Beam-Beam Studies of SuperKEKB Relevant to FCC-ee

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Outline

- Introduction
- Computational tool used in this study
- Application to the SuperKEKB beam-beam study
- Preliminary results of simulation of FCCee Z mode
- Summary
- Future work

FCCee and SuperKEKB Share Some Common Features

Shared Design Feature	**Description**	**Purpose / Benefit**
Nano-Beam Collision Scheme	Beams collide at a large crossing angle rather than head-on, meaning the bunches only overlap in a tiny region at their absolute center.	Overcomes the "hourglass effect," allowing the colliders to reach massive luminosities without requiring unmanageable beam currents.
Crab-Waist Optics	Dedicated sextupole magnets are used to twist (or "crab") the focal waist of the beam so it perfectly aligns with the opposing beam's trajectory.	Suppresses the destructive X-Y coupling and betatron resonances caused by the large crossing angle, keeping the beam stable.
Ultra-Low Squeezing (β_y^*)	Highly complex superconducting final-focus quadrupole magnets squeeze the vertical beam size to nanometer scales (sub-millimeter β_y^*) at the interaction point.	Maximizes particle density at the exact moment of collision to drive up the interaction rate (luminosity).
Continuous Top-Up Injection	Fresh electrons and positrons are continuously injected into the main rings at full energy while the detectors are actively taking data.	Compensates for the extremely short beam lifetimes caused by the intense beam-beam interactions and high collision rates.
Instability Mitigation	Both machines require specialized vacuum chamber coatings, clearing electrodes, and extremely smooth internal components.	Suppresses collective beam instabilities like the electron cloud effect and geometric wakefields that plague high-current, low-emittance beams.

Nano-Beam Used to Avoid Hourglass Effect for Large Luminosity

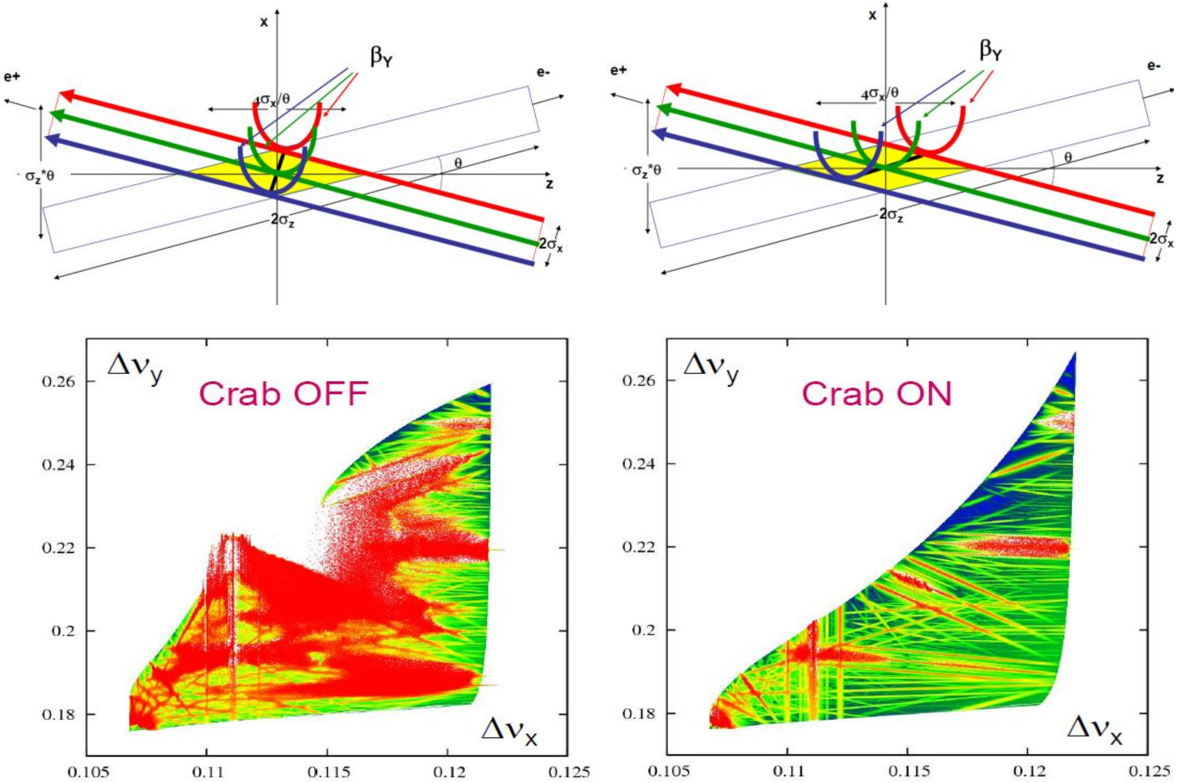
$$L = L_0 \cdot R_{H,\phi} \qquad L_0 = \frac{N_1 N_2 f_{rev} n_b}{4\pi \sigma_x^* \sigma_y^*}$$

$$R_{H,\phi} = \frac{\cos(\frac{\theta_c}{2})}{\pi} \int_{-\infty}^{\infty} \frac{\exp\left[-u^2 \cos^2\left(\frac{\theta_c}{2}\right)\left(1 + \frac{\Phi^2}{1+(u/u_x)^2}\right)\right]}{(1+(u/u_x)^2)\,(1+(u/u_y)^2)}\, du$$

u	Dimensionless integration variable representing longitudinal position (z/σ_s)
u_x, u_y	Ratio of beta function to bunch length $(u_x = \beta_x^*/\sigma_s,\ u_y = \beta_y^*/\sigma_s)$

- In order to minimize the hourglass effect, beta at IP should be greater than bunch length.
- This can be achieved using large crossing angle.
- Smaller effective bunch length results in smaller beta at IP and nano-beam.

Crab Waist Scheme Used to Mitigate the Adverse Effects from Large-Angle Collision



Courtesy of M. Zobov

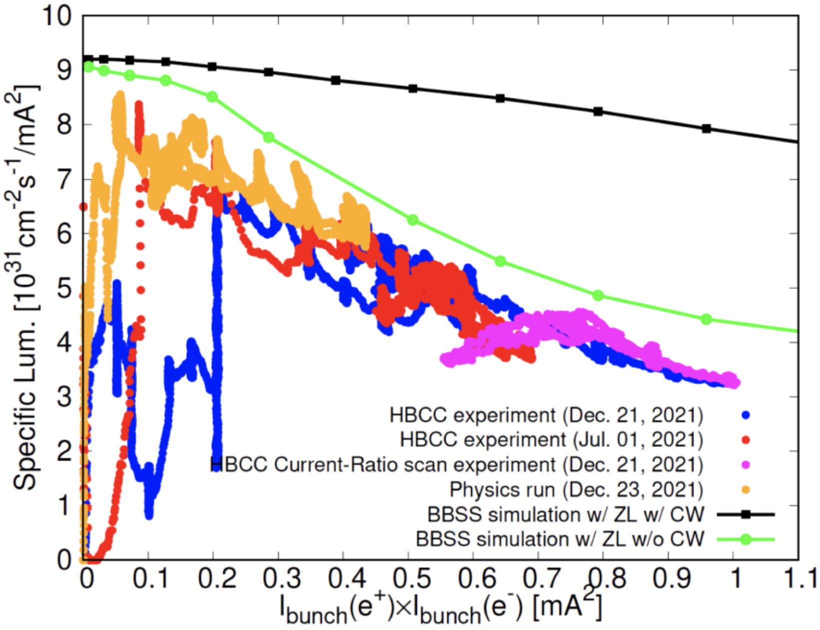
SuperKEKB Operation Status

- **New Luminosity Records:** SuperKEKB continues to break its own world records for peak instantaneous luminosity. In March 2026, it reached $5.2 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$, and by the end of June 2026, it pushed that record even higher to $5.32 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$.

While SuperKEKB is currently delivering world-leading performance, achieving its ultimate, aggressive design luminosity of $8 \times 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ remains a long-term, incremental challenge that the international collaboration is tackling through continuous daily tuning and machine upgrades.

Specific Luminosity vs. Current Products w. and w/o Crab Waist

Strong-Strong Beam-Beam simulation (D. Zhou)

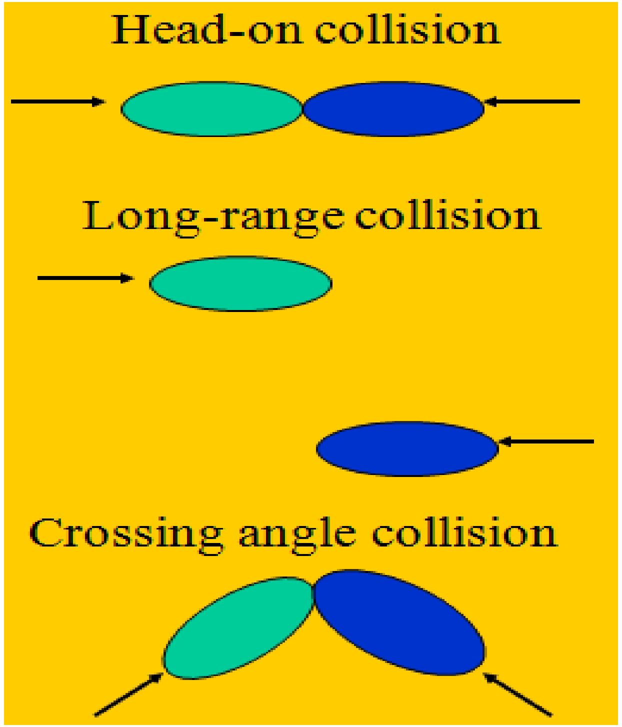


- Simulation shows significantly higher luminosity than the measurements

Courtesy of Y. Funakoshi

Modelling the Beam-Beam Effects Using a Parallel Colliding Beam Simulation Code: BeamBeam3D

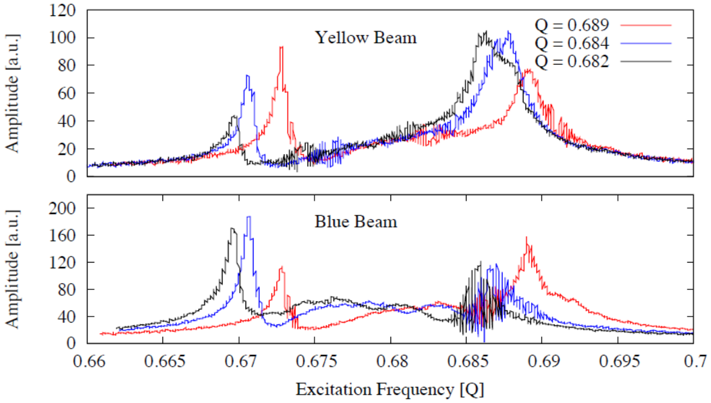
https://github.com/beam-beam/BeamBeam3D



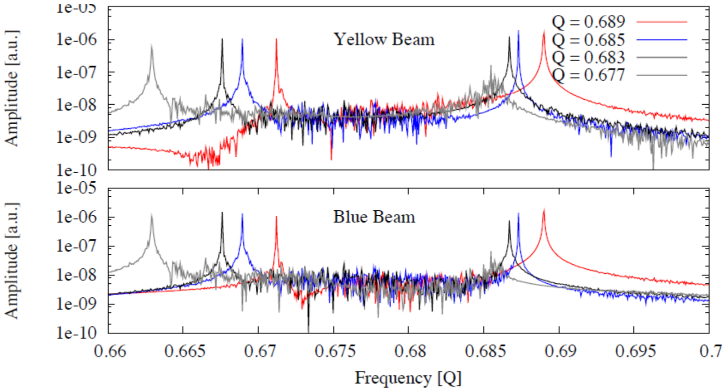
Some key features of the BeamBeam3D

- Multiple-slice model for finite bunch length
- New algorithm -- shifted Green function -- efficiently models long-range collisions
- Parallel particle-field based decomposition to achieve perfect load balance
- Lorentz boost to handle crossing angle
- Arbitrary closed-orbit separation
- Multiple bunches, multiple collision points
- Linear transfer matrix + one turn chromaticity or nonlinear model
- Conducting wire, crab cavity, e-lens compensation model, crab waist
- Feedback model
- Impedance model
- Bremsstrahlung model

BeamBeam3D Simulation Reproduced RHIC BFT Measurement Data



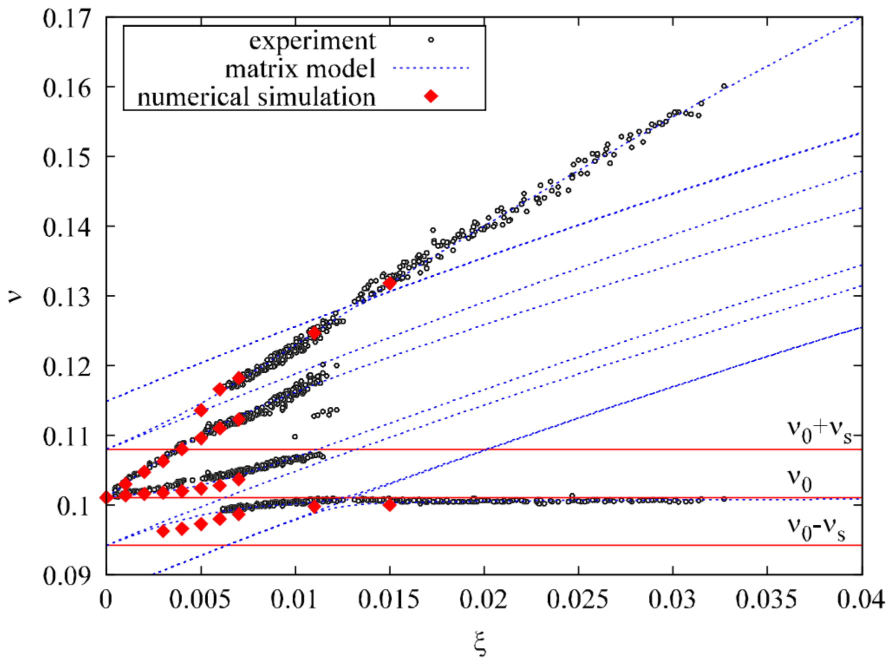
measurements



simulations

S. White, M. Blaskiewicz, W. Fischer, Y. Luo, "**Coherent beam-beam experiments and implications for head-on compensation**", CERN-2014-004.

Synchrobetatron Modes from BeamBeam3D Simulations, Matrix Model, and Experiment Data Show Good Agreement



E. G. Stern, J. F. Amundson, P. G. Spentzouris, and A. A. Valishev, Phys. Rev. ST Accel. Beams 13, 024401 (2010).

Parameters Used for SuperKEKB Beam-Beam Simulations

Typical Machine Parameters for Simulation

Parameters	LER (e^+)	HER (e^-)	Units
E	4	7.007	GeV
I_b	Variable (I_b^+)	$I_b^- = 0.77 \times I_b^+$	mA
ε_x	4.0	4.6	nm
ε_y	25	25	pm
(β_x^*, β_y^*)	(60, 1.0)	(60, 1.0)	mm
(ν_x, ν_y)	(44.525, 46.589)	(45.529, 43.599)	
ν_z	0.023	0.027	
σ_z	5.0	5.0	mm
($\lambda_x, \lambda_y, \lambda_z$)	(-1.899, -1.898, -3.795)	(-1.736, -1.736, -3.471)	$\times 10^{-4}$
CW	80	60	%

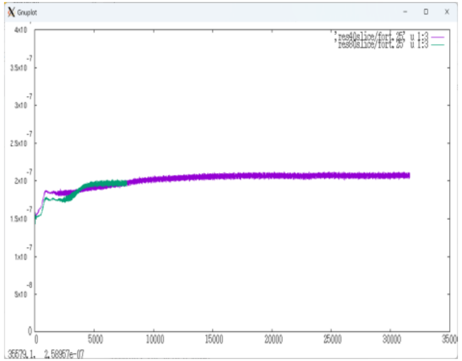
Notes:

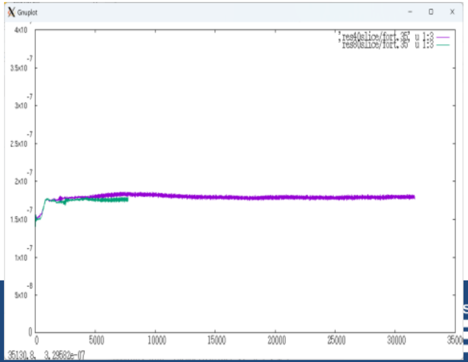
- I_b : Bunch current
- (ε_x ε_y) : Horizontal and vertical emittances
- (β_x^*, β_y^*) : Betatron functions at the interaction point
- (ν_x, ν_y) : Horizontal and vertical tunes
- ν_z : Synchrotron tune
- σ_z : Bunch length in root-mean-square
- (λ_x, λ_y, λ_z) : Horizontal, vertical and longitudinal damping per one revolution due to synchrotron radiation
- CW : Crab waist ratio
  https://link.springer.com/article/10.1140/epjp/s13360-021-01979-8
- Ring circumference $C = 3016.3151$ m

Courtesy of H. Sugimoto

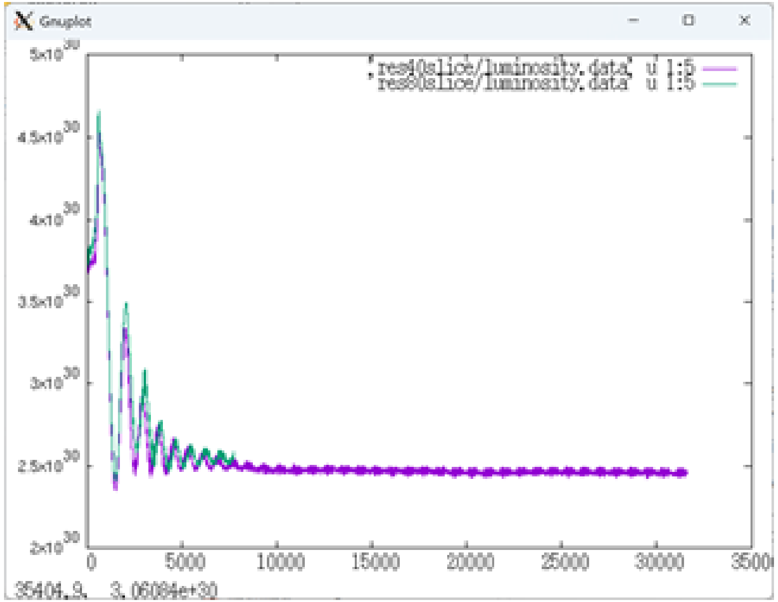
Numerical Convergence Check: 40 Slices vs. 80 Slices
(1M macroparticle/beam, 128x64 transverse grid)

Horizontal RMS Size Evolution

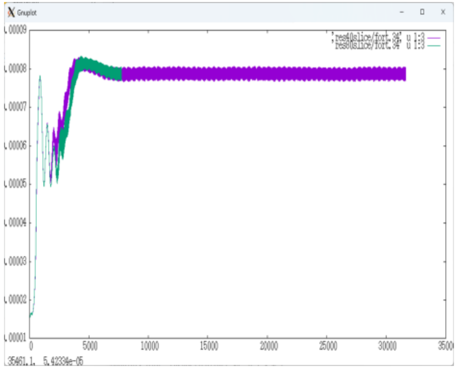


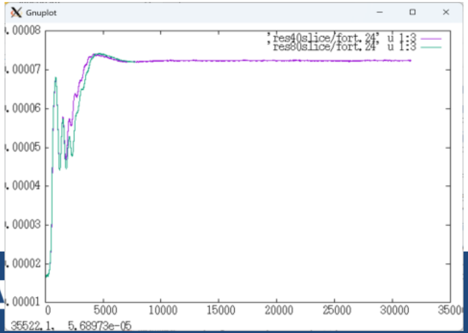


Luminosity Evolution



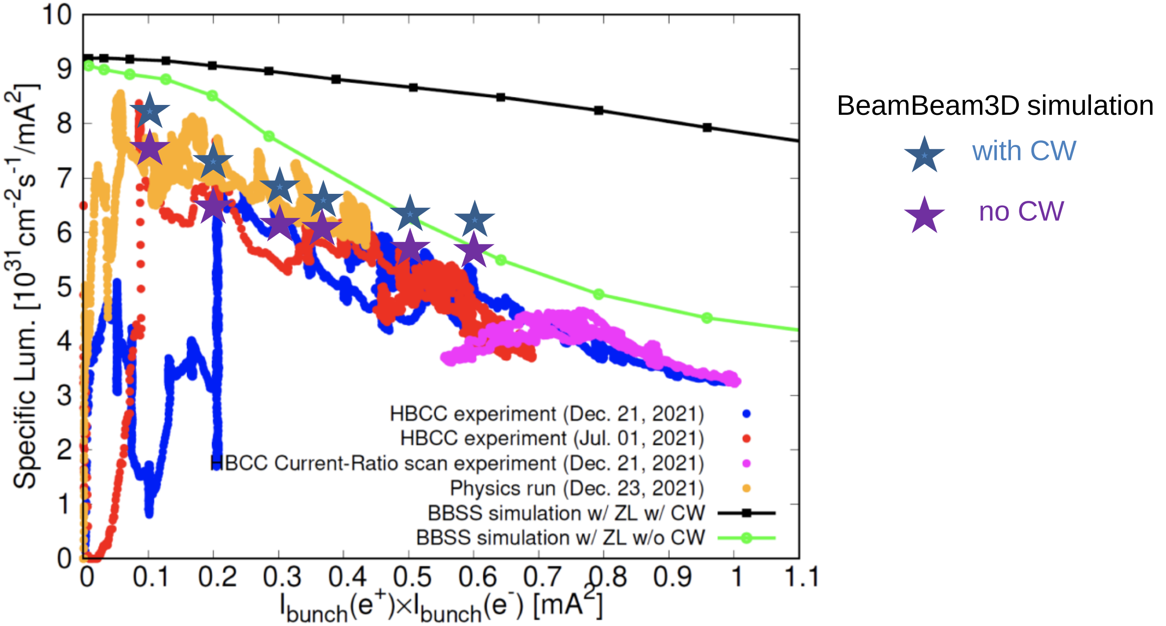
Verticall RMS Size Evolution





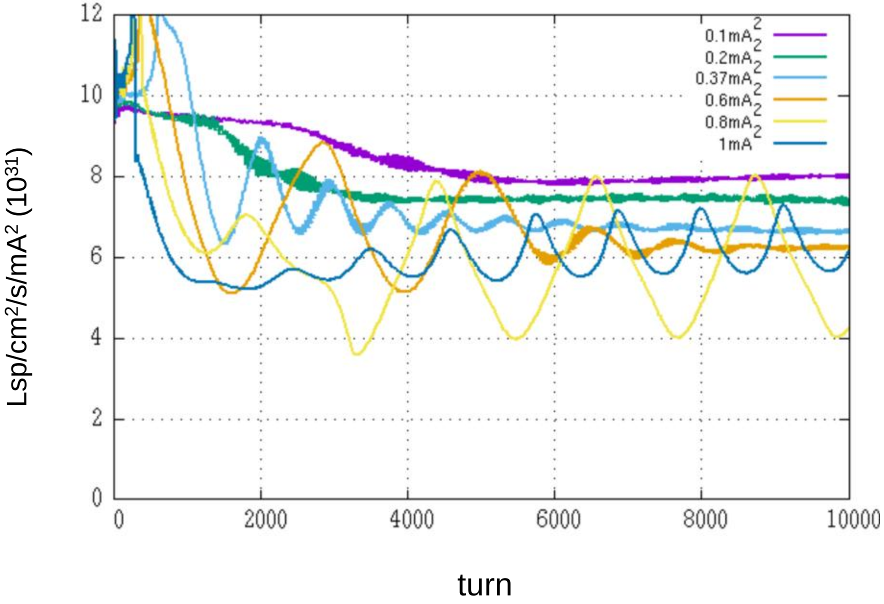
- It looks like 40 slices is sufficient

Specific Luminosity vs. Current Products w. and w/o Crab Waist



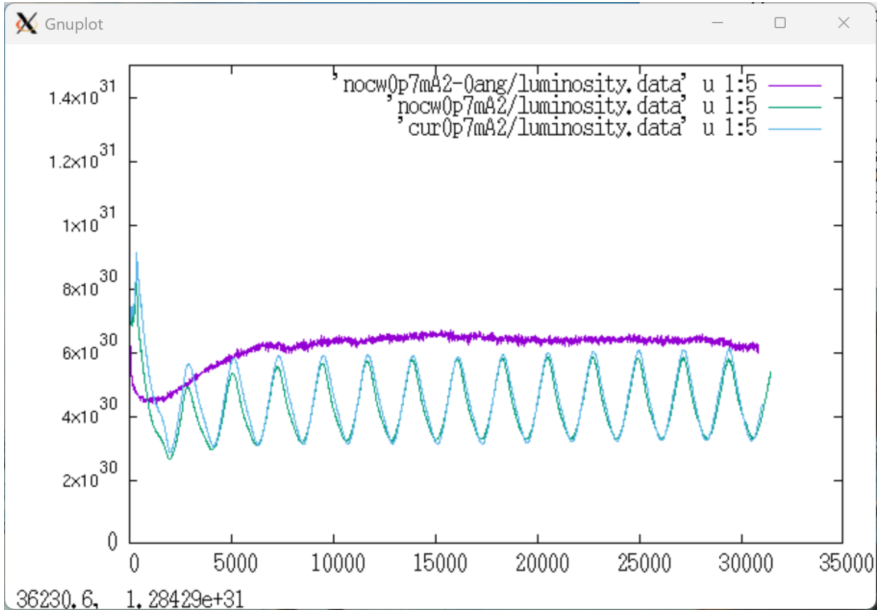
- Simulation results fall within measurements with low current products, but above measurements with high current products.
- Difference between with CW or without CW is not very large.

Specific Luminosity Evolution with Several Current Products



- Luminosity oscillation observed with current product beyond 0.6 mA^2.

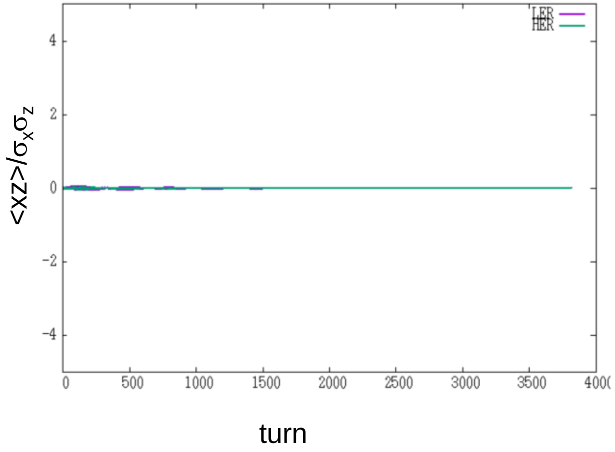
Evolution of Luminosity with 0.7 mA^2 Current Products w. and w/o crab waist, & no crossing angle



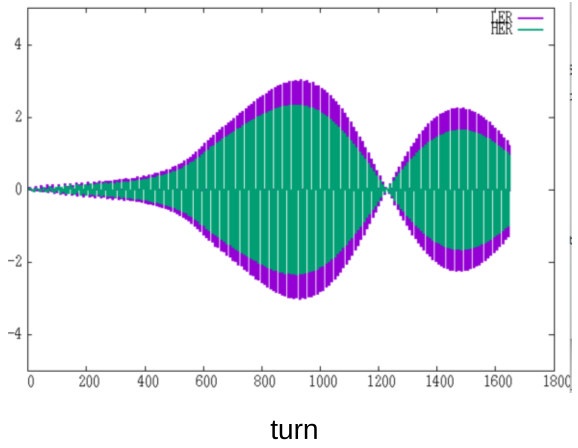
- Crab waist does not affect the luminosity oscillation
- No crossing angle suppresses the oscillation

<XZ> Evolution with Three Current Products

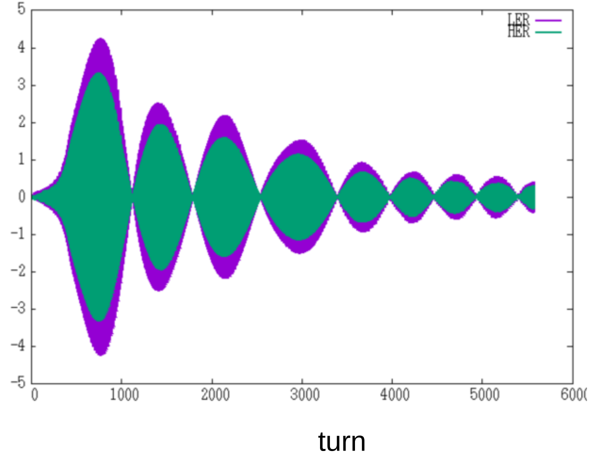
$I^+I^-=0.1mA^2$



$I^+I^-=0.37mA^2$



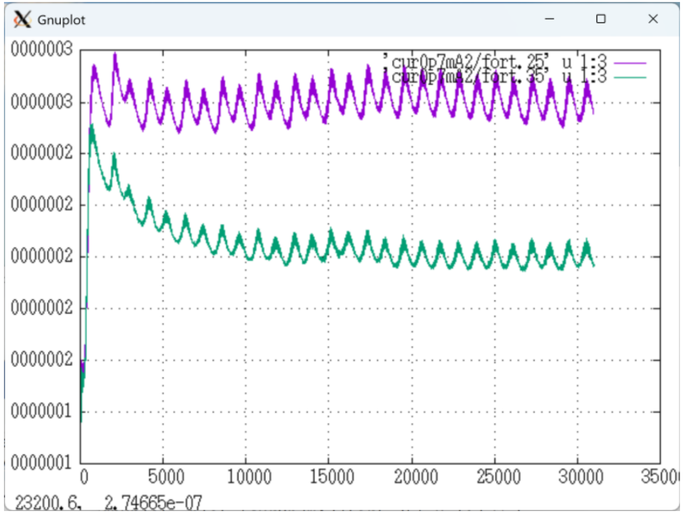
$I^+I^-=0.5mA^2$



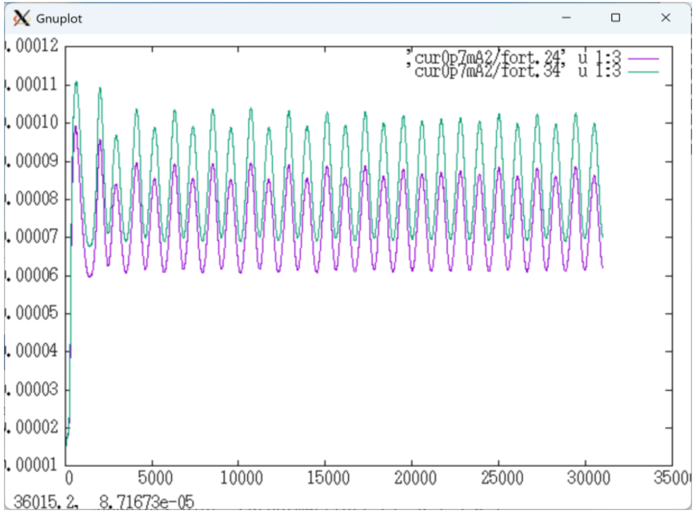
- <xz> shows instability for larger current products

Evolution of Both Beams Horizontal and Vertical RMS Sizes with 0.7 mA^2 current products

Horizontal RMS Size



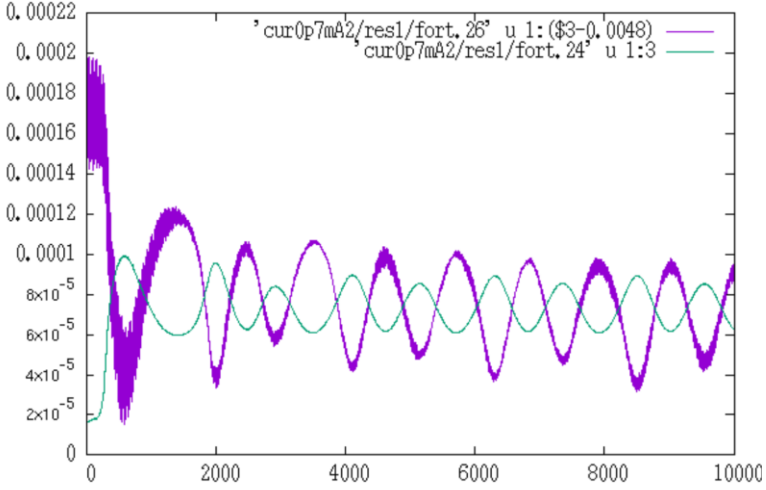
Vertical RMS Size



- Luminosity oscillation is due to RMS size oscillation

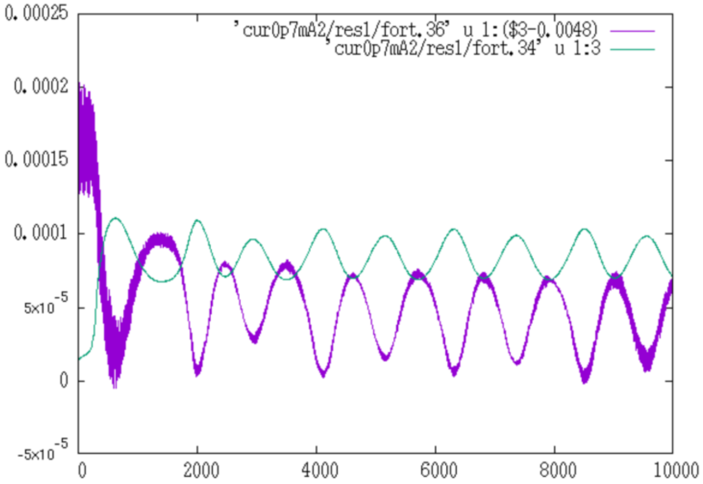
Evolution of Horizontal and Longitudinal RMS Sizes with 0.7 mA^2 Current Products

electron beam



turn

positron beam

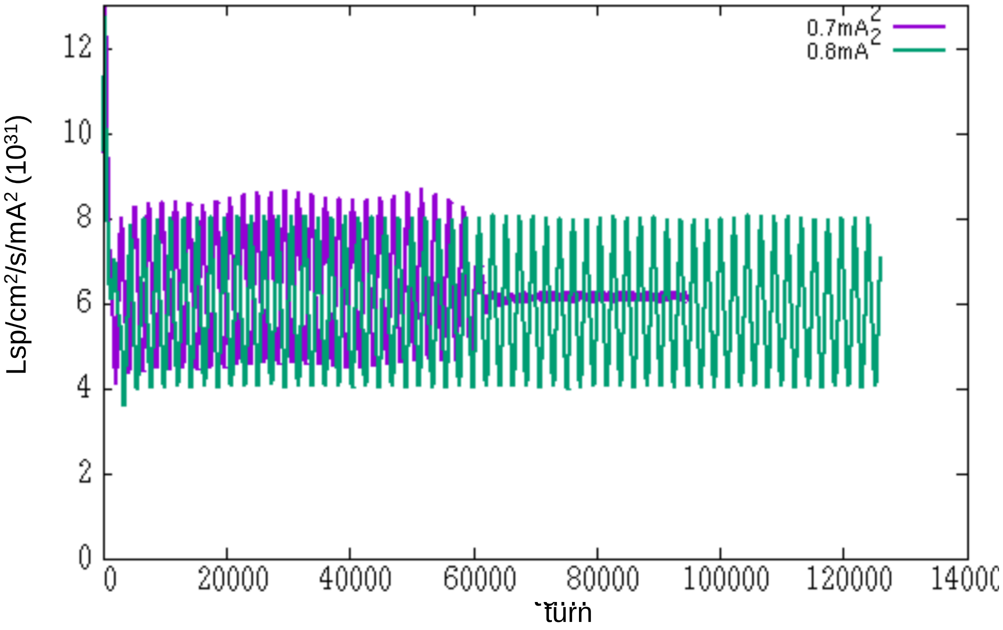


turn

$$\nu_x - \nu_s = N/2$$

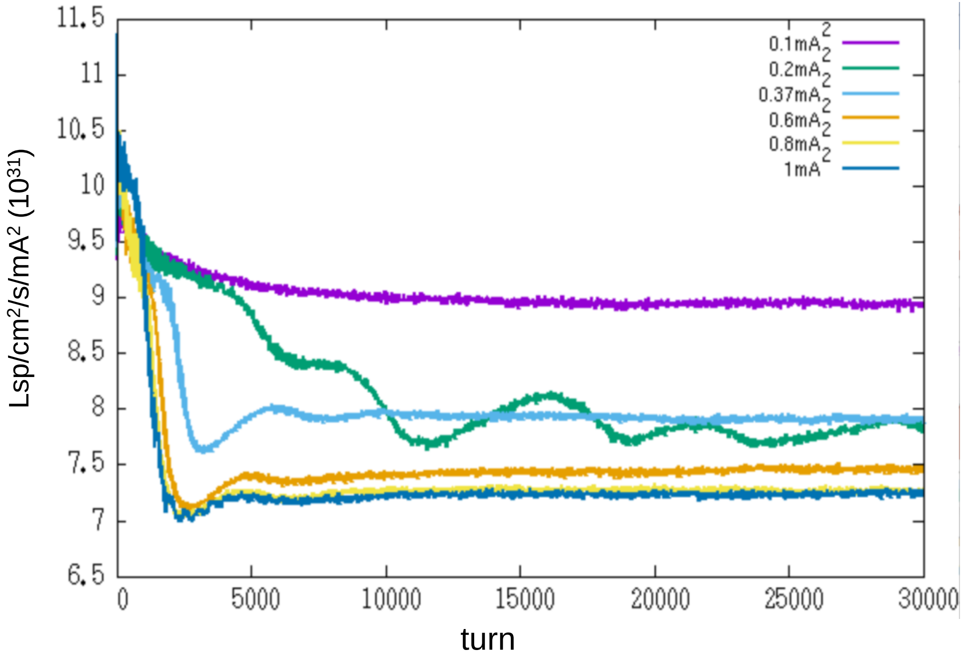
- Synchrobetatron resonance is excited between horizontal and longitudinal envelope motion

Specific Luminosity Evolution with Two Current Products (0.7 and 0.8)

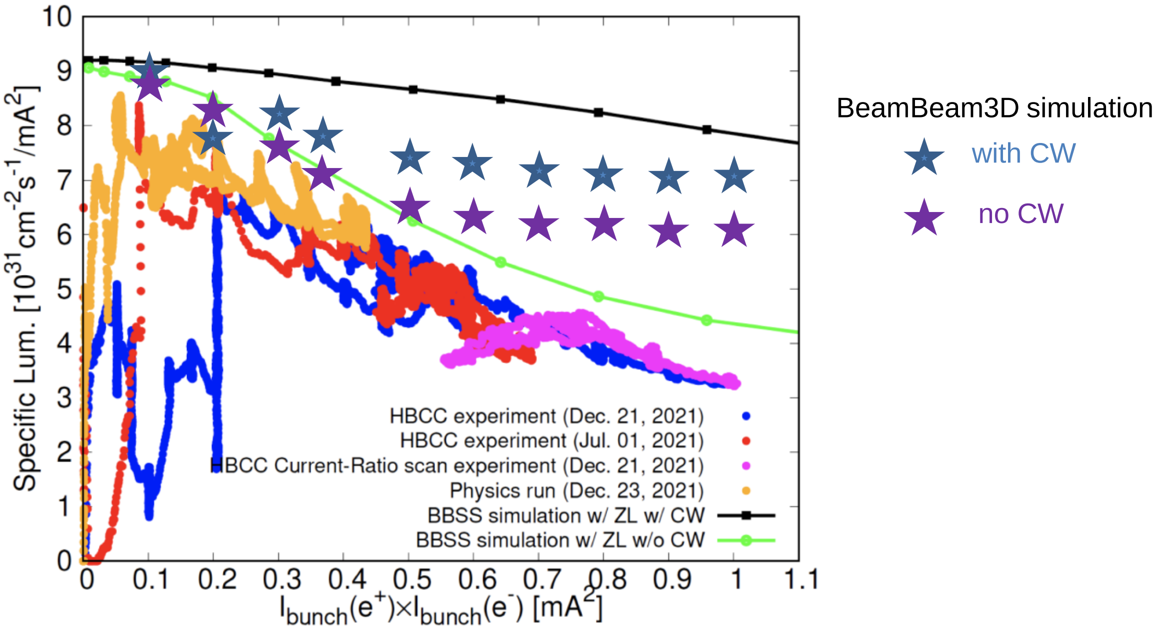


- Coherent luminosity oscillation could be damped out for longer simulation.

Specific Luminosity Evolution with Several Current Products and New LER Tune (0.53, 0.589)



Specific Luminosity vs. Current Products w. and w/o Crab Waist with LER Tunes (0.53,0.589)

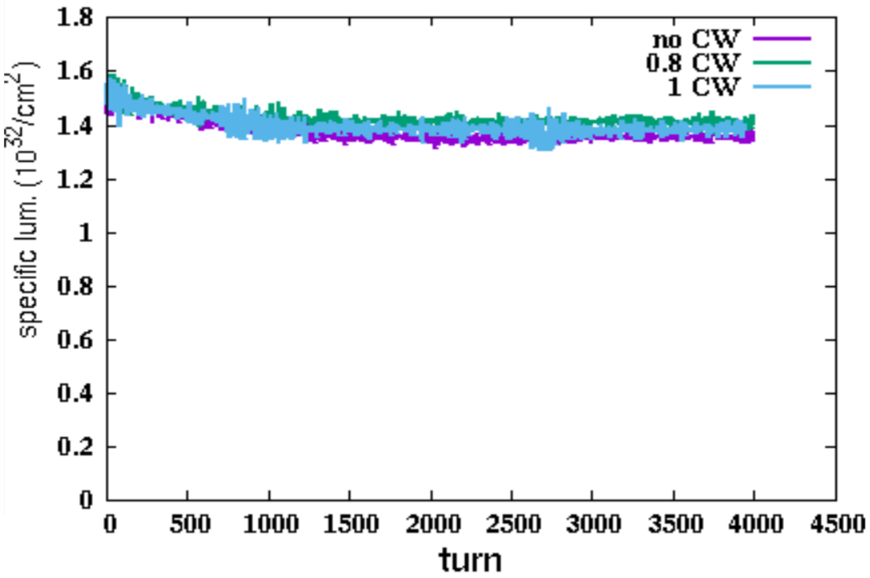


- Simulation results over predict the specific luminosity with new tune working point

Preliminary Strong-Strong Beam-Beam Simulation of FCCee Z mode (2 IPs) with and without Crab Waist

Parameter	Symbol	CDR Value (Z-mode)
Beam Energy	E_b	$45.6\ \mathrm{GeV}$
Full Crossing Angle	θ	$30\ \mathrm{mrad}$
Particles per Bunch	N	1.7×10^{11}
Horizontal Emittance	ϵ_x	$0.27\ \mathrm{nm} \cdot \mathrm{rad}$
Vertical Emittance	ϵ_y	$1.0\ \mathrm{pm} \cdot \mathrm{rad}$
Beta function at IP (x/y)	β_x^*/β_y^*	$15\ \mathrm{cm}/0.8\ \mathrm{mm}$
SR-only Bunch Length	$\sigma_{z,\mathrm{SR}}$	$3.5\ \mathrm{mm}$
Total Bunch Length (SR + BS)	σ_z	$12.1\ \mathrm{mm}$
Piwinski Angle	Φ	≈ 28.5

Tunes (0.26,0.38,0.025)



- Less than 10% luminosity degradation is seen from simulations.
- The effects of crab waist is weak.

Summary

- **BeamBeam3D simulation results can reproduce some measurements at lower current products.**

- **High current products over predict the specific luminosity and show coherent oscillation due to synchrobetatron coupling resonance.**

- **Moving the LER horizontal fraction tune from 0.525 to 0.53 avoids the coupling resonance and luminosity oscillation, but results in higher specific luminosity than measurements.**

- **Preliminary simulation of FCCee Z mode shows less than 10% luminosity degradation and the effect of crab waist is weak.**

Future Work

- Understand the discrepancies between the BeamBeam3D simulation results and the KEK simulations.

- Include other physical effects such as machine impedance, machine nonlinearity and imperfection to the current beam-beam simulation for the benchmark.

- Systematically benchmark simulations with measurements using updated experimental parameters.

- Compare the self-consistent strong-strong and soft-Gaussian strong-strong for the X-Z instability in the FCCee Z mode.

- Modernize the BeamBeam3D with GPU based codes WarpX/ImpactX.

Acknowledgements

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Thank You for Your Attention!