Beam-beam at SuperKEKB

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Acknowledgments

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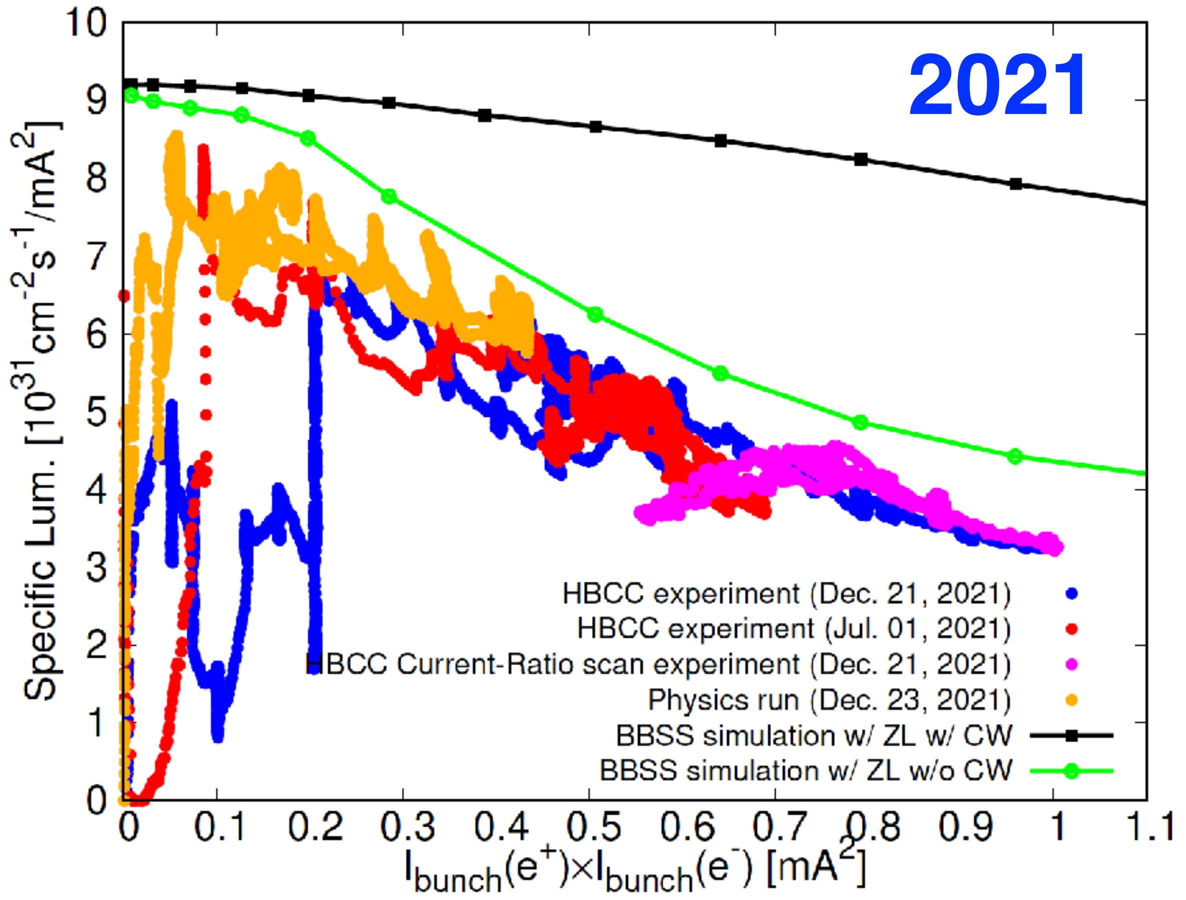
Status of beam-beam simulations

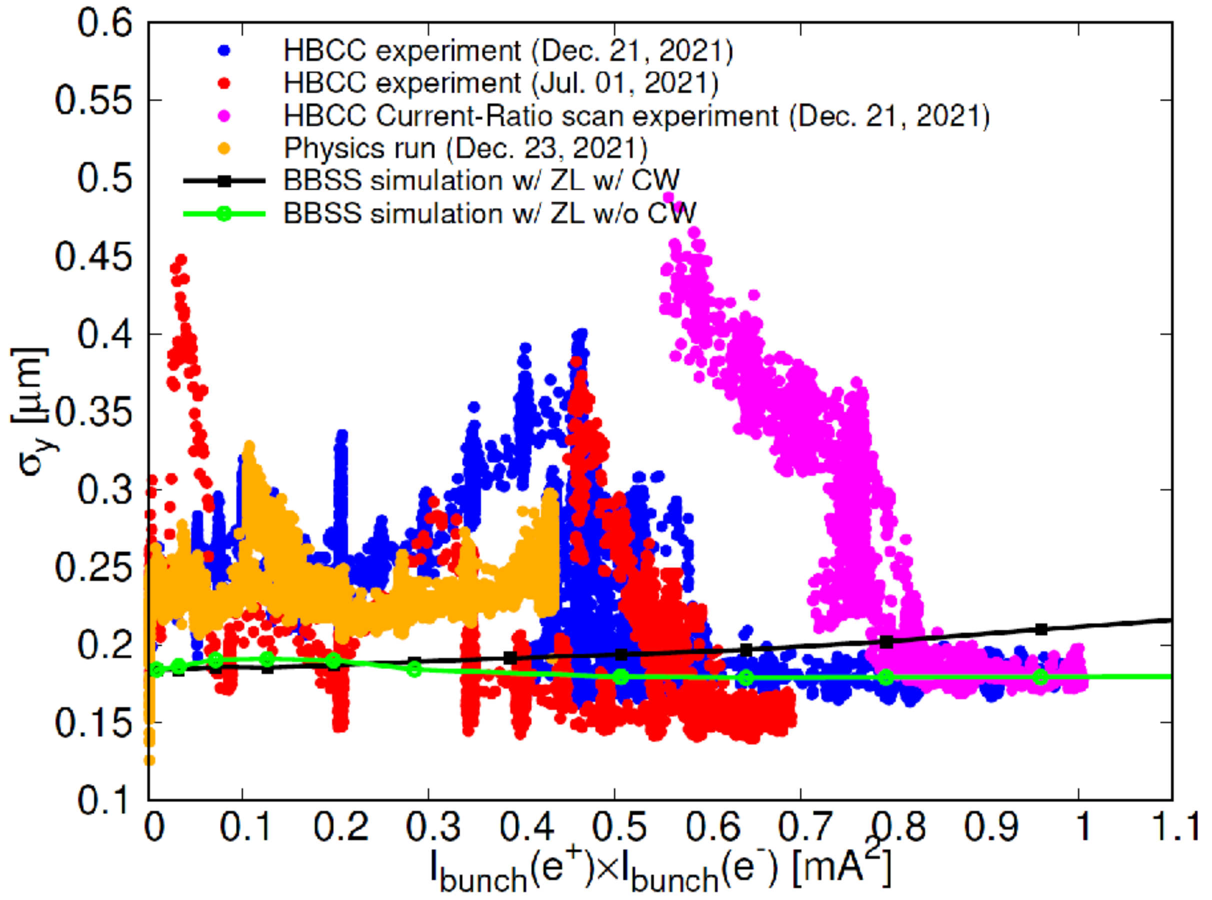
- Weak-strong model + simple one-turn map: BBWS code [1]
  - The weak beam is represented by N macro-particles (statistical errors ~ $1/\sqrt{N}$). The strong beam has a rigid charge distribution with its EM fields expressed by the Bassetti-Erskine formula.
  - The simple one-turn map contains lattice transformation (Tunes, alpha functions, beta functions, X-Y couplings, dispersions, etc.), chromatic perturbation, synchrotron radiation damping, quantum excitation, crab waist, etc.
- Weak-strong model + full lattice: SAD code
  - The BBWS code was implemented into SAD as a type of BEAMBEAM element, where the beam-beam map is called during particle tracking.
  - Tracking using SAD: 1) Symplectic maps for elements of BEND, QUAD, MULT, CAVI, etc. 2) Element-by-element SR damping/excitation; 3) Distributed weak-strong space-charge; 4) MAP element for arbitrary perturbation maps (such as crab waist, wakefields, artificial SR damping/excitation, etc.); …
- Strong-strong model + simple one-turn map: BBSS code [1]
  - Both beams are represented by N macro-particles
  - The one-turn map is the same as weak-strong code. The Beamstrahlung model is also available. Choices of numerical techniques: PIC, Gaussian fitting for each slice, …
  - For SuperKEKB, it is hard to include lattice.
- GPU-powered strong-strong model + full lattice: SCTR code
  - Under development (K. Ohmi) with KEK/IHEP/J-PARC collaboration

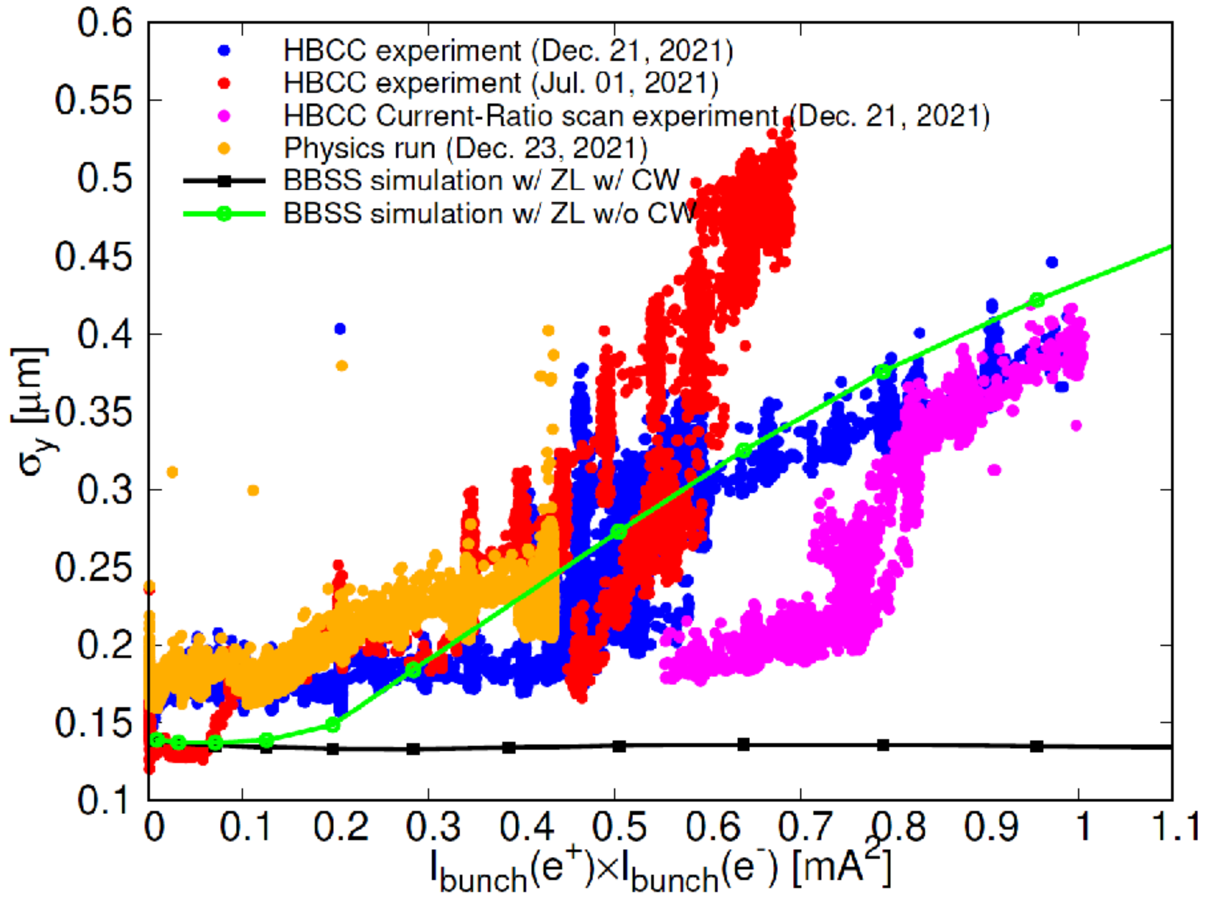
[1] K. Ohmi, Talk presented at the 2019 SAD workshop, https://conference-indico.kek.jp/event/75/.

Comparison of simulations and experimental results

- HBCC machine studies with $\beta_y^* = 1$ mm in 2021 and 2022:
  - After fine-tuning of BxB FB system in 2022, observed vertical beam sizes blowup became much more “normal” and closer to simulations



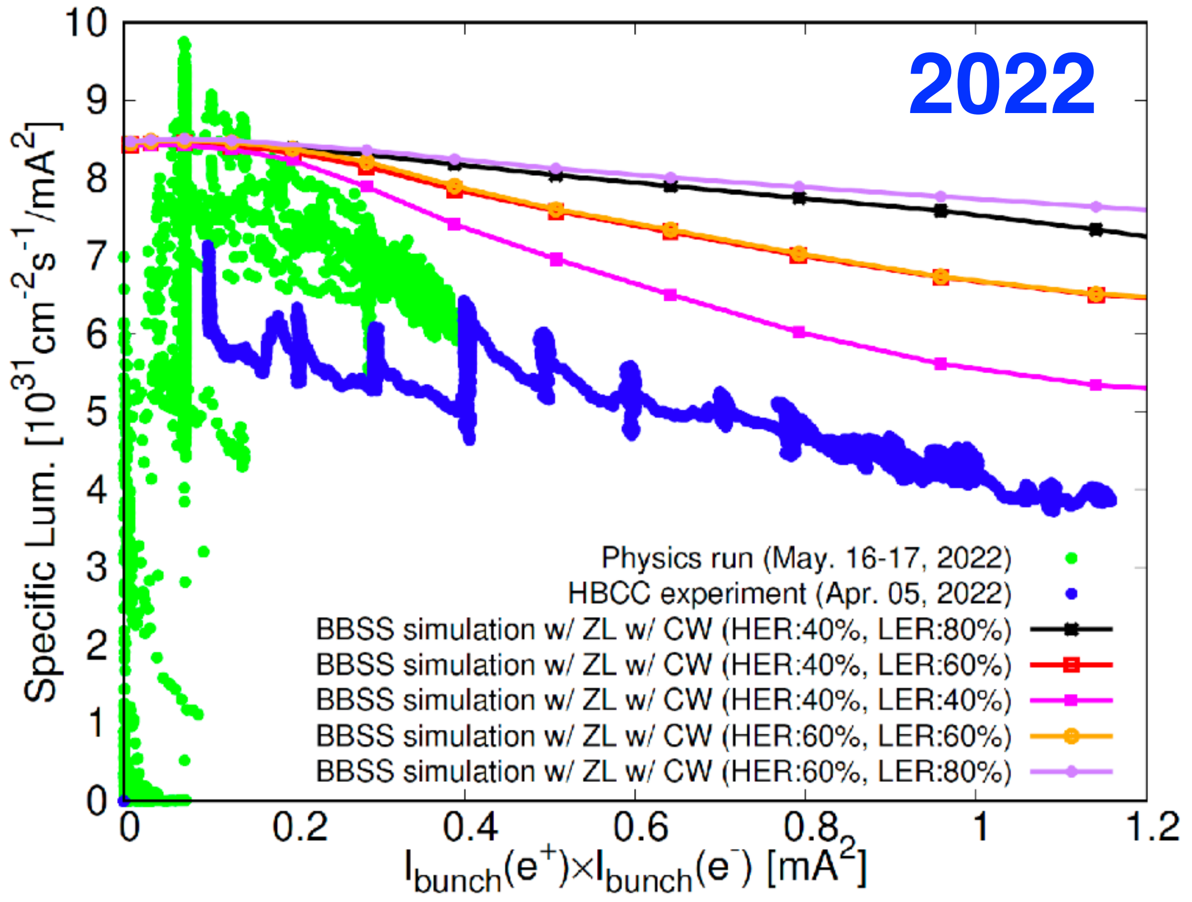


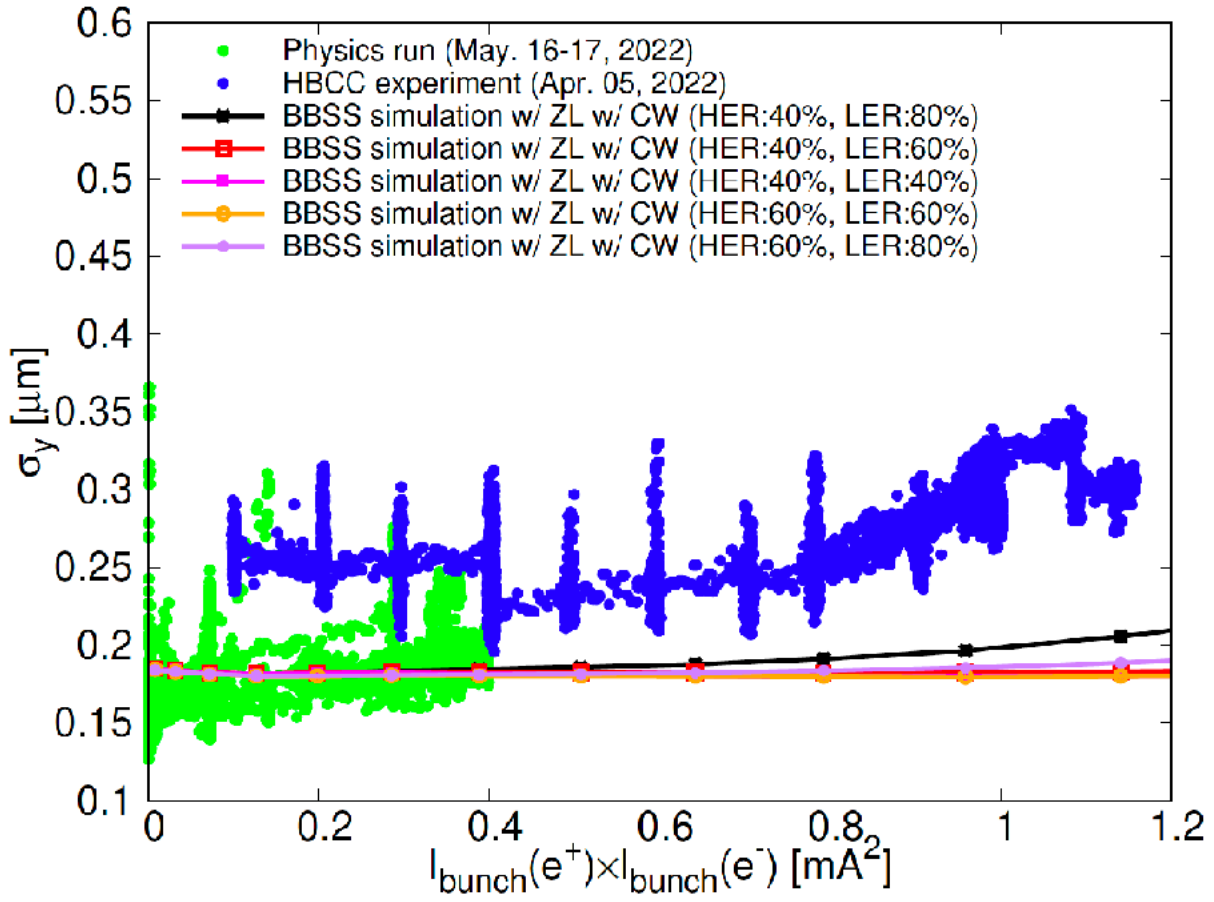


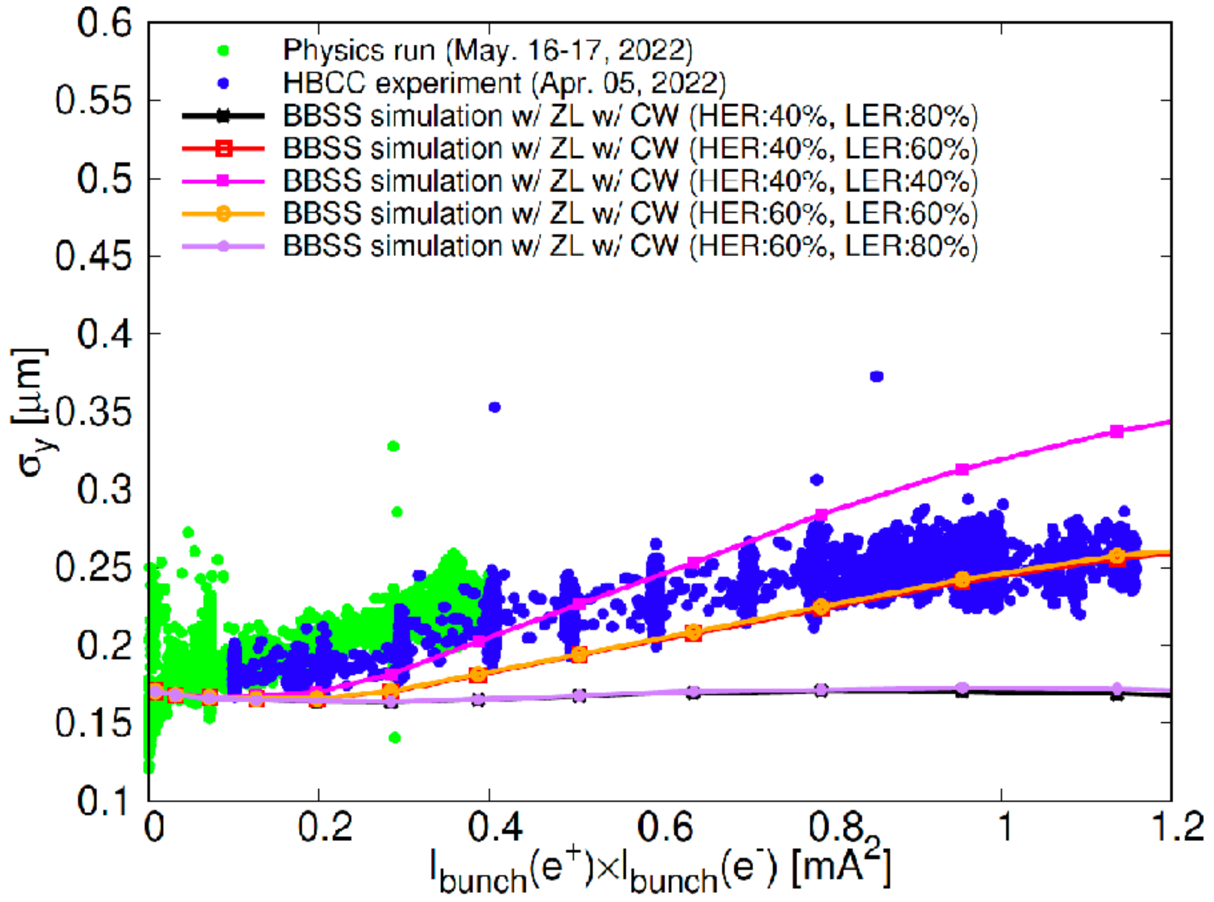
Specific luminosity

Electron σ_y^*

Positron σ_y^*







Summary

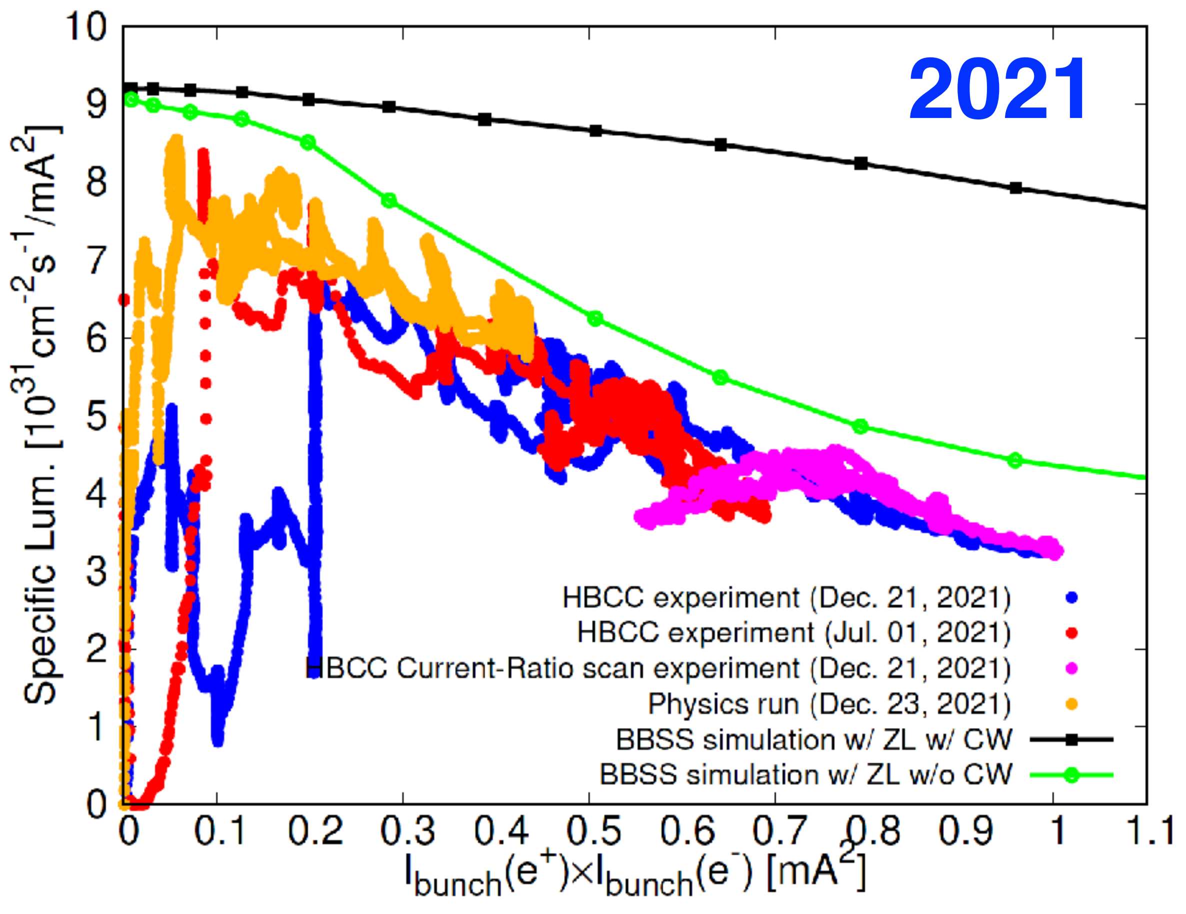
- Prediction of luminosity via beam-beam simulations requires reliable models of 1) beam-beam interaction, 2) machine imperfections, and 3) other collective effects.
- With progress in machine tunings, the measured luminosity of SuperKEKB is approaching predictions of BB simulations (BB + Simple lattice model + Impedance models).

- The main focuses on simulations for SuperKEKB
  - SS BB simulations with inclusion of multiple dynamics
  - Speedup of SS simulations with GPU-acceleration
- The main focuses on experimental studies at SuperKEKB
  - Solve the problem of sudden beam losses → Remove the limit on total currents
  - Solve the problem of the interplay between vertical impedance and BxB FB system → Remove its impact on beam-beam at high bunch currents.
  - Solve the problem of linear optics distortion at high total beam currents → Remove its impact on beam-beam, luminosity and detector background
  - Solve the problem of luminosity “loss” related with injection → Remove the impact of injection on luminosity measurement (ECL detector)
  - Investigate crab waist settings → Reduce the imperfections in crab waist

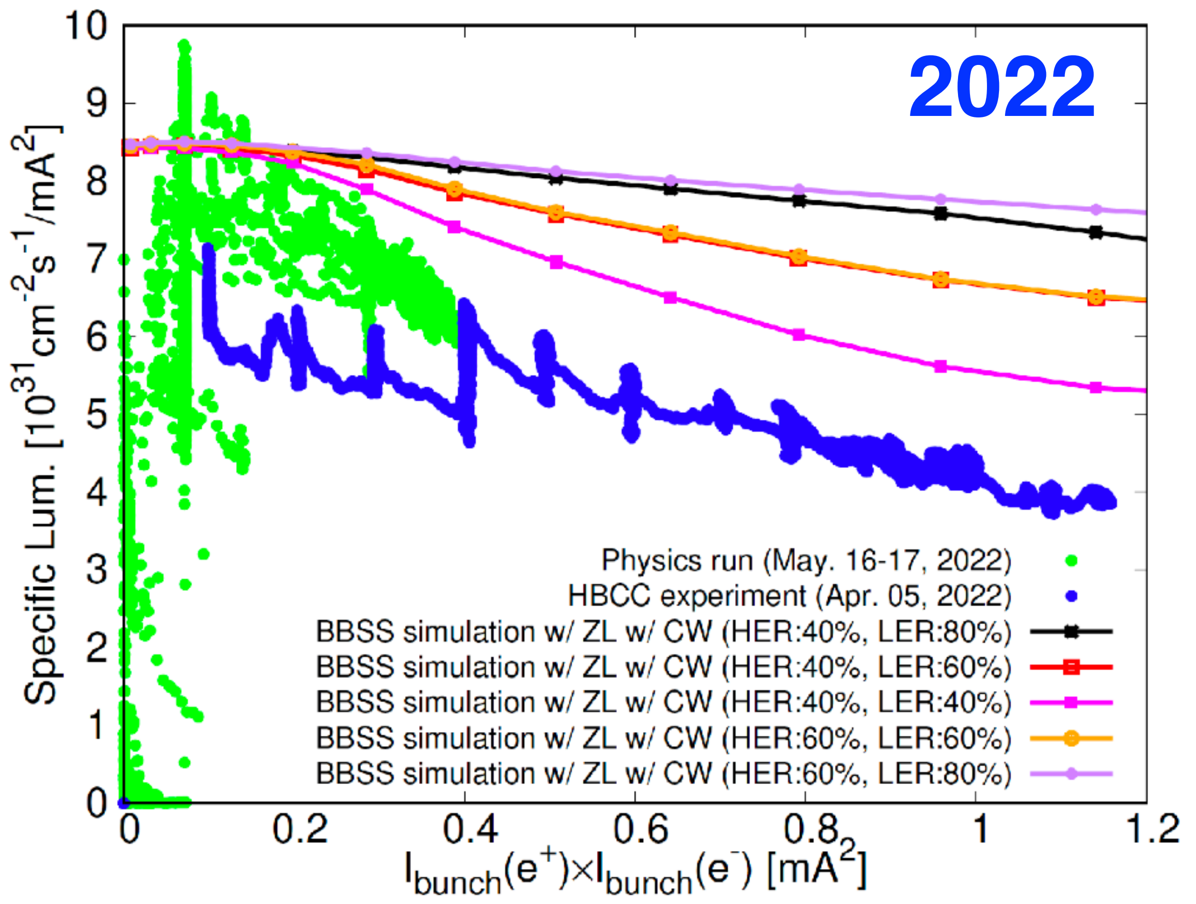
Backup

Comparison of simulations and experimental results

- HBCC machine studies with $\beta_y^* = 1$ mm in 2021 and 2022:
  - High-bunch current collision (HBCC) machine studies were done to extract the luminosity performance
  - Lsp slope (experiments) improved in 2022, but it still dropped fast



Specific luminosity



	2021.12.21		2022.04.05		Comments
	HER	LER	HER	LER	
I_{bunch} (mA)	Ie	1.25*Ie	Ie	1.25*Ie	
# bunch	393		393		Assumed value
ε_x (nm)	4.6	4.0	4.6	4.0	w/ IBS
ε_y (pm)	35	20	30	35	Estimated from XRM data
β_x (mm)	60	80	60	80	Calculated from lattice
β_y (mm)	1	1	1	1	Calculated from lattice
σ_{z0} (mm)	5.05	4.60	5.05	4.60	Natural bunch length (w/o MWI)
ν_x	45.53	44.524	45.532	44.524	Measured tune of pilot bunch
ν_y	43.572	46.589	43.572	46.589	Measured tune of pilot bunch
ν_s	0.0272	0.0233	0.0272	0.0233	Calculated from lattice
Crab waist	40%	80%	40%	80%	Lattice design

Status of beam-beam simulations

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

"Vertical blowup" "Longitudinal blowup"

- BBSS simulations: PIC vs. Gaussian fitting model
  - PIC method predicts lower luminosity (~5%).
  - Using workstations(8 cores), one PIC simulation requires ~8 months, and a Gaussian-fitting simulation takes ~1.2 days.
  - Significant progress has been achieved recently in developing GPU-based BB codes. Preliminary tests showed a speed-up factor of ~50 for PIC simulations based on the CUDA compiler (K. Ohmi, in collaboration with Y. Zhang and Z. Li (IHEP), T. Yasui (J-PARC)).
    - This will speed up our investigations, especially of the interplay between beam-beam and machine imperfections.

	2021.12.21		Comments
	HER	LER	
I_{bunch} (mA)	0.8	1.0	
# bunch	-		
ε_x (nm)	4.6	4.0	w/ IBS
ε_y (pm)	35	20	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	4.60	Natural bunch length (w/o MWI)
ν_x	45.53	44.524	Measured tune of pilot bunch
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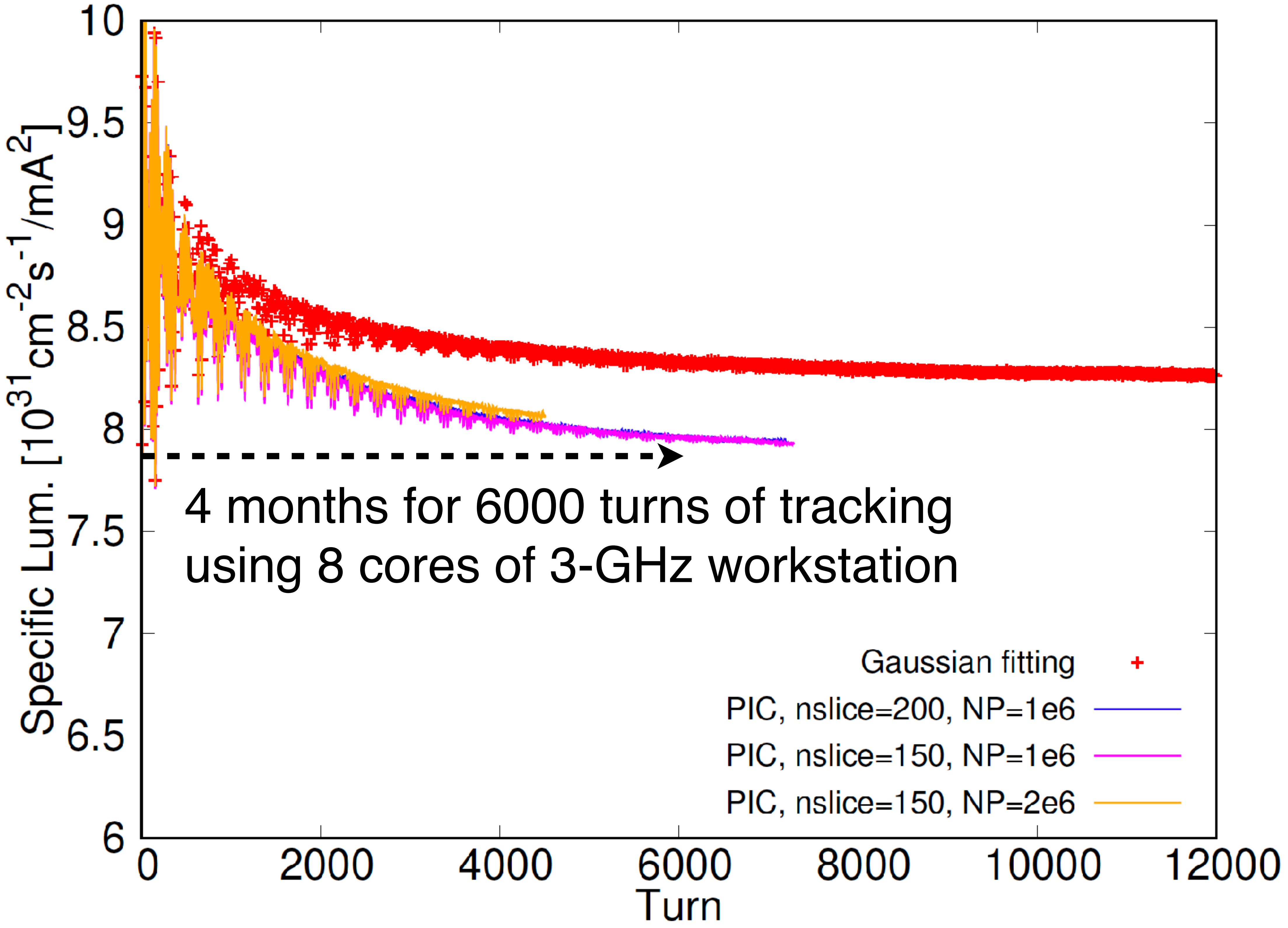
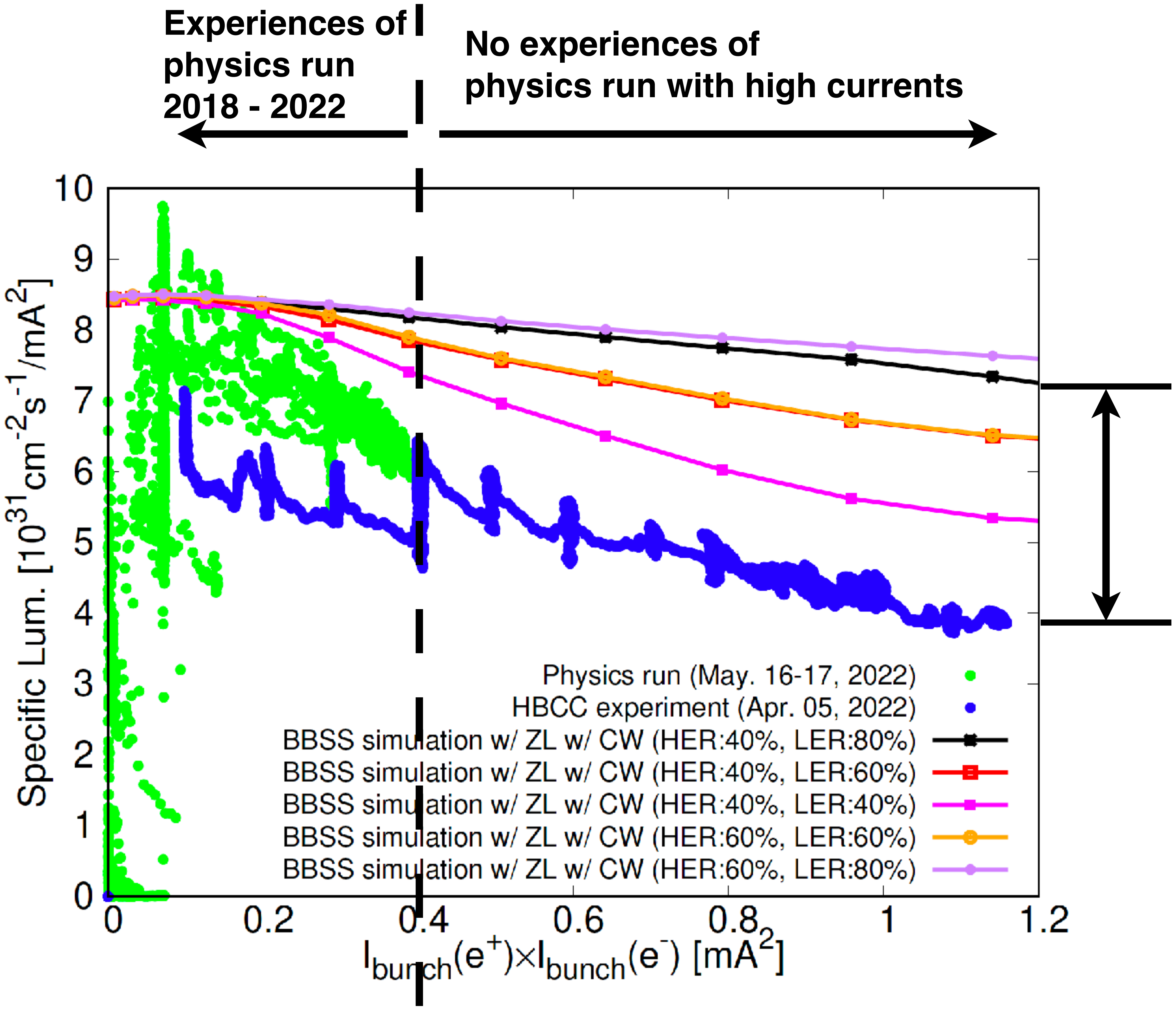


Comparison of simulations and experimental results

- Filling the gap between simulated and measured Lsp
  - BBSS+PIC simulation showed 5% less Lsp at $I_{b+}I_{b-} = 0.8$ mA^2.
  - Impedance effects:
    - Simulations showed less bunch lengthening than measurements. If measured bunch lengthening is applied, it gives ~10% extra loss of Lsp at $I_{b+}I_{b-} = 0.8$ mA^2.
    - Vertical beam tilt due to monopolar wakes.
    - “-1 mode instability” due to interplay of FB and vertical impedance.
  - Lsp loss correlated with injection: ~10% at $I_{b+}I_{b-} = 0.3$ mA^2 (not sure how much loss at high bunch currents).
  - Other sources of Lsp degradation without quantitative estimate.

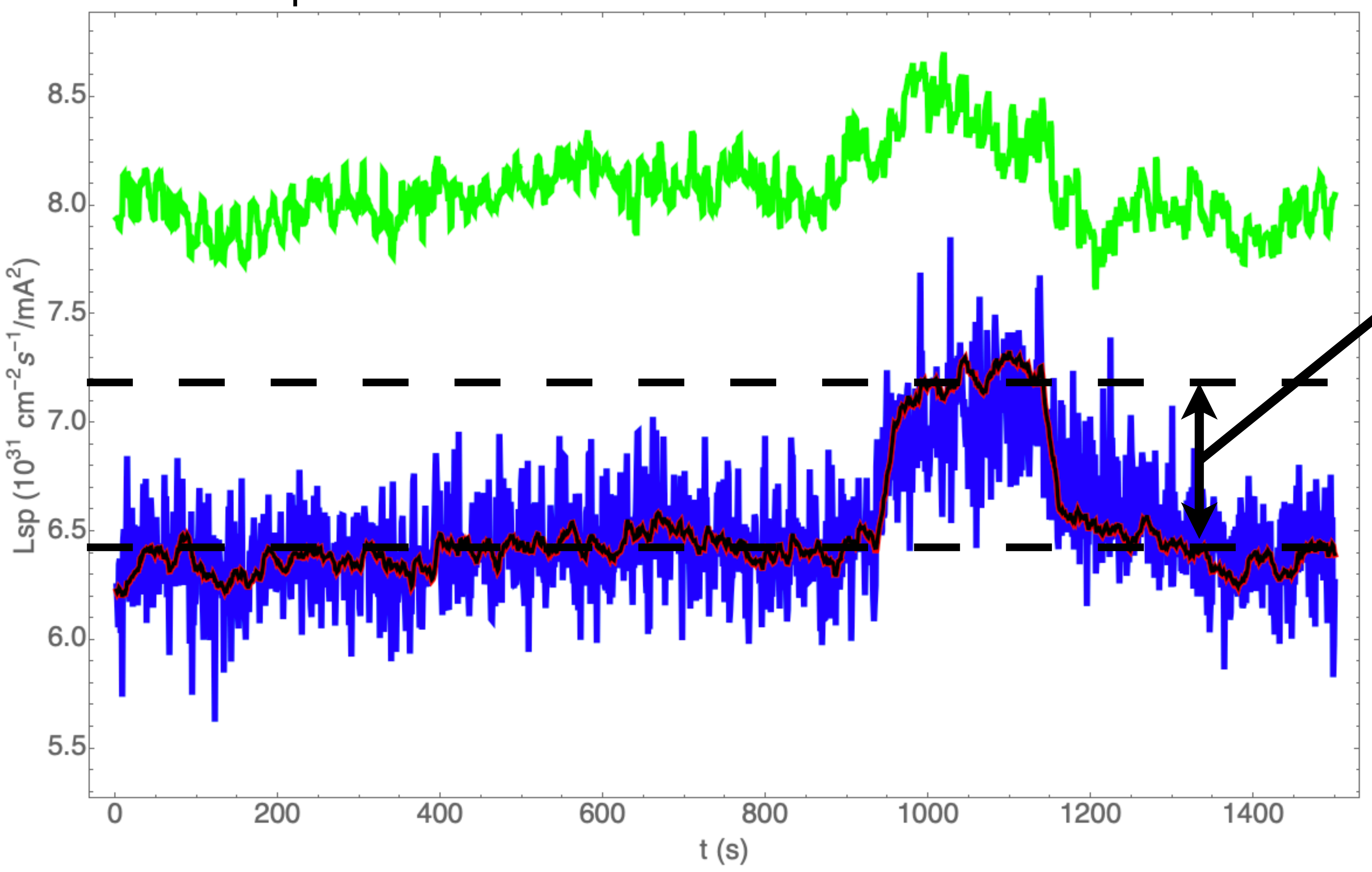


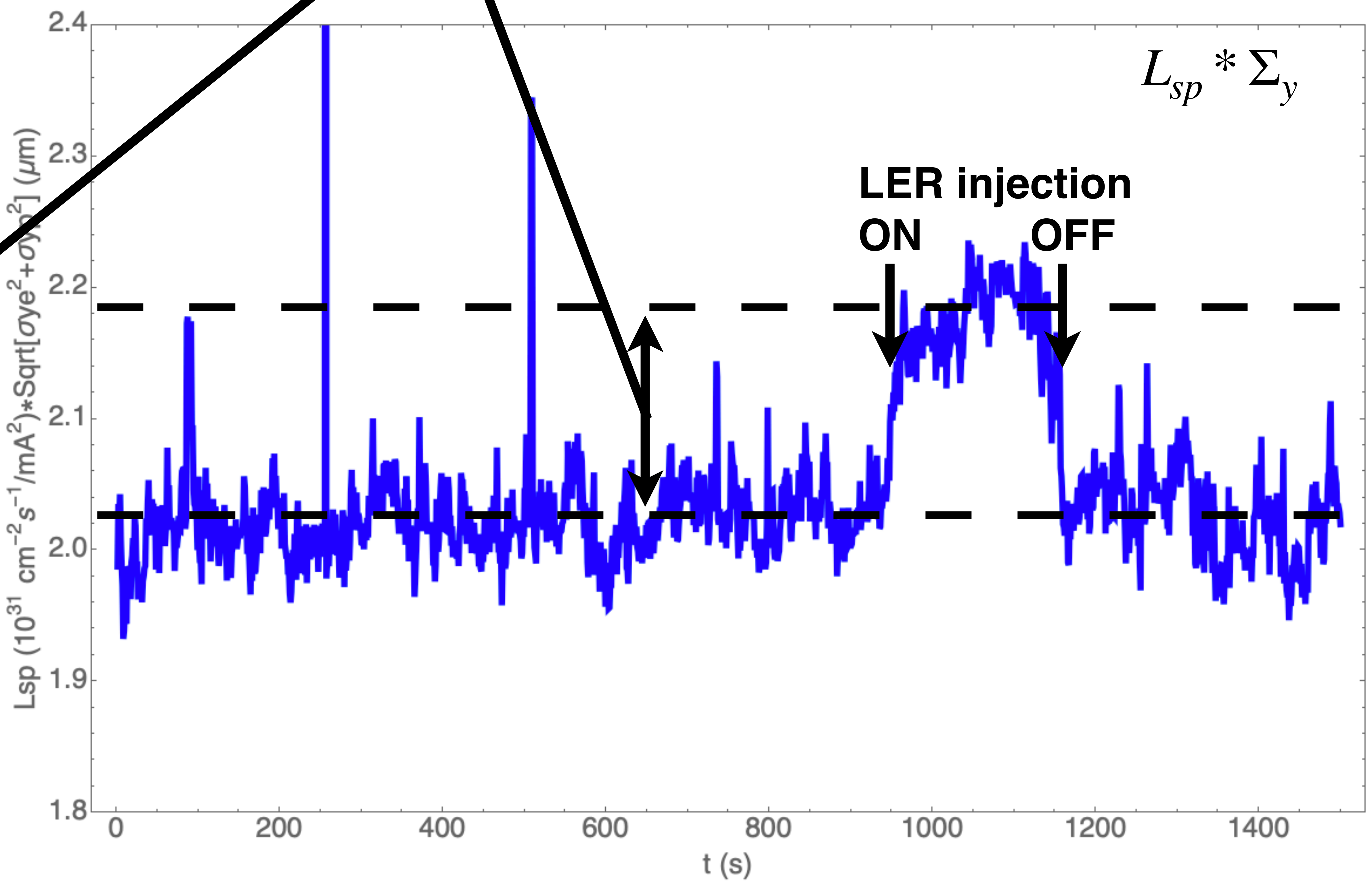
Comparison of simulations and experimental results

- A mysterious phenomenon: Lsp is correlated with beam injection
  - All luminosity PVs gave a similar jump-response to injection stop/start.
  - $L_{sp} \cdot \sqrt{\sigma_{y+}^{*2} + \sigma_{y-}^{*2}}$ still shows jump-response. It means there is a geometric loss of luminosity.

Blue: Luminosity by ECL
Red: Luminosity by ECL (averaged)
Green:Luminosity by ZDLM
Black: Lsp

Lsp degradation by ~10%, independent to vertical emittances





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