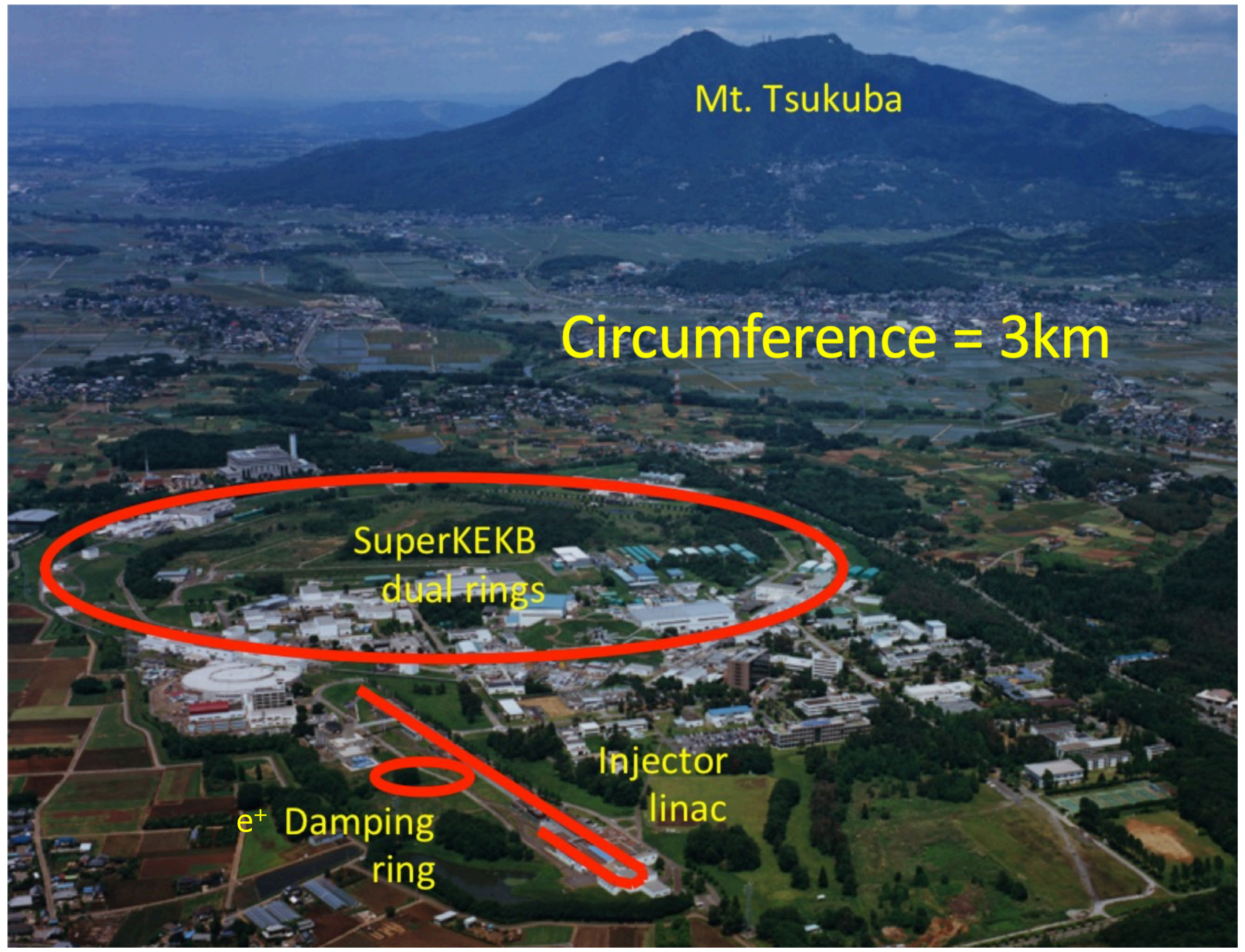
NAPAC 25 2025 North American Particle Accelerator Conference

Recent Experience with High-Luminosity Operation of SuperKEKB

Yukiyoshi Ohnishi (KEK)

on behalf of the SuperKEKB accelerator team



e^+e^- Double Ring Collider

4 GeV e^+ LER x **7 GeV e^- HER**

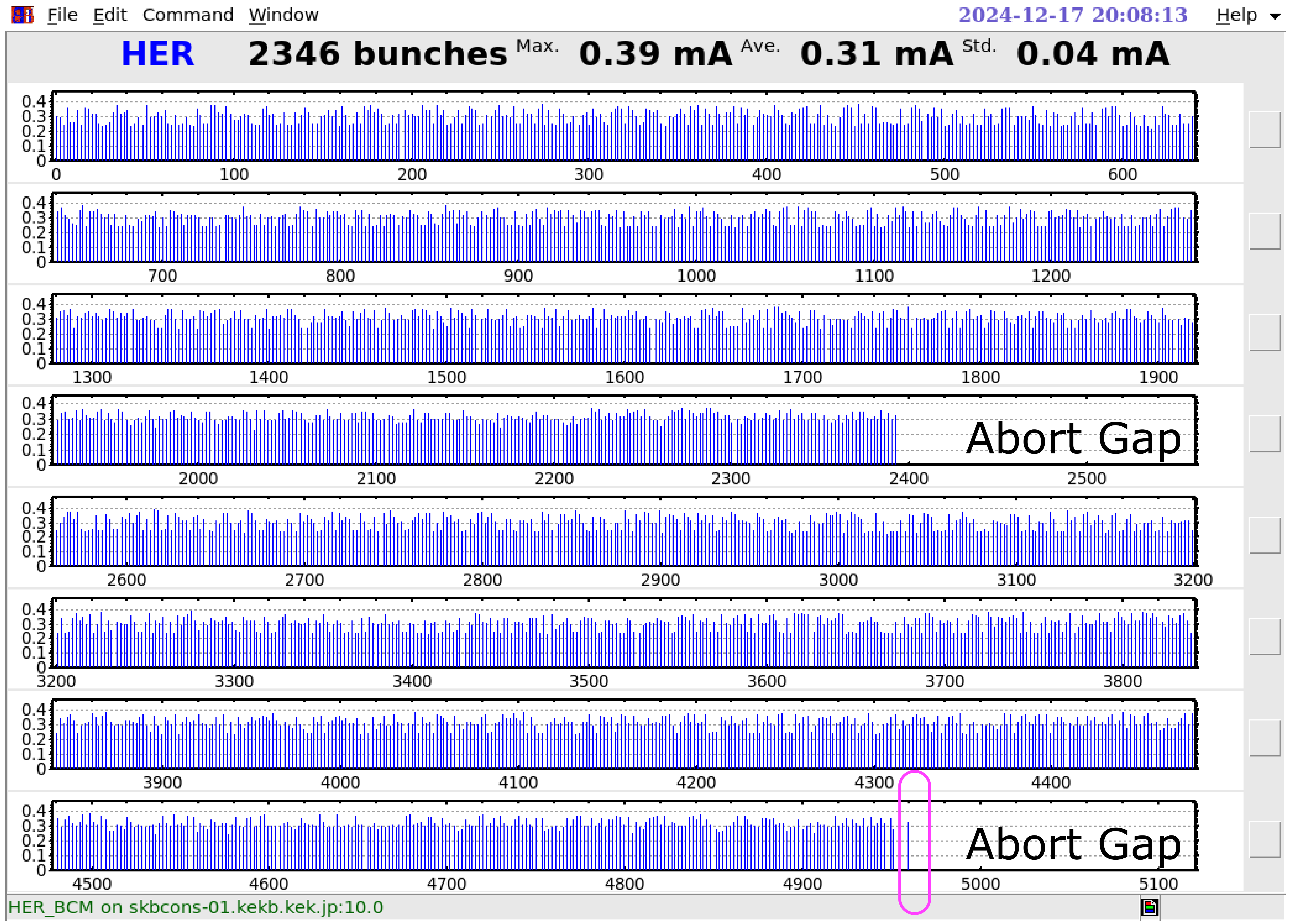
Crossing Angle: 83 mrad

Number of Bunches: 2346

Harmonic Number: 5012

Off-Axis Top-Up Injection

2346 Bunches , Two Trains



Pilot Bunch
(Non Collision)

Utilized for Tune Feedback

Pilot Bunch
(Non Collision)

Utilized for Tune Feedback

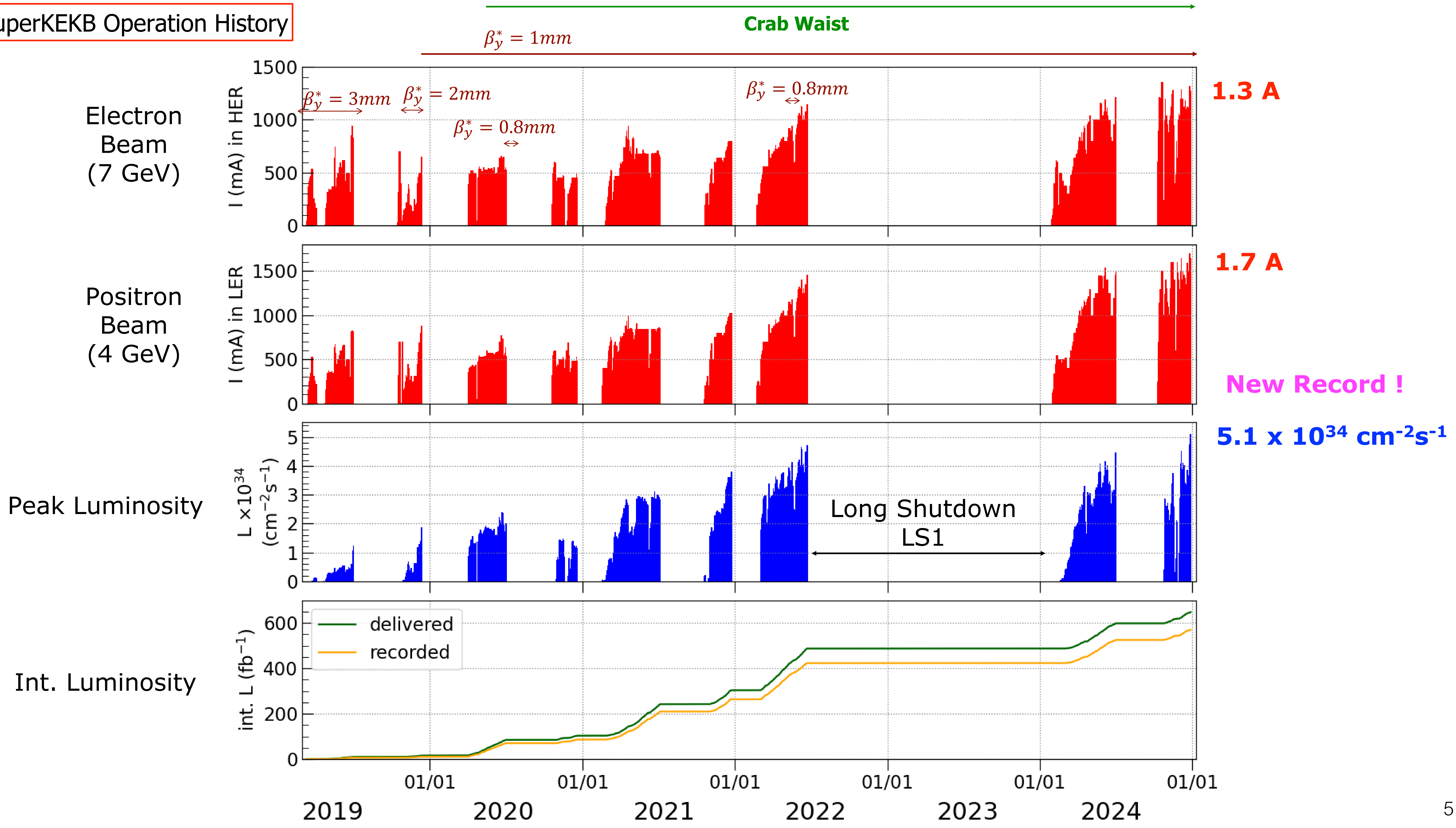
Achievements in 2024

	LER	HER
Beam Current	1.7 A	1.3 A
Emittance	4.0 nm	4.6 nm
Hor./Ver. Beta (IP)	60 mm / 1 mm	
Ver. Beam Size (IP)	265 nm*	
Beam-Beam (ξ_y)	0.036	0.027
Luminosity	5.1×10^{34} cm^{-2}s^{-1}	

Highest Luminosity in the World

* Estimated by luminosity and equal size between LER and HER is assumed.

SuperKEKB Operation History

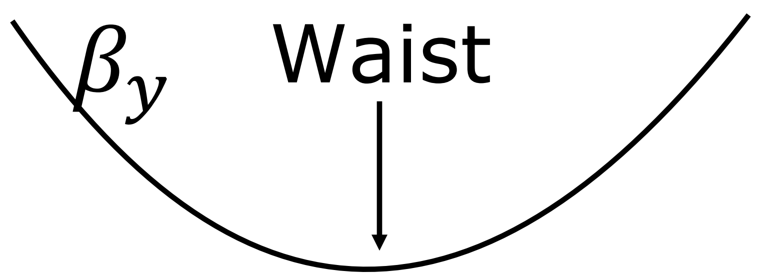


Two Advanced Technologies

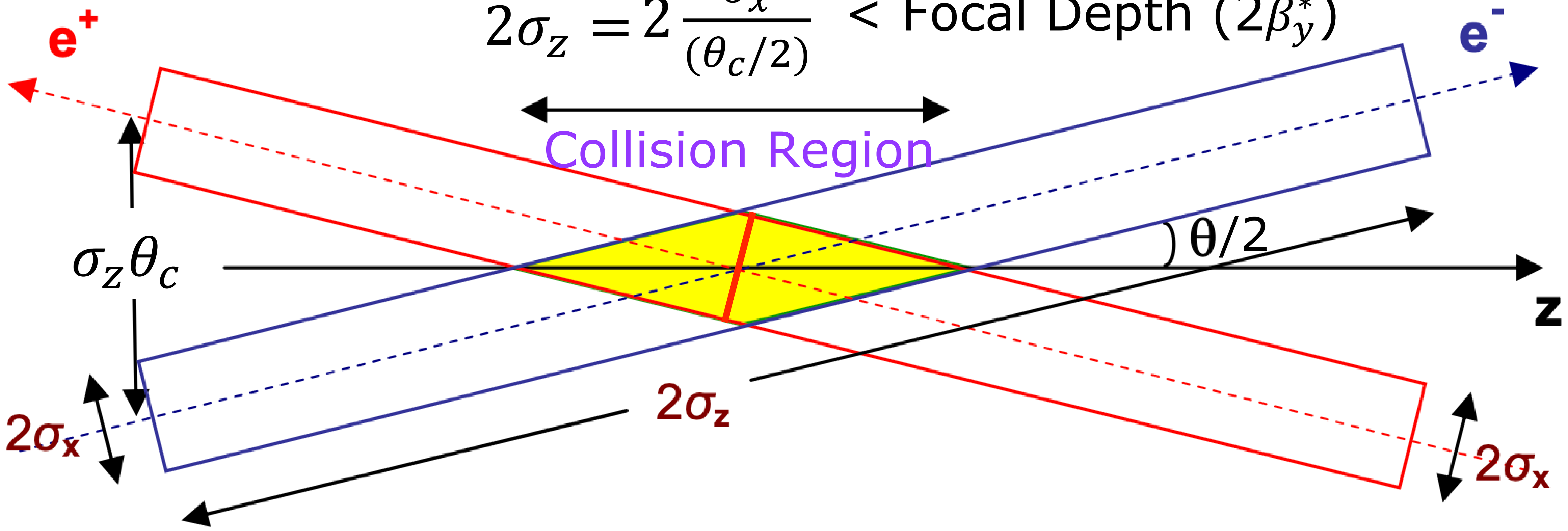
P. Raimondi et al., LNF-07/003

1. Nano-Beam Scheme

Large Crossing Angle with Low ε_x



$2\tilde{\sigma}_z = 2\frac{\sigma_x^*}{(\theta_c/2)}$ < Focal Depth ($2\beta_y^*$)



Effectively Very Short Bunch with "Head-On" Collision
→ Mitigates "Hourglass" Effect

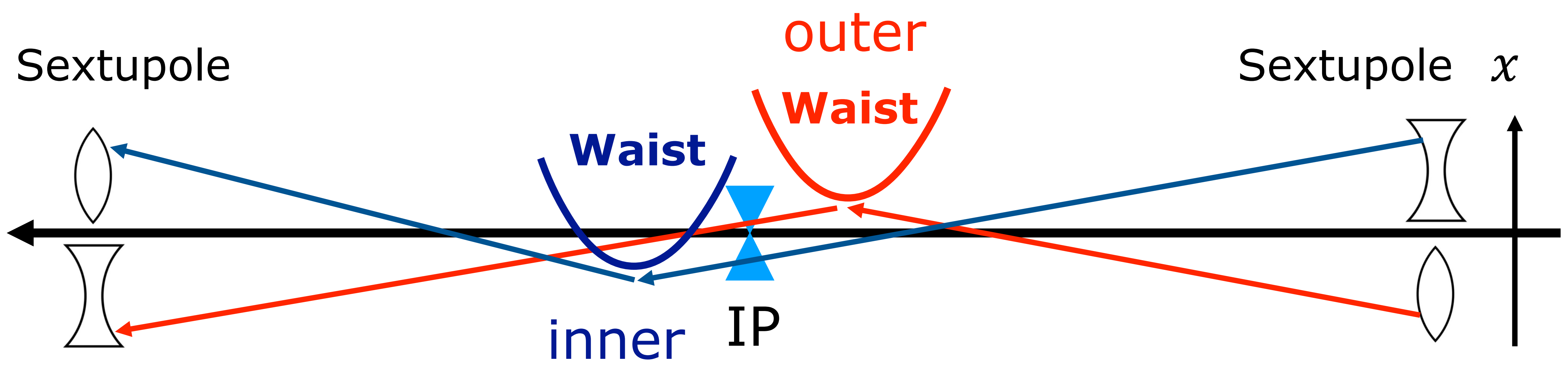
$$\beta_y^* > \tilde{\sigma_z} = \frac{\sigma_z}{\sqrt{1+\Phi^2}} \simeq \frac{\sigma_x^*}{(\theta_c/2)} < 1mm$$

⟷ SuperKEKB
σ_z = 6 mm
Φ =~ 12
$\tilde{\sigma}_z$ = 0.5 mm

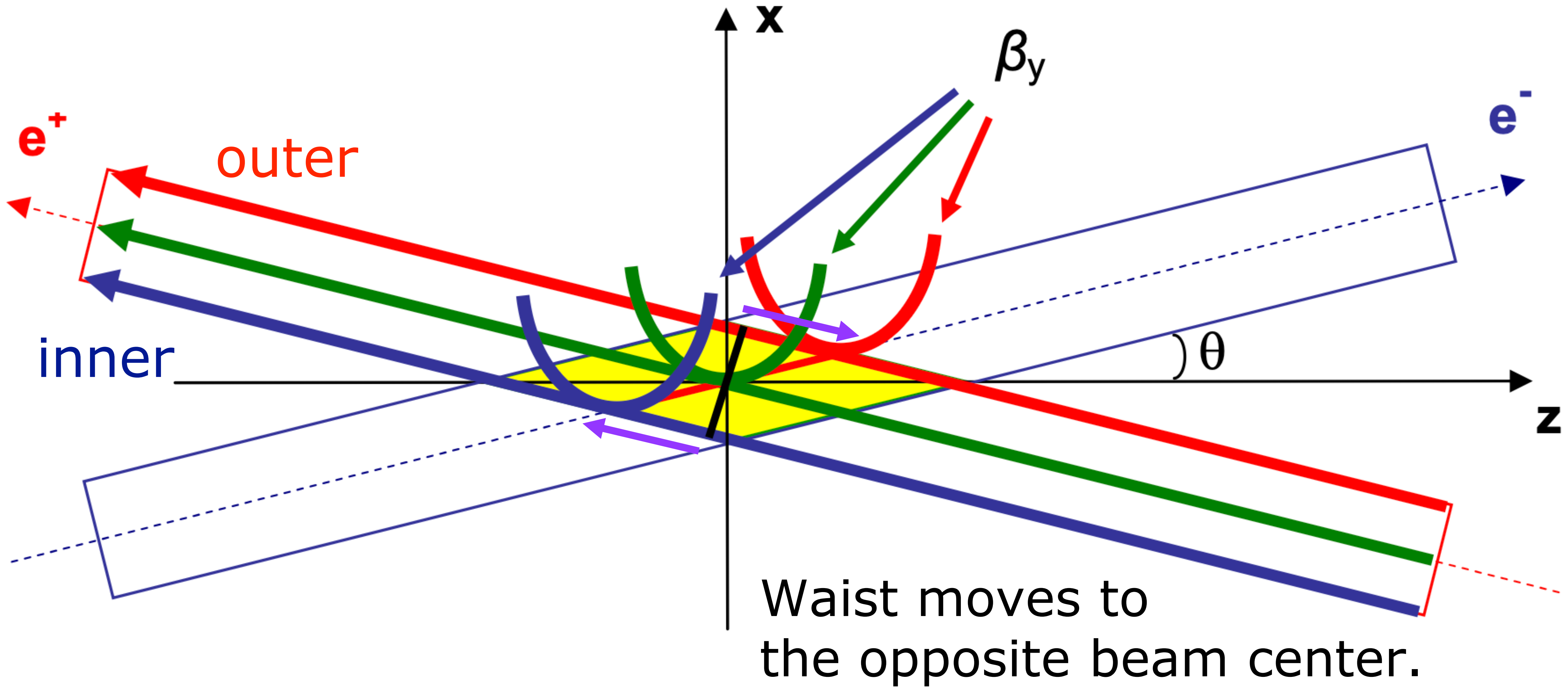
Large Piwinski Angle Φ

2. Crab-Waist Scheme

Strong Sextupoles with Specific Optics

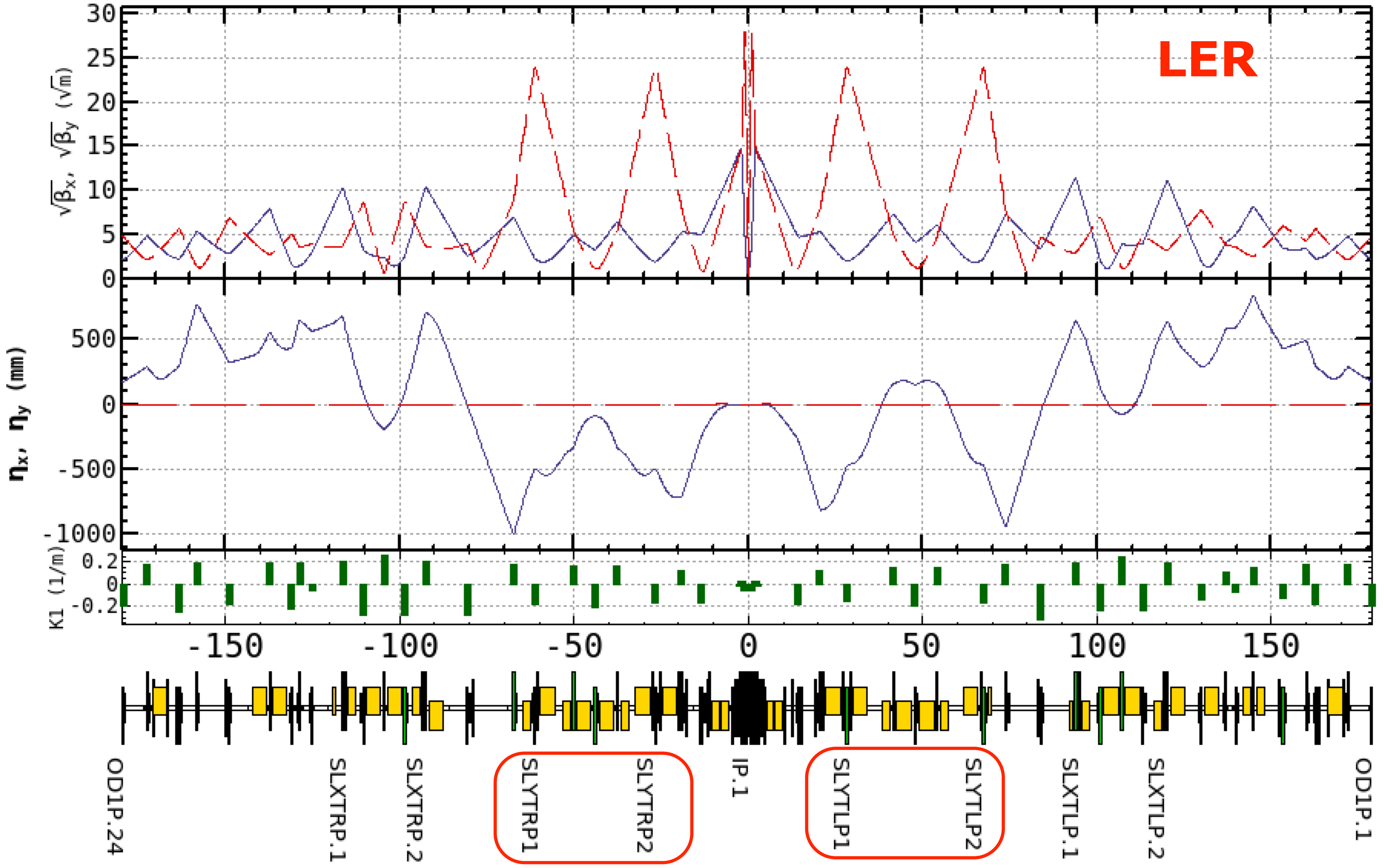


$\Delta\psi_x = \pi \Delta\psi_y = \pi/2$

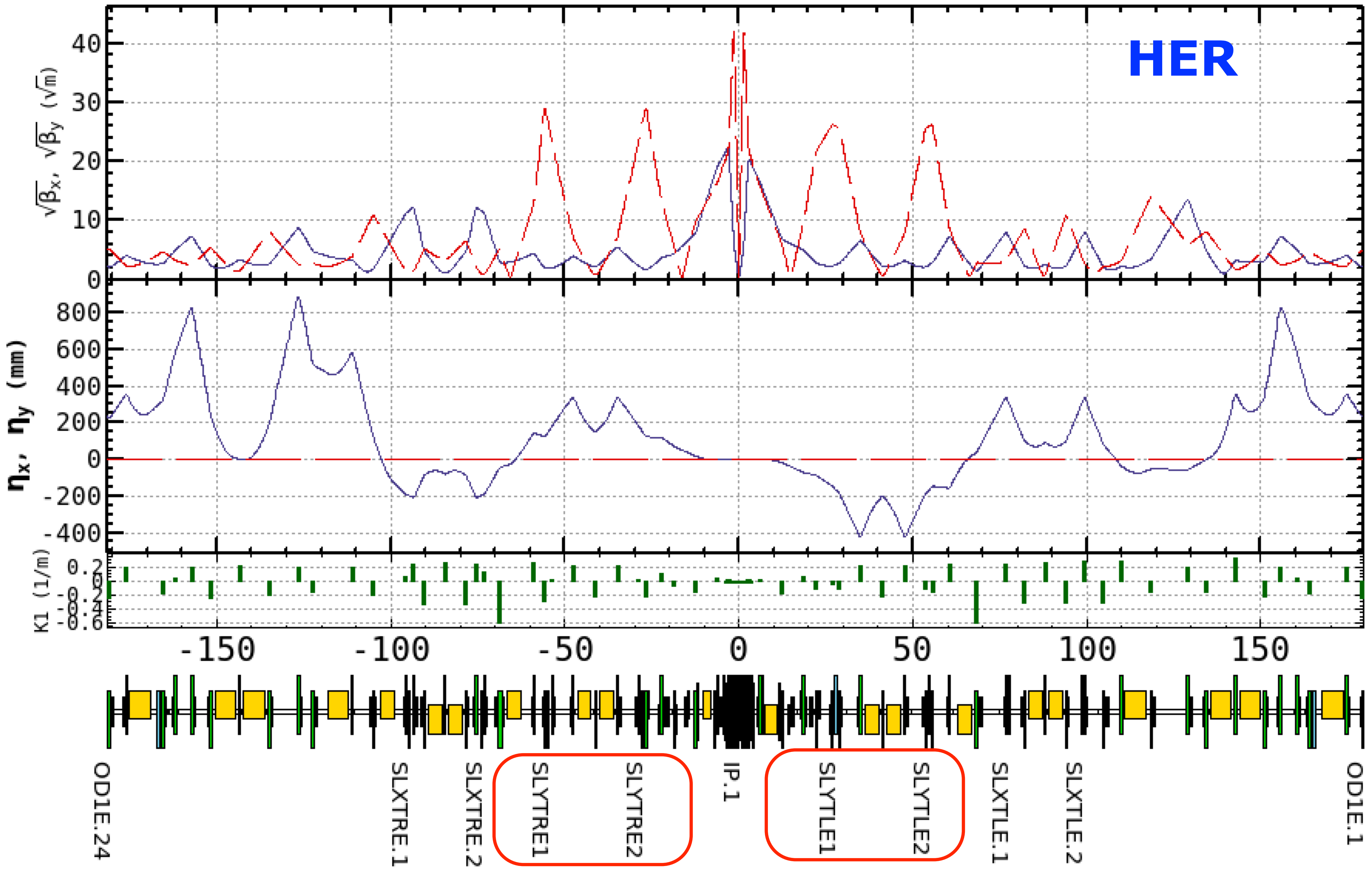


Suppression of Betatron Resonance
Related to Beam-Beam Interaction

Local Chromaticity Correction and Crab Waist Scheme



Local chromaticity correction and crab-waist sextupoles



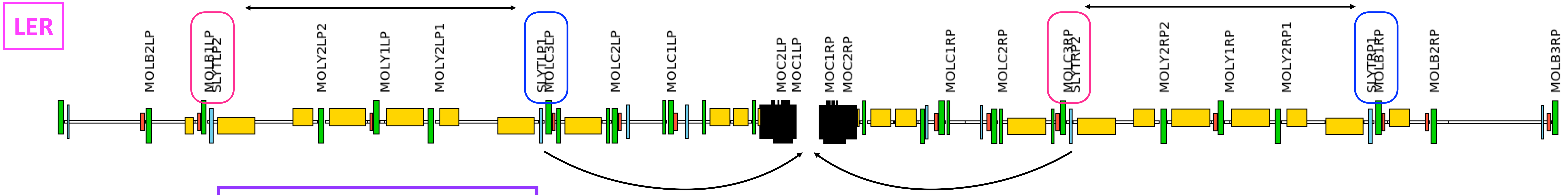
Local chromaticity correction and crab-waist sextupoles

Vertical Local Chromaticity Correction Can also Function as Crab-Waist Scheme.

Crab-Waist Scheme in SuperKEKB

$$H^*_{cw} = \frac{R_{cw}}{2\tan\theta_c} x^* p_y^{*2} \quad \Rightarrow \quad K_{2,cw} = \frac{R_{cw}}{\tan\theta_c}\frac{1}{\beta_y^s \beta_y^*}\sqrt{\frac{\beta_x^*}{\beta_x^s}}$$

CW Sextupole(2) — $M_{ss} = -I'$ — CW Sextupole (1) — IP — CW Sextupole (2) — $M_{ss} = -I'$ — CW Sextupole (1)



$$K_2^{(1)} = K_2 - K_{2,cw}/2$$
$$K_2^{(2)} = K_2 + K_{2,cw}/2$$

$$\Delta\psi_x = \psi_x^s - \psi_x^* \sim \pi$$
$$\Delta\psi_y = \psi_y^s - \psi_y^* \sim \frac{3}{2}\pi$$

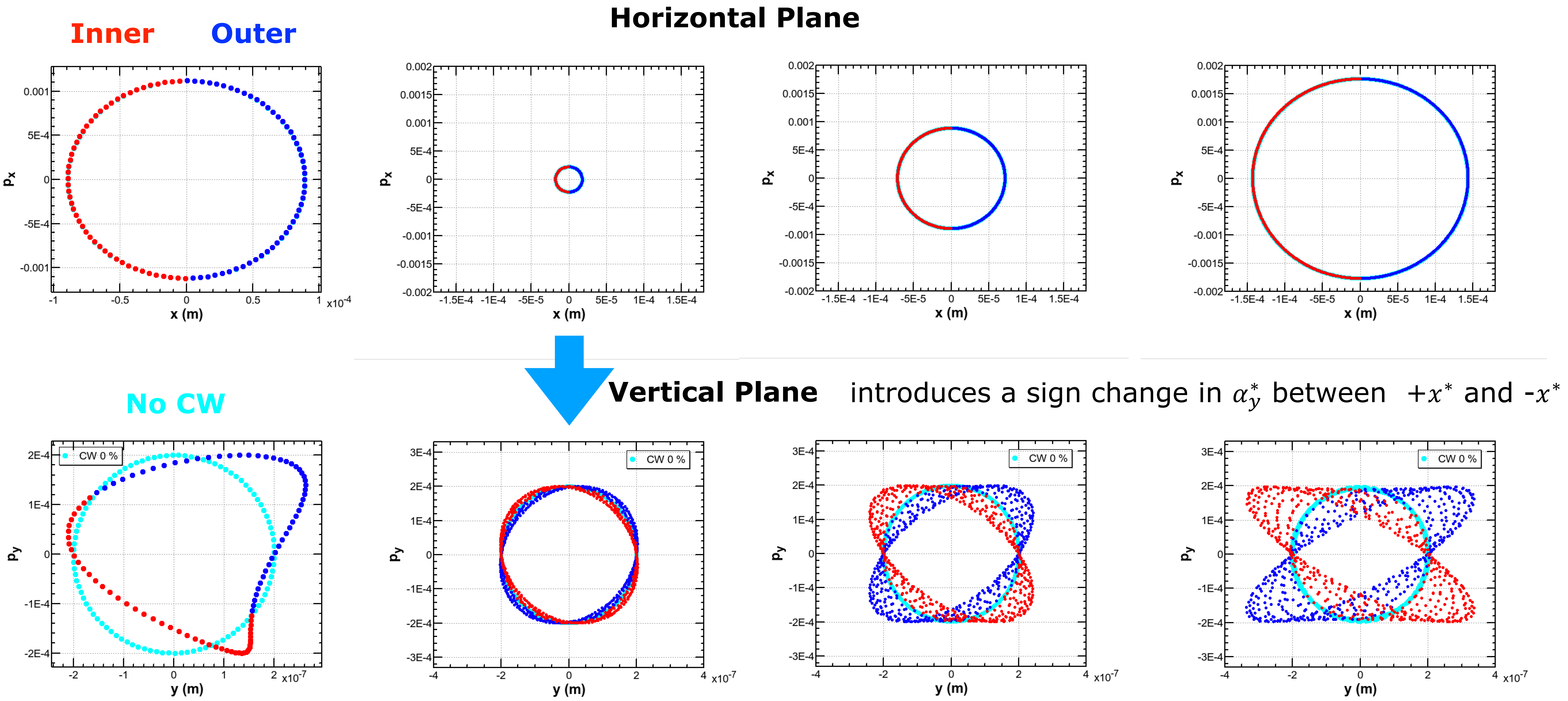
Appropriate Phase Advance

← Positron Beam

Crab-Waist Ratio: $R_{cw} = 0.6 - 0.8$

$K_2^{(1)} + K_2^{(2)} = 2K_2$	Chromaticity Correction
$K_2^{(2)} - K_2^{(1)} = K_{2,cw}$	Crab-Waist Effect

Crab Waist Scheme: Waist Rotation by Sextupoles



introduces a sign change in α_y^* between $+x^*$ and $-x^*$

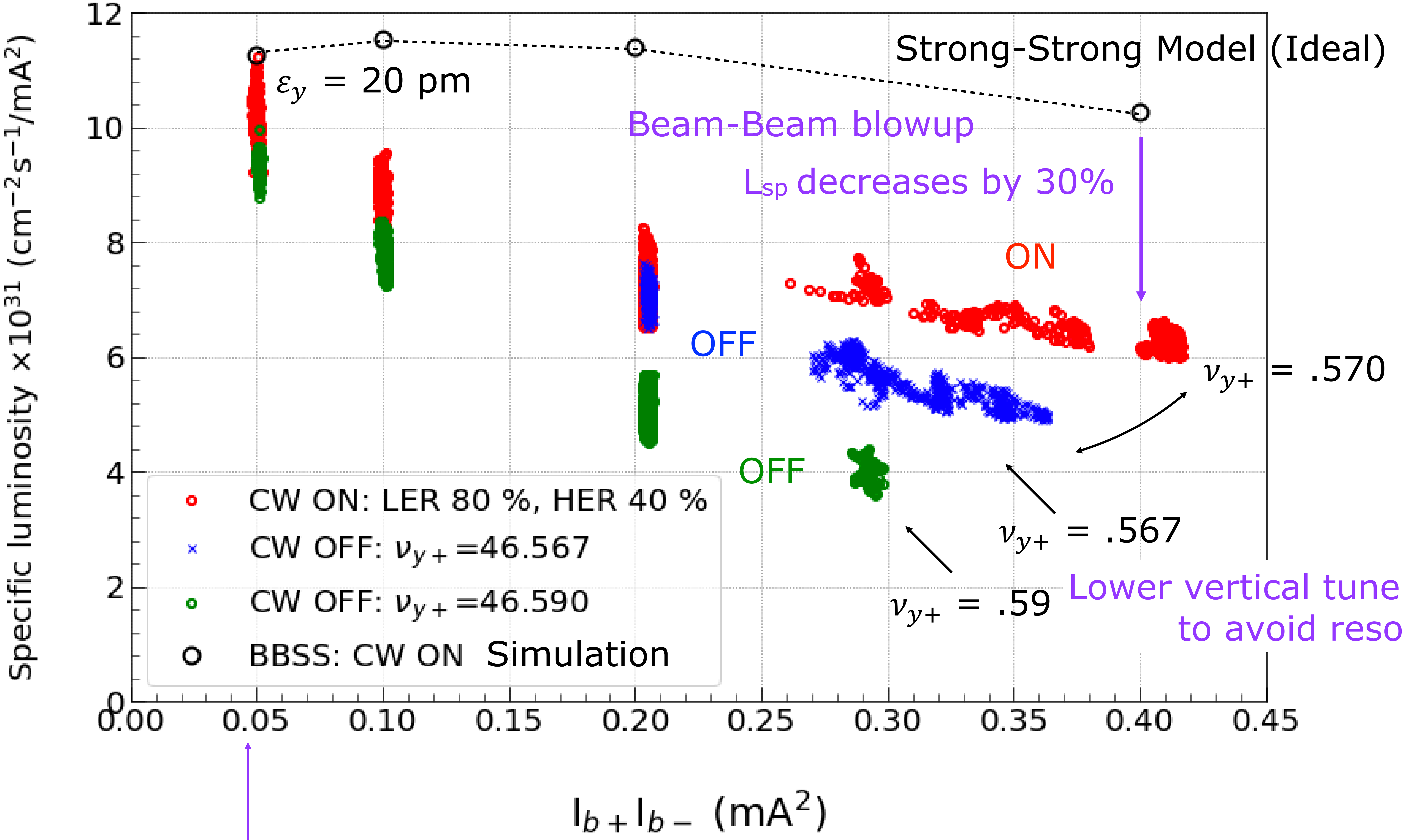
Single-Turn

Muti-Turn (Single Particle)

Beam-Beam Interaction

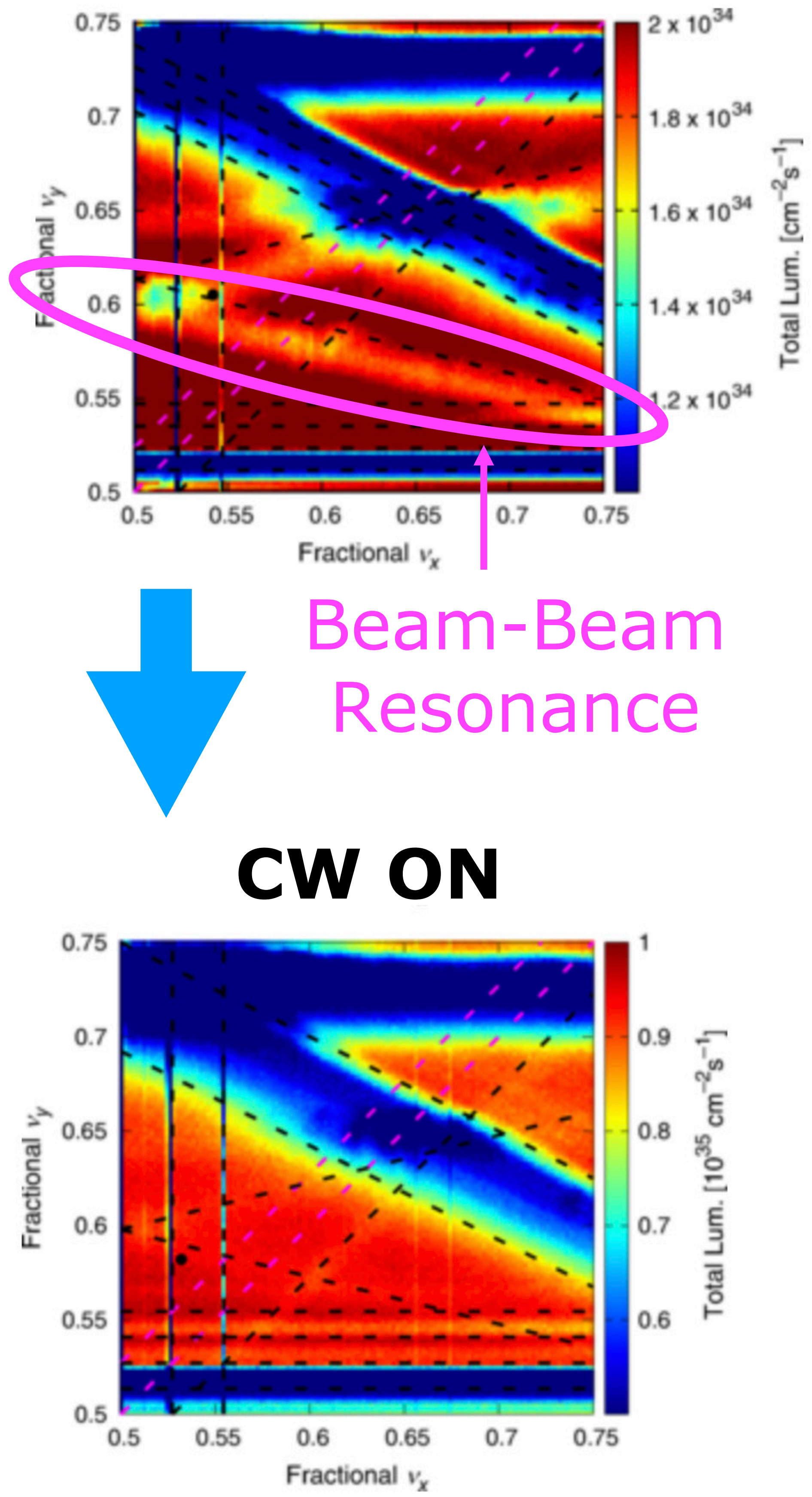
Crab-Waist ON and OFF

$$L_{sp} = \frac{L}{I_{b+}I_{b-}n_b} \propto \frac{1}{\sigma_y^*}$$



Lower vertical tune is preferable to avoid resonance.

No Beam-Beam blowup for small $I_{b+}I_{b-}$.



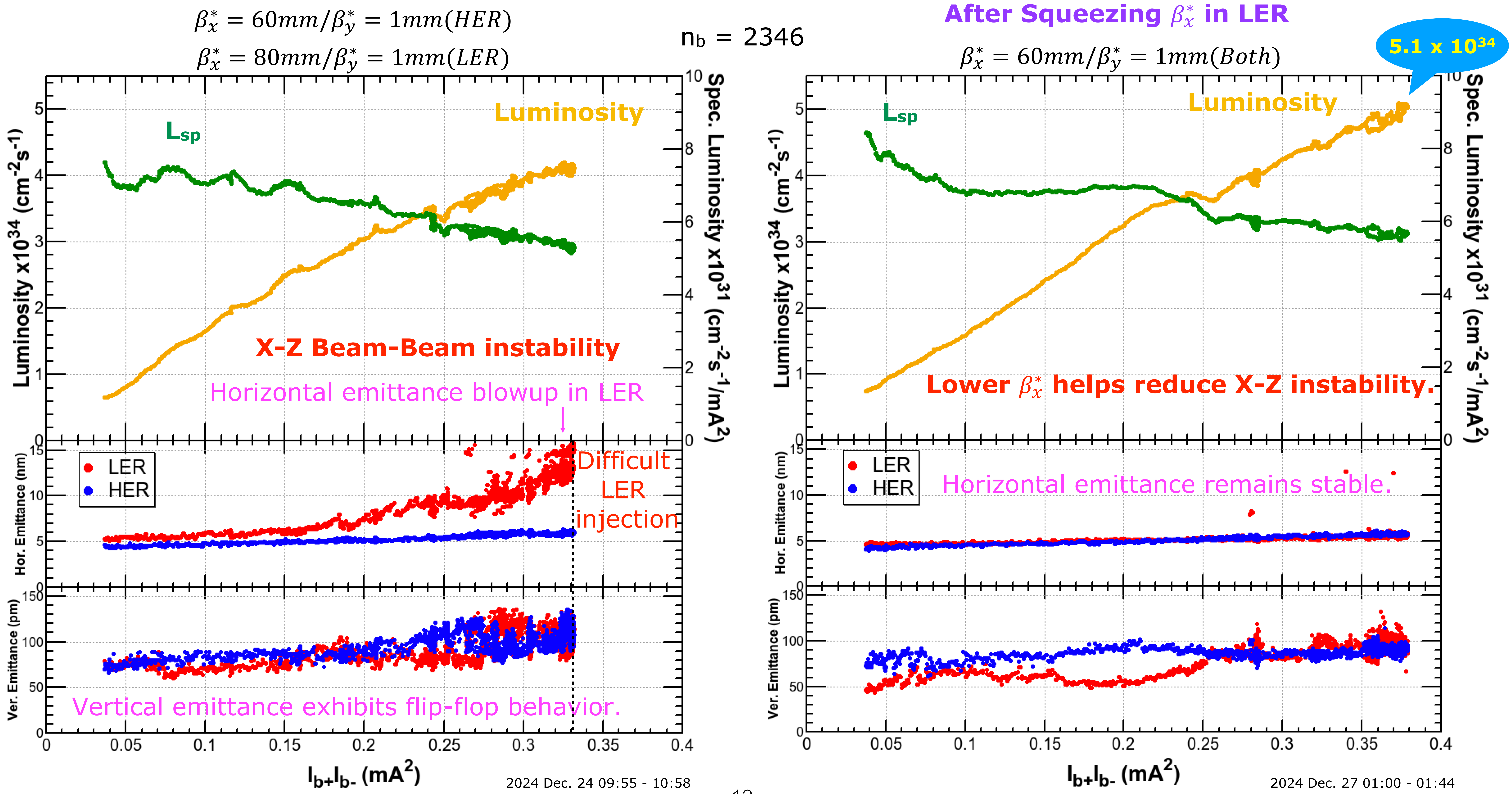
Beam-Beam Simulations
D. Zhou et al.,
Phys. Rev. AB 26 071001

Crab-waist suppresses betatron resonance.

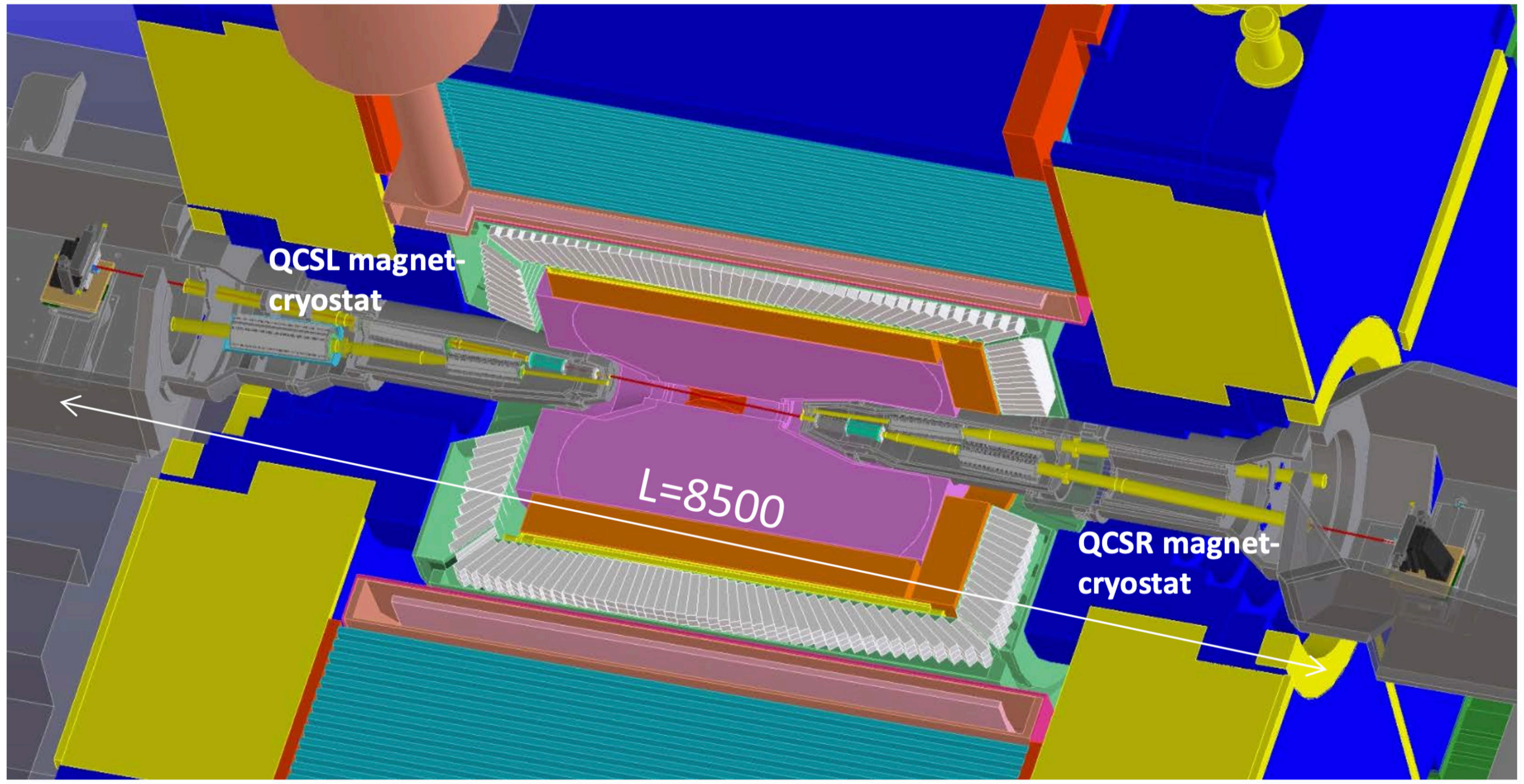
The crab waist is effective at high intensity.

Large Crossing-Angle Collision

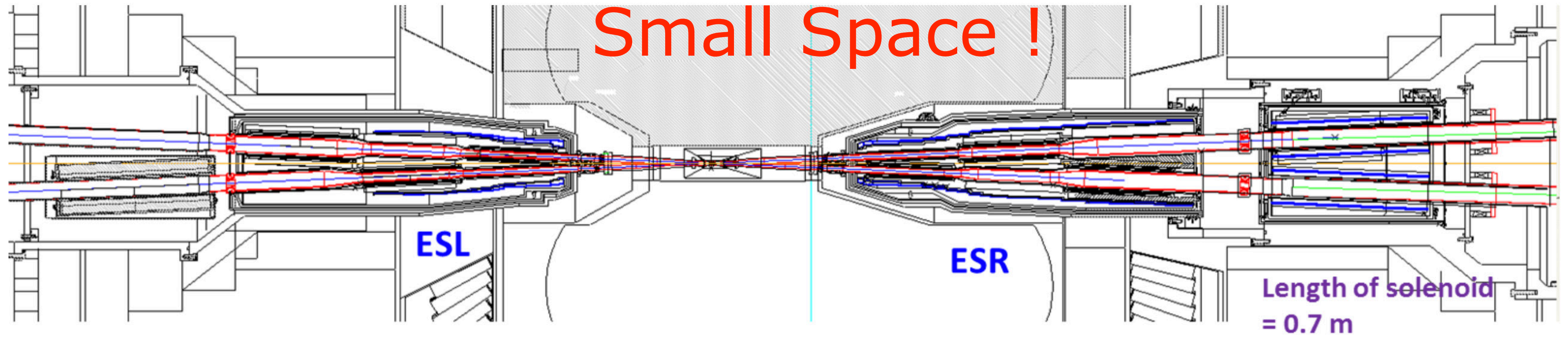
$\theta_c = 83mrad$



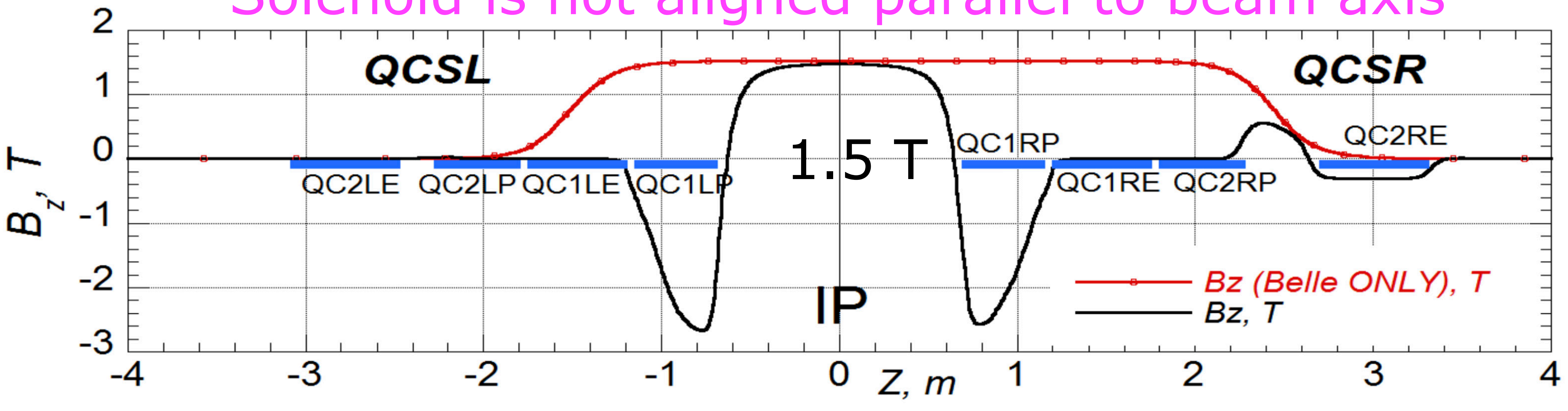
Interaction Region at SuperKEKB

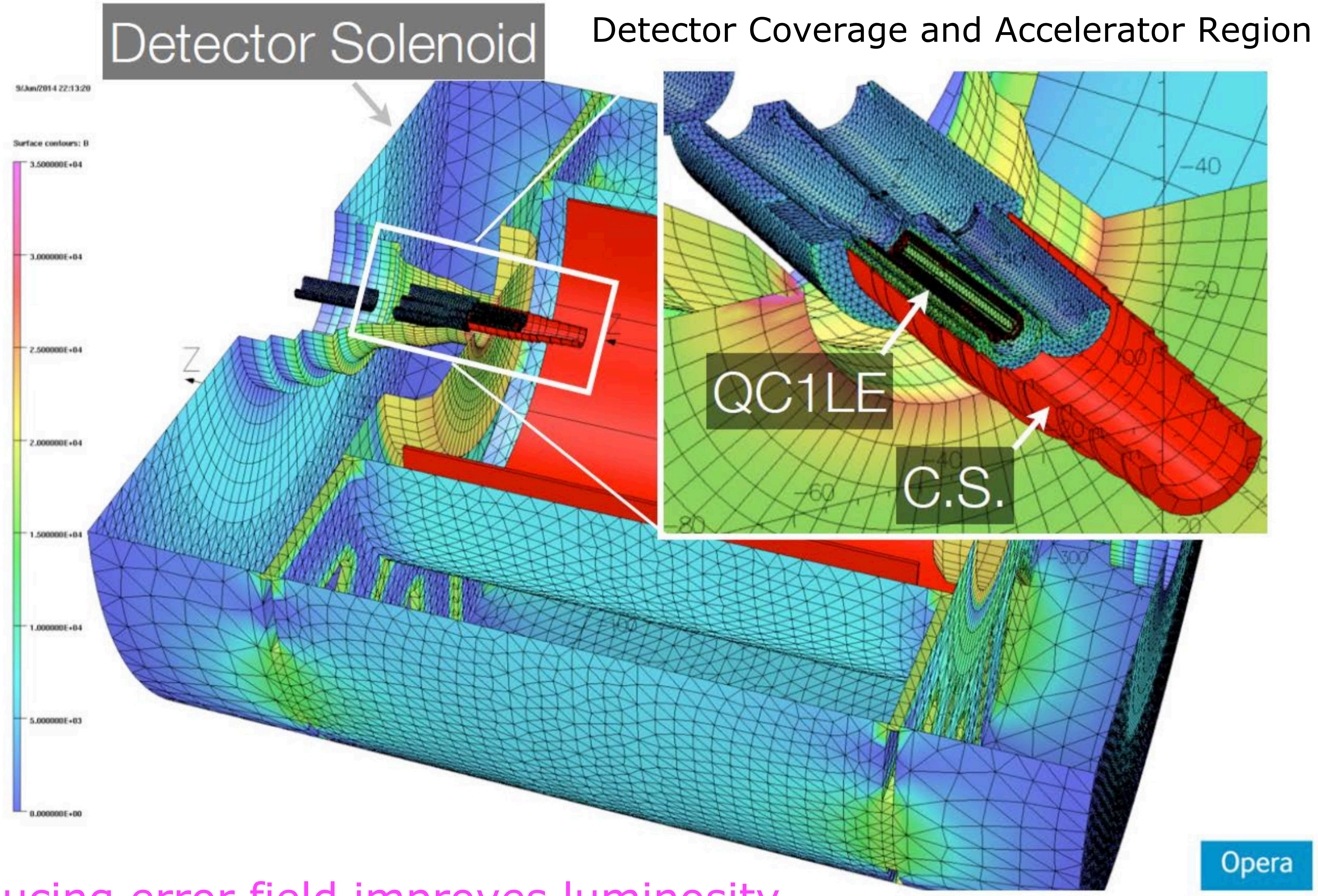


Alignment of each component affects luminosity performance.



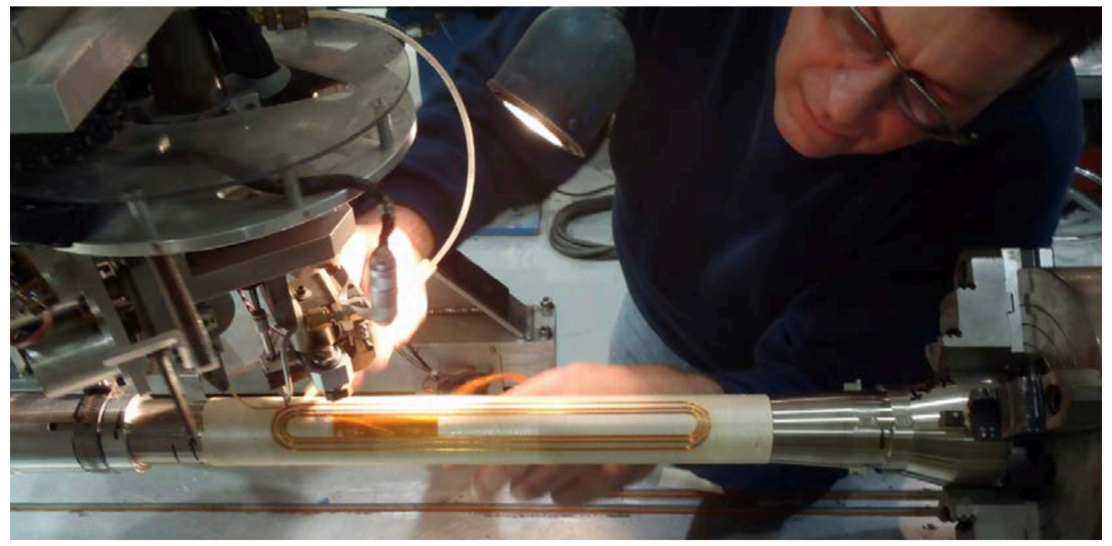
Solenoid is not aligned parallel to beam axis





Reducing error field improves luminosity.

Direct Winding of SC Corrector Coil (BNL)



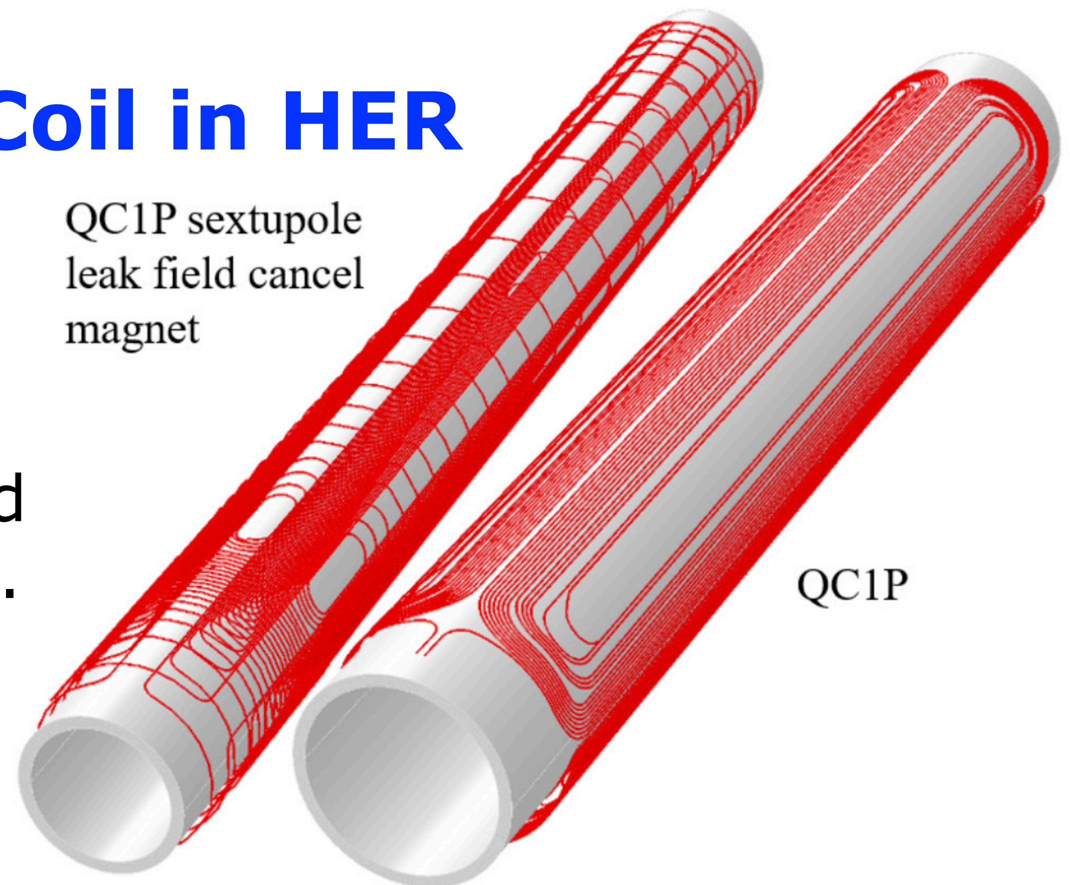
Many corrector coils
are installed
to correct error field

Manufacturing Defect of Cancel Coil in HER

The design compensates normal and skew multipole leakage fields from QC1P using a single power supply with special wiring.

Cancel Coil in HER

Leakage dipole and quadrupole are used in the optics design.



Final Focus

QC1P in LER

No-Iron Shield

Skew sextupole and skew octupole are not cancelled due to manufacturing defect.

Modeled in *SAD* using 1 cm-thick slices of multipole elements (up to K21 and SK21)

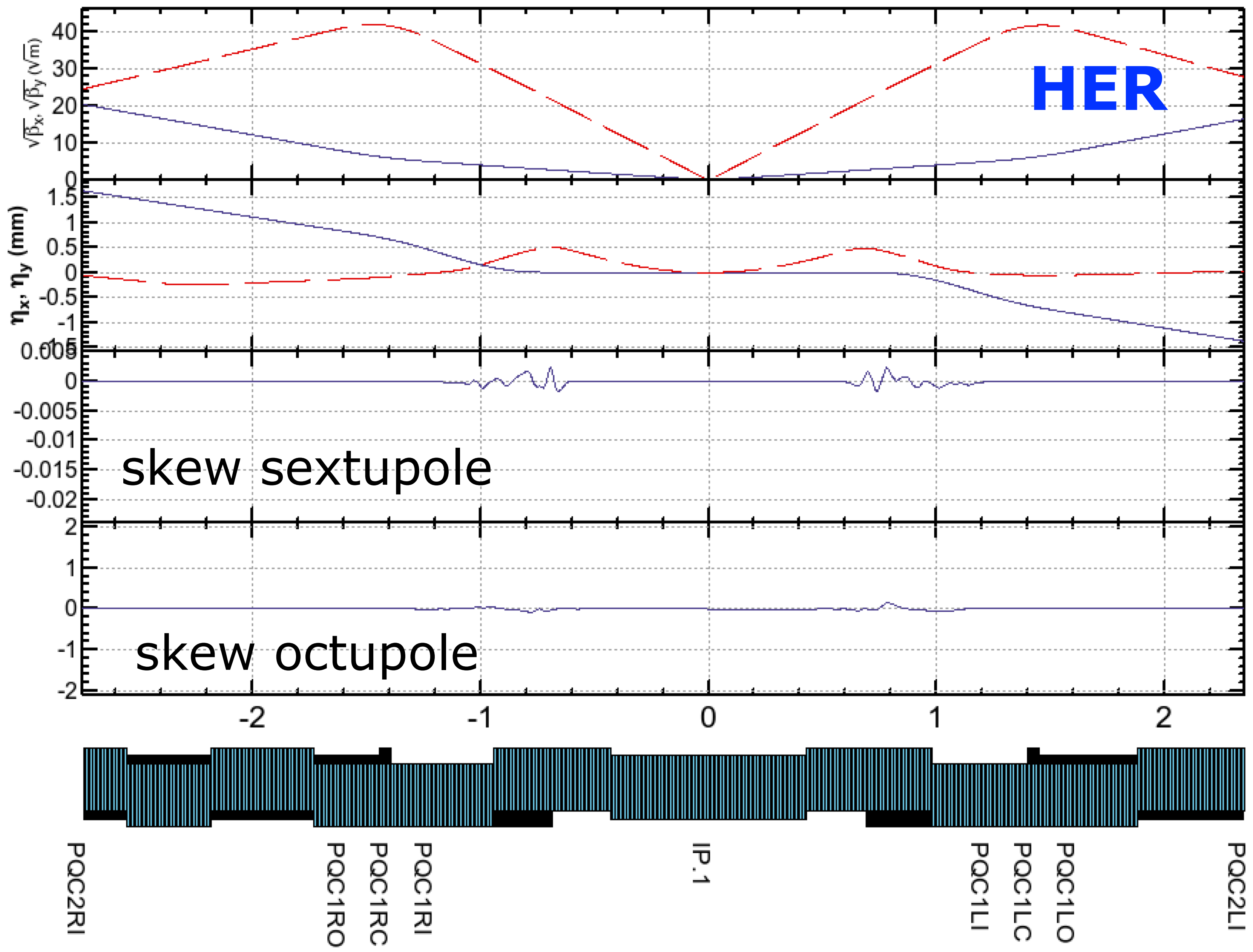
The beam trajectory is different from the nominal beam line and the final focus coils have an offset.

"Feed-Down Effect"
to calculate Effective Hamiltonian

w/o Error

Skew K2 (1/m2)

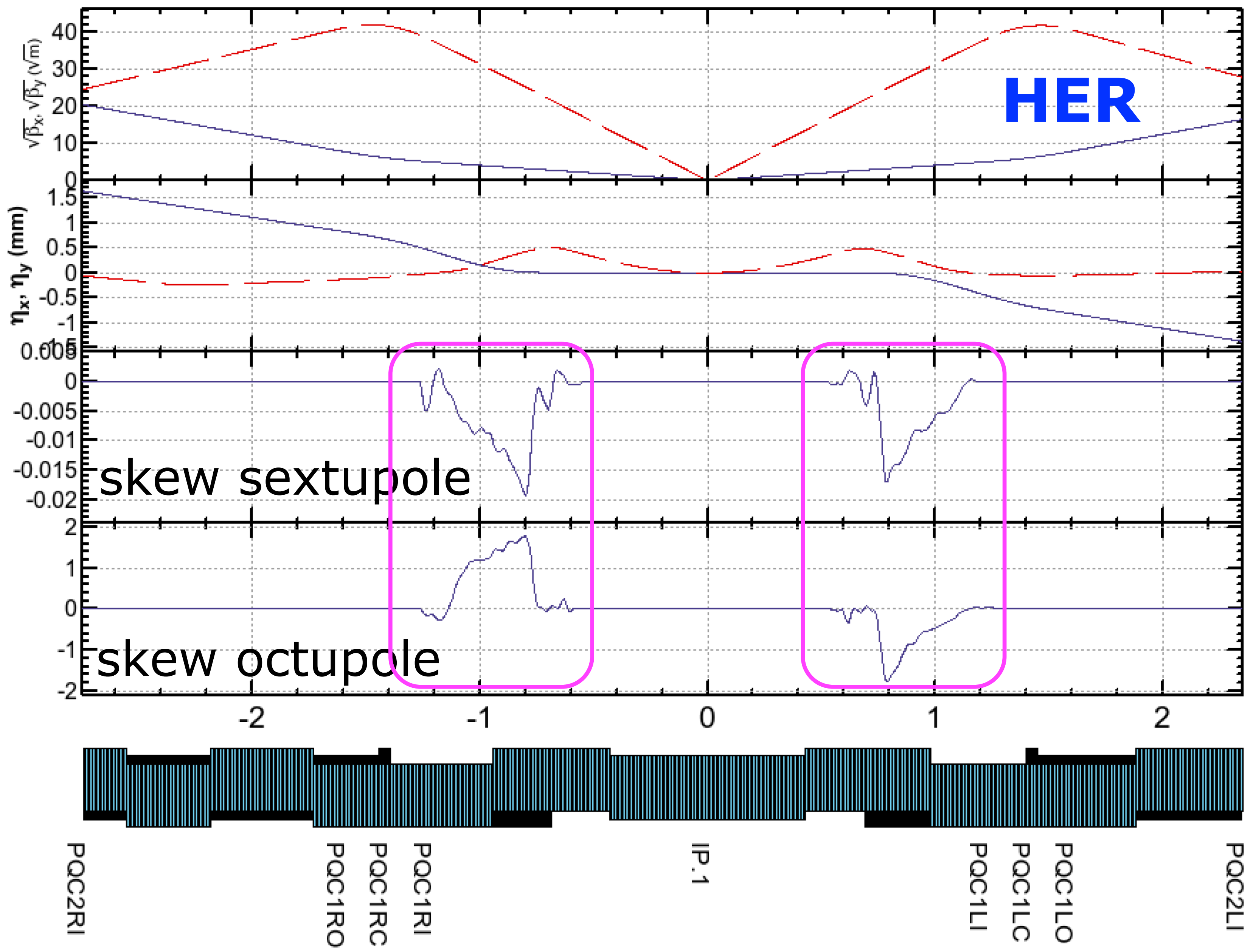
Skew K3 (1/m^3)



with Error

Skew K2 (1/m^2)

Skew K3 (1/m^3)



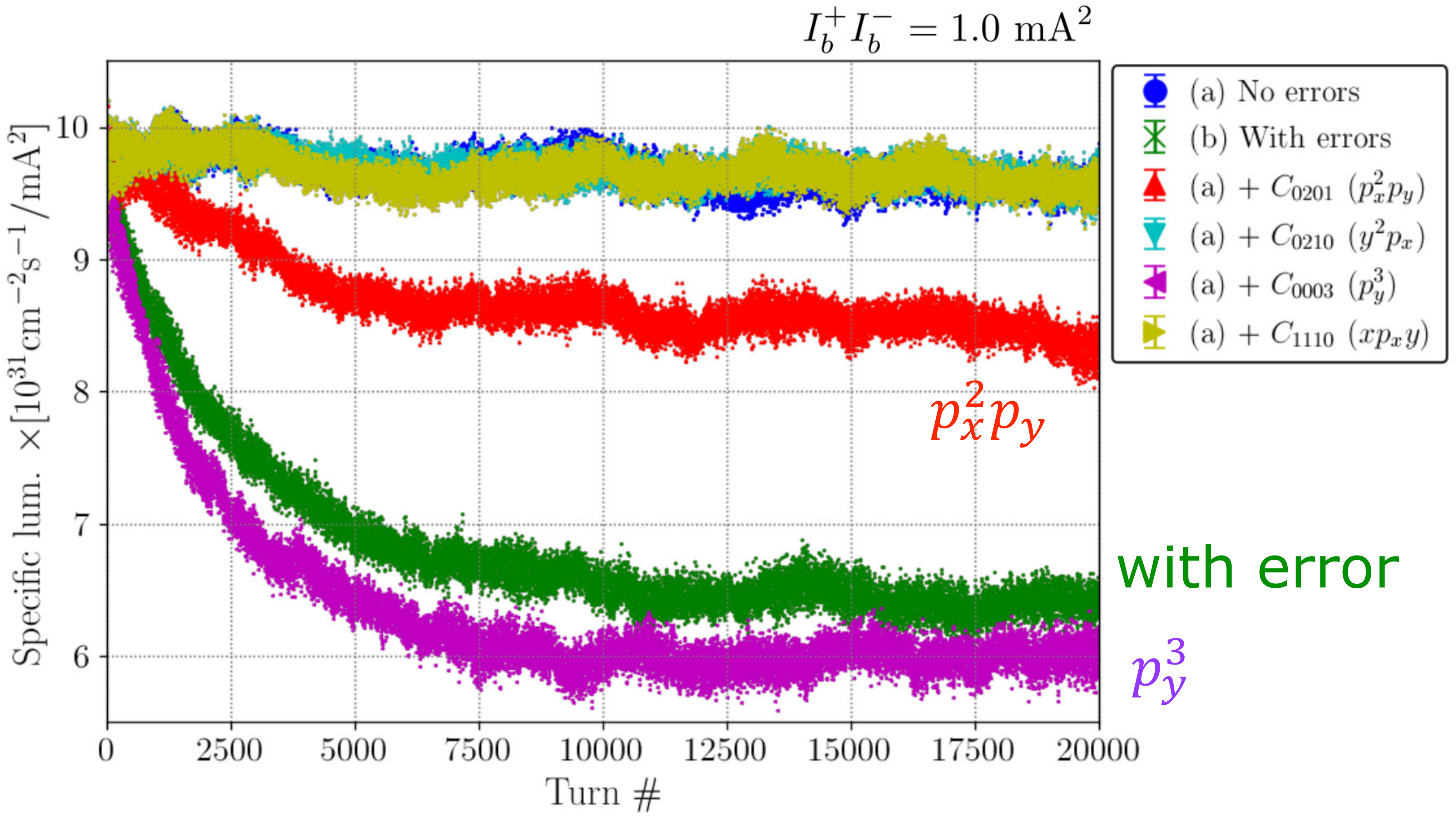
Effective Hamiltonian for 3rd Order Nonlinear Terms

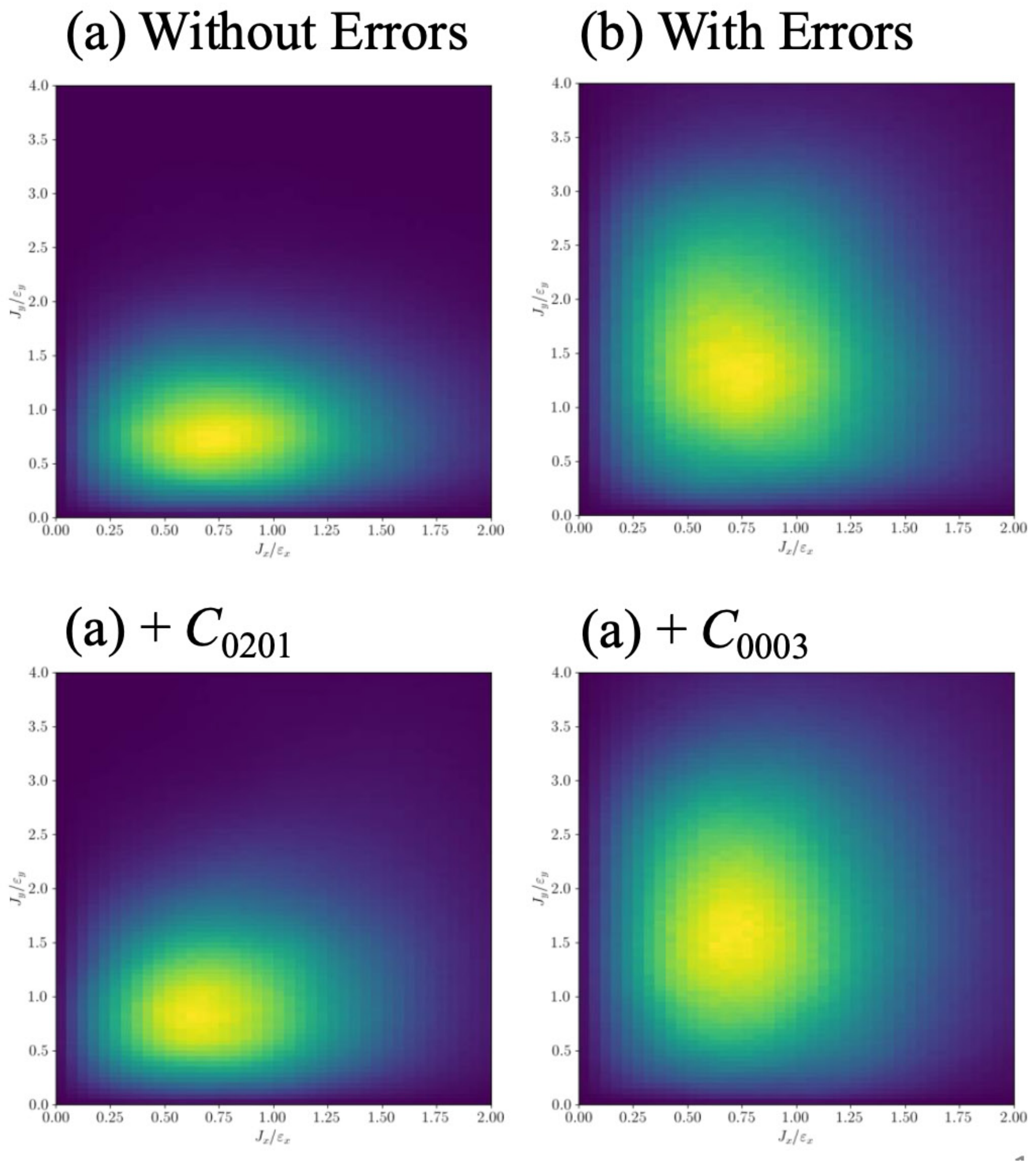
$$M(s) \simeq e^{-:H_{eff}(x):} M(s)$$

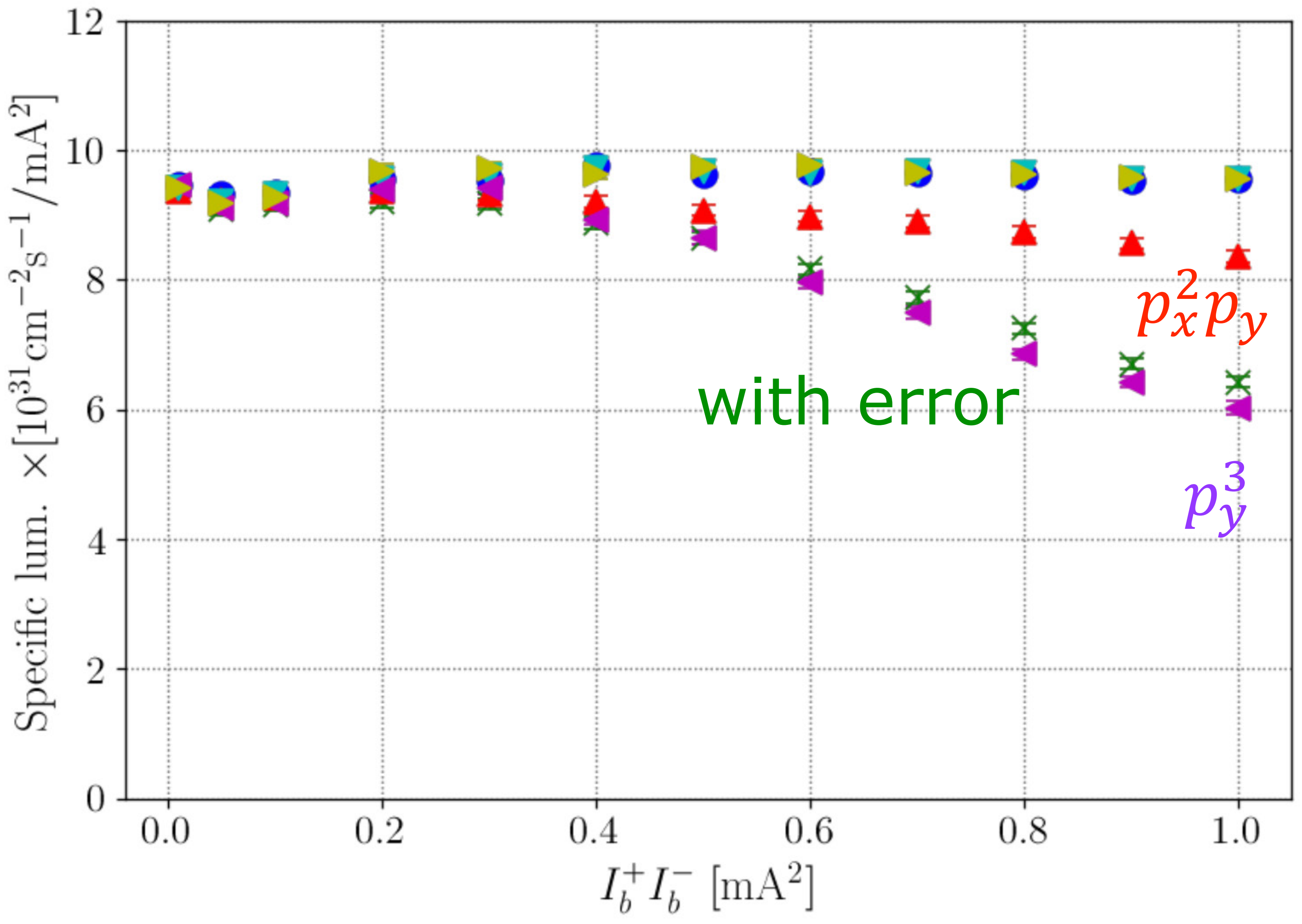
$$H_{eff} = \sum_{i,j,k,l \geq 0} C_{i,j,k,l} \times x^i \, p_x^j \, y^k \, p_y^l \qquad i + j + k + l = 3$$

$$H_{eff}(x) = \int H(M(s,s')x, s')ds'$$

Multipole field error enhances the nonlinear terms.
Cancel coil error in the HER reduces luminosity.
p_y^3 and $p_x^2 p_y$ significantly reduce luminosity. Investigating by Beam-Beam Simulations with Weak-Strong Model







We are also exploring ways to correct error fields such as skew sextupole component.

H. Sugimoto, K. Ohmi (KEK)

Sudden Beam Loss

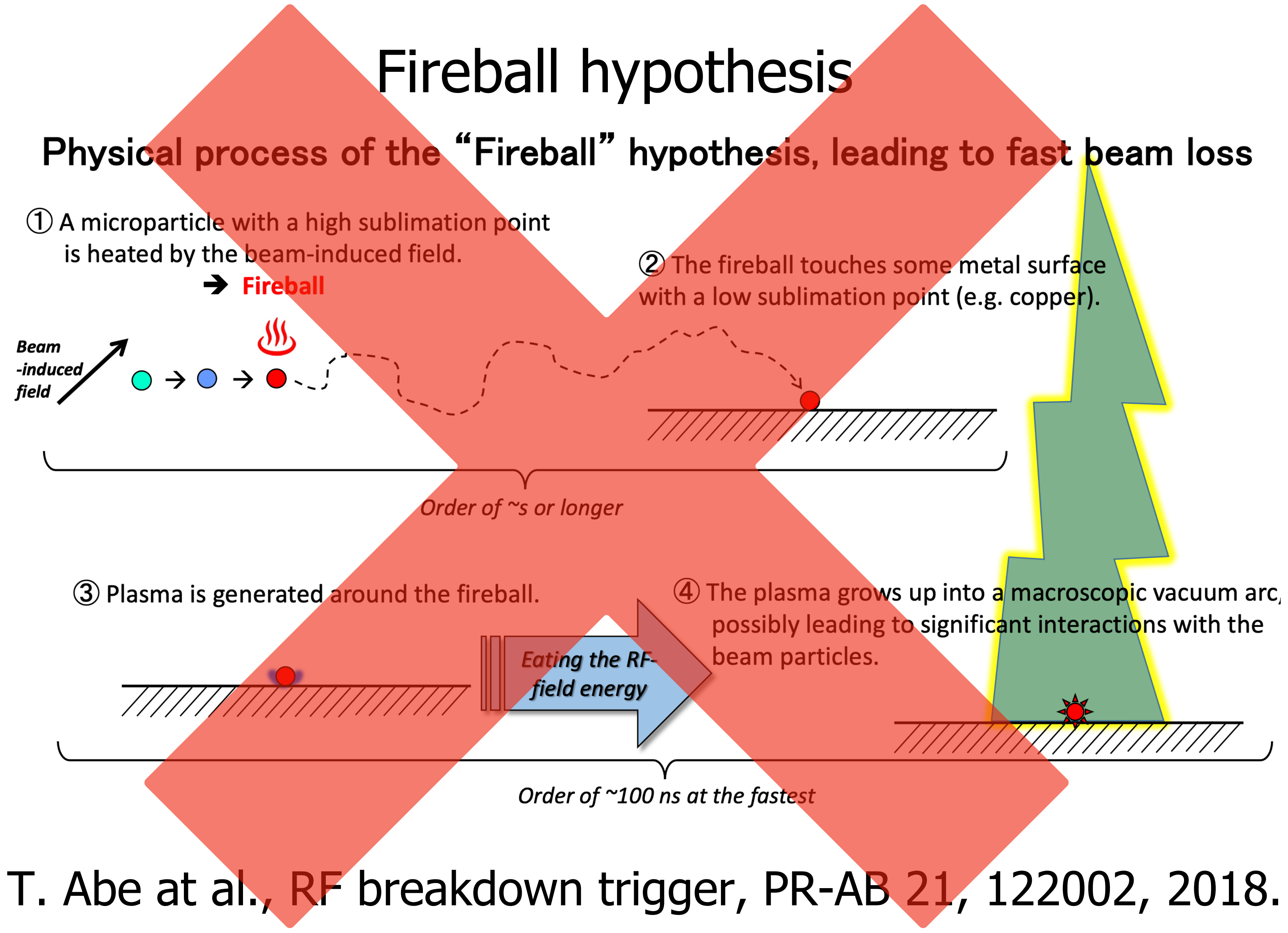
Sudden Beam Loss - Obstacle to Increase Beam Current

Sudden Beam Loss → Quench of Final Focus Magnet, Collimator Damage, Detector Damage

Large Beam Loss (~40 %) within a few turns

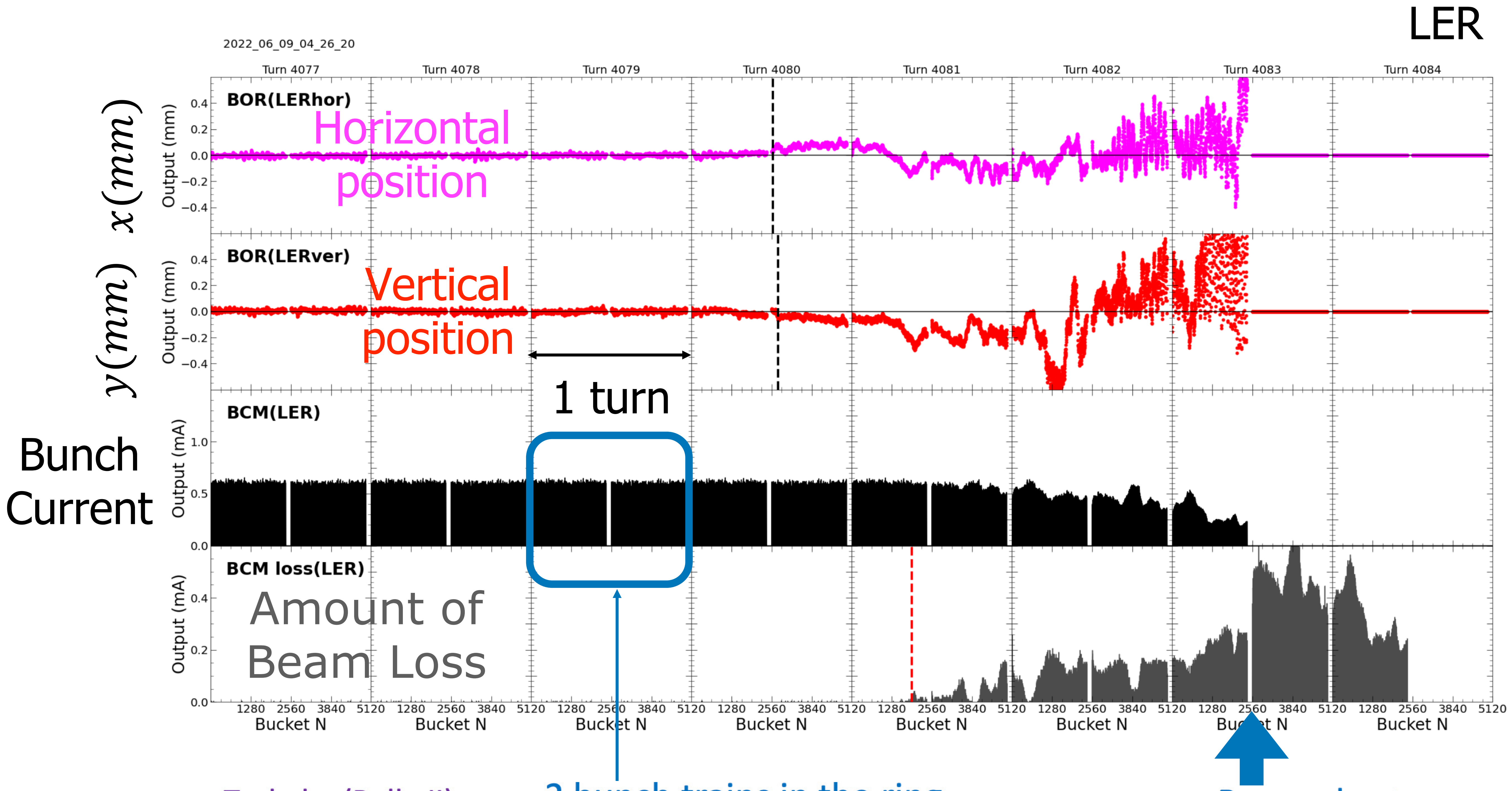
Small Coherent Motion

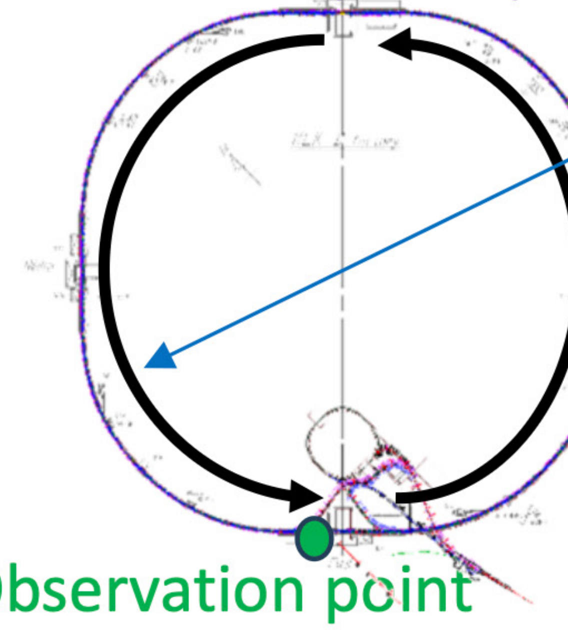
Distinct from Known Beam Instabilities



T. Abe at al., RF breakdown trigger, PR-AB 21, 122002, 2018.

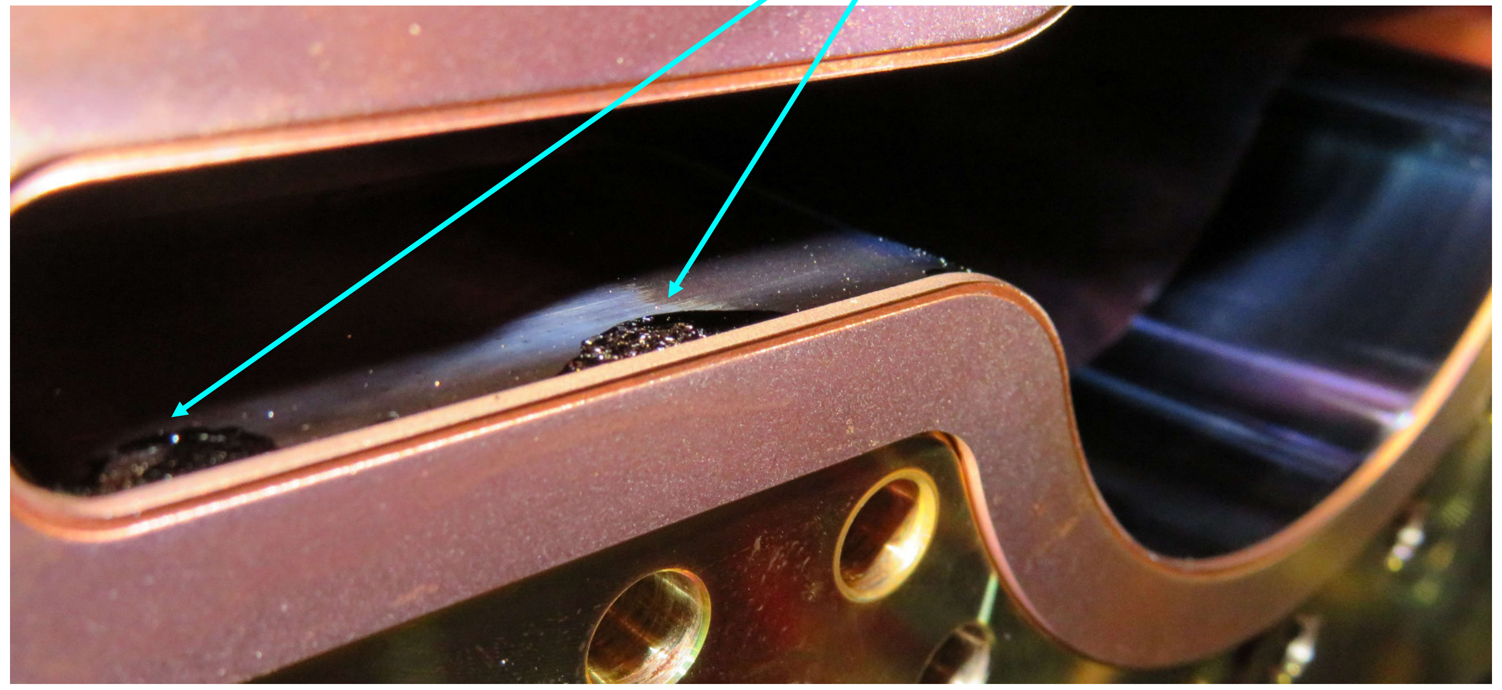
Trigger source can be collimator head.





Copper coating of collimator head will be effective if different sublimation point is problem.

Black stains identified as "VACSEAL" (Vacuum Sealant)



MO-Type Flange

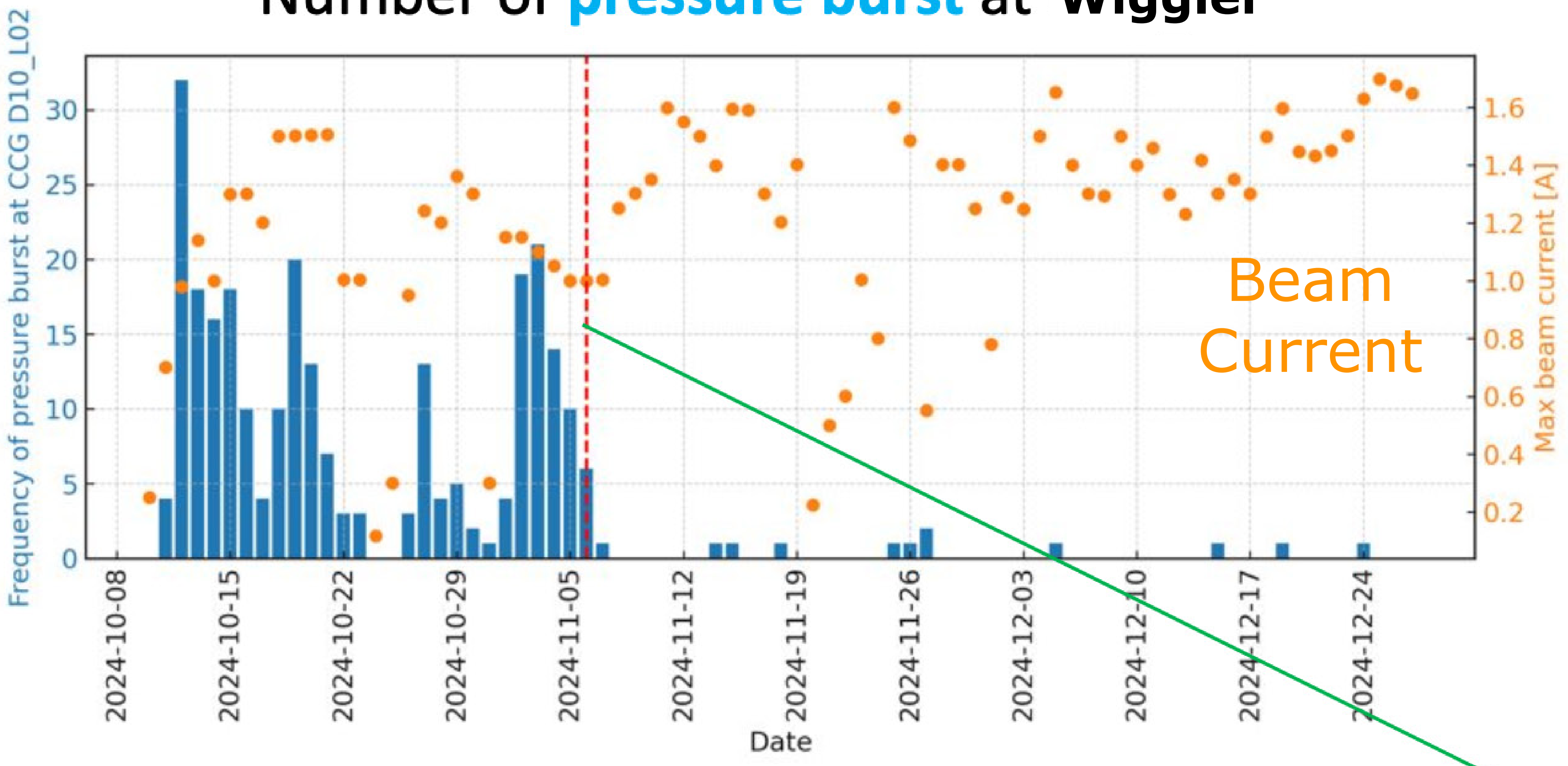
SBLs with vacuum pressure bursts were often observed.

Black stains were observed in the wiggler section.

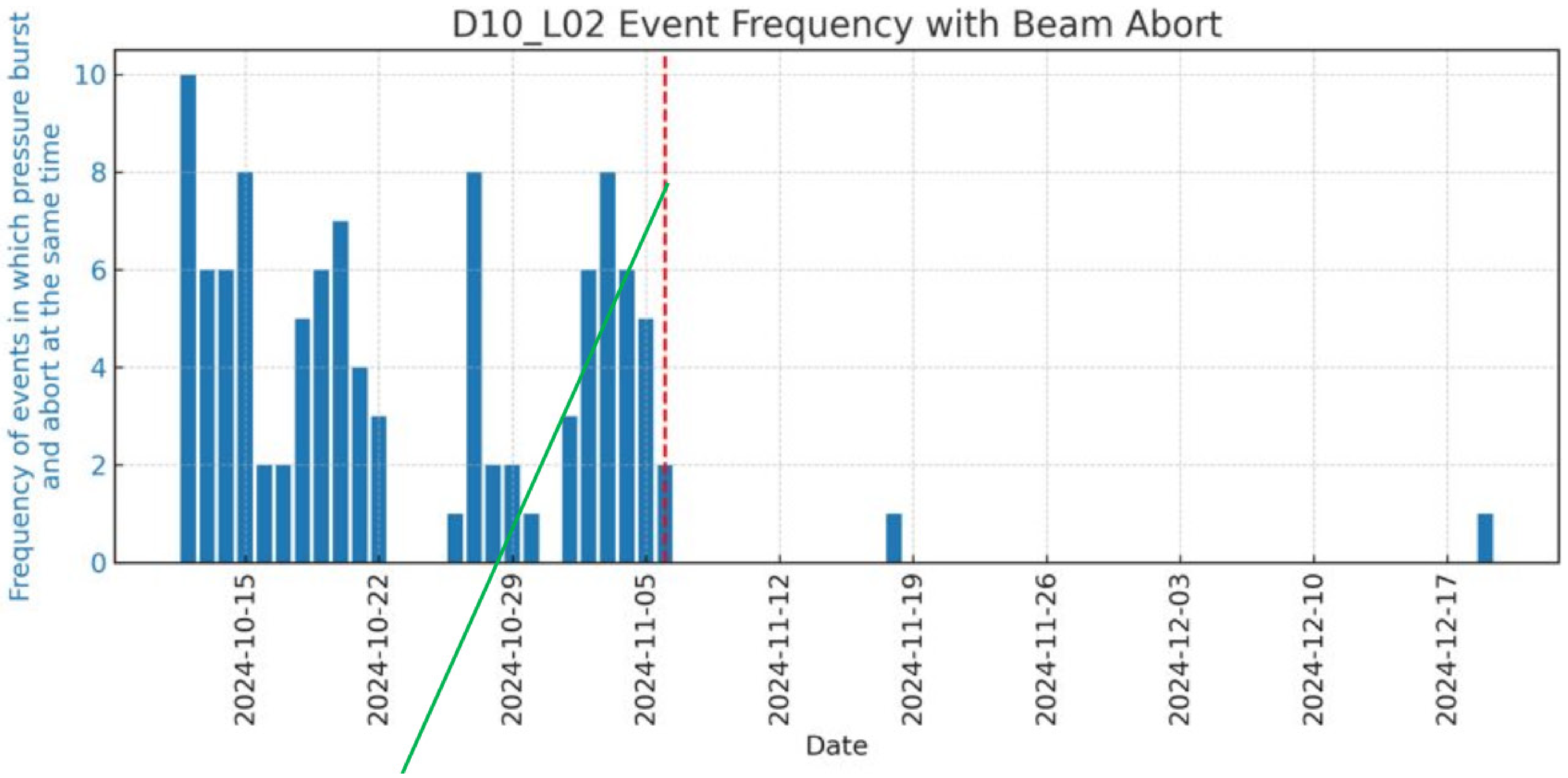
VACSEAL was used at the specific location, wiggler and IR.

VACSEAL was exposed to SR → Amorphous Graphite

Number of **pressure burst** at **Wiggler**



Number of **beam abort accompanied by pressure burst** at **Wiggler**



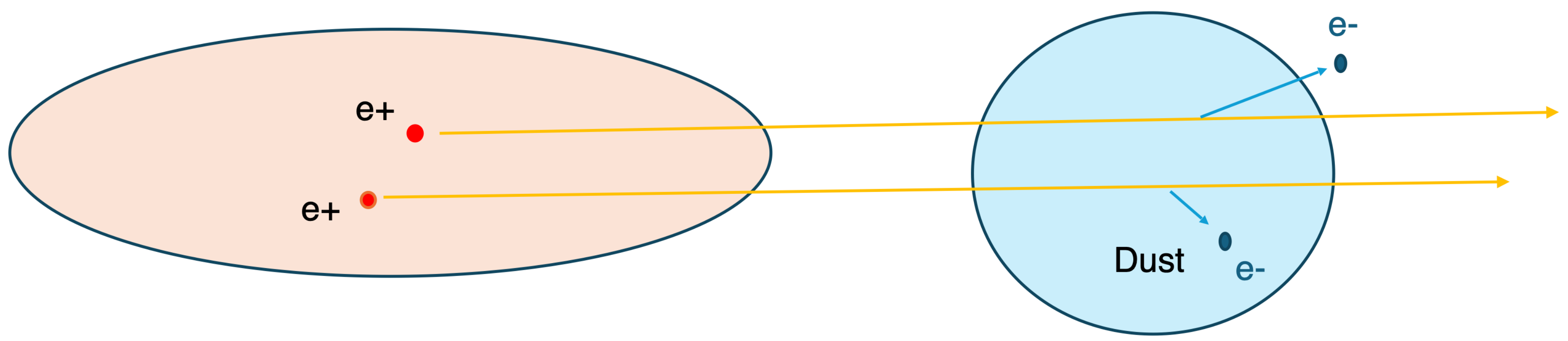
Cleaning Work at Wiggler Flange on November 6

After Cleaning Work → SBL events were significantly reduced.

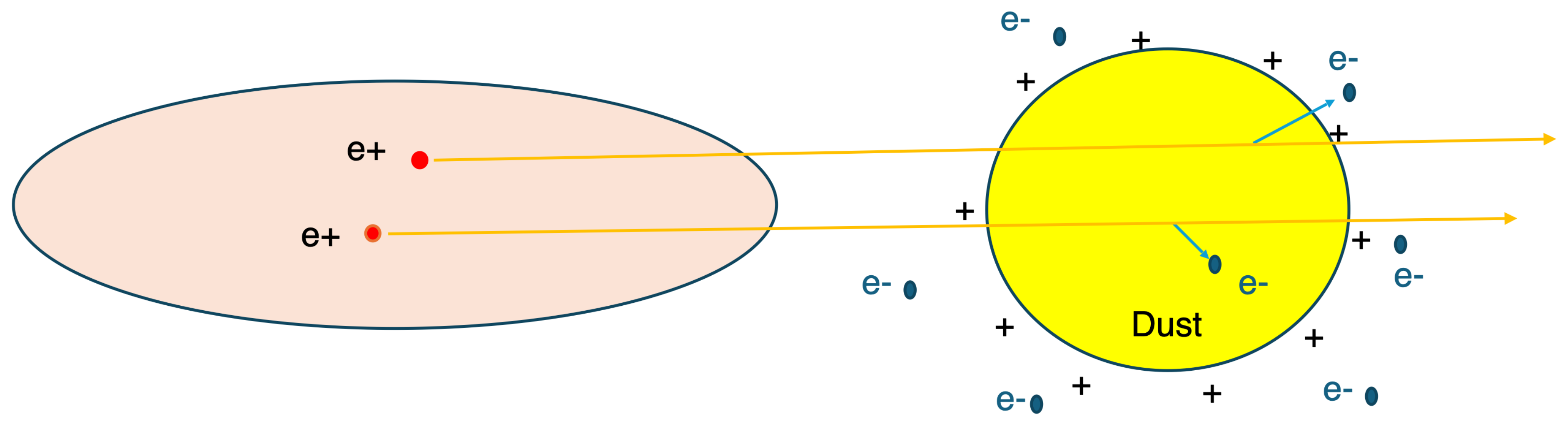
Beam-Dust interaction is a candidate of SBL events.

Simulation of Beam-Dust, Ion, Electron Cloud Interaction

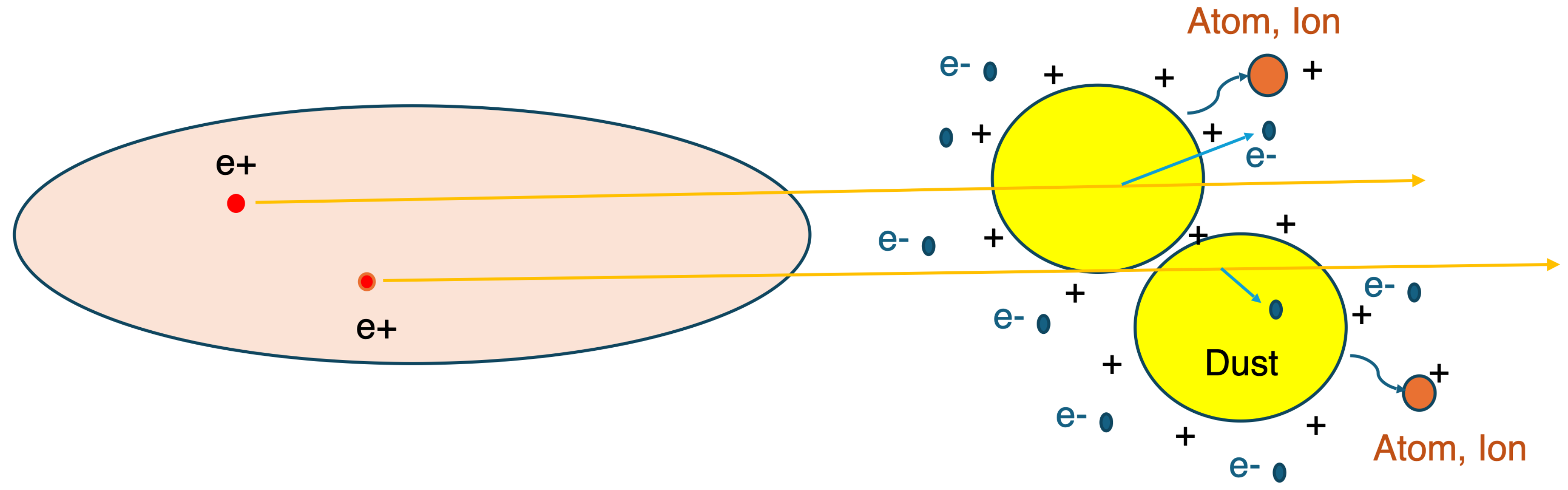
Ionization



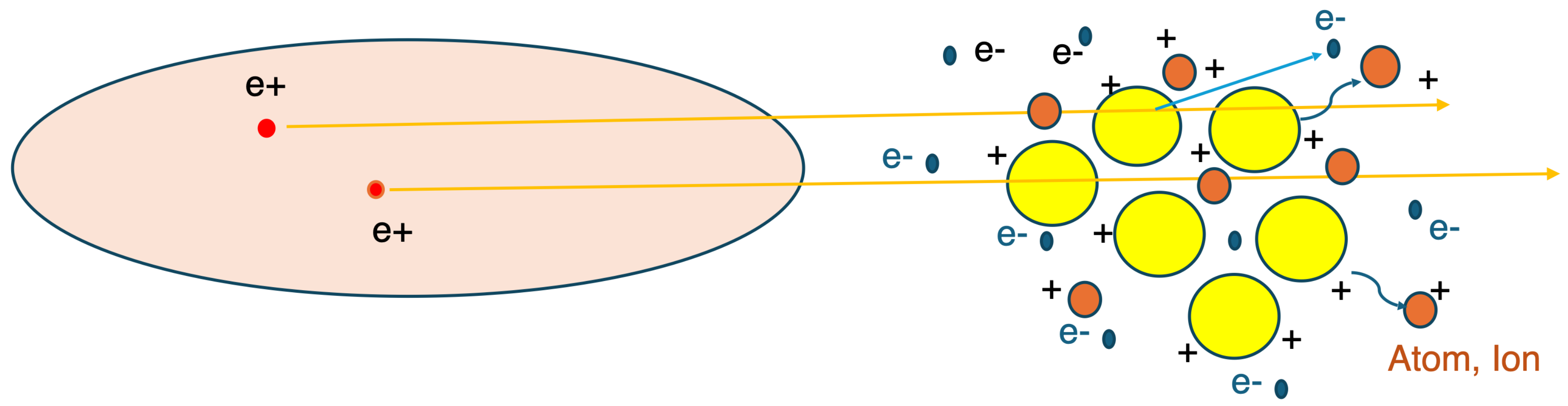
Heating



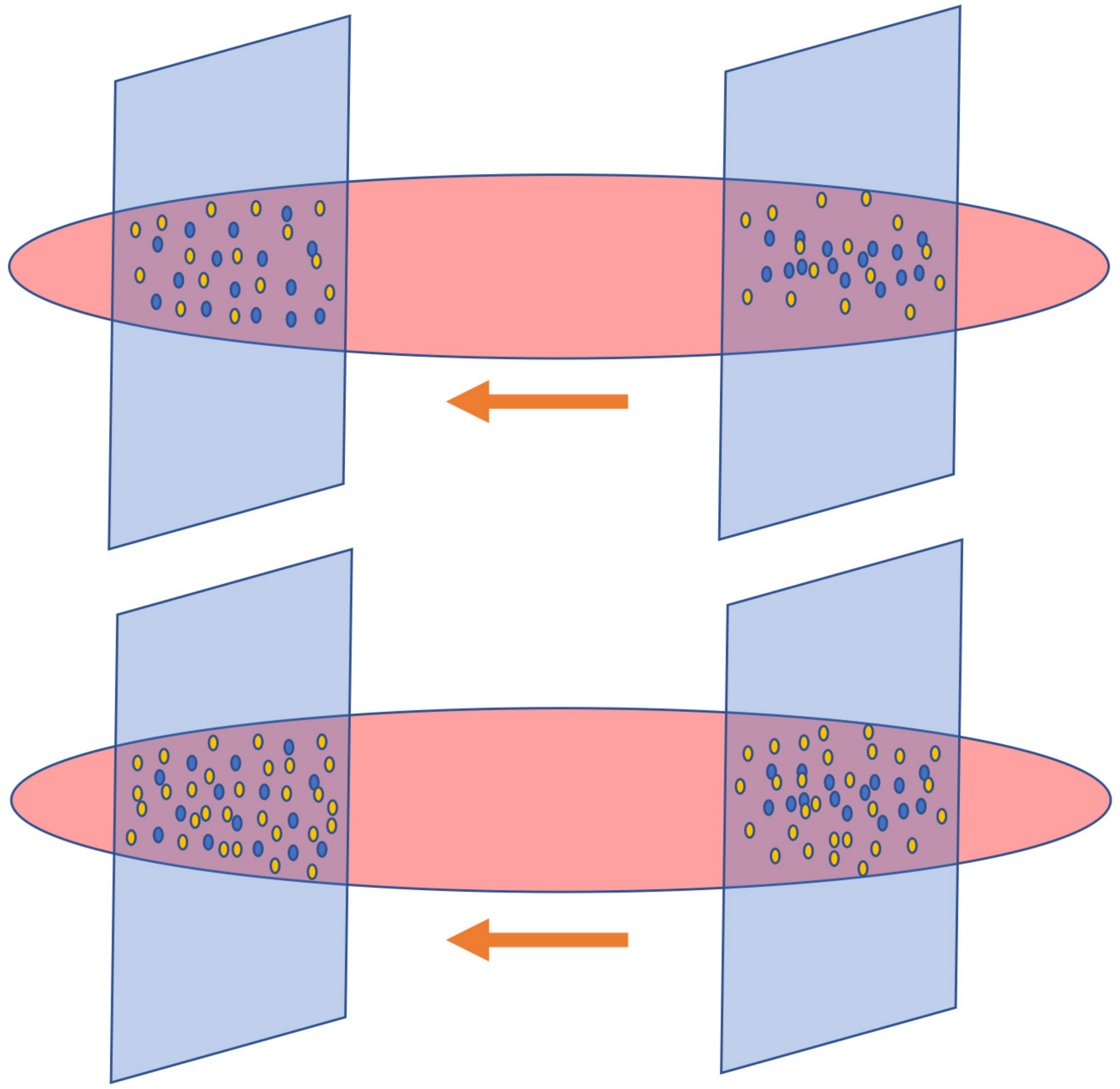
Fission and Evaporation



Charged Dust, Ion and Electron Clouds



Particle-In-Cell Simulation



[1] Collision with gas/material

[2] Electrons are squeezed at collision with the tail of bunch. The bunch tail is focused.

[3] After collisions with some bunches, electrons disappear.

[4] Ions remain near the bunch. The bunch is defocused.

K. Ohmi, eeFACT2025; S. Heifets, PR ST-AB 8 061002 (2005)

[1] Vertical Beam Size Enlargement in SBL Event

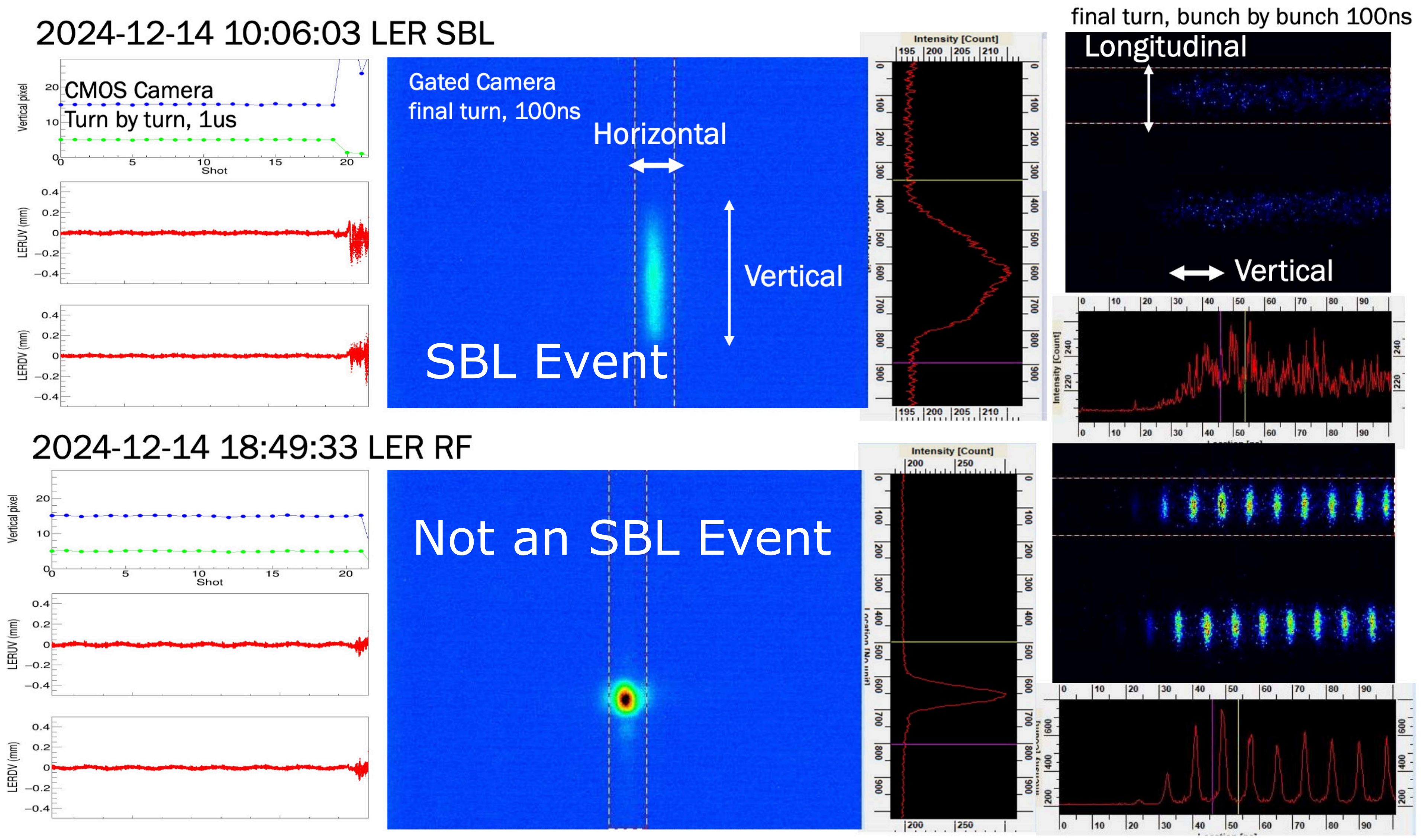
Charged Dust Distribution Resembles Flat Beam

$$\Delta p_x \propto \frac{1}{\sigma_x(\sigma_x + \sigma_y)} \simeq \frac{1}{\sigma_x^2}$$

$$\Delta p_y \propto \frac{1}{\sigma_y(\sigma_x + \sigma_y)} \simeq \frac{1}{\sigma_x \sigma_y}$$

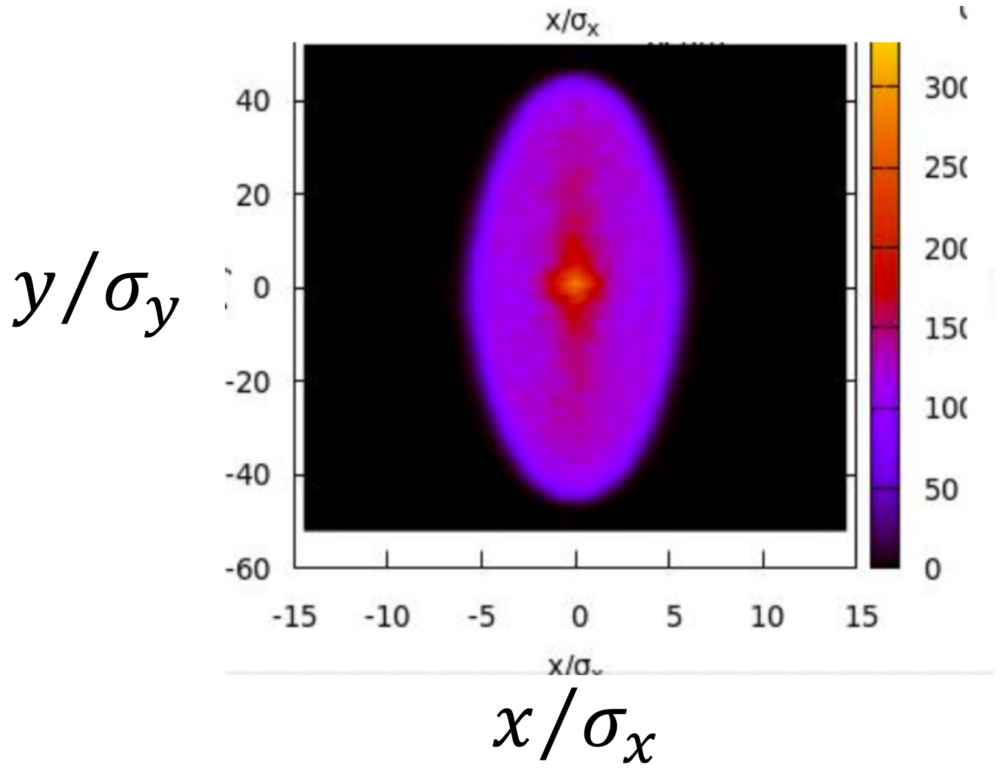
$$\sigma_y \ll \sigma_x \longrightarrow \Delta p_y > \Delta p_x$$

Observation by Streak Camera



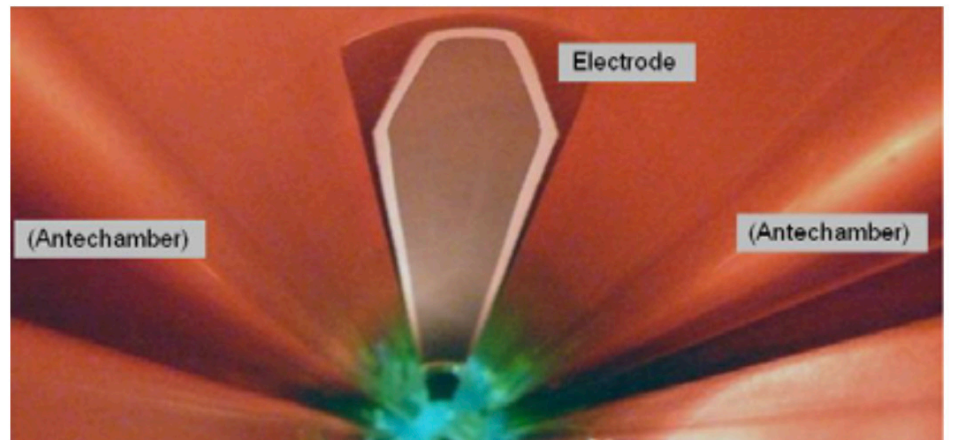
Particle-In-Cell Simulation

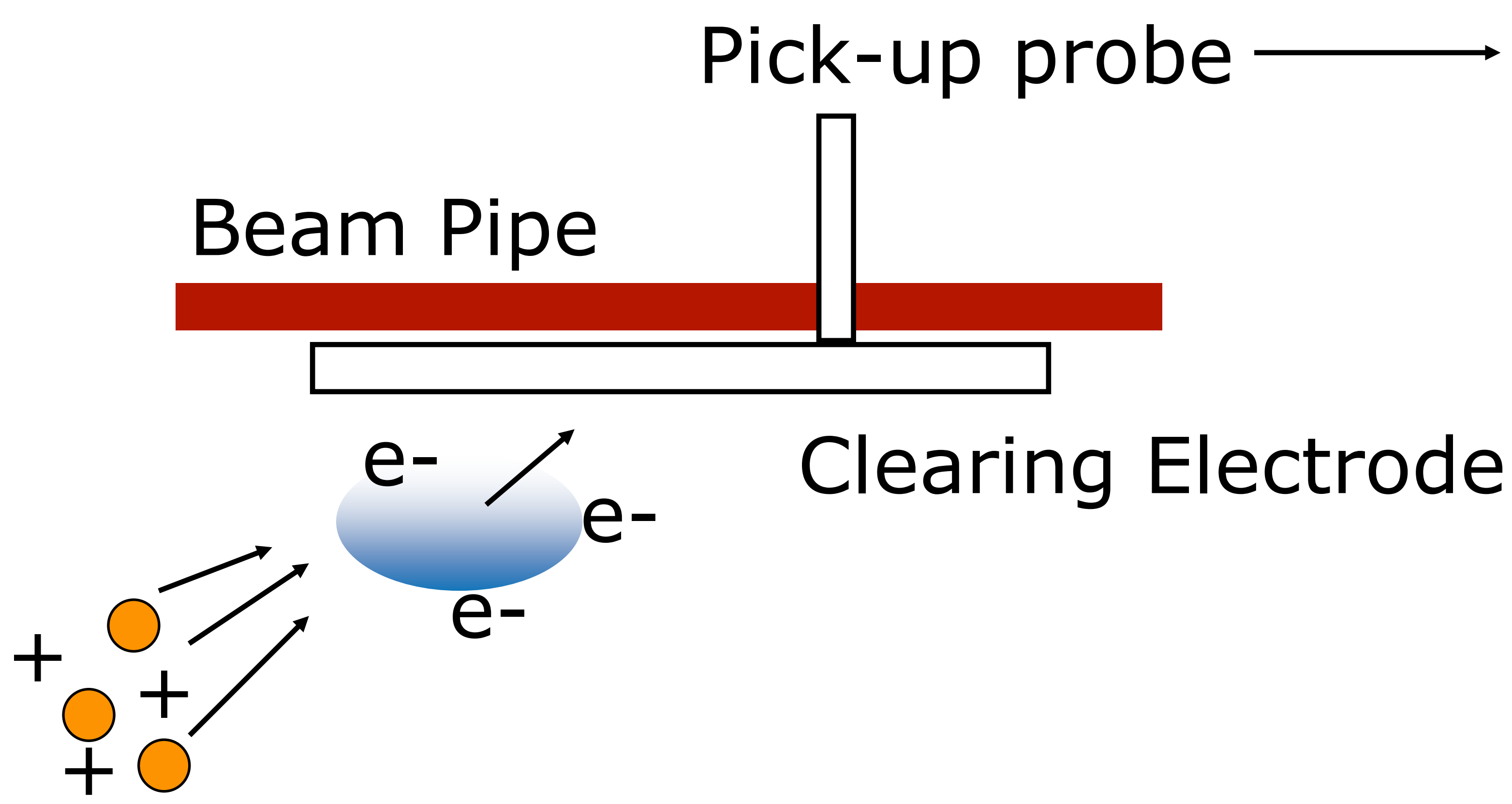
4th turn: e^+ beam

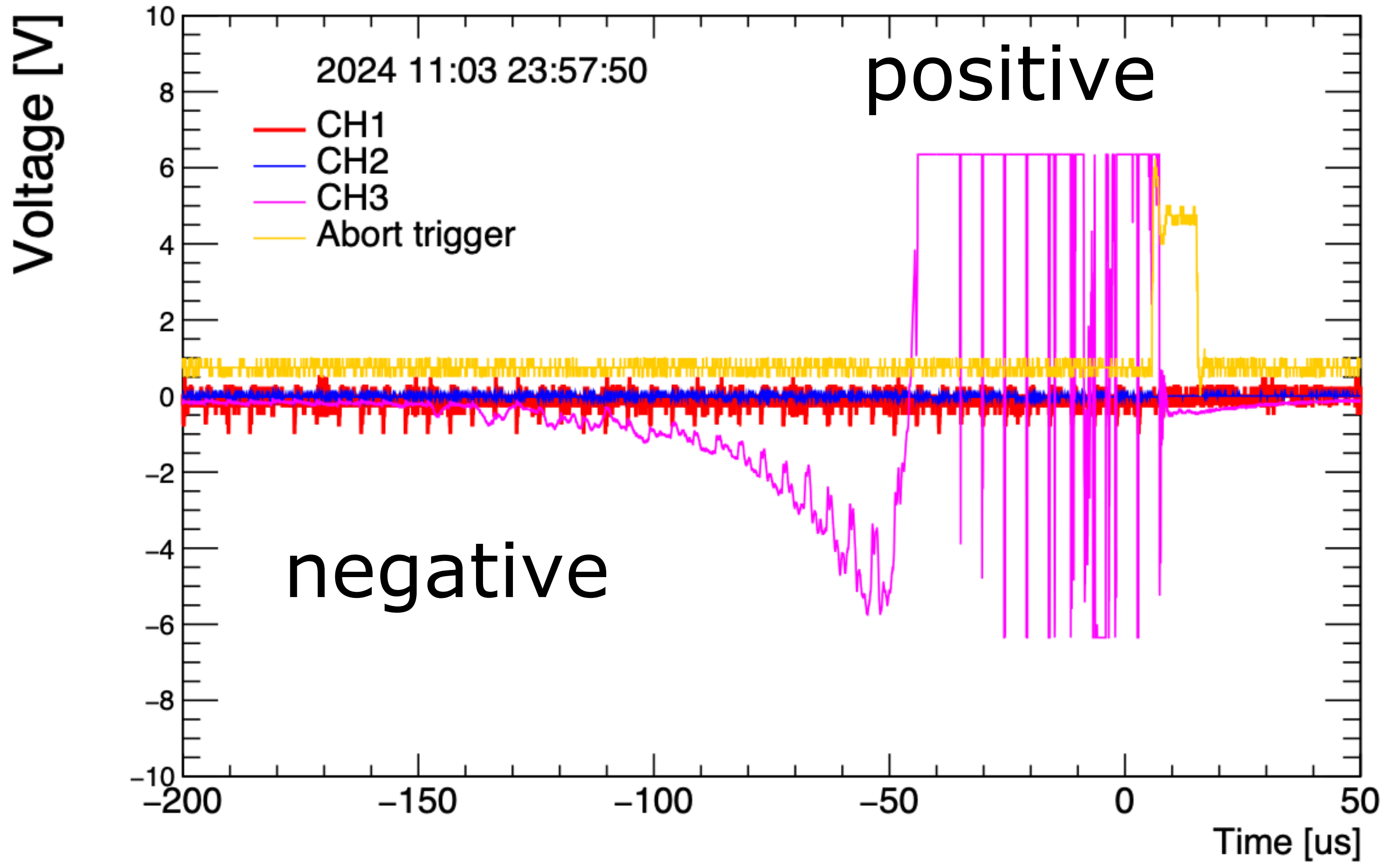


Electrons are lost quickly and defocusing effect remains in the vertical plane due to positive ions. → Beta-Beating

[2] Signal from SBL Event Observed by Clearing Electrode







Electron mobility is higher than ion mobility.

Summary and Conclusion

Machine Parameters of SuperKEKB

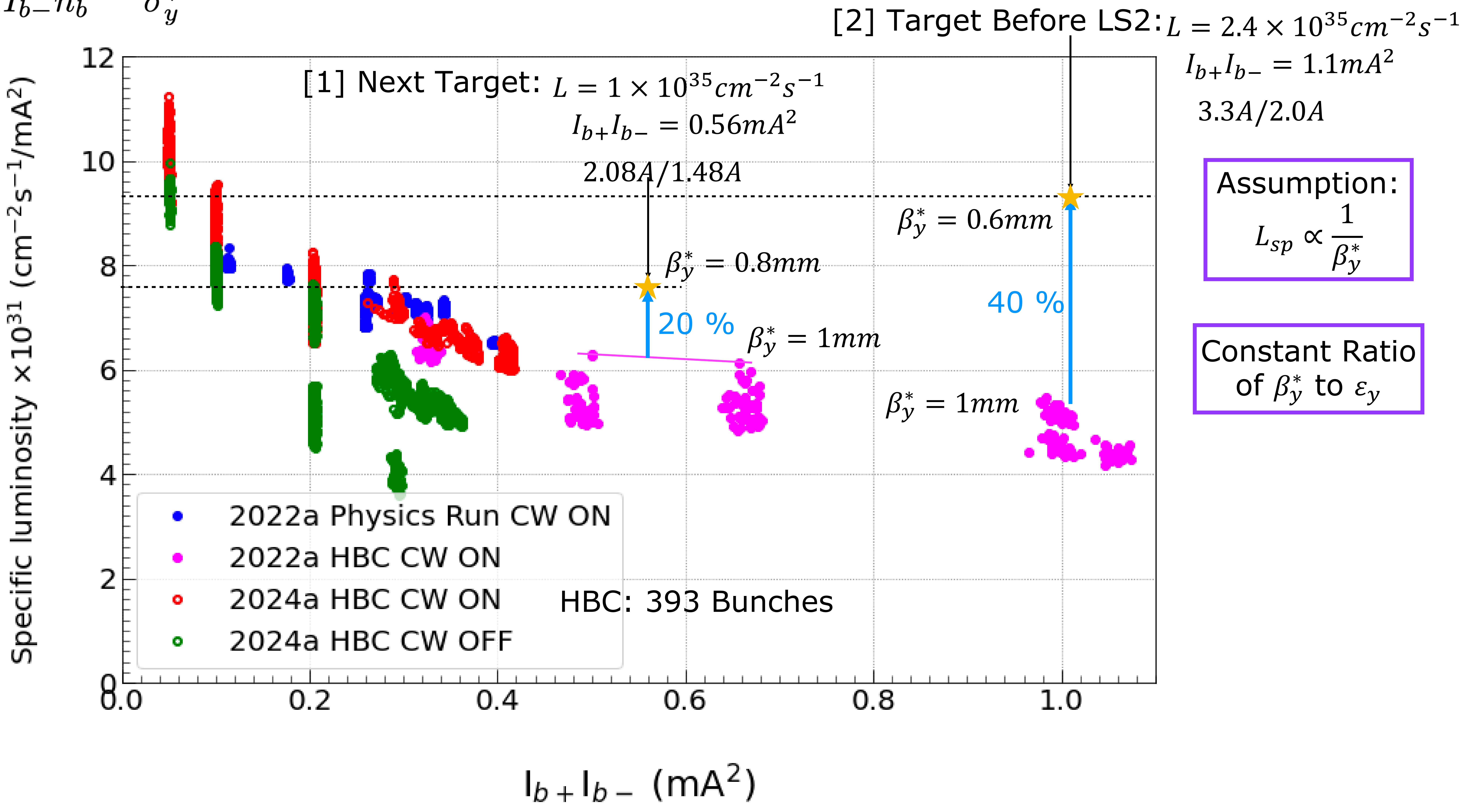
Step-by-Step Improvement

	December 27, 2024		Next Target		Target before LS2		Unit
Ring	LER	HER	LER	HER	LER	HER	
Emittance	4.0	4.6	4.0	4.6	4.0	4.6	nm
Beam Current	1632	1259	2080	1480	3026	2000	mA
Number of bunches	2346		2346		2346		
Bunch current	0.696	0.537	0.89	0.63	1.29	0.85	mA
Horizontal size σ_x*	15.5	16.6	15.5	16.6	15.5	16.6	µm
Vertical cap sigma Σ_y*	375		217		159		mm
Vertical size σ_y*	265		154		112		nm
Betatron tunes ν_x / ν_y	44.525 / 46.589	45.531 / 43.599	44.525 / 46.589	45.532 / 43.573	44.525 / 46.589	45.532 / 43.573	
β_x* / β_y*	60 / 1.0	60 / 1.0	60 / 0.8	60 / 0.8	60 / 0.6	60 / 0.6	mm
σ_z	4.6 (6.0*)	5.1 (6.1*)	4.6 (6.5*)	5.1 (6.4*)	4.6 (7.5*)	5.1 (6.9*)	mm
Piwinski angle	12.3	12.7	12.3	12.7	12.3	12.7	
Crab waist ratio	80	60	80	80	80	80	%
Beam-Beam ξ_y	0.036	0.027	0.0444	0.0356	0.0549	0.0475	
Specific luminosity	5.8×10^{31}		7.62×10^{31}		9.30×10^{31}		$cm^{-2}s^{-1}/mA^2$
Luminosity	**5.1×10^{34}**		**1×10^{35}**		**2.4×10^{35}**		$cm^{-2}s^{-1}$

Luminosity is expected from the achieved values obtained at the beam-beam study.

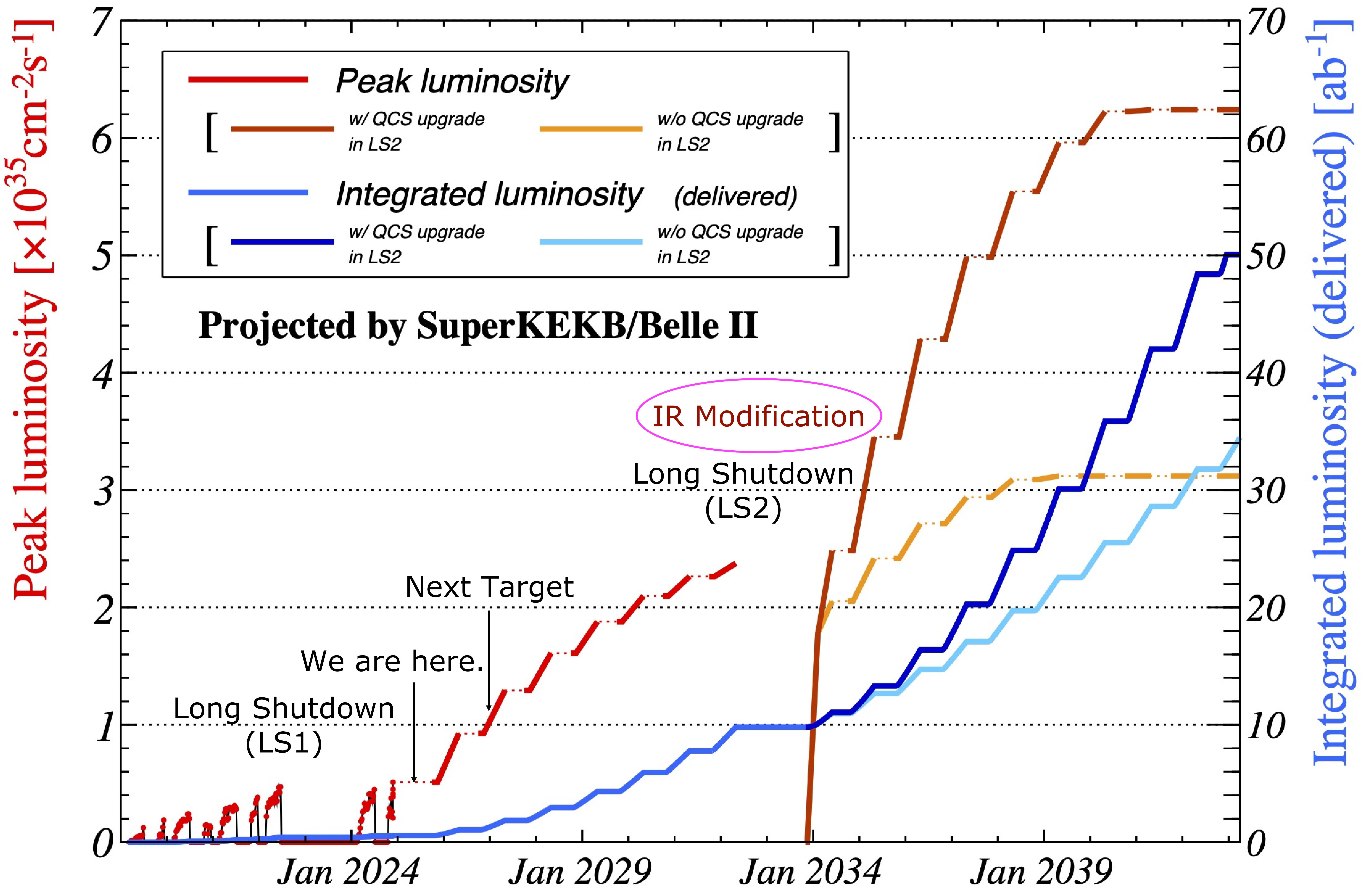
Luminosity Prediction Based on Beam-Beam Experiment

$$L_{sp} = \frac{L}{I_{b+}I_{b-}n_b} \propto \frac{1}{\sigma_y^*}$$



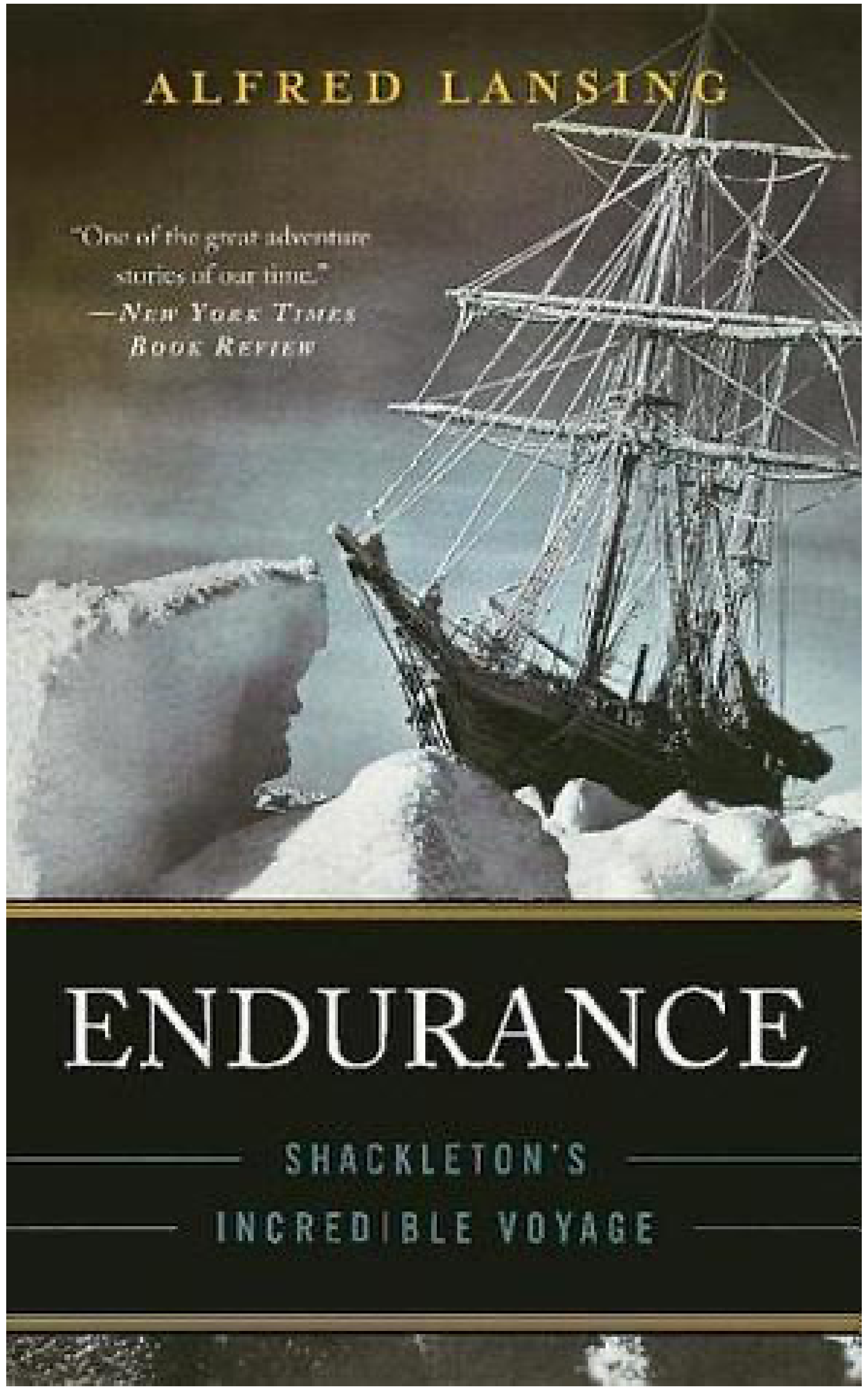
Assumption:
$L_{sp} \propto \frac{1}{\beta_y^*}$

Constant Ratio of β_y^* to ε_y


Peak luminosity
w/ QCS upgrade in LS2
w/o QCS upgrade in LS2
Integrated luminosity (delivered)
w/ QCS upgrade in LS2
w/o QCS upgrade in LS2
Projected by SuperKEKB/Belle II
IR Modification
Long Shutdown (LS2)
Next Target
We are here.
Long Shutdown (LS1)
Peak luminosity [×10^35cm^-2s^-1]
Integrated luminosity (delivered) [ab^-1]
Jan 2024
Jan 2029
Jan 2034
Jan 2039
0
1
2
3
4
5
6
7
10
20
30
40
50
60
70

Conclusion

- Sudden Beam Loss in SuperKEKB
  - Beam-Dust interactions; Amorphous Graphite: VACSEAL was exposed to intense SR in the MO-Flange.
  - Black stains were observed in many MO-flanges. → Cleaning in progress → Expected to Be Solved
  - Comparison with simulations is ongoing.
- Beam-Beam Issues
  - X-Z instability can be mitigated. Cause of Beam-Beam blowup still under investigation.
  - GPU-based Strong-Strong simulations with Lattice ongoing
  - Studying Combined Effects of Beam-Beam, Lattice Nonlinear, Wakefield (Short Range)
- Short Lifetime in Nano-Beam Scheme with Crab-Waist Scheme → Injection Performance
  - Small dynamic aperture and Beam-Beam effects → Sextupole Optimization and Synchrotron Injection.
- Impedance Reduction
  - Nonlinear collimator helps reduce the impedance while mitigating backgrounds. (installed in LS1)
- Increasing Beam Current and Squeezing Beta* : Standard Path to Higher Luminosity.



Original Plan: Trans-Antarctic Expedition
→ From Endurance Beset to Final Rescue

This is not a success story.

But their refusal to give up brought about a miracle.

"The luminosity frontier is an endurance game."