



IHEP-KEK collaboration on SuperKEKB beam-beam studies

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IHEP

Many thanks to:

J. Gao, Y. Funakoshi, K. Ohmi

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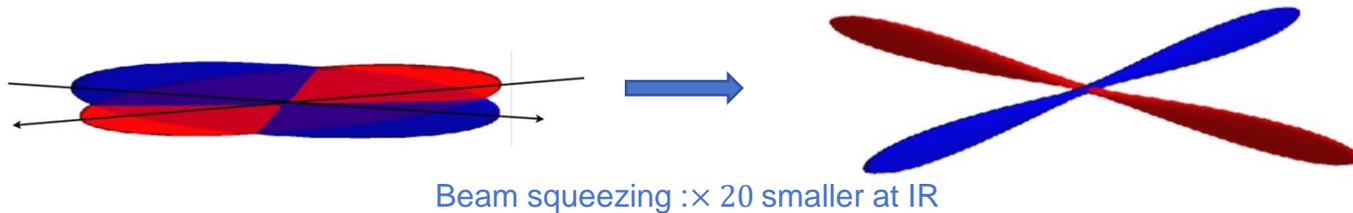
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Introduction-SuperKEKB

Future circular electron–positron colliders—such as the CEPC and FCC—commonly adopt a large crossing-angle "crab waist" collision scheme, with SuperKEKB serving as a prime example.

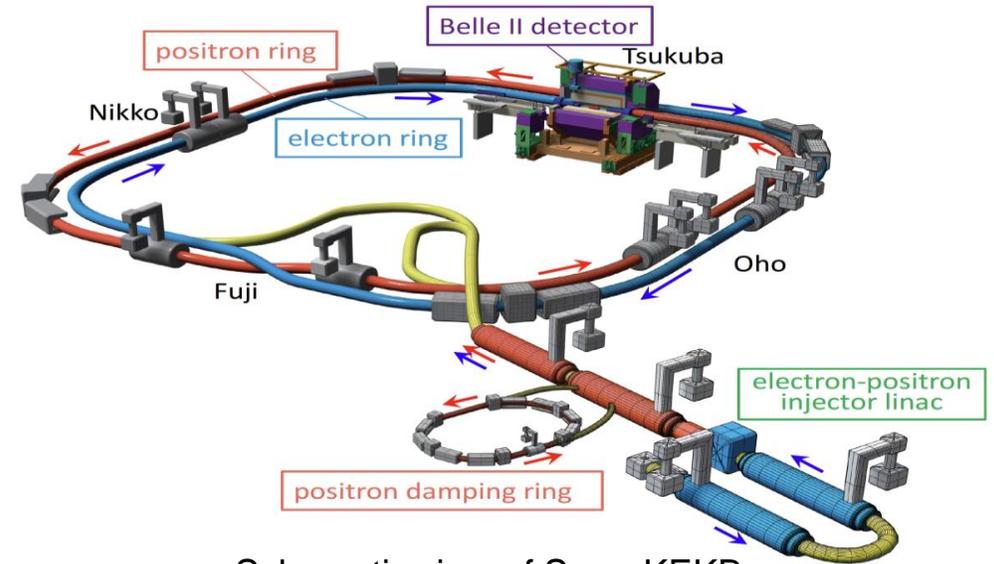
SuperKEKB uses a nano-beam scheme with superconducting final focus magnets, reducing the vertical beam size at the IP to 1/20 of KEKB's. Its design luminosity is $8 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$, 40× higher than KEKB's record.

However, in actual operation, SuperKEKB faces significant challenges that severely limit its performance. As of December 27, 2024, the achieved peak luminosity was $5.11 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ —still far below the design goal. This luminosity was obtained with beam currents only at half of the design intensity. Reaching the target luminosity will require extensive and prolonged commissioning efforts.



KEKB crab crossing: small angle,
high beam-beam parameter

SuperKEKB nano-beam scheme:
large angle, low emittance, low beta



Schematic view of SuperKEKB
<https://arxiv.org/pdf/1809.01958>

Machine parameters

	SuperKEKB: Dec.27, 2024		SuperKEKB: Design		Unit
Ring	LER	HER	LER	HER	
Crossing angle (ϕ_c)	+/- 41.5		+/- 41.5		mrad
Beam energy	4.0	7.0	4.0	7.0	GeV
Beam current	1632	1259	3600	2600	mA
# of bunches	2346		2500		
IP ver. Cap sigma (Σ_v^{*1})	0.375		0.0788		μm
Betatron tunes (ν_x/ν_y)	44.525/46.589	45.531/43.599	44.53/46.57	45.53/43.57	
β_x^*/β_y^*	60/1.0	60/1.0	32/0.27	25/0.30	mm
Crab waist ratio	80	60	0	0	%
Beam-Beam parameters ξ_y	0.036	0.027	0.0881	0.0807	
Luminosity	5.11×10^{34}		8.0×10^{35}		$\text{cm}^{-2}\text{s}^{-1}$

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

Limiting factors to luminosity:

- Total beam currents (I_{\pm})
- Vertical beta function at IP ($\beta_{y\pm}^*$)
- Vertical beam-beam parameters ($\xi_{y\pm}$)



- LER beam injection largely affected by beam-beam interaction and betatron tunes
- Dynamic aperture is largely reduced by CW sextupoles
- Beam lifetime
- Vertical beam-beam blowup
- large vertical beta function
- Chromatic coupling for both two rings
- Manufacturing errors at IP in the HER beamline
- ...

HER ring chromatic coupling

Simulation settings

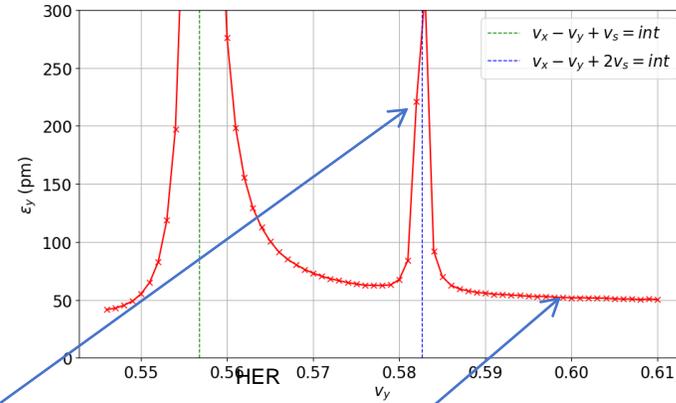
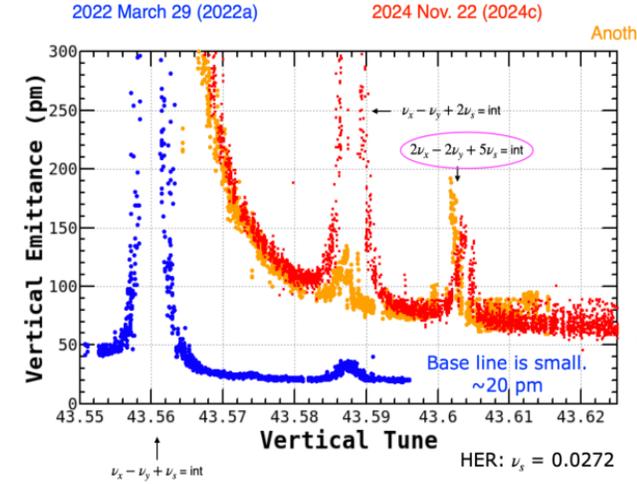
Simulation parameters are based on 2024 c run (Dec. 27, 2024) in which peak luminosity was achieved. Gaussian based beam-beam strong-strong simulation to speed up the computation.

	LER	HER	unit
(v_x, v_y)	(0.525, 0.589)	(0.531, 0.599)	
ε_x	4.6	4.0	nm
ε_y	25	25	pm
σ_z	6.0 (5.0)	5.0	mm
σ_δ	7.5257E-4	6.3044E-4	
v_s	-0.0233	-0.0258	
CW	80	60	%
I_{bunch}	0.696 (I_{b+})	$I_{b-}=0.77*I_{b+}$	mA
(β_x^*, β_y^*)	(60,1)	(60,1)	mm

HER chromatic coupling reproduce

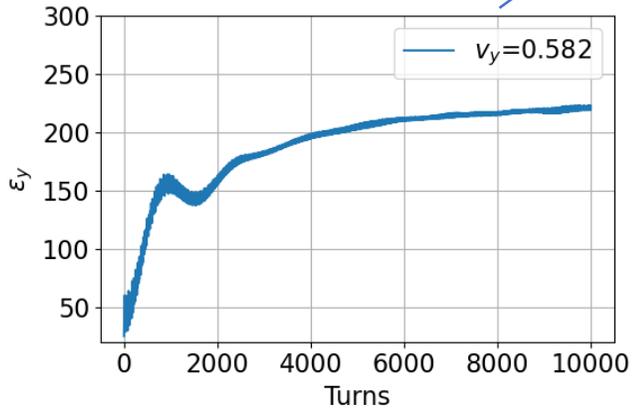
Y.Funakoshi, International collaboration meeting on beam-beam effects at SuperKEKB (1)

HER single beam emittance with chromatic coupling

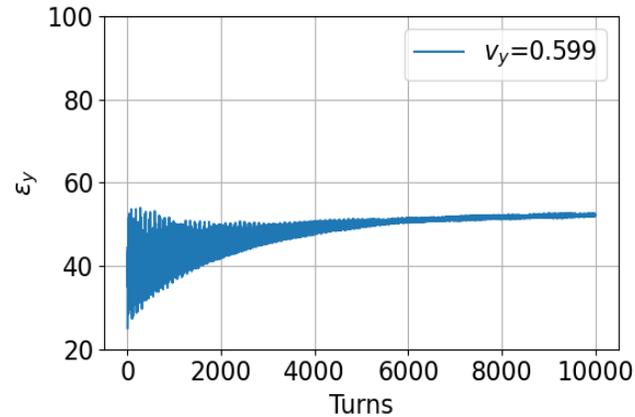


Without impedance

case 1: large emittance growth



case 2: small emittance growth



One-turn transfer map \mathbf{T} (four-dimensional) with chromatic coupling \mathbf{R} :

$$\mathbf{T} = \mathbf{R}^{-1}\mathbf{U}\mathbf{R}$$

$$\mathbf{U} = \begin{pmatrix} A & 0 \\ 0 & B \end{pmatrix}, \quad \mathbf{R} = \begin{pmatrix} bI & J_2 R_2^T J_2 \\ R_2 & bI \end{pmatrix}$$

$$b = \sqrt{1 - |R_2|}, \quad R_2 = \begin{pmatrix} r_{11} & r_{12} \\ r_{21} & r_{22} \end{pmatrix}, \quad J_2 = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

HER ring without collision, considering up to second order chromatic coupling, and only r_{11} is non-zero.

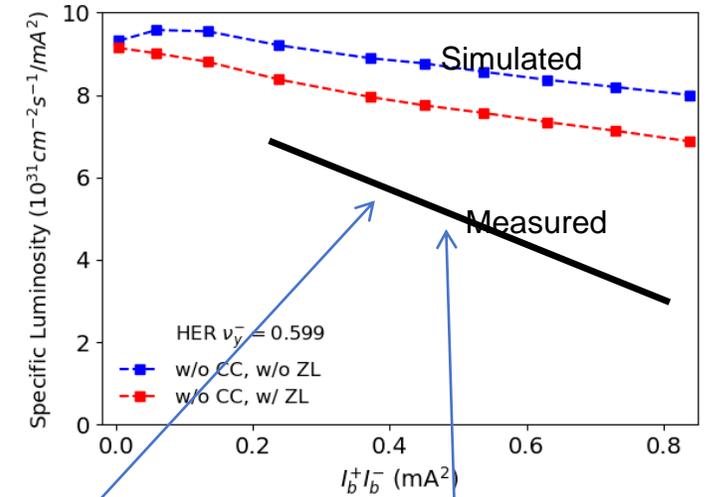
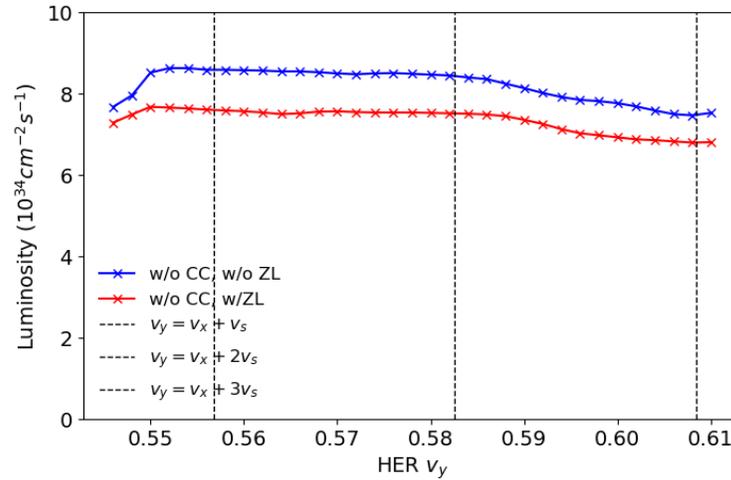
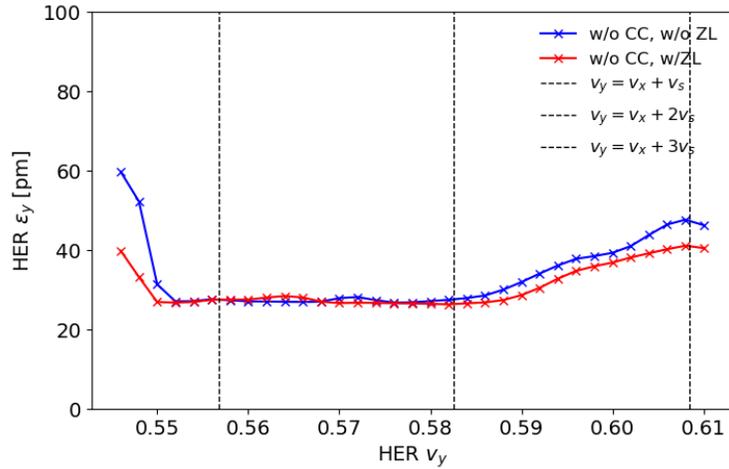
$$r_{11} = 0 + r'_{11}\delta + r''_{11}\delta^2$$

$$r'_{11} = 8 \quad r''_{11} = 1000$$

$$r_{12} = r_{21} = r_{22} = 0$$

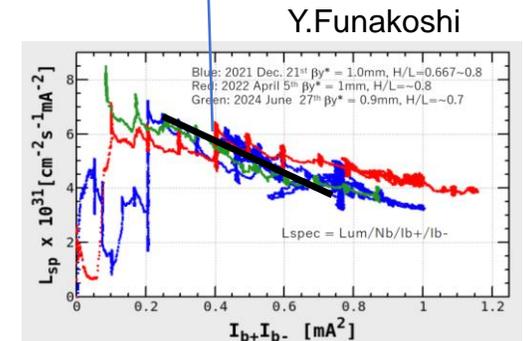
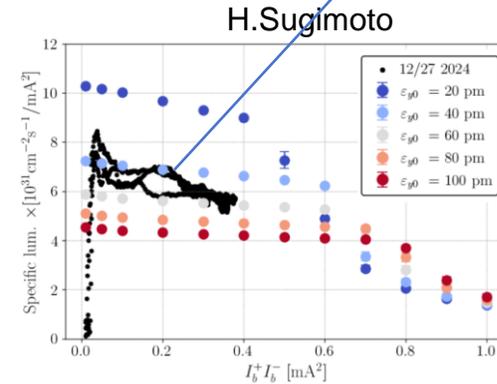
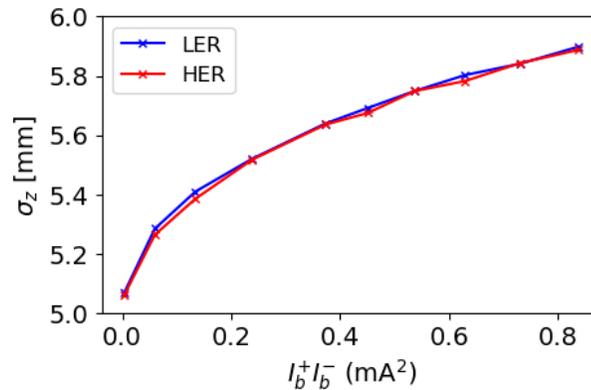
Longitudinal impedance

$$L_{sp} = \frac{L}{N_b I_{b+} I_{b-}}$$



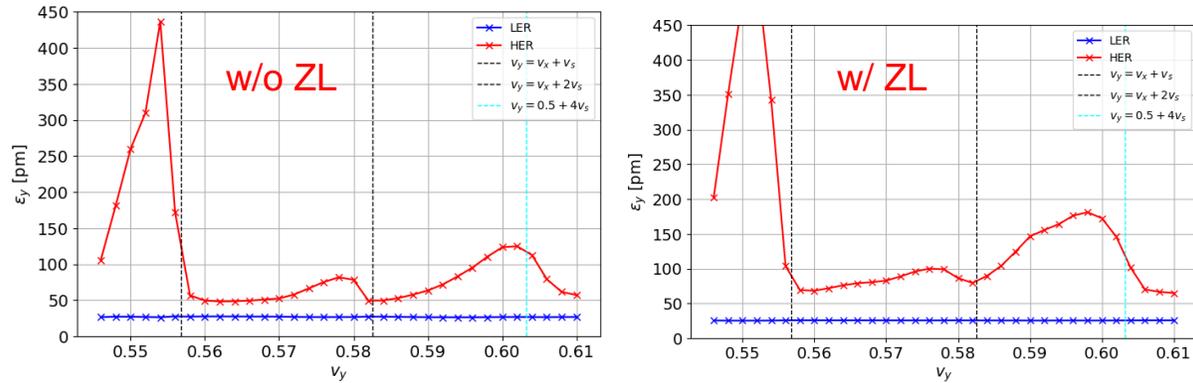
Luminosity degradation is caused by bunch lengthening due to longitudinal impedance. **However, the slope (decreasing rate) is smaller than that observed in measurements.**

$$L \propto \frac{N \xi_y}{\beta_y^*}, \quad \xi_y \propto \frac{N \sqrt{\beta_y / \epsilon_y}}{\sigma_z \theta}$$

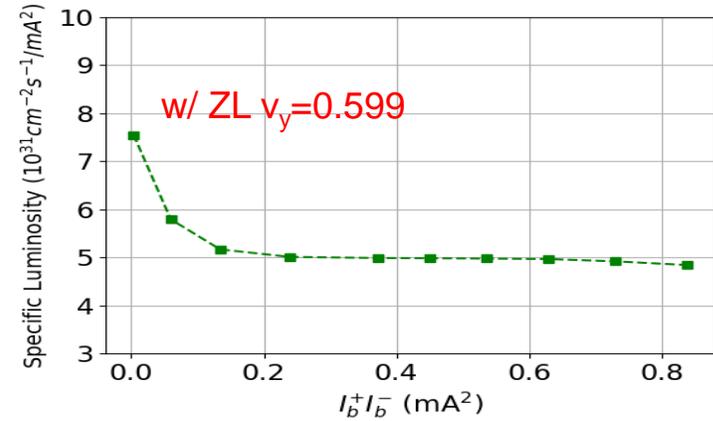


Measured vs. simulated luminosity

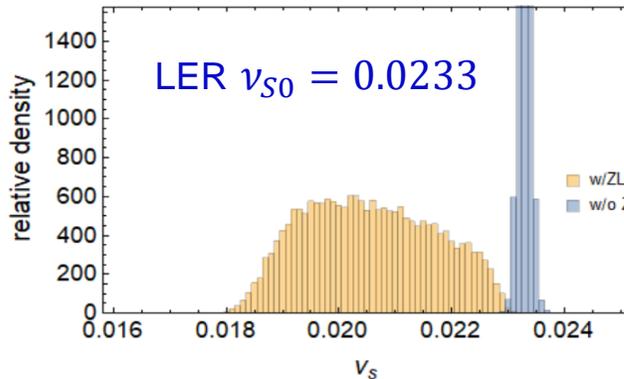
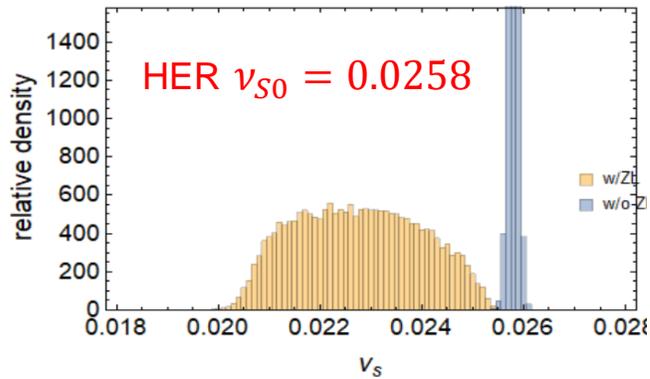
Effects of chromatic coupling



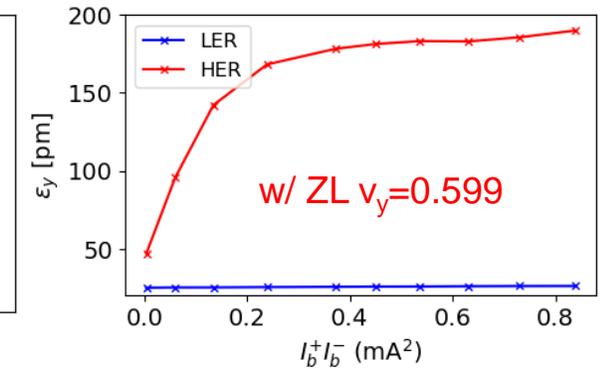
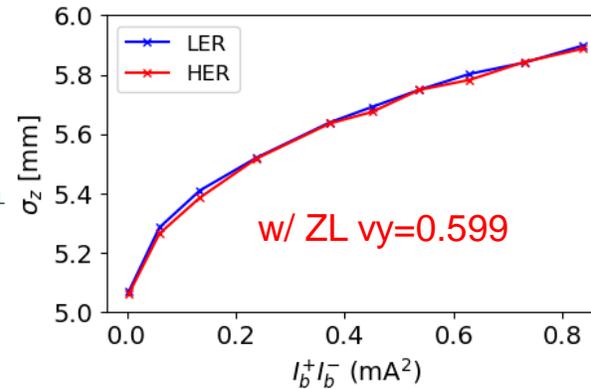
- ZL induces a shift in the emittance vs. working point curve. This shift can be attributed to a reduction in the synchrotron tune.
- The emittance near resonances increases significantly. One possible explanation is that synchrotron tune spread broadens the resonance lines.



Sp. luminosity is nearly independent of beam current when beam current exceeds 0.2, although bunch lengthening persists. This behavior is likely due to the saturation of vertical emittance growth.



ZL introduces an incoherent synchrotron tune spread. The central synchrotron tune of both rings is reduced by $\Delta\nu_s \approx 0.003$, resulting in a significant tune spread.

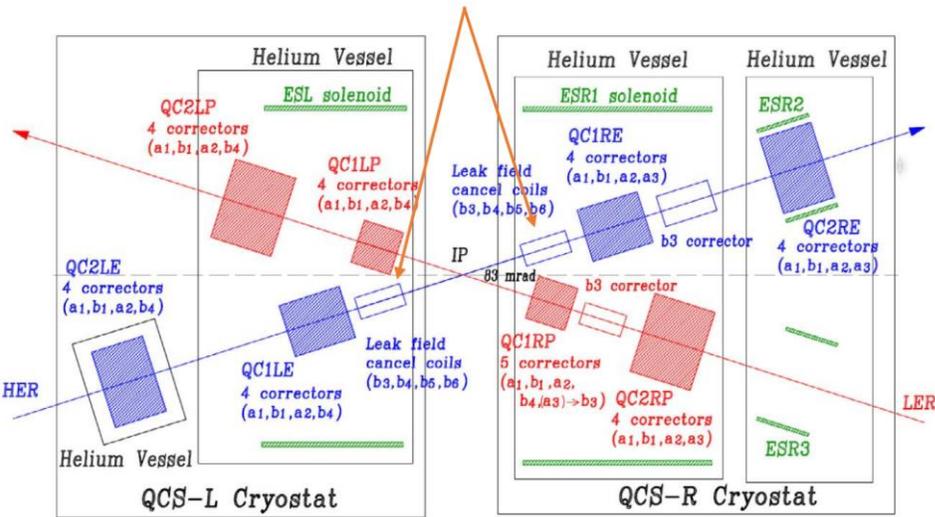


Simulations suggest that the chosen coupling coefficients may be too large.

HER cancel coil manufacturing errors

The cancellation coils used to compensate the QC1P leakage field in the HER beamline have manufacturing errors. These errors induce additional skew sextupole and skew octupole field components in the HER beamline, which can be approximated by an effective Hamiltonian H_{eff} at IP, with $H_{eff} = C p_y^3$ term contributing most significantly to luminosity degradation.

Leak Field Cancellation Coils



Errored effective-Hamiltonian for third-order nonlinear terms:

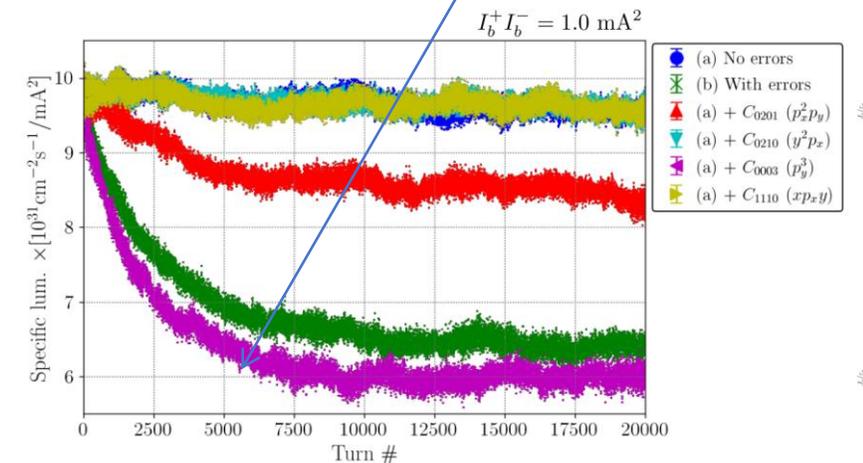
$$H_{eff} = \sum_{\substack{i,j,k,l \geq 0 \\ i+j+k+l=3}} C_{ijkl} \times x^i p_x^j y^k p_y^l$$

Nonlinear kick at IP from H_{eff}

$$M(ip)\mathbf{x} = e^{-:H_{eff}:}\mathbf{x}$$

Weak-Strong Simulation

- Individually insert nonlinear terms at the interaction point of an e
- Significant contributions from p_y^3 and $p_x^2 p_y$ is observed.



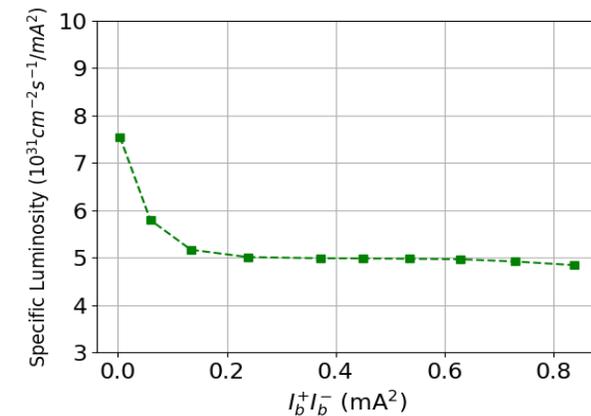
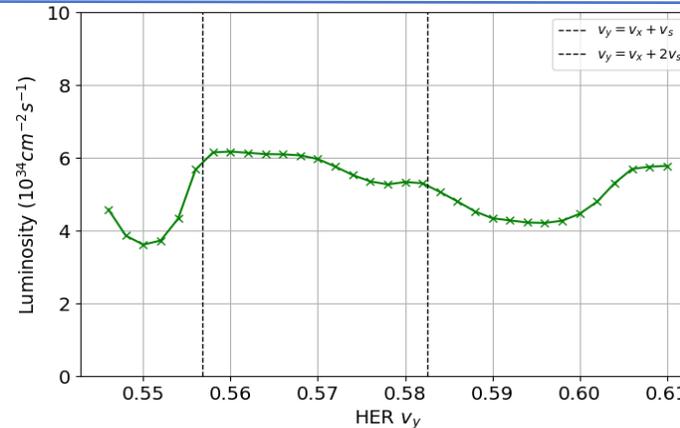
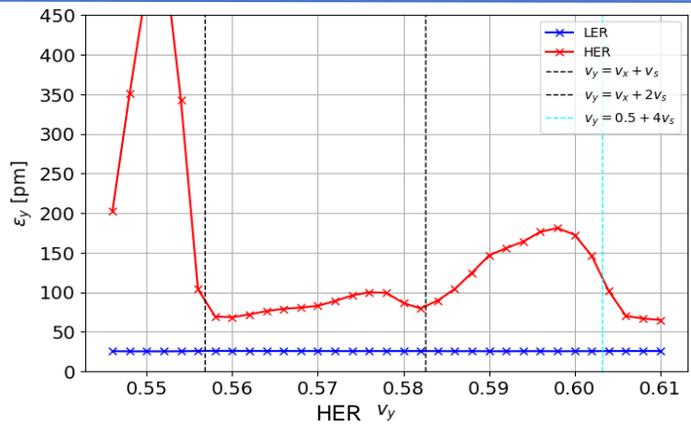
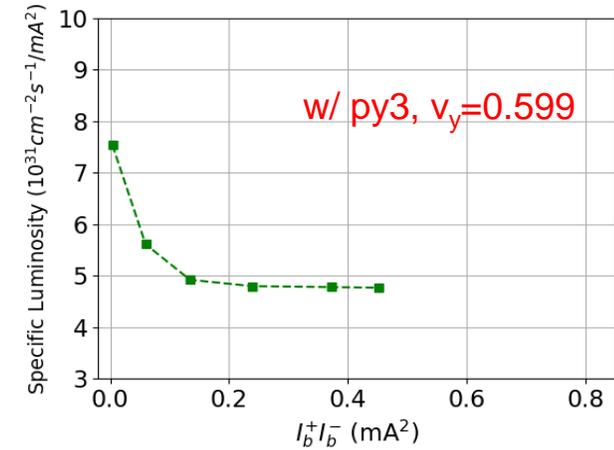
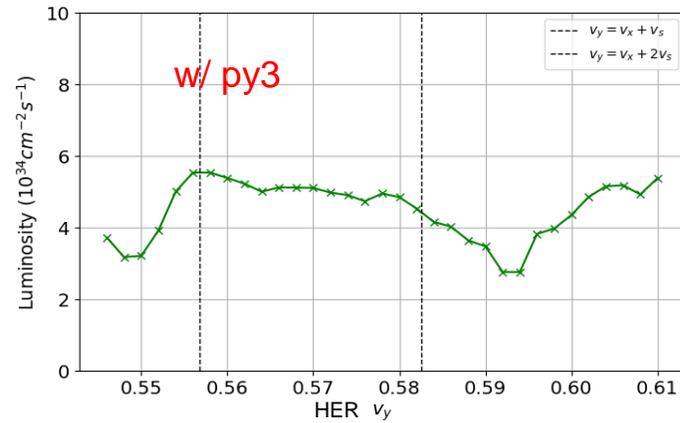
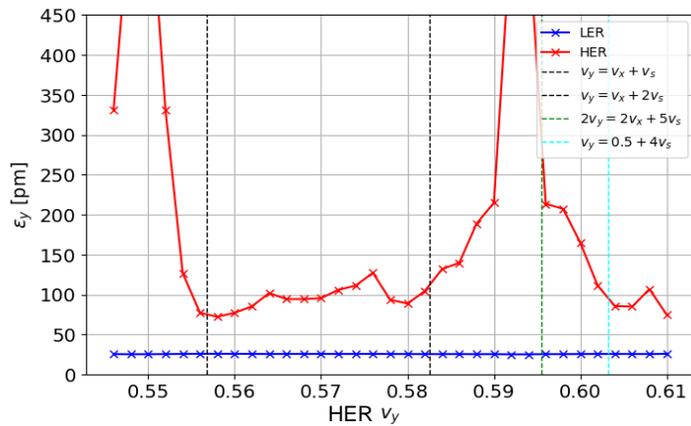
H.Sugimoto, 2025/4/28

International collaboration meeting on beam-beam effects at SuperKEKB (2)

The perturbation $H_{eff} = C p_y^3$ ($C = 0.06957$) is inserted at the IP for HER ring

Combination of cancel coil errors (py3) and chromatic coupling

LER $\nu_y=0.589$

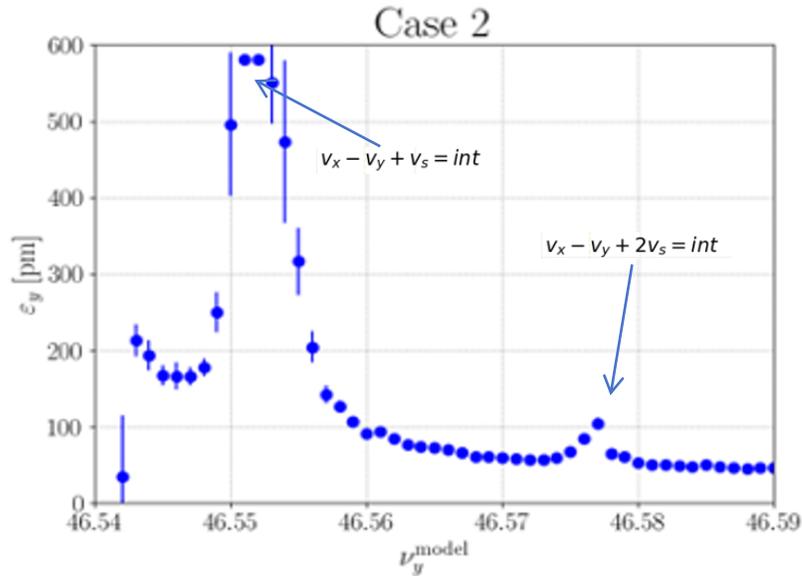


ν_y 3 shift the curve towards 0.5 slightly, and increase the vertical emittance. But if the vertical emittance is already very strong at a specific working tune, the specific luminosity see no significant differences with and without ν_y 3 error.

LER ring chromatic coupling

LER chromatic coupling

LER ring , no collision, w/ ZL and w/ ZT for different beam intensity.



Courtesy of Y.Funakosh. Measured LER emittance vs. tune at low beam intensity

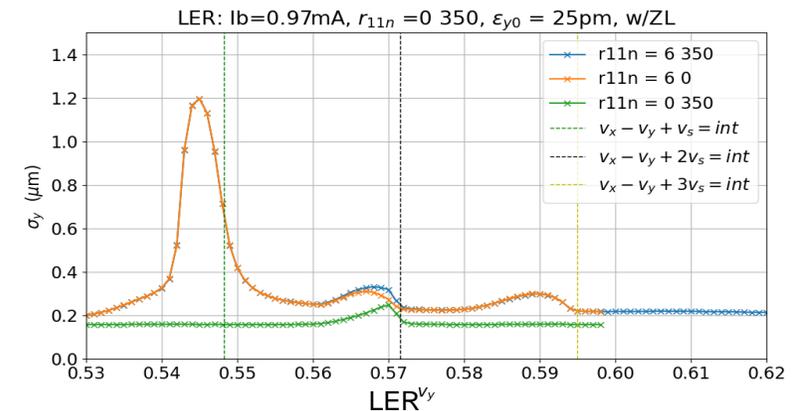
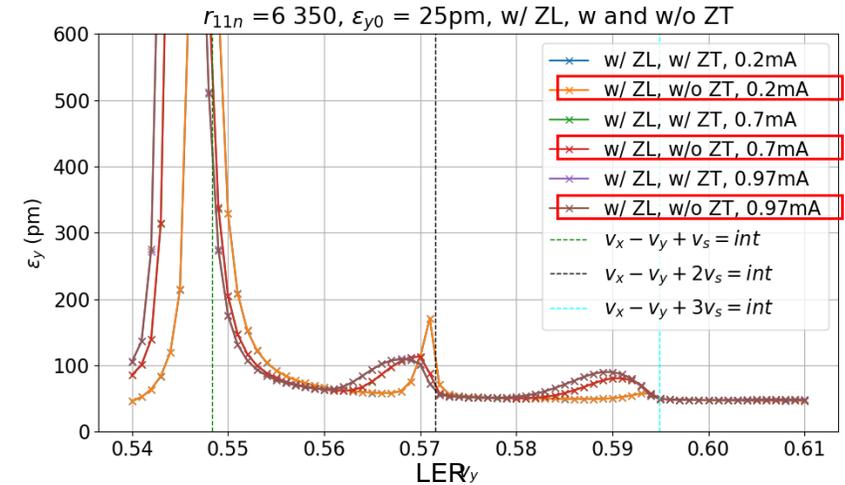
$$R = \begin{pmatrix} bI & J_2 R_2^t J_2 & 0 \\ R_2 & bI & 0 \\ 0 & 0 & I \end{pmatrix}$$

$$b = \sqrt{1 - |R_2|}, \quad R_2 = \begin{pmatrix} r_{11} & r_{12} \\ r_{21} & r_{22} \end{pmatrix}$$

$$r_{11} = 0 + r'_{11}\delta + r''_{11}\delta^2$$

$$r'_{11} = 6 \quad r''_{11} = 350$$

$$r_{12} = r_{21} = r_{22} = 0$$



ZL affects the emittance; as the beam current increases, third-order resonance appears, and no higher-order resonances exist.

ZT has almost no effect (even at high beam currents).

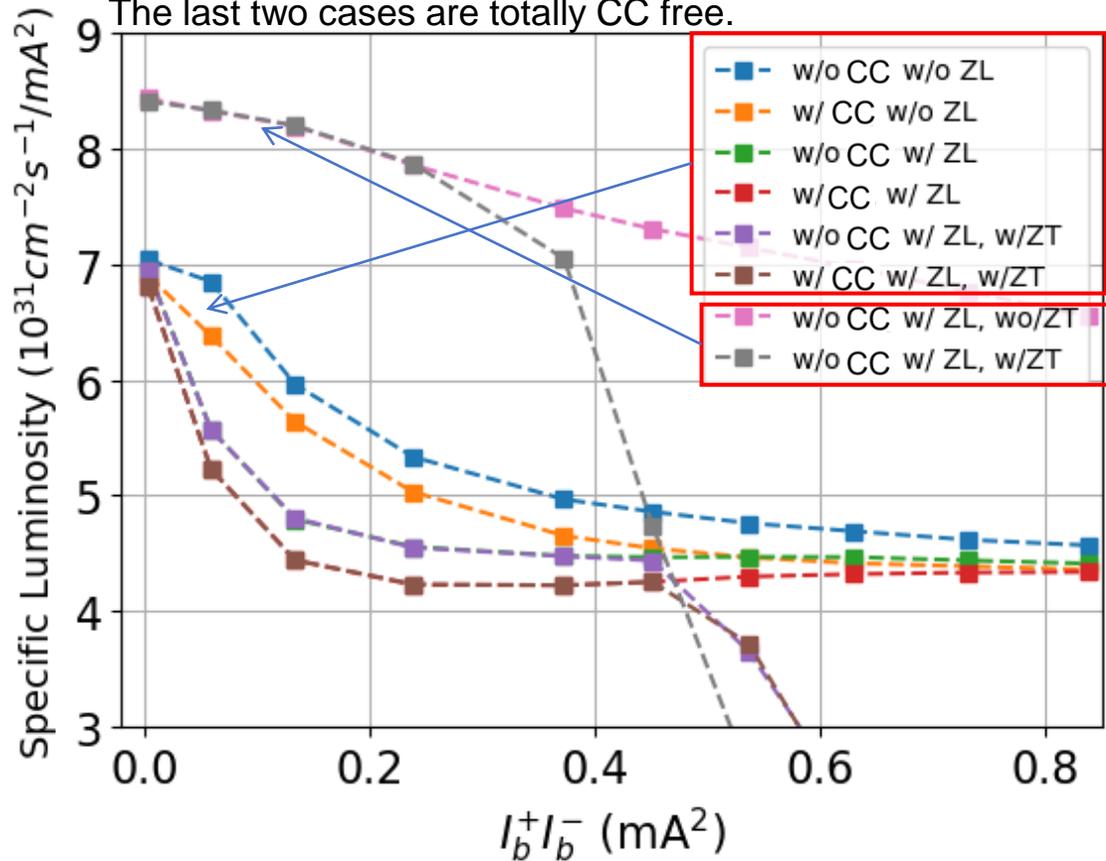
Has the emittance been measured at high beam currents ?

With ZL, the first-order chromatic coupling could also lead to second and third order synchro-betatron resonance.

Effects of impedance and chromatic coupling (CC)

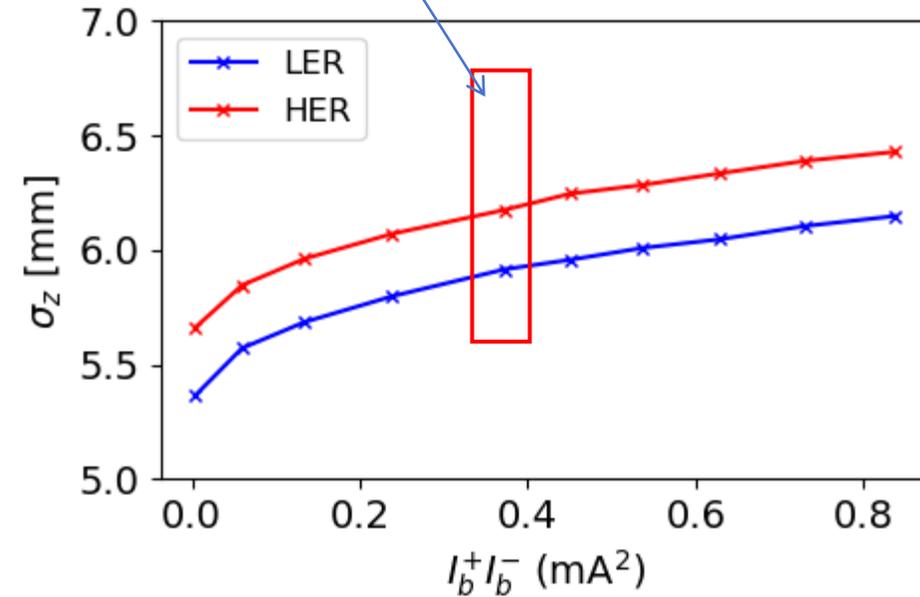
LER CC is not considered but with HER CC in the first six cases.

The last two cases are totally CC free.



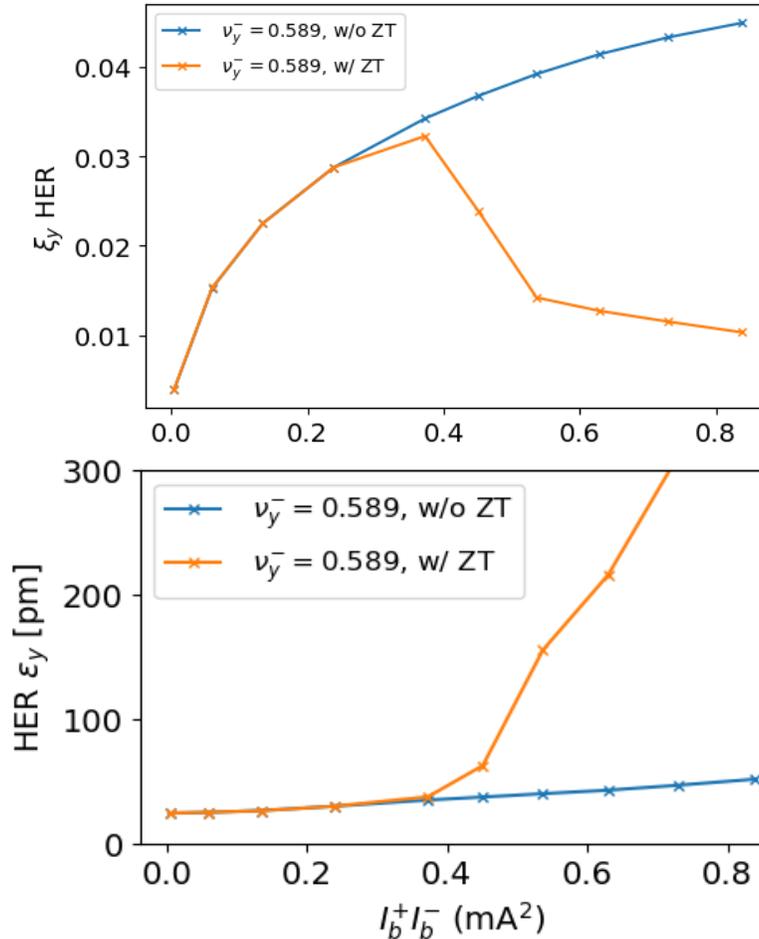
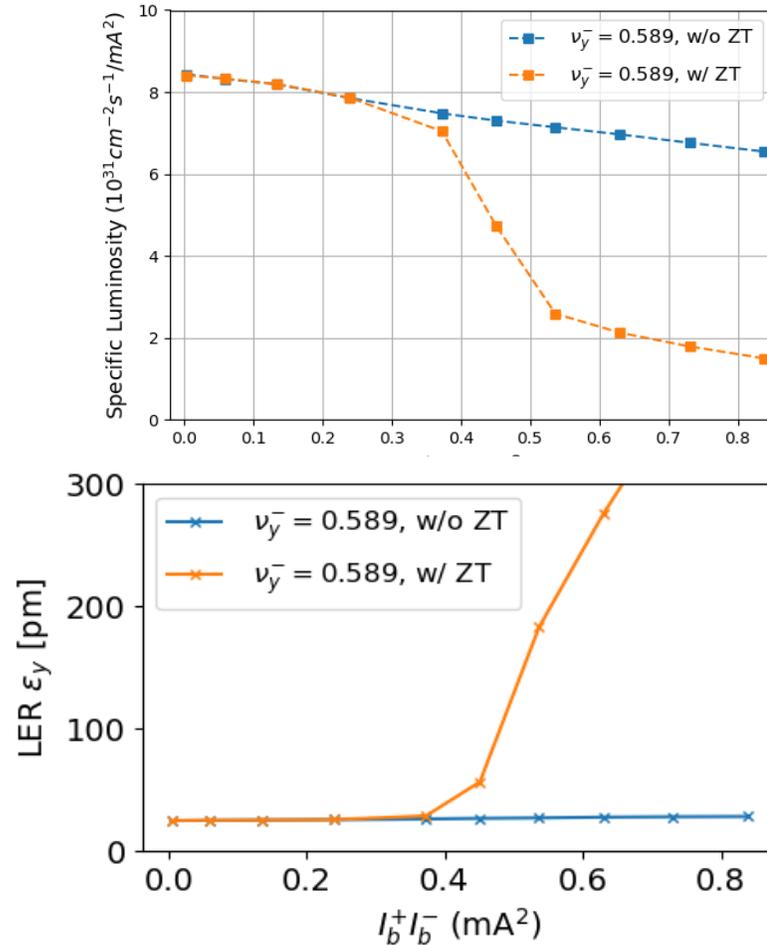
Operation current in 2024c run

	LER	HER
(v_x, v_y)	(0.525, 0.589)	(0.531, 0.599)



- At low beam currents, ZL and chromatic coupling cause a reduction in luminosity; ZT has negligible effect.
- At high beam currents, the luminosity degradation is primarily caused by Y-Z instability due to ZT.
- While LER coupling degrades luminosity, its impact is much smaller than that of HER coupling.

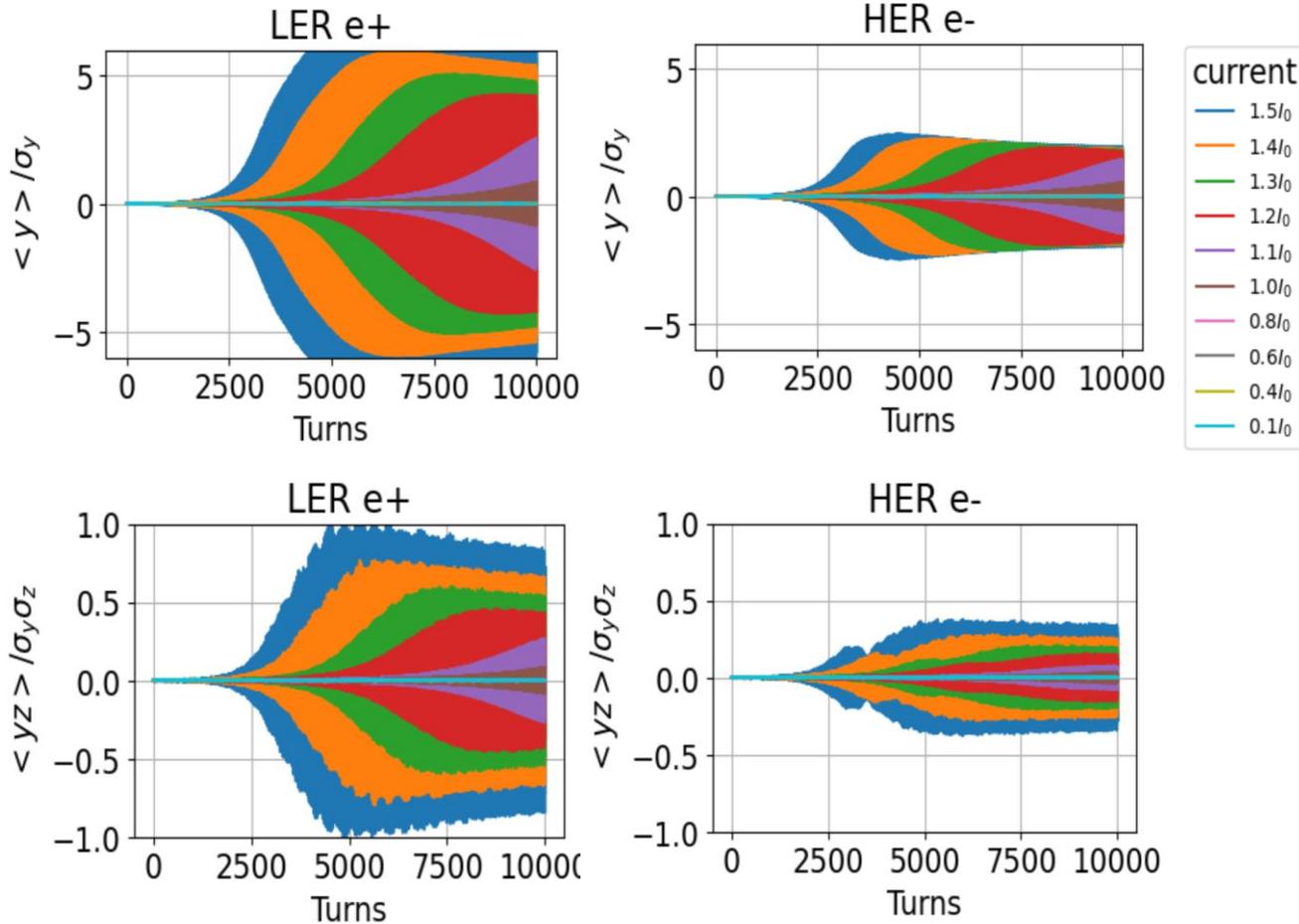
Instability induced by transverse impedance



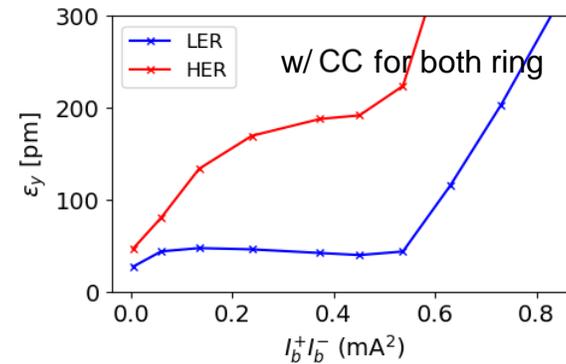
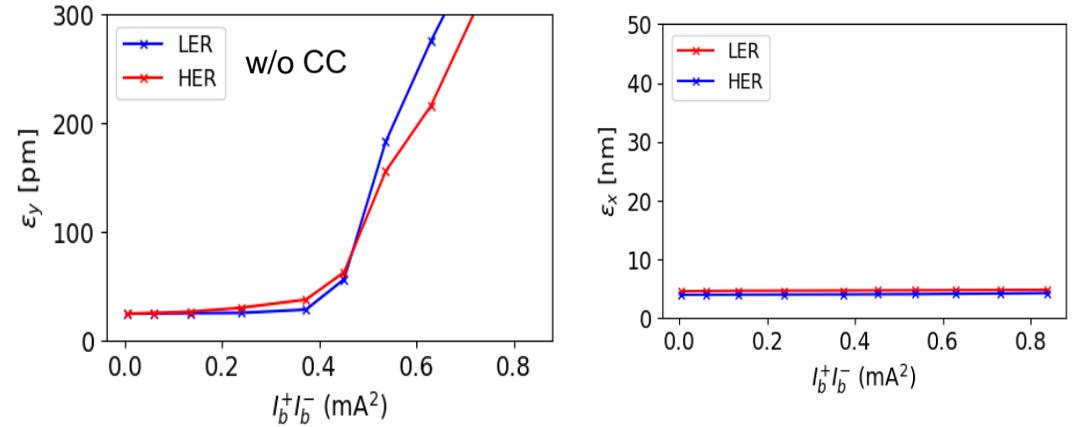
TMCI-like instability can arise at currents much lower than the designed value. While the instability threshold is extremely high when considering either beam–beam effects or transverse impedance alone, it drops sharply when both are present simultaneously.

Coherent instability

Oscillation of dipole and skew moment in vertical direction.



Y-Z inst. caused by coupling of ZT and beam-beam
No X-Z inst

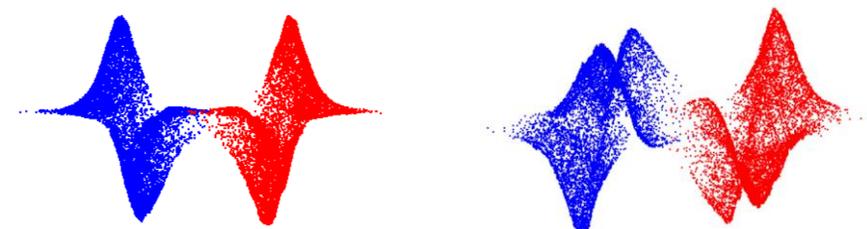


HER chromatic coupling is larger than that of LER.

At low current, chromatic coupling only cause incoherent beam size blowup. However, if the chromatic coupling differs significantly between the two rings it can cause asymmetric emittance growth — one ring blows up while the other stays stable. Hence, coupling should be matched to preserve symmetric emittance evolution.

Instability mitigation

The instability exhibits coherent σ mode, in which the two bunch oscillate in phase.

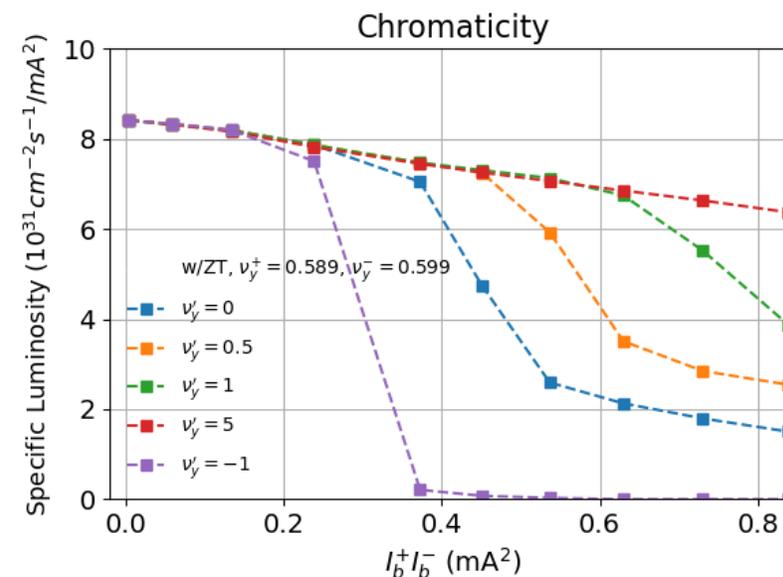
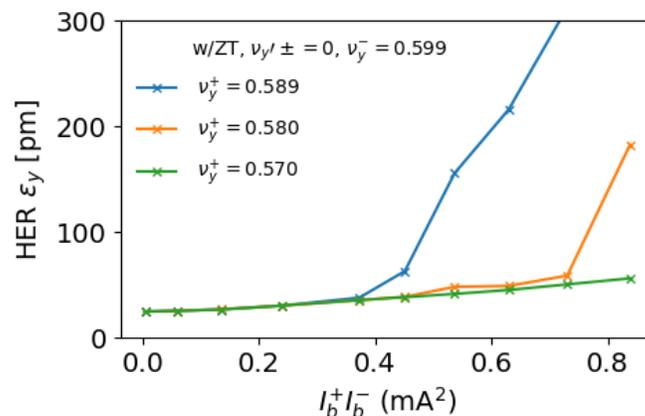
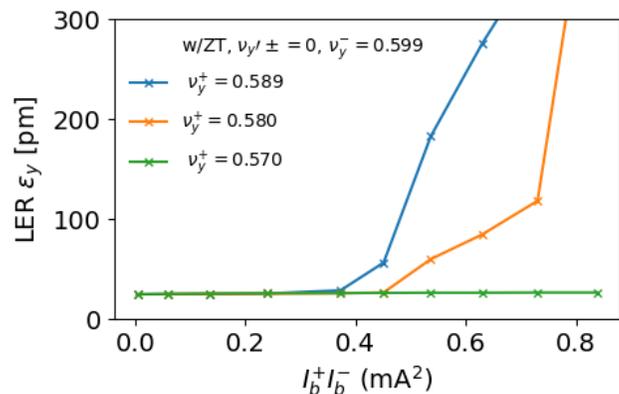
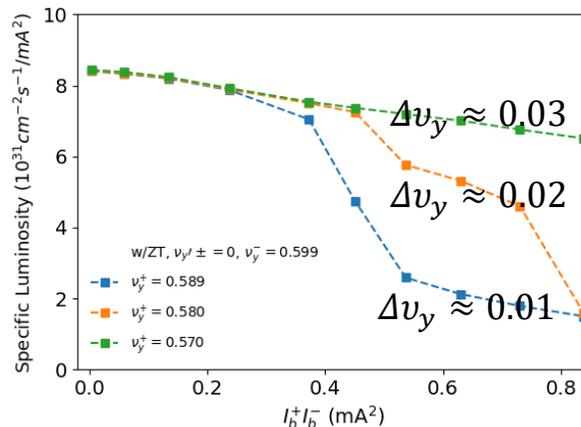
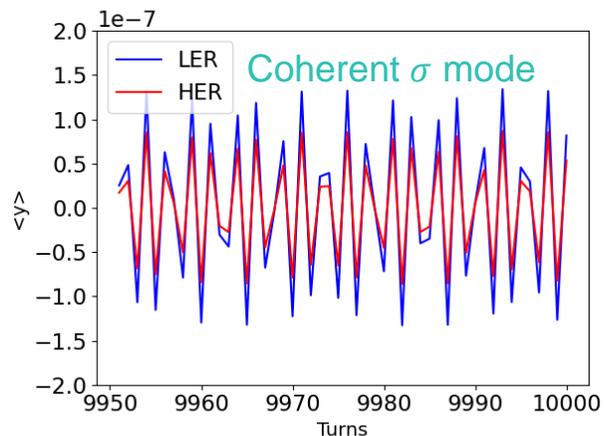


σ mode

π mode

The instability is head-tail type caused by the combination of transverse impedance and beam-beam. The chromaticity works.

Asymmetric tunes

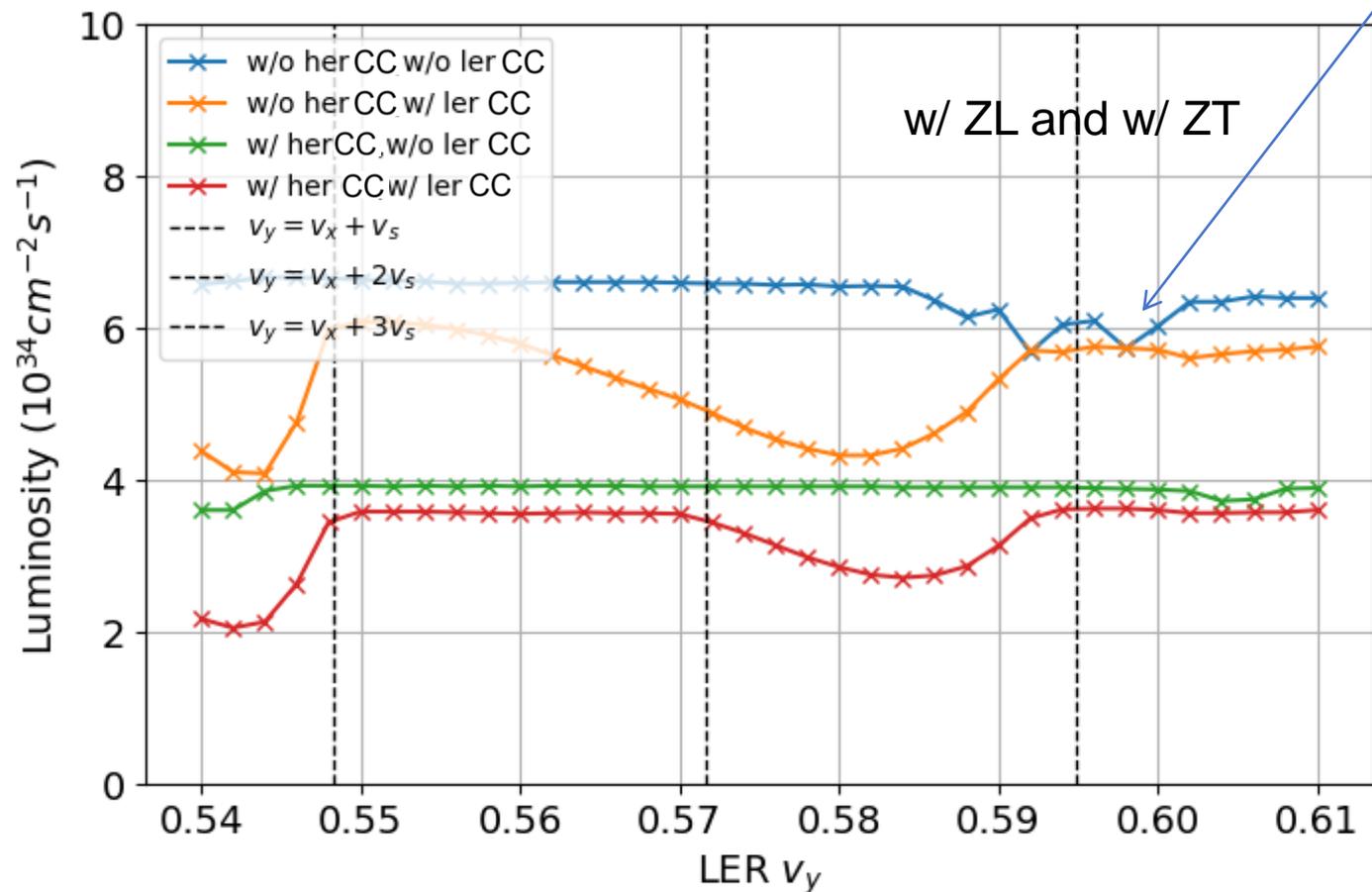


Negative chromaticity enhances the instability.

Luminosity vs. tune in different chromatic configurations

At operation current (LER $I_b=0.7\text{mA}$)

	LER	HER
(ν_x, ν_y)	(0.525, variable)	(0.531, 0.599)



w/ ZL and w/ ZT

Without coupling, when $\nu_{y,HER} \approx \nu_{y,LER}$ the luminosity is low, since the instability exhibits σ mode. Different working points between colliding beams (asymmetric tunes) help mitigate the instability.

The LER chromatic coupling will lower the luminosity. But if the $\nu_{y,LER}$ is far away from half integer, the influence become small. While LER coupling degrades luminosity, its impact is much smaller than that of HER coupling.

Asymmetric tunes strategy remains effective when there are chromatic coupling.

Preliminary beam-beam simulation
with lattice using APES

Simulation settings

sler_1802_60_1_v2.sad

tune = [0.532,0.593,-.0237]

emit = [4.03e-9,5.52e-13,0.0046,0.00074]

beta = [0.06,0.001,6.19]

HER_5781_60_1_cw60.sad

tune = [0.531,0.598,-0.0272]

emit = [4.46e-9,5.67e-13,0.005,0.0006]

beta = [0.06,0.001,8.00]

Current:

ler: 0.70mA

her: 0.54mA

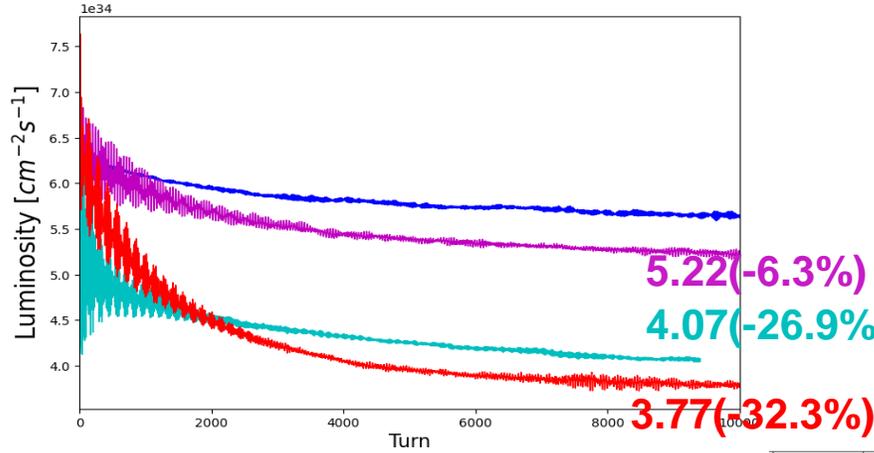
LER: emitx = 4.60e-9 emity = 25e-12 emit_couple = 0.0054
 sigmaz = 6.00e-3 sigmap = 7.5e-4

HER: emitx = 4.00e-9 emity = 40e-12 emit_couple = 0.01
 sigmaz = 6.20e-3 sigmap = 6.3e-4

Lattice without error

HER_5781_60_1_cw60.lat & sler_1802_60_1_v2.sad

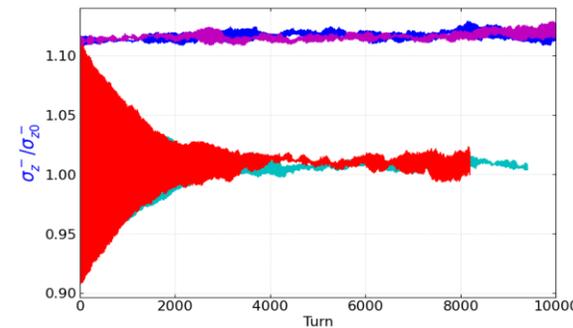
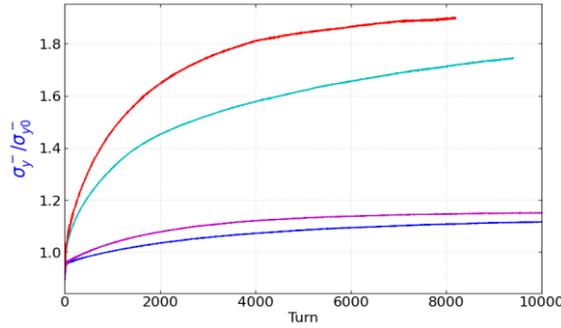
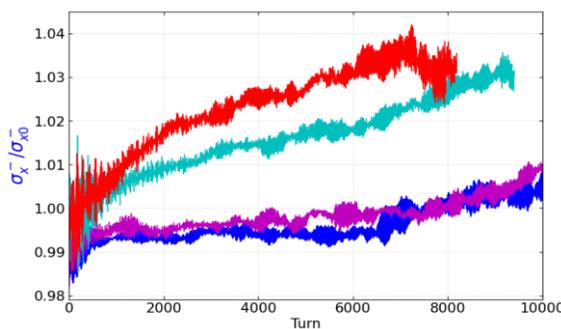
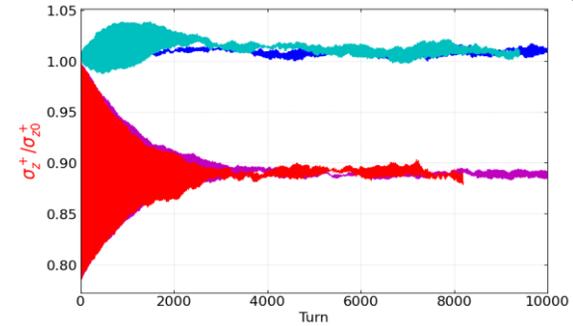
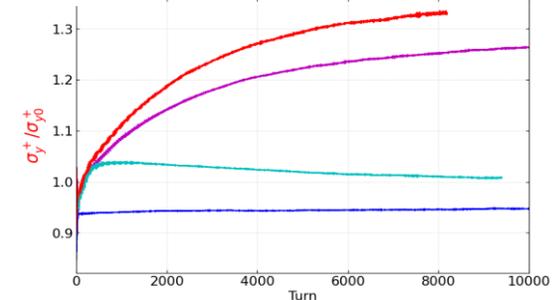
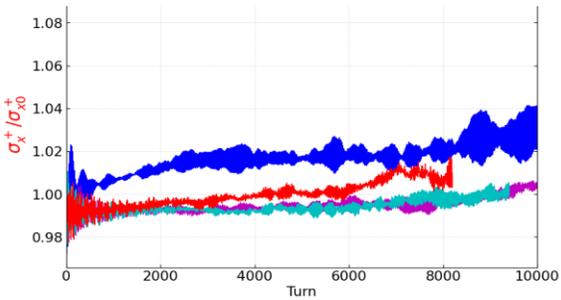
- case1 (linear) + LER(linear)
- case2 (linear) + LER(lattice)
- case3 (lattice) + LER(linear)
- case4 (lattice) + LER(lattice)



case2:LER(lattice) Resulting in a luminosity decrease (-6.4%)

case3:HER(lattice) Causing a larger vertical size increase (>1.7x) and luminosity decrease (-26.9%)

case4: Luminosity decrease is approximately the superposition of the two lattices' effects (-32.3%)

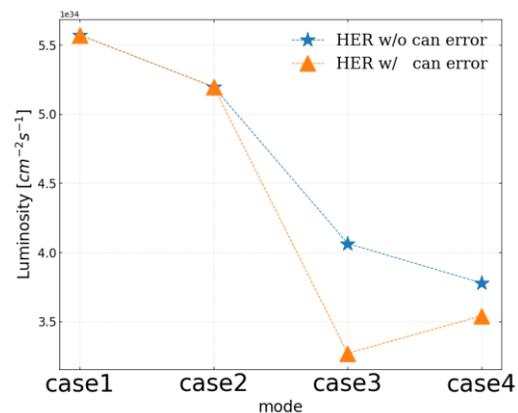
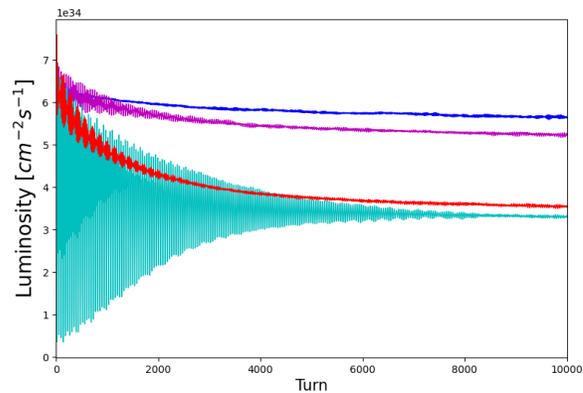


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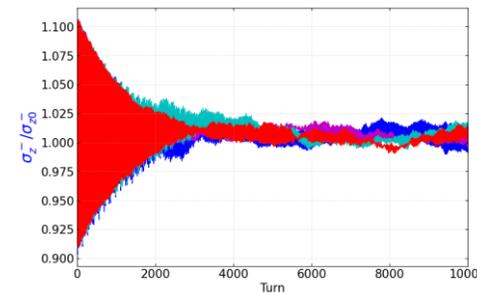
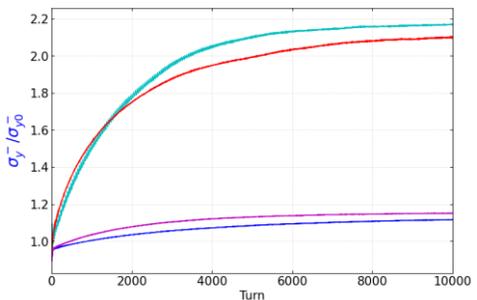
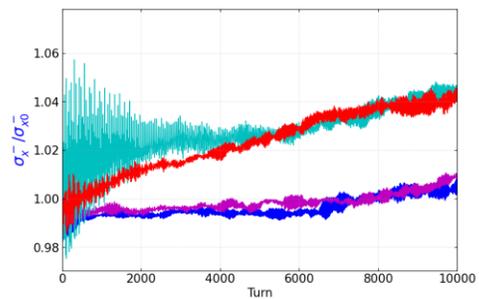
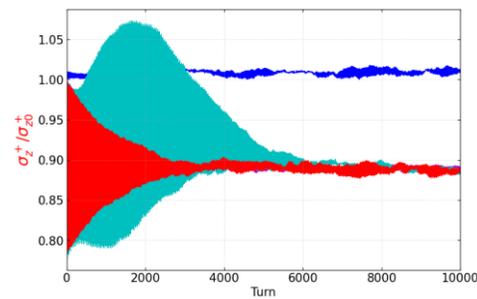
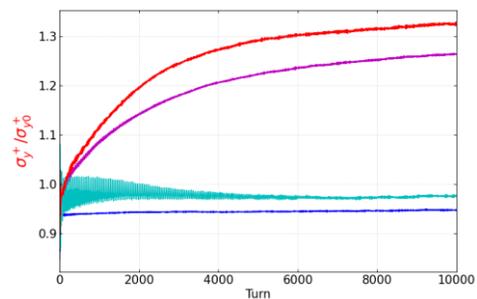
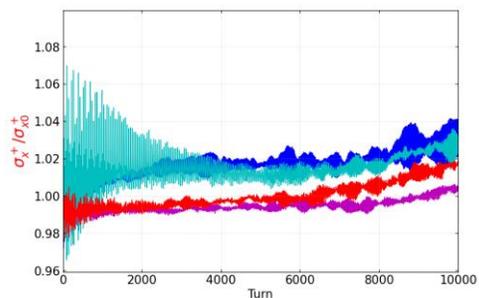
Lattice with error

HER_5781_60_1_cw60-can.lat & sler_1802_60_1_v2.sad

- case1 (linear) + LER(linear)
- case2 (linear) + LER(lattice)
- case3 (lattice) + LER(linear)
- case4 (lattice) + LER(lattice)



The imperfect HER lattice leads to enhanced vertical beam size growth and greater luminosity loss.



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Summary

- HER chromatic coupling strongly drives vertical emittance growth and luminosity loss at low currents; In contrast, chromatic coupling in the LER has a much weaker influence.
- The luminosity impact of the p_y^3 error is reduced when HER chromatic coupling is strong.
- At low beam currents, ZL and coupling cause a noticeable reduction in luminosity; ZT has negligible effect. At high beam currents, the luminosity degradation is primarily caused by ZT (Y-Z instability). The larger asymmetric-tune and chromaticity can recover the luminosity.
- Including the lattice lowers the luminosity by ~30%; with HER lattice errors, the loss is even larger.



Thank you for your attention!