Beam-beam interaction in SuperKEKB: simulations and experimental results

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Acknowledgments

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SuperKEKB ITF team (K. Oide, D. Shatilov, M. Zobov,
T. Nakamura, T. Browder, Y. Cai, C. Lin, et al.)

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Outline

- Luminosity and beam-beam tune shifts
- Status of beam-beam simulations
- Crab waist applied to SuperKEKB
- Comparison of simulations and experimental results
- Summary

Luminosity and beam-beam tune shifts

- "Nano-beam scheme" for SuperKEKB
  - The hourglass effect on luminosity and the incoherent beam-beam tune is weak. Vertical beam sizes are the most crucial.

$$L \approx \frac{N_b N_+ N_- f}{2\pi\sqrt{\sigma_{y+}^{*2}+\sigma_{y-}^{*2}}\sqrt{\sigma_{z+}^2+\sigma_{z-}^2}\tan\frac{\theta_c}{2}} e^{-\frac{\Delta^2}{2(\sigma_{y+}^{*2}+\sigma_{y-}^{*2})}}$$

$$\sigma_y^{*2} = \beta_y^* \epsilon_y \left(1+\frac{\Delta s^2}{\beta_y^{*2}}\right) + \eta_y^{*2}\sigma_\delta^2 + \epsilon_x \beta_x^* \left[\frac{(r_2^* + r_4^* \Delta s)^2}{\beta_x^{*2}} + (r_1^* + r_3^* \Delta s)^2\right]$$

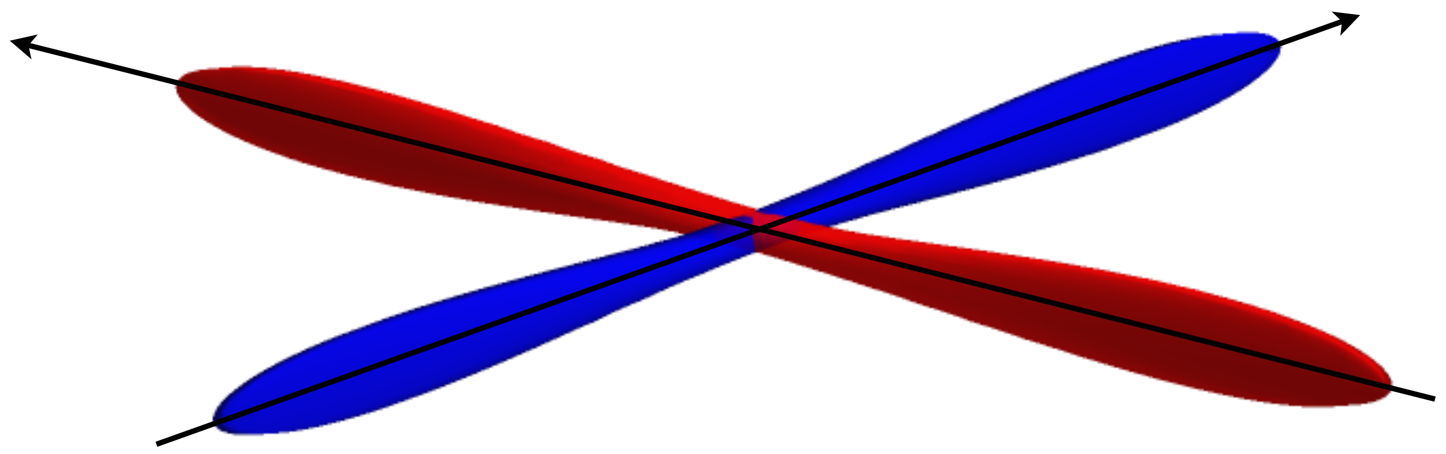
$$\xi_{x+}^i \approx \frac{r_e}{2\pi\gamma_+}\frac{N_- \beta_{x+}^*}{\sigma_{z-}^2 \tan^2\frac{\theta_c}{2} + \sigma_{x-}^{*2}}$$

$$\xi_{y+}^i \approx \frac{r_e}{2\pi\gamma_+}\frac{N_- \beta_{y+}^*}{\sigma_{y-}^* \sqrt{\sigma_{z-}^2 \tan^2\frac{\theta_c}{2} + \sigma_{x-}^{*2}}}$$

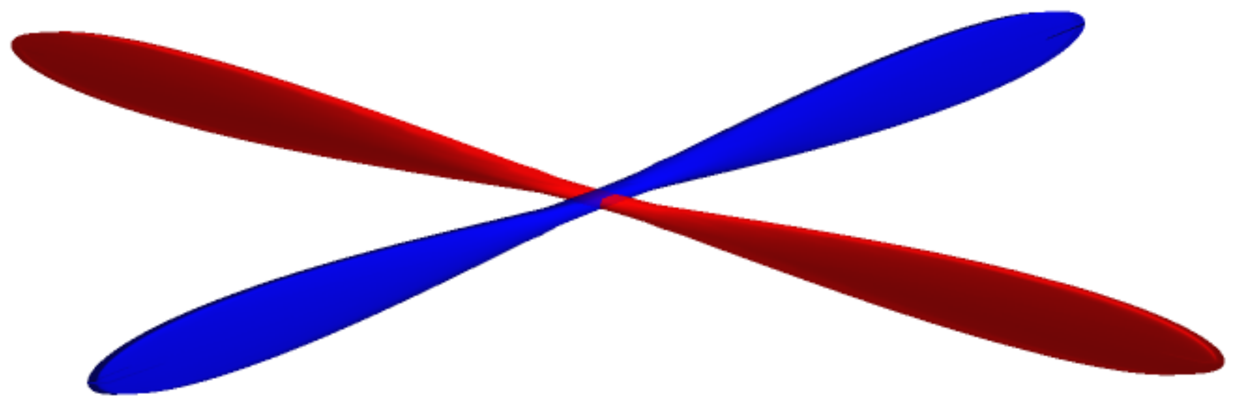
Piwinski angle: $\Phi_P = \frac{\sigma_z}{\sigma_x^*}\tan\frac{\theta_c}{2} \gg 1$

Hourglass condition: $\frac{\beta_y^*}{\sigma_x^*}\tan\frac{\theta_c}{2} \gtrsim 1$

Schematic view of collision schemes



SuperKEKB (2021c)



SuperKEKB (Final design)

Luminosity and beam-beam tune shifts

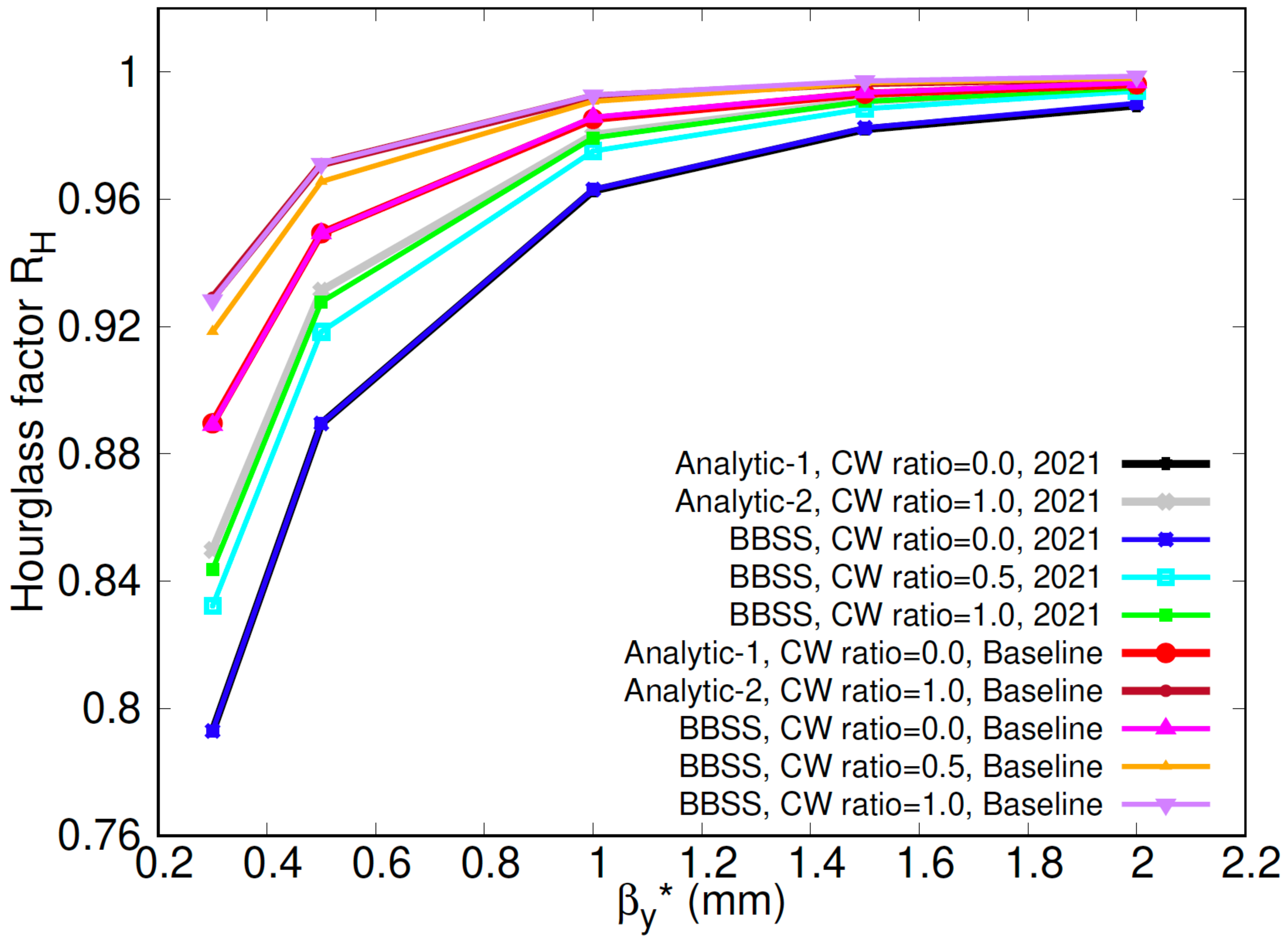
- "Nano-beam scheme" for SuperKEKB
  - Analytic formulae are useful to estimate the hourglass effect on luminosity.
  - Luminosity gain from crab waist is a few percent.

Parameters	Baseline design		Phase-3 (2021)	
	LER	HER	LER	HER
I_b (mA)	1.44	1.04	0.673	0.585
ϵ_x (nm)	3.2	4.6	4.0	4.6
ϵ_y (pm)	8.64	11.5	52.5	52.5
β_x^* (mm)	32	25	80	60
β_y^* (mm)	0.27	0.3	1	1
σ_z (mm)	6	5	4.6	5.1
N_b	2500		1174	
ξ_x^i	0.0028	0.0012	0.0028	0.0030
ξ_y^i	0.083	0.074	0.043	0.031
ξ_x^{ih}	0.0017	0.0005	0.0027	0.0029
ξ_y^{ih}	0.085	0.071	0.043	0.031
Φ_{XZ}	22.0		11.6	
Φ_{HC}	0.8		1.7	
L (10^{34} cm^{-2}s^{-1})	83.5		3.0	

Hourglass factor $R_H = R_{HC}/R_C \quad R_C = \left(1 + \frac{\Sigma_z^2}{\Sigma_x^{*2}} \tan^2 \frac{\theta_c}{2}\right)^{-1/2}$

w/o CW, $R_{HC} \approx \sqrt{\frac{2}{\pi}} a e^b K_0(b)$

w/ full CW, $R_{HC}^{CW} \approx \frac{\Sigma_x^* \Sigma_z \tan\frac{\theta_c}{2}}{\Sigma_z^2 \tan^2\frac{\theta_c}{2} + \sigma_{x+}^* \sigma_{x-}^*} f(d)$



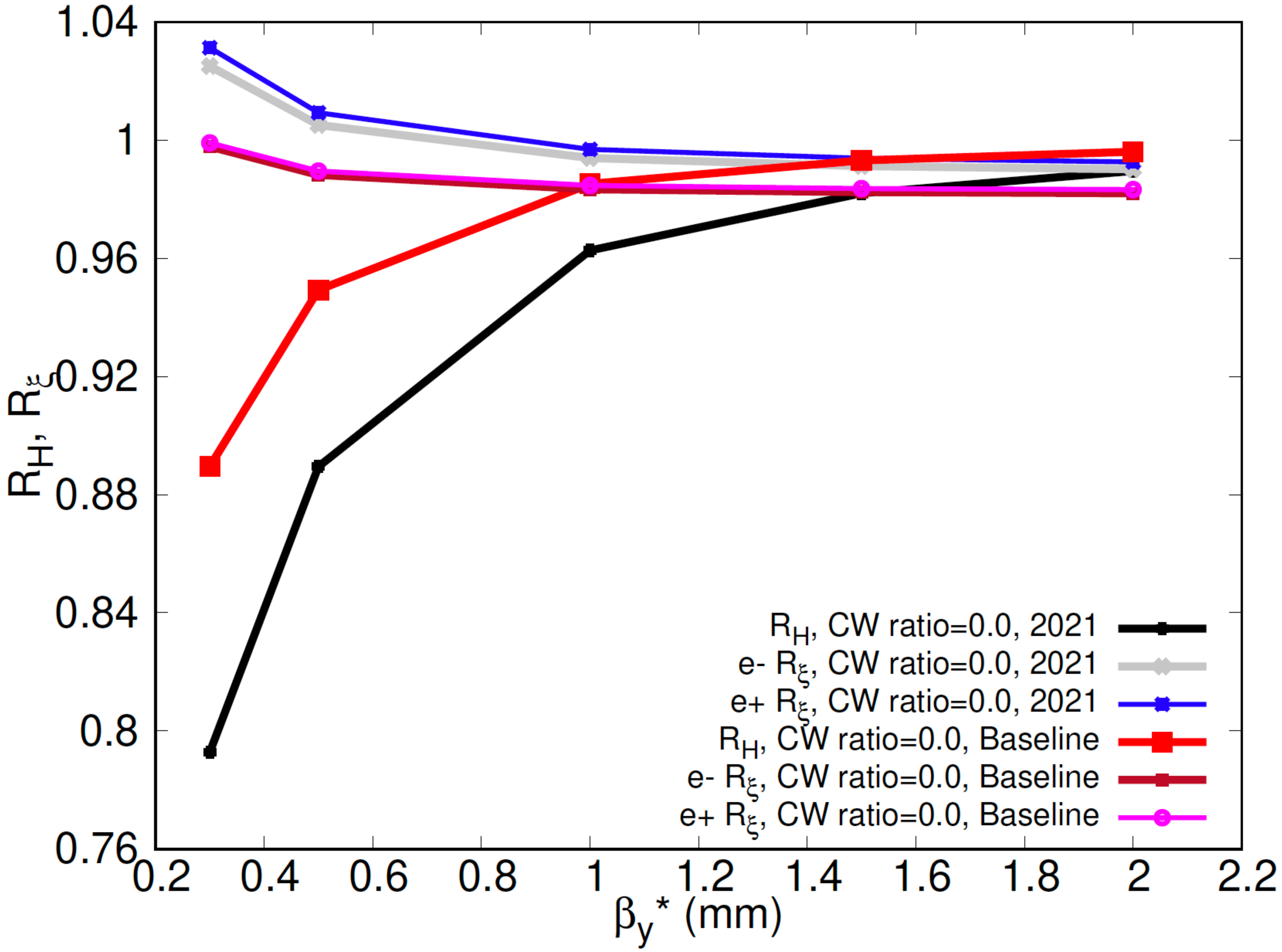
Luminosity and beam-beam tune shifts

- "Nano-beam scheme" for SuperKEKB
  - Hourglass effect causes luminosity loss.
  - Beam-beam tune shift is less sensitive because of β-weighting.

w/o CW, $\xi^i_{u\pm} = \dfrac{r_e}{2\pi\gamma_\pm}\dfrac{N_\mp \beta^*_{u\pm}}{\bar{\sigma}_{u\mp}(\bar{\sigma}_{x\mp}+\bar{\sigma}_{y\mp})}$

Hourglass factor $R_{\xi u\pm} = \xi^{ih}_{u\pm}/\xi^i_{u\pm}$

Parameters	Baseline design LER	Baseline design HER	Phase-3 (2021) LER	Phase-3 (2021) HER
I_b (mA)	1.44	1.04	0.673	0.585
ϵ_x (nm)	3.2	4.6	4.0	4.6
ϵ_y (pm)	8.64	11.5	52.5	52.5
β^*_x (mm)	32	25	80	60
β^*_y (mm)	0.27	0.3	1	1
σ_z (mm)	6	5	4.6	5.1
N_b	2500		1174	
ξ^i_x	0.0028	0.0012	0.0028	0.0030
ξ^i_y	0.083	0.074	0.043	0.031
ξ^{ih}_x	0.0017	0.0005	0.0027	0.0029
ξ^{ih}_y	0.085	0.071	0.043	0.031
Φ_{XZ}	22.0		11.6	
Φ_{HC}	0.8		1.7	
L (10^{34} cm^{-2}s^{-1})	83.5		3.0	

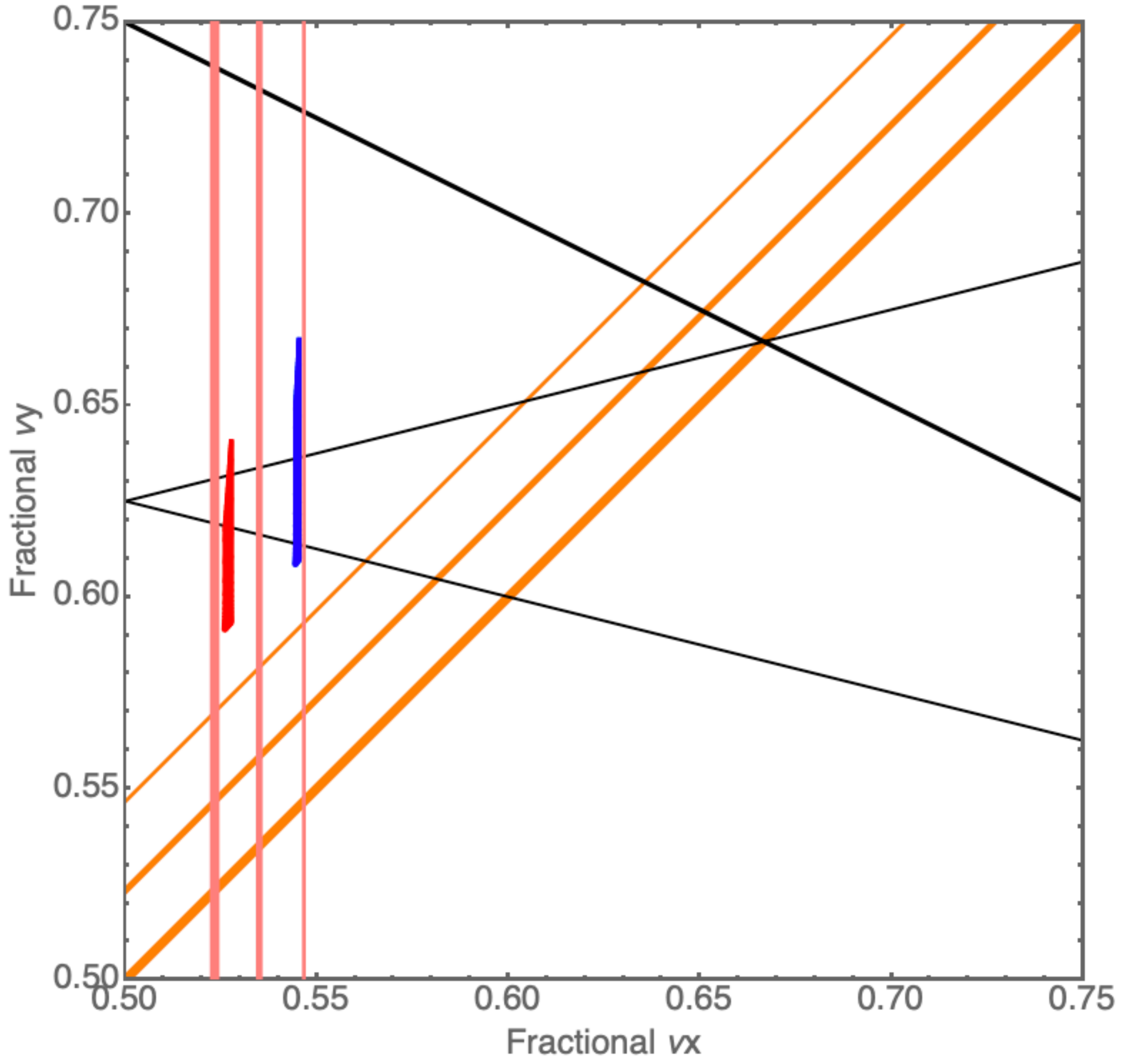


Luminosity and beam-beam tune shifts

- "Nano-beam scheme" for SuperKEKB
  - Beam-beam-driven footprint in tune space is useful for understanding beam-beam effects.
  - The choice of working point dynamically depends on machine conditions.

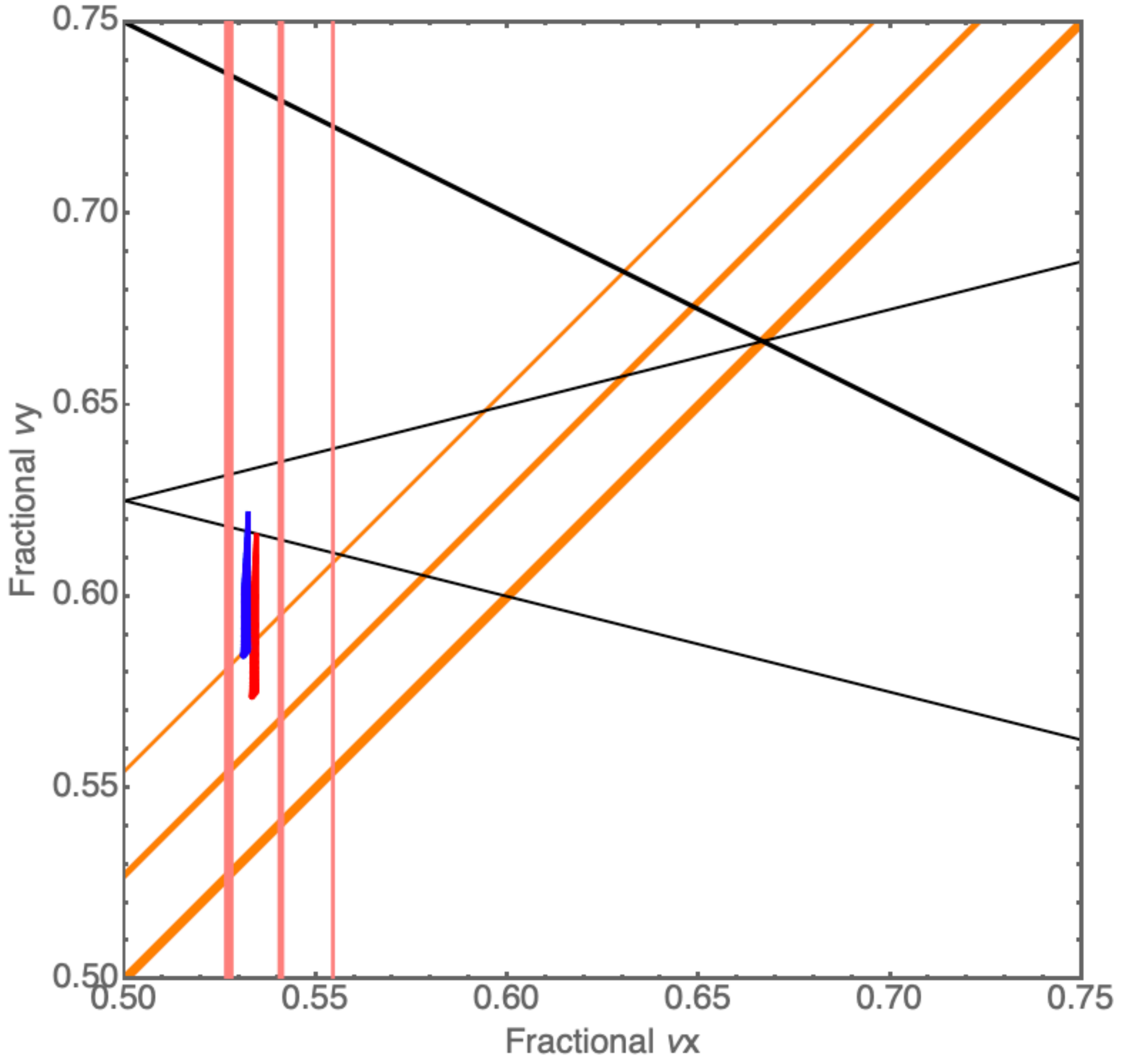
Parameters	2019.07.01 LER	2019.07.01 HER	2022.04.05 LER	2022.04.05 HER
I_b (mA)	0.51	0.51	0.71	0.57
ϵ_x (nm)	2.0	4.6	4.0	4.6
ϵ_y (pm)	40	40	30	35
β_x (mm)	80	80	80	60
β_y (mm)	2	2	1	1
σ_{z0} (mm)	4.6	5.0	4.6	5.1
ν_x	44.542	45.53	44.524	45.532
ν_y	46.605	43.583	46.589	43.572
ν_s	0.023	0.027	0.023	0.027
Crab waist ratio	0	0	80%	40%
N_b	1174		1174	
ξ_x^i	0.0034	0.0023	0.0036	0.0024
ξ_y^i	0.062	0.039	0.052	0.044
ξ_x^{ih}	0.0032	0.0021	0.0034	0.0023
ξ_y^{ih}	0.062	0.038	0.051	0.044
Φ_{XZ}	12.3		11.7	
Φ_{HC}	3.6		1.7	
L (10^{34} cm^{-2}s^{-1})	1.7		3.9	

LER
Red: 2022.04.05, w/ CW
Blue: 2019.07.01, w/o CW



Notes:
* Hourglass effect ignored in calculation of BB footprint
* Resonances $m\nu_x \pm n\nu_y = N$ not plotted
* Collective effects dynamically shift the resonances

HER
Red: 2022.04.05, w/ CW
Blue: 2019.07.01, w/o CW



Luminosity and beam dynamics

- Beam dynamics behind the luminosity at SuperKEKB

$$L \approx \frac{N_b N_+ N_- f}{2\pi\sqrt{\sigma_{y+}^{*2} + \sigma_{y-}^{*2}}\sqrt{\sigma_{z+}^2 + \sigma_{z-}^2}\tan\frac{\theta_c}{2}} e^{-\frac{\Delta^2}{2(\sigma_{y+}^{*2} + \sigma_{y-}^{*2})}}$$

N_b:
* Tolerance of hardwares
* Injection
* …

$N_+ N_-$:
* Impedance effects (TMCI, PWD, HOM, etc.)
* Beam-beam blowup
* …

Δ:
* Vertical orbit offset at IP
* Orbit feedback
* iBump fast feedback

$\sigma_{y+}^{*2} + \sigma_{y-}^{*2}$:
* TMCI (Y-Z instability)
* Beam-beam blowup
* β_y^*, ϵ_y
* Optics correction
* Tunes $\nu_{x,y}$
* Machine imperfections
* IP knobs
* …

$\sigma_{z+}^2 + \sigma_{z-}^2$:
* Impedance effects
* Beam-beam ϵ_y blowup
* …

$\theta_c/2$:
* Coherent X-Z instability
* Beam-beam resonances (X-Y coupling)
* β_x^*
* Crab waist
* …

Note:
* $\sigma_{x\pm}^*$ do not appear in this luminosity formulae. But they play a role of "invisible hand" and have very important impact on beam dynamics, eventually affecting the luminosity.

Specific luminosity: $L_{sp} = \dfrac{L}{N_b N_+ N_- (ef)^2}$

Status of 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 the 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
  - The BBWS code was implemented into SAD as a type of BEAMBEAM element, where the beam-beam map is called during 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, wakefields, artificial SR damping/excitation, etc.); …

```
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                    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. The Beamstrahlung model is also available. Choices of numerical techniques: PIC, Gaussian fitting for each slice, …
  - For SuperKEKB, it is hard to include lattice.
- GPU-powered strong-strong model + full lattice: SCTR code
  - Under development (K. Ohmi)
  - KEK/IHEP/J-PARC collaboration

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

Status of beam-beam simulations

- Beam-beam simulations have shown that multiple factors can strongly interplay with beam-beam interaction
  - Imperfections in linear optics: beta beat, linear couplings, dispersions, etc. at the IP
  - Geometric nonlinearities: It is crucial when $\beta_y^* < 1$ mm
  - Coupling impedances: Longitudinal and transverse (See C. Lin and Y. Zhang's talks)
  - Space charge
  - BxB feedback
- Predictability of beam-beam simulations: The case of SuperKEKB sets demands on
  - Accurate modeling of linear optics
  - Strong-strong model of beam-beam interaction
    - X-Z instability(i.e. Beam-beam head-tail instability)
    - Synchro-betatron resonances with working points near half integers
  - Reliable impedance modeling
    - Longitudinal impedance: potential-well distortion and synchrotron tune spread
    - Transverse impedance: Betatron tune shift and spread
    - Monopolar (longitudinal potential-well distortion and transverse beam tilt), dipole (TMCI), and quadrupolar (tune shift)

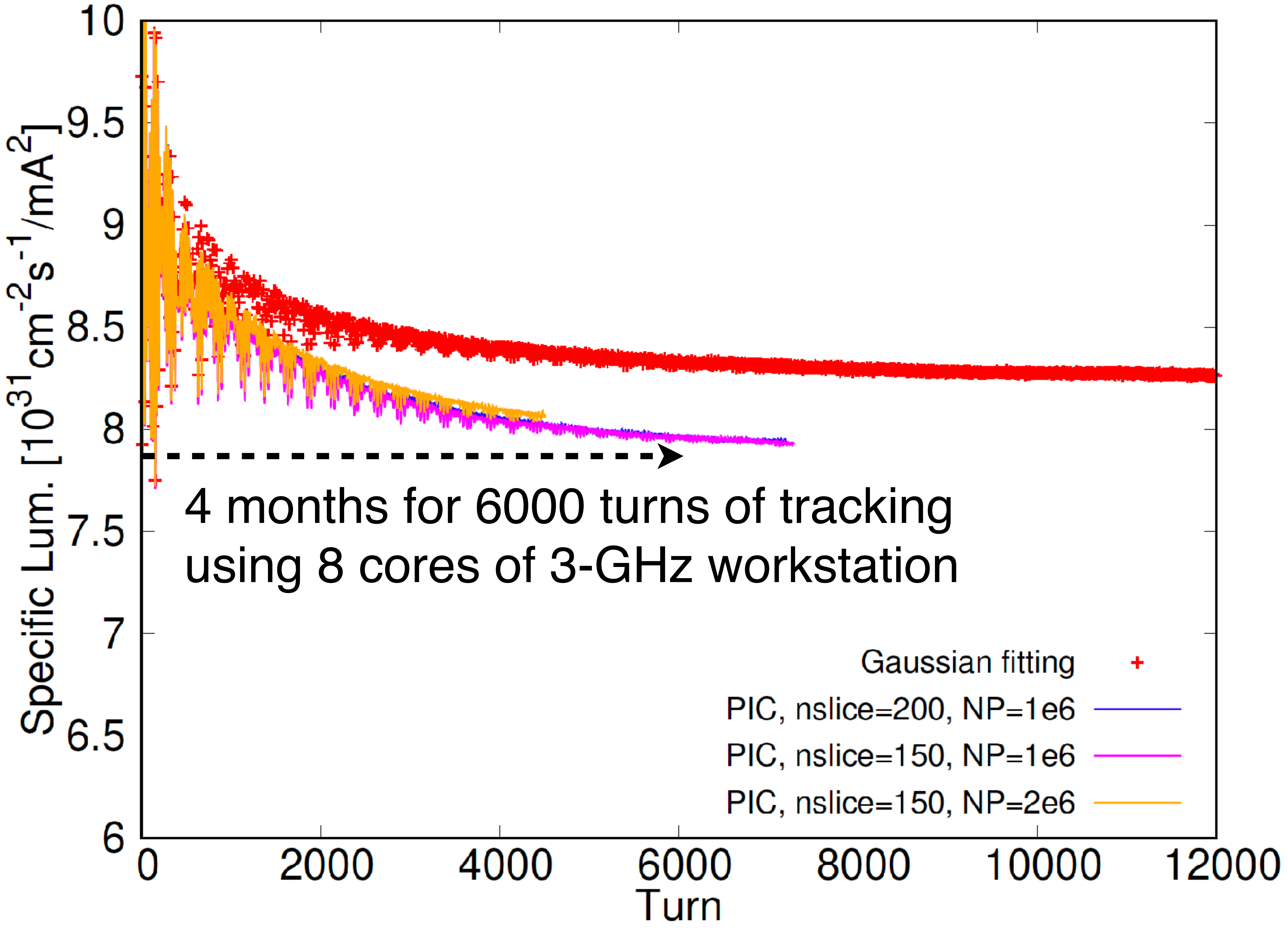
Status of beam-beam simulations

$$L_{sp} \approx \frac{1}{2\pi e^2 f \sqrt{\sigma_{y+}^{*2} + \sigma_{y-}^{*2}} \sqrt{\sigma_{z+}^2 + \sigma_{z-}^2} \tan\frac{\theta_c}{2}}$$

"Vertical blowup" "Longitudinal blowup"

- BBSS simulations: PIC vs. Gaussian fitting model
  - PIC method predicts lower luminosity (~5%).
  - Using workstations(8 cores), one PIC simulation requires ~8 months, and a Gaussian-fitting simulation takes ~1.2 days.
  - Significant progress has been achieved recently in developing GPU-based BB codes. Preliminary tests showed a speed-up factor of ~50 for PIC simulations based on the CUDA compiler (K. Ohmi, in collaboration with Y. Zhang and Z. Li (IHEP), T. Yasui (J-PARC)).
    - This will speed up our investigations, especially of the interplay between beam-beam and machine imperfections.

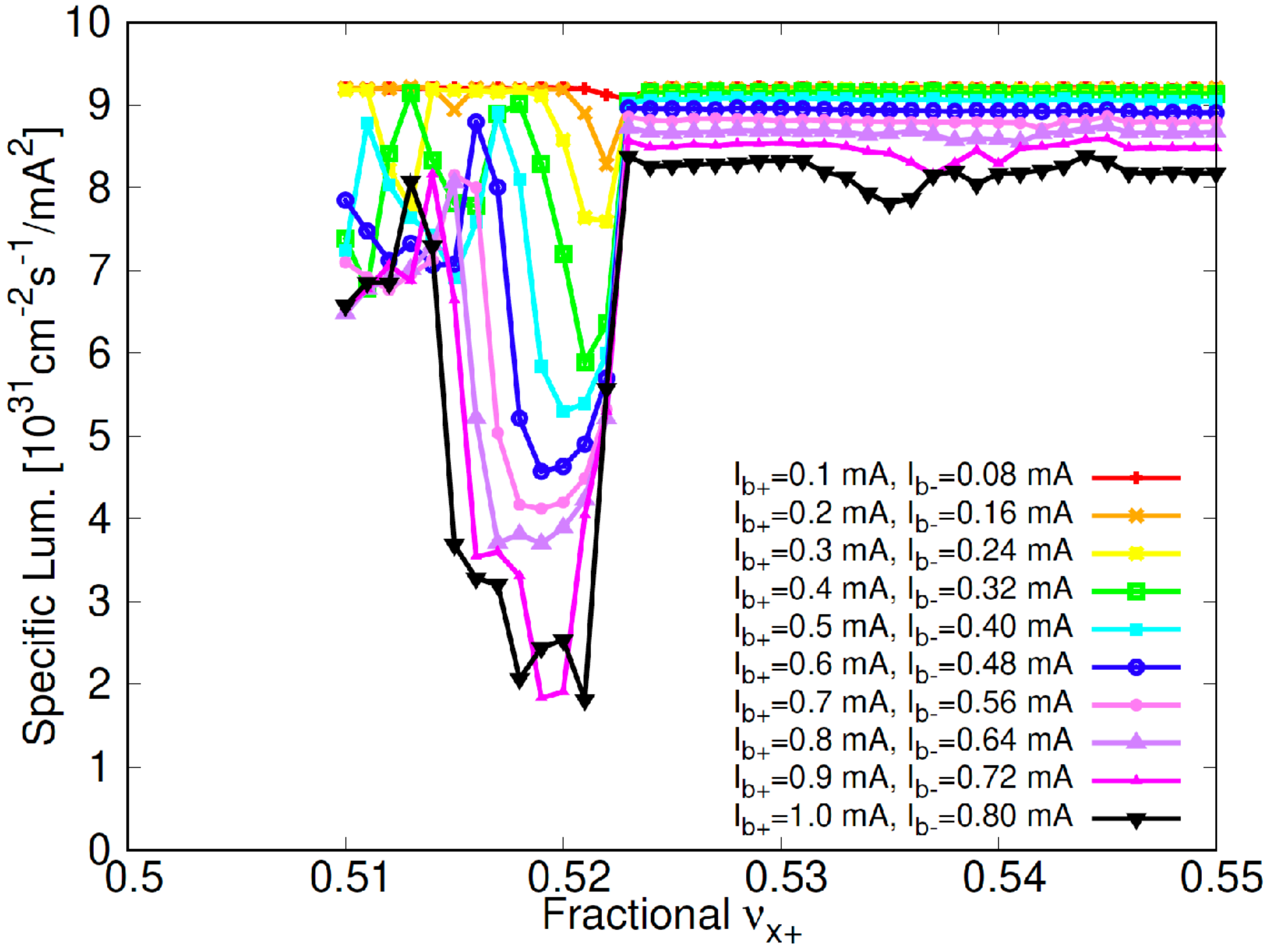
	2021.12.21		Comments
	HER	LER	
I_{bunch} (mA)	0.8	1.0	
# bunch	-		
ε_x (nm)	4.6	4.0	w/ IBS
ε_y (pm)	35	20	Estimated from XRM data
β_x (mm)	60	80	Calculated from lattice
β_y (mm)	1	1	Calculated from lattice
σ_{z0} (mm)	5.05	4.60	Natural bunch length (w/o MWI)
ν_x	45.53	44.524	Measured tune of pilot bunch
ν_y	43.572	46.589	Measured tune of pilot bunch
ν_s	0.0272	0.0233	Calculated from lattice
Crab waist	40%	80%	Lattice design

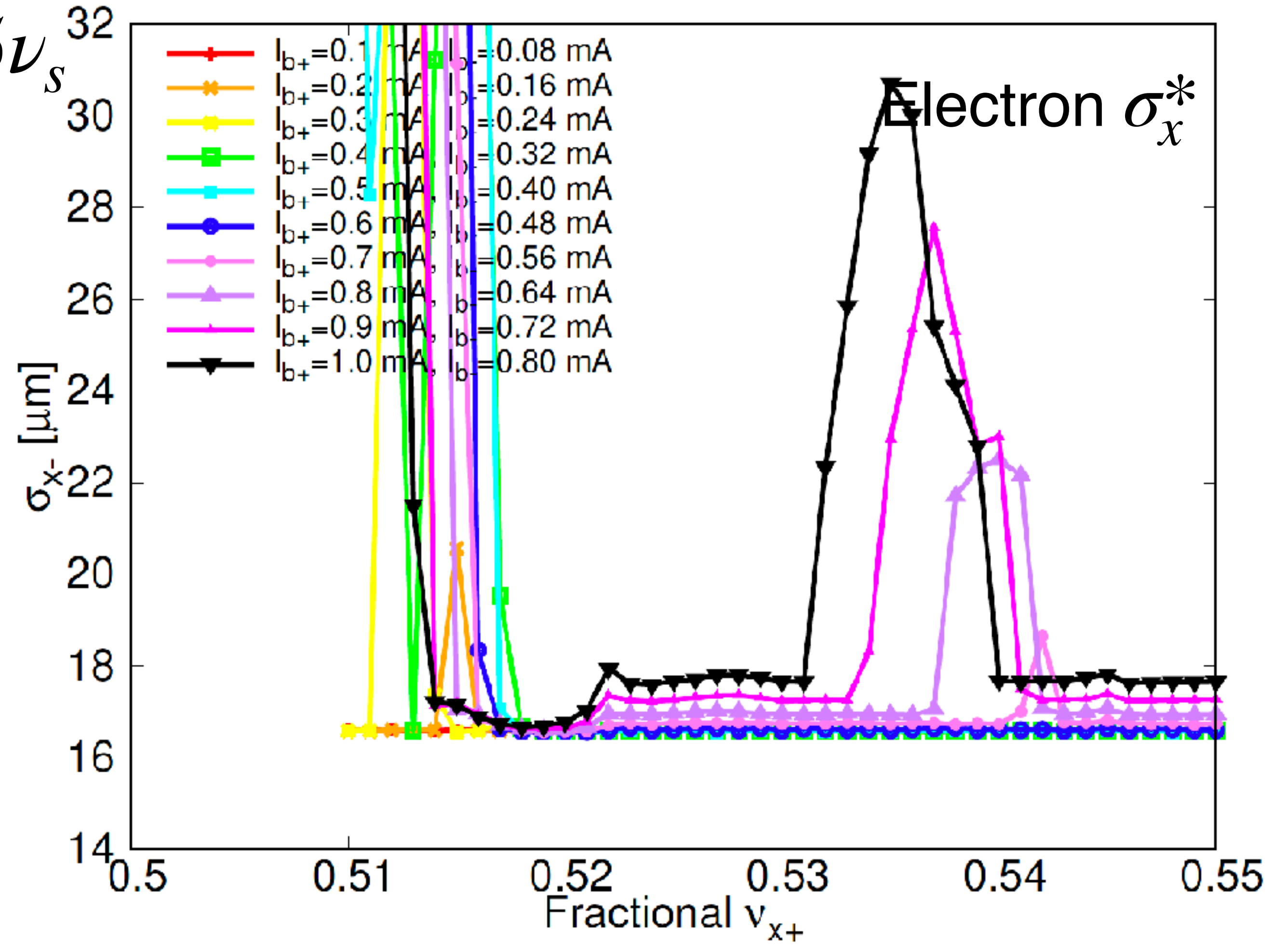


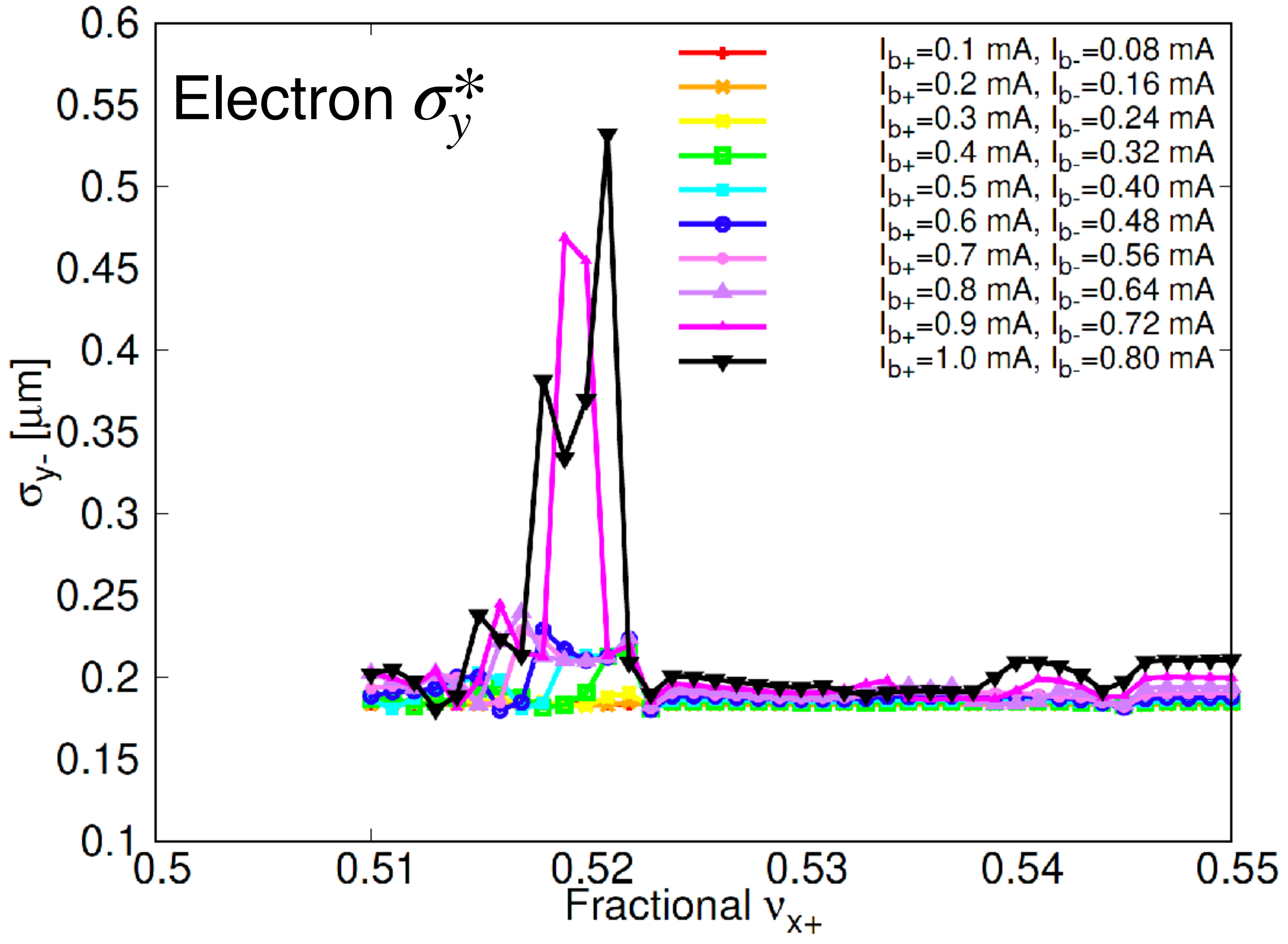
Status of beam-beam simulations

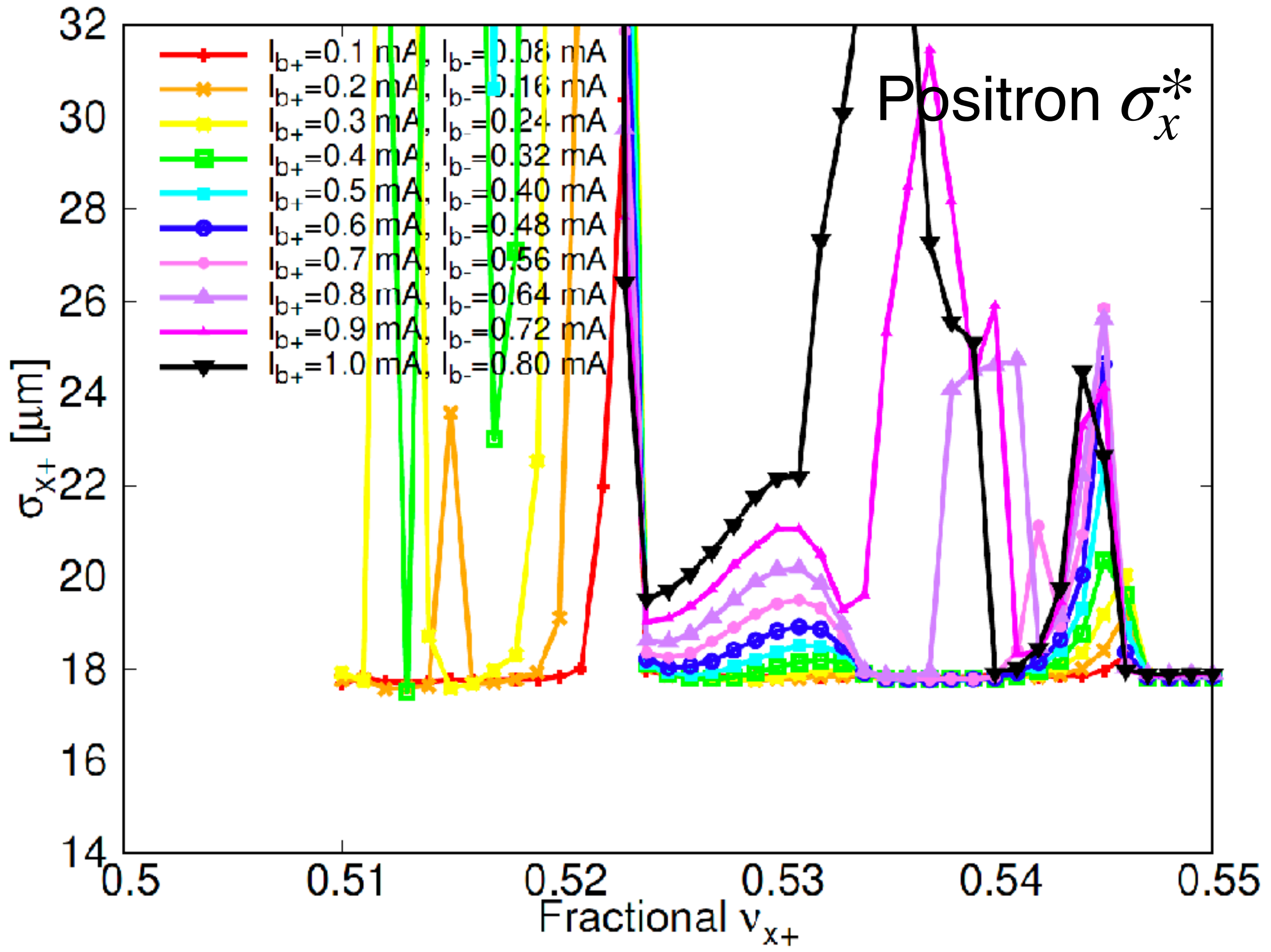
- Scan LER ν_x (with LER ν_y and HER $\nu_{x,y}$ fixed as the values of the parameter table of 2021.12.21)
  - Coupling impedances included
  - Weak horizontal blowup when $0.5 + \nu_s < [\nu_x] < 0.5 + 1.5\nu_s$

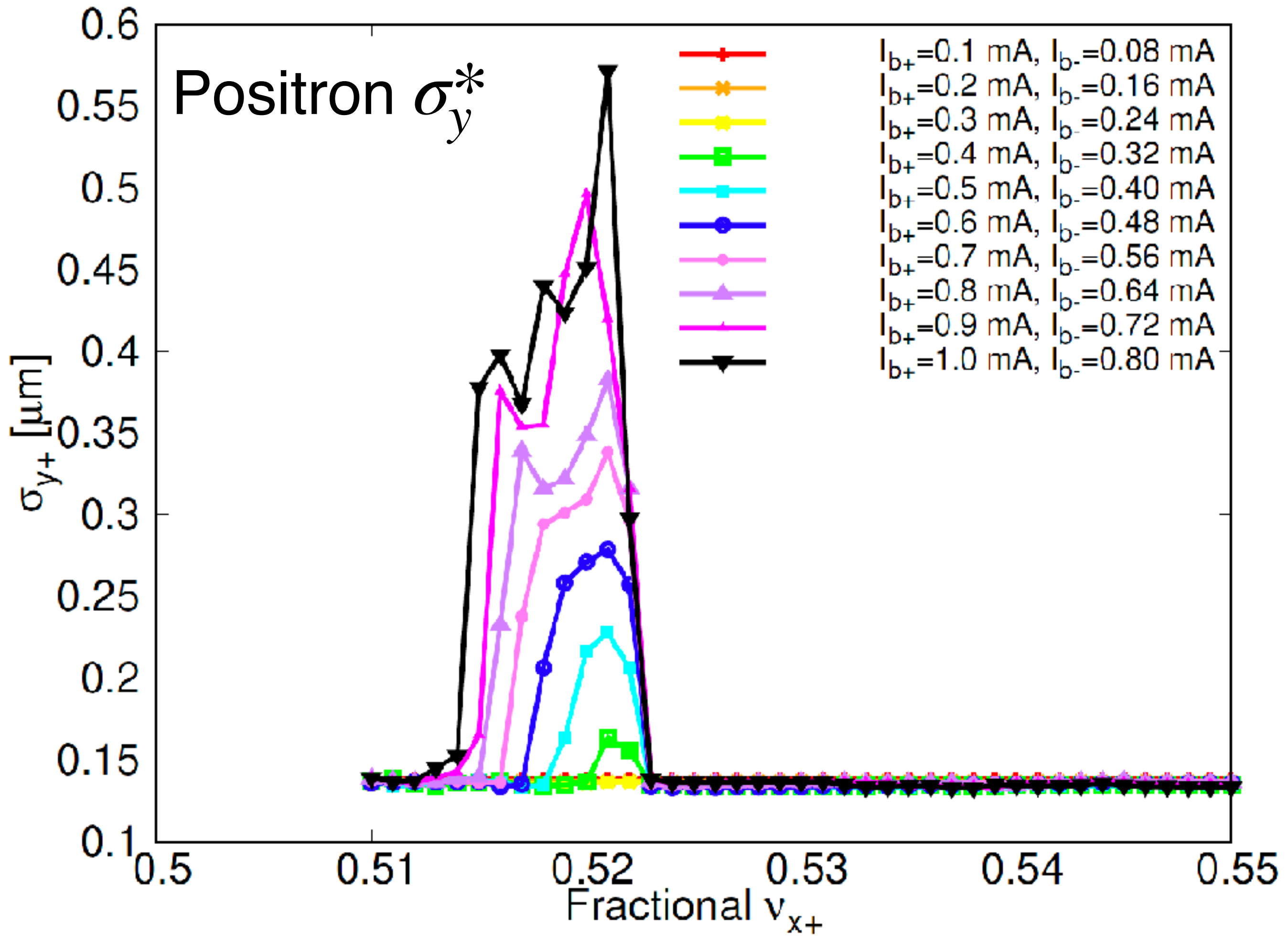
X-Z instability is sensitive to ν_x.









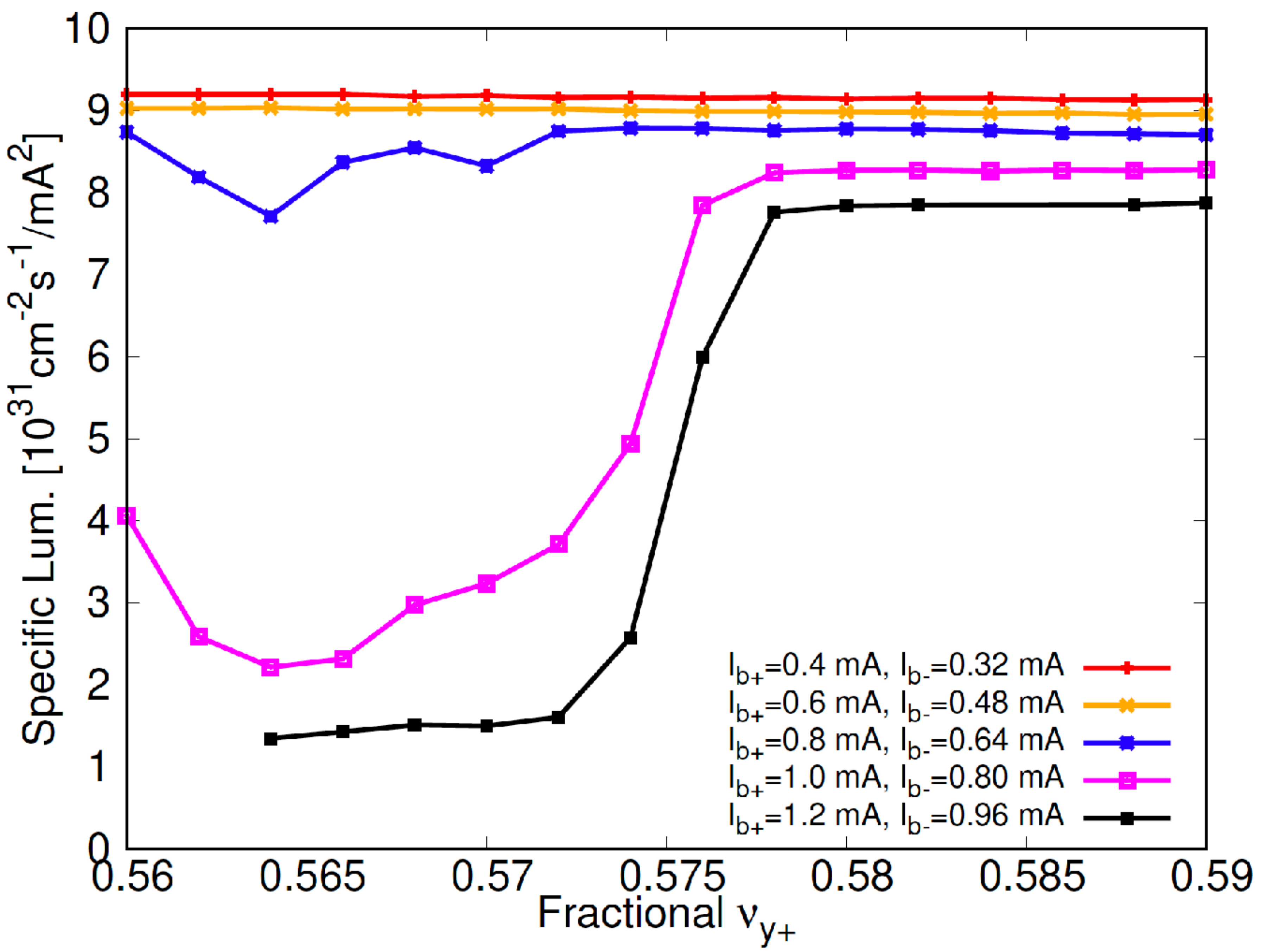


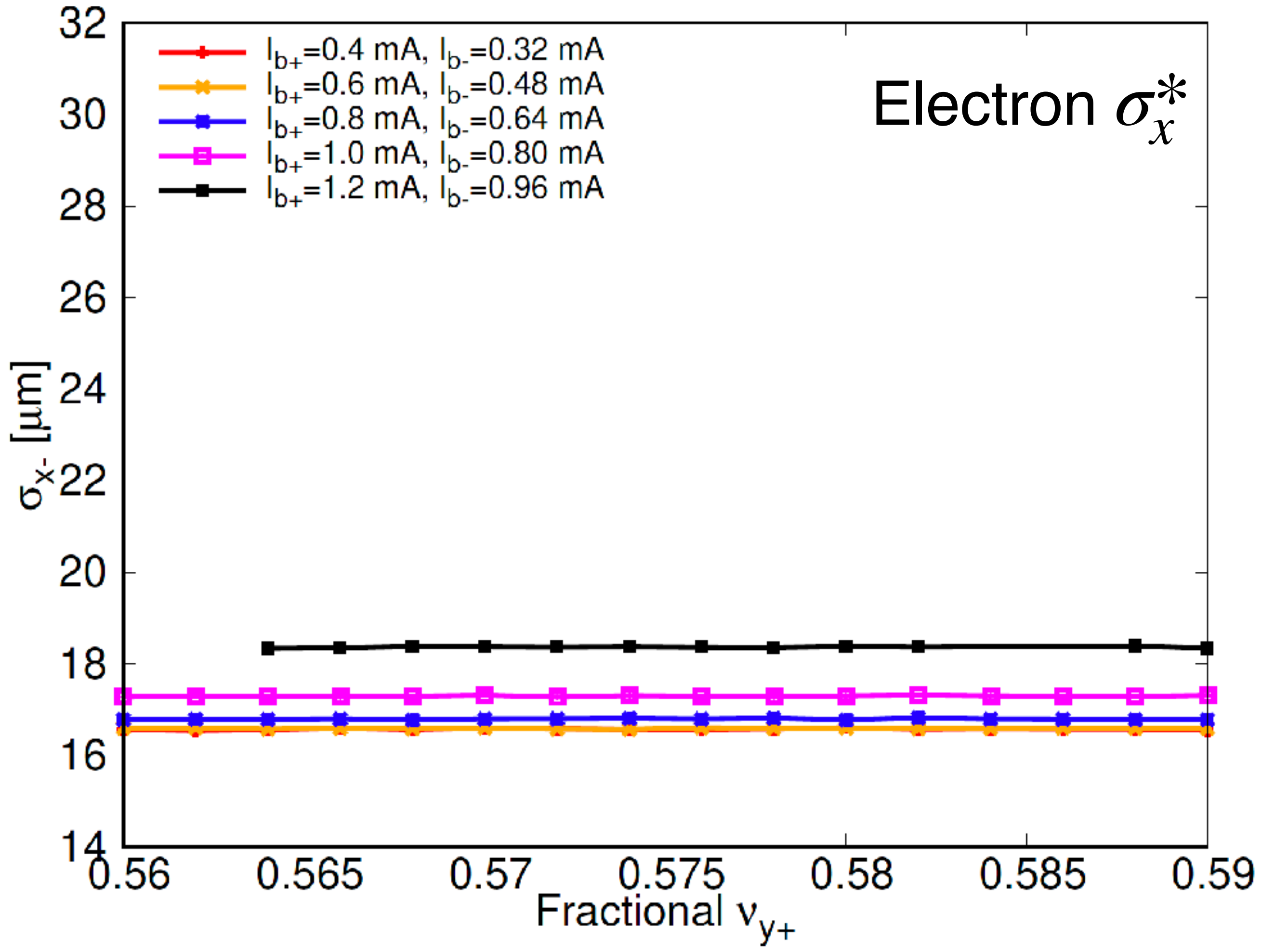
Status of beam-beam simulations

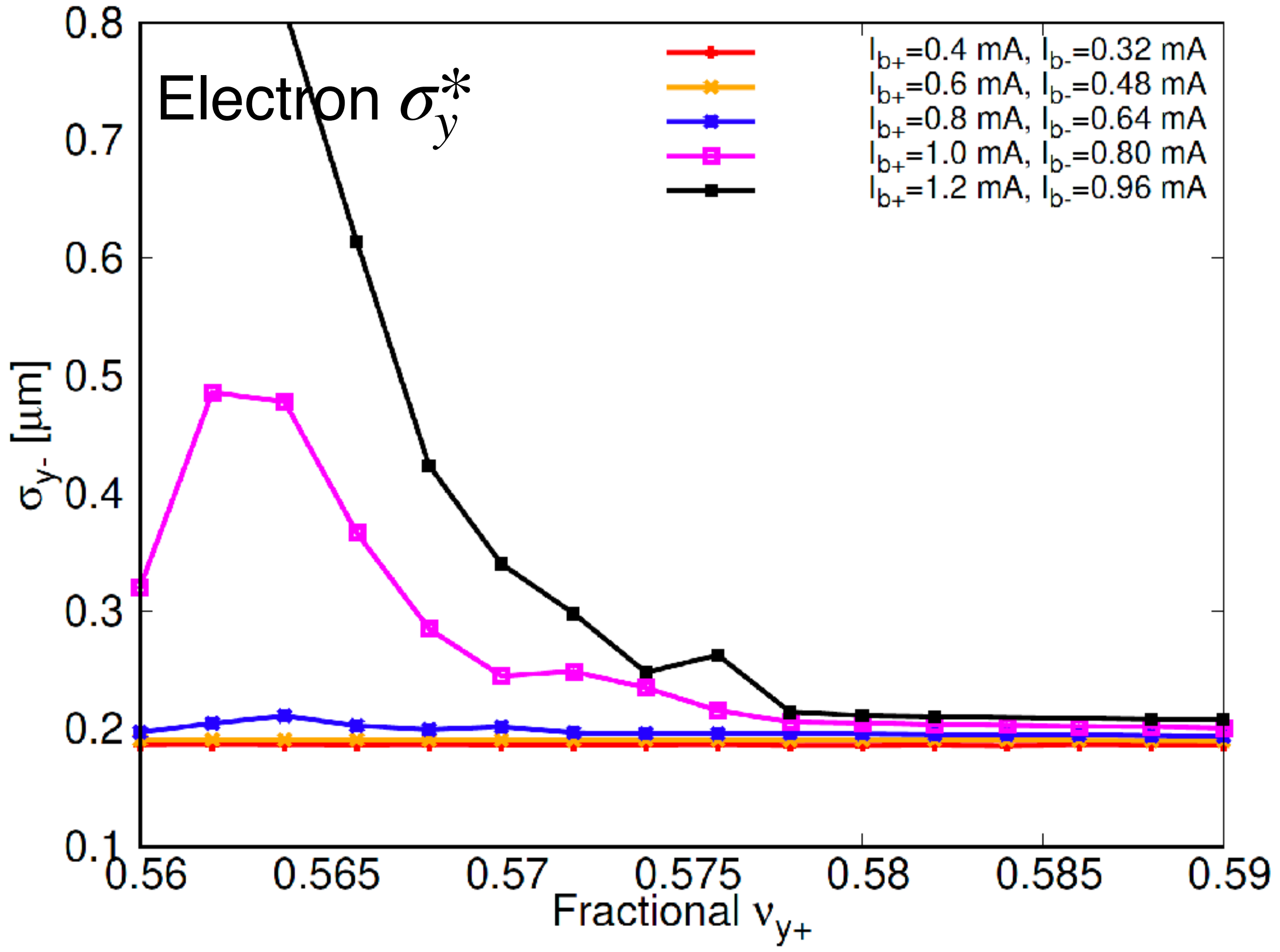
- BBSS simulations: Scan LER ν_y with bunch currents varied (with LER ν_x and HER $\nu_{x,y}$ fixed as the values of the parameter table of 2021.12.21, BB+Wxy+Wz)

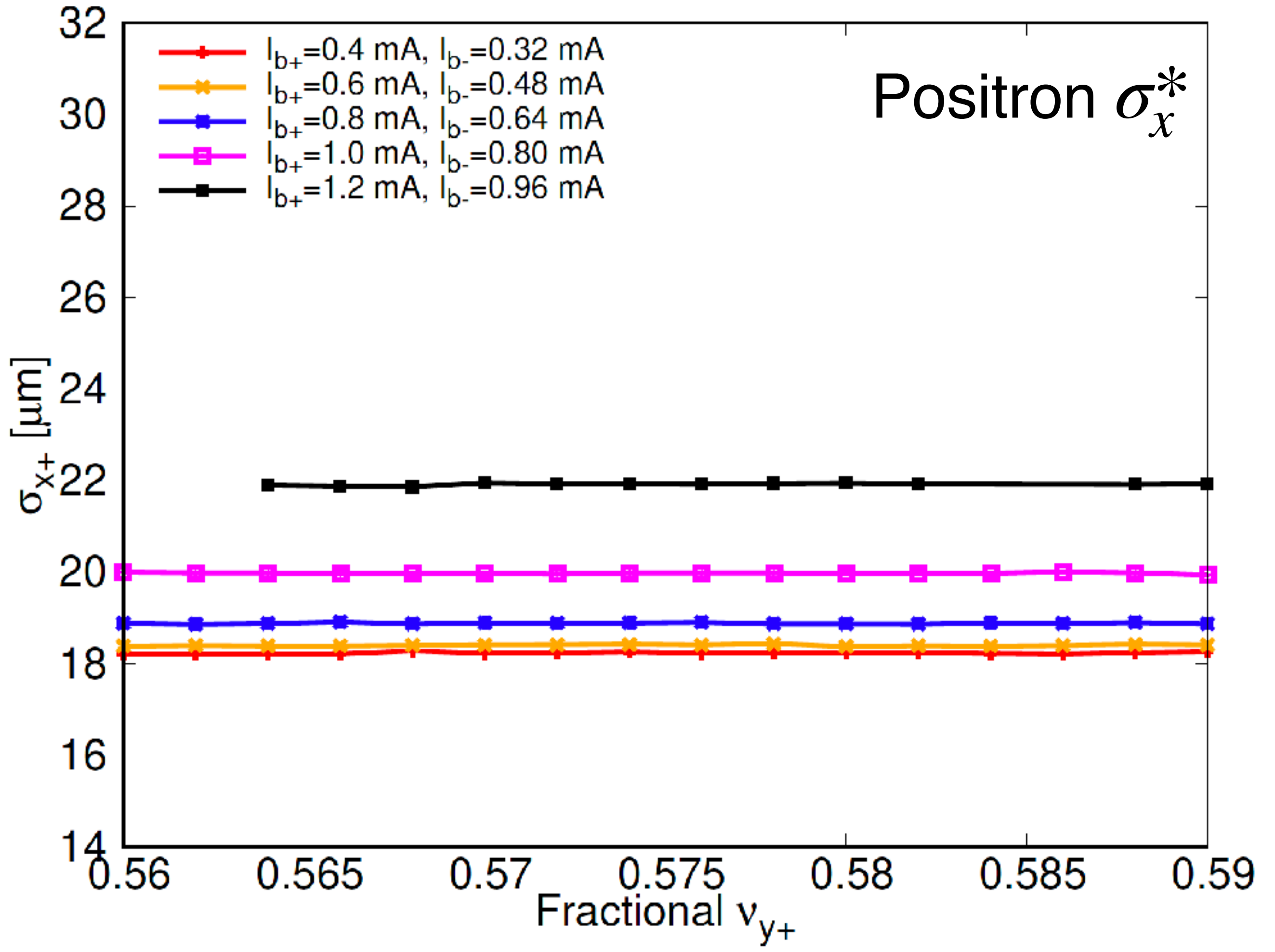
* The interplay of BB+Wx,y+Wz causes instability, consistent with Y. Zhang and K. Ohmi's findings.

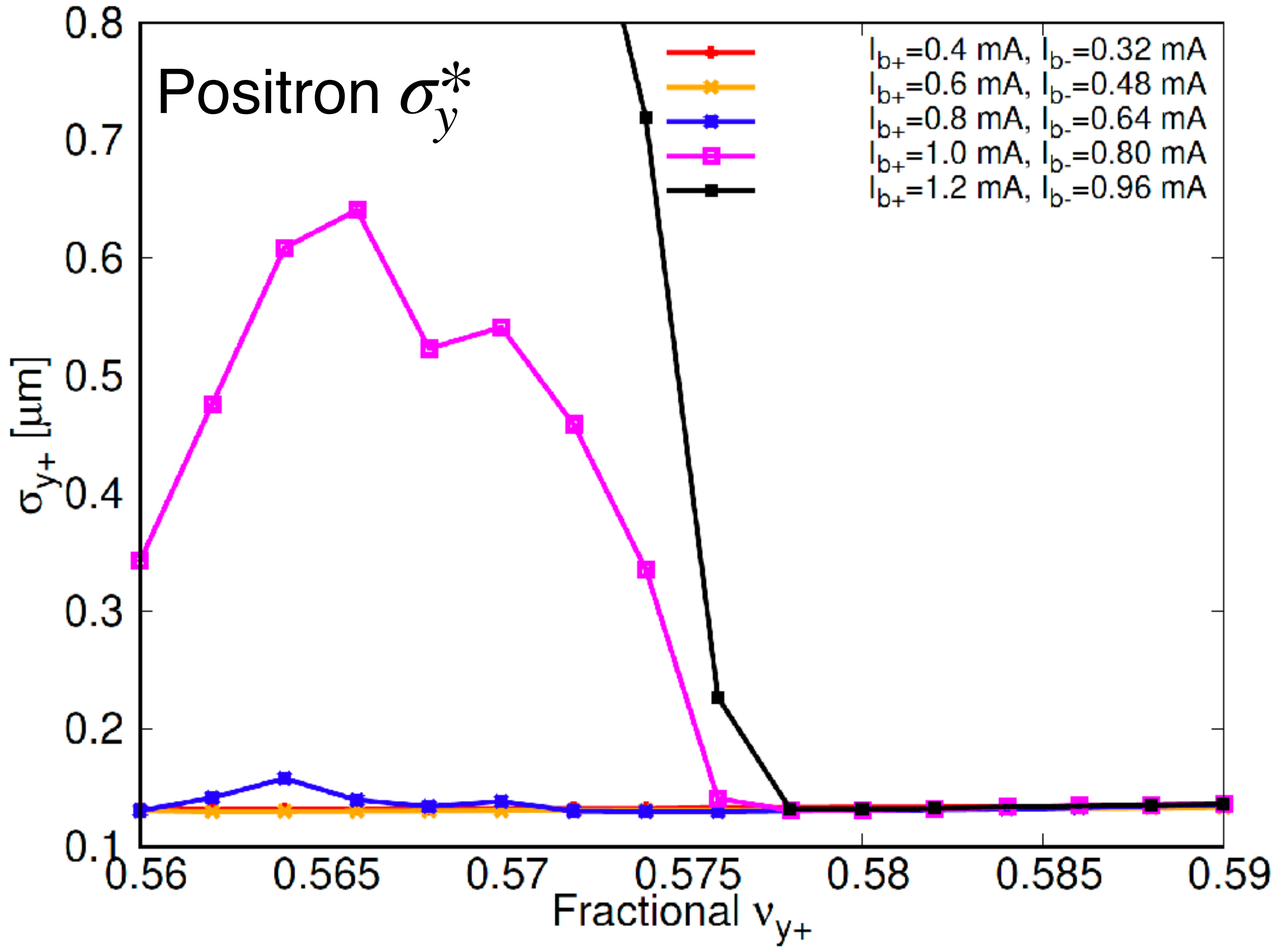
* This instability has a threshold that is ν_y-dependent.





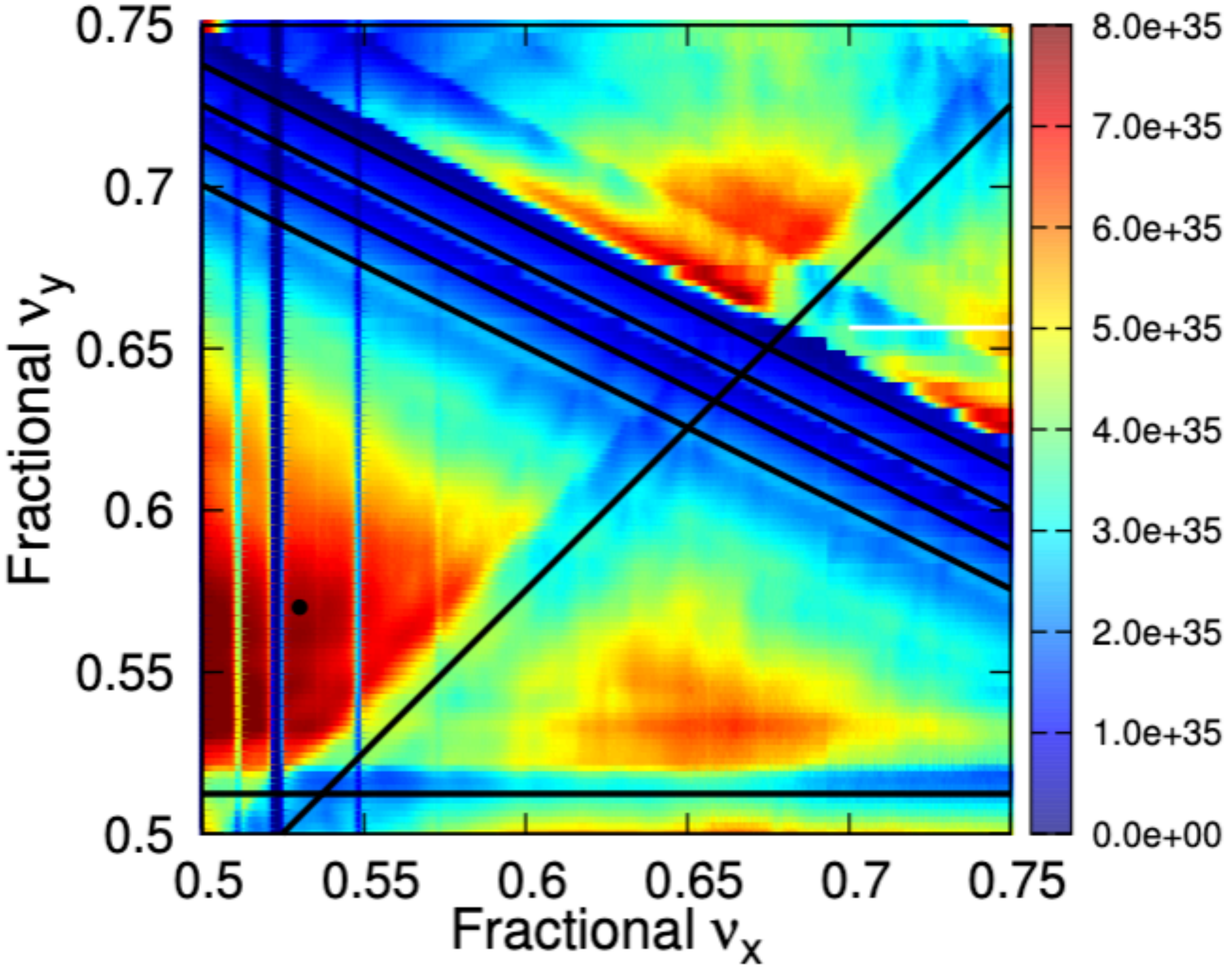


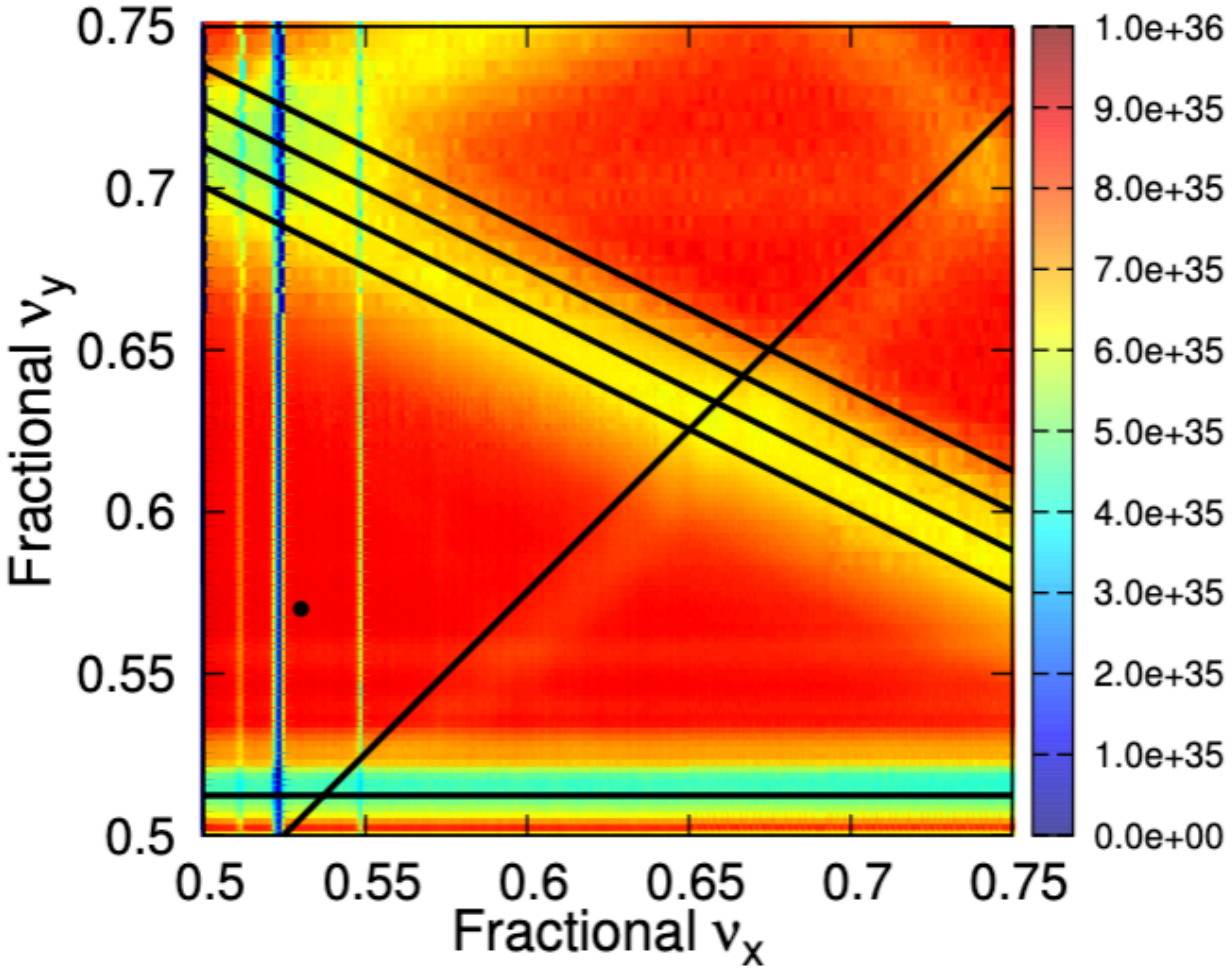




Crab waist applied to SuperKEKB

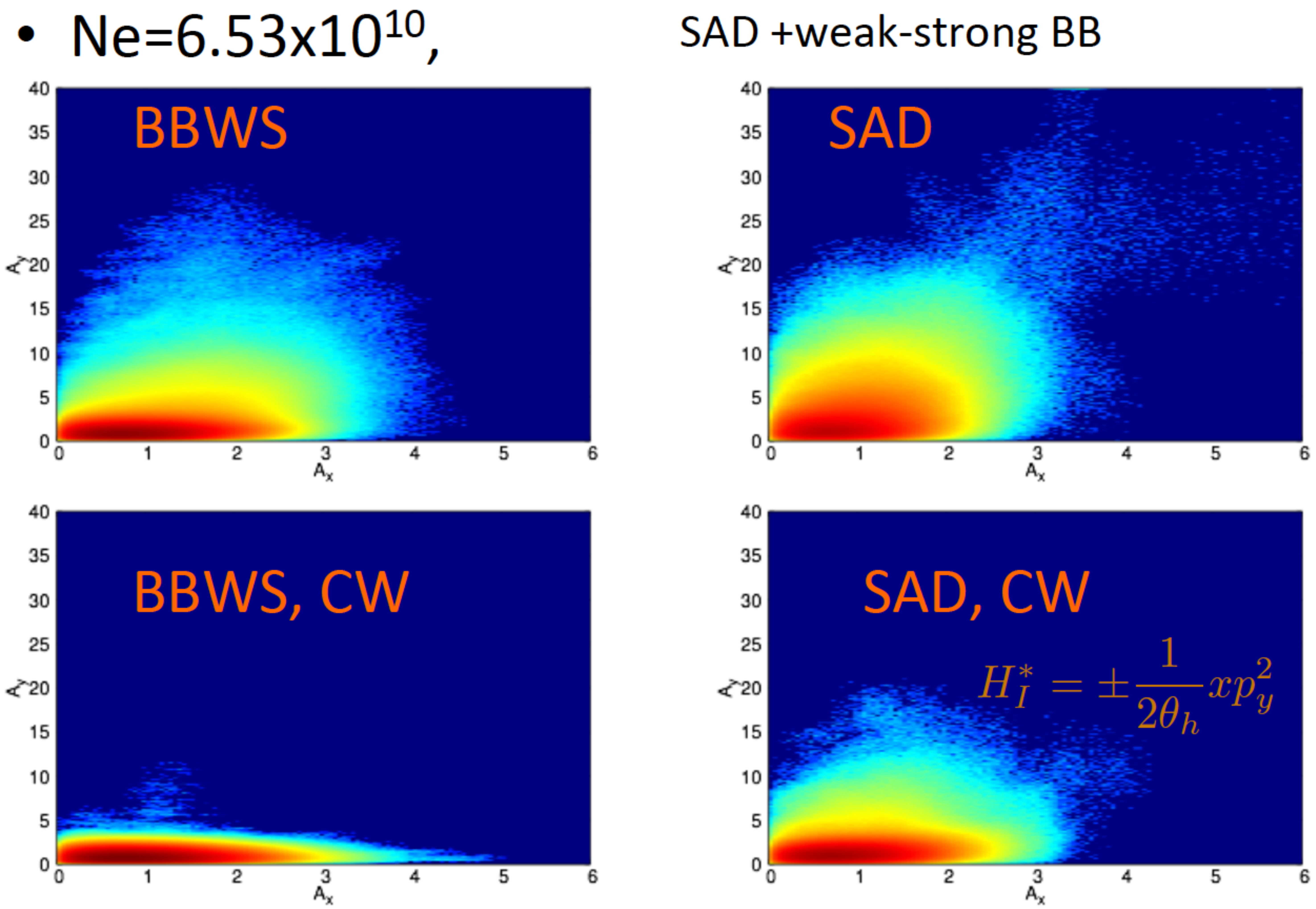
- SuperKEKB final design ($\beta_y^* = 0.3/0.27$ mm) with ideal crab waist
  - Tune scans using BBWS
  - Crab waist creates large area in tune space for choice of working point





Crab waist applied to SuperKEKB

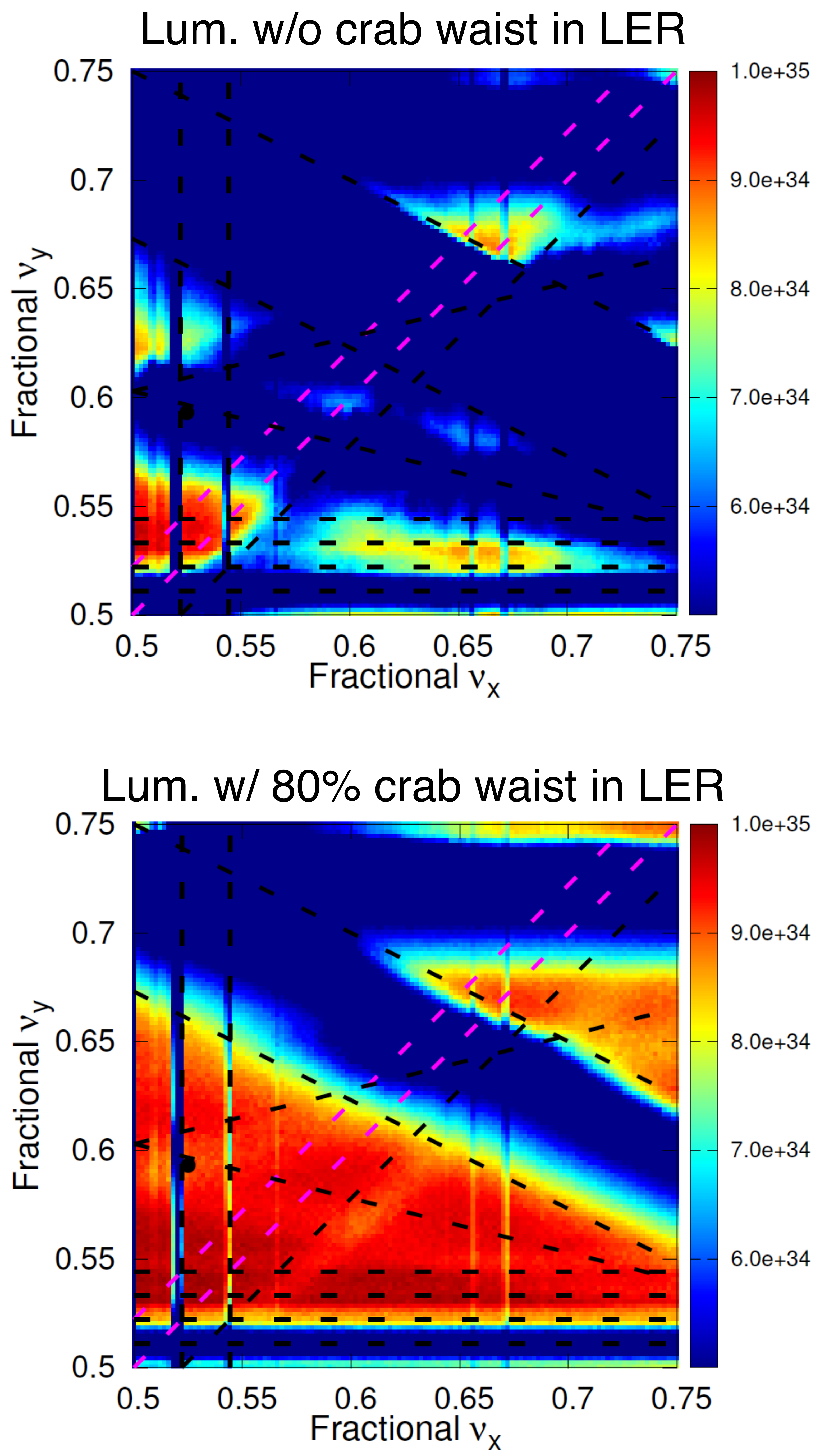
- SuperKEKB final design ($\beta_y^* = 0.3/0.27$ mm) with ideal crab waist
  - Beam-beam driven halo can be suppressed



Crab waist applied to SuperKEKB

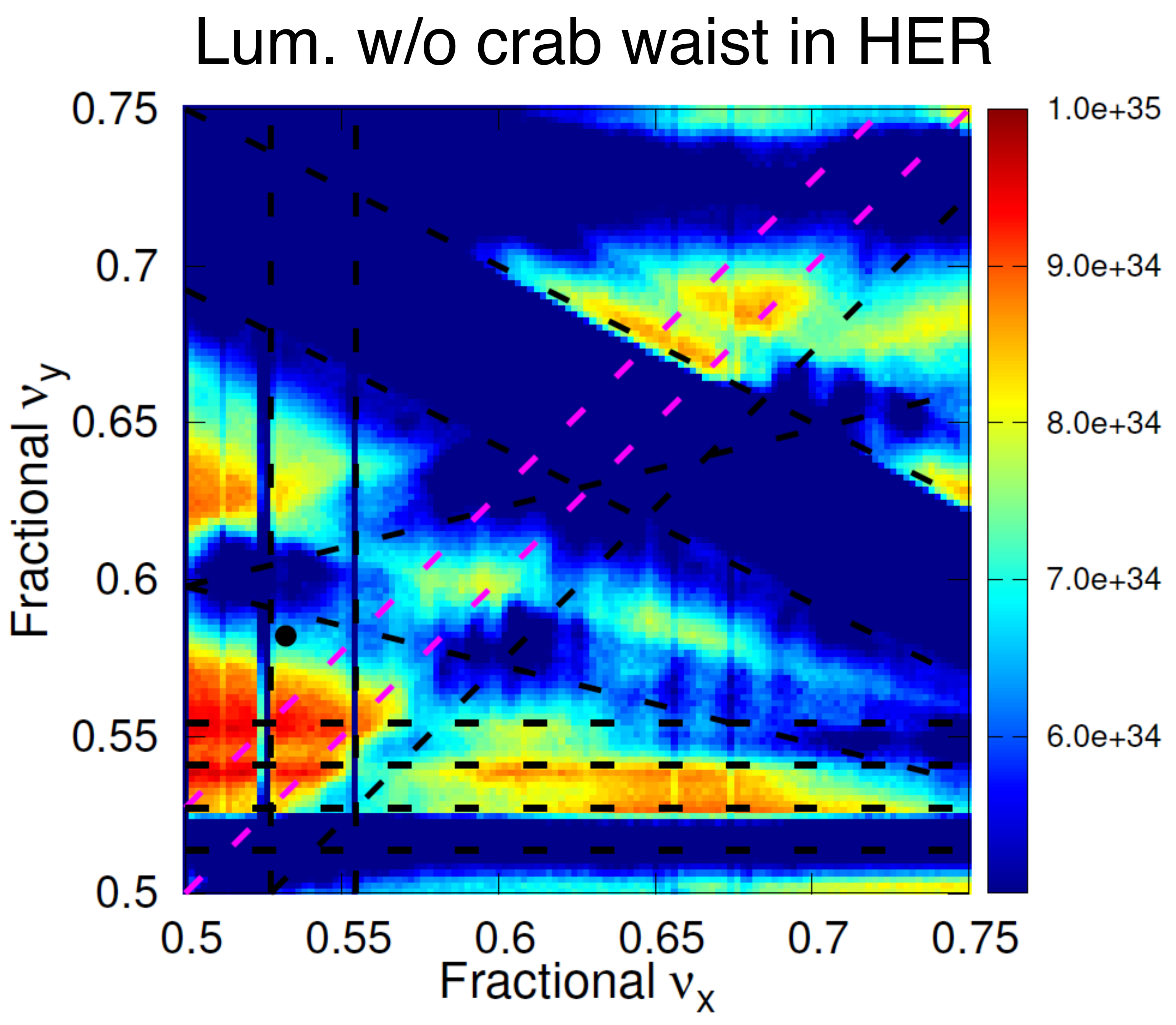
- SuperKEKB 2021b run ($\beta_y^* = 1$ mm) with ideal crab waist
  - Tune scan using BBWS showed that 80% crab waist ratio in LER is effective in suppressing vertical blowup caused by beam-beam resonances (mainly $\nu_x \pm 4\nu_y + \alpha = N$).

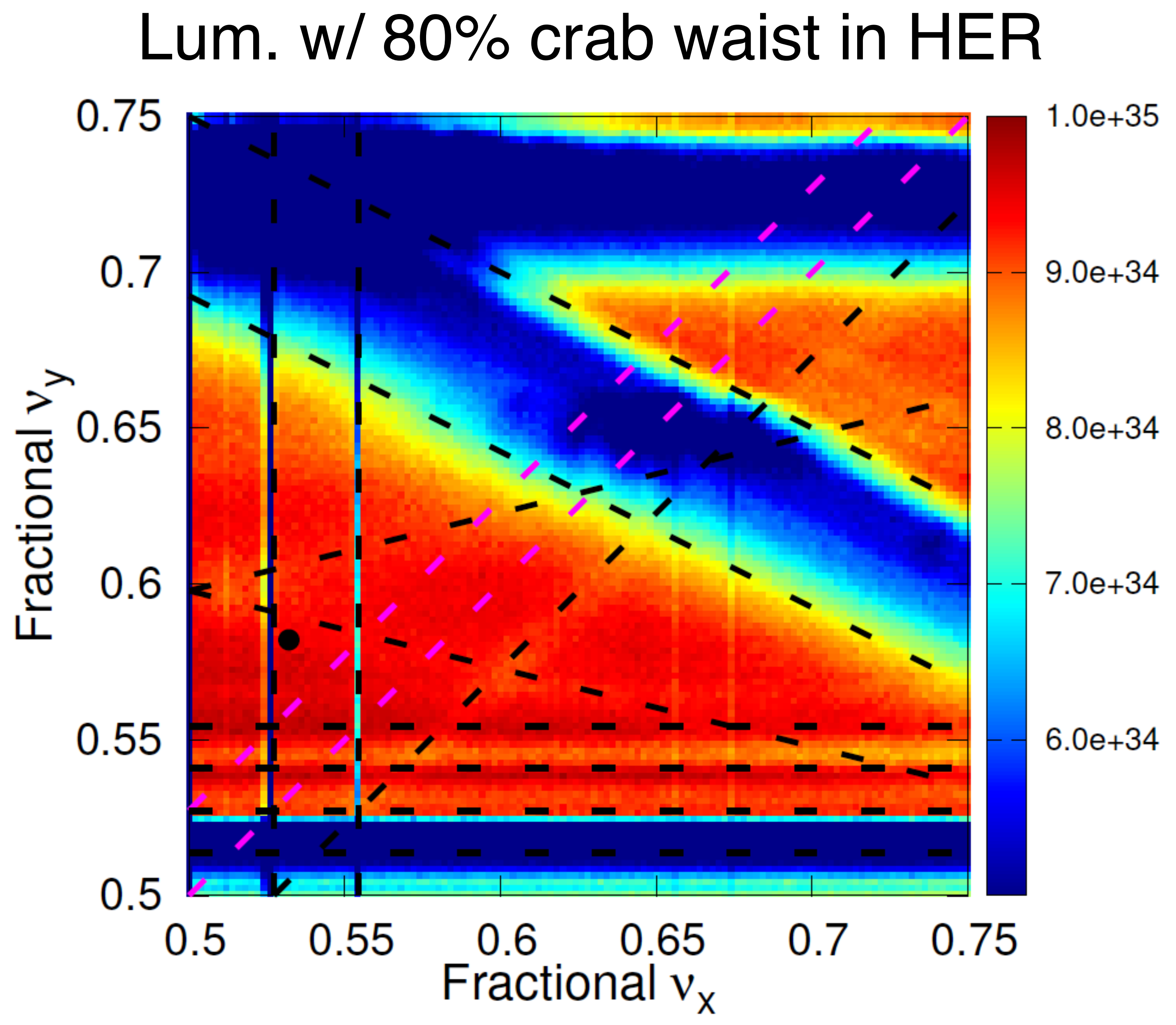
	2021.07.01		Comments
	HER	LER	
I_{bunch} (mA)	0.80	1.0	
# bunch	1174		Assumed value
ε_x (nm)	4.6	4.0	w/ IBS
ε_y (pm)	23	23	Estimated from XRM data
β_x (mm)	60	80	Calculated from lattice
β_y (mm)	1	1	Calculated from lattice
σ_{z0} (mm)	5.05	4.84	Natural bunch length (w/o MWI)
ν_x	45.532	44.525	Measured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

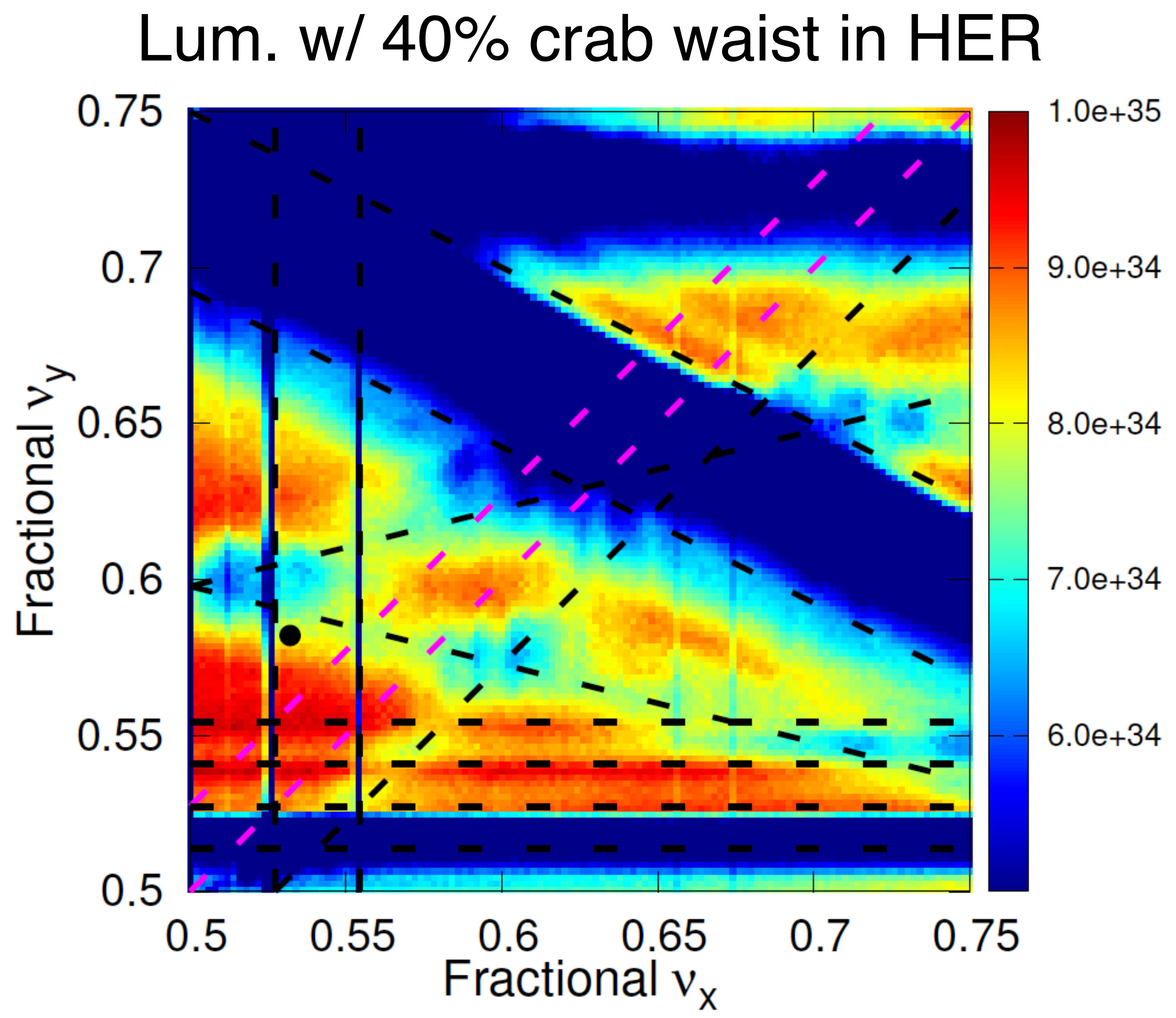


Crab waist applied to SuperKEKB

- SuperKEKB 2021b run ($\beta_y^* = 1$ mm) with ideal crab waist
  - Tune scan using BBWS showed that 40% crab waist ratio (current operation condition) in HER is not enough for suppressing vertical blowup caused by beam-beam resonances (mainly $\nu_x \pm 4\nu_y + \alpha = N$).

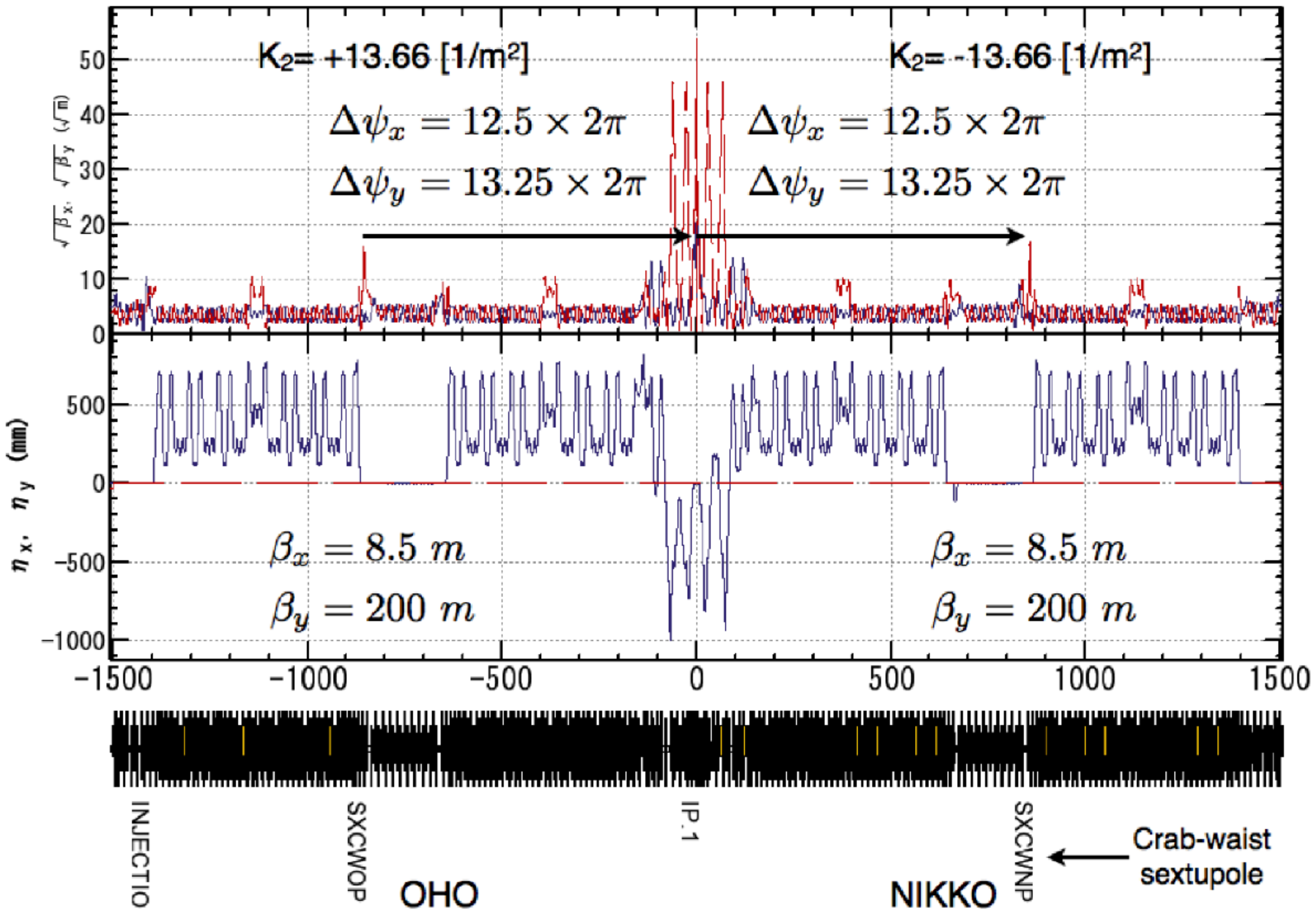






Crab waist applied to SuperKEKB

- SuperKEKB final design ($\beta_y^* = 0.3/0.27$ mm) with practical crab waist
  - CW scheme with CW sextupoles outside IR
  - CW reduces dynamic aperture and Touschek lifetime, and was not chosen as baseline for TDR



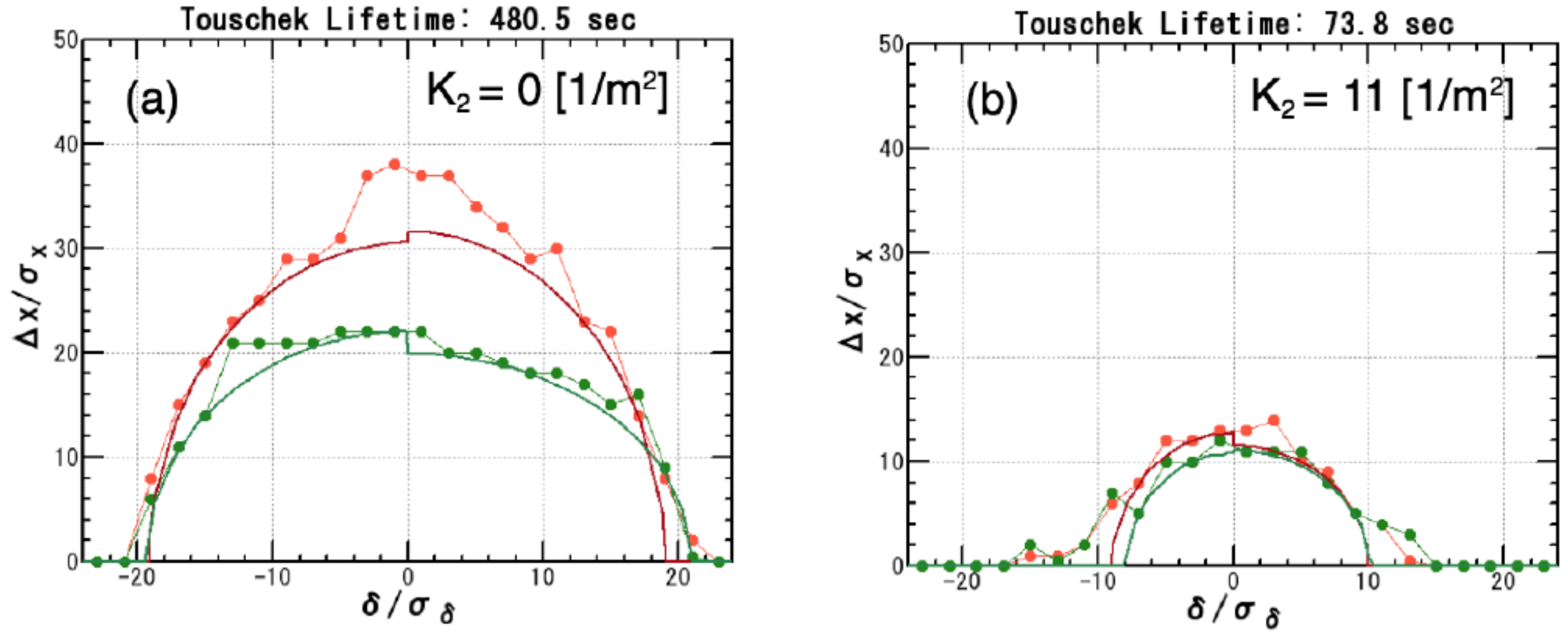
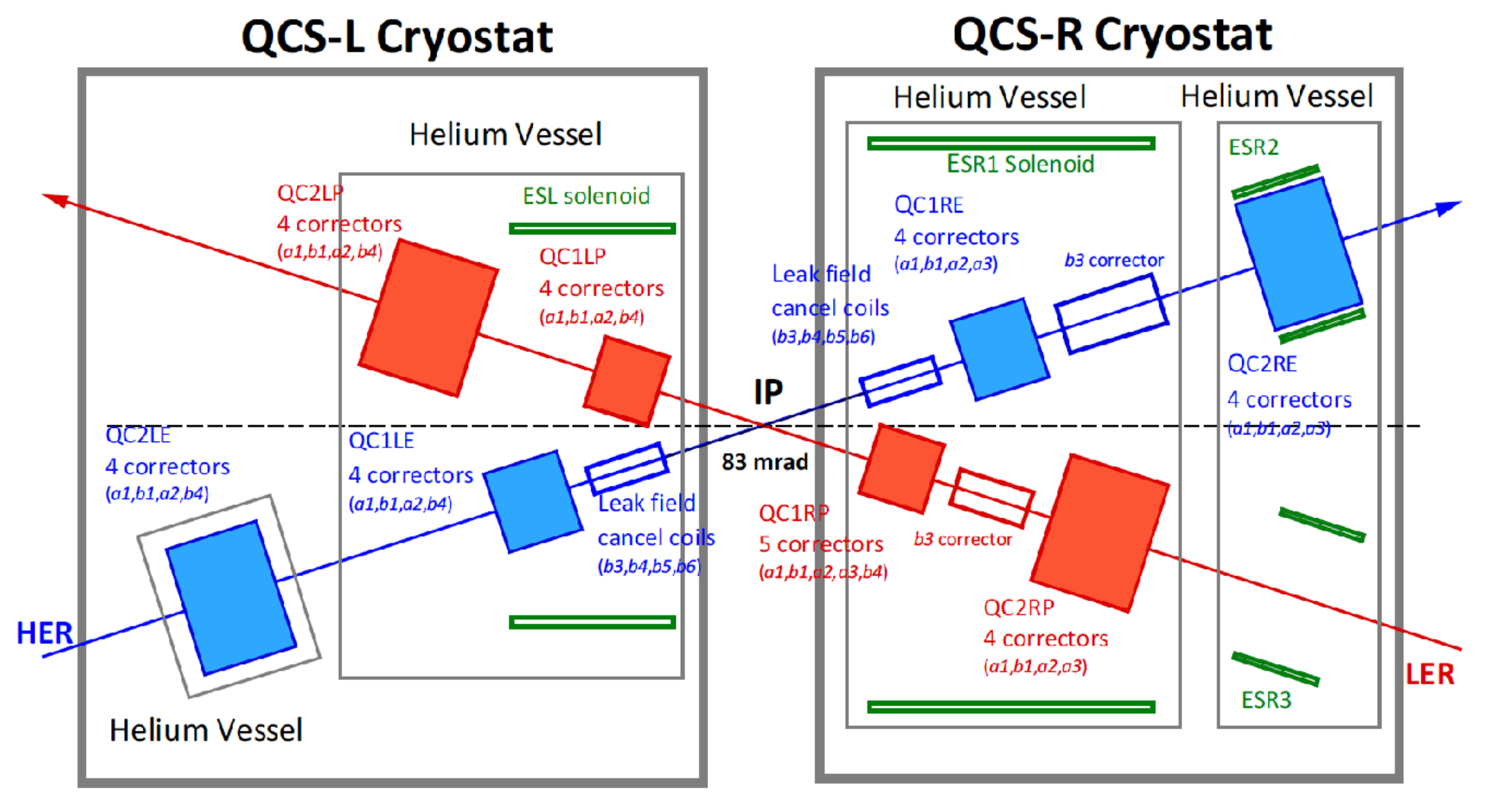


Figure 4.28: Dynamic aperture in the LER crab-waist lattice without beam-beam effect. Initial ratio of the vertical to the horizontal amplitude is 0.27 %. (a) $K_2 = 0$ [1/m^2], (b) $K_2 = 11$ [1/m^2].

[2] SuperKEKB TDR.

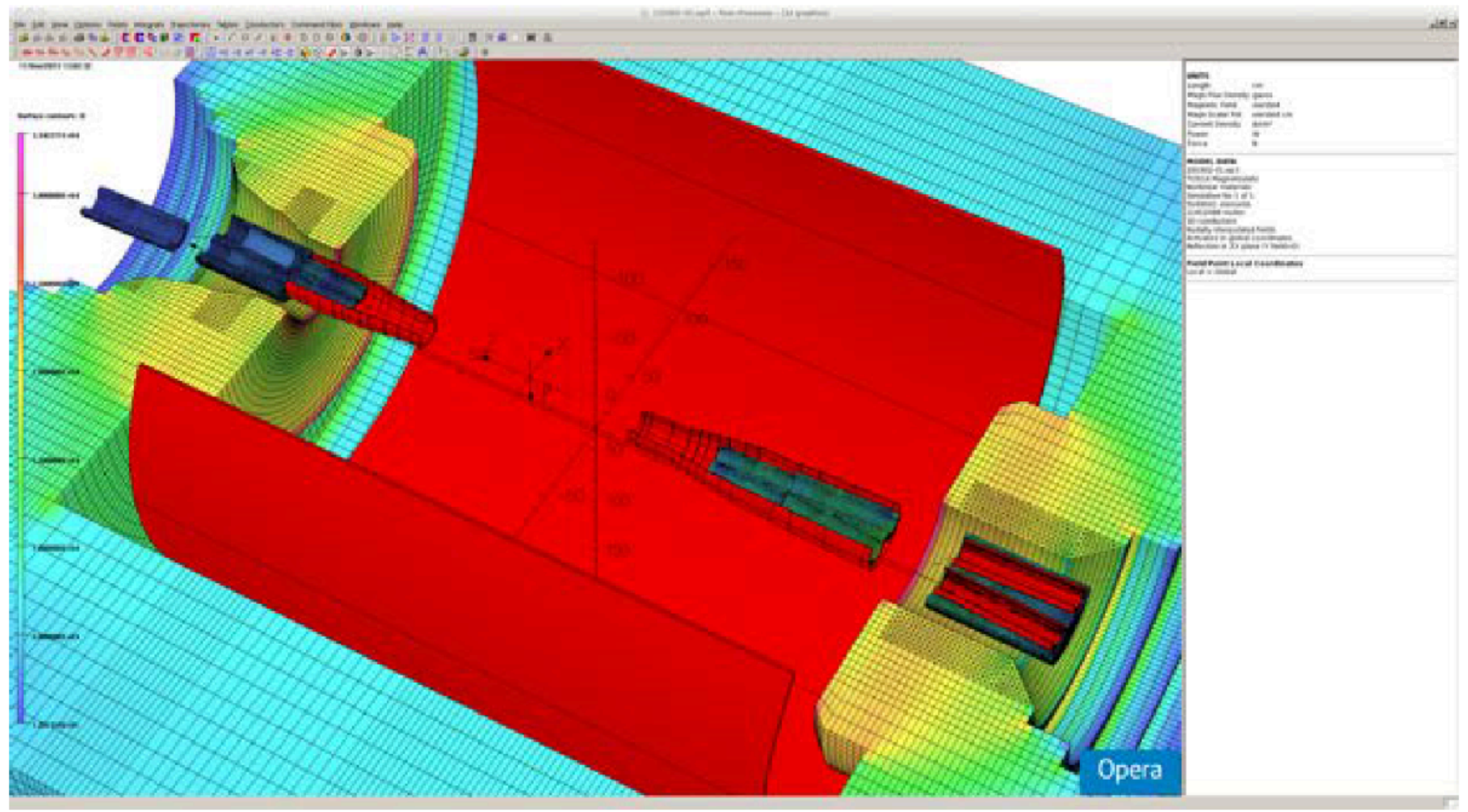
Crab waist applied to SuperKEKB

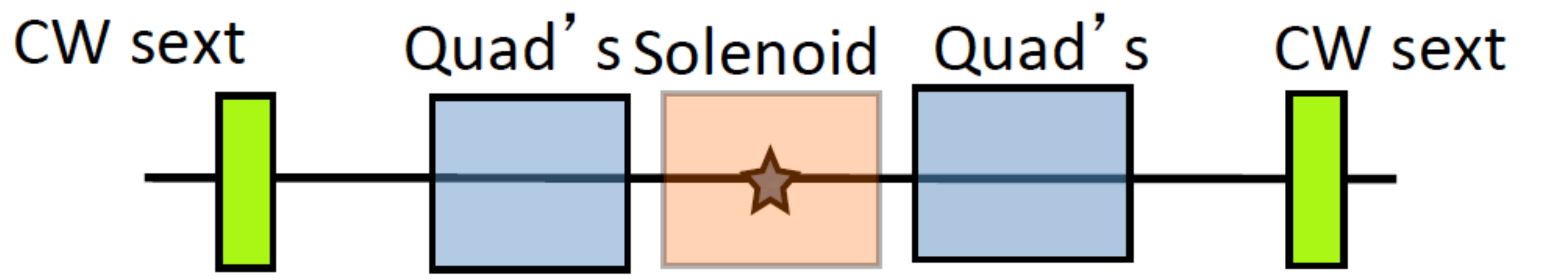
- SuperKEKB final design ($\beta_y^* = 0.3/0.27$ mm) with practical crab waist
  - CW does not work well because of the nonlinear IR. The nonlinearity scales as $1/\beta_y^*$.
  - SuperKEKB design lattice include nonlinear fields extracted from 3D model



4 SC main quadrupole magnets: 1 collared magnet, 3 yoked magnets
16 SC correctors: a1, b1, a2, b4
4 SC leak field cancel magnets: b3, b4, b5, b6
1 compensation solenoid

4 SC main quadrupole magnets: 1 collared magnet, 3 yoked magnets
19 SC correctors: a1, b1, a2, a3, b3, b4
4 SC leak field cancel magnets: b3, b4, b5, b6
3 compensation solenoid





$$\mathcal{M}_{IR} = e^{-axy^2} e^{-H_{Q's}} e^{-H_{Sol}} e^{-H_{BB}} e^{-H_{Sol}} e^{-H_{Q's}} e^{-axy^2}$$

crab waist sext — crab waist sext

$\neq$

ideal crab waist — ideal crab waist

$$e^{-H_{Q's}} e^{-H_{Sol}} e^{-xp_y^2/2\phi} e^{-H_{BB}} e^{-xp_y^2/2\phi} e^{-H_{Sol}} e^{-H_{Q's}}$$

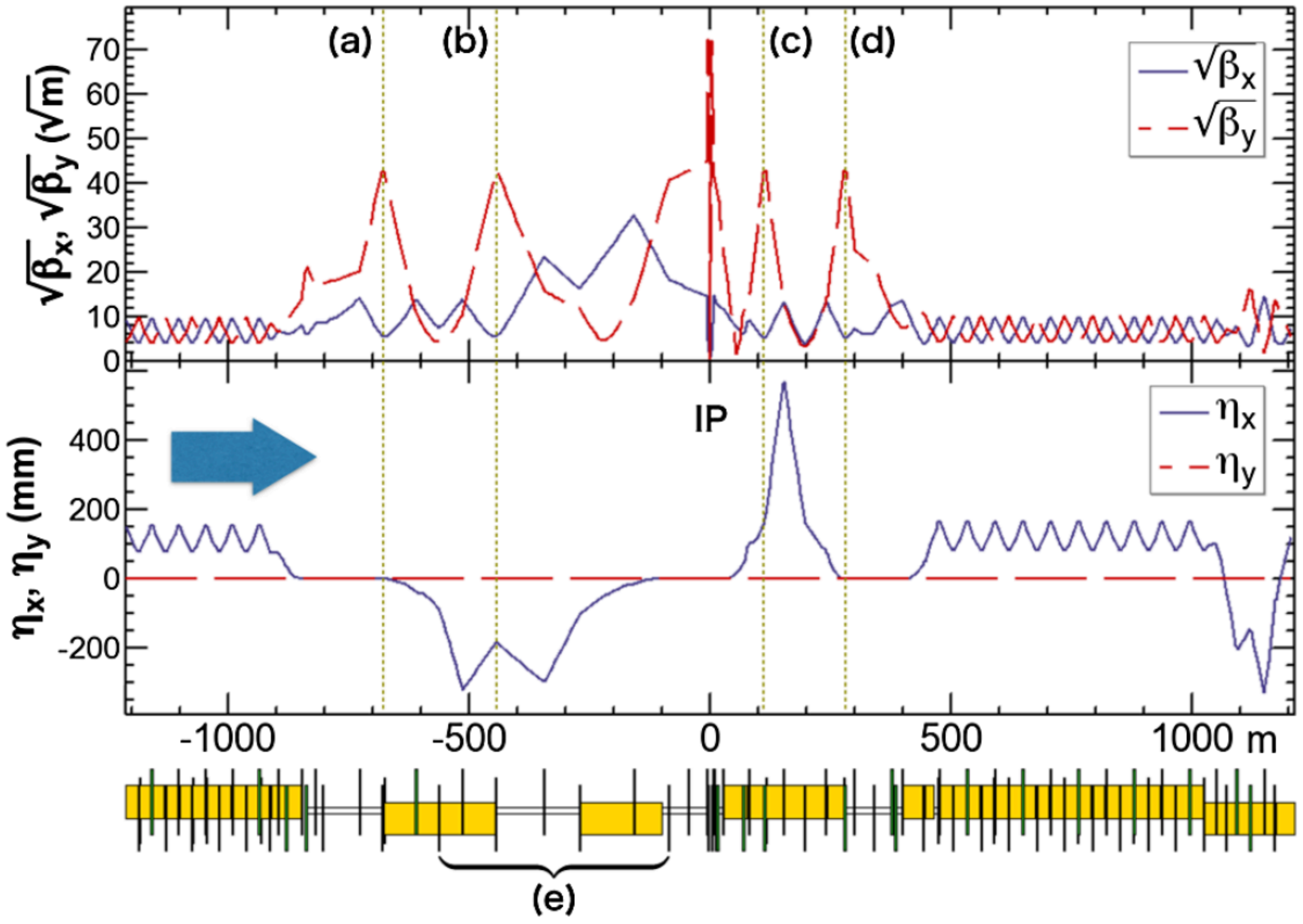
[4] K. Ohmi, EIC workshop, March, 2014.

[3] N. Ohuchi, SuperKEKB ARC, 2018.

Crab waist applied to SuperKEKB

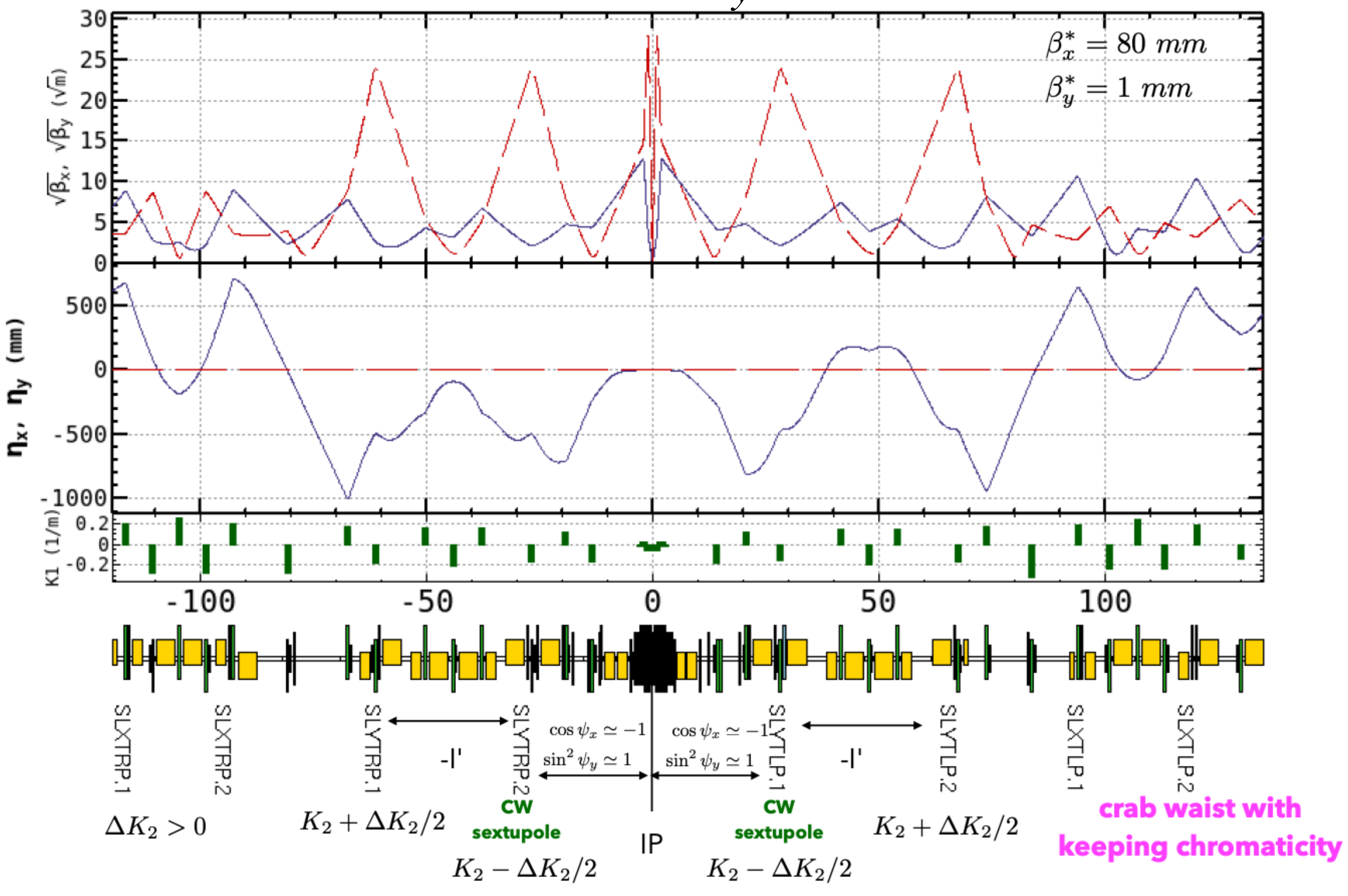
- Optics design with crab waist for $\beta_y^* = 1$ mm
  - In 2020, K. Oide introduced the FCC-ee CW scheme to SuperKEKB.
  - FCC-ee CW scheme utilizes the sextupoles (a-d) for local chromaticity correction and crab waist.

FCC-ee



[5] K. Oide et al., PRAB 19, 111005 (2016).

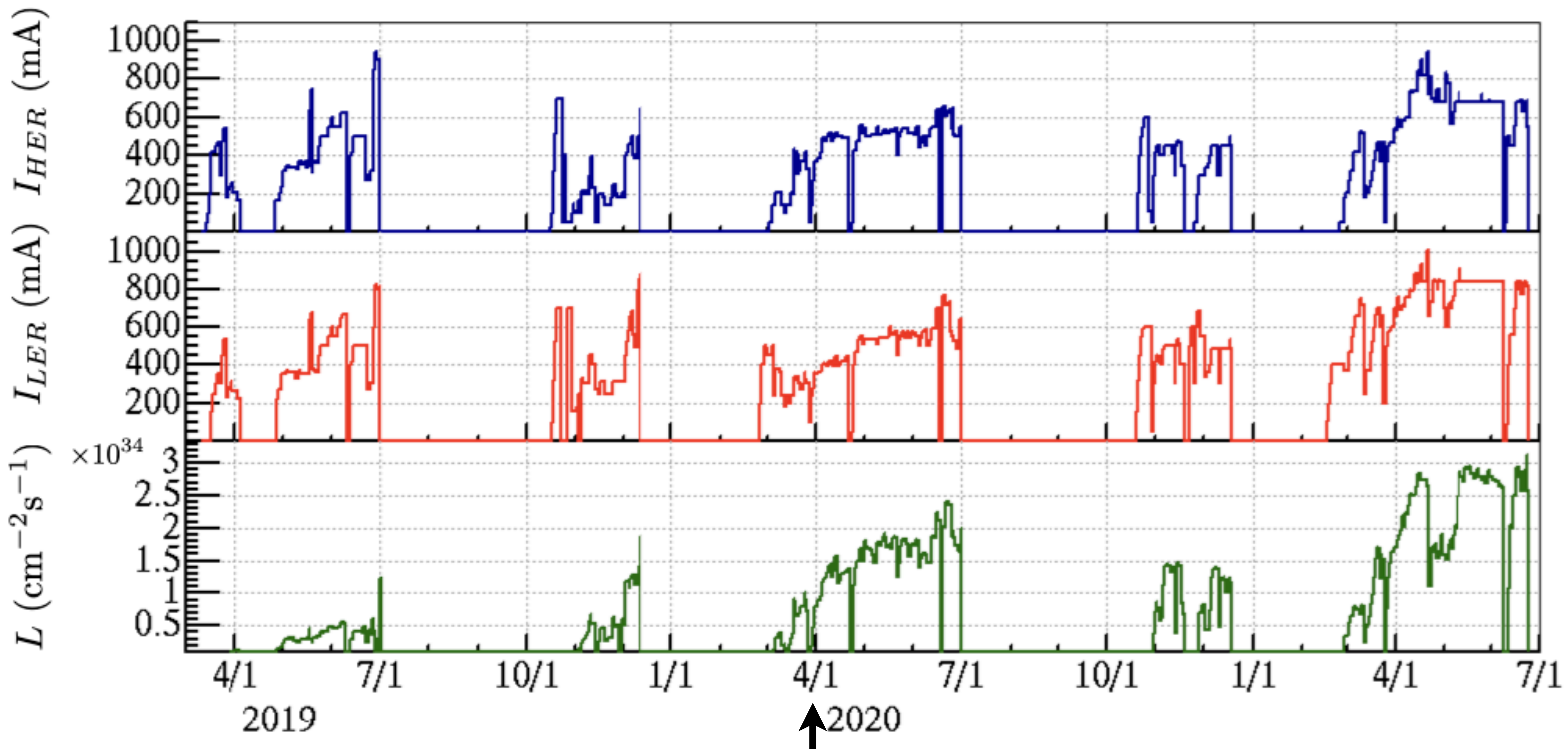
SuperKEKB w/ $\beta_y^* = 1$ mm



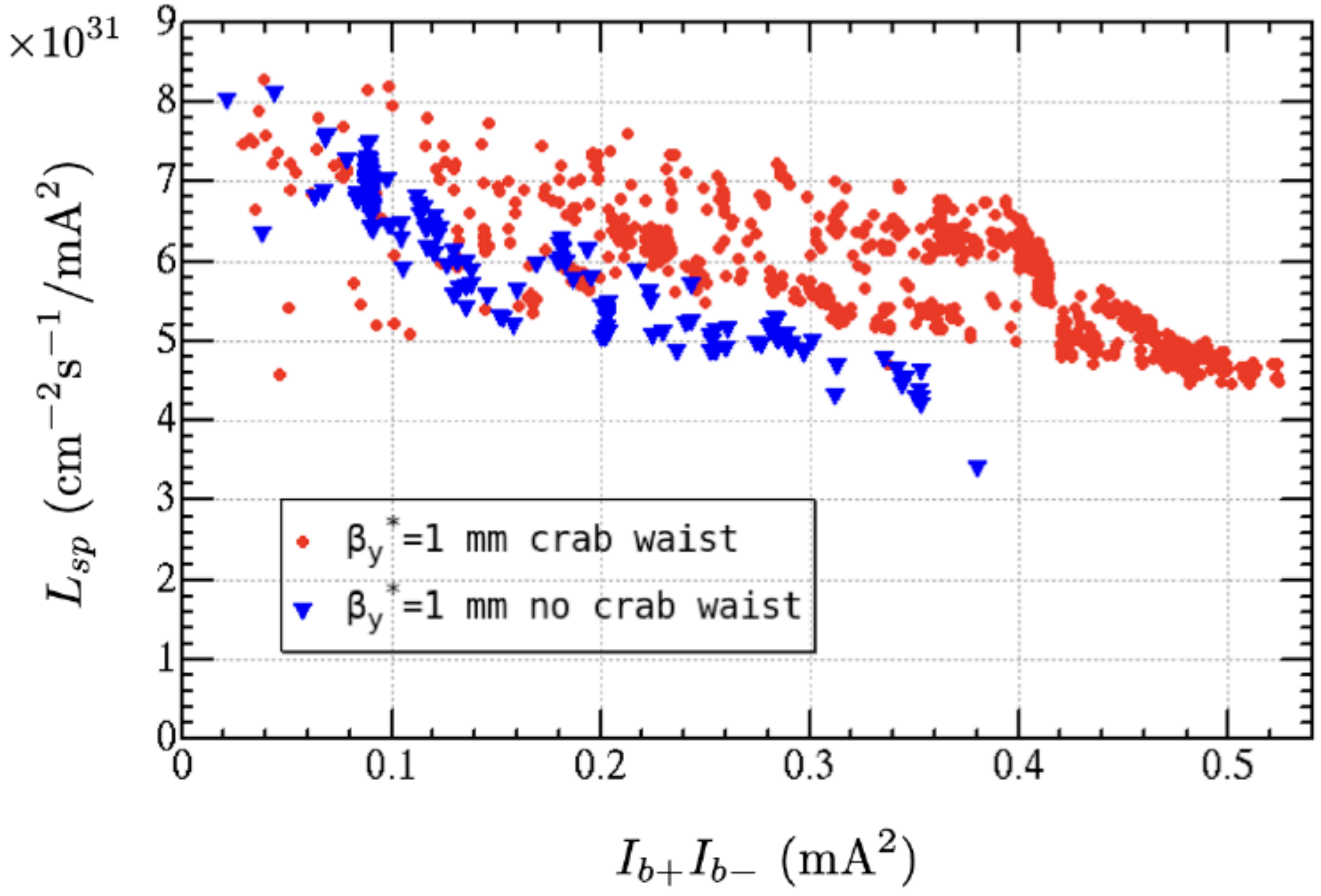
[6] Y. Ohnishi, SuperKEKB ARC 2020.

Crab waist applied to SuperKEKB

- SuperKEKB beam operation with crab waist for $\beta_y^* = 1$ mm
  - Operation with CW has been successful.



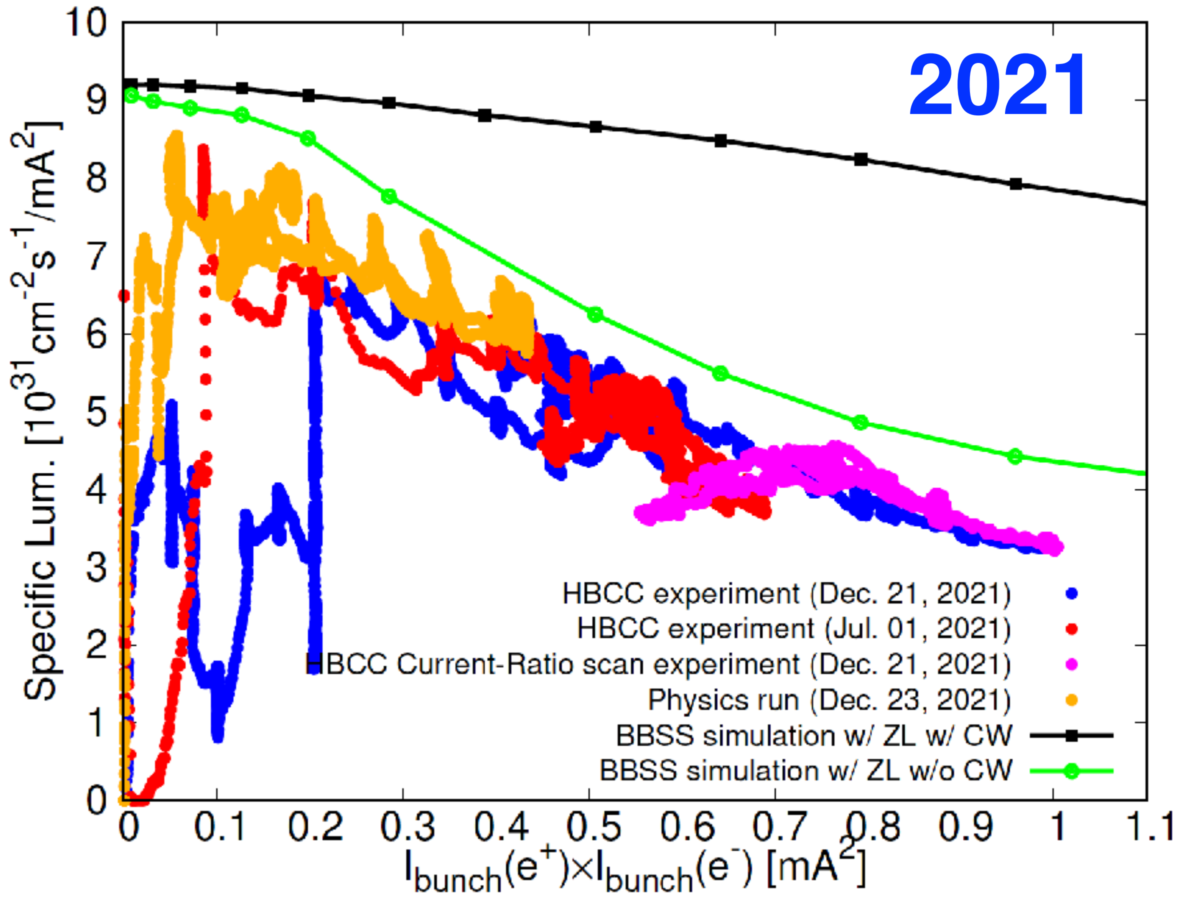
Crab waist introduced since April 2020



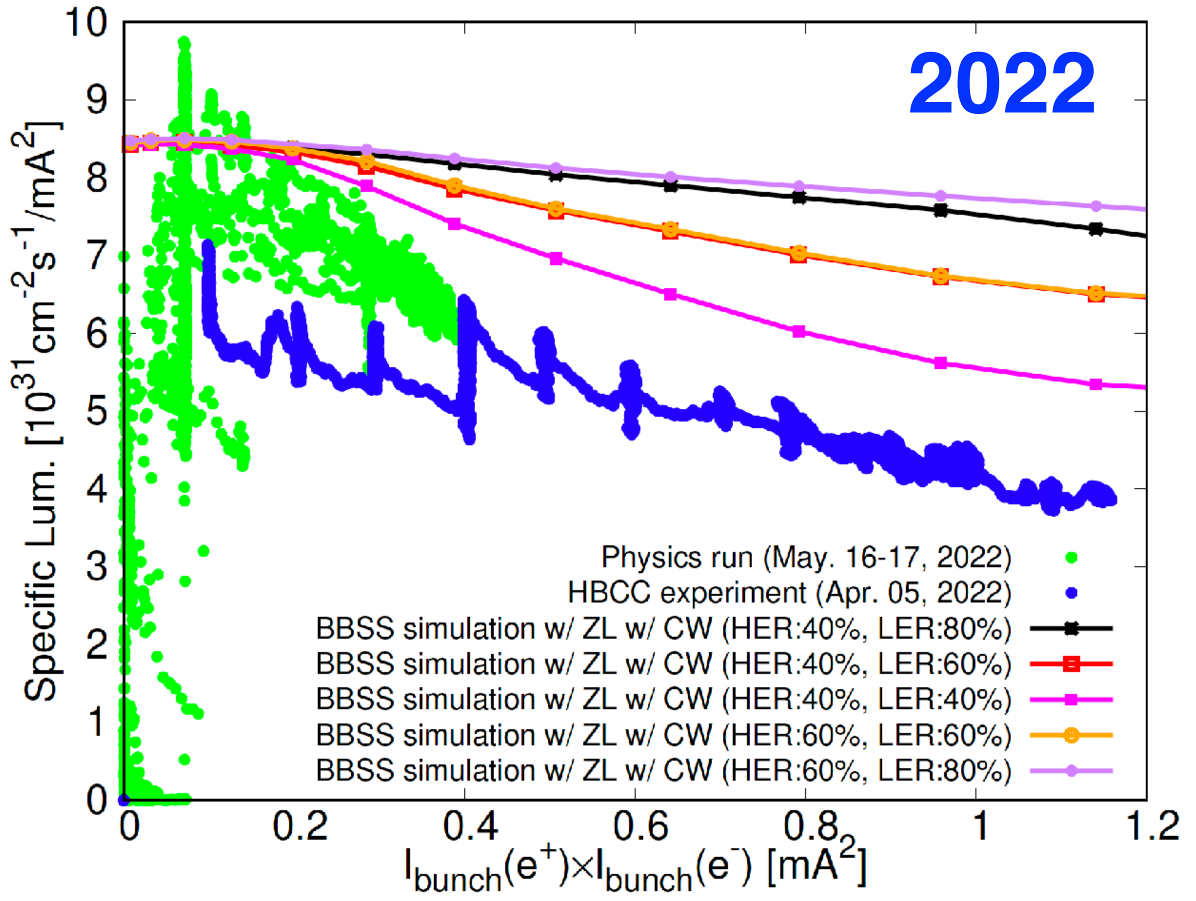
[7] Y. Ohnishi, The European Physical Journal Plus volume 136, 1023 (2021).

Comparison of simulations and experimental results

- HBCC machine studies with $\beta_y^* = 1$ mm in 2021 and 2022:
  - High-bunch current collision (HBCC) machine studies were done to extract the luminosity performance
  - Lsp slope (experiments) improved in 2022, but it still dropped fast



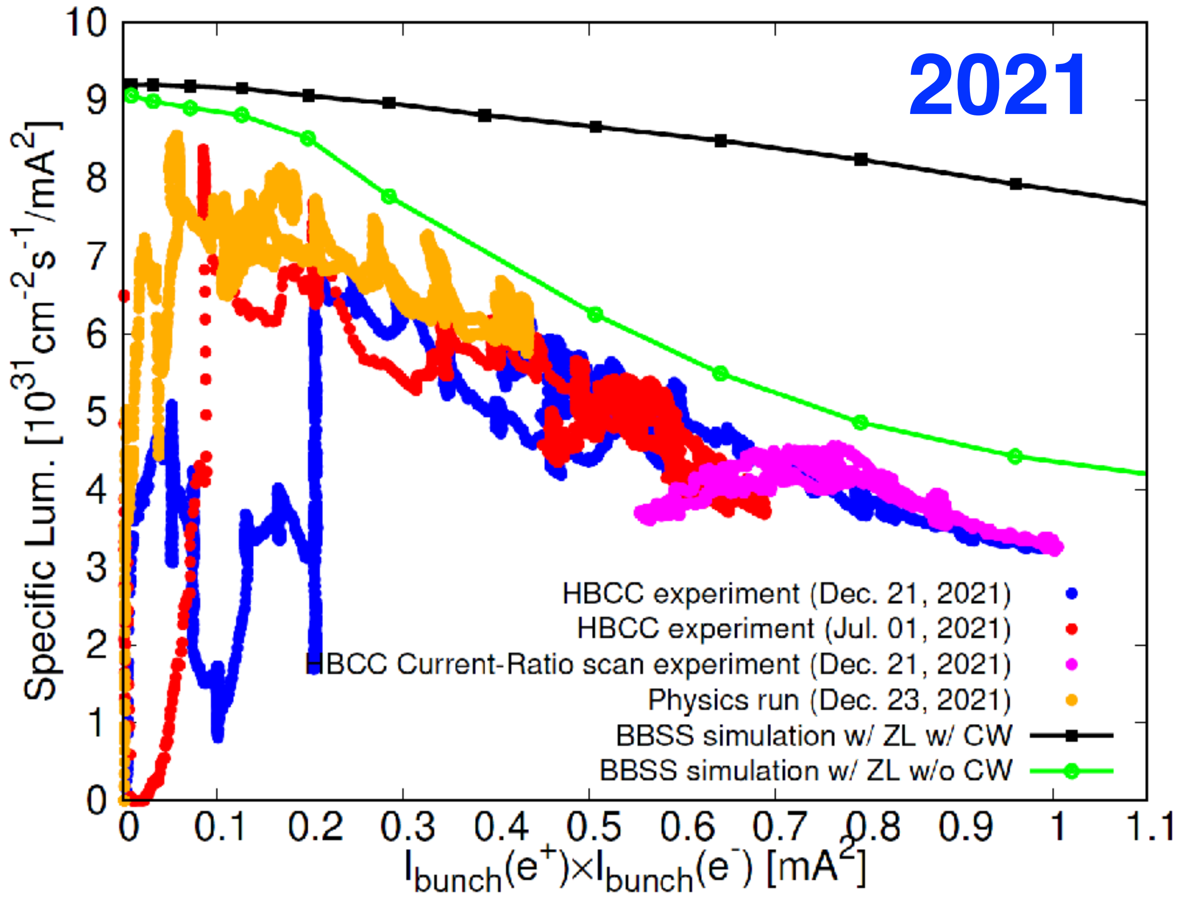
Specific luminosity

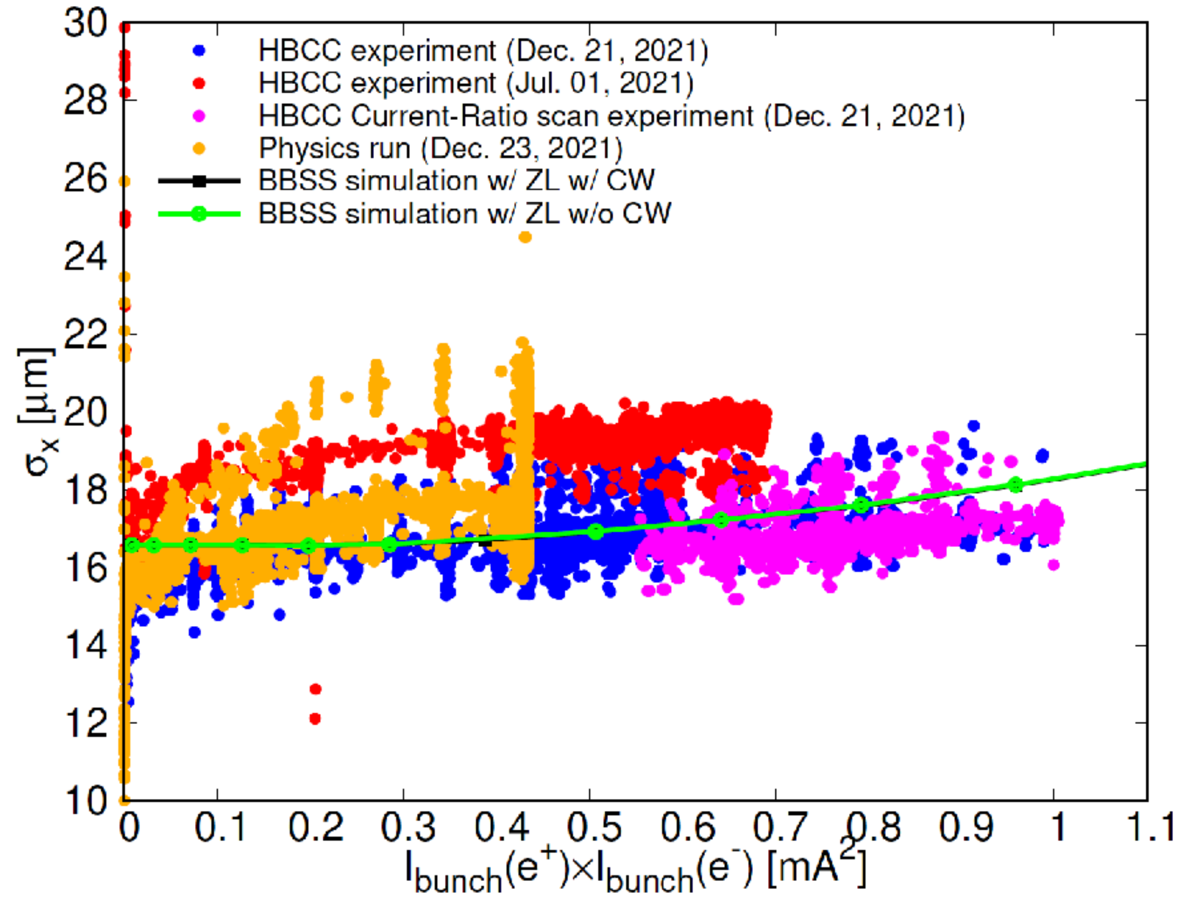


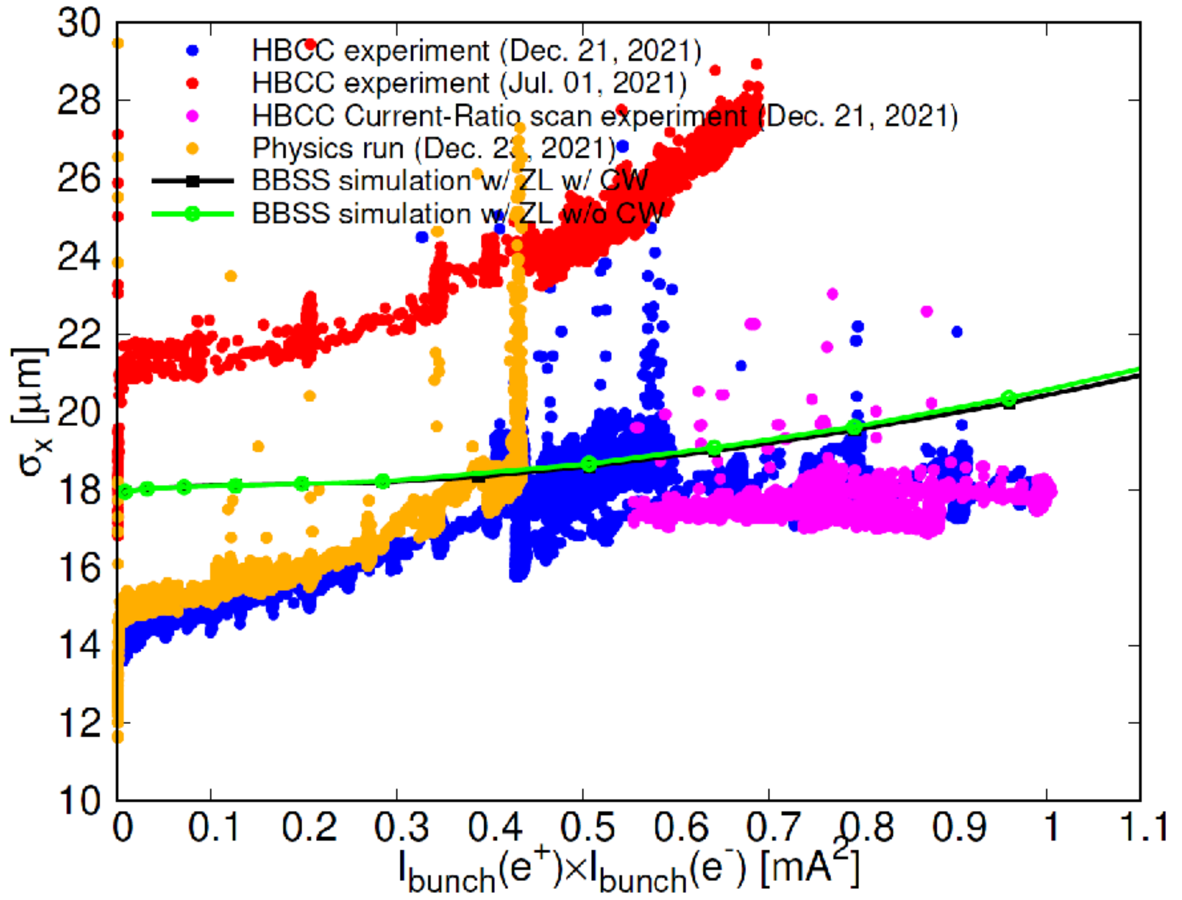
	2021.12.21		2022.04.05		Comments
	HER	LER	HER	LER	
I_{bunch} (mA)	Ie	1.25*Ie	Ie	1.25*Ie	
# bunch	393		393		Assumed value
ε_x (nm)	4.6	4.0	4.6	4.0	w/ IBS
ε_y (pm)	35	20	30	35	Estimated from XRM data
β_x (mm)	60	80	60	80	Calculated from lattice
β_y (mm)	1	1	1	1	Calculated from lattice
σ_{z0} (mm)	5.05	4.60	5.05	4.60	Natural bunch length (w/o MWI)
ν_x	45.53	44.524	45.532	44.524	Measured tune of pilot bunch
ν_y	43.572	46.589	43.572	46.589	Measured tune of pilot bunch
ν_s	0.0272	0.0233	0.0272	0.0233	Calculated from lattice
Crab waist	40%	80%	40%	80%	Lattice design

Comparison of simulations and experimental results

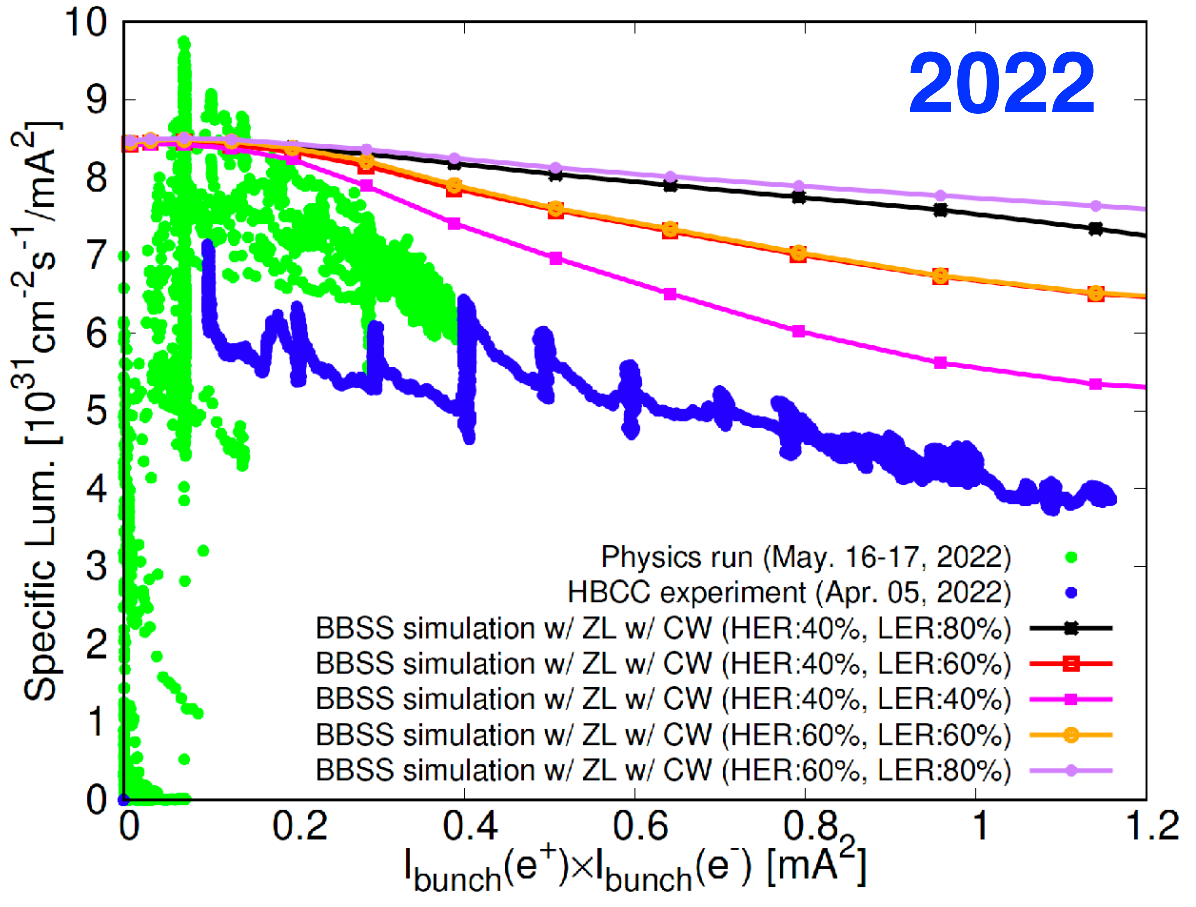
- HBCC machine studies with $\beta_y^* = 1$ mm in 2021 and 2022:
  - Weak blowup of horizontal beam size (see page.11): qualitative agreements between simulations and experiments
  - Horizontal blowup is sensitive to horizontal tune (see page.11 for simulations of tune scan)

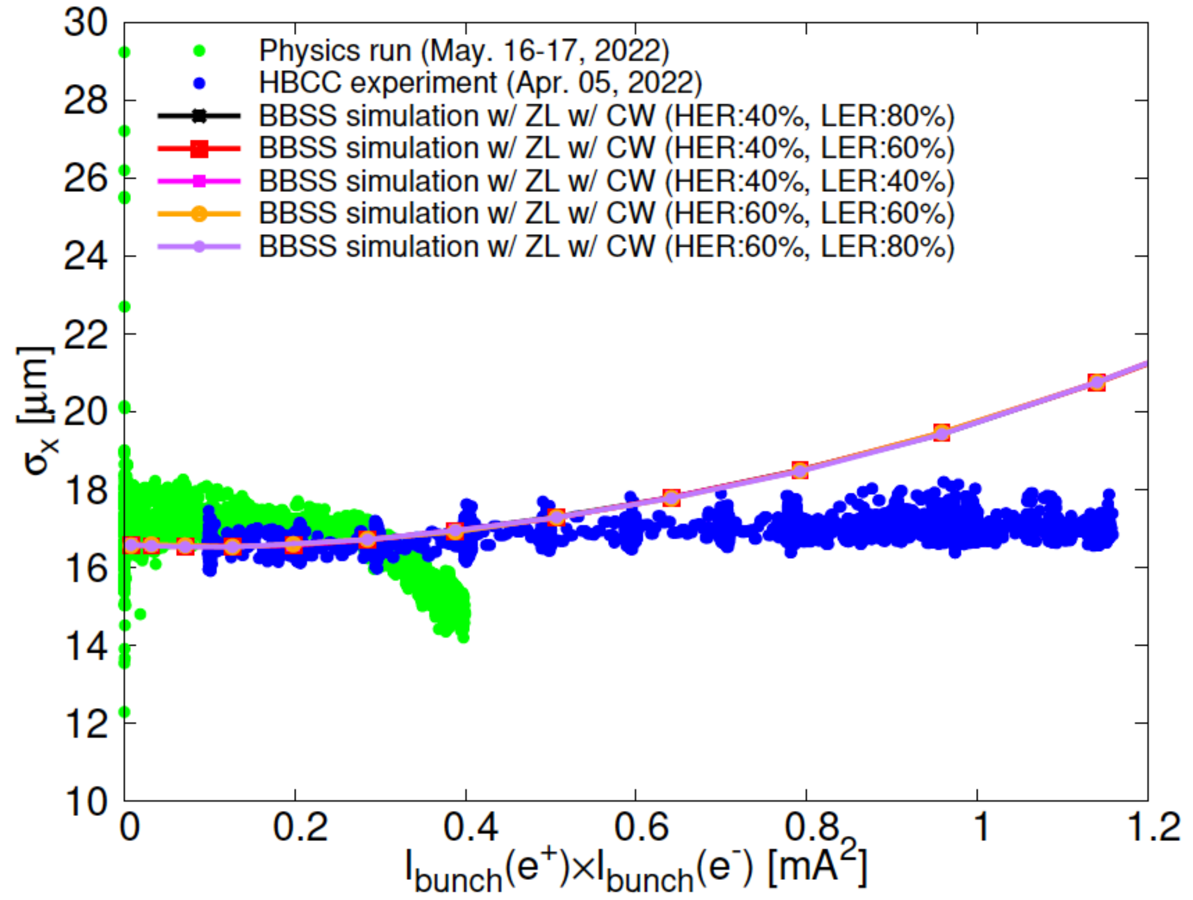


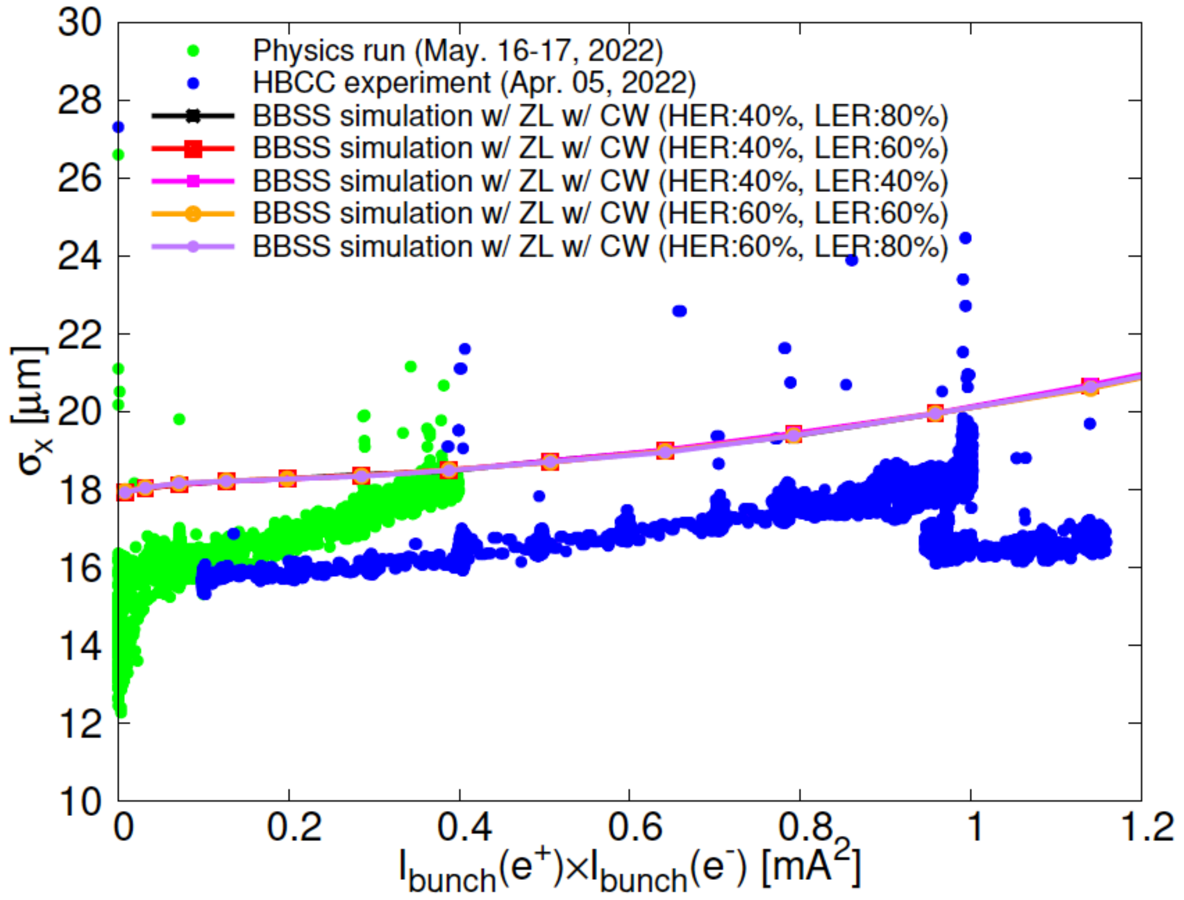




Specific luminosity | Electron σ_x^* | Positron σ_x^*

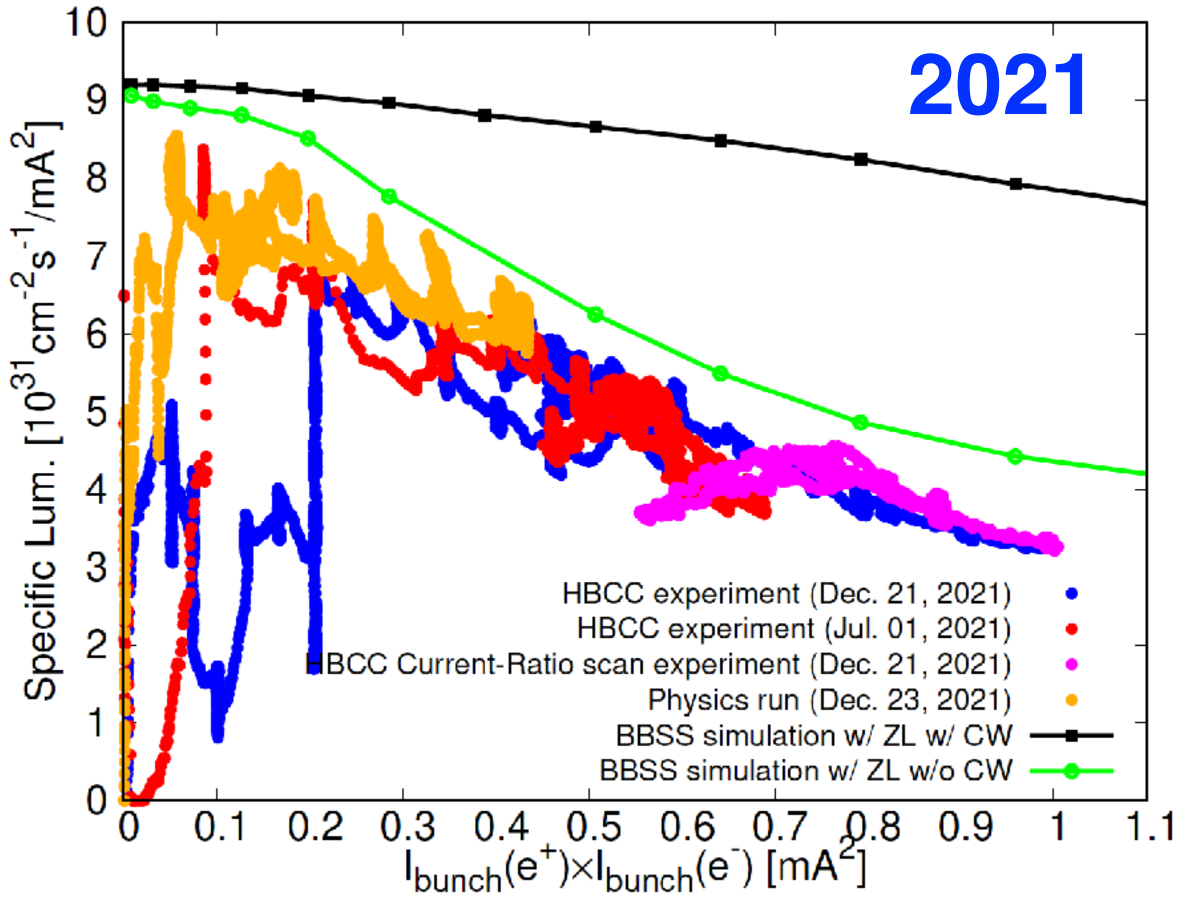


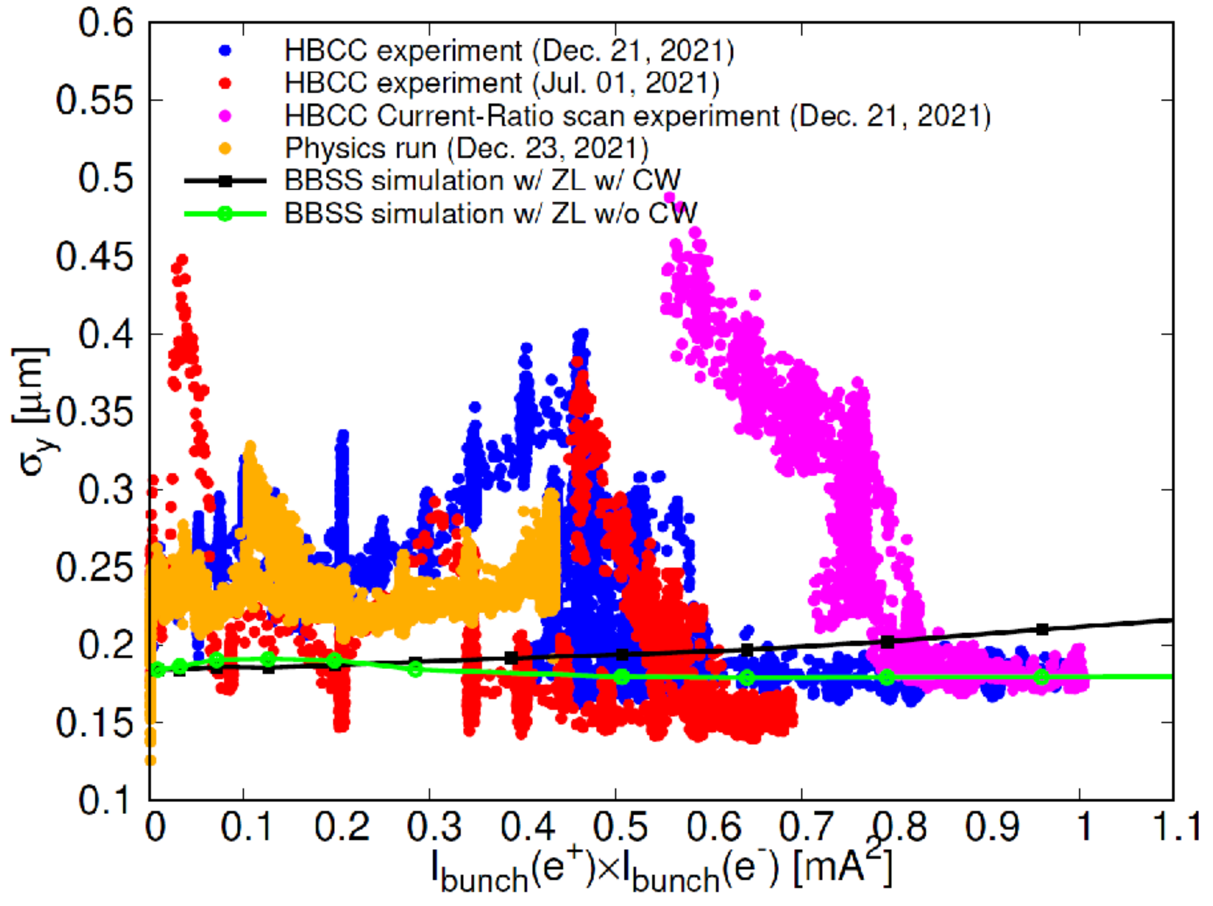


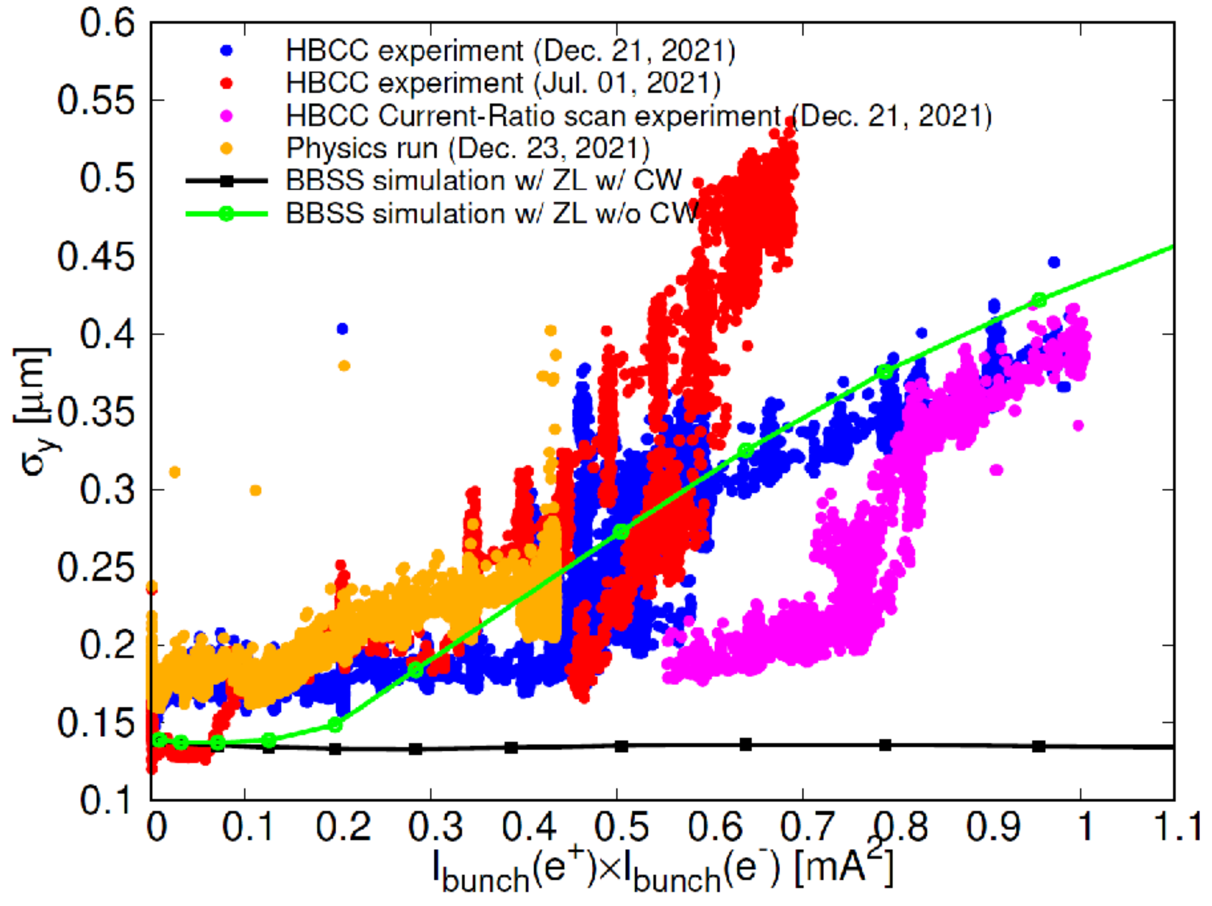


Comparison of simulations and experimental results

- HBCC machine studies with $\beta_y^* = 1$ mm in 2021 and 2022:
  - After fine-tuning of BxB FB system in 2022, observed vertical beam sizes blowup became much more "normal" and closer to simulations



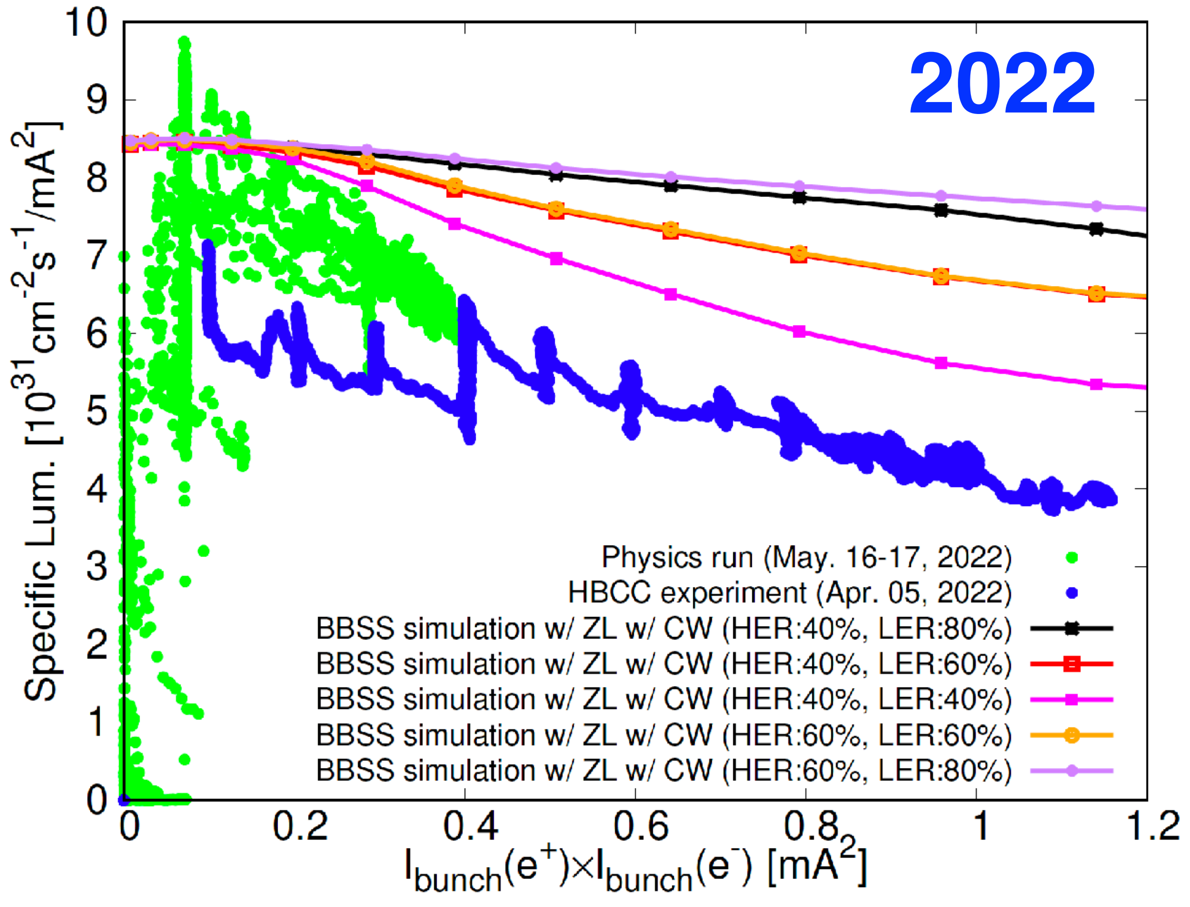


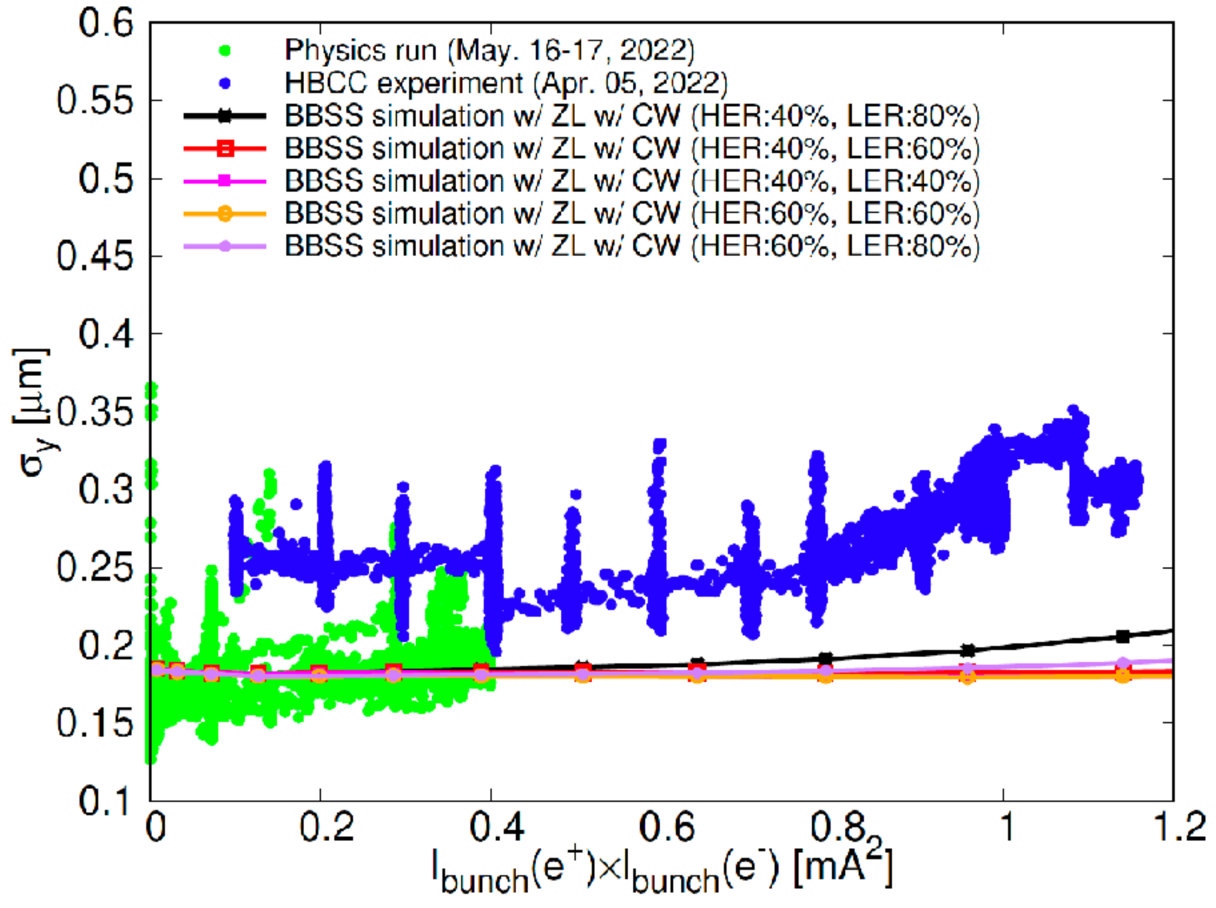


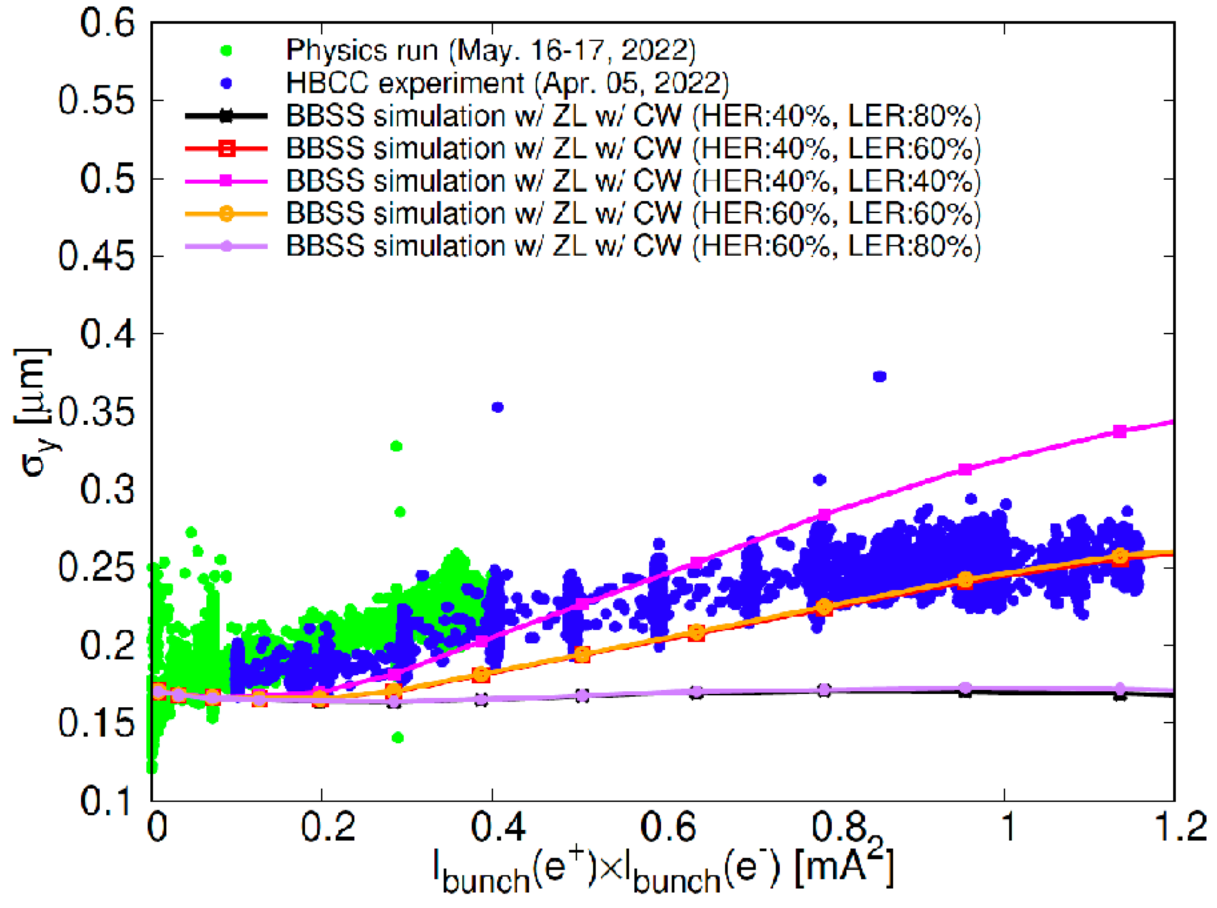
Specific luminosity

Electron σ_y^*

Positron σ_y^*

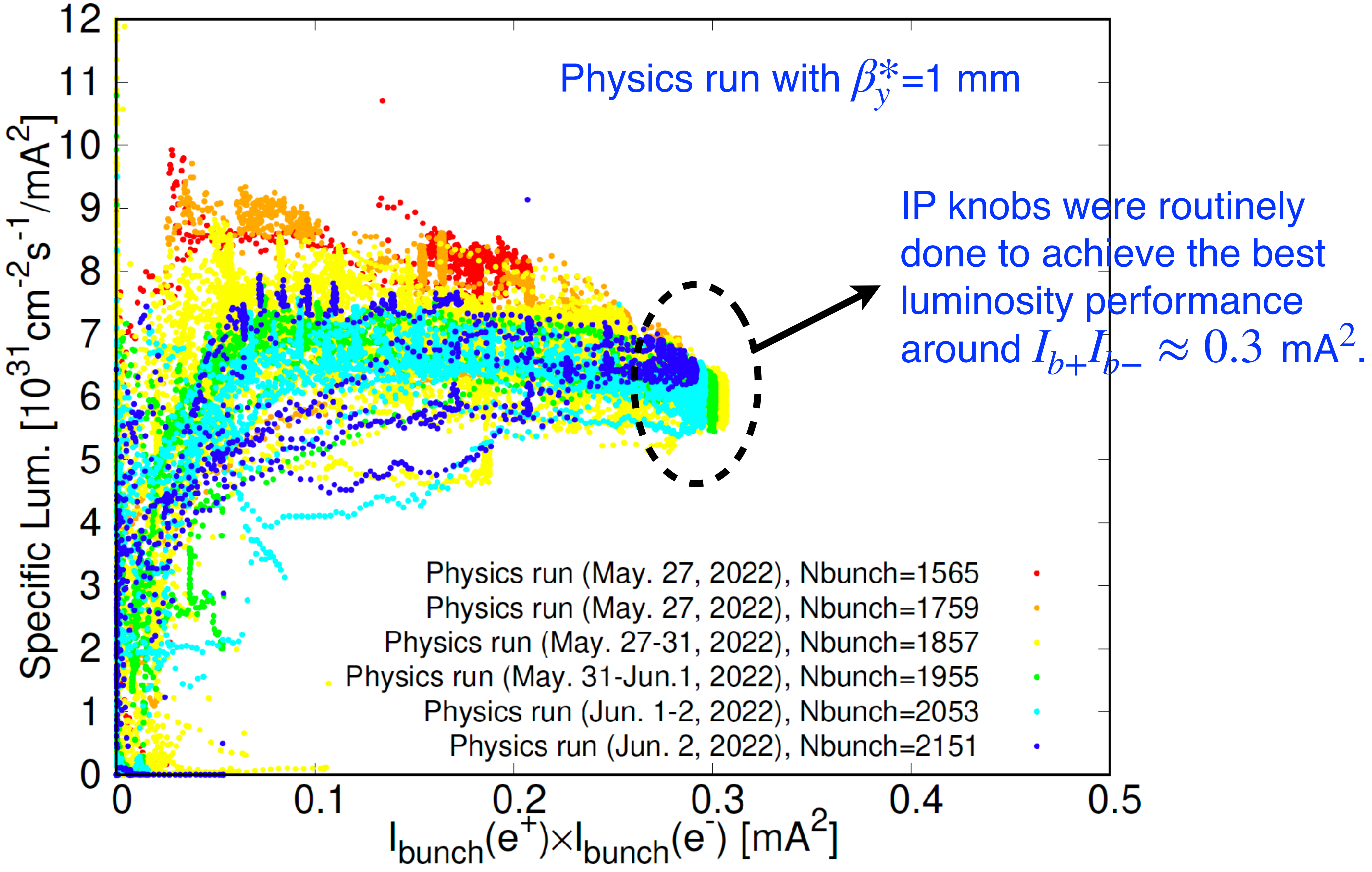


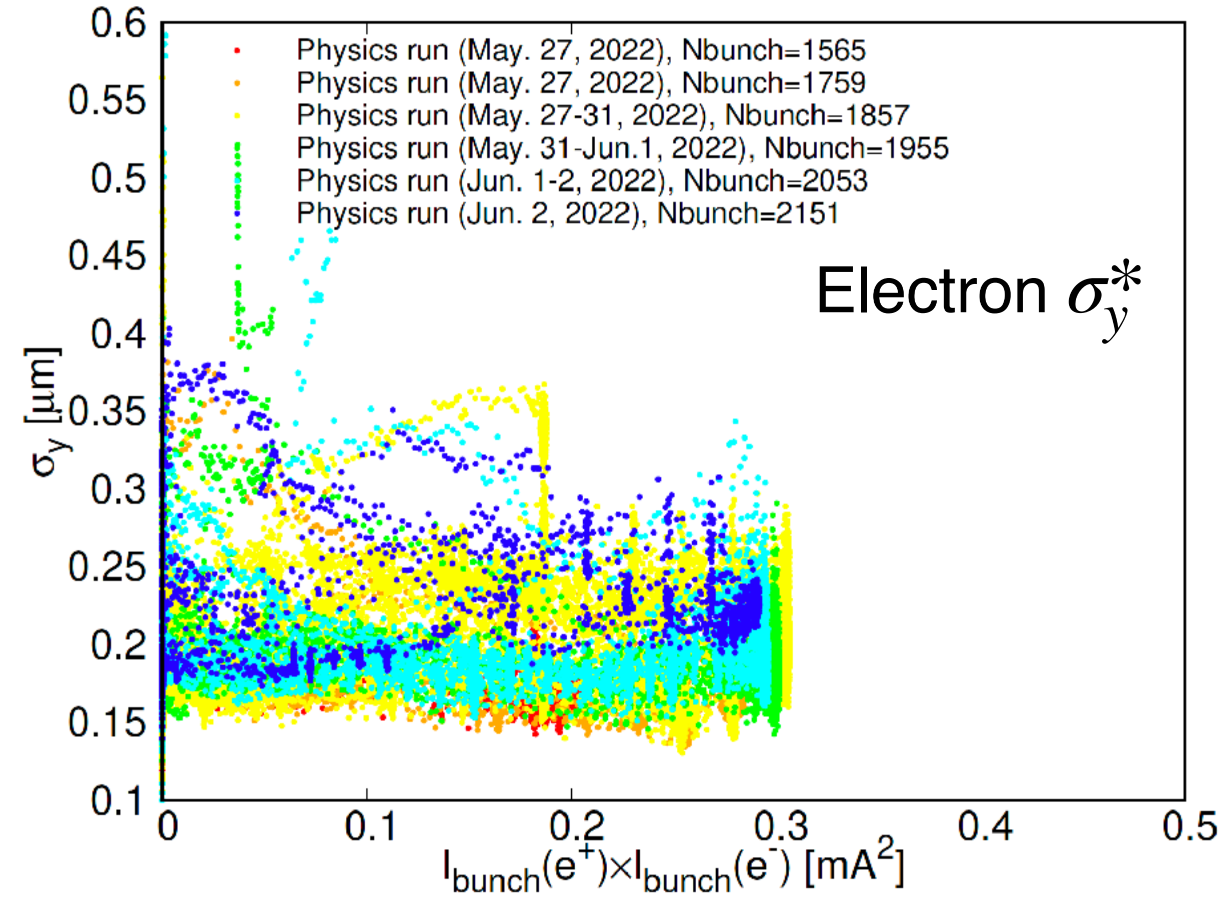


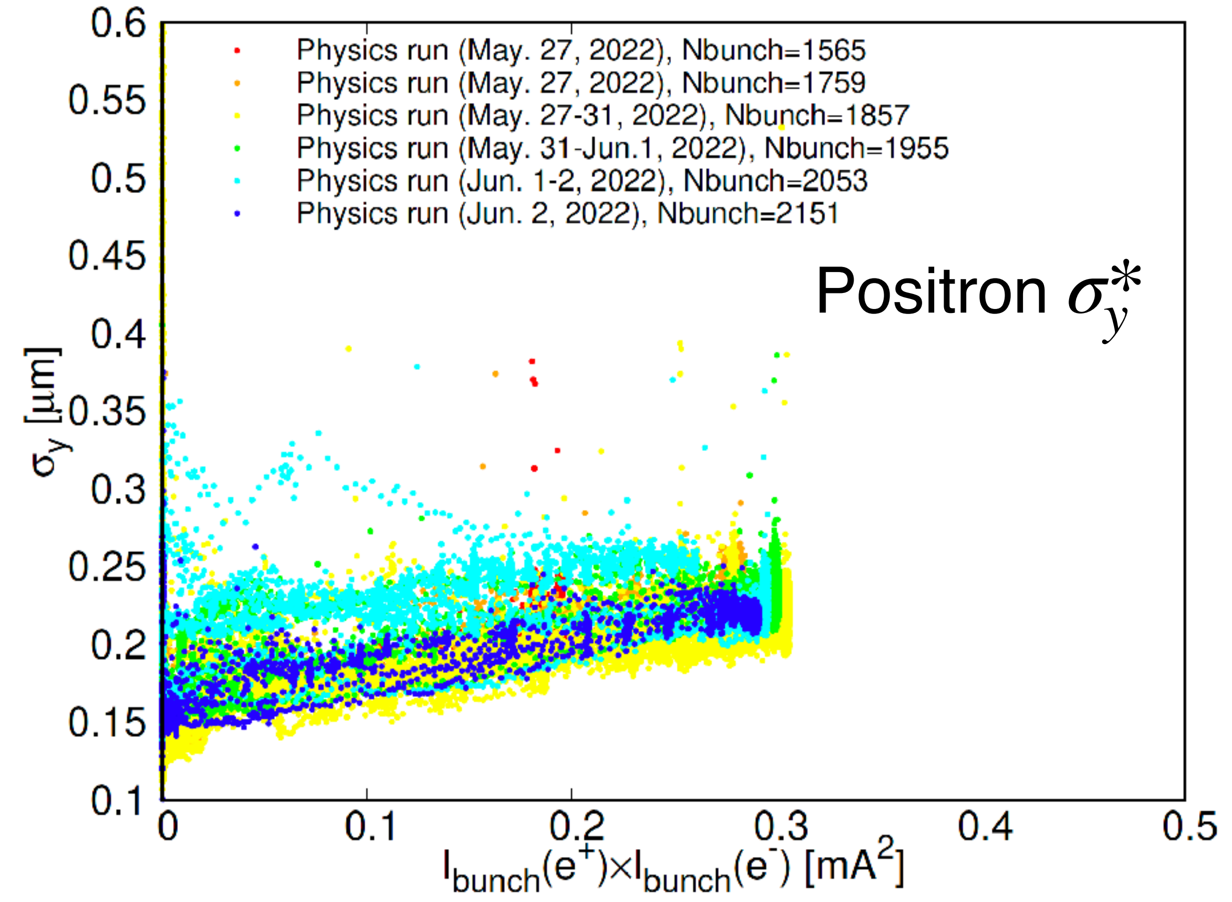


Multi-bunch effects

- No clear evidence of Lsp degradation due to multi-bunch effects
  - The BxB FB system suppressed coupled-bunch instabilities.
  - Flat BxB luminosity was observed.
  - Electron-cloud instability was not observed.





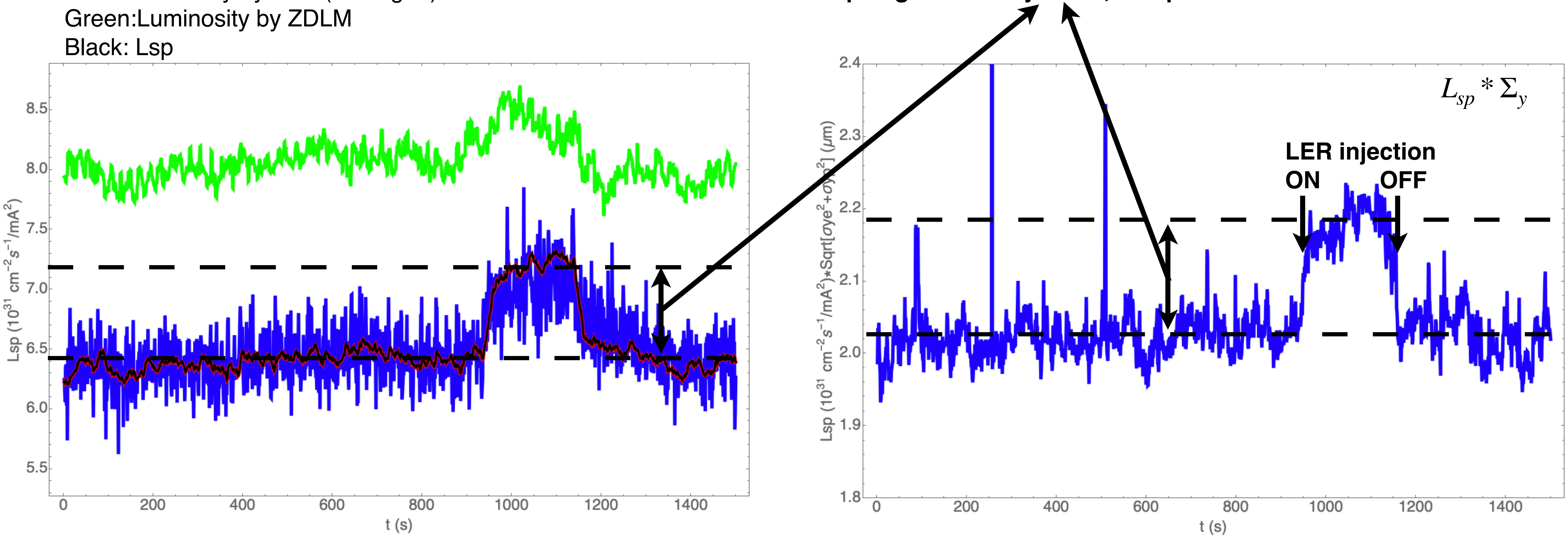


Comparison of simulations and experimental results

- A mysterious phenomenon: Lsp is correlated with beam injection
  - All luminosity PVs gave a similar jump-response to injection stop/start.
  - $L_{sp} \cdot \sqrt{\sigma_{y+}^{*2} + \sigma_{y-}^{*2}}$ still shows jump-response. It means there is a geometric loss of luminosity.

Blue: Luminosity by ECL
Red: Luminosity by ECL (averaged)
Green:Luminosity by ZDLM
Black: Lsp

Lsp degradation by ~10%, independent to vertical emittances



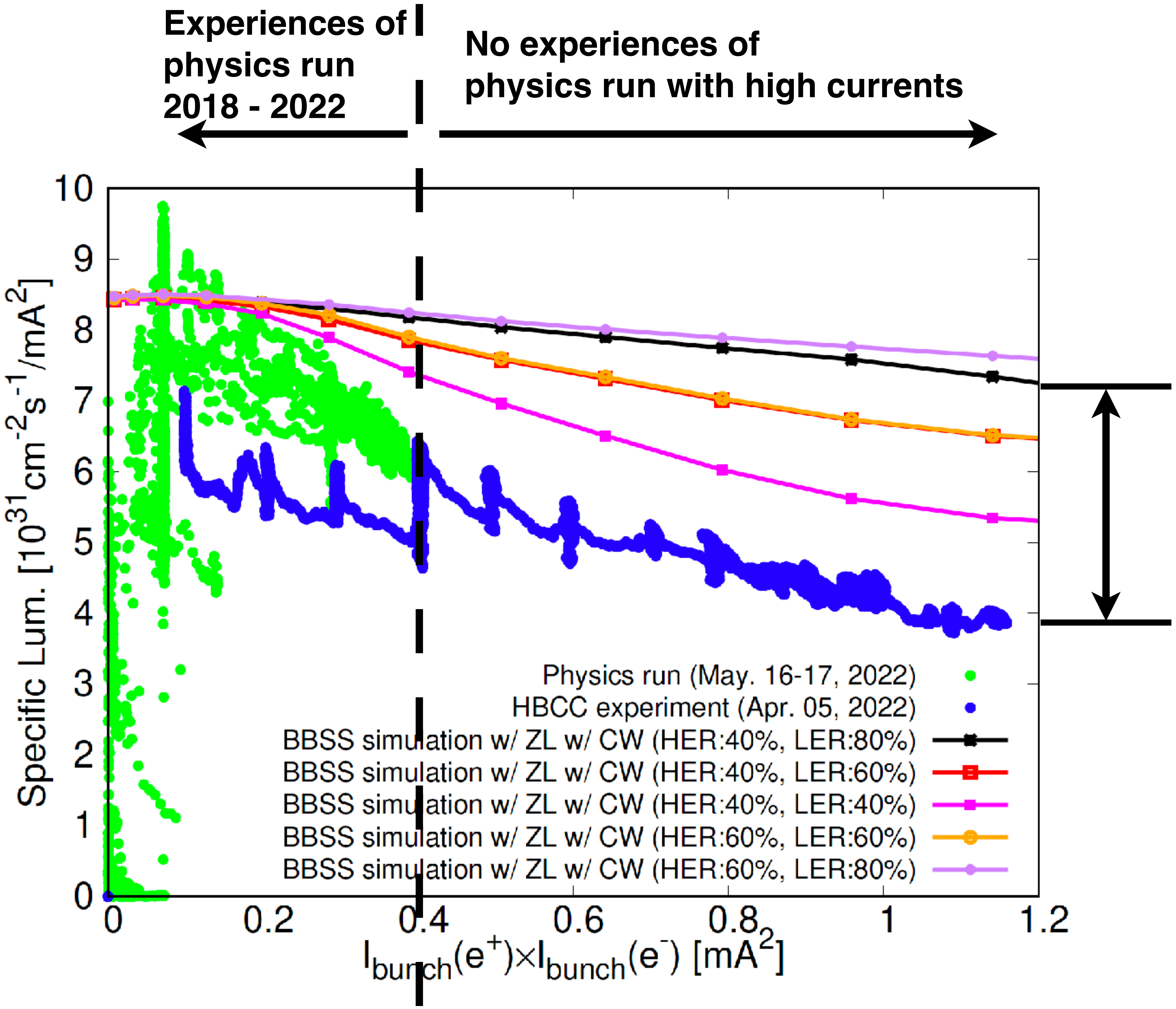
Online data: 2022-06-02 21:05 PM

Comparison of simulations and experimental results

- Known sources of luminosity degradation
  - Bunch lengthening
  - Chromatic couplings (See Y. Ohnishi's talk)
  - Single-beam blowup in LER (Impedance effects and its interplay with FB, see K. Ohmi's talk)
  - Optics distortion due to SR heating (see Y. Ohnishi's and H. Sugimoto's talks) } Identified in 2022
  - Luminosity "loss" correlated with injection.
- Sources to be investigated via experiments
  - Imperfect crab waist
  - Beam-beam driven synchro-betatron resonances
  - Interplay of BB, longitudinal and transverse impedances, and feedback system
  - Global couplings (side effects of IP knobs)
  - Interplay of BB and nonlinear lattices
  - Coupled bunch instabilities

Comparison of simulations and experimental results

- Filling the gap between simulated and measured Lsp
  - BBSS+PIC simulation showed 5% less Lsp at $I_{b+}I_{b-} = 0.8$ mA^2.
  - Impedance effects:
    - Simulations showed less bunch lengthening than measurements. If measured bunch lengthening is applied, it gives ~10% extra loss of Lsp at $I_{b+}I_{b-} = 0.8$ mA^2.
    - Vertical beam tilt due to monopolar wakes.
    - “-1 mode instability” due to interplay of FB and vertical impedance.
  - Lsp loss correlated with injection: ~10% at $I_{b+}I_{b-} = 0.3$ mA^2 (not sure how much loss at high bunch currents).
  - Other sources of Lsp degradation without quantitative estimate.



Summary

- Prediction of luminosity via beam-beam simulations requires reliable models of 1) beam-beam interaction, 2) machine imperfections, and 3) other collective effects.
- Crab waist is powerful in the suppression of nonlinear beam-beam effects.
- With progress in machine tunings, the measured luminosity of SuperKEKB is approaching predictions of BB simulations (BB + Simple lattice model + Impedance models).
- Many subjects/ideas are to investigated/tried (both simulations and experiments) to achieve higher luminosity at SuperKEKB.

Backup

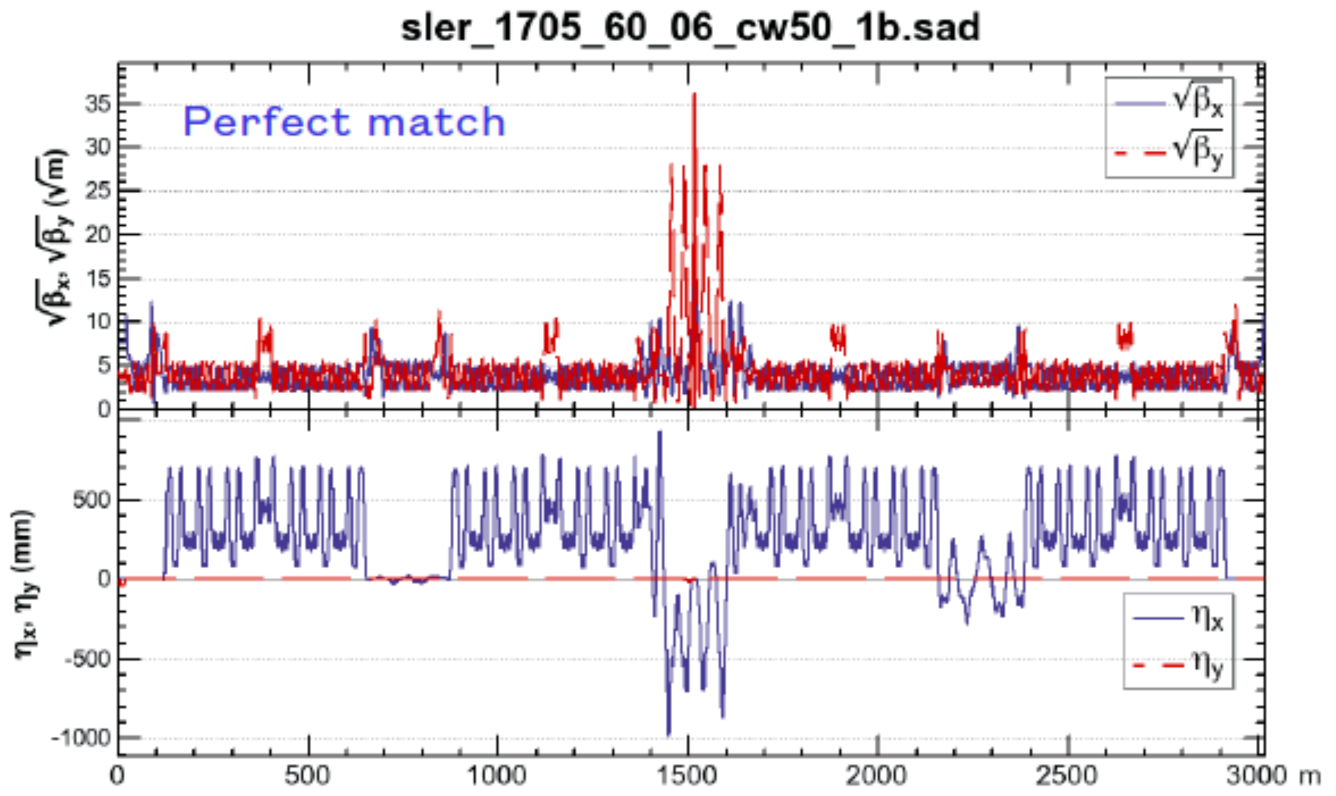
Status of beam-beam simulations

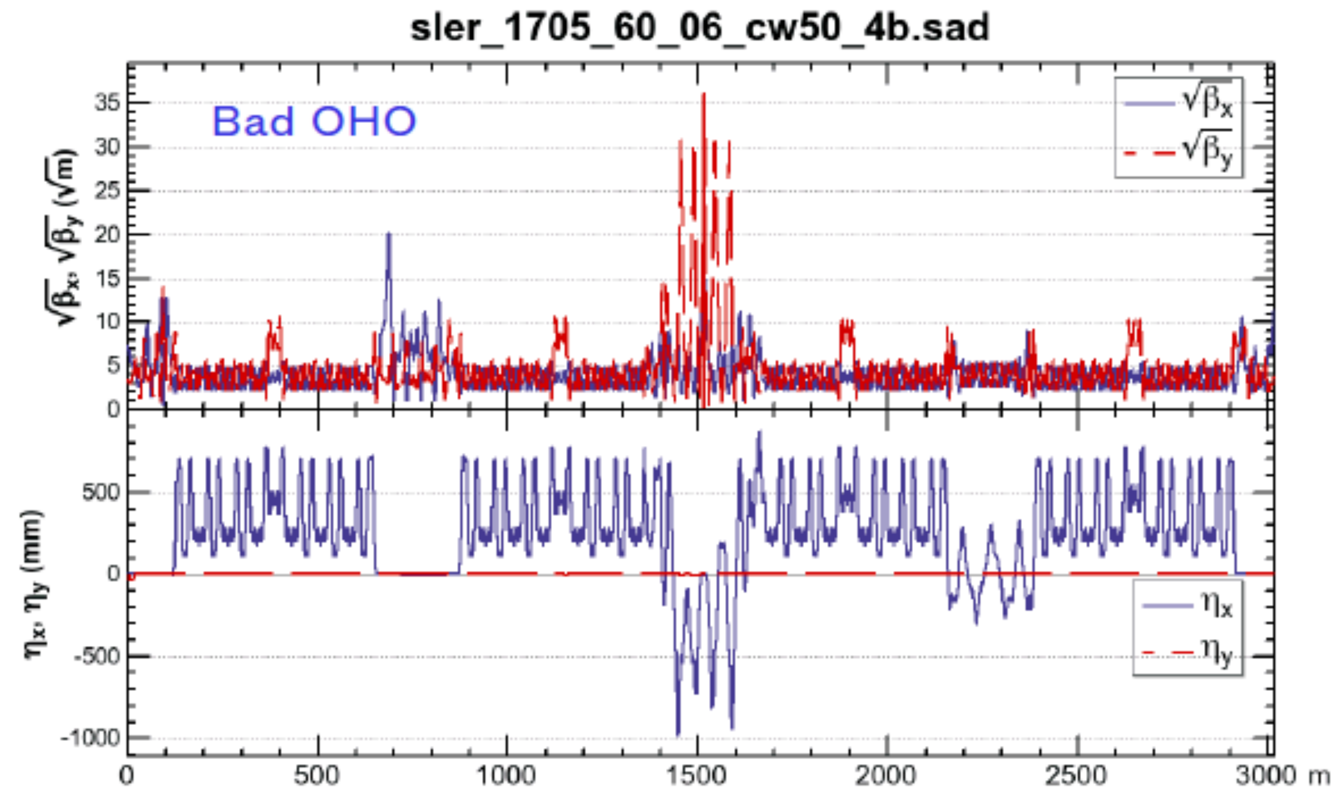
- Weak-strong model + simple one-turn map: BBWS code
  - Pros: Fast simulation of luminosity and beam-beam effects. Not require much computing resources. Used for tune survey, fast luminosity calculation, etc..
  - Cons: Strong beam frozen. Crab waist of strong beam not implemented. Not sensitive to 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.

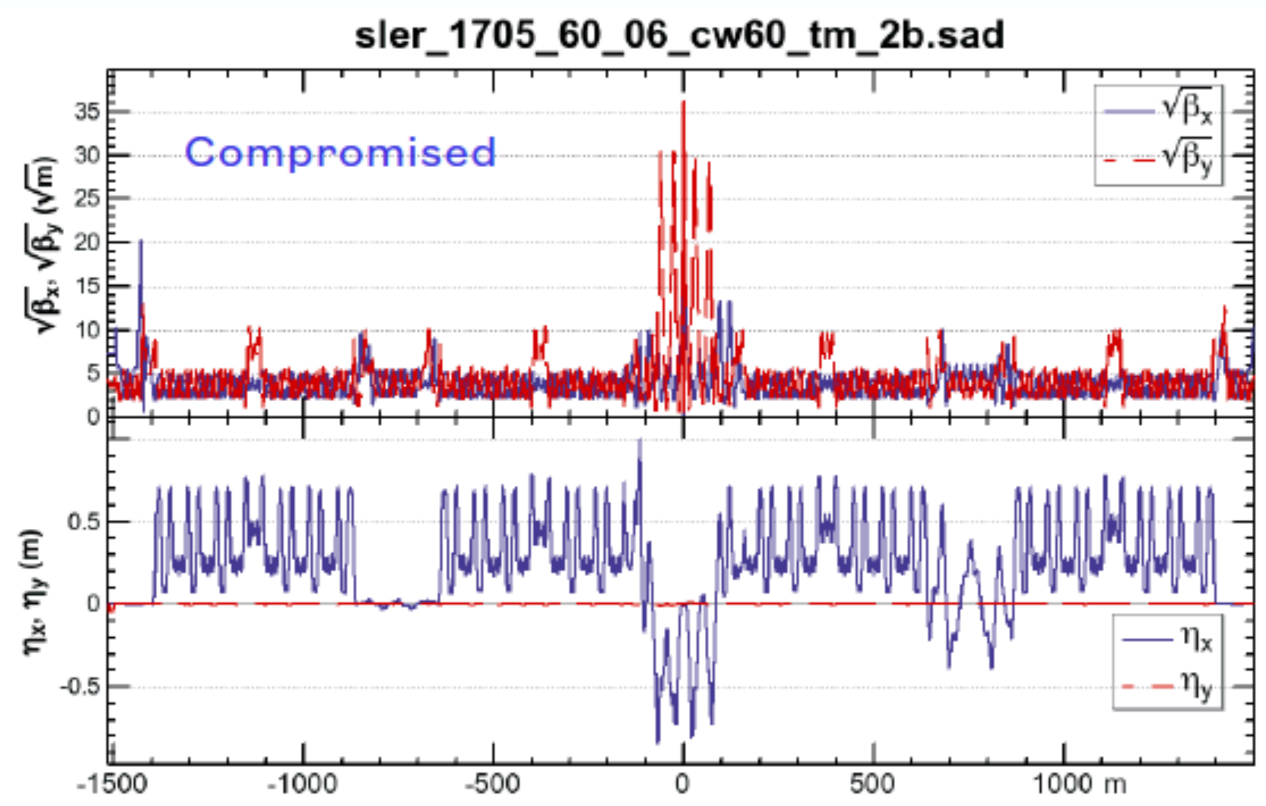
Crab waist applied to SuperKEKB

- Optics design with crab waist for $\beta_y^* = 0.6$ mm by K. Oide

Comparison of optics







Parameters		"Bad OHO"	"compromised"	"perfect"
$\beta^* x/y$, LER=HER	mm		60 / 0.6	
Hor. emittance LER/HER	nm	4.2 / 4.5	4.4 / 4.5	3.6 / 4.5
$\varepsilon_{y0}/\varepsilon_x$, LER=HER	%		1.5	
Bunch current LER/HER	mA		1.0 / 0.81	
Bunches/ring			2200	
Bunch length[1] LER/HER	mm		4.8 / 5.5	
Energy spread[1] LER/HER	10^{-4}		7.6 / 6.3	
Luminosity	10^{34}/cm^{2}s	11.4	11.1	12.2
$\Delta\psi_{x,y}/2\pi$ btw. IP & SLY		0.003	0.009	0.001
$\Delta\beta/\beta$ btw. SLY	%	0.13	3.6	0.011
$\Delta\eta_{px}$ @PQLY1C		0.01	0.01	0.0002
R_1, R_4 @IP		1×10^{-8}	0.012	1×10^{-10}
R_2 @IP	m	8×10^{-14}	7×10^{-6}	2×10^{-14}
R_3 @IP	1/m	5×10^{-6}	0.21	3×10^{-10}
η_y @IP	m	1×10^{-14}	2×10^{-6}	5×10^{-15}
η_{py} @IP		3×10^{-14}	1×10^{-5}	6×10^{-13}

3

[1] @zero impedance

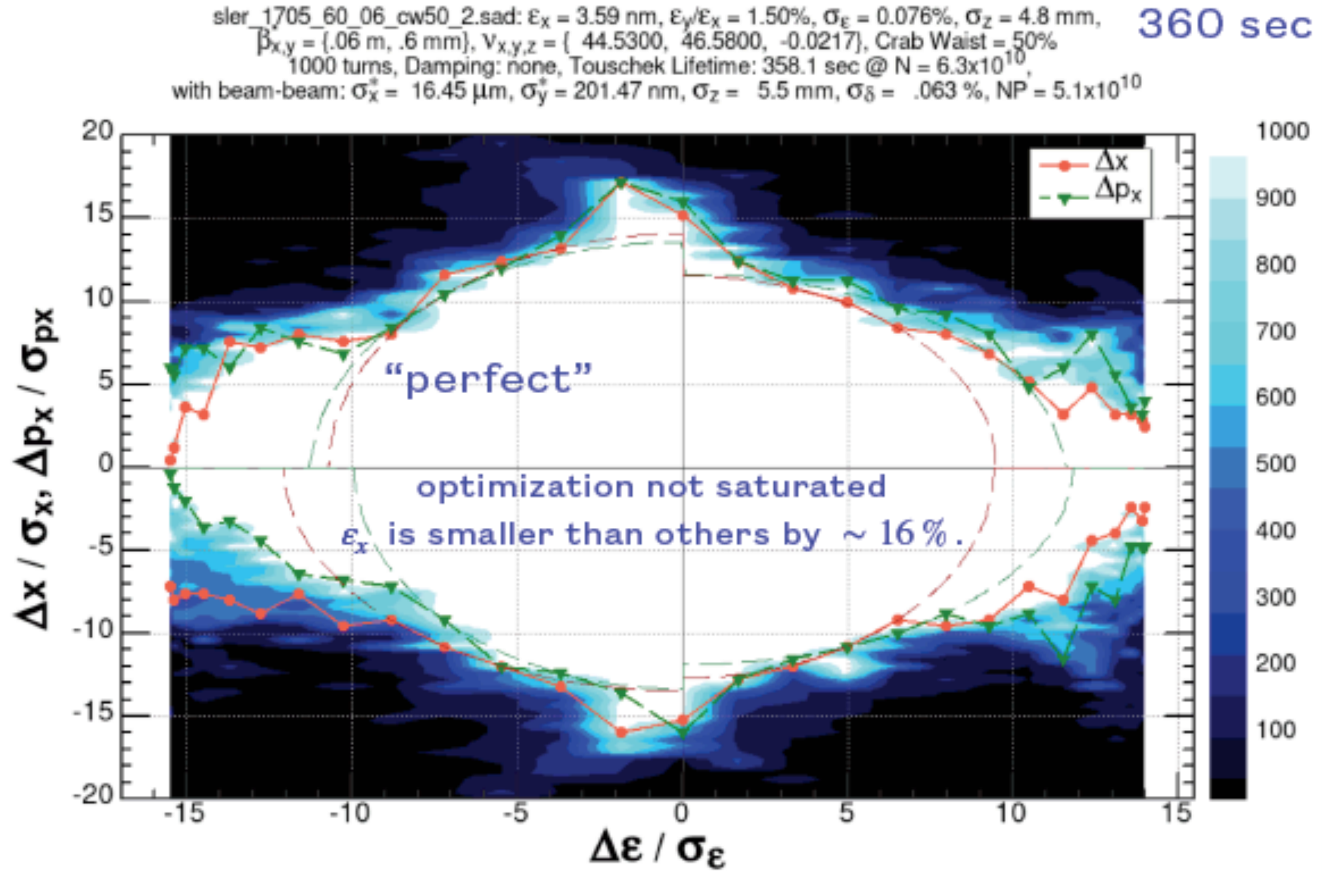
Aug. 27, 2021 K. Oide

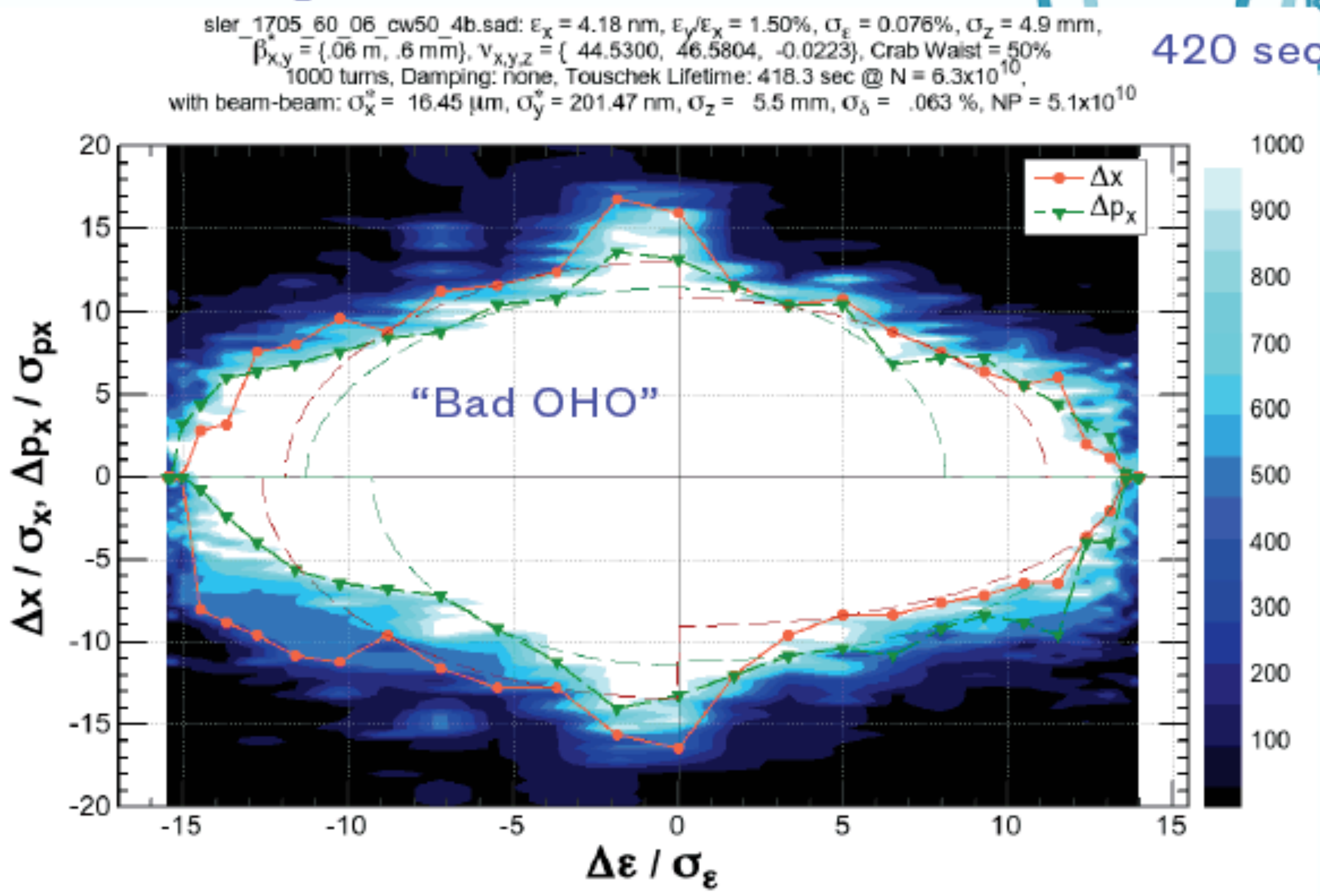
Ref.[9] K. Oide, SuperKEKB ARC, 2021.

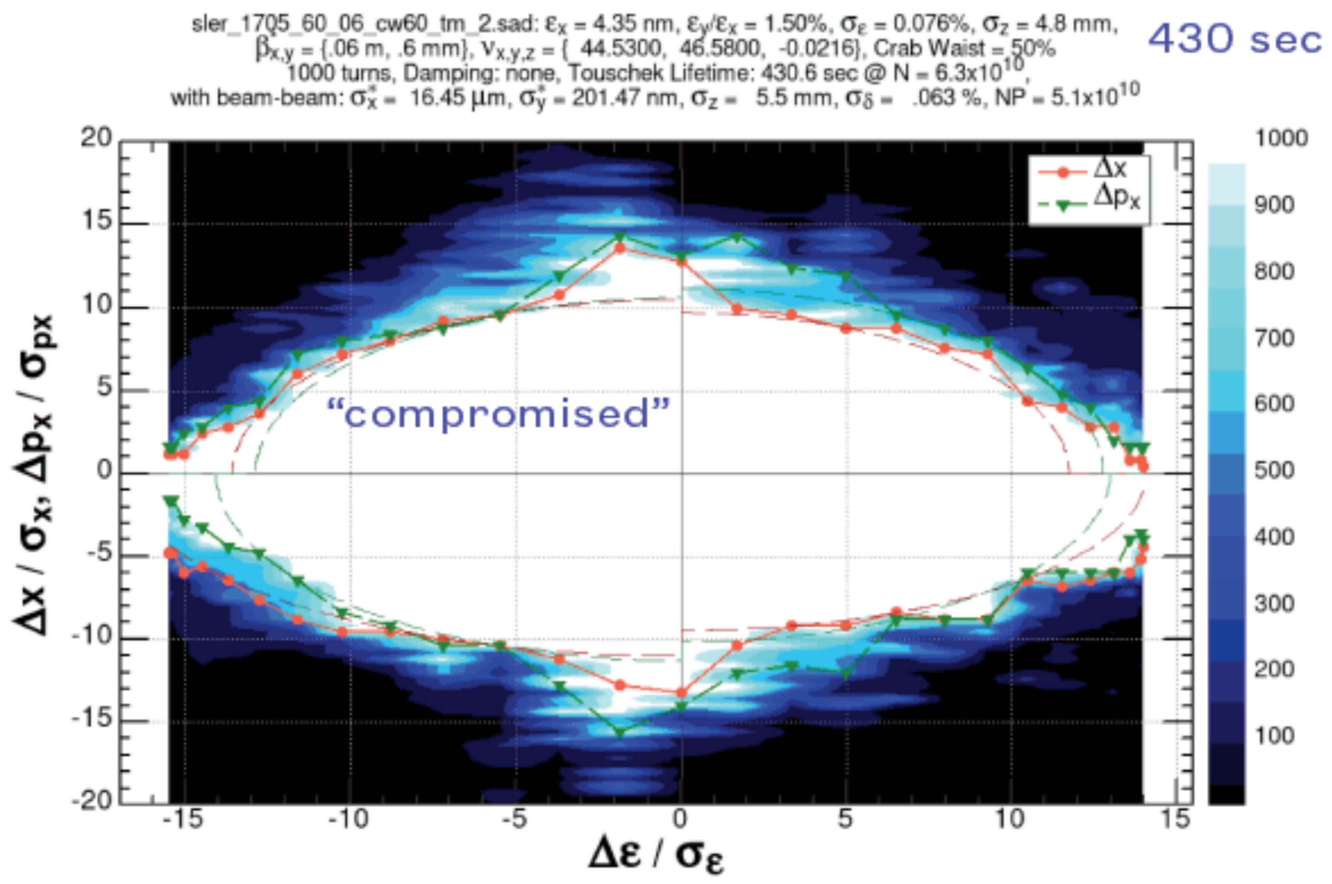
Crab waist applied to SuperKEKB

- Optics design with crab waist for $\beta_y^* = 0.6$ mm by K. Oide
  - With 50% CW strength, lifetime is acceptable for beam operation

Dynamic aperture (with beam-beam, CW = 50%)







Parameters		"Bad OHO"	“compromised”	“perfect”
$\beta^* x/y$, LER=HER	mm		60 / 0.6	
Hor. emittance LER/HER	nm	4.2 / 4.5	4.4 / 4.5	3.6 / 4.5
$\varepsilon_{y0}/\varepsilon_x$, LER=HER	%		1.5	
Bunch current LER/HER	mA		1.0 / 0.81	
Bunches/ring			2200	
Bunch length[1] LER/HER	mm		4.8 / 5.5	
Energy spread[1] LER/HER	10^{-4}		7.6 / 6.3	
Luminosity	$10^{34}/\mathrm{cm}^2\mathrm{s}$	11.4	11.1	12.2
$\Delta\psi_{x,y}/2\pi$ btw. IP & SLY		0.003	0.009	0.001
$\Delta\beta/\beta$ btw. SLY	%	0.13	3.6	0.011
$\Delta\eta_{px}$ @PQLY1C		0.01	0.01	0.0002
R_1, R_4 @IP		1×10^{-8}	0.012	1×10^{-10}
R_2 @IP	m	8×10^{-14}	7×10^{-6}	2×10^{-14}
R_3 @IP	1/m	5×10^{-6}	0.21	3×10^{-10}
η_y @IP	m	1×10^{-14}	2×10^{-6}	5×10^{-15}
η_{py} @IP		3×10^{-14}	1×10^{-5}	6×10^{-13}

[1] @zero impedance

4

Aug. 27, 2021 K. Oide

Ref.[9] K. Oide, SuperKEKB ARC, 2021.

B simulations w/ final design configuration

- Findings [8]
  - K. Ohmi and K. Hirosawa developed a simple method to calculate 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.**

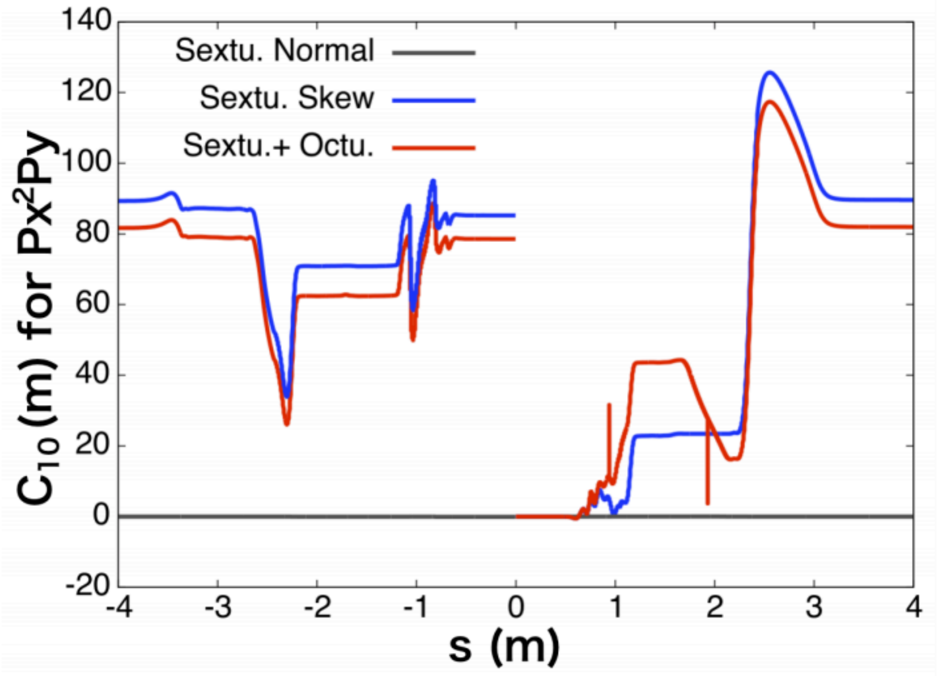


Figure 4: Coefficient of $P_X^2 P_Y$ caused by skew sextupole (SK_2) and octupole ($K_3 + SK_3$) fields.

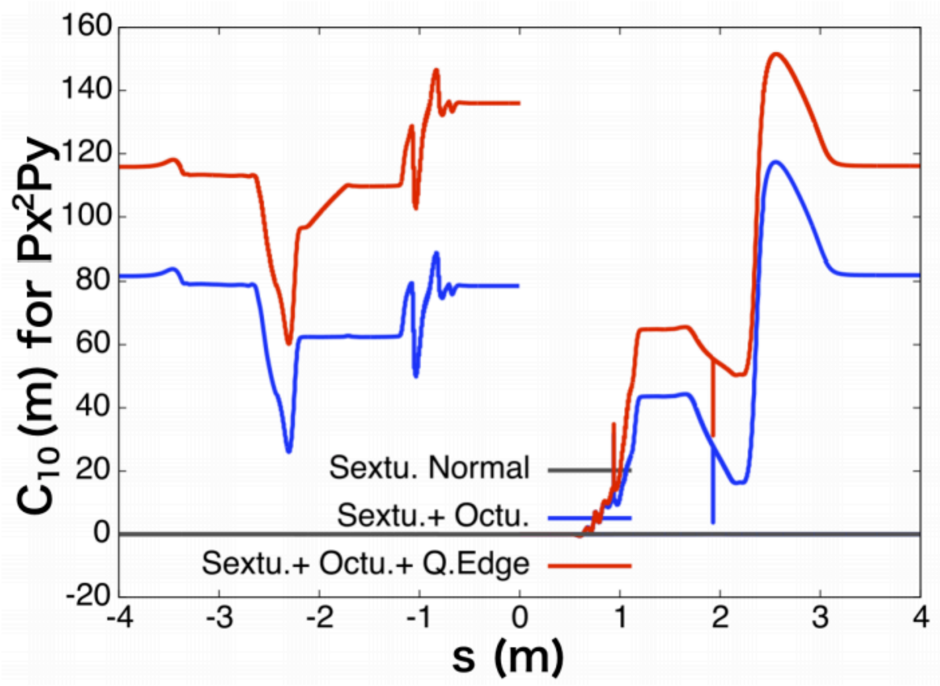


Figure 5: Coefficient of $P_X^2 P_Y$ for sextupole and octupole ($SK_2 + K_3 + SK_3$) and quadrupole hard-edge fringe ($SK_2 + K_3 + SK_3 + Q.edge$) fields.

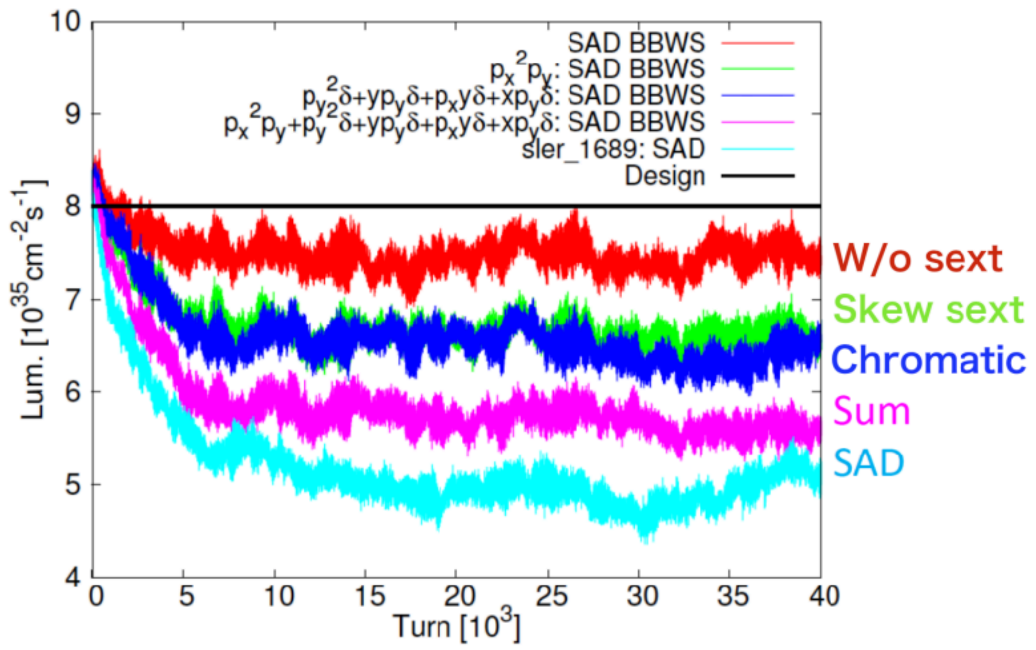
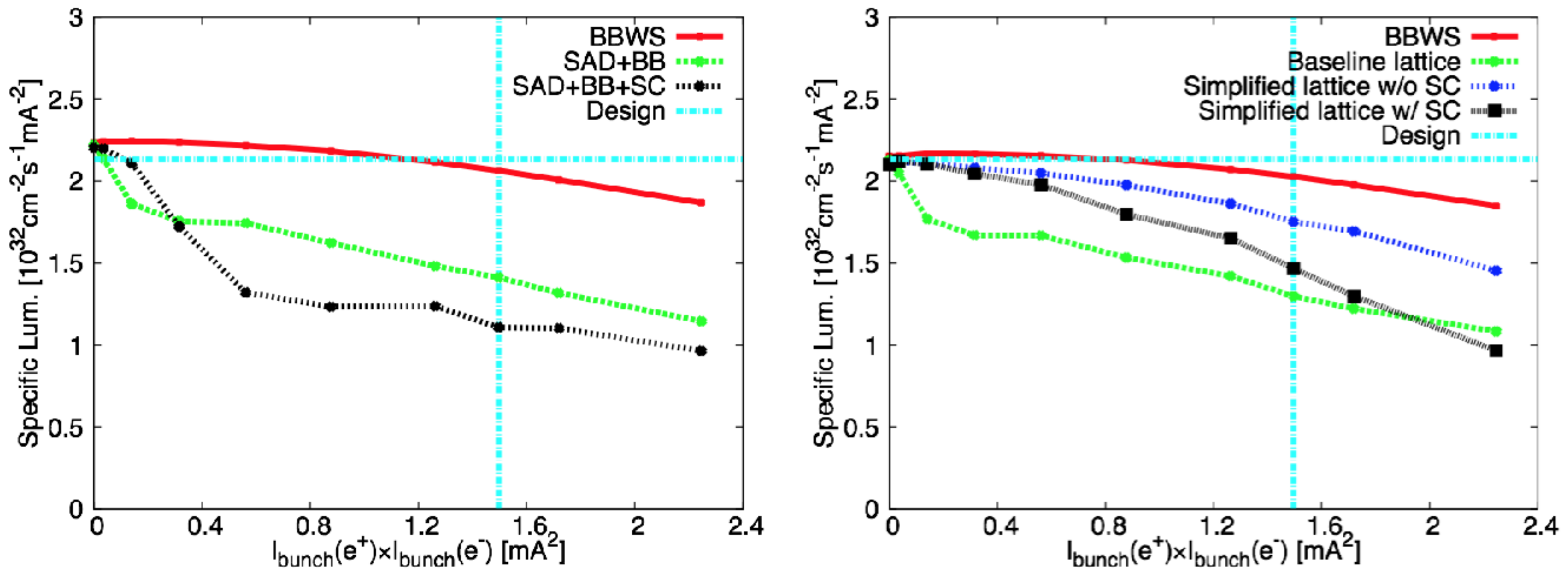


Figure 6: Luminosities for sextupole term (: $P_X^2 P_Y$), chromatic twiss, and SAD.



[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.