Overview of collective effects

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Acknowledgments

X. Wang, H. Sugimoto, K. Matsuoka, Y. Arimoto, K. Shibata,
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A. Blednykh, K. Bane, Y. Cai, M. Migliorati, P. Kicsiny, X. Buffat, F. Zimmermann,
members of SuperKEKB and Belle II teams

The 27th KEKB Accelerator Review Committee meeting, Mar. 26, 2024, KEK

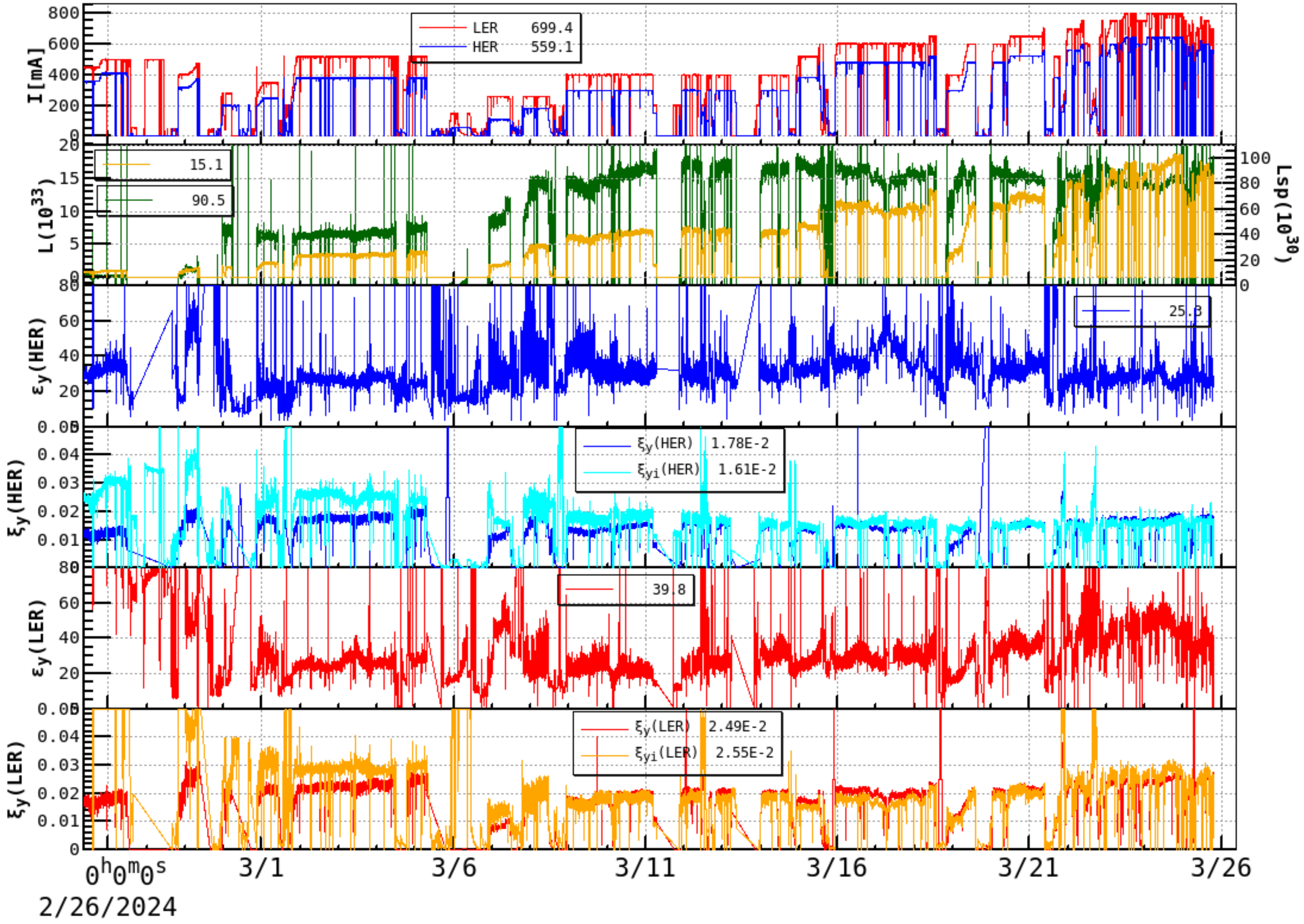
2024 updates: Conditions for discussing collective effects in SuperKEKB

- **Breakthroughs** in machine operation: Injection BG effects on **lum. measurement** removed (thanks to Belle II team); **Single-beam emittance** ϵ_y<20 pm (Talks by Y. Ohnishi and H. Sugimoto); **FB noises** significantly suppressed (Talk by G. Mitsuka); Impedance reduction by **NLC** installed in LER (Talk by S. Terui); Orbit control around **CW sextupoles** (Talk by Y. Ohnishi); Both LER and HER can operate around design **working point** (.53, .57) (Talk by Y .Ohnishi).

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

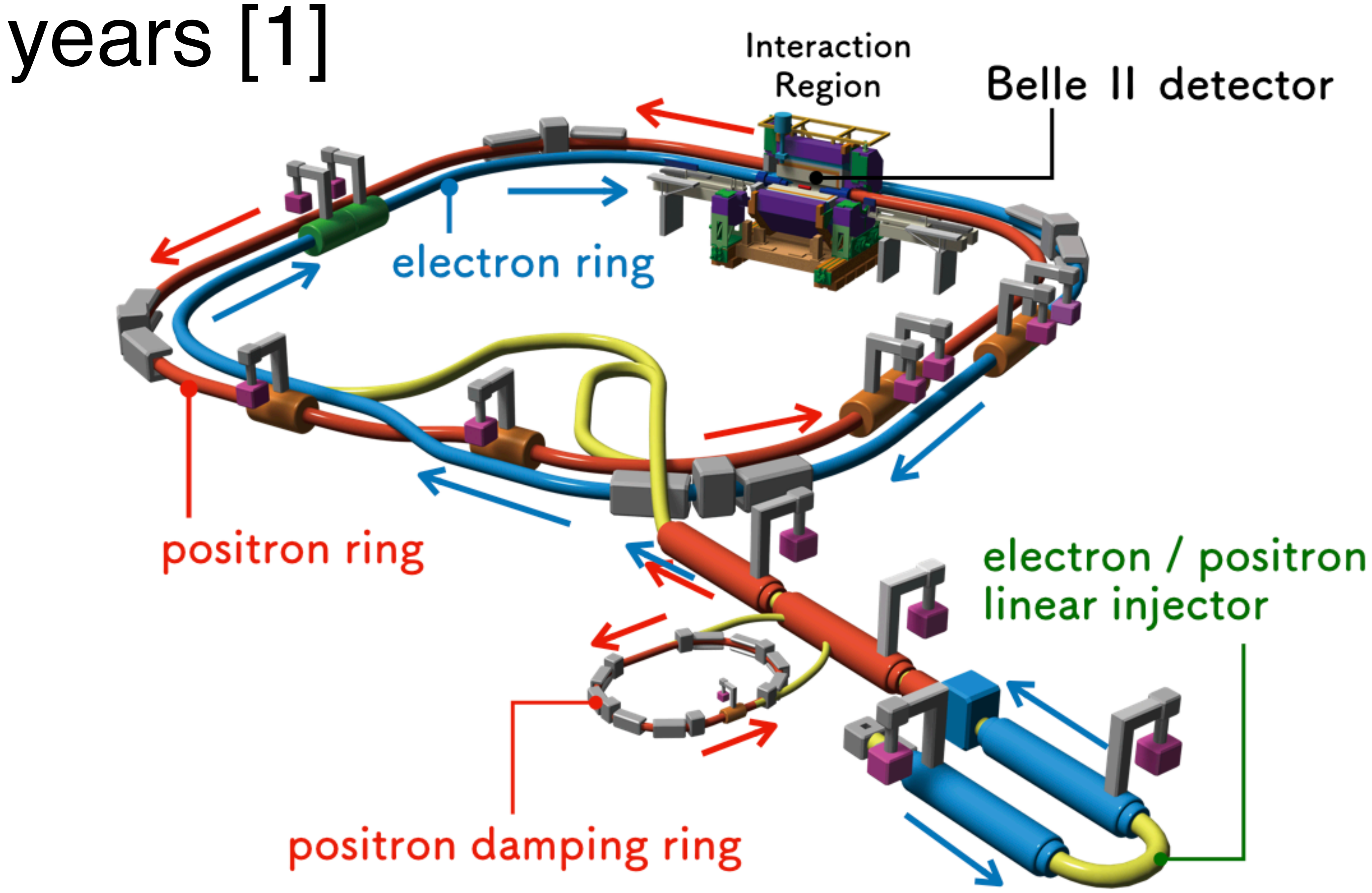
$$L = \frac{1}{2er_e}\frac{\gamma_\pm I_\pm}{\beta_{y\pm}^*}\xi_{y\pm}^L$$

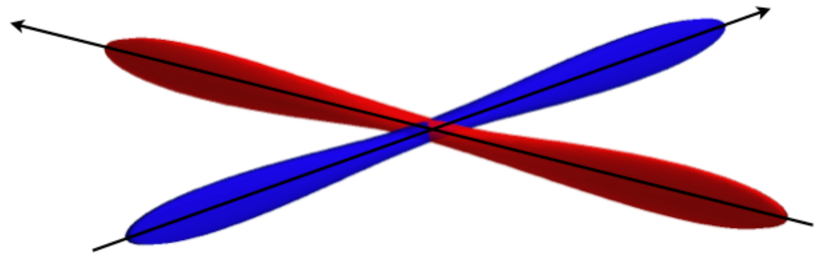
$$\xi_{yi\pm} \approx \frac{r_e}{2\pi\gamma_\pm}\frac{N_\mp \beta_{y\pm}^*}{\sigma_{y\mp}^*\sqrt{\sigma_{z\mp}^2\tan^2\frac{\theta_c}{2}+\sigma_{x\mp}^{*2}}}$$

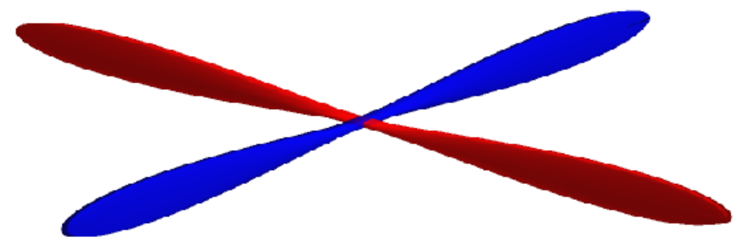


Collective instability mechanisms over the years [1]

- …
- 1960 resistive wall instability
- …
- 1969 head-tail instability
- 1969 microwave instability
- …
- 1971 beam-beam limit in colliders
- 1971 potential well distortion
- …
- 1980 transverse mode coupling instability
- …
- 1990 coherent synchrotron radiation instability
- …
- 1996 electron beam-ion instability
- 1997 electron cloud instability
- …
- 2013 **interplay of multiple instability mechanisms**




SuperKEKB (2021c)


SuperKEKB (Final design)

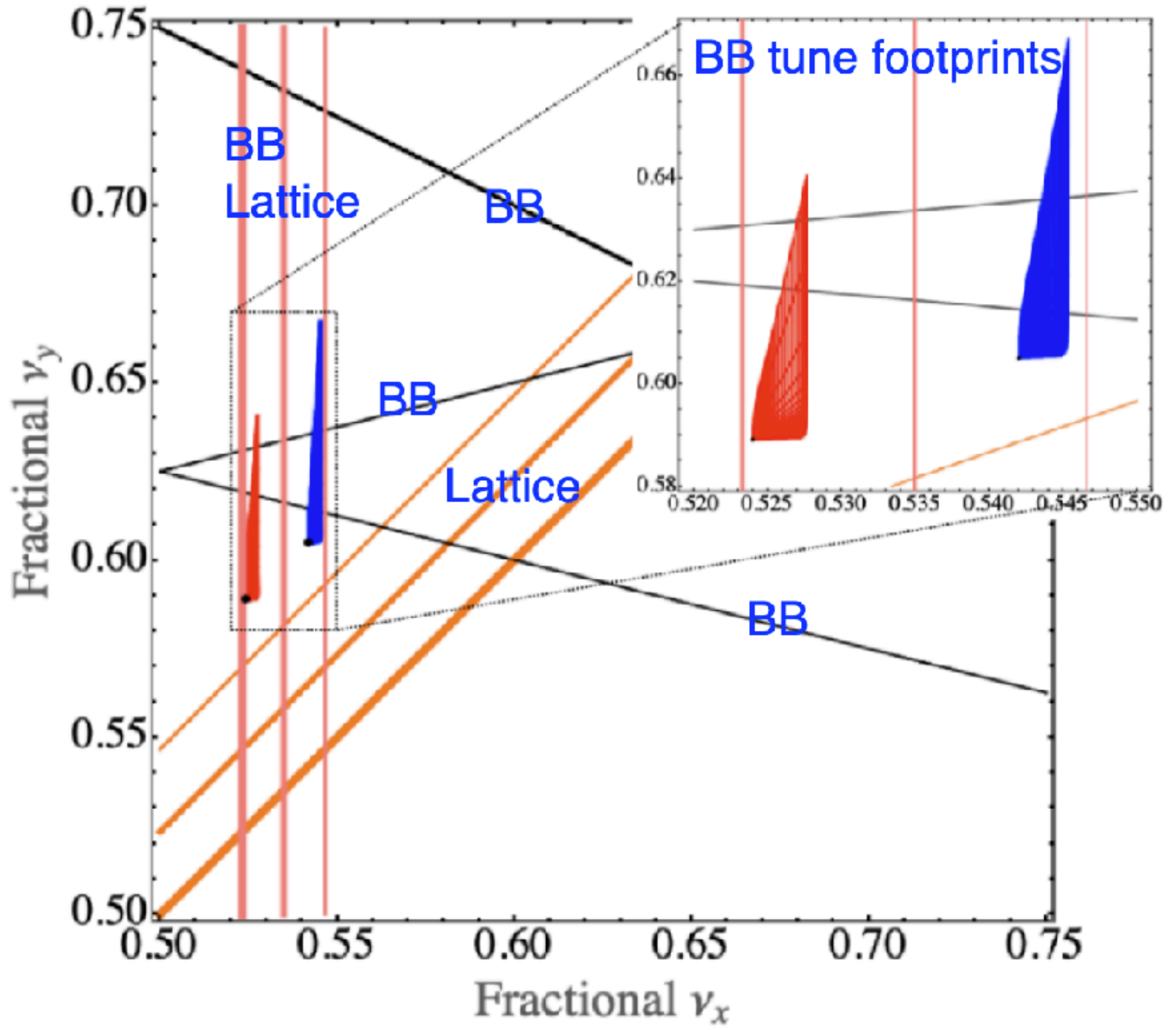
$$L \approx \frac{N_b N_+ N_- f}{2\pi \sqrt{\sigma_{y+}^{*2} + \sigma_{y-}^{*2}} \sqrt{\sigma_{z+}^2 + \sigma_{z-}^2} \tan\frac{\theta_c}{2}} e^{-\frac{\Delta_y^2}{2(\sigma_{y+}^{*2} + \sigma_{y-}^{*2})}}$$

Interplay (of multiple physics aspects) is the buzzword.
It essentially defines the luminosity performance of SuperKEKB [2].

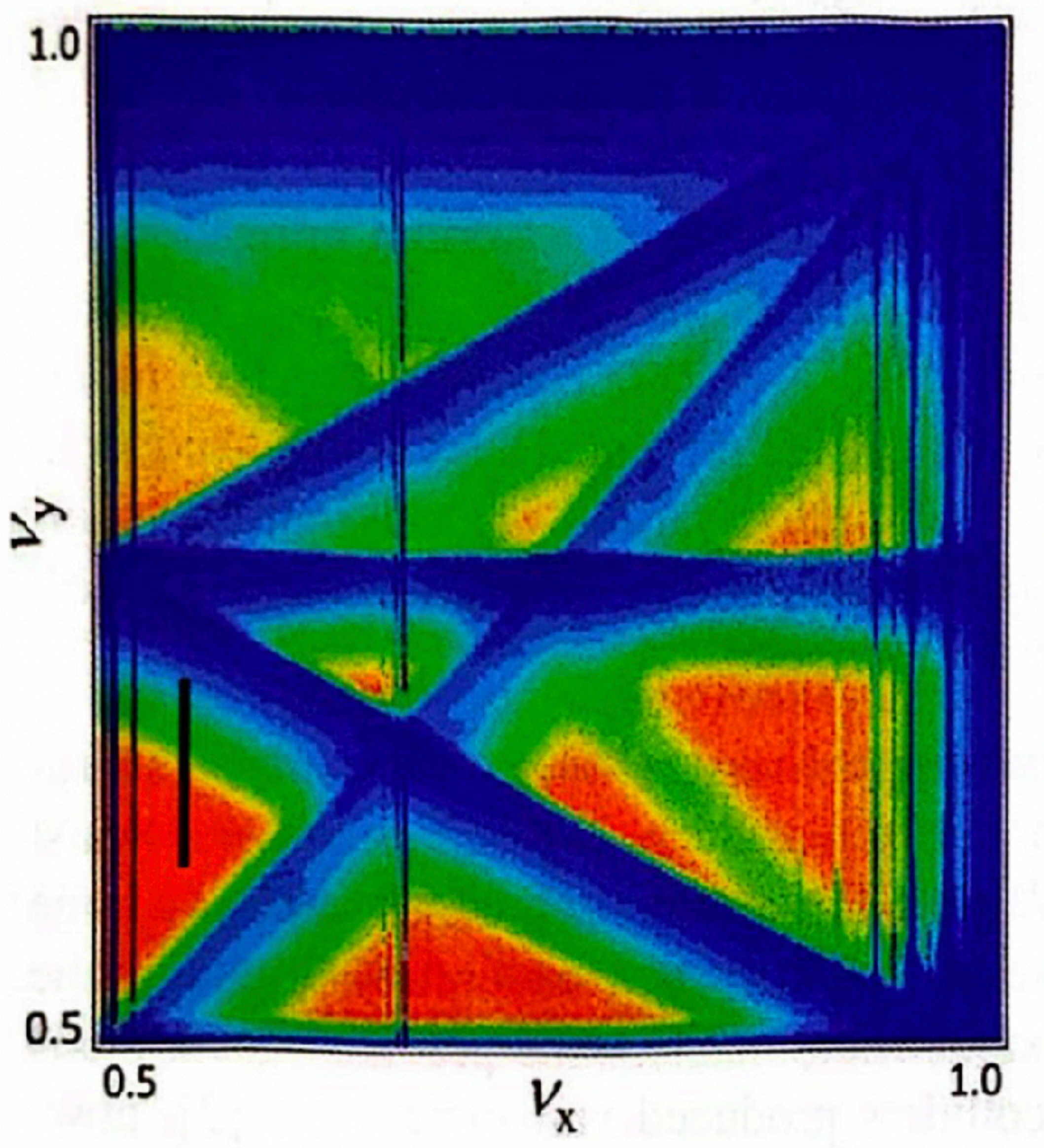
[1] A. Chao, "Lectures on accelerator physics", World Scientific, 2020. [2] D. Zhou et al., PRAB 26, 071001 (2023).

On beam dynamics

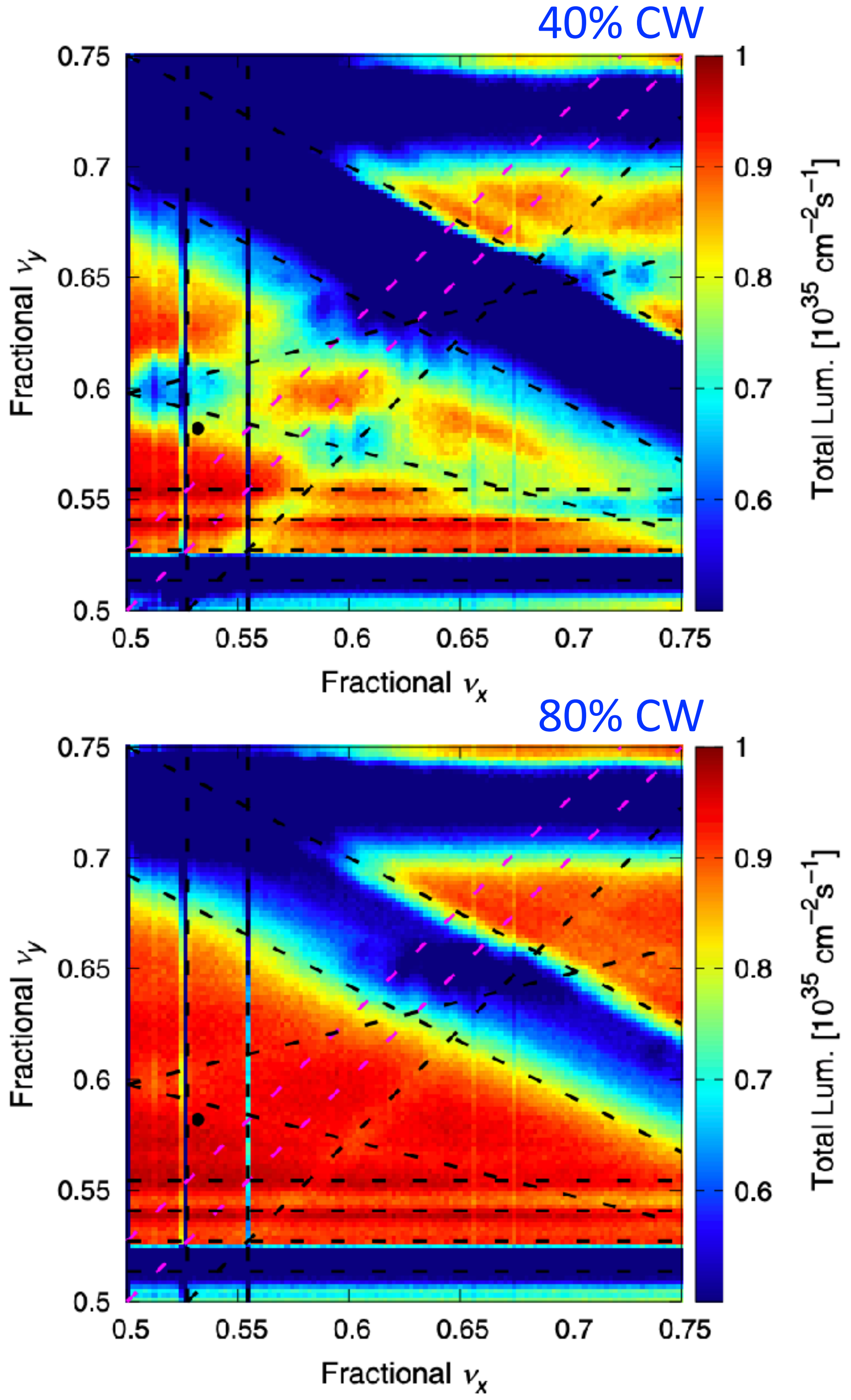
- “The beam dynamics is all contained in ψ.” (P. 196, [1])
- Beam-beam and its interplay with other physics aspects
  - For crab-waist colliders, beam-beam couples with other nonlinear problems.
  - The key is looking at $m\nu_x + n\nu_y + k\nu_s = N$, considering the tunes as functions of many variables $\nu_{x\pm,y\pm,s\pm}(I_{b\pm}, I_{b\mp}, J_{x\pm,y\pm,z\pm}, \beta^*_{x\pm,y\pm}, \beta^*_{x\mp,y\mp}, \epsilon_{x\mp,y\mp}, \ldots)$ due to multiple beam physics aspects.
  - For coherent instabilities, one should look at coherent tunes.
  - For incoherent (weak-strong) effects, one should look at incoherent tunes.
- SuperKEKB is comprehensible
  - At SuperKEKB, multiple dynamics and hardware problems couple with each other.
  - The key is to decouple (solve) the problems one by one.



Tune diagram for SuperKEKB LER [2]



Luminosity of crab-waist colliders [3]



SuperKEKB HER [2]

[1] A. Chao, “Lectures on accelerator physics”, World Scientific, 2020. [2] D. Zhou et al., PRAB 26, 071001 (2023).
[3] D. Shatilov and A. Valishev, Sec. 4.11.1 of “Handbook of Accelerator Physics and Engineering”, World Scientific, 2023.

CHECKLIST

- MAC comments
- ITF activities on collective effects
- Potential well distortion and microwave instability
- Transverse modeling coupling instability and “-1 mode instability”
- Resistive wall instability
- Electron cloud
- IR nonlinearity
- Combined effects of beam-beam and impedances
  - Coherent X-Z instability
  - Synchrobetatron resonances
  - Beam-beam mode coupling
- Recent beam-beam machine studies
- Perspective on 1E35 luminosity

Only **luminosity** is of concern, impact of collective effects on **beam lifetime, injection, and detector background** is also important, but not covered in this talk.

MAC comments

20. Beam-Beam Experiment and Simulations

Findings & comments:

SuperKEKB operates with the nanobeam plus crab-waist scheme, with a large Piwinski angle. Vertical emittance is critical. At the time of the luminosity record, the vertical emittances were of order 50-60 pm, still much larger than design. After tuning of the bunch-by-bunch feedback the agreement of simulations and measurements has much improved. Actual specific luminosity is some 5%-50% worse than predicted by simulations, perhaps due to insufficient tuning during the high bunch current machine study, but the almost constant value of the specific luminosity towards high bunch-current products is consistent with expectation. The measured specific luminosity does not seem to depend on the number of bunches. There is no evidence that SuperKEKB has already reached the beam-beam limit. In machine studies with fewer bunches, vertical beam-beam tune shifts of 0.056 and 0.043 could be achieved. A correlation between top-up injection and specific luminosity was observed. The LER injection kicker contributed to ~3% of luminosity loss.

Multi-physics beam-beam simulation code development including the nonlinear lattice, space charge, and impedance effects, etc., is proceeding at KEK. Similar complementary efforts are underway in Europe, China and the US.

A path to the design luminosity was outlined, with 3.3 times smaller β_y^*, 2.5 times higher beam-beam tune shift, and 2.5 times higher LER beam current.

A significant IR upgrade is required to achieve 0.3 mm β_y^*. The IR upgrade should avoid overlapping solenoid and quadrupole fields. It could, e.g., be based on CCT magnet technology.

Recommendations:

R20.1: Develop a concrete IR upgrade proposal and demonstrate the expected performance gain through comprehensive simulations including beam-beam, nonlinear lattice, and impedance.

Response:

* On "IR upgrade proposal", see M. Masuzawa's talk to this meeting.

* On "comprehensive simulations":
  - K. Ohmi's **STCR-CUDA** and Z. Li's **APES-T** (IHEP) are ready for strong-strong (PIC) simulations with full lattices (KEK-IHEP collaboration). Further efforts wished: 1) Simplified SuperKEKB lattices to speed up lattice trackings; 2) **GPU** parallel computers to be managed.
  - **Xsuite** (CERN, P. Kicsiny, X. Buffat, et al.) has been applied to SuperKEKB (beam-beam + impedances, KEK-CERN collaboration) with support of EAJADE program. Further efforts wished: 1) Modeling SuperKEKB lattices in Xsuite. 2) …
  - **Overview of collective effects** (this talk).

ITF activities on collective effects [1]

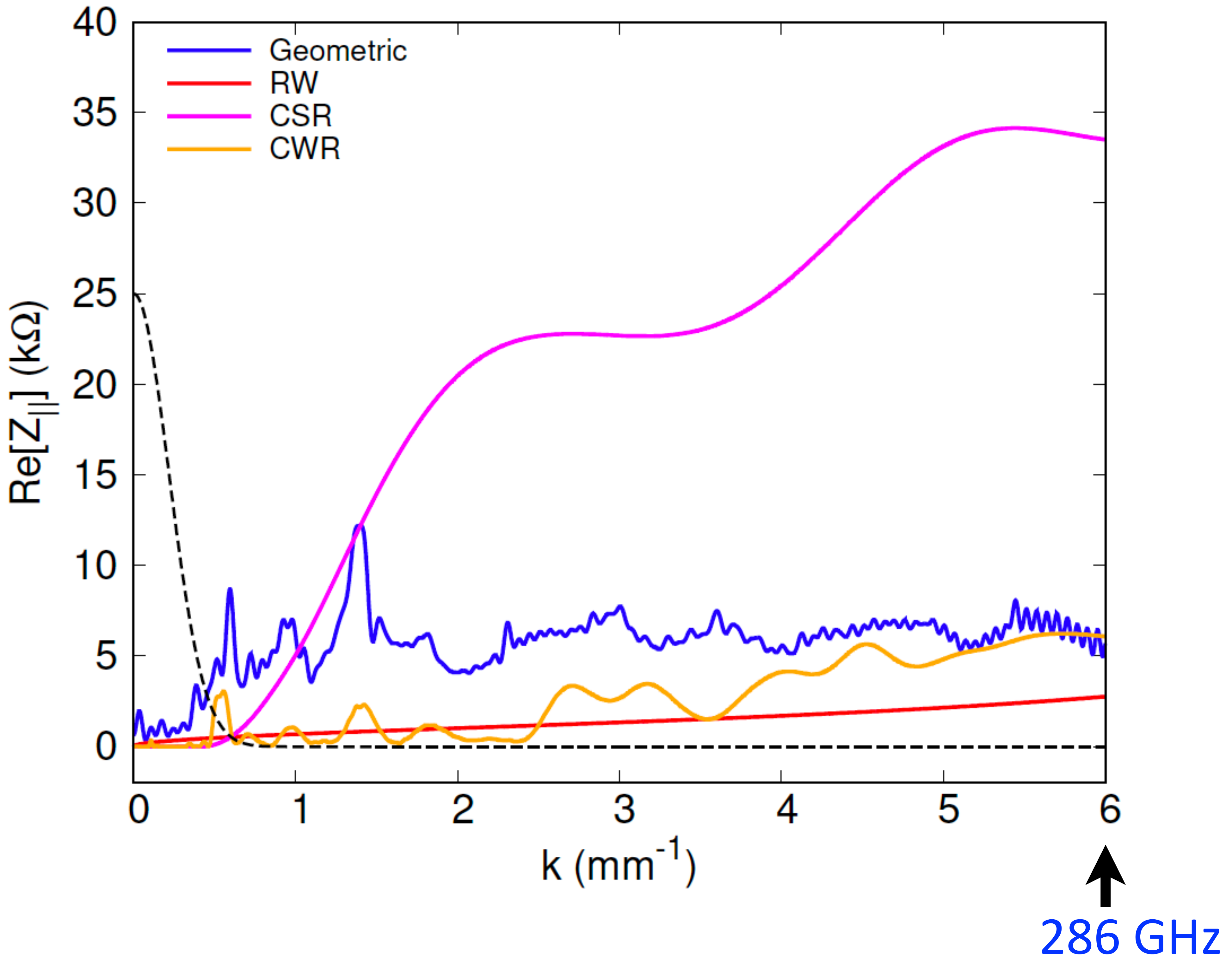
- 2021-2022 (chair: M. Masuzawa)
  - TMCI ITF subgroup, led by T. Ishibashi and M. Migliorati
    - Achievements: Detailed impedance database constructed [2], “-1 mode instability” identified to be an interplay of vertical impedance effect and BxB feedback system, accurate predictions of impedance-driven tune shifts, …
  - Beam-beam ITF subgroup, led by D. Zhou and K. Ohmi
    - Achievements: Comprehension of beam-beam effects in SuperKEKB, effective international collaborations (KEK/IHEP/CERN), …

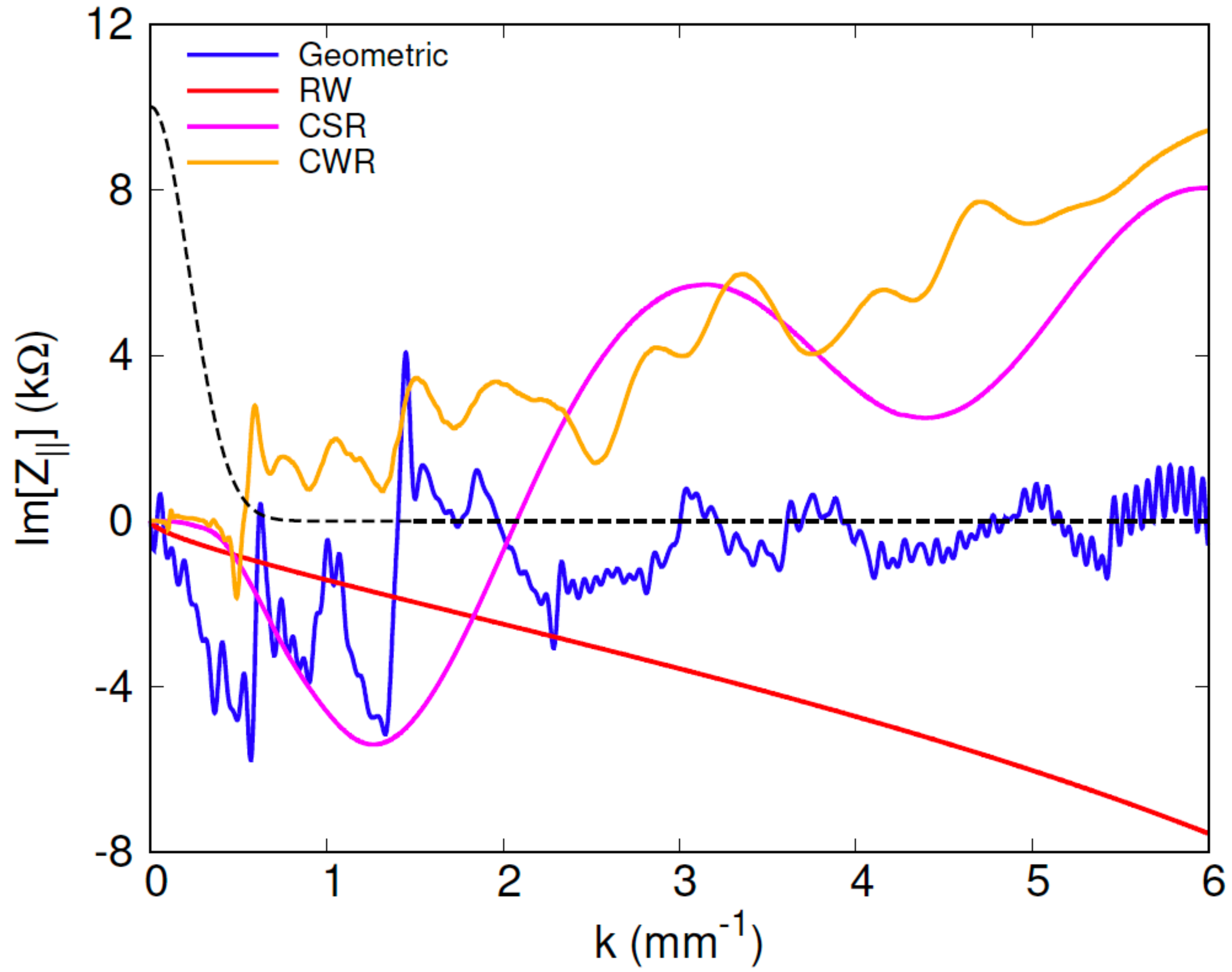
- 2023- (chair: Y. Ohnishi [3])
  - Collective effects ITF subgroup, led by G. Mitsuka, T. Ishibashi, M. Migliorati, N. Wang, D. Zhou.
    - Achievements on impedance effects: Detailed impedance modeling w/o and w/ NLC, predictions of impedance effects, investigations of impedance measurements (streak camera, BPM, etc.), machine study planning, …
    - Achievements on beam-beam effects: Detailed theory/simulation investigations followed by publishing series of papers (K. Ohmi served as a leading role), machine studies, …
  - IR-Upgrade ITF subgroup, led by D. Zhou and X. Wang
    - This IR-Upgrade ITF subgroup **investigates IR upgrade in 2030s**, not LS2 (see [4] for IR upgrade during LS2)
    - Achievements: Comprehension of IR complexity, challenges in IR upgrade, …

[1] https://kds.kek.jp/category/2242/. [2] https://kds.kek.jp/event/40318/. [3] Y. Ohnishi, “ITF”, Talk to this meeting. [4] M. Masuzawa, “LS2”, Talk to this meeting.

Potential well distortion and microwave instability

- Since 2021, T. Ishibashi has been serving as “impedance manager” for SuperKEKB
  - Reliable impedance models (**reproducing measure tune shifts very well**, though plausible discrepancy in predicting measured bunch lengthening) have been constructed and applied to simulations
- Impedance modeling: SuperKEKB LER as an example
  - Geometric wakes by GdfidL, CST, and ECHO3D [1]; RW by IW2D [1]; CSR/CWR by CSRZ





[1] T. Ishibashi et al. 2024 JINST 19 P02013.

Potential well distortion and microwave instability

- To bridge the gap between computations and beam-based measurements
  - Theories of potential-well bunch lengthening and phase shift revisited [1]
  - Continuous efforts on searching for overlooked impedance sources [2]
  - Continuous efforts on examining systematic errors in streak camera measurements [3]
- In general, the computation-experiment gap became significantly smaller

VFP equation: $\frac{\partial \psi}{\partial s} + \frac{dz}{ds}\frac{\partial \psi}{\partial z} + \frac{d\delta}{ds}\frac{\partial \psi}{\partial \delta} = \frac{2}{ct_d}\frac{\partial}{\partial \delta}\left[\delta\psi + \sigma_{\delta 0}^2 \frac{\partial \psi}{\partial \delta}\right]$

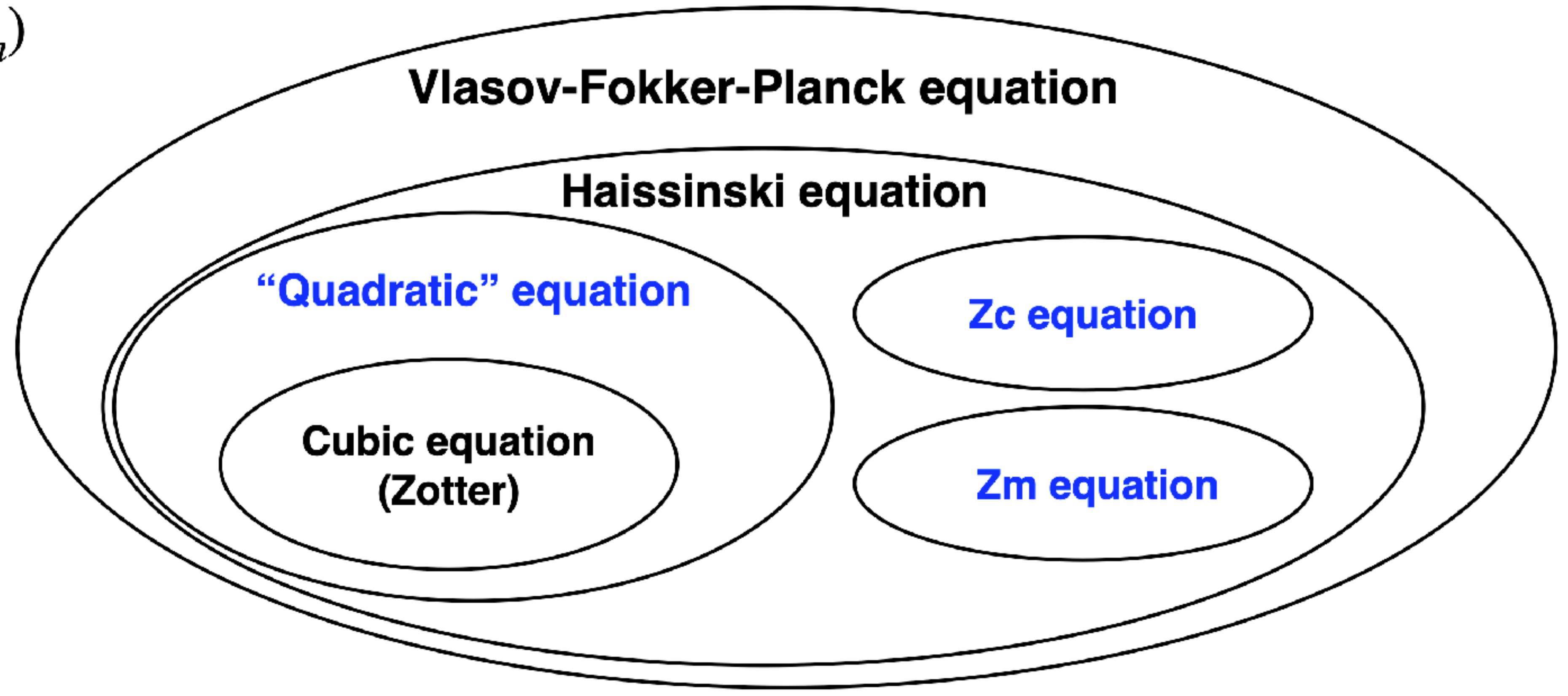
Haissinski equation: $\lambda_0(z) = Ae^{-\frac{z^2}{2\sigma_{z0}^2} - \frac{I}{\sigma_{z0}}\int_z^\infty dz' \mathbb{W}_\parallel(z')}$

"Quadratic" equation: $x^2 - 1 - \frac{cI}{2\pi\sigma_{z0}} Z_\parallel^{eq}(x) = 0$

Zotter's equation: $x^3 - x + \frac{cI_b}{\kappa\eta\omega_0\sigma_{z0}\sigma_{\delta 0}^2(E/e)} \mathrm{Im}\left(\frac{Z_\parallel}{n}\right)_{eff}^{m=1} = 0$

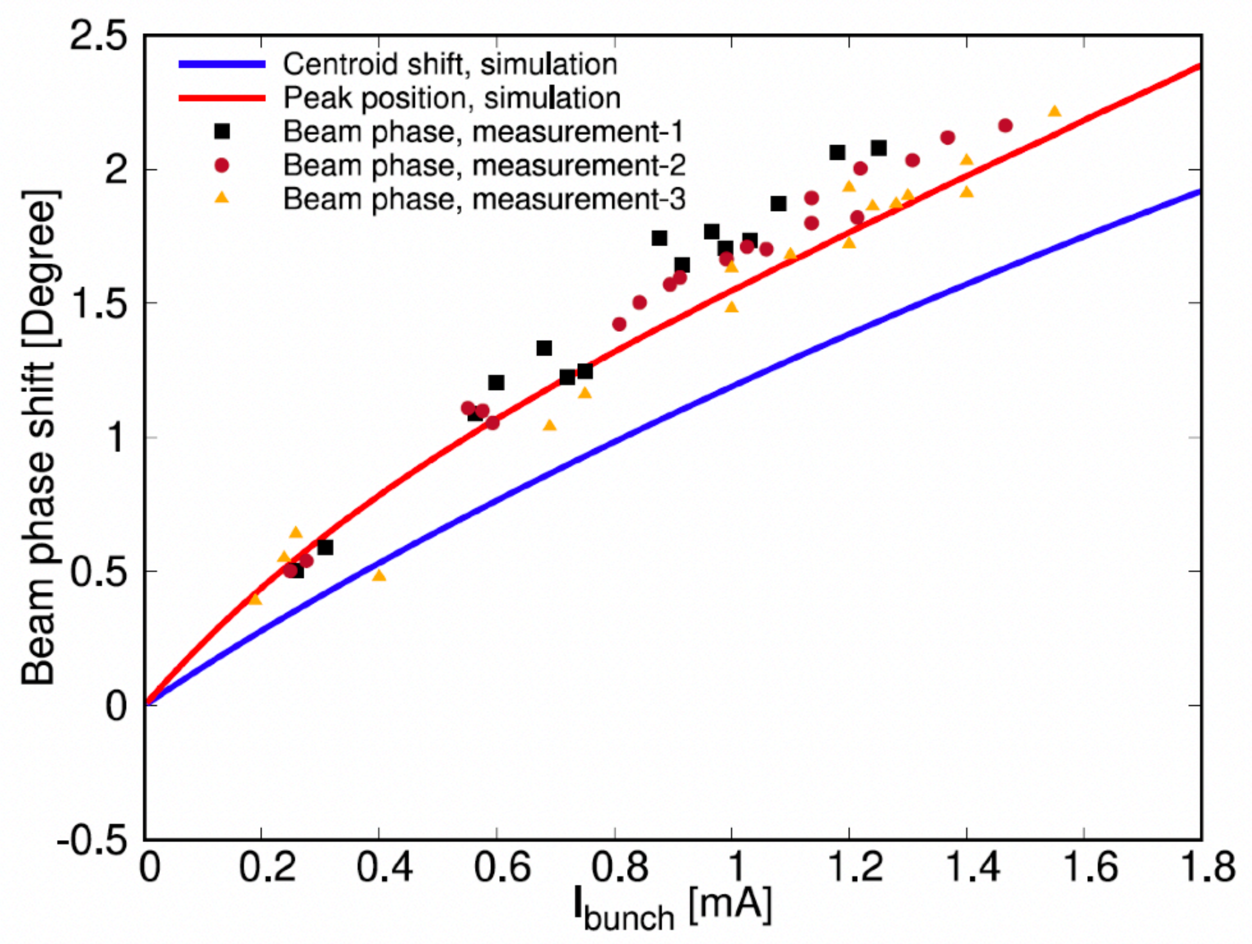
Zc equation: $z_c(I) = I\sigma_{z0}\kappa_\parallel$

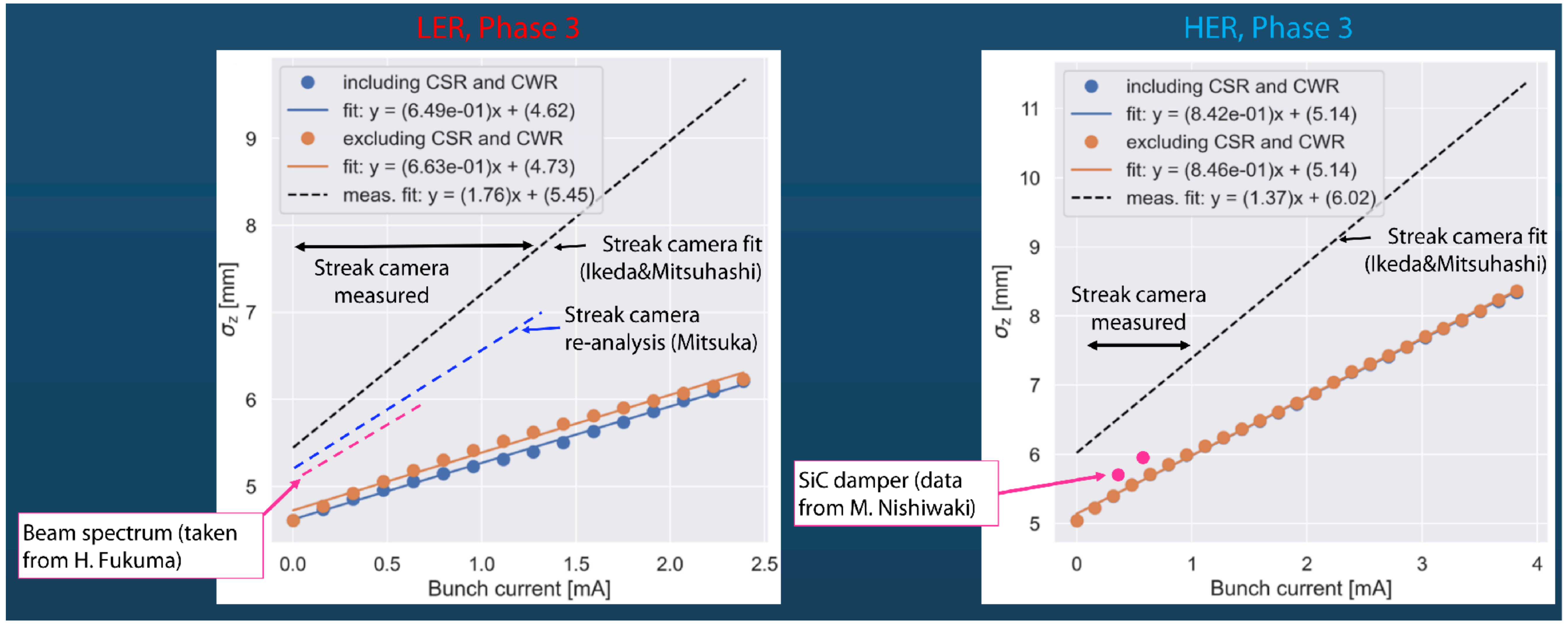
Zm equation: $z_m = I\sigma_{z0}\mathbb{W}_\parallel(z_m)$



Subset diagram

Measured phase shift (BPM-based) better agrees with simulated peak shift, not centroid shift [1]





T. Ishibashi [2] and G. Mitsuka [3]

[1] D. Zhou et al., NIM-A 1063 (2024) 169243. [2] T. Ishibashi et al 2024 JINST 19 P02013. [3] G. Mitsuka, https://kds.kek.jp/event/46959/.

Potential well distortion and microwave instability

- SuperKEKB LER
  - VFP simulations: Different combinations of impedance sources show that CSR-driven **MWI threshold is around 1.2 mA** (< design value of 1.44 mA)
  - Consistent with prediction of CSR instability theory [1,2]: CSR threshold is independent of bending radius of dipoles
  - CSR instability is not verified by experiments yet

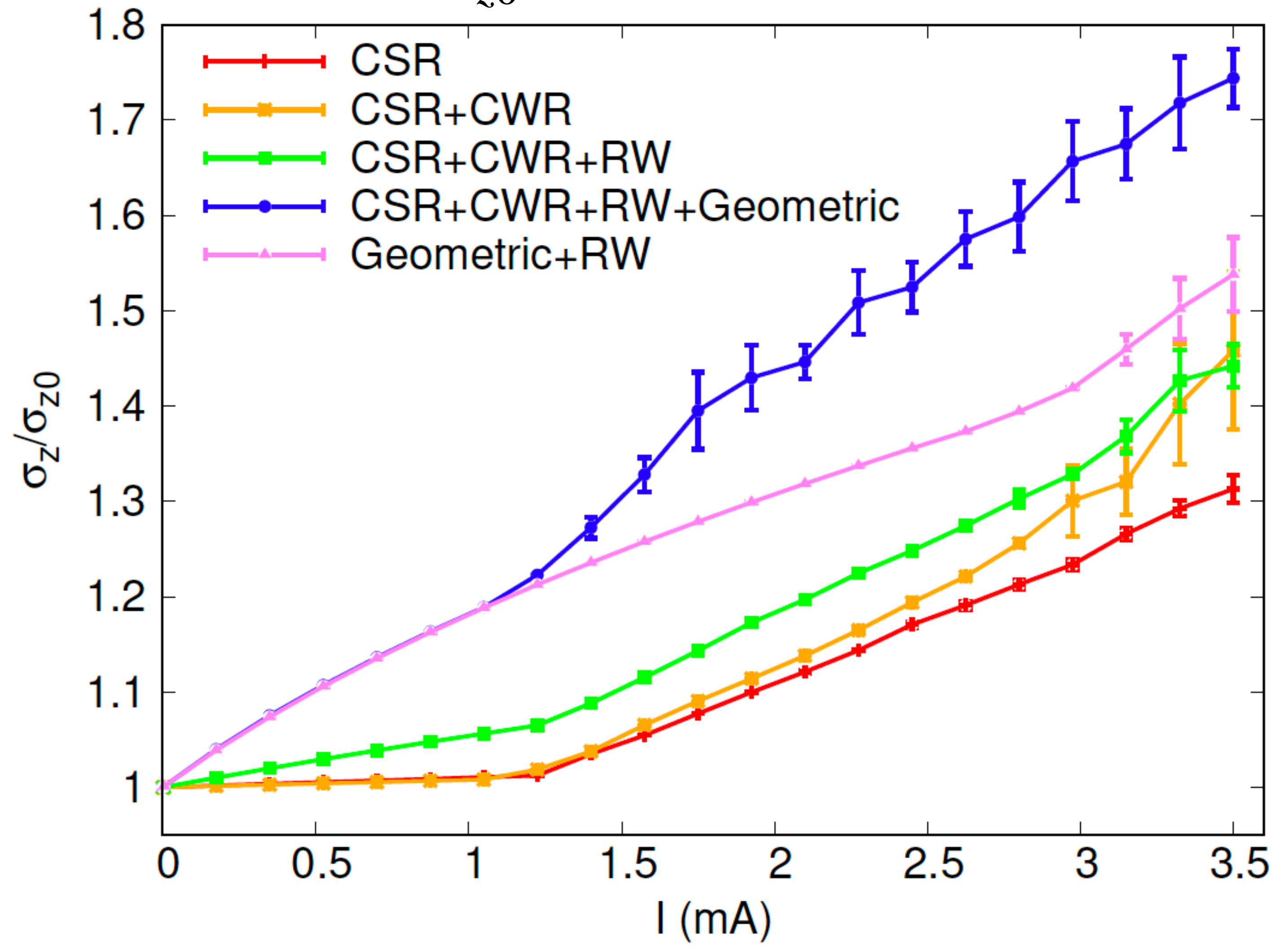
$$I_{\rm th}({\rm CSR}) = \frac{4\pi(E/e)\eta\sigma_\delta^2\sigma_z^{1/3}}{Z_0\rho^{1/3}}S_{\rm th} \propto \frac{E\eta\sigma_\delta^2\sigma_z}{h}$$

$$S_{\rm th} \approx 0.384\Pi^{2/3}$$

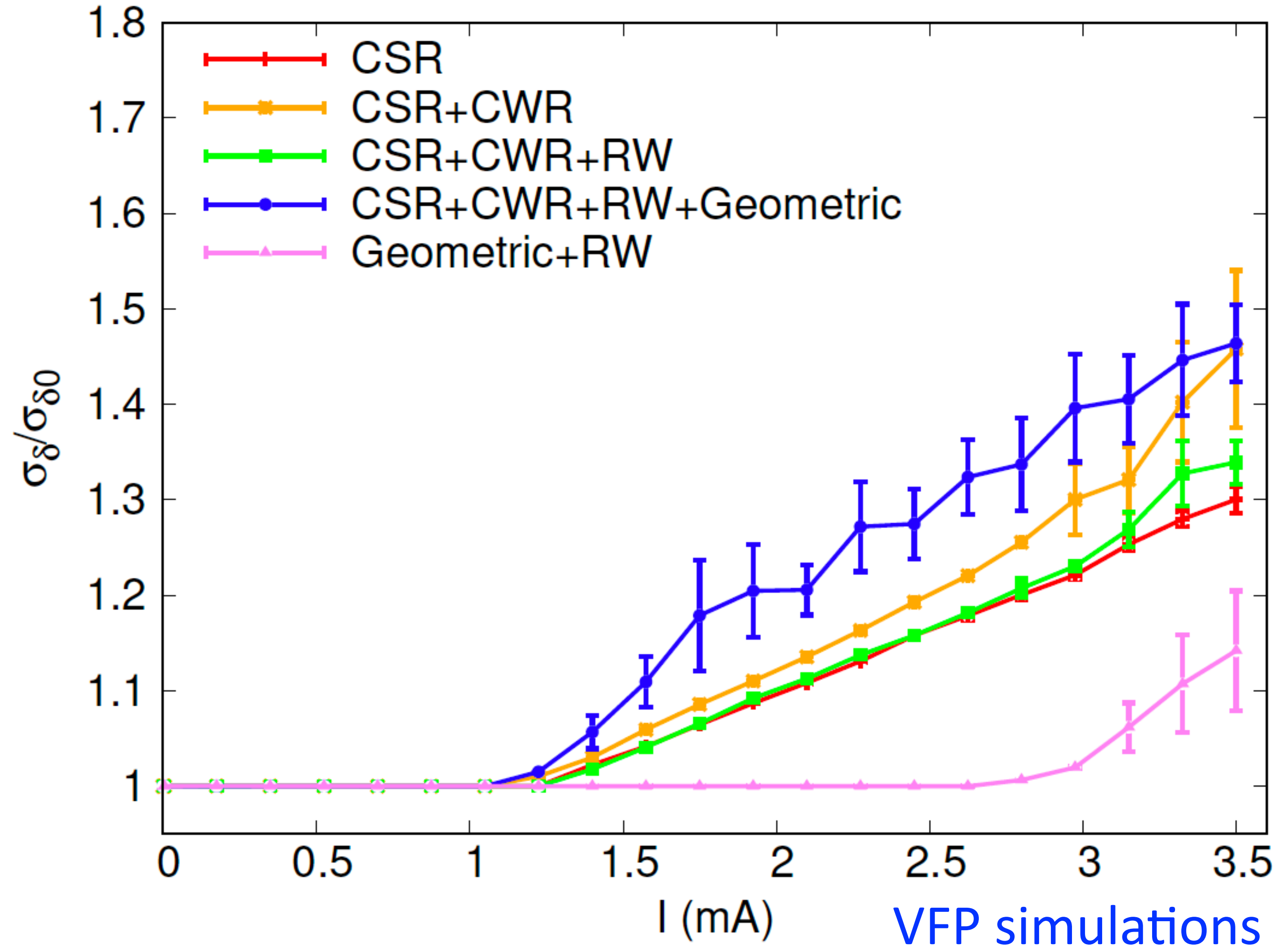
$$\Pi \equiv \sigma_z\sqrt{\rho/h^3}$$

$h = 45$ mm, $\rho = 74.7$ m

$\sigma_{z0} = 4.6$ mm



$\sigma_{\delta 0} = 7.53 \times 10^{-4}$



VFP simulations

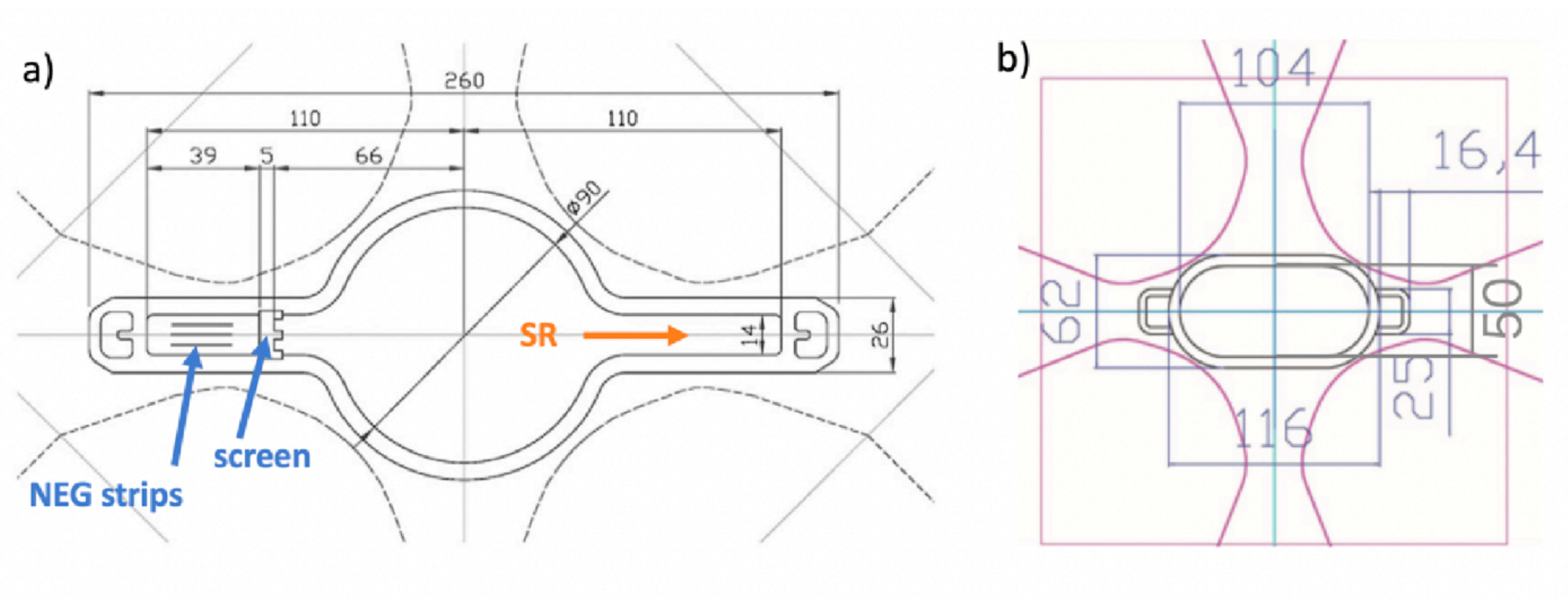
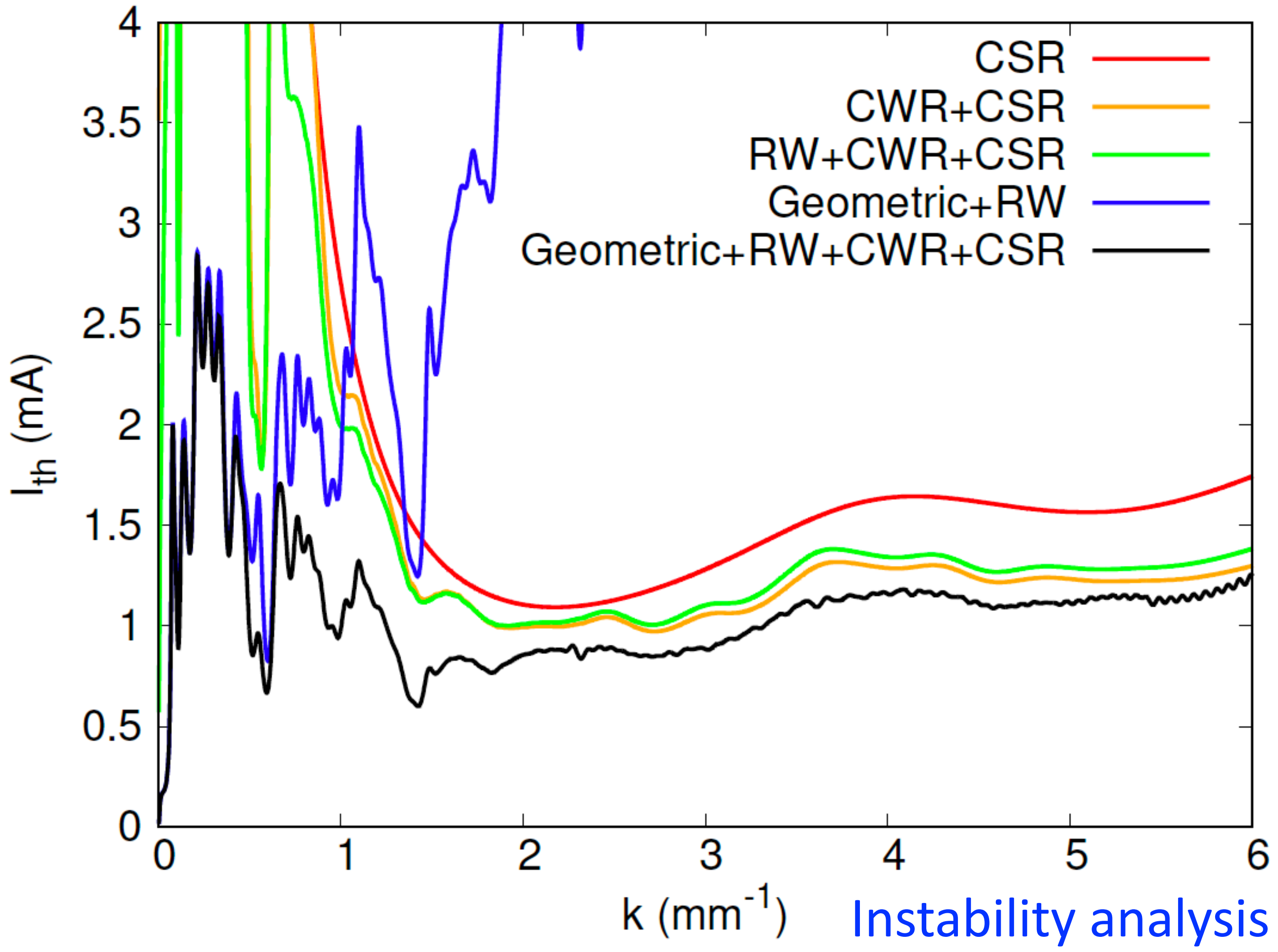


Figure 3. Cross-sectional view of standard beam-pipes installed in the rings. a) Beam-pipe with antechambers in LER. b) Racetrack-shaped beam-pipe in HER.

Chamber geometries [3]

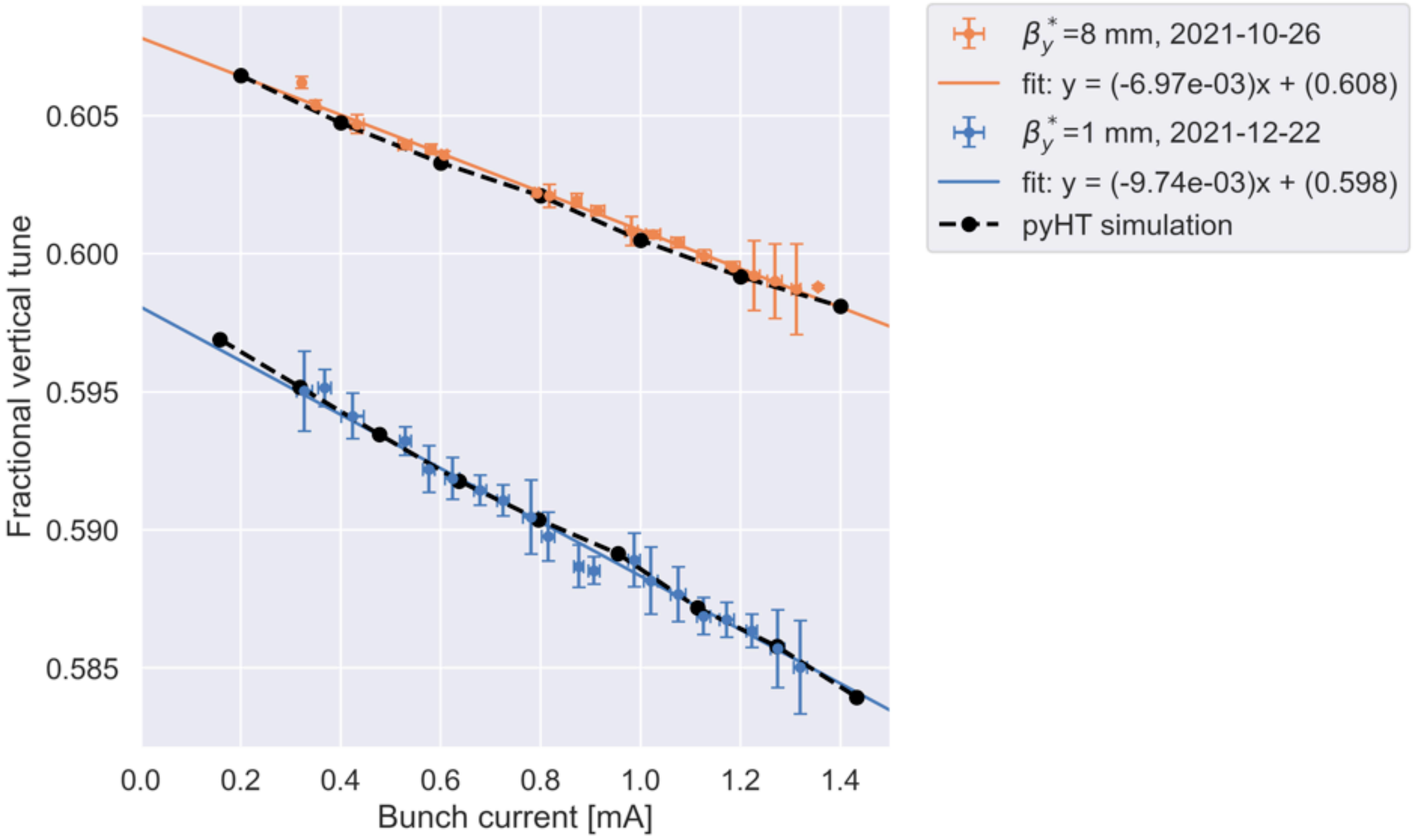


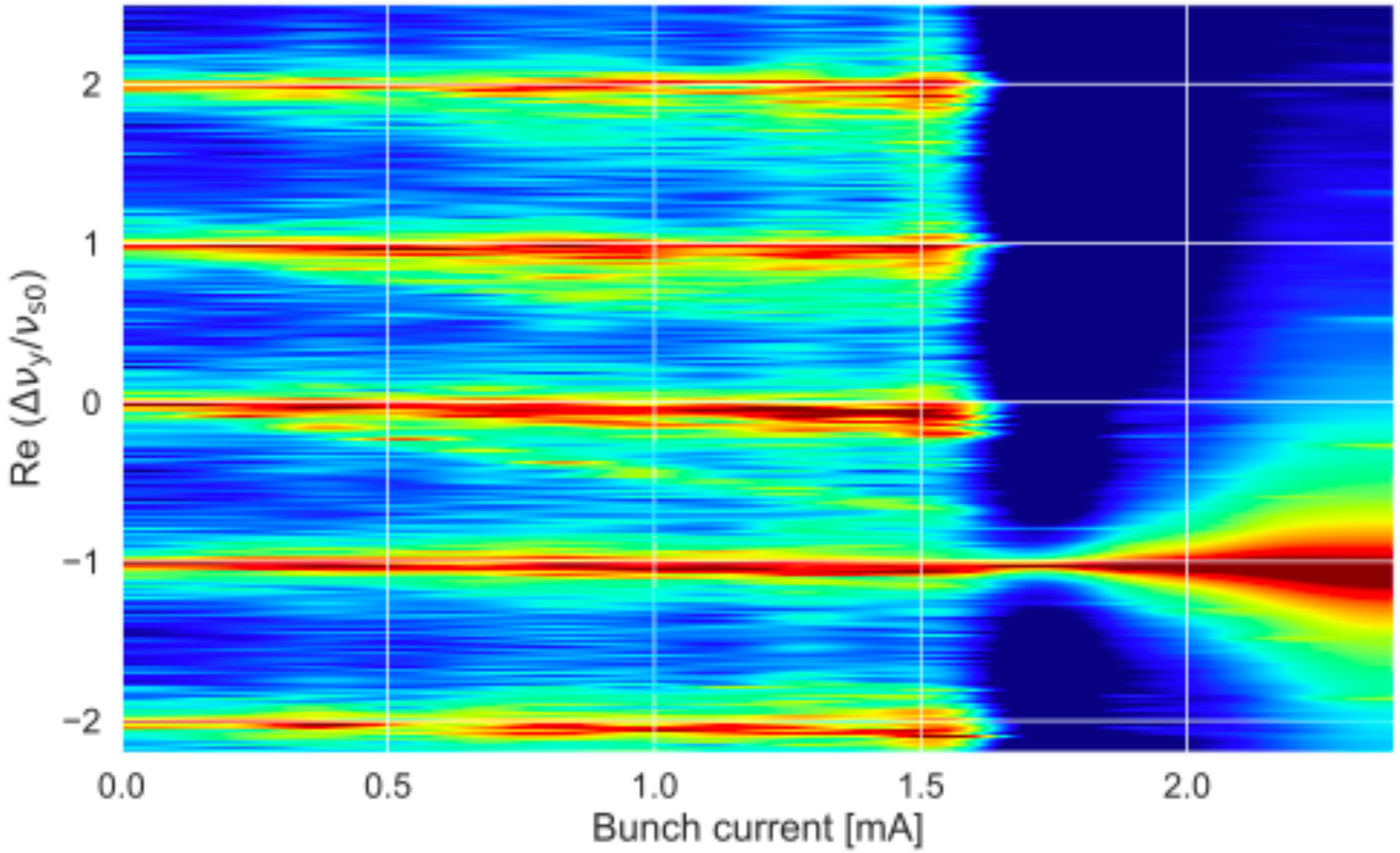
Instability analysis

[1] Y. Cai, IPAC2011, FRXAA01. [2] A. Blednykh, D. Zhou et al., PRAB **26**, 051002 (2023). [3] T. Ishibashi et al. 2024 JINST 19 P02013.

Transverse modeling coupling instability and “-1 mode instability”

- TMCI in LER [1]
  - Tune shift and TMCI simulated by PyHEADTAIL (T. Ishibashi and M. Migliorati)
  - With machine configurations of β_y^*=1 mm: Simulations using impedance models well reproduced the measured tune shifts. Simulated **TMCI threshold is 1.8 mA**.

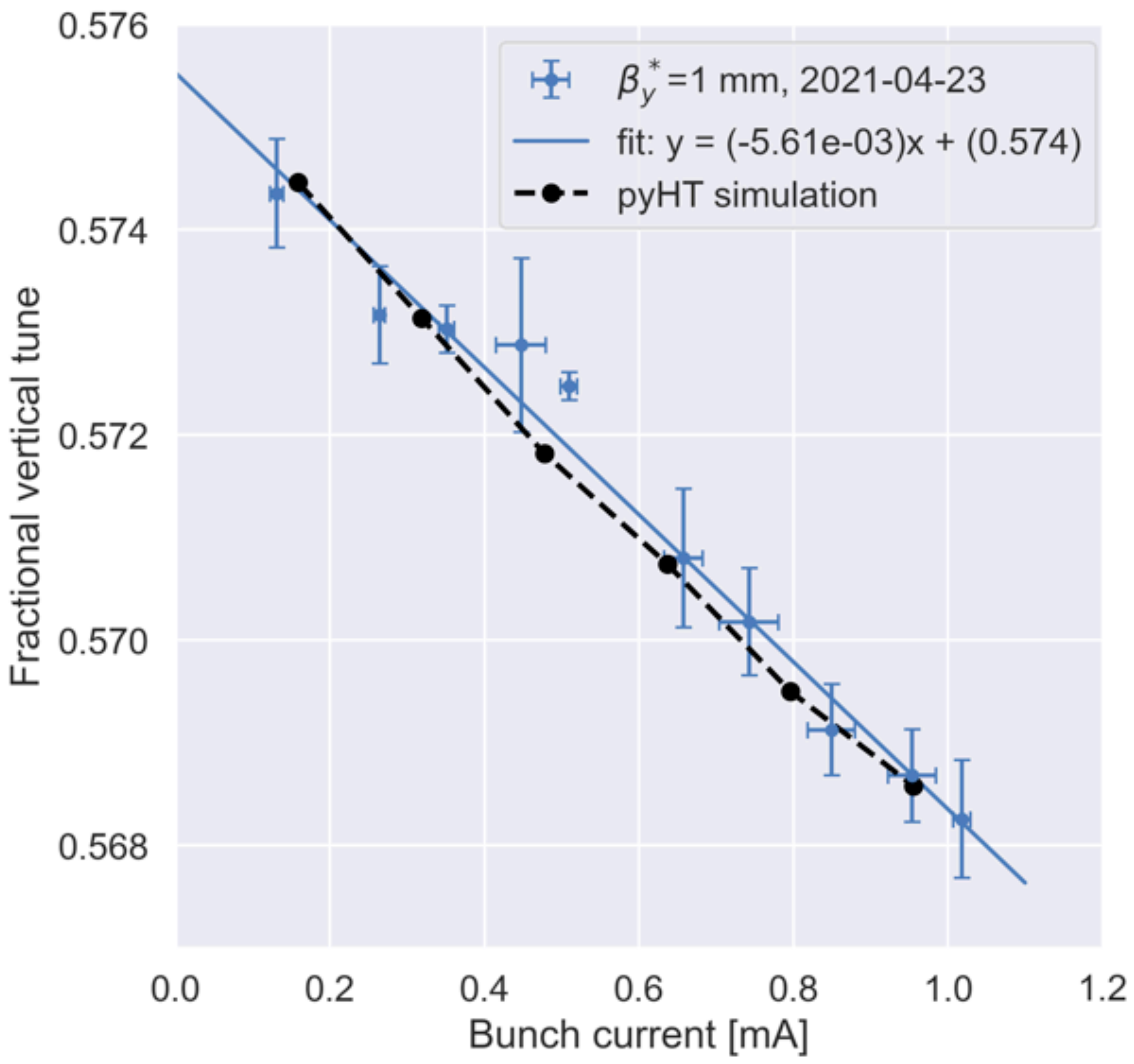


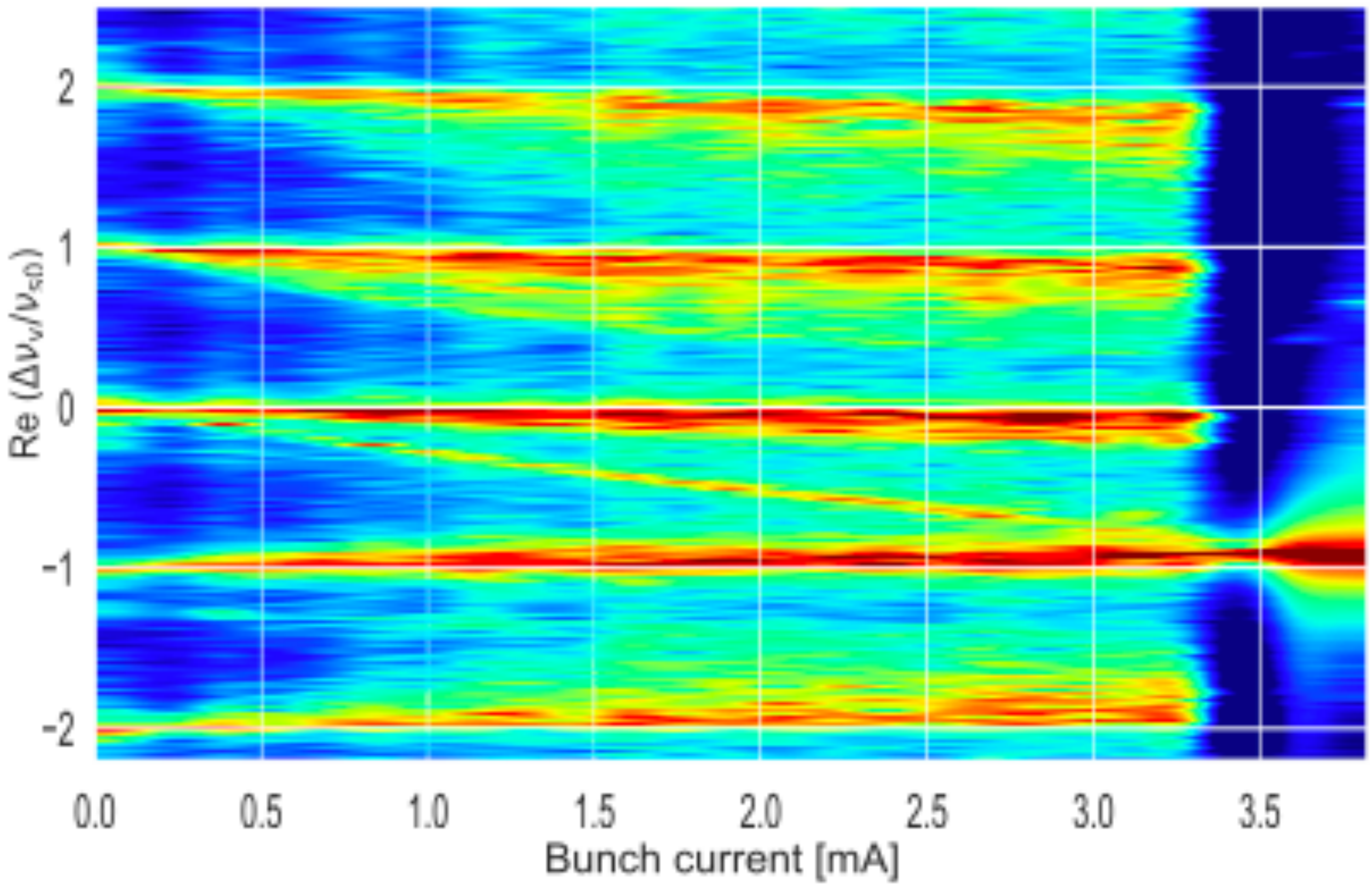


[1] T. Ishibashi et al. 2024 JINST 19 P02013.

Transverse modeling coupling instability and “-1 mode instability”

- TMCI in HER [1]
  - Tune shift and TMCI simulated by PyHEADTAIL (T. Ishibashi and M. Migliorati)
  - With machine configurations of β_y^*=1 mm: Simulations using impedance models well reproduced the measured tune shifts. Simulated **TMCI threshold is 3.5 mA**.





[1] T. Ishibashi et al. 2024 JINST 19 P02013.

Transverse modeling coupling instability and “-1 mode instability”

- “-1 mode instability” in LER [1,2,3,4]
  - Observed instability **threshold is significantly lower than TMCI** threshold. Both **vertical impedance effects** (tune shift in 0 mode, $d\nu_y/dI$~-0.01/mA) and **bunch-by-bunch (BxB) feedback (FB)** (excitation of -1 mode) play important roles in this phenomenon.
  - Simulations using PyHEADTAIL consider **resistive damper** and show ITSR (Imaginary Tune Split and Repulsion) instability [5]. Simulations by K. Ohmi consider **multi-tap scheme** of BxB FB and show that BxB FB can reactively drive -1 mode [2]. However, FB gain much higher than operation setting is required to reproduce the observed instability [2].
  - Countermeasure: **Noise suppression and fine tuning of FB system** (see [6] for details). Another countermeasure (proposal): The “easiest” way to escape from this instability is **increasing ν_s of LER**.

2022 [3]

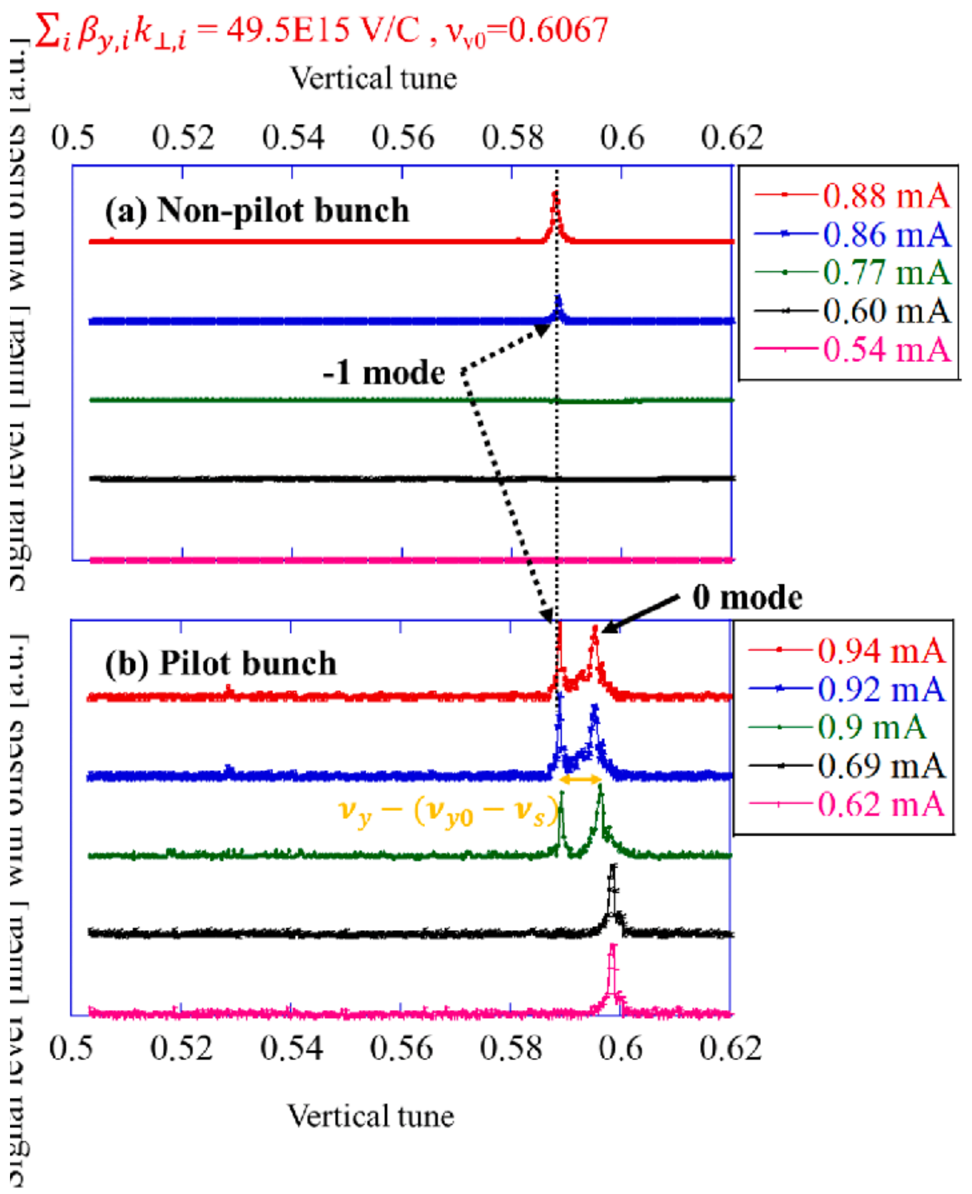


FIG. 9. Results of the FFT analysis of vertical beam motion data collected using the LER BOR.

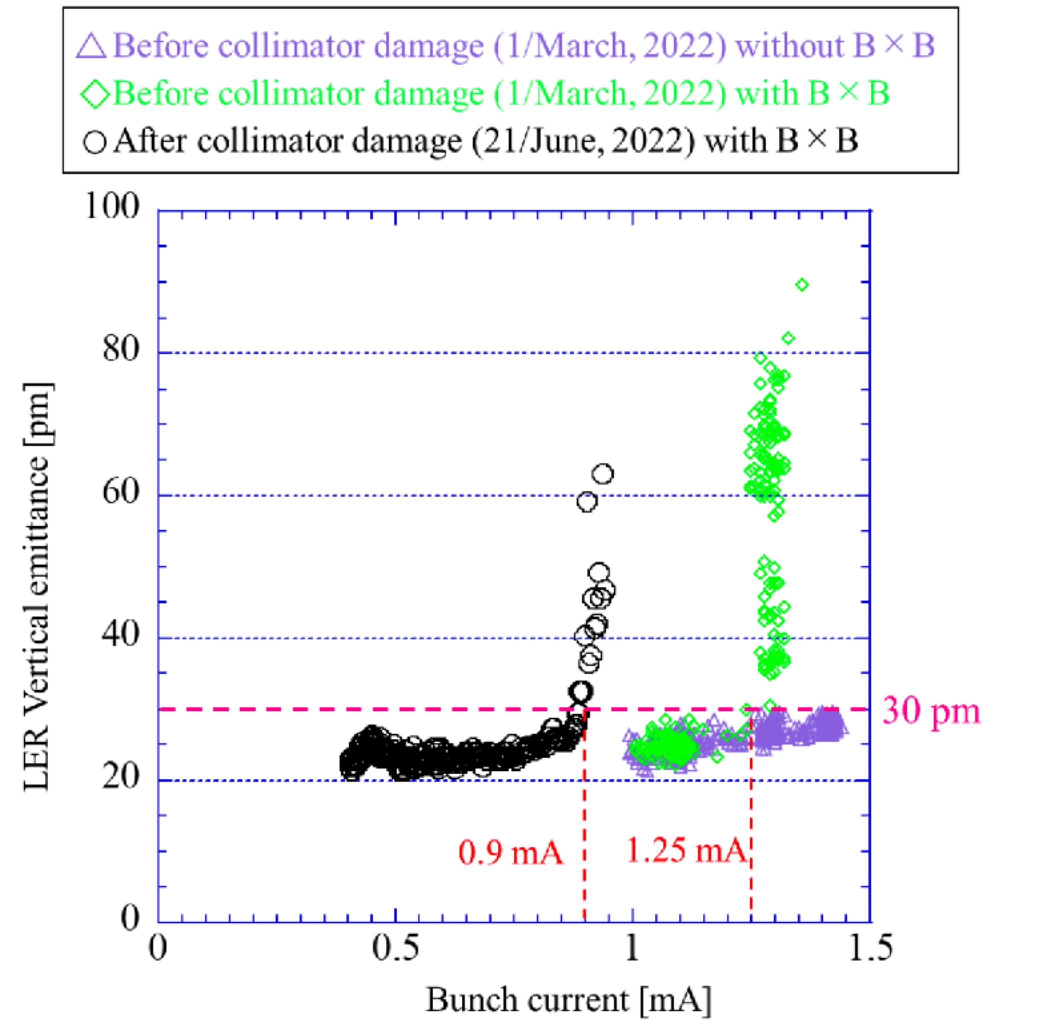
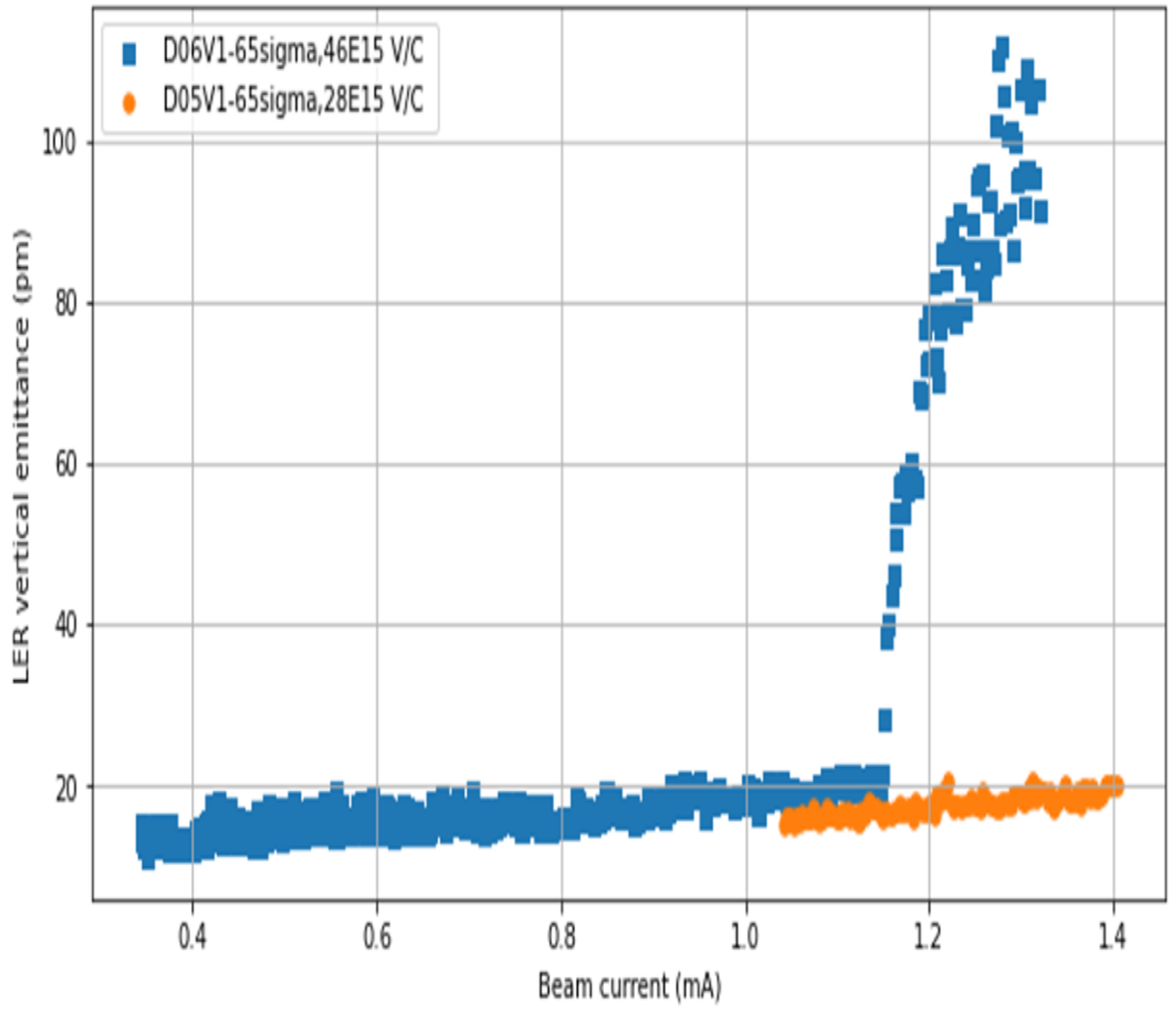
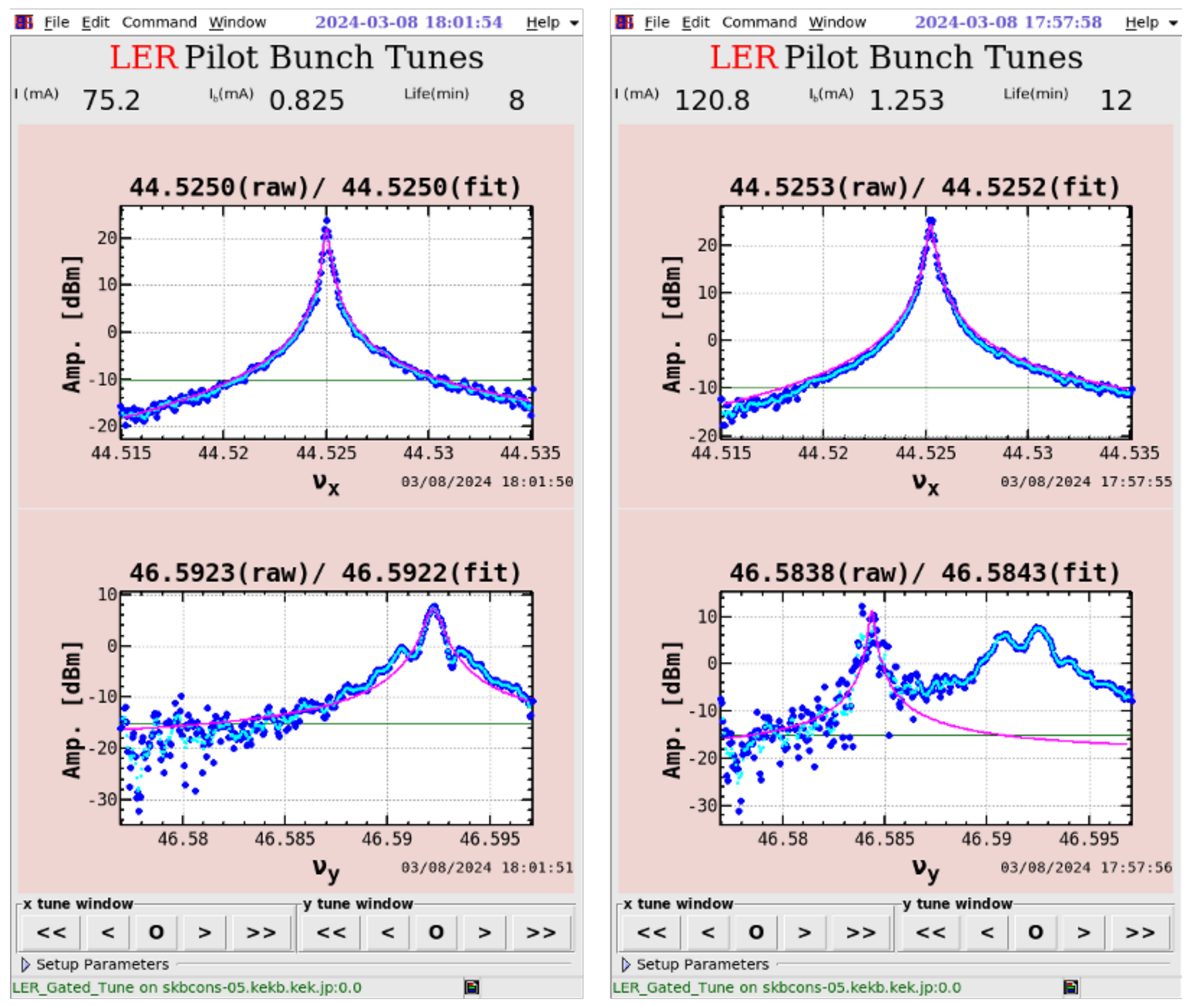


FIG. 10. The vertical beam emittance versus bunch current with β_y^* = 1 mm, before (green diamonds) and after (black circles) the event of collimator jaw damage with BxB feedback on. The data of purple triangles show the measurement with BxB feedback off.

2024 [4]





Courtesy of S. Terui

Need to confirm if BxB FB still excites -1 mode

[1] T. Ishibashi et al. 2024 JINST 19 P02013. [2] K. Ohmi et al., eeFACT2022, WEXAT0102. [3] S. Terui, “Collimator challenges at SuperKEKB and their countermeasures using nonlinear collimator”, submitted to PRAB. [4] S. Terui, Talk to this meeting. [5] E. Metral and M. Migliorati, Phys. Rev. Accel. Beams 23 (2020) 071001. [6] G. Mitsuka, talk to this meeting

Resistive wall instability

- Transverse coupled-bunch instability driven by low-frequency resistive wall impedance [1,2]
  - For SuperKEKB LER, by theory (counting RW impedances of normal chambers, IR chamber and collimators) the growth time is τ_y^{Theory}=1.0 ms at I_{beam}=600 mA; by experiment, it is τ_y^{Exp}=3.8 ms.
  - For SuperKEKB HER, by theory (counting RW impedances of normal chambers, IR chamber and collimators) the growth time is τ_y^{Theory}=0.5 ms at I_{beam}=600 mA; by experiment, it is τ_y^{Exp}=1.6 ms.

$$\frac{1}{\tau} = -\frac{Ice}{2EC}\sum_i \beta_{\perp i} Z_{1i}^{\perp}(k_p) \qquad \frac{1}{\tau_{yt}} = \frac{1}{\tau_{y1}} + \frac{1}{\tau_{y2}} + \frac{1}{\tau_{y3}} + \frac{1}{\tau_{ySR}} + \frac{1}{\tau_{yHT}}$$

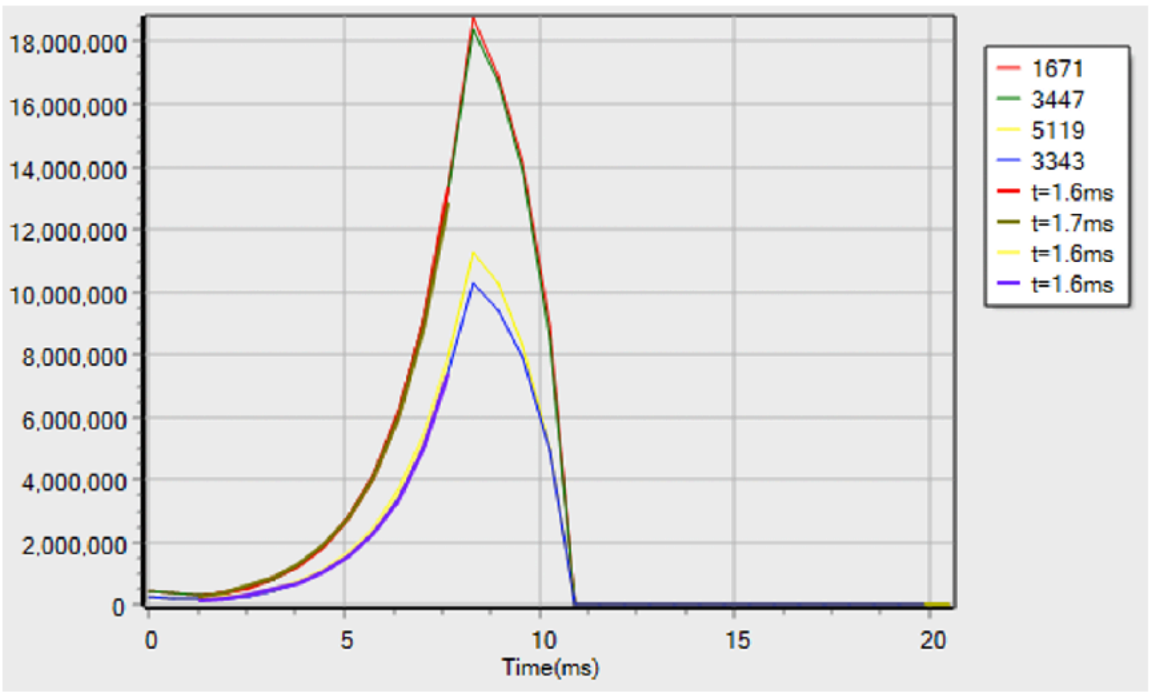


Figure 2: Evolution of vertical unstable modes with by-3.06 fill pattern in HER at a beam current of 600 mA (Jun. 29, 2021).

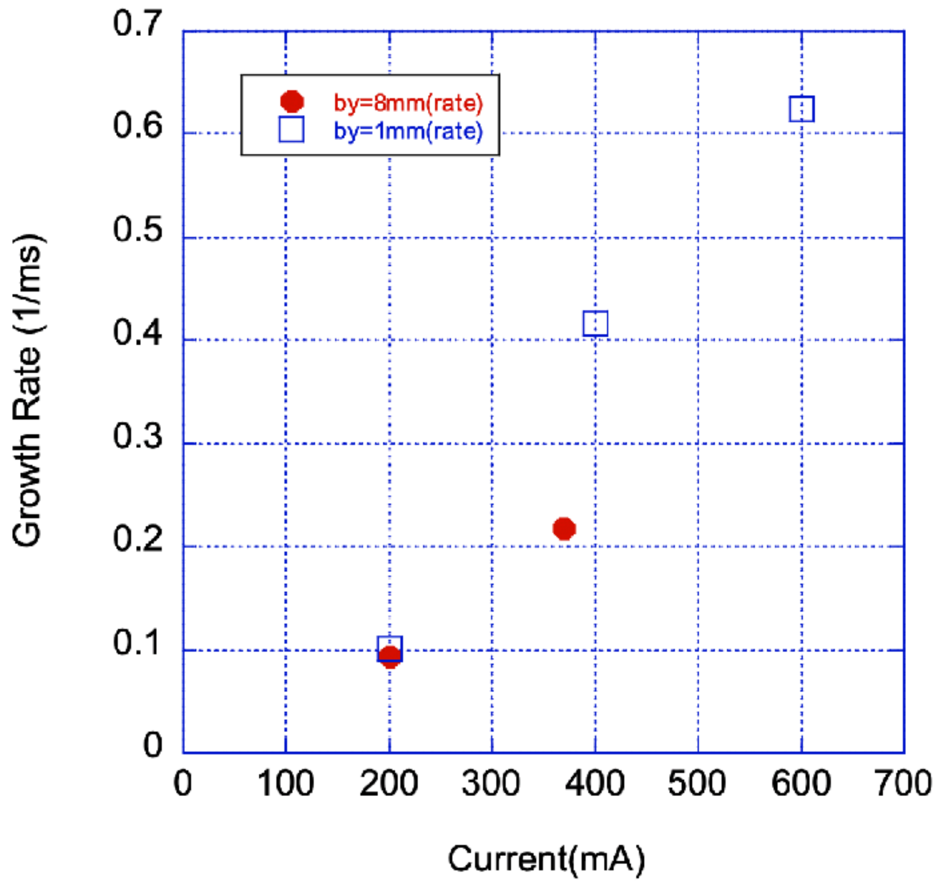


Figure 3: Measured growth rates as a function of beam current in HER (Jun. 29, 2021). The red circles and blue squares indicate measured results with β_y^*=8 and 1 mm, respectively.

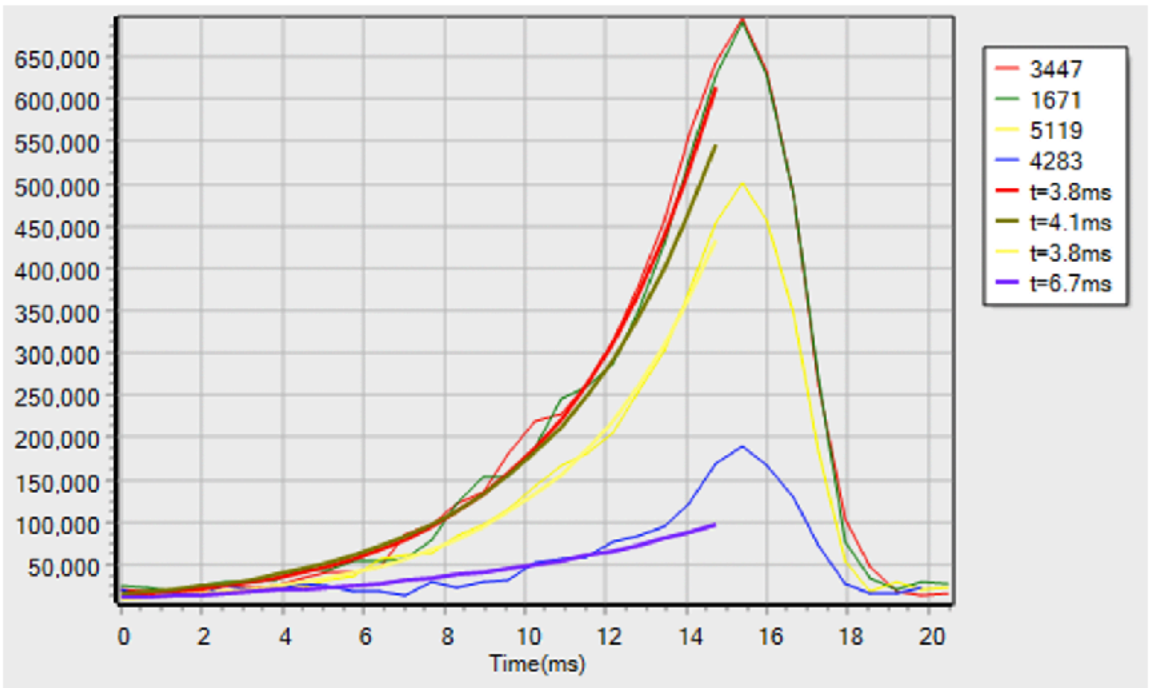


Figure 6: Evolution of vertical unstable modes with by-3.06 fill pattern in LER at a beam current of 600 mA (Mar. 28, 2022).

[1] D. Zhou et al., IPAC'23, WEPL187. [2] D. Zhou, Talk to mini-impedance workshop at KEK, 2022.

Electron cloud

- Electron cloud in SuperKEKB LER [1]
  - “**No significant electron cloud effect has been observed in the LER** after installing solenoids in drift spaces in 2017 which apply magnetic fields in the beam direction.”

TABLE II. Countermeasures used to minimize the ECE in the SuperKEKB LER. The circular dots indicate the countermeasures applied for each main section in the ring.

Sections	Length (m)	n_e (circular) (m^{-3})	Countermeasures: Antechamber (1/5)	TiN coating (3/5)	Solenoid (B_z;1/50)[a]	Groove (1/2)	Electrode (1/100)	n_e (expected m^{-3})
Drift space (arc)	1629	8×10^{12}	•	•	•			2×10^{10}
Corrector magnets	316	8×10^{12}	•	•	•			2×10^{10}
Bending magnets	519	1×10^{12}	•	•		•		6×10^{10}
Wiggler magnets	154	4×10^{12}	•	•[b]			•	5×10^{9}
Quadrupole and Sextupole magnets	254	4×10^{10}	•	•				5×10^{9}
rf cavity section	124	1×10^{11}		•	•			1×10^{9}
IR	20	5×10^{11}		•	•			6×10^{9}
Total	3016							
Average		5.5×10^{12}						2.4×10^{10}

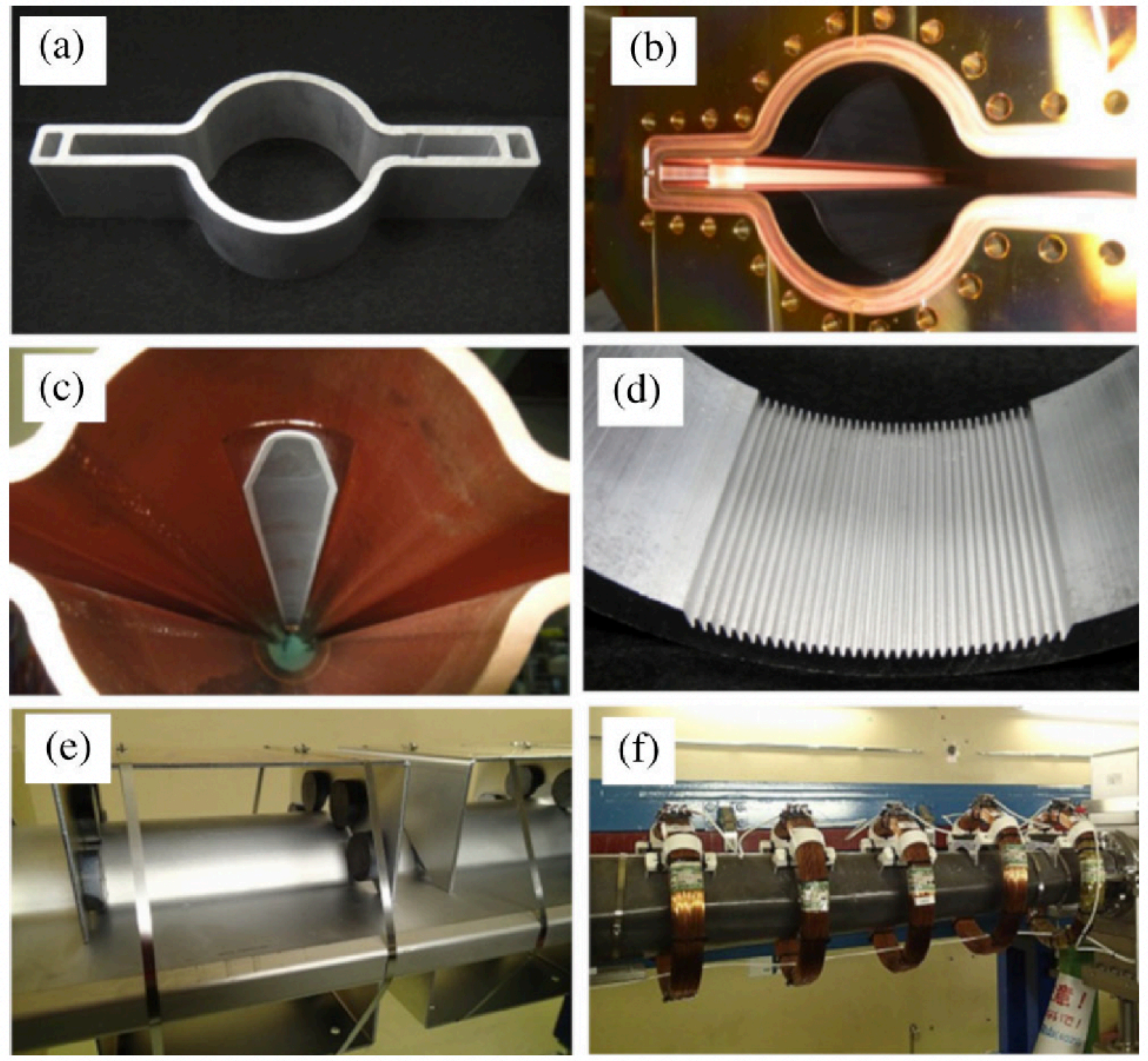


FIG. 19. Typical views of countermeasures adopted to the SuperKEKB LER: (a) beam pipes with antechambers, (b) TiN-film coating, (c) clearing electrode, (d) groove structure, magnetic fields in the beam direction by (e) permanent magnets and (f) solenoids.

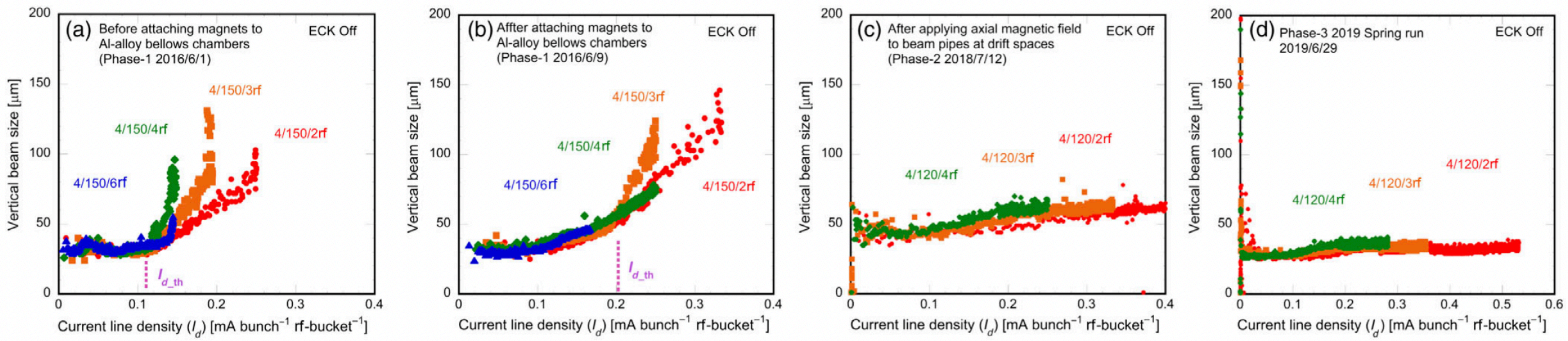
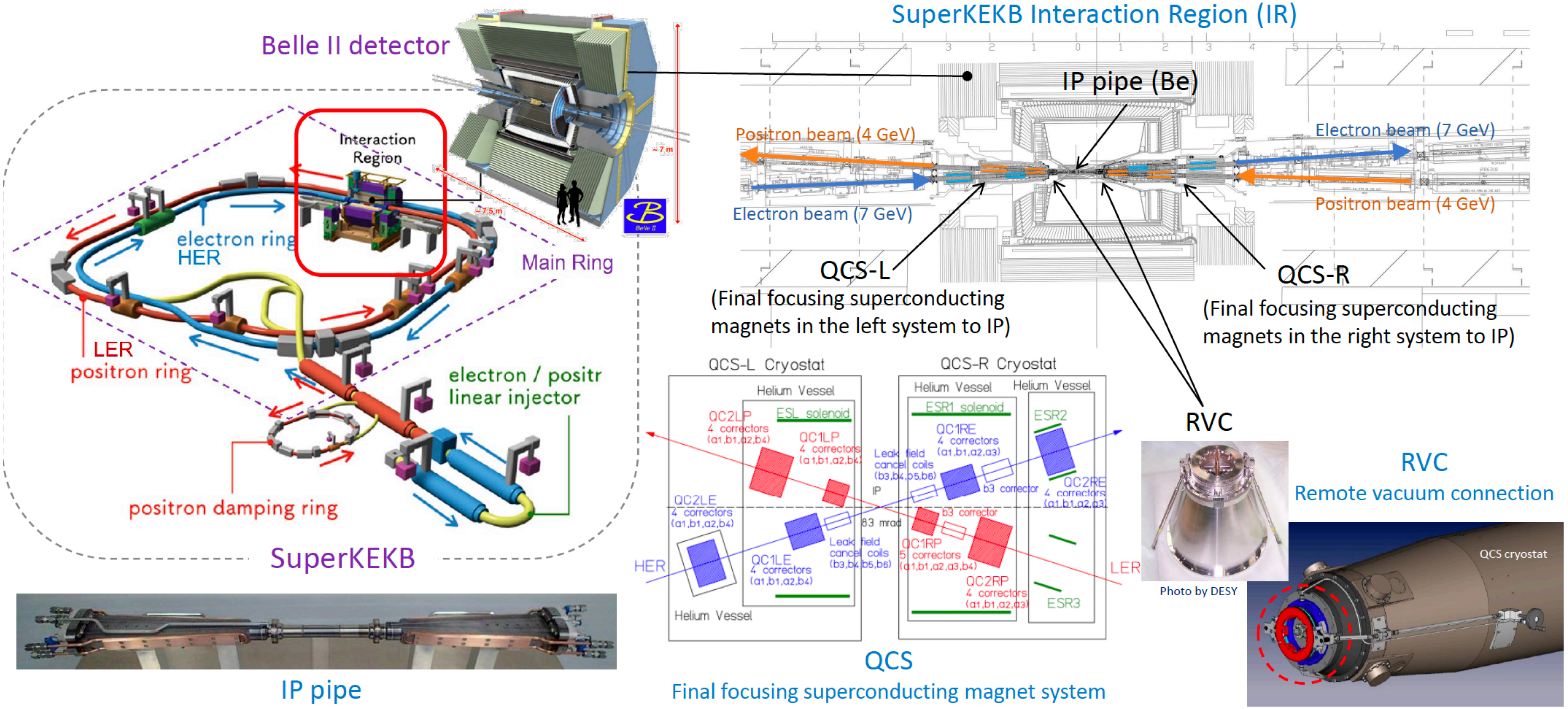


FIG. 20. Vertical beam sizes as a function of the current line density (I_d) for several bunch filling patterns measured (a) before and (b) after attaching PM units to Al-alloy bellows chambers in Phase-1 commissioning, (c) Phase-2 commissioning, and (d) Phase-3 commissioning.

[1] Y. Suetsugu et al., “SuperKEKB vacuum system operation in the last 6 years operation”, PRAB 26, 013201 (2023).

IR nonlinearity: converged understandings

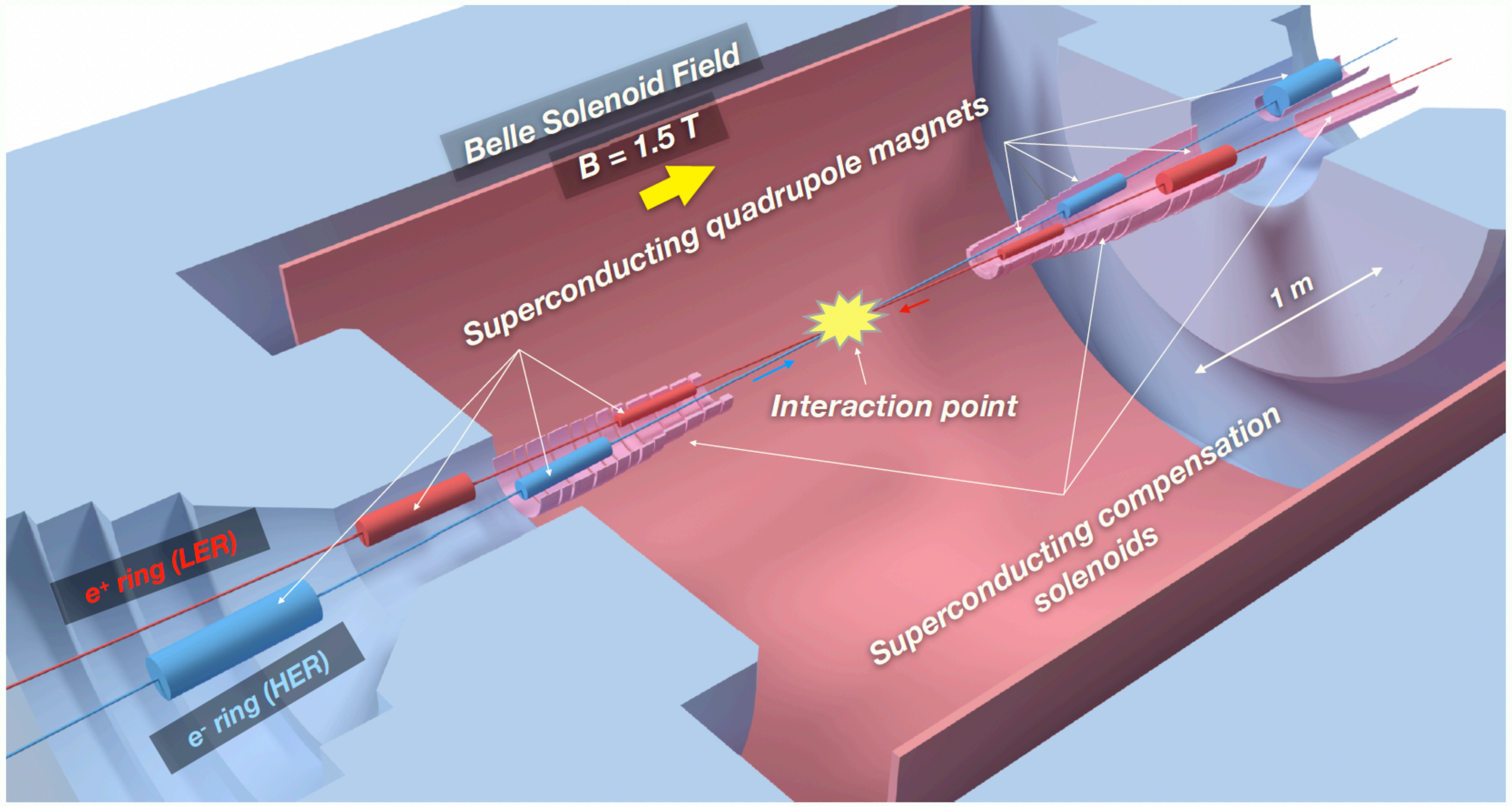
- Complicated interaction region (IR) [1]

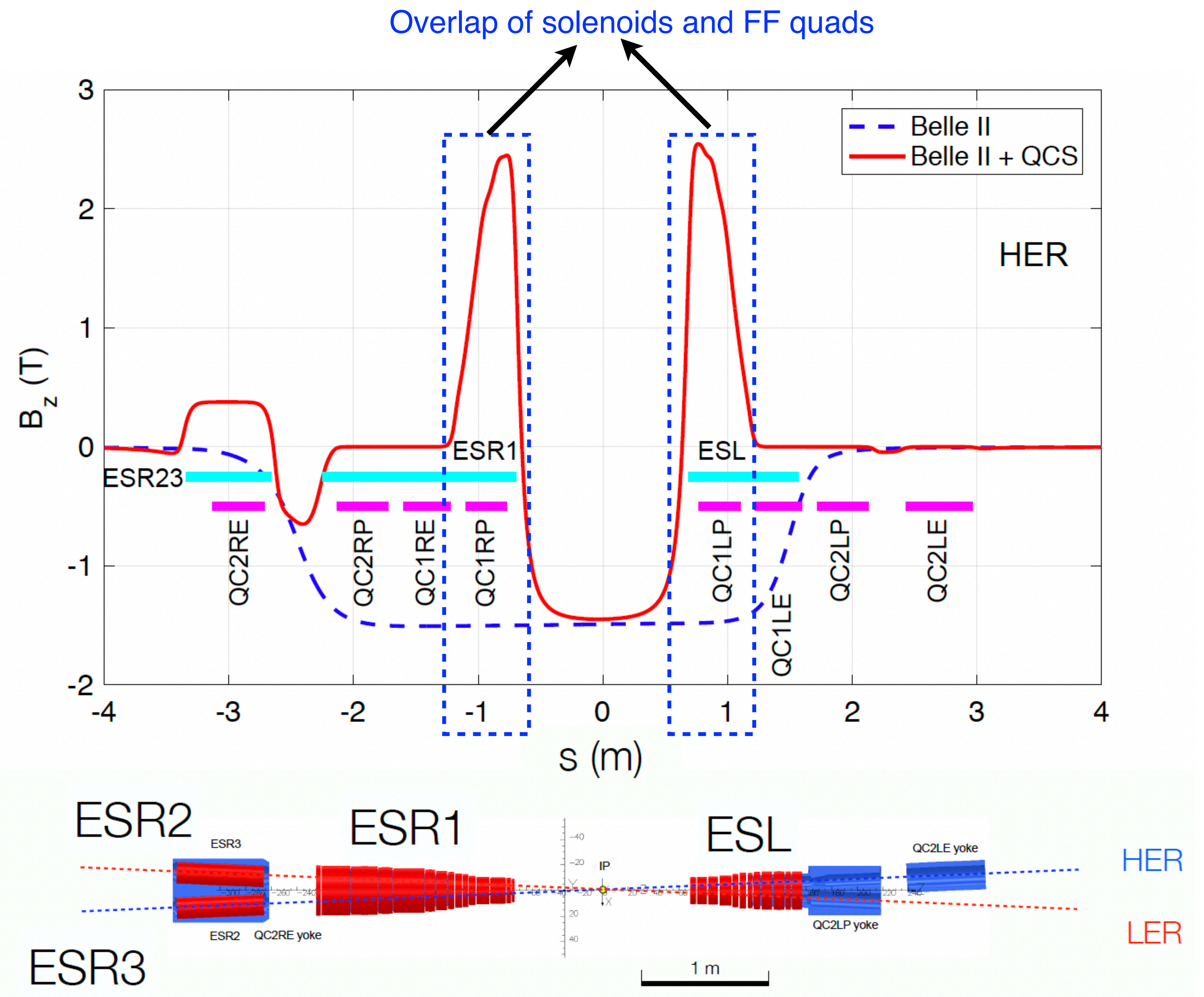


[1] K. Shibata, "Overview of SuperKEKB IR".

IR nonlinearity: converged understandings

- Complicated interaction region (IR) [1]
  - Large crossing angle (required by collision scheme) and limited spaces for hardwares increase the complexity of optics.

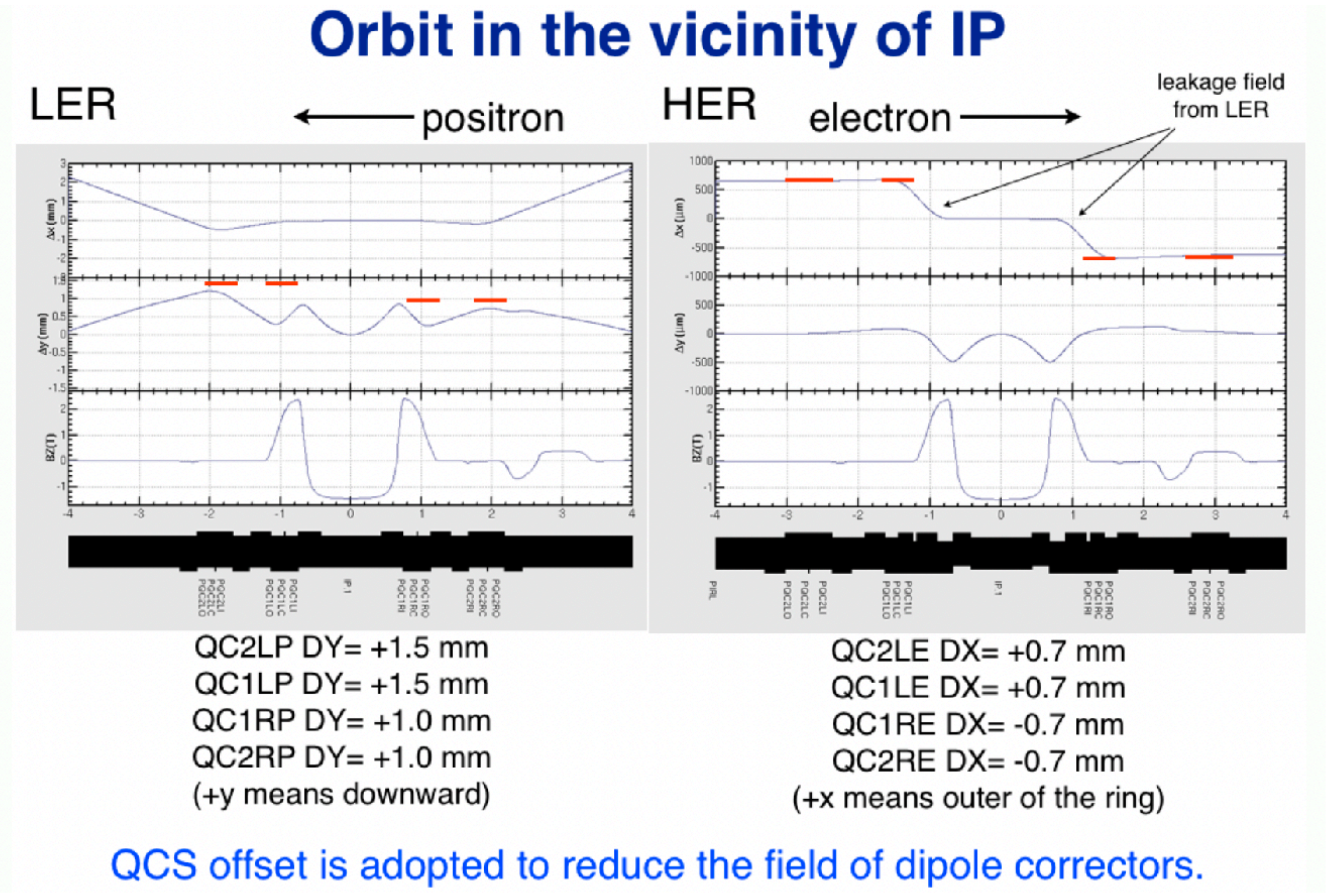


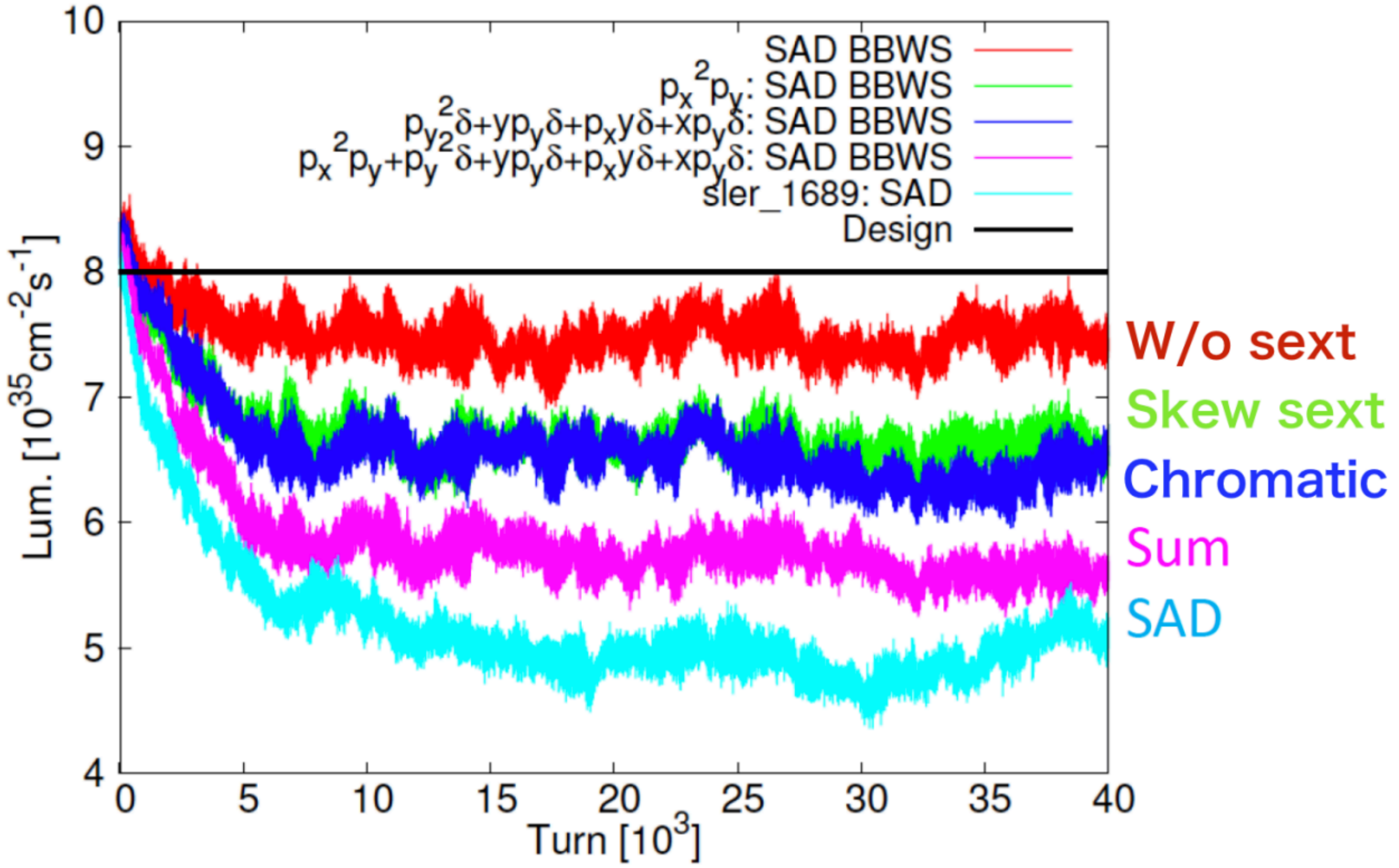


[1] Y. Arimoto, “Current QCS magnet system”.

IR nonlinearity: converged understandings

- Complicated interaction region (IR): Side effects from beam physics viewpoint
  - Extremely small β_y^* → Nonlinear effects from kinematic term of IP drift and fringe fields of final focus (FF) quadrupoles [1] → Fundamental limit on dynamic aperture and lifetime [1,2,3] → Poor injection efficiency [4] and high detector background [5].
  - Overlap of solenoid and FF quadrupoles, offsets of FF quadrupoles, etc. → Vertical emittance growth (single-beam) due to local linear and chromatic couplings [6] → Vertical emittance growth (two-beam) from interplay of beam-beam and lattice nonlinearity [7,8] → Imperfect crab waist due to nontransparent IR [2].

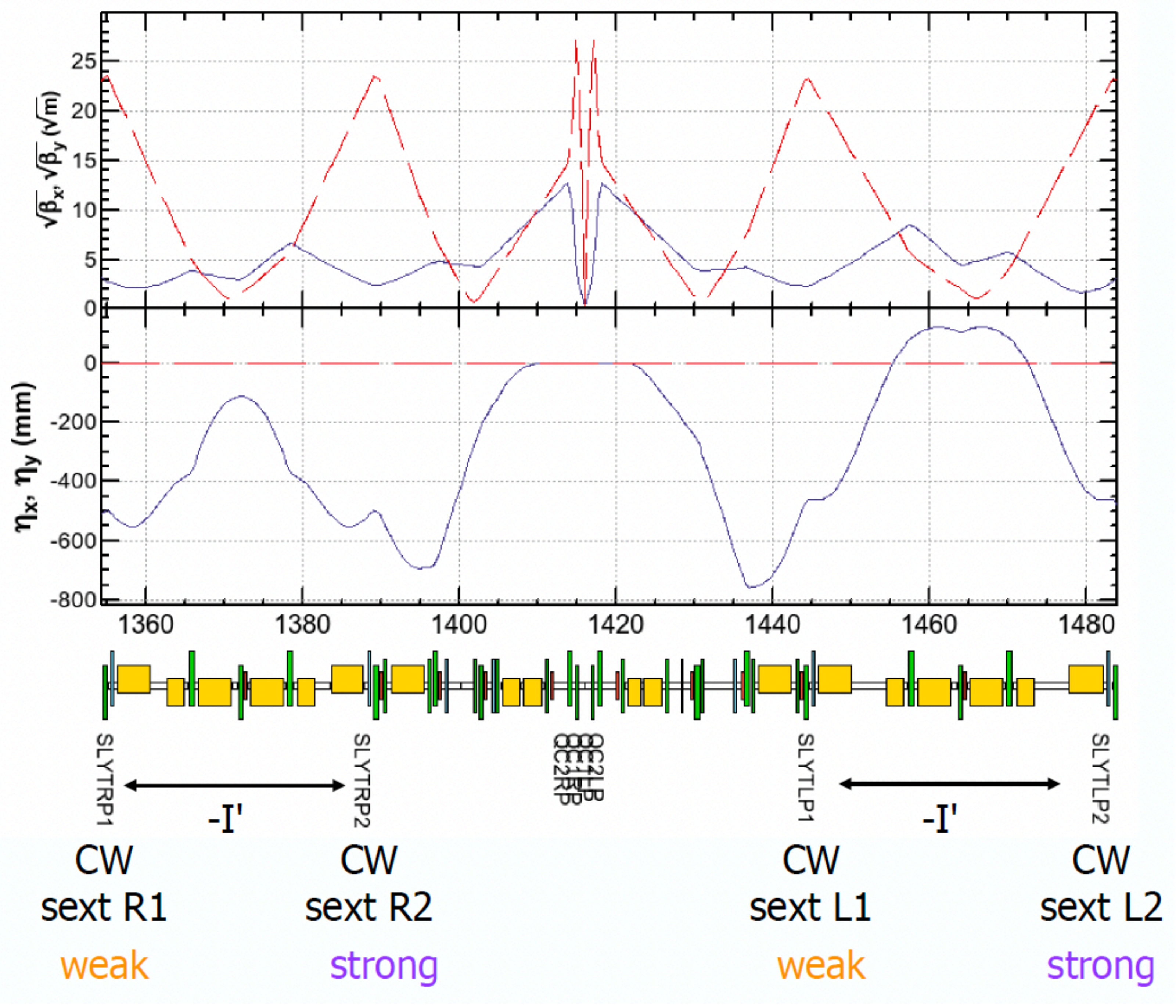


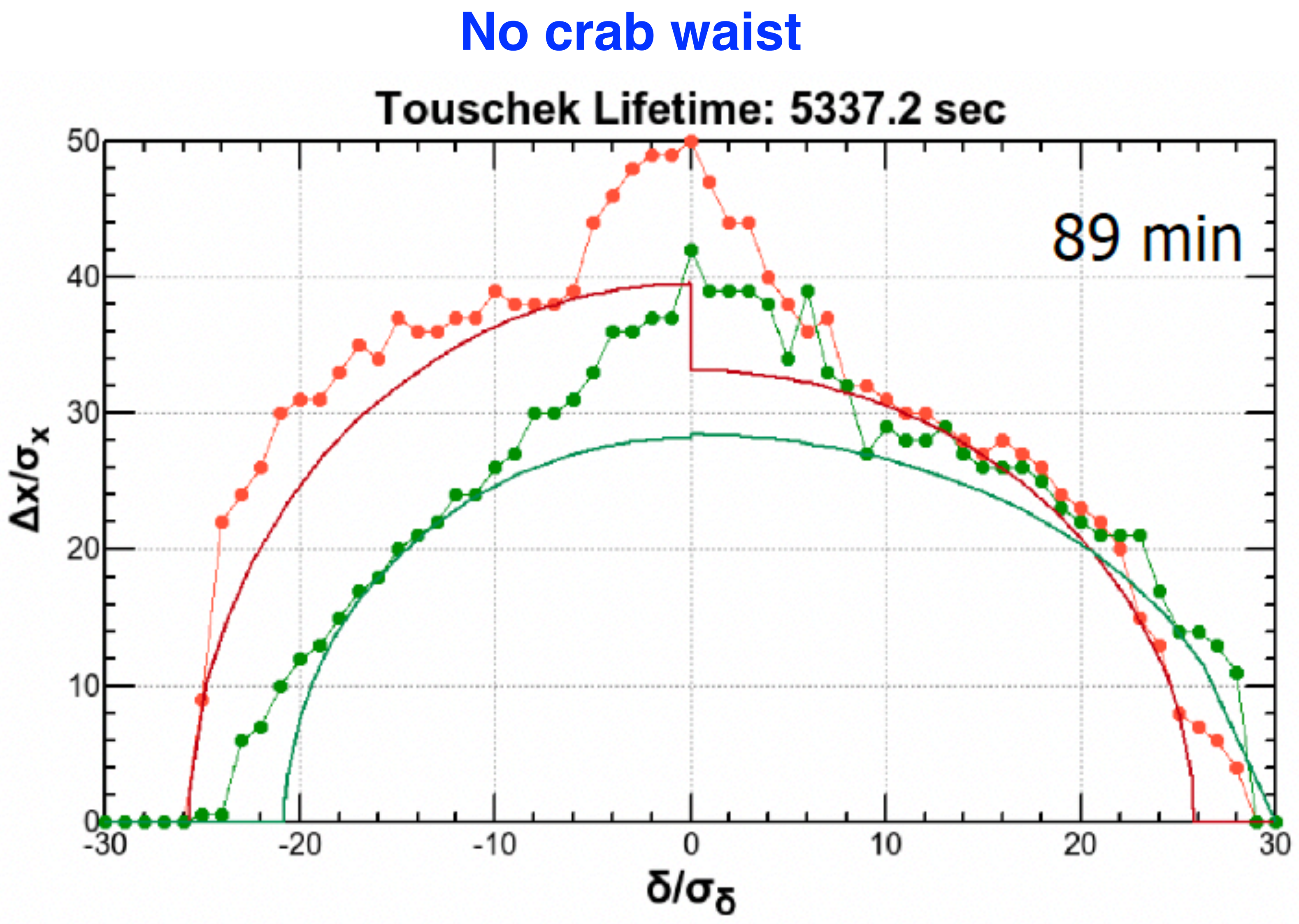


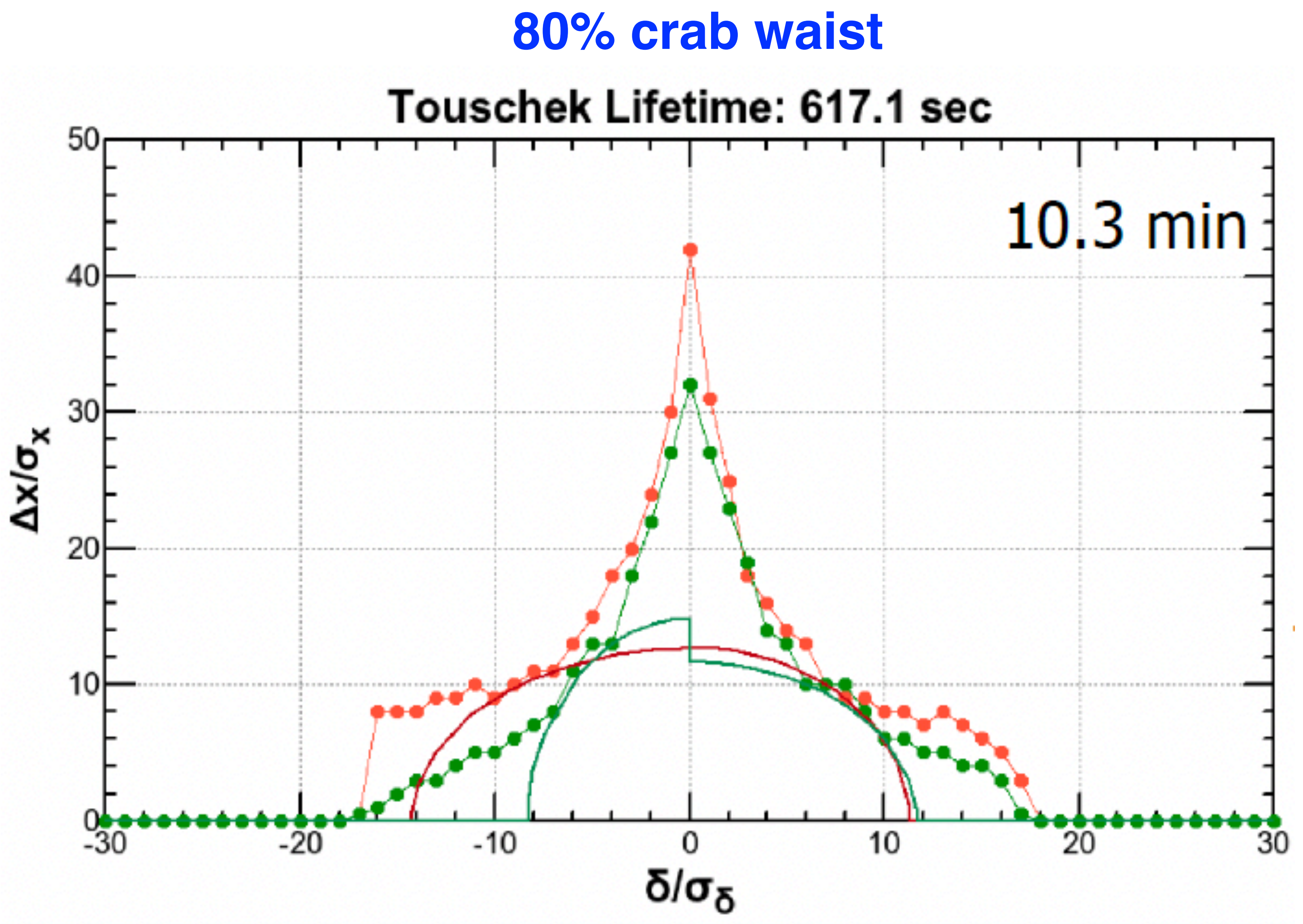
[1] K. Oide and H. Koiso, Phys. Rev. E 47, 2010 (1993). [2] SuperKEKB TDR. [3] Y. Suetsugu, et al., PRAB 26, 013201 (2023). [5] A. Natochii, et al., "Beam background expectations for Belle II at SuperKEKB".
[6] M. Masuzawa, IPAC'22. [7] D. Zhou et al., "Beam Dynamics Issues in the SuperKEKB". [8] K. Hirosawa et al., J. Phys.: Conf. Ser. 1067 062004 (2018).

IR nonlinearity: converged understandings

- 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 (at high bunch currents), but cause significant loss of dynamic aperture and lifetime at SuperKEKB with β_y^*=1 mm [4]. **Careful machine tunings might be necessary to improve the efficiency of CW (this talk)**.



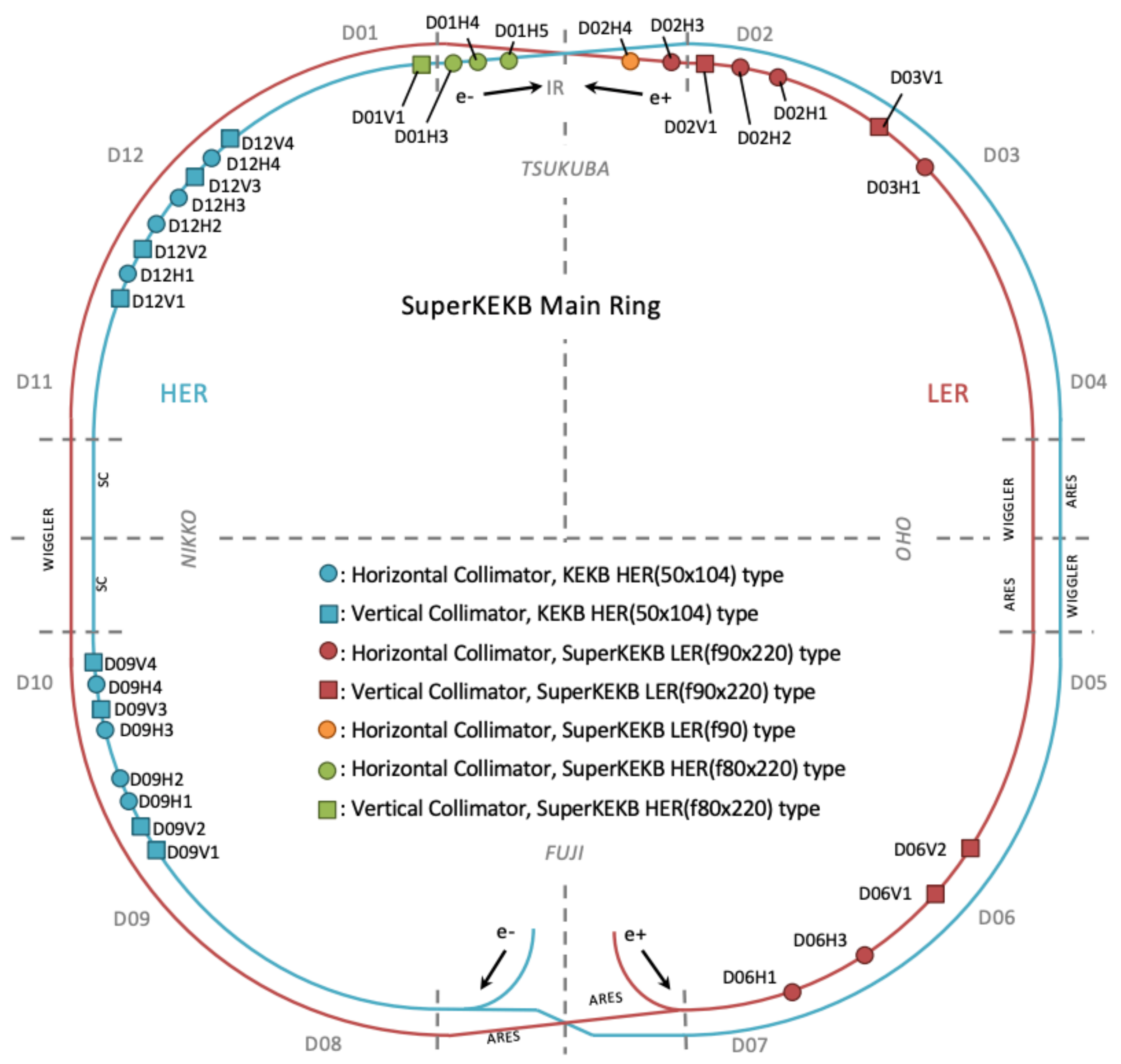


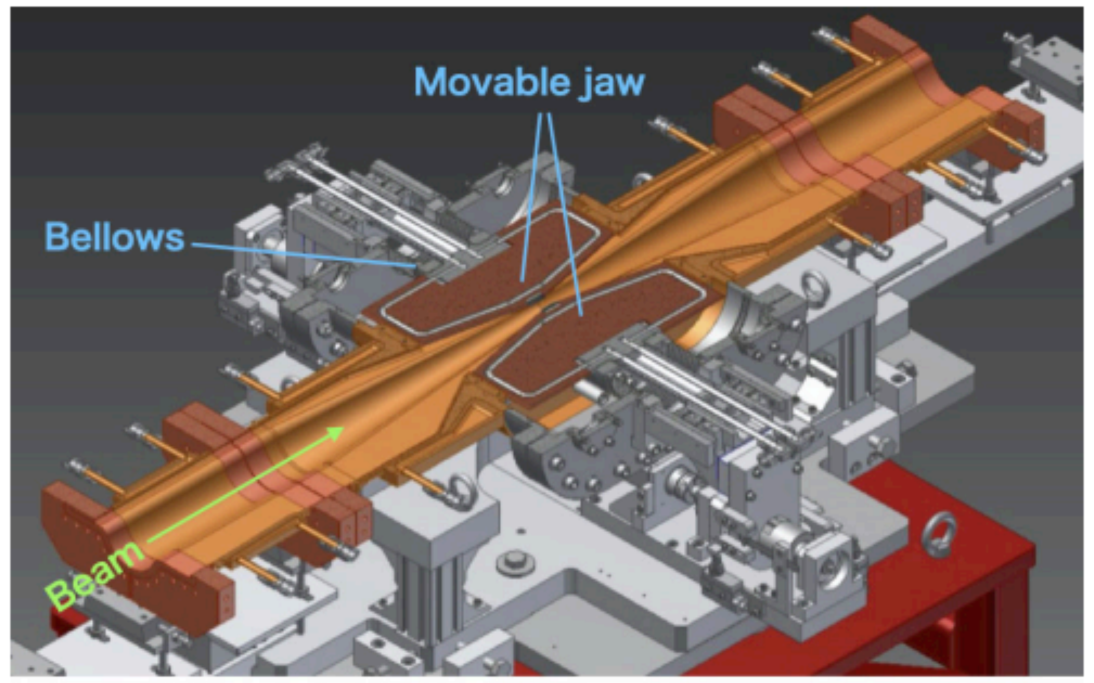


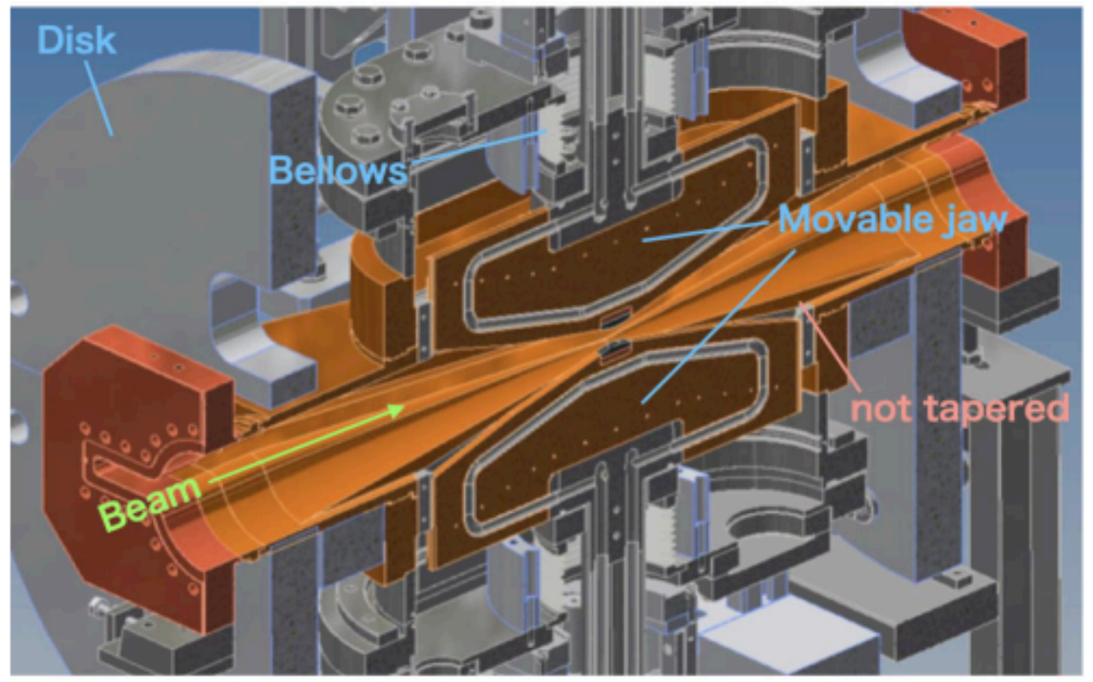
[1] M. Zobov et al., Phys. Rev. Lett. 104, 174801 (2010). [2] SuperKEKB TDR. [3] K. Oide et al., Phys. Rev. Accel. Beams 19, 111005 (2016). [4] Y. Ohnishi, "Dynamic Aperture for Crab Waist in LER".

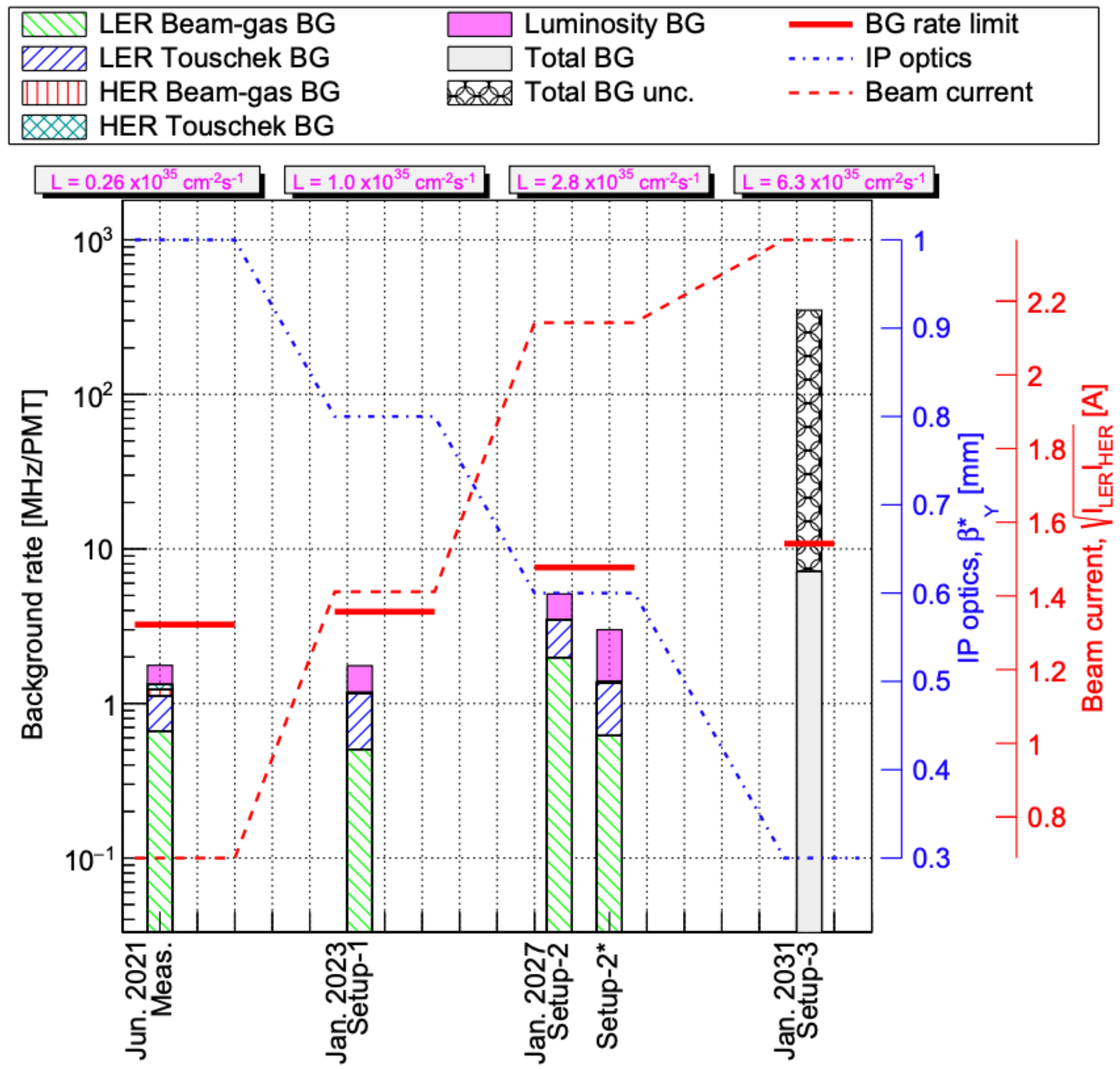
IR nonlinearity: converged understandings

- High detector background
  - The short lifetime and poor injection efficiency cause high background to Belle II [1,2], requiring tight configurations of collimation system [3].
  - Small-gap collimators contribute large impedance (especially after head damages) and caused vertical emittance blowup (“noise” in bunch-by-bunch feedback, interplay with beam-beam, etc.) [4].







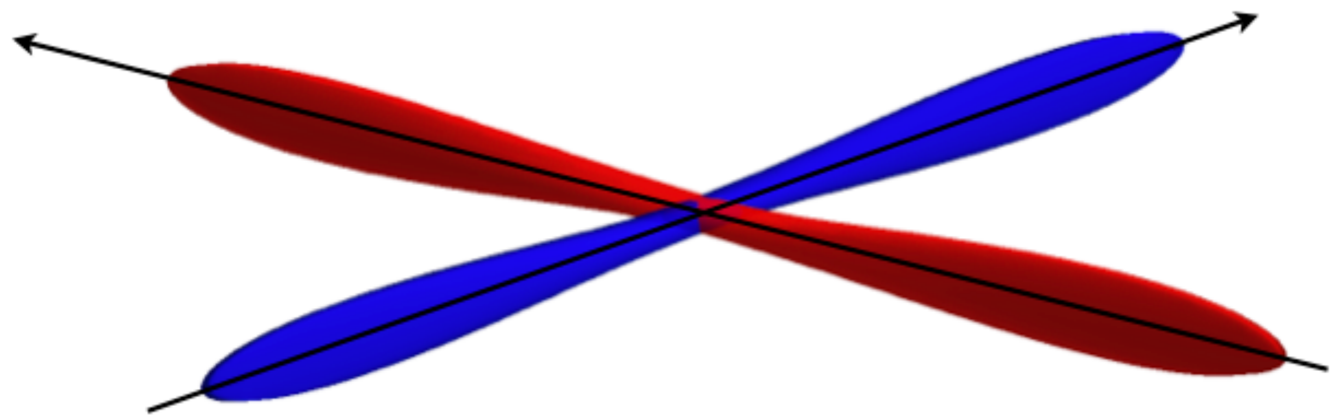


[1] A. Natochii, et al., “Beam background expectations for Belle II at SuperKEKB”. [2] A. Natochii et al., PRAB 24, 081001 (2021).

[3] T. Ishibashi et al., PRAB 23, 053501 (2020). [4] T. Ishibashi et al. 2024 JINST 19 P02013.

Beam-beam related topics in crab-waist colliders

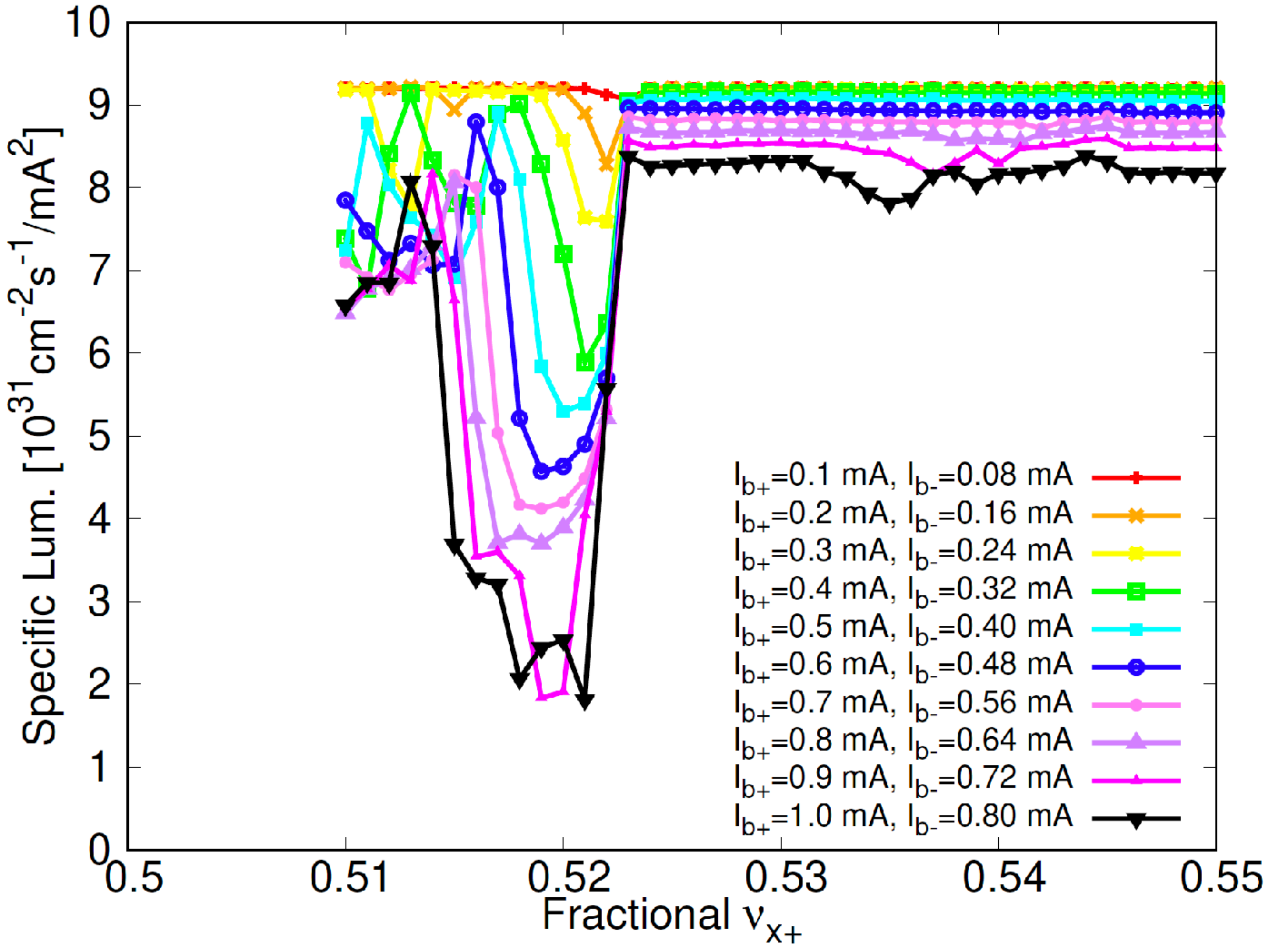
- Mechanisms of **pure beam-beam effects**
  - Horizontal: (coherent two-beam) X-Z instability [Ohmi 2017 (PRL), Kuroo 2018 (PRAB)] and (single-beam) synchrobetatron resonances [Zhou 2023 (PRAB)]
  - Vertical: Nonlinear X-Y resonances [Ohmi 2004 (PRST-AB), Ohmi 2007 (PRST-AB), Zobov 2010 (PRL)]
- Mechanisms of **interplay between beam-beam and impedances**
  - Horizontal: modified X-Z instability [Lin 2022 (PRAB), Zhang 2020 (PRAB), Migliorati 2021 (EPJP)] (key issue: potential distortion and synchrotron tune spread due to impedance)
  - Vertical: TMCI-like head-tail instability [White 2024 (PRAB), Zhang 2023 (PRAB), Zhou 2023 (PRAB), Ohmi 2023 (PRAB)] (key issues: spread of synchrotron and vertical betatron tunes due to impedance)
- Mechanism of **interplay between 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)]
  - Nonlinear IP X-Y couplings [Zhou 2015 (ICFA BDN)]
  - Non-perfect crab waist [To be investigated]

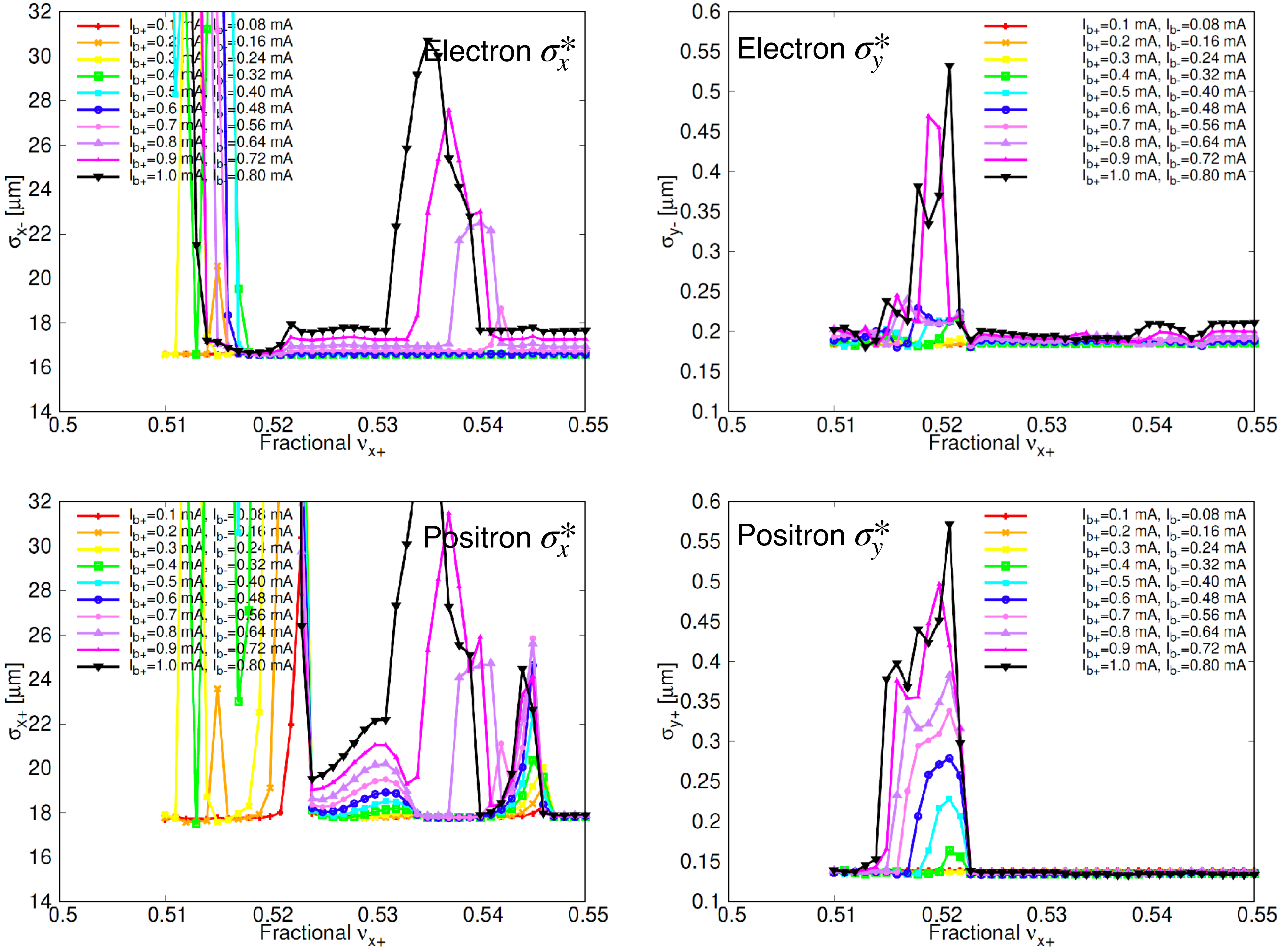


The recent papers of K. Ohmi, Y. Zhang et al. showcase full collaborations.
More papers triggered by collaborations on SuperKEKB are expected.

Combined effects of beam-beam and impedances

- Simulated ν_x-dependent horizontal instability in SuperKEKB
  - Strong **coherent X-Z instability** around resonance $\nu_x - k\nu_s(J_z) = N/2$ and weak blowup due to **synchrobetatron (SB) resonances** [1]
  - Mitigation: **Squeezing β_x^*** [2]

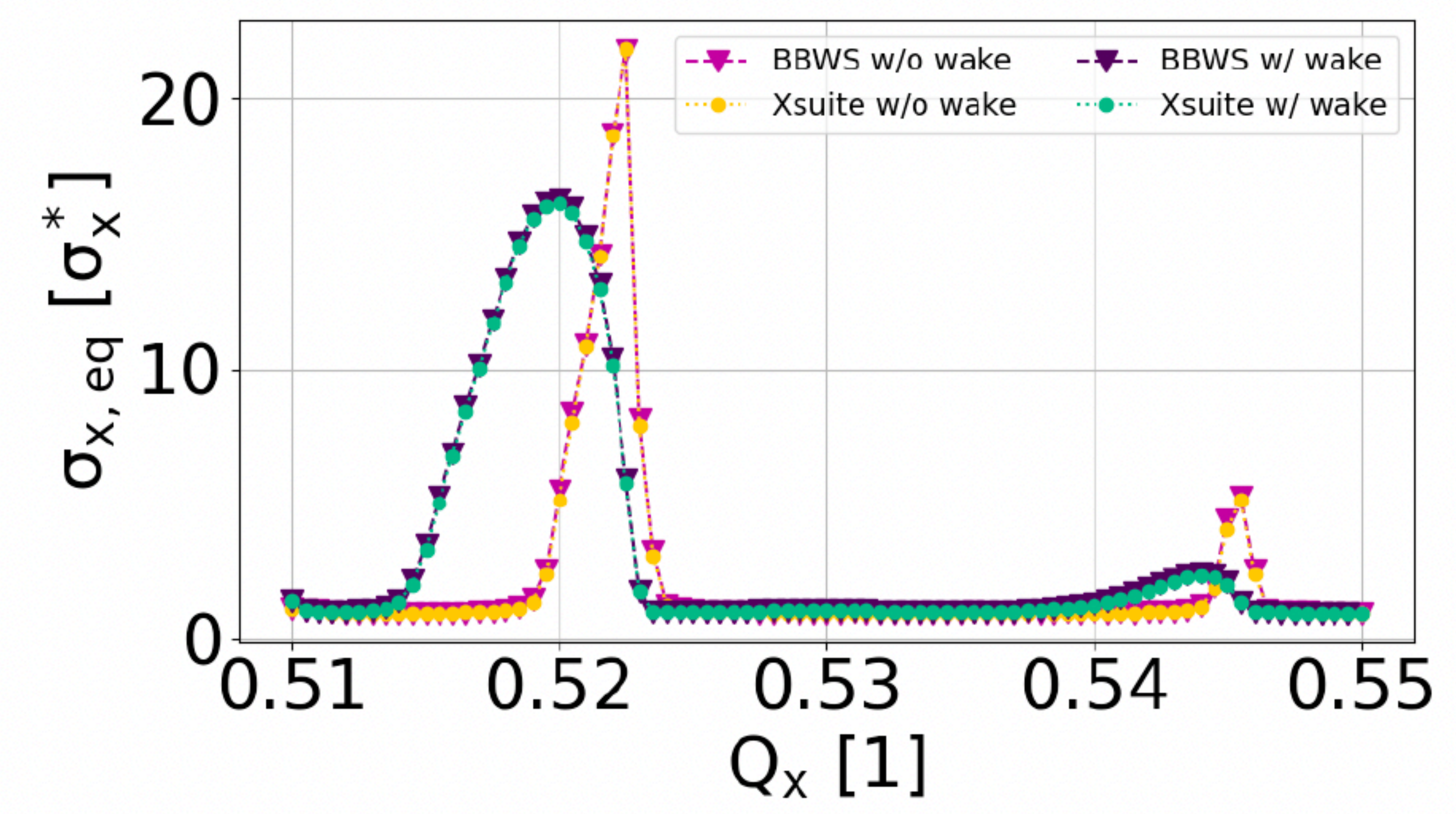


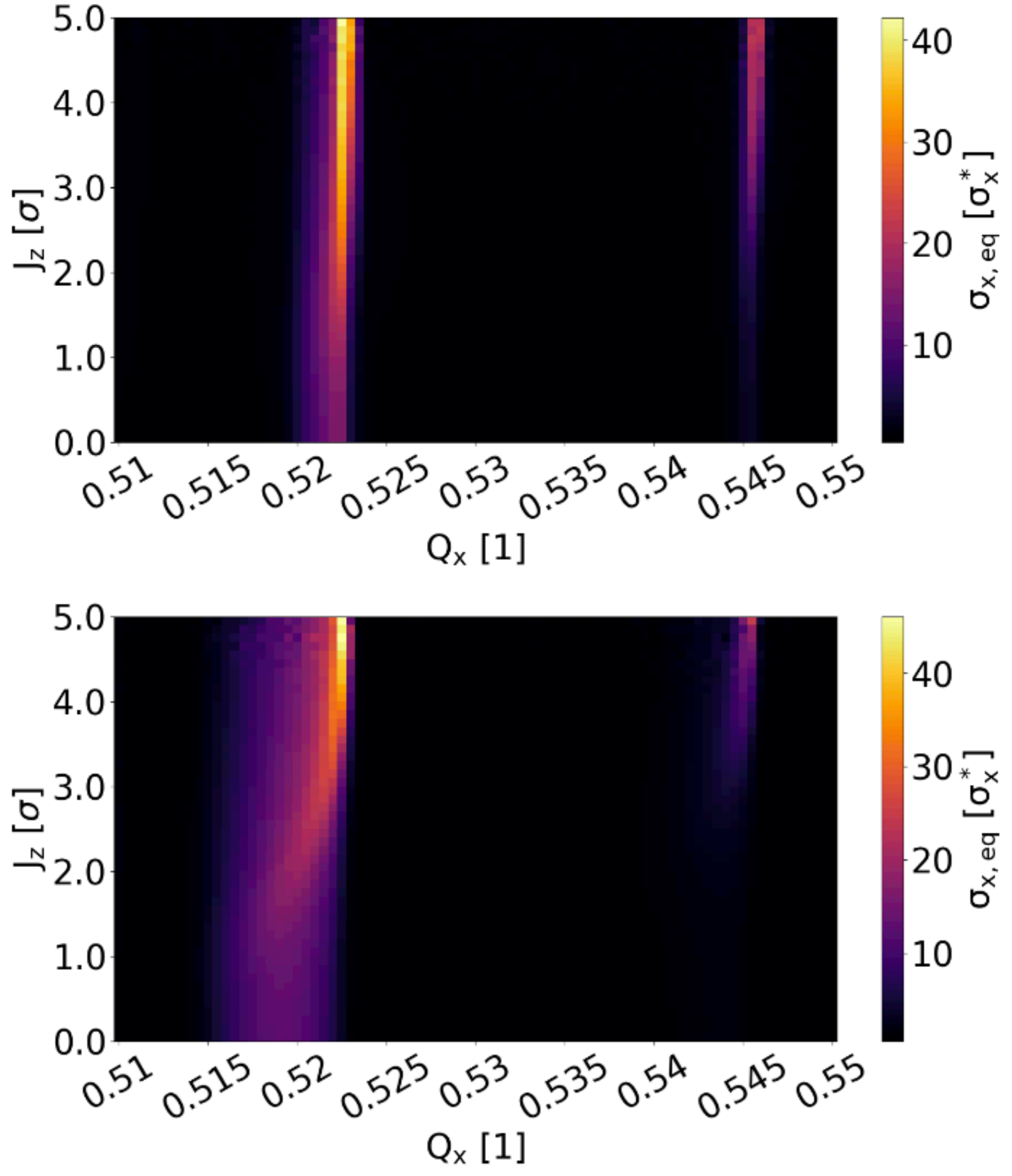


[1] D. Zhou et al., PRAB 26, 071001 (2023). [2] K. Ohmi et al., PRL 119, 134801.

Combined effects of beam-beam and impedances

- Simulated ν_x-dependent horizontal instability in SuperKEKB
  - Beam-beam driven **SB resonances** have been investigated since 1970s.
  - Investigations are ongoing to study the SB resonances in the presence of impedance effects [1, 2].





[1] D. Zhou et al., PRAB 26, 071001 (2023). [2] P. Kicsiny et al., paper under preparation.

Combined effects of beam-beam and impedances

- Simulated vertical TMCI-like instability in SuperKEKB
  - First found by K. Ohmi in simulations, followed by detailed investigations [1,2,3].
  - **Beam-beam mode coupling** theory reproduces the results of the beam-beam simulation [3].

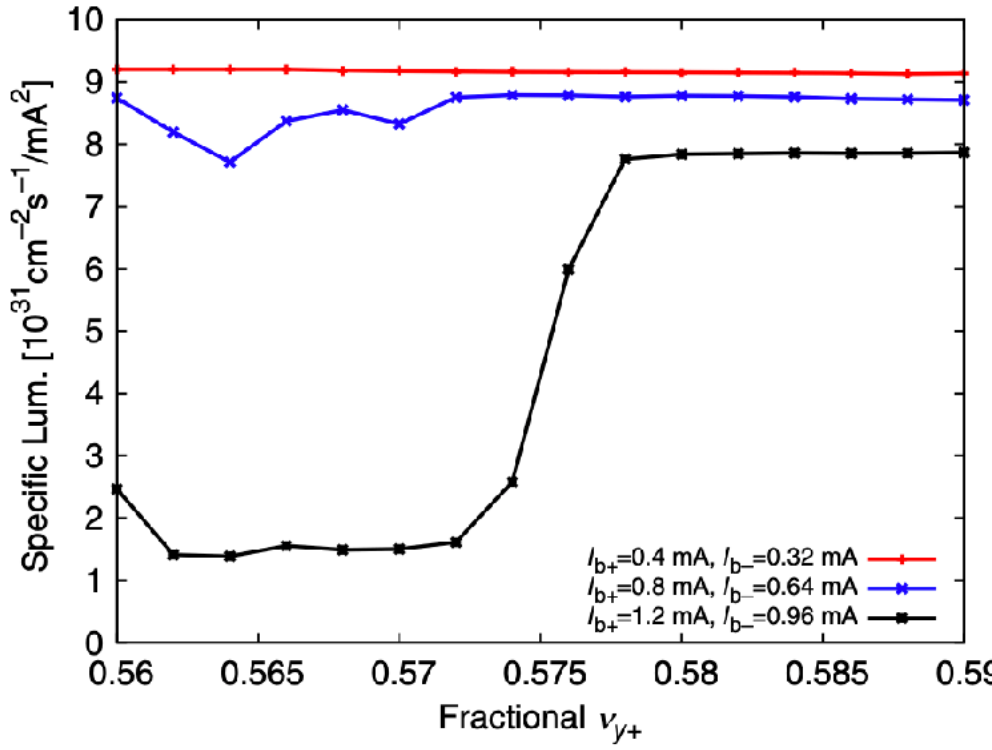


FIG. 14. Specific luminosity predicted by BBSS simulations with the inclusion of longitudinal impedances of both HER and LER and transverse impedance of only LER. Simulations were done by scanning the vertical tune of LER and varying the two beams' bunch currents. Other beam parameters are frozen the same as April 5, 2022, of Table II except that $\epsilon_{y-}/\epsilon_{y+} = 35/20$ pm (single-beam emittances observed on December 21, 2021).

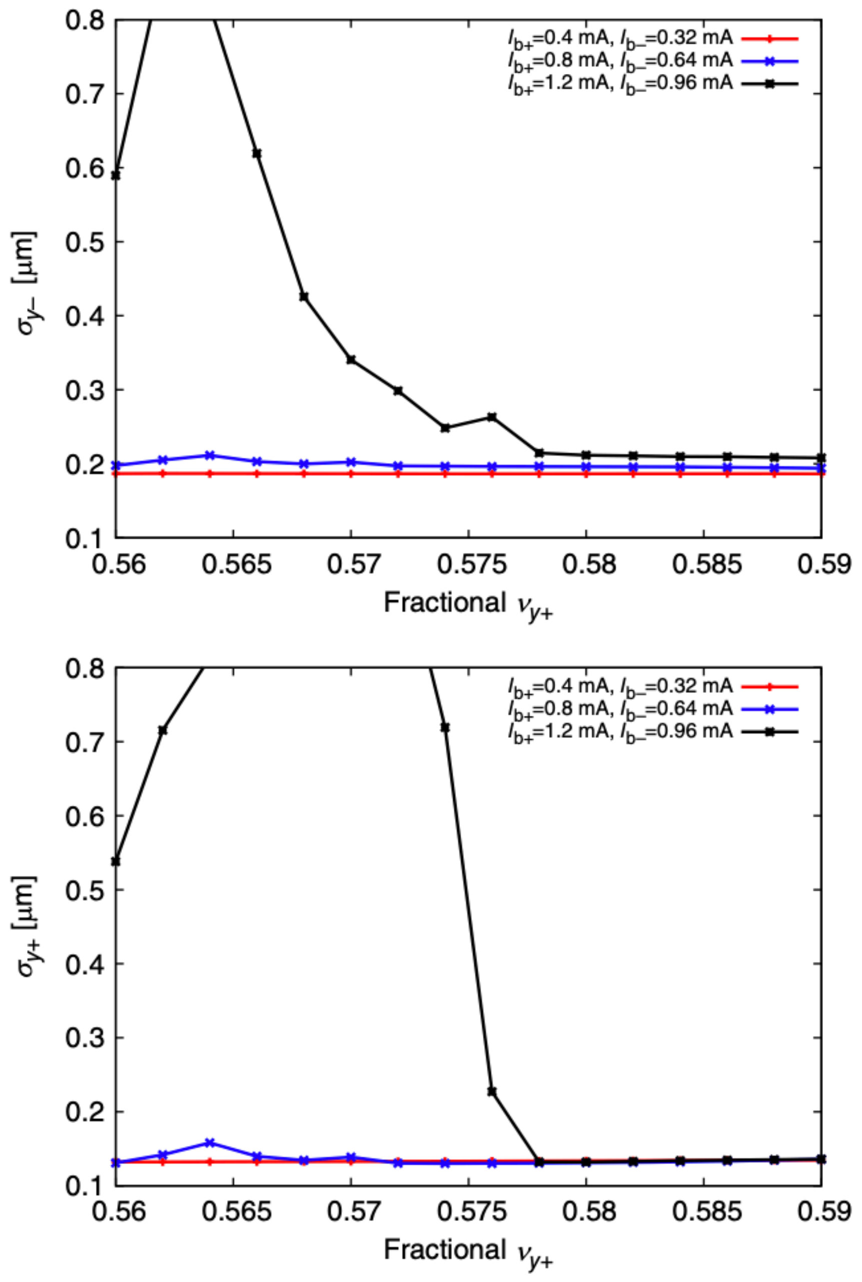


FIG. 15. Vertical beam sizes of electron (upper) and positron (lower) beams at the IP, corresponding to Fig. 14.

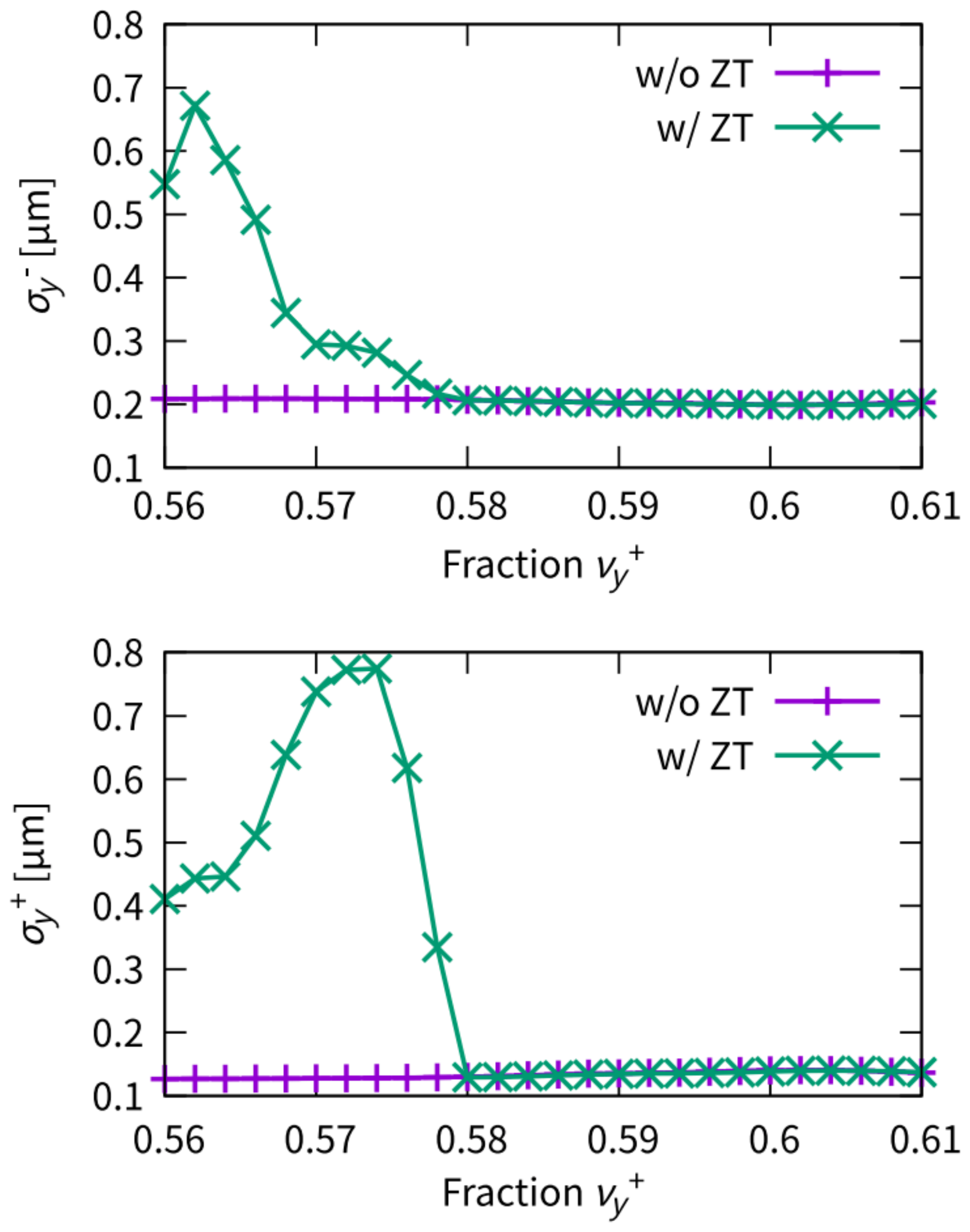


FIG. 17. Colliding beam size versus LER vertical tune with and without transverse impedance at SuperKEKB. The vertical tune of HER is fixed at 0.572.

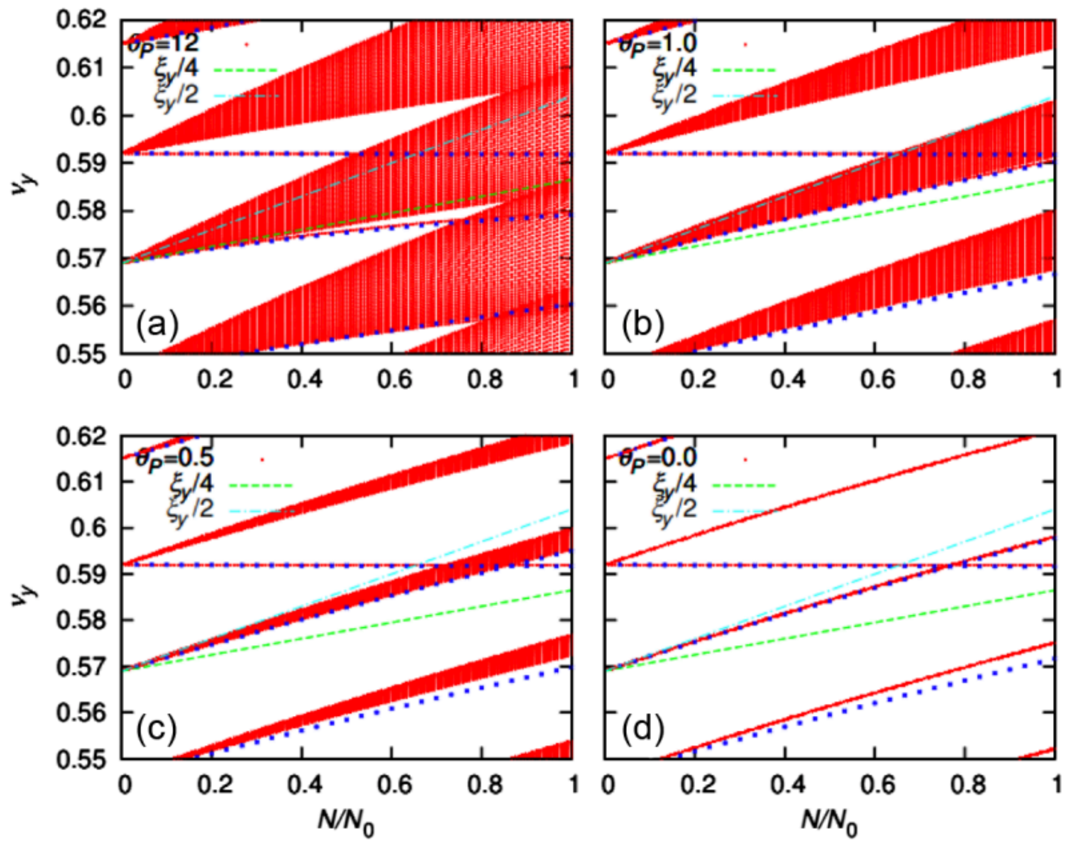


FIG. 1. Tune variation of beam-beam σ modes for the beam-beam cross wake as functions of bunch population. Plots (a)–(d) show tune variation for $\theta_P = 12$, 1, 0.5, 0, respectively. The blue dots are given for the flat mode in Eqs. (9) and (11). Lines for $\xi/2$ (green) and $\xi/4$ (cyan) are drawn.

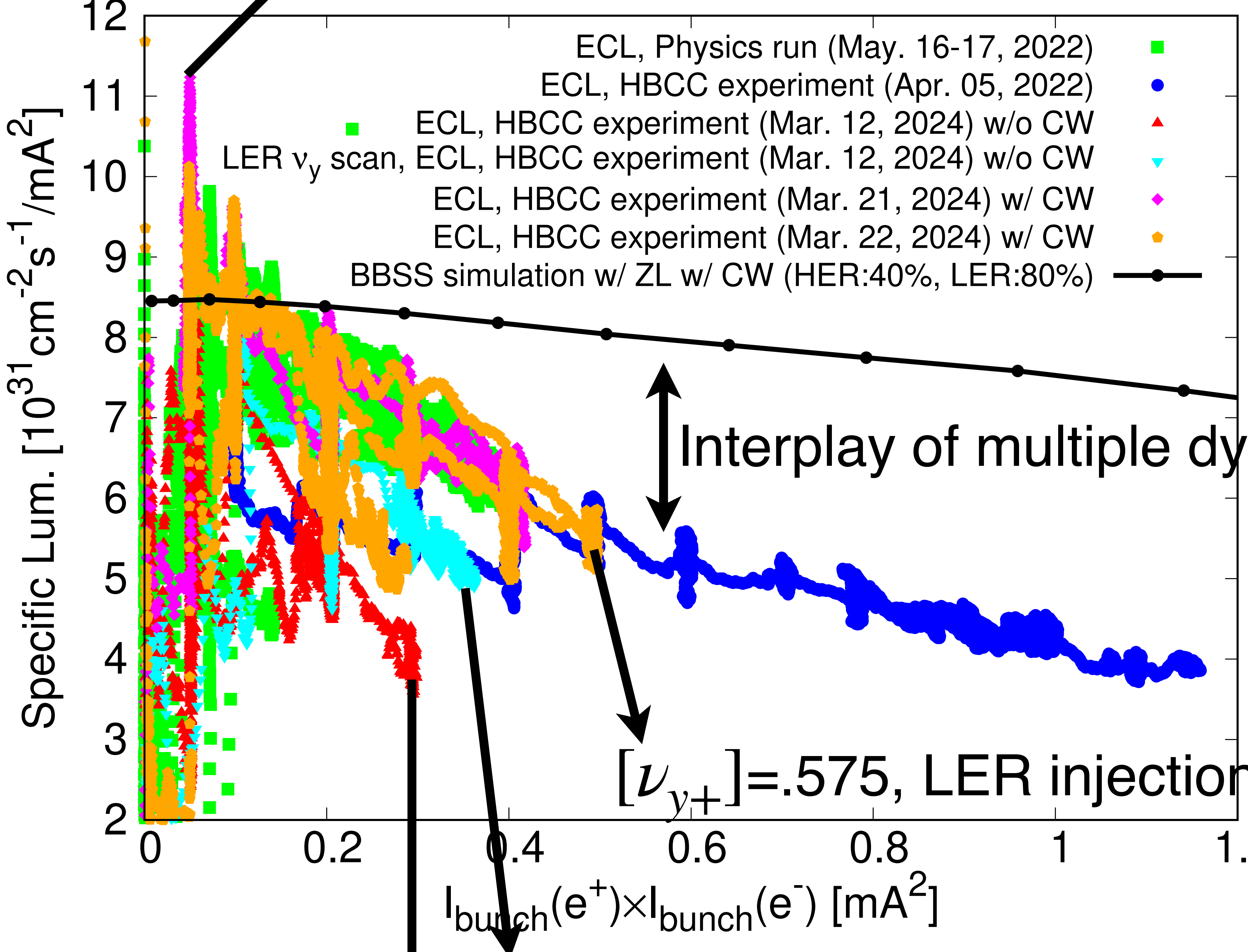
[1] D. Zhou et al., PRAB 26, 071001 (2023). [2] Y. Zhang et al., PRAB 26, 064401 (2023); [3] K. Ohmi et al., PRAB 26, 111001 (2023);

Recent beam-beam machine studies

Crab waist is a MUST

- HBCC studies compared
  - w/ CW, 2024.03.22
  - w/ CW, 2024.03.21
  - w/o CW, 2024.03.12
  - w/ CW, 2022.04.05

Better geometric luminosity in 2024a

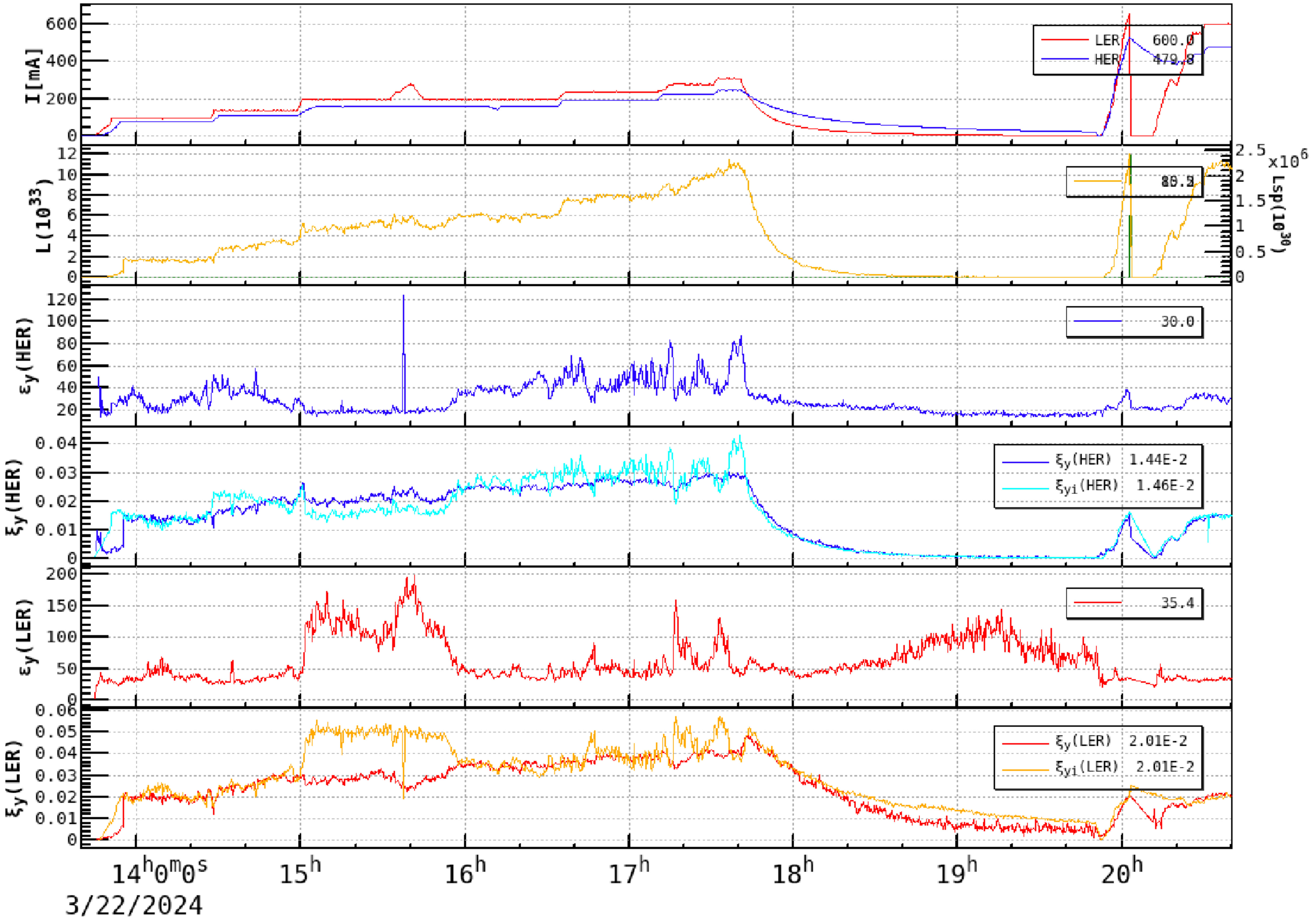


Interplay of multiple dynamics

$[\nu_{y+}]$=.575, LER injection OK

$[\nu_{y+}]$=.567, LER injection trouble

$[\nu_{y+}]$=.59, LER injection impossible at hight bunch currents

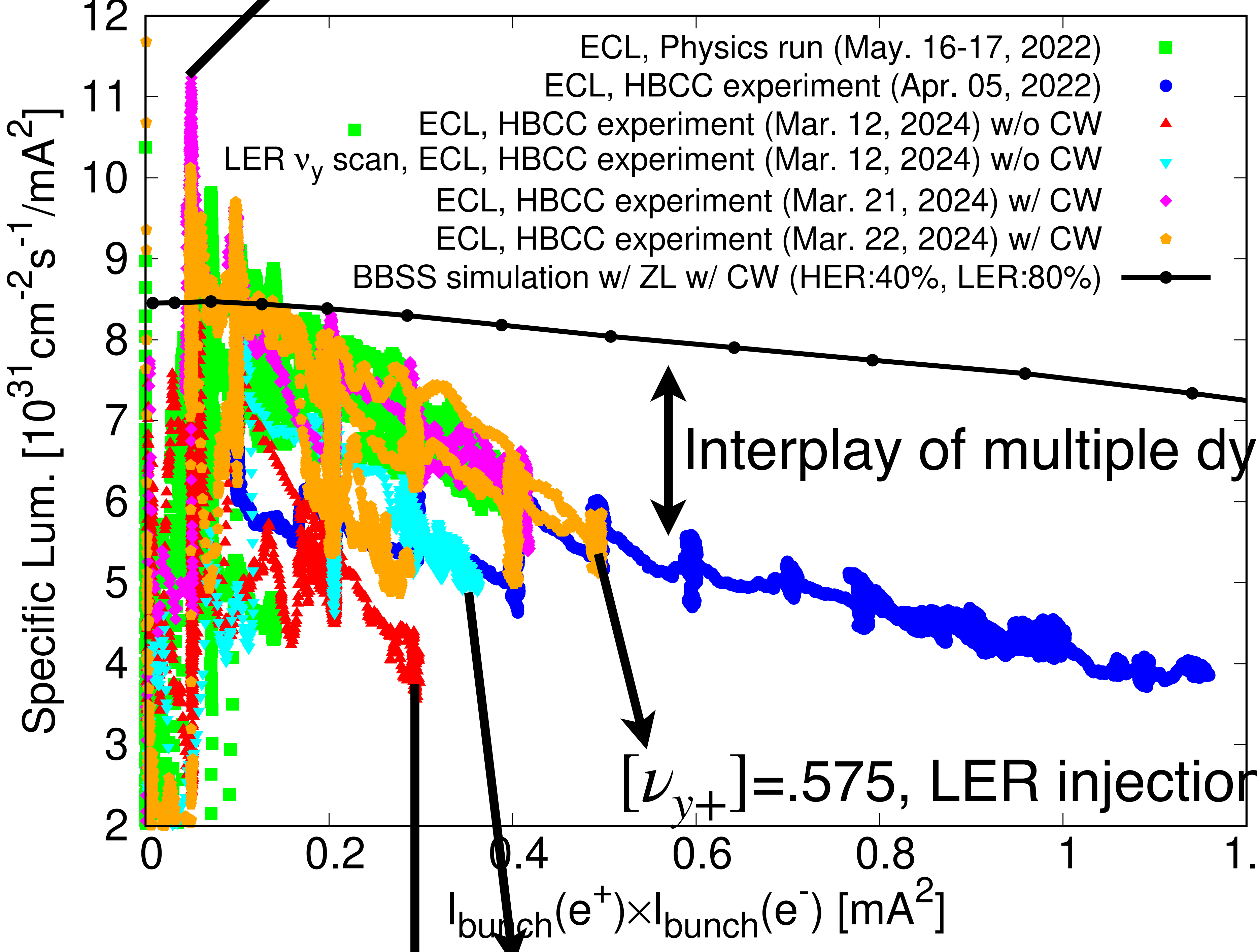


Recent beam-beam machine studies

- HBCC studies compared
  - w/ CW, 2024.03.22
  - w/ CW, 2024.03.21
  - w/o CW, 2024.03.12
  - w/ CW, 2022.04.05

Crab waist is a MUST

Better geometric luminosity in 2024a



Interplay of multiple dynamics

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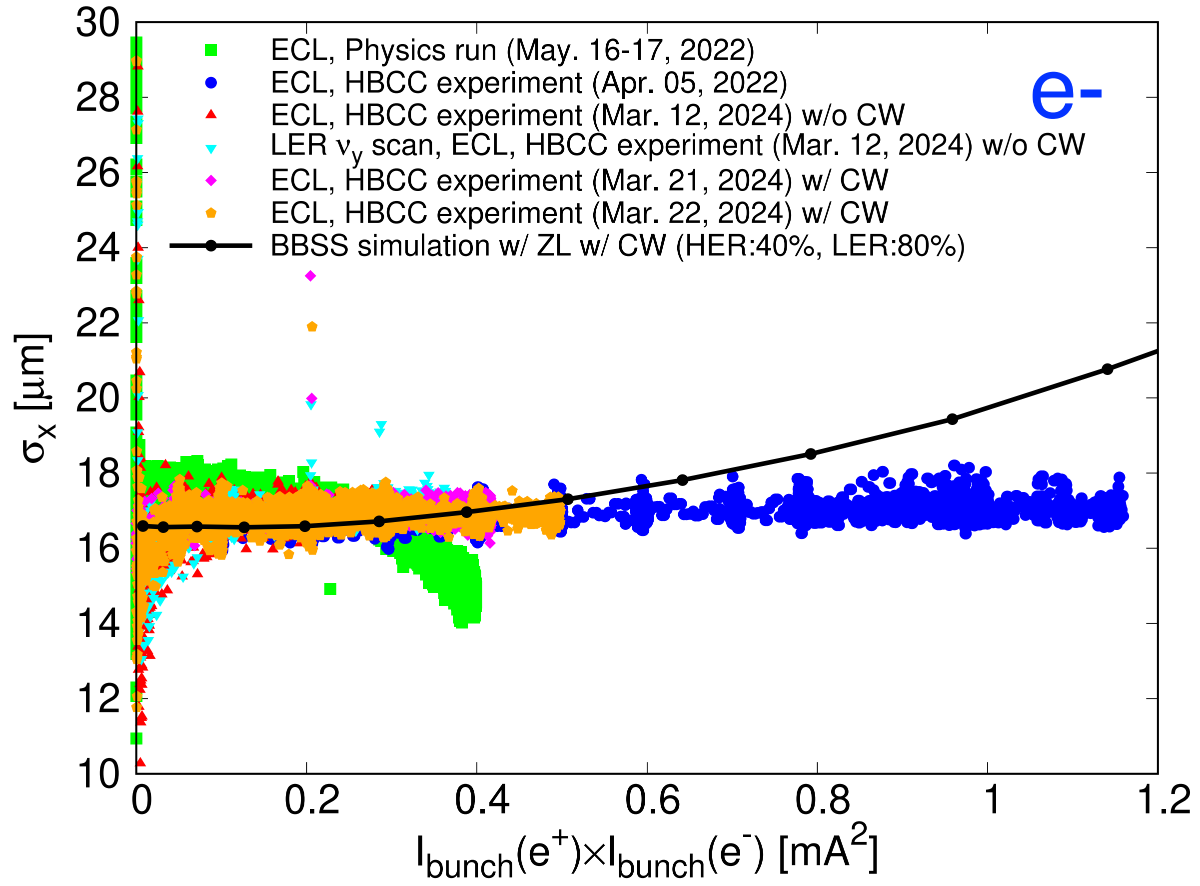
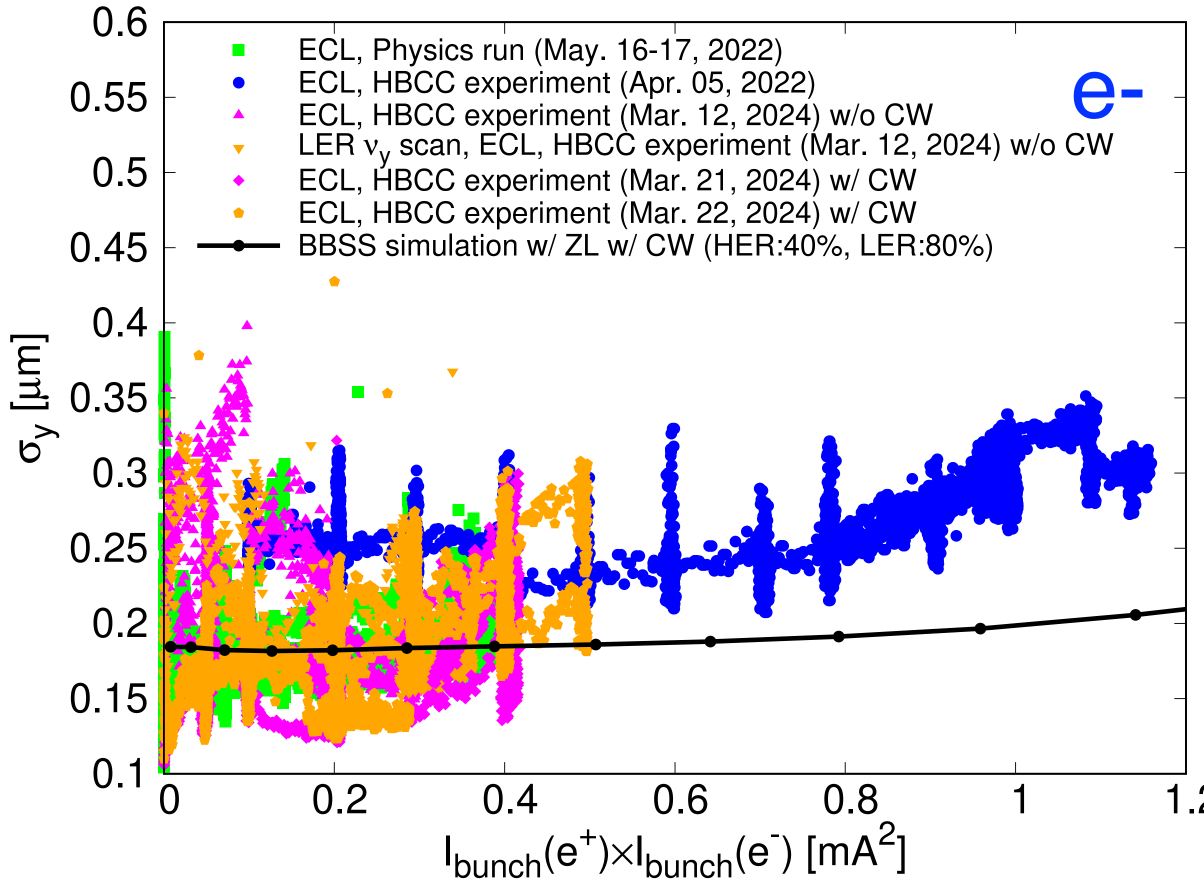
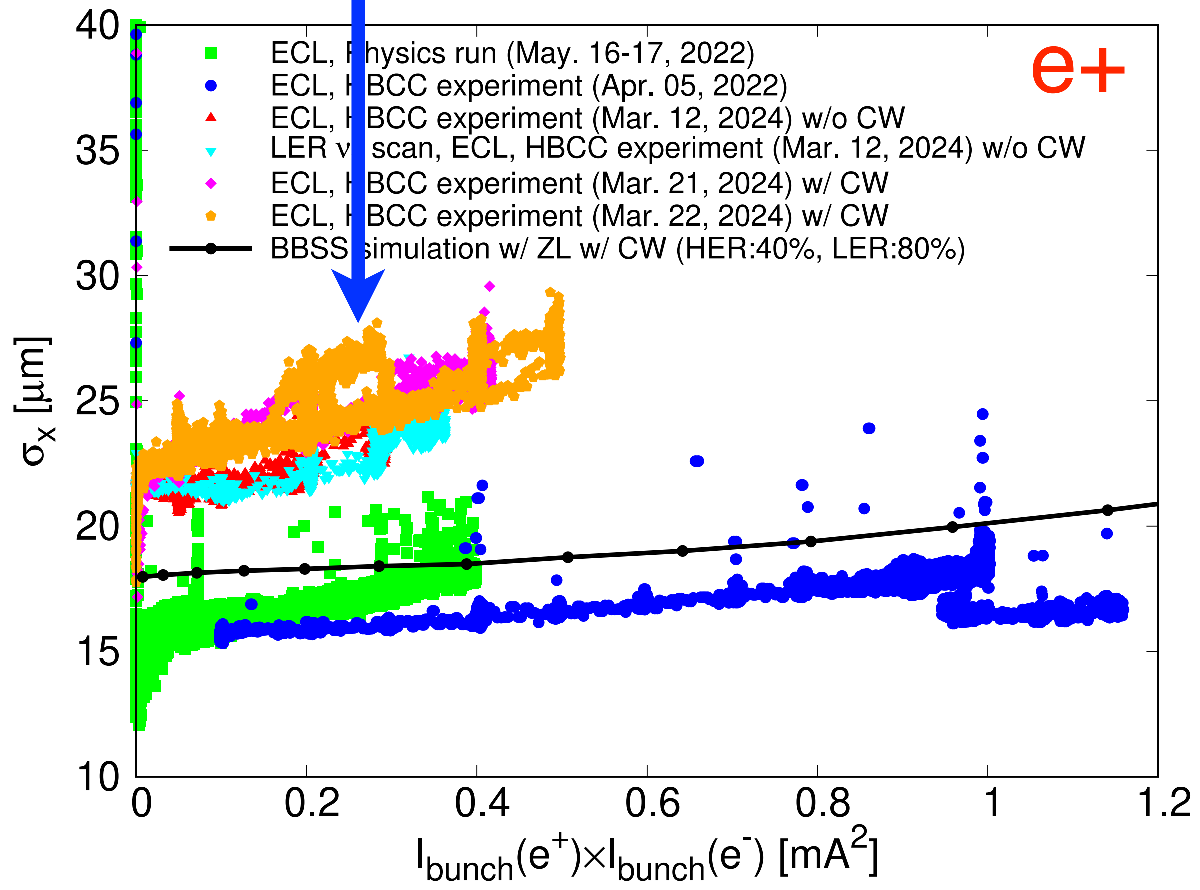
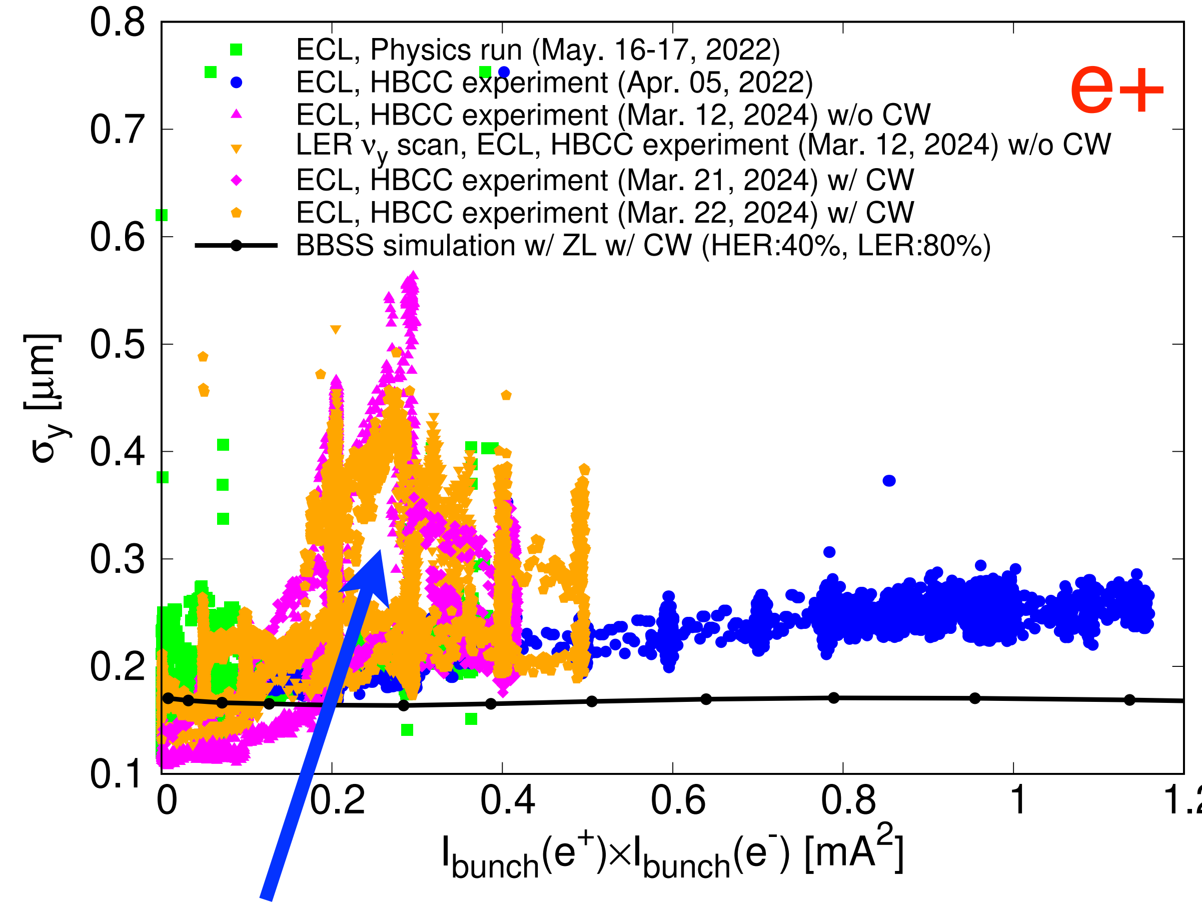




Horizontal blowup will be the next BIG problem

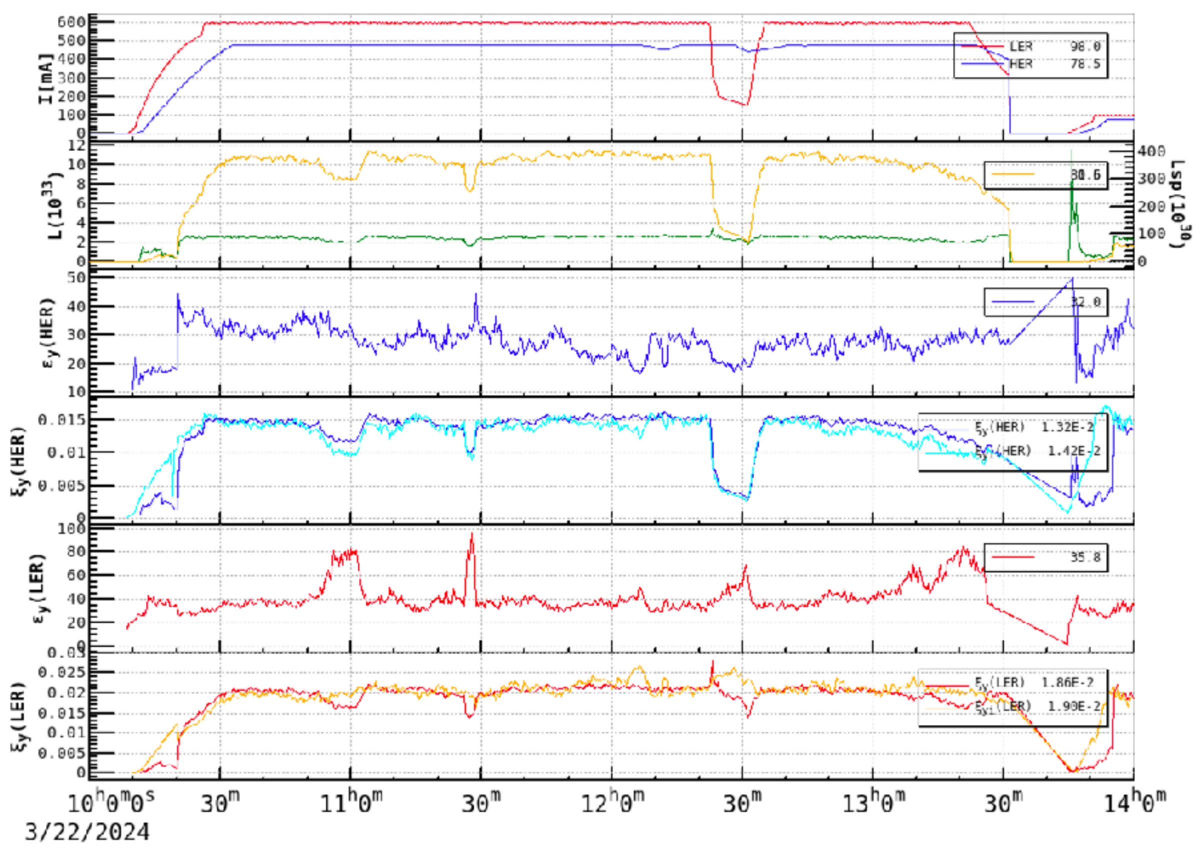


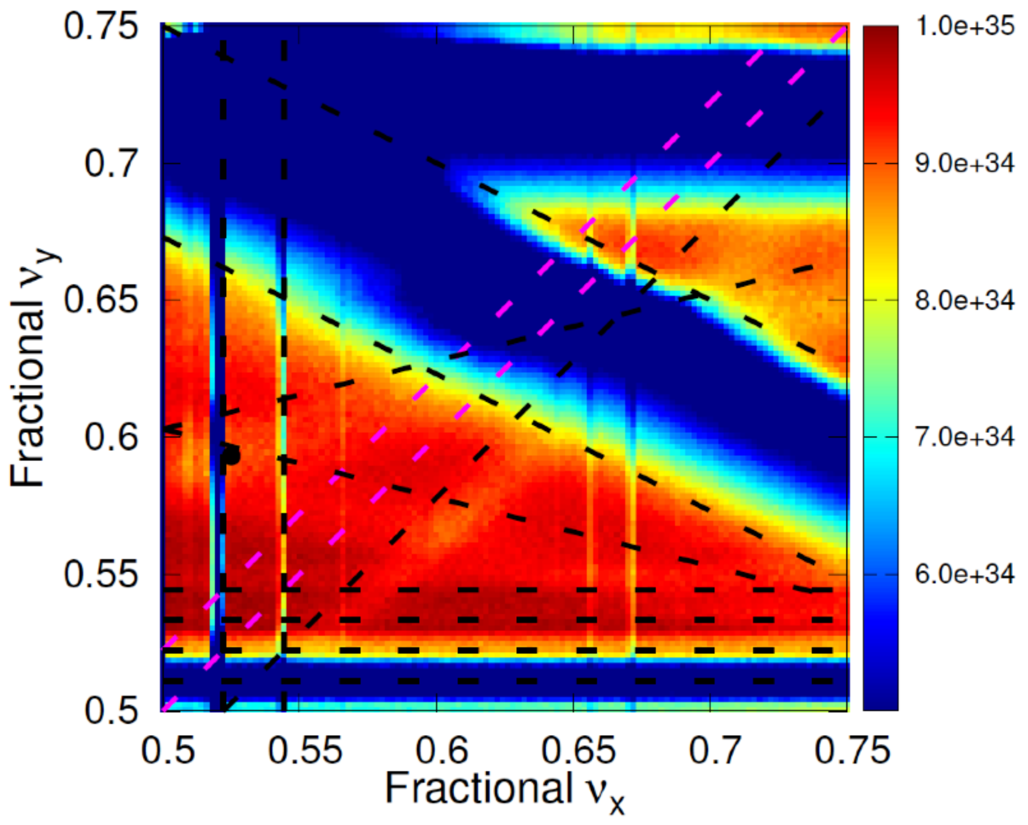


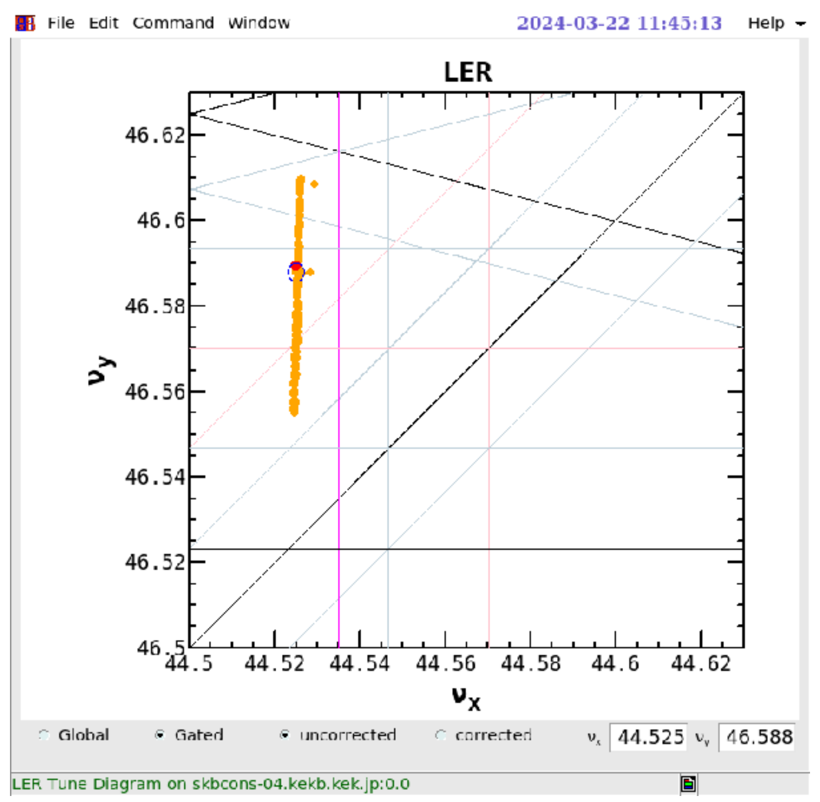
Vertical blowup is complicated
Multiple factors to be identified
HER emittance knobs used to achieve balanced collision

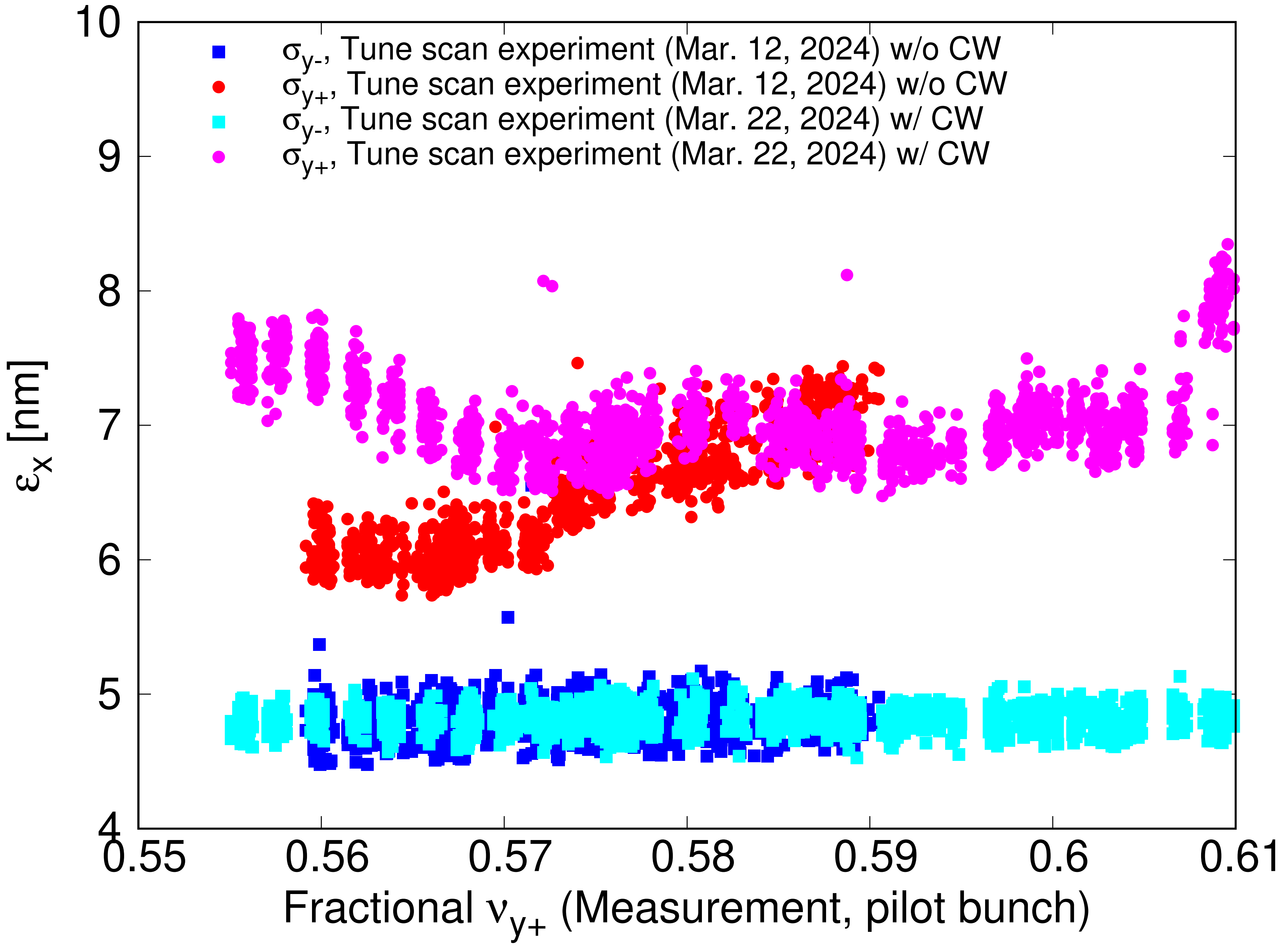
Recent beam-beam machine studies

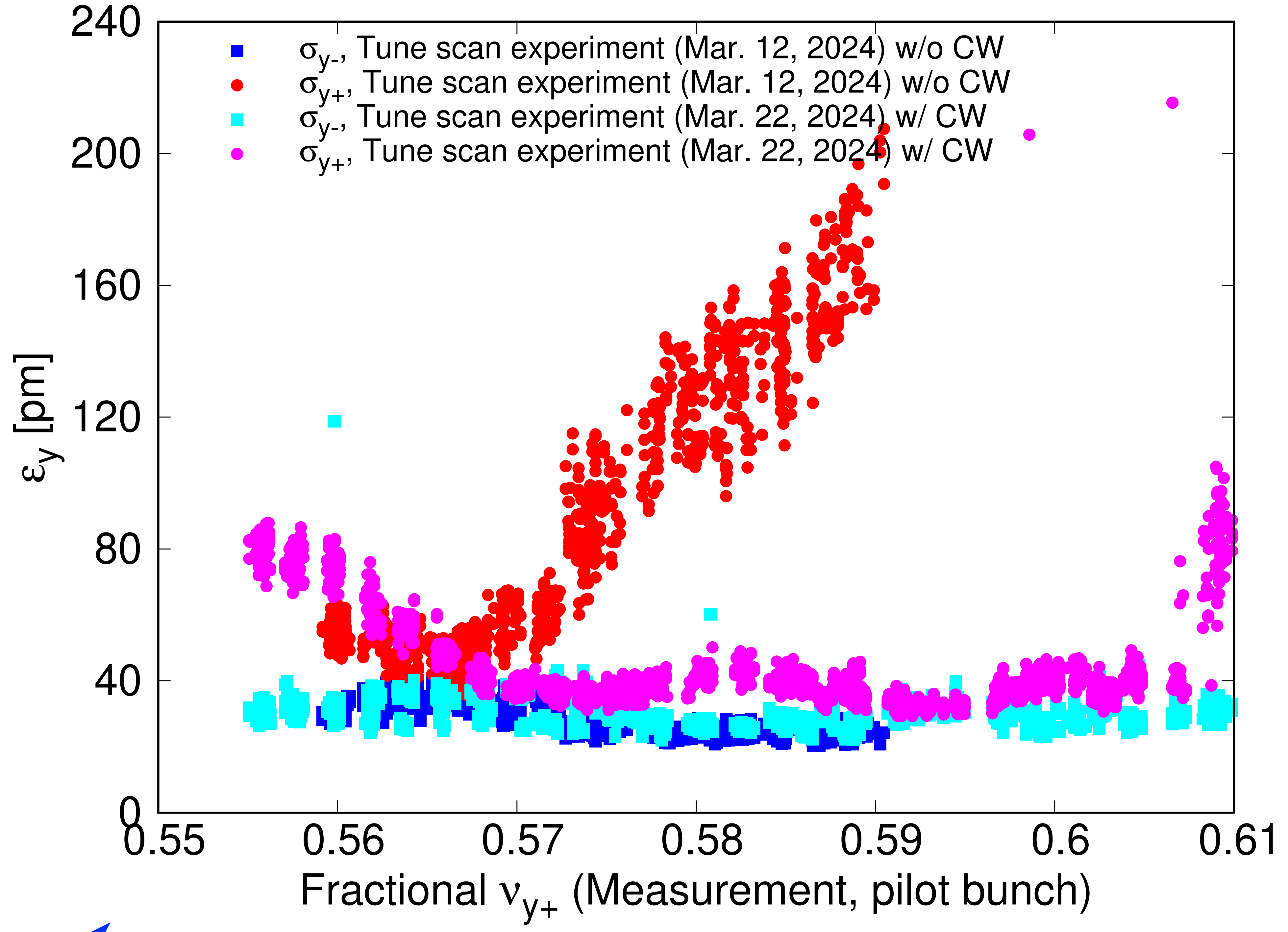
- LER vertical tune scan compared
  - β_y^*=1 mm, w/o CW, 2024.03.12
  - β_y^*=1 mm, w/ CW, 2024.03.22







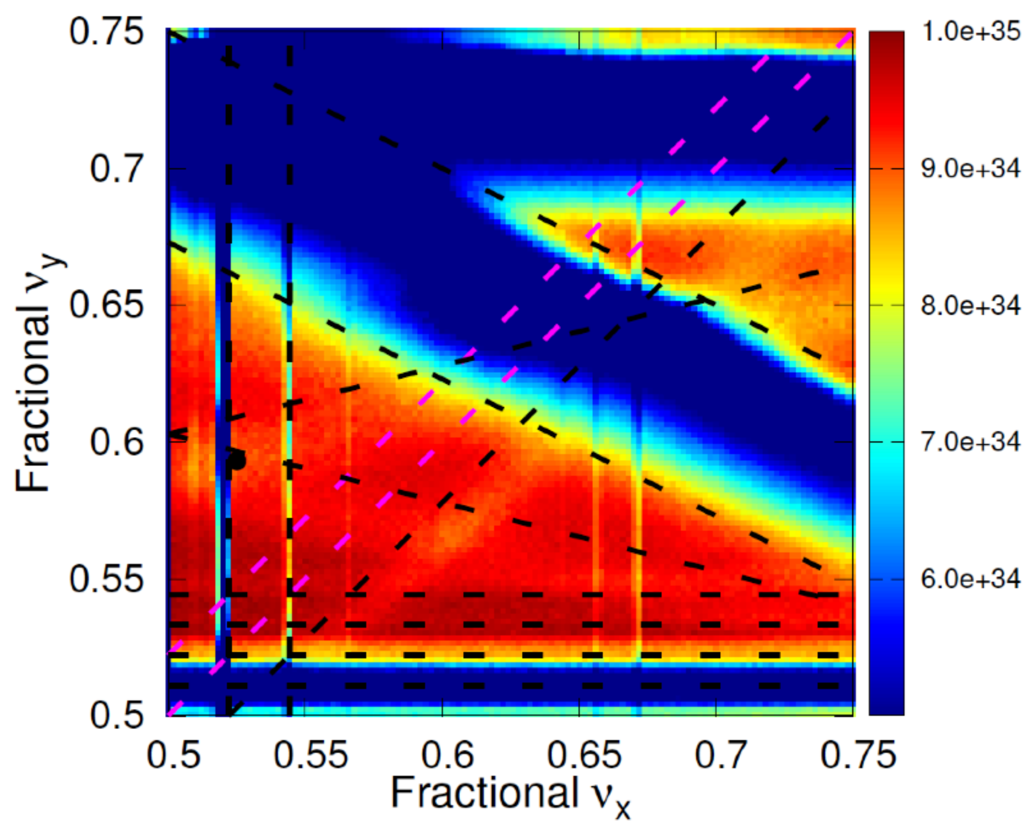


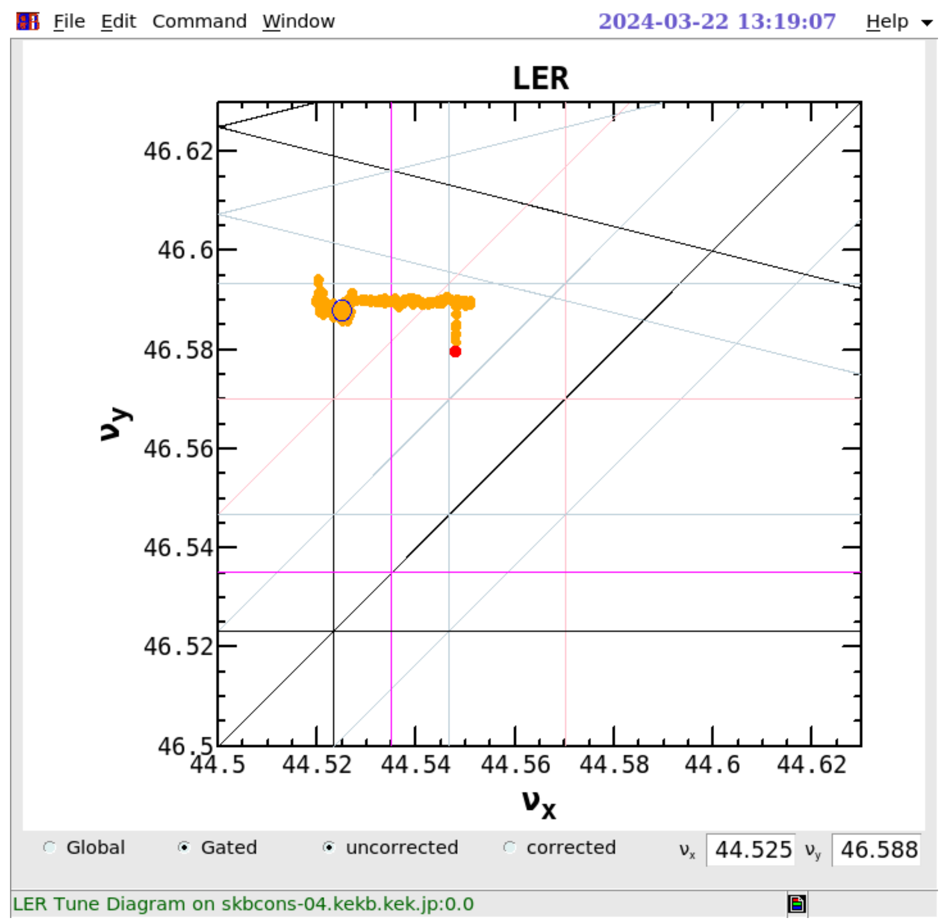


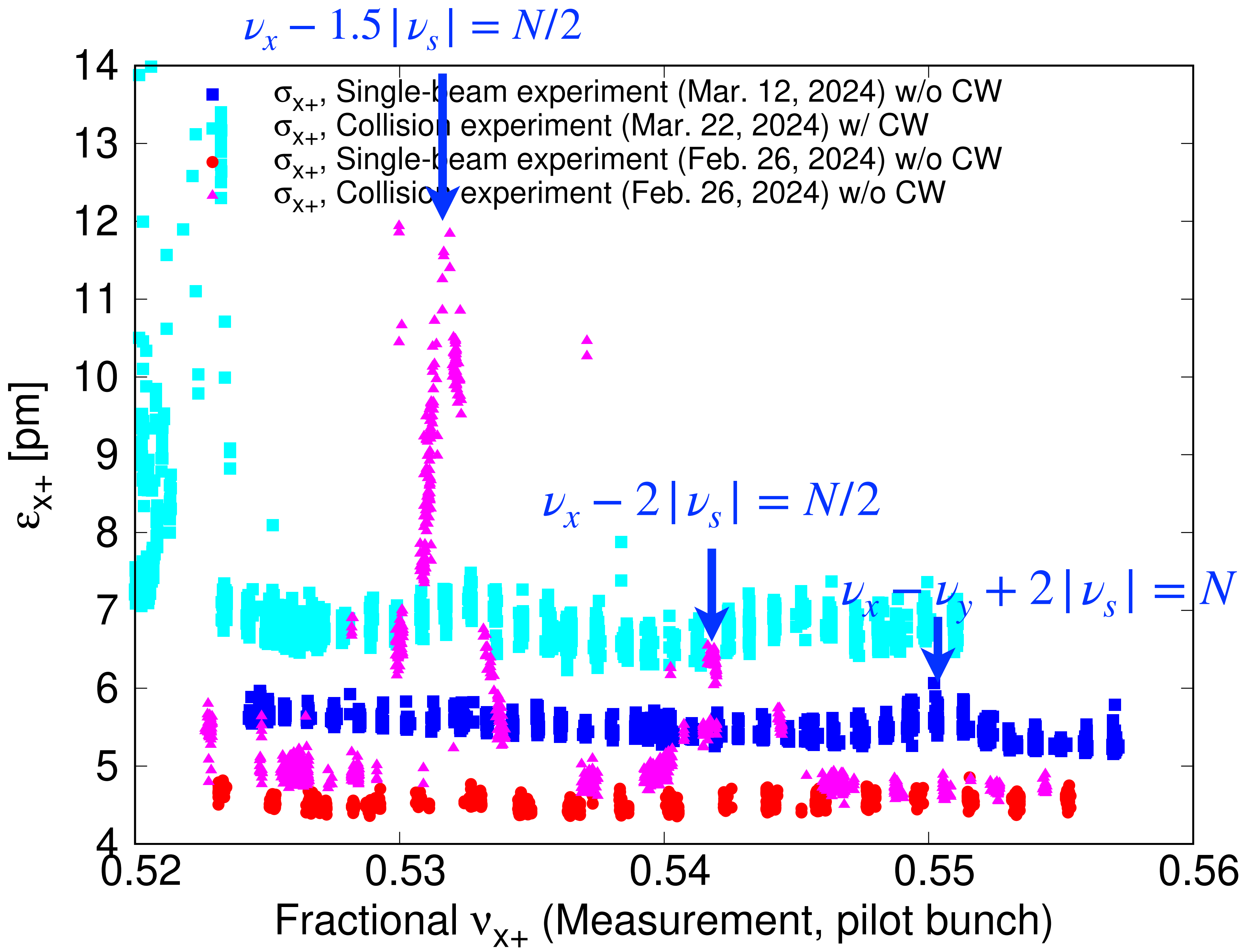
Escaping from resonance $\nu_x + 4(\nu_y + \xi_y) = N$

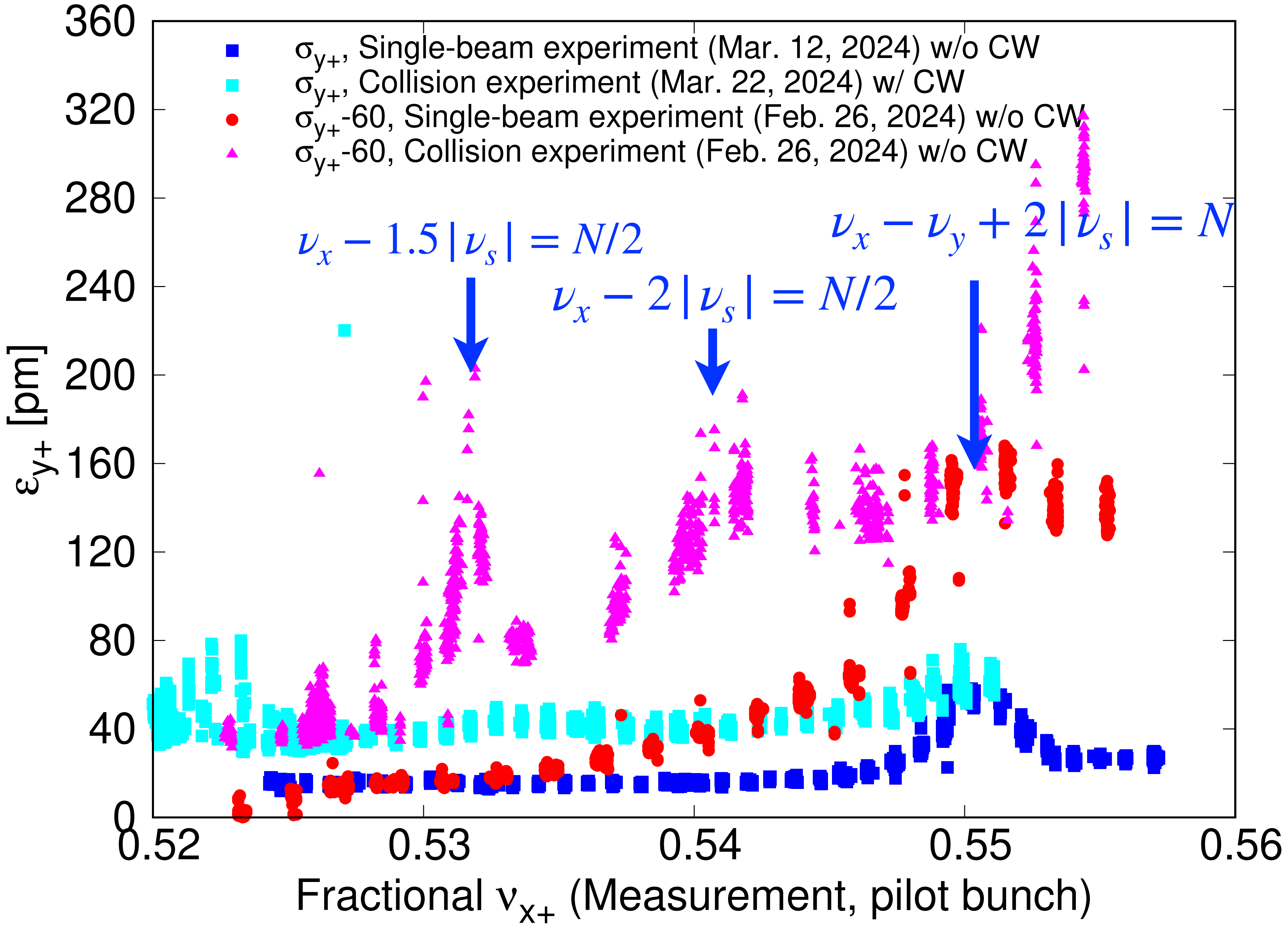
Recent beam-beam machine studies

- LER horizontal tune scan compared
  - β_y^*=8 mm, w/o CW, 2024.02.26
  - β_y^*=1 mm, w/o CW, 2024.03.12
  - β_y^*=1 mm, w/ CW, 2024.03.22





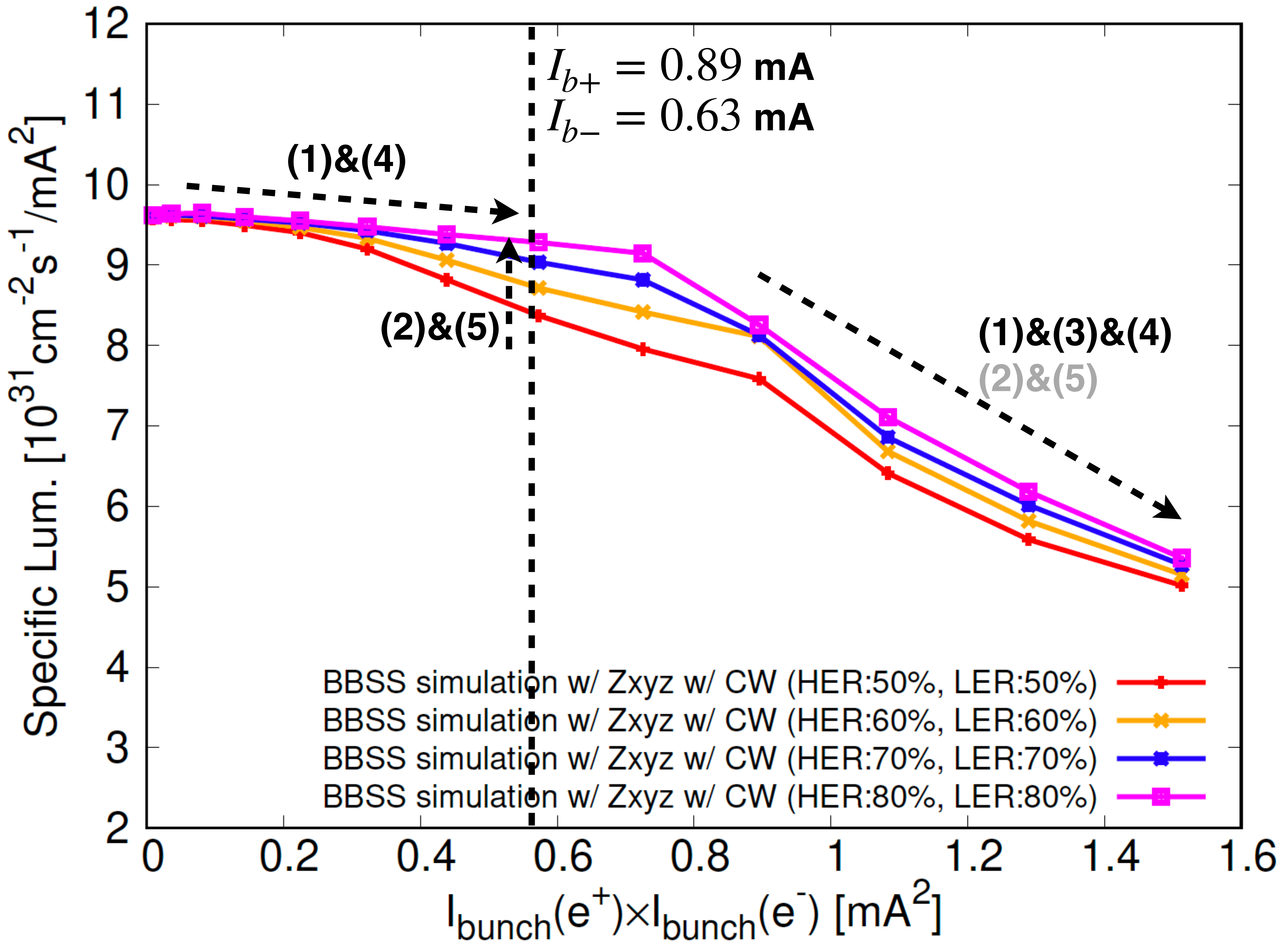




Perspective on 1E35 luminosity

- **1E35 luminosity is achievable**, if crab waist works well. Factors affecting luminosity:
  - (1) Bunch lengthening and synchrotron tune spread caused by longitudinal impedance → Unavoidable
  - (2) Beam-beam-driven fifth-order betatron resonances $\nu_x \pm 4(\nu_y + \xi_y) = N$ → 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

Achieved in 2024a run:
* ϵ_y <20 pm
* $[\nu_{y+}]$ =0.57

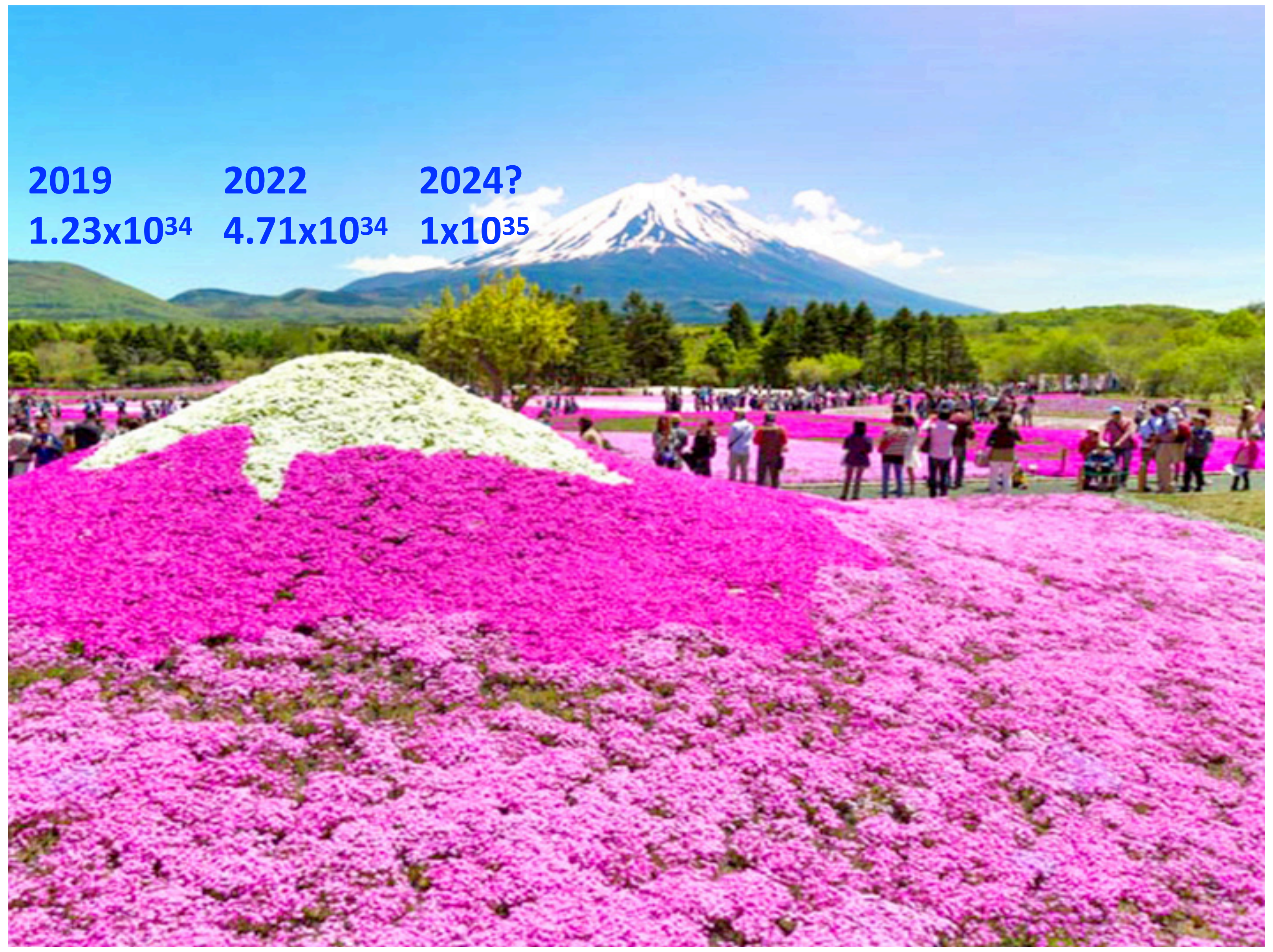


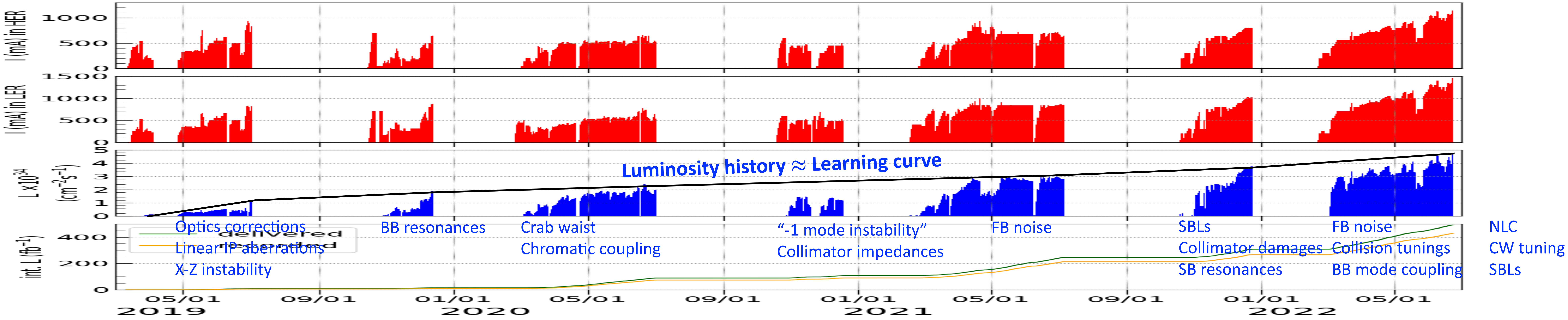
	post-LS1 1E35		Comments
	HER	LER	
I_{bunch} (mA)	0.63	0.89	
# bunch	2345		2022a operation value
ε_x (nm)	4.6	4.0	w/o IBS
ε_y (pm)	30	30	Single-beam emittance
β_x (mm)	60	60	Lattice design value
β_y (mm)	0.8	0.8	Lattice design value
σ_{z0} (mm)	5.1	4.6	Natural bunch length (w/o MWI)
ν_x	45.532	44.524	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); K. Ohmi et al., PRAB 26, 111001 (2023).

SuperKEKB as a demonstrator of crab-waist colliders:

* After years of investigation, SuperKEKB has become comprehensible from the perspective of **collective effects**.
* Collaborations within the collider community have accelerated the learning curve of understanding collective effects.





https://www-superkekb.kek.jp/

WISHLIST

- Send **young accelerator physicists** (domestic and international) to SuperKEKB
  - EAJADE project is excellent
- Manage **GPU** computers for strong-strong (PIC) simulations with full lattices
  - A model including everything has been a dream 30 years ago, but feasible now
- Beam time for **machine studies**
  - Experiments tell more than theories and simulations (?)
- Plan **nonlinear optics tunings/optimizations** (see H. Sugimoto's talk to this meeting)
  - The crab waist concept: brilliant, yet challenging (see crab cavity experience in KEKB)
  - AI/ML techniques have become trendy
- Plan **NLC** studies (See S. Terui's talk to this meeting)
  - Less BG and impedances

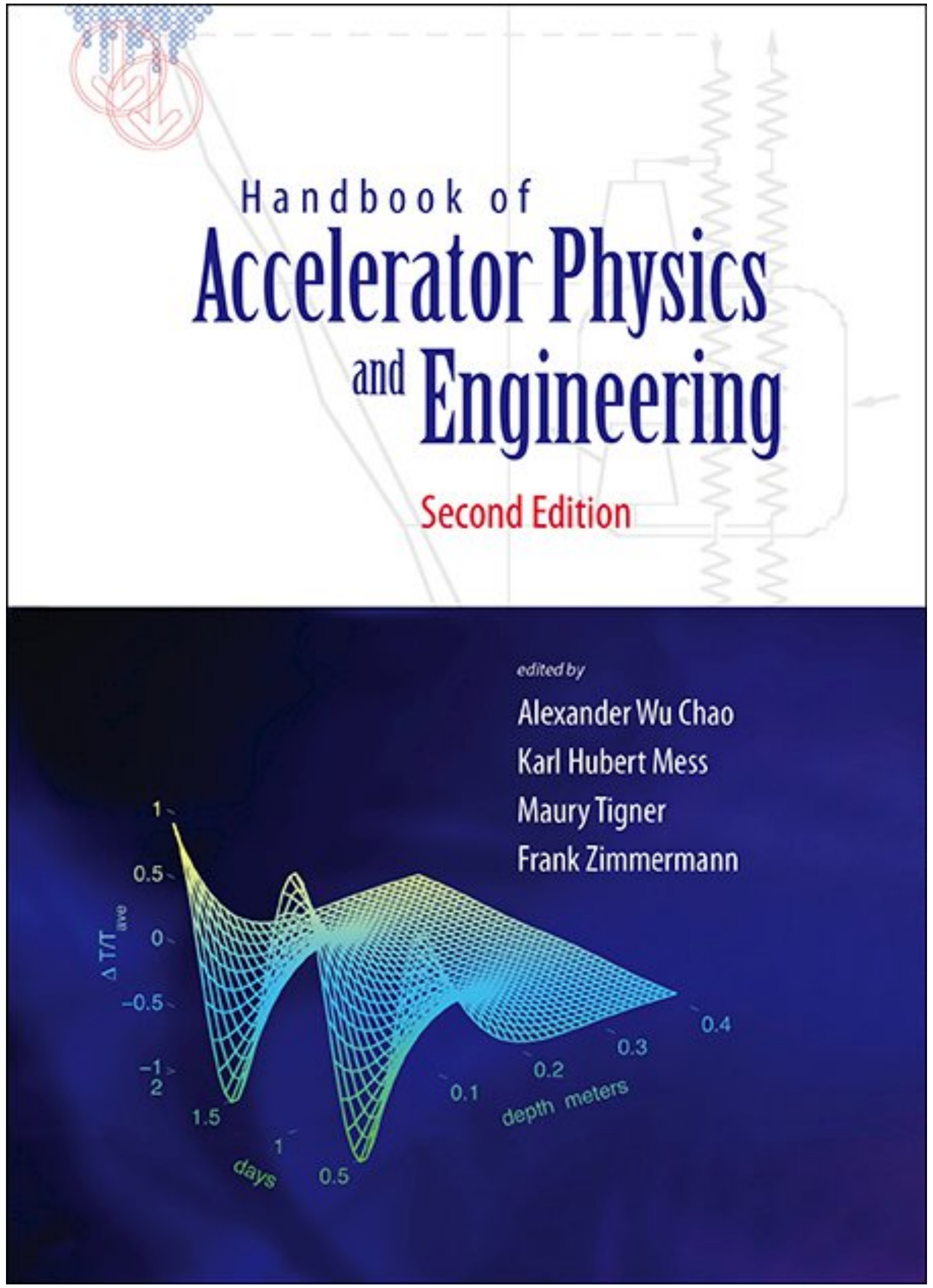
$$H_{\mathrm{cw}} = -\frac{K_2}{2}\beta_y^s\beta_y^*\sqrt{\frac{\beta_x^s}{\beta_x^*}}\cos\Delta\psi_x \sin^2\Delta\psi_y x^* p_y^{*2}$$

Y. Ohnishi, EPJP 136:1023 (2021)

- Think of **global parameter optimizations**, such as increasing ν_s of LER
  - Big ideas are written in the Handbook, though requires lots of R&D work
- … …

WISHLIST

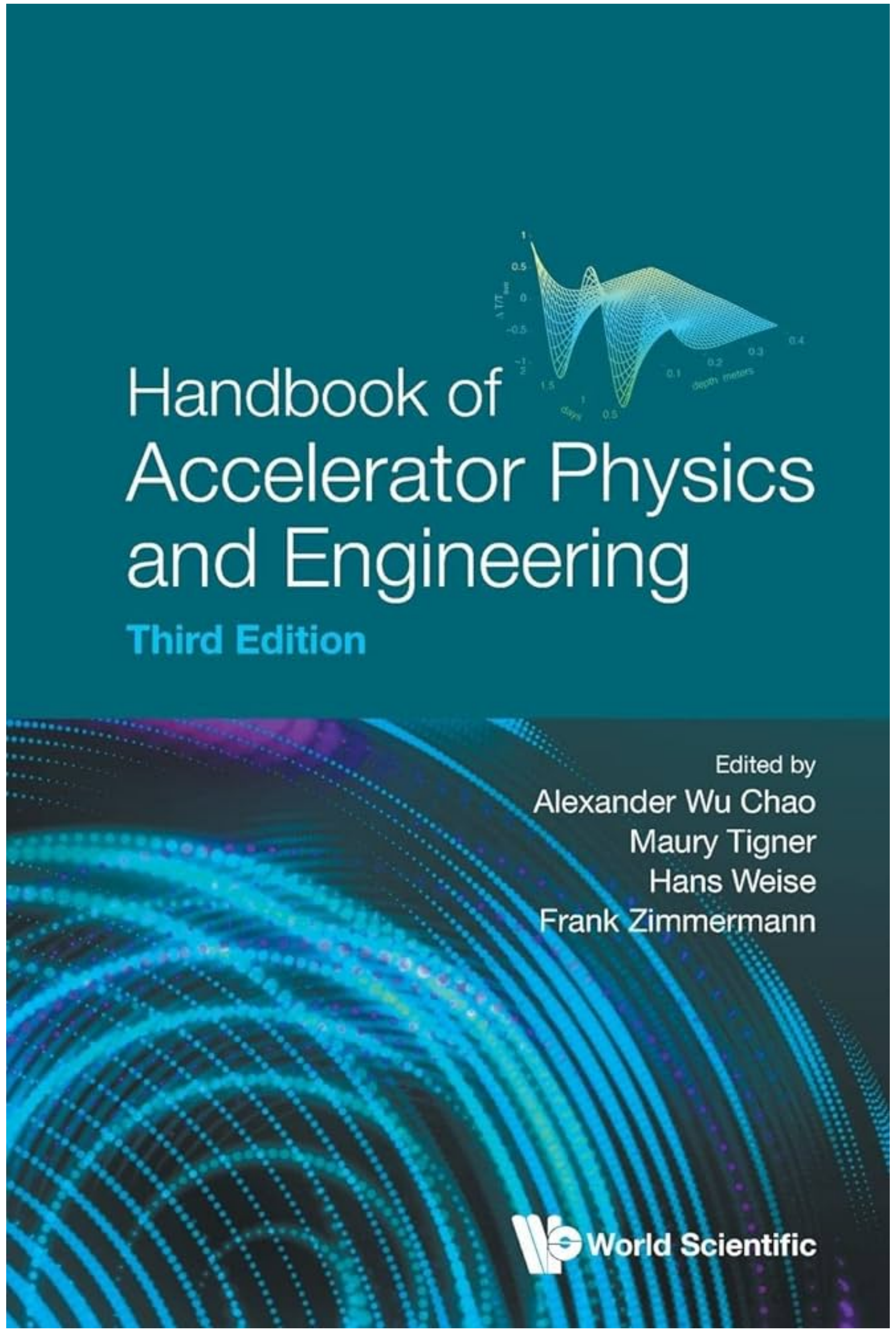
2013



Many exciting updates relevant to crab-waist colliders!

To Frank: Send a few copies to SuperKEKB control room?

2023



Backup

Status and activities of ITF-BB sub-group and ITF-IR sub-group

- Beam-beam sub-group
  - Re-organized under the collective effects sub-group.
  - Two ITF-BB meetings organized: Feb. 7, 2023 [1]; Jul. 1, 2023 [2].
  - More activities under private collaboration mode (to be reviewed in this talk).
  - Presentations
    - K. Ohmi, “SCTR-CUDA” [1].
    - D. Shatilov, “Computation of Complex Error Function, comparison of accuracy and speed” [1].
    - K. Ohmi, “Beam-beam mode coupling” [2].
    - D. Zhou, “Beam-beam simulations for post-LS1 target luminosity 1E35” [2].
- IR upgrade sub-group
  - Focus on investigations of “Much Larger scale modification” of SuperKEKB IR in 2030s [3].
  - Should not be confused with the existing IR upgrade team (investigating “Moderate scale modification around 2027” and “Larger scale modification” [3]).
  - Five ITF-IR meetings organized: Feb. 17, 2023 [3]; Mar. 7, 2023 [4]; Mar. 28, 2023 [5]; Apr. 18, 2023 [6]; May. 23, 2023 [7].
  - Presentations
    - Y. Ohnishi, “Opening remark” [3].
    - K. Shibata, “Overview of SuperKEKB IR” [3].
    - D. Zhou, “Discussions on tasks/goals of ITF-IR subgroup in 2023” [3].
    - M. Koratzinos, “A proposal for the upgrade of the final focus system of SuperKEKb” [4].
    - P. Raimondi, “Final Focus beam dynamics studies” [4].
    - Y. Arimoto, “Current QCS magnet system” [5].
    - D. Zhou, “Constraints on investigations of SuperKEKB IR-Upgrade under the ITF-IR framework” [5].
    - A. Natochii, “Beam-induced background status and expectation in Belle II” [6].
    - Y. Ohnishi, “Dynamic Aperture for Crab Waist in LER” [6].
    - F. Forti, “Comments on detector constraints on IR design” [7].
    - D. Zhou, “Tentative parameter table for post-LS2 SuperKEKB and strategy for ITF-IR workgroup” [7].

Mainly understanding the challenges in IR.

So far, no activities of IR optics design for upgrade.

[1] https://kds.kek.jp/event/45407/.

[2] https://kds.kek.jp/event/46663/

[3] https://kds.kek.jp/event/45534/.

[4] https://kds.kek.jp/event/45877/.

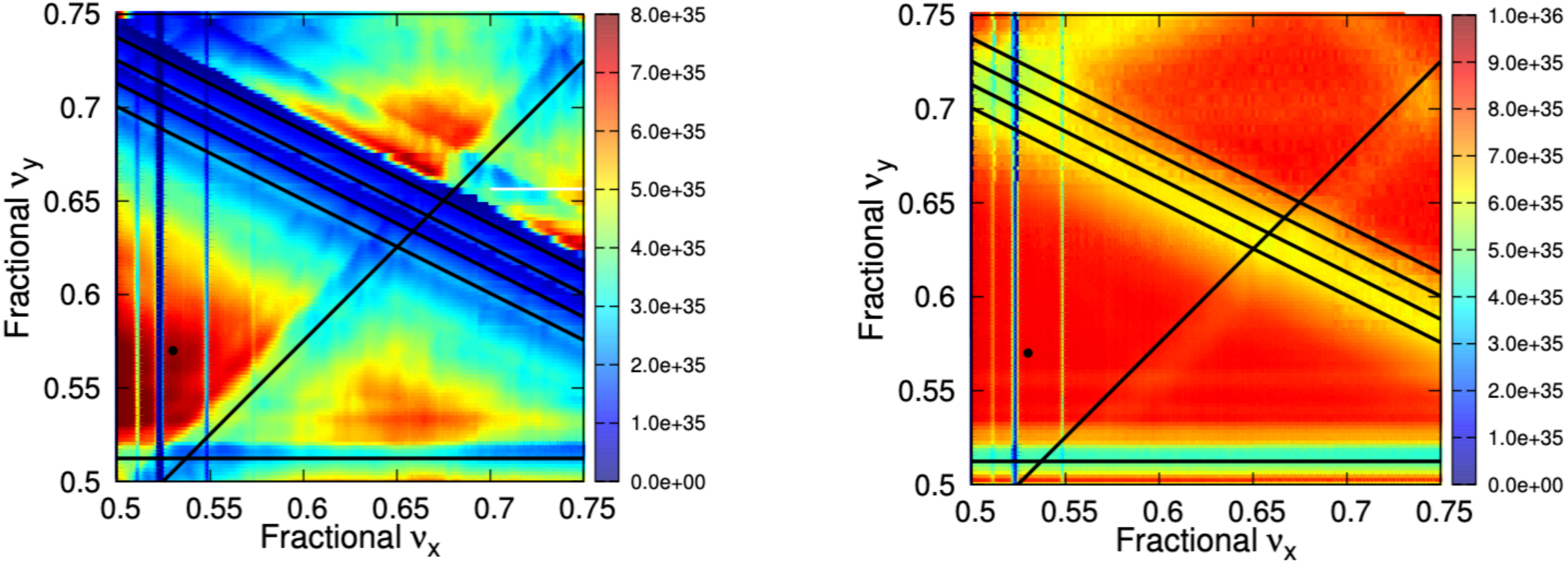
[5] https://kds.kek.jp/event/46026/.

[6] https://kds.kek.jp/event/46234/.

[7] https://kds.kek.jp/event/46574/.

Crab waist applied to SuperKEKB

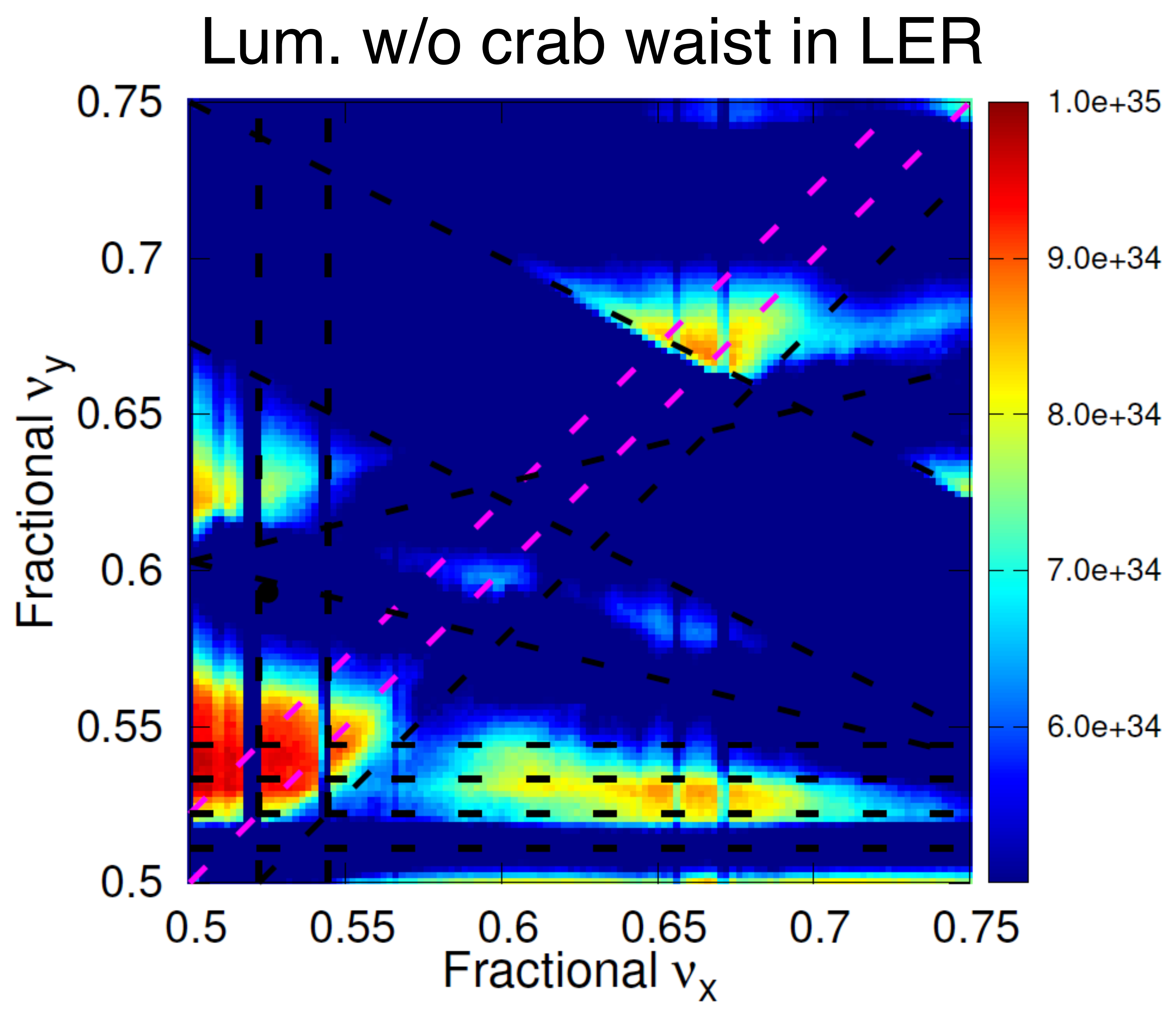
- SuperKEKB final design ($\beta_y^* = 0.3/0.27$ mm) with ideal crab waist
  - Tune scans using BBWS
  - Crab waist creates large area in tune space for choice of working point

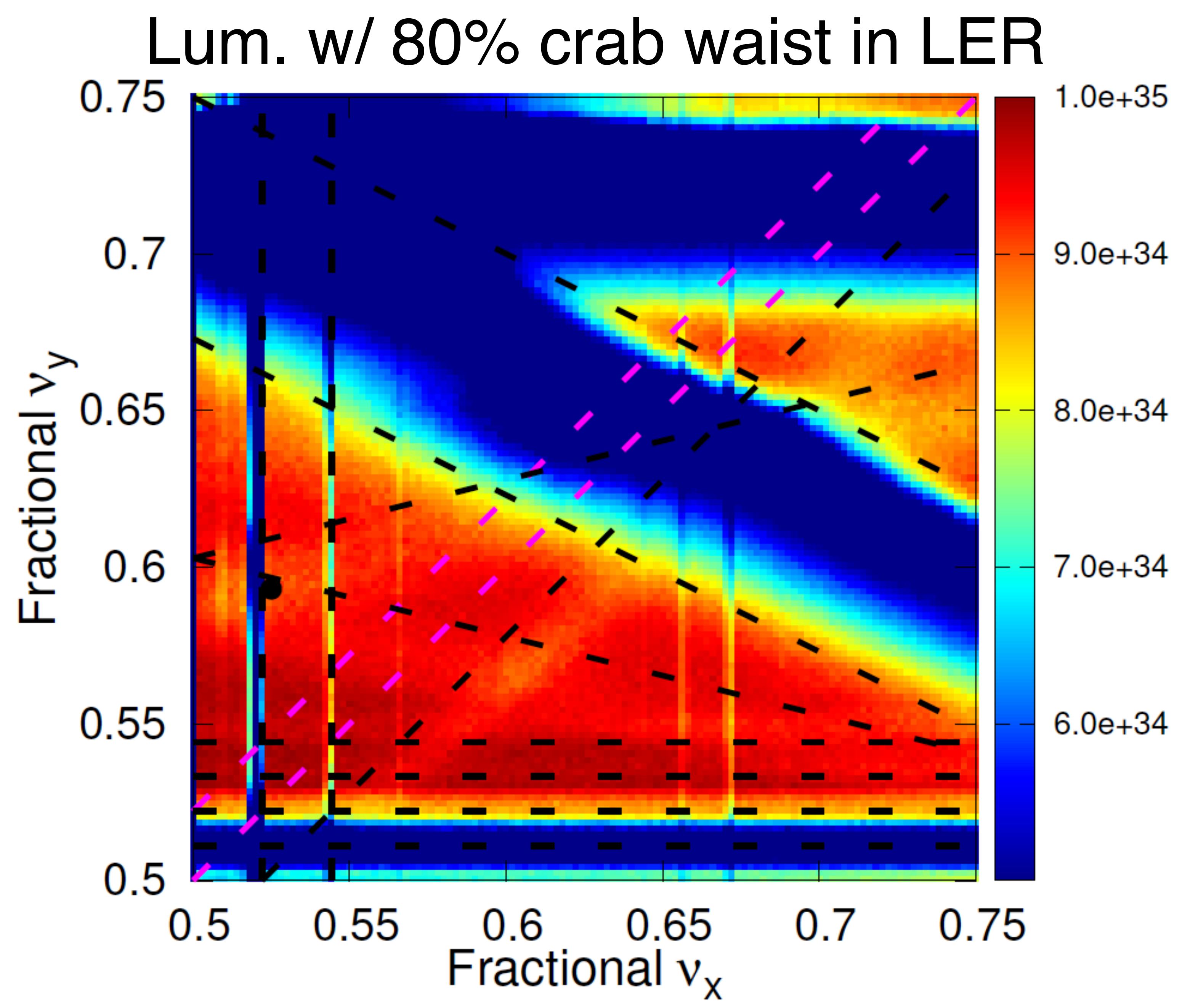


Crab waist applied to SuperKEKB

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

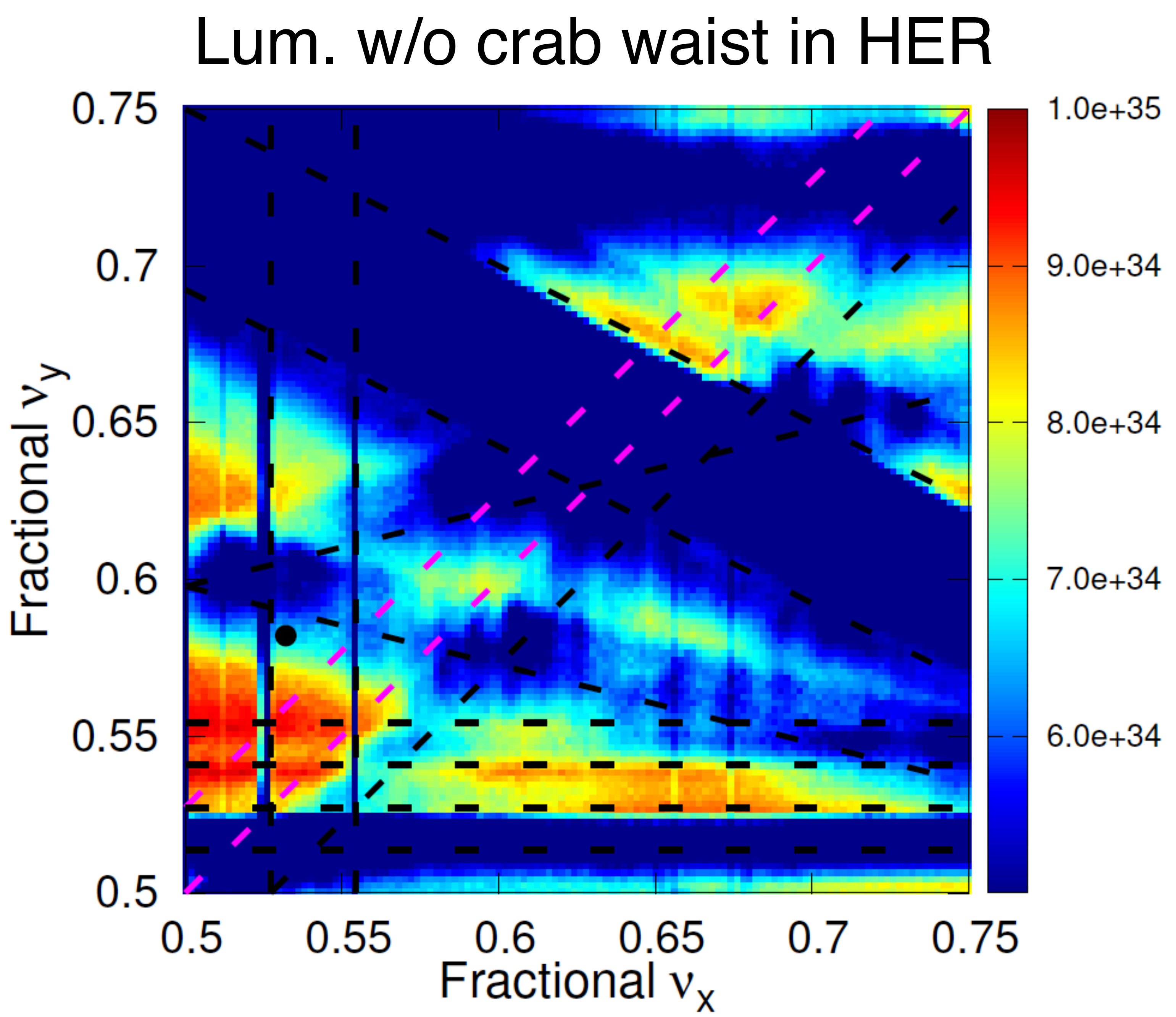
	2021.07.01		Comments
	HER	LER	
I_{bunch} (mA)	0.80	1.0	
# bunch	1174		Assumed value
ε_x (nm)	4.6	4.0	w/ IBS
ε_y (pm)	23	23	Estimated from XRM data
β_x (mm)	60	80	Calculated from lattice
β_y (mm)	1	1	Calculated from lattice
σ_{z0} (mm)	5.05	4.84	Natural bunch length (w/o MWI)
ν_x	45.532	44.525	Measured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

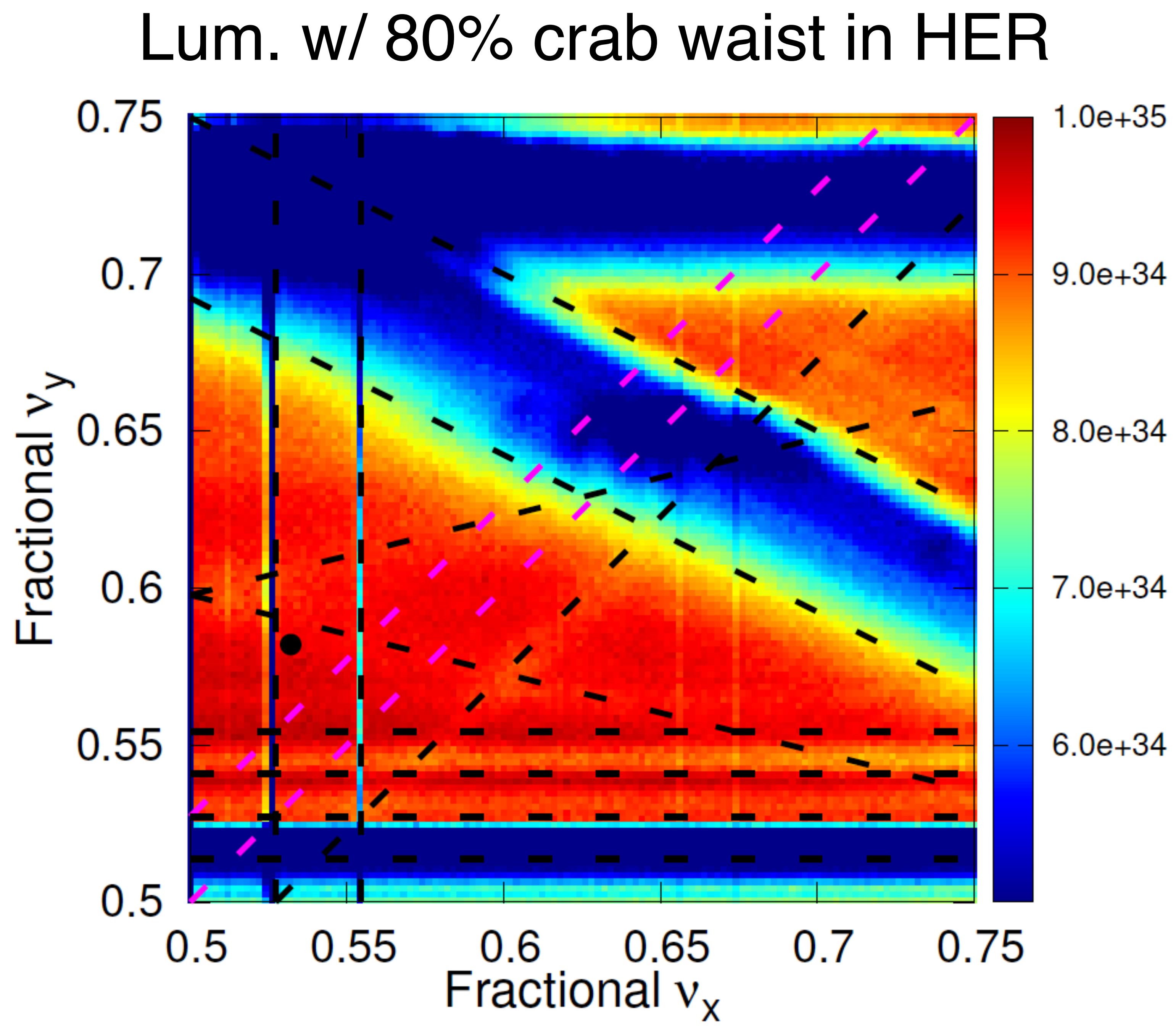


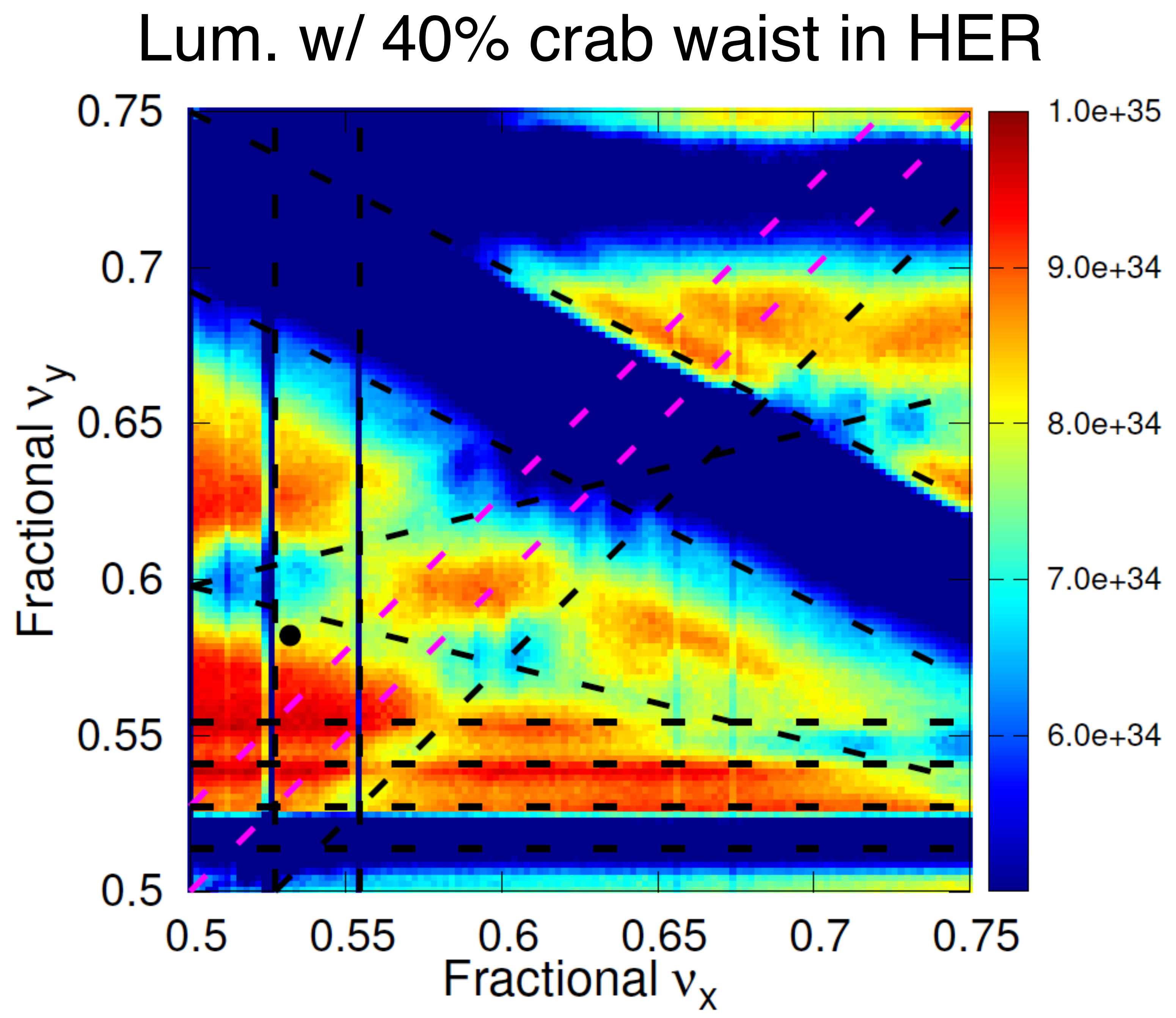


Crab waist applied to SuperKEKB

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







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.

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

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

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

We achieved $\epsilon_{y0} < 20$ 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

Beam-beam viewpoints on achieving higher luminosity

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

We achieved ~11×10^{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}

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

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