# Beam-beam effects at SuperKEKB: simulations and experimental results

Demin Zhou

Accelerator theory group, Accelerator laboratory, KEK

Acknowledgments

K. Ohmi, Y. Zhang, Y. Ohnishi, Y. Funakoshi, J. Tang,
SuperKEKB commissioning team,
SuperKEKB ITF (K. Oide, D. Shatilov, M. Zobov,
T. Nakamura, T. Browder, Y. Cai, C. Lin, et al.)

The 2024 International Workshop on Future Tau Charm Facilities,
Jan. 16, 2024, USTC, Hefei, China

# Outline

- Introduction
- Beam-beam simulations
- Comparison of simulations and experimental results
- Summary

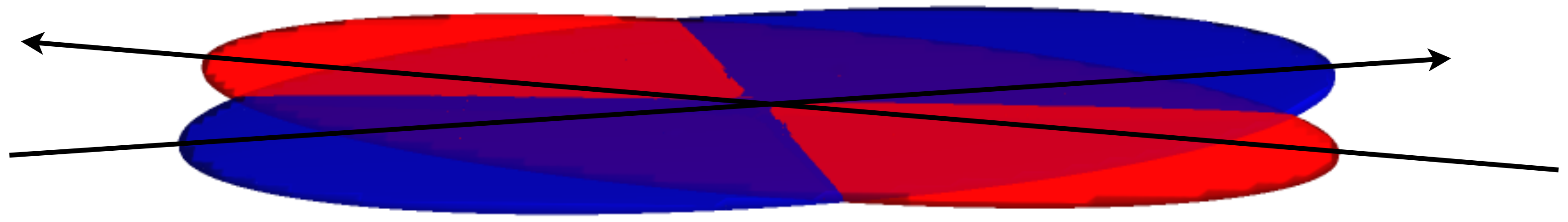
# Introduction

- Collision scheme (KEKB → SuperKEKB [1])
  - Beam energy $E$ (LER/HER): 3.5/8 ⇒ 4/7 GeV.
  - Vertical beam-beam parameter $\xi_y$: 0.09 ⇒ 0.09.
  - Crab waist: Optional (installed in 2020).
  - Luminosity $L$: 2.1 ⇒ 80 $\times 10^{34}$ cm$^{-2}$s$^{-1}$.

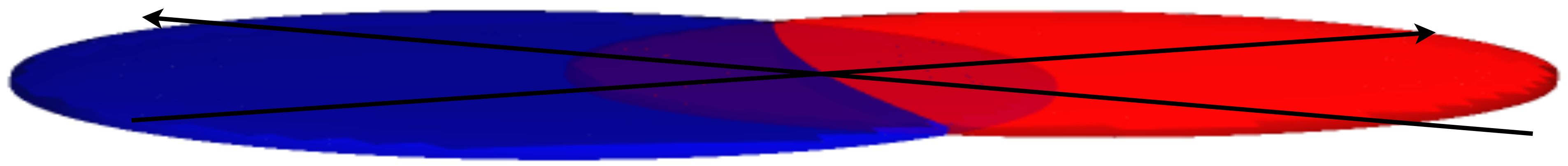
| | KEKB (2009.06.17) | | SKEKB (2021c) | | SKEKB (Final design) | |
|---|---|---|---|---|---|---|
| | HER | LER | HER | LER | HER | LER |
| $I_{bunch}$ (mA) | 1.2 | 1.0 | 0.64 | 0.8 | 2.6 | 3.6 |
| # bunch | 1585 | | 1272 | | 2500 | |
| $\varepsilon_x$ (nm) | 24 | 18 | 4.6 | 4.0 | 4.6 | 3.2 |
| $\varepsilon_y$ (pm) | 150 | 150 | 40 | 40 | 12.9 | 8.64 |
| $\beta_x$ (mm) | 1200 | 1200 | 60 | 80 | 25 | 32 |
| $\beta_y$ (mm) | 5.9 | 5.9 | 1 | 1 | 0.3 | 0.27 |
| $\sigma_z$ (mm) | 6 | 6 | 5 | 6 | 5 | 6 |
| $\nu_x$ | 44.511 | 45.506 | 45.533 | 44.525 | 45.53 | 44.53 |
| $\nu_y$ | 41.585 | 43.561 | 43.581 | 46.595 | 43.57 | 46.57 |
| $\nu_s$ | 0.0209 | 0.0246 | 0.0272 | 0.0233 | 0.028 | 0.0245 |
| Crab waist | - | | 40% | 80% | - | |
| Crossing angle (mrad) | 0 (22) | | 83 | | 83 | |

Schematic view of collision schemes

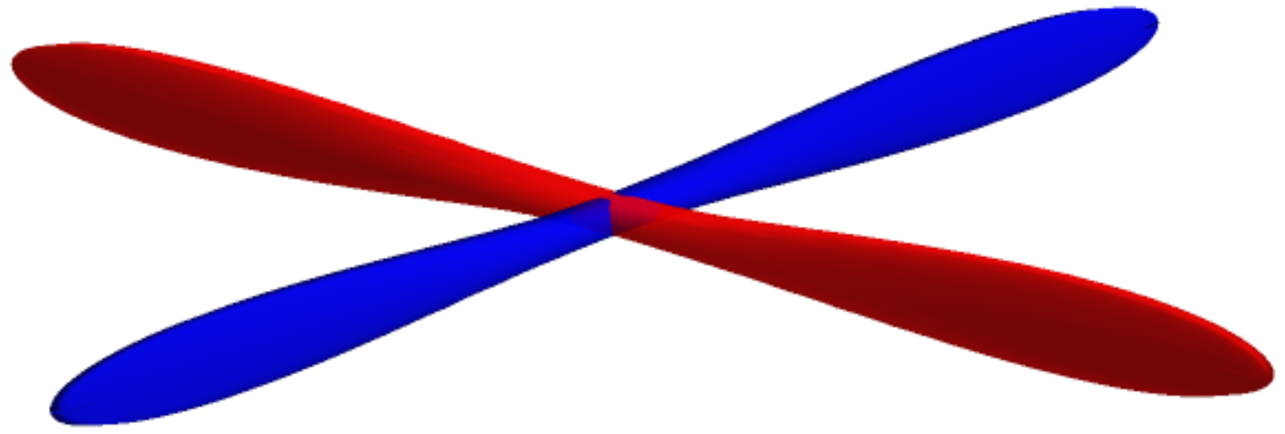
KEKB (Crossing angle)



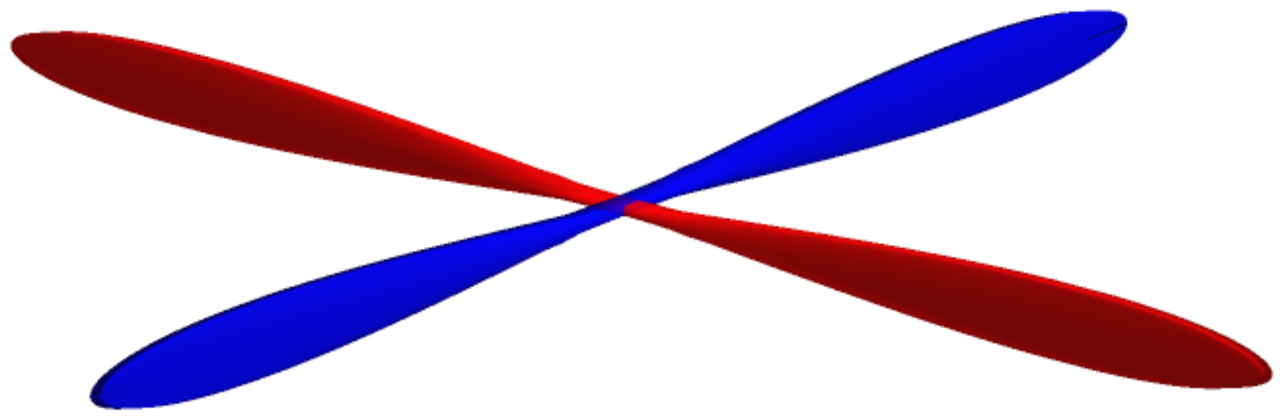
KEKB (Crab cavity)



SuperKEKB (2021c)



SuperKEKB (Final design)



[1] Y. Ohnishi, et al., "Accelerator design at SuperKEKB".

# Status of beam-beam simulations

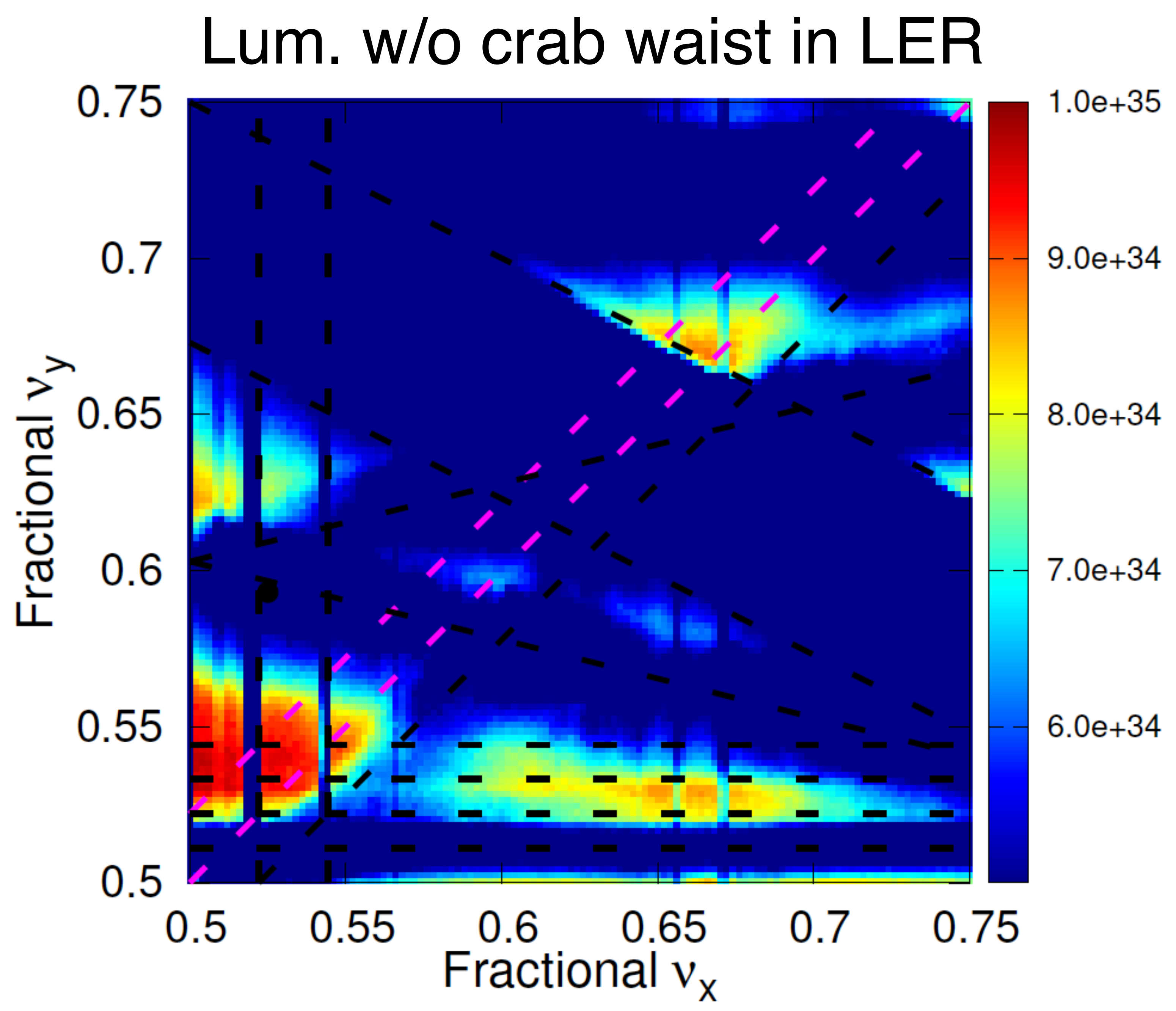
- Weak-strong model + simple one-turn map: BBWS code [1]
  - The weak beam is represented by N macro-particles (statistical errors ~ $1/\sqrt{N}$). The strong beam has a rigid charge distribution with its EM fields expressed by the Bassetti-Erskine formula.
  - The simple one-turn map contains lattice transformation (Tunes, alpha functions, beta functions, X-Y couplings, dispersions, etc.), chromatic perturbation, synchrotron radiation damping, quantum excitation, crab waist, etc.
- 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.); …
- Strong-strong model + simple one-turn map + perturbation maps: 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 lattices:
  - SCTR-CUDA, Ready for investigations (K. Ohmi)
  - APES-T, Ready for investigations (Z. Li, Y. Zhang)
  - KEK/IHEP collaboration

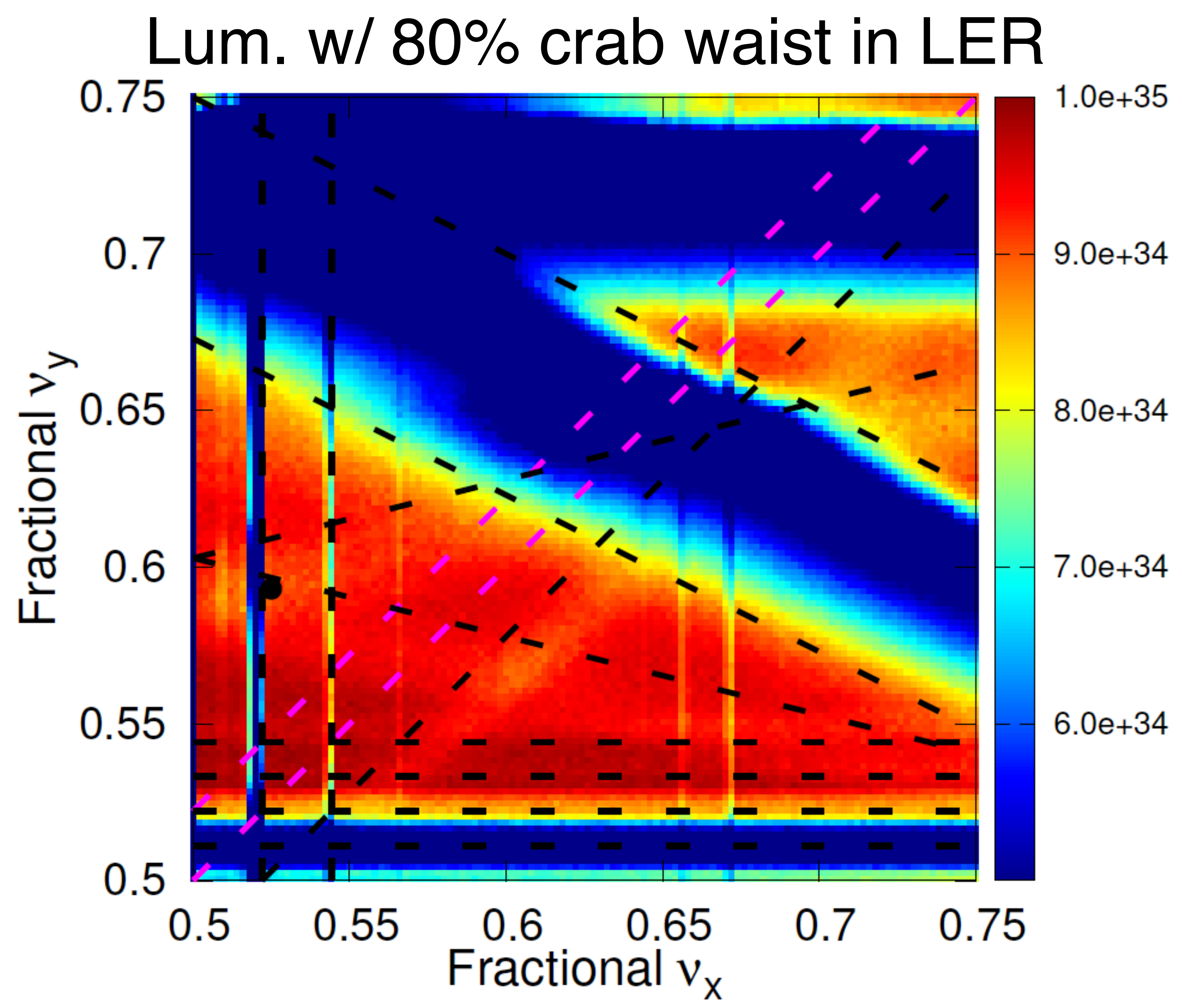
[1] K. Ohmi, Talk presented at the 2019 SAD workshop, https://conference-indico.kek.jp/event/75/.

# Weak-strong beam-beam simulations

- SuperKEKB 2021b run ($\beta_y^* = 1$ mm) with ideal crab waist
  - Tune scan to identify important beam-beam resonances (mainly $\nu_x + 2\nu_y + \alpha_1 = N$, $\nu_x \pm 4\nu_y + \alpha_2 = N$, $2\nu_x - k\nu_s = N$) [1].

| | 2021.07.01 | | Comments |
|---|---|---|---|
| | HER | LER | |
| $I_{bunch}$ (mA) | 0.80 | 1.0 | |
| # bunch | 1174 | | Assumed value |
| $\varepsilon_x$ (nm) | 4.6 | 4.0 | w/ IBS |
| $\varepsilon_y$ (pm) | 23 | 23 | Estimated from XRM data |
| $\beta_x$ (mm) | 60 | 80 | Calculated from lattice |
| $\beta_y$ (mm) | 1 | 1 | Calculated from lattice |
| $\sigma_{z0}$ (mm) | 5.05 | 4.84 | Natural bunch length (w/o MWI) |
| $\nu_x$ | 45.532 | 44.525 | Measured tune of pilot bunch |
| $\nu_y$ | 43.582 | 46.593 | Measured tune of pilot bunch |
| $\nu_s$ | 0.0272 | 0.0221 | Calculated from lattice |
| Crab waist | 40% | 80% | Lattice design |

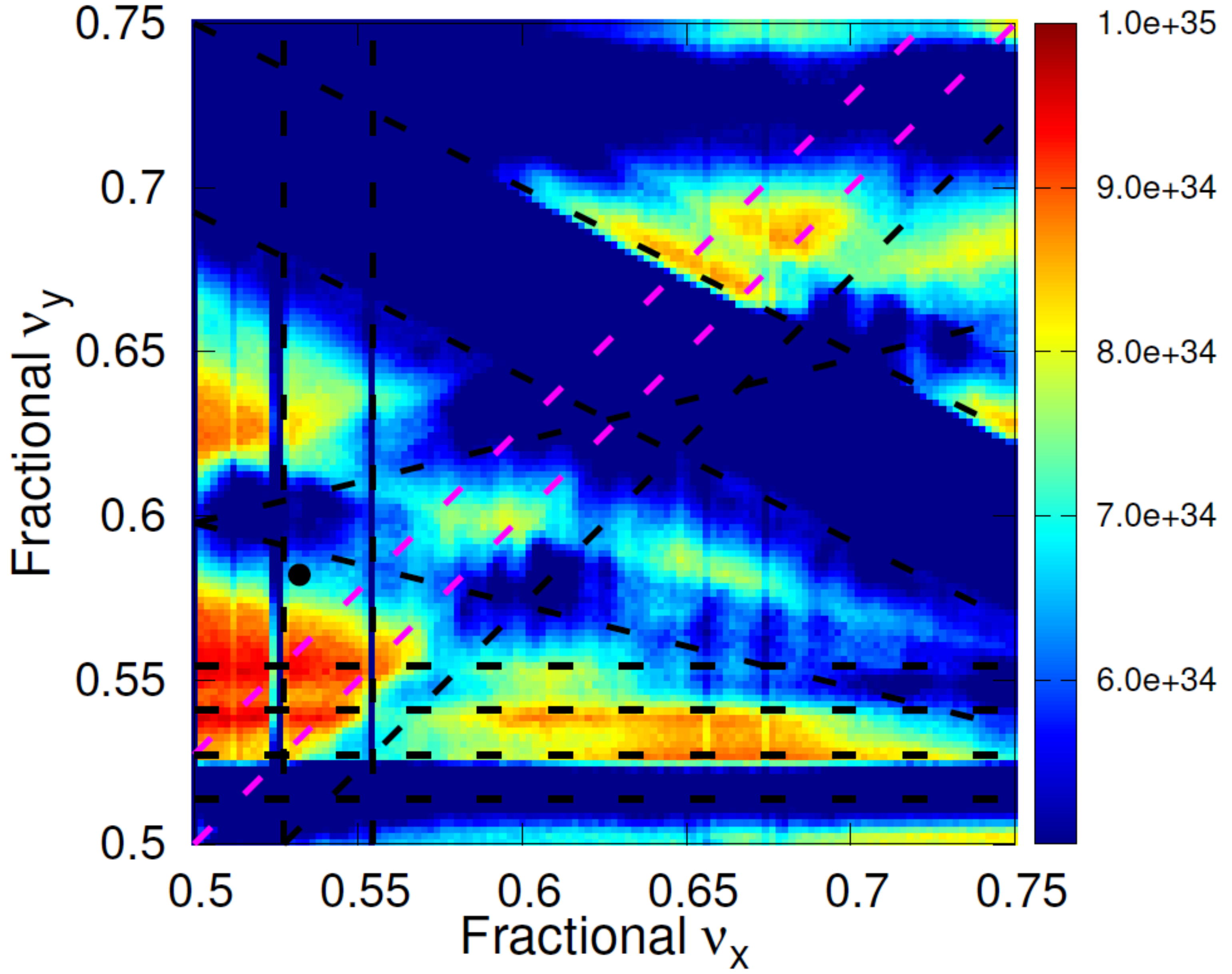


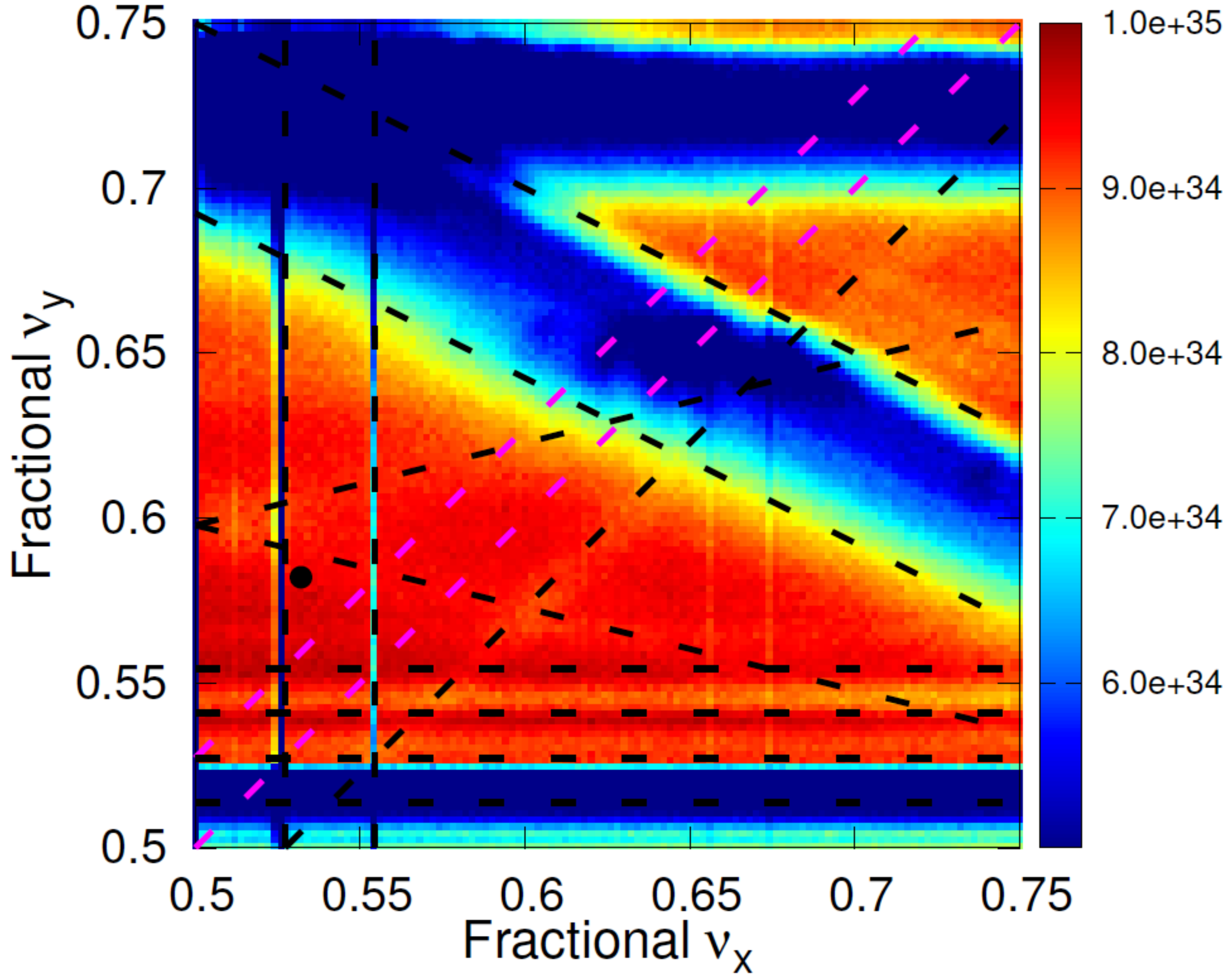



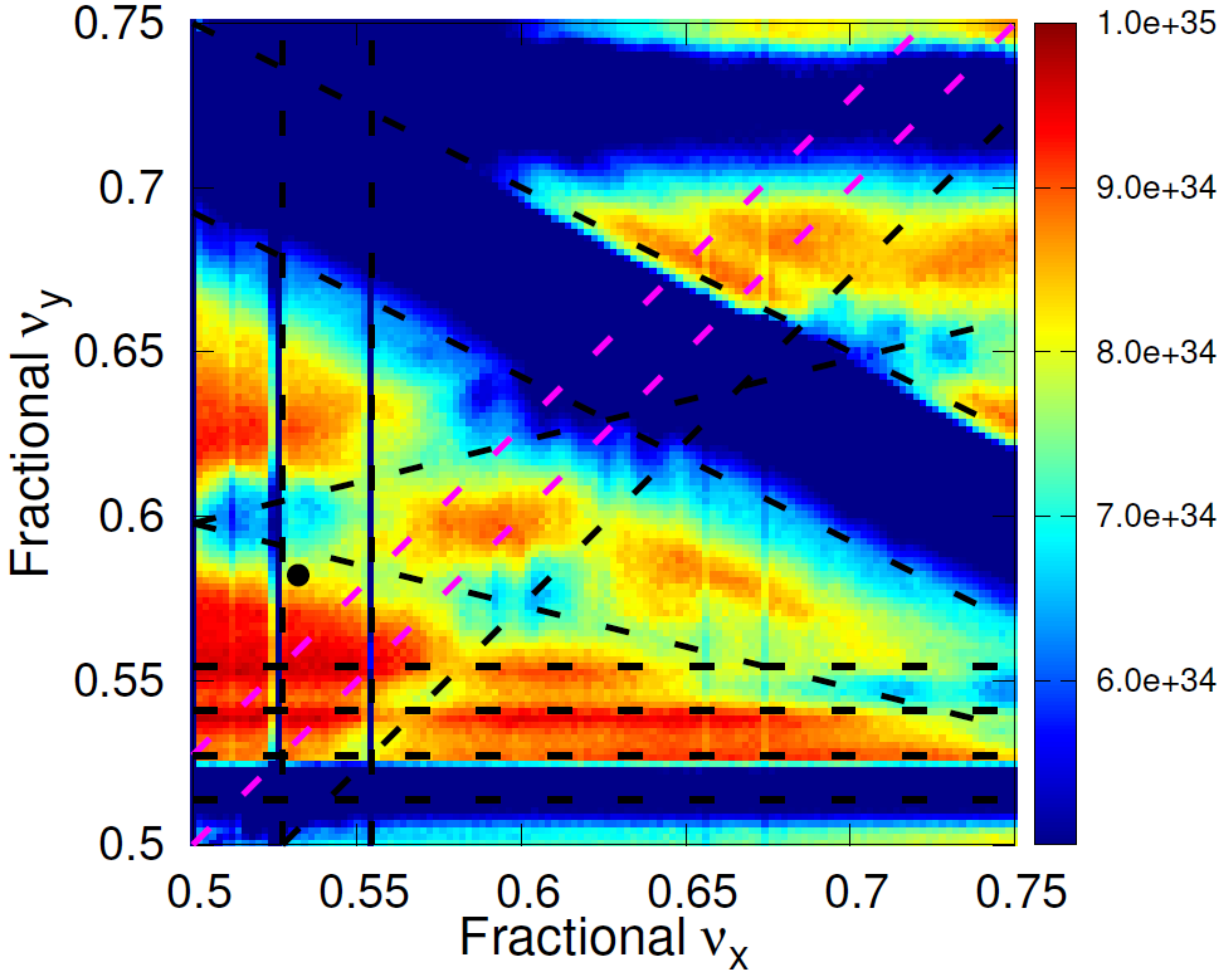

[1] D. Zhou et al., PRAB 26, 071001 (2023).

# Weak-strong beam-beam simulations

- SuperKEKB 2021b run ($\beta_y^* = 1$ mm) with ideal crab waist
  - Tune scan to identify important beam-beam resonances (mainly $\nu_x + 2\nu_y + \alpha_1 = N, \nu_x \pm 4\nu_y + \alpha_2 = N, 2\nu_x - k\nu_s = N$) [1].



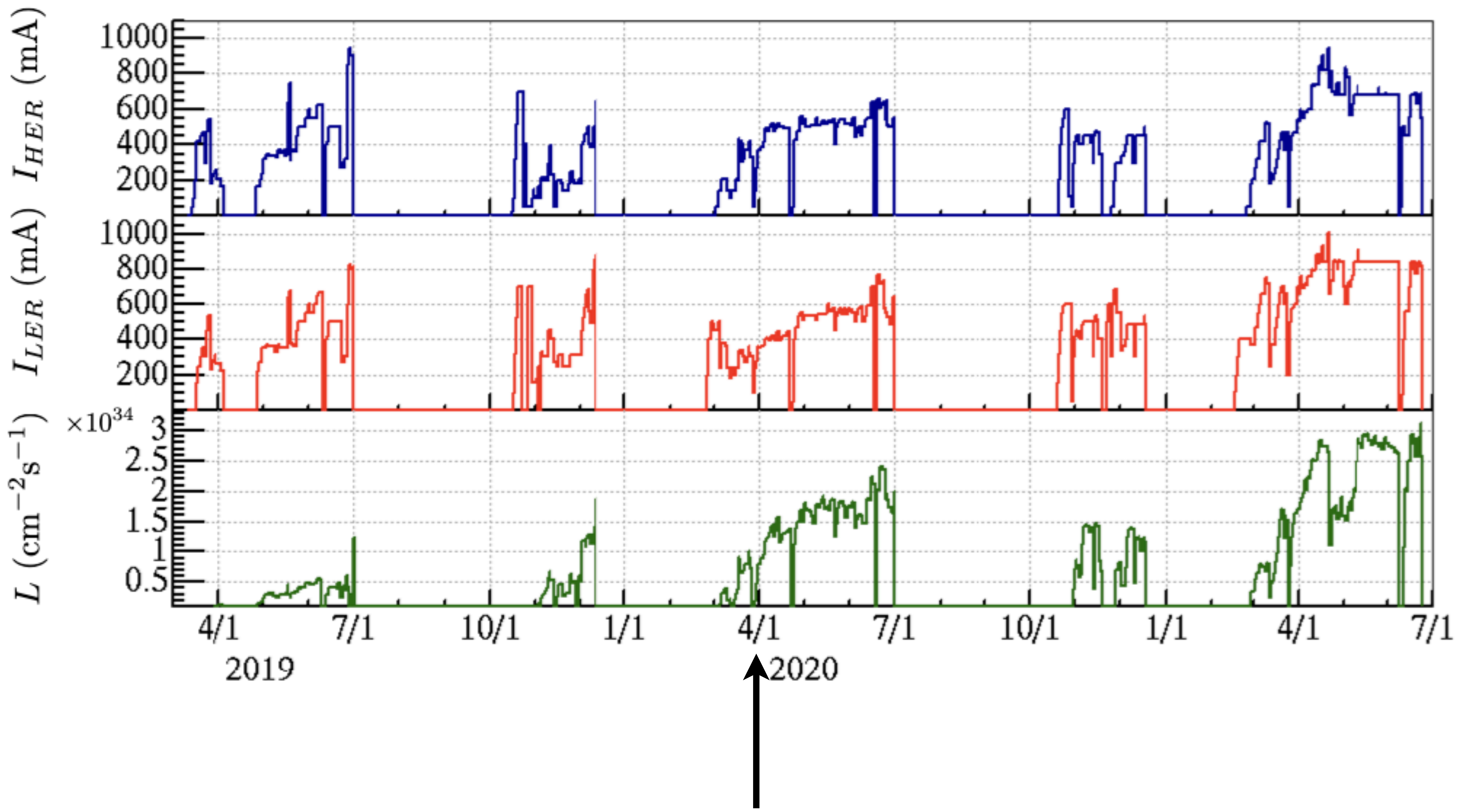



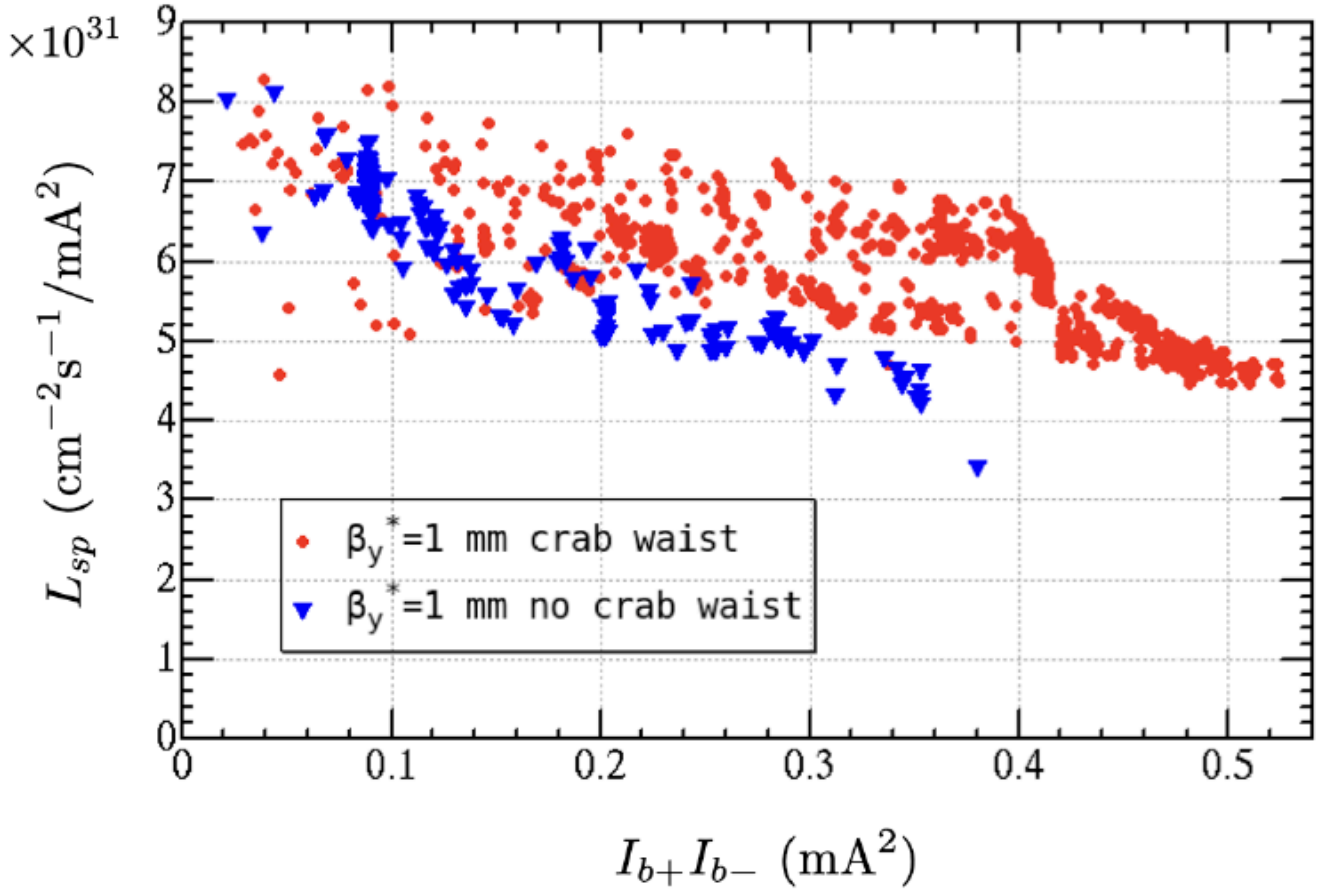

[1] D. Zhou et al., PRAB 26, 071001 (2023).

# Crab waist applied to SuperKEKB

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



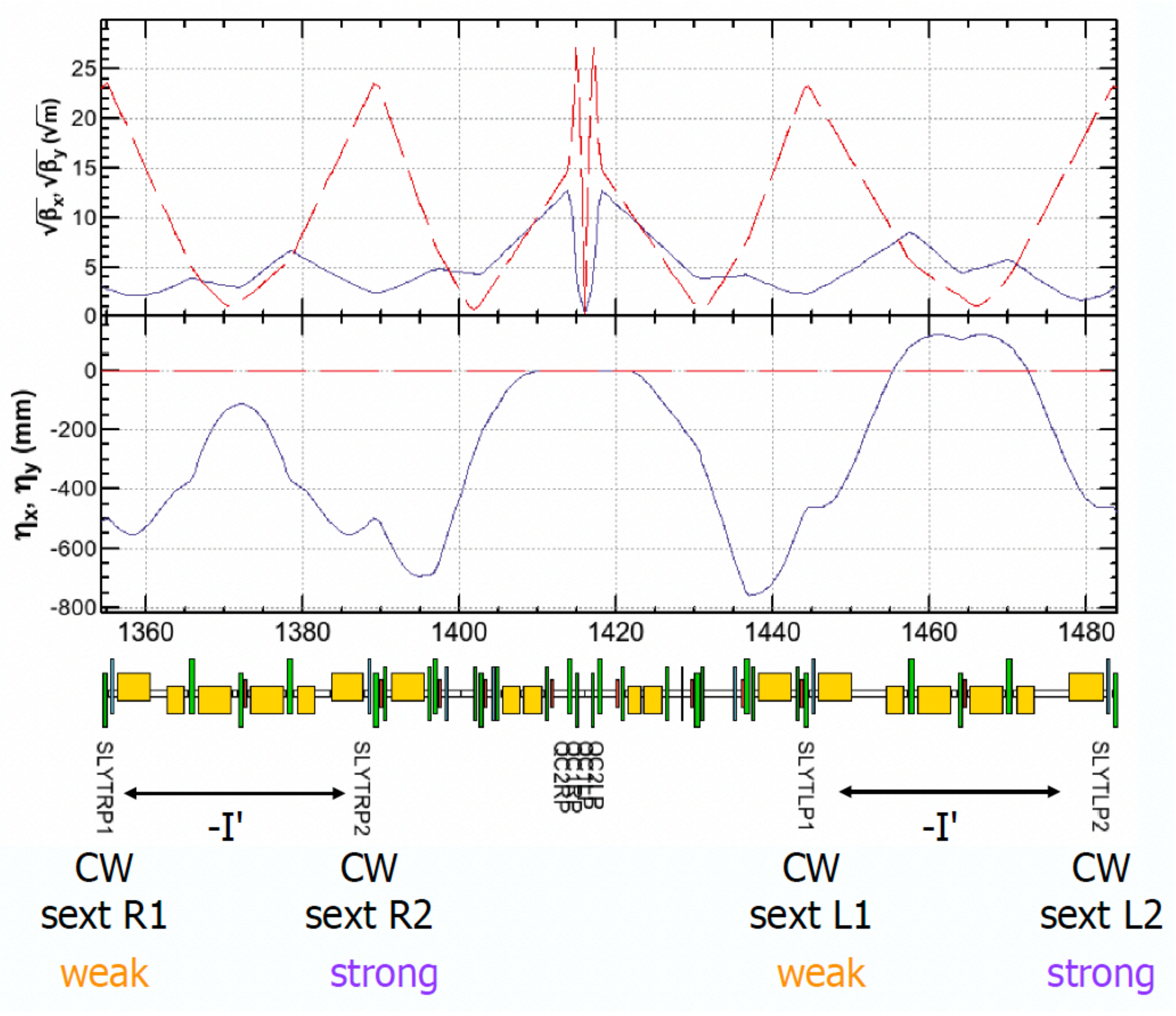

Crab waist introduced since April 2020



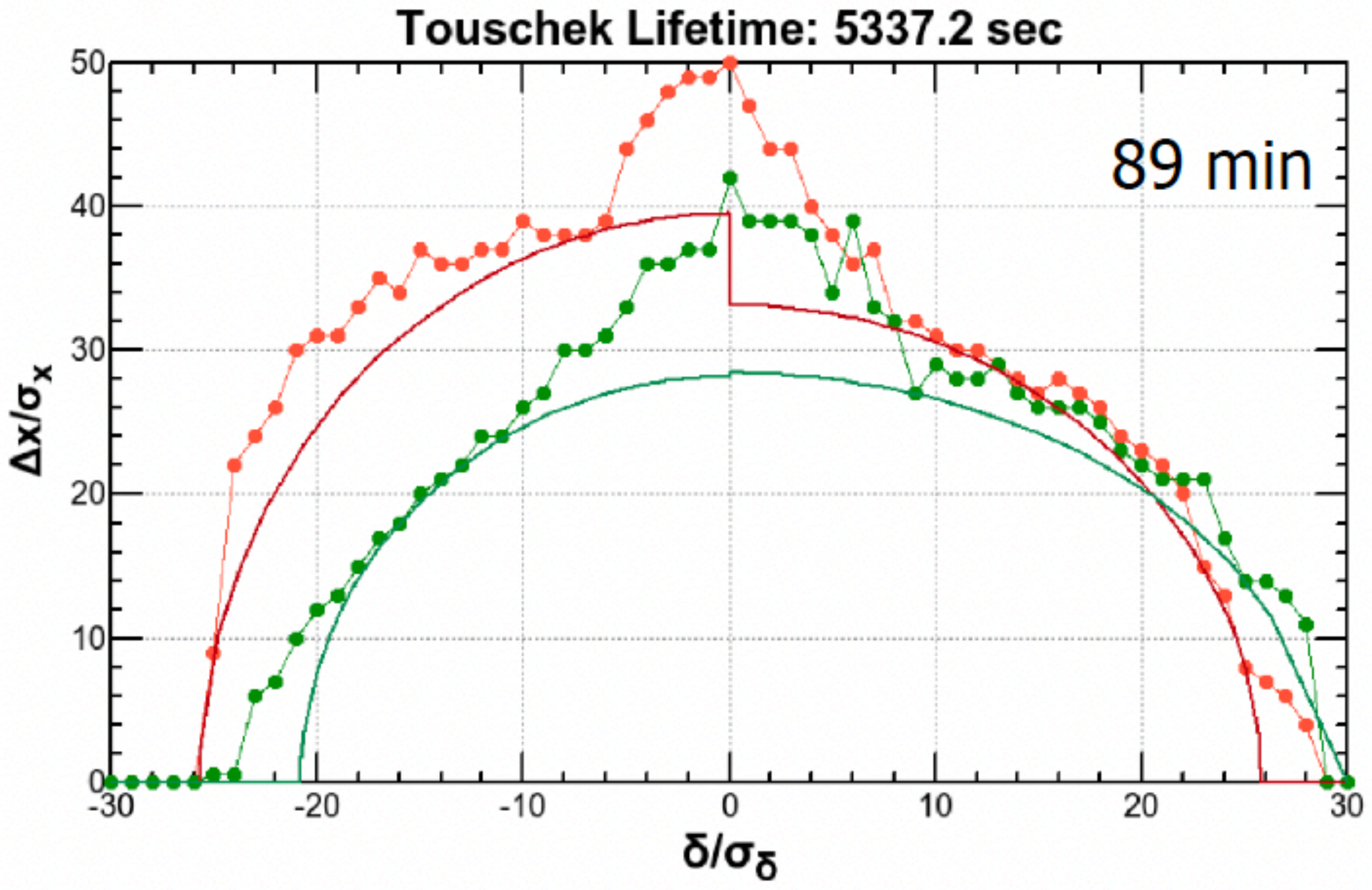

[1] Y. Ohnishi, The European Physical Journal Plus volume 136, 1023 (2021).

# Crab waist applied to SuperKEKB

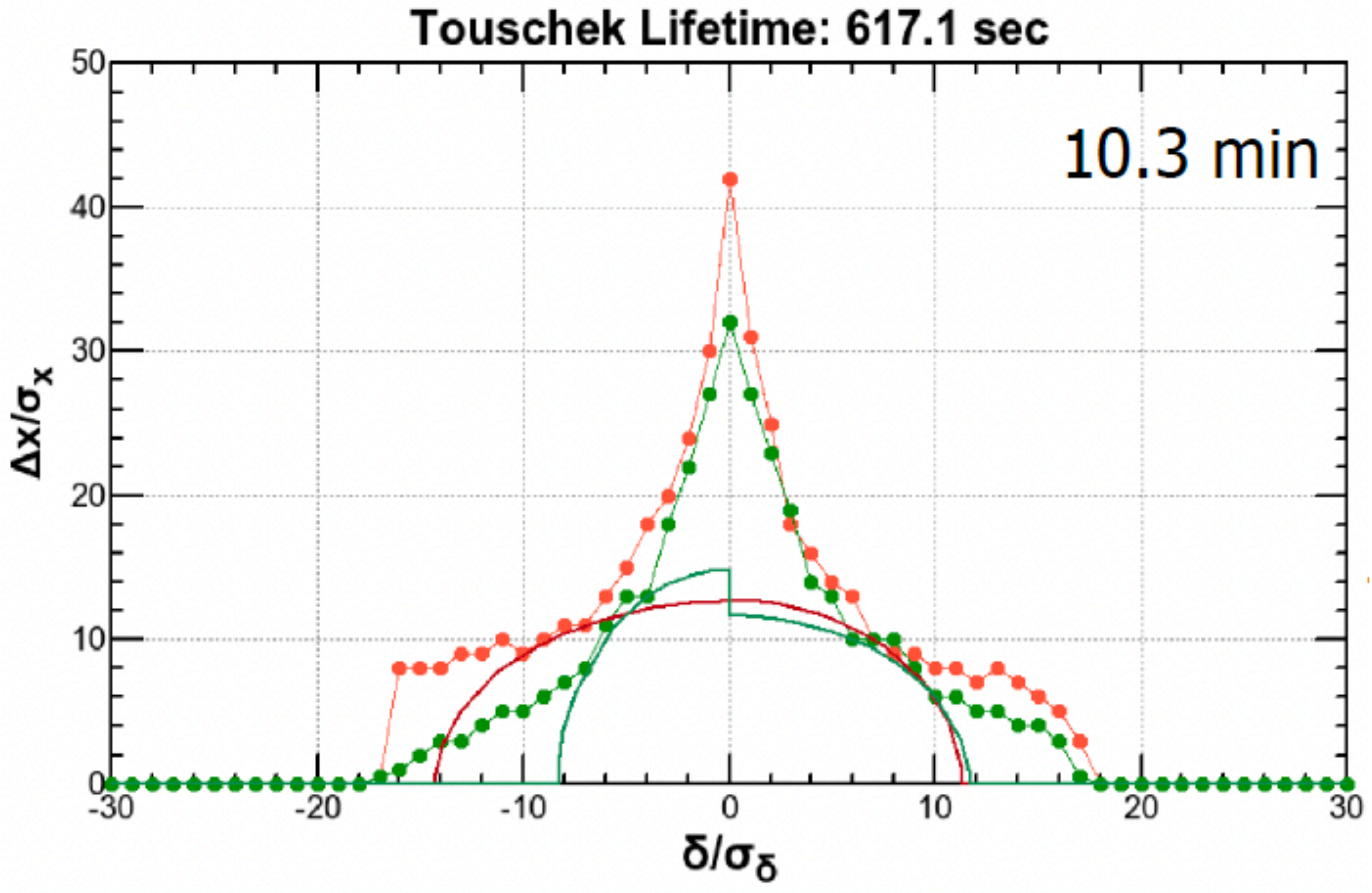
- Implementation of crab waist at SuperKEKB
  - Crab waist [1] was optional in SuperKEKB final design, because it significantly reduces dynamic aperture and lifetime (from optics design with a realistic IR) [2].
  - Beam commissioning experienced severe emittance blowup and poor luminosity, forcing implementation of crab waist (Oide's scheme [3]).
  - Crab waist is efficient in suppressing beam-beam blowup, but cause significant loss of dynamic aperture and lifetime at SuperKEKB with $\beta_y^*$=1 mm [4].




No crab waist



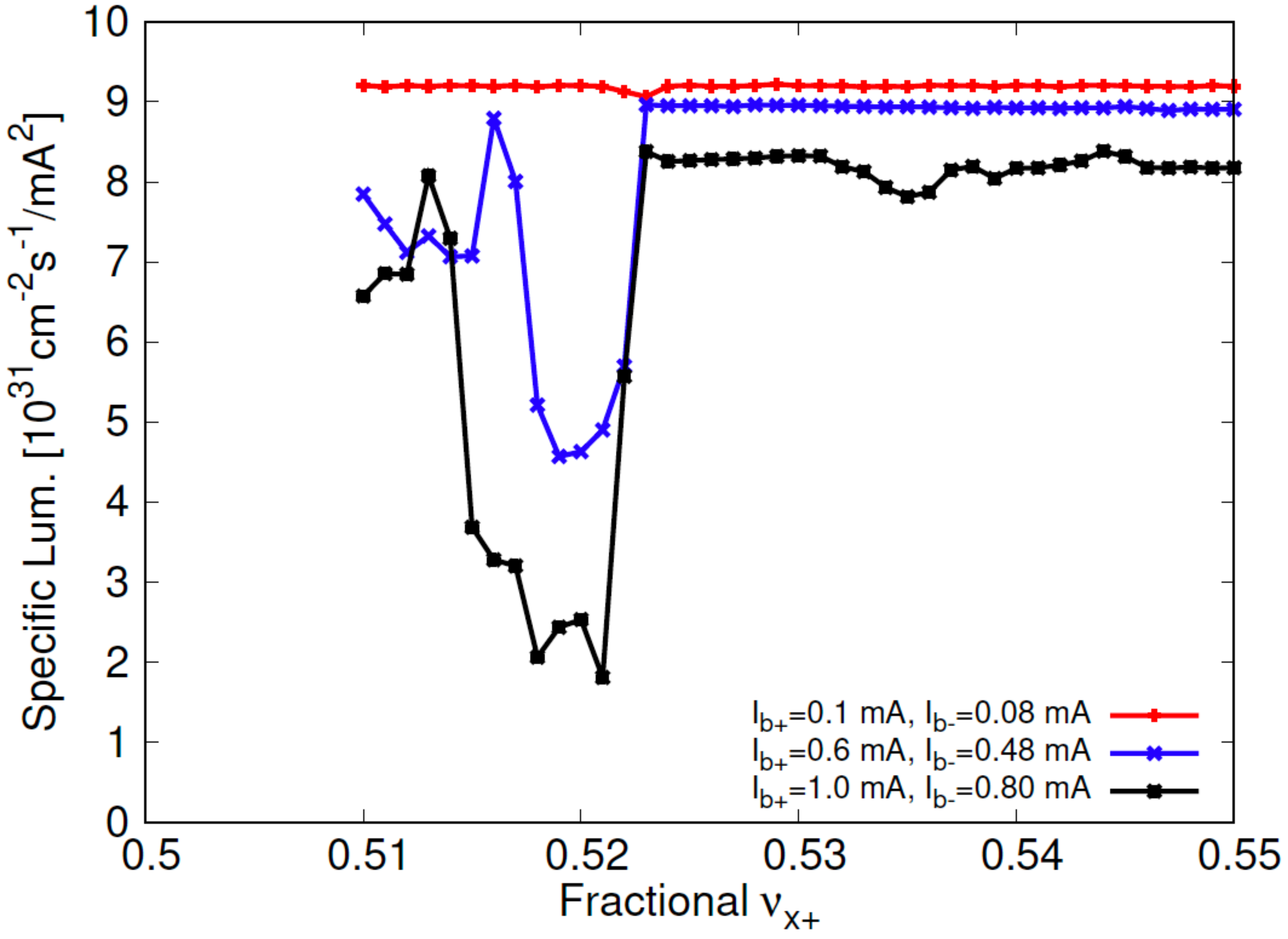

80% crab waist

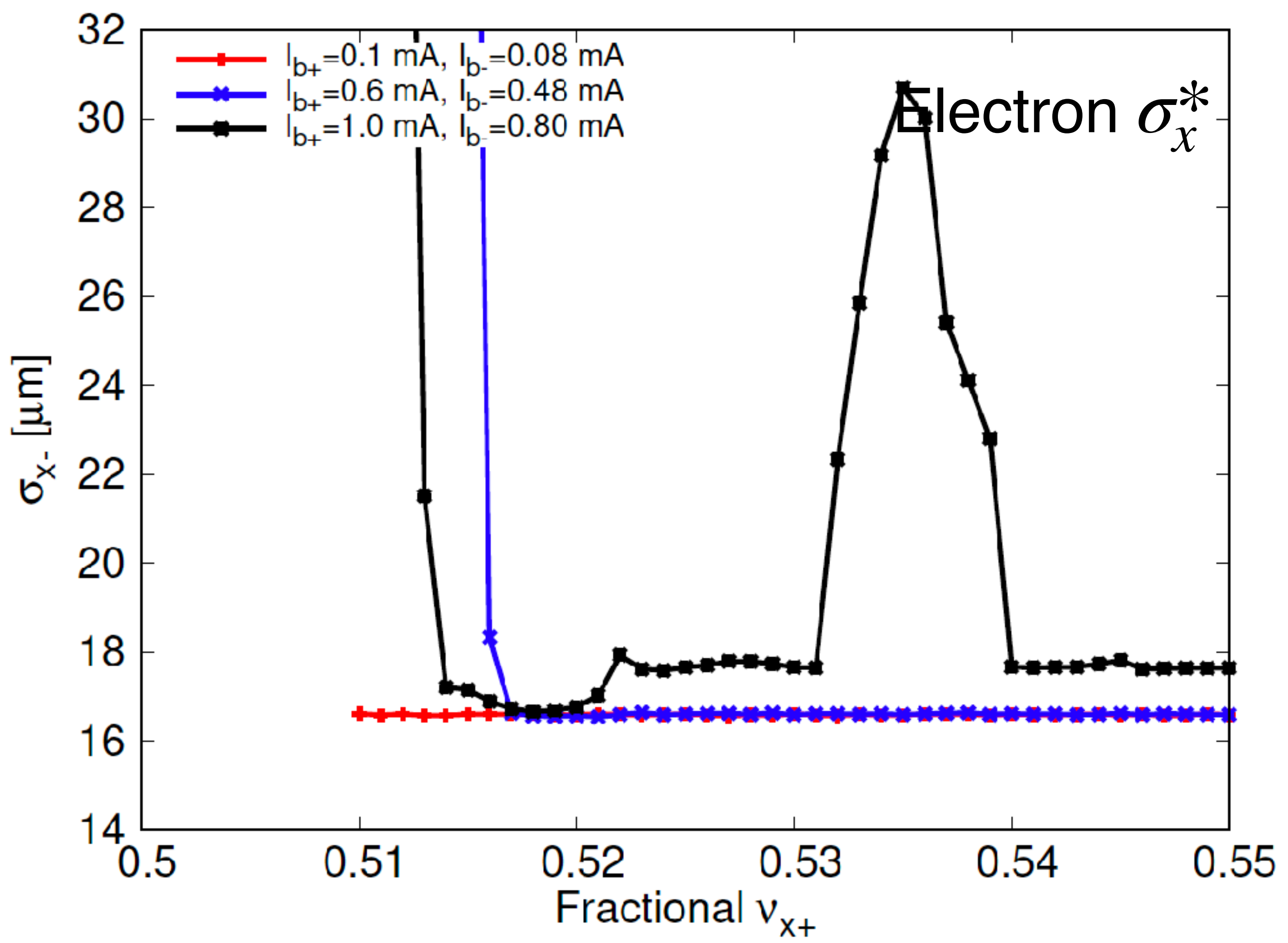


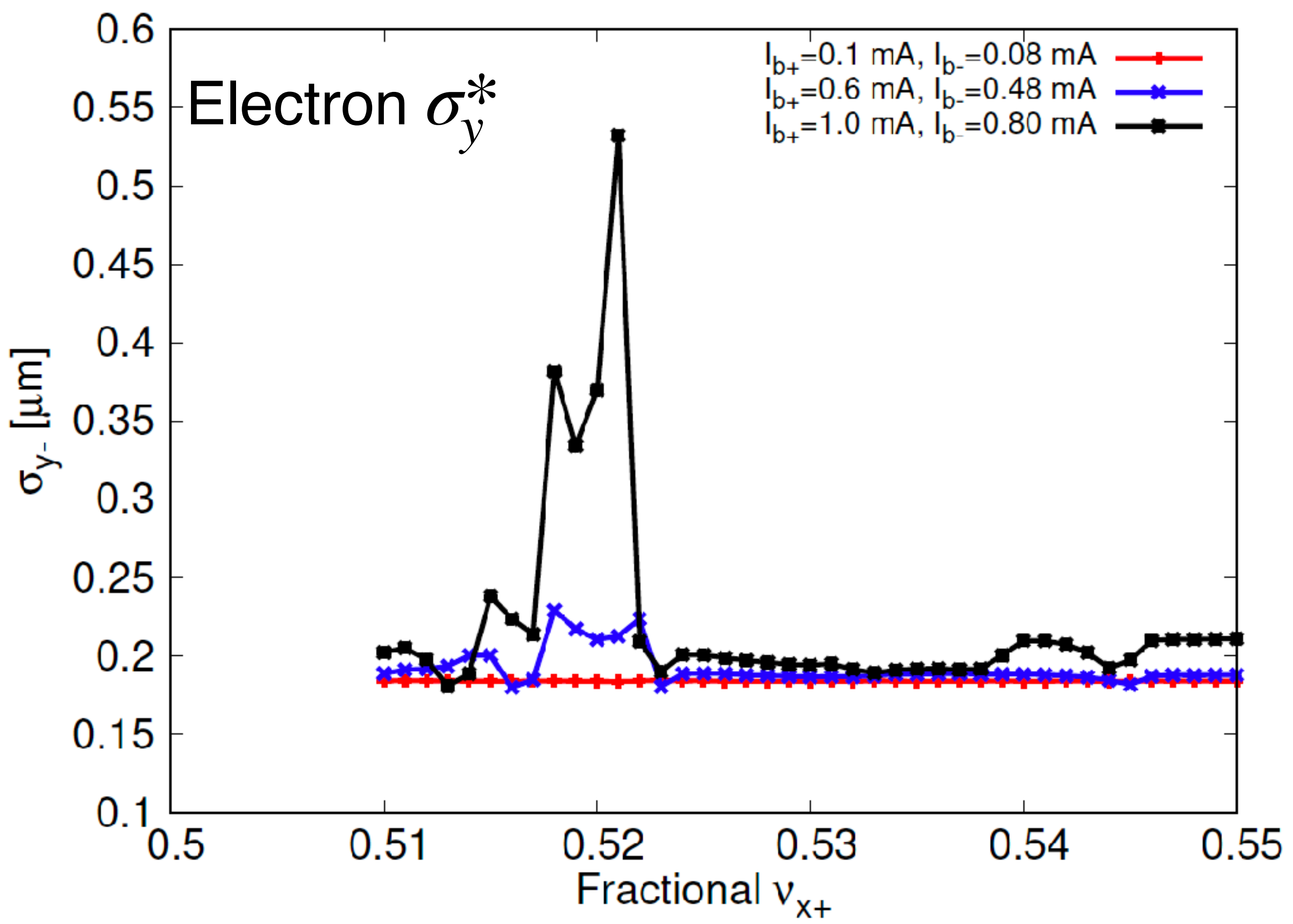

[1] M. Zobov et al., Phys. Rev. Lett. 104, 174801 (2010). [2] SuperKEKB TDR. [3] K. Oide et al., Phys. Rev. Accel. Beams 19, 111005 (2016). [4] Y. Ohnishi, "Dynamic Aperture for Crab Waist in LER".

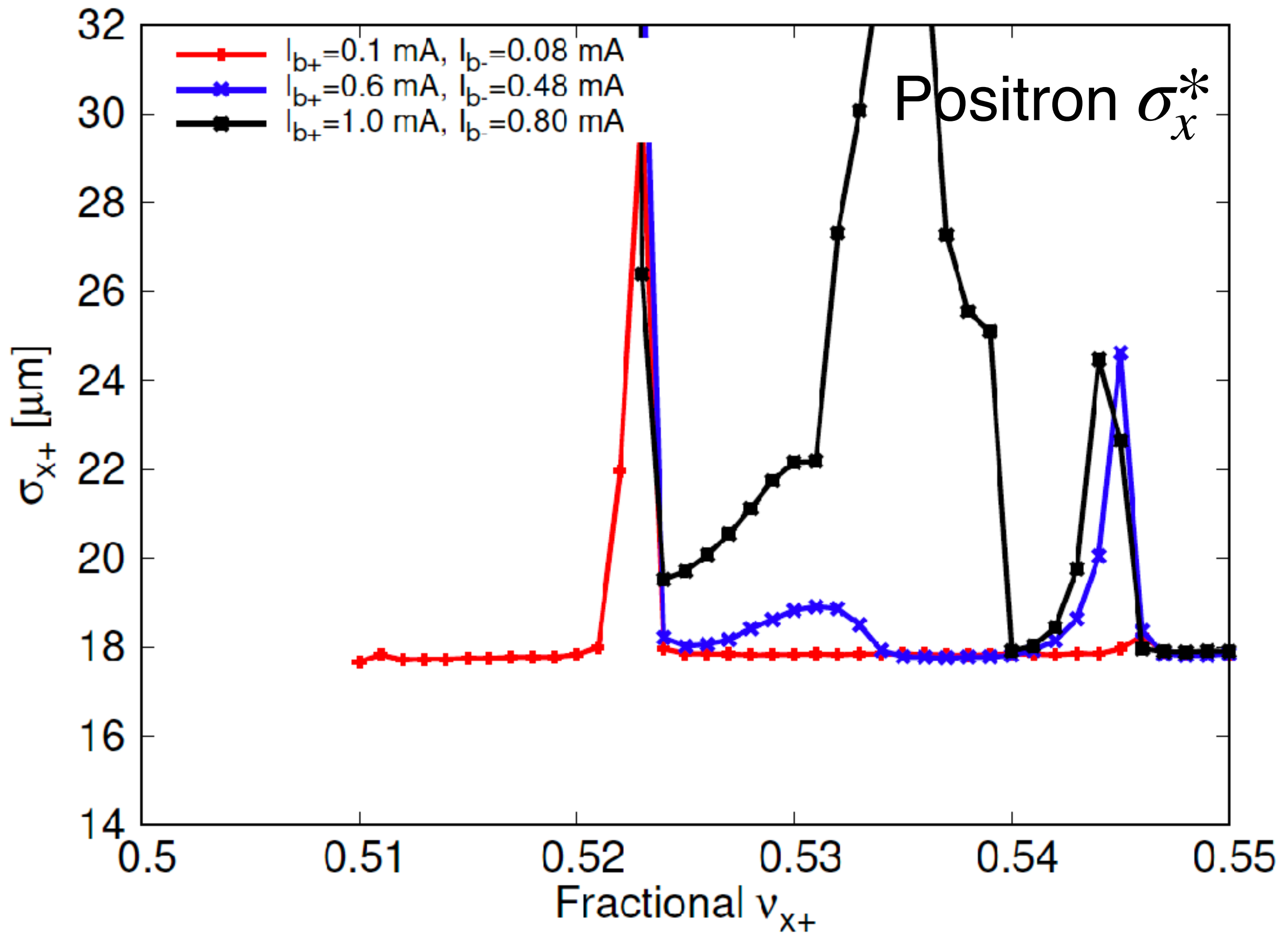
# Strong-strong beam-beam simulations

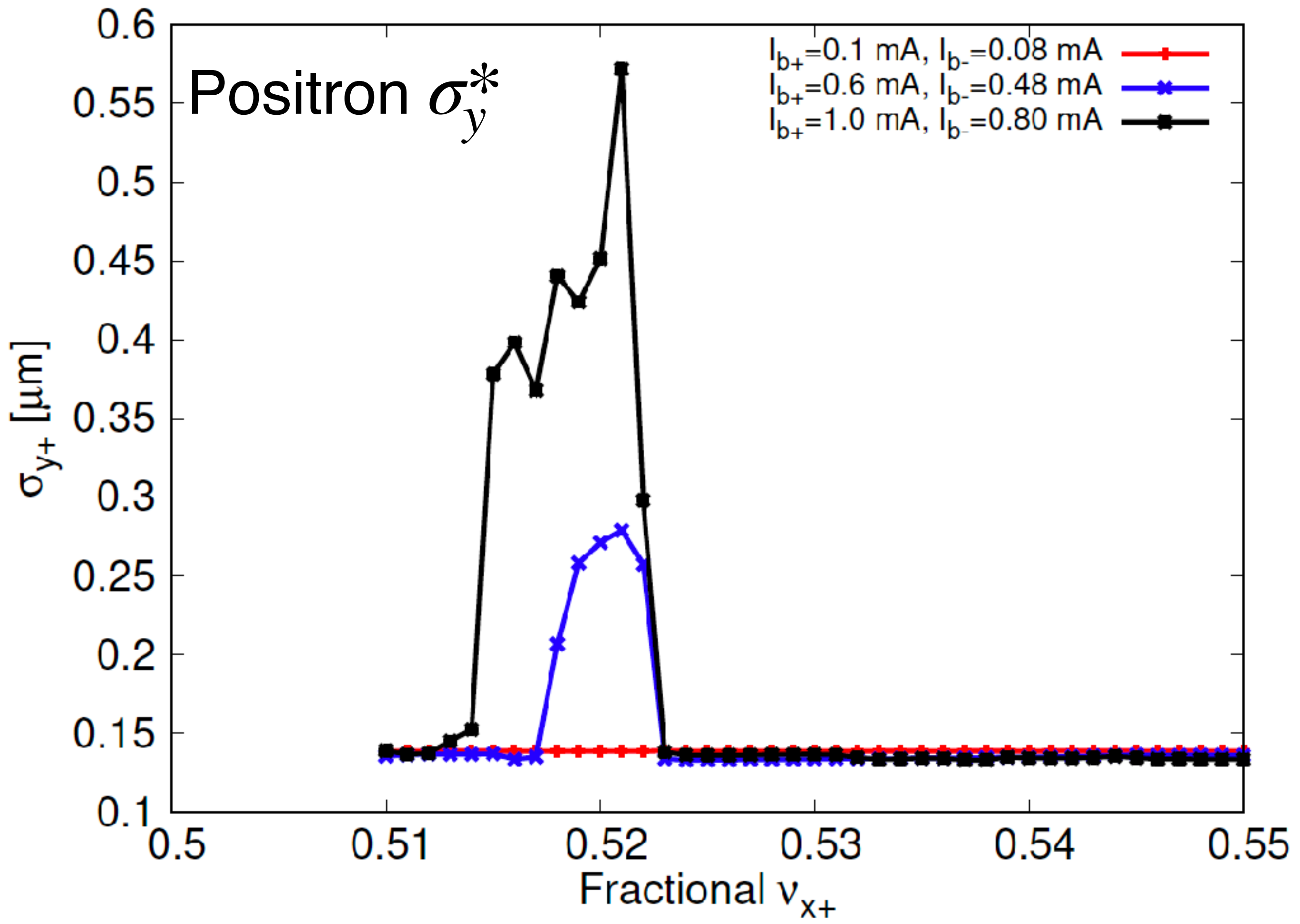
- Scan LER $\nu_x$ (LER $\nu_y$ and HER $\nu_{x,y}$ fixed) with impedance effects [1]
    - To identify coherent X-Z instabilities
    - To identify synchro-betatron resonances



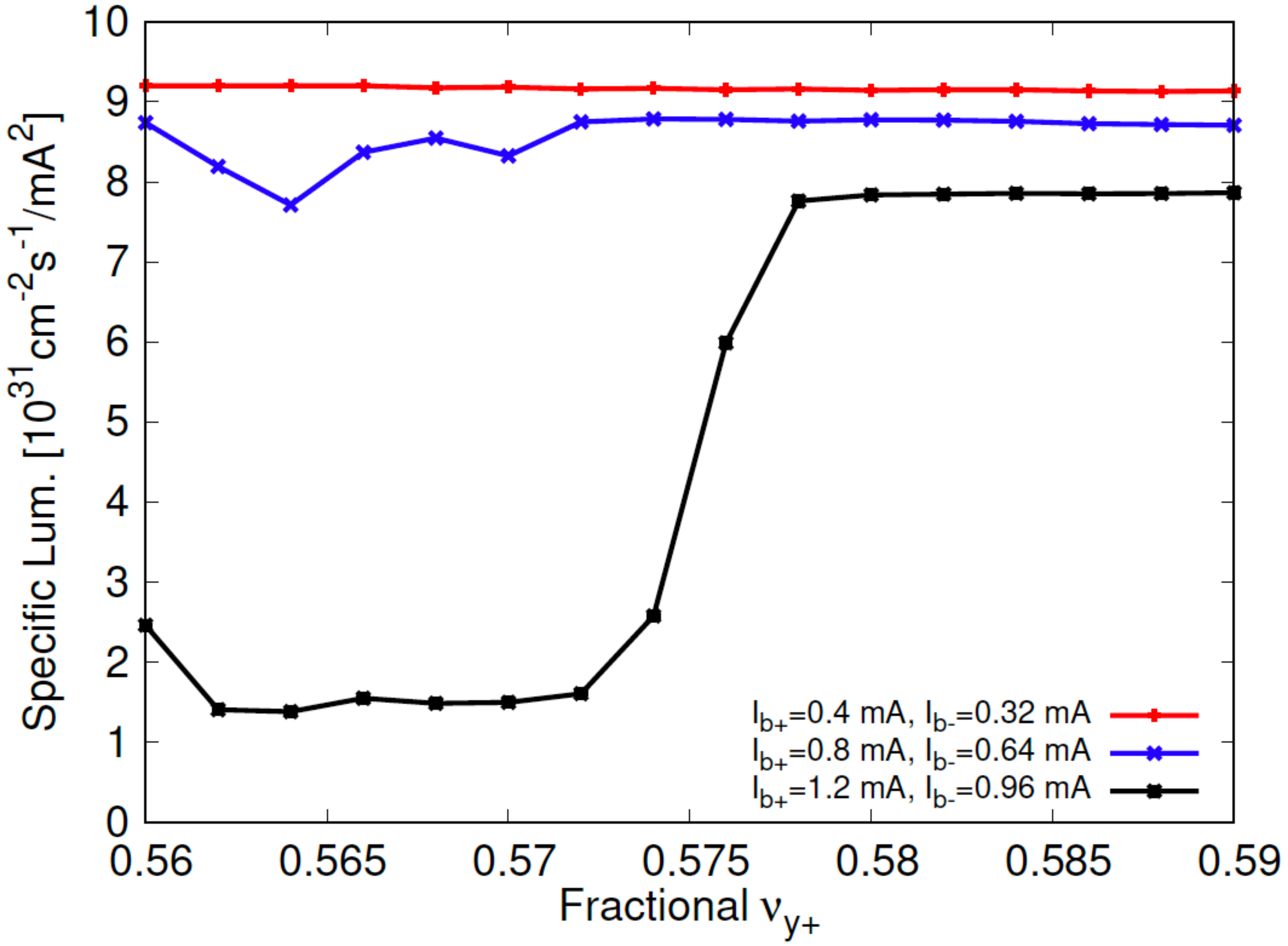



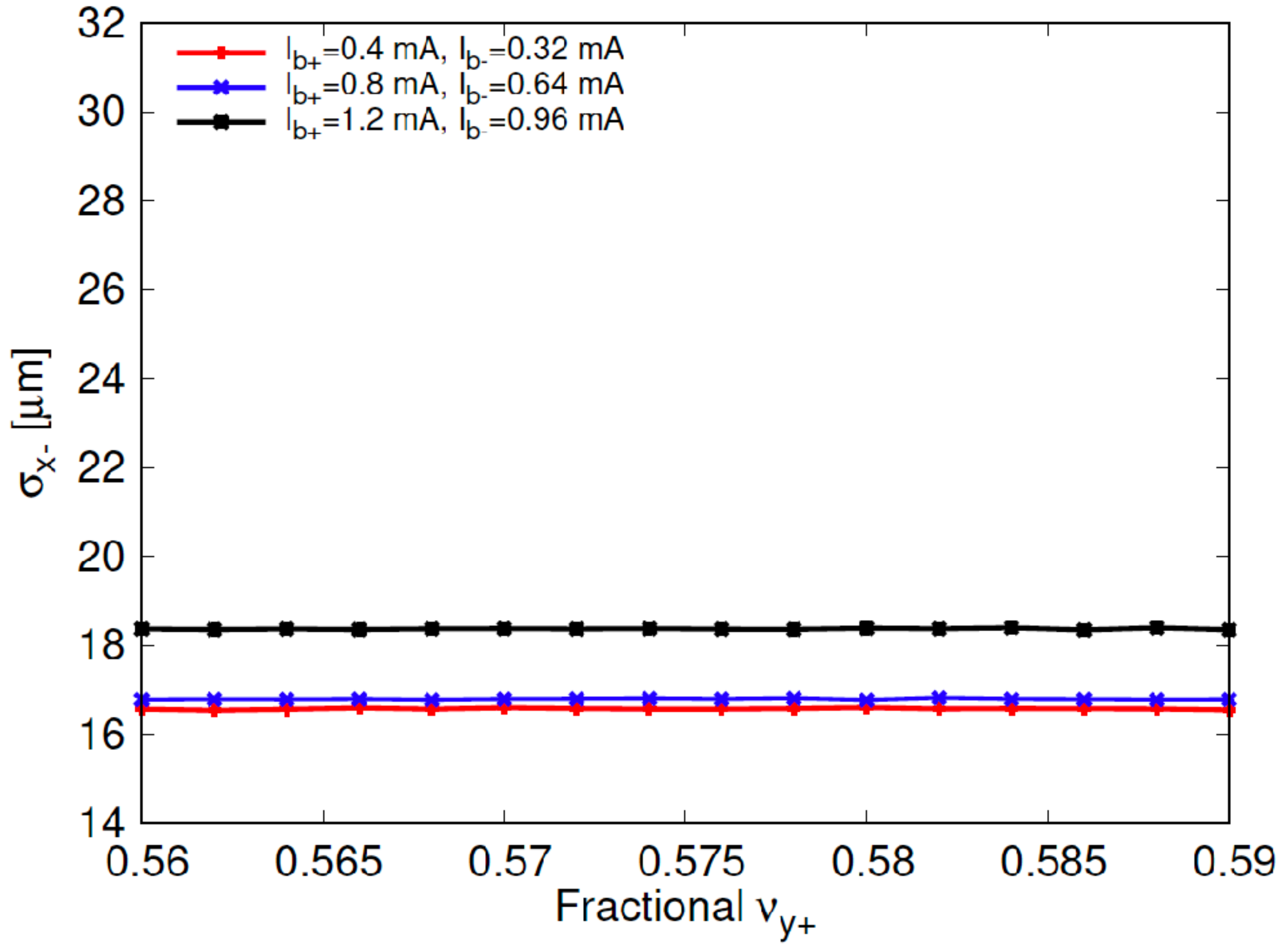



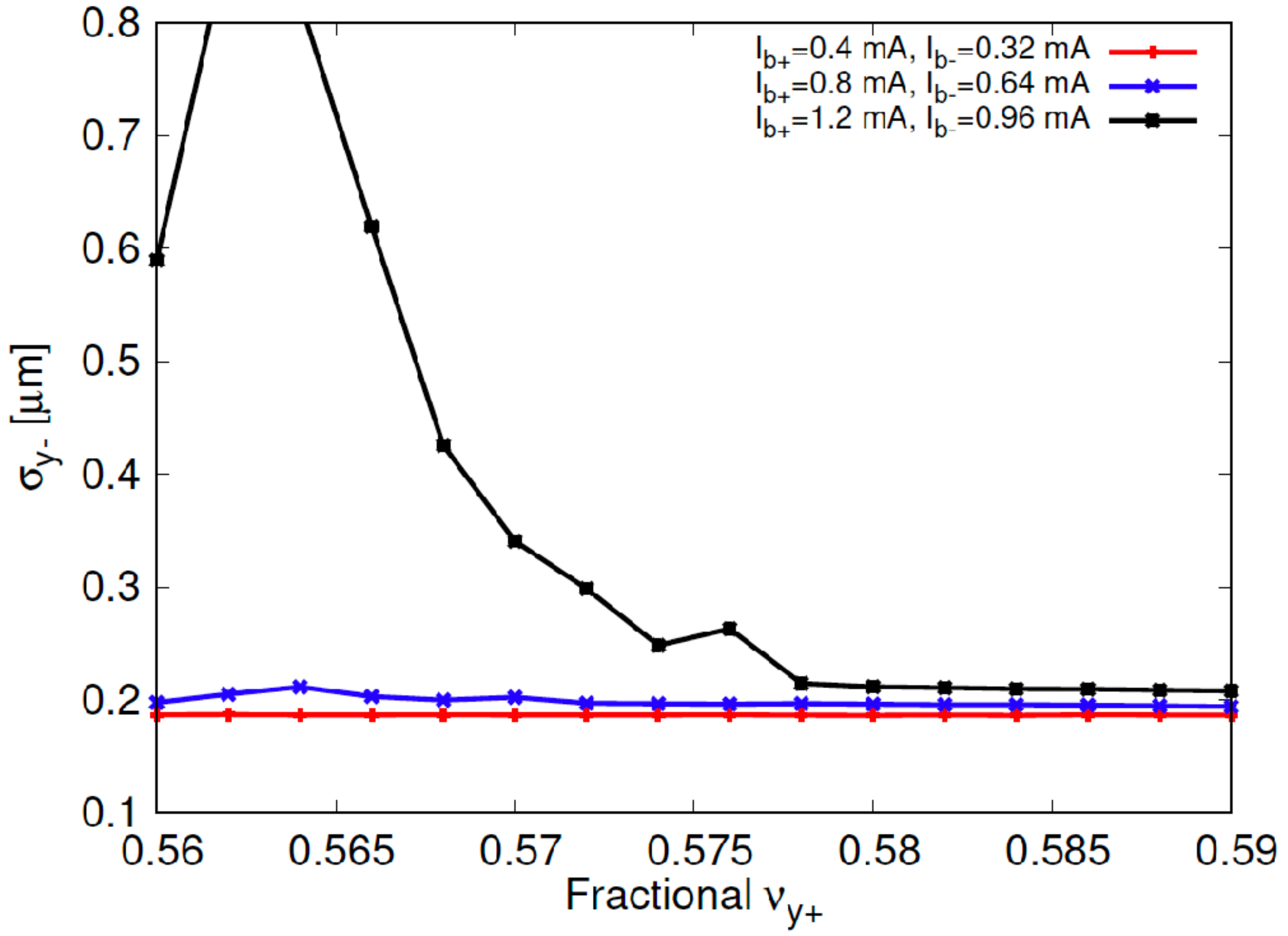

[1] D. Zhou et al., PRAB 26, 071001 (2023).

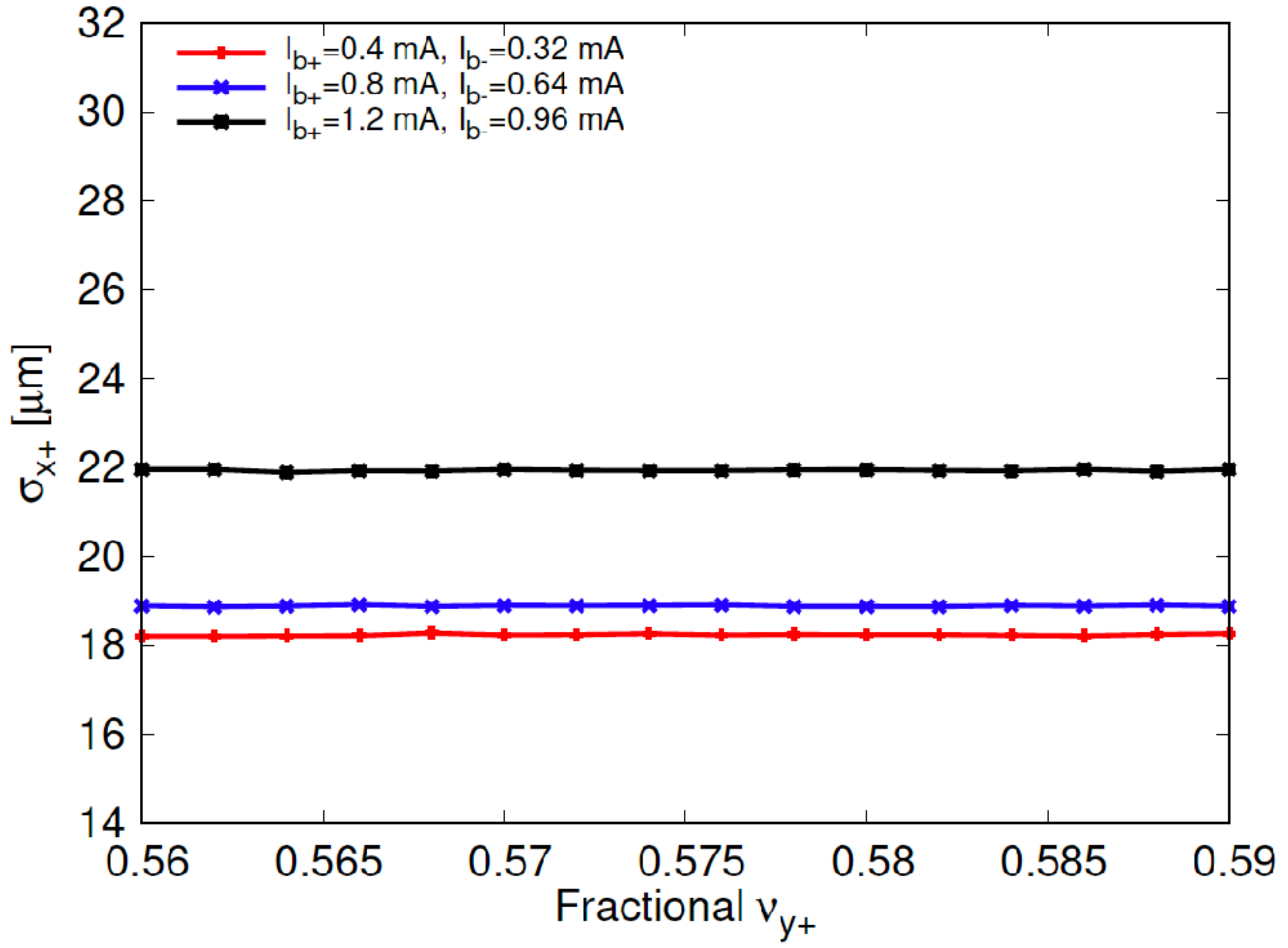
# Strong-strong beam-beam simulations

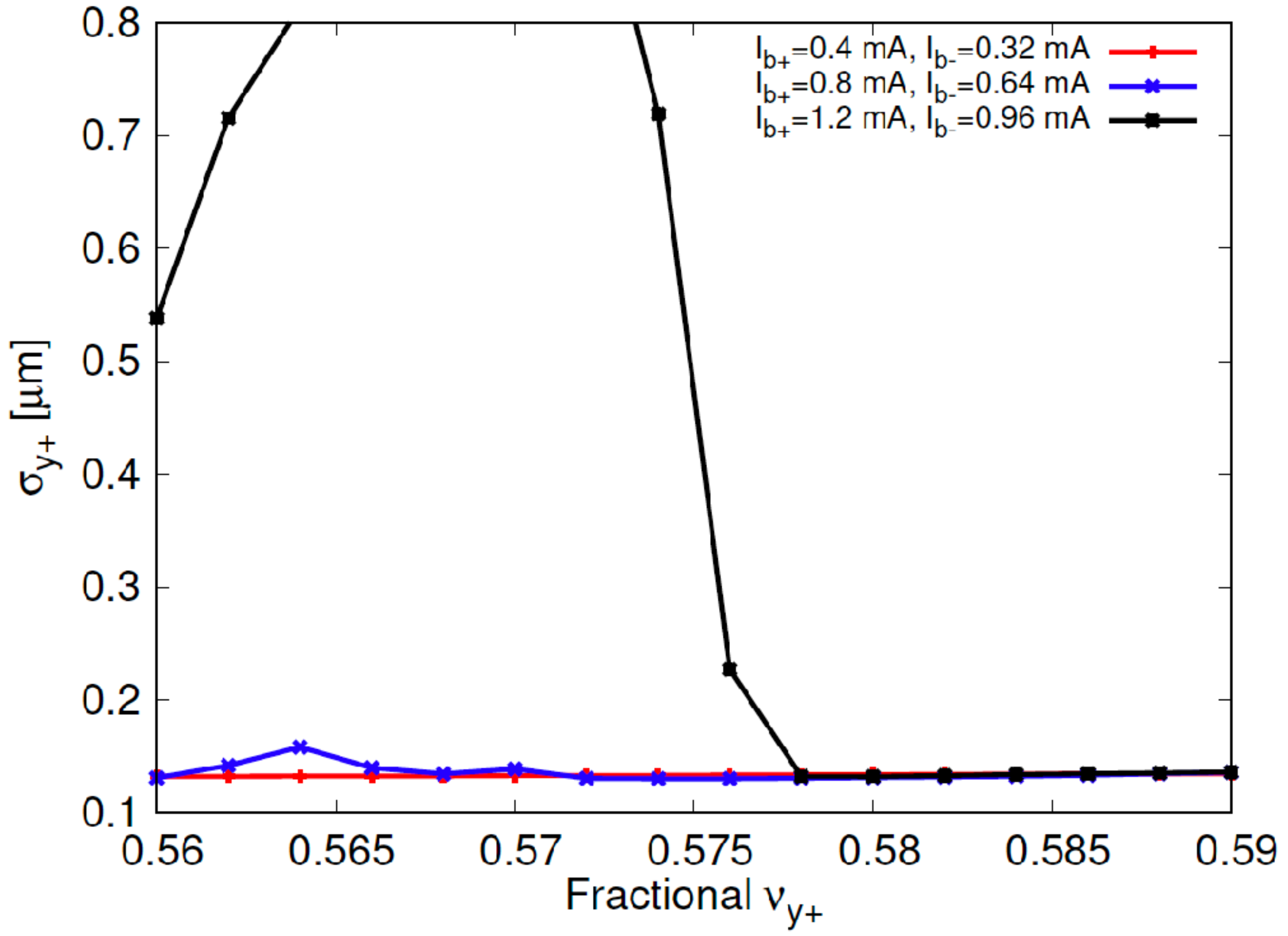
- Scan LER $\nu_y$ (LER $\nu_x$ and HER $\nu_{x,y}$ fixed) with impedance effects [1]
  - To identify coherent head-tail (Y-Z) instabilities [1,2,3]



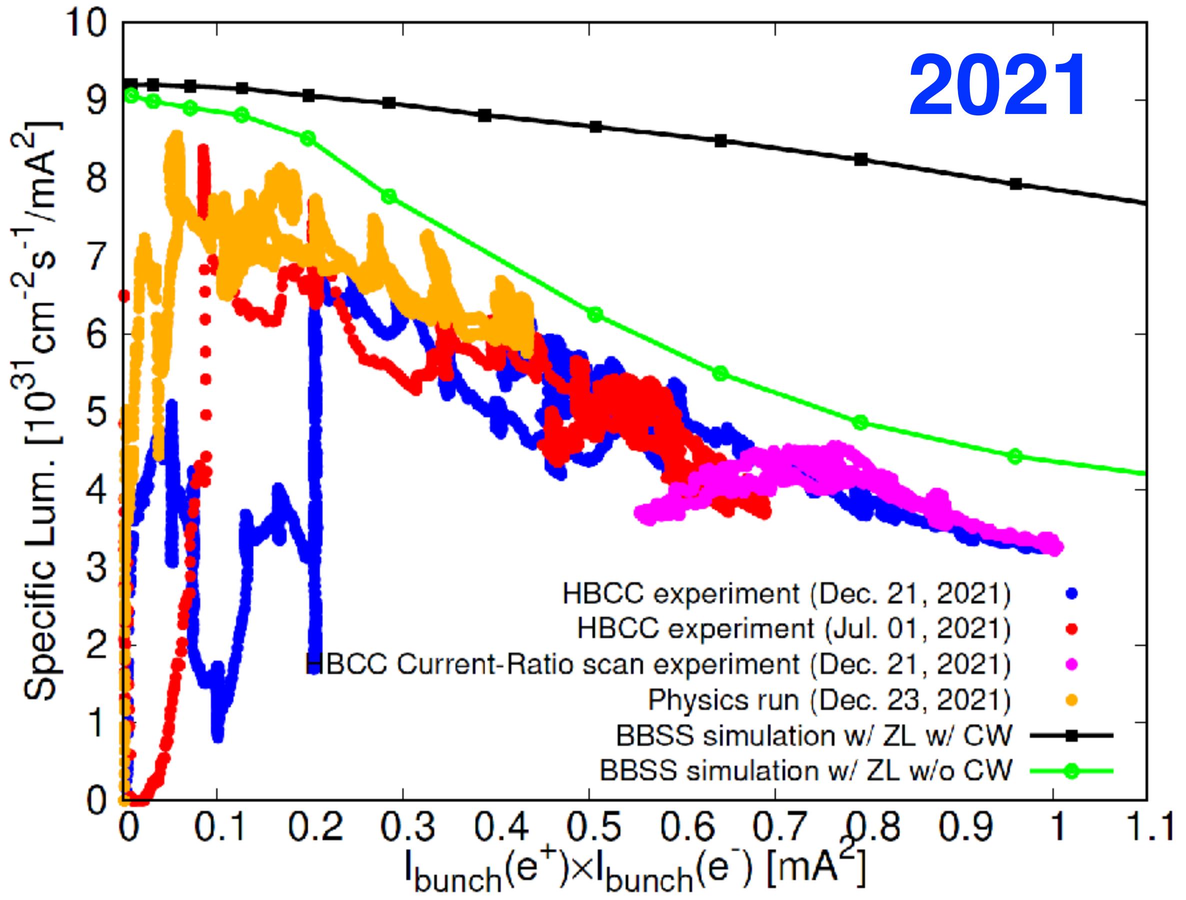



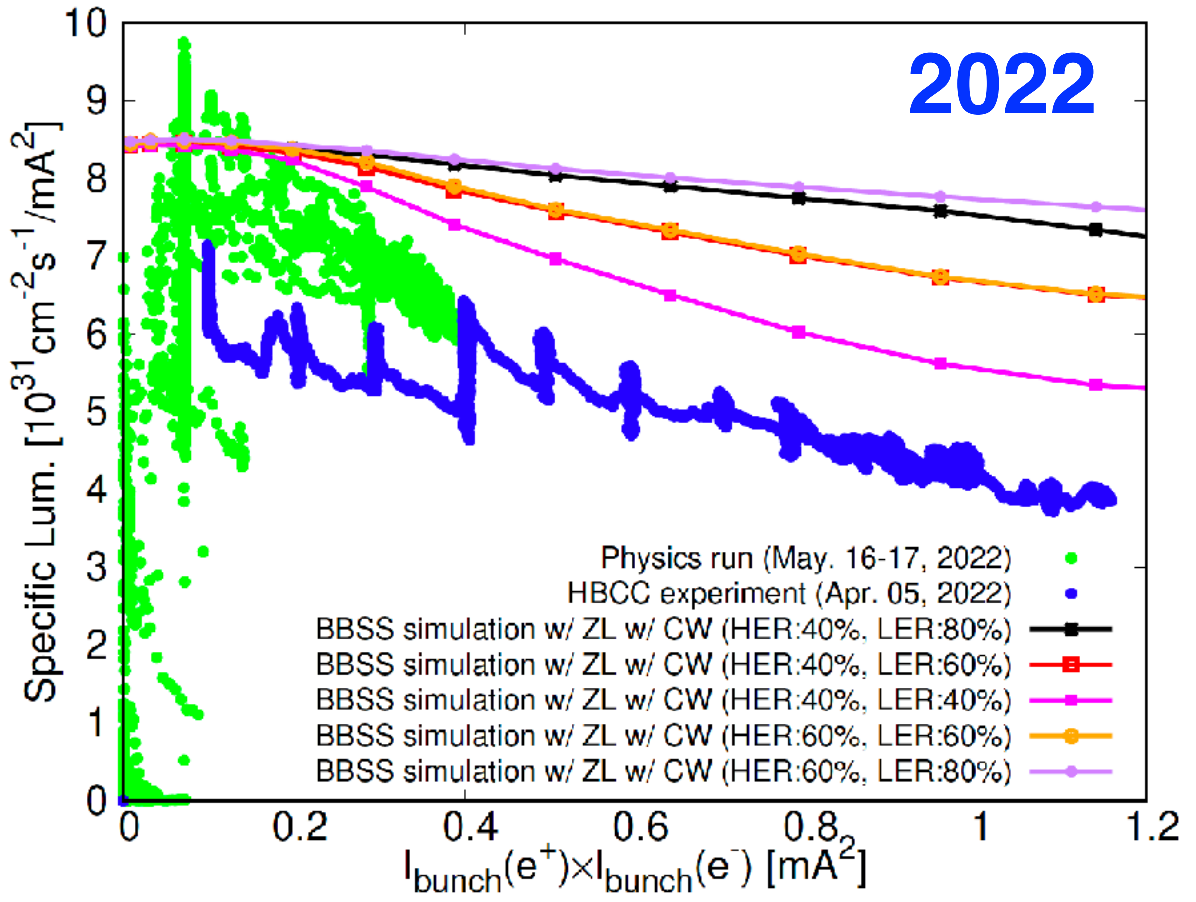

[1] D. Zhou et al., PRAB 26, 071001 (2023); [2] Y. Zhang et al., PRAB 26, 064401 (2023); [3] K. Ohmi et al., PRAB 26, 111001 (2023).

# Comparison of simulations and experimental results

- HBCC machine studies with $\beta_y^* = 1$ mm in 2021 and 2022 [1]:
  - 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

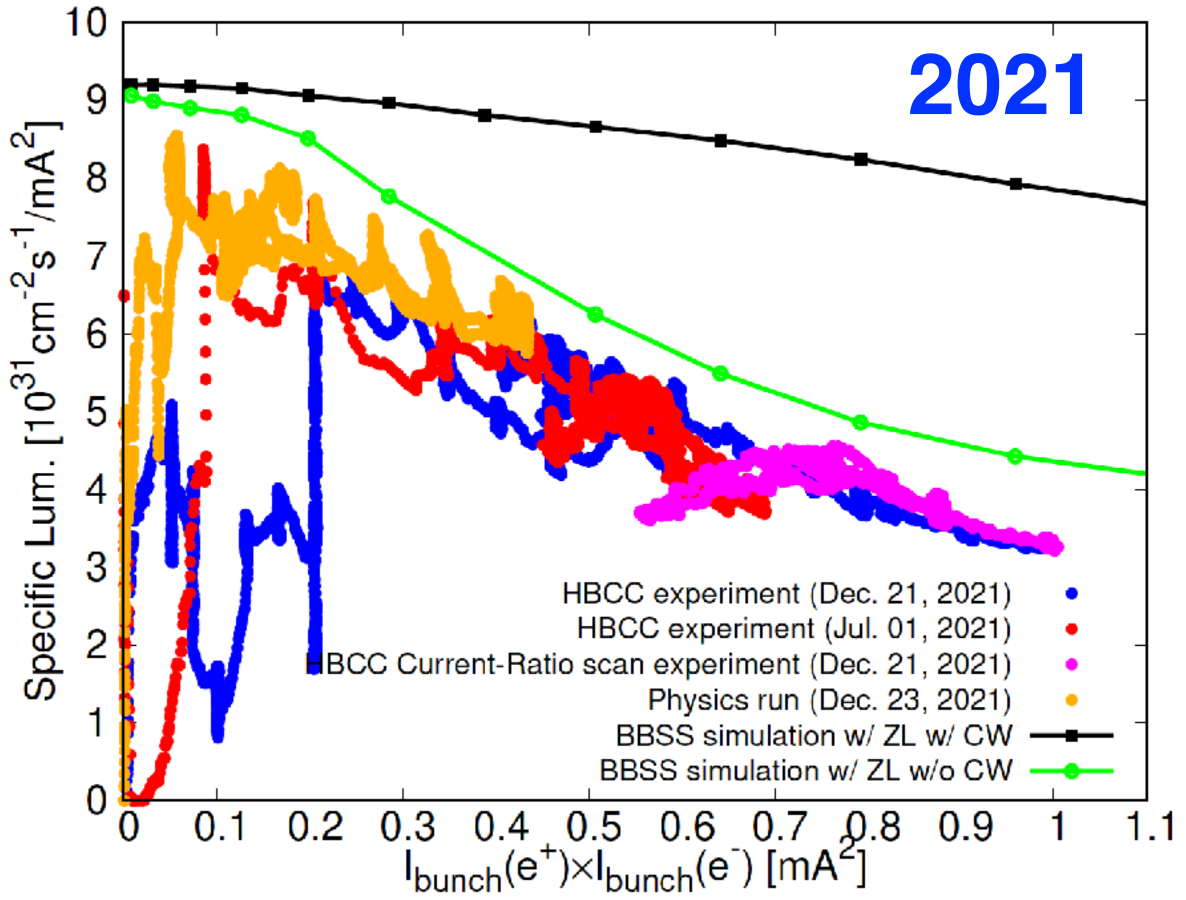


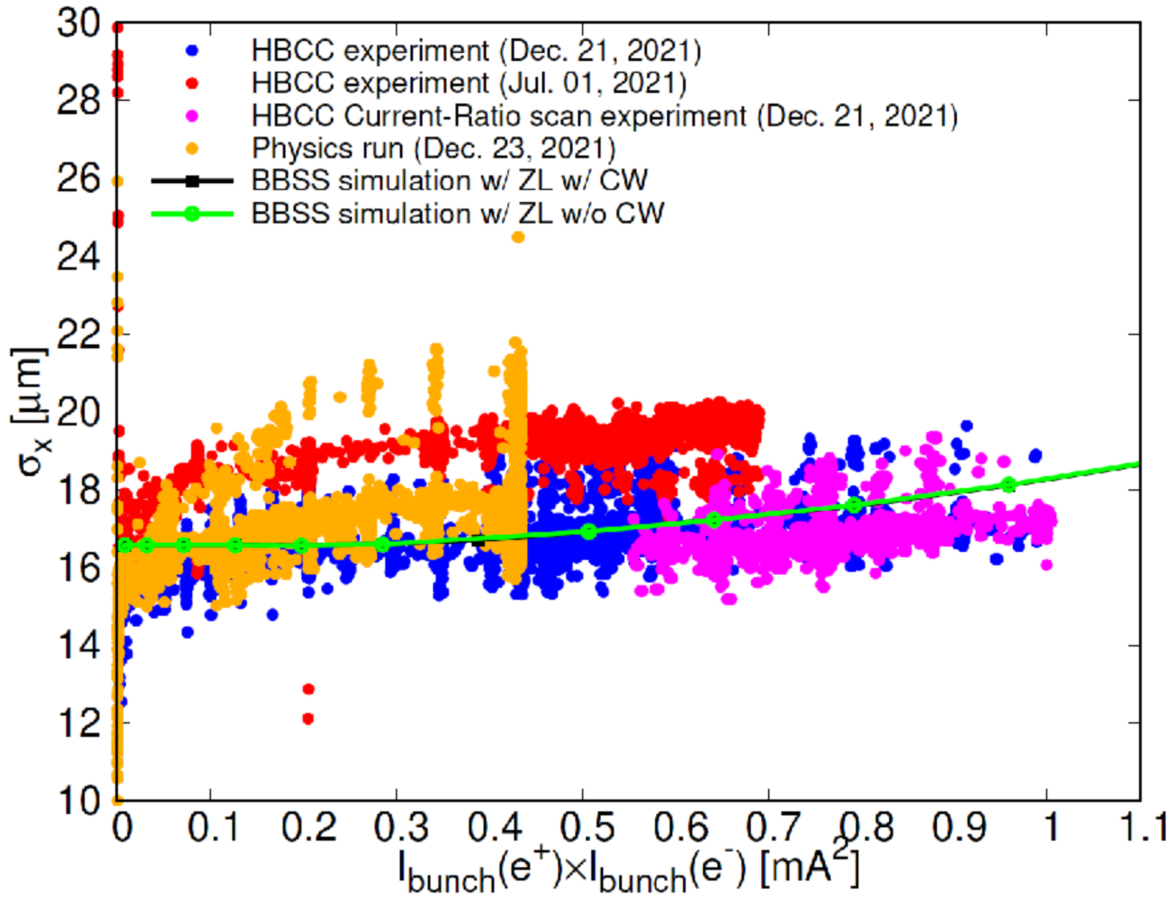

| | 2021.12.21 | | 2022.04.05 | | Comments |
|---|---|---|---|---|---|
| | HER | LER | HER | LER | |
| $I_{bunch}$ (mA) | Ie | 1.25*Ie | Ie | 1.25*Ie | |
| # bunch | 393 | | 393 | | Assumed value |
| $\varepsilon_x$ (nm) | 4.6 | 4.0 | 4.6 | 4.0 | w/ IBS |
| $\varepsilon_y$ (pm) | 35 | 20 | 30 | 35 | Estimated from XRM data |
| $\beta_x$ (mm) | 60 | 80 | 60 | 80 | Calculated from lattice |
| $\beta_y$ (mm) | 1 | 1 | 1 | 1 | Calculated from lattice |
| $\sigma_{z0}$ (mm) | 5.05 | 4.60 | 5.05 | 4.60 | Natural bunch length (w/o MWI) |
| $\nu_x$ | 45.53 | 44.524 | 45.532 | 44.524 | Measured tune of pilot bunch |
| $\nu_y$ | 43.572 | 46.589 | 43.572 | 46.589 | Measured tune of pilot bunch |
| $\nu_s$ | 0.0272 | 0.0233 | 0.0272 | 0.0233 | Calculated from lattice |
| Crab waist | 40% | 80% | 40% | 80% | Lattice design |

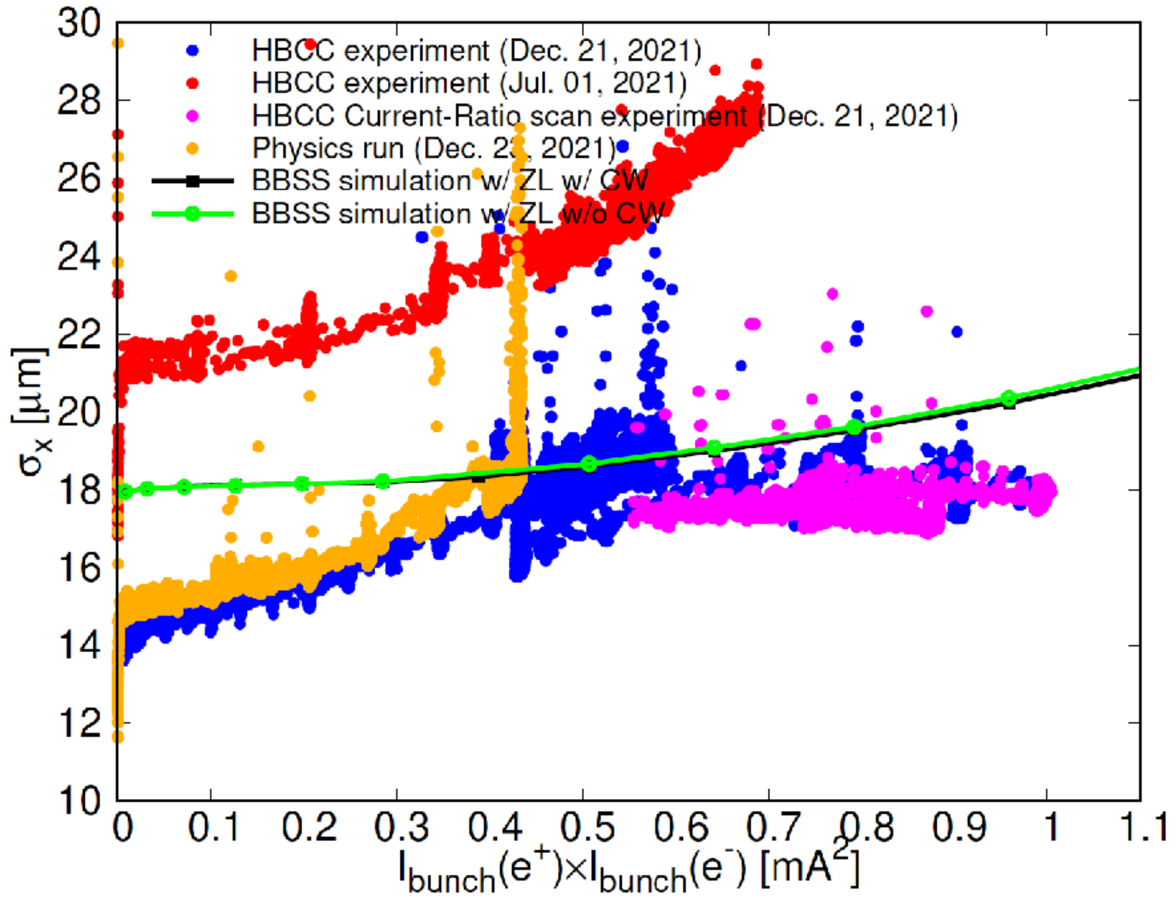
[1] D. Zhou et al., PRAB 26, 071001 (2023).

# Comparison of simulations and experimental results

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



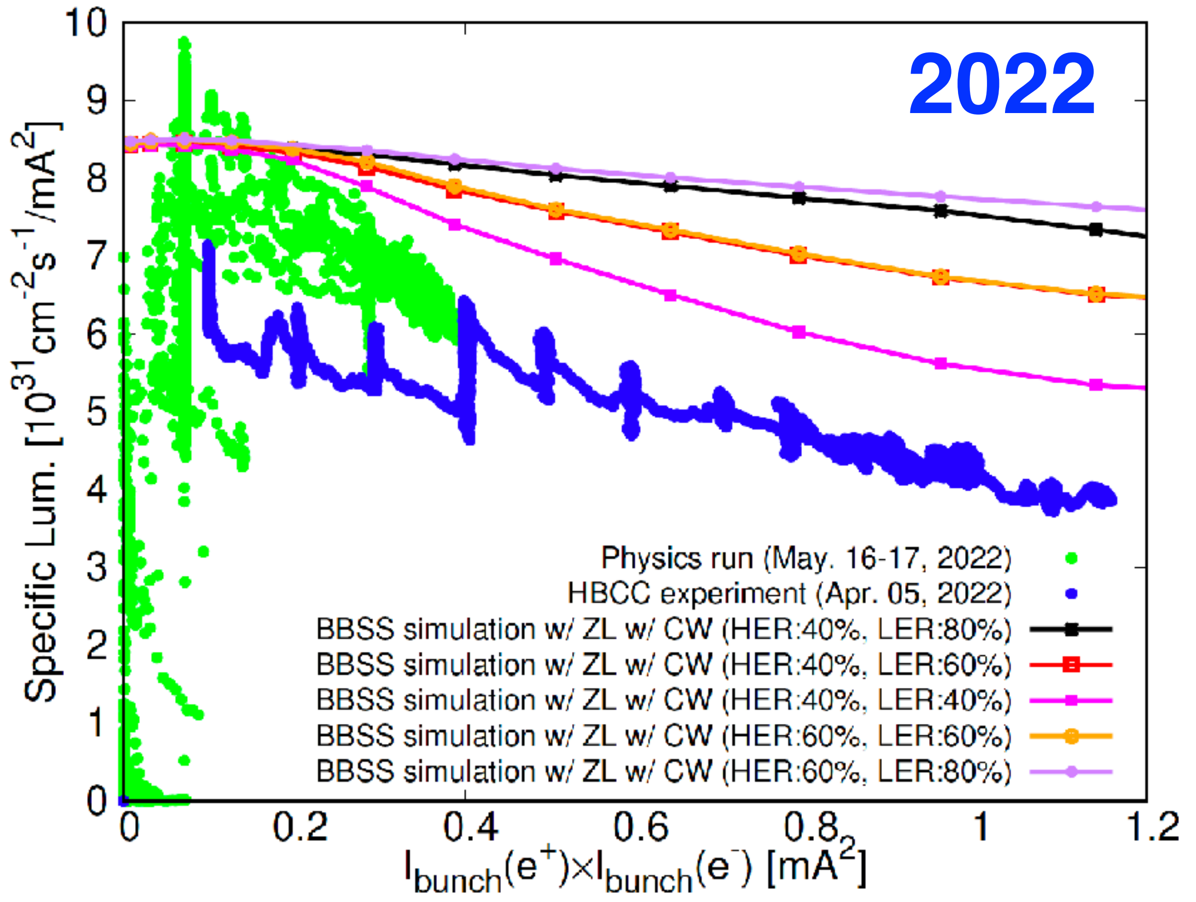



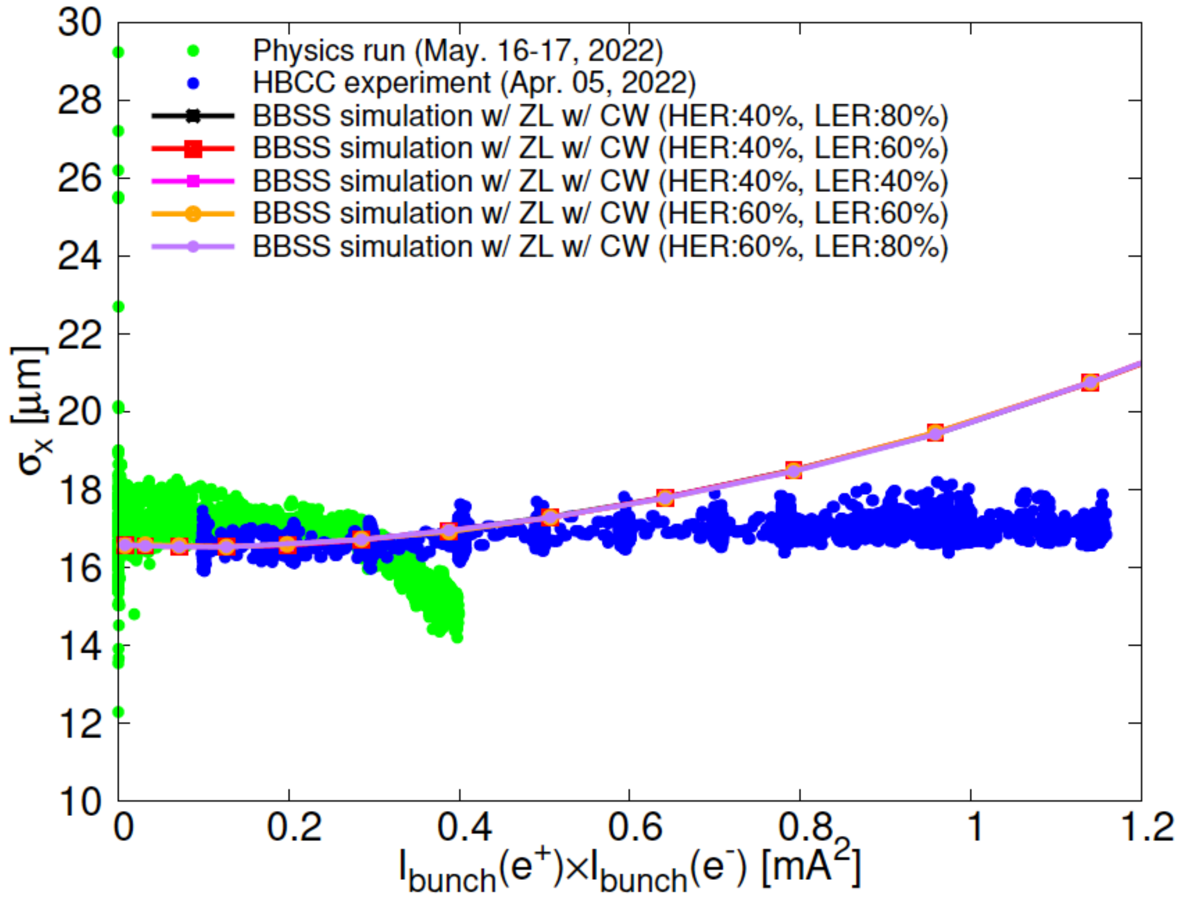



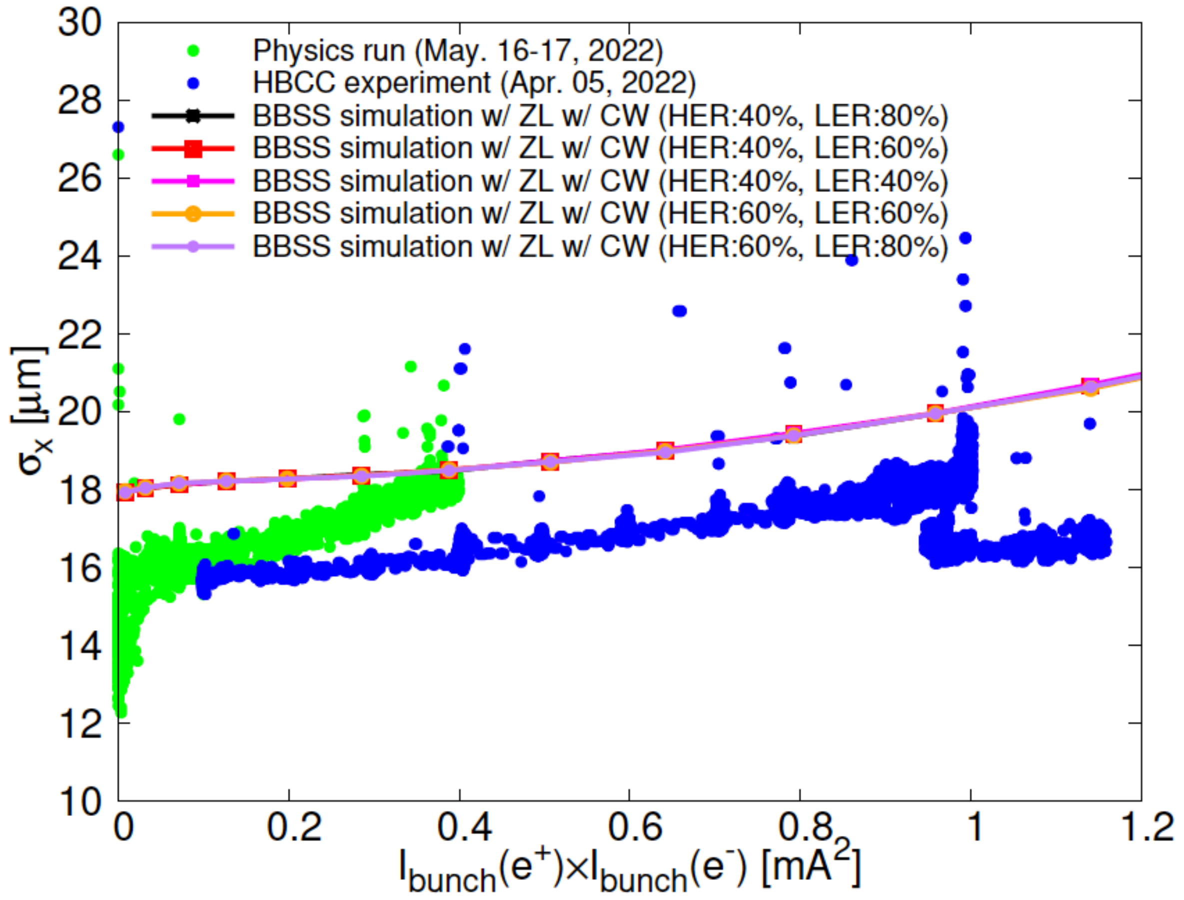

Specific luminosity

Electron $\sigma_x^*$

Positron $\sigma_x^*$



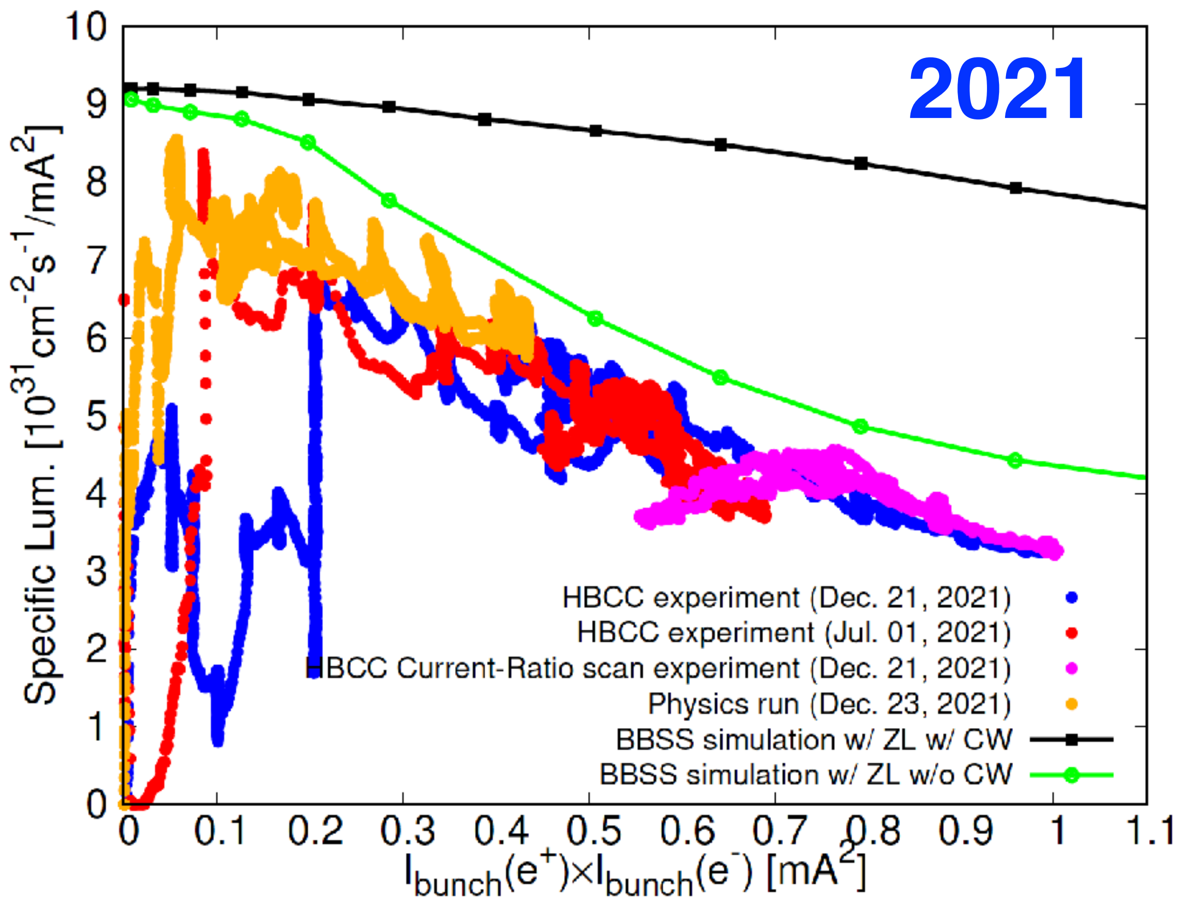



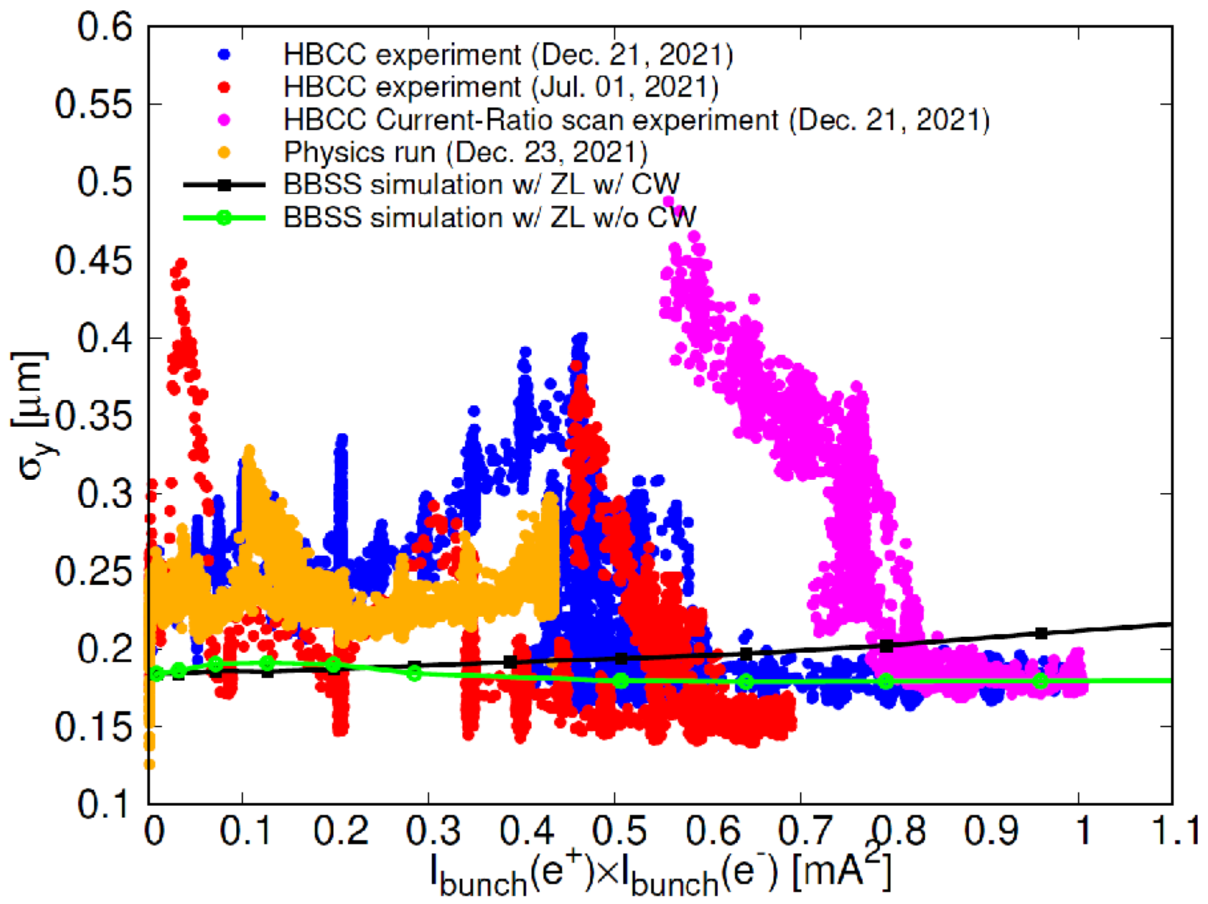



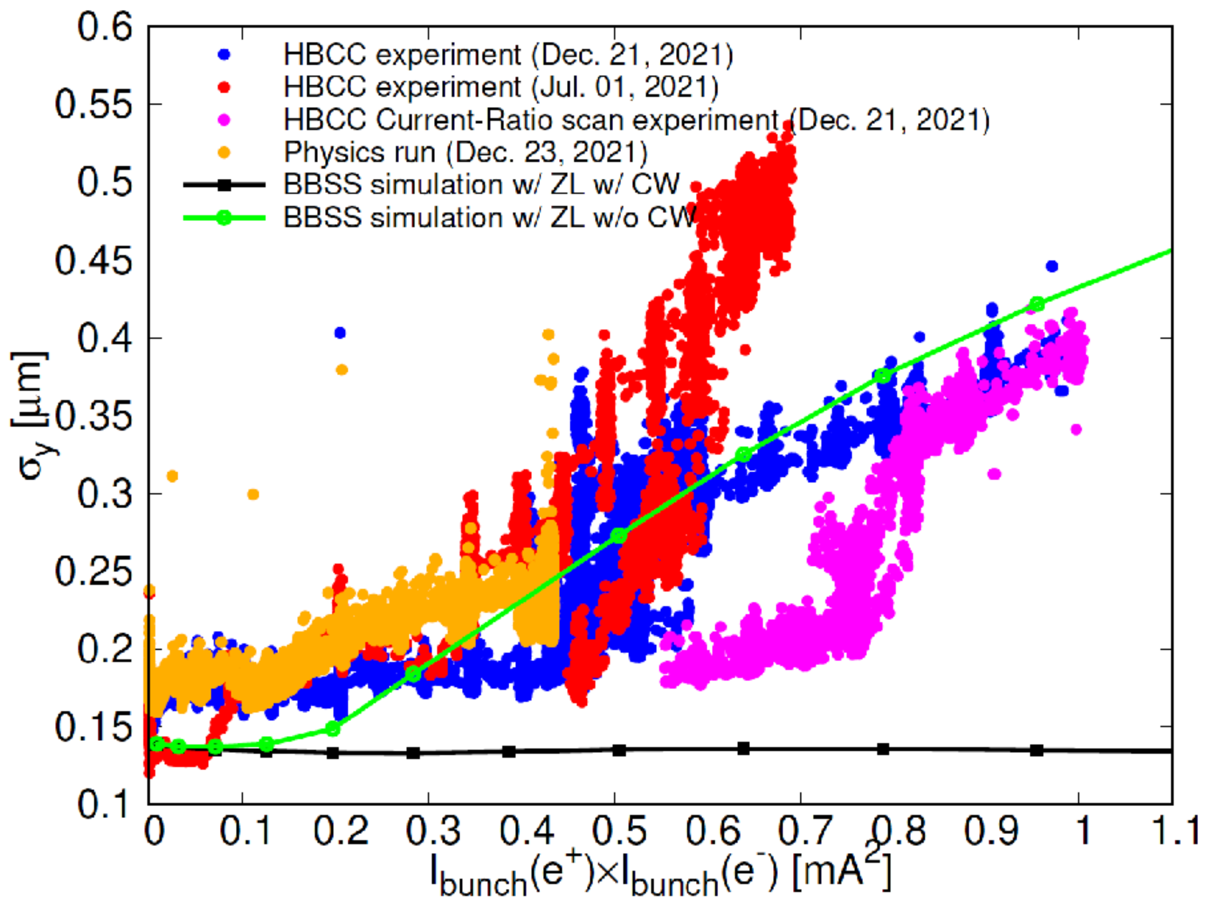

[1] D. Zhou et al., PRAB 26, 071001 (2023).

# Comparison of simulations and experimental results

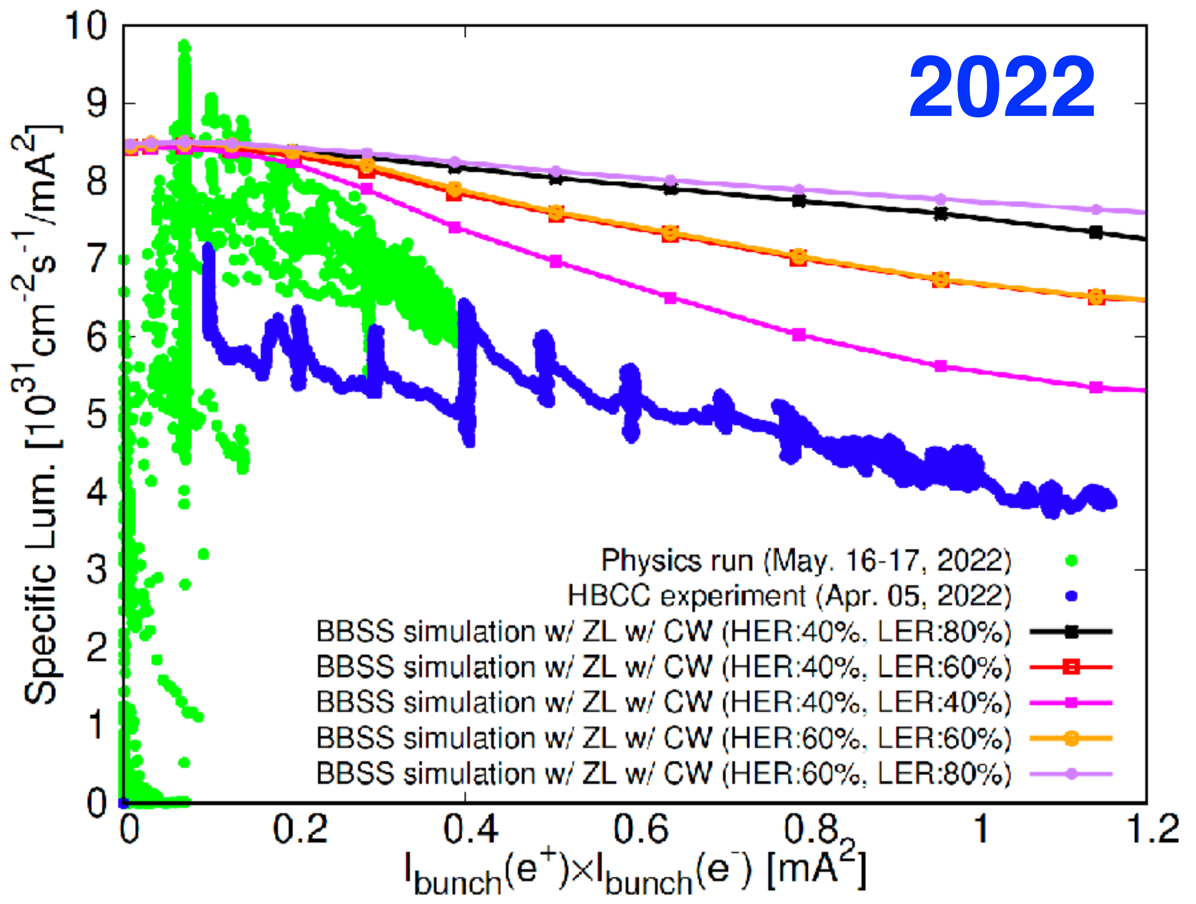
- HBCC machine studies with $\beta_y^* = 1$ mm in 2021 and 2022 [1]:
  - After fine-tuning of BxB FB system in 2022, observed vertical beam sizes blowup became much more “normal” and closer to simulations

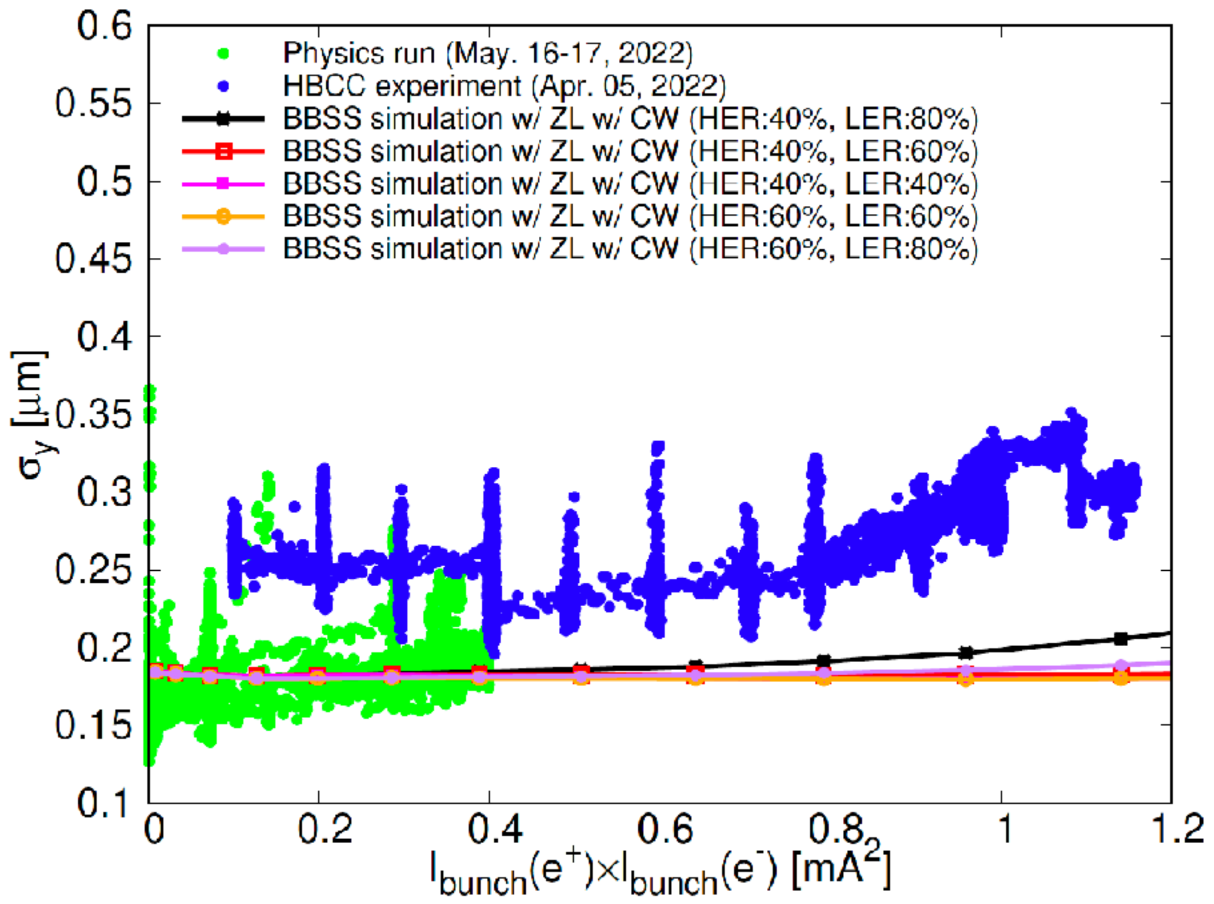


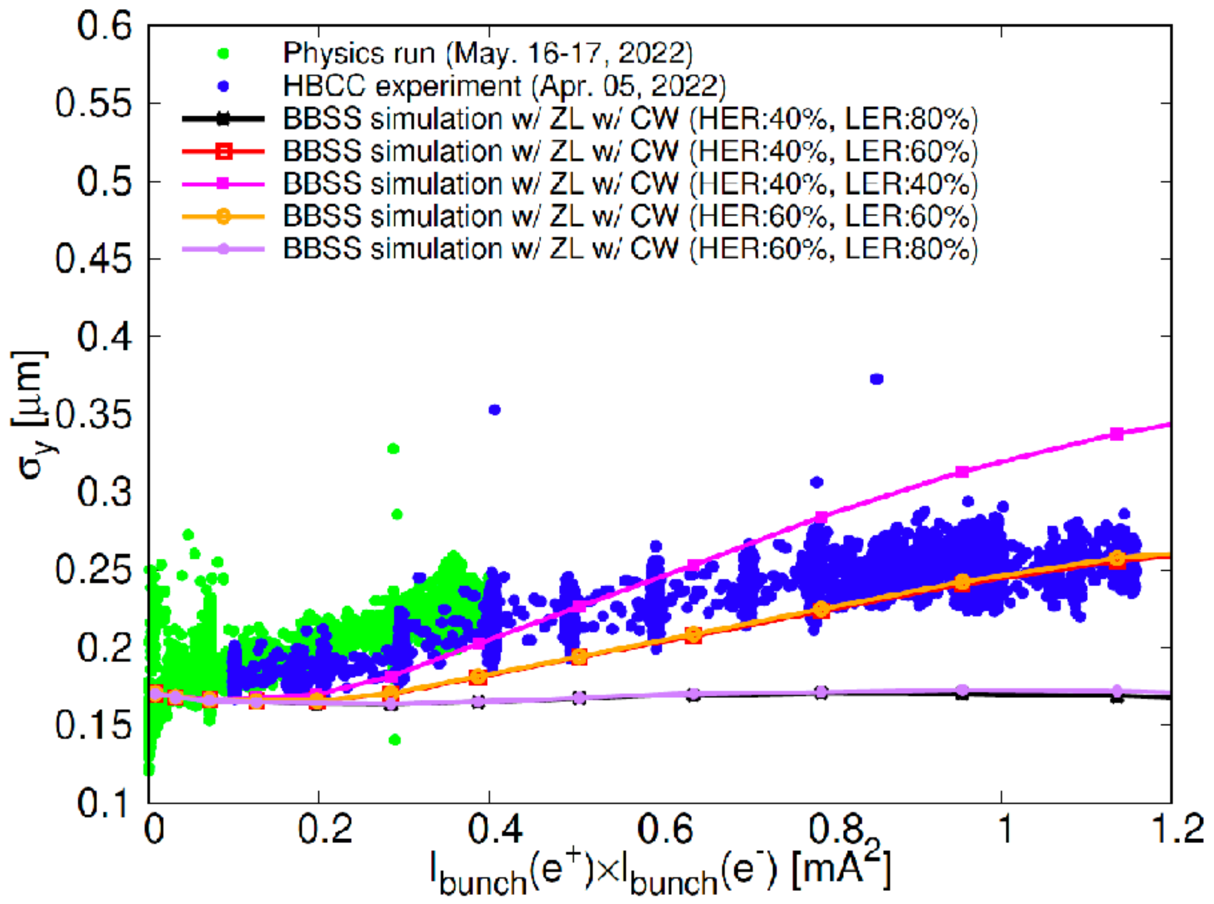




Specific luminosity | Electron $\sigma_y^*$ | Positron $\sigma_y^*$



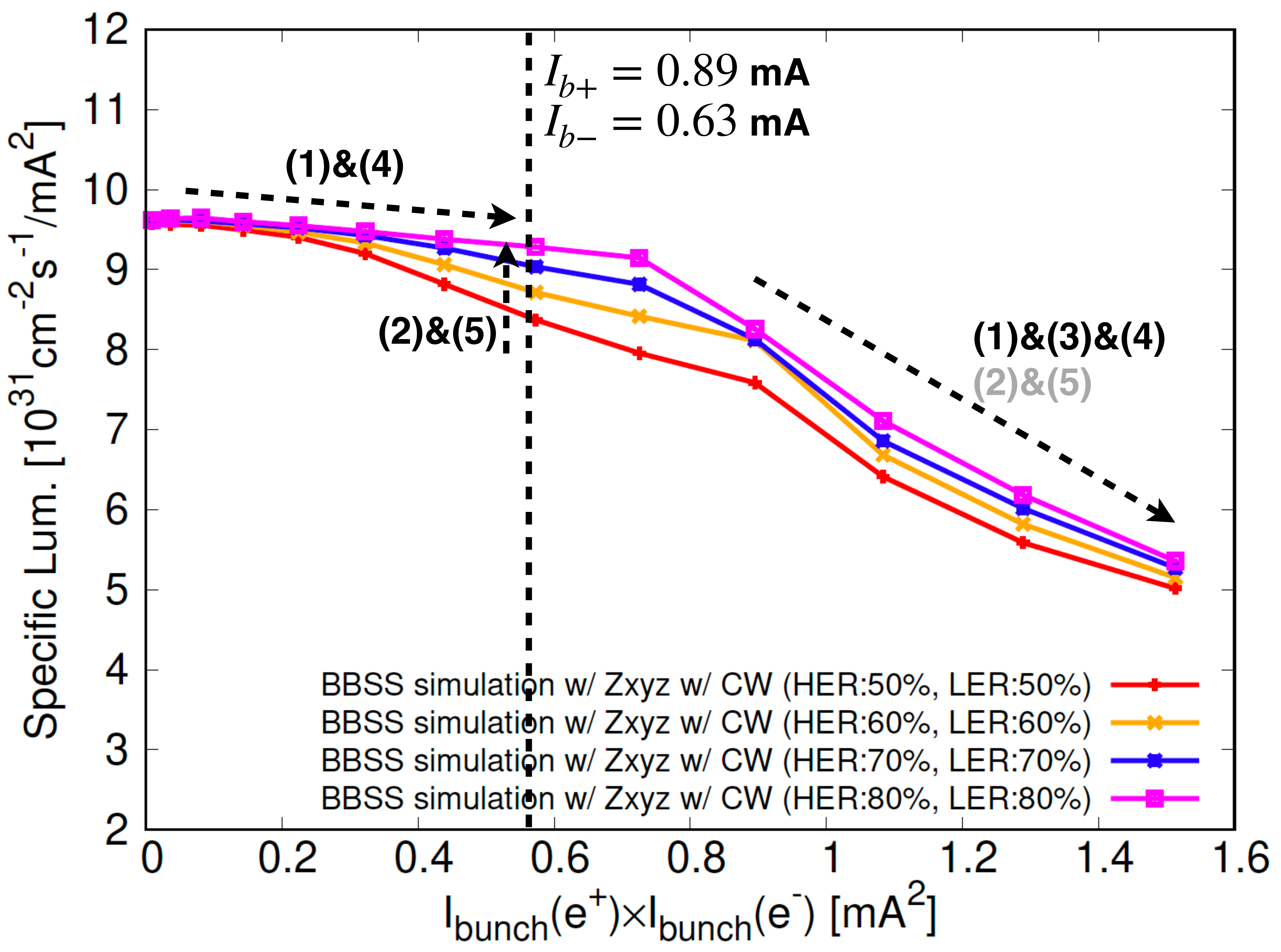




[1] D. Zhou et al., PRAB 26, 071001 (2023).

# Strong-strong beam-beam simulations for post-LS1 operation

- Beam-beam simulations for post-LS1 operation (1E35 luminosity). 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 [1,2]
  - (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

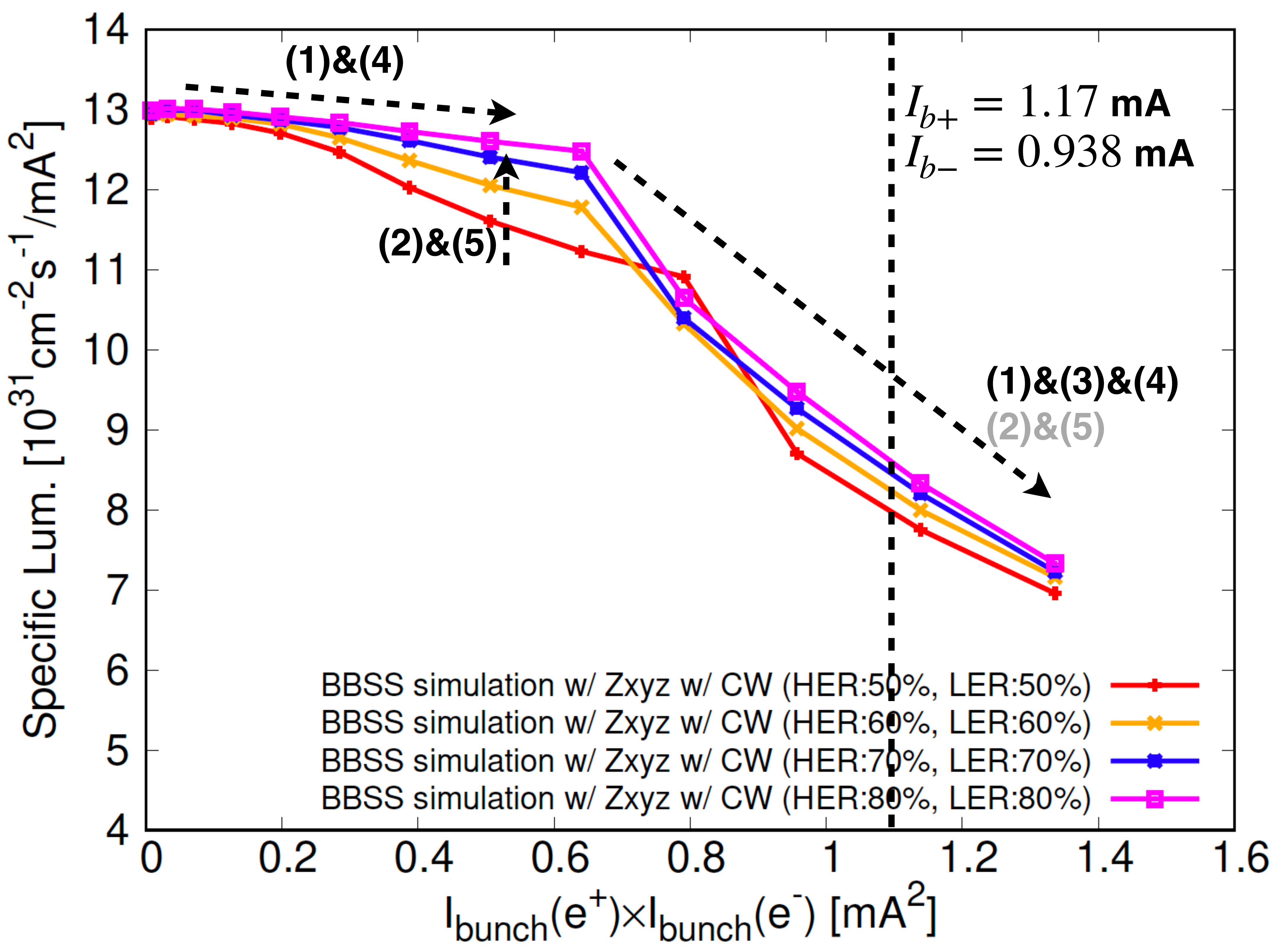



| | post-LS1 1E35 | | Comments |
|---|---|---|---|
| | HER | LER | |
| $I_{bunch}$ (mA) | 0.63 | 0.89 | |
| # bunch | 2345 | | 2022a operation value |
| $\varepsilon_x$ (nm) | 4.6 | 4.0 | w/o IBS |
| $\varepsilon_y$ (pm) | 30 | 30 | Single-beam emittance |
| $\beta_x$ (mm) | 60 | 60 | Lattice design value |
| $\beta_y$ (mm) | 0.8 | 0.8 | Lattice design value |
| $\sigma_{z0}$ (mm) | 5.1 | 4.6 | Natural bunch length (w/o MWI) |
| $\nu_x$ | 45.532 | 44.524 | 2022a operation value |
| $\nu_y$ | 43.574 | 46.589 | 2022a operation value |
| $\nu_s$ | 0.0272 | 0.0222 | Calculated from lattice |
| $\tau_{x,y}$ (ms) | 58.0 | 53.1 | Transverse damping time (w/ NLC) |
| $\tau_z$ (ms) | 29.0 | 26.6 | Longitudinal damping time |
| Crab waist | 80% | 80% | Lattice design |

[1] Y. Zhang et al., PRAB 26, 064401 (2023); K. Ohmi et al., PRAB 26, 111001 (2023).

# Strong-strong beam-beam simulations for post-LS1 operation

- Beam-beam simulations for post-LS1 operation (2.4E35 luminosity). 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 [1,2]
  - (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 |
| $\varepsilon_x$ (nm) | 4.6 | 4.0 | w/o IBS |
| $\varepsilon_y$ (pm) | 21 | 21 | Single-beam emittance |
| $\beta_x$ (mm) | 60 | 60 | Lattice design value |
| $\beta_y$ (mm) | 0.6 | 0.6 | Lattice design value |
| $\sigma_{z0}$ (mm) | 5.1 | 4.6 | Natural bunch length (w/o MWI) |
| $\nu_x$ | 45.532 | 44.524 | 2022a operation value |
| $\nu_y$ | 43.574 | 46.589 | 2022a operation value |
| $\nu_s$ | 0.0272 | 0.0222 | Calculated from lattice |
| $\tau_{x,y}$ (ms) | 58.0 | 53.1 | Transverse damping time (w/ NLC) |
| $\tau_z$ (ms) | 29.0 | 26.6 | Longitudinal damping time |
| Crab waist | 80% | 80% | Lattice design |

[1] Y. Zhang et al., PRAB 26, 064401 (2023); K. Ohmi et al., PRAB 26, 111001 (2023).

# Beam-beam related topics

- On beam-beam:
  - Mechanisms of pure beam-beam 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), Ohmi 2023 (PRAB)] (key issues: spread of synchrotron and vertical betatron tunes due to impedance)
  - On interplay of beam-beam and other problems (Zhou 2023 (PRAB))
    - 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]

# Summary

- Beam dynamics behind the luminosity at SuperKEKB (shared with future circular e+e- colliders)

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

$N_b$:
* Tolerance of hardwares
* Injection
* …

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

$\Delta^2$:
* Vertical orbit offset at IP
* Orbit feedback
* iBump fast feedback

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

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

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

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

# 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.