Beam–Beam

(1) Observations and Beam Studies in 2026ab

(2) Beam-Beam Simulations

(3) Summary and Plans for 2027ab

Hiroshi Sugimoto

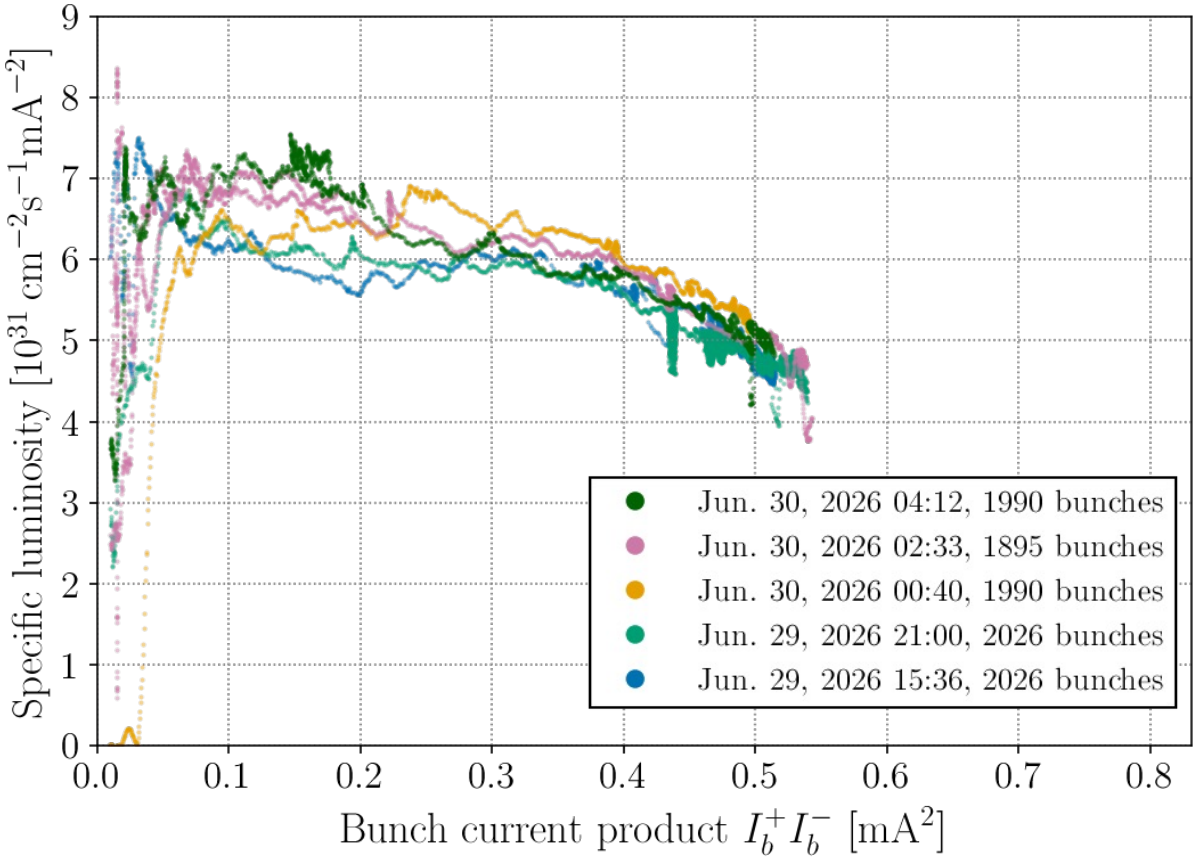
on behalf of the Beam-Beam Task Force

Observations and Beam Studies in 2026ab

2026ab Specific Luminosity (Lsp)

- Five fills from the peak-luminosity studies on June 29–30 are shown.
- Lsp shows substantial scatter below a bunch-current product of 0.4 mA^2 and decreases rapidly above this value.

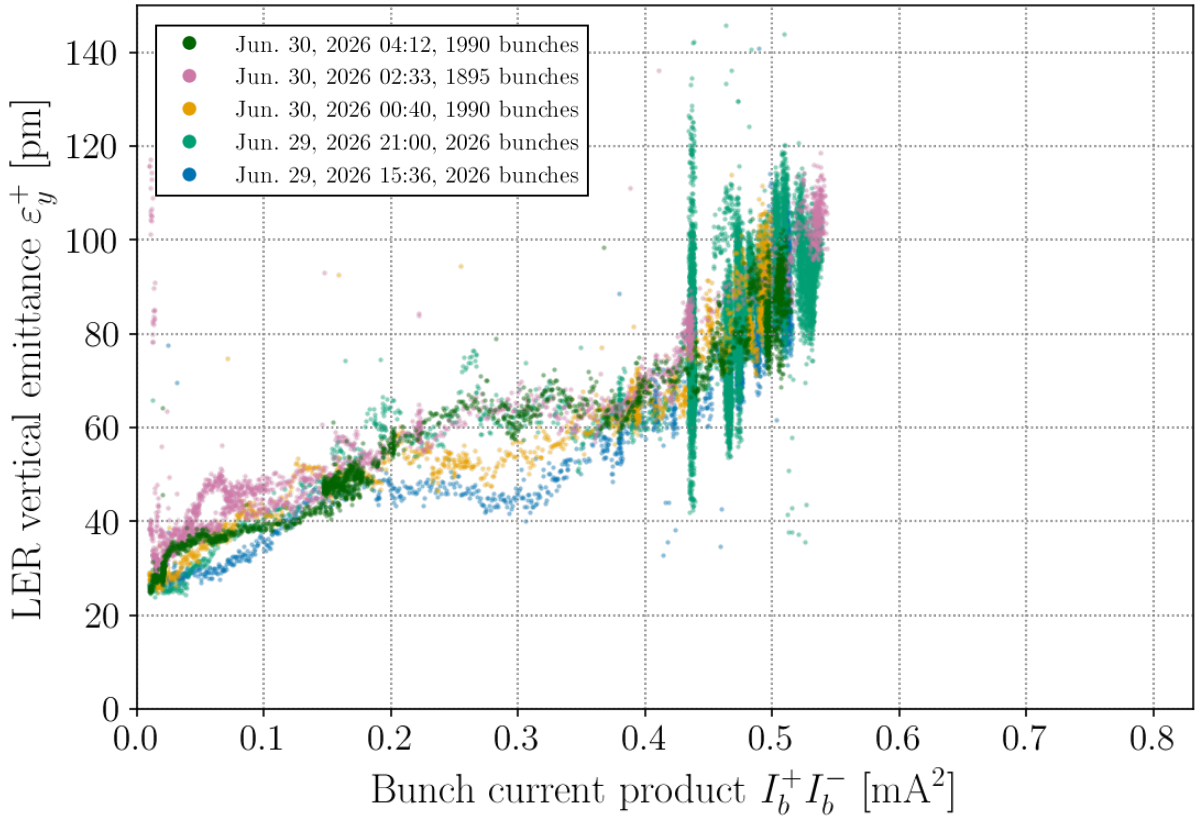
Parameters	LER (e^+)	HER (e^-)	Units
I_b	I_b^+ (variable)	$I_b^- = 0.75 \times I_b^+$	mA
ε_x	4.05	4.43	nm
ε_y	40	40	pm
$(\beta_x^*,\ \beta_y^*)$	(55, 0.9)	(55, 0.9)	mm
$(\nu_x,\ \nu_y)$	(44.537, 46.584)	(45.531, 43.607)	
ν_z	0.0237	0.0272	
σ_z	4.6	5.1	mm
(τ_x, τ_y, τ_z)	(53.0, 53.0, 26.5)	(58.0, 58.0, 29.0)	ms
CW ratio	80	60	%



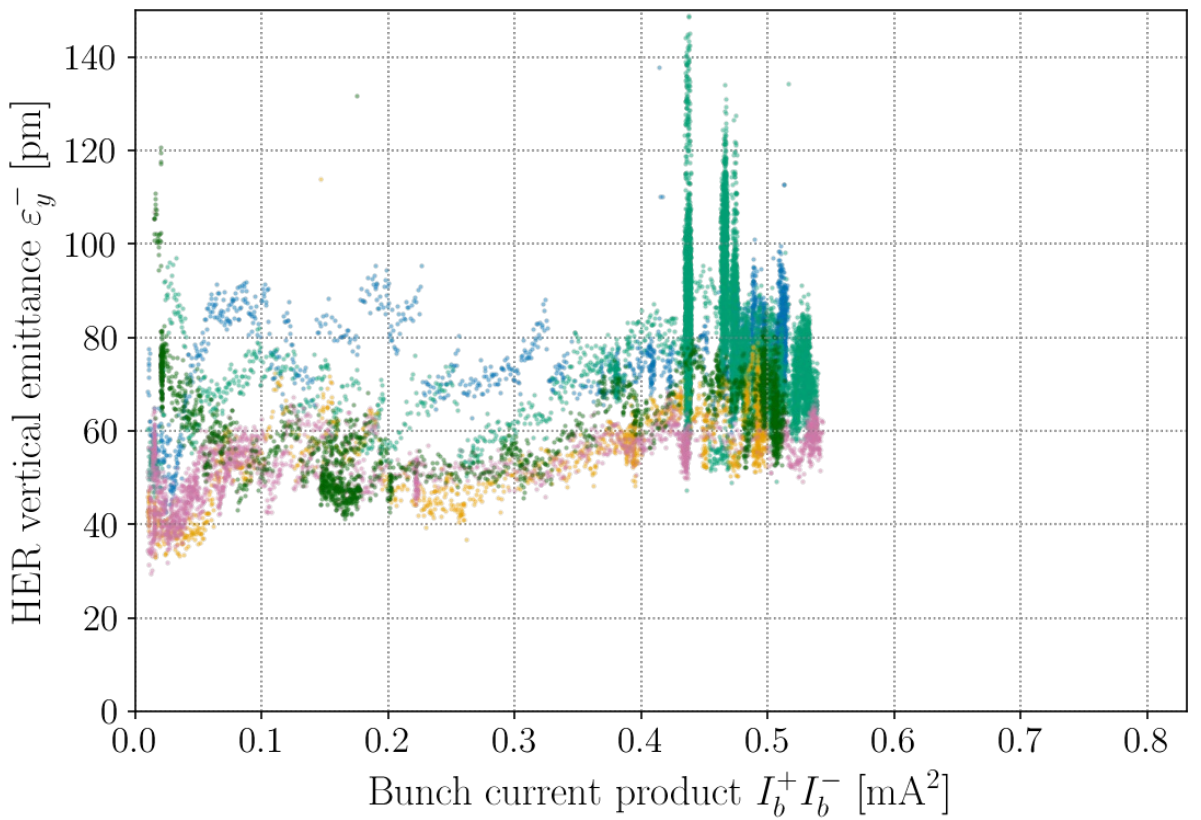
Vertical Beam-Size Blowup

- The LER vertical emittance depends more strongly on current than the HER emittance.
- The sharp Lsp drop near 0.4 mA² coincides with a sharp increase in LER vertical emittance.

LER



HER



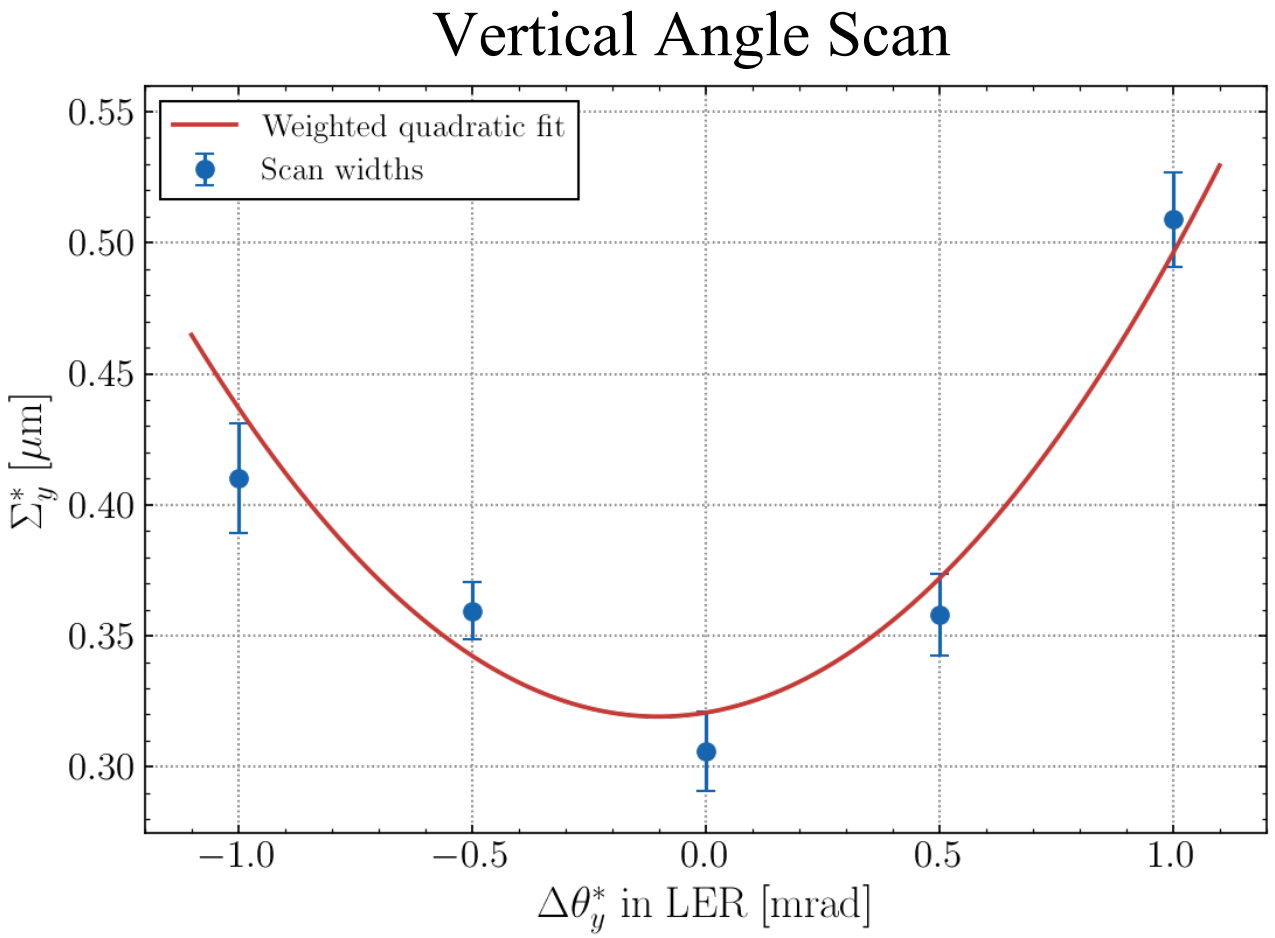
Study Items in 2026ab

- Low-Current Beam-Beam Scan
  - Use the lowest bunch current and fewest bunches compatible with measurable luminosity and beam size. (783 bunches, ~0.08 mA/bunch)
  - Evaluate the geometrical luminosity before studying its current dependence.

- High Bunch Current (HBC) Study
  - Measure luminosity with 393 bunches at bunch currents above those reached in normal physics operation.
  - Provide a benchmark for beam–beam simulations under simpler conditions.
  - We measured the LER beam size versus bunch current before the collision study.

Low-Current Beam-Beam Scan - LER Vertical-Angle Scan -

- Low-current benchmark: 783 bunches, about 0.08 mA/bunch.
- LER vertical-angle scan with optics corrections at each setting.
- The collision width broadly agrees with the XRM estimate.



Collision scan

$$\Sigma_y^{*2} = \sigma_{y,\mathrm{LER}}^{*2} + \sigma_{y,\mathrm{HER}}^{*2}$$

$$\Sigma_y^* = 0.306\,\mu\mathrm{m} \longrightarrow \sigma_y^* = \frac{\Sigma_y^*}{\sqrt{2}} = 0.216\,\mu\mathrm{m}$$

X-ray beam-size estimate (XRM)

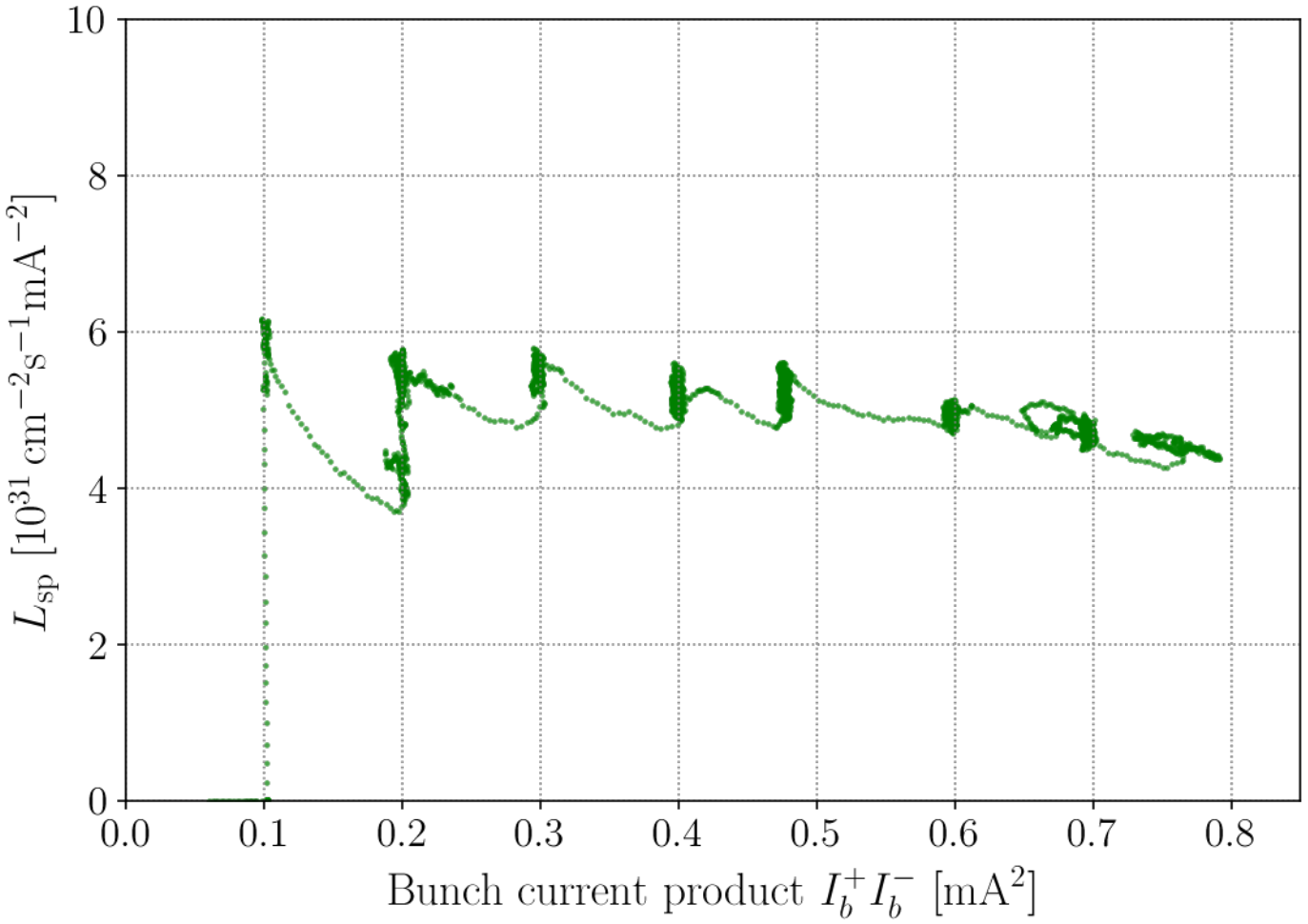
$$\varepsilon_y = 50\,\mathrm{pm}$$

$$\beta_y^* = 0.9\,\mathrm{mm}$$

$$\longrightarrow \quad \sigma_y^* = \sqrt{\varepsilon_y \beta_y^*} \simeq 0.21\,\mu\mathrm{m}$$

Σ : convolved vertical beam size.
The conversion assumes equal beam sizes.

High Bunch Current Collision Study



393 bunches, 16 June 2026

$\beta_y^* = 0.9$ mm

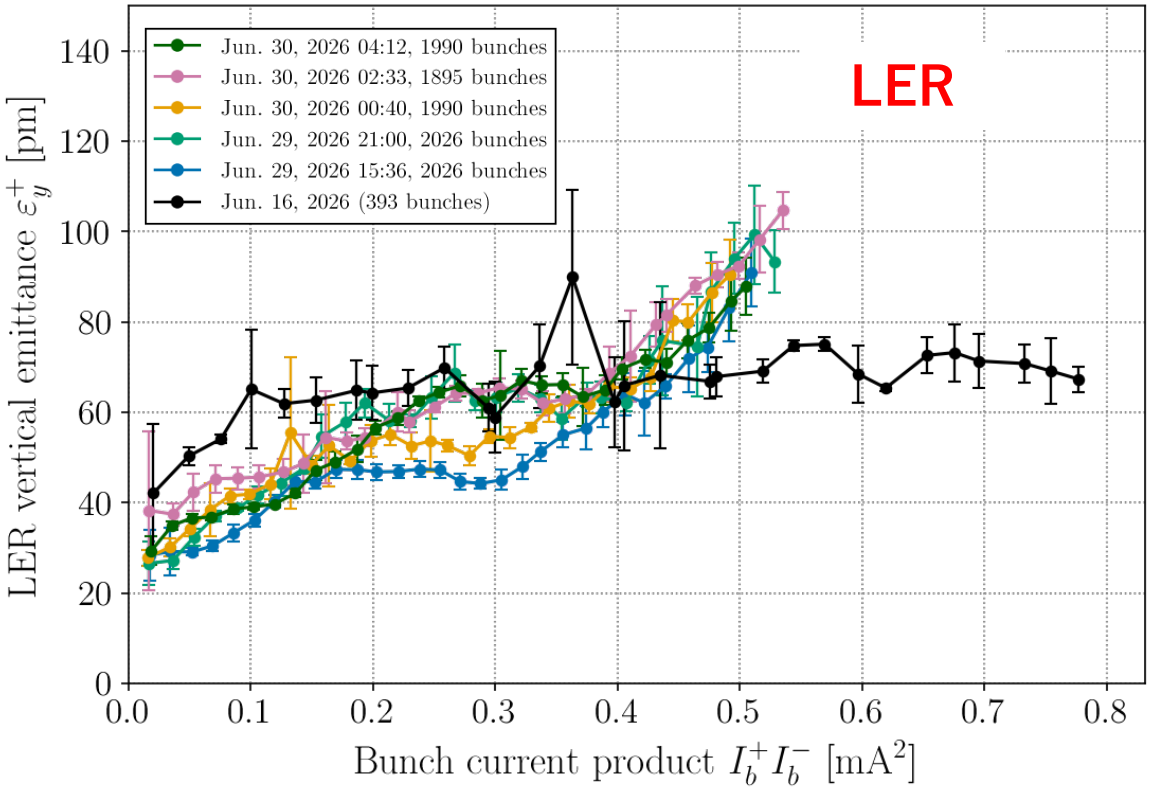
- No abrupt Lsp drop over the measured range.

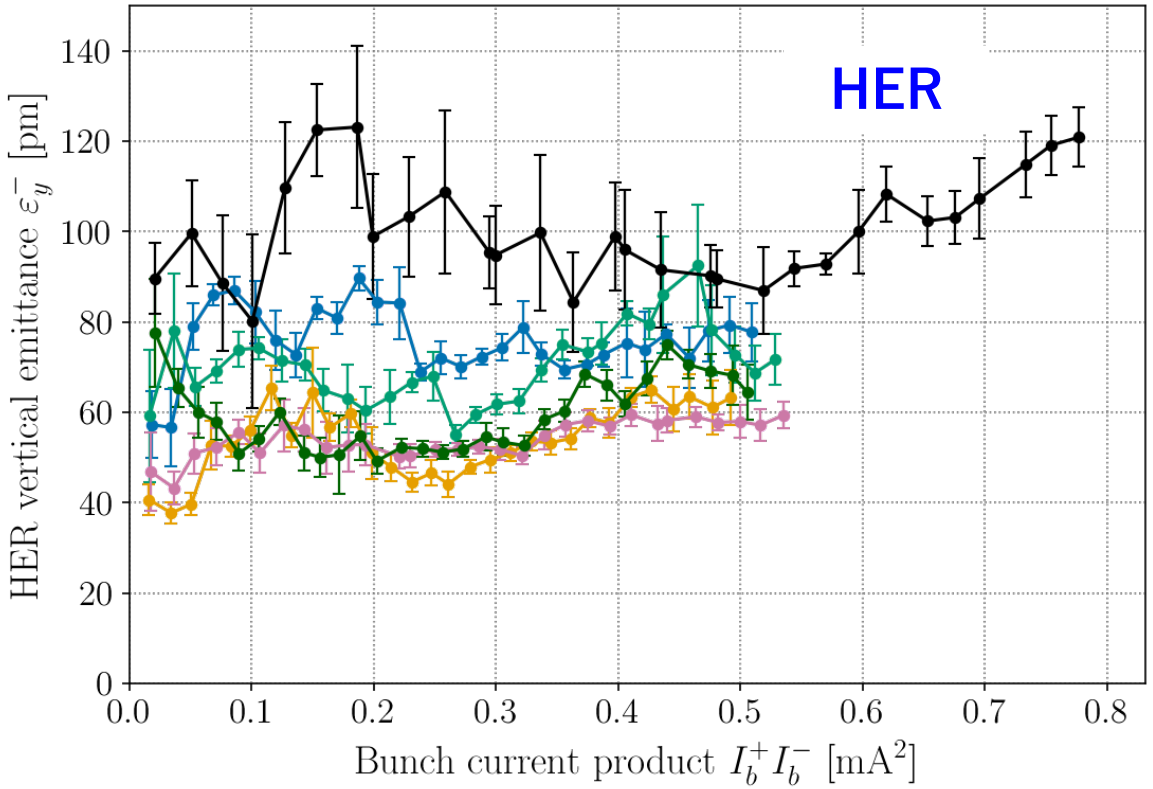
- The sharp LER blowup is absent.

- HER emittance differ from many-bunch operation as shown in the next slide.

393-Bunch and Many-Bunch Collisions

- With 393 bunches, the beam size depends weakly on beam current in both rings.
- The HER BxB feedback was not fully optimized during this study.
- The weaker beam-beam force from the HER may suppress LER blowup.
- Differences in HER feedback performance and emittance complicate this comparison.

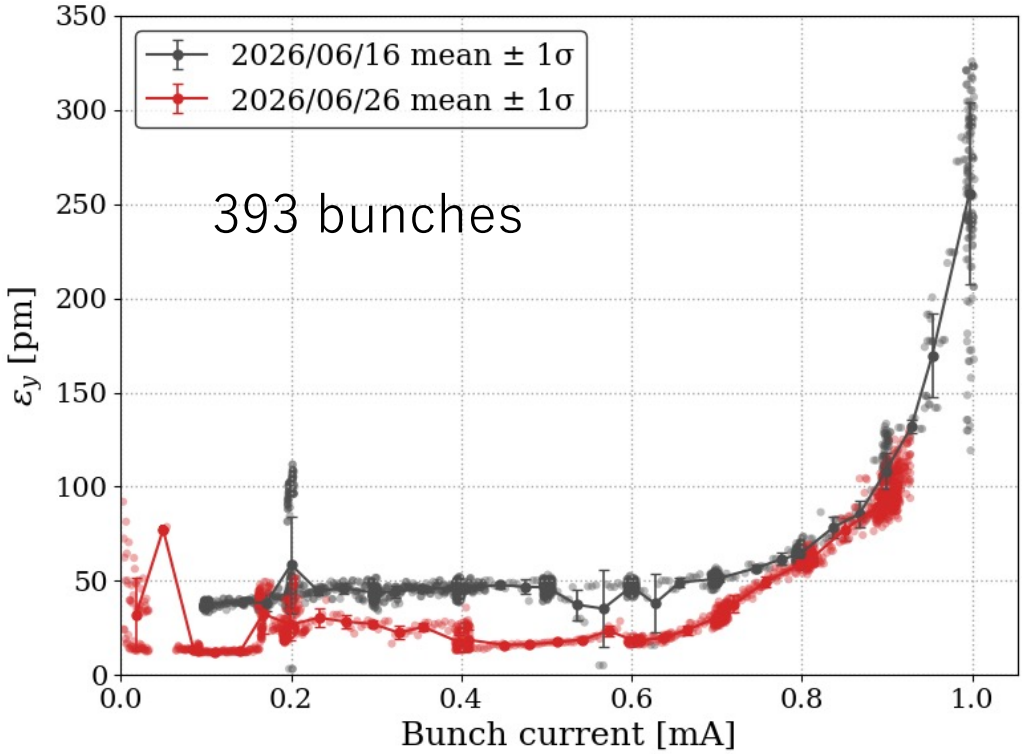




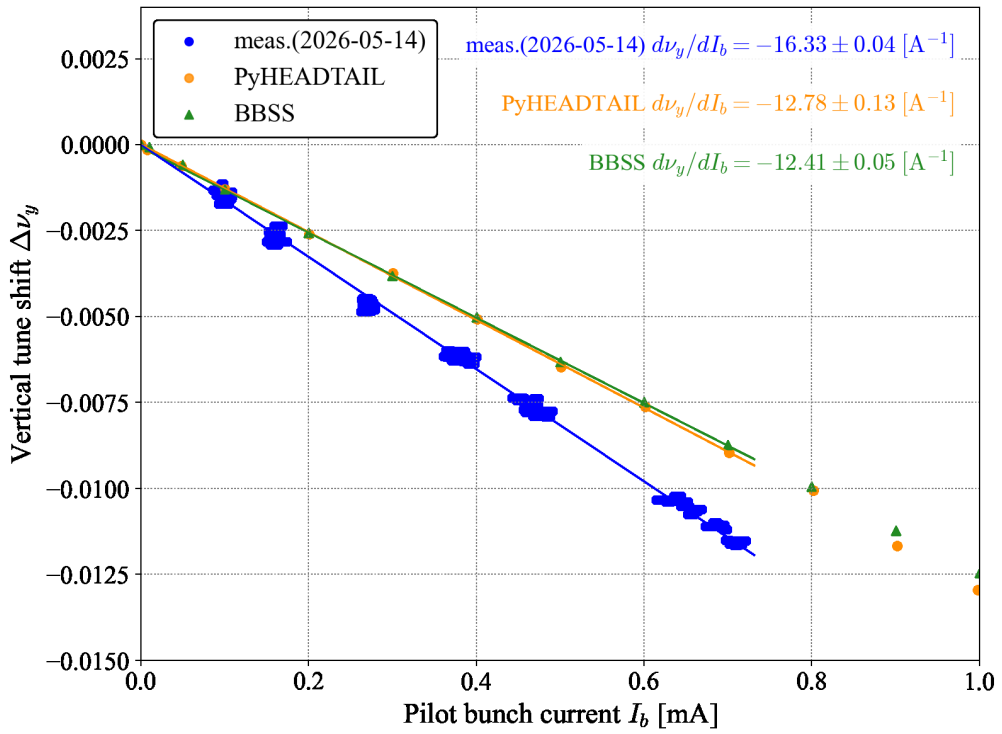
LER Single Beam Size Blowup

- Before the collision study, we measured the LER beam size versus bunch current and observed a rapid increase in vertical emittance at high current.
- Measured tune shifts suggest stronger transverse wakefields than assumed in the model.
- Collimator damage is a possible source of additional impedance.
- The connection between the single-beam blowup and collision performance remains unclear.

Single Beam Size Blowup



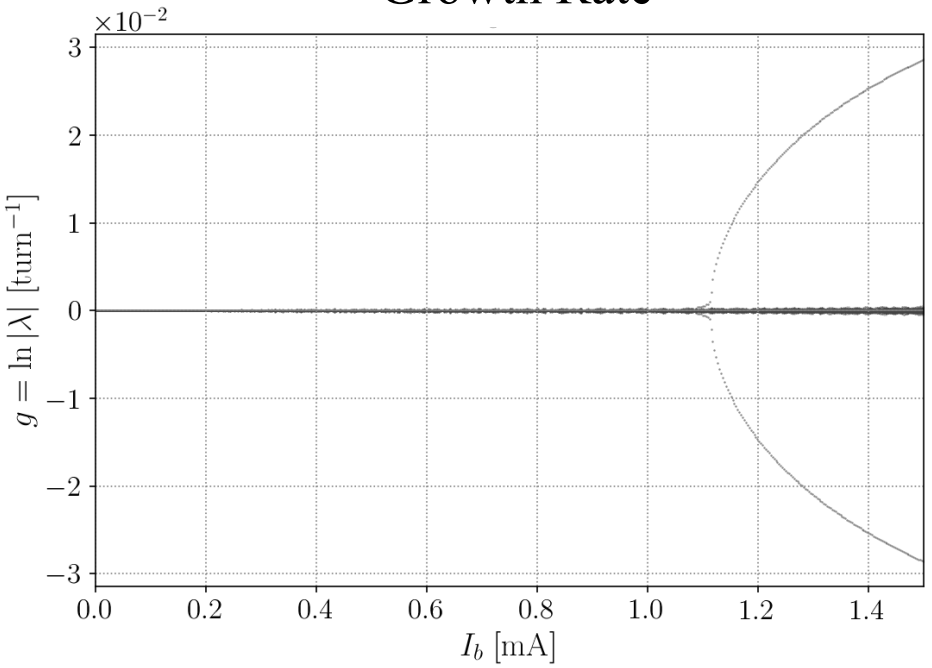
Pilot bunch Tune Shift



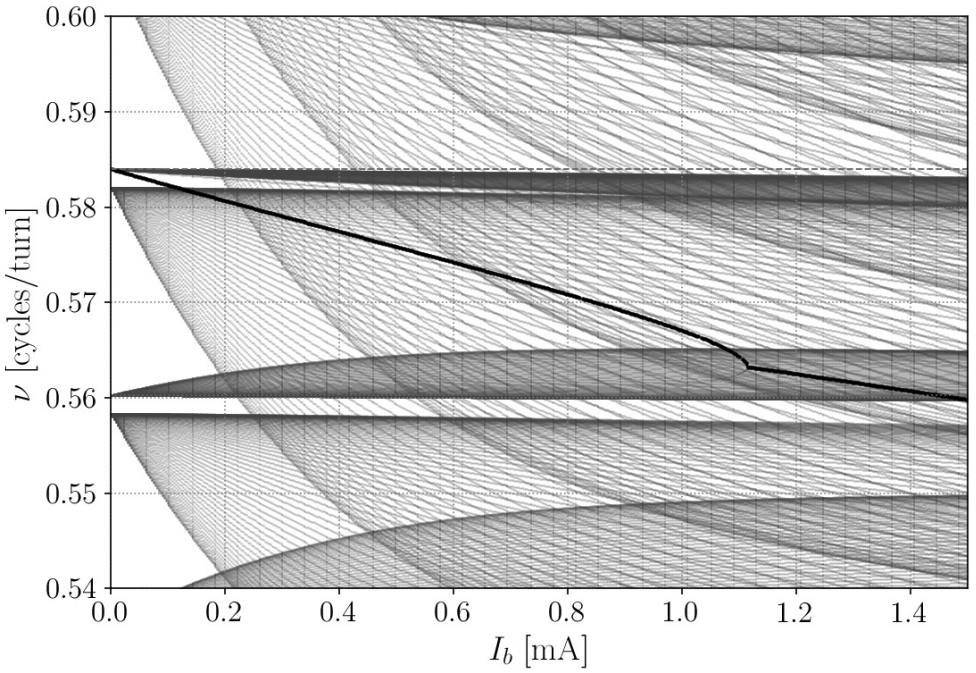
TMCI or − 1 Mode Instability ?

- Coherent mode analysis with the scaled ring impedance predicts a TMCI threshold of about 1.1 mA/bunch.
- The observed beam-size blowup occurs below this calculated threshold.
- A signal consistent with the − 1 mode appears in the pilot-bunch tune spectrum.
- These observations suggest that a −1 mode instability may explain the blowup.

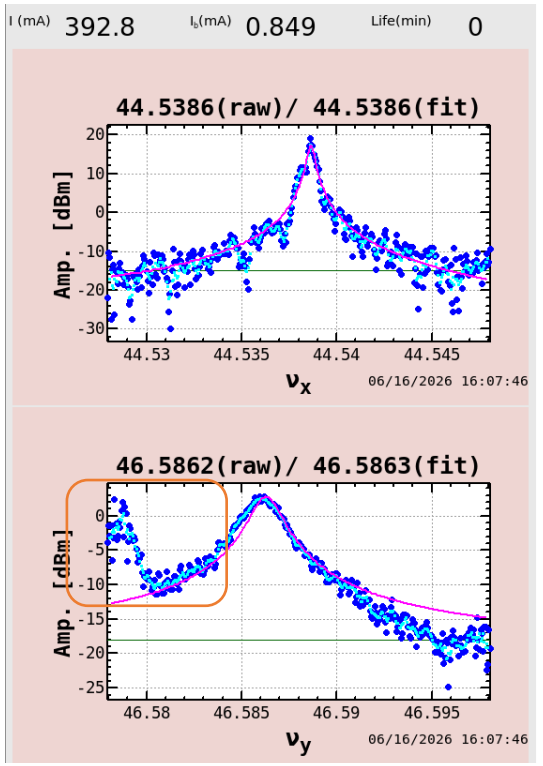
Growth Rate



Coherent Tunes



Tune Spectrum



Beam-Beam Simulations

Beam–Beam Simulation Models

	BBWS (SAD)	BBSS	BBSCL
Beam–beam model	Weak–strong	Strong–strong	Strong–strong
Ring transport	Element-by-element	One-turn linear / nonlinear maps	Element-by-element on GPU
Short-range wakes	SAD wake function	Included	Included
Space charge	Gaussian weak–strong	No included	Distributed sliced PIC

BBSS / BBSCL: PIC or soft-Gaussian beam–beam fields.

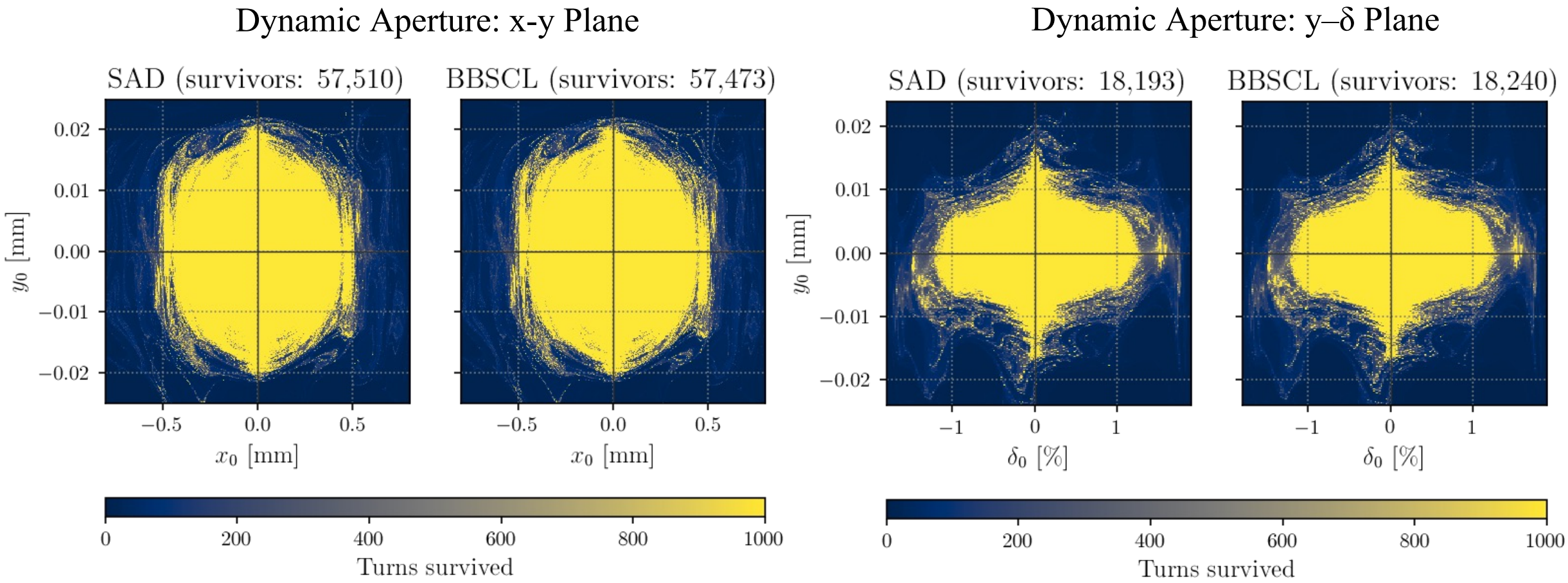
- Element-by-element tracking includes lattice nonlinearities and coupling.
- Map-based tracking provides a controlled reference for comparison.

Codes originally developed by K. Ohmi.

I recently joined the development, focusing on SuperKEKB applications.

BBSCL Benchmarks

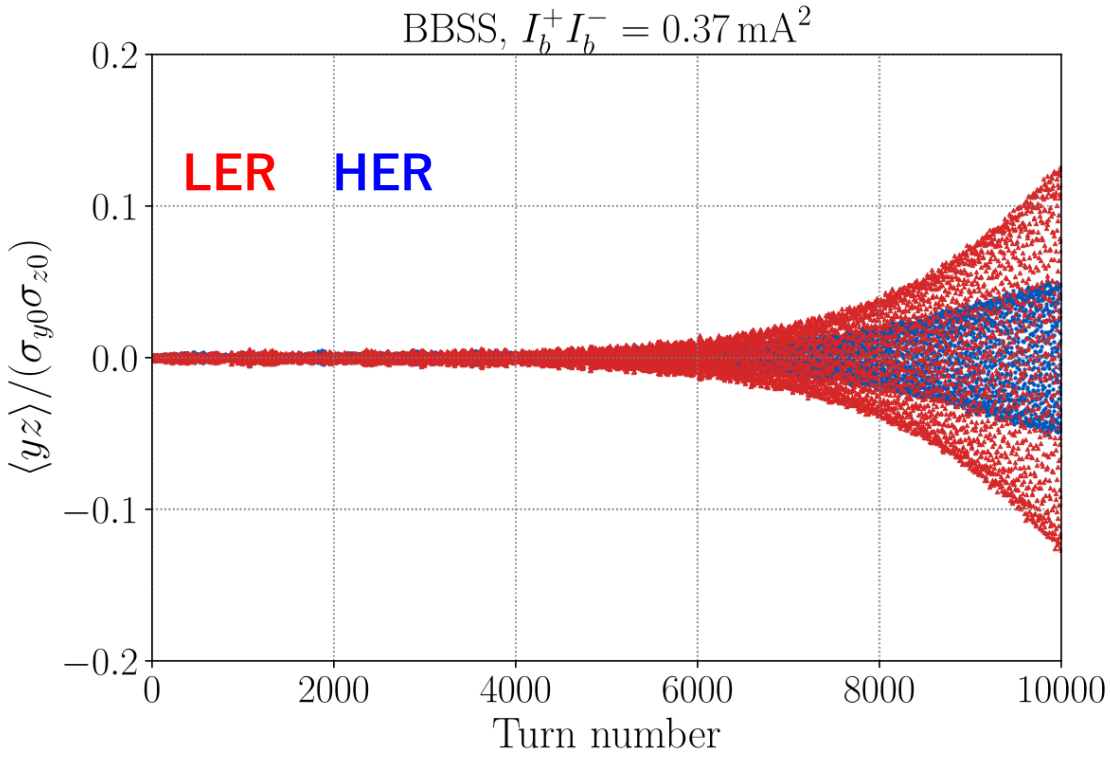
- Single-particle tracking is benchmarked against SAD.
- BBSCL closely reproduces the dynamic aperture obtained with SAD.



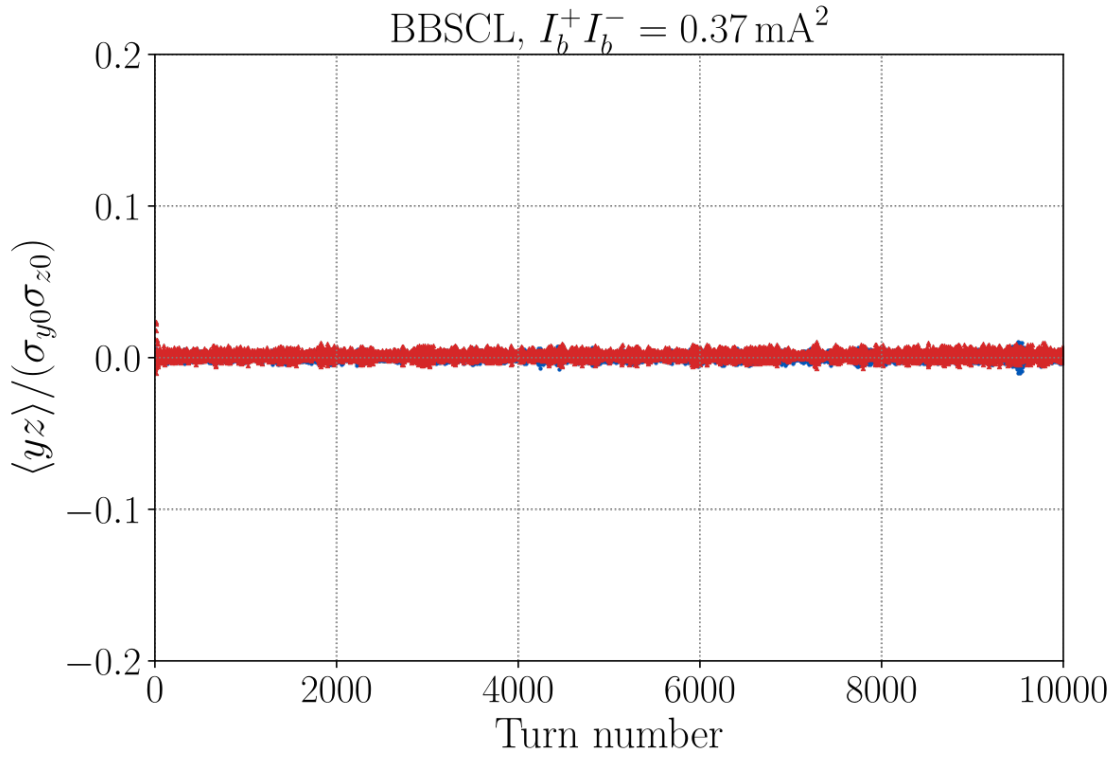
Effect of Lattice Tracking on Beam Motion

- The tunes and vertical emittances were deliberately changed to study the YZ instability.
- At 0.37 mA², BBSCL remains stable over 10^4 turns while BBSS shows growing ⟨yz⟩ motion.
- Lattice tune spread may reduce the growth rate. The detailed analysis will be performed.

BBSS: one-turn linear map



BBSCL: element-by-element tracking

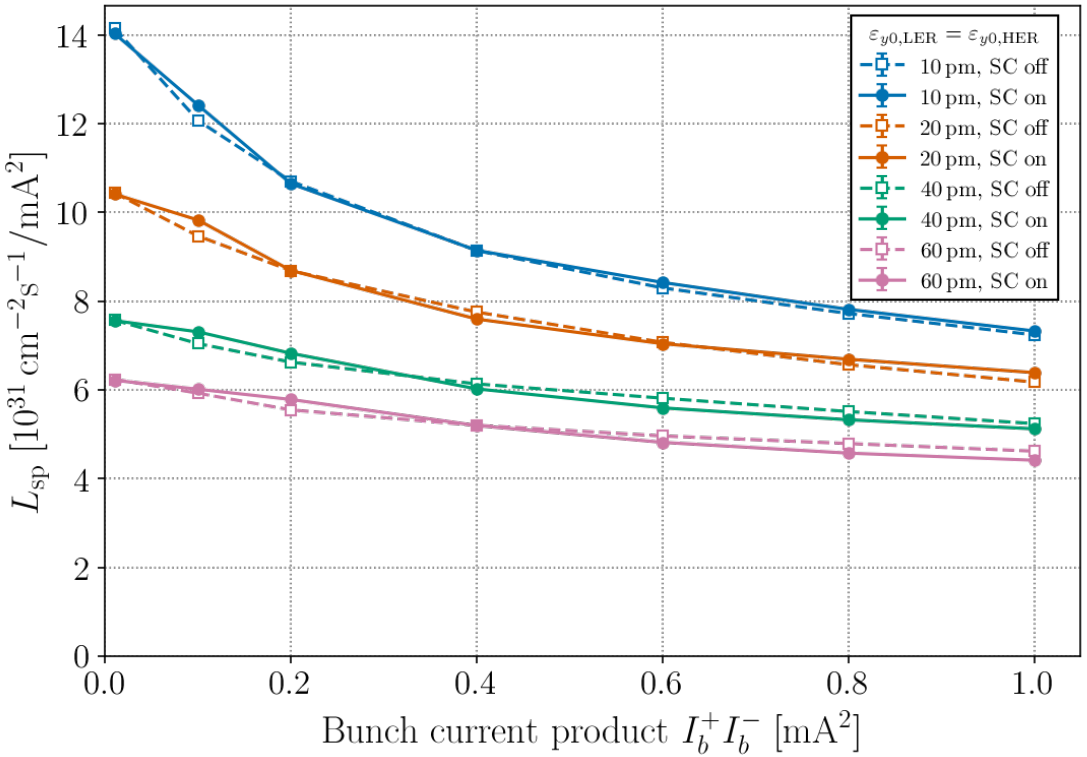


Nominal vertical emittance: 25 pm (both rings). Tunes (ν x, ν y): LER (44.525, 46.589), HER (45.529, 43.599).

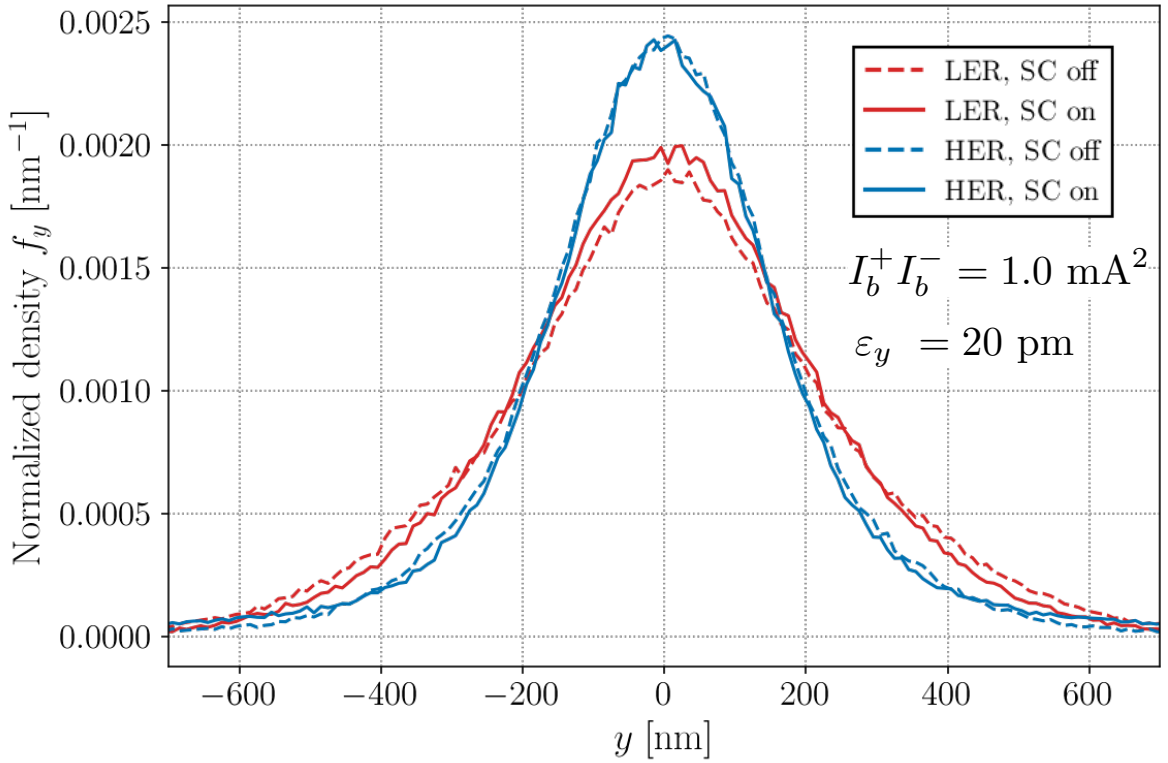
Space Charge Effects

- Full-lattice BBSCL with wakes. Sliced PIC / FFT kicks distributed around both rings.
- Modest Lsp changes so far: less than 5% at 1.0 mA² in the tested cases.
- No extensive systematic study yet.
- Adding SC increases runtime by about 50%.

Specific Luminosity



Particle distribution

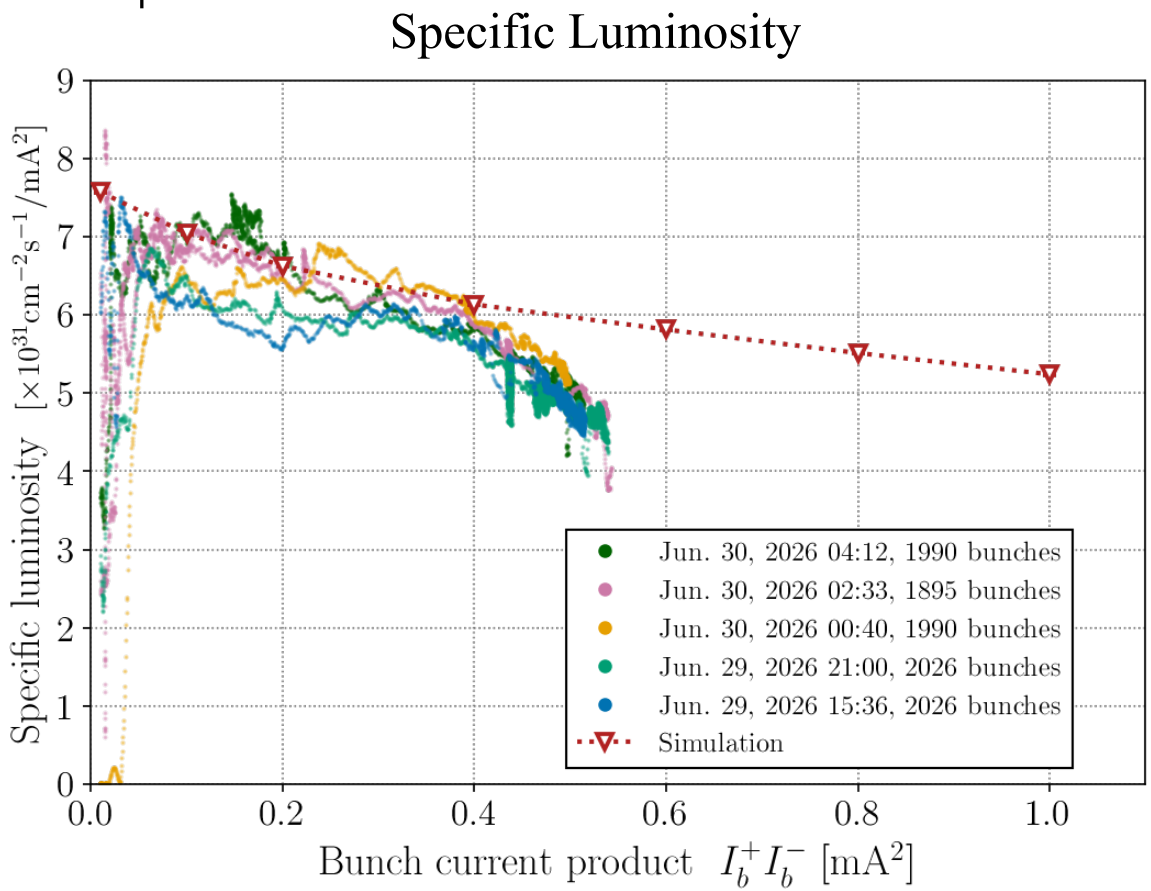


Comparison with Measurements in 2026ab

- The model uses the nominal lattice without errors, with transverse wakes scaled to the measured tune shifts. The space charge is not included.
- Lsp drops sharply above a bunch-current product of about 0.4 mA².
- The simulation does not reproduce this sudden drop.

Simulation Parameters

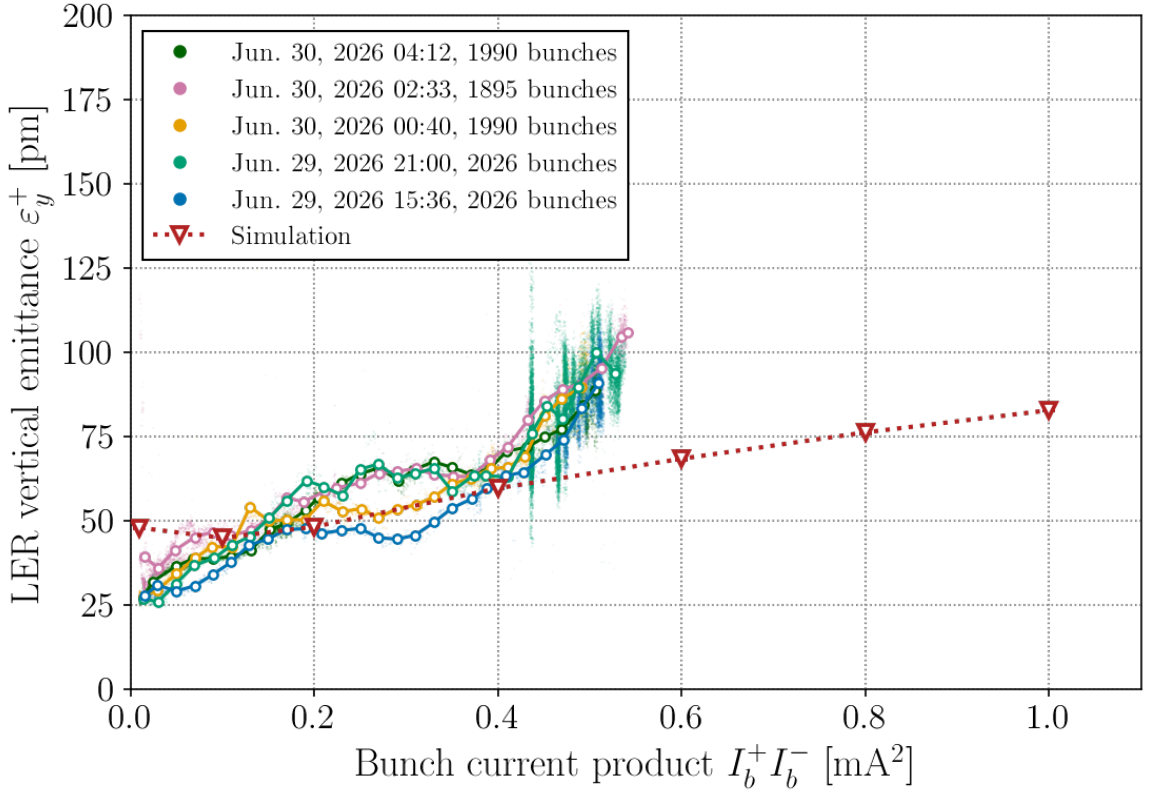
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I_b	I_b^+ (variable)	$I_b^- = 0.75 \times I_b^+$	mA
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ε_y	40	40	pm
$(\beta_x^*,\ \beta_y^*)$	(55, 0.9)	(55, 0.9)	mm
$(\nu_x,\ \nu_y)$	(44.537, 46.584)	(45.531, 43.607)	
ν_z	0.0237	0.0272	
σ_z	4.6	5.1	mm
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CW ratio	80	60	%



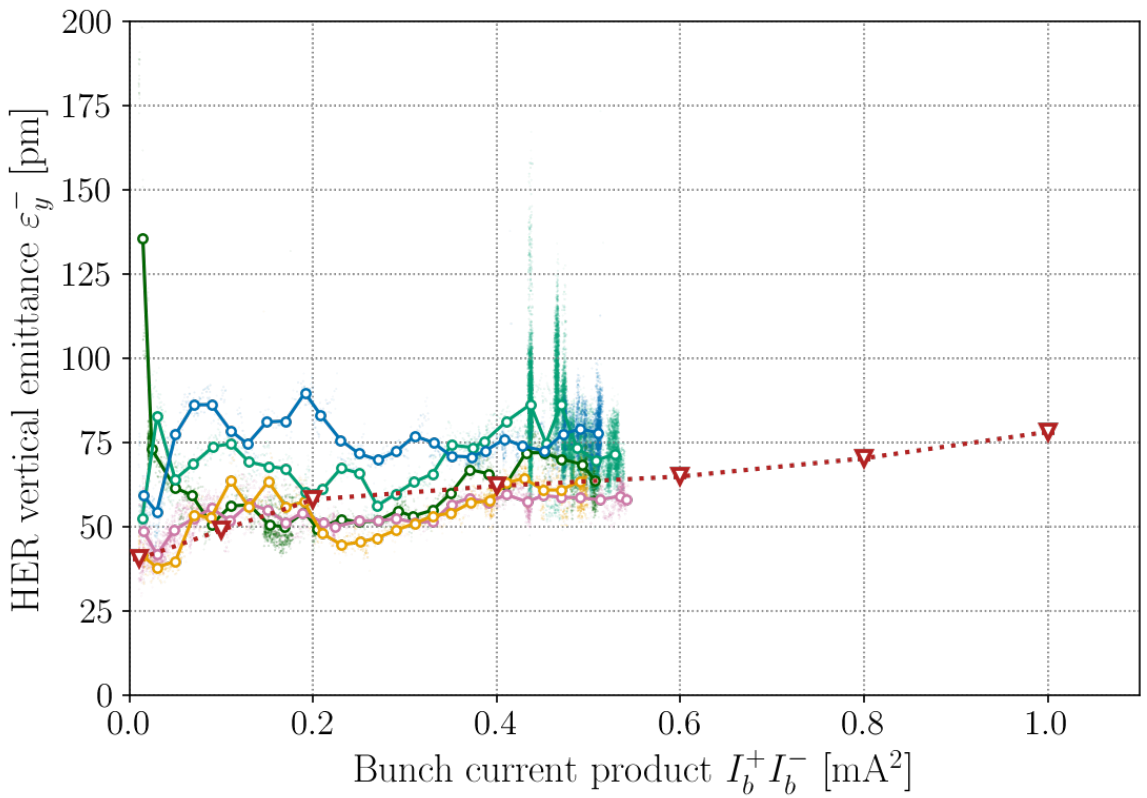
Vertical Emittance: Measurements and Simulation

- Measured LER vertical emittance rises sharply above a current product of 0.4 mA².
- Effects that depend on total current, such as beamline deformation, may limit performance.
- Systematic measurements with properly tuned feedback are needed to distinguish single-bunch effects from multi-bunch effects.

LER



HER



Summary of 2026ab

- With about 2,000 bunches, Lsp drops sharply above a bunch-current product of 0.4 mA^2, together with rapid LER emittance growth.

- At low current, the collision width broadly agrees with the XRM estimate, assuming equal beam sizes and the nominal optics.

- Single-beam LER blowup appears near 0.8 mA/bunch. Its cause and its connection to collision performance remain unclear.

- With 393 bunches, no abrupt Lsp drop is seen over the measured range. HER BxB feedback was not fully optimized, and the HER emittance was large, limiting comparison with many-bunch operation.

- Full-lattice simulations with scaled wakes do not yet reproduce the measured high-current deterioration.

Summary of Vertical Blowup

- With 393 bunches, the LER showed sharp blowup in single-beam operation, but not during collisions.
- However, HER feedback was not fully optimized during the 393-bunch collision study.
- We therefore cannot say that the difference from ~2,000-bunch collisions is due to bunch number alone.
- No clear threshold-like blowup was found in the many-bunch single-beam data examined.

#	Date 2026	Bunches	Beam condition	HER BxB feedback	Observed vertical blowup
(1)	16, 26 Jun	393	LER single beam	–	LER: sharp blowup
(2)	16 Jun	393	HER single beam	Not fully optimized	HER: blowup
(3)	26 Jun	393	HER single beam	Optimized	HER: no blowup
(4)	16 Jun	393	Collision	Not fully optimized, as in (2)	LER: sharp blowup absent
(5)	29–30 Jun	~2,000	Collision	–	LER: sharp blowup
(6)	June	1900 ~2000	LER single beam, HER current ≈ 0	–	LER: no clear threshold-like blowup in the data reviewed.

Plans and Proposals for 2027ab

Proposed studies, in order of priority

1. High bunch current

Compare few and many bunches at similar bunch currents, with recorded FB settings.

Use turn-by-turn data to characterize the motion and guide follow-up studies.

2. Low-current and off-momentum collision scans

Compare XRM, scan and luminosity estimates, and test momentum dependence.

3. Common IP position and angle

Keep the relative LER–HER geometry fixed and probe collision sensitivity.

Continuing research

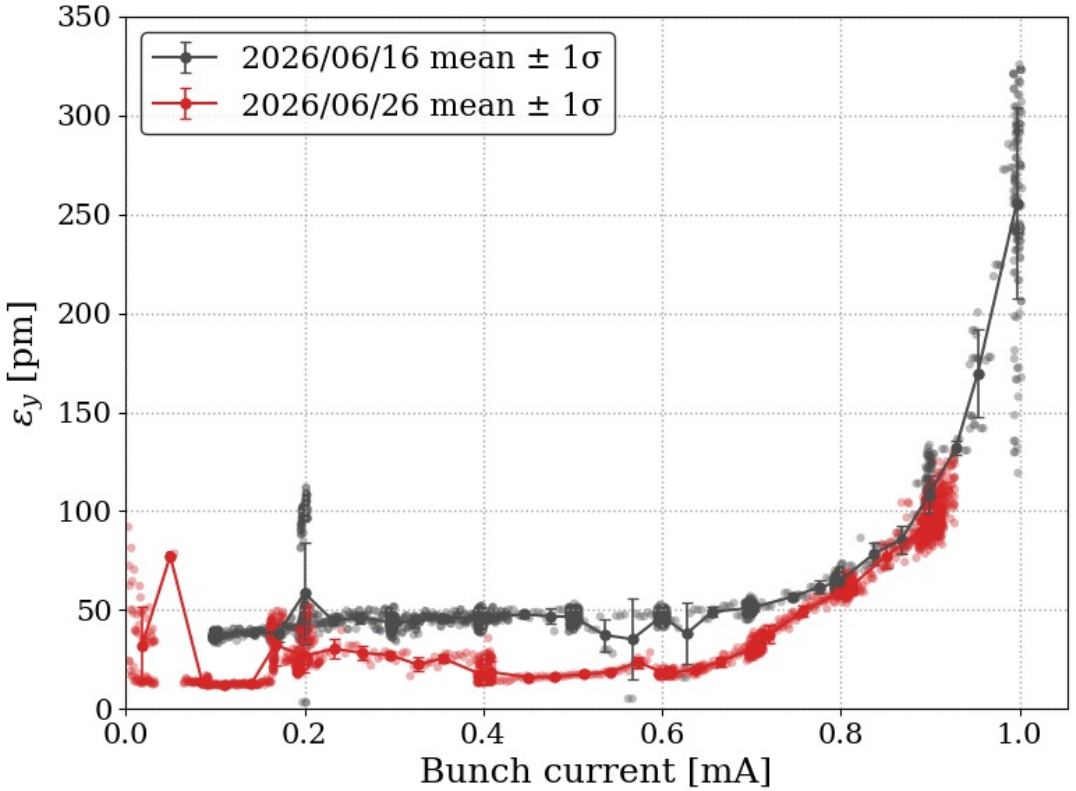
- Study the combined effects of beam–beam interactions, wakefields and BxB feedback.
- Improve beam–beam simulation models. Benchmark with Xsuite / BeamBeam3D.
- Explore the use of rotatable sextupoles for chromatic coupling correction.

Appendix

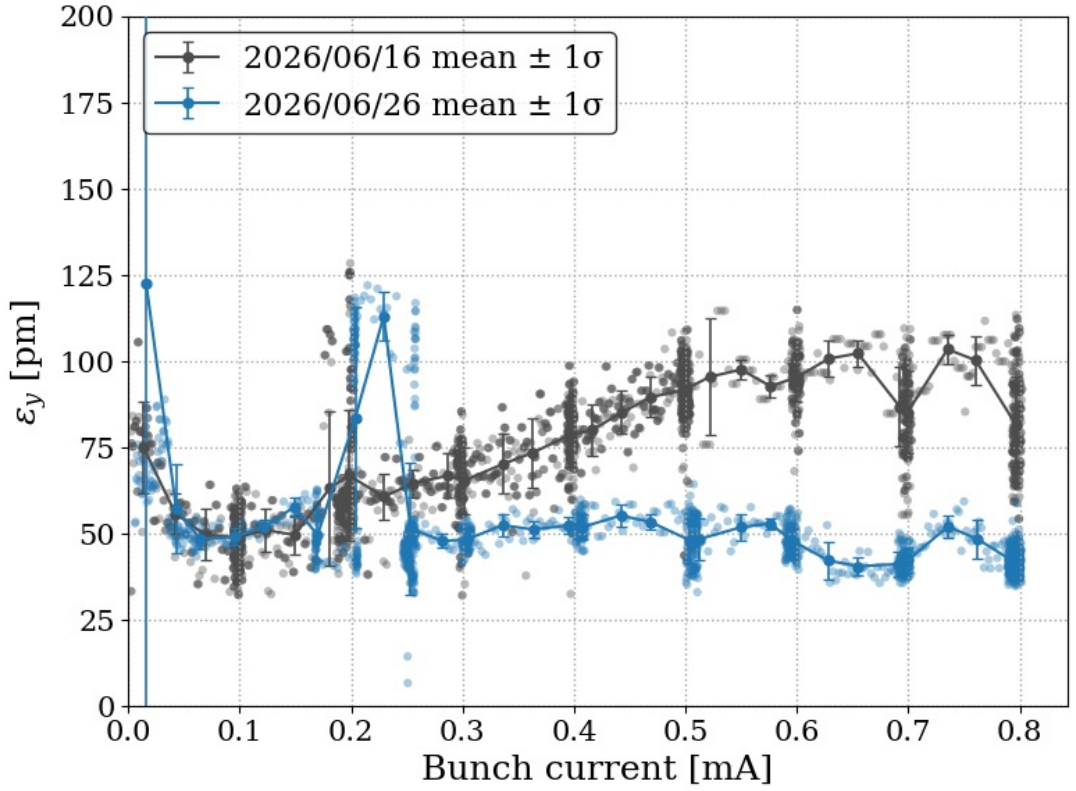
High Bunch Current Study: 393 Bunches

- Single-beam size without collision
- The strong current dependence of the HER beam size seen on June 16 had almost disappeared by June 26.
- A later report linked this difference to the HER bunch-by-bunch (BxB) feedback settings.

LER



HER



-1 mode Instability Observation Before LS1

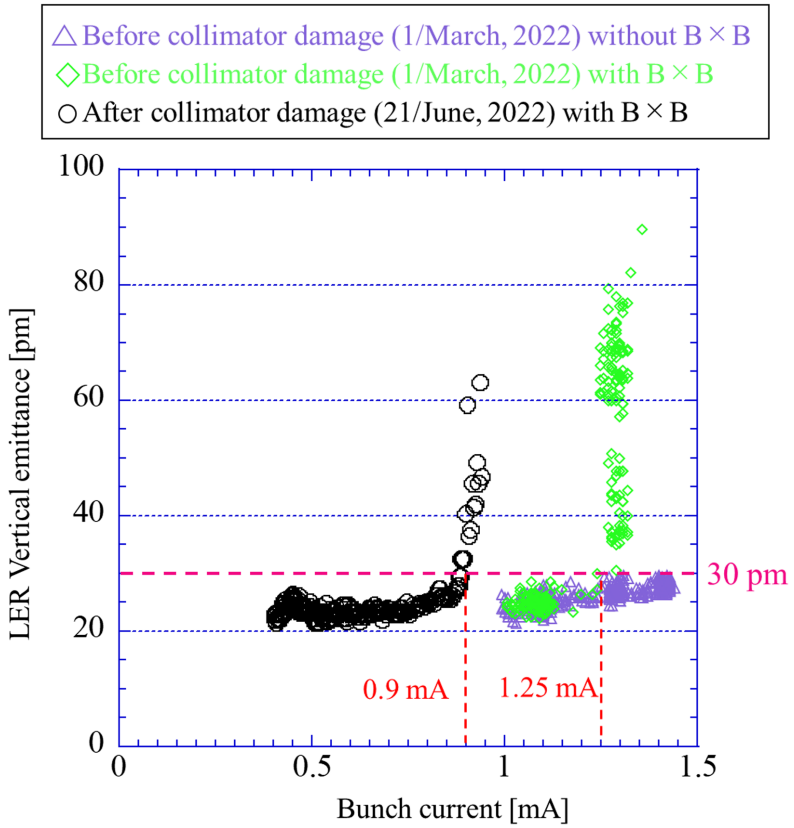


FIG. 10. Vertical beam emittance versus bunch current with $\beta_y^* = 1$ mm, before (green diamonds) and after (black circles) the event of collimator jaw damage with B × B feedback on. The data of purple triangles show the measurement with B × B feedback off.

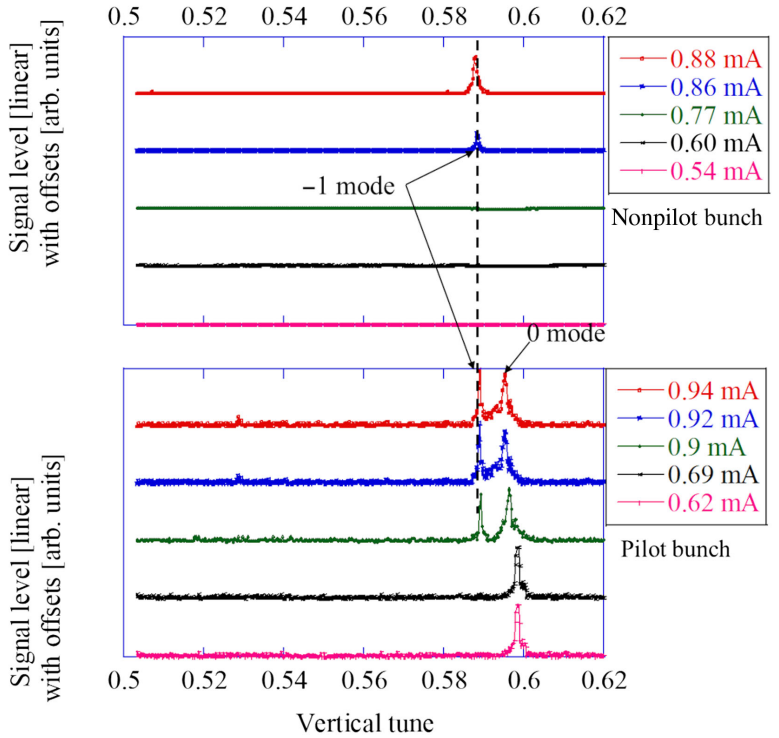
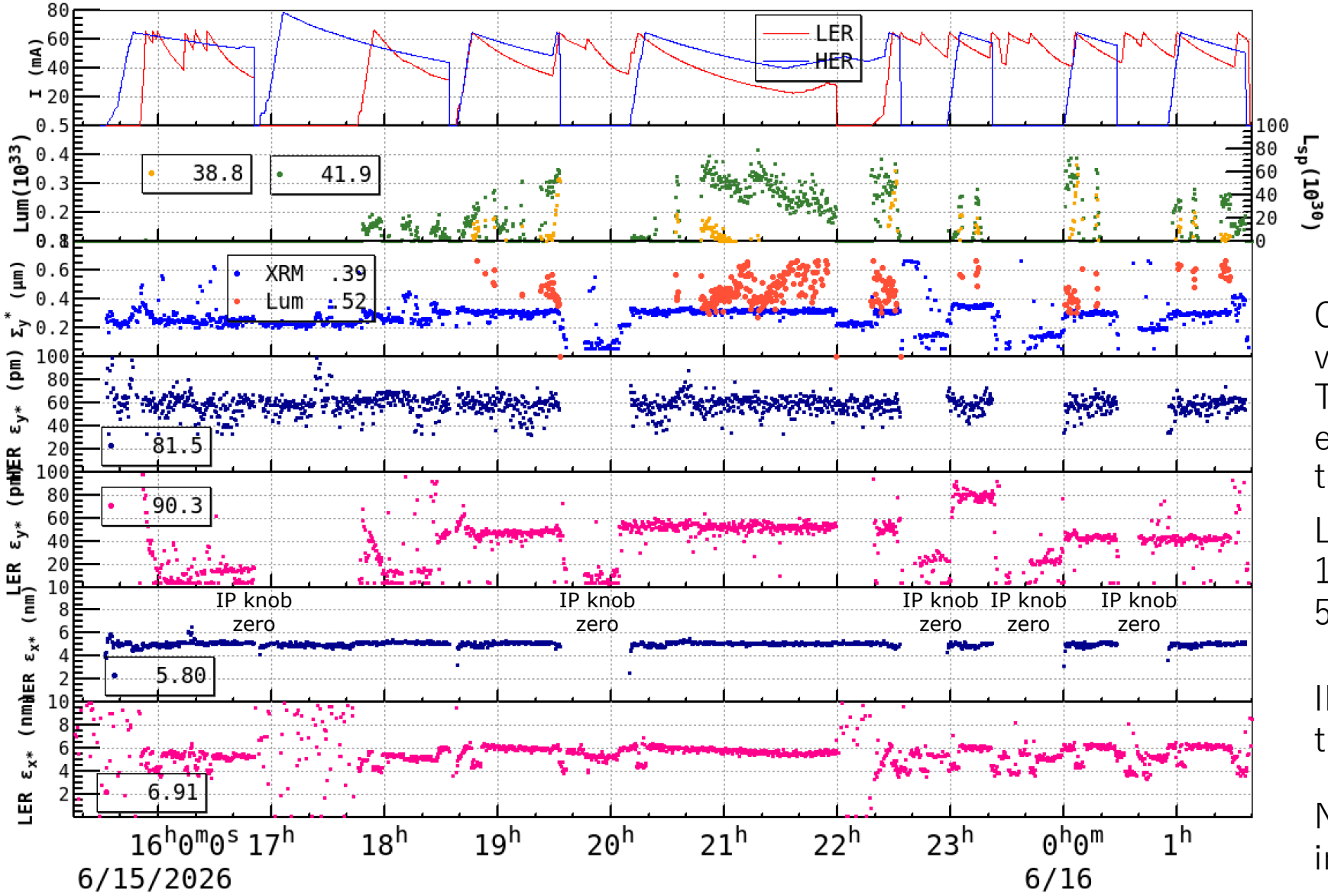


FIG. 9. Results of the FFT analysis of vertical beam motion data collected using the LER BOR.

conducted in a single-beam mode, excluding beam-beam effects, with a reduced number of bunches (93) compared to the harmonic number (5120) to exclude multibunch effects. The results, depicted in Fig. 10, illustrate the bunch

S. Terui *et al.*, Phys. Rev. Accel. Beams 27, 081001 (2024).

Low-Current Beam-Beam Scan



Y. Ohnishi

Only the LER vertical angle is varied.
The optics are corrected after each angle change, without using the IP knobs.

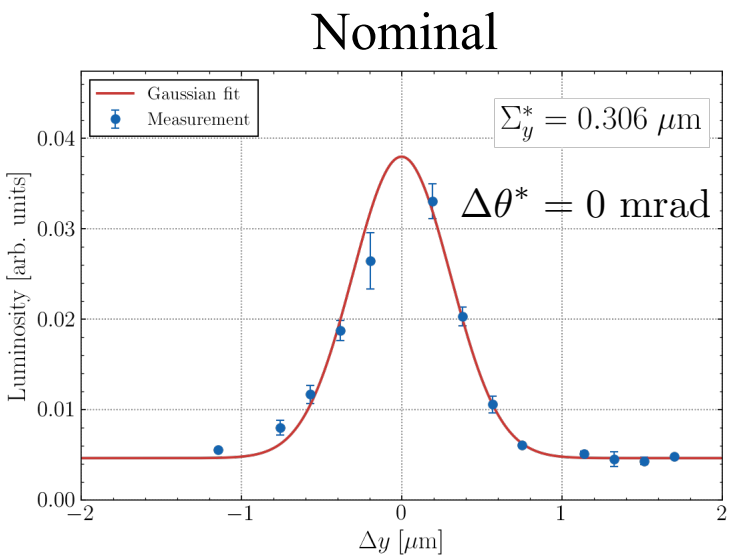
LER vertical emittance:
10 pm with IP knobs at zero
50 pm at nominal settings

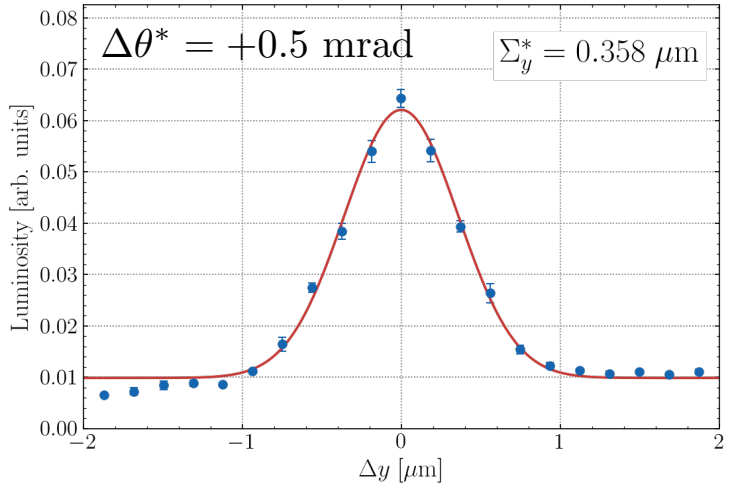
IP-knob settings strongly affect the LER vertical emittance.

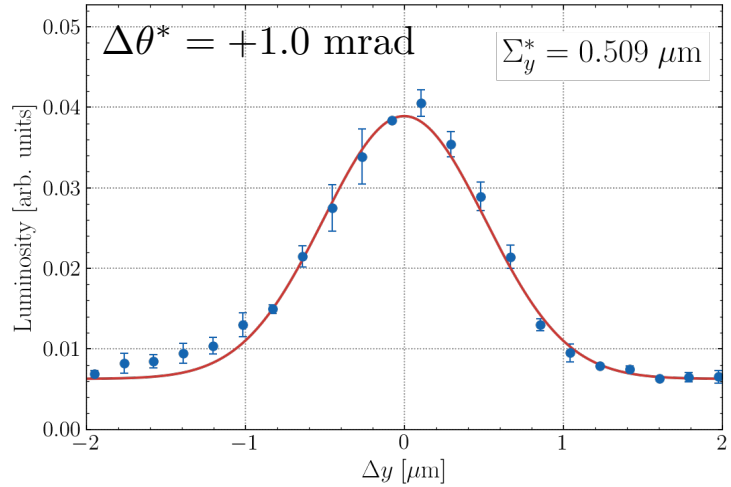
No beam-beam blowup is evident in either ring.

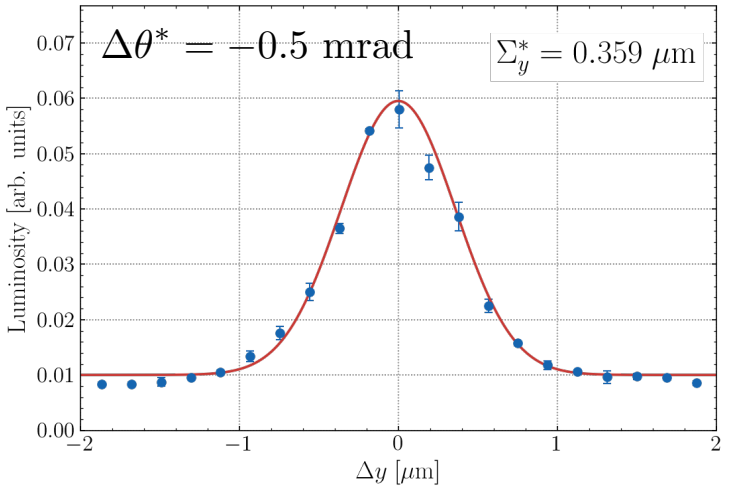
Low-Current Beam-Beam Scan - LER Vertical-Angle Scan -

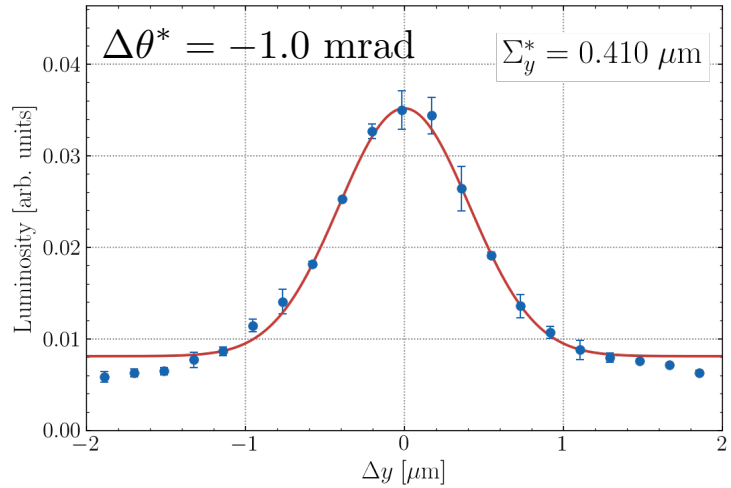
- We scanned the LER vertical angle at the IP while keeping the HER orbit fixed.
- We corrected the optics at each angle setting, particularly the vertical dispersion.







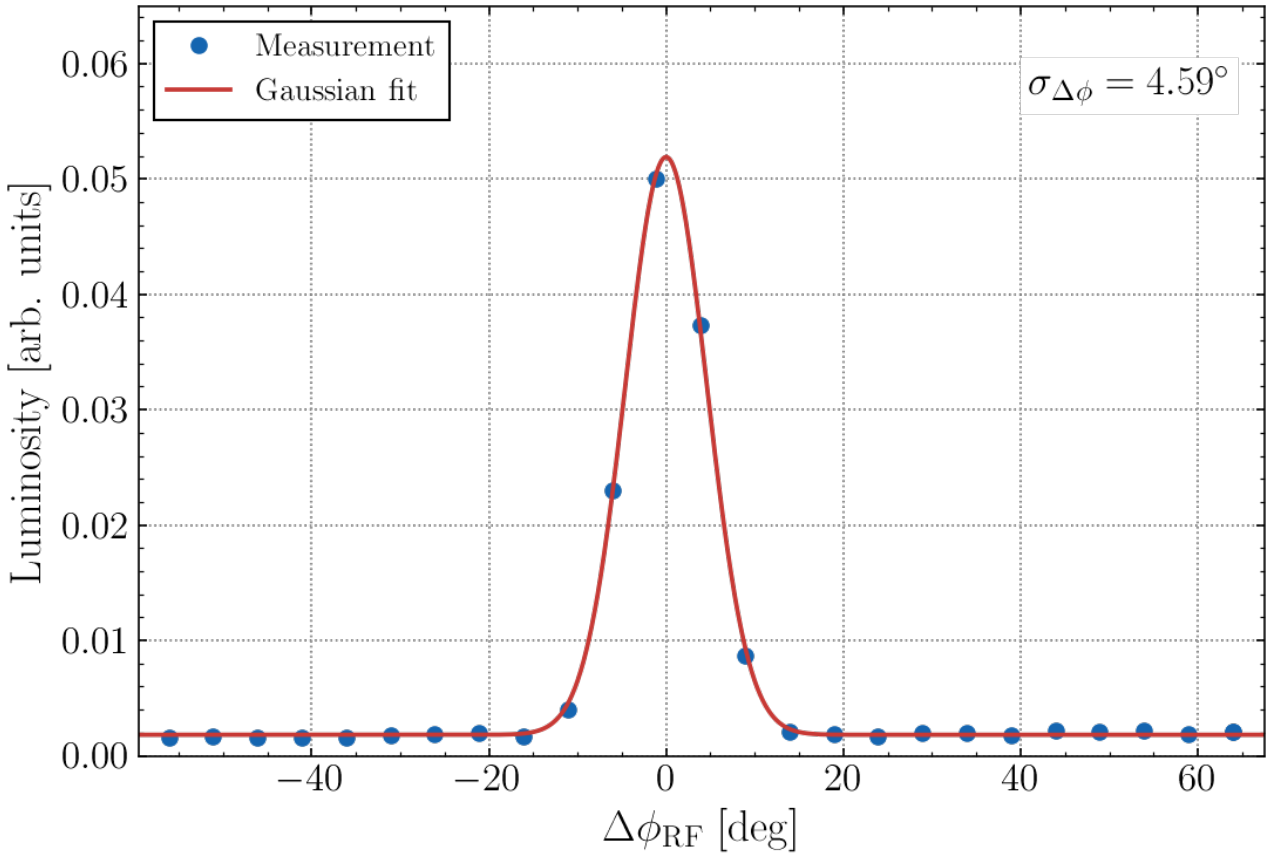




Low-Current Beam-Beam Scan - Convolved Bunch Length -

- The RF-phase scan measures the convolved bunch length.

$$\Sigma_z^2 = \sigma_{z,\mathrm{LER}}^2 + \sigma_{z,\mathrm{HER}}^2$$



Measurement

$$\Sigma_z = 7.50 \pm 0.13 \text{ mm}$$

(fit uncertainty only)

Haïssinski calculation

$$\Sigma_z = 6.96 \text{ mm}$$

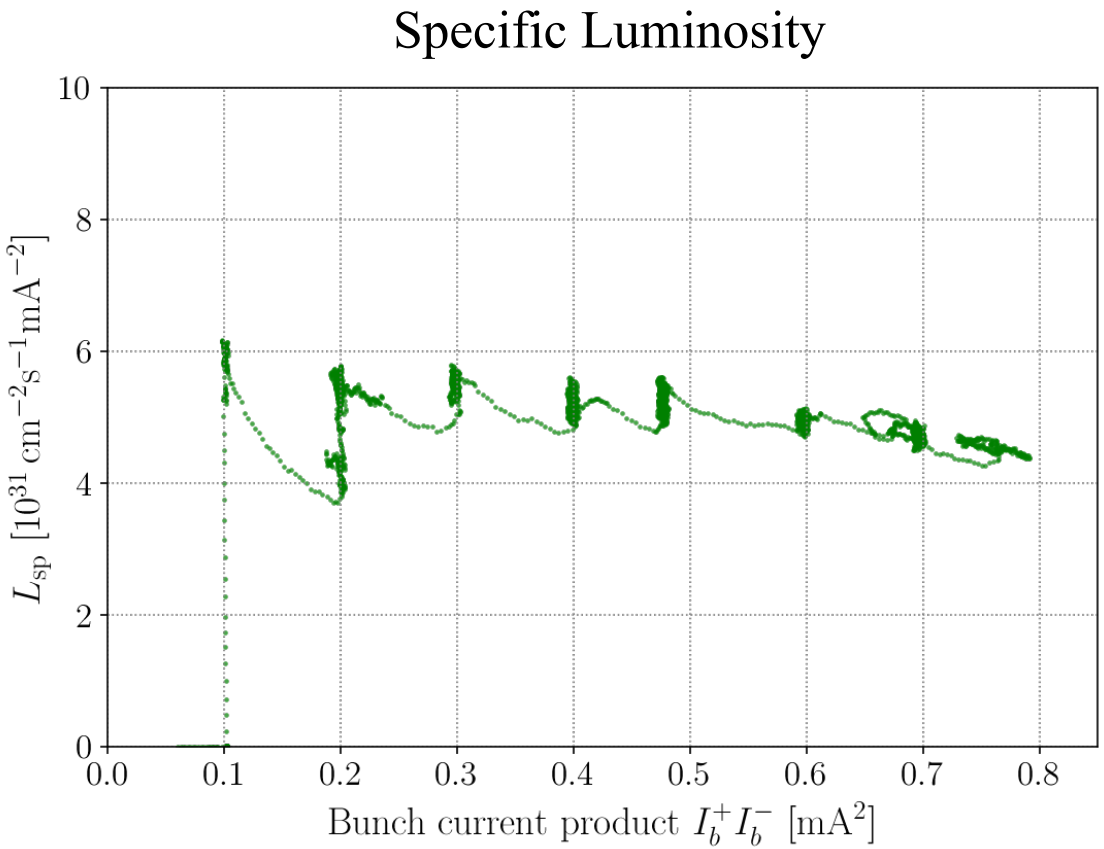
LER: 4.675 mm HER: 5.149 mm

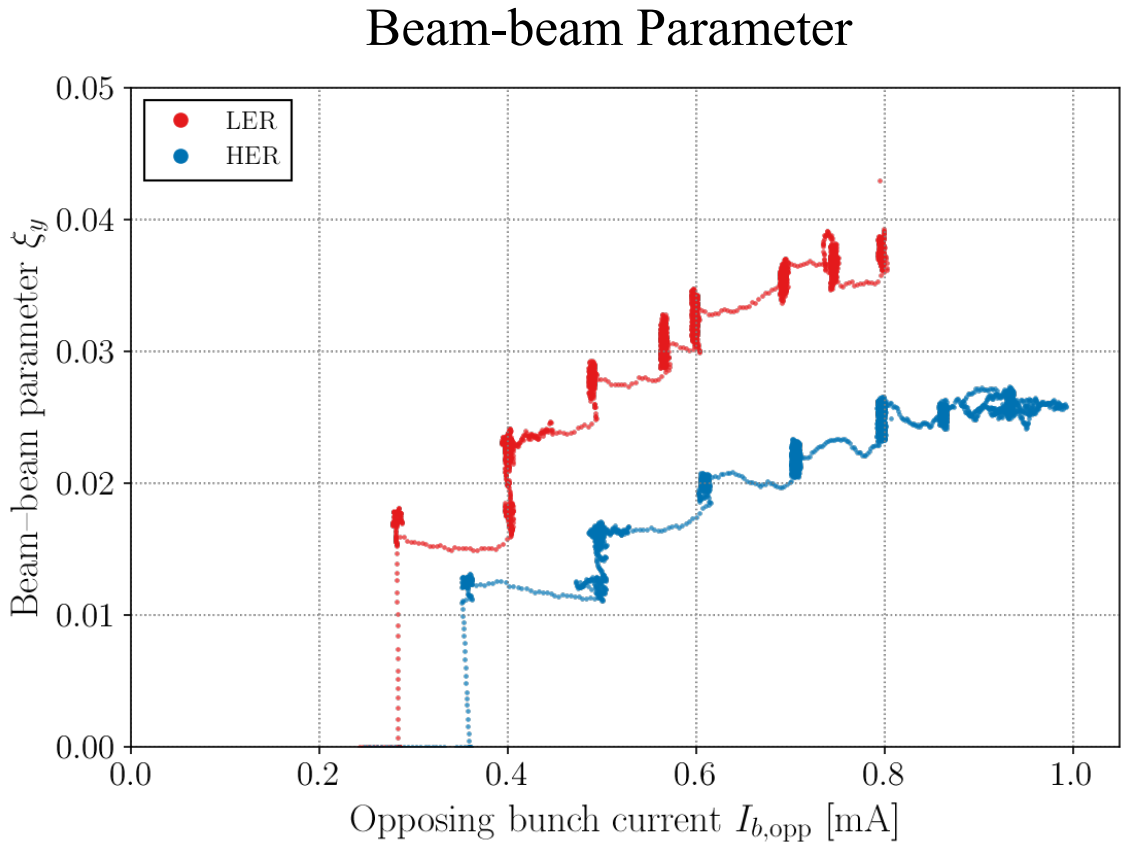
RF: LER 9.17 MV / HER 14.2 MV

I_b = 0.077 mA/bunch (both rings)

High Bunch Current Collision Study

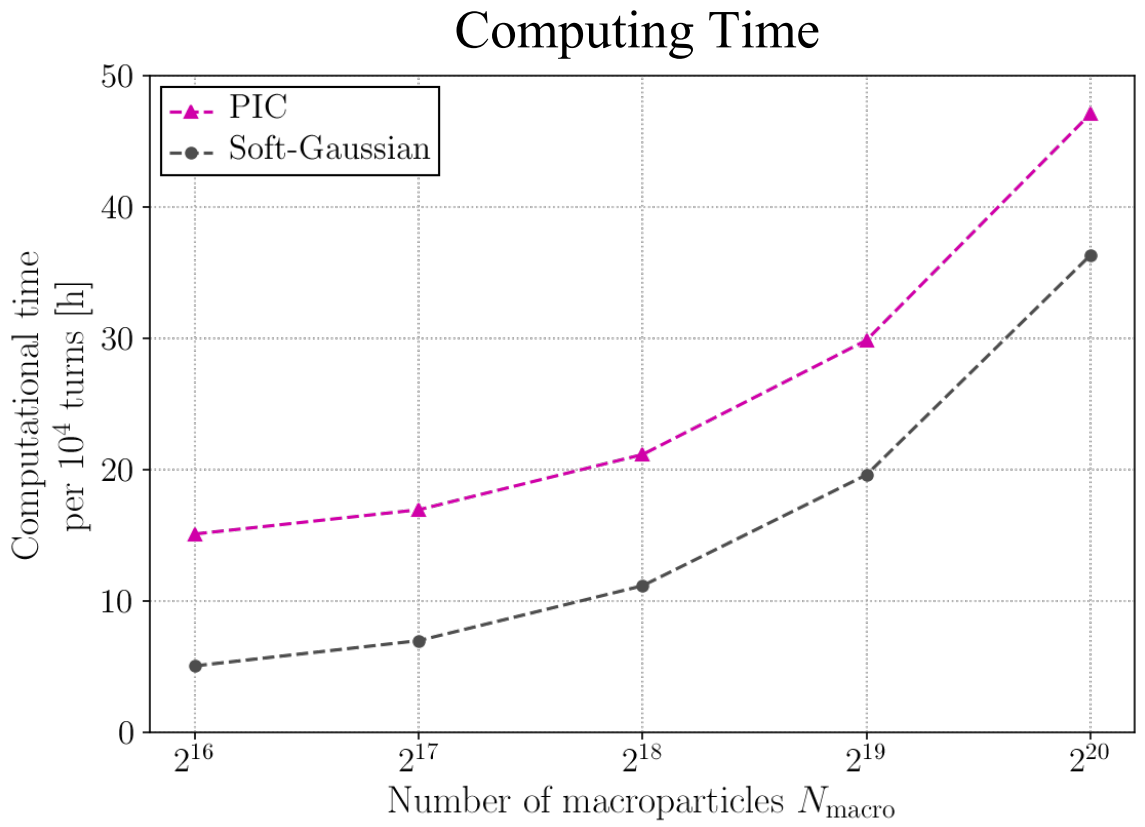
- 2026/06/16, 393 bunches, $\beta_y^* = 0.9$ mm
- Specific luminosity shows no abrupt drop over the measured range.
- The sharp blowup seen in the LER single-beam study is absent in this collision scan.





Computing Time: PIC and Soft-Gaussian Models

- Simulations were performed at the University of Tsukuba using an NVIDIA H100 GPU with 80 GB of memory.
- Subsequent PIC runs use $N_{\mathrm{macro}} = 2^{18}$–$2^{19}$ macroparticles.
- At $N_{\mathrm{macro}} = 2^{18}$ tracking 10^4 turns takes 21 hours with PIC and 11 hours with the soft-Gaussian model.
- Full-lattice PIC is now practical for selected cases. Systematic scans remain costly.



University of Tsukuba
Center for Computational Sciences

筑波大学
University of Tsukuba

Multidisciplinary Cooperative Research Program
筑波大学計算科学研究センター 学際共同利用プログラム

Pegasus System

node	CPU	Intel Xeon Platinum 8468 (codenamed Sapphire Rapids) 2.1GHz/48c (3.2256 TFlops)
	GPU	NVIDIA H100 Tensor Core GPU with PCIe (51 Tflops in FP64 Tensor Core)
	Memory	128GiB DDR5-4800 (282 GB/s)
	Persistent memory	2TiB Intel Optane persistent memory 300 series
	SSD	2x3.2TB NVMe SSD (7 GB/s)
	Network	NVIDIA Quantum-2 InfiniBand platform (200 Gbps)
Number of nodes		120
Peak performance		6.5 PFlops
Parallel file system		7.1PB DDN EXAScaler (40 GB/s)
System vendor		NEC



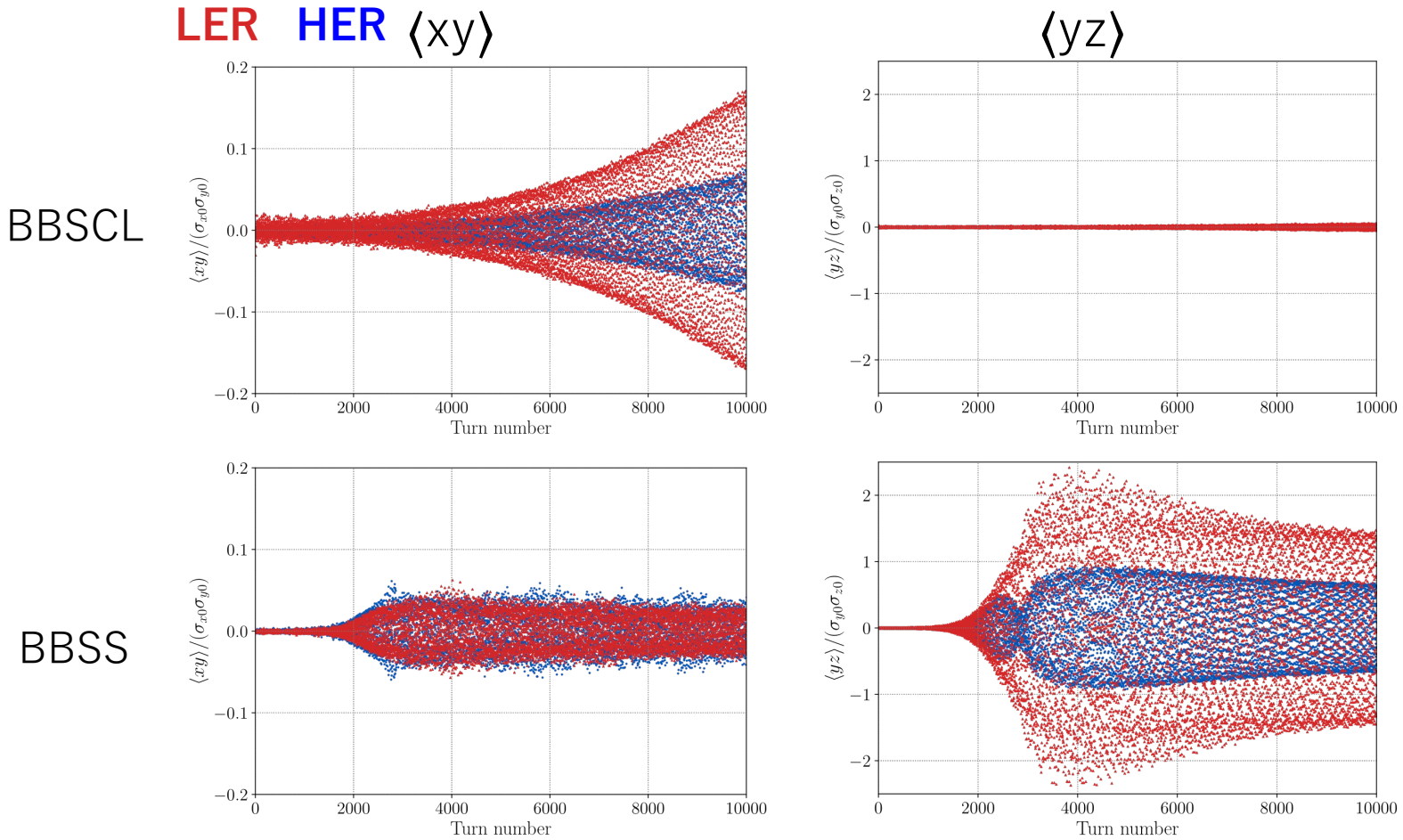
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Advanced Interdisciplinary Computational Science Collaboration Initiative (the MEXT of Japan)

BBSCL–BBSS: ⟨xy⟩ and ⟨yz⟩ Motion

$I_b^+ I_b^- = 1.00\ \mathrm{mA}^2$

- BBSCL has larger ⟨xy⟩ but smaller ⟨yz⟩ oscillations than BBSS at 1.00 mA².

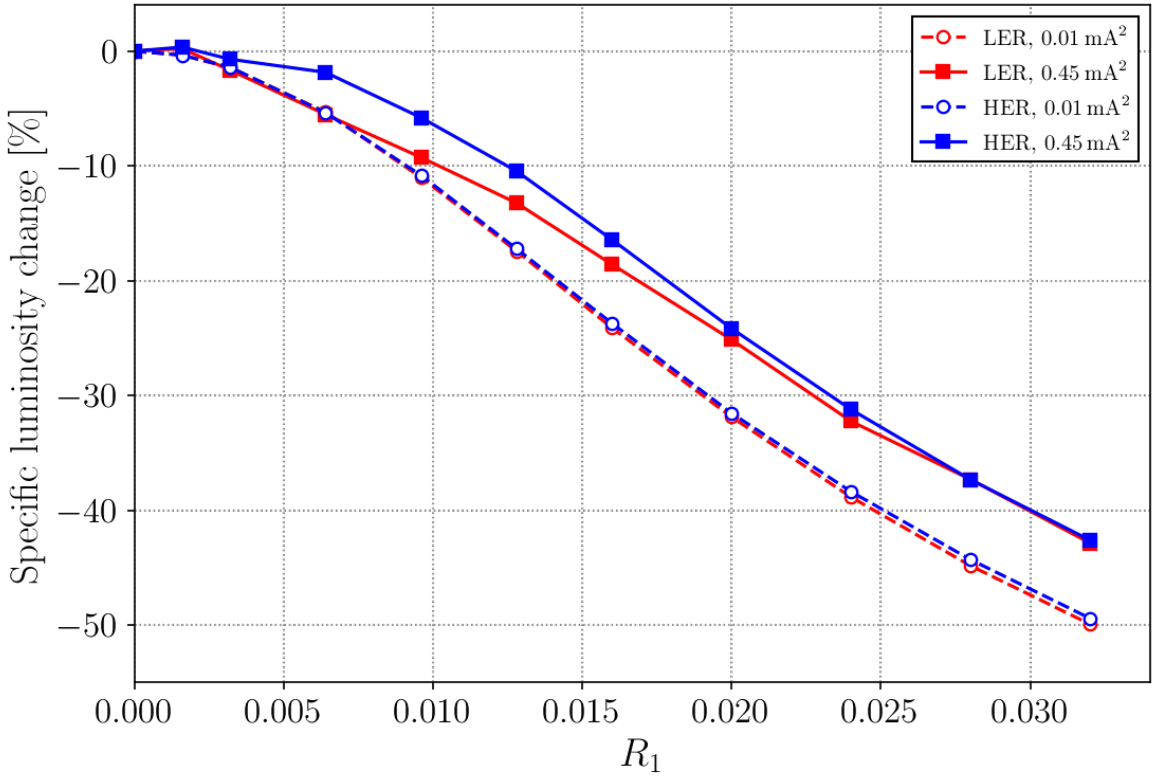
Nominal vertical emittance: 25 pm (both rings). Tunes (ν x, ν y): LER (44.525, 46.589), HER (45.529, 43.599).

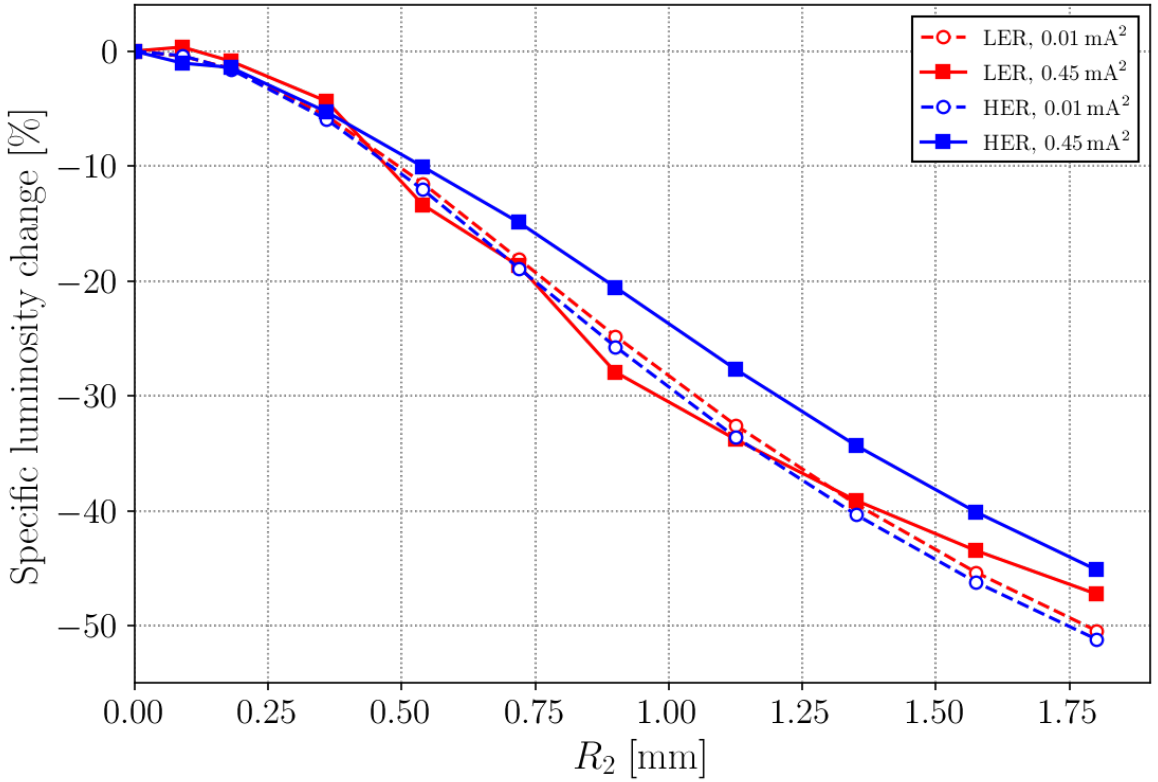


IP Coupling Sensitivity

BBSS: one coupling component varied in one ring. Bunch-current products: 0.01 and 0.45 mA².

Lsp change relative to zero coupling at the same current.





10,000-turn runs, averaged over turns 9,010–10,000. High-current cases retain time dependence.

Comparison with operational coupling-knob scans remains to be made.

Responses to Previous Review Recommendations (1/3)

R20.1: The ARC recommends the further development of realistic and comprehensive simulations of beam-beam effects as a focus for the international scientific collaboration between KEK and its partner laboratories.

Response: We are developing full-lattice beam–beam simulations, including impedance, space charge and BxB feedback. We will continue this work and pursue benchmarking with Xsuite and BeamBeam3D through international collaboration.

R20.2: Further efforts should focus on more realistic simulations of beam injection during collisions, aiming to optimize injection schemes and minimize beam loss at injection.

Response: We have not yet studied injection during collisions in dedicated simulations.

R20.3: Achieving high luminosity will require smaller β y* values. However, reducing β y* introduces numerous complex optics-related challenges. At this stage, it is recommended to prioritize addressing the discrepancies in beam-beam performance between simulations and actual machine behavior.

Response: We are comparing full-lattice simulations with measured luminosity and beam sizes. The abrupt luminosity drop at high current remains unexplained and is a priority for further investigation.

Responses to Previous Review Recommendations (2/3)

R20.4: Although the SuperKEKB team is under significant pressure to achieve high luminosity, a prudent starting point may be to investigate the discrepancies observed at low bunch currents.

> **Response:** We performed low-current collision scans in 2026ab. The inferred vertical beam sizes broadly agree with X-ray monitor estimates. Further comparisons with simulations remain necessary.

R20.5: A further step involves analyzing performance during weak-strong collisions, where one beam operates at high current (normal status) and the other at sufficiently low bunch current. In the absence of coherent instabilities, such experiments are expected to help identify the distinct limiting factors of the two rings.

> **Response:** This remains a possible study, but we have not yet developed a dedicated experimental plan.

R20.6: Horizontal beam-beam instability could serve as a valuable benchmark for comparing simulations with actual machine performance. It is suggested to consider longitudinal impedance, local transverse impedance, feedback, and chromaticity both independently and in combination.

> **Response:** We have yet to carry out a systematic benchmark of this instability, including the individual and combined effects listed above.

Responses to Previous Review Recommendations (3/3)

R20.7: To achieve a comprehensive analysis, strong-strong beam-beam simulations should incorporate lattice effects, impedance, space charge, feedback etc., step-by-step. Try to evaluate the tolerance of linear errors (referring to the most-frequently used luminosity tuning knobs) to facilitate comparison with tuning experience in the real machine.

Response: Full-lattice simulations include impedance and space charge. BBSS scans have evaluated luminosity sensitivity to IP coupling and its momentum dependence in both rings. Comparison with operational tuning and feedback modelling require further work.

R20.8: Perform beam-beam simulation with the inferred residual IP coupling.

Response: We are preparing a dedicated calculation using the residual HER IP coupling inferred in the previous review.

R20.9: Use the lattice with a vertical tilt angle of the detector (presented by Oide-san) to determine how such a misalignment might affect the luminosity performance.

Response: Beam–beam simulations can proceed once a suitable lattice model is available. Preparing this model requires coordinated work on 3D magnetic-field calculations, lattice modelling, and orbit and optics rematching, with staff time allocated to these tasks.