Accelerator physics challenges for SuperKEKB commissioning

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Acknowledgments

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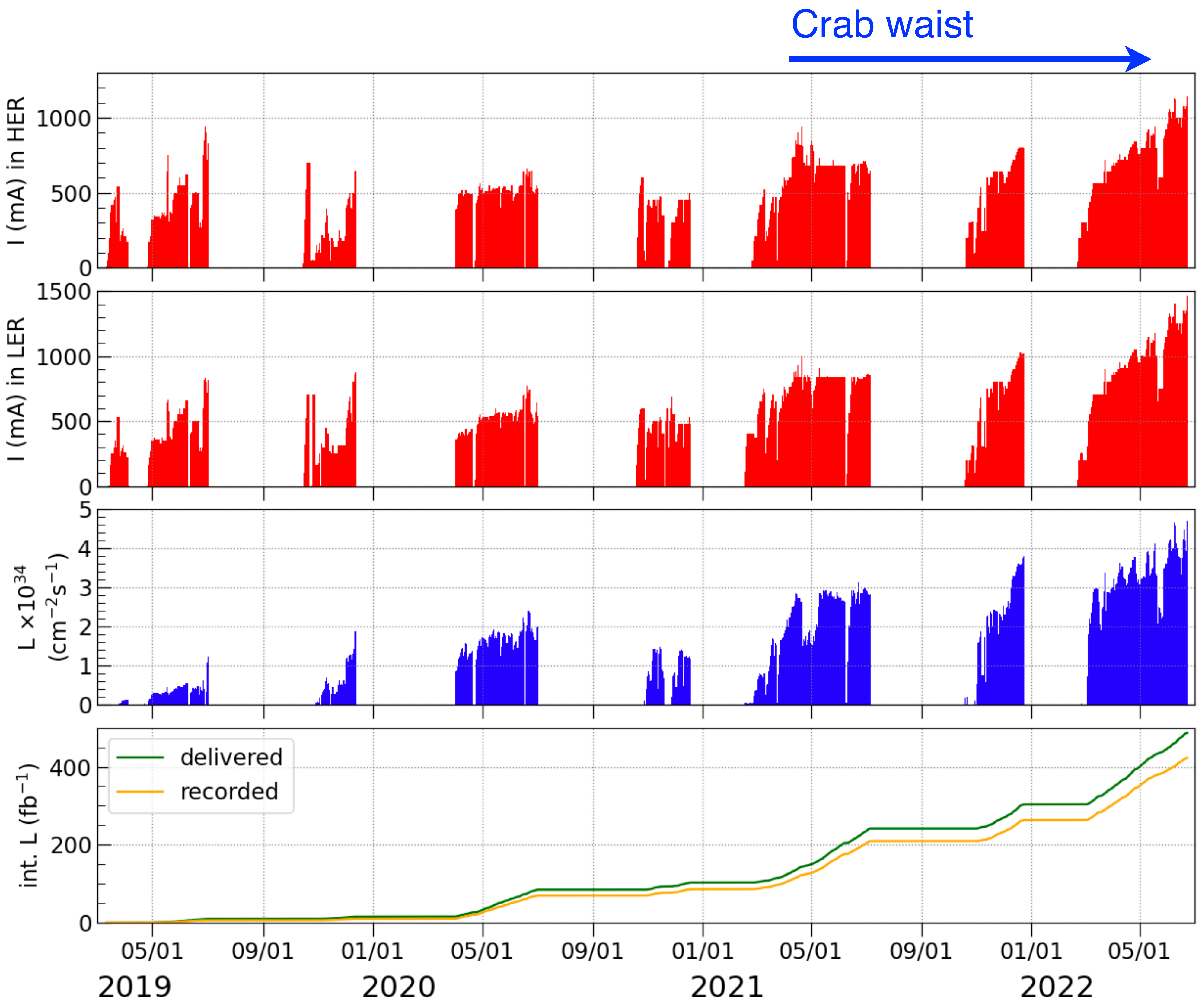
Outline

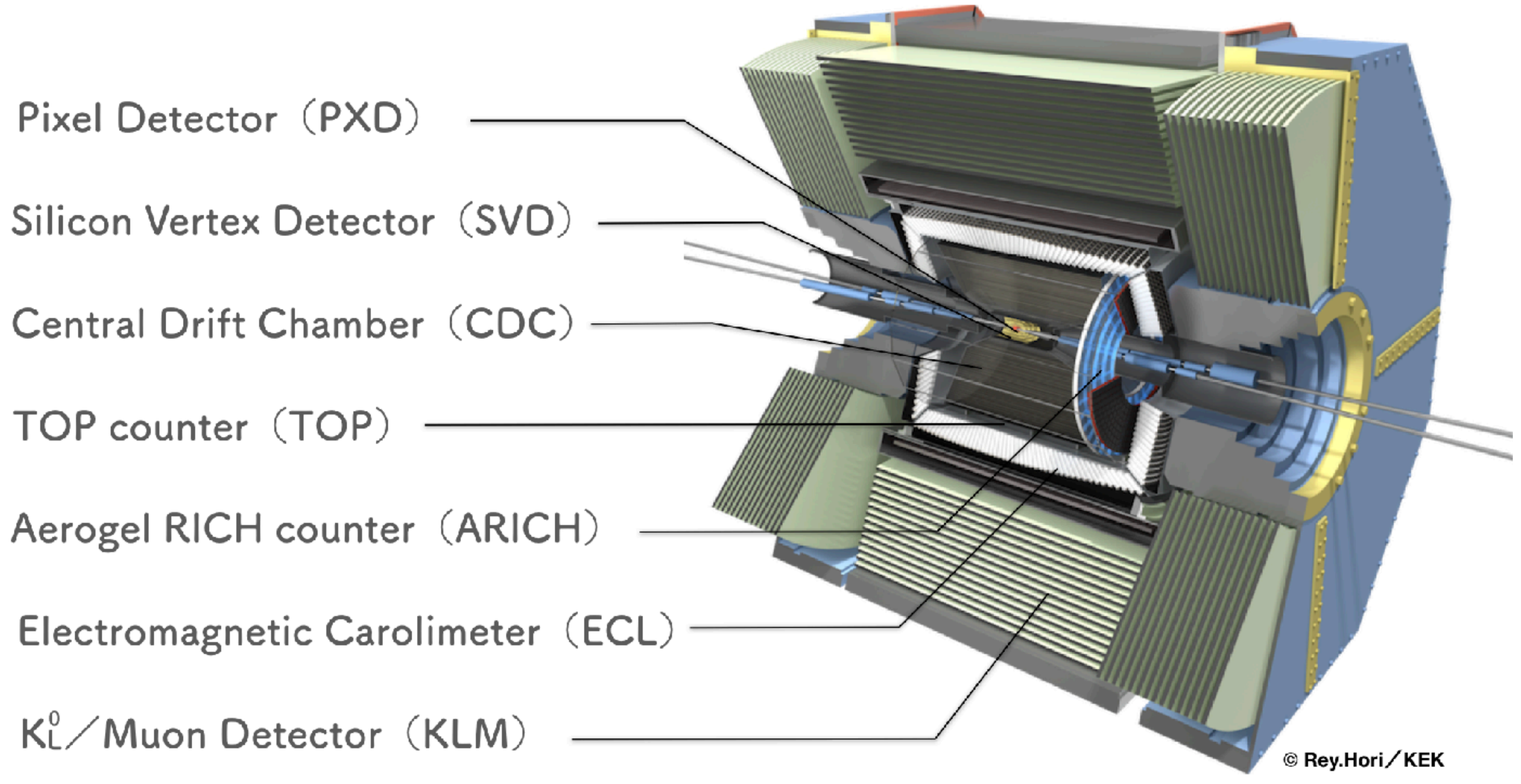
- Status of SuperKEKB
- Luminosity performance
- Accelerator physics challenges
- Beam-beam simulations for post-LS1 operation
- Beam-beam perspective on achieving target luminosity
- Summary

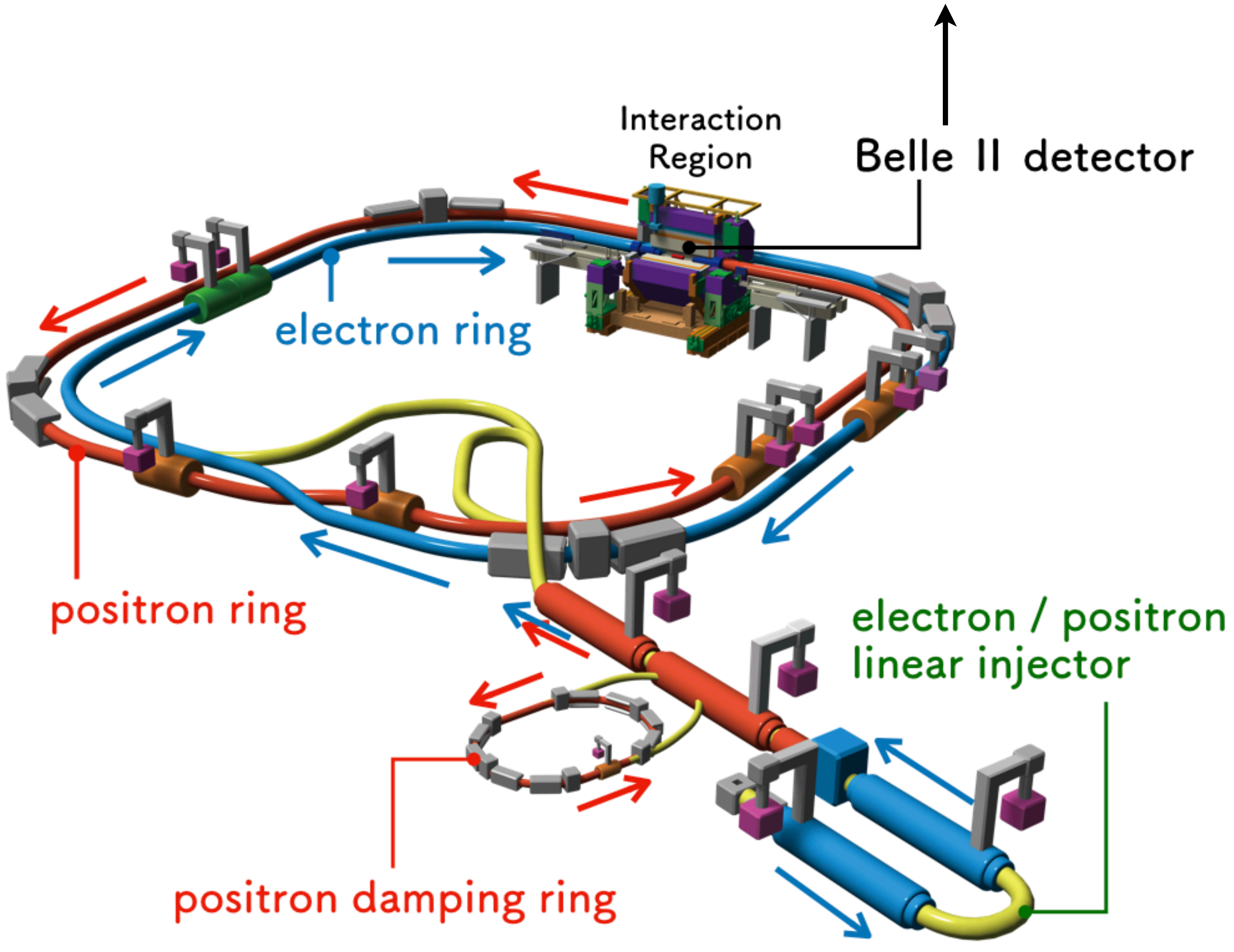
Status of SuperKEKB

- Phase-1: Feb. 2016 - Jun. 2016 w/o QCS mag. and Belle II.
- Phase-2: Feb. 2018 - Jul. 2018 w/ QCS and Belle II, w/o Vertex detector.
- Phase-3: March, 2019 - w/ Full Belle II.
- LS1: Jul. 2022 - Dec. 2023, Belle II upgrade and NLC installation.



Belle II Collaboration is an international worldwide scientific community





SuperKEKB accelerator is a Japanese domestic project

Status of SuperKEKB: Schedule of post-LS1operation

Beam tuning and machine study at Linac/e+DR/BT will be 2 weeks before LER start.
Vacuum scrubbing and machine study in the LER will be 5 weeks and 3 weeks for the HER.
Machine study will be a higher priority even though during physics run.

	2023c				2024a												2024b											
	December				January				February				March				April				May				June			
Linac							Jan. 15 start																					
e+DR							Jan. 15 start																					
BT							Jan. 15 start																					
LER			Dec. 11 start	Dec. 28 end				Jan. 29 start																				Jun. 30 end
HER								Jan. 29 start																				Jun. 30 end
Physics											mid of Feb.																	

Vacuum scrubbing and Machine study

Physics run will be available from mid. of February.

[1] Y. Ohnishi, https://kds.kek.jp/event/48117/

Luminosity performance

- "Nano-beam" + crab waist in SuperKEKB
  - Simple scaling laws are good enough to discuss luminosity and beam-beam parameters/tune shifts for the case of $\beta_y^* = 1$ mm [1].

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

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

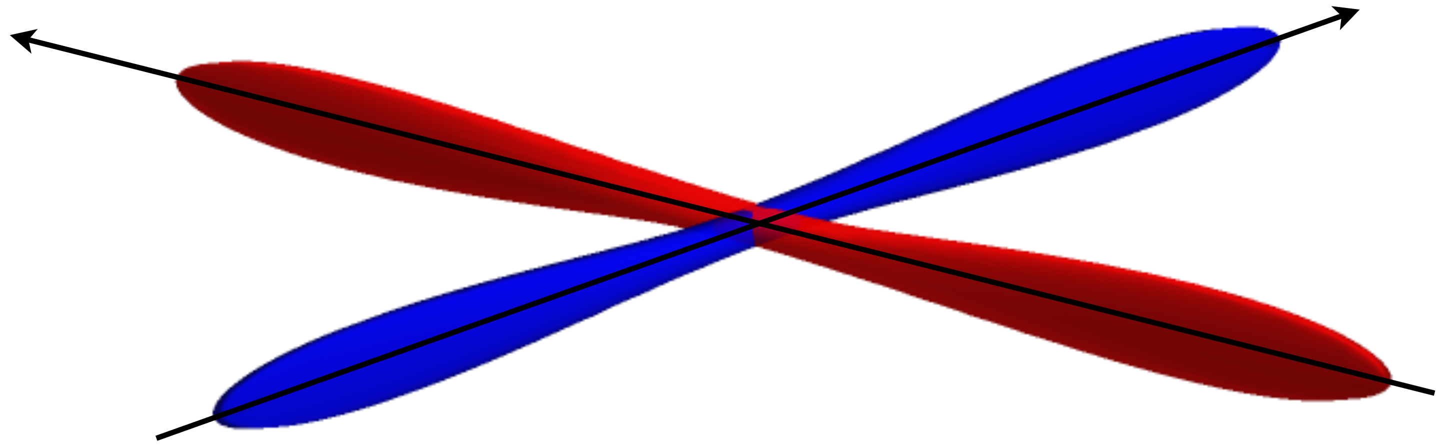
$$L = \frac{1}{2er_e}\frac{\gamma_\pm I_\pm}{\beta_{y\pm}^*}\boxed{\xi_{y\pm}^L} \longrightarrow \text{Beam-beam parameter [2]}$$

$$\text{Beam-beam tune shift [3]} \longleftarrow \boxed{\xi_{y+}^i} \approx \frac{r_e}{2\pi\gamma_+}\frac{N_-\beta_{y+}^*}{\sigma_{y-}^*\sqrt{\sigma_{z-}^2\tan^2\frac{\theta_c}{2} + \sigma_{x-}^{*2}}}$$

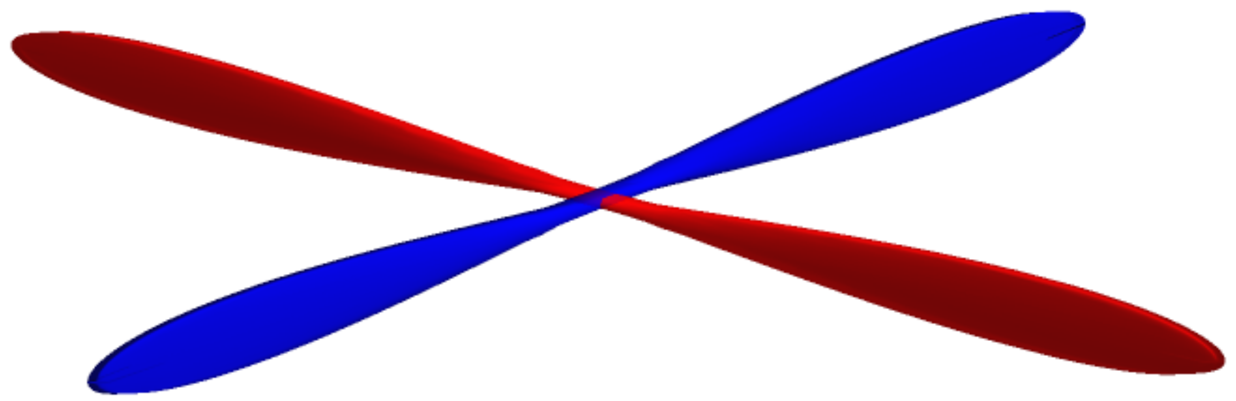
Piwinski angle: $\Phi_P = \frac{\sigma_z}{\sigma_x^*}\tan\frac{\theta_c}{2} \gg 1$

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

Schematic view of collision schemes



SuperKEKB (2021c)



SuperKEKB (Final design)

[1] D. Zhou, https://arxiv.org/pdf/2212.12706. [2] K. Ohmi et al., PRST-AB 7, 104401 (2004). [3] BB parameter and tune shift refer to different terms in this talk.

Luminosity performance

- Overview of beam-beam parameters with crab waist [1, 2]
  - The achieved beam-beam parameters during the physics run of SuperKEKB (i.e., the high voltage of Belle II was on.) in 2022 were 0.0407/0.0279 in LER/HER ($\gamma_+ I_{b+} \neq \gamma_- I_{b-}$, β_y^*=1 mm).
  - In 2022, 0.0565/0.0434 were achieved in LER/HER during HBCC machine studies (β_y^*=1 mm).
  - There was no clear evidence showing SuperKEKB had already reached the beam-beam limit.

Table 1. Comparison of KEKB and SuperKEKB machine parameters.

	KEKB Achieved		SuperKEKB 2020 May 1st		SuperKEKB 2022 June 22nd		SuperKEKB Design	
	LER	HER	LER	HER	LER	HER	LER	HER
I_{beam} [A]	1.637	1.188	0.438	0.517	1.363	1.118	3.6	2.6
# of bunches	1585		783		2249		2500	
I_{bunch} [mA]	1.033	0.7495	0.5593	0.6603	0.606	0.497	1.440	1.040
β_y^* [mm]	5.9	5.9	1.0	1.0	1.0	1.0	0.27	0.30
ξ_y	$0.129^{a)}$	$0.090^{a)}$	$0.0236^{b)}$	$0.0219^{b)}$	$0.0398^{b)}$	$0.0278^{b)}$	$0.0881^{c)}$	$0.0807^{c)}$
	$0.10^{b)}$	$0.060^{b)}$			$0.0565^{d)}$	$0.0434^{d)}$	$0.069^{b)}$	$0.061^{b)}$
$\mathcal{L}$ [10^{34}cm^{-2}s^{-1}]	2.11		1.57		4.71		80	
$\int \mathcal{L}dt$ [ab^{-1}]	1.04		0.03		0.424		50	

a) $$\mathcal{L} = \frac{1}{2er_e}\frac{\gamma_\pm I_\pm}{\beta_{y\pm}^*}\xi_{y\pm}^{ih}\frac{R_\mathcal{L}}{R_{\xi y}^\pm}$$

b,d) $$L = \frac{1}{2er_e}\frac{\gamma_\pm I_\pm}{\beta_{y\pm}^*}\xi_{y\pm}^L$$

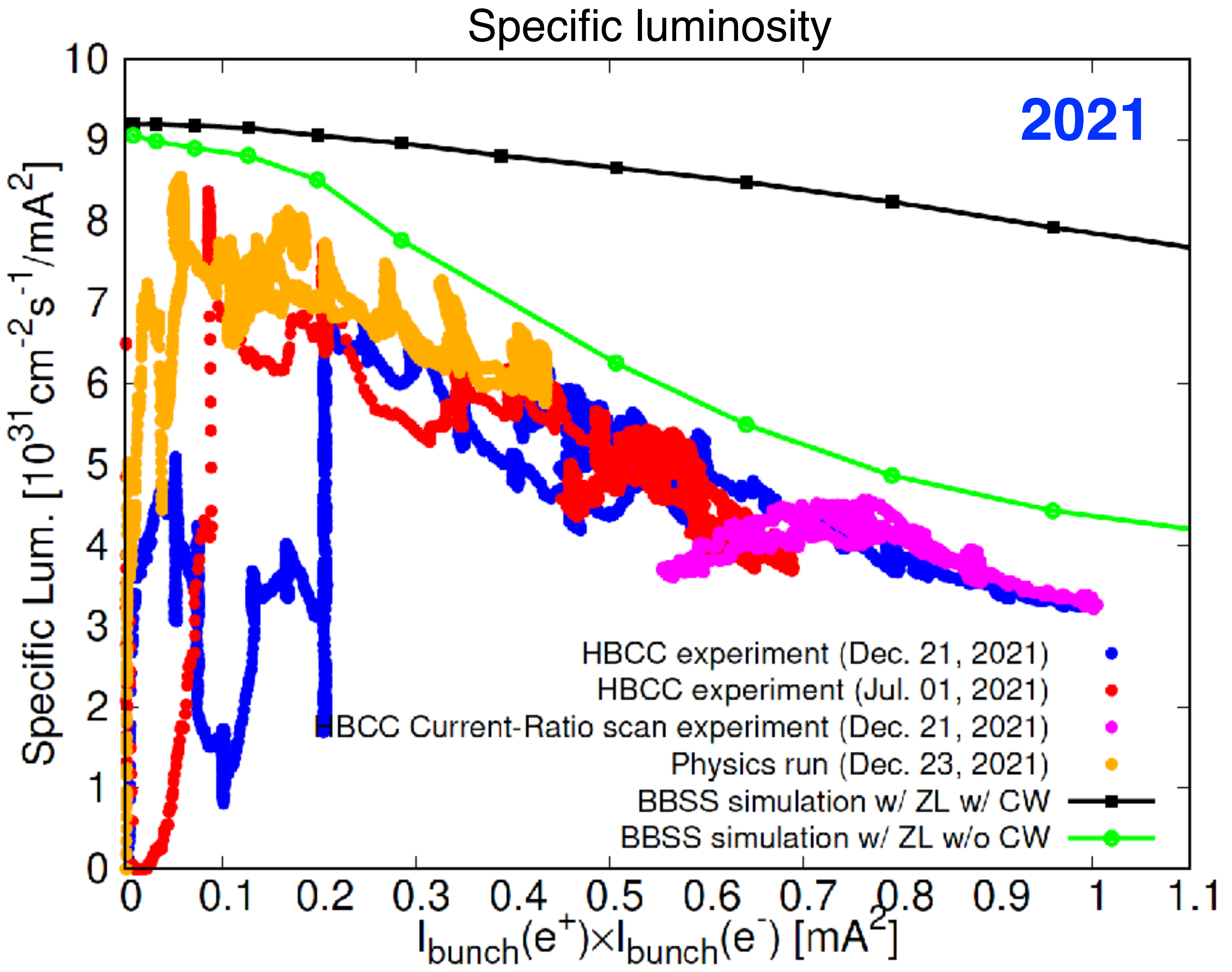
c) $$\xi_{y+}^{ih} = \frac{1}{4\pi p_0 c}\int_{-\infty}^{\infty} ds\beta_{y+}(s)\frac{\partial F_{y+}}{\partial y'}$$

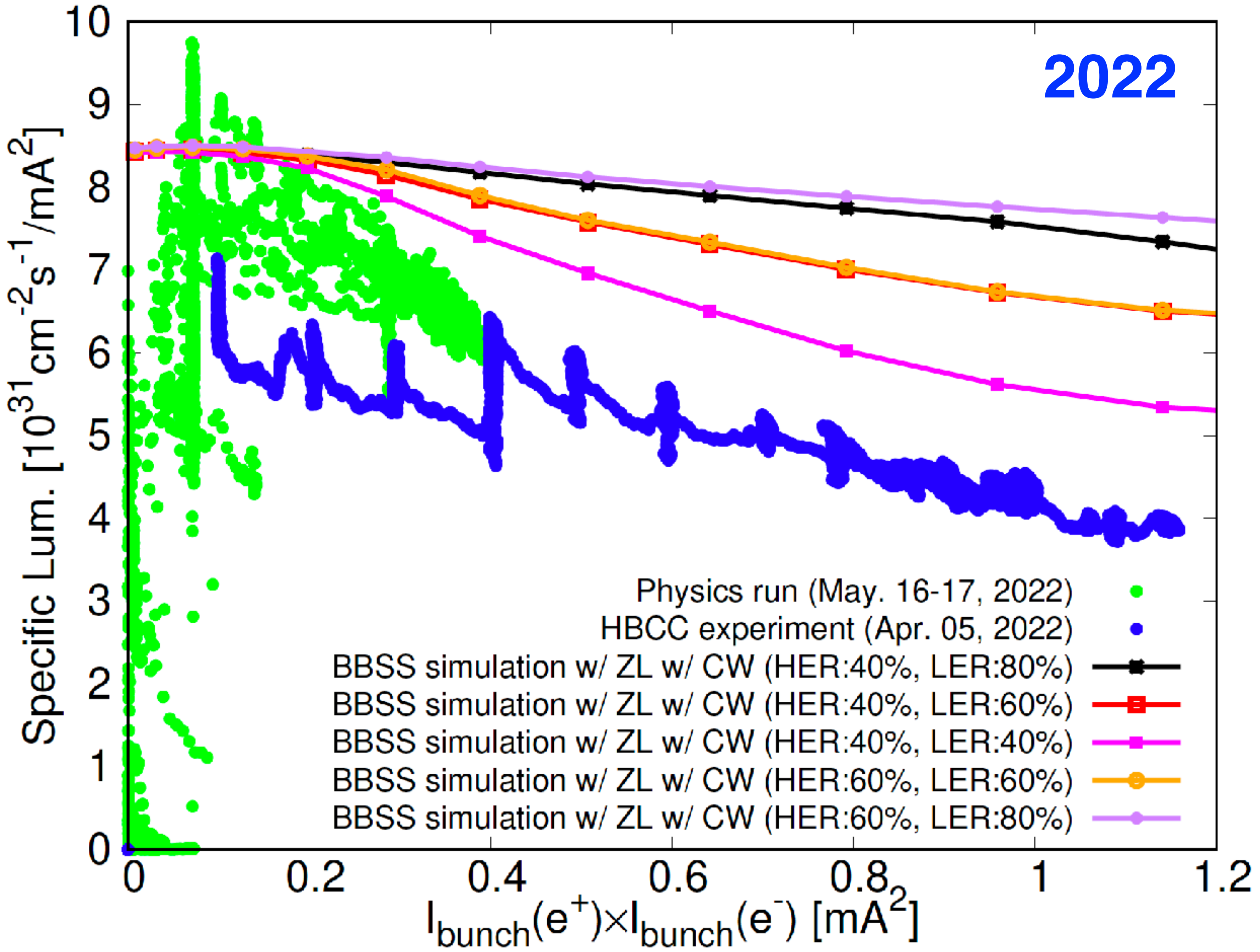
[1] Y. Funakoshi, IPAC'22.   [2] D. Zhou, ICFA Beam Dynamics Newsletter #85, 2023.

Luminosity performance

- HBCC (High Bunch Current Collision) machine studies with $\beta_y^* = 1$ mm in 2021 and 2022:
  - HBCC machine studies were done to extract the luminosity performance.
  - Lsp (specific luminosity) slope vs. product of beam currents improved in 2022 but still drops quickly due to vertical blowup.

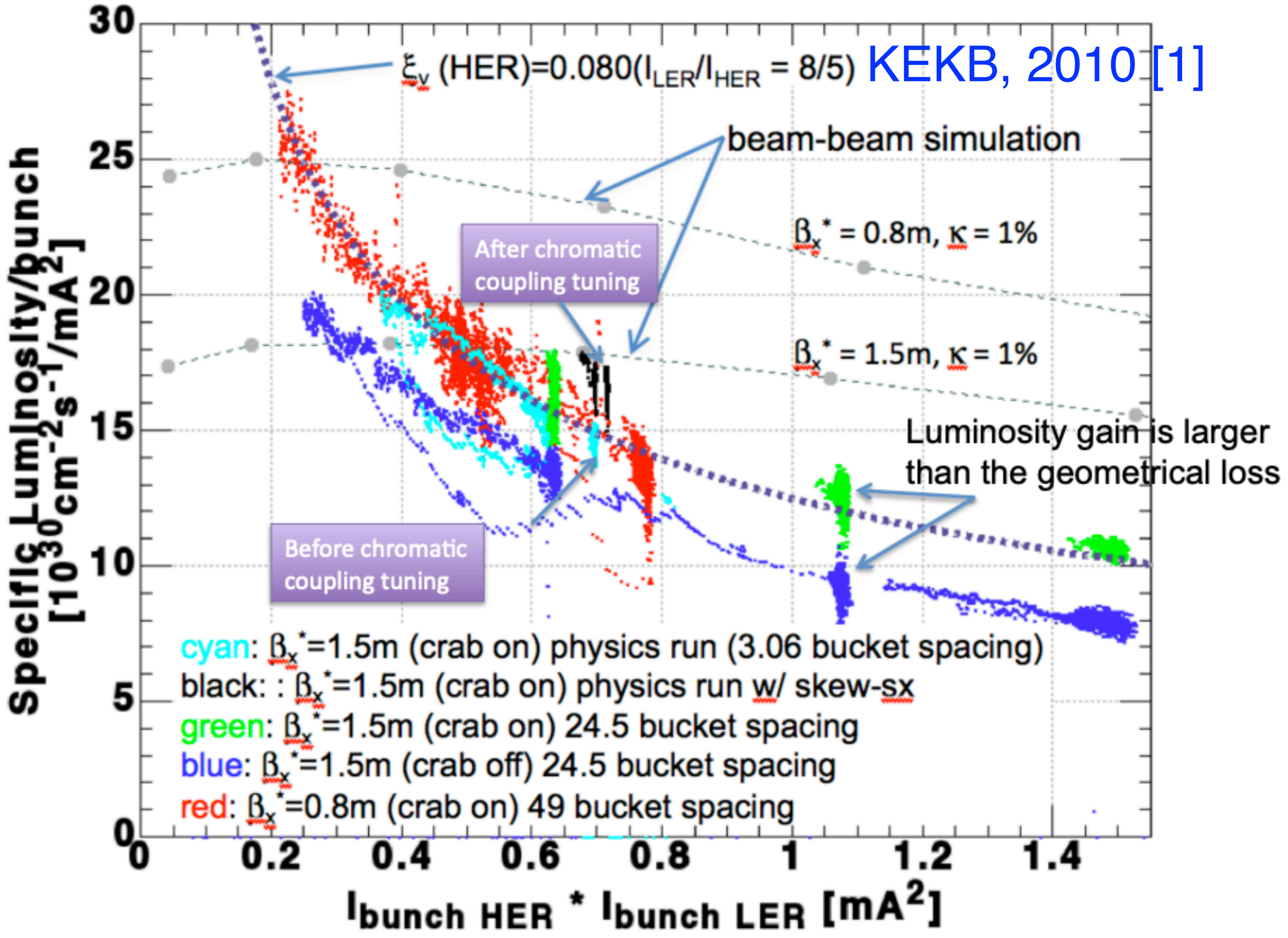
	2021.12.21		2022.04.05		Comments
	HER	LER	HER	LER	
I_{bunch} (mA)	Ie	1.25*Ie	Ie	1.25*Ie	
# bunch	393		393		Assumed value
ε_x (nm)	4.6	4.0	4.6	4.0	w/ IBS
ε_y (pm)	35	20	30	35	Estimated from XRM data
β_x (mm)	60	80	60	80	Calculated from lattice
β_y (mm)	1	1	1	1	Calculated from lattice
σ_{z0} (mm)	5.05	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



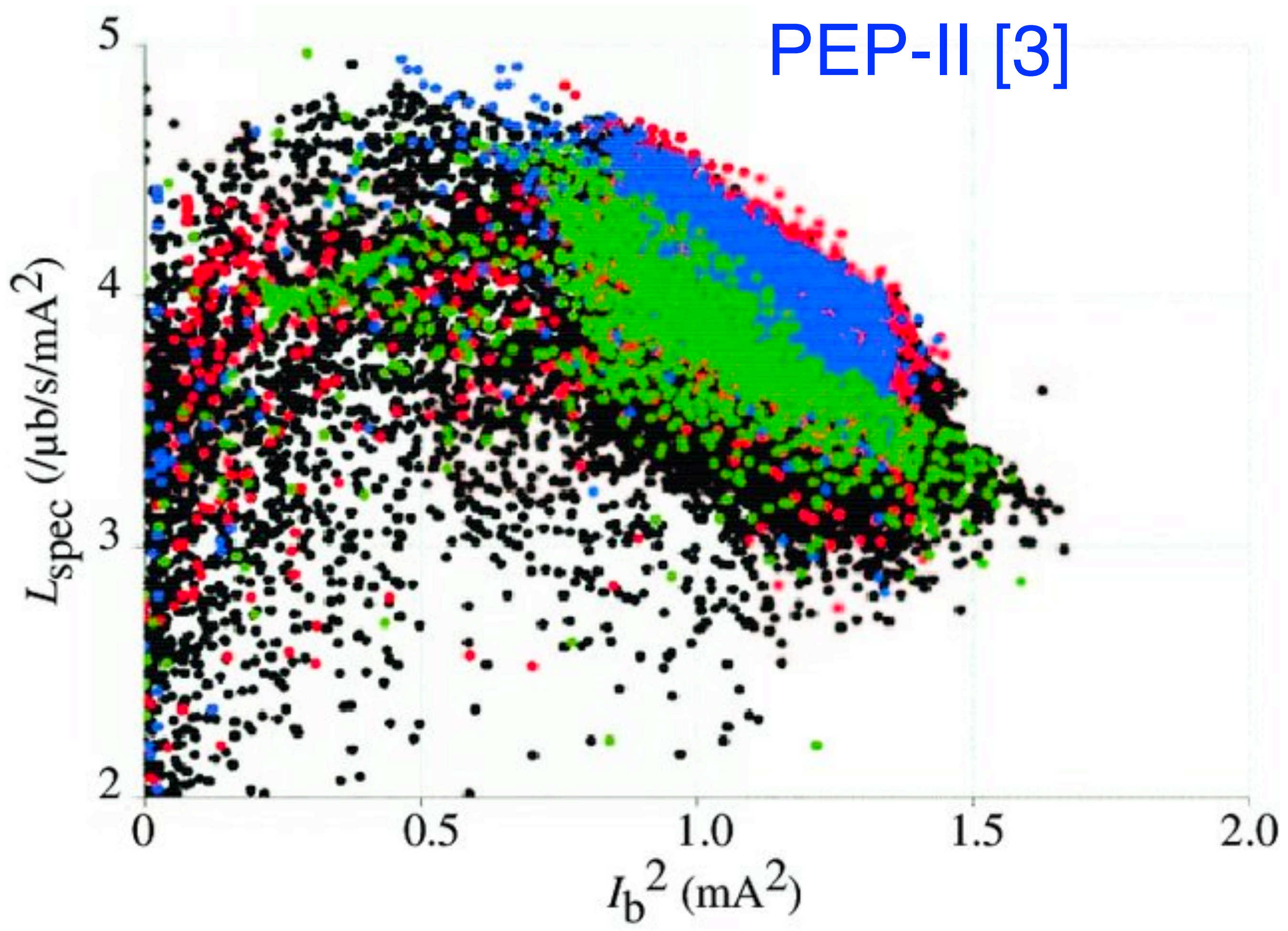


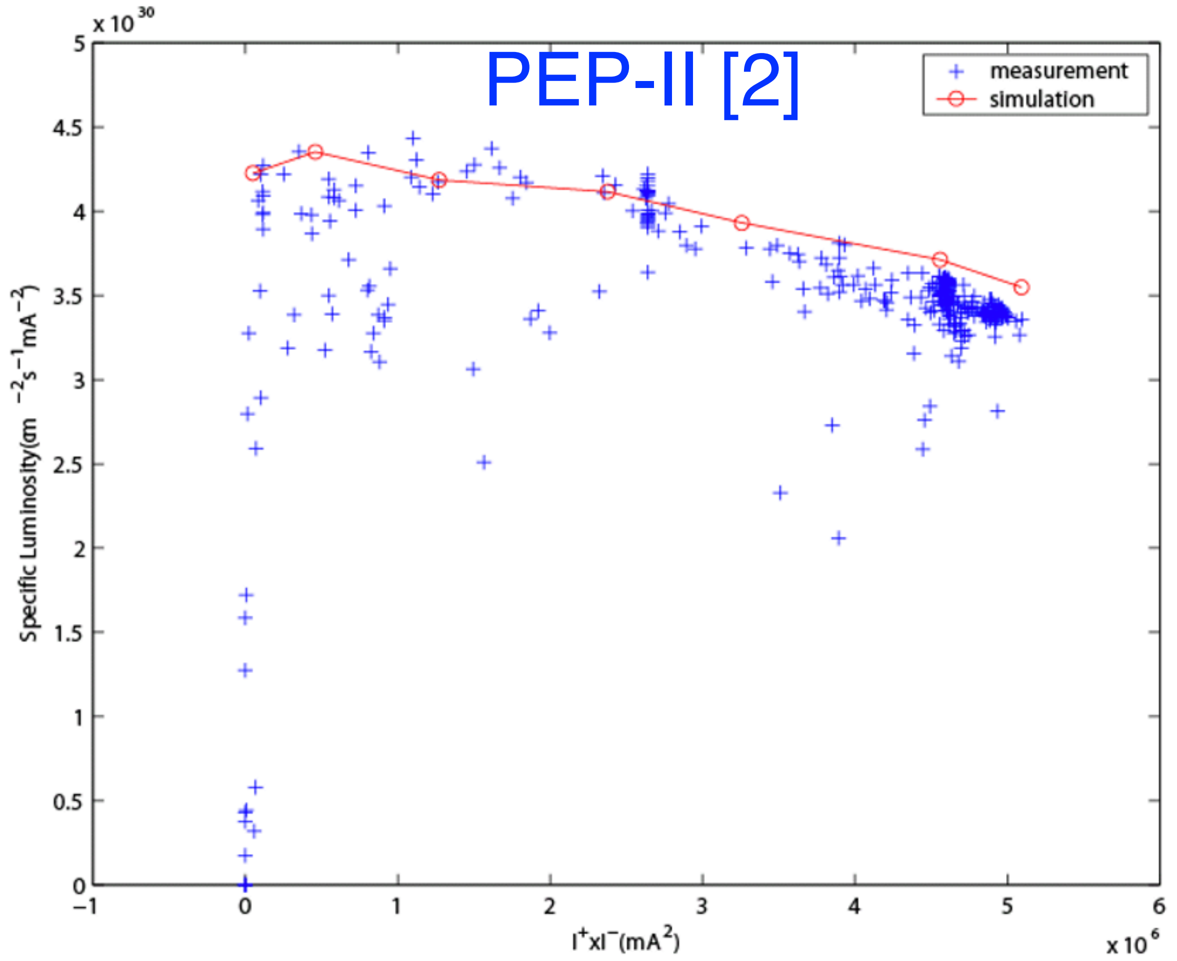
Luminosity performance

- The “Lsp puzzle” (large discrepancy between beam-beam simulations and experiments)
  - The “Lsp puzzle” in KEKB.
  - The “Lsp puzzle” in SuperKEKB.
  - Lsp in PEP-II

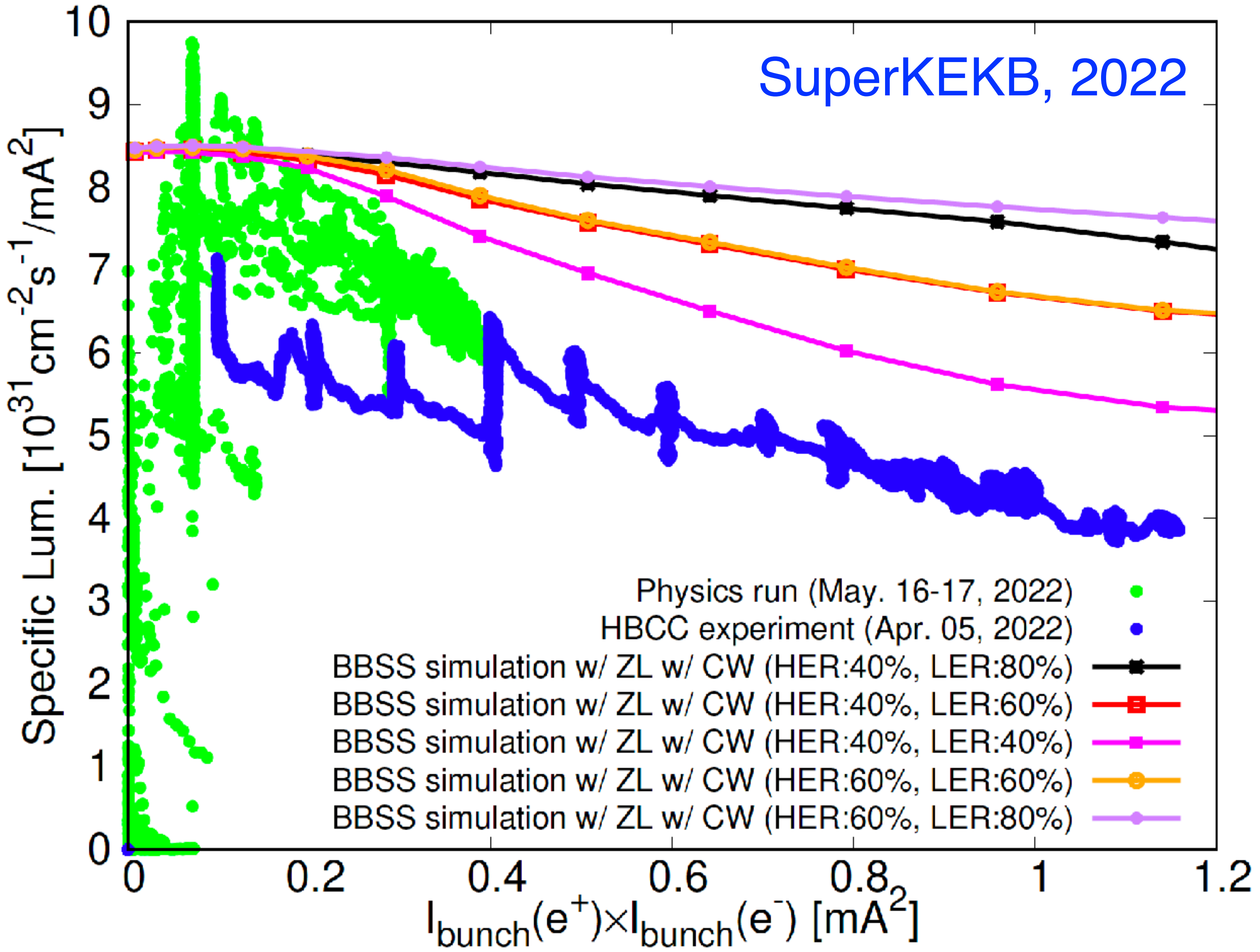


Specific Luminosity October 10, 2005
(I^+=2940mA, I^-=1733mA, n_b=1732)





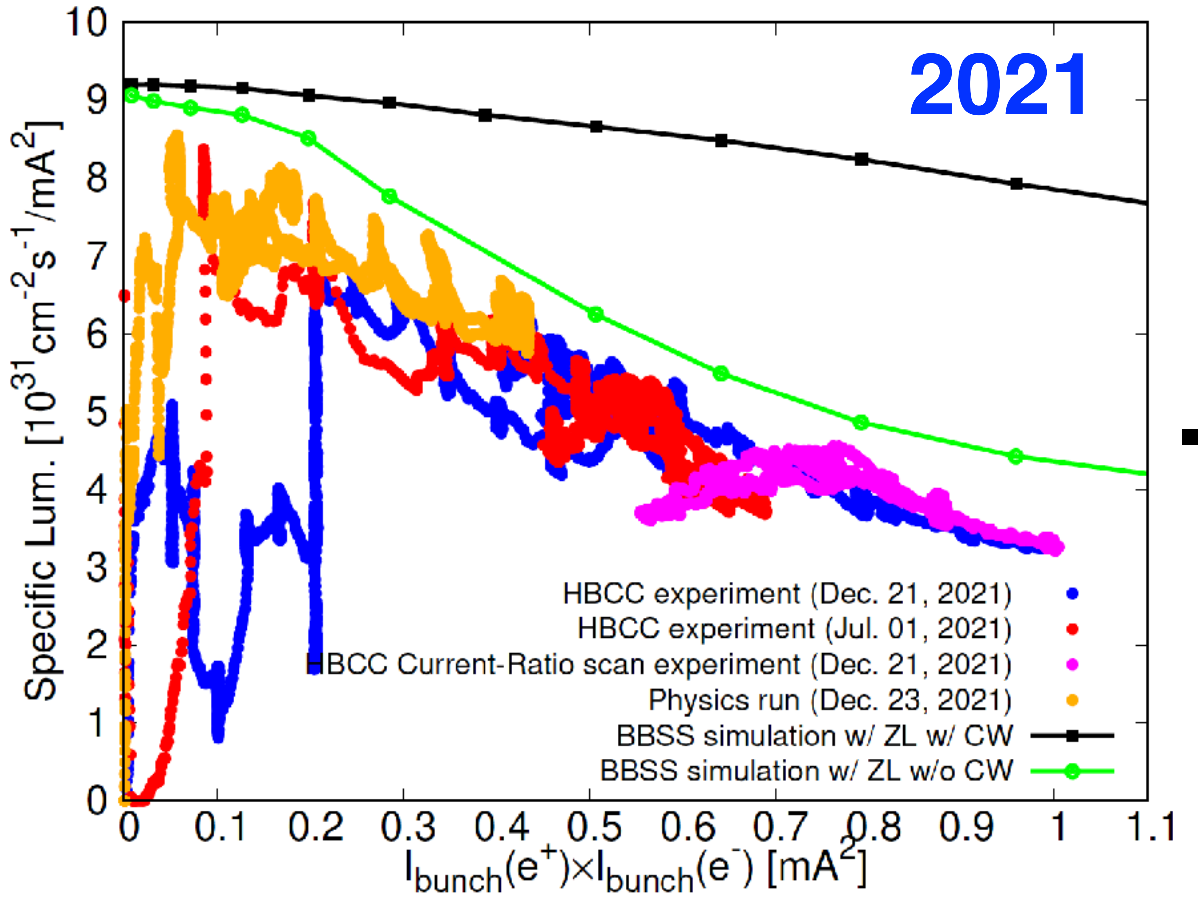
Data taken in the history buffer for a 24 hours period.
The simulation used an approximately fixed current ratio.

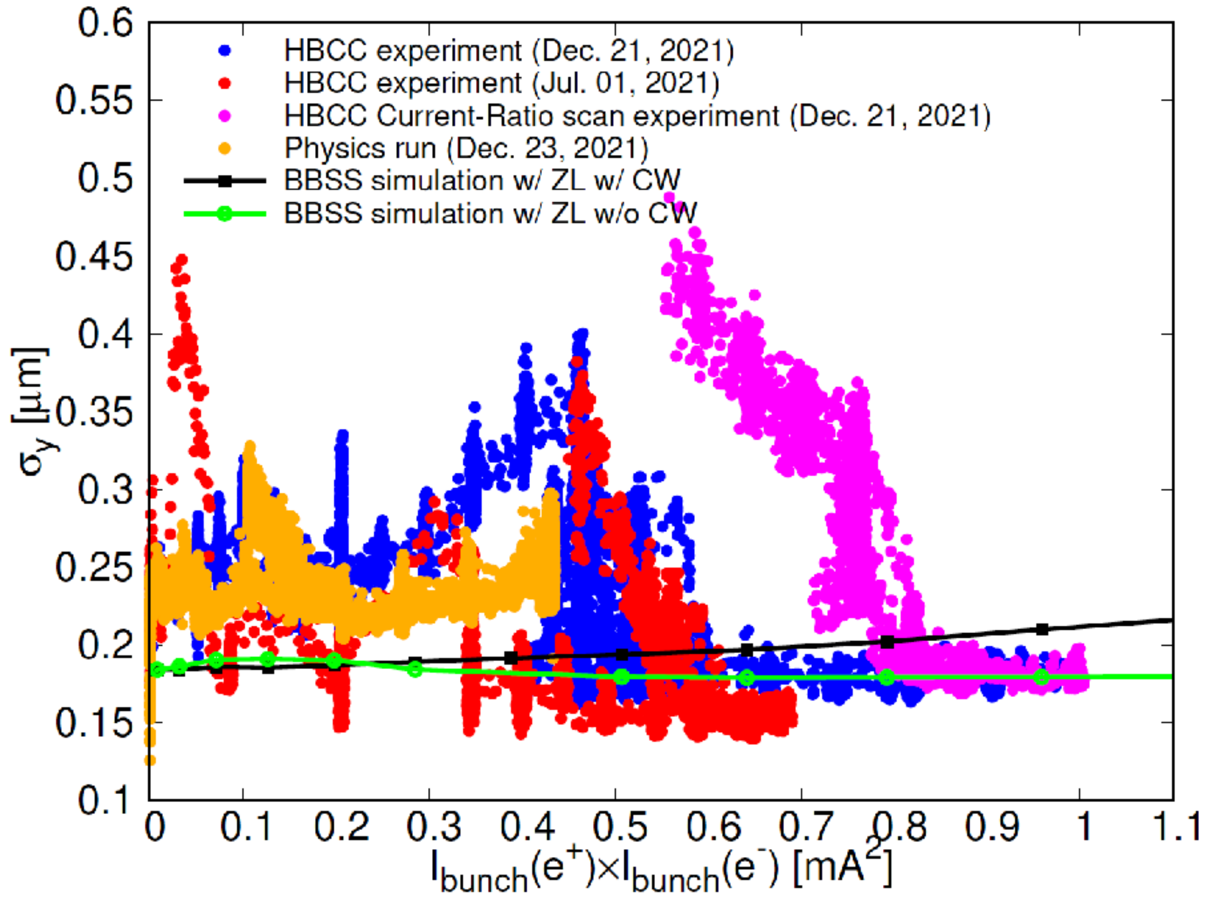


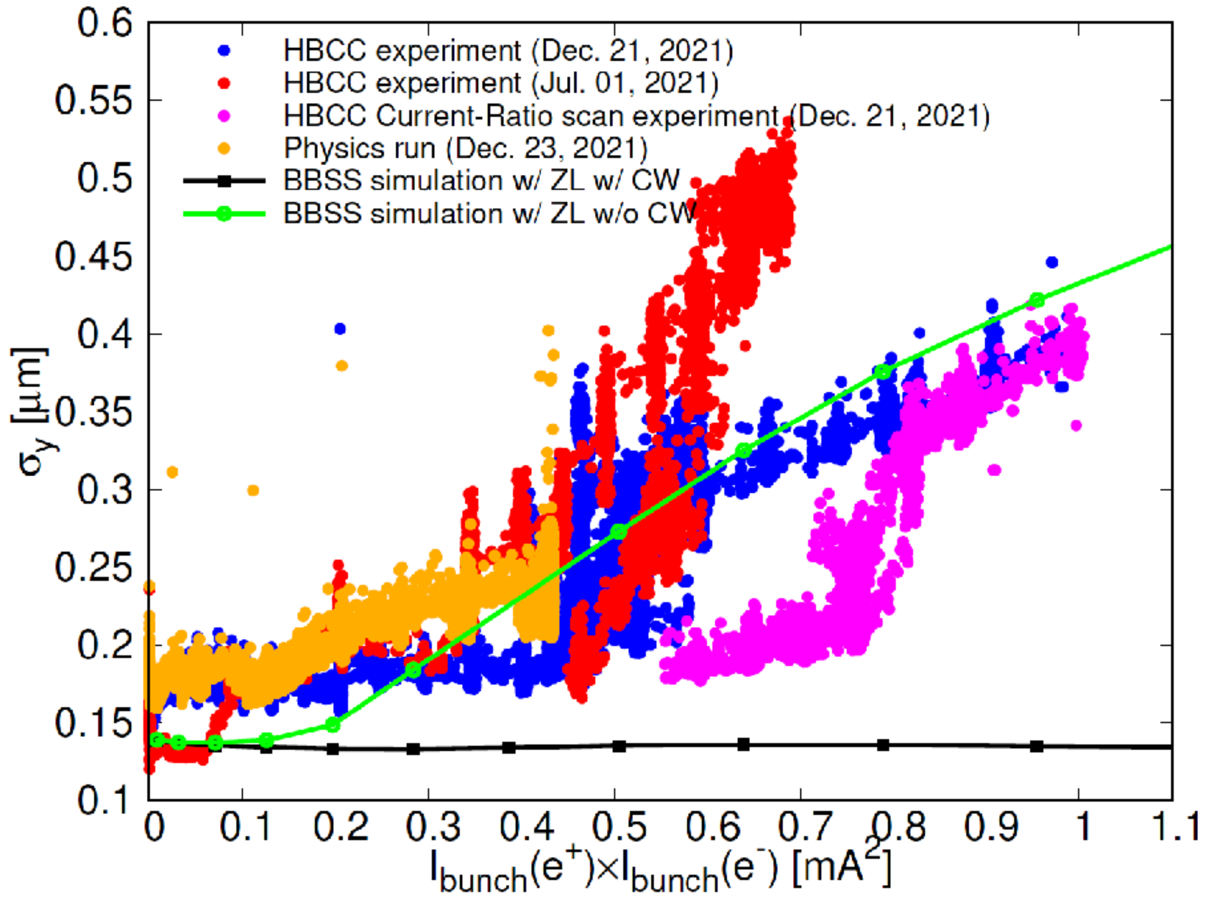
[1] Y. Funakoshi, KEKB MAC 2010; [2] Y. Cai, KEKB MAC 2006; [3] U. Wienands, PAC07.

Luminosity performance

- HBCC machine studies with $\beta_y^* = 1$ mm in 2021 and 2022:
    - After fine-tuning of BxB FB system in 2022, the observed vertical beam sizes blowup became much more “normal” (a breakthrough in 2022) and closer to simulations. The origin of vertical blowup remains to be explained.





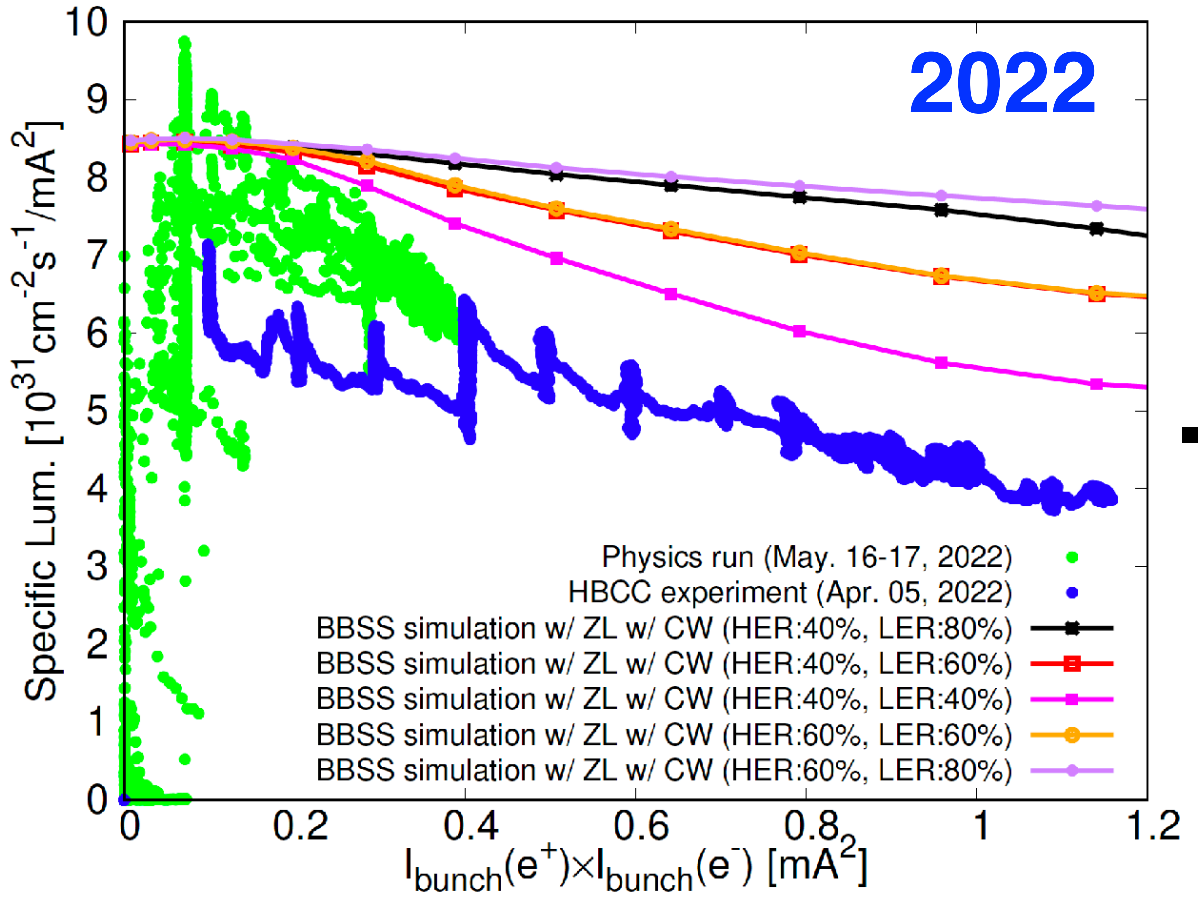


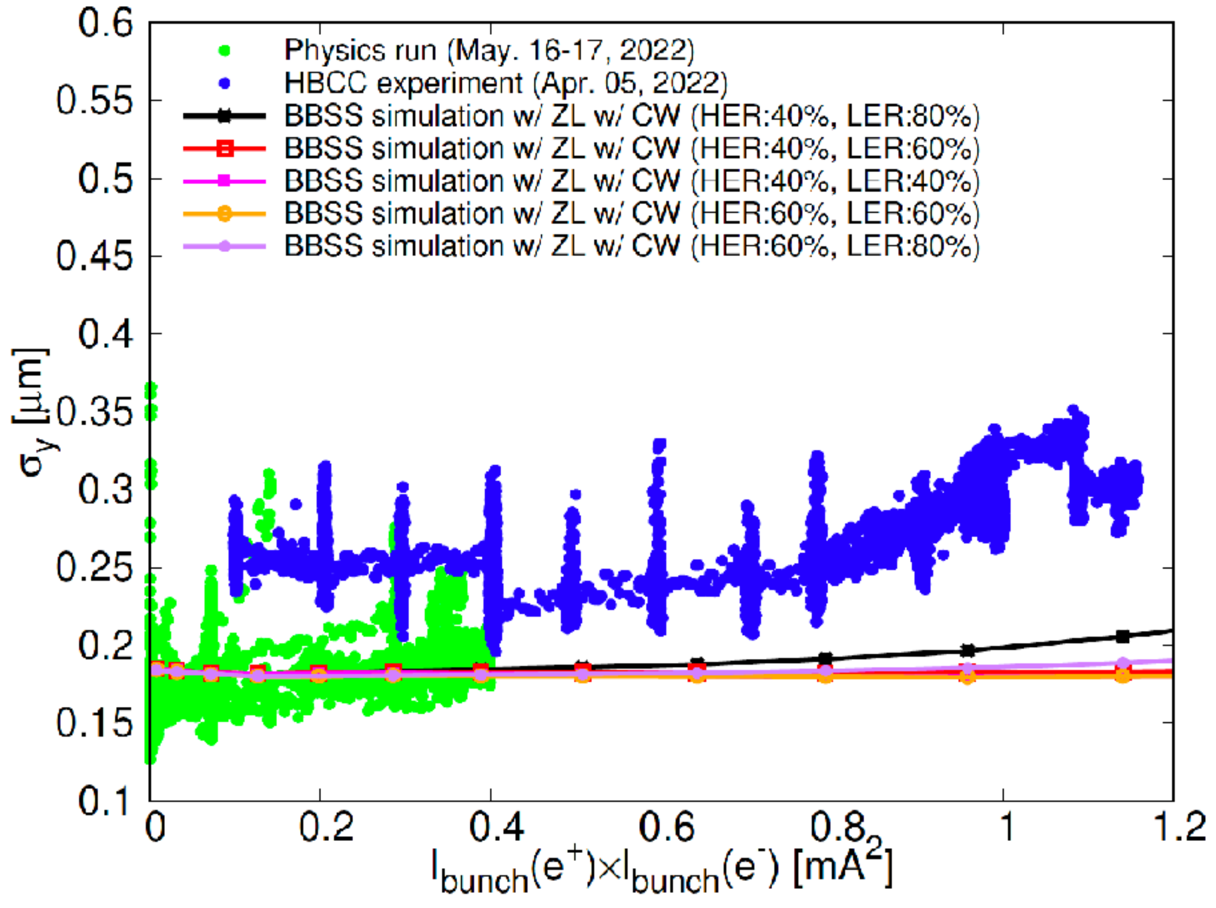
In 2021, there was a “flip-flop” correlation between σ_{y+}^* and σ_{y-}^*

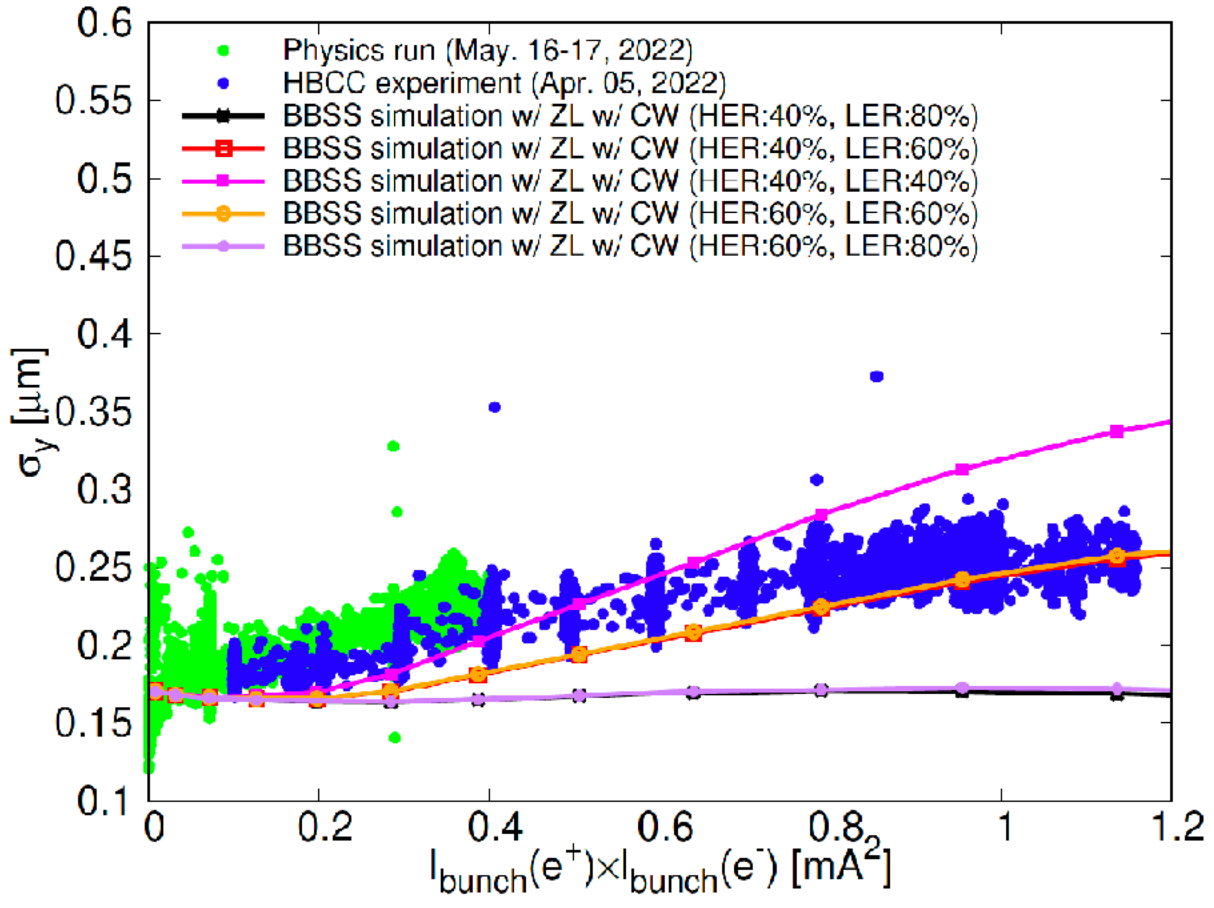
Specific luminosity

Electron σ_y^*

Positron σ_y^*







In 2022, this “flip-flop” problem was cured after fine-tuning of FB system

Accelerator physics challenges

- From the beam-beam perspective, we list some important issues [1]:
  - Issue 1: Limits on bunch currents
  - Issue 2: Multi-bunch effects
  - Issue 3: Optics distortion at high beam currents
  - Issue 4: Impedance effects
  - Issue 5: Lsp injection correlation

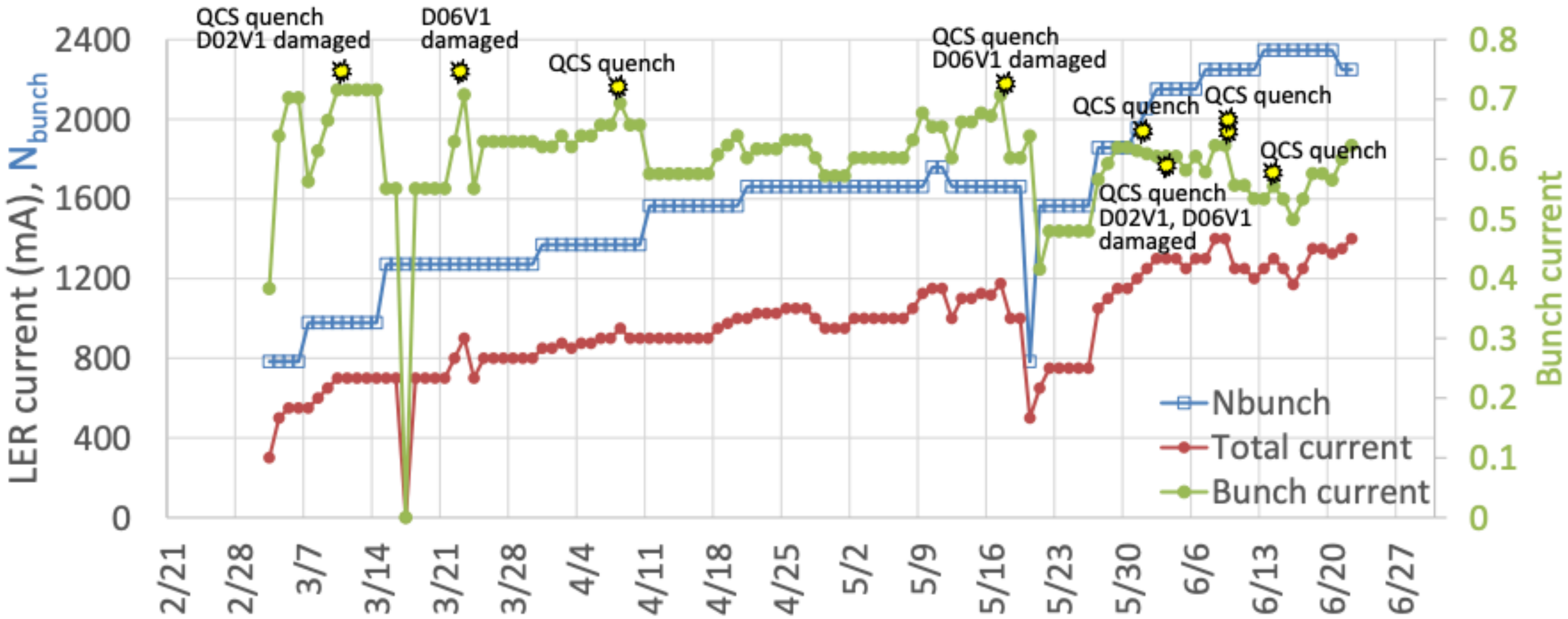
$$\overset{\#5}{\boxed{L}} \approx \frac{\overset{\#1,2,3,4,5}{\boxed{N_b N_+ N_-}}\, f}{2\pi \sqrt{\underset{\#1,2,3,4,5}{\boxed{\sigma_{y+}^{*2}+\sigma_{y-}^{*2}}}}\, \sqrt{\underset{\#4}{\boxed{\sigma_{z+}^{2}+\sigma_{z-}^{2}}}}\, \tan \underset{\text{BB, CW, …}}{\boxed{\frac{\theta_c}{2}}}}\, e^{-\frac{\overset{\#2,5}{\boxed{\Delta^2}}}{2(\sigma_{y+}^{*2}+\sigma_{y-}^{*2})}}$$

[1] D. Zhou et al., Phys. Rev. Accel. Beams 26, 071001 (2023).

Issue-1: Limit on bunch currents by Sudden Beam Losses (SBLs)

- Severe machine failures occurred at high beam currents when $I_{b+} > 0.7$ mA/bunch
- Bunch current $I_{b+} \lesssim 0.7$ mA (keeping $I_{b-}/I_{b+} = 0.8$) was respected in 2022ab run [1]

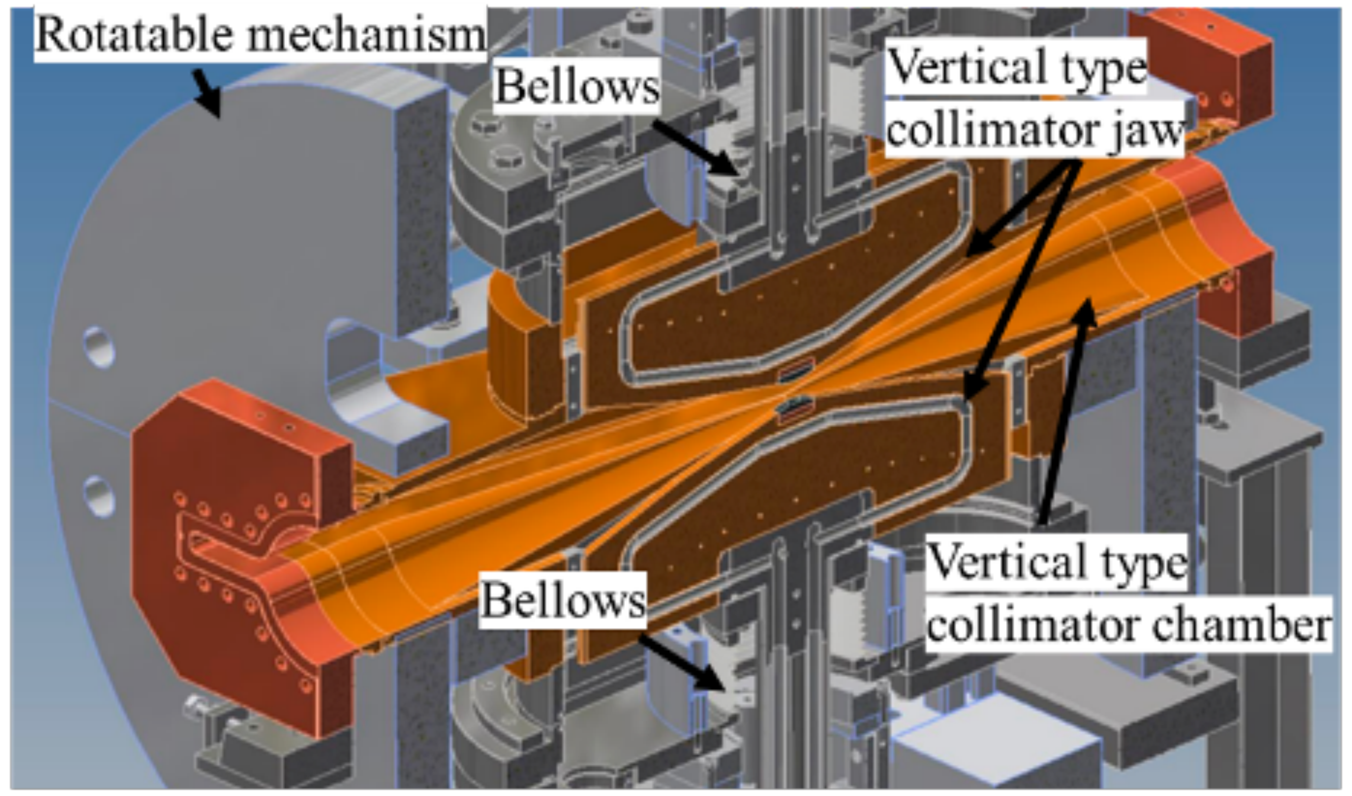
Beam loss accidents and bunch current

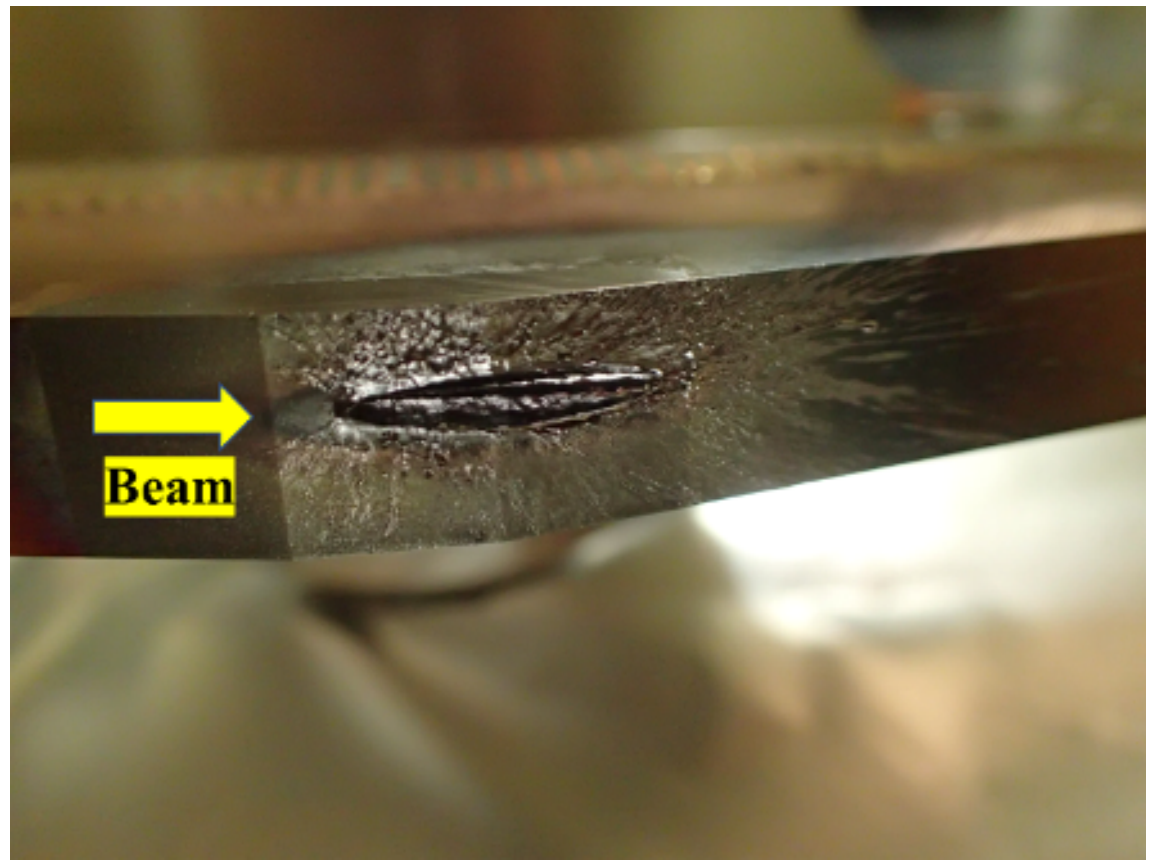


Courtesy of K. Matsuoka

The first four accidents of LER beam loss in 2022 happened at $I_b \gtrsim 0.7$ mA/bunch within a day after increasing the beam current at each different N_{bunch}.
The threshold became somehow lower after the D06V1 damage on May 17.
It might be due to the D06V1 damage, different collimator configuration than usual to mitigate the beam background, or something else. Need investigation.

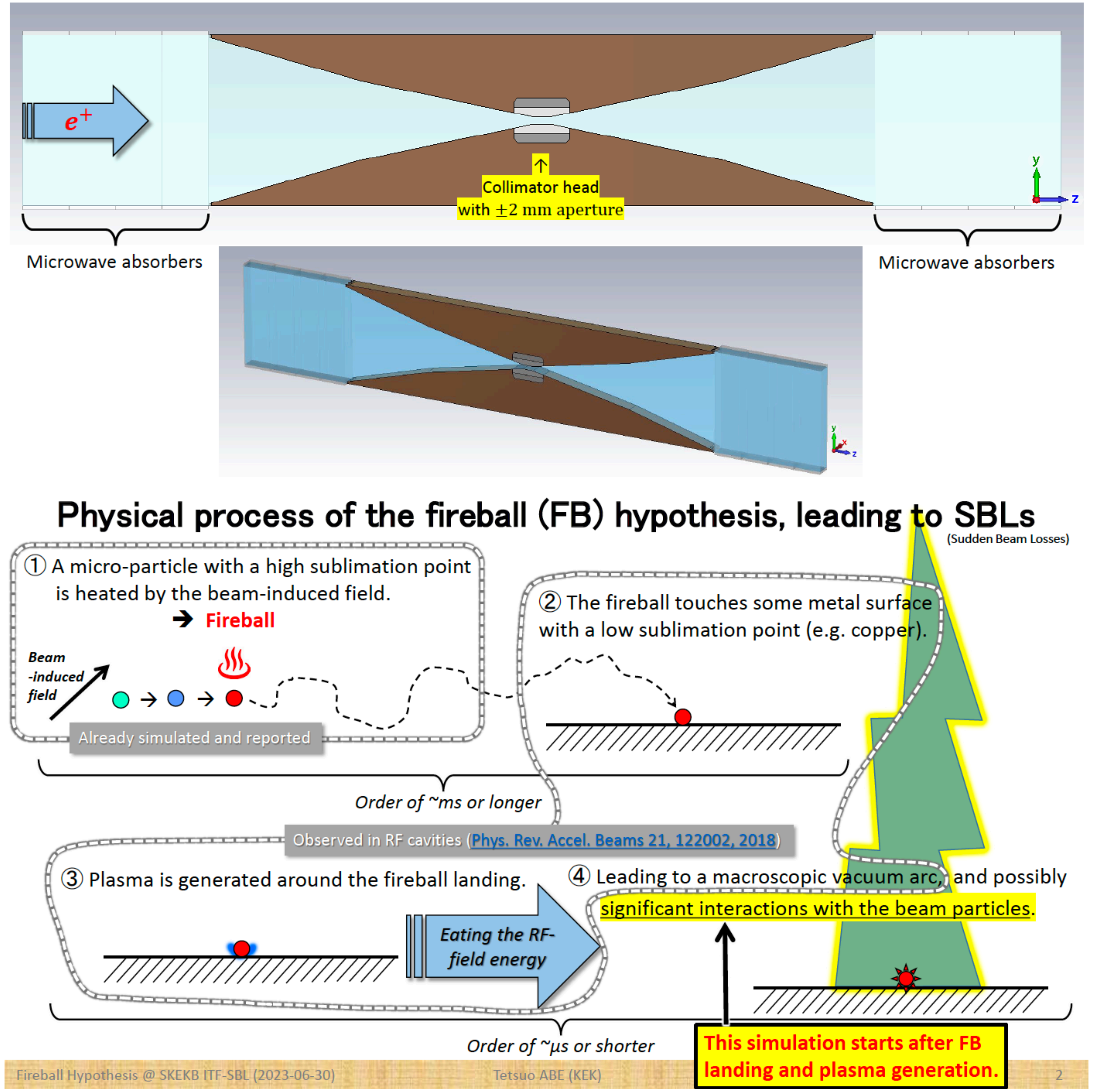
$$L \approx \frac{\boxed{N_b N_+ N_-} f}{2\pi\sqrt{\sigma_{y+}^{*2}+\sigma_{y-}^{*2}}\sqrt{\sigma_{z+}^{2}+\sigma_{z-}^{2}}\tan\frac{\theta_c}{2}}\, e^{-\frac{\Delta^2}{2(\sigma_{y+}^{*2}+\sigma_{y-}^{*2})}}$$



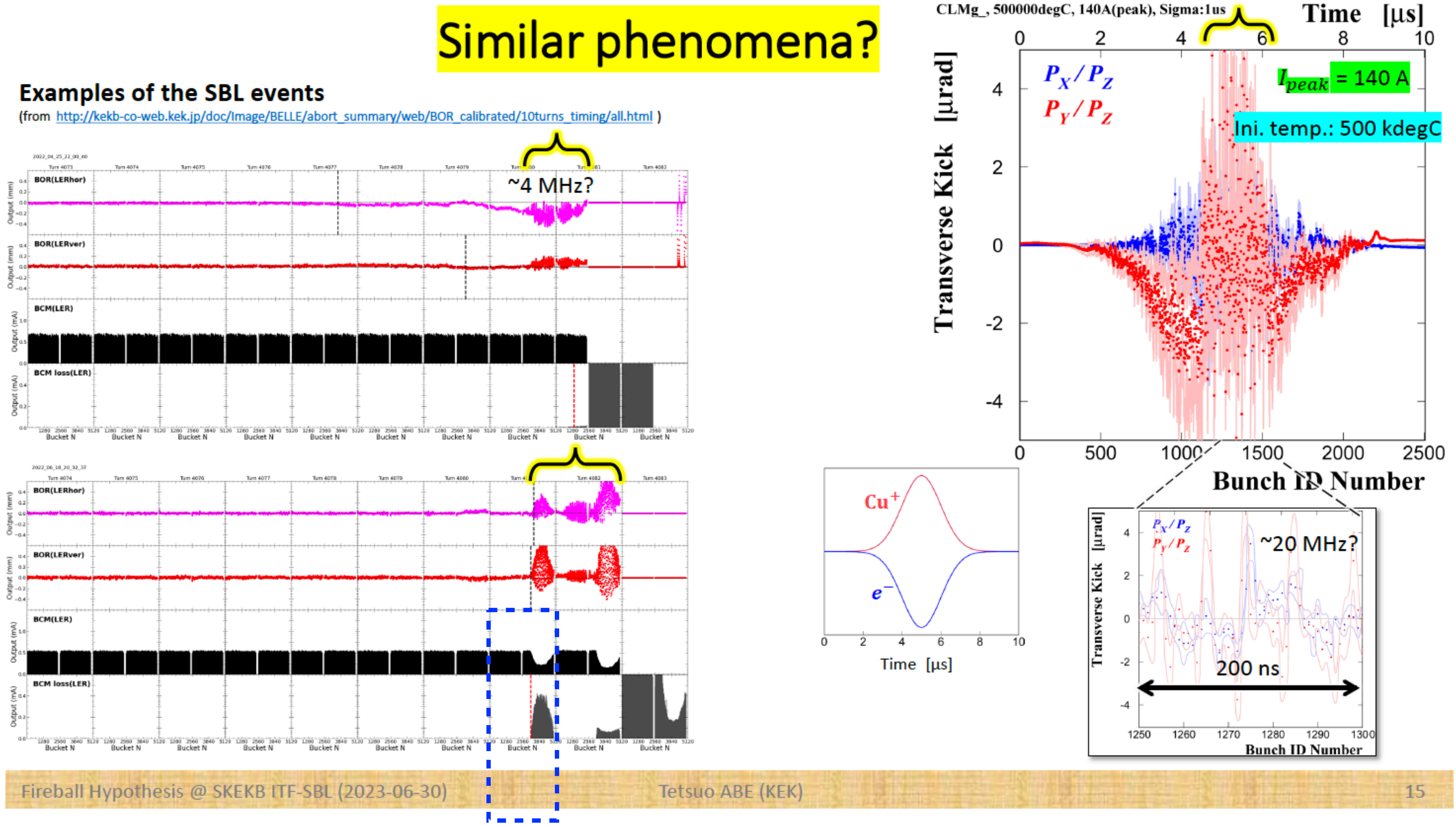


[1] K. Matsuoka, "Belle II Report", SuperKEKB 2022ab summary meeting, https://kds.kek.jp/event/42954/.

Issue-1: Limit on bunch currents by Sudden Beam Losses (SBLs)



"Fireball" hypothesis for SBLs
Proposed by T. Abe



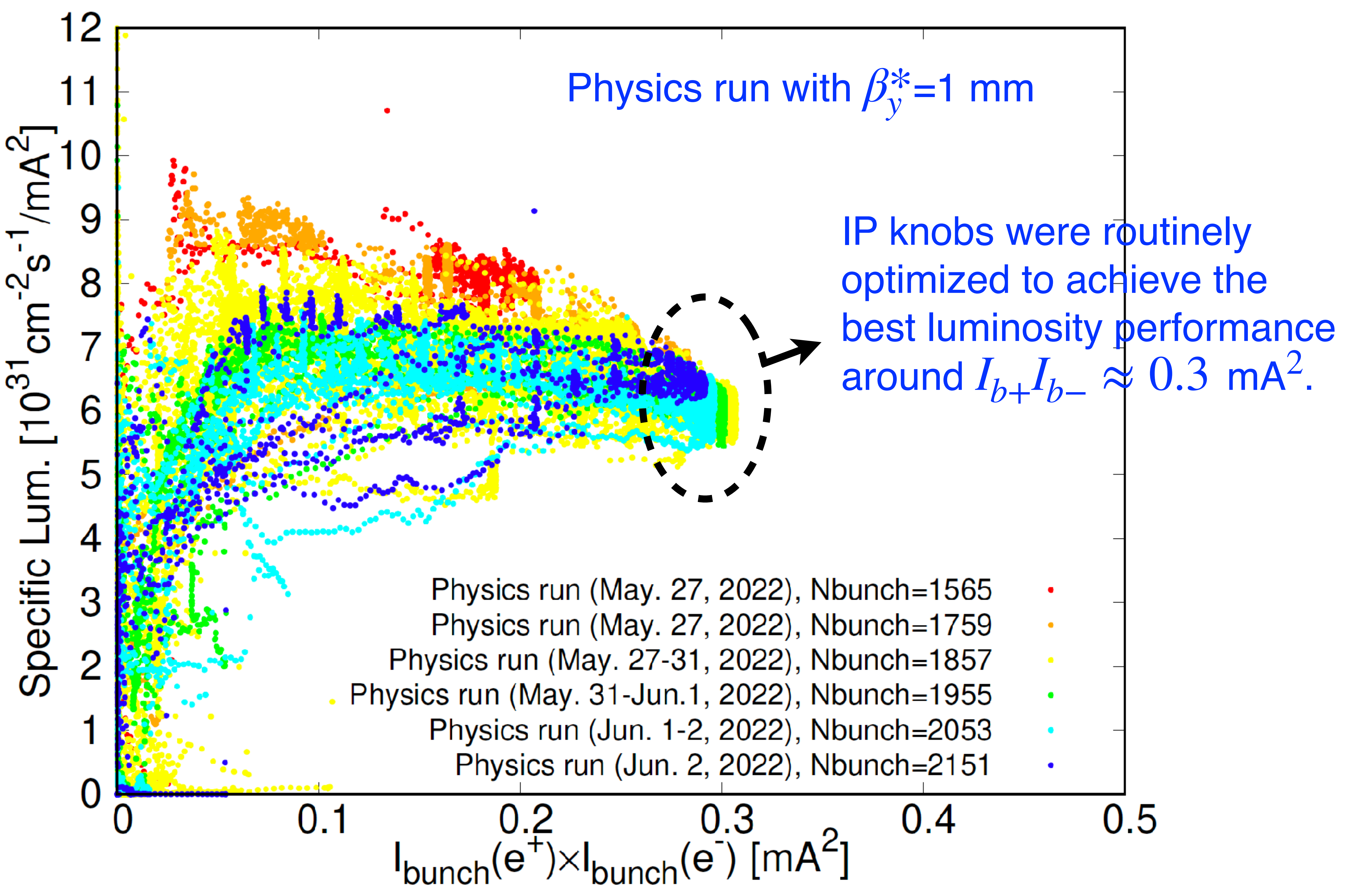
Huge beam loss in a single turn
Causing QCS quench, collimator damage, and huge Belle II background

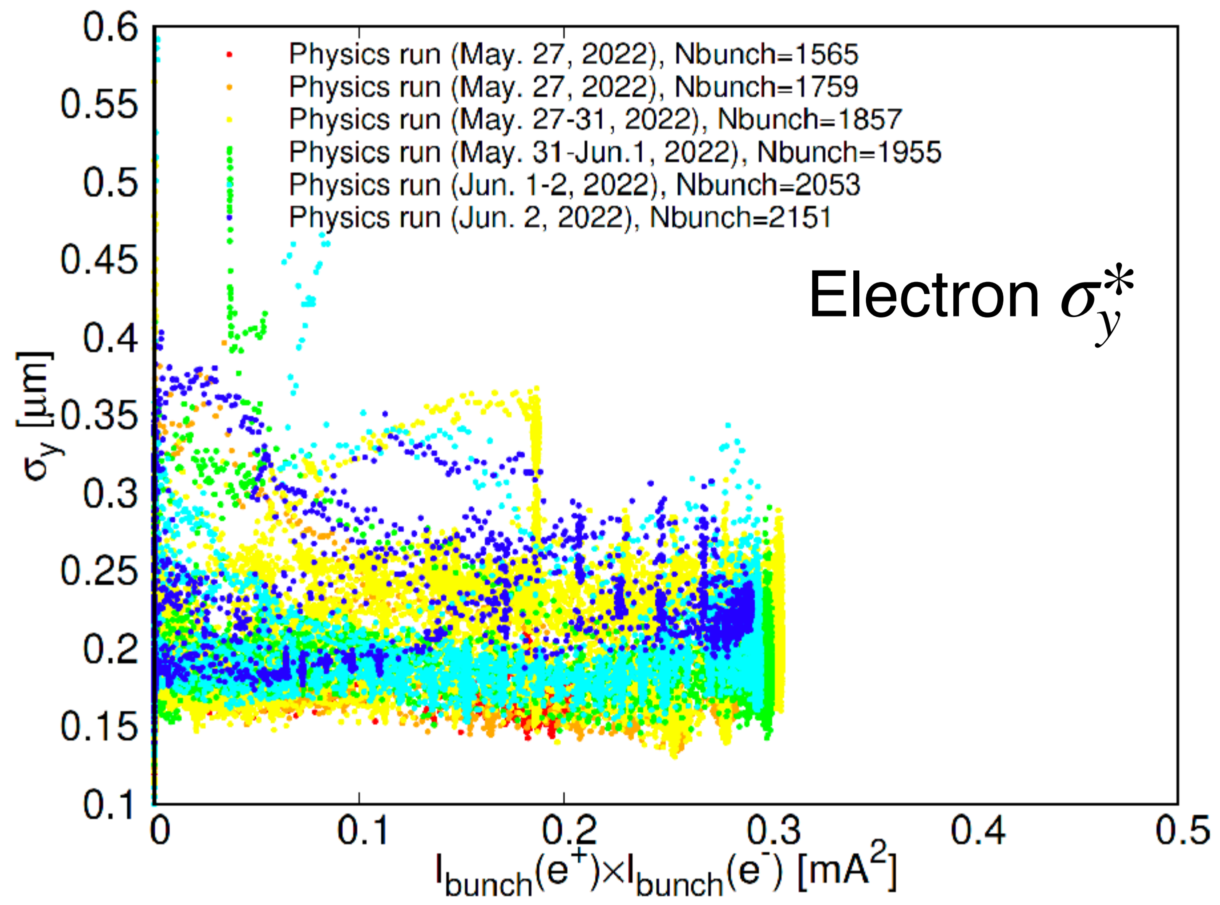
[1] Y. Abe, "The 1st results of beam simulation for the fireball SBL hypothesis", https://kds.kek.jp/event/46940/

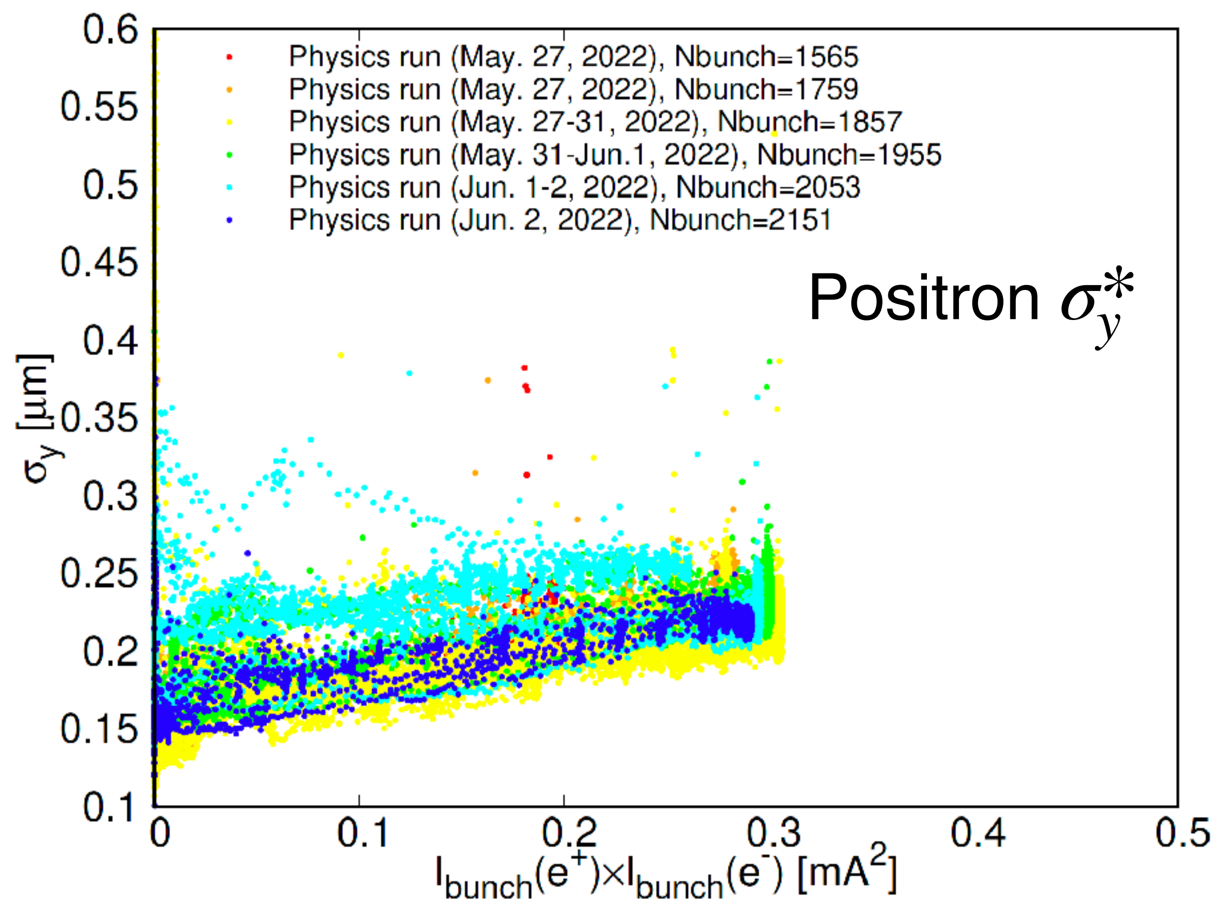
Issue-2: Multi-bunch effects

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

- No clear evidence of Lsp degradation due to multi-bunch effects
  - Coupled-bunch instabilities were suppressed by the BxB FB system (M. Tobiyama).
  - Flat BxB luminosity was observed (S. Uehara).
  - Electron-cloud instability for e+ beam was not observed (Y. Suetsugu et al.).





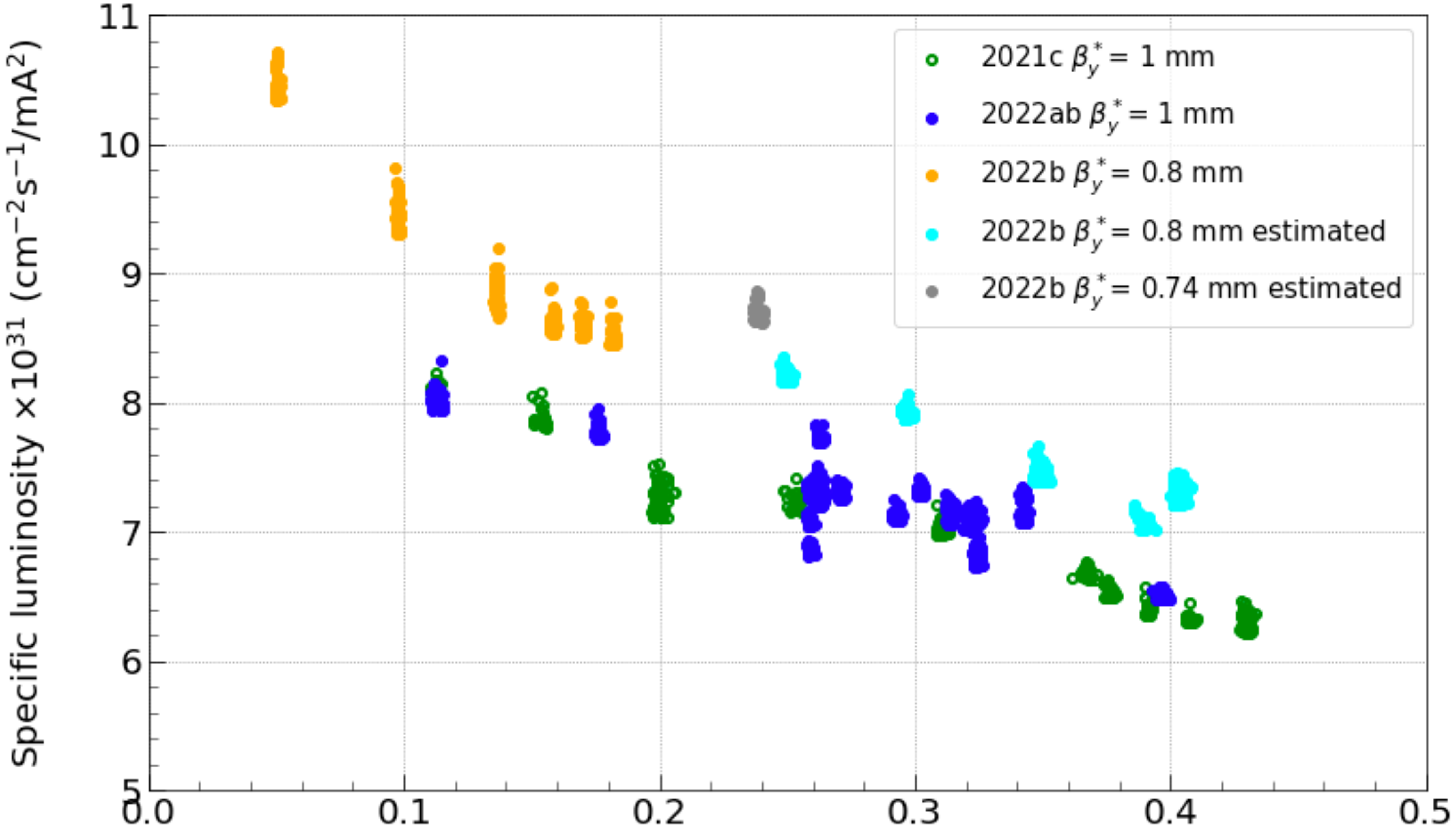


Issue-3: Optics distortion at high beam currents

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

- Current-dependent optics distortion
  - Beta-beat and global coupling become worse at high currents.
  - An unexpected β_y^* squeeze explains the Lsp gain.

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

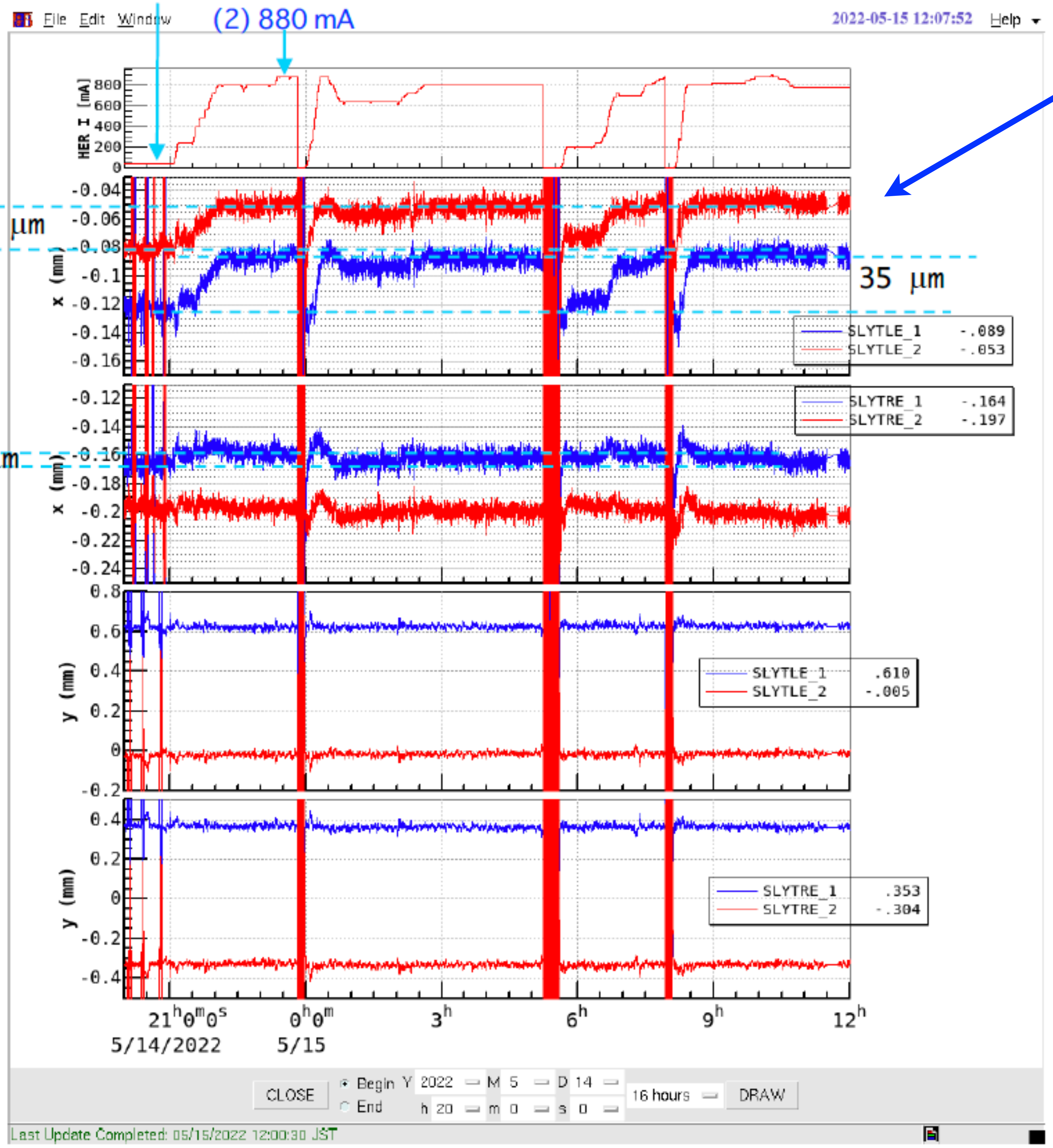


$I_{b+}I_{b-}$ (mA^2) Courtesy of Y. Ohnishi

Issue-3: Optics distortion at high beam currents

$$\xi^i_{y+} \approx \frac{r_e}{2\pi\gamma_+} \frac{N_- \boxed{\beta^*_{y+}}}{\sigma^*_{y-}\sqrt{\sigma^2_{z-}\tan^2\frac{\theta_c}{2} + \sigma^{*2}_{x-}}}$$

- Current-dependent orbit offsets at SLY* magnets

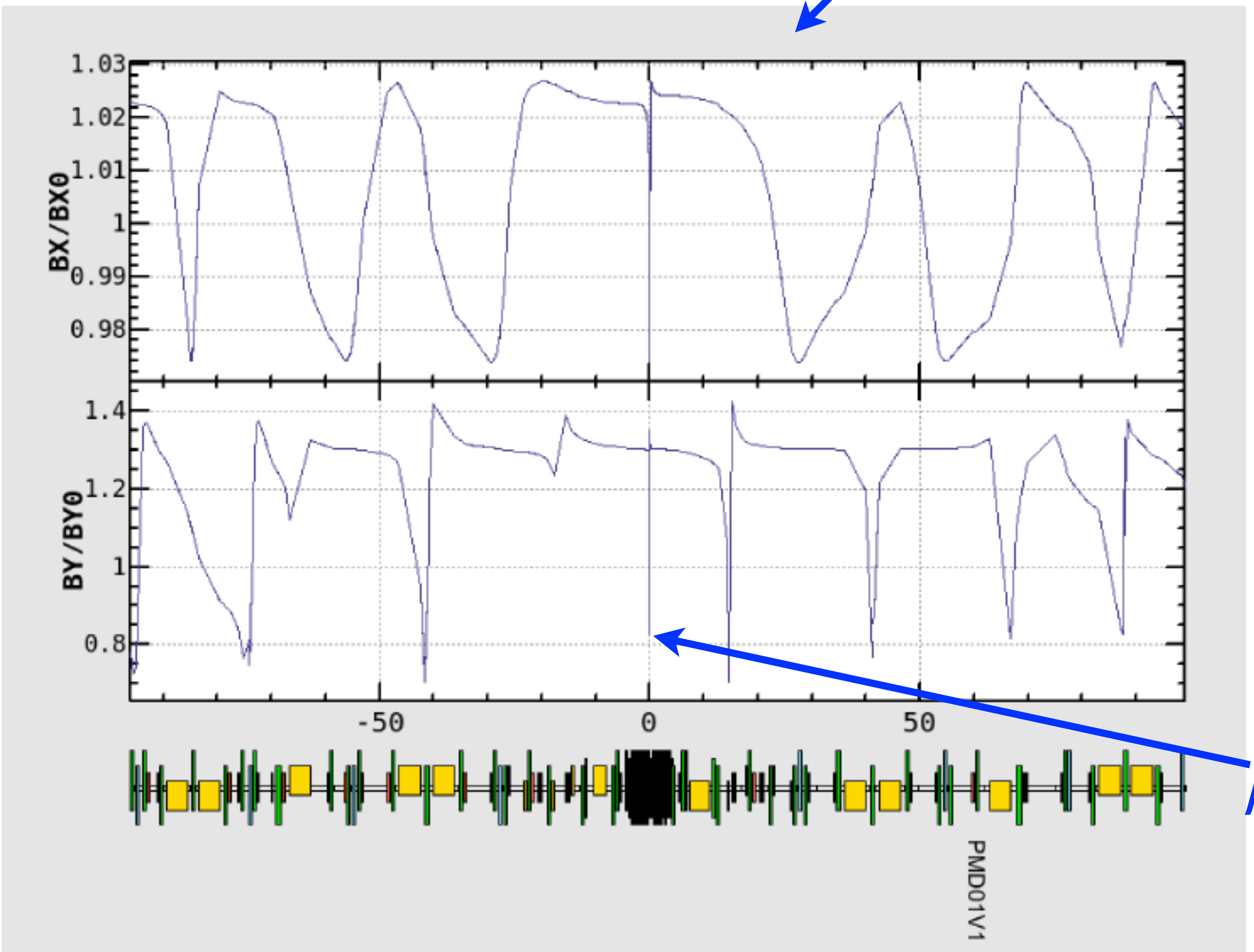


Observed offsets with beam

The following horizontal offsets of SLY* magnets are used to estimate the beta beats:

SLYTRE1	-8 µm
SLYTRE2	0
SLYTLE1	-35 µm
SLYTLE2	-33 µm

Resulting beta-beat (SAD simulation)



β^*_y squeezed

Courtesy of H. Koiso

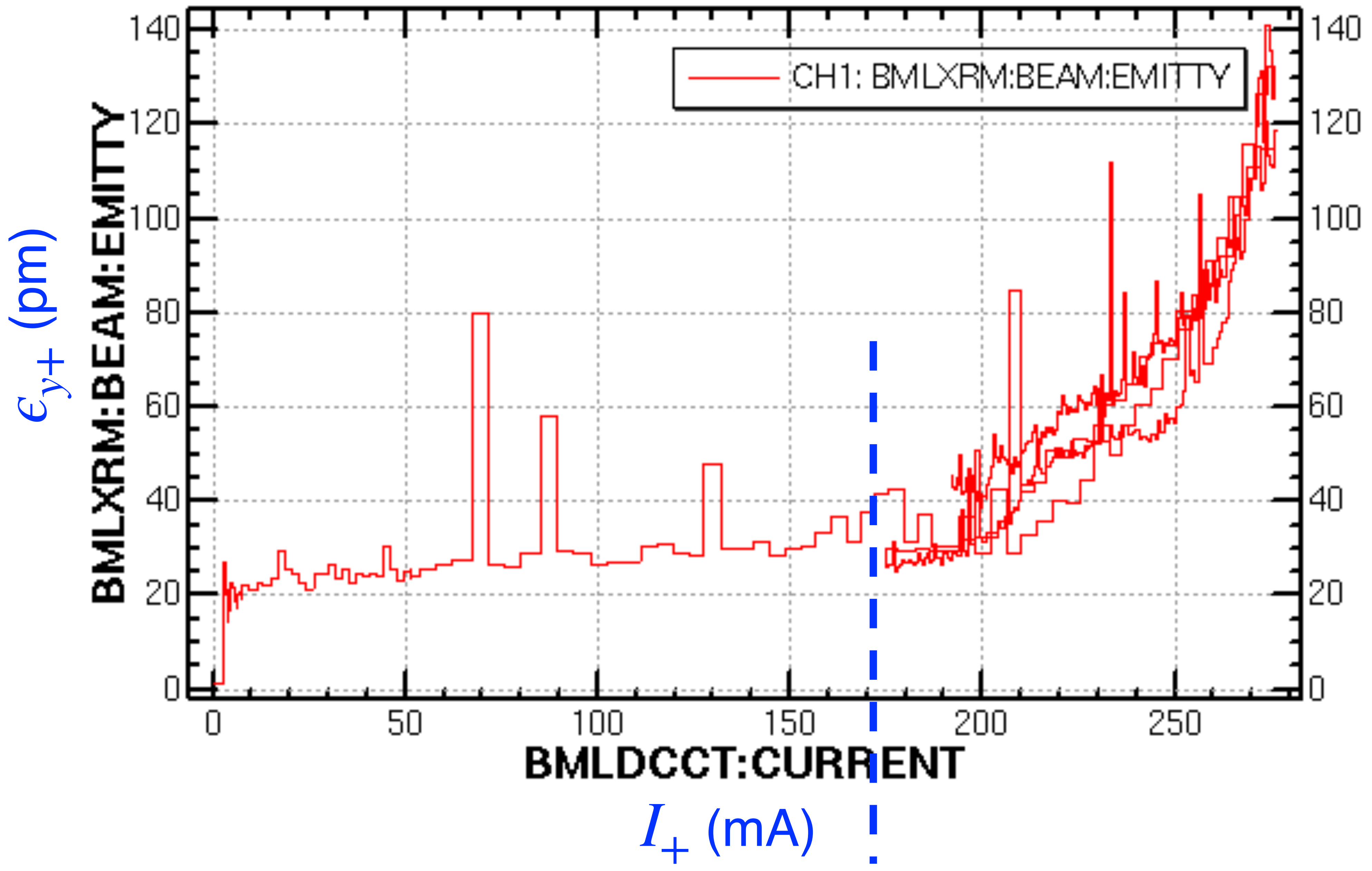
Issue-4: Impedance effects (LER)

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

- Current-dependent single-beam blowup in LER
  - This problem was partially solved by fine-tuning the FB system in Mar. 2022. After new damage to collimators (D06V1 and D02V1), the LER beam blowup problem re-appeared.
  - On Jun. 21, 2022, tunings were done to improve the blowup threshold (from 0.5 mA/bunch to ~0.87 mA/bunch). This contributed to achieving the luminosity record 4.71×10^{34} cm^{-2}s^{-1} on Jun. 22, 2022.

Machine conditions:
Single-beam, 393 bunches

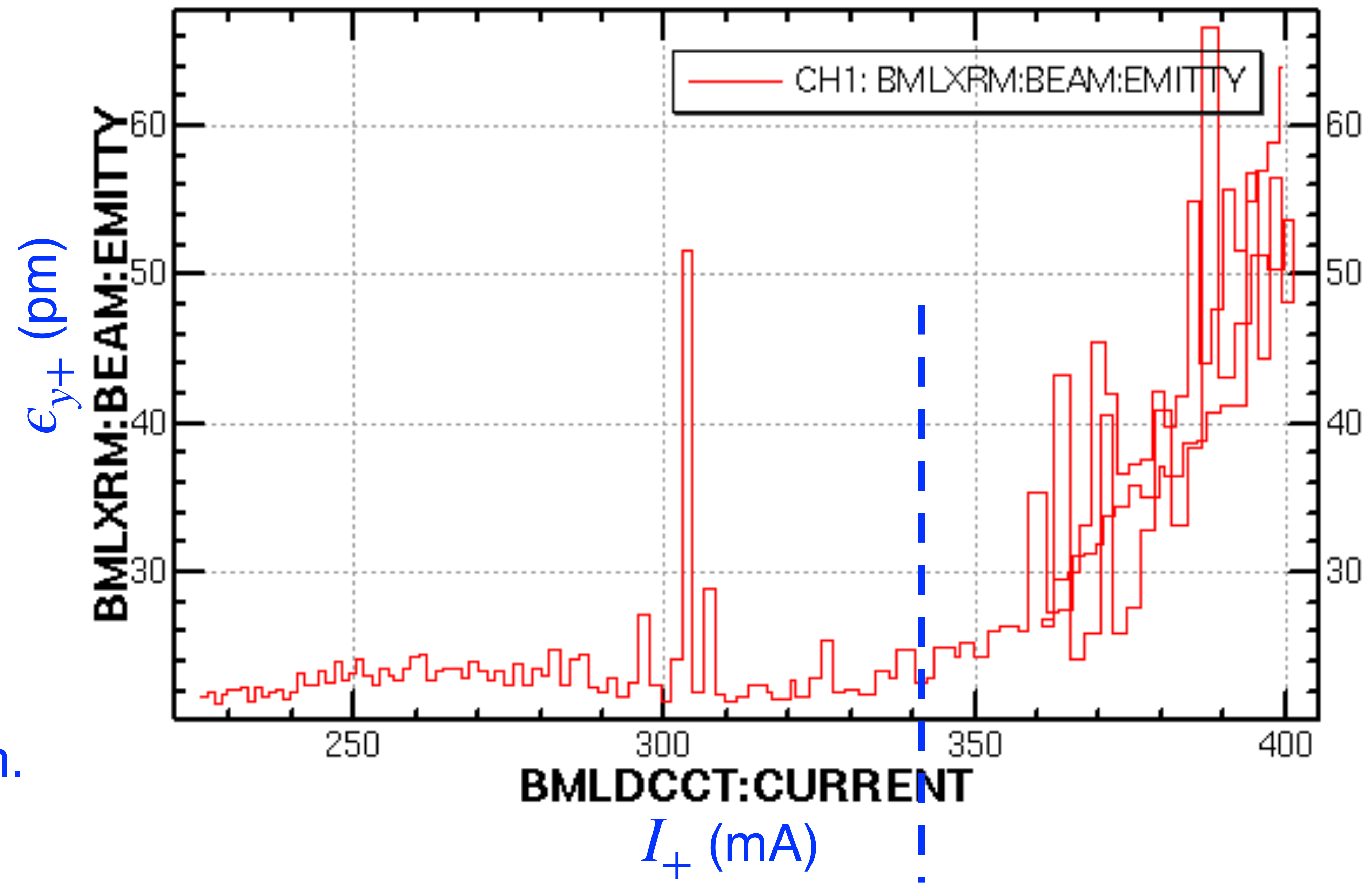
KCG shift report on LER vertical blowup study
By S. Terui, T. Ishibashi, K. Yoshihara, M. Nishiwaki
Jun. 21, 2022



Threshold <0.5mA/bunch

LER vertical tune:
ν_y .582 → .595;

D06V1 gap:
TOP 4.2 mm,
BTM -5.1 → -8.0 mm.



After tunings ~0.87mA/bunch

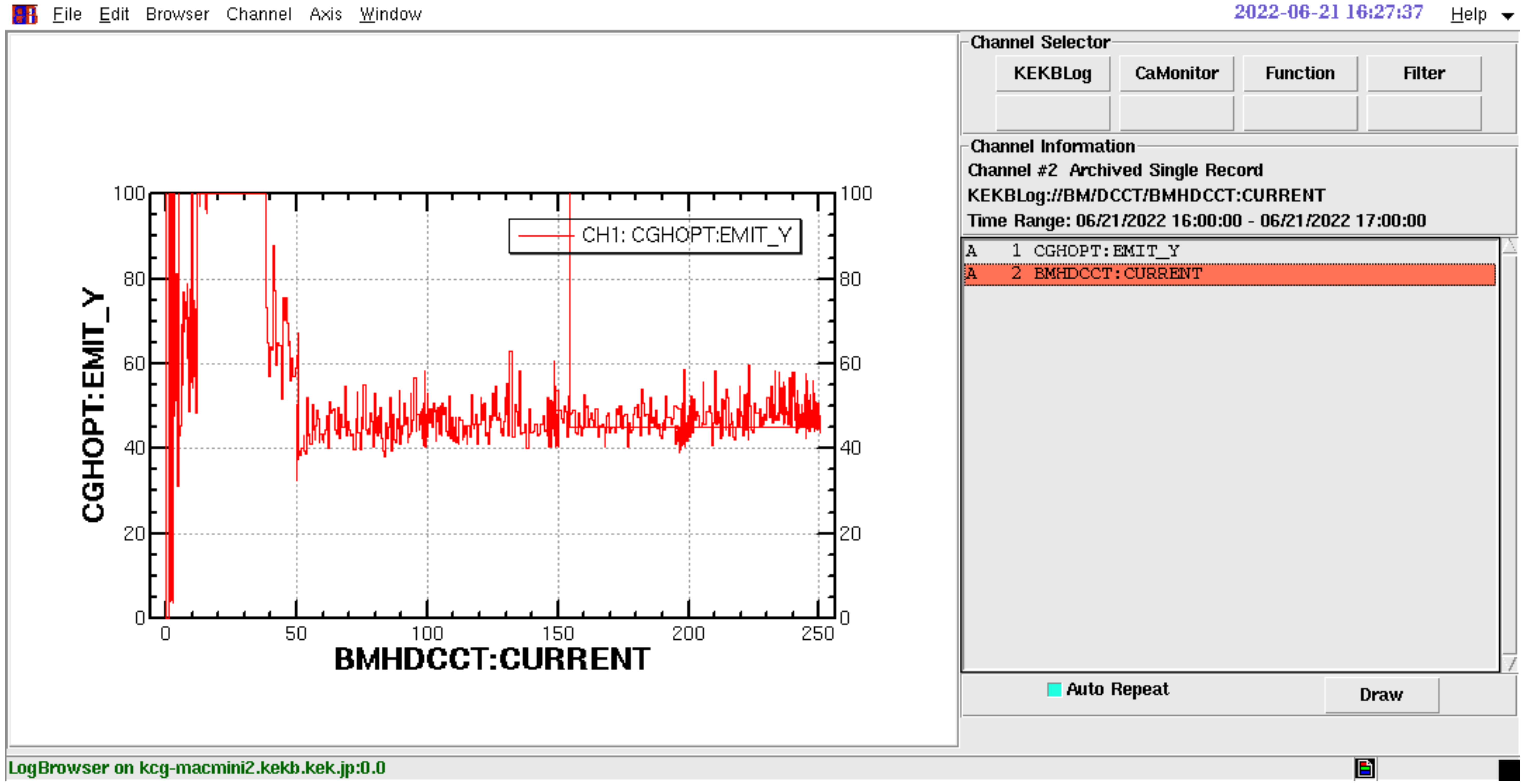
Issue-4: Impedance effects (HER)

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

- Current-dependent single-beam vertical emittance in HER
  - No clear evidence of single-beam blowup (up to 0.64 mA/bunch) in HER

Machine conditions:
Single-beam, 393 bunches

KCG shift report on high bunch-current collision study
By D. Zhou, R. Ueki, M. Nishiwaki
Jun. 21, 2022



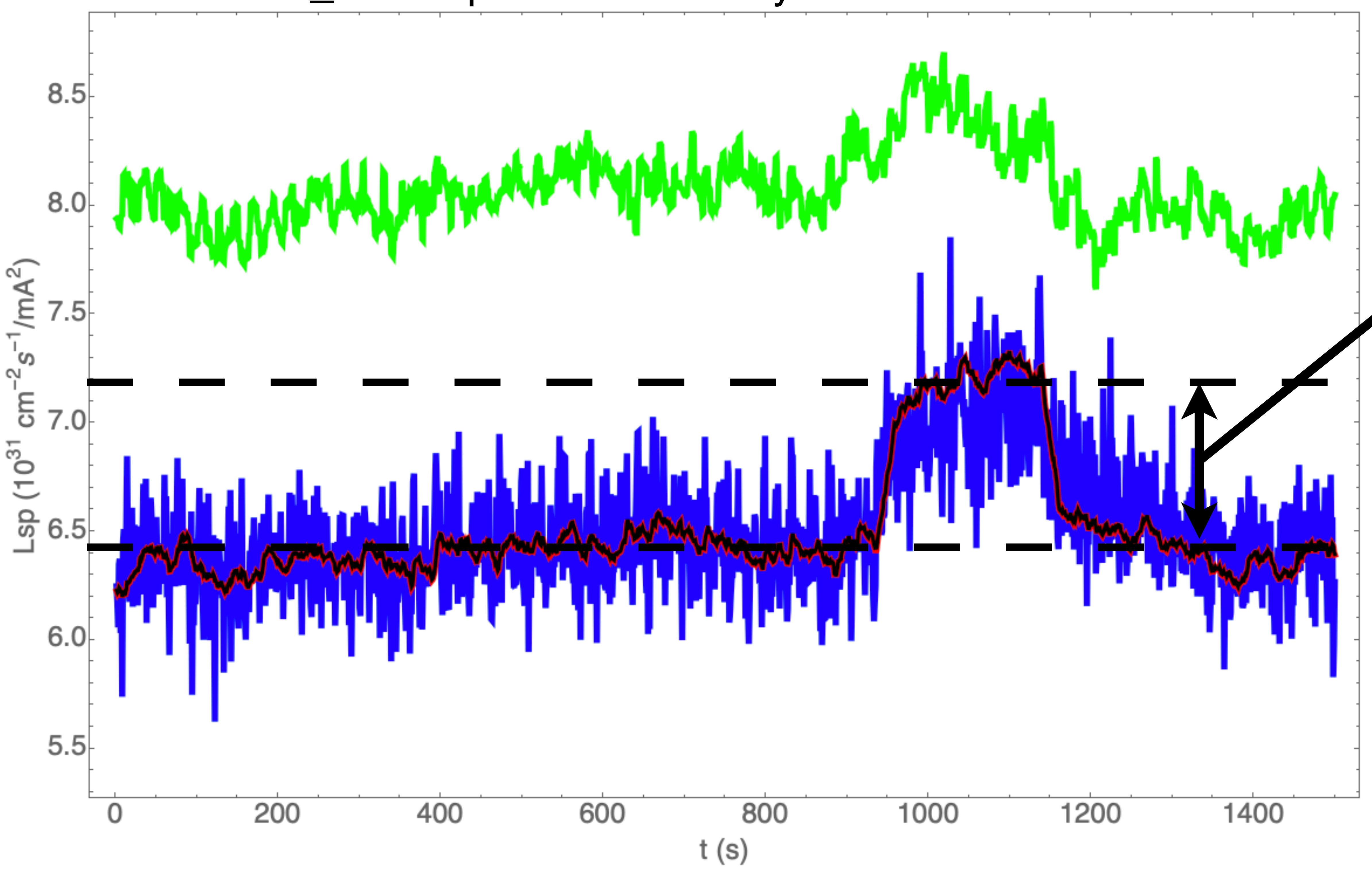
Issue-5: Lsp-Injection correlation

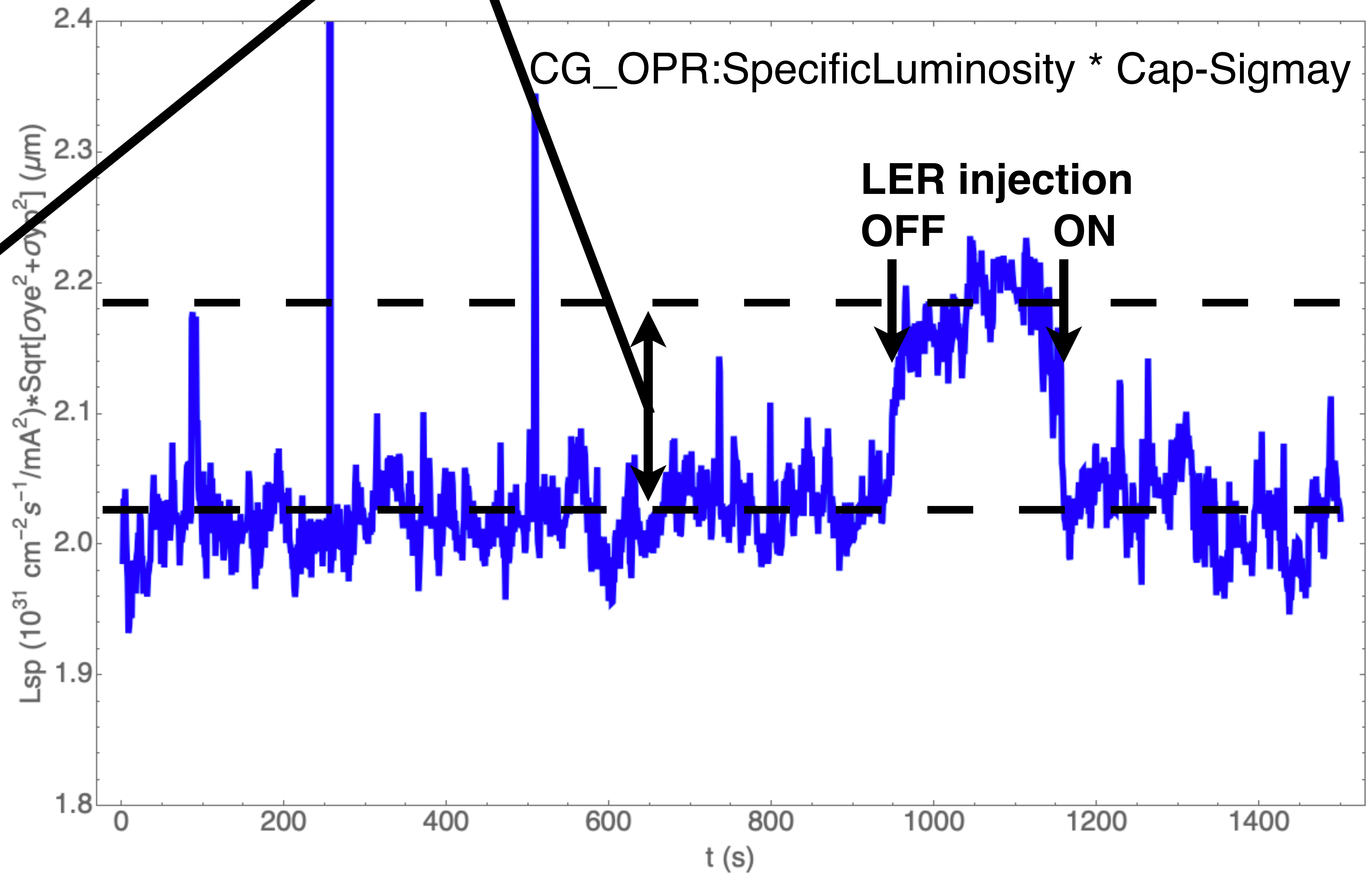
$$\boxed{L_{sp}} \approx \frac{1}{2\pi e^2 f \sqrt{\sigma_{y+}^{*2}+\sigma_{y-}^{*2}}\sqrt{\sigma_{z+}^2+\sigma_{z-}^2}\tan\frac{\theta_c}{2}} e^{-\frac{\boxed{\Delta^2}}{2(\sigma_{y+}^{*2}+\sigma_{y-}^{*2})}}$$

- The phenomenon: 2022-06-02 21:05 PM
  - 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: B2_nsm:get:ECL_LUM_MON:lum_acc_corrected
Red: B2_nsm:get:ECL_LUM_MON:lum_acc_20
Green: B2_nsm:get:MONZDLMINT:ZDLM_INTVAL:value
Black: CG_OPR:SpecificLuminosity

Lsp degradation by ~10%, independent to vertical emittances

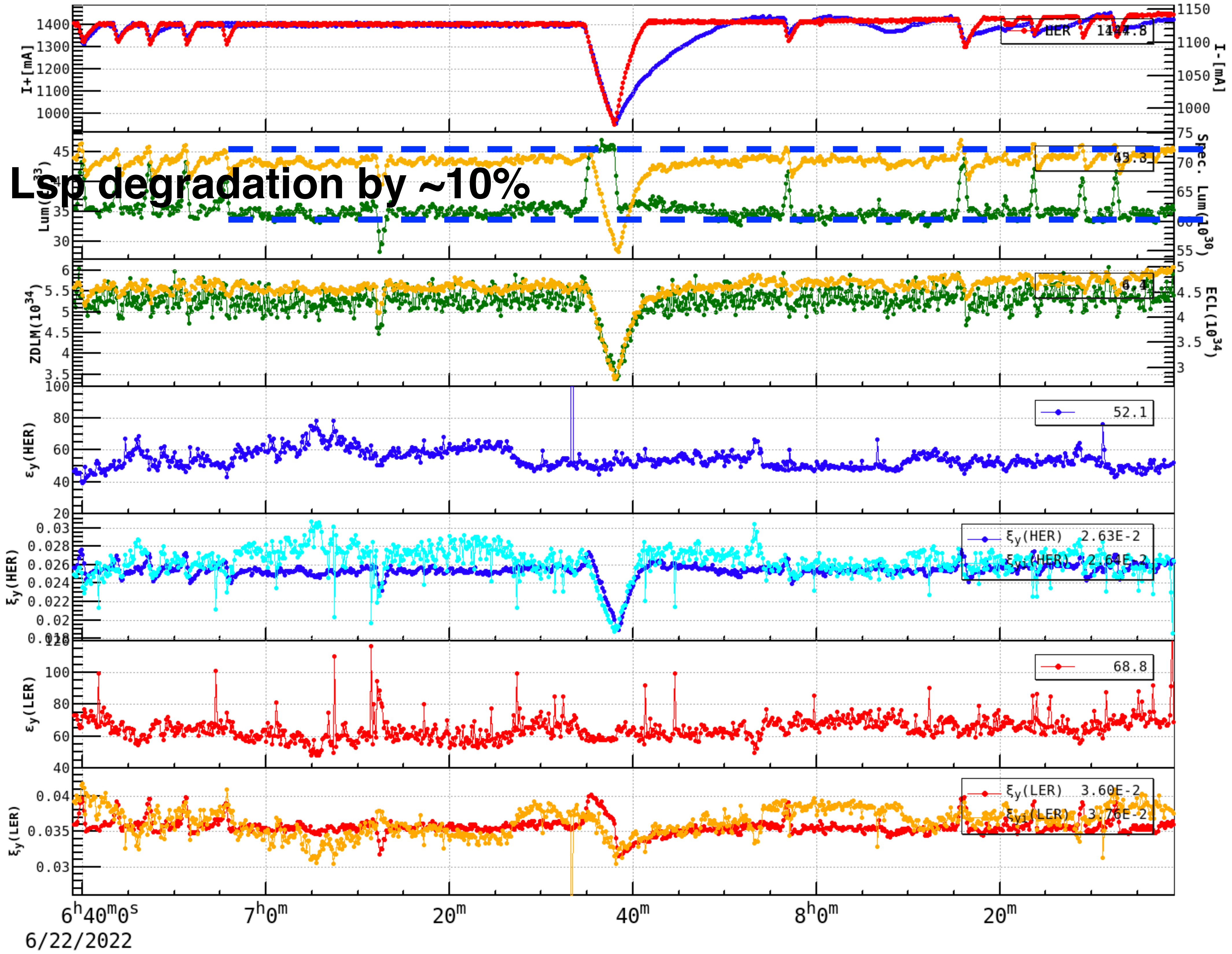


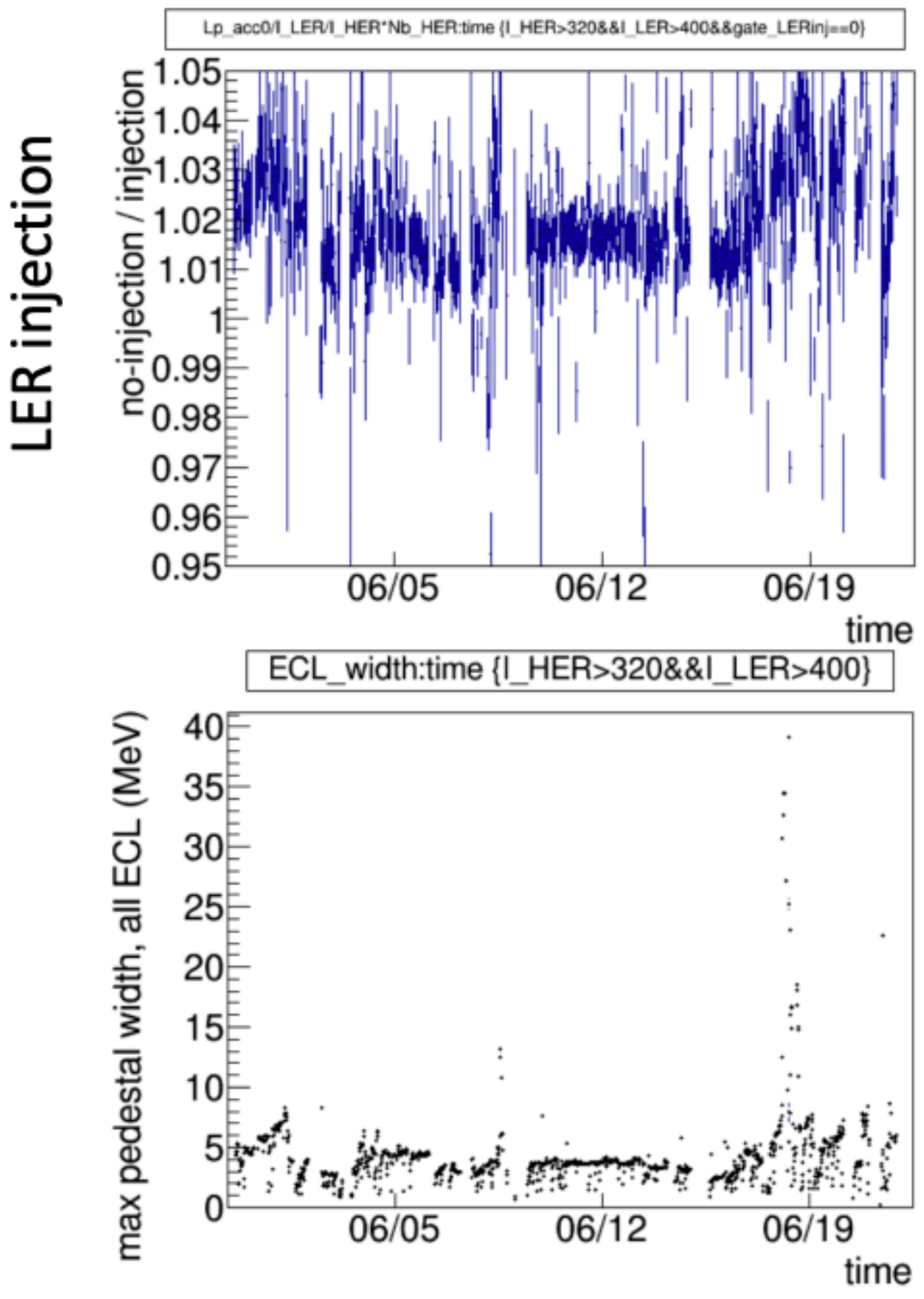


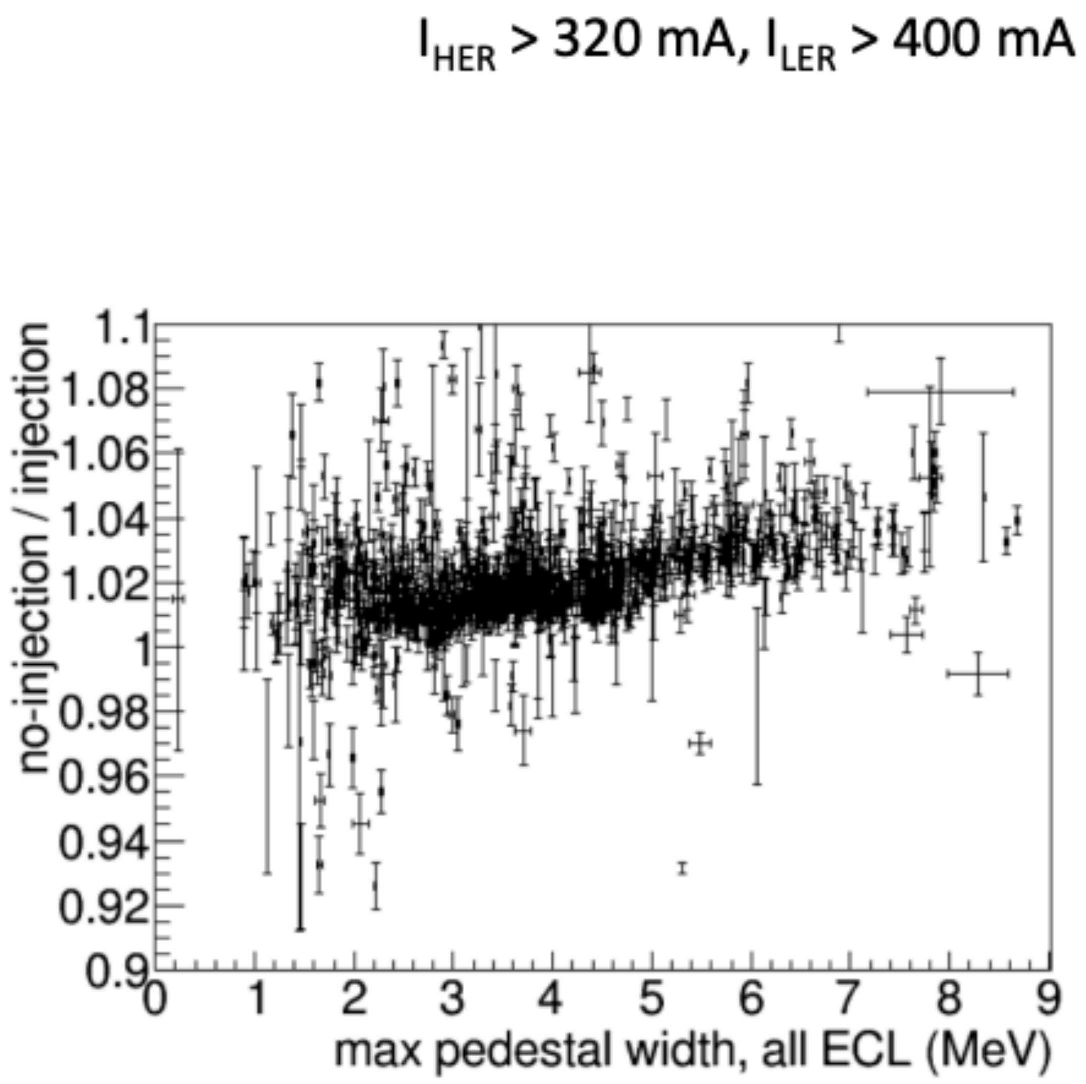
Issue-5: Lsp-Injection correlation

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

- Injection background affected ECL luminosity [1]
- Data of Jun. 2022: Injection background contributed to ~5% luminosity “loss”







Drop of ECL luminosity during LER injection depends on the injection beam background on ECL.

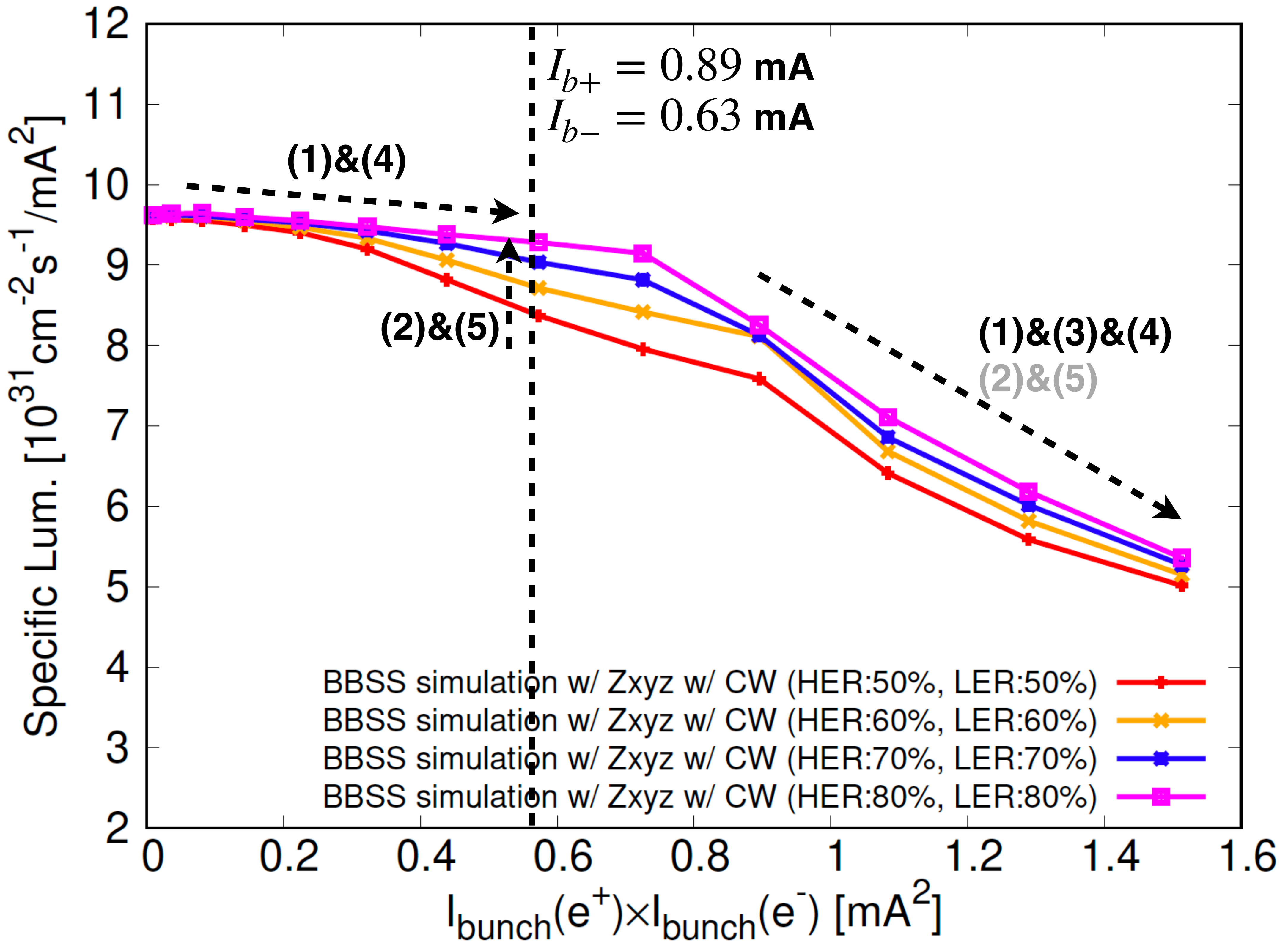
Still not clear if the ratio becomes 1 at 0 beam background. There might be some other effects on the luminosity.

Courtesy of K. Matsuoka

[1] K. Matsuoka, Oct. 14, 2022, https://kds.kek.jp/event/44070/.

Beam-beam simulations for post-LS1 operation (1E35 luminosity)

- BBSS simulations: Assume equal crab waist ratio (varied from 50% to 80%). Factors affecting luminosity:
  - (1) Bunch lengthening and synchrotron tune spread caused by longitudinal impedance → Unavoidable
  - (2) Beam-beam-driven fifth-order betatron resonances $\nu_x \pm 4\nu_y + \alpha = N$ → Cured by crab waist
  - (3) Vertical TMCI-like instability driven by the interplay of beam-beam and vertical impedance [1]
  - (4) Dynamic beta and dynamic emittance caused by linear transverse beam-beam force ($\beta_y^* \searrow$, $\epsilon_y \nearrow$)
  - (5) Crab waist (CW) suppresses the fifth-order beam-beam resonances

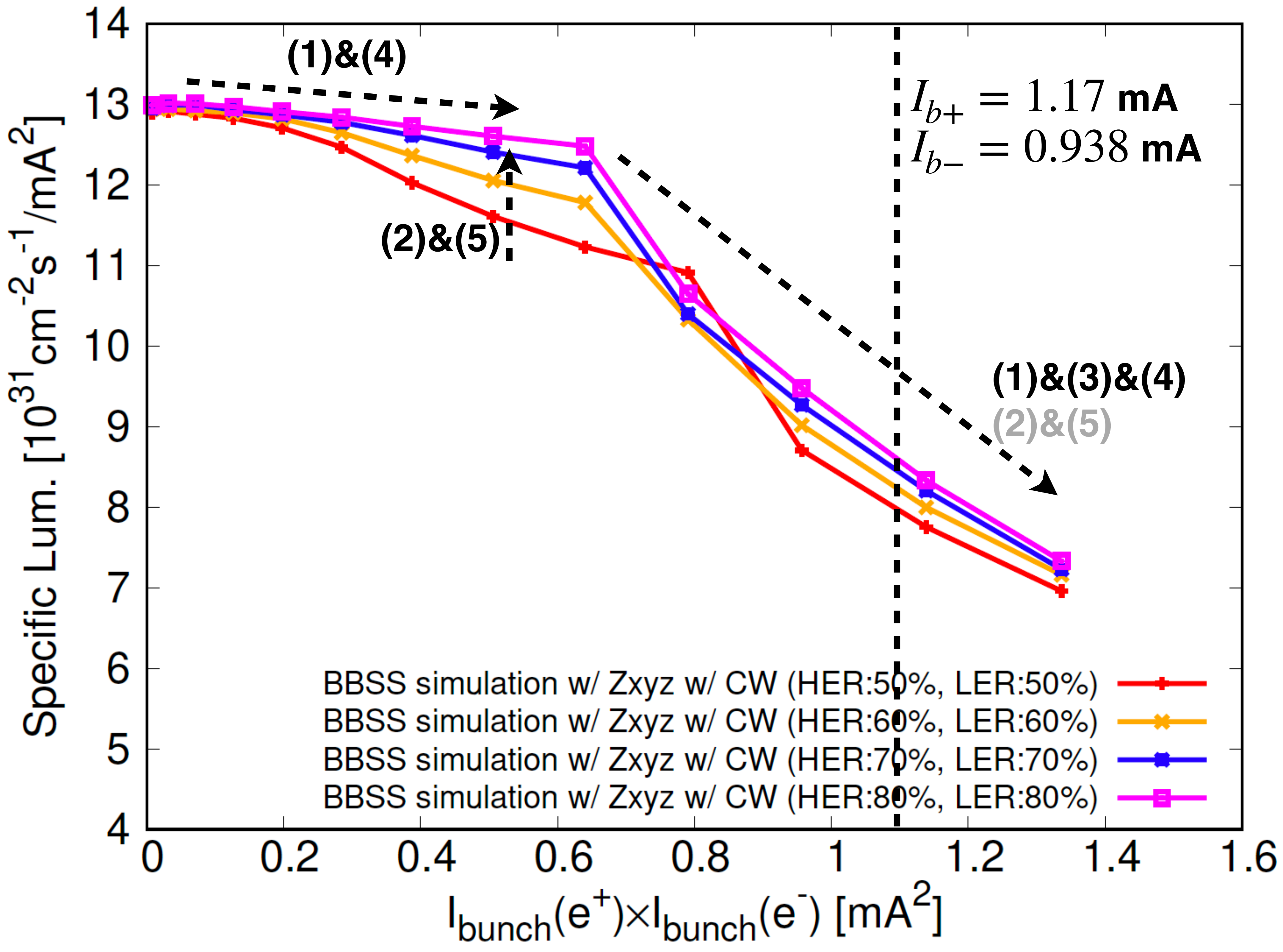


	post-LS1 1E35		Comments
	HER	LER	
I_{bunch} (mA)	0.63	0.89	
# bunch	2345		2022a operation value
ε_x (nm)	4.6	4.0	w/o IBS
ε_y (pm)	30	30	Single-beam emittance
β_x (mm)	60	60	Lattice design value
β_y (mm)	0.8	0.8	Lattice design value
σ_{z0} (mm)	5.1	4.6	Natural bunch length (w/o MWI)
ν_x	45.532	44.524	2022a operation value
ν_y	43.574	46.589	2022a operation value
ν_s	0.0272	0.0222	Calculated from lattice
$\tau_{x,y}$ (ms)	58.0	53.1	Transverse damping time (w/ NLC)
τ_z (ms)	29.0	26.6	Longitudinal damping time
Crab waist	80%	80%	Lattice design

[1] Y. Zhang et al., PRAB 26, 064401 (2023)

Beam-beam simulations for post-LS1 operation (2.4E35 luminosity)

- BBSS simulations: Assume equal crab waist ratio (varied from 50% to 80%). Factors affecting luminosity:
  - (1) Bunch lengthening and synchrotron tune spread caused by longitudinal impedance → Unavoidable
  - (2) Beam-beam-driven fifth-order betatron resonances $\nu_x \pm 4\nu_y + \alpha = N$ → Cured by crab waist
  - (3) Vertical TMCI-like instability driven by the interplay of beam-beam and vertical impedance [1]
  - (4) Dynamic beta and dynamic emittance caused by linear transverse beam-beam force ($\beta_y^* \searrow$, $\epsilon_y \nearrow$)
  - (5) Crab waist (CW) suppresses the fifth-order beam-beam resonances



	post-LS1 2.4E35		Comments
	HER	LER	
I_{bunch} (mA)	0.938	1.17	
# bunch	2345		2022a operation value
ε_x (nm)	4.6	4.0	w/o IBS
ε_y (pm)	21	21	Single-beam emittance
β_x (mm)	60	60	Lattice design value
β_y (mm)	0.6	0.6	Lattice design value
σ_{z0} (mm)	5.1	4.6	Natural bunch length (w/o MWI)
ν_x	45.532	44.524	2022a operation value
ν_y	43.574	46.589	2022a operation value
ν_s	0.0272	0.0222	Calculated from lattice
$\tau_{x,y}$ (ms)	58.0	53.1	Transverse damping time (w/ NLC)
τ_z (ms)	29.0	26.6	Longitudinal damping time
Crab waist	80%	80%	Lattice design

[1] Y. Zhang et al., PRAB 26, 064401 (2023)

Beam-beam perspective on achieving target luminosity

- Achieving 10^{35} cm^{-2}s^{-1}: SBLs, "-1 mode instability", etc. → Non-Linear Collimator (NLC)
- Achieving 6×10^{35} cm^{-2}s^{-1}: DA (Dynamic aperture), lifetime, perfect CW, etc. → IR model (better understanding of the current IR) and upgrade ("Clean IR")

Luminosity measurement:
1) Fake luminosity loss in ECL
This is not a problem at all

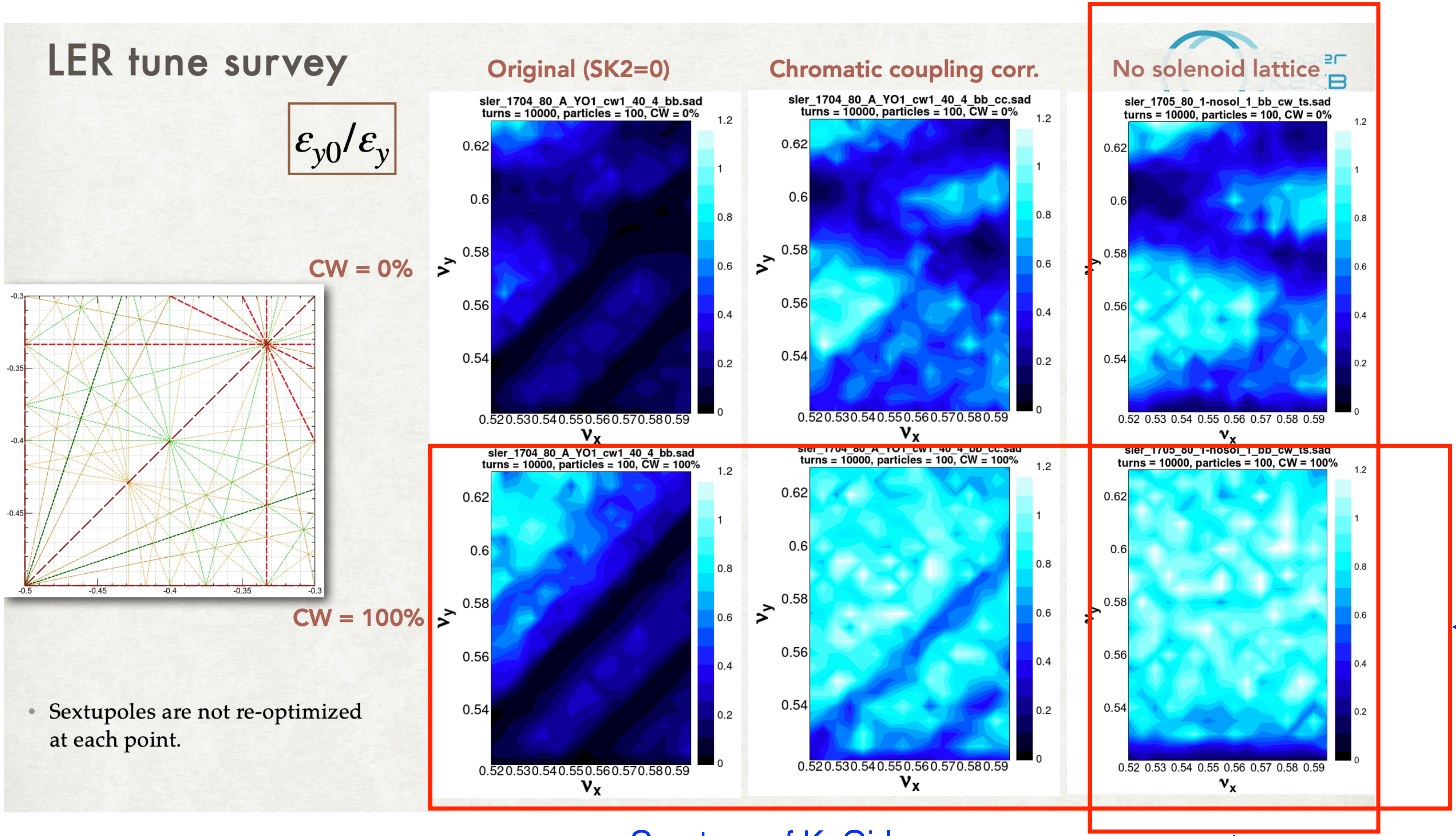
$$L = \frac{1}{2er_e} \frac{\gamma_{\pm} I_{\pm}}{\beta^*_{y\pm}} \xi^L_{y\pm}$$

Total beam currents:
We achieved 1.4 A in LER (Jun. 2022)
If we can achieve 3.6 A, we will gain by 2.5
Obstacles:
1) Sudden beam losses (SBLs)
2) Short lifetime (challenging injection power)

IR optics:
We achieved $\beta^*_y = 1$ mm
If we can achieve $\beta^*_y = 0.3$ mm, we will gain by 3.3
Obstacles:
1) DA and lifetime resulted from IR nonlinearity (+BB+CW)
2) Optics tuning at high currents

Beam-beam limit:
We achieved 0.04 in Jun. 2022
We expect the upper limit is ~0.1 (including the hourglass effect), then we will gain by 2.5
Obstacles:
1) Vertical blowup by "-1 mode instability" (NLC is the hoped solution)
2) Vertical blowup by BB (+Lattice nonlinearity+Impedance)
3) Imperfect crab waist (to be verified)

Beam-beam perspective on achieving target luminosity



← Crab waist

Courtesy of K. Oide

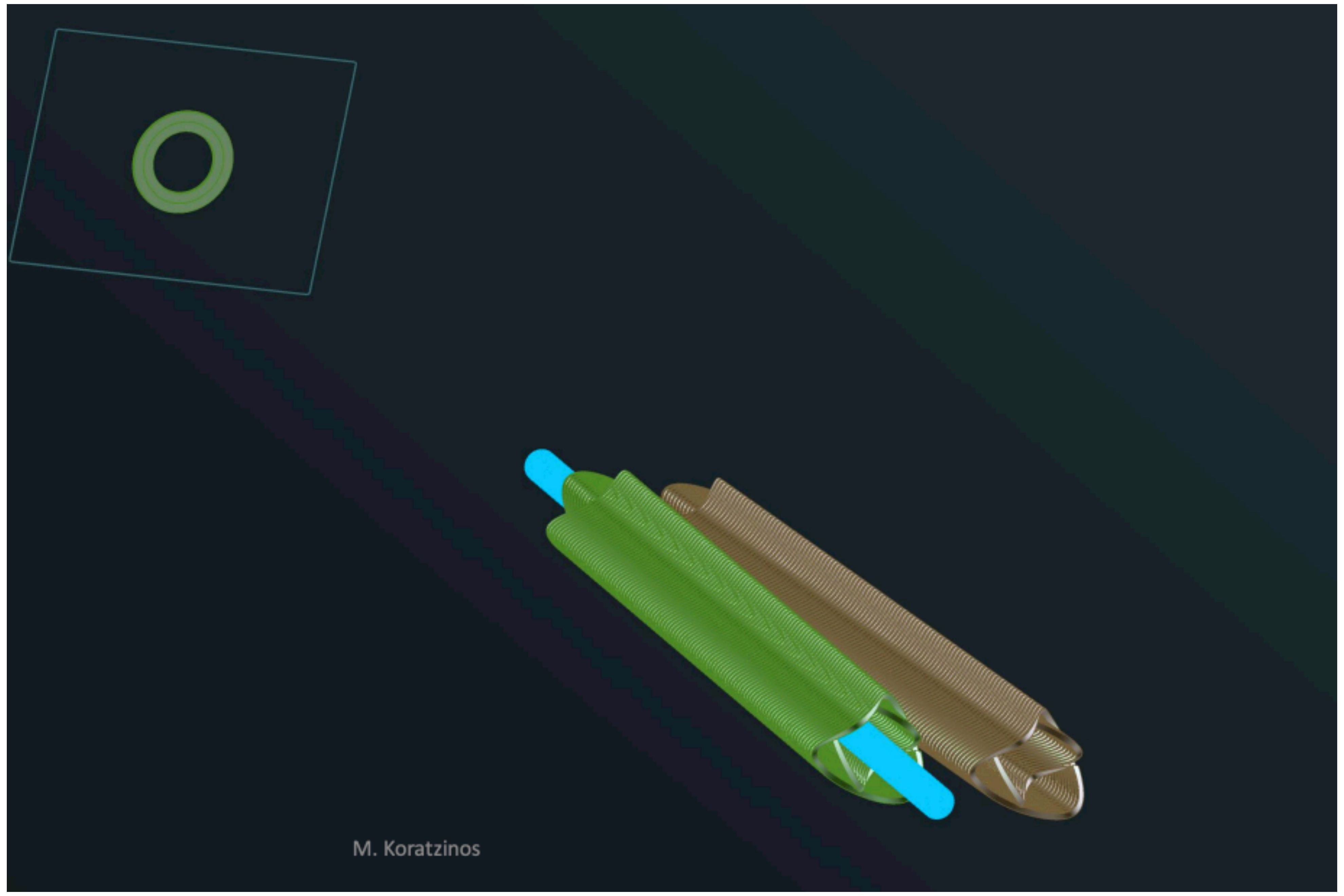
↑ "Clean IR"

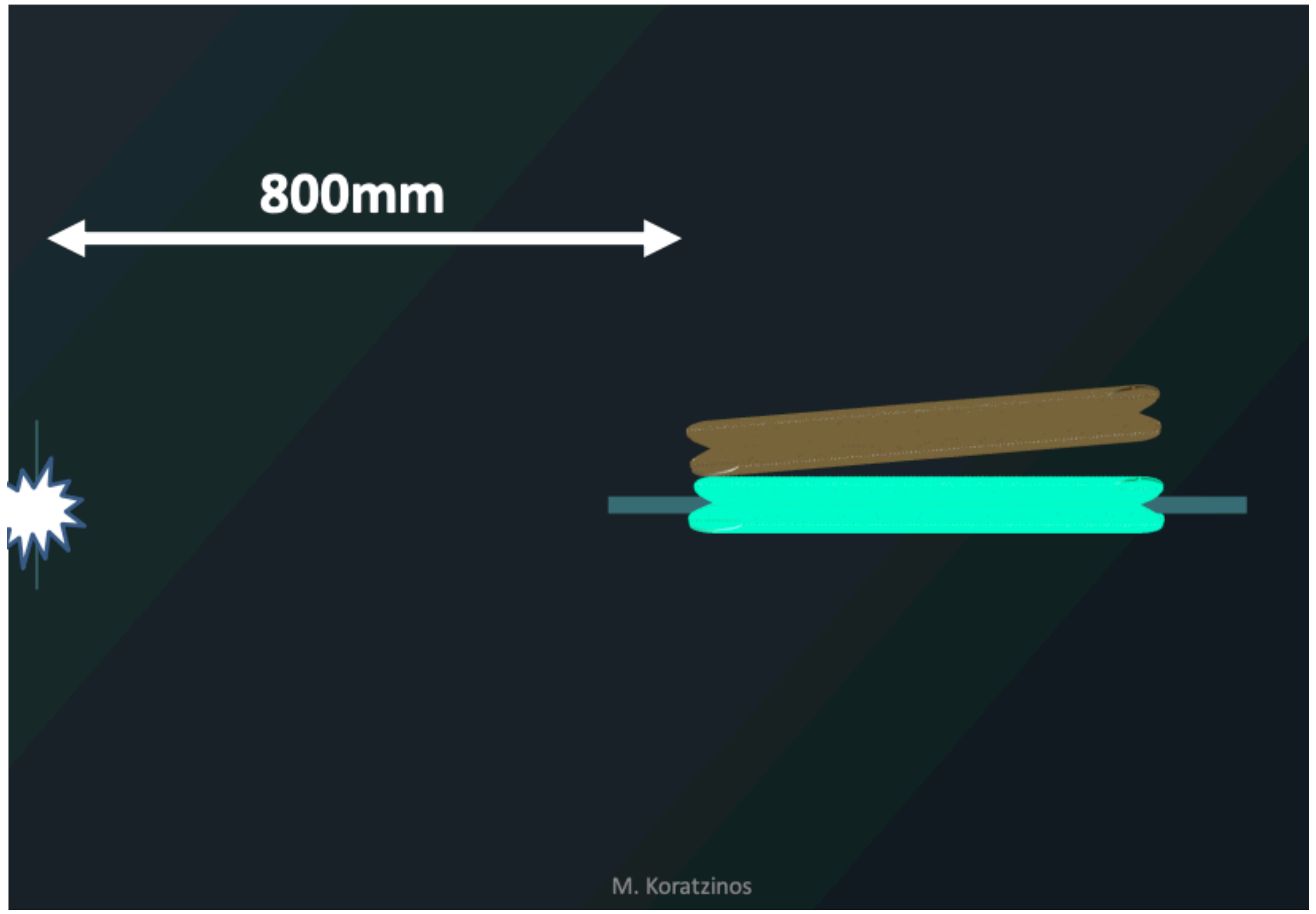
[1] K. Oide, https://kds.kek.jp/event/44644/.

"Clean IR": A transparent IR with minimal amplitude-dependent and chromatic nonlinearities

Beam-beam perspective on achieving target luminosity

- How to achieve a “clean IR”
  - IR remodeling (the mainstream upgrade plan (see M. Masuzawa’s talk) under investigation)
  - Using CCT (Canted Cosine Theta) magnets: M. Koratzinos did the first exercise (considering constraints from the technology and infrastructure of SuperKEKB) and showed encouraging results. Using the CCT magnets, a compact and cleaner IR is conceivable (Idea: “The current distribution of any canted layer generates a pure harmonic field as well as a solenoid that can be canceled with a similar but oppositely canted layer.” [2]).





Courtesy of M. Koratzinos

  - From the beam-beam perspective, we invite full international collaboration on IR upgrades to achieve the target luminosity of SuperKEKB.

[1] M. Koratzinos, https://kds.kek.jp/event/44644/. [2] S. Caspi et al., “Canted-Cosine-Theta magnet (CCT)-A concept for high field accelerator magnets” , IEEE Trans. Appl. Supercond. 24, 1. (2014).

Summary

- On beam-beam blowup (see K. Ohmi's talk, Sep. 15, 2023)
  - On mechanisms of pure beam-beam (=space-charge force) effects
    - Horizontal: (coherent two-beam) X-Z instability [Ohmi 2017 (PRL), Kuroo 2018 (PRAB)] and (single-beam) synchro-beta resonances [Zhou 2023 (PRAB)]
    - Vertical: Nonlinear X-Y resonances [Ohmi 2004 (PRST-AB), Ohmi 2007 (PRST-AB), Zobov 2010 (PRL)]
  - On mechanisms of interplay between beam-beam and impedances
    - Horizontal: modified X-Z instability [Lin 2022 (PRAB)] (key issue: potential distortion and synchrotron tune spread due to impedance)
    - Vertical: TMCI-like head-tail instability [Zhang 2023 (PRAB), Zhou 2023 (PRAB)] (key issues: spread of synchrotron and vertical betatron tunes due to impedance)
  - On interplay of beam-beam and other problems (see Zhou 2023 (PRAB) for detailed discussions)
    - BxB feedback: "-1 mode instability" [Ohmi 2022 (eeFACT), Ishibashi 2023 (JINST)]
    - Linear IP X-Y couplings [Ohmi 2018 (eeFACT)]
    - Chromatic IP X-Y couplings [Zhou 2009 (PRST-AB)]
    - Higher-order IP X-Y couplings [Zhou 2015 (ICFA Newsletter)]
    - Non-perfect crab waist [To be investigated]
  - On machine commissioning
    - Beam-beam: Need enough beam time for machine studies
    - Machine parameters [$\nu_{x,y,z}$, $\beta^*_{x,y}$]: Make careful choices
    - Linear and nonlinear IP aberrations [$R^*_{1,2,3,4}$]: Suppress them as much as possible
    - Crab waist: Make sure it works well
    - Impedances: Reduce the sources as much as possible
    - Hardware: Make sure each subsystem works well as expected

$$M = M_{\mathrm{RAD}} \circ M_{\mathrm{BB}} \circ M_{\mathrm{CW}} \circ M_{\mathrm{Z}} \circ M_0$$

Summary

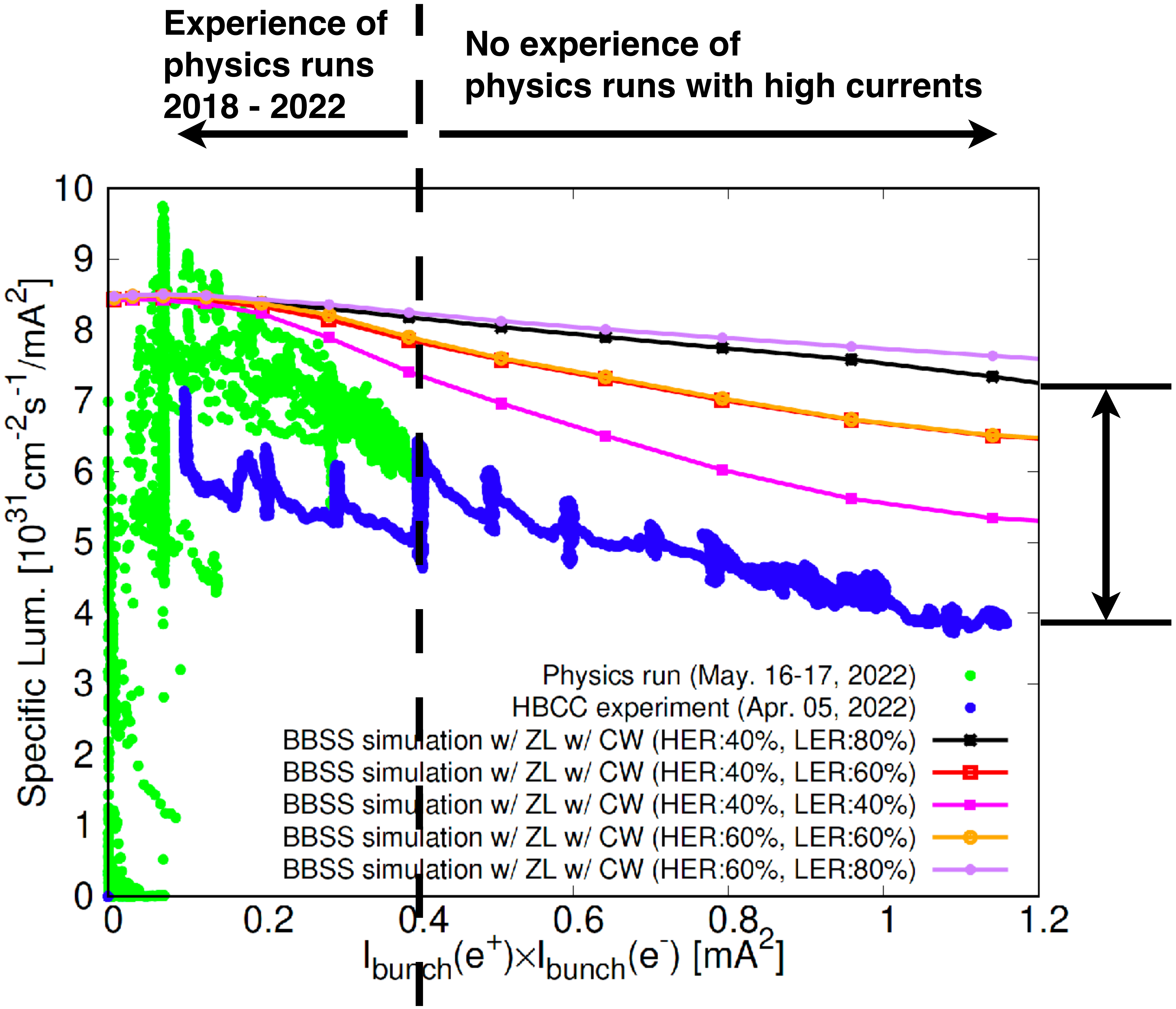
- With progress in machine tuning, the measured luminosity of SuperKEKB is approaching predictions of BB simulations (SS BB + Simple lattice model + Impedance models).
- Prediction of luminosity via beam-beam simulations requires reliable models of multiple dynamics, such as the beam-beam interaction, machine imperfections, impedance models, etc.
- Several sources of luminosity degradation in the current SuperKEKB have been well identified.
- Many subjects will be investigated via experiments (after LS1) and simulations.

- From the beam-beam perspective, with β_y^*=0.3 mm, a significant IR upgrade is required to achieve the target luminosity in SuperKEKB (after LS2).
- We invite full international collaboration on beam-beam simulations and an IR upgrade R&D program.

Backup

Comparison of simulations and experiments

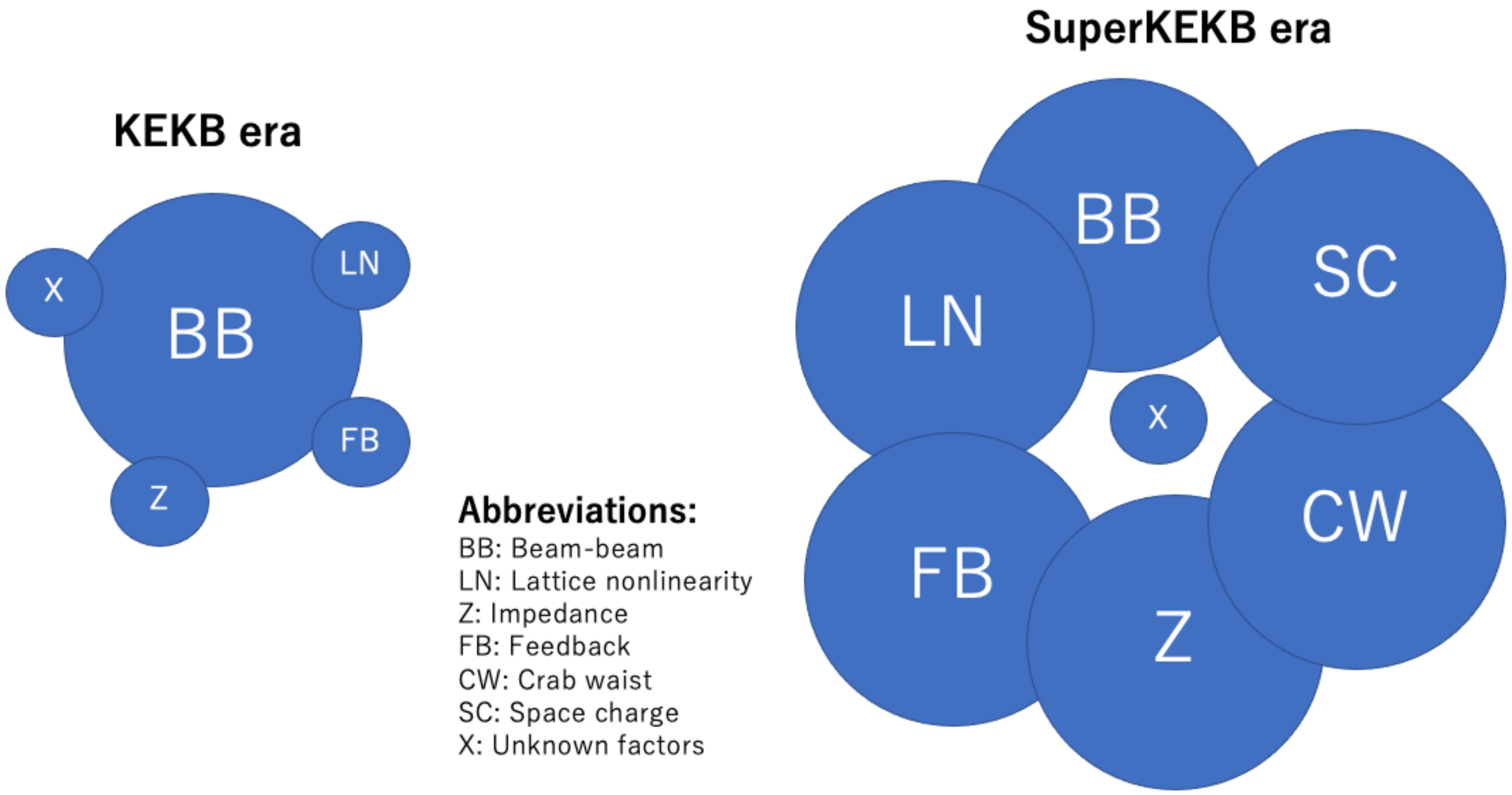
- Filling the gap between simulated and measured Lsp
    - BBSS+PIC simulation showed 5% less Lsp at $I_{b+}I_{b-} = 0.8$ mA^2 [see p.12].
    - Impedance effects:
        - Simulations showed less bunch lengthening than measurements. If measured bunch lengthening is applied, it gives ~10% extra loss of Lsp at $I_{b+}I_{b-}$ =0.8 mA^2.
        - "-1 mode instability" due to the interplay of FB and vertical impedance.
    - Found a large systematic in ECL luminosity at high injection background. This could explain a ~10% difference between simulation and measured data at $I_{b+}I_{b-}$=0.3 mA^2. There remains a difference of ~10% [see p.20-24]. No physics data was taken at high bunch currents, and this systematic's impact is unknown.
    - The machine conditions for HBCC experiments were not optimal due to the limited beam time for machine studies.



Status of beam-beam simulations

- Beam-beam (BB) simulations
  - Available tools: BBWS (weak-strong BB model + simple one-turn map + perturbation maps); BBSS and IBB (strong-strong BB model + simple one-turn map + perturbation maps); SAD (BBWS's BB model + complete lattice + perturbation maps).
  - SuperKEKB is challenging the predictability of BB simulations: It requires reliable models of multiple physics (BB, impedances, lattice nonlinearity, crab waist, realistic machine errors, space charge, etc.), not only BB.

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

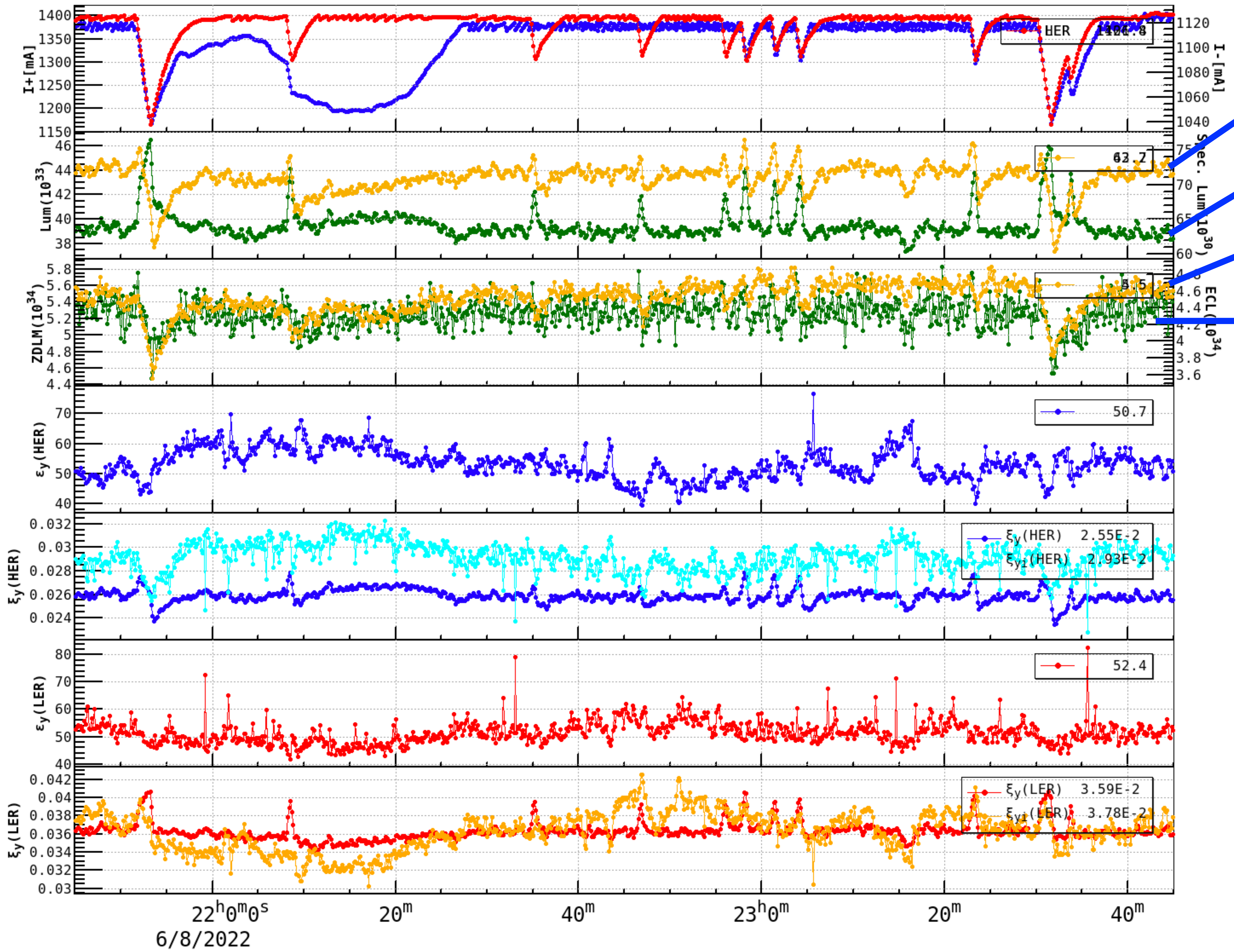


Schematic plot on interplay of multiple physics

Issue-5: Lsp-Injection correlation

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

- Luminosity record of 4.65×10^{34} cm^{-2}s^{-1} was achieved with Belle II HV ON when the injection was intentionally stopped (Jun. 8, 2022).



Yellow: Total luminosity ECL (20-second average)

Green: Specific luminosity by ECL (Lsp)

Yellow: Total luminosity ZDLM

Green: Total luminosity ECL (updated per 2.5 second)

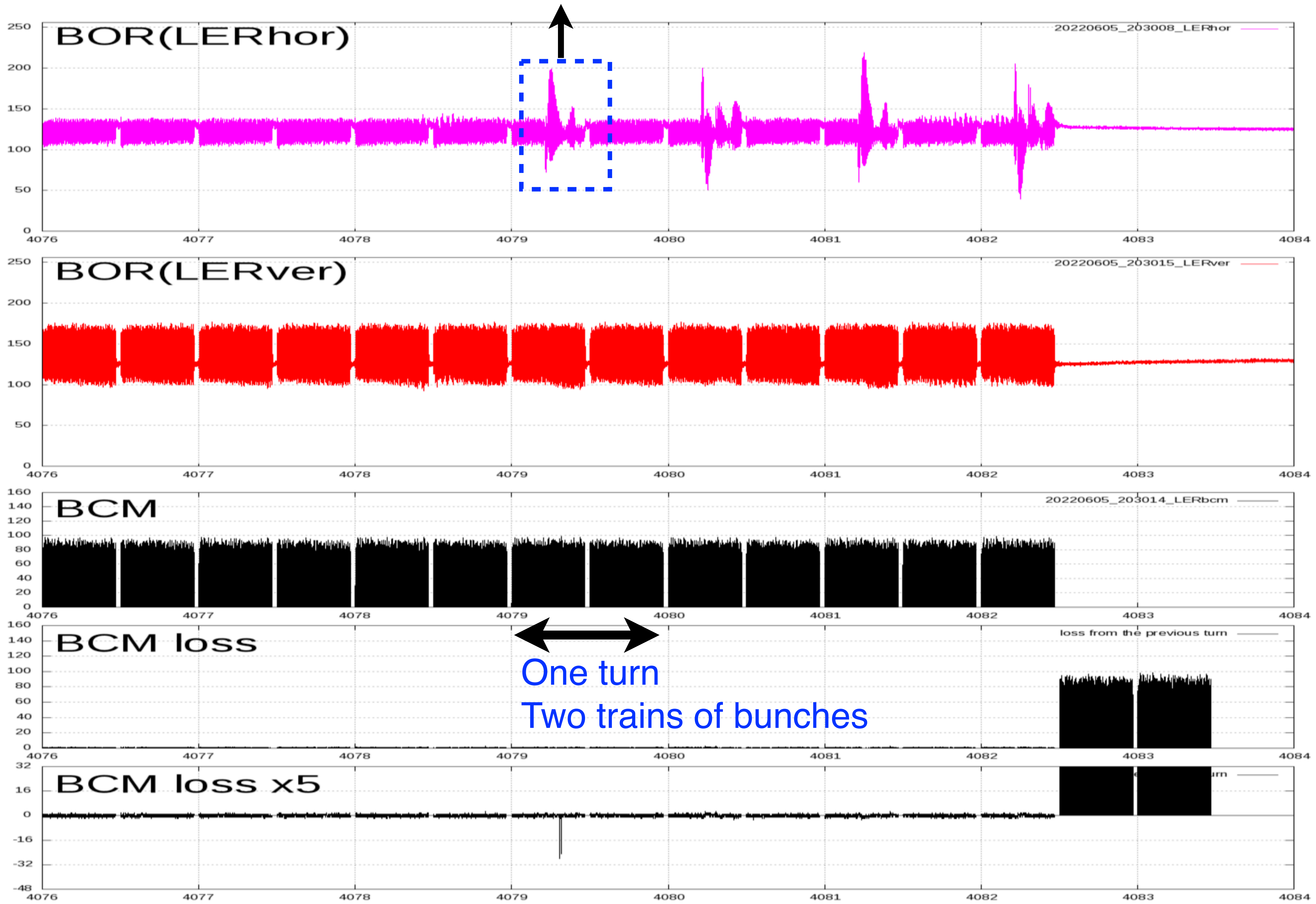
* Peak luminosity always appears after injection stopped
* Lsp always jump up after injection stopped

Issue-5: Lsp-Injection correlation

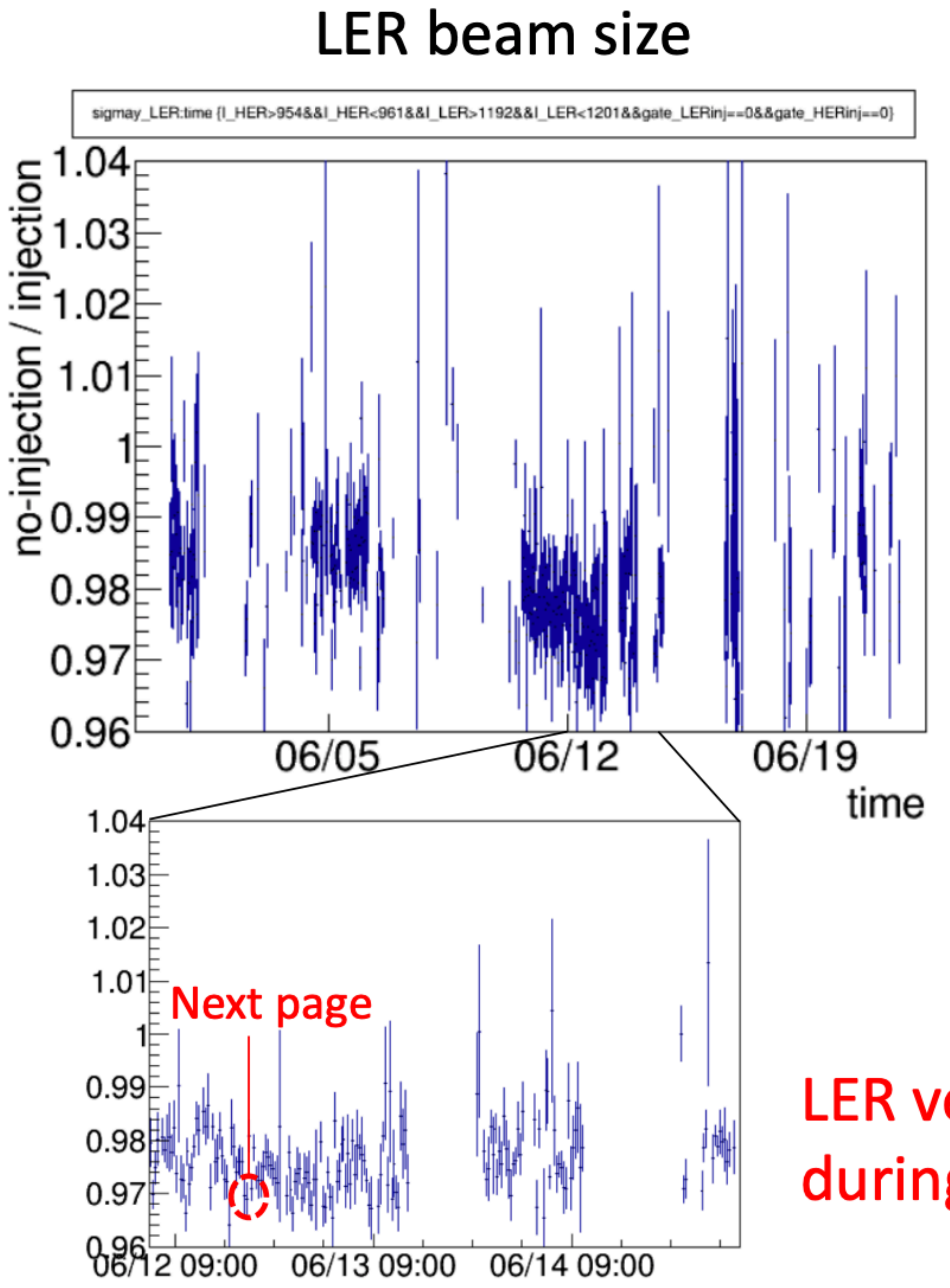
$$L_{sp} \approx \frac{1}{2\pi e^2 f \sqrt{\boxed{\sigma_{y+}^{*2} + \sigma_{y-}^{*2}}}\sqrt{\sigma_{z+}^2 + \sigma_{z-}^2}\,\tan\frac{\theta_c}{2}}\, e^{-\frac{\boxed{\Delta^2}}{2(\sigma_{y+}^{*2} + \sigma_{y-}^{*2})}}$$

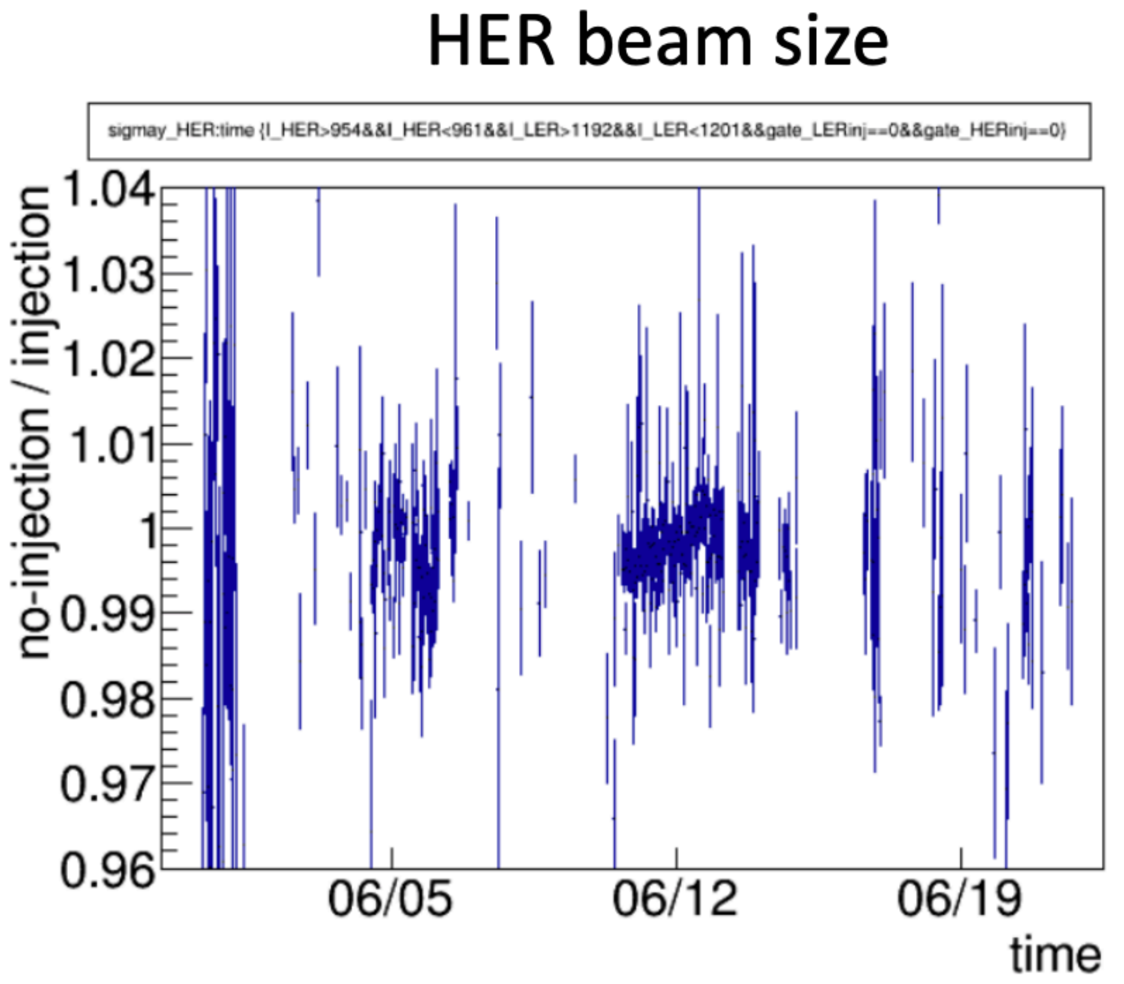
- Injection background on ECL was identified [1]
- Data of Jun. 2022: LER injection kicker (leakage fields) contributed to ~3% of luminosity loss

About 20% of the stored bunches are excited by the leakage fields of injection kickers in LER



Vertical beam size at IP measured by XRM





$954 < I_{HER} < 961$ mA, $1192 < I_{LER} < 1201$ mA

LER vertical beam size at IP was enlarged during LER injection.

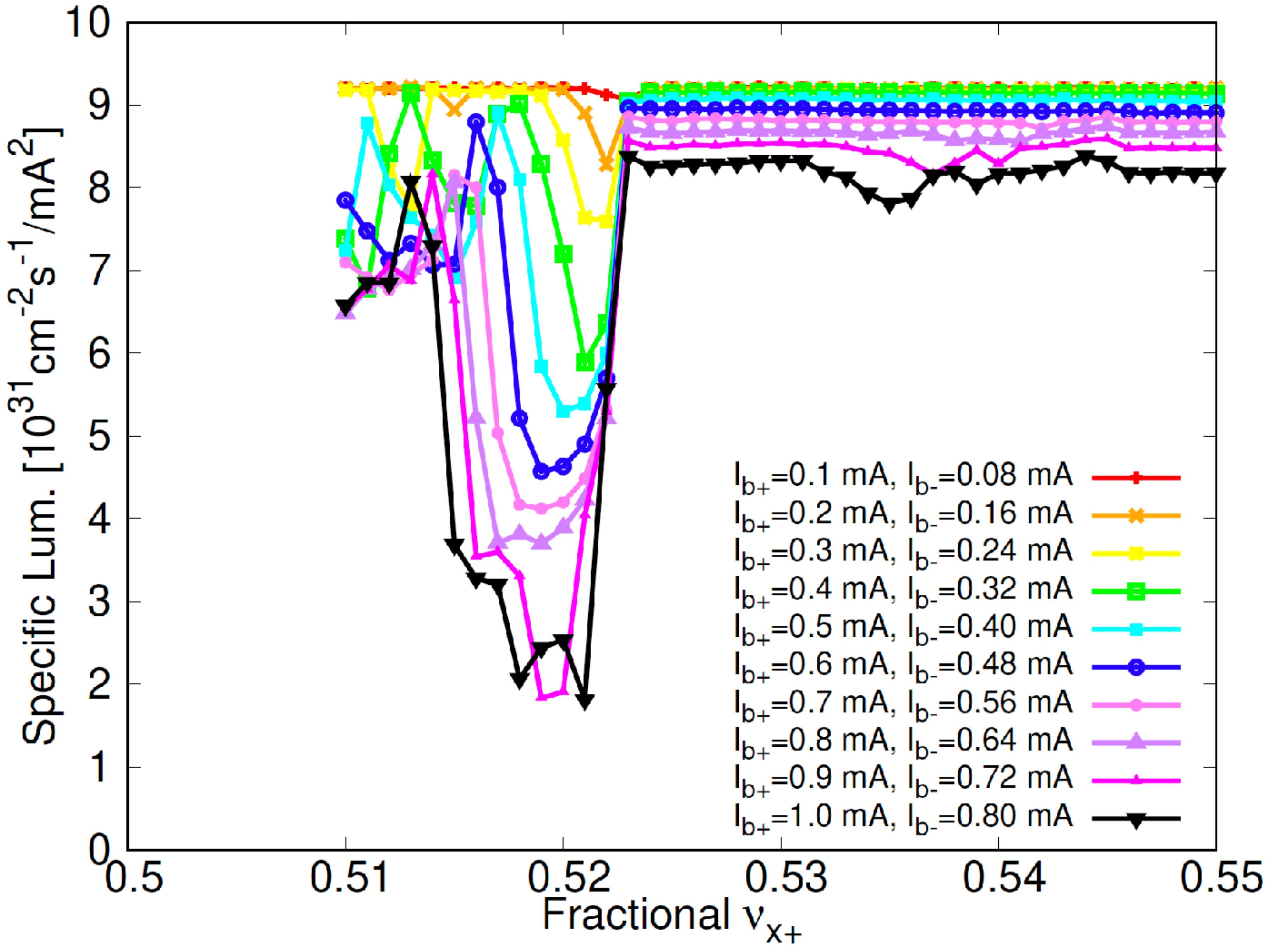
Courtesy of K. Matsuoka

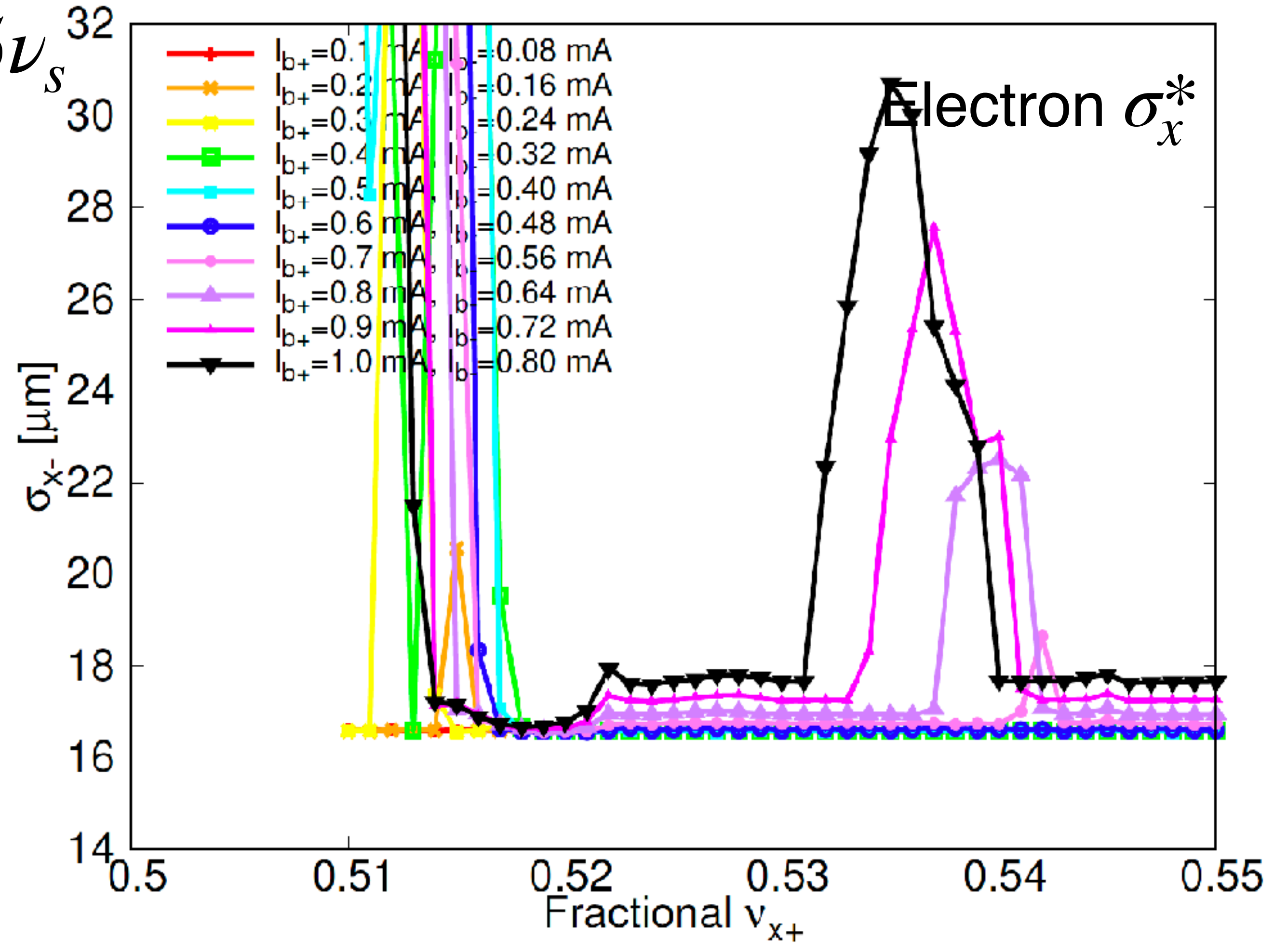
[1] K. Matsuoka, Oct. 14, 2022, https://kds.kek.jp/event/44070/.

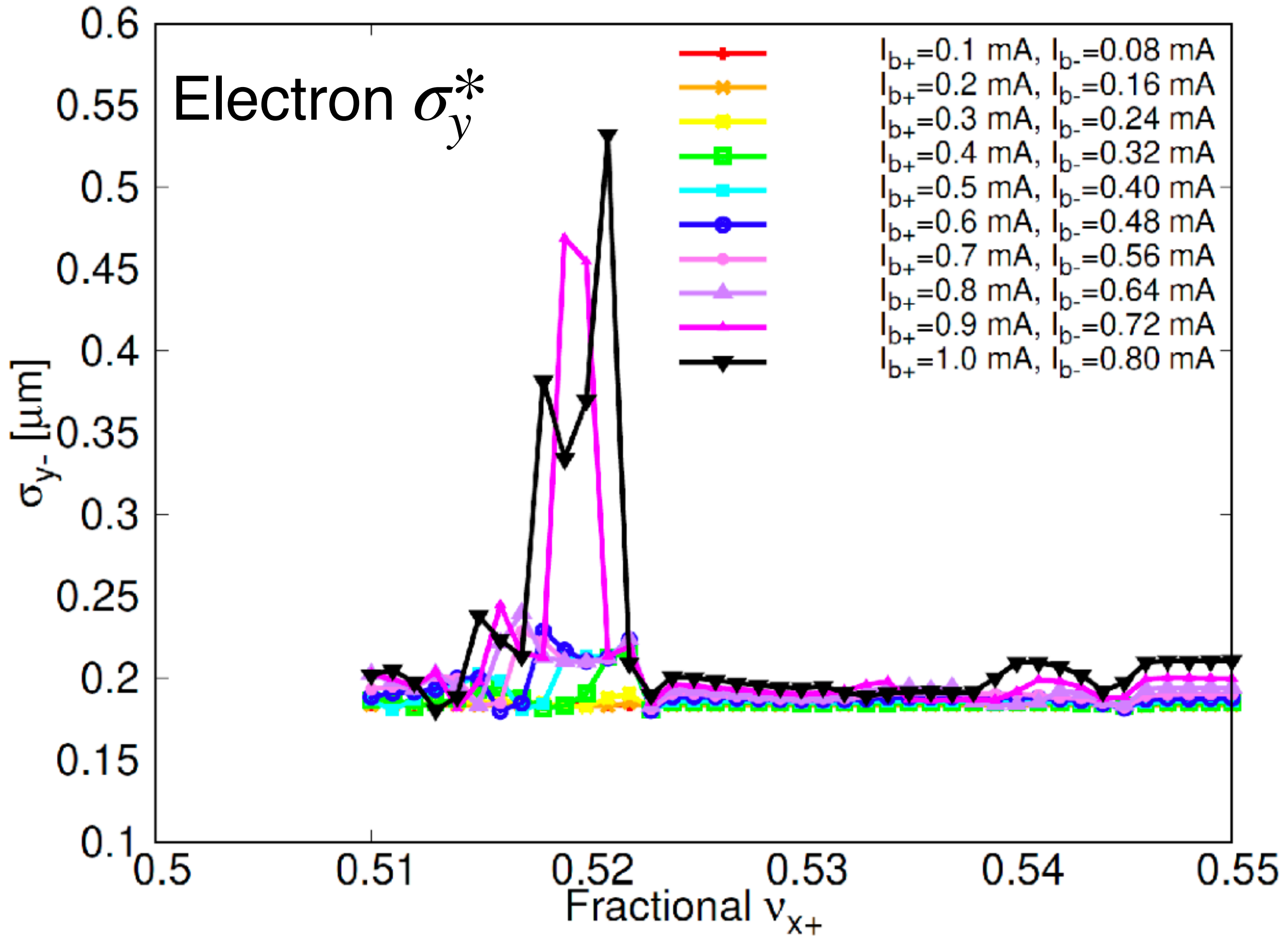
Status of beam-beam simulations

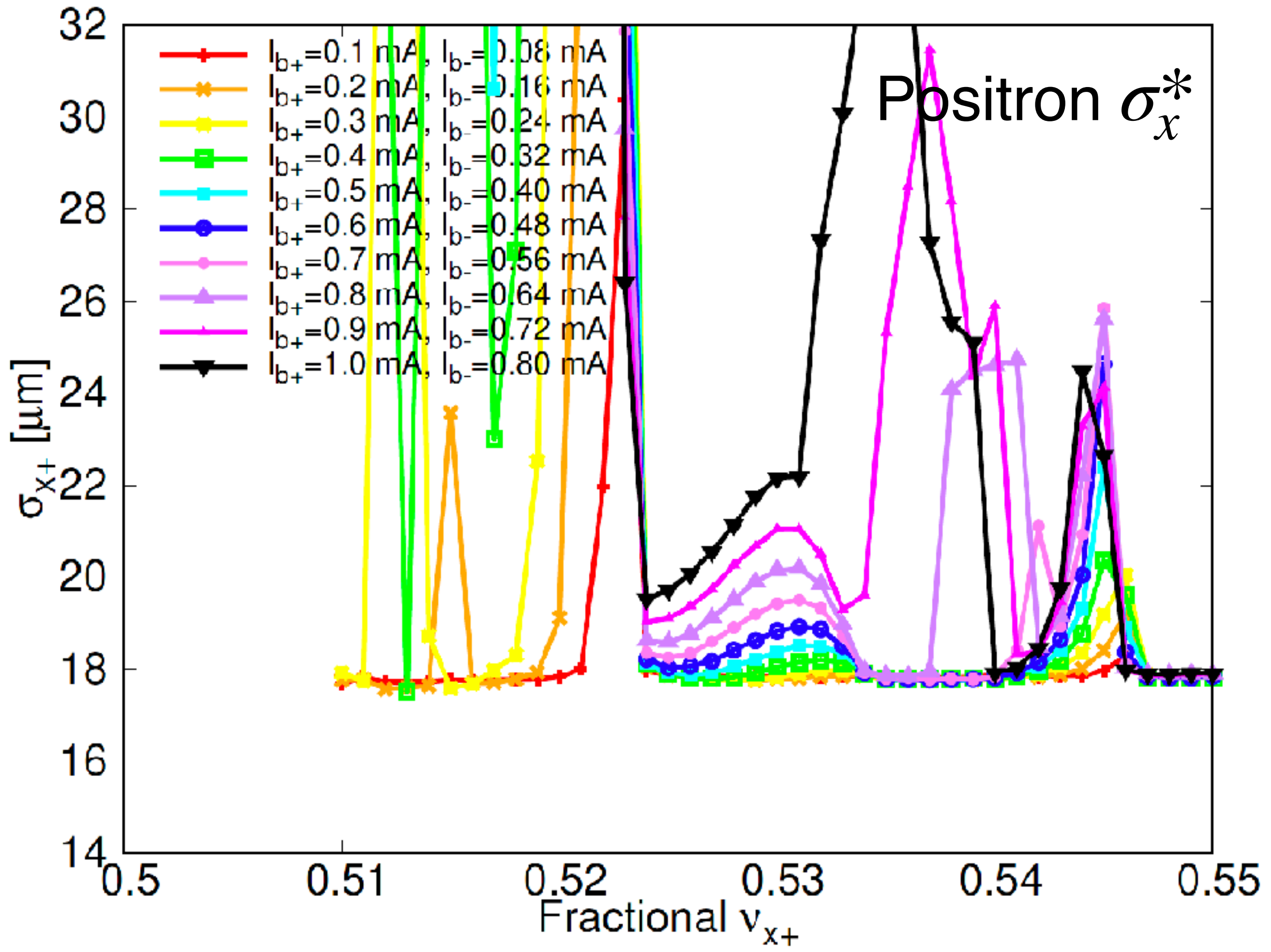
- Scan LER ν_x (with LER ν_y and HER $\nu_{x,y}$ fixed as the values of the parameter table of 2021.12.21)
  - Coupling impedances included
  - Weak horizontal blowup when $0.5 + \nu_s < [\nu_x] < 0.5 + 1.5\nu_s$

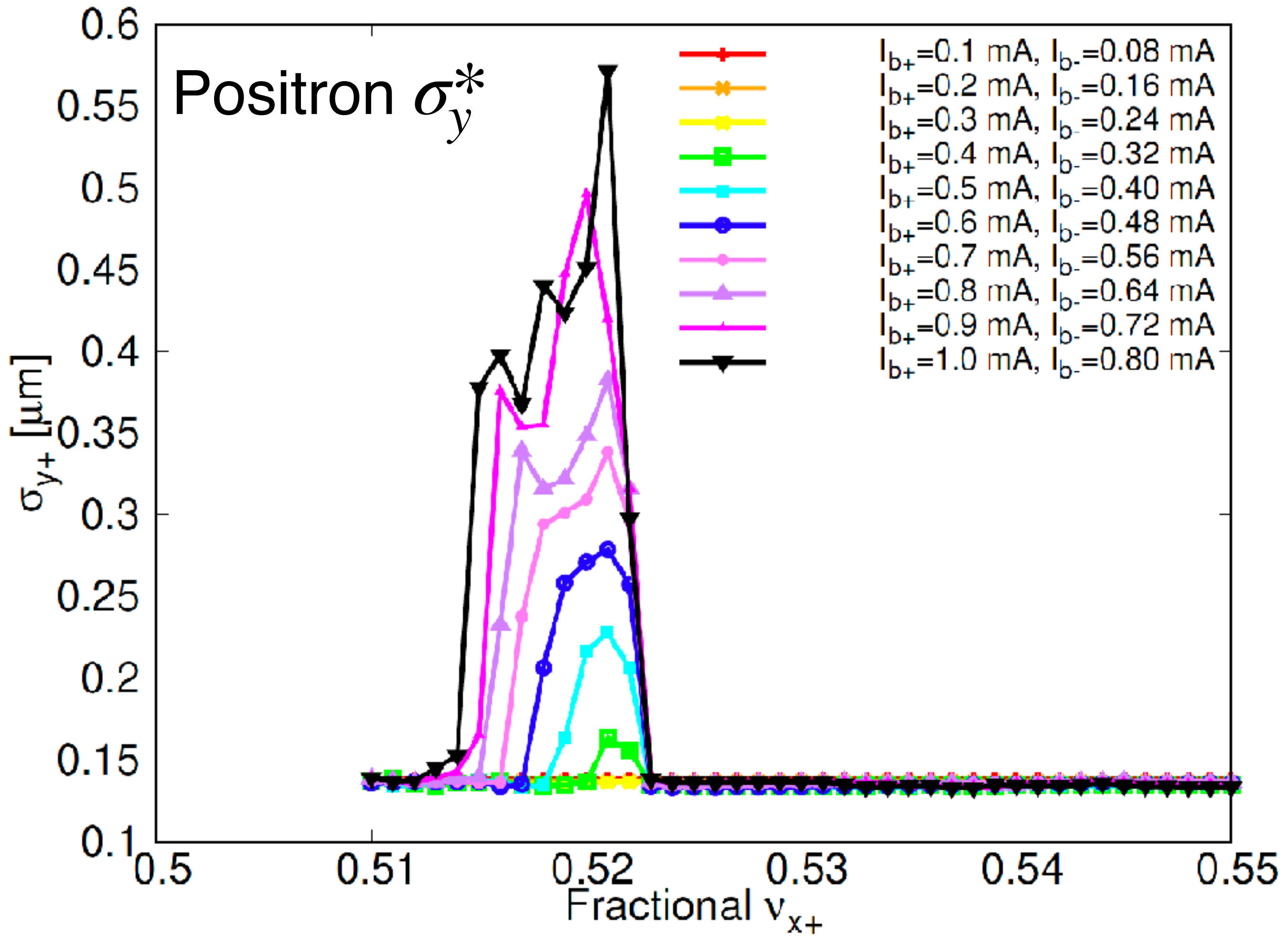
X-Z instability is sensitive to ν_x.









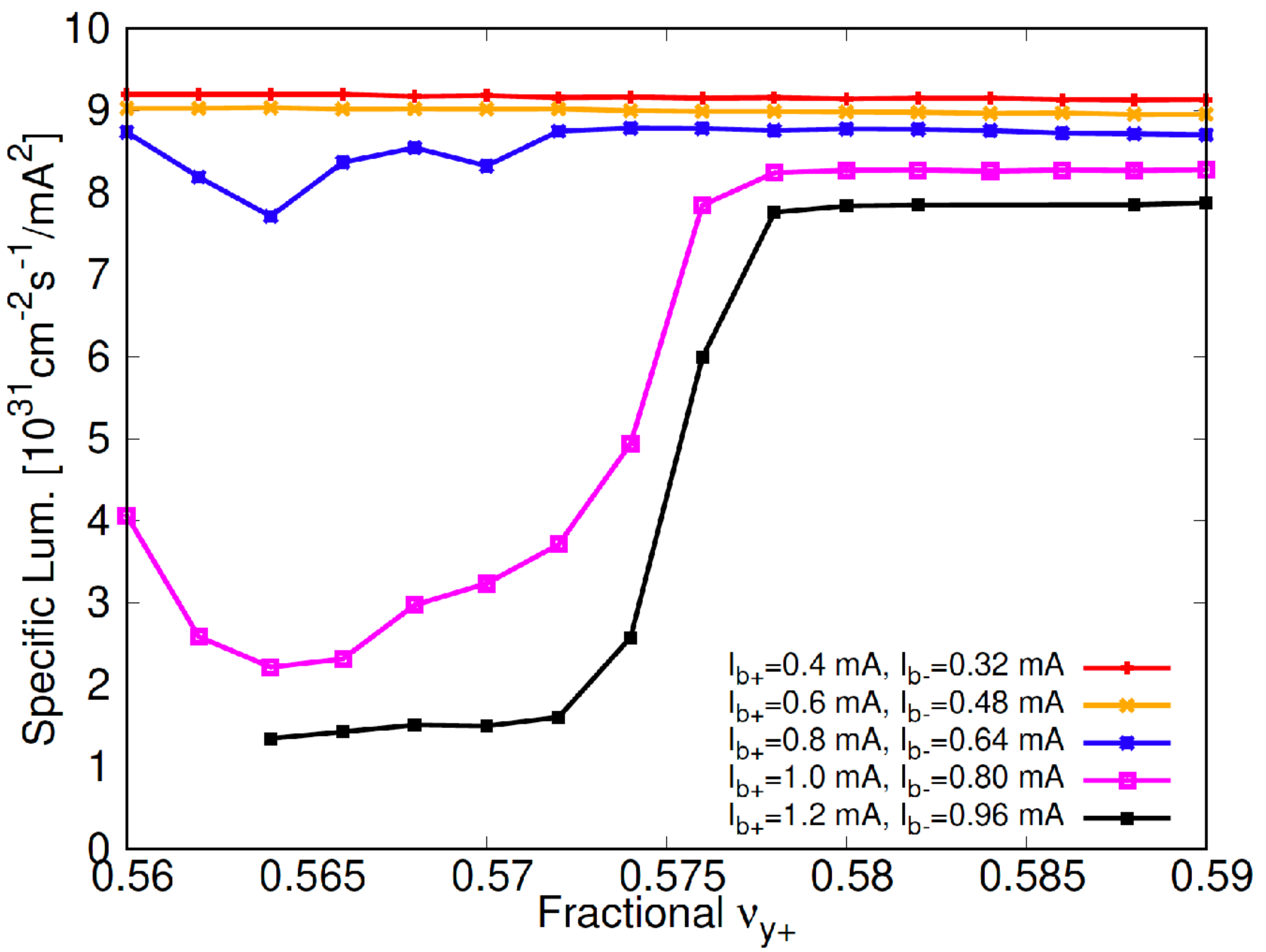


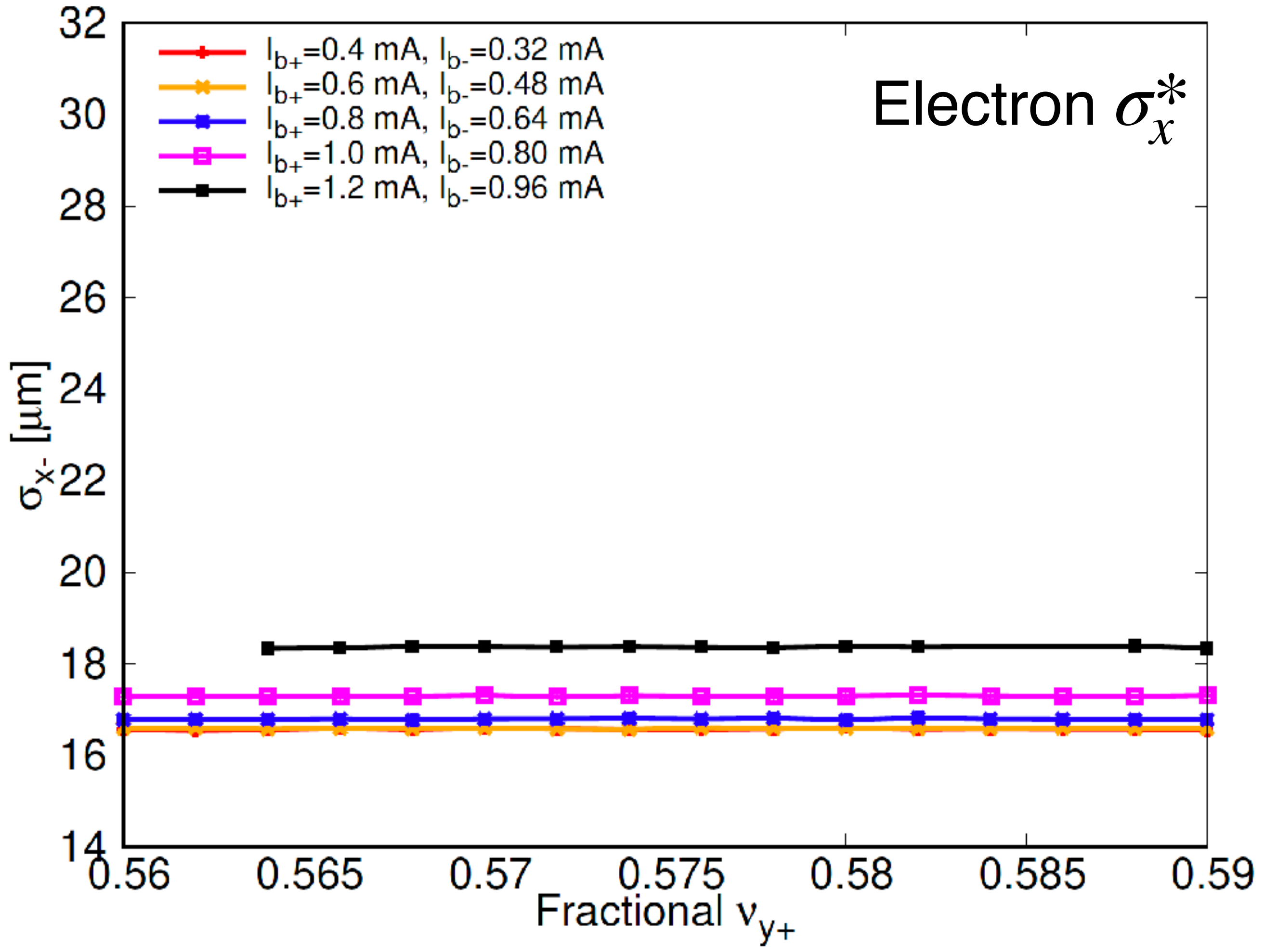
Status of beam-beam simulations

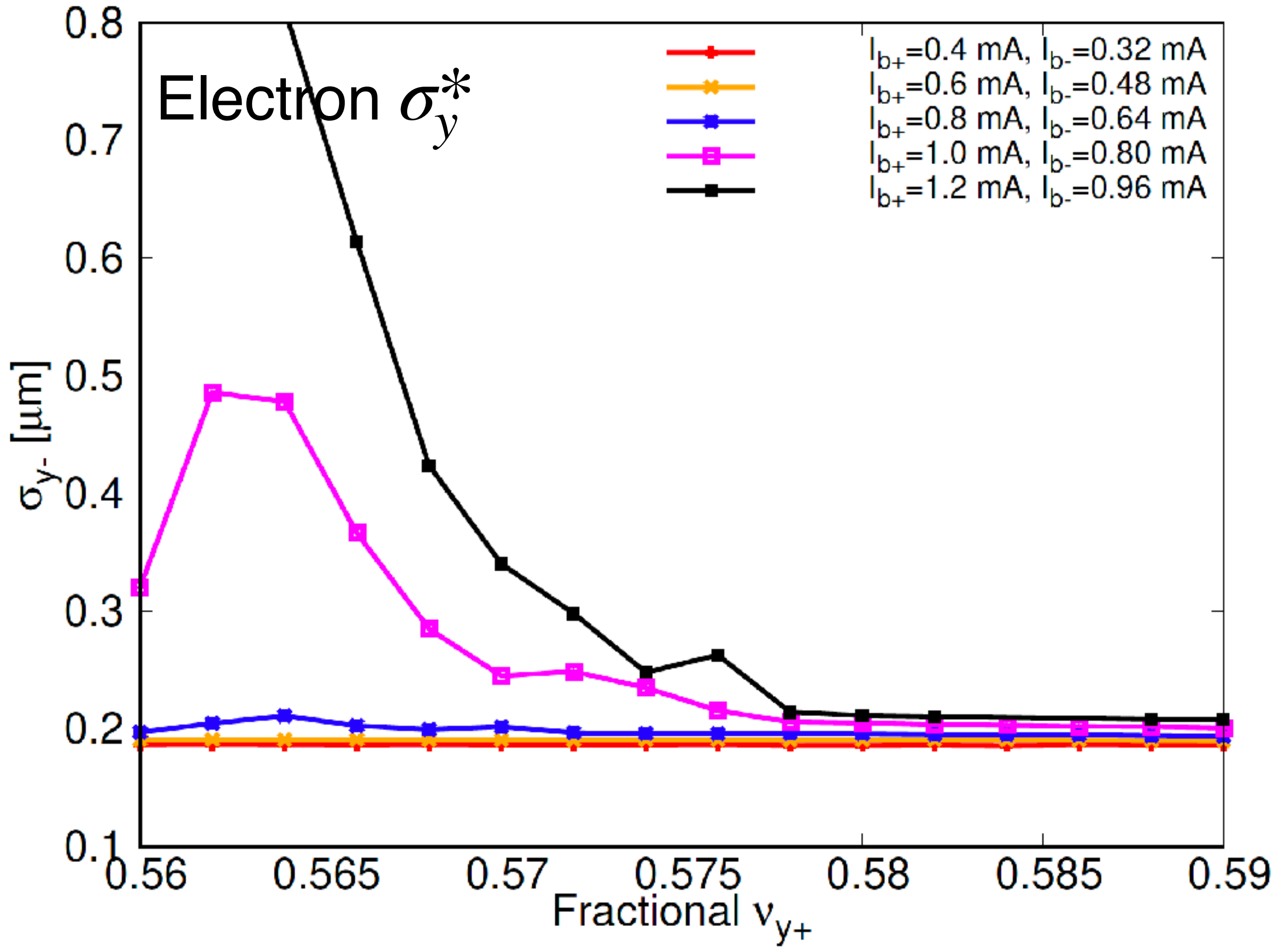
- BBSS simulations: Scan LER ν_y with bunch currents varied (with LER ν_x and HER $\nu_{x,y}$ fixed as the values of the parameter table of 2021.12.21, BB+Wxy+Wz)

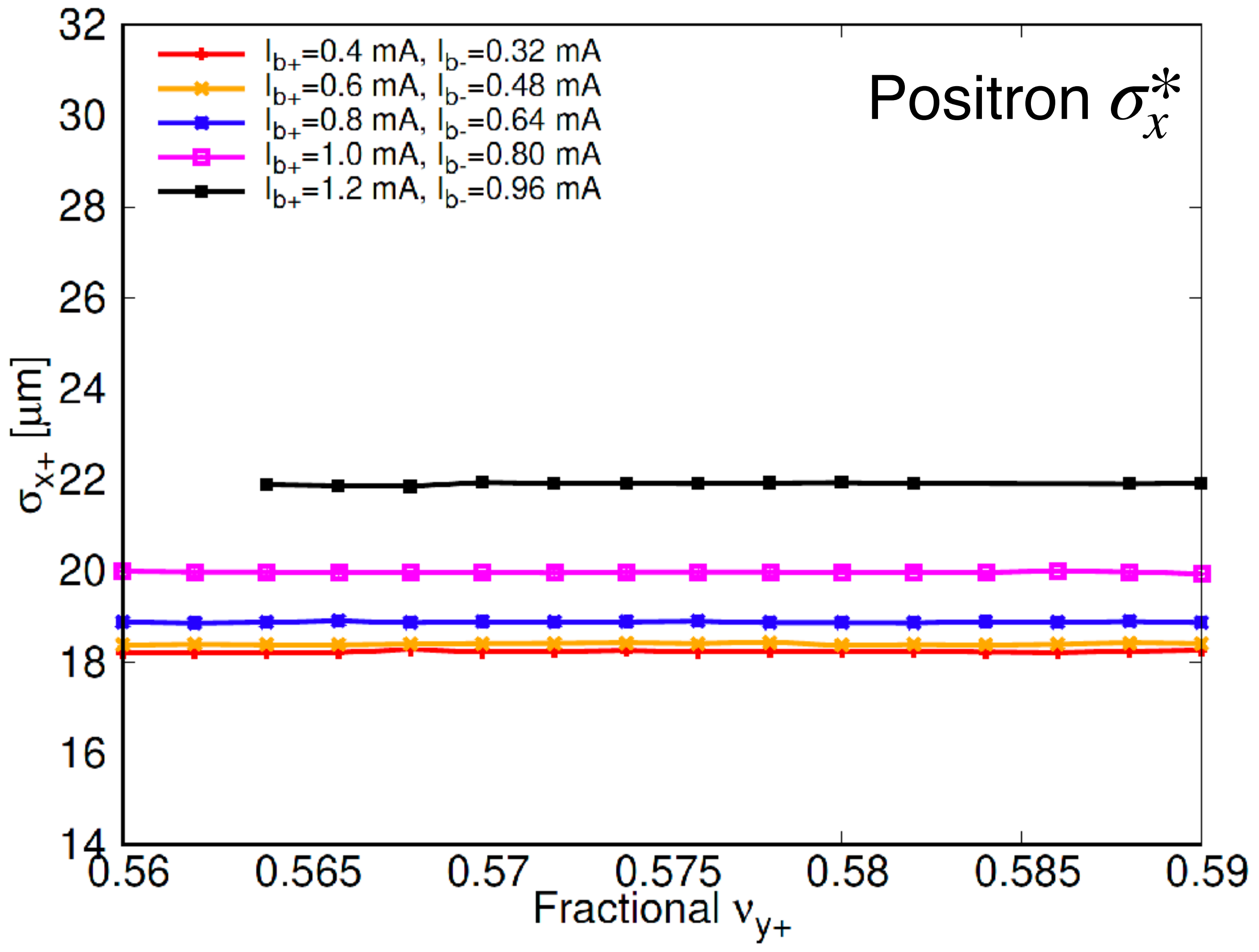
* The interplay of BB+Wx,y+Wz causes instability, consistent with Y. Zhang and K. Ohmi's findings.

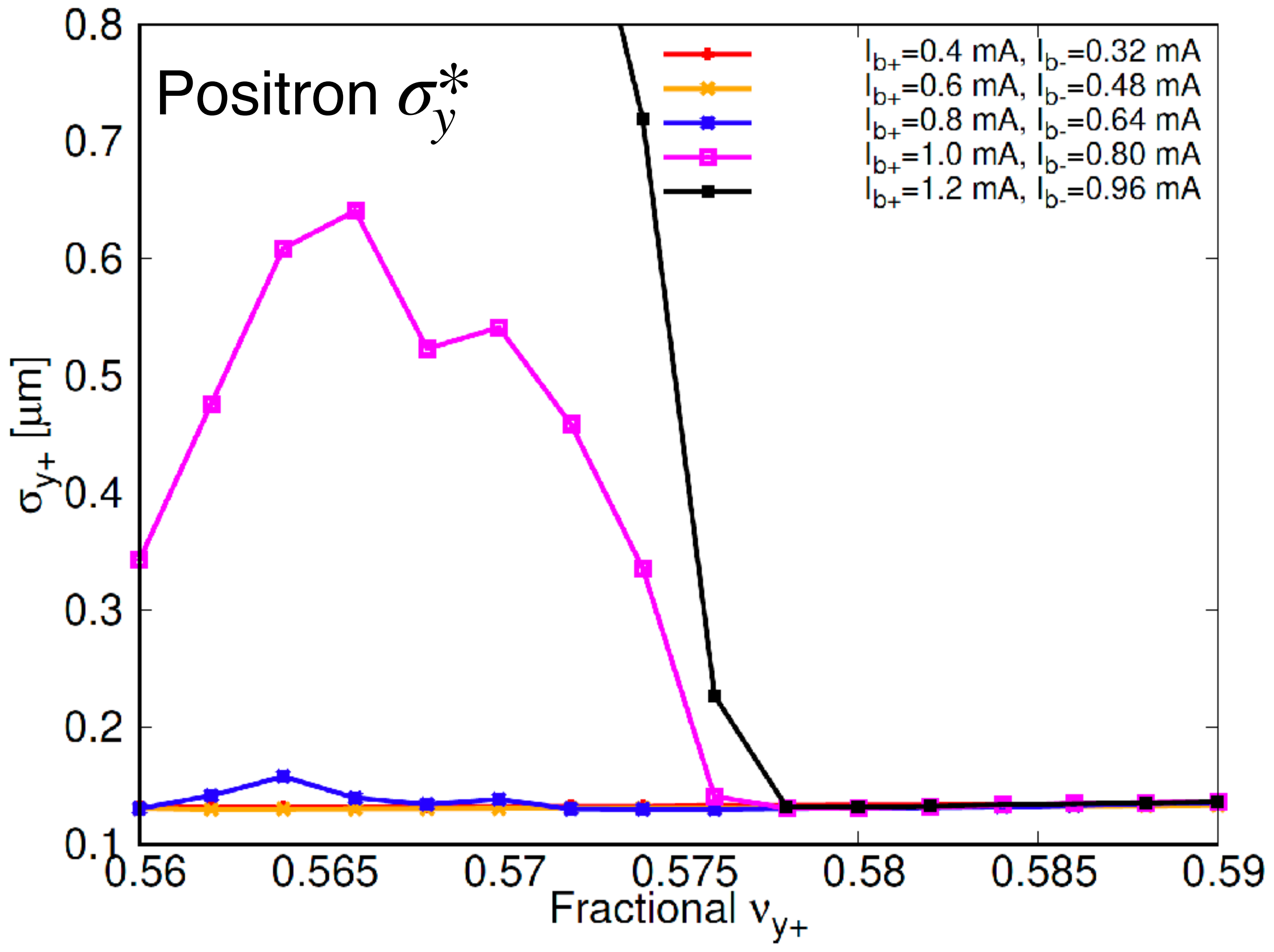
* This instability has a threshold that is ν_y-dependent.







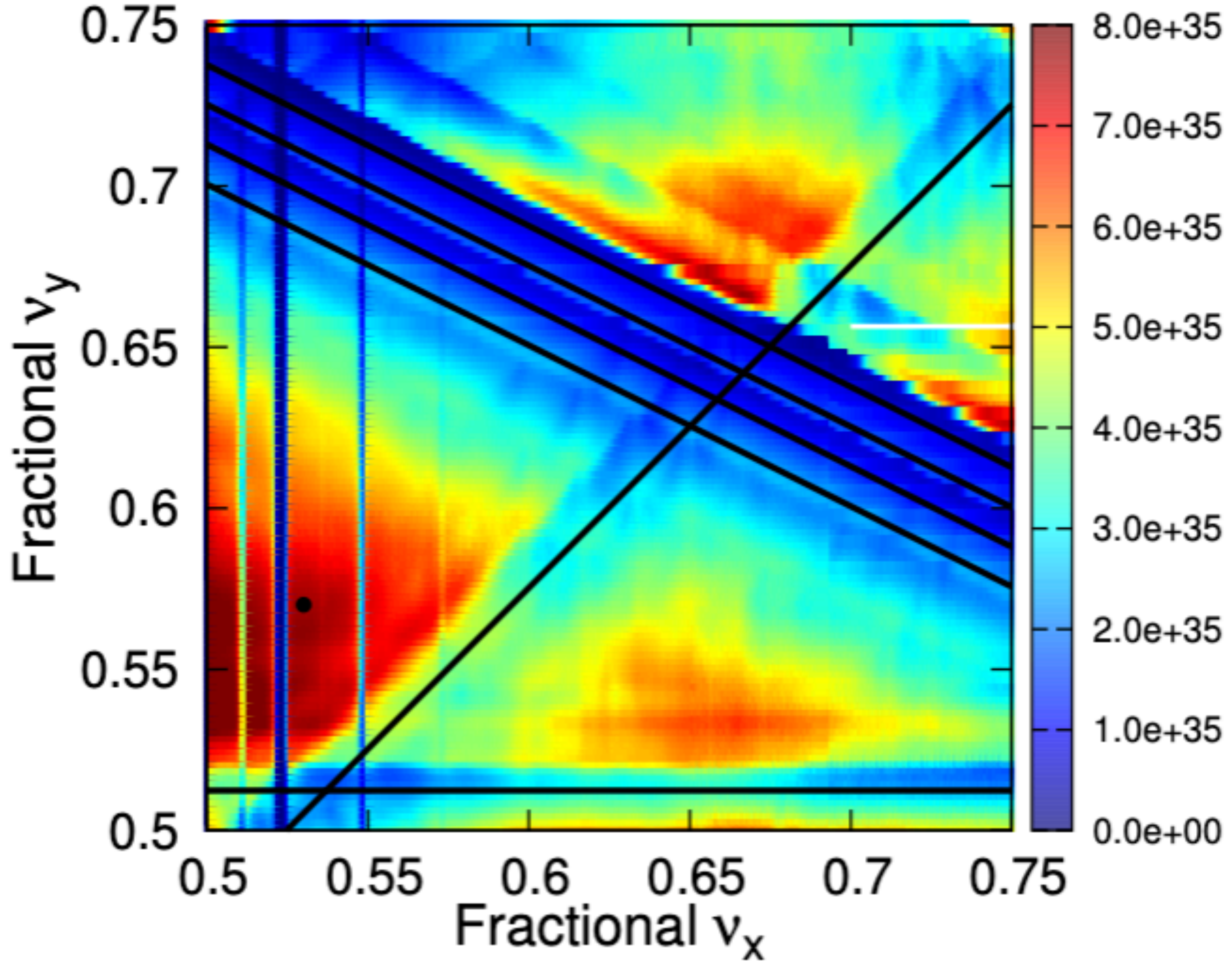




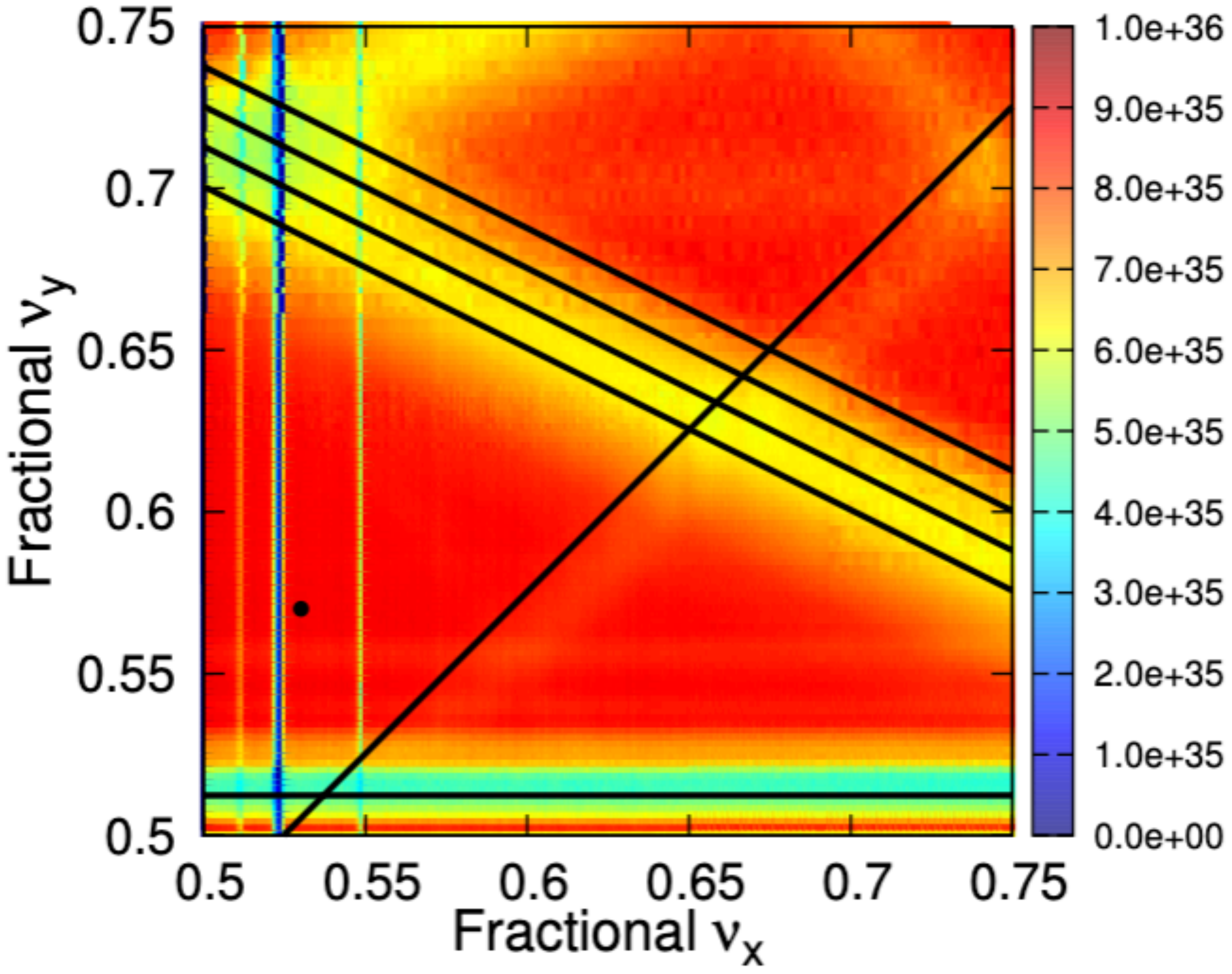
Crab waist applied to SuperKEKB

- 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

w/o crab waist

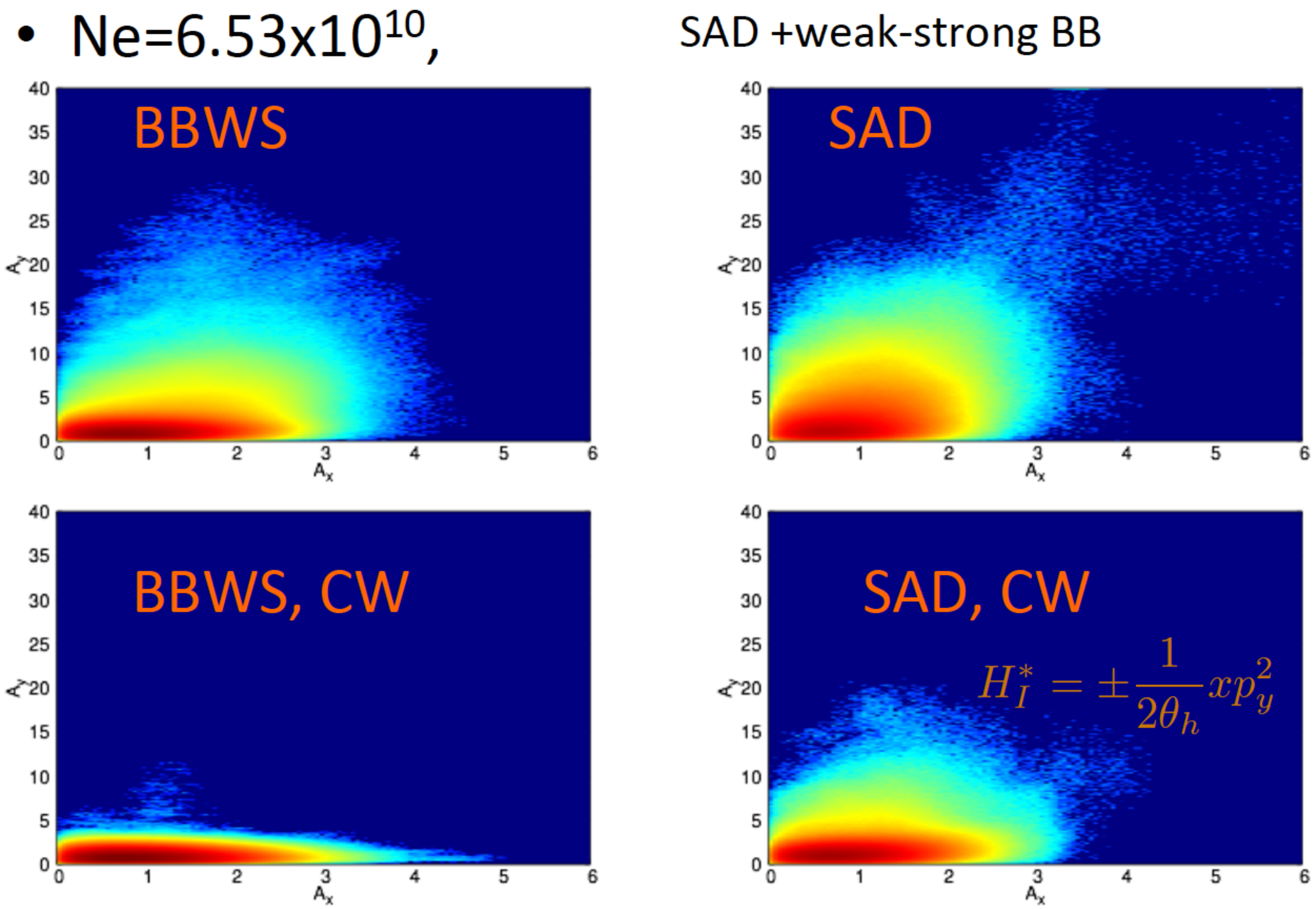


w/ crab waist



Crab waist applied to SuperKEKB

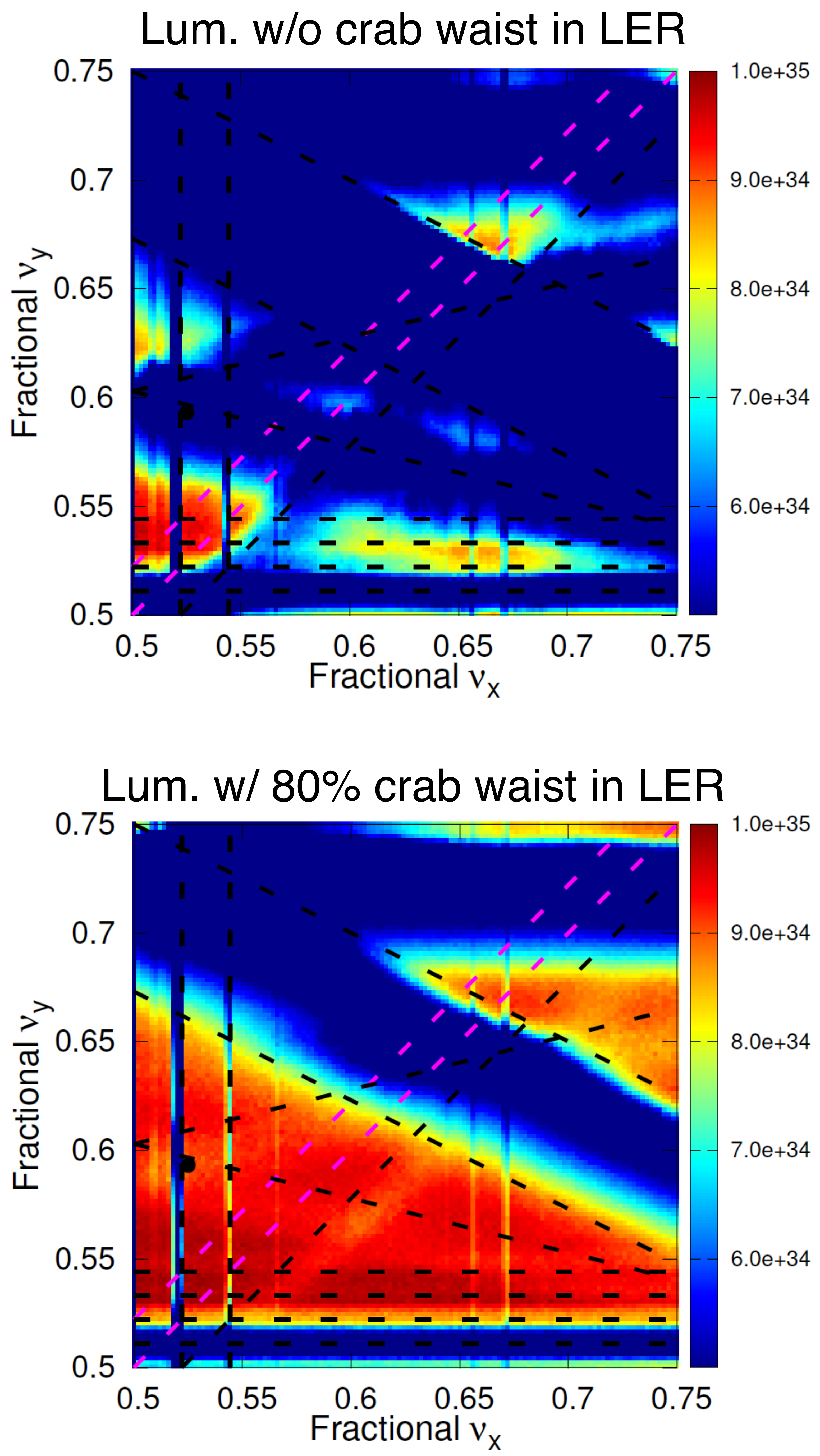
- SuperKEKB final design ($\beta_y^* = 0.3/0.27$ mm) with ideal crab waist
  - Beam-beam driven halo can be suppressed



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 $\nu_x \pm 4\nu_y + \alpha = N$).

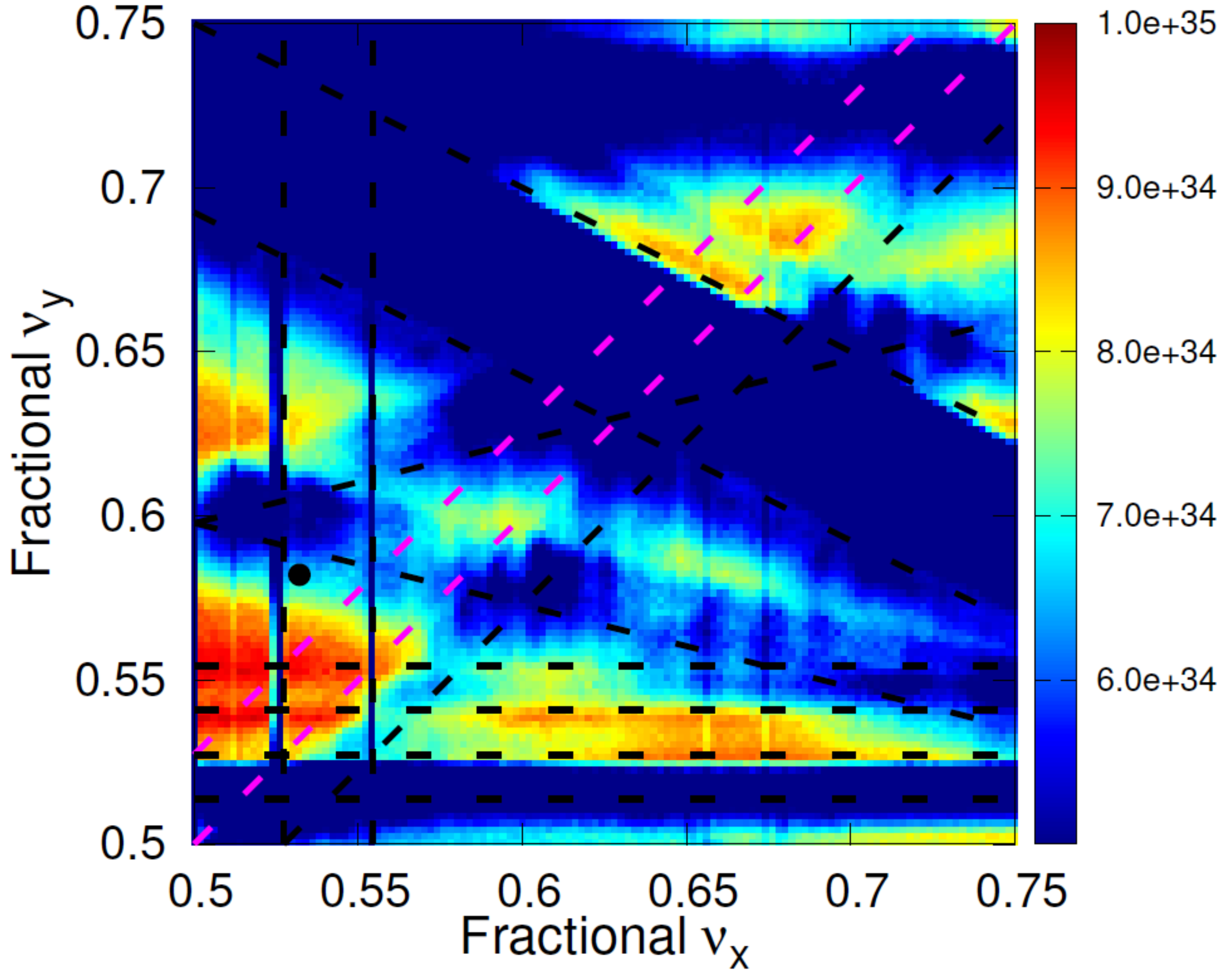
	2021.07.01		Comments
	HER	LER	
I_{bunch} (mA)	0.80	1.0	
# bunch	1174		Assumed value
ε_x (nm)	4.6	4.0	w/ IBS
ε_y (pm)	23	23	Estimated from XRM data
β_x (mm)	60	80	Calculated from lattice
β_y (mm)	1	1	Calculated from lattice
σ_{z0} (mm)	5.05	4.84	Natural bunch length (w/o MWI)
ν_x	45.532	44.525	Measured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



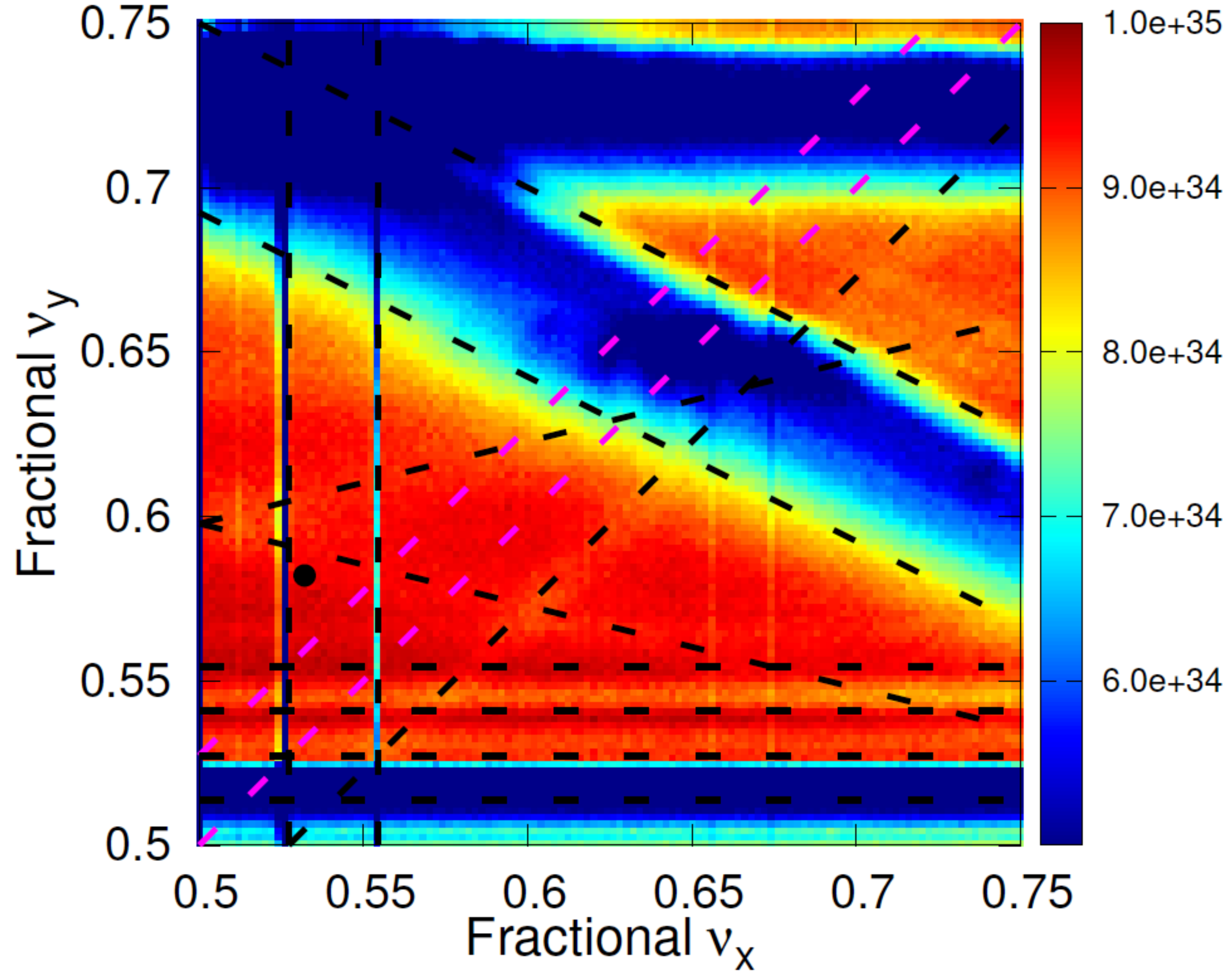
Crab waist applied to SuperKEKB

- 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 $\nu_x \pm 4\nu_y + \alpha = N$).

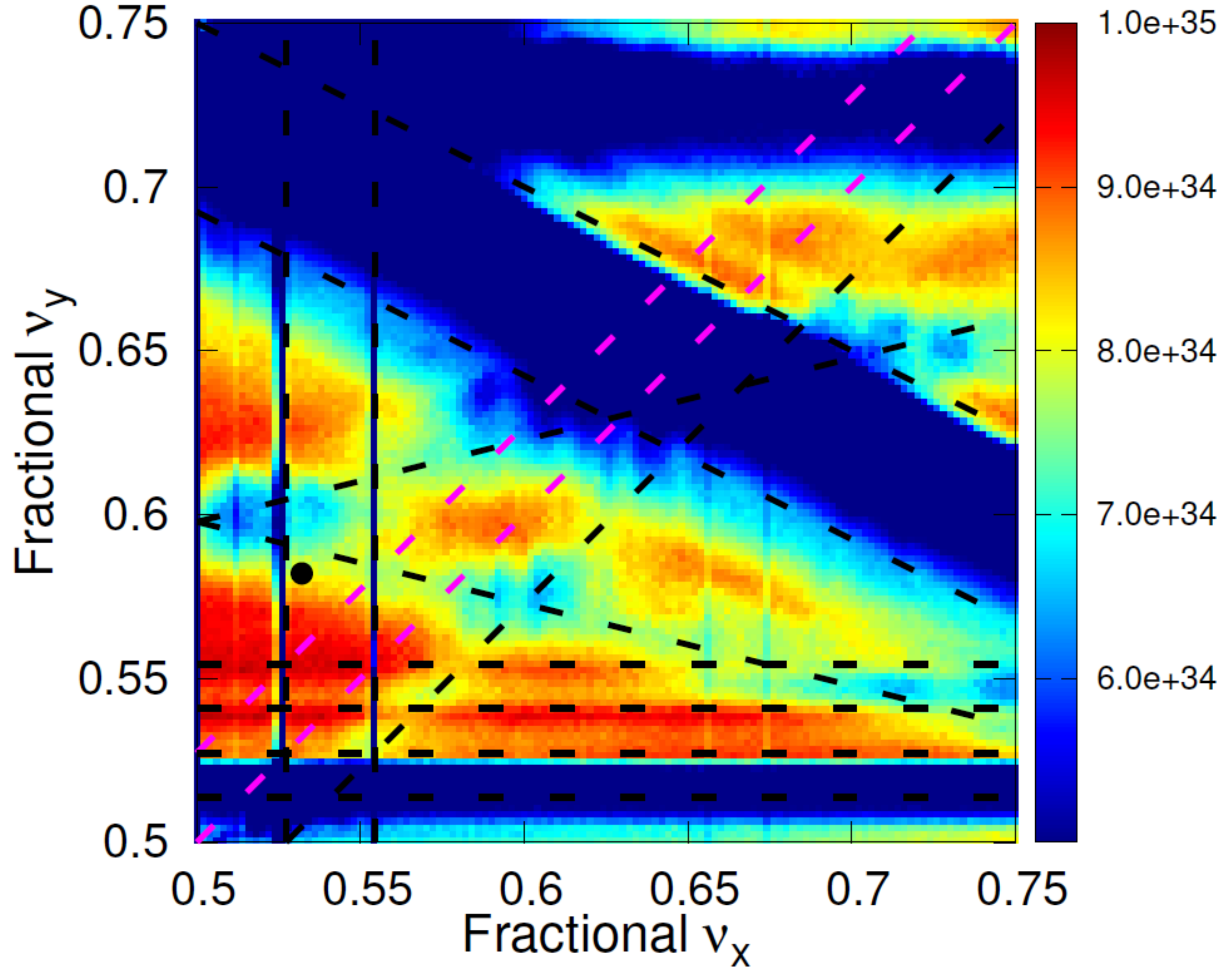
Lum. w/o crab waist in HER



Lum. w/ 80% crab waist in HER

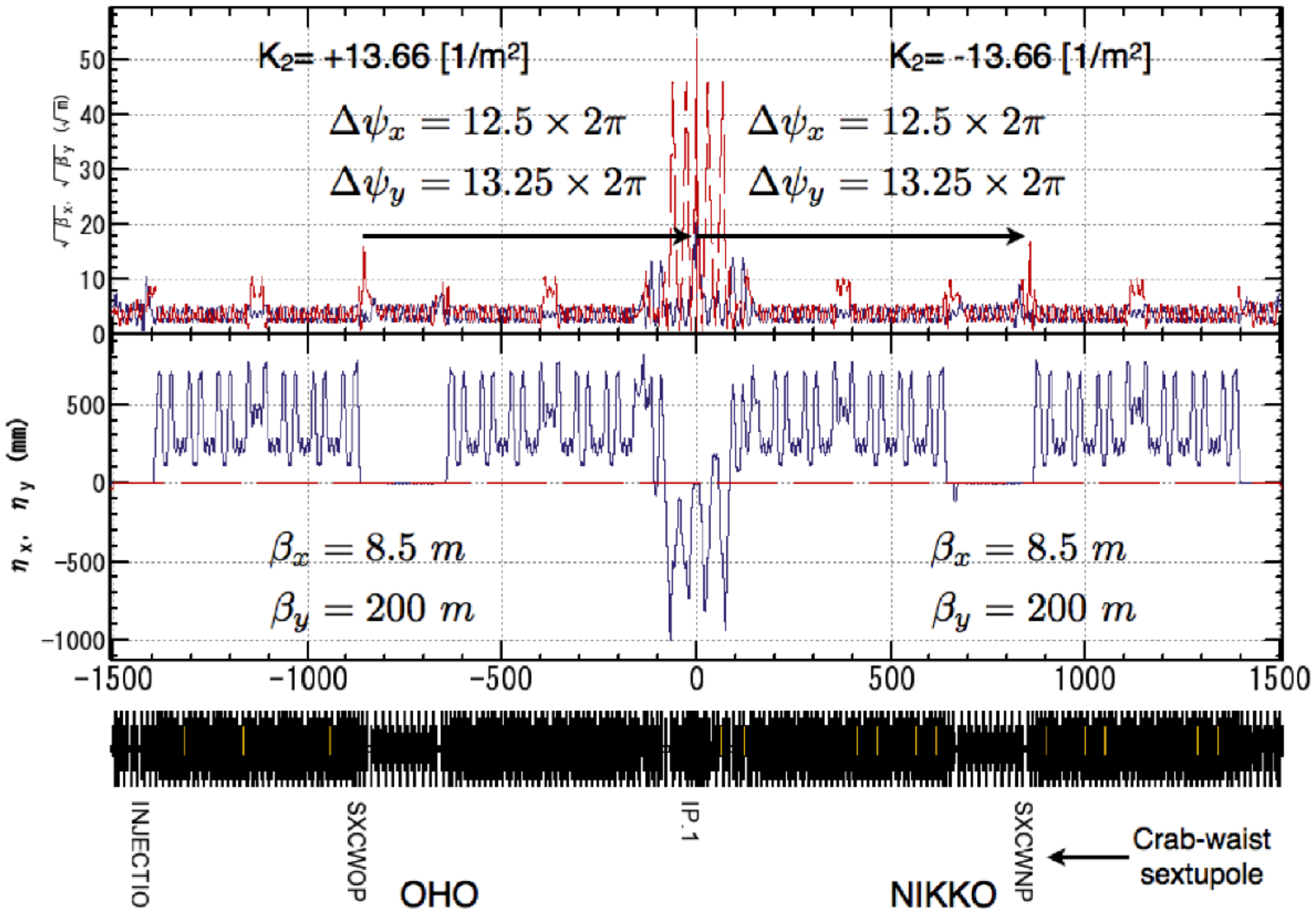


Lum. w/ 40% crab waist in HER



Crab waist applied to SuperKEKB

- SuperKEKB final design ($\beta_y^* = 0.3/0.27$ mm) with practical crab waist [1]
  - CW scheme with CW sextupoles outside IR
  - CW reduces dynamic aperture and Touschek lifetime, and was not chosen as baseline for TDR



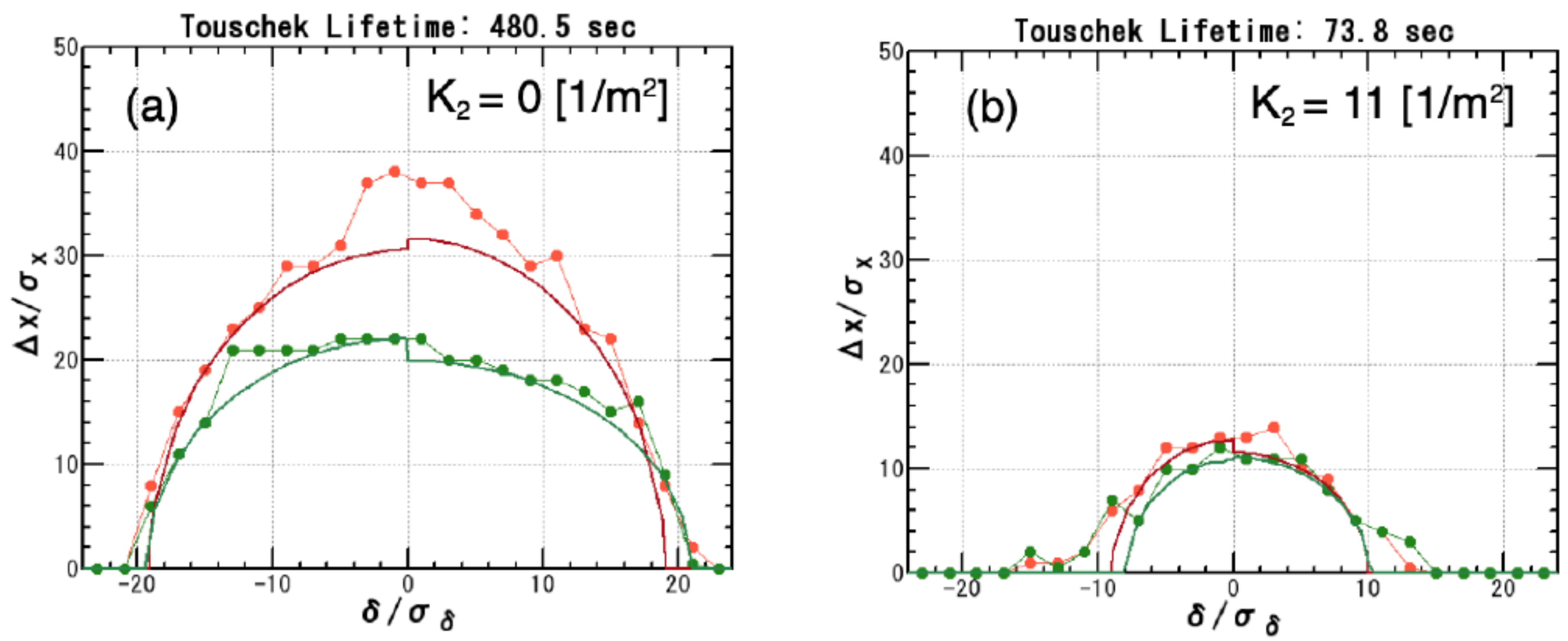
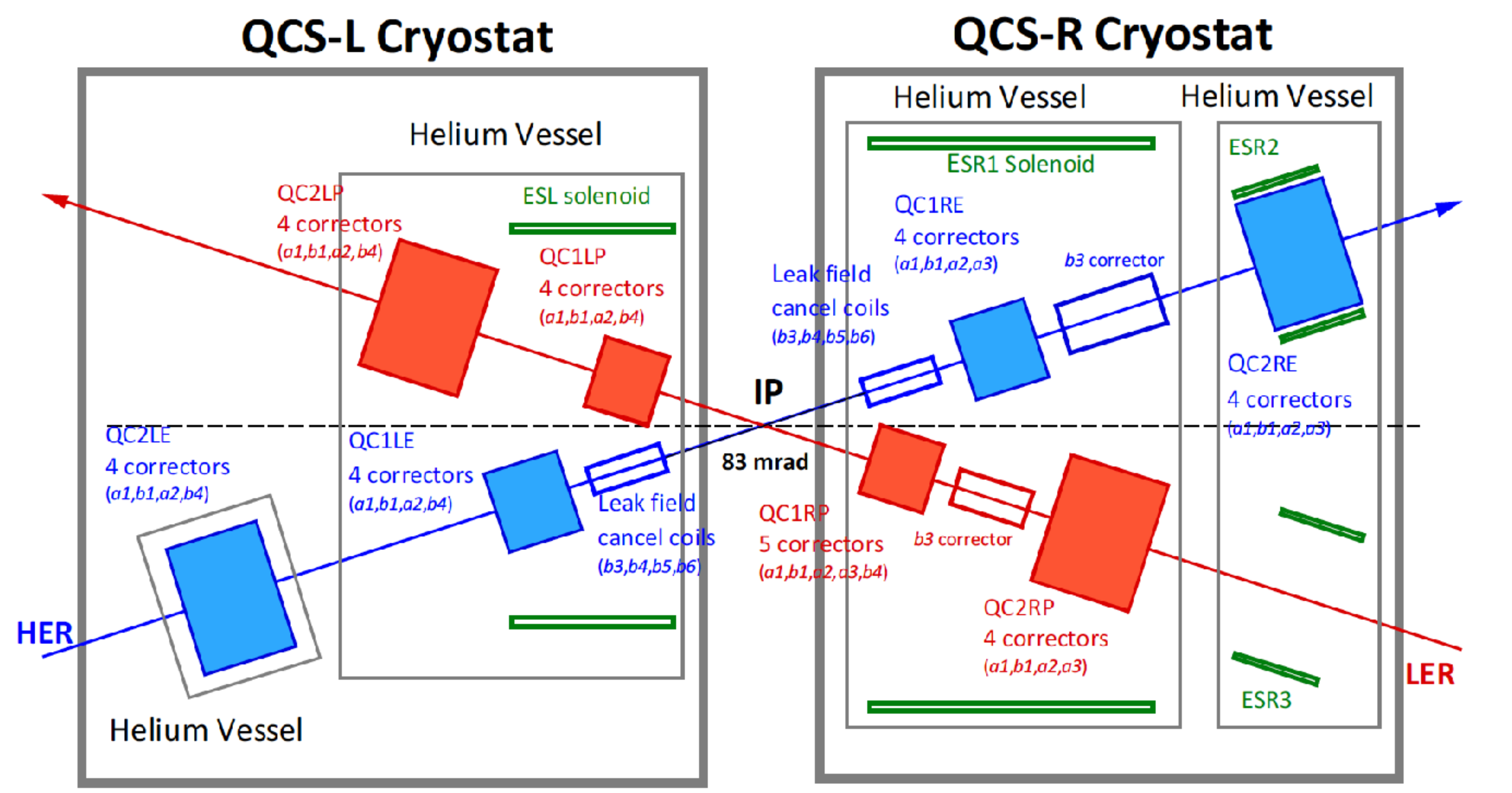


Figure 4.28: Dynamic aperture in the LER crab-waist lattice without beam-beam effect. Initial ratio of the vertical to the horizontal amplitude is 0.27 %. (a) $K_2 = 0$ $[1/m^2]$, (b) $K_2 = 11$ $[1/m^2]$.

[1] SuperKEKB TDR.

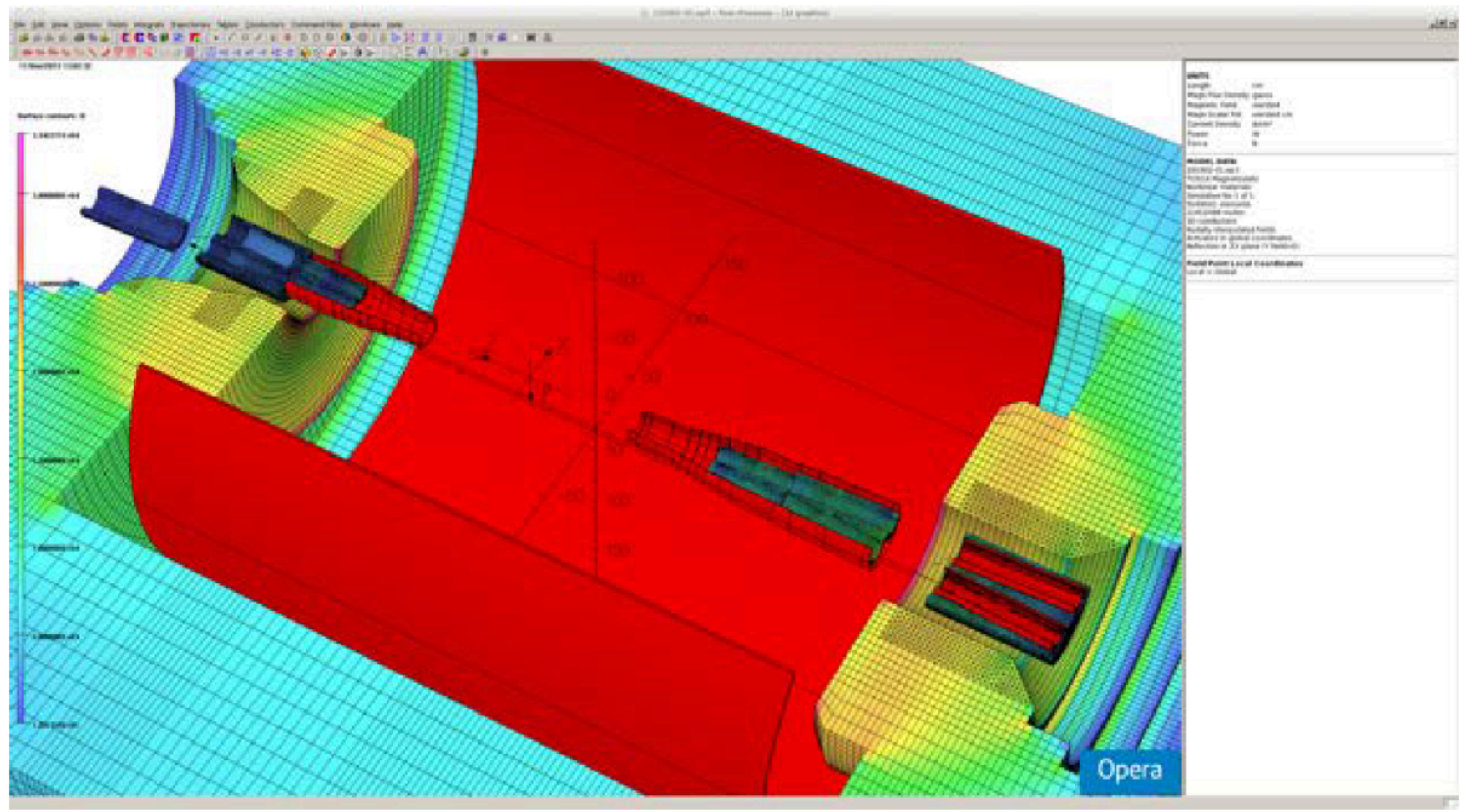
Crab waist applied to SuperKEKB

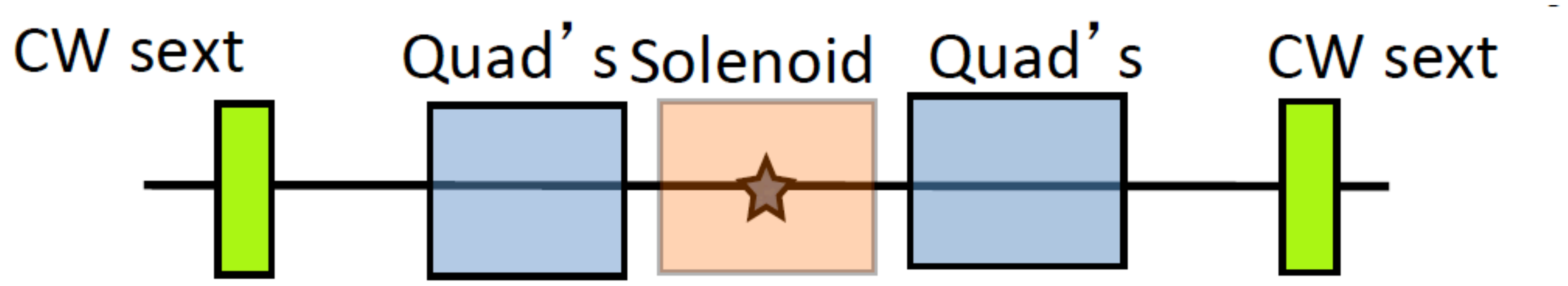
- SuperKEKB final design ($\beta_y^* = 0.3/0.27$ mm) with practical crab waist
  - CW does not work well because of the nonlinear IR. The nonlinearity scales as $1/\beta_y^*$ [1].
  - SuperKEKB design lattice includes nonlinear fields extracted from 3D model [2]



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





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

$$\neq$$

$$e^{-H_{Q's}} e^{-H_{Sol}} \underbrace{e^{-xp_y^2/2\phi}}_{\text{ideal crab waist}} e^{-H_{BB}} \underbrace{e^{-xp_y^2/2\phi}}_{\text{ideal crab waist}} e^{-H_{Sol}} e^{-H_{Q's}}$$

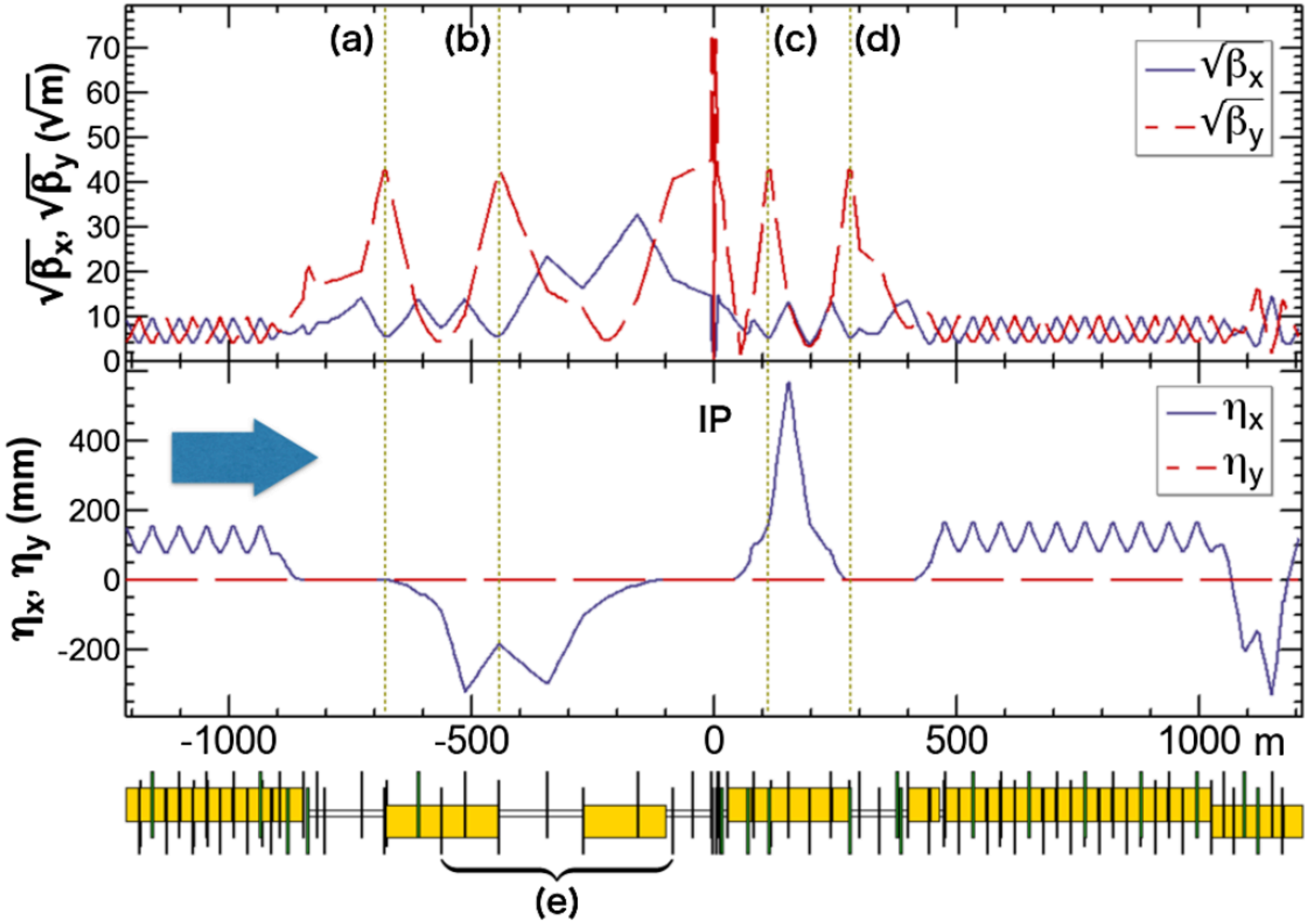
[1] K. Ohmi, EIC workshop, March, 2014.

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

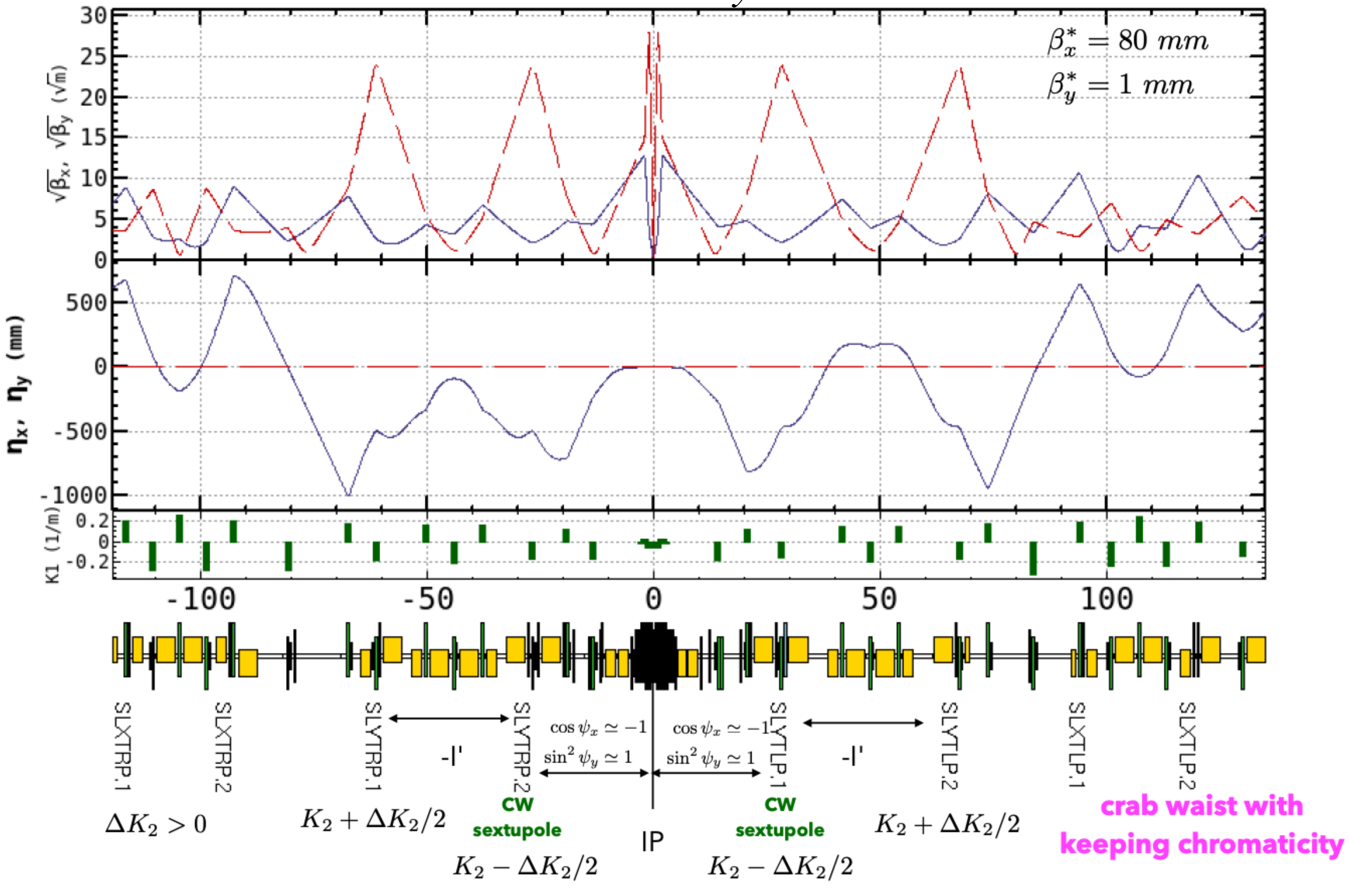
Crab waist applied to SuperKEKB

- Optics design with crab waist for $\beta_y^* = 1$ mm
  - In 2020, K. Oide introduced the FCC-ee CW scheme [1] to SuperKEKB [2].
  - FCC-ee CW scheme utilizes the sextupoles (a-d) for local chromaticity correction and crab waist.

FCC-ee



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



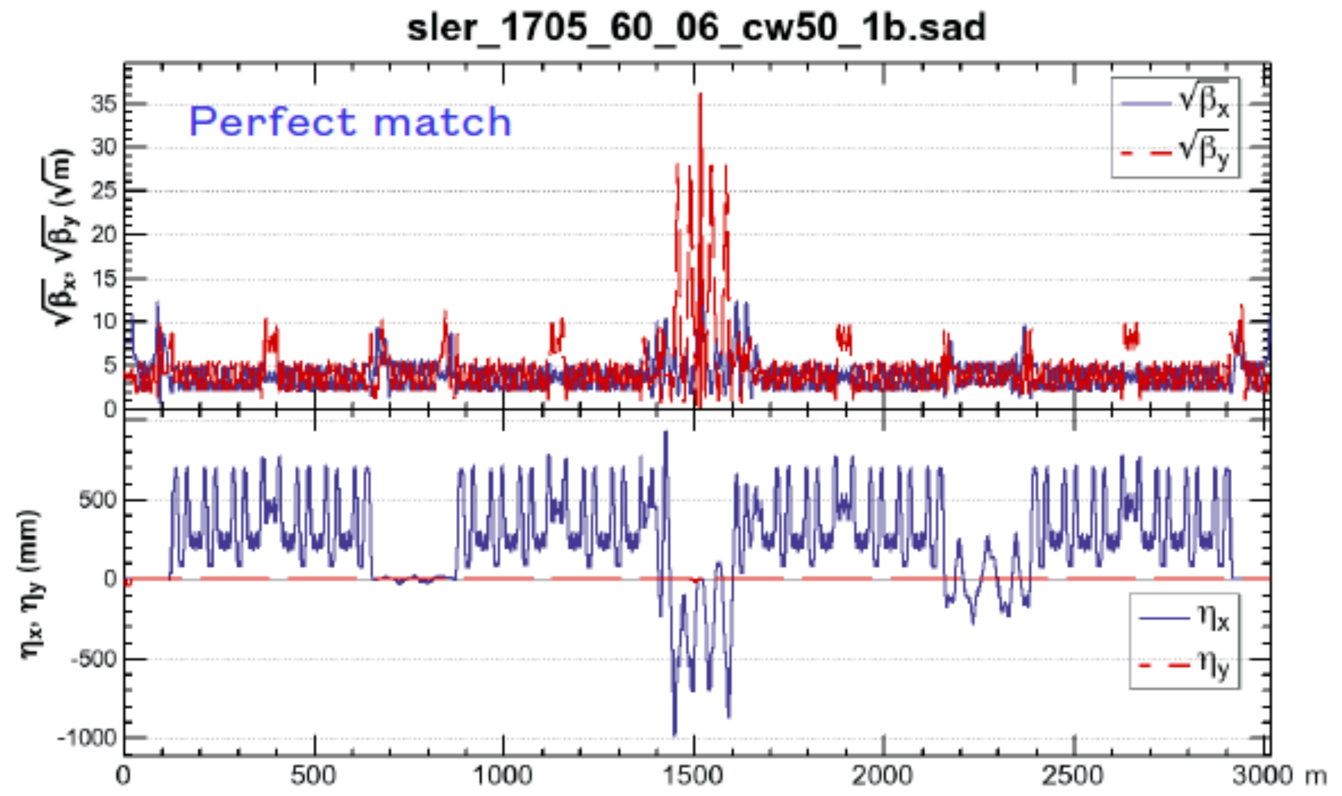
[2] Y. Ohnishi, SuperKEKB ARC 2020.

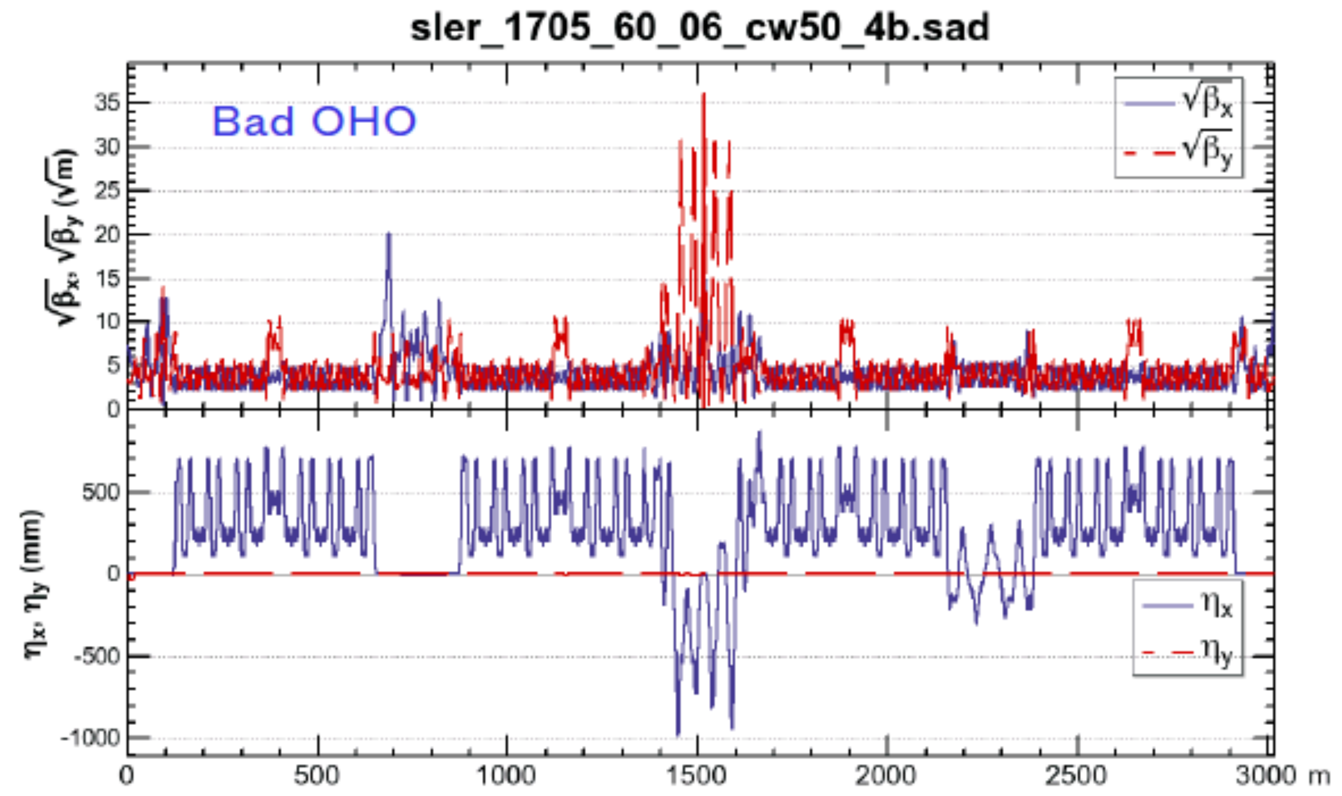
[1] K. Oide et al., PRAB 19, 111005 (2016).

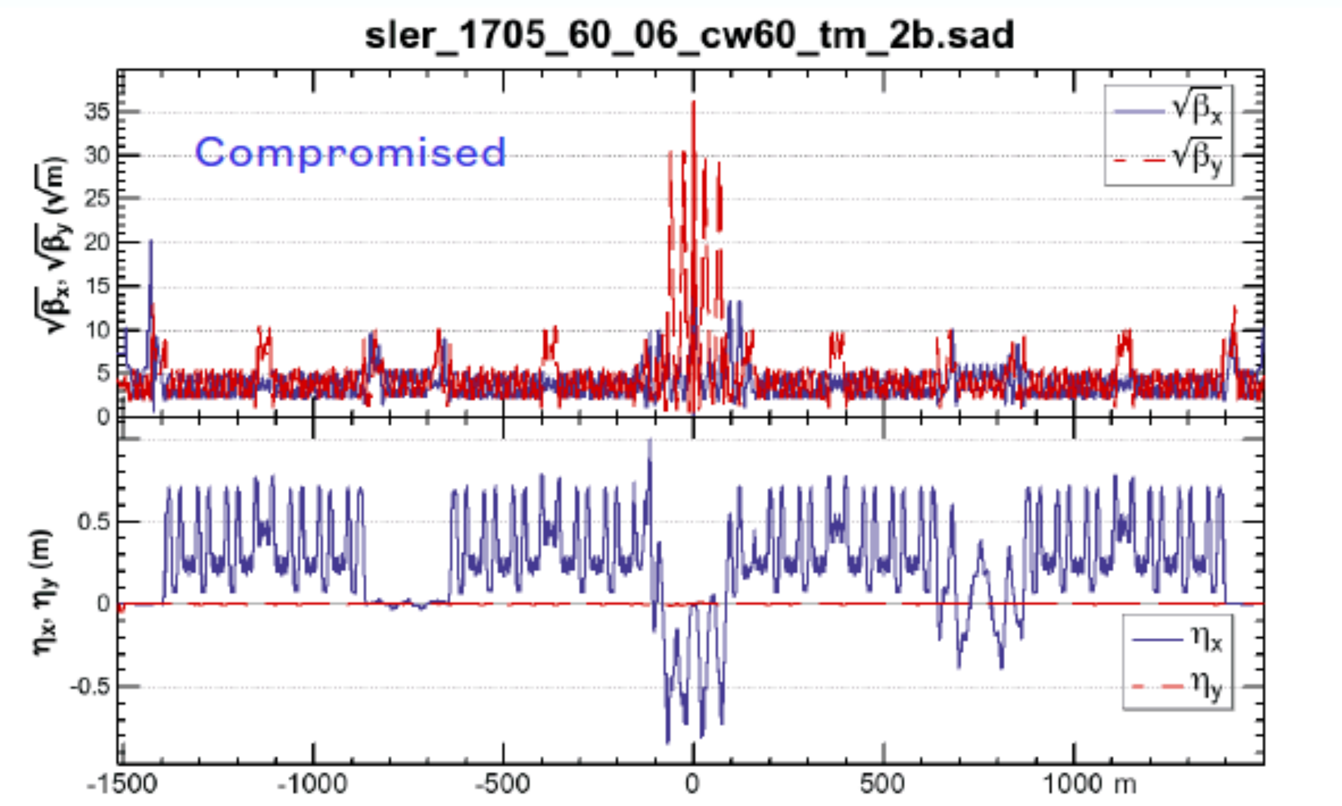
Crab waist applied to SuperKEKB

- Optics design with crab waist for $\beta_y^* = 0.6$ mm by K. Oide [1]

Comparison of optics







Parameters		"Bad OHO"	"compromised"	"perfect"
β^*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}

3

[1] @zero impedance

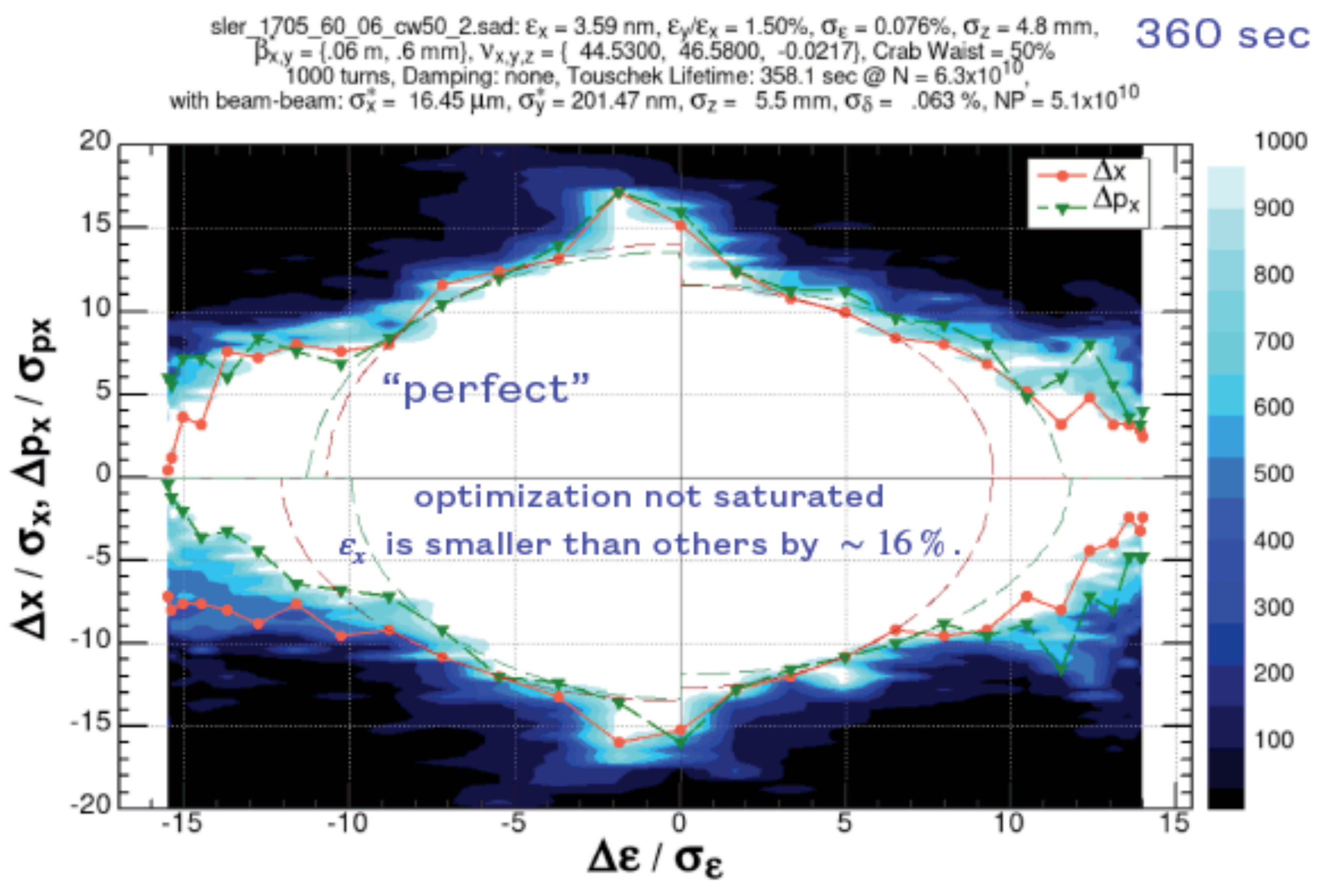
Aug. 27, 2021 K. Oide

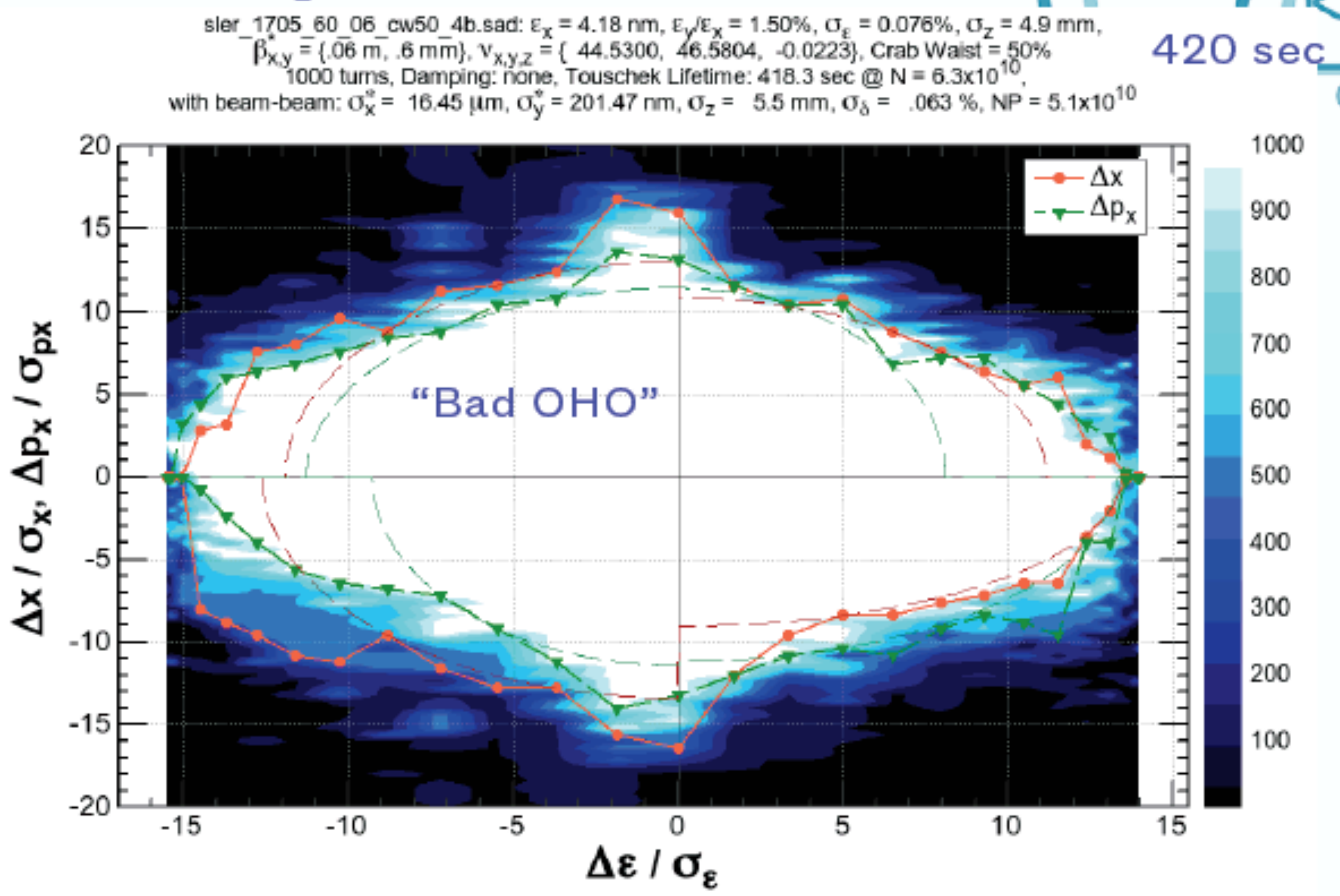
[1] K. Oide, SuperKEKB ARC, 2021.

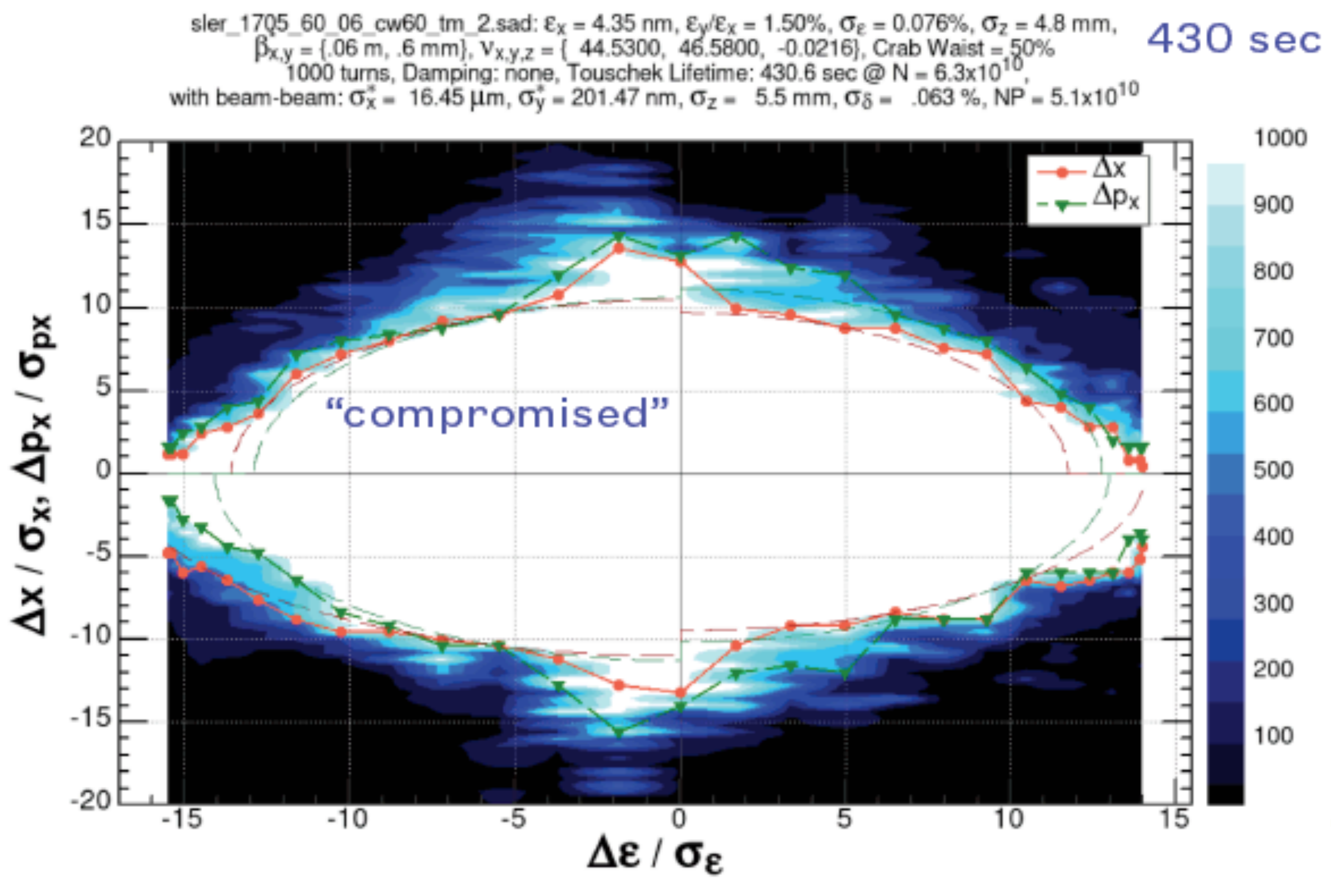
Crab waist applied to SuperKEKB

- Optics design with crab waist for $\beta_y^* = 0.6$ mm by K. Oide [1]
  - 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

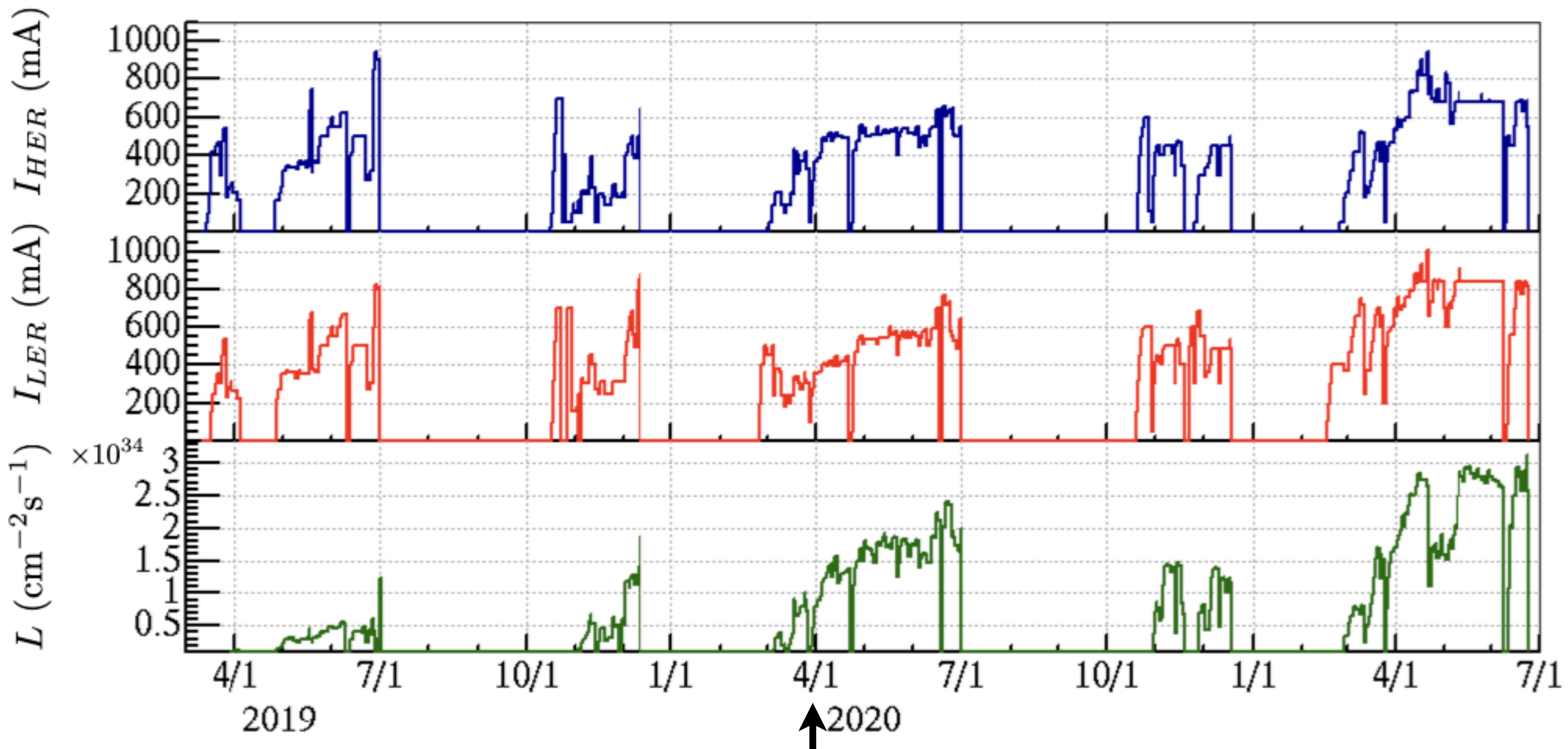
4

Aug. 27, 2021 K. Oide

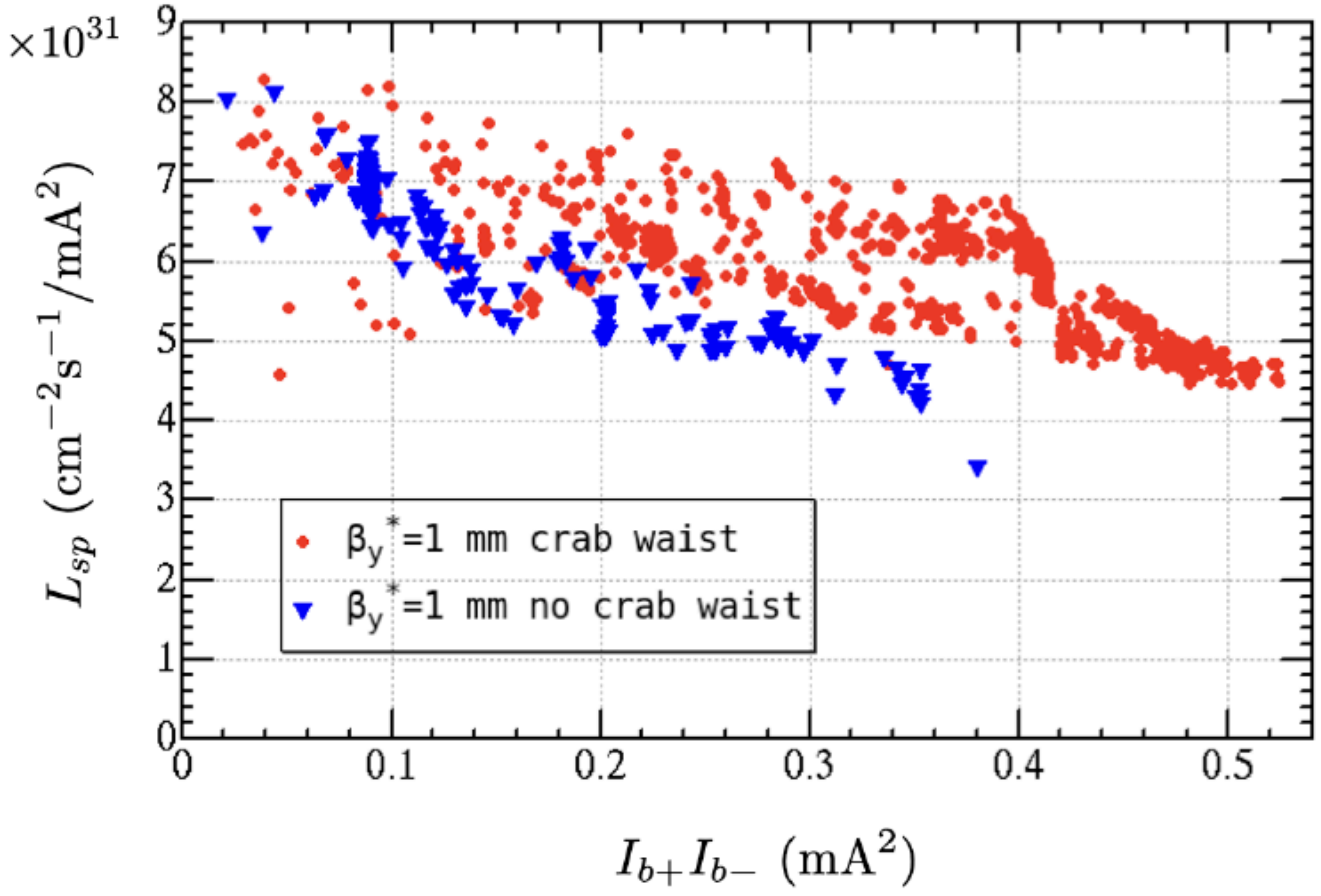
[1] K. Oide, SuperKEKB ARC, 2021.

Crab waist applied to SuperKEKB

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



Crab waist introduced since April 2020



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

BB simulations w/ final design configuration

- Findings [1]
  - 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.**

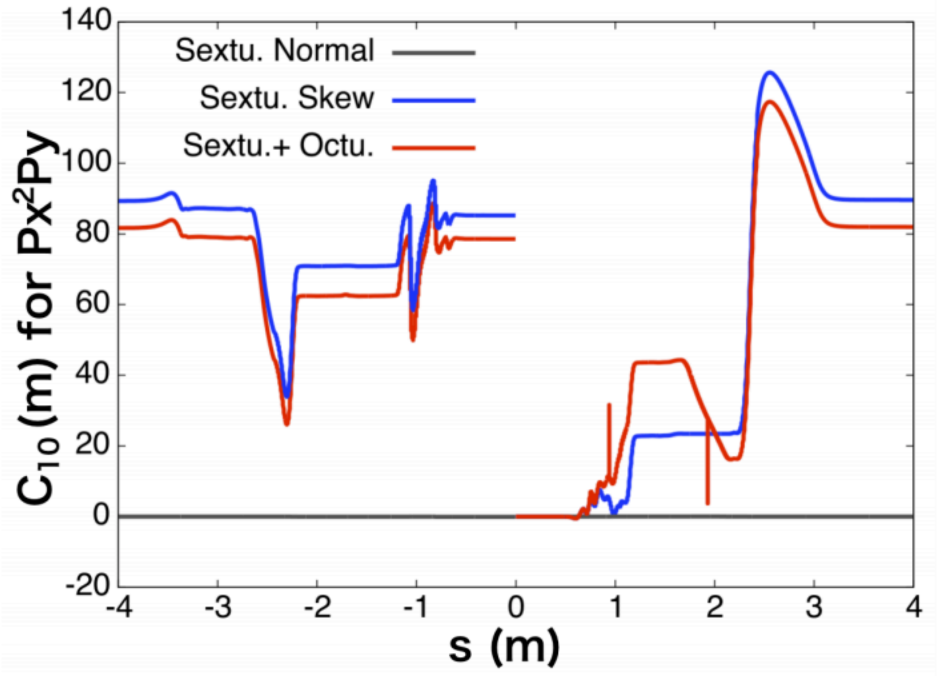


Figure 4: Coefficient of $P_X^2 P_Y$ caused by skew sextupole (SK_2) and octupole ($K_3 + SK_3$) fields.

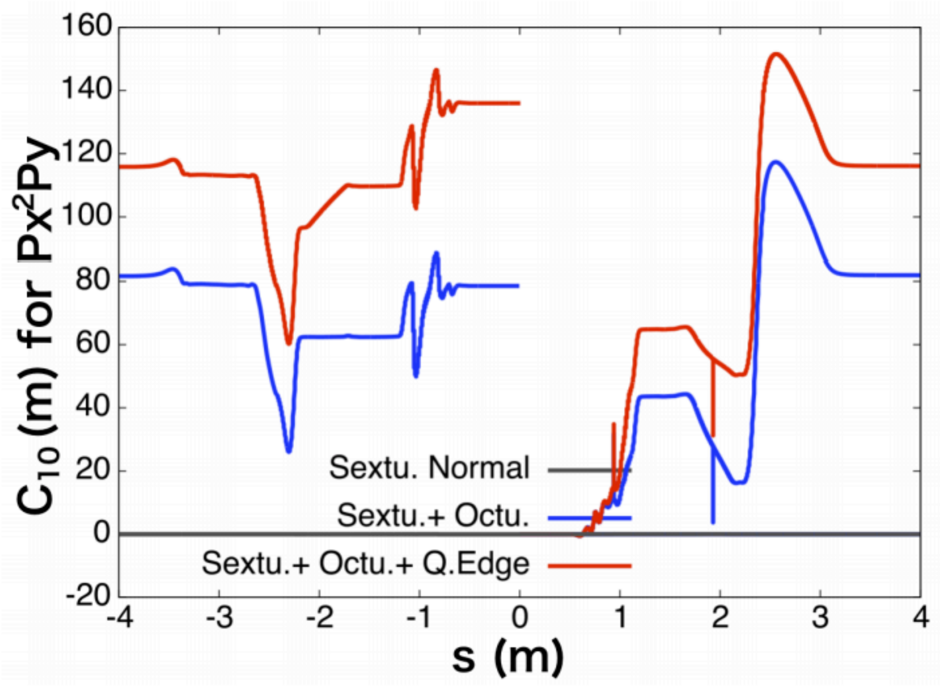


Figure 5: Coefficient of $P_X^2 P_Y$ for sextupole and octupole ($SK_2 + K_3 + SK_3$) and quadrupole hard-edge fringe ($SK_2 + K_3 + SK_3 + Q.edge$) fields.

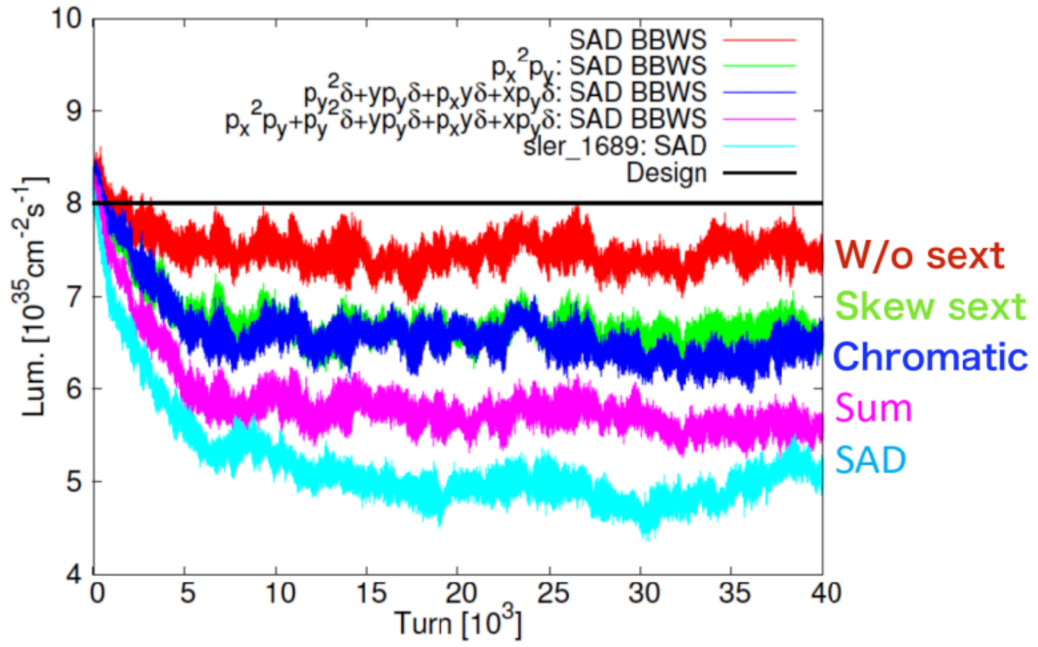
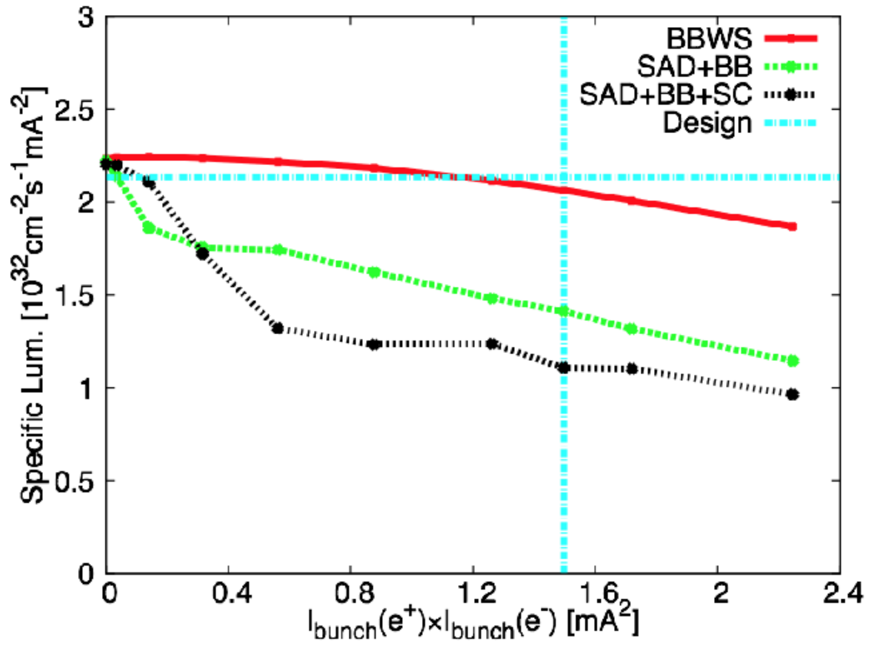
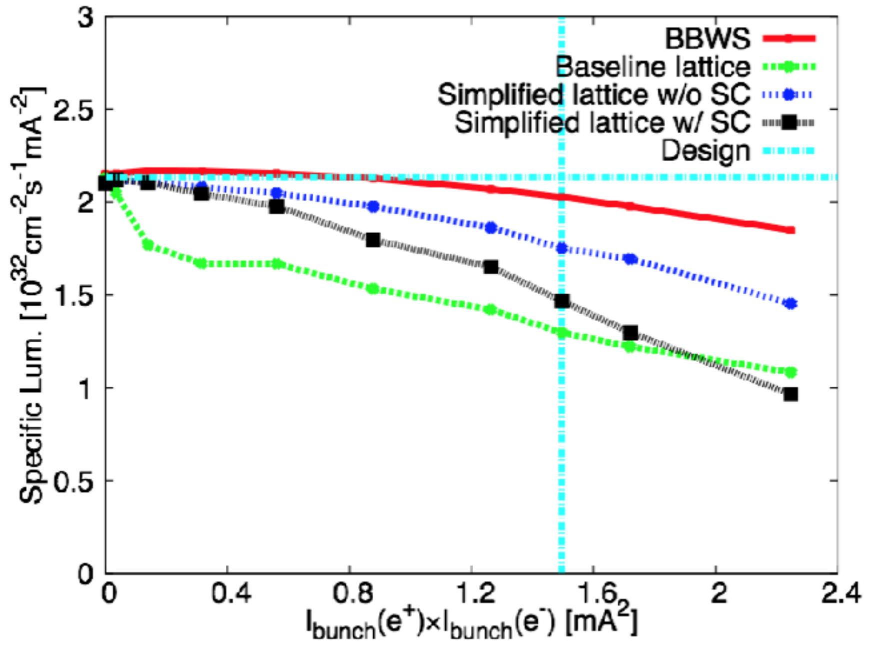


Figure 6: Luminosities for sextupole term (: $P_X^2 P_Y$), chromatic twiss, and SAD.





[1] 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 viewpoints on achieving higher luminosity

- Assume balanced collision: $\beta^*_{y+} = \beta^*_{y-} = \beta^*_y$, $\epsilon_{y+} = \epsilon_{y-} = \epsilon_y$ and the hourglass effect is not strong, we can look into the formula of beam-beam parameter and discuss the challenges
- Note that we have to respect the constraints of real machines.

Beam-beam limit requires:
$\xi_y \leq 0.1$

To keep $\xi_y \leq 0.1$, higher currents requires smaller β^*_y

If we must accept $\xi_y \leq 0.1$, then smaller β^*_y is always preferred

$$\xi^i_{y\pm} \approx \frac{r_e}{2\pi e f_0 \gamma_\pm \tan\frac{\theta_c}{2}} \frac{I_{b\mp}}{\sigma_{z\mp}} \sqrt{\frac{\beta^*_y}{\epsilon_y}}$$

We achieved $\epsilon_{y0} \approx 20$ pm
$\xi_y \leq 0.1$ sets a lower limit on the achievable ϵ_y (at a given β^*_y).
It is not feasible to achieve $\epsilon_y \approx 10$ pm at $\beta^*_y = 1$ mm

Crossing angle:
1) IR layout (constraints from optics design)
2) Reducing θ_c does not create a gain of luminosity if there the beam-beam limit exists.

Impedance effects
Longer σ_{z0} can be beneficial

Beam-beam viewpoints on achieving higher luminosity

- Specific luminosity only depends on the geometric parameters (beam sizes and crossing angle).

We achieved ~9×10^{31} cm^{-2}s^{-1}mA^{-2} with $\beta_y^* = 1$ mm
The baseline design is ~21×10^{31} cm^{-2}s^{-1}mA^{-2}

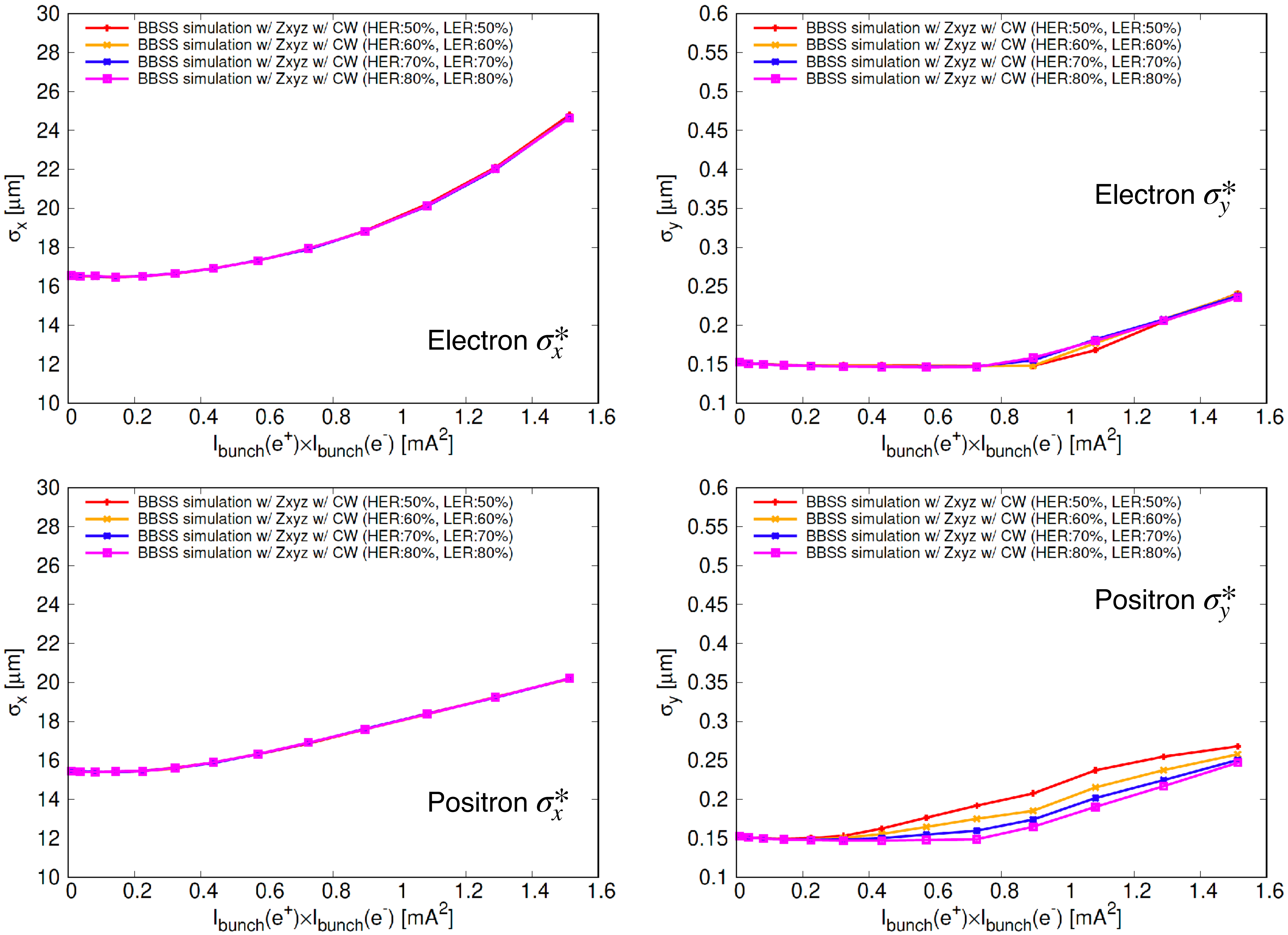
$$\boxed{L_{sp}} \approx \frac{1}{2\pi e^2 f \sqrt{\boxed{\sigma_{y+}^{*2} + \sigma_{y-}^{*2}}} \sqrt{\boxed{\sigma_{z+}^2 + \sigma_{z-}^2}} \tan\frac{\theta_c}{2}}$$

The fundamental limit lies in vertical beam sizes
Challenges: High currents, beam-beam, crab waist, lattice imperfections, …

Impedance effects
modify the synchrotron motion,
indirectly playing a role in many issues

Beam-beam simulations for post-LS1 operation (1E35 luminosity)

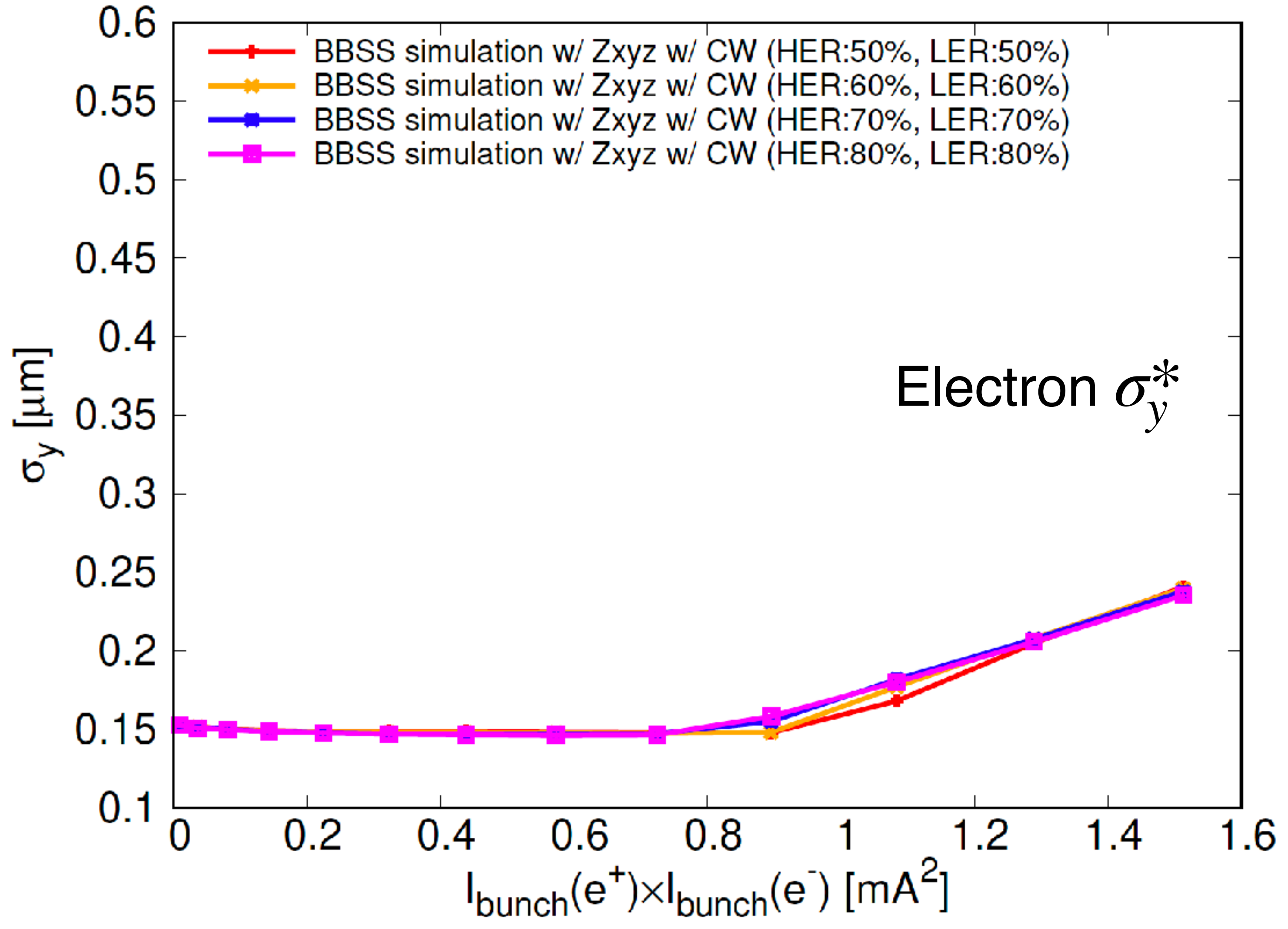
- BBSS simulations: Scan bunch currents (keeping bunch current ratio)
- Horizontal blowup is from X-Z coupling (NOT X-Z instability) driven by beam-beam with a horizontal crossing angle. It depends on ν_x.
  - Analytic theory is possible for estimate of horizontal blowup
- Vertical blowup is from two effects: 5th-order X-Y resonances (X-Y coupling) and TMCI (Y-Z coupling). The TMCI (with a clear threshold) can be seen when the crab waist suppresses X-Y resonances.

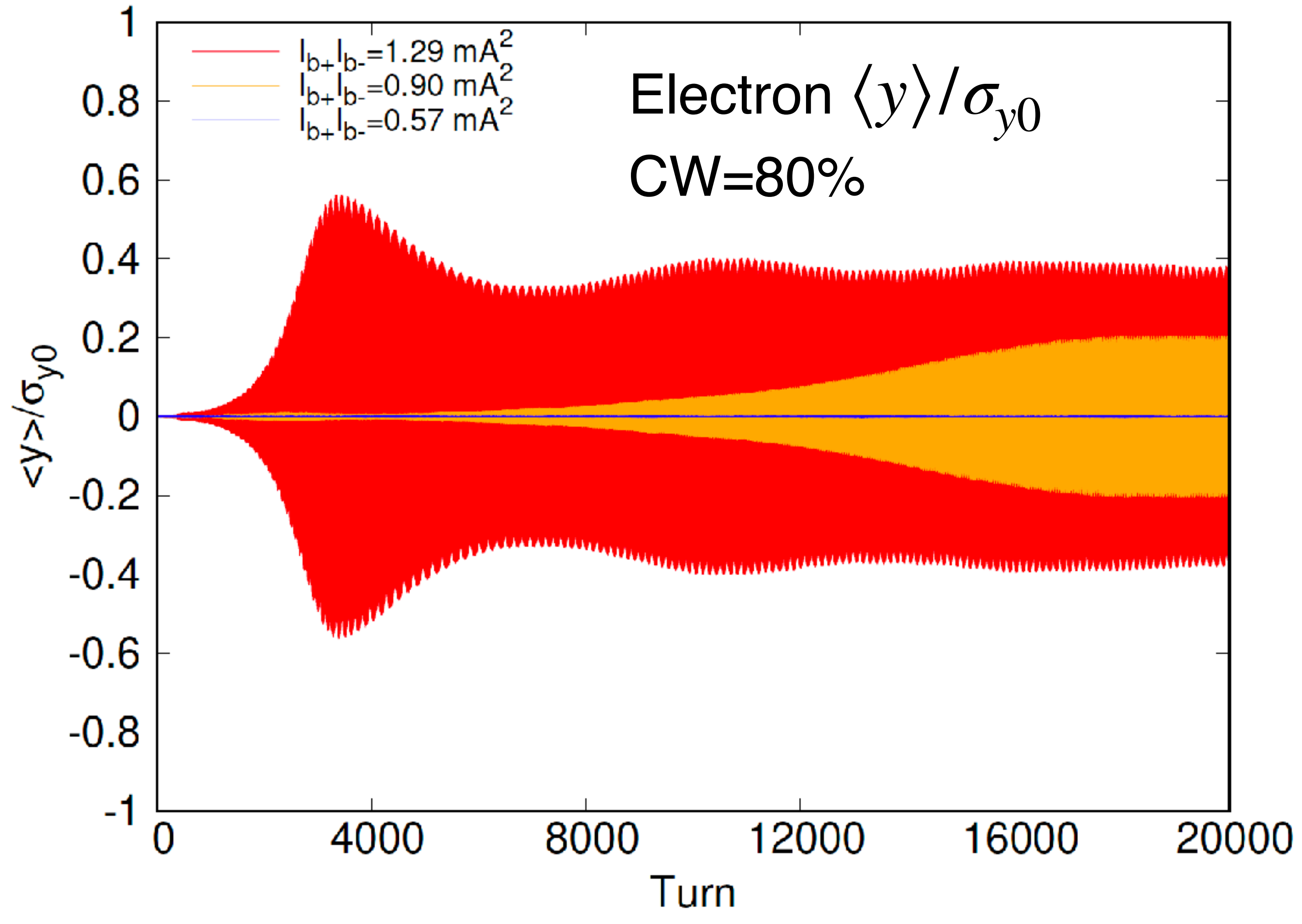


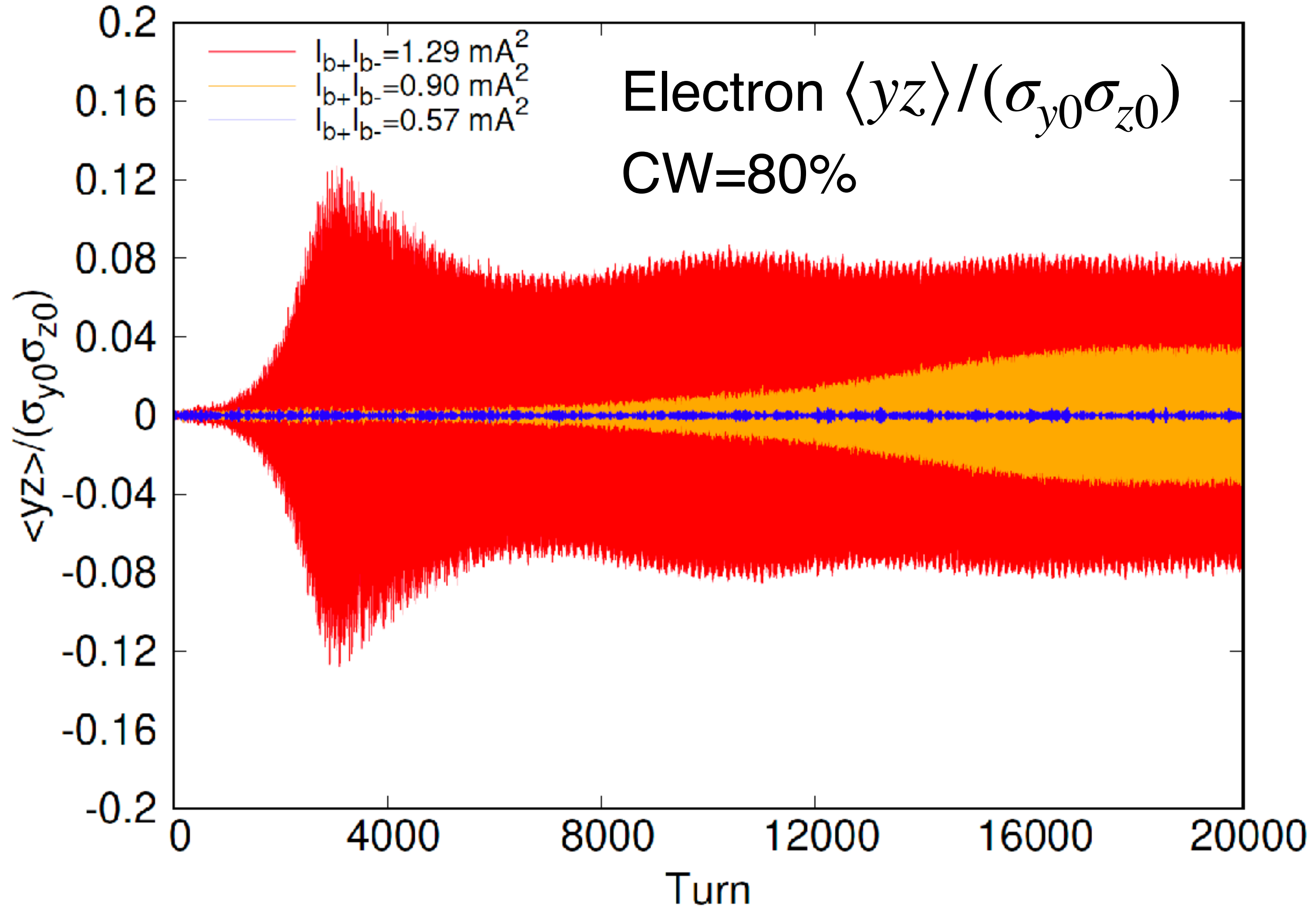
Beam-beam simulations for post-LS1 operation (1E35 luminosity)

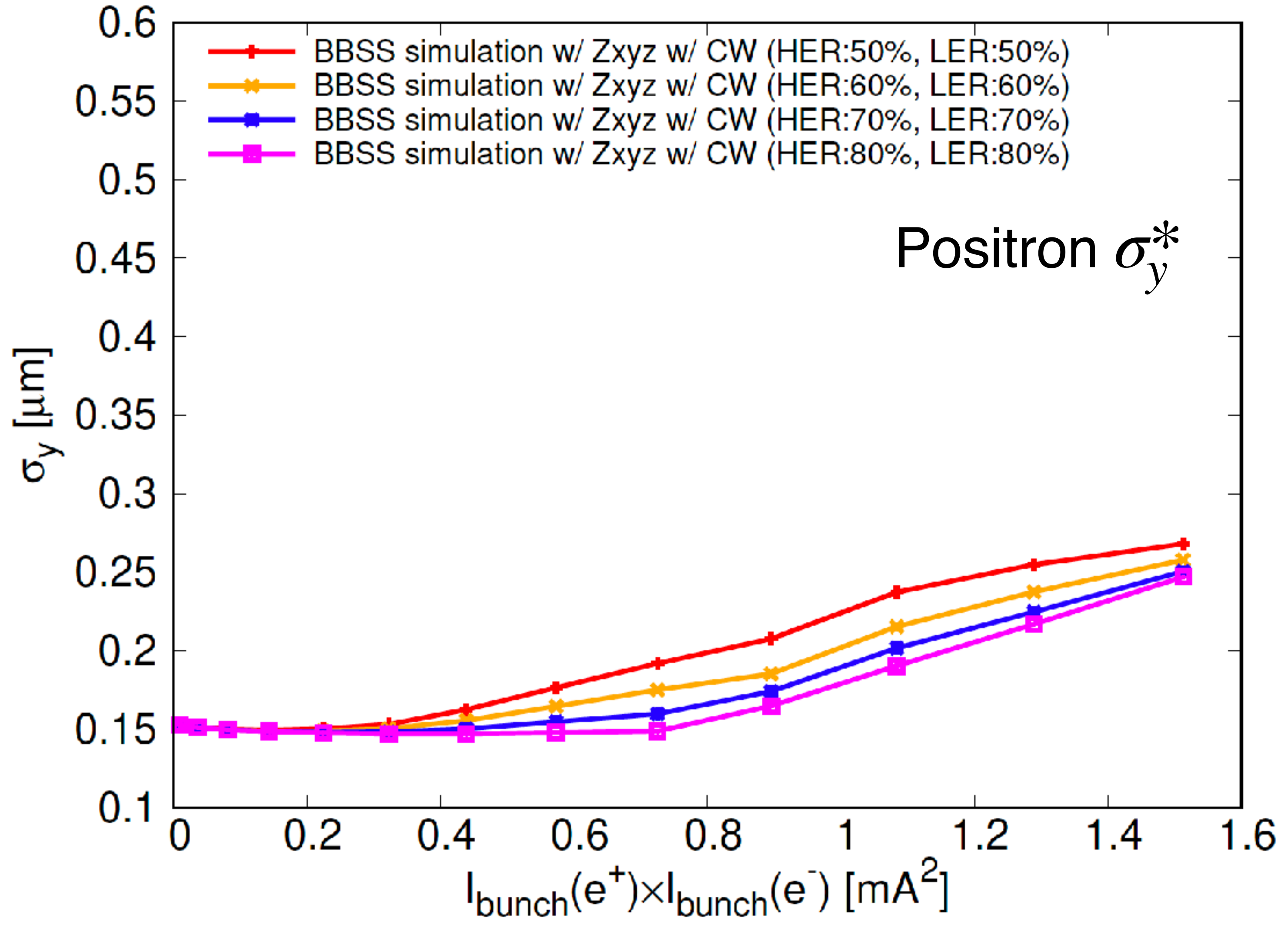
Question:
Does Ohmi-san's theory show a well-defined TMCI threshold, depending on β_y^* and ν_y?

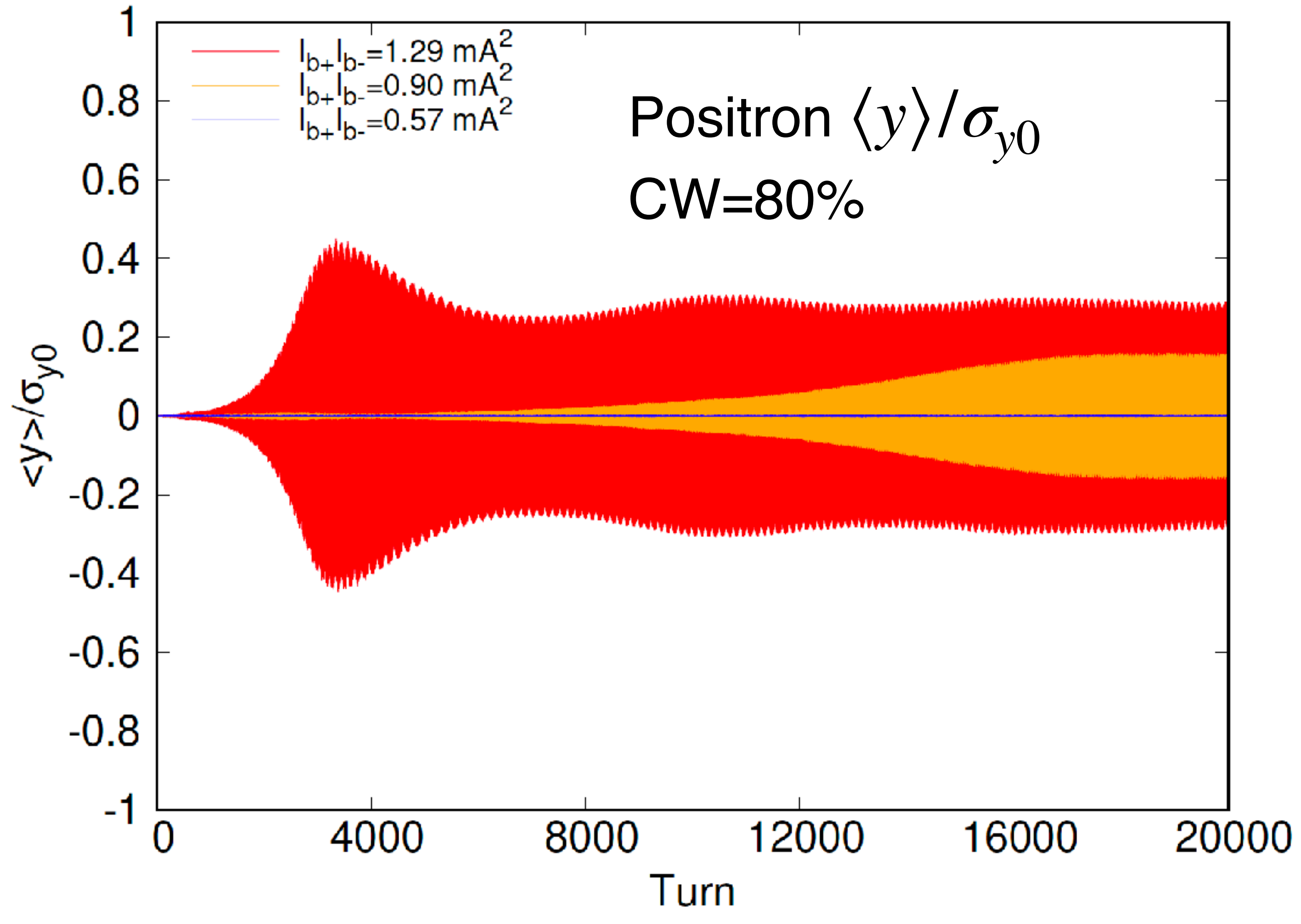
- BBSS simulations: Vertical emittance growth
- With CW, TMCI appears above the threshold bunch currents. Clear TMCI threshold is seen when beam-beam resonances are suppressed.

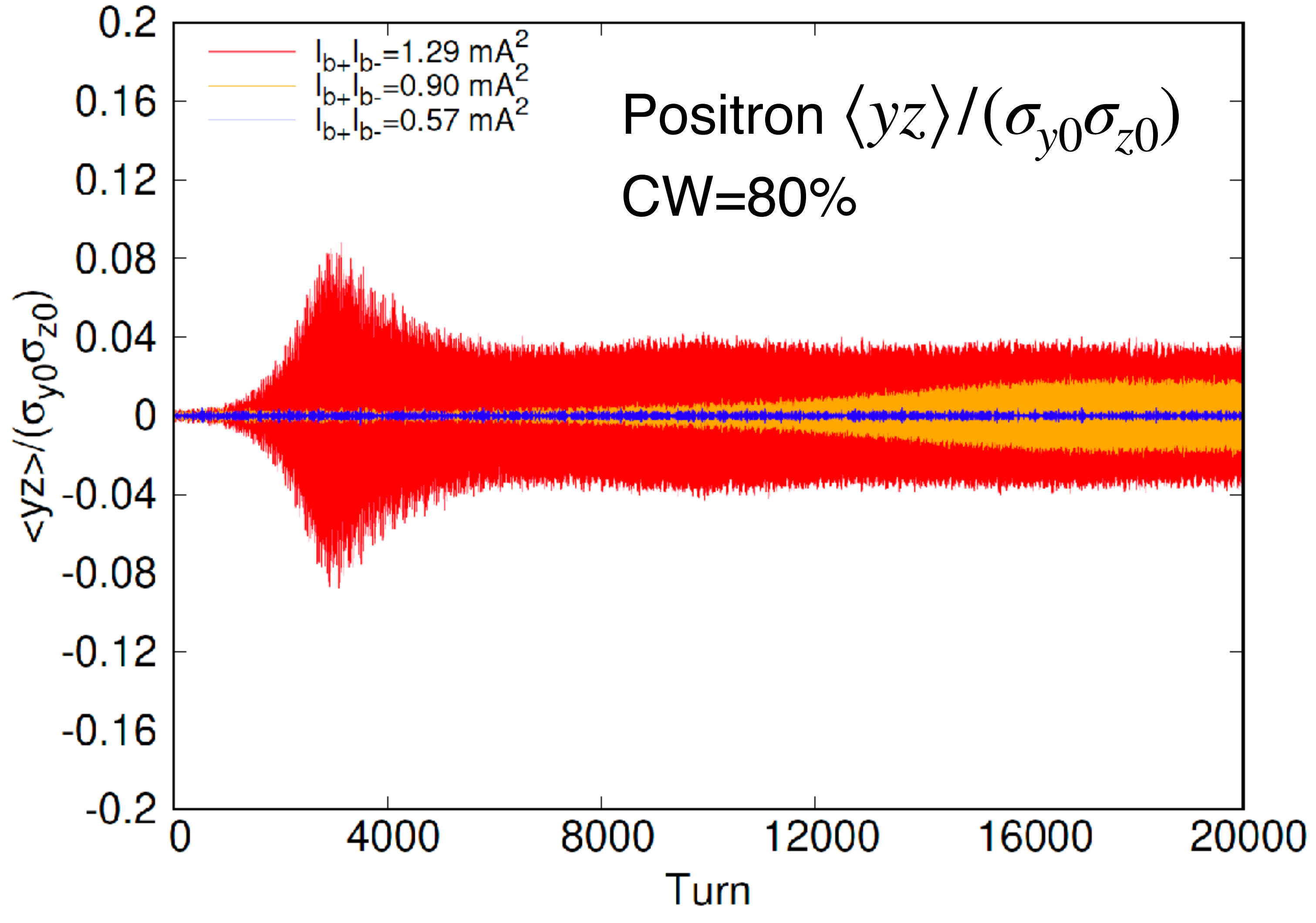






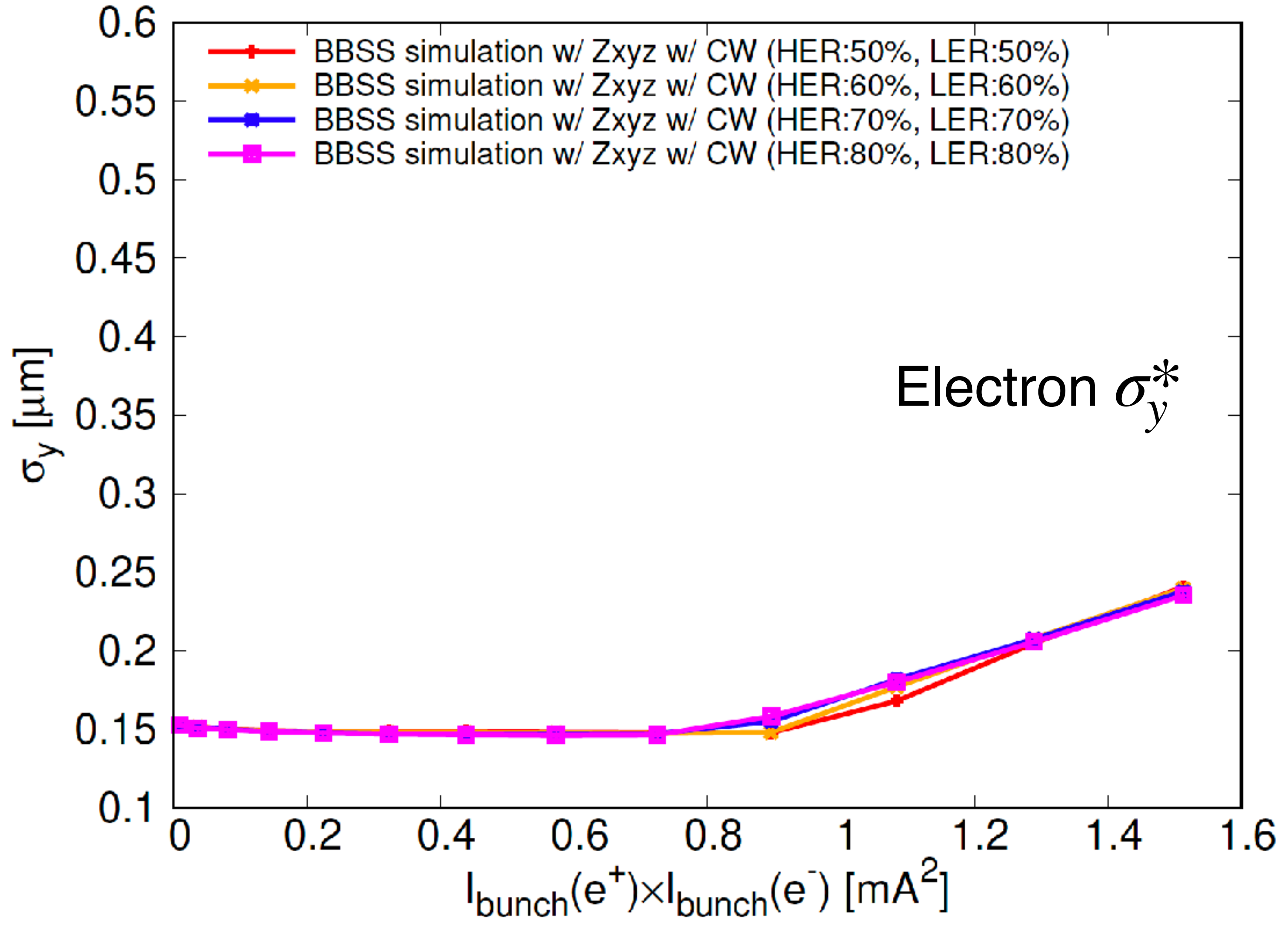


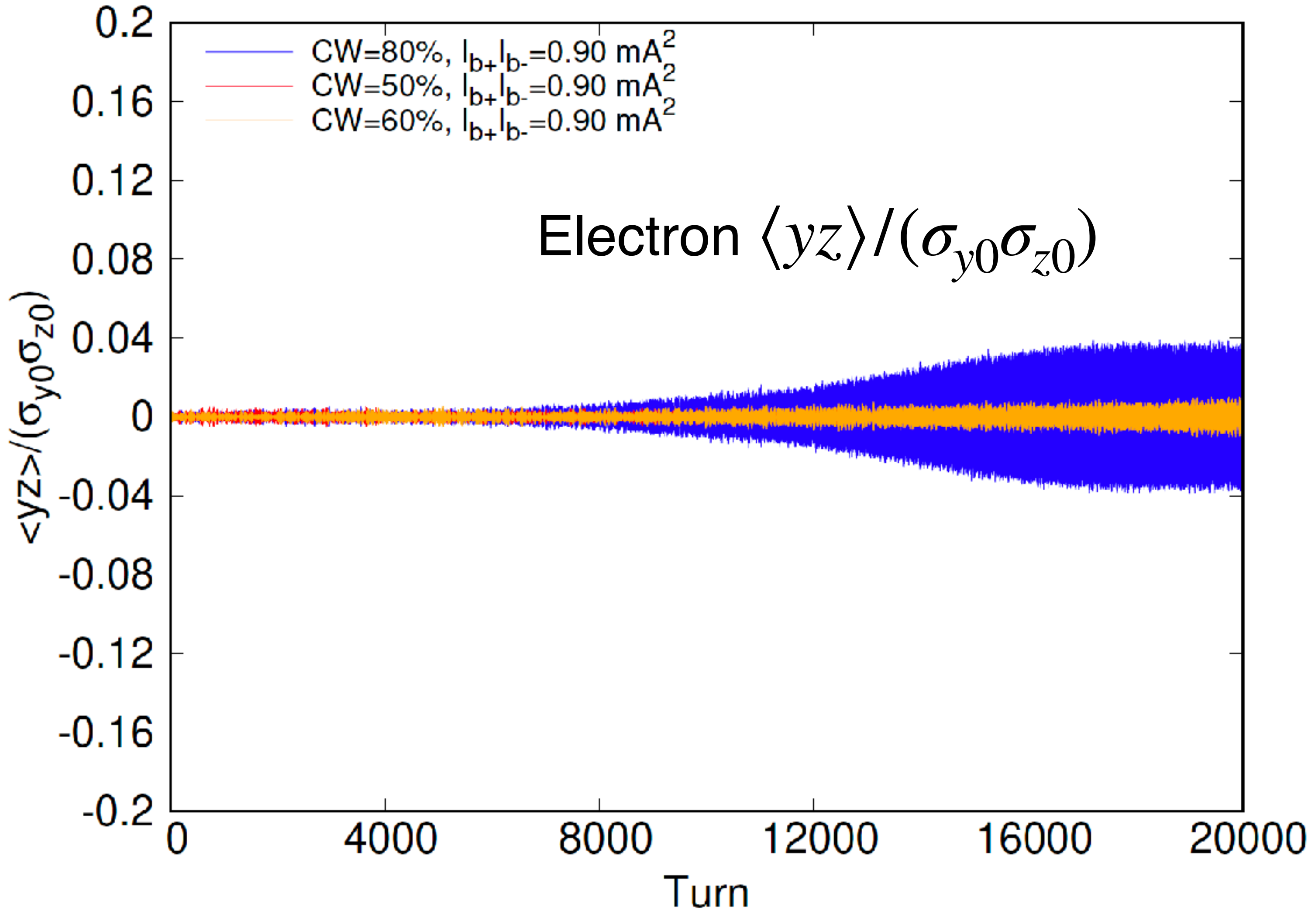


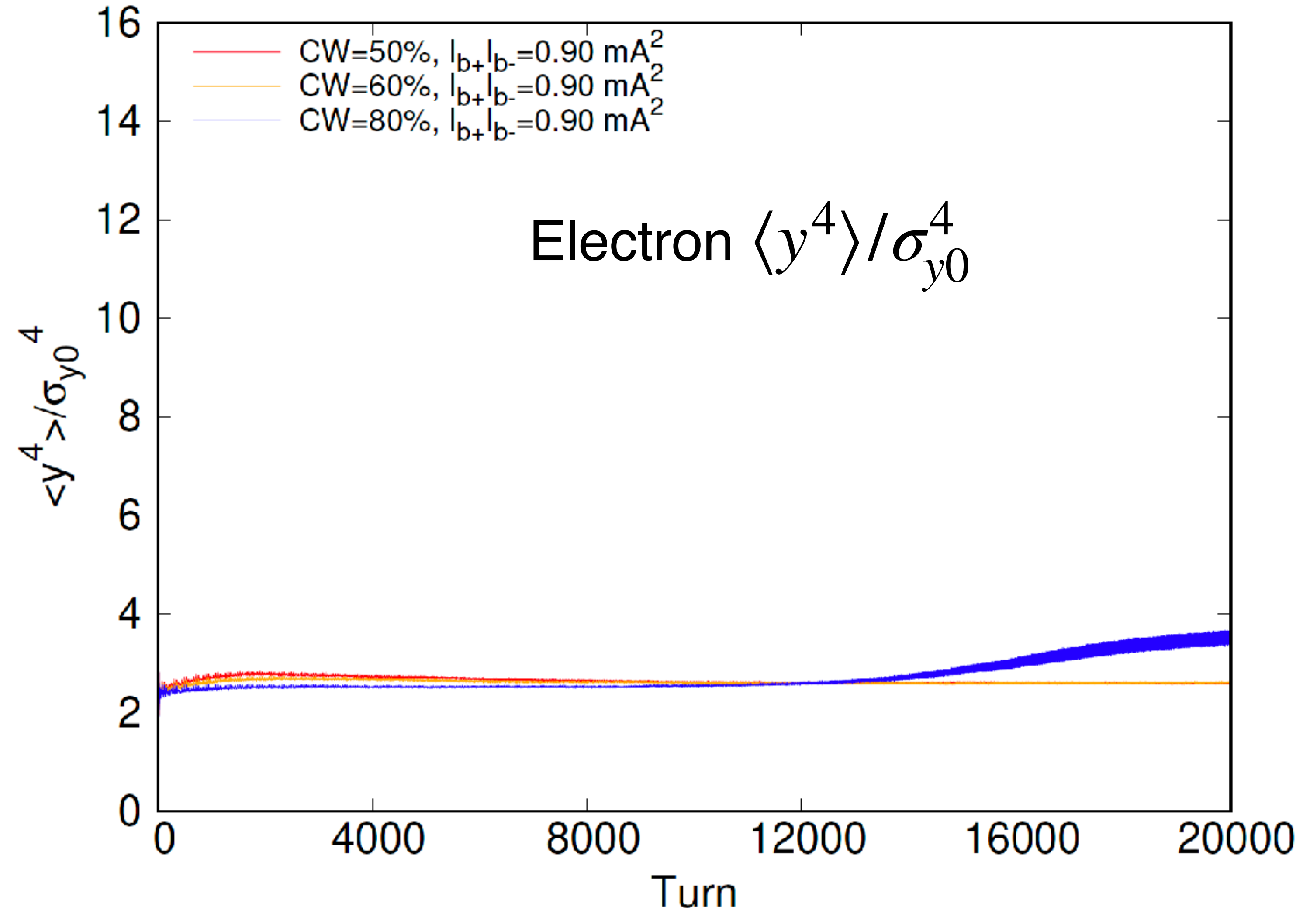


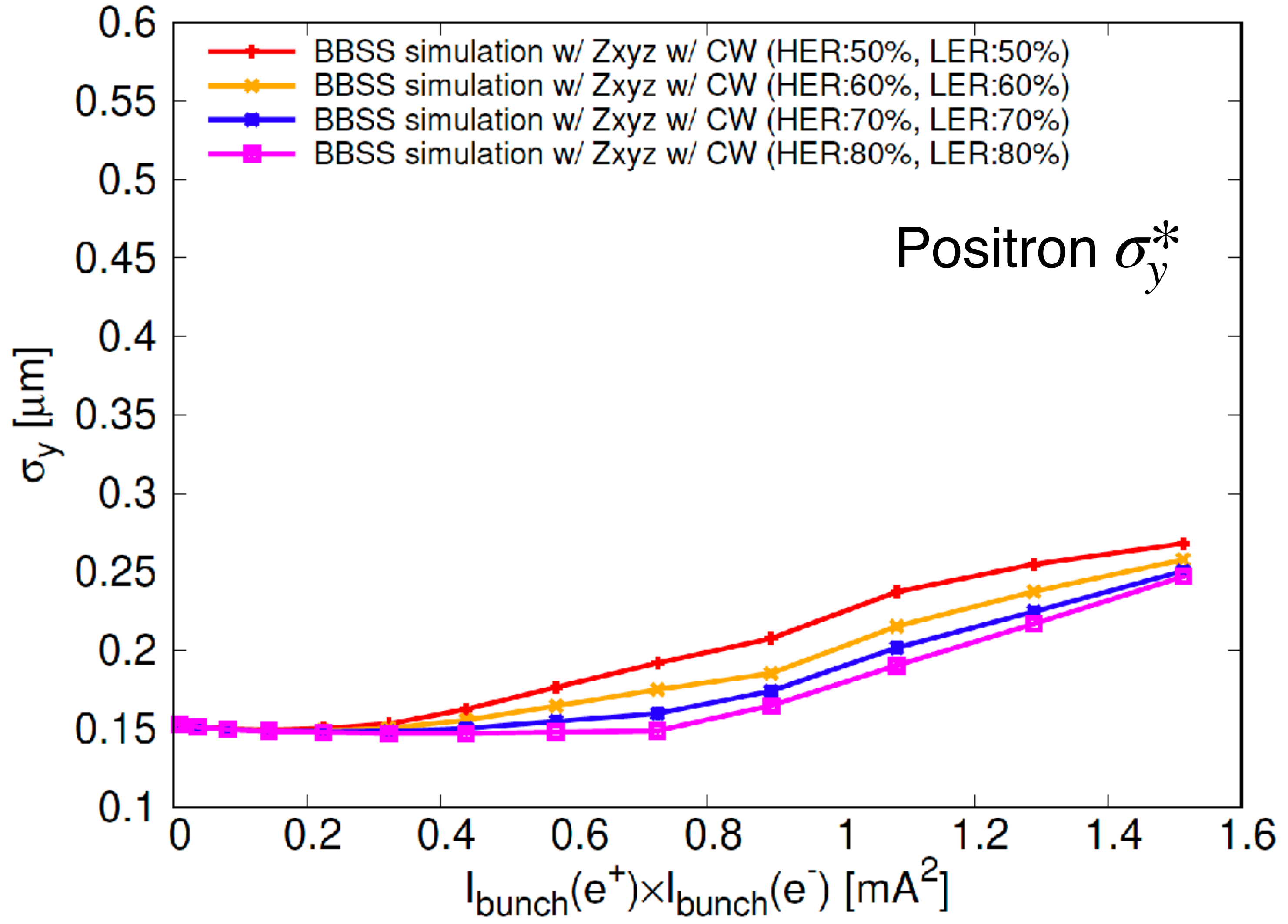
Beam-beam simulations for post-LS1 operation (1E35 luminosity)

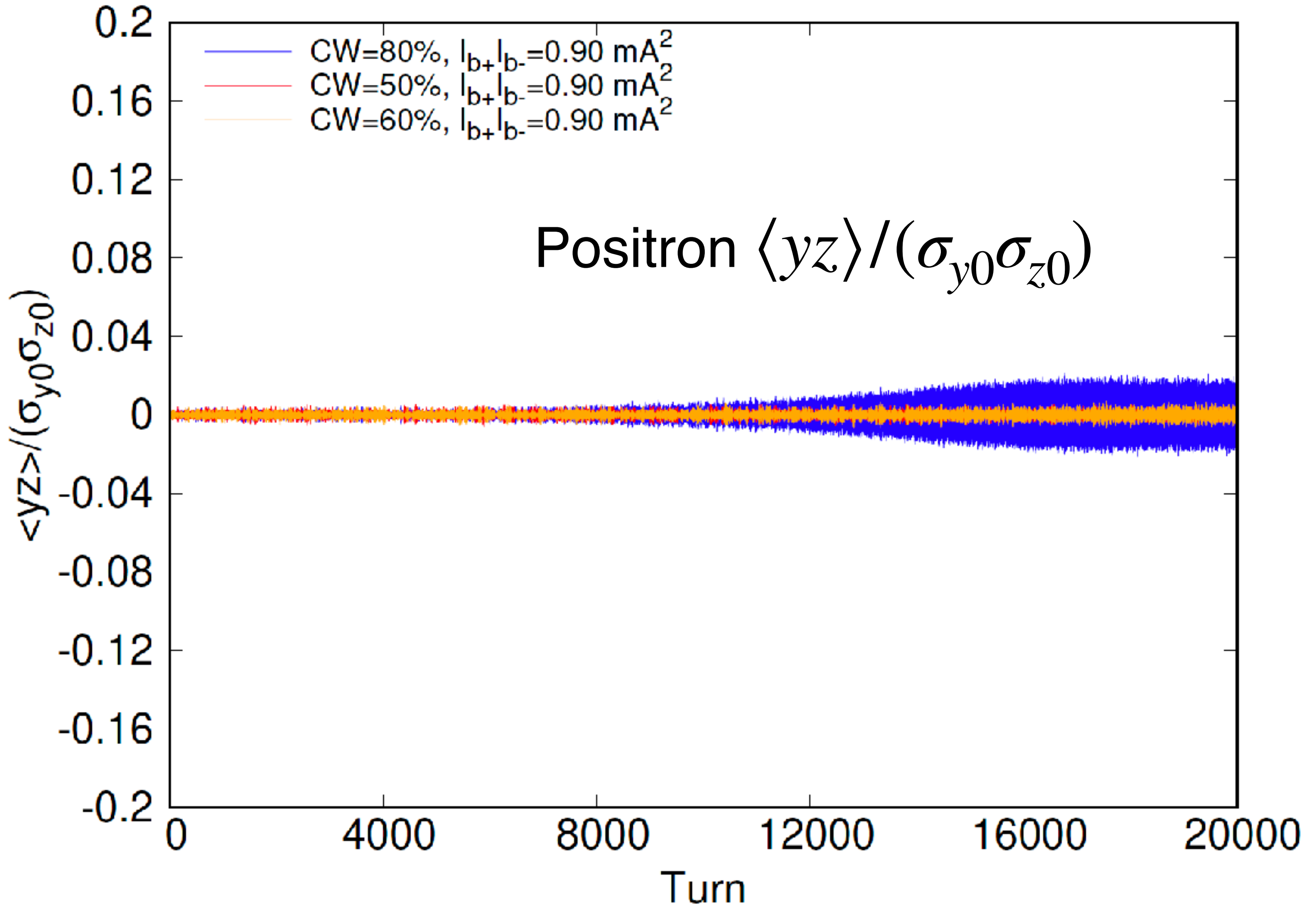
- BBSS simulations: Vertical emittance growth
- TMCI-like instability (two-beam instability?): Coherent motion seen in $\langle yz \rangle$. Beam-beam resonances: Incoherent motion (?) seen in $\langle xy^4 \rangle$ (also $\langle y^4 \rangle$)

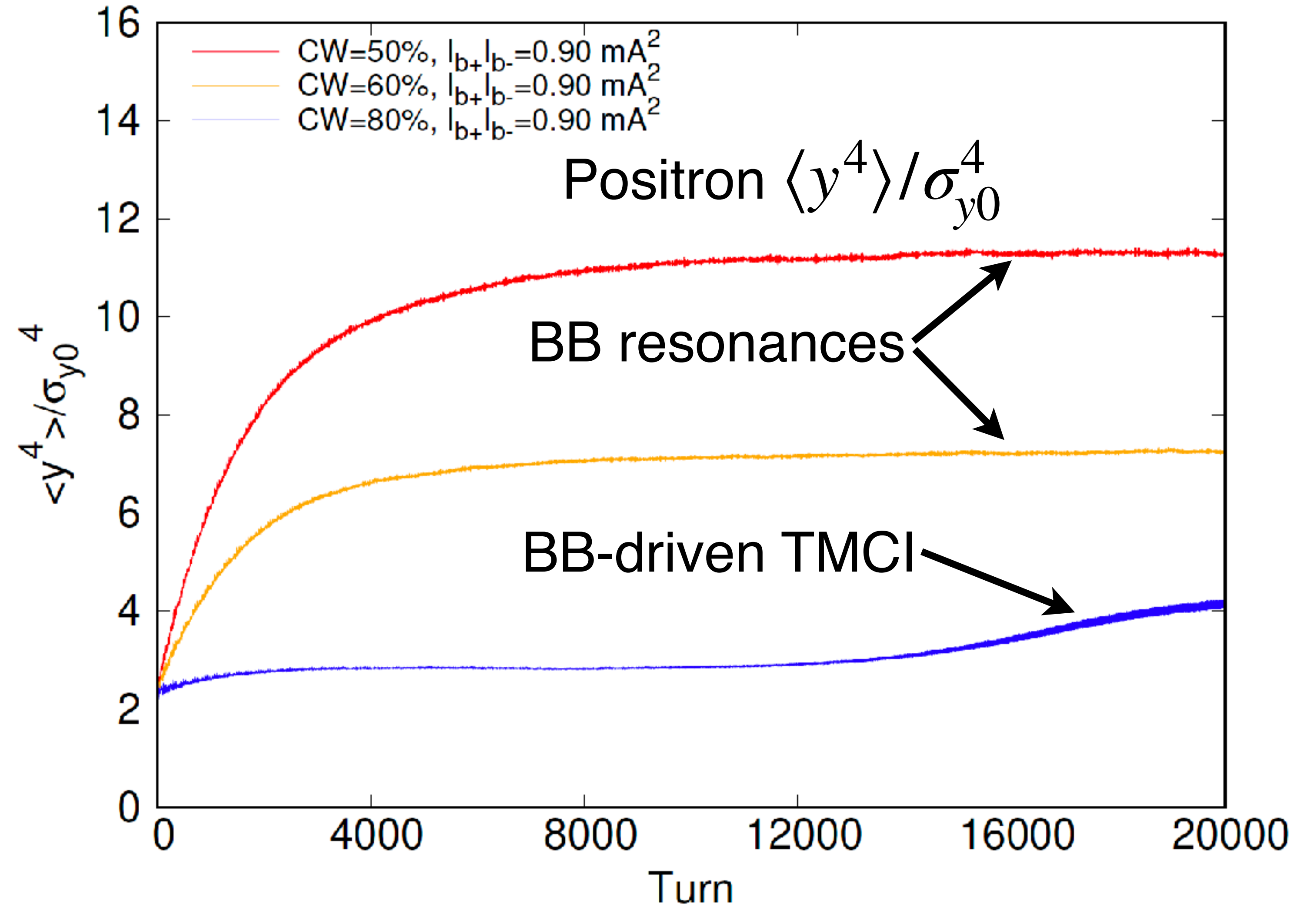






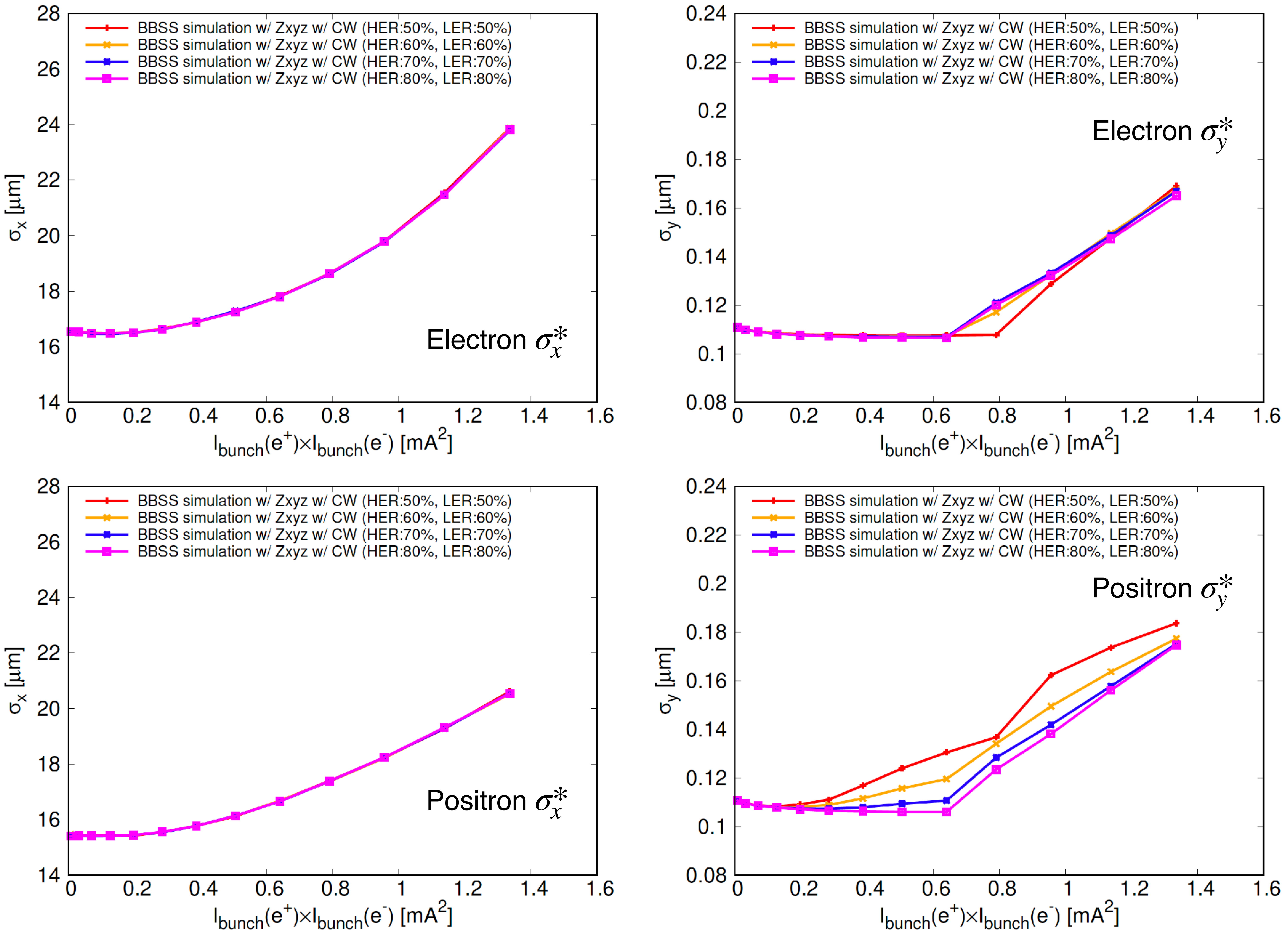






Beam-beam simulations for post-LS1 operation (2.4E35 luminosity)

- BBSS simulations: Scan bunch currents (keeping bunch current ratio)
- Horizontal blowup is from X-Z coupling (NOT X-Z instability) driven by beam-beam with a horizontal crossing angle. It depends on ν_x.
- Vertical blowup is from two effects: 5th-order X-Y resonances (X-Y coupling) and TMCI (Y-Z coupling). The TMCI (with a clear threshold) can be seen when the crab waist suppresses X-Y resonances.

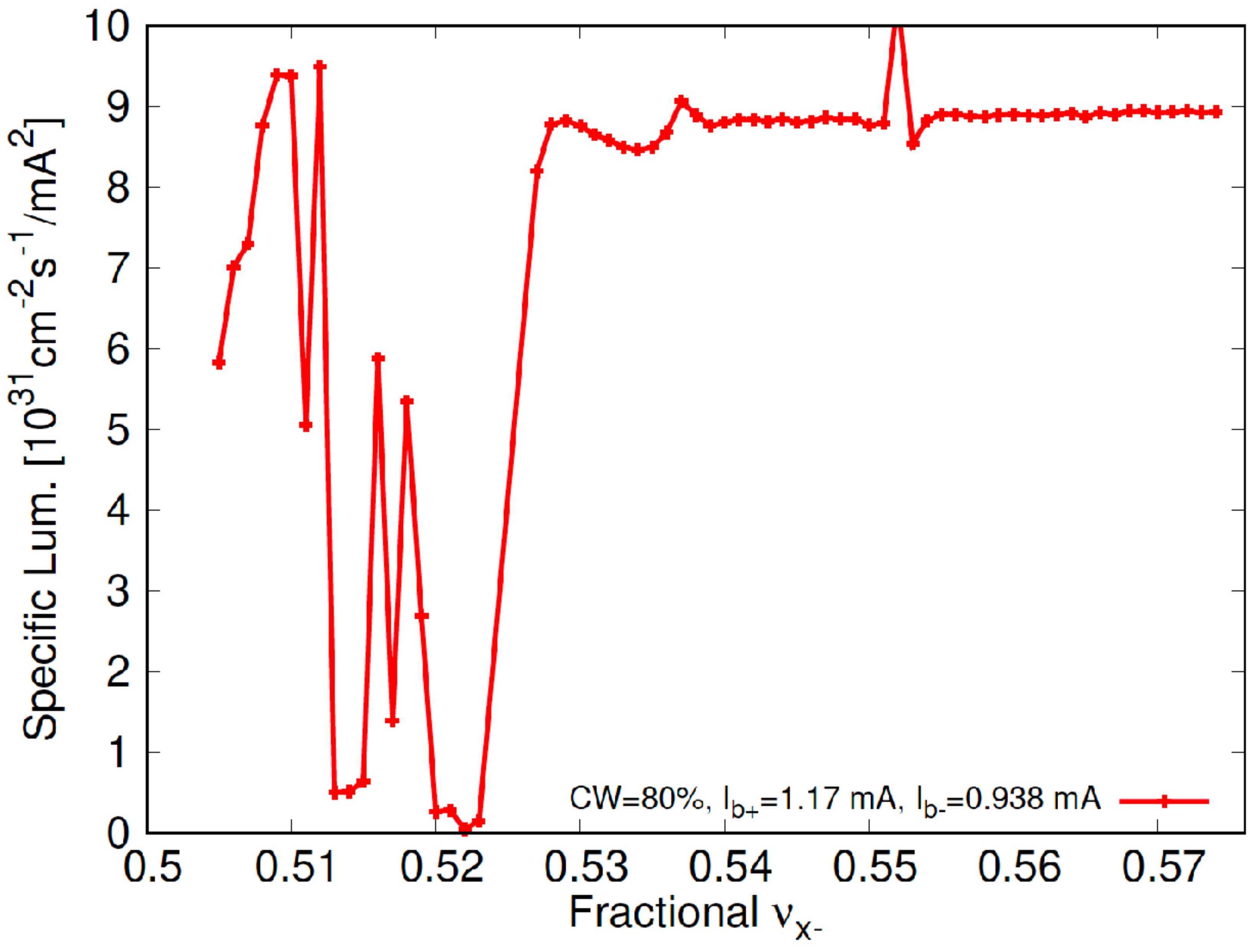


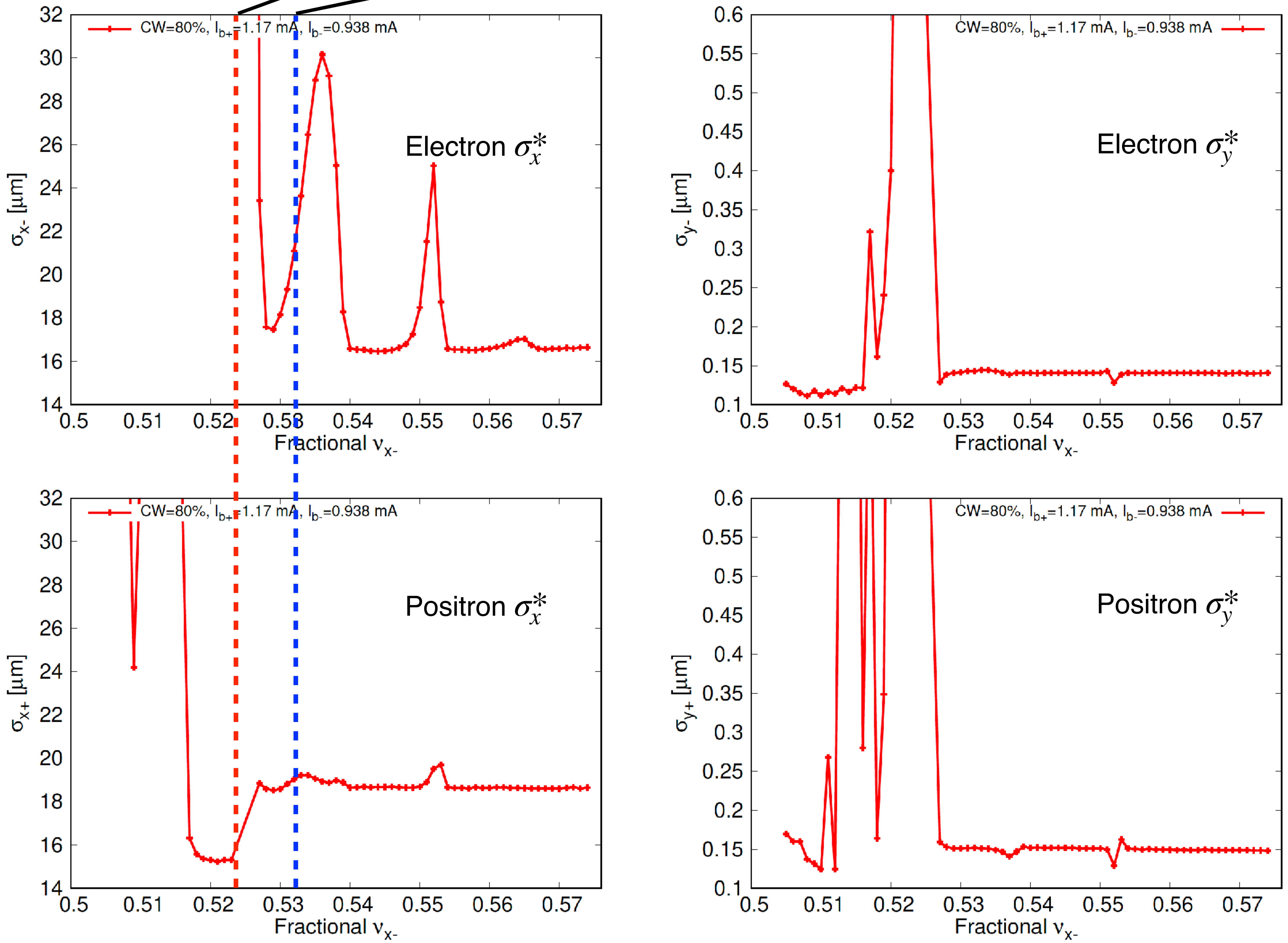
Beam-beam simulations for post-LS1 operation (2.4E35 luminosity)

- BBSS simulations: Scan of HER ν_x (with LER ν_x=44.524)
- HER Fractional[ν_x]>.54 seems good for avoiding horizontal blowup.

2022ab (and simulation) choice $[\nu_{x+}] = 0.524$ (LER)

2022ab choice $[\nu_{x-}] = 0.532$ (HER)





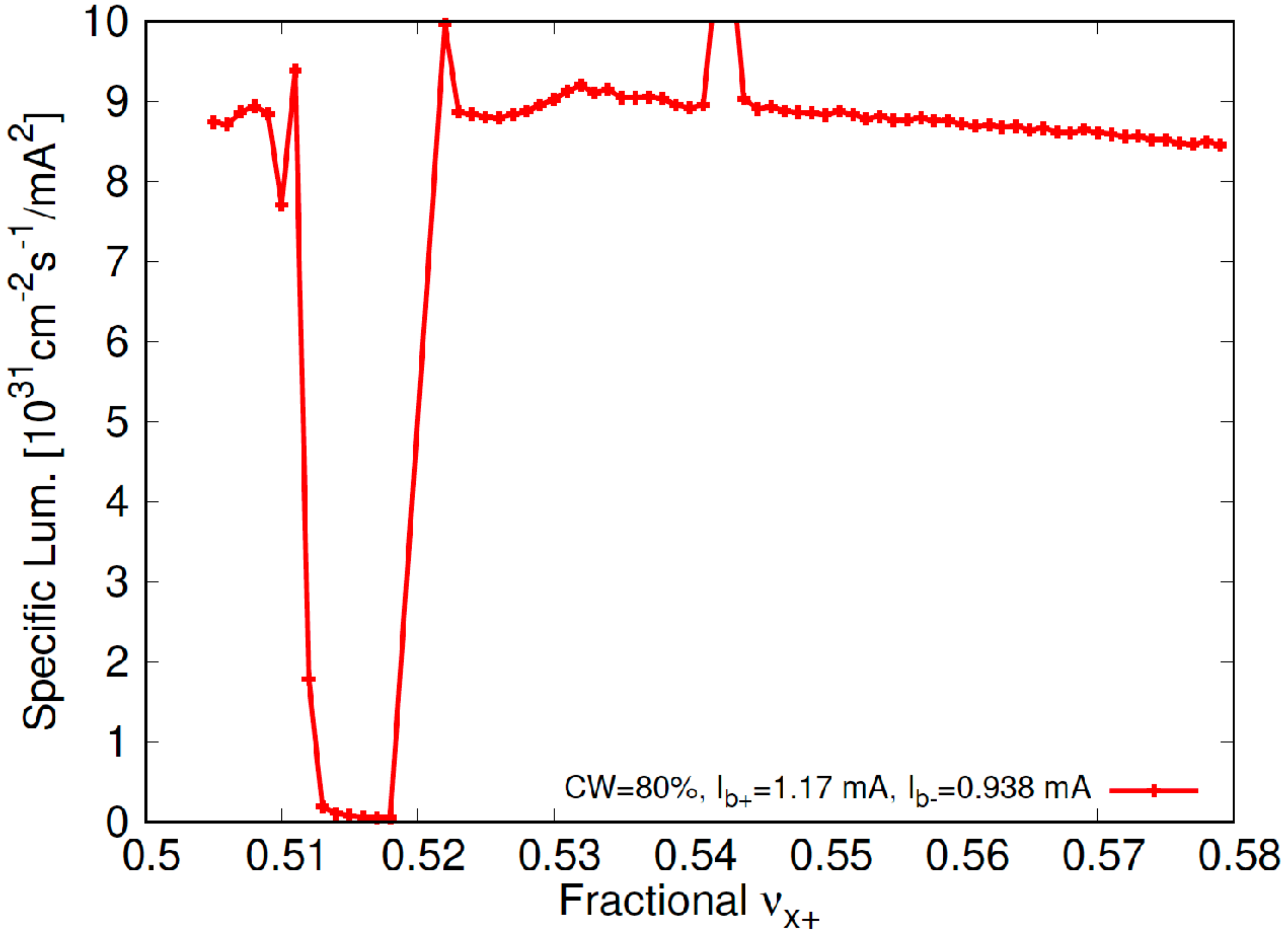
Warning messages:
* Horizontal blowup does not cause luminosity loss if it does not excite the vertical blowup. But we cannot conclude it's not dangerous to machine operation.
* BB-driven horizontal blowup (including beam tail) will be amplified by lattice nonlinearity and eventually cause troubles to beam lifetime, injection efficiency, detector background, etc.

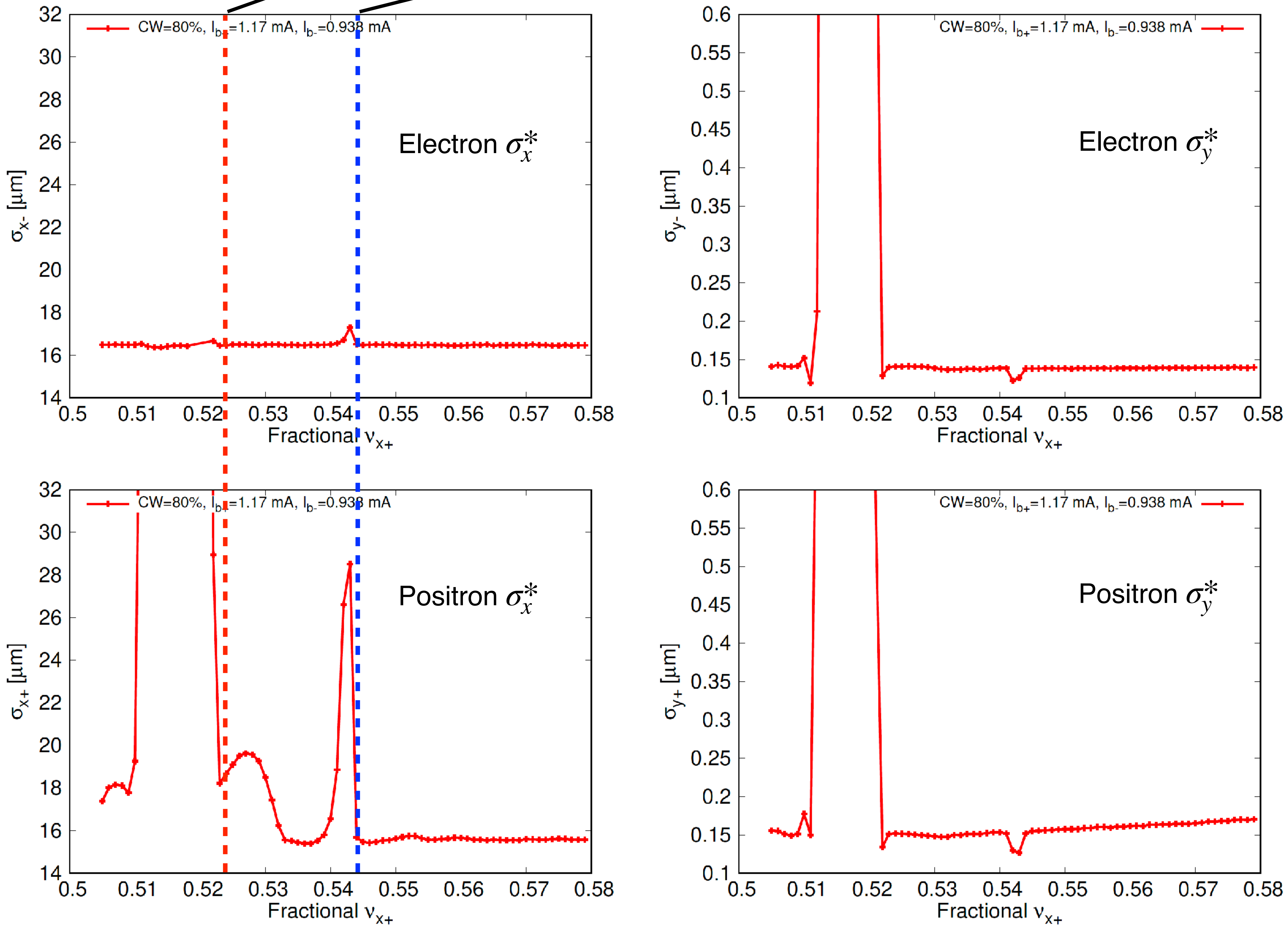
Beam-beam simulations for post-LS1 operation (2.4E35 luminosity)

- BBSS simulations: Scan of LER ν_x (with HER ν_x=44.544)
- LER Fractional[ν_x]>.545 seems good for avoiding horizontal blowup.

2022ab choice $[\nu_{x+}] = 0.524$ (LER)

Simulation choice $[\nu_{x-}] = 0.544$ (HER)





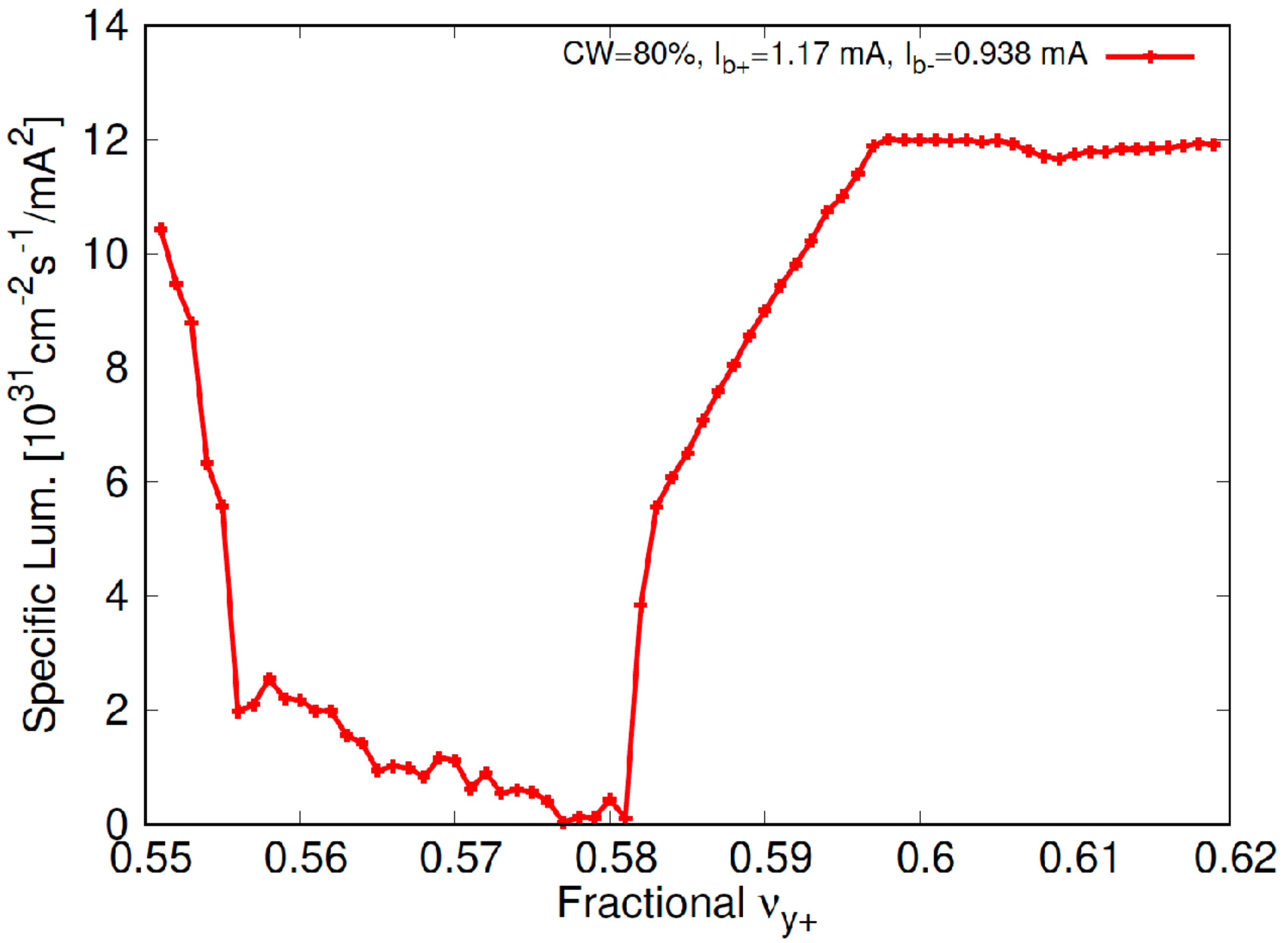
Warning messages:
* Horizontal blowup does not cause luminosity loss if it does not excite the vertical blowup. But we cannot conclude it's not dangerous to machine operation.
* BB-driven horizontal blowup (including beam tail) will be amplified by lattice nonlinearity and eventually cause troubles to beam lifetime, injection efficiency, detector background, etc.

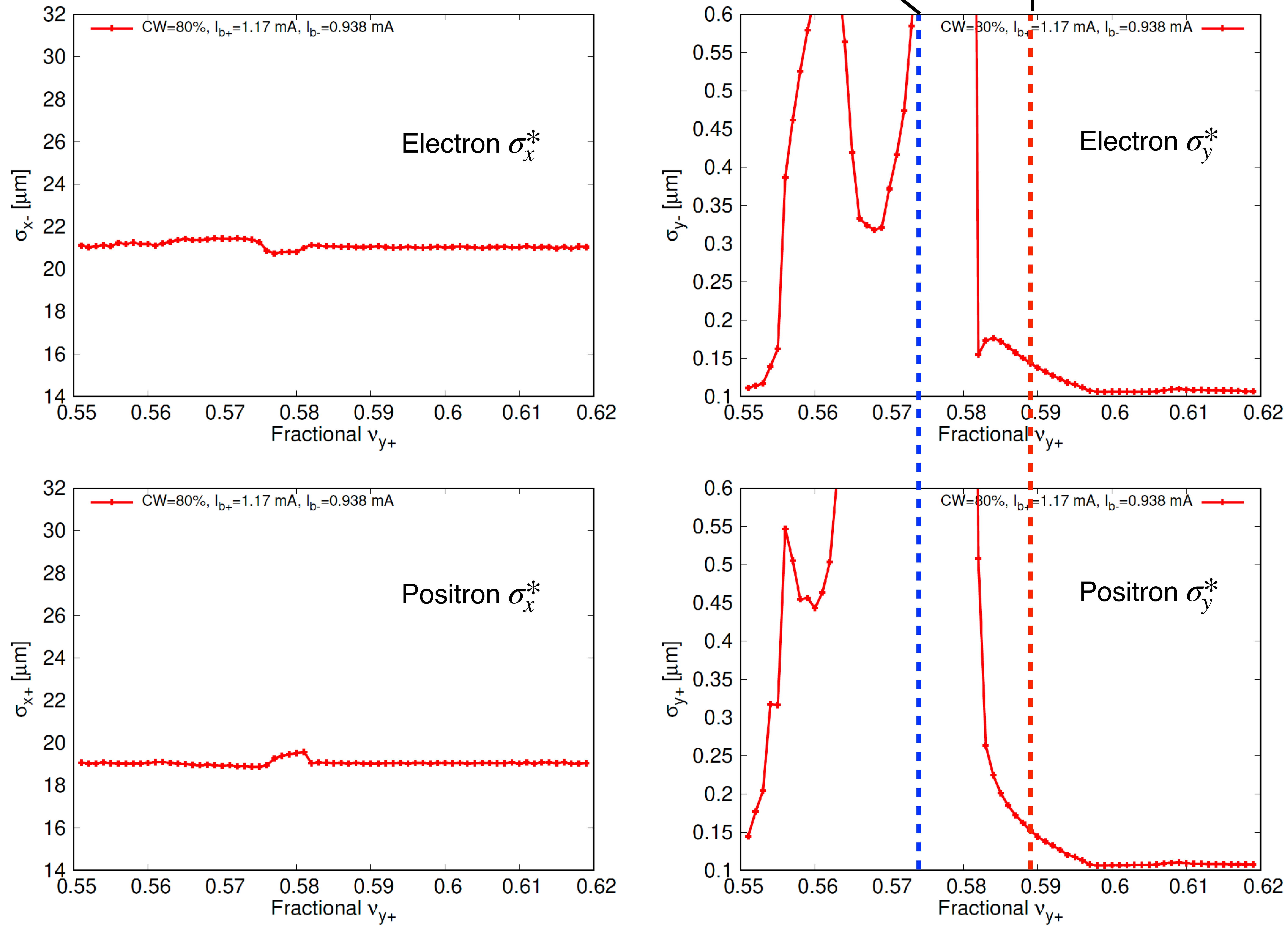
Beam-beam simulations for post-LS1 operation (2.4E35 luminosity)

2022ab choice $[\nu_{y+}] = 0.589$ (LER)

Simulation choice $[\nu_{y-}] = 0.574$ (HER)

- BBSS simulations: Scan of LER ν_y (with HER ν_y=43.574)
- LER Fractional $[\nu_y]$ has to be high enough to avoid TMCI instability.

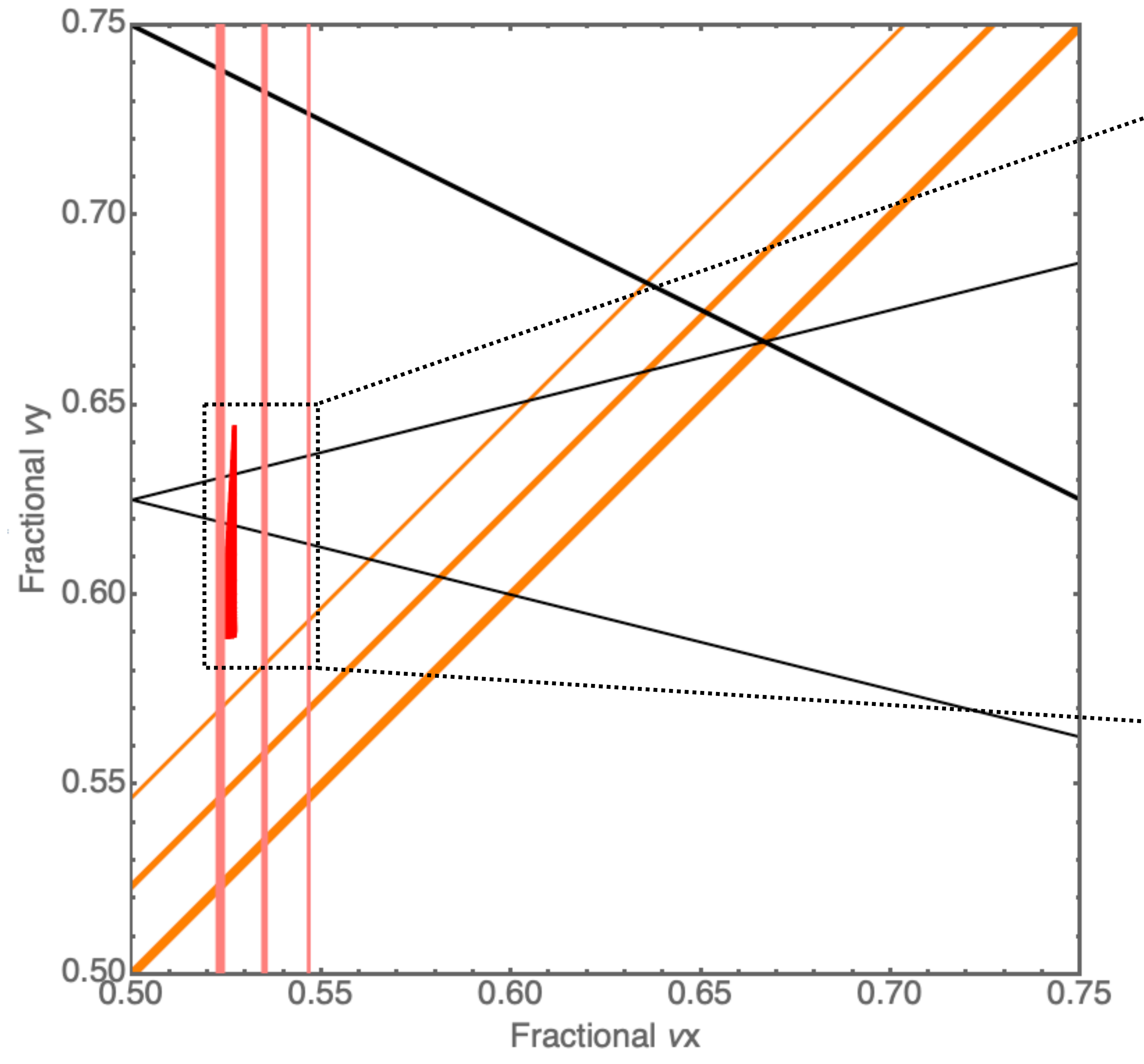


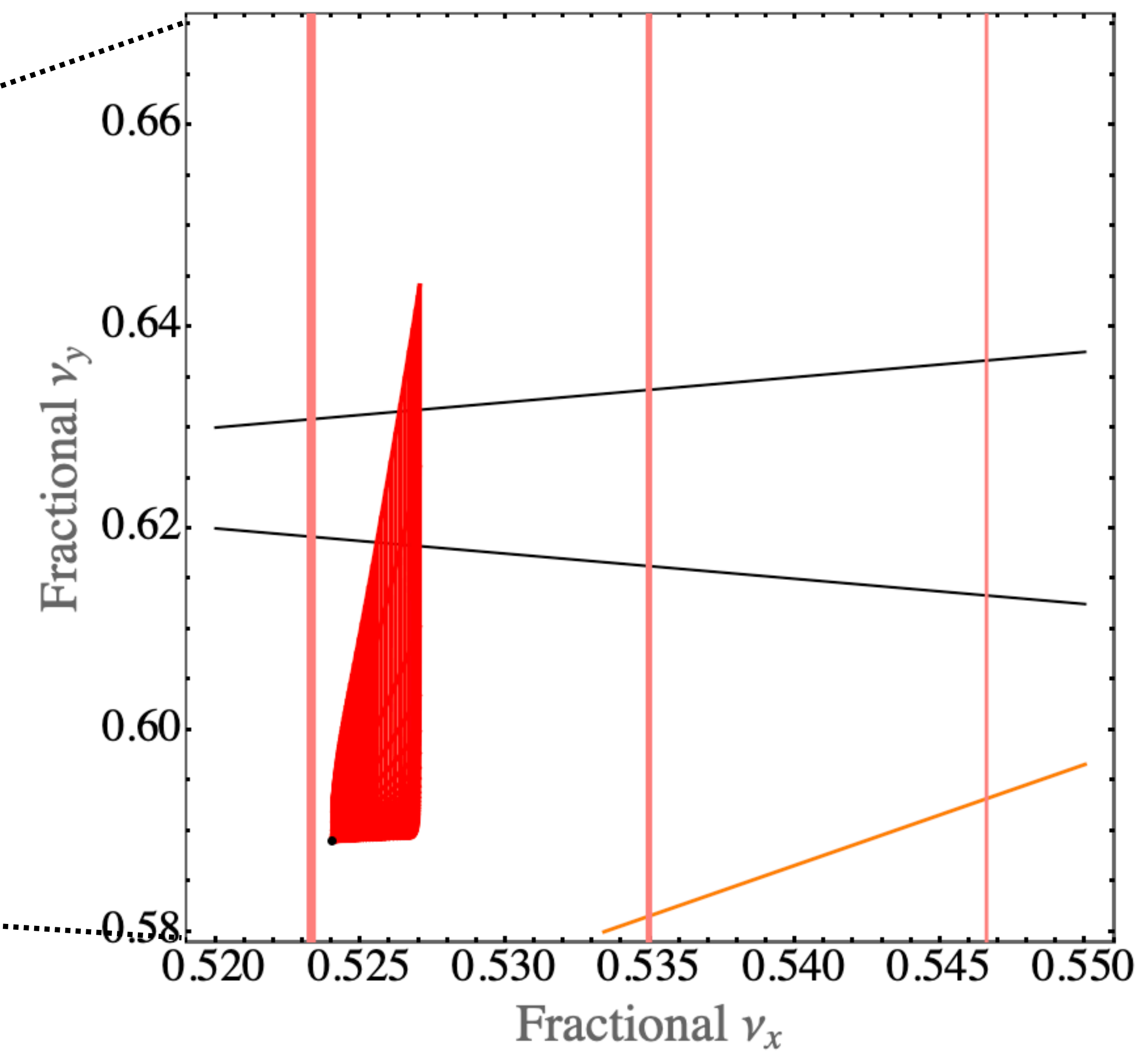


Warning messages:
* Lattice couplings (linear and chromatic couplings, higher-order couplings) affect choice of ν_y.
* ν_y cannot be too close to chromatic coupling resonances.
* $[\nu_y] > 0.6$ seems not good from operational experience.

Discussion

- Comments:
  - Simulations show complicated phenomena, even only beam-beam and impedances are used.
  - The real machine show super complicated phenomena (two colorful to distinguish multiple physics).
  - A typical process of understanding the machine: Simulations → Experiments → Theories → …
  - Tunes (ν_x, ν_y, ν_s) are the keys to understand the important physics at SuperKEKB.
  - The footprint of the beam in tune space can be stretched by nonlinear lattice, beam-beam force, wakefields, …The stretching from collective effects scales as bunch current. The stretching from nonlinear lattice scales as $1/\beta_y^*$.





Footprint only by beam-beam