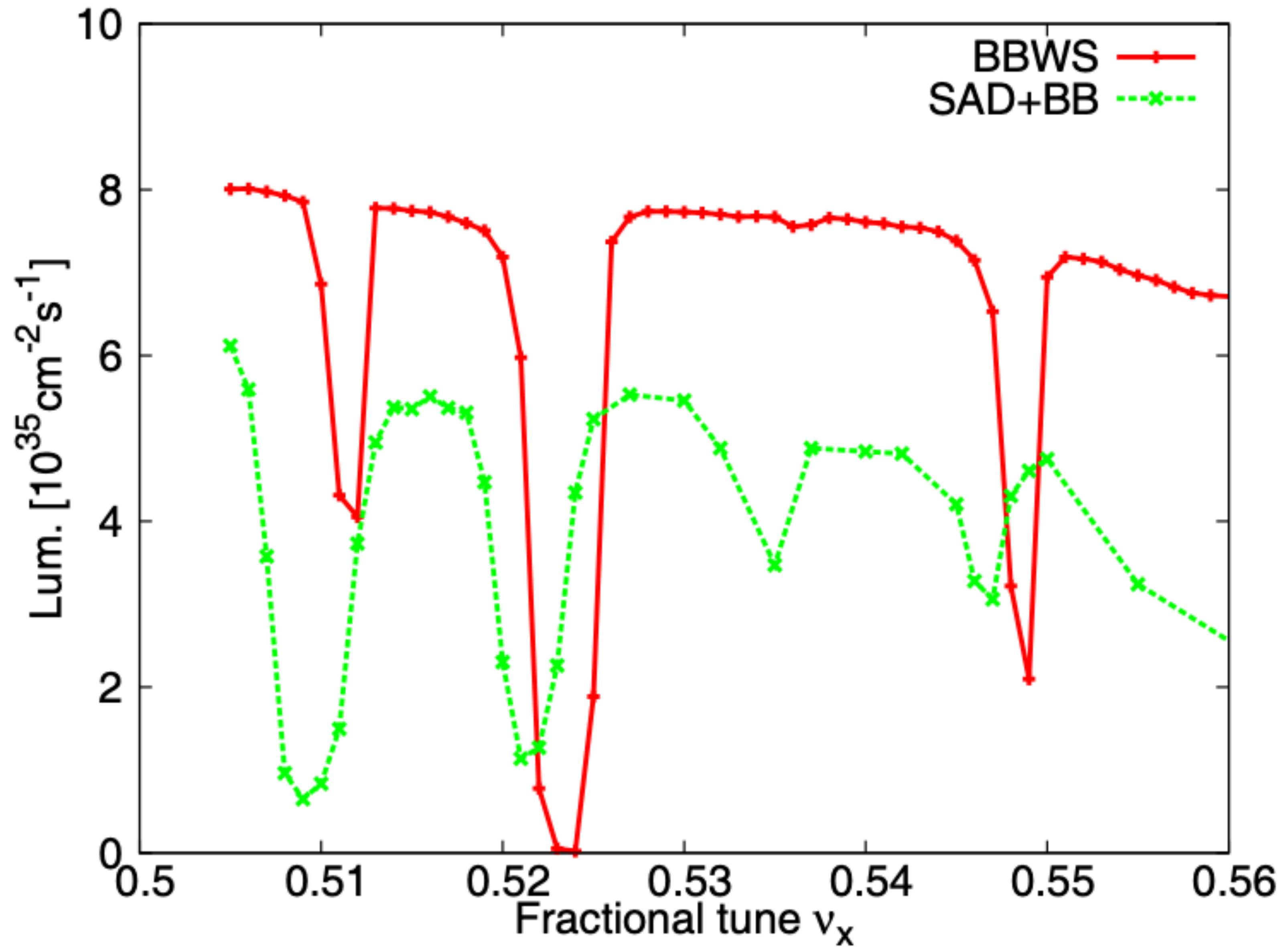
[6] Y. Funakoshi et al., WEOAMH02, IPAC'10 (2010).

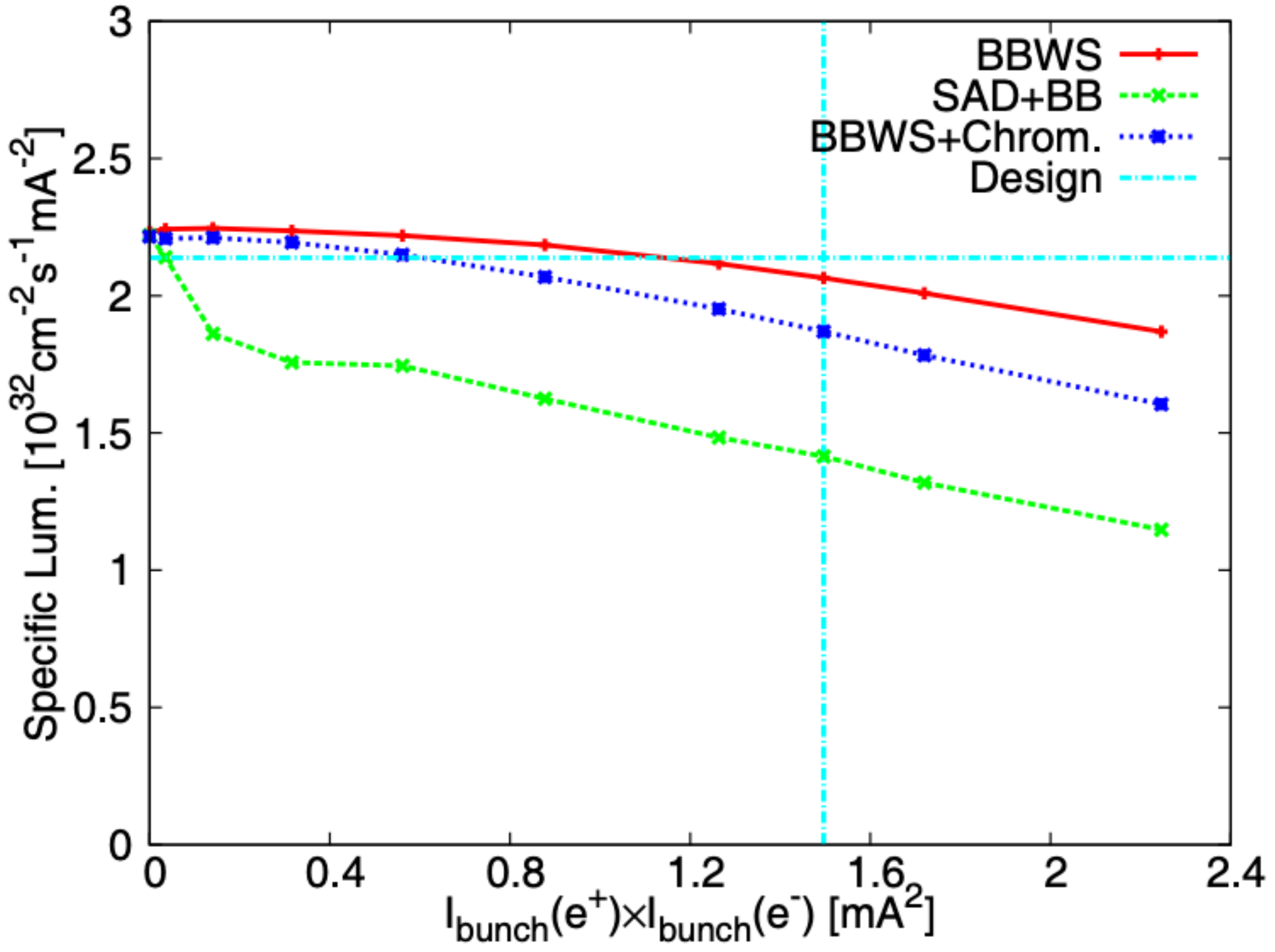
Beam-beam simulations for SuperKEKB

- Interplay of beam-beam and lattice nonlinearity with final design configuration ($\beta^*_{y\pm}$=0.27/0.3 mm) [7]
  - Cause direct luminosity loss due to very nonlinear IR.
  - Strongly affect dynamic aperture and Touschek lifetime.
  - In addition to chromatic effects, other nonlinear effects were found 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





BBWS simulations for LER

[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.

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 be important in addition to chromatic couplings.

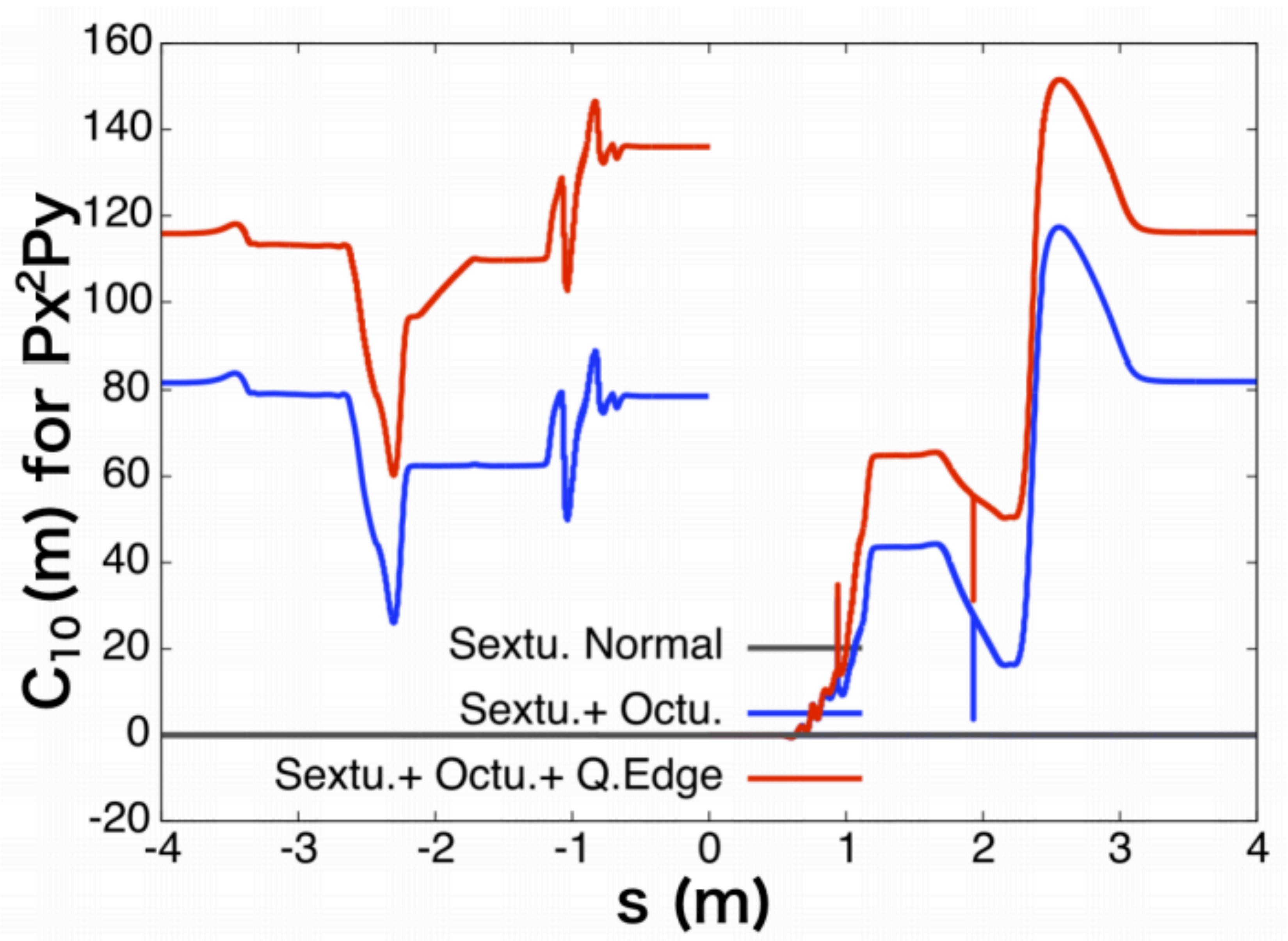


Figure 5: Coefficient of $P_X^2 P_Y$ for sextupole and octupole ($SK_2 + K_3 + SK_3$) and quadrupole hard-edge fringe ($SK_2 + K_3 + SK_3 + Q.edge$) fields.

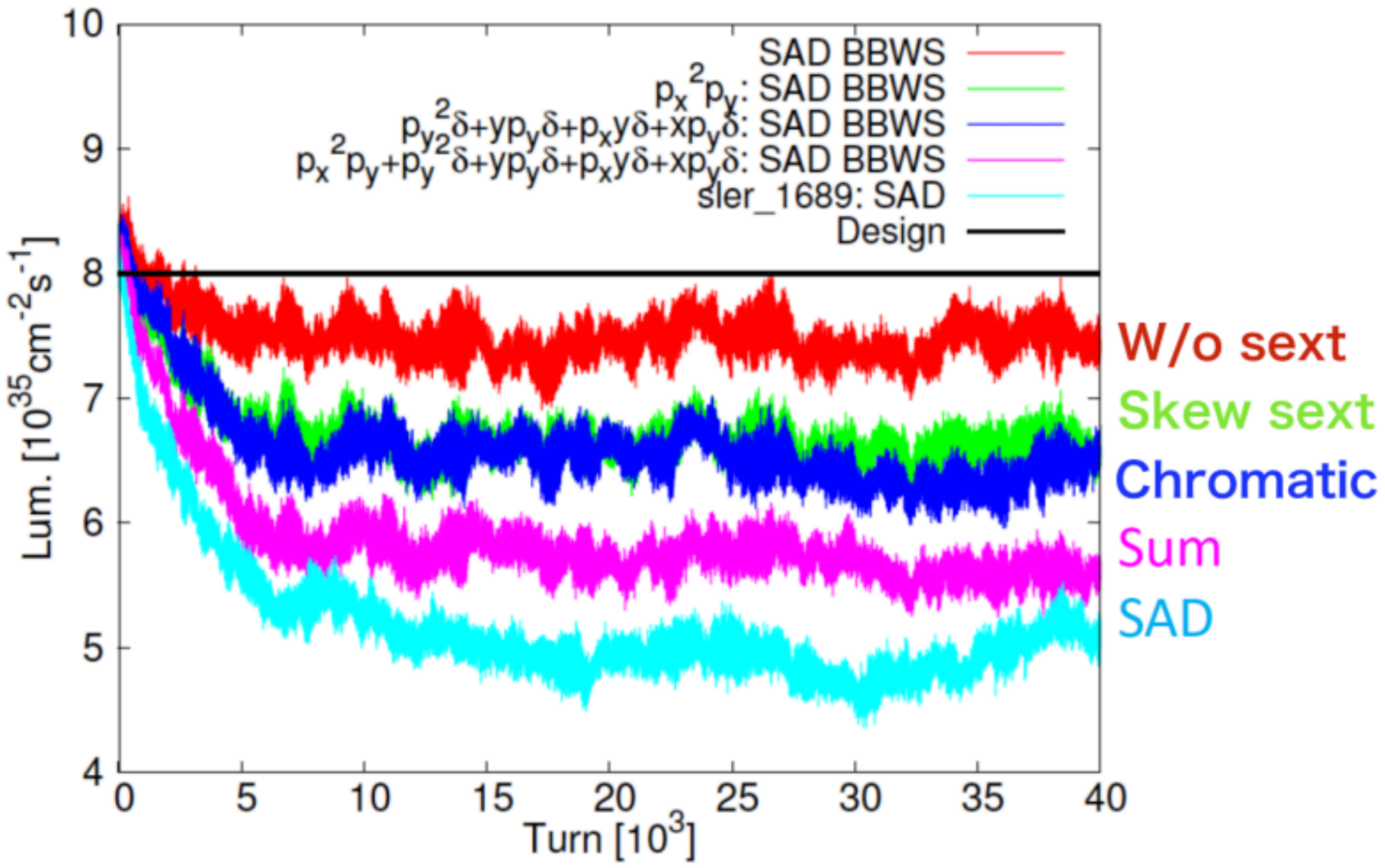
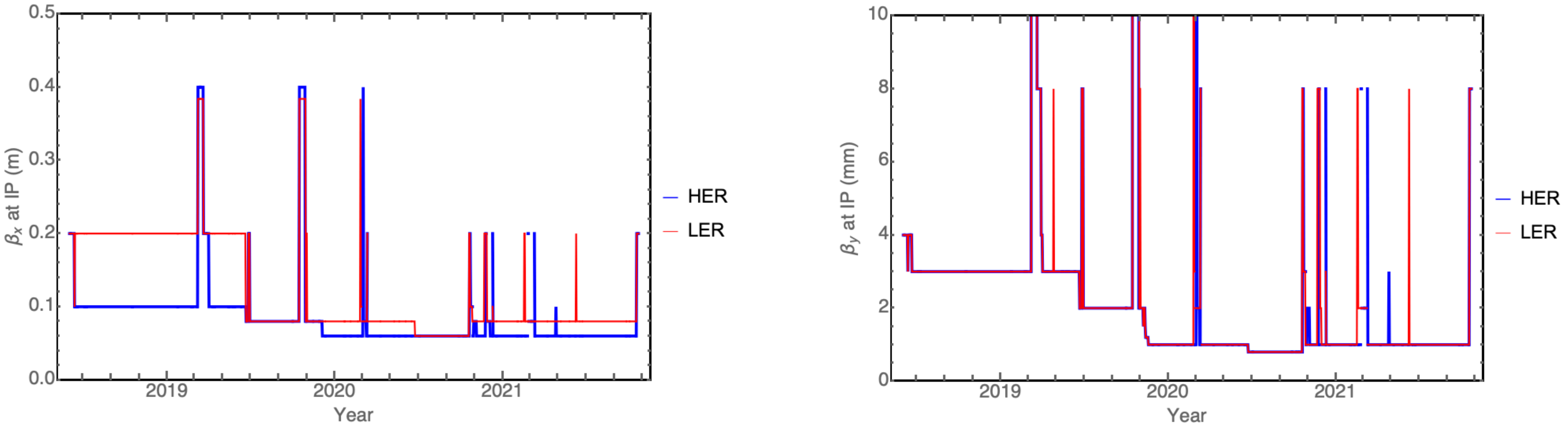


Figure 6: Luminosities for sextupole term (: $P_X^2 P_Y$), chromatic twiss, and SAD.

[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 and Phase-3
  - Phase-2 started in March 2018 with Belle2 detector.
  - Phase-3 started in March 2019 with VXD detector.
  - Crab waist (FCC-ee scheme) was introduced to SuperKEKB since March 2020.
  - Since Phase-2, $\beta^*_{x,y}$ were gradually squeezed as machine tuning improved.

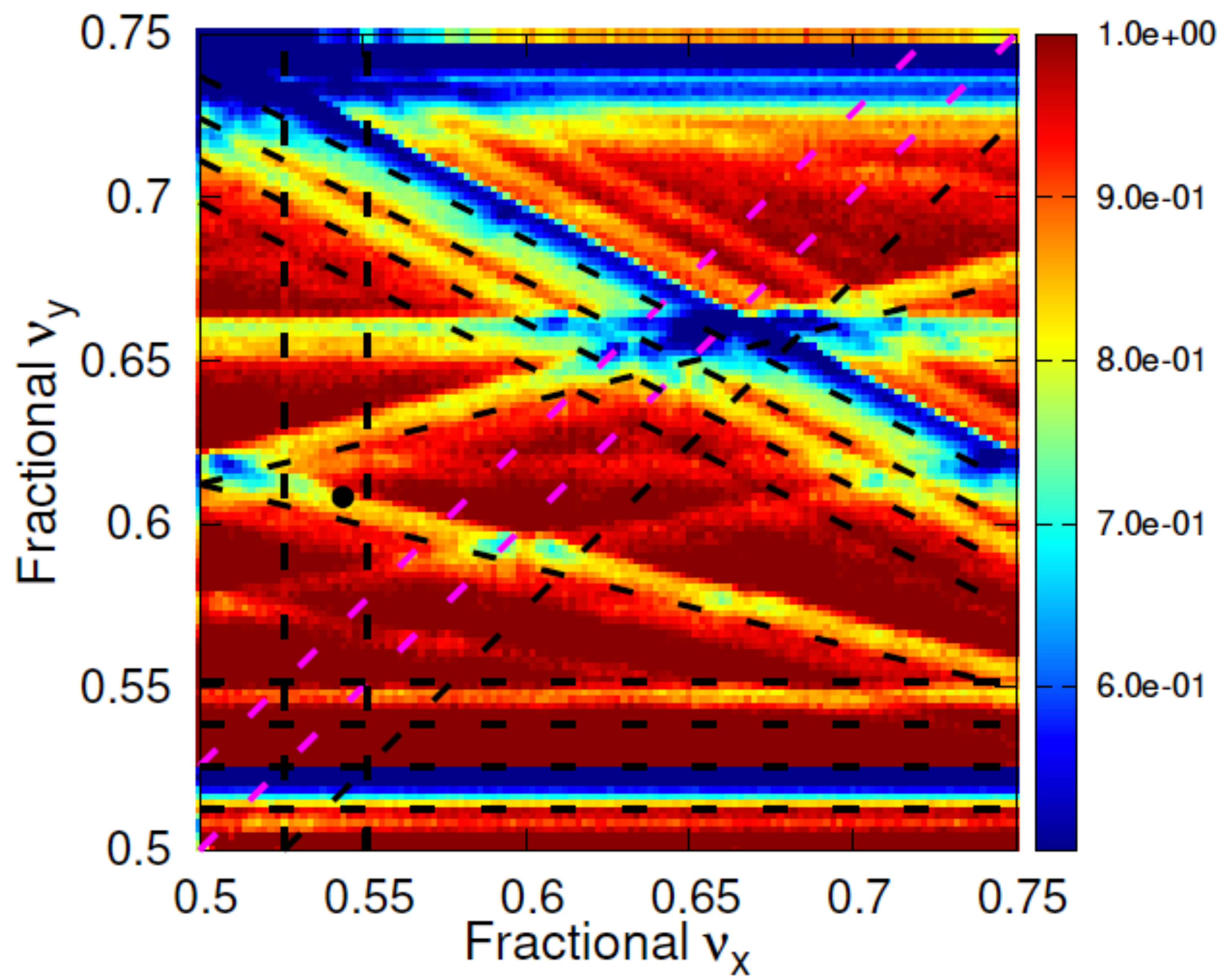


History of $\beta^*_{x,y}$ at SuperKEKB since June 2019

Beam-beam simulations for SuperKEKB (cont'd)

- Beam-beam simulations with machine parameters of Phase-2 and early Phase-3
  - Machine observations without crab waist: 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 with observed beam parameters showed that the beam-beam resonances of $\pm\nu_x + 4\nu_y + \alpha = N$ (they appear without crab waist) could be important [9].
  - Collision with small ϵ_y would be very challenging: vertical emittance blowup seemed unavoidable.

	2019.03.30		2019.04.02		2019.07.01	
	HER	LER	HER	LER	HER	LER
I_b (A)	0.21	0.26	0.17	0.22	0.8	0.8
# bunch	789		789		1576	
ε_x (nm)	4.728	1.731	4.537	1.641	4.49	1.93
ε_y (pm)	122.5	40	53.33	13.33	16.2	6.05
β_x (mm)	200	200	100	200	80	80
β_y (mm)	4	4	3	3	2	2
σ_z (mm)	6	6	6	6	5.5	5.2
ν_x	45.564	44.571	45.5439	44.5568	45.53	44.542
ν_y	43.603	46.610	43.6082	46.618	43.583	46.605
ν_s	0.0256	0.0219	0.02576	0.02205	0.02717	0.02349

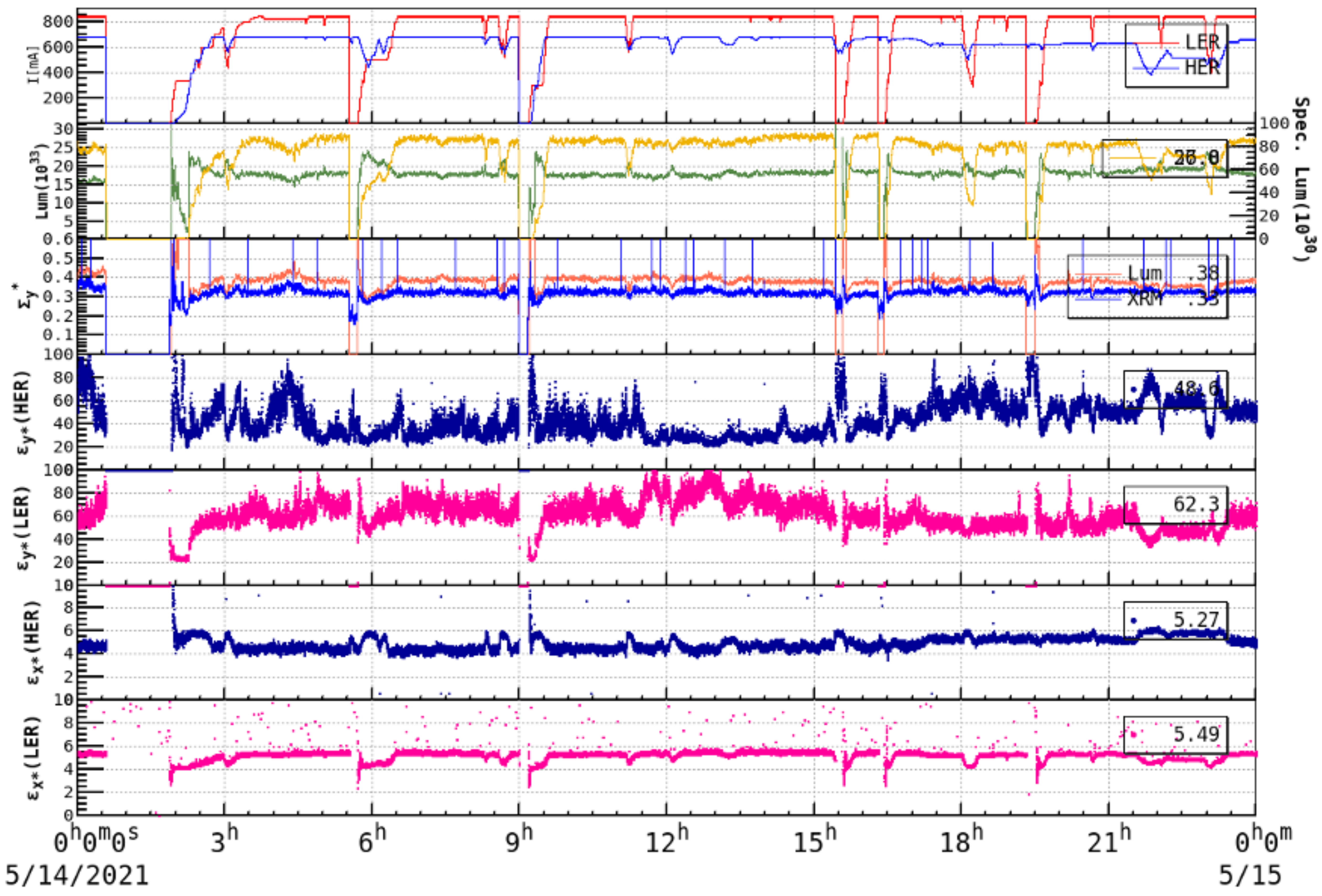


Luminosity tune scan: BBWS simulations with weak e- beam using parameter set of 2019.04.02

[9] D. Zhou, Talk presented at the 1st SuperKEKB Beam Dynamics Mini-Workshop, KEK, Jul. 17, 2019 (https://kds.kek.jp/event/31793/).

Beam-beam simulations for SuperKEKB (cont'd)

- Beam-beam simulations with machine parameters of Phase-3 including crab waist
  - Crab waist suppresses beam-beam resonances but vertical blowup still exists.



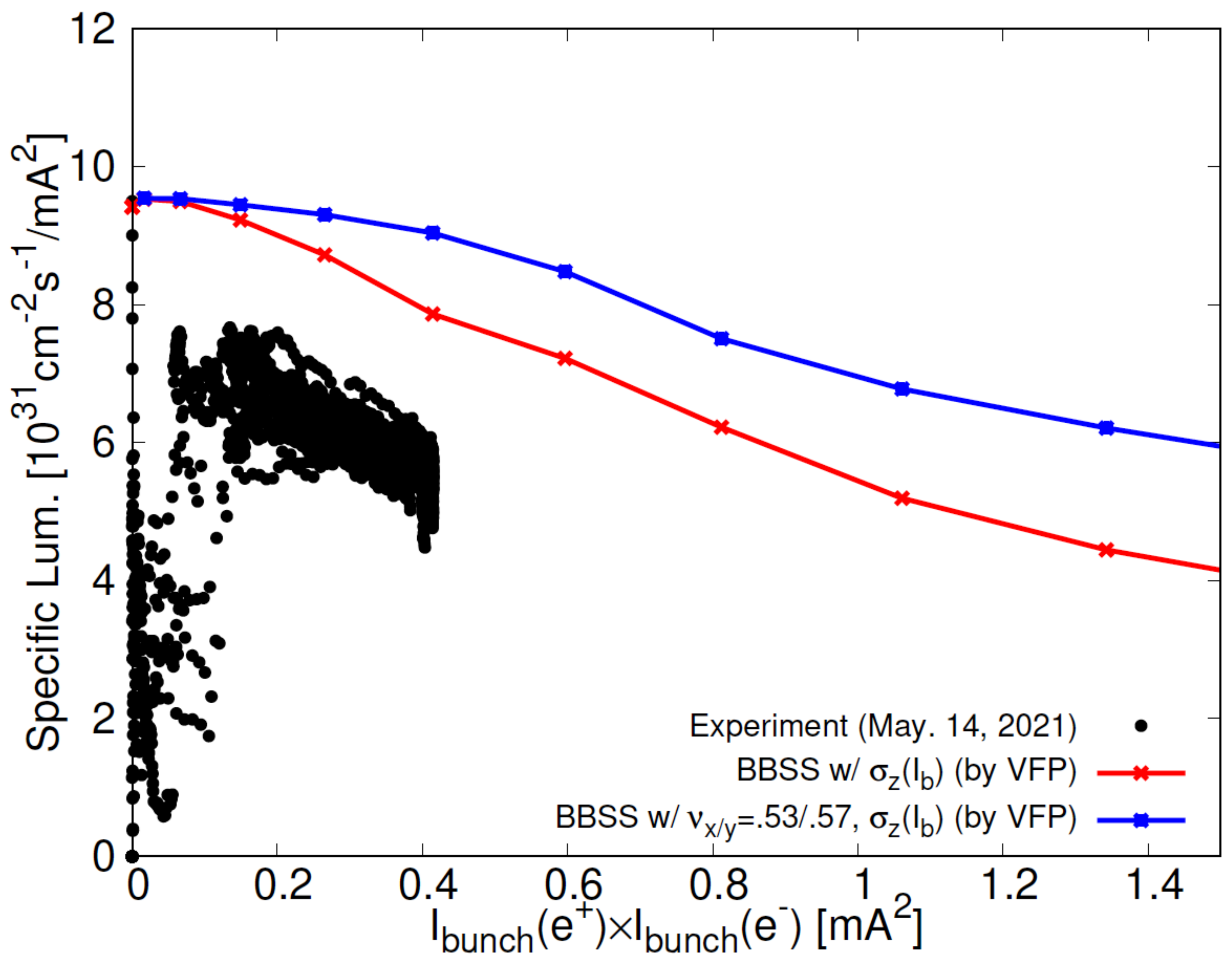
One-day history of luminosity and beam parameters of SuperKEKB

Beam-beam simulations for SuperKEKB (cont'd)

- Beam-beam simulations with machine parameters of Phase-3 including crab waist
  - Taking into account bunch lengthening by impedance and non-optimal working point, BBSS predicted a luminosity about 20% higher than the measured value at bunch current product ~0.4 mA^2.

	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

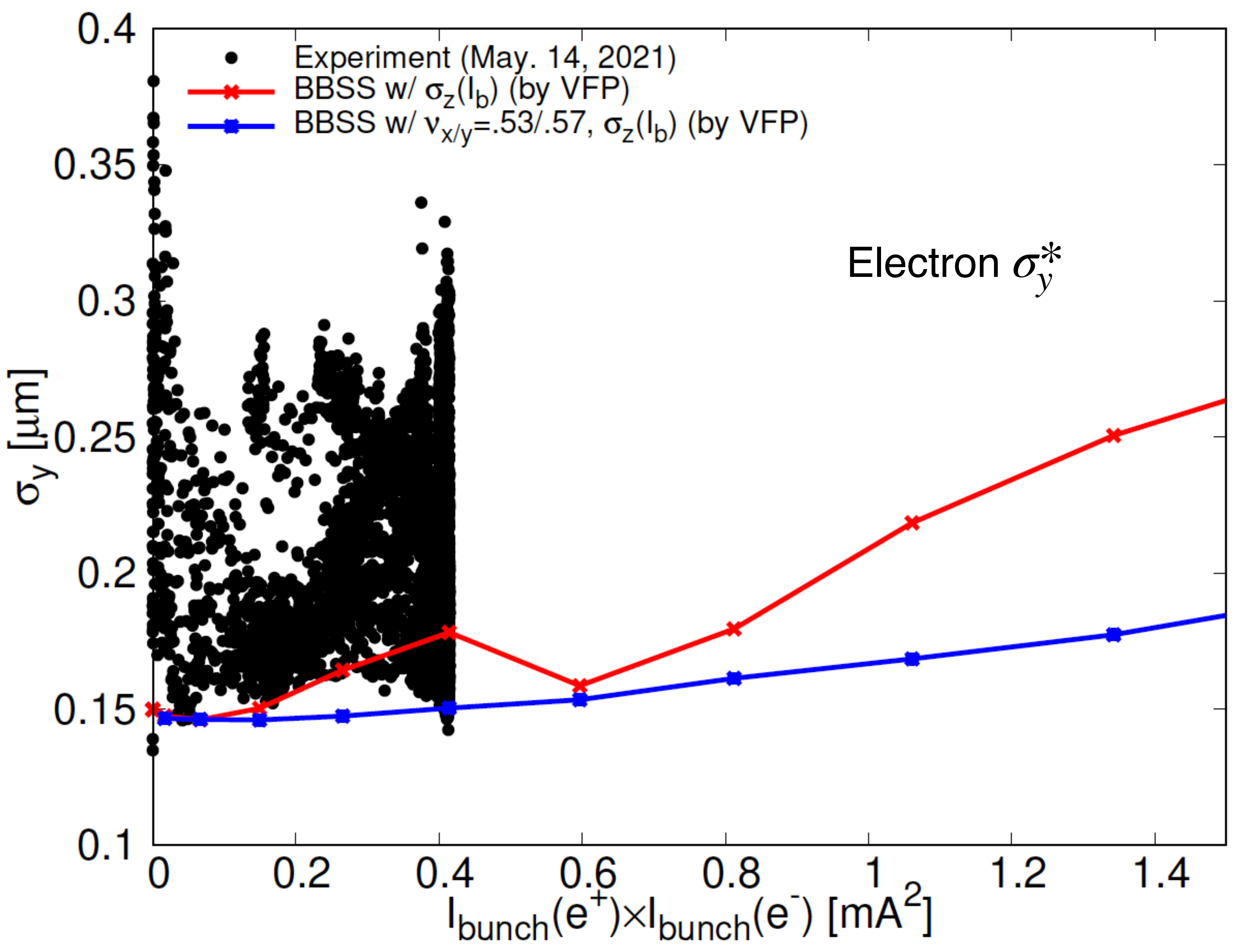
Beam parameters of SuperKEKB on May 14, 2021

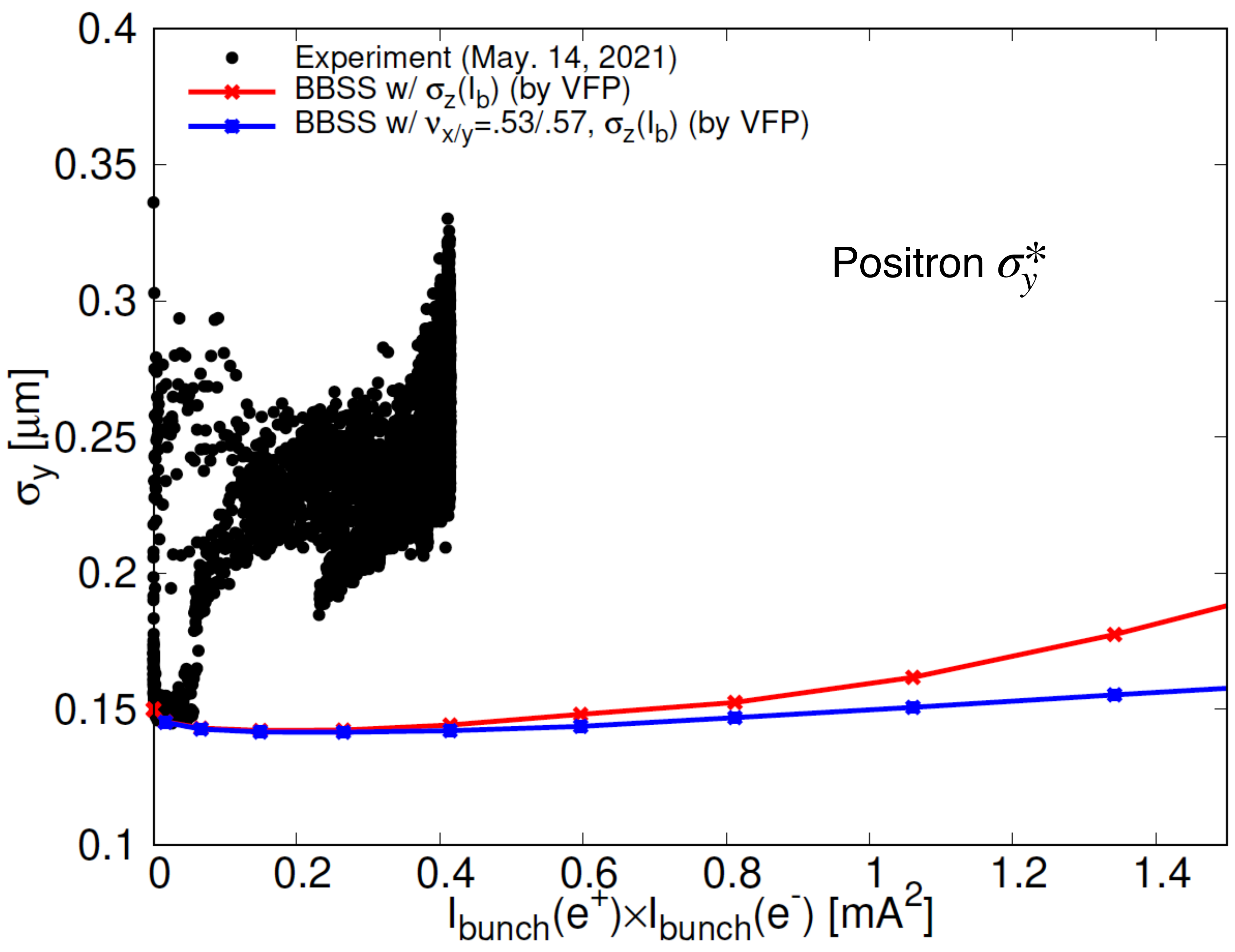


Specific luminosity: BBSS simulation compared to observations

Beam-beam simulations for SuperKEKB (cont'd)

- Beam-beam simulations with machine parameters of Phase-3 including crab waist
  - The observed blowup of σ_y^* of both electron and positron beams were complicated. BBSS simulations did not well predict the trends of σ_y^* blowup.

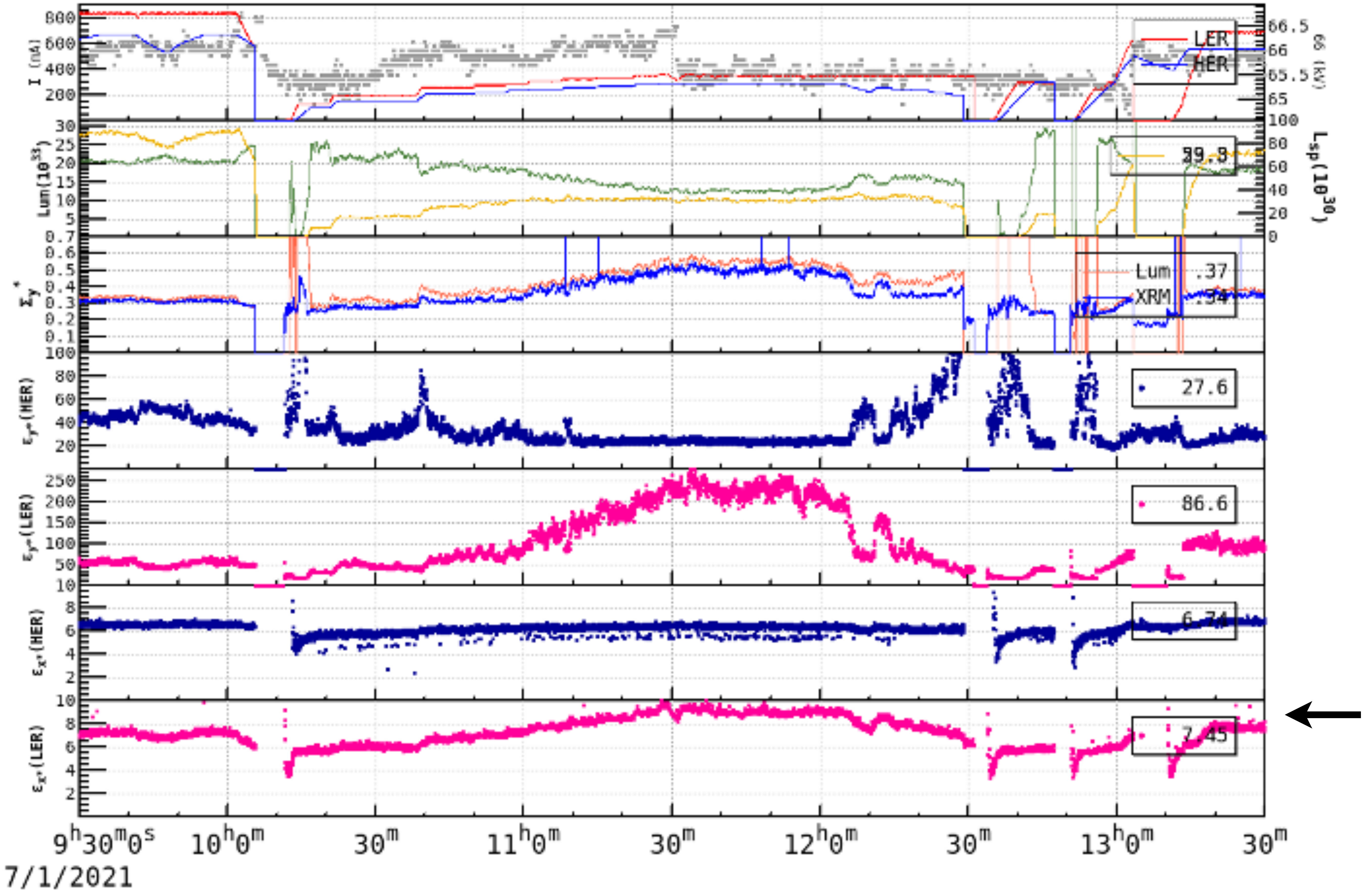




Vertical beam sizes: BBSS simulation compared to observations on May 14, 2021

Beam-beam simulations for SuperKEKB (cont'd)

- Beam-beam simulations with machine parameters of Phase-3 including crab waist
  - Beam-beam can also drive horizontal blowup in SuperKEKB.
  - BBSS simulations with inclusion of longitudinal wakes in a self-consistent way were done to compare the observations of high-bunch current machine study.

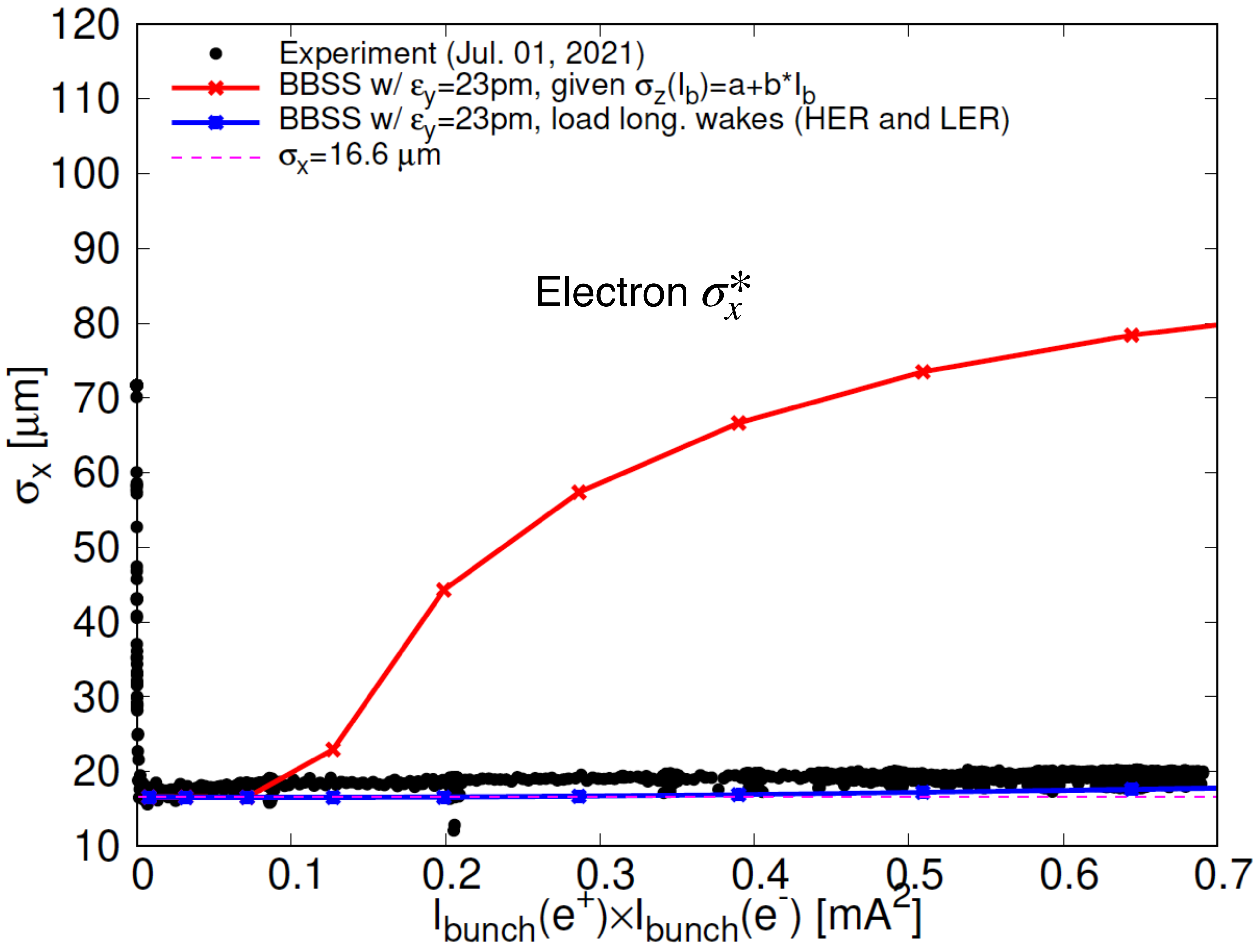


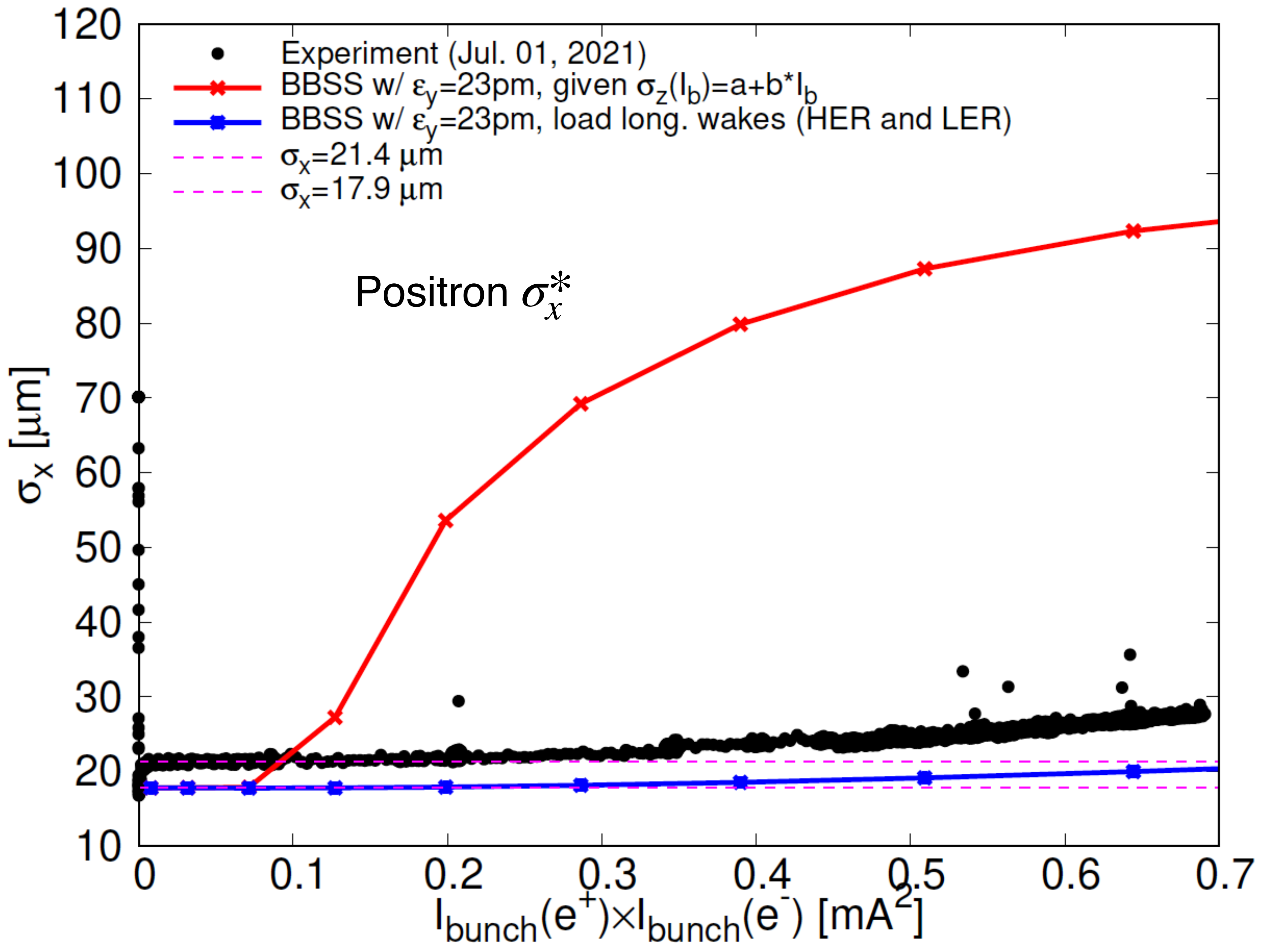
Horizontal blowup

History of luminosity and beam parameters during high-bunch current machine study on Jul. 1, 2021

Beam-beam simulations for SuperKEKB (cont'd)

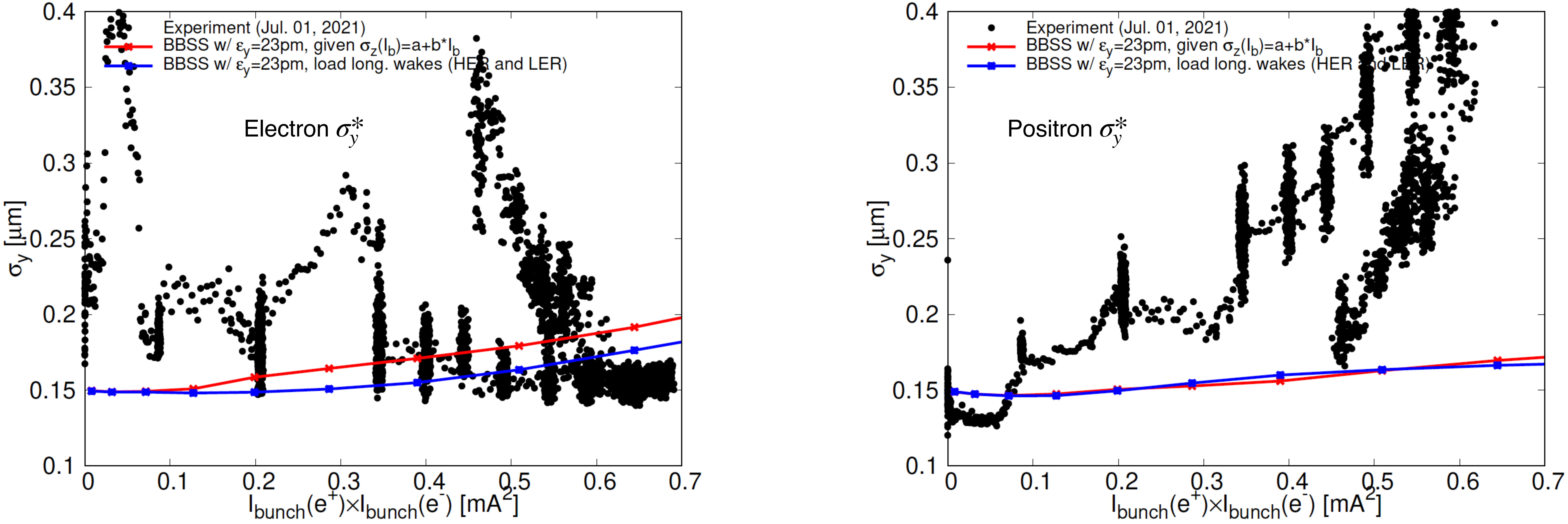
- Beam-beam simulations with machine parameters of Phase-3 including crab waist
  - Blowup of horizontal beam sizes is visible in simulations. Blowup in LER beam is stronger than that in HER beam. Somehow simulations agreed with experiment.
  - Horizontal blowup at low bunch currents was attributed to a feature of X-ray monitors.





Beam-beam simulations for SuperKEKB (cont'd)

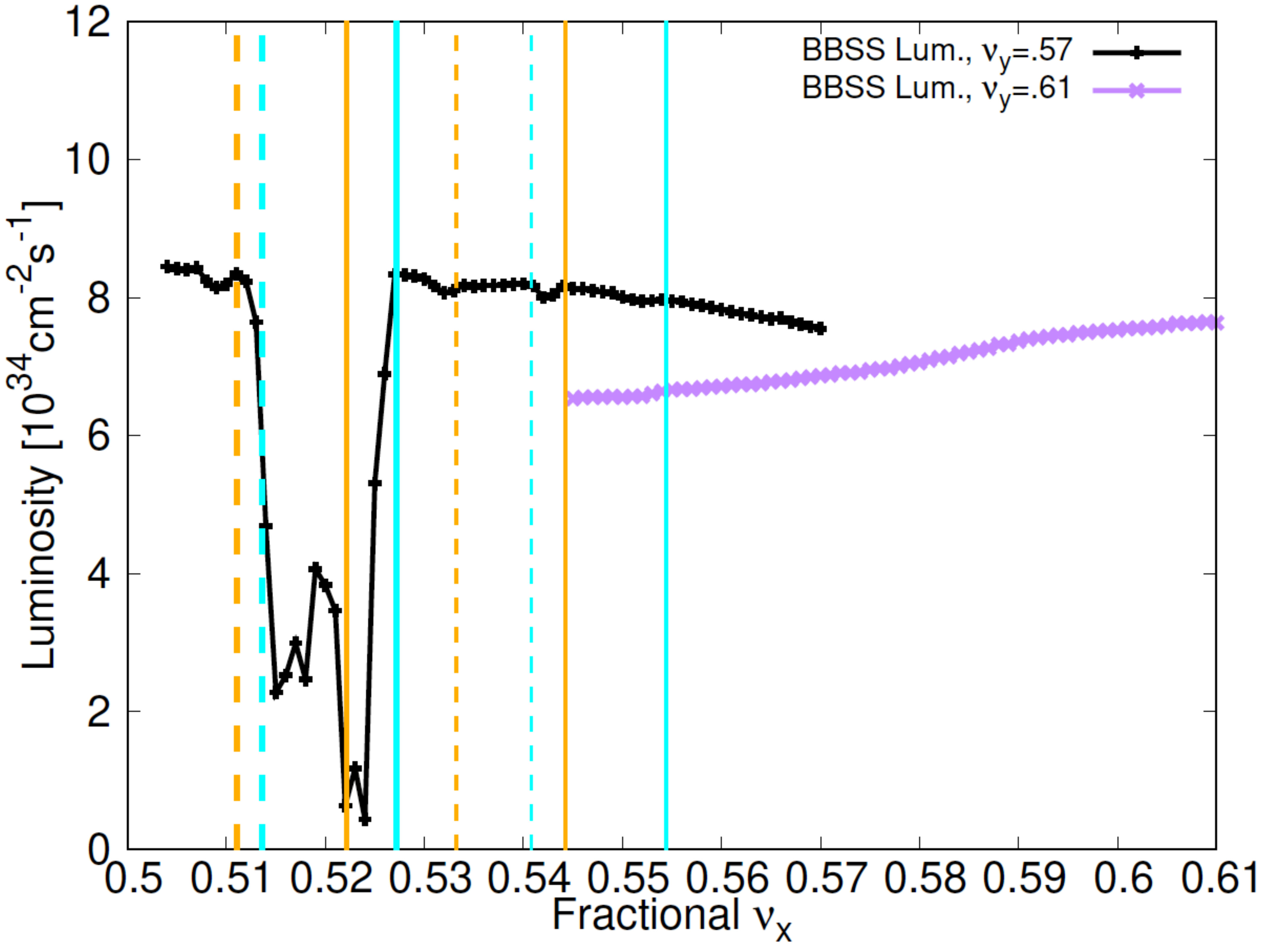
- Beam-beam simulations with machine parameters of Phase-3 including crab waist
  - Prediction of vertical blowup remains to be a challenge.
  - To predict the experiments, other sources are necessary to be included in beam-beam simulations.
  - Candidates sources: Transverse wakes, collision offset noise, IP aberrations (chromatic coupling, third-order RDTs, etc.), and others to be identified.



Beam-beam simulations for SuperKEKB (cont'd)

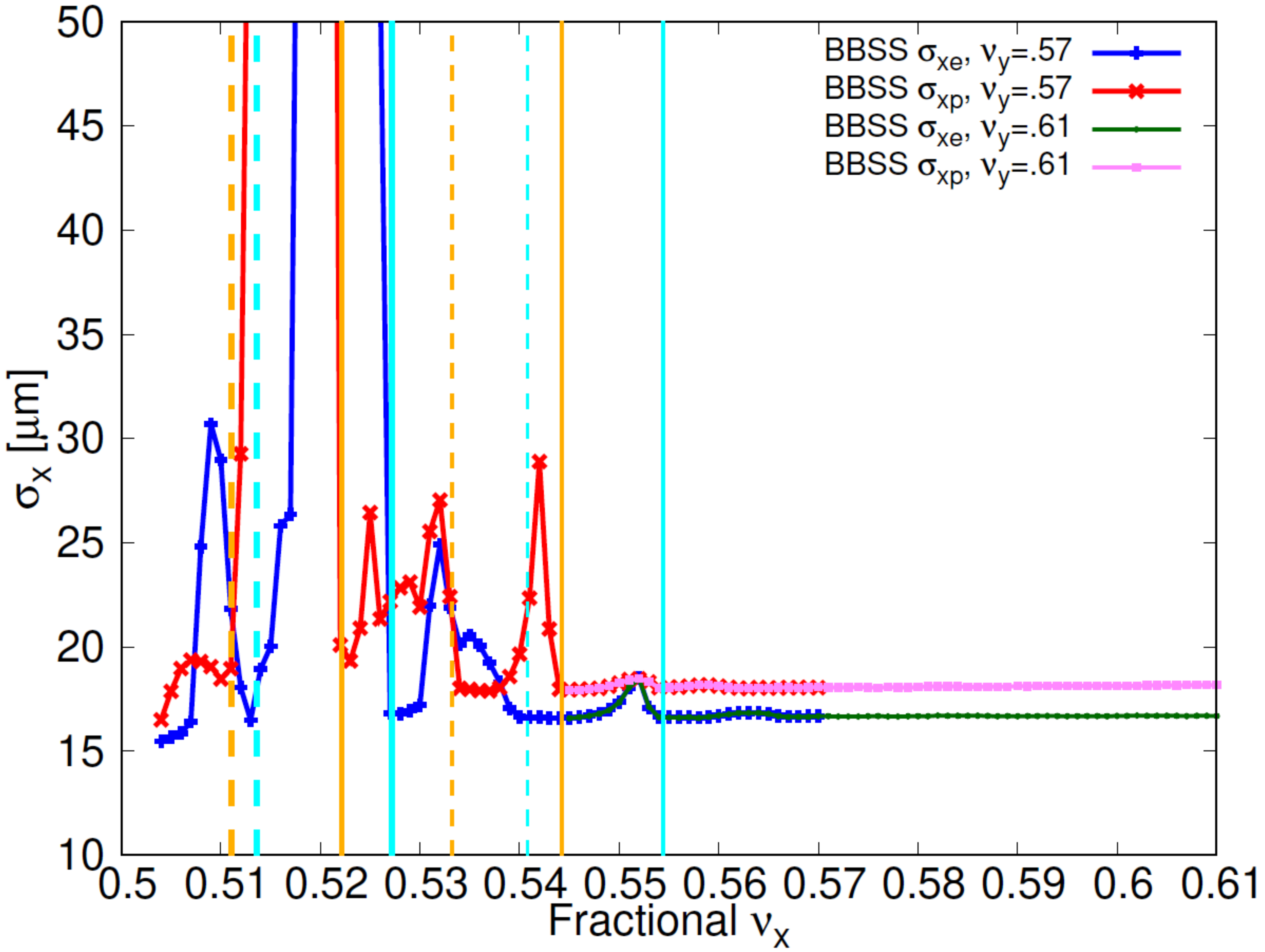
- Beam-beam simulations with machine parameters of Phase-3 including crab waist
  - The effects of beam-beam on choice of working point were investigated using BBSS simulations.
  - Beam parameters similar to observations on Jul. 1, 2021.
  - Assume equal ν_x for HER and LER. Fractional vertical tune set as $\nu_y = .57/.61$, scan ν_x. Track 2e6 macro particles to 12000 turns.

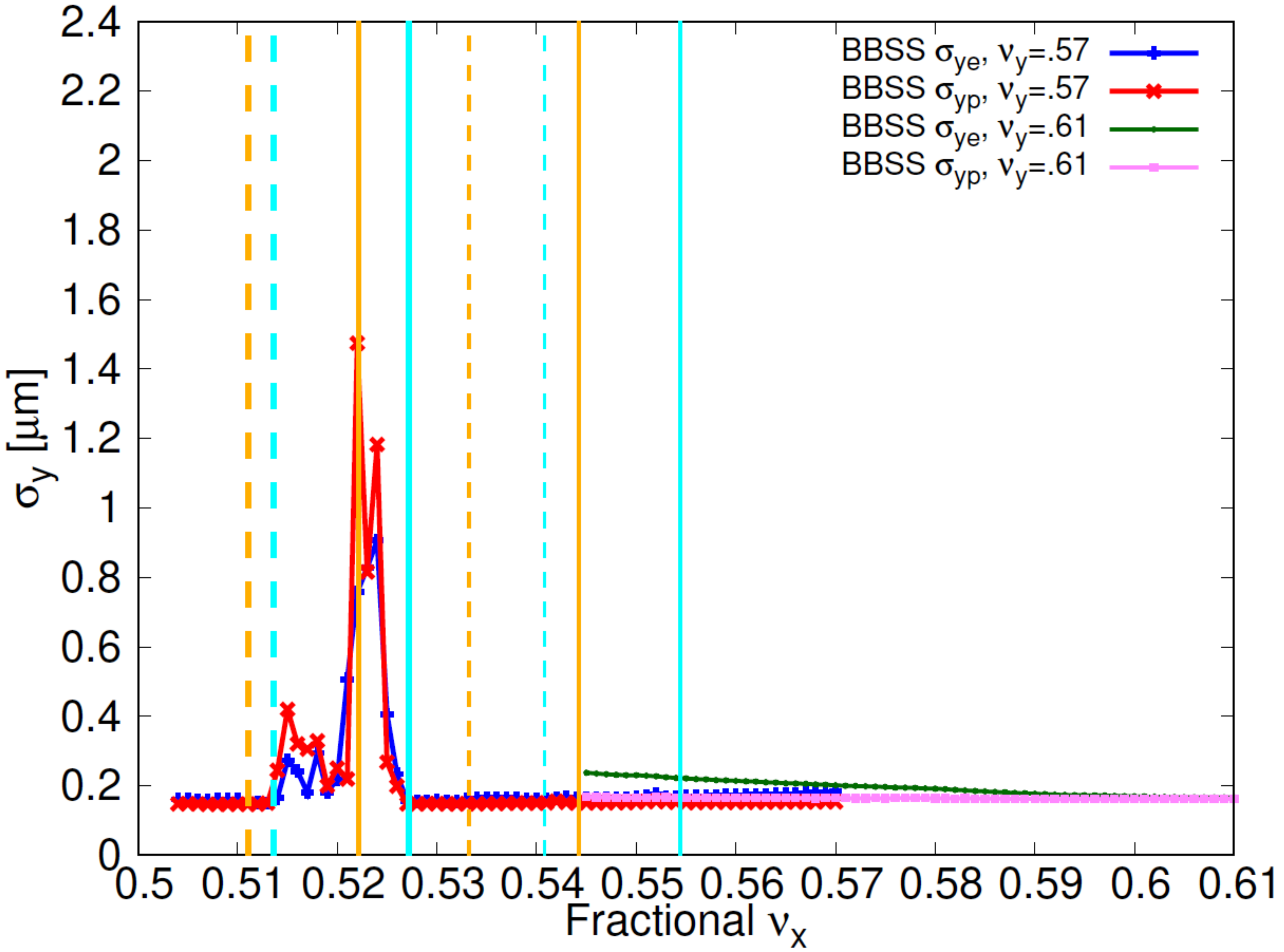
	2021.07.01		Comments
	HER	LER	
I_{bunch} (mA)	0.80	1.0	
# bunch	1174		Assumed value
ε_x (nm)	4.6	4.0	w/ IBS
ε_y (pm)	23	23	Estimated from XRM data
β_x (mm)	60	80	Calculated from lattice
β_y (mm)	1	1	Calculated from lattice
σ_{z0} (mm)	5.05	4.84	Natural bunch length (w/o MWI)
ν_x	45.532	44.525	Measured 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



Beam-beam simulations for SuperKEKB (cont'd)

- Beam-beam simulations with machine parameters of Phase-3 including crab waist
  - With horizontal tune on the left of resonance line $\nu_x - 2\nu_s = N/2$, beam-beam drives horizontal blowup.
  - The X-Y emittance coupling is not included in BBSS simulations. But in realistic machine operation, there will be nonzero emittance coupling, therefore horizontal blowup will cause vertical blowup [10].
  - Avoiding horizontal blowup is a challenge to SuperKEKB.





[10] D. Shatilov, "FCC-ee Parameter Optimization", ICFA Beam Dynamics Newslett. 72 (2017) 30-41.

Summary and outlook

- Beam-beam simulations for KEKB
  - Chromatic effects were found to be important.
- Beam-beam simulations for SuperKEKB: Final design configuration
  - 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.
  - Beam-beam drives horizontal blowup. Simulations showed that careful choice of working point is necessary.
  - Crab waist is effective in suppressing beam blowup and boosting luminosity.
- Outlook
  - The interplay of beam-beam and other effects (machine imperfections, longitudinal and transverse wake fields, space charge, etc.) is important and should be properly included in beam-beam simulations.

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. 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: PIC tracking quite slow. Not feasible for survey in tune space. No effective method of parallelization.