

Beam–Beam

- (1) Observations and Beam Studies in 2026ab
- (2) Beam-Beam Simulations
- (3) Plans and Proposals for 2027ab

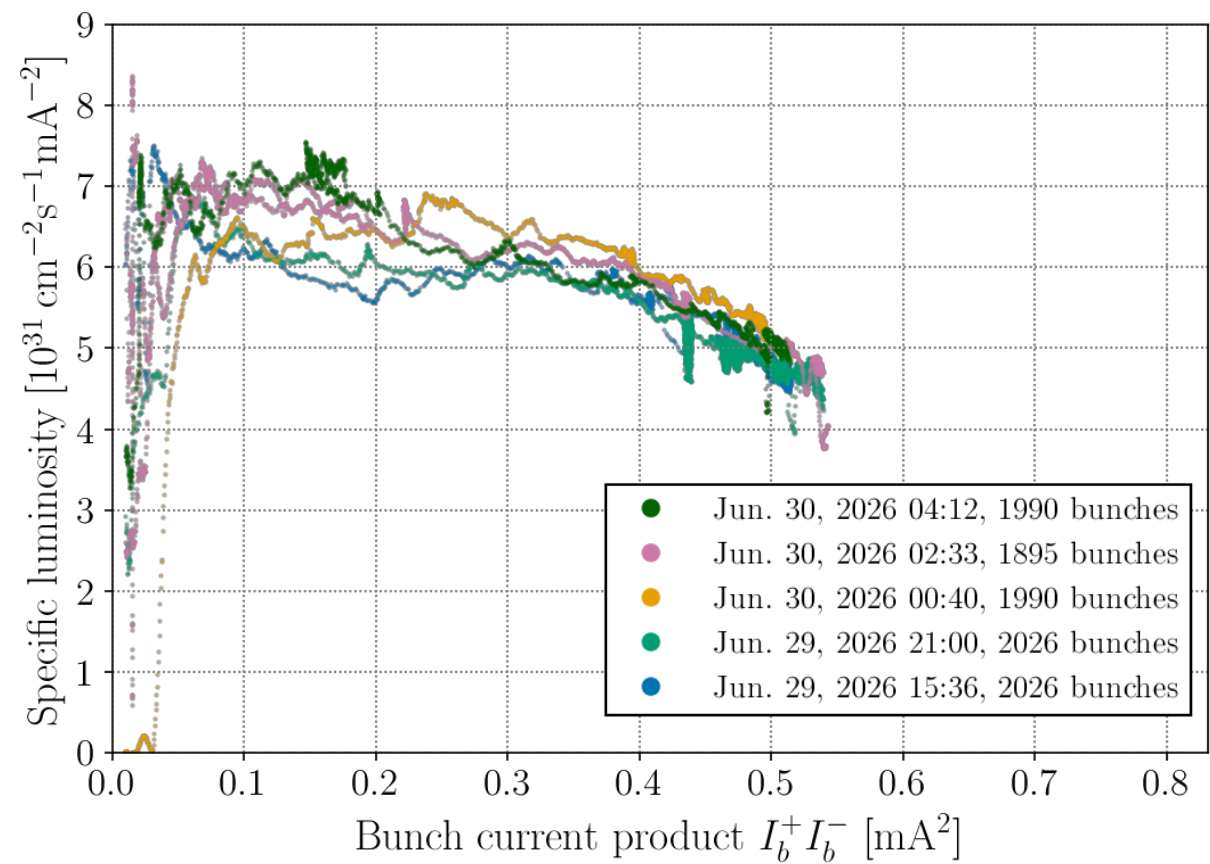
Hiroshi Sugimoto
on behalf of the Beam-Beam Task Force

Observations and Beam Studies in 2026ab

2026ab Specific Luminosity (Lsp)

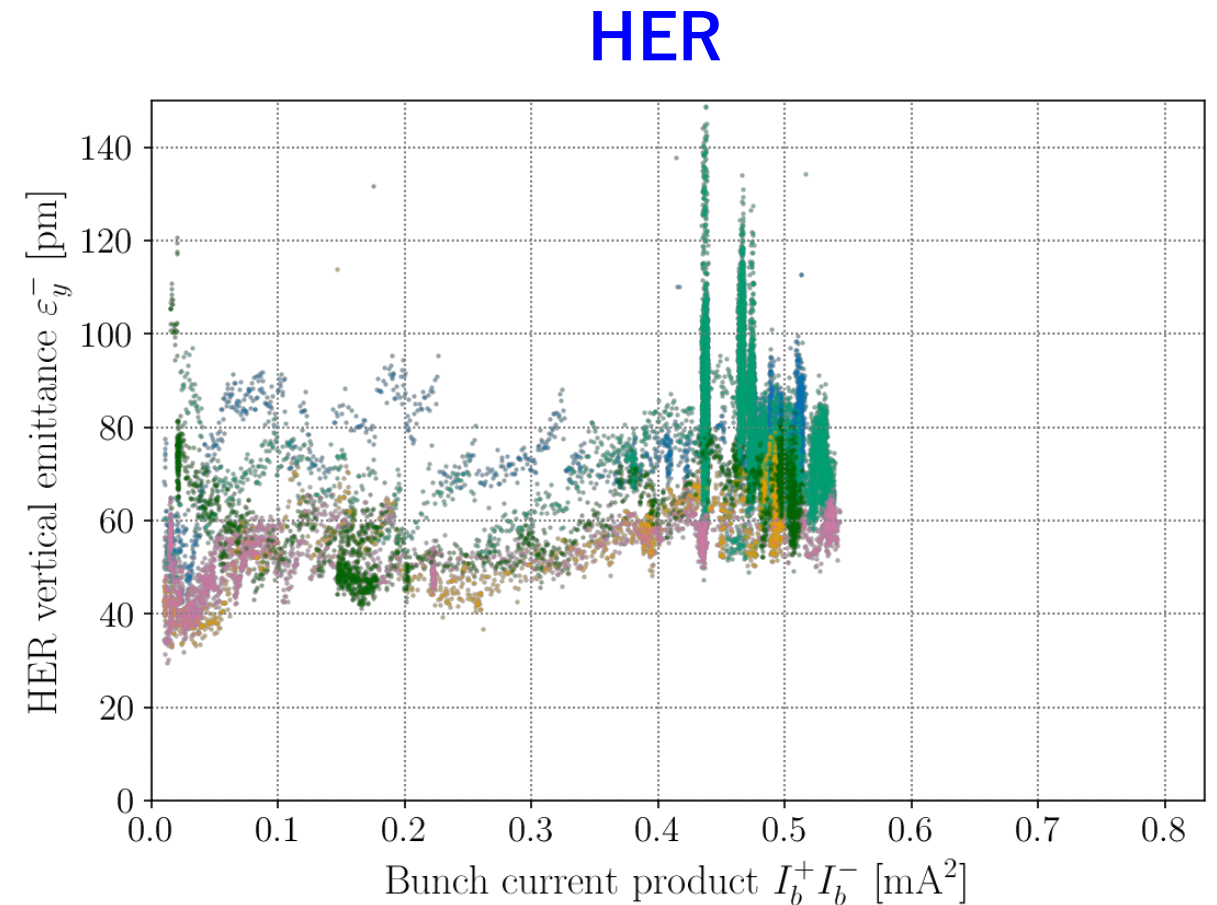
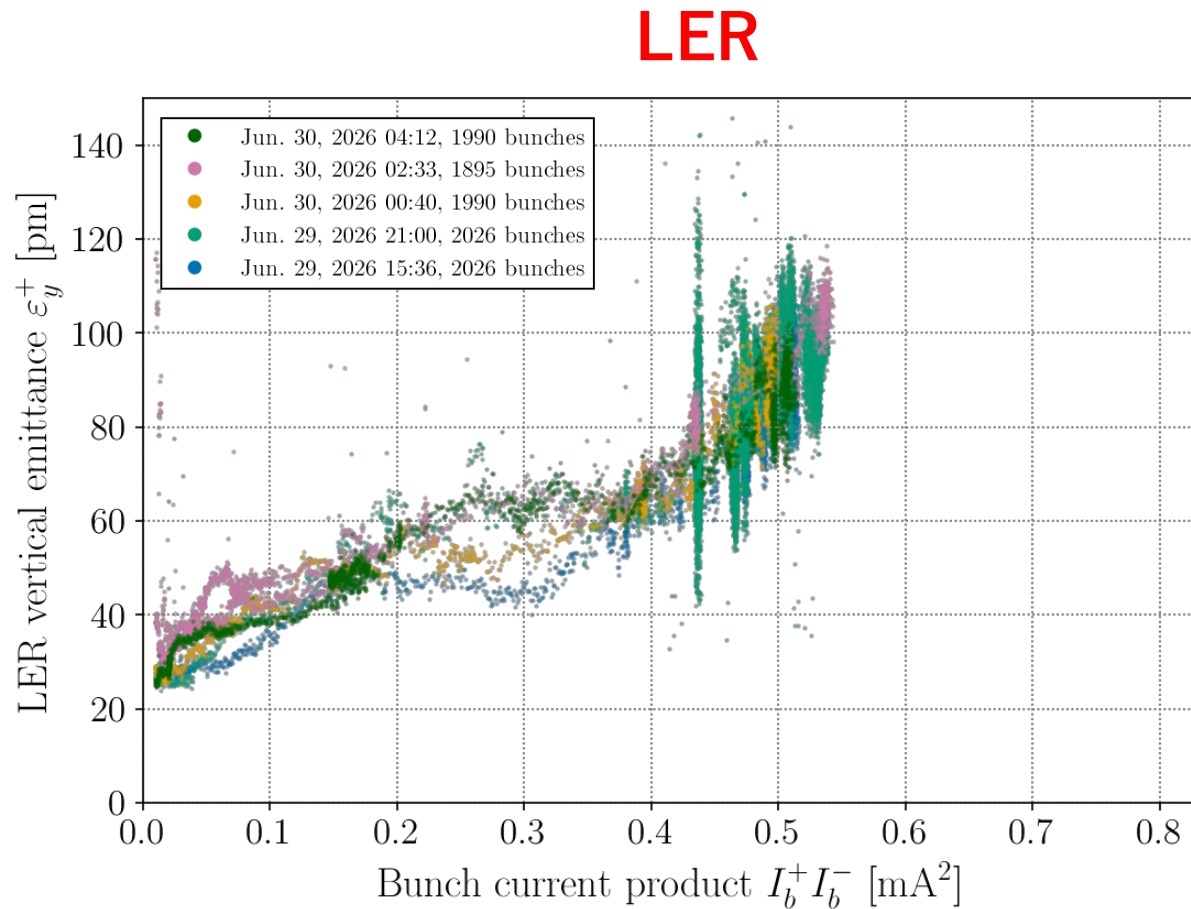
- Five fills from the peak-luminosity studies on June 29–30 are shown.
- Lsp shows substantial scatter below a bunch-current product of 0.4 mA² and decreases rapidly above this value.

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
(β_x^*, β_y^*)	(55, 0.9)	(55, 0.9)	mm
(ν_x, ν_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 mA^2 coincides with a sharp increase in LER vertical emittance.



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.

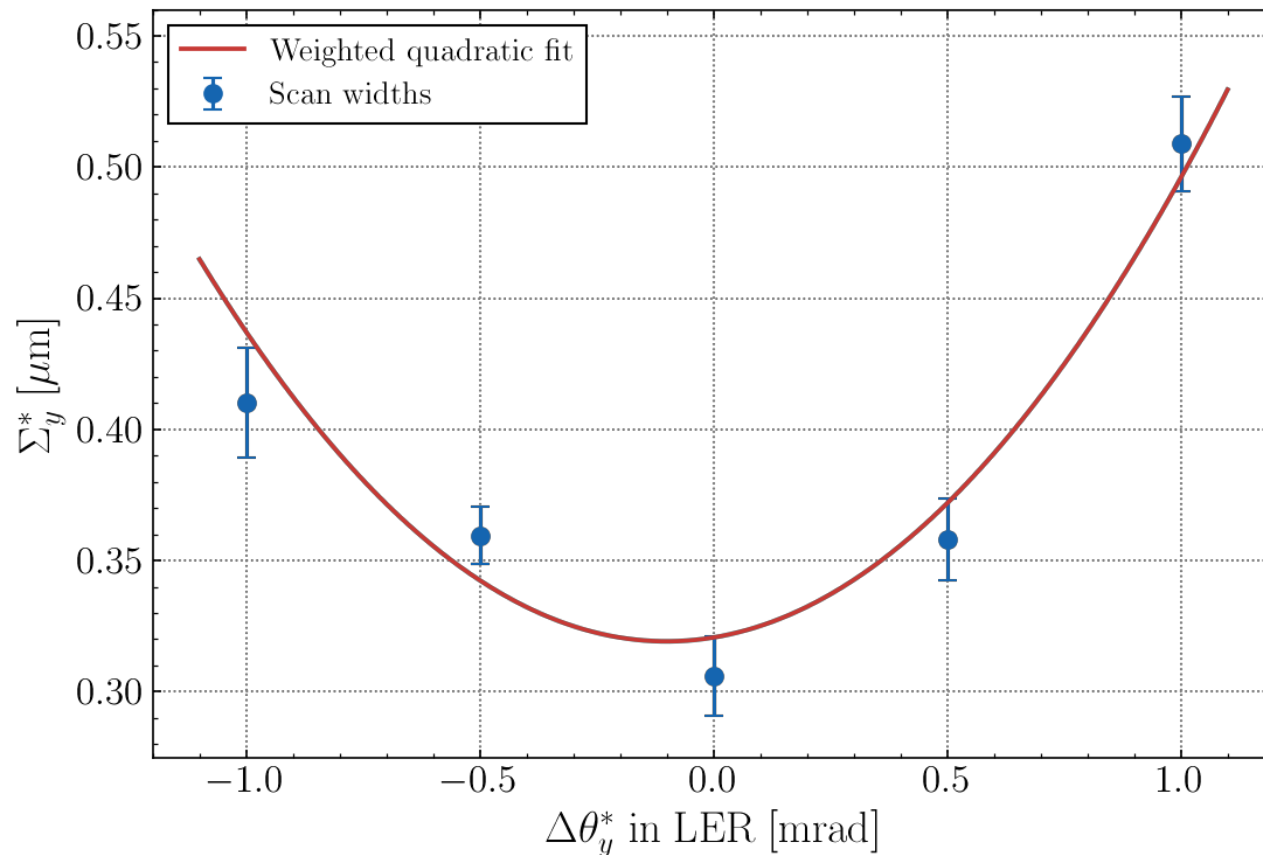
- High Bunch Current (HBC) Study

- 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.

Vertical Angle Scan



Collision scan

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

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

X-ray beam-size estimate (XRM)

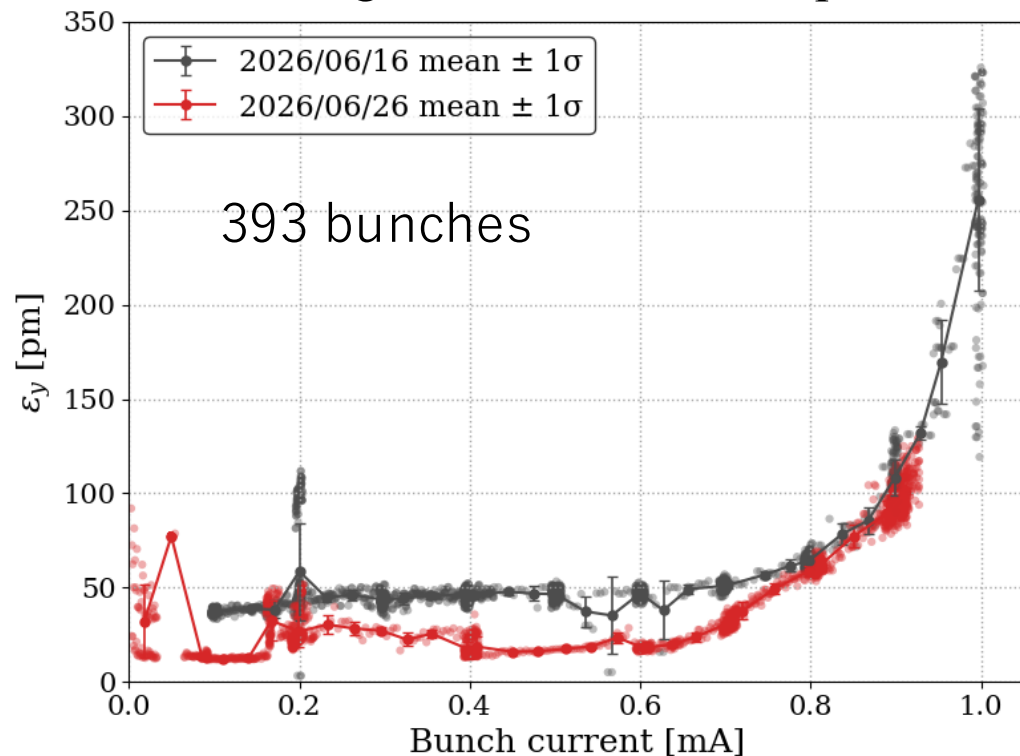
$$\begin{aligned} \varepsilon_y &= 50 \text{ pm} \\ \beta_y^* &= 0.9 \text{ mm} \end{aligned} \longrightarrow \sigma_y^* = \sqrt{\varepsilon_y \beta_y^*} \simeq 0.21 \mu\text{m}$$

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

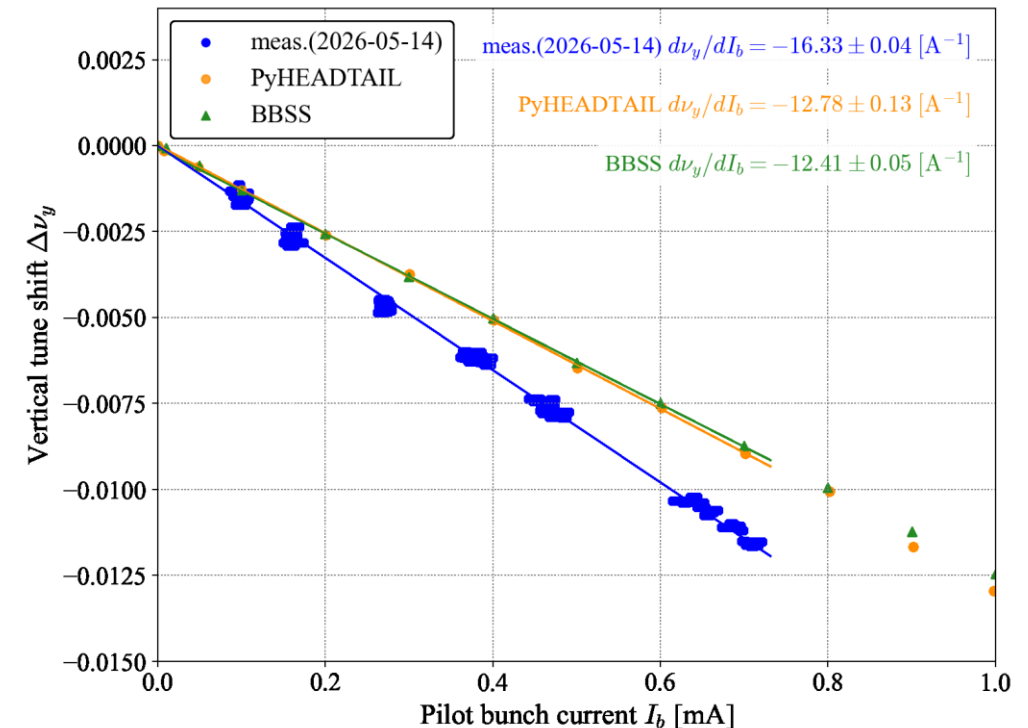
High Bunch Current (HBC) Study

- 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, but this has not been established.
- The connection between the single-beam blowup and collision performance remains unclear.

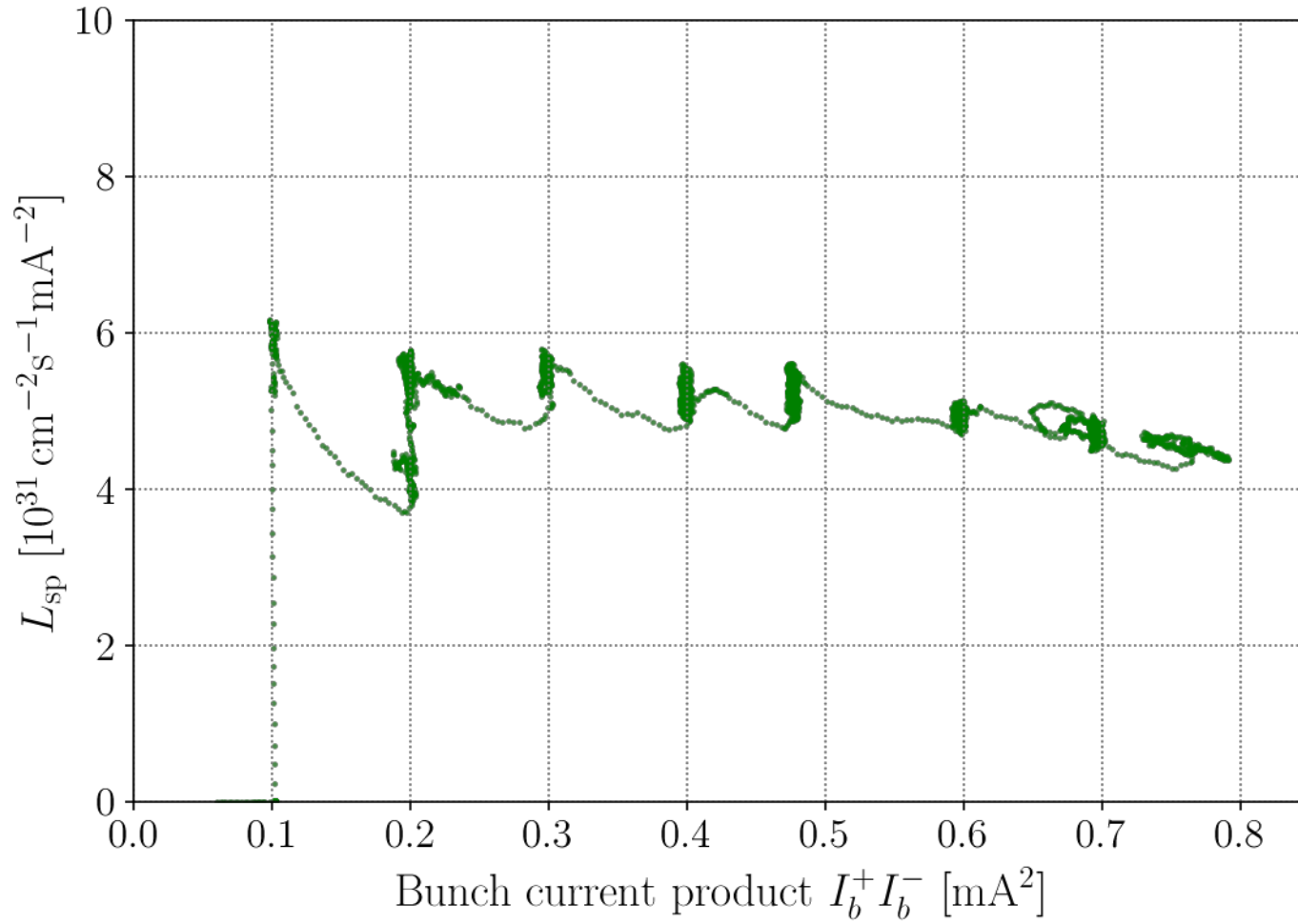
Single Beam Size Blowup



Pilot bunch Tune Shift



High Bunch Current Collision Study



393 bunches, 16 June 2026

$$\beta_y^* = 0.9 \text{ mm}$$

High bunch current at lower total current: a benchmark for simulations.

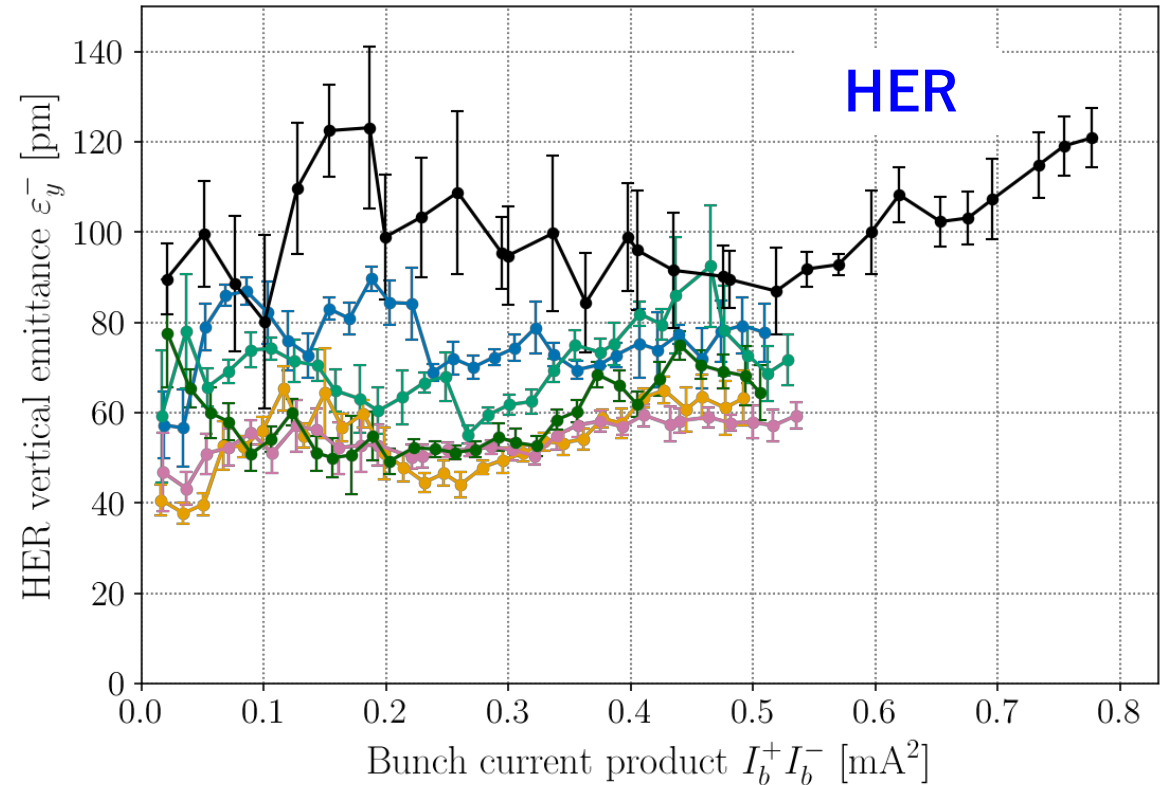
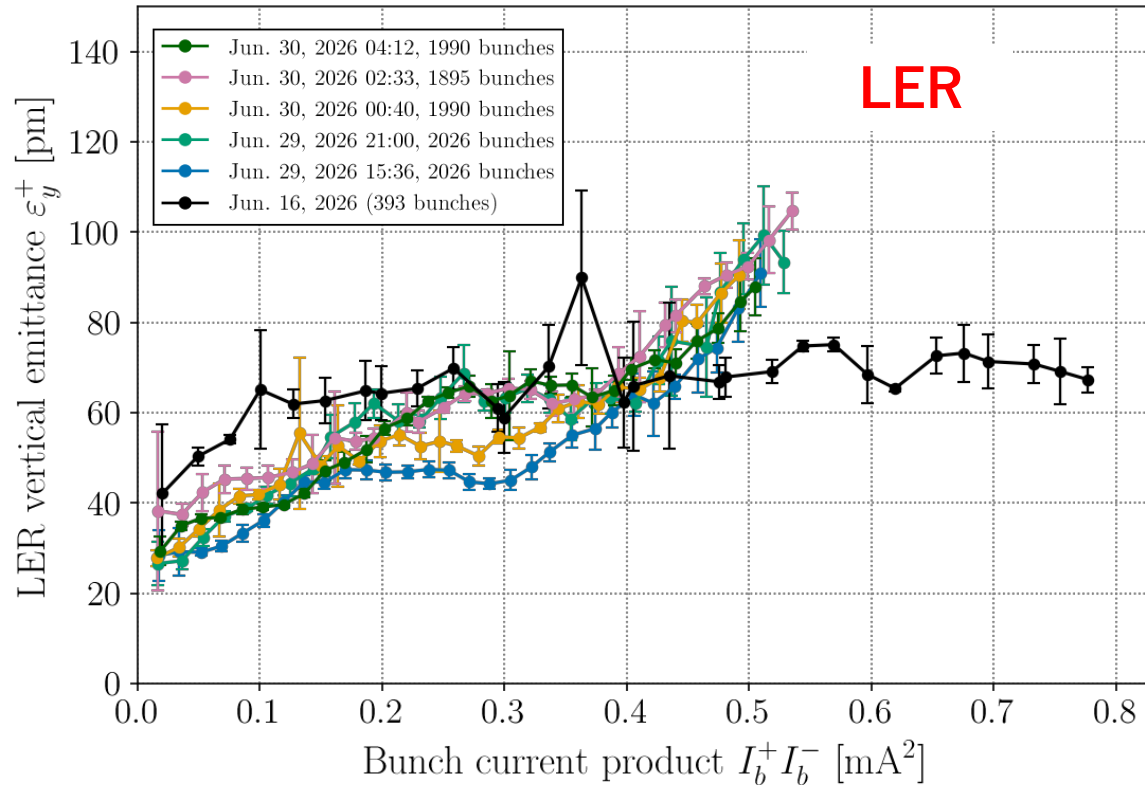
No abrupt L_{sp} drop over the measured range.

The sharp single-beam LER blowup is absent in this scan.

HER feedback and emittance differ from many-bunch operation.

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.



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 / section maps	Element-by-element on GPU
Short-range wakes	SAD wake function	Included	Included
Space charge	Gaussian weak–strong	No dedicated ring model	Distributed sliced PIC

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

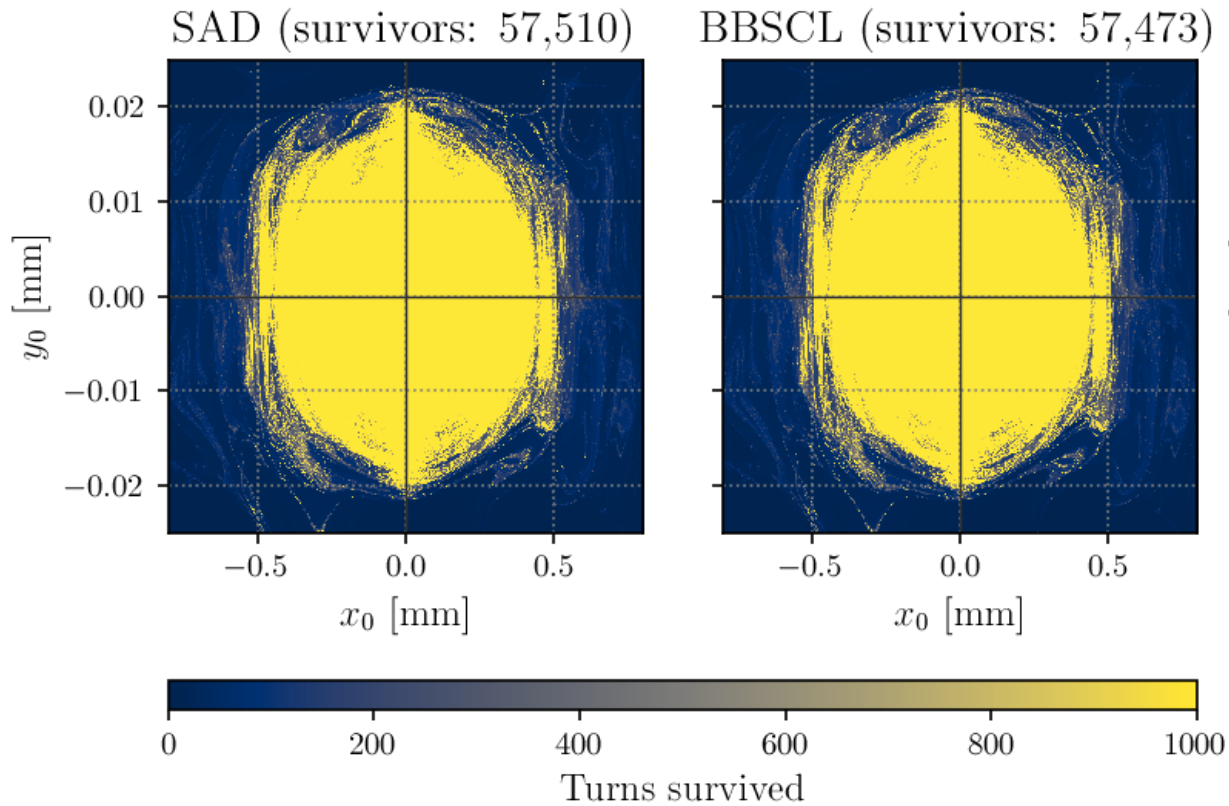
- Element-by-element tracking includes lattice nonlinearities and coupling.
- Map-based tracking provides a controlled reference for comparison.

Codes originally developed by K. Ohmi.
I recently joined their development, focusing on SuperKEKB applications.

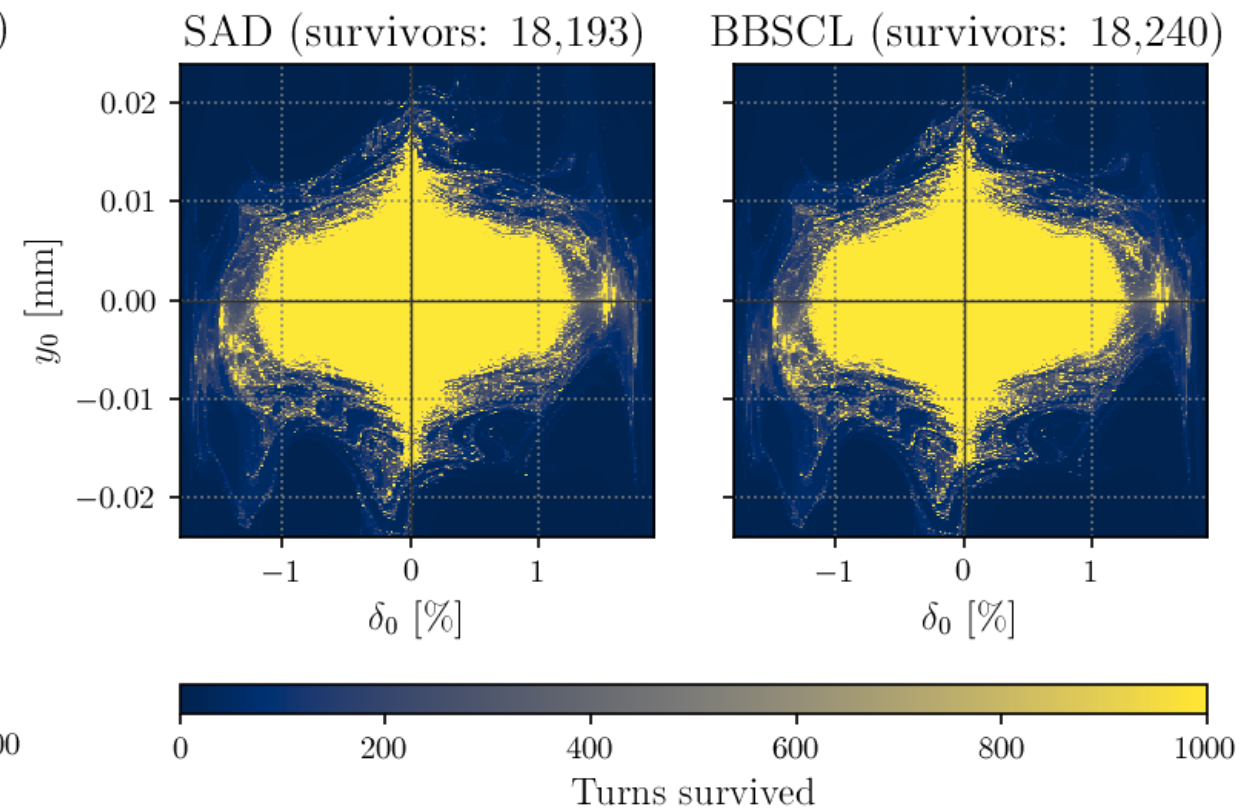
BBSCCL Benchmarks

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

Dynamic Aperture: x-y Plane

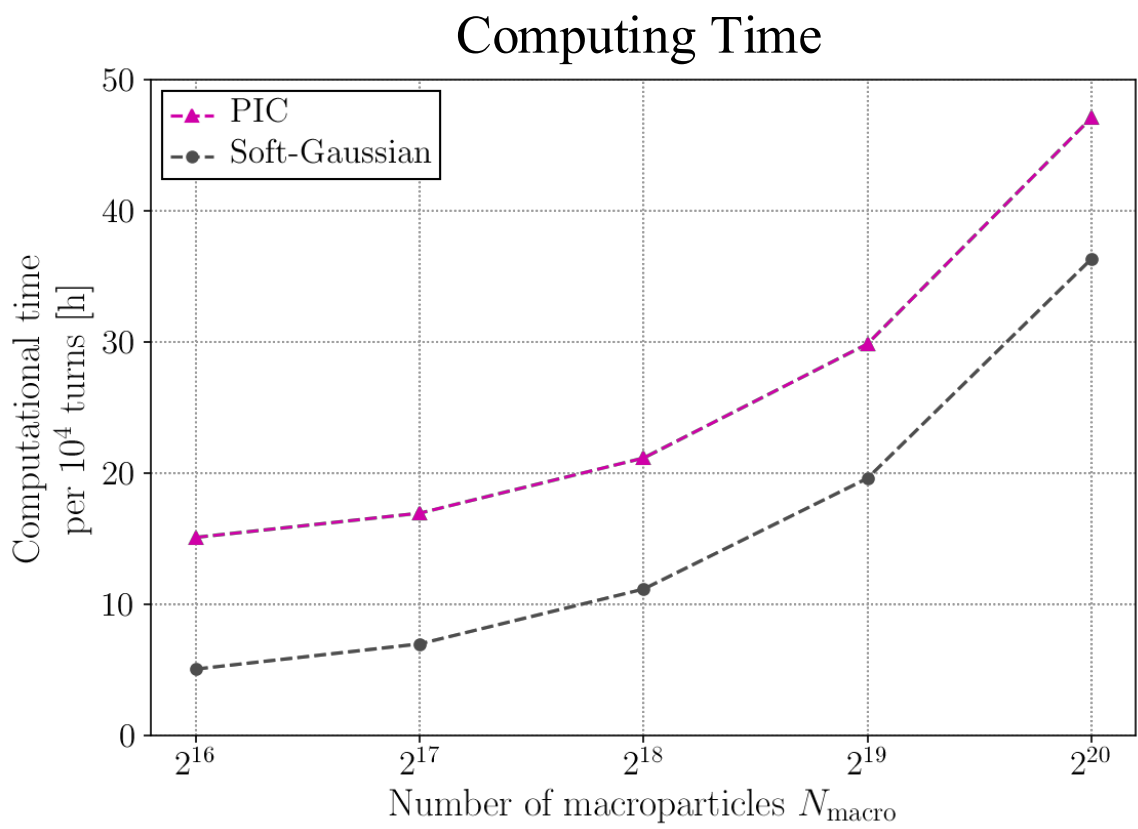


Dynamic Aperture: y- δ Plane



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 $N_{\text{macro}} = 2^{18} - 2^{19}$ macroparticles.
- At $N_{\text{macro}} = 2^{18}$ 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

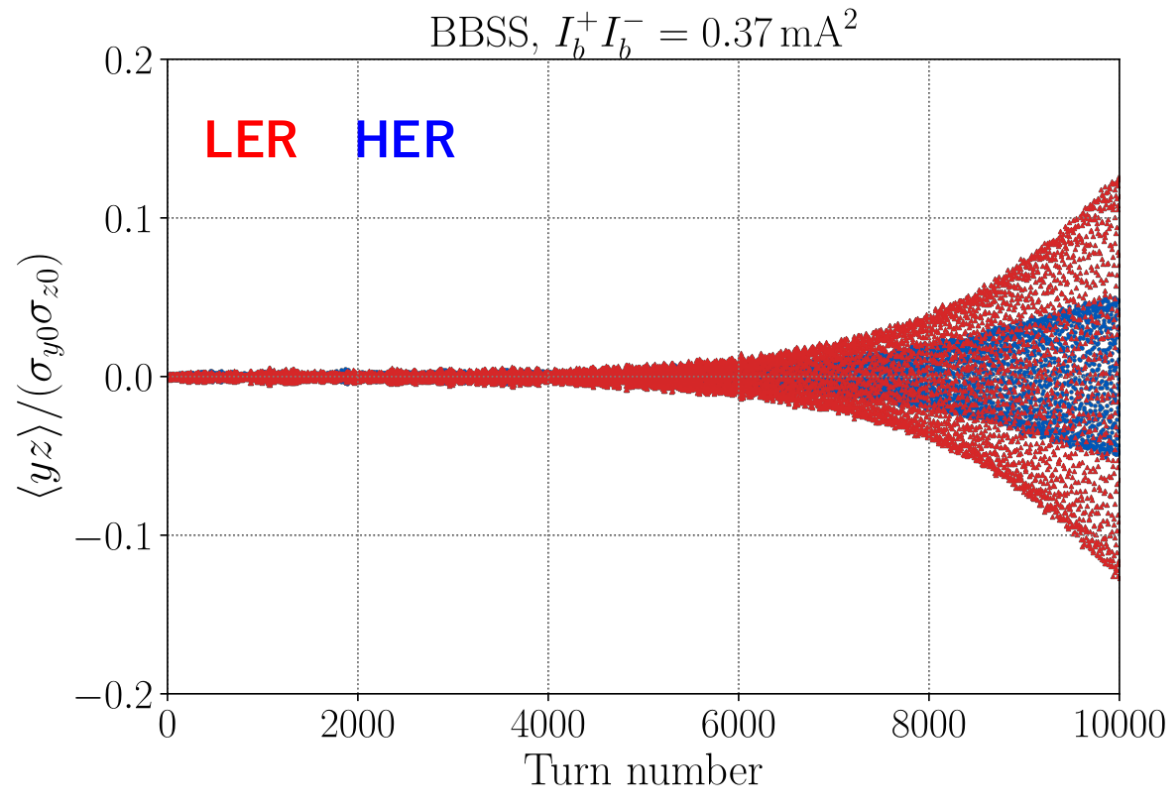


共同利用・共同研究拠点
「先端学際計算科学共同研究拠点」(文部科学省)
Advanced Interdisciplinary Computational Science
Collaboration Initiative (the MEXT of Japan)

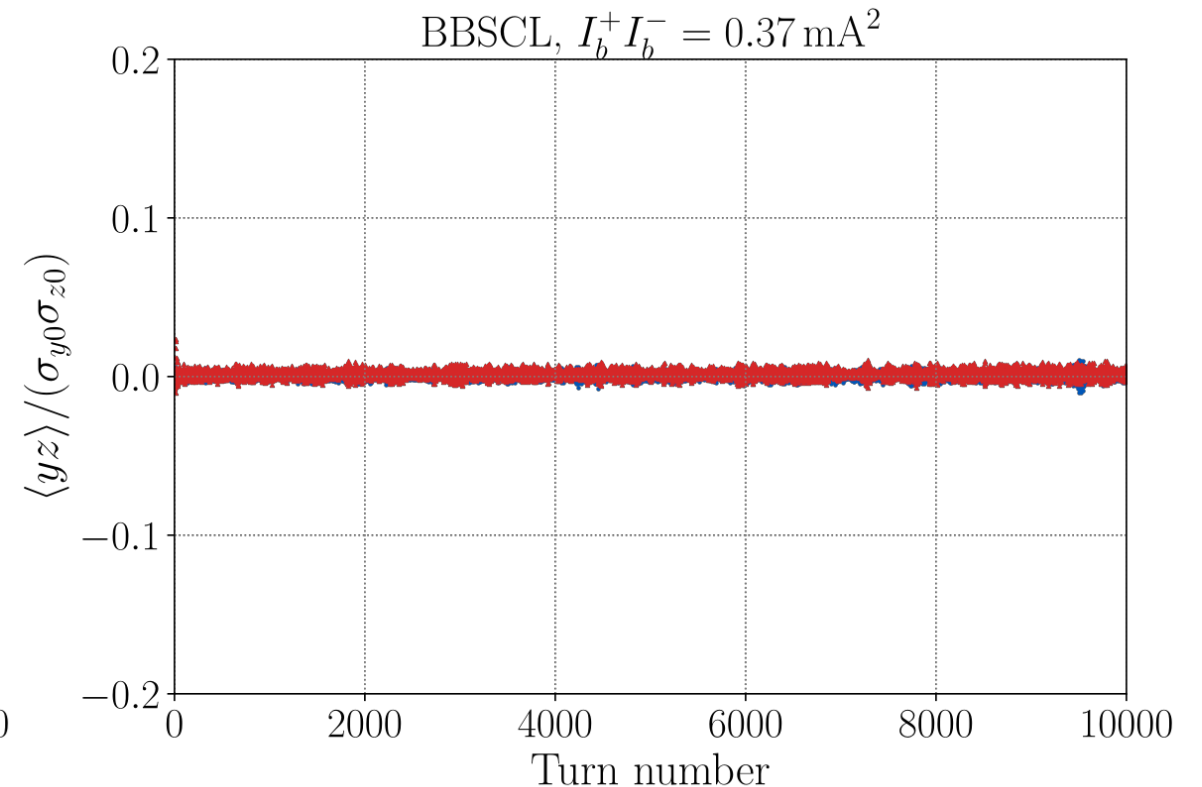
Effect of Lattice Tracking on Beam Motion

- At 0.37 mA^2 , BBSCl remains stable over 10^4 turns while BBSS shows growing $\langle yz \rangle$ motion.
- Lattice tune spread may reduce the growth rate. The mechanism is still under study.
- Other moments respond differently: $\langle xy \rangle$ oscillations are larger in BBSCl.

BBSS: one-turn linear map



BBSCl: element-by-element tracking

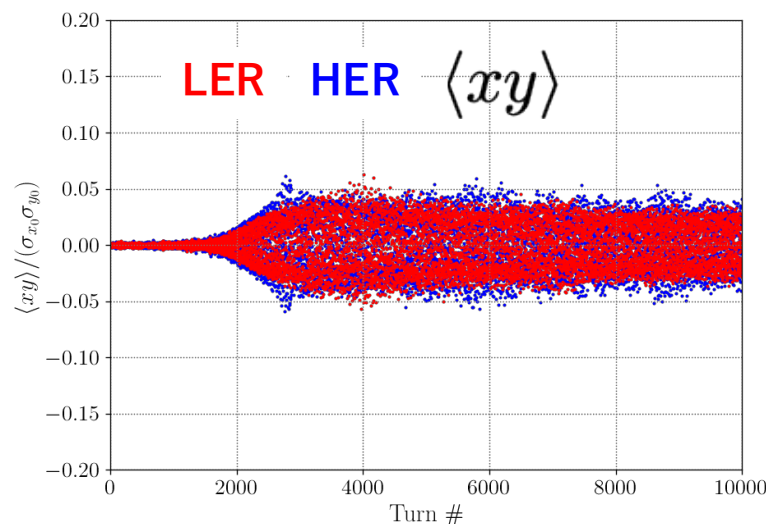


$$I_b^+ I_b^- = 1.00 \text{ mA}^2$$

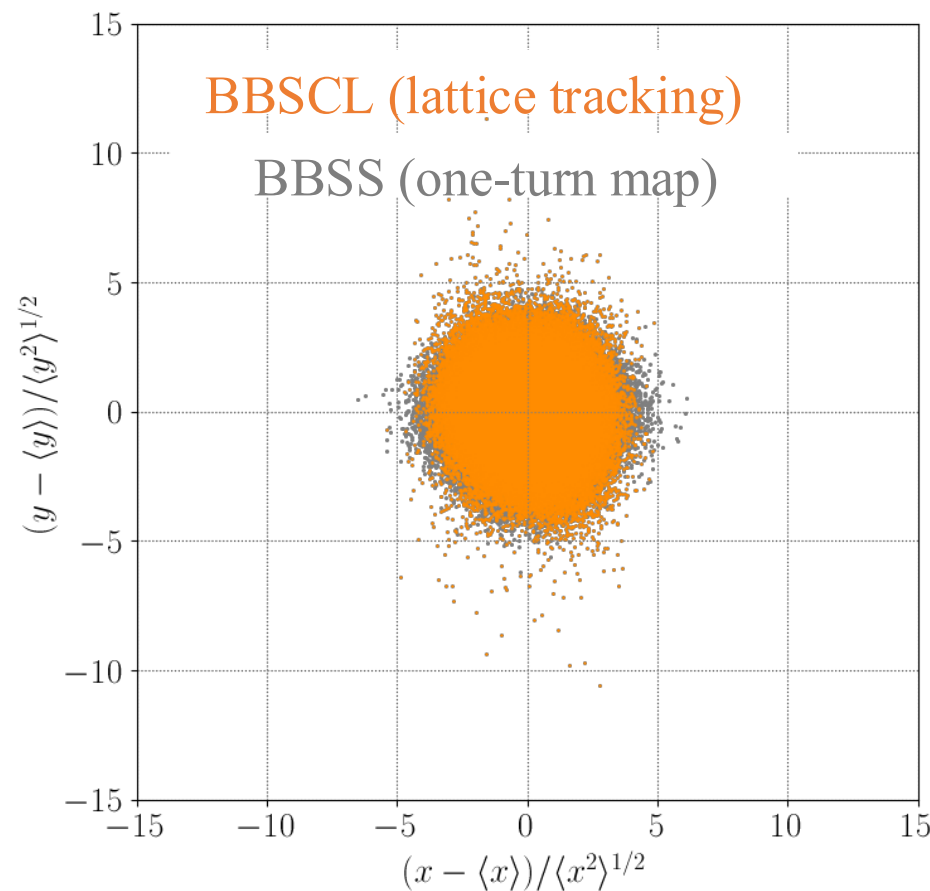
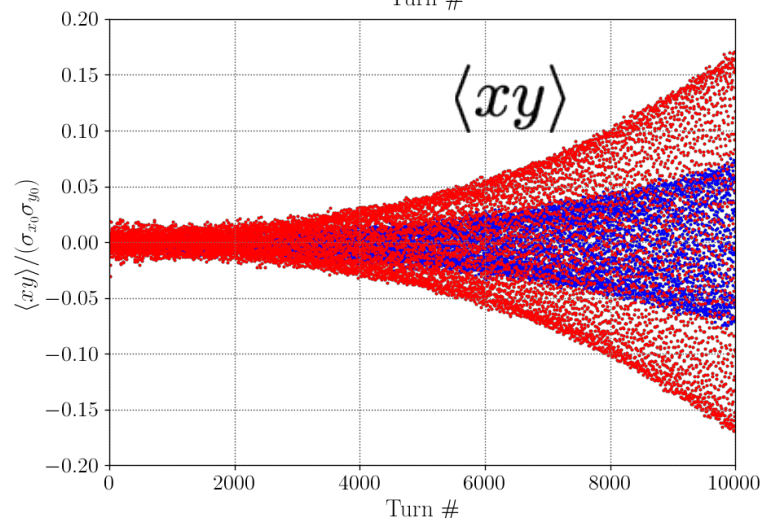
BBSCL-BBSS Comparison: $\langle xy \rangle$ Motion

- BBSCL shows larger $\langle xy \rangle$ oscillations than BBSS, despite smaller $\langle yz \rangle$ oscillations.
- The larger $\langle xy \rangle$ oscillations may arise from linear and nonlinear x-y coupling in the IR lattice.

BBSS



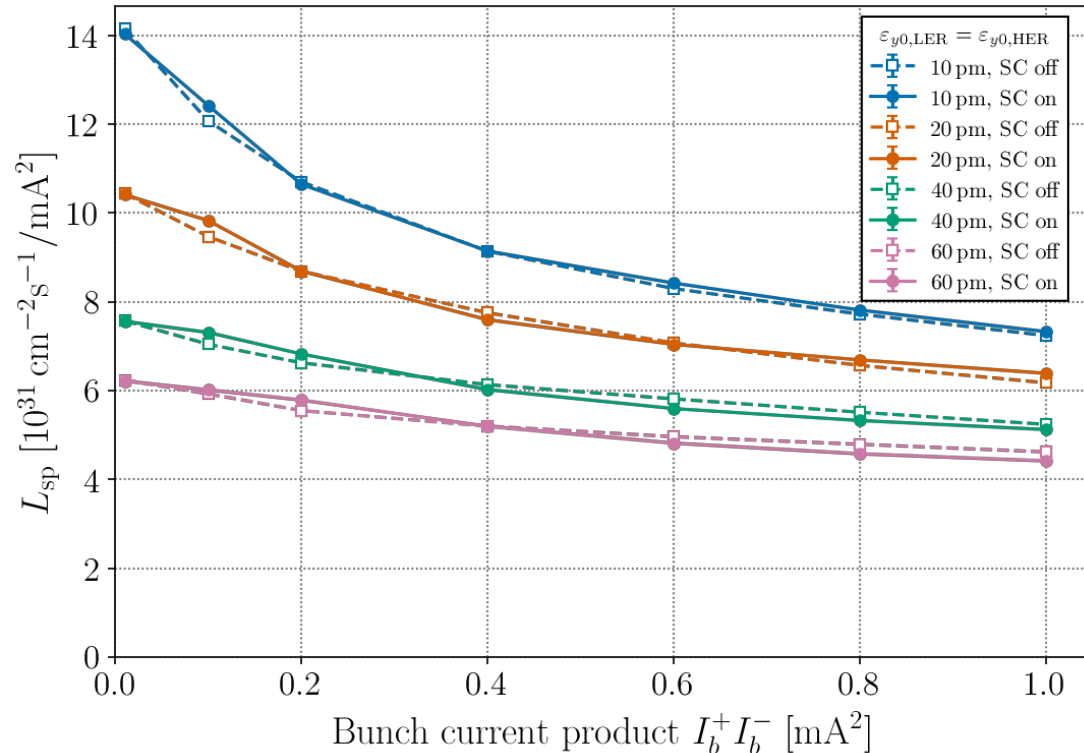
BBSCL



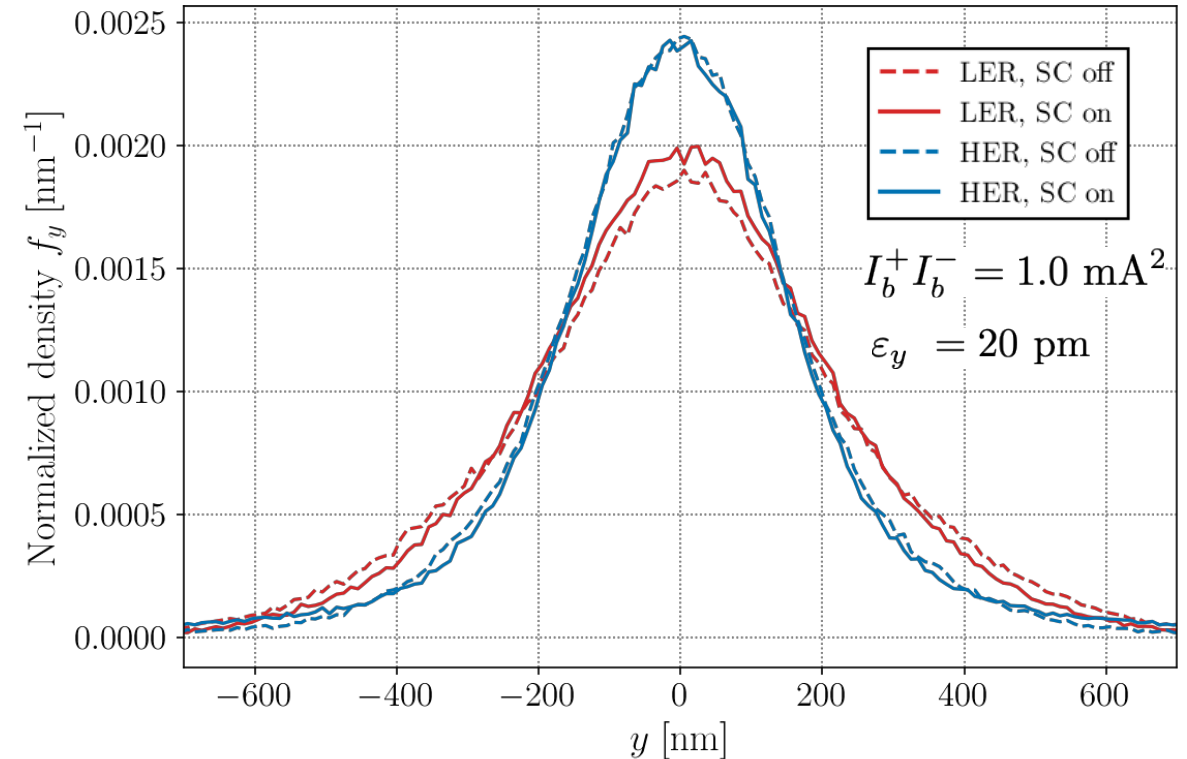
Space Charge: Luminosity and Particle Distributions

- Full-lattice BBSCL with wakes. Sliced PIC / FFT kicks distributed around both rings.
- Modest Lsp changes so far: -4.4% to $+3.5\%$ at 1.0 mA^2 in the tested cases.
- No extensive systematic study yet.
- Adding SC increases runtime by about 50%.

Specific Luminosity



Particle distribution

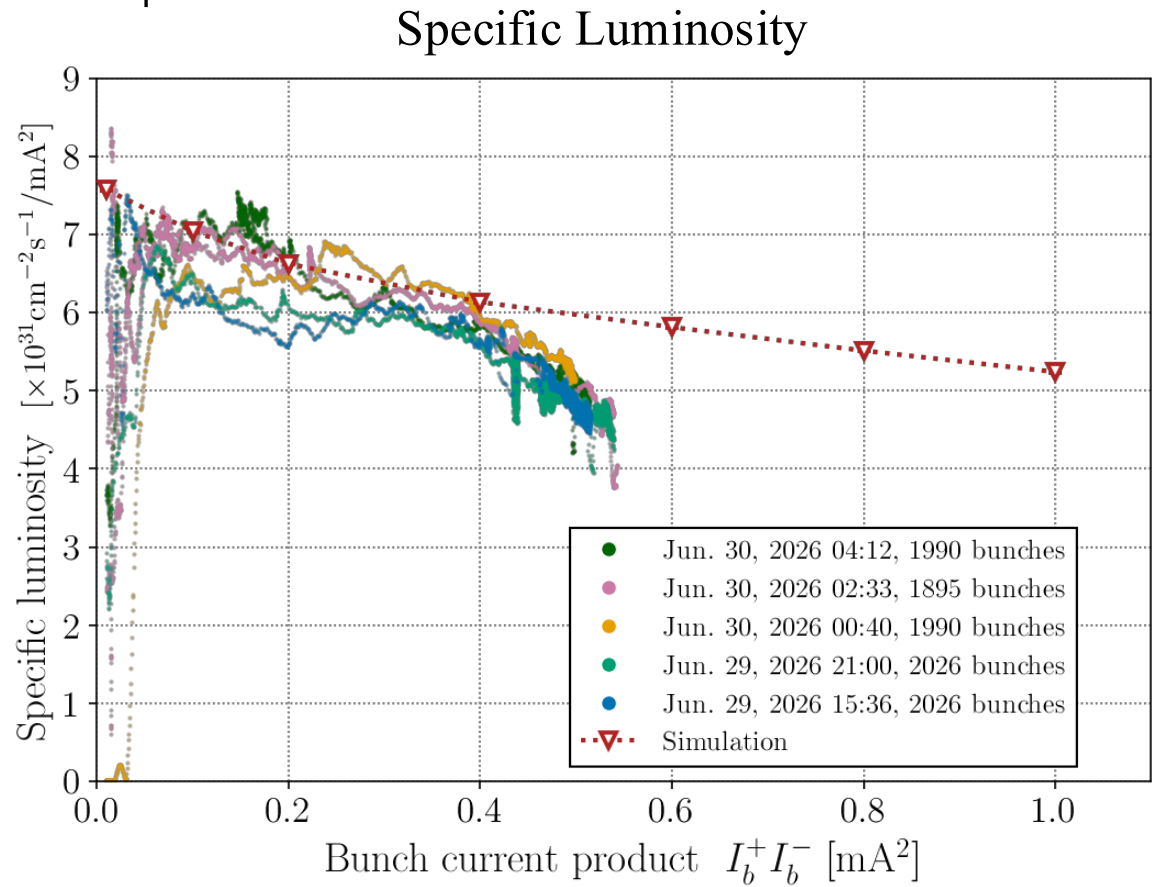


Comparison with Measurements in 2026ab

- 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

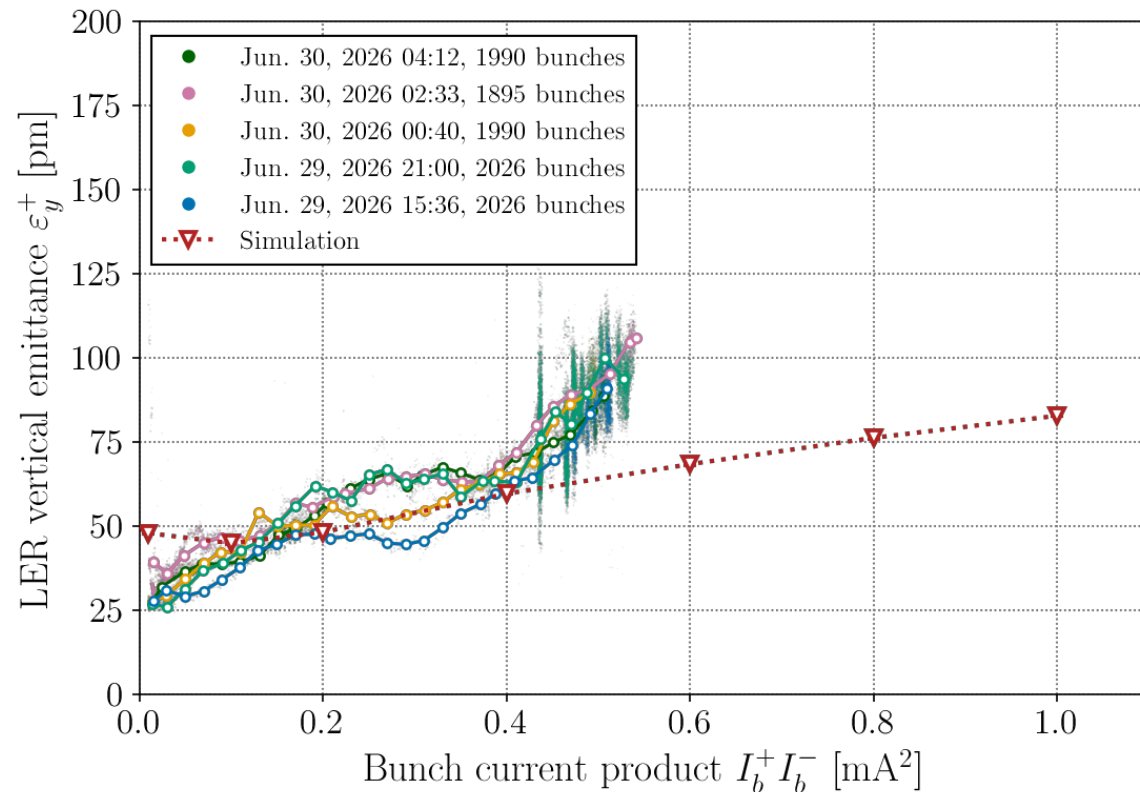
Parameters	LER (e ⁺)	HER (e ⁻)	Units
I_b	I_b^+ (variable)	$I_b^- = 0.75 \times I_b^+$	mA
ε_x	4.05	4.43	nm
ε_y	40	40	pm
(β_x^*, β_y^*)	(55, 0.9)	(55, 0.9)	mm
(ν_x, ν_y)	(44.537, 46.584)	(45.531, 43.607)	
ν_z	0.0237	0.0272	
σ_z	4.6	5.1	mm
(τ_x, τ_y, τ_z)	(53.0, 53.0, 26.5)	(58.0, 58.0, 29.0)	ms
CW ratio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



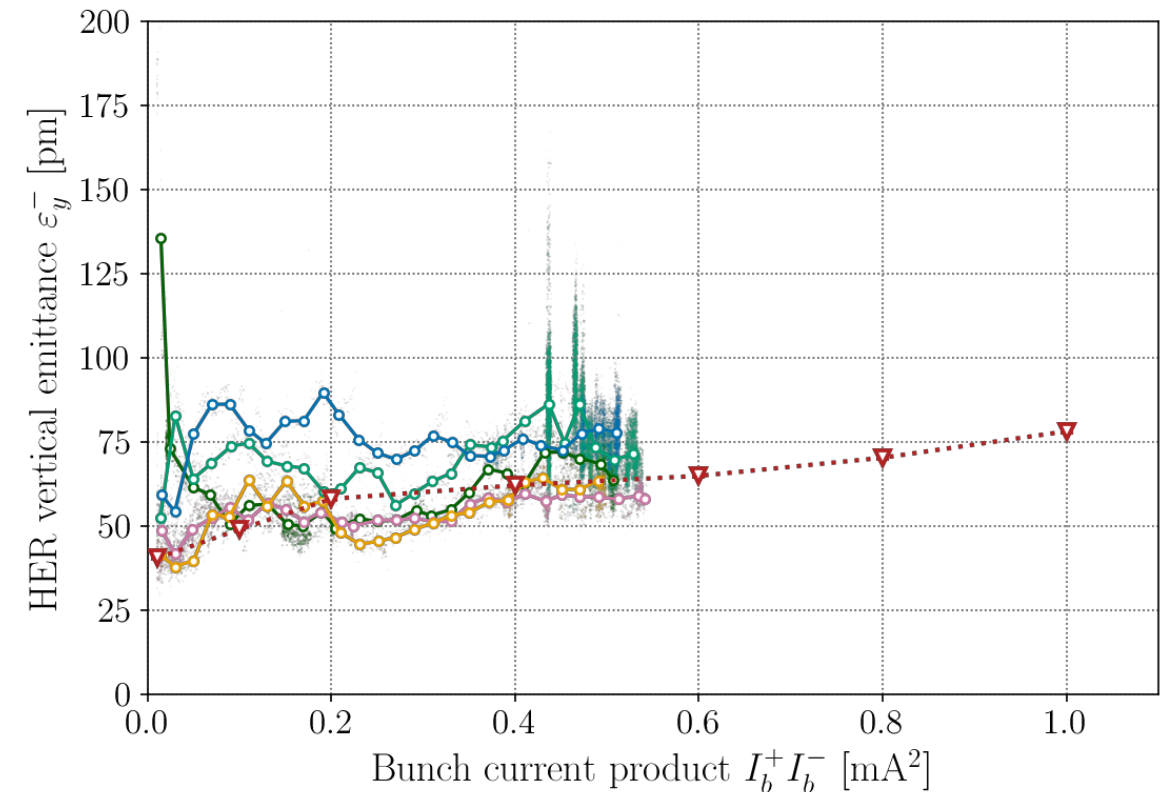
Vertical Emittance: Measurements and Simulation

- 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 many-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.

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.

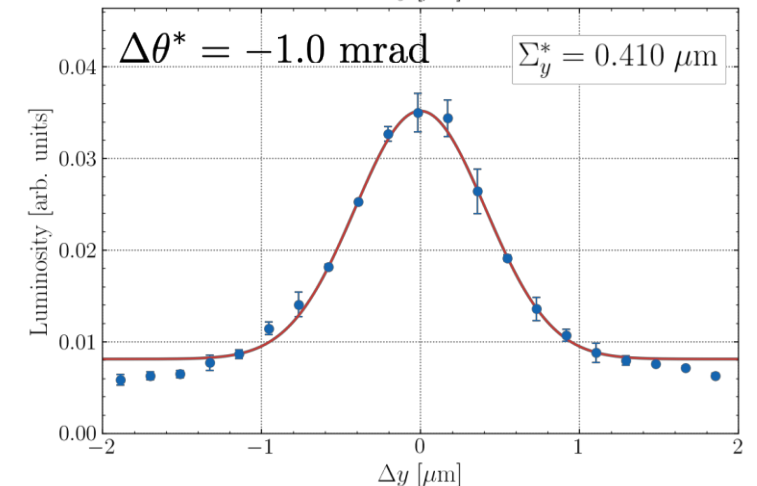
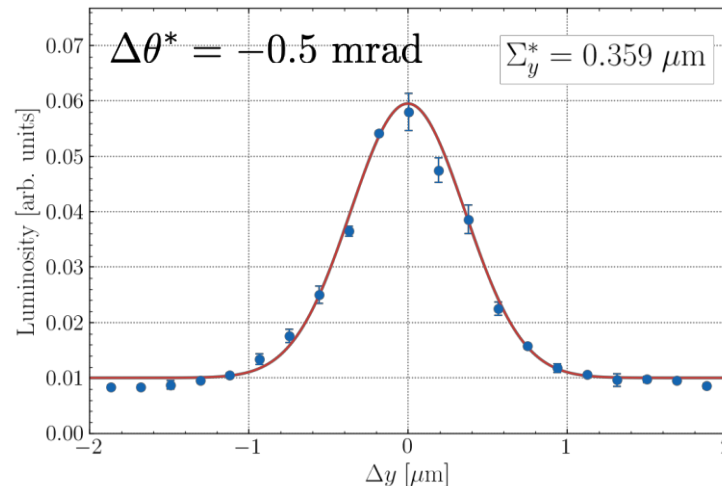
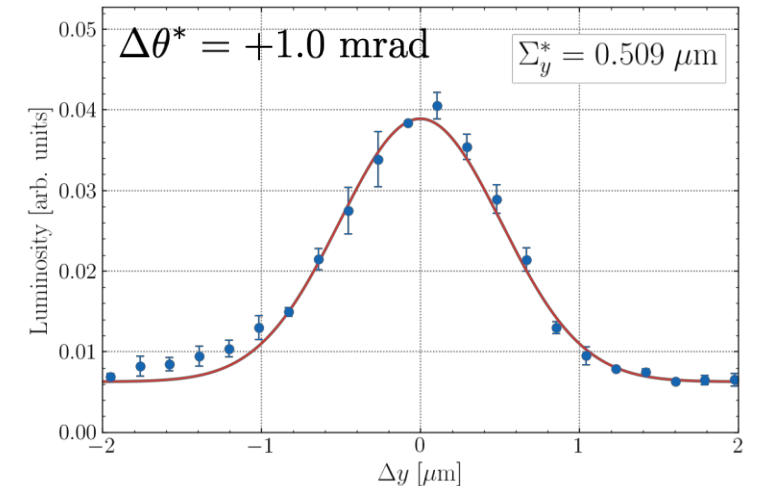
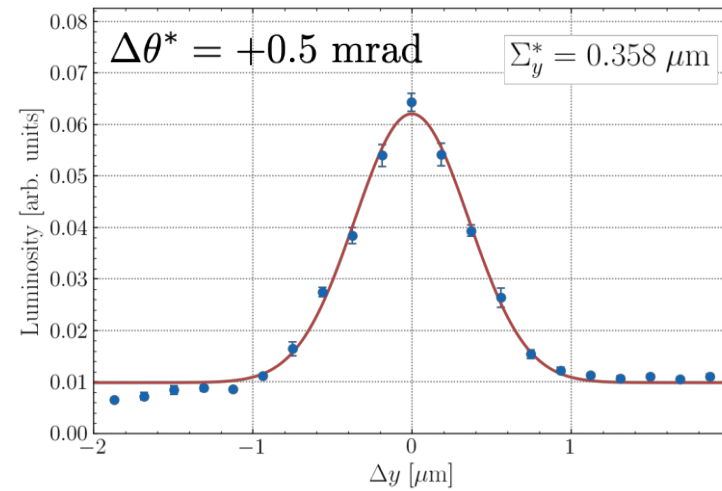
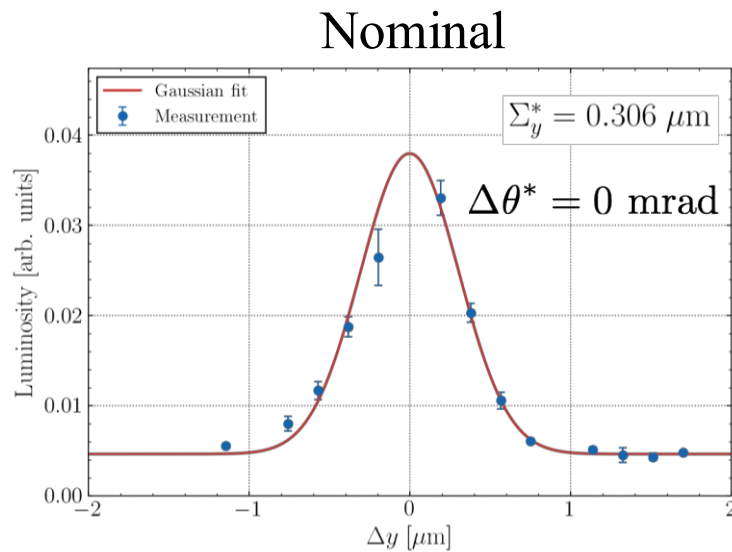
Continuing research

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

Appendix

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

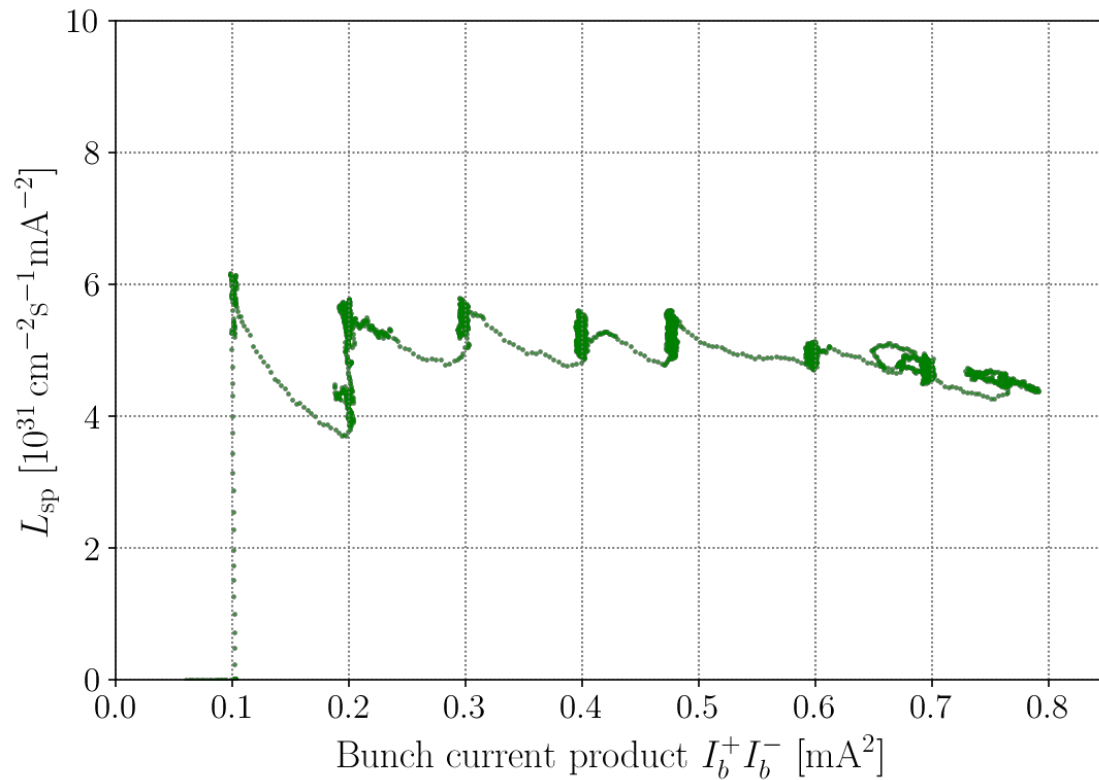
- We scanned the LER vertical angle at the IP while keeping the HER orbit fixed.
- We corrected the optics at each angle setting, particularly the vertical dispersion.



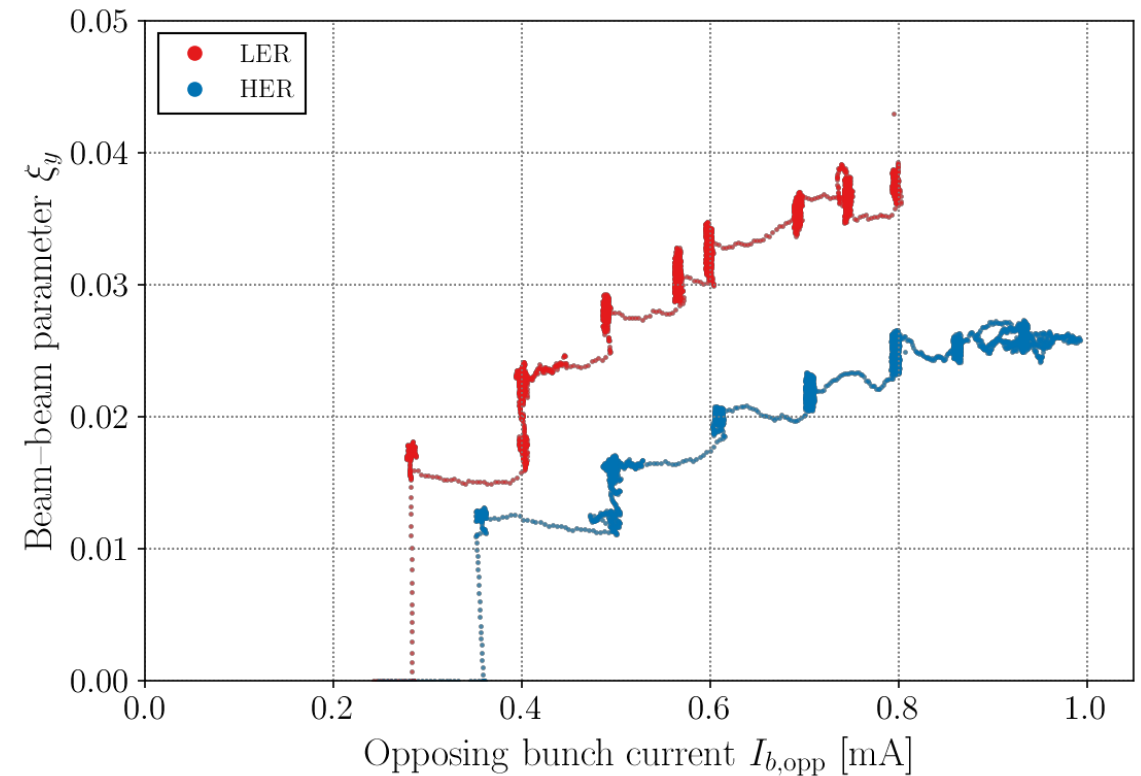
High Bunch Current Collision Study

- 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.

Specific Luminosity



Beam-beam Parameter



Beam-Beam Simulation Models

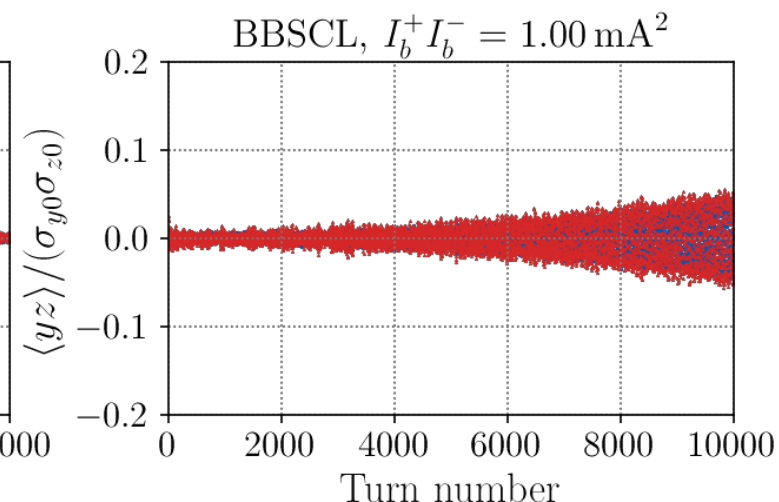
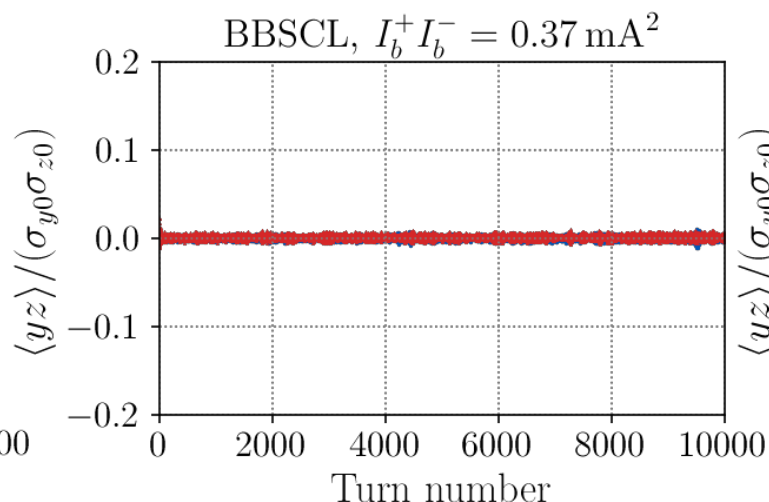
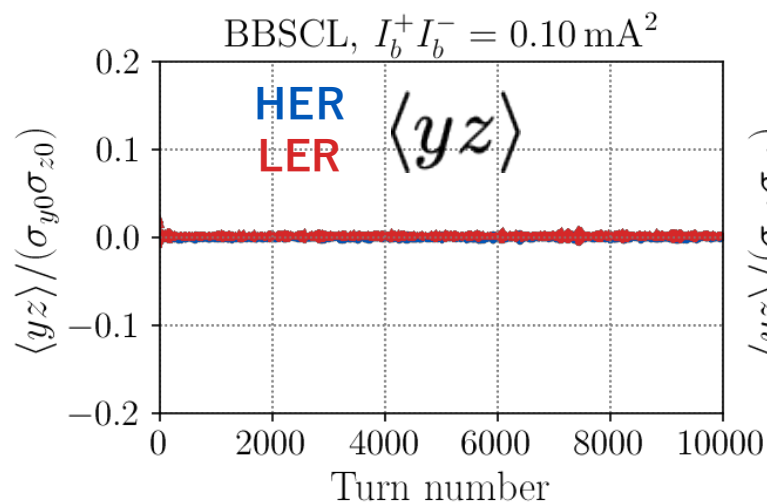
Item	BBWS	BBSS	BBACL
Beam-beam dynamics			
Model	Weak-Strong	Strong-Strong	Strong-Strong
Field solver	Fixed opposing distribution	Soft-Gaussian / PIC	Soft-Gaussian / PIC
Machine model			
Ring transport	Element-by-element in SAD	One-turn / section maps	Element-by-element on GPU
Nonlinear / chromatic effects	Individual lattice elements	Map terms	Individual lattice elements
Collective effects			
Short-range wakefields	SAD WakeFunction	Implemented	Implemented on GPU
Space charge	WSPAC Gaussian Weak-Strong	No dedicated ring model	PIC model on GPU

- These codes were originally developed by K. Ohmi.
- I recently joined their development, focusing on SuperKEKB applications.

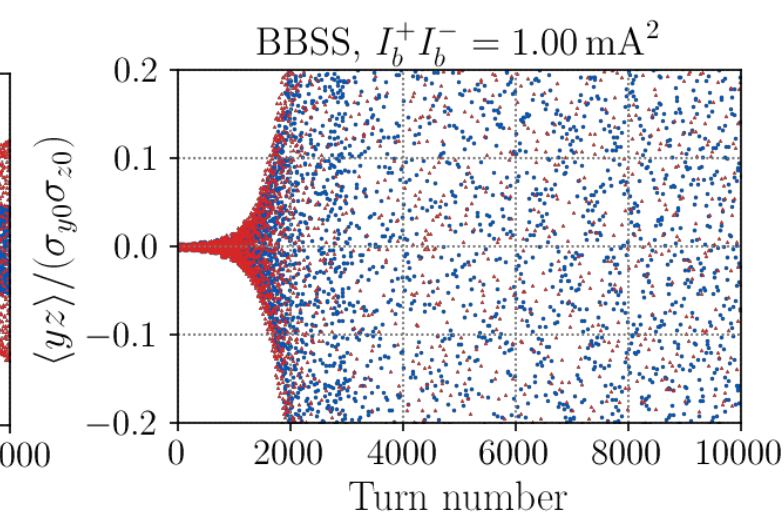
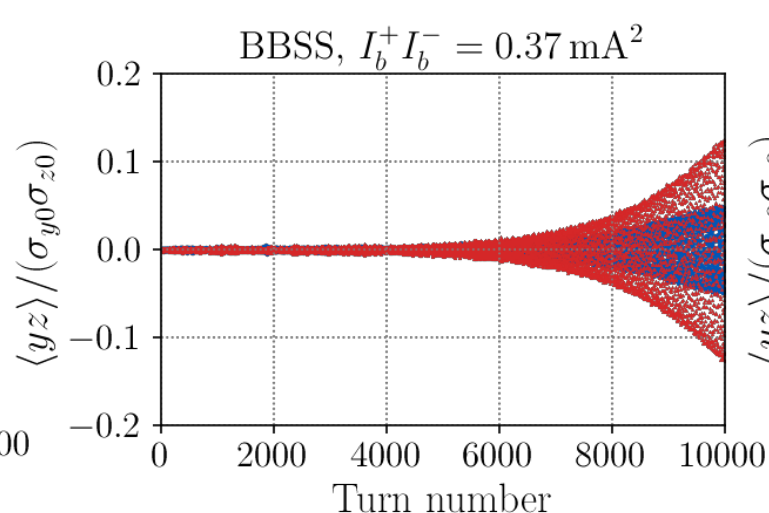
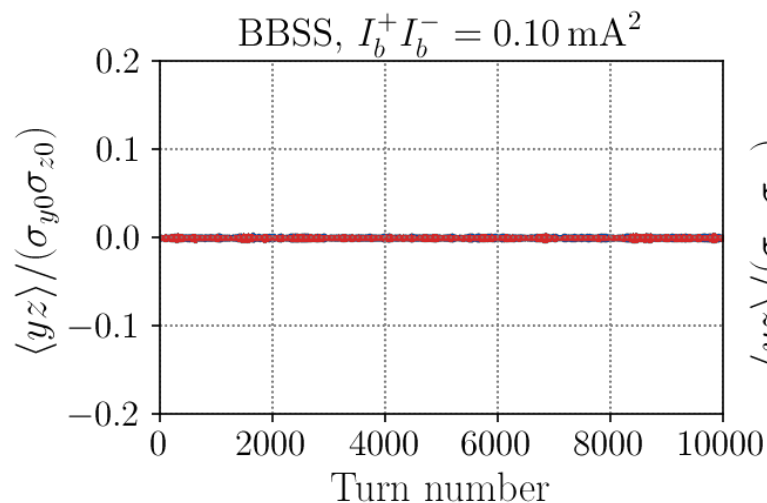
Example: Comparison of BBSCL and BBSS

- BBSS is unstable at a bunch-current product of 0.37 mA^2 ; BBSCL remains stable over 10^4 turns.
- Tune spread from lattice nonlinearities and chromaticity may enhance phase mixing and reduce the growth rate.

Element-by-element tracking



One-turn linear map

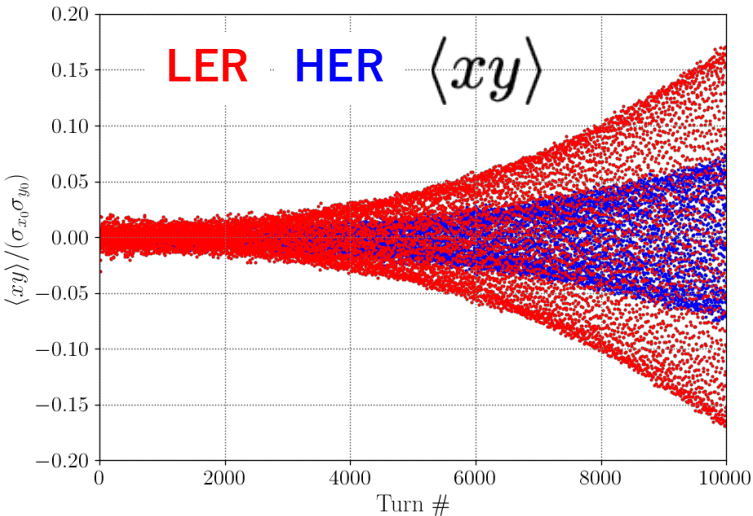


$$I_b^+ I_b^- = 1.00 \text{ mA}^2$$

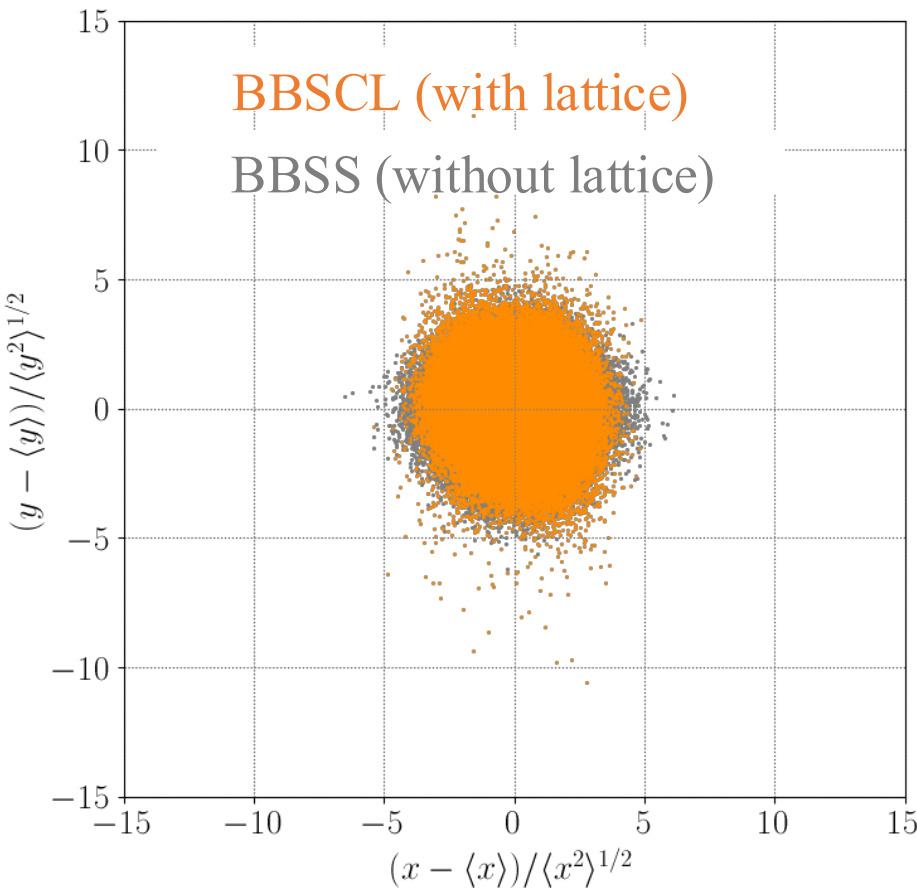
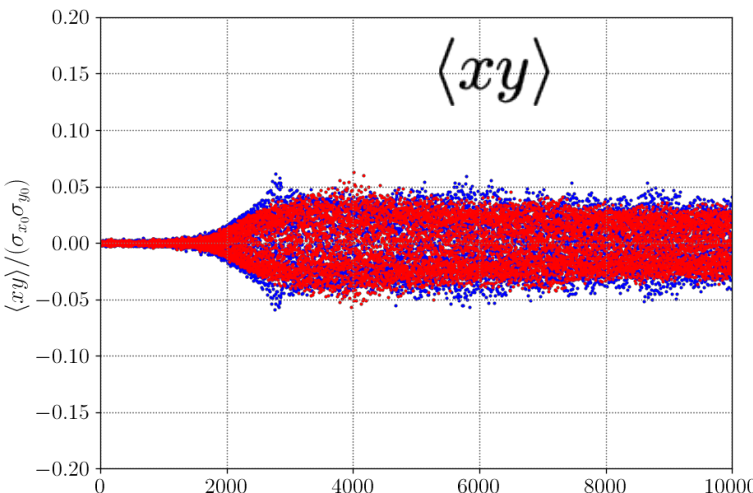
BBSCL–BBSS Comparison: $\langle xy \rangle$ Motion

- BBSCL shows larger $\langle xy \rangle$ oscillations than BBSS, despite smaller $\langle yz \rangle$ oscillations.
- The larger $\langle xy \rangle$ oscillations may arise from linear and nonlinear x–y coupling in the IR lattice.

BBSCL



BBSS



Plans and Proposals for 2027ab

Proposed studies, in order of priority

1. High bunch current

Compare quantities that do and do not depend on the number of bunches.

Investigate instabilities using turn-by-turn oscillation data.

2. Low-current and off-momentum scans

Compare widths from XRM, collision scans and luminosity.

Test for off-momentum optics distortions at the IP by changing the RF frequency.

3. Common IP position and angle

Probe collision sensitivity while keeping the relative LER–HER geometry fixed.

Supporting activities

BxB feedback: provide more staff for tuning and study support.

Consider regular measurements of single-beam sizes and pilot-bunch tune shifts.

Continue simulation development and benchmark with Xsuite / BeamBeam3D.

Investigate chromatic x–y coupling correction using rotatable sextupoles.

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 βy^* values. However, reducing βy^* 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.