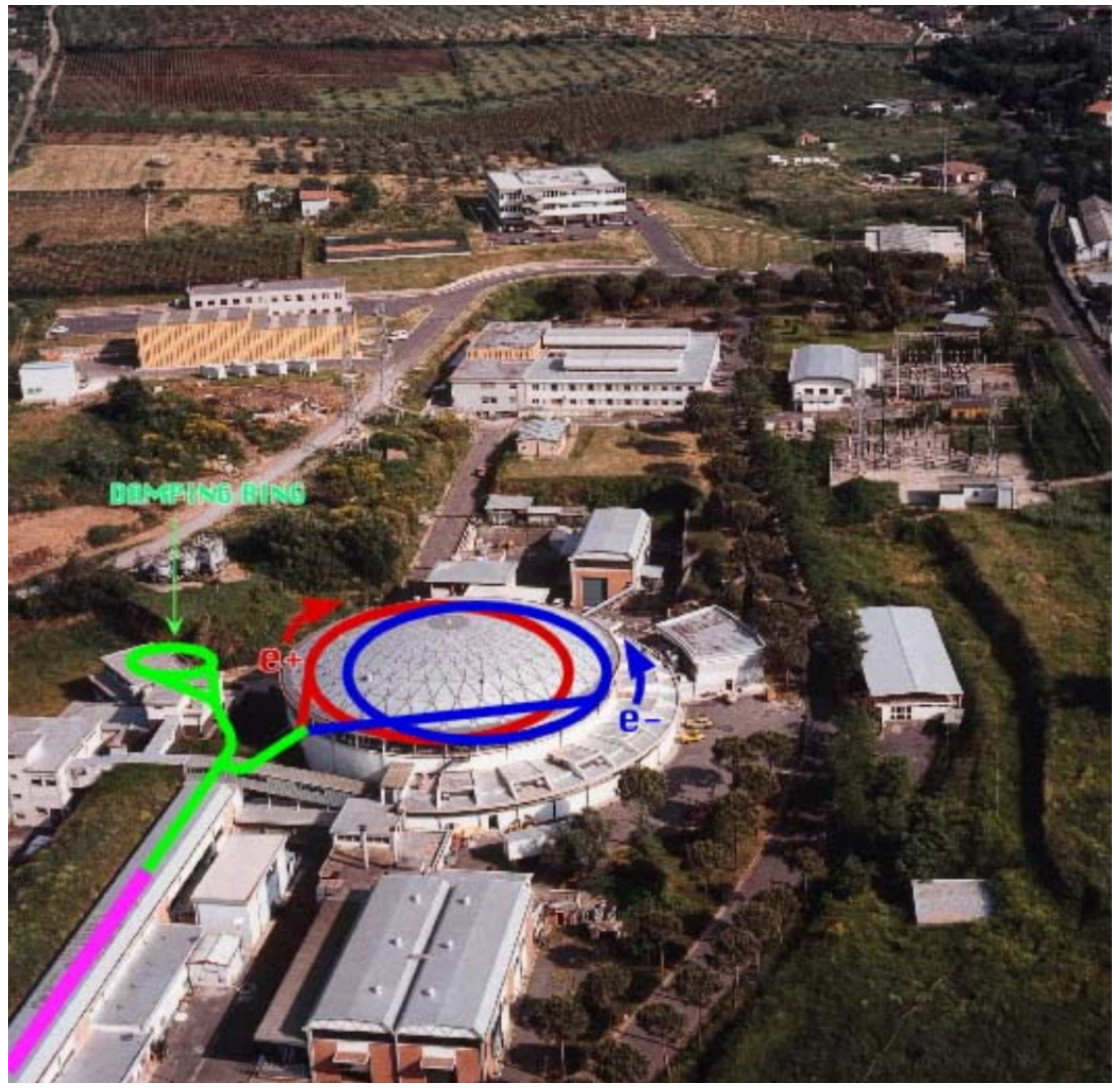
European Strategy for Particle Physics

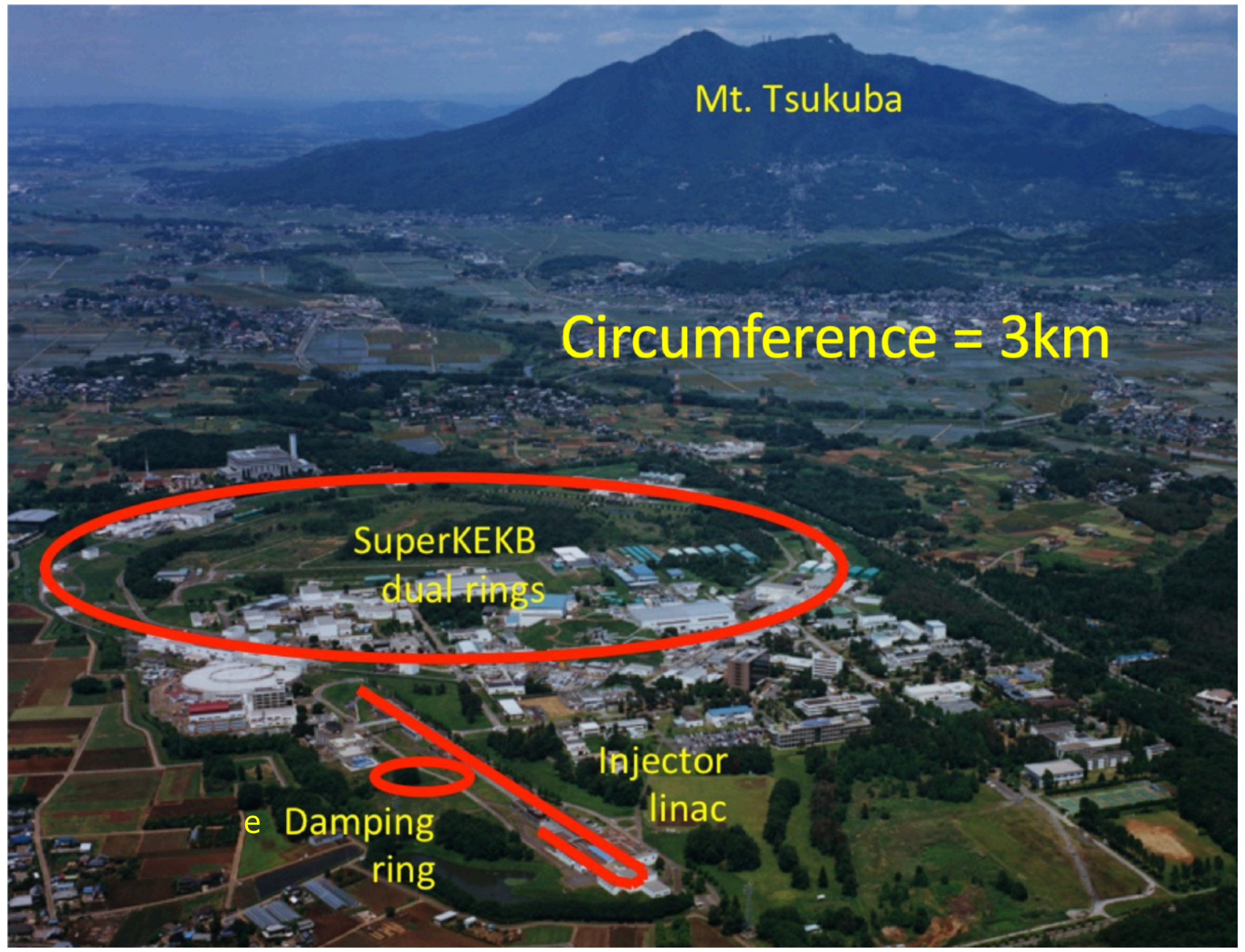
PARALLEL 2 / **ACCELERATOR TECHNOLOGIES**

Lessons from Current e^+e^- Colliders

Yukiyoshi / Ohnishi (KEK)

23-27 JUNE 2025 Lido di Venezia





- Ring Colliders: DAΦNE and SuperKEKB
- Current Status and Achievements
- Experiences and What is Challenge ?
- Path Forward and Useful Experiences for Future Collider Projects

$$L = \frac{N_+ N_- n_b f_0}{2\pi \sqrt{\sigma_{x+}^{*2} + \sigma_{x-}^{*2}} \sqrt{\sigma_{y+}^{*2} + \sigma_{y-}^{*2}}} R_L$$

Geometrical Loss
Hourglass Effect, Crossing Angle.

In the flat beam, σ_y^* = **30 - 50 nm** is a target. → β_y^* **< 1 mm and** ε_y **< 10 pm**

Overcoming **hourglass effect** to squeeze β_y^*

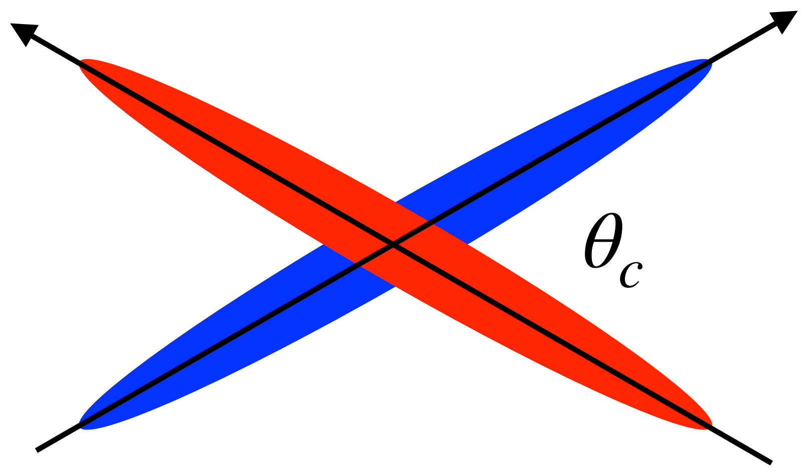
$$\beta_y^* > \frac{\sigma_z}{\sqrt{1+\Phi^2}} \qquad \Phi = \frac{\sigma_z}{\sigma_x^*} \tan\frac{\theta_c}{2}$$

Difficult to make σ_z shorter

← **Creating a Large Piwinski Angle to Make Short "Bunch"**

→ Large Crossing Angle and Low Emittance = **Nano-Beam Scheme**

$$R_L = \left(1 + \frac{\sigma_{z+}^2 + \sigma_{z-}^2}{\sigma_{x+}^{*2} + \sigma_{x-}^{*2}} \tan^2\frac{\theta_c}{2}\right)^{-\frac{1}{2}} R_H$$



$$L = \frac{N_+ N_- n_b f_0}{\pi \theta_c \sqrt{\sigma_{z+}^2 + \sigma_{z-}^2} \sqrt{\sigma_{y+}^{*2} + \sigma_{y-}^{*2}}}$$

DAΦNE:	Φ = 1.7
SuperKEKB:	Φ = 12.3 / 12.7

Luminosity Challenge (cont'd)

$$L = \frac{N_+ N_- n_b f_0}{\pi\theta_x \sqrt{\sigma_{z+}^2 + \sigma_{z-}^2}\sqrt{\sigma_{y+}^{*2} + \sigma_{y-}^{*2}}}$$

$$\xi_{y\pm} = \frac{r_e}{\pi\gamma_\pm}\frac{\beta_{y\pm}^* N_\mp}{\theta_x \sigma_{z\mp}\sigma_{y\mp}^*} \propto N_\mp \sqrt{\frac{\beta_y^*}{\varepsilon_{y\mp}}}$$

Beam-Beam Parameter

Ratio of β_y^* to ε_y

Vertical Beam Size at the IP

$$\sigma_y^{*2} = \mu^2 \varepsilon_y \beta_y^* + (\eta_y^* \sigma_\delta)^2 + \varepsilon_x \frac{(r_2^*)^2}{\beta_x^*} + \varepsilon_x \beta_x^* (r_1^*)^2$$

$\mu \simeq 1$ Waist position is adjusted.

Vertical Dispersion — X-Y Couplings ← Machine Imperfection

Vertical Emittance

Combined Effect of Collimator Impedance and BxB Feedback Noise → -1 Mode Instability
Optics Distortion due to Machine Imperfection

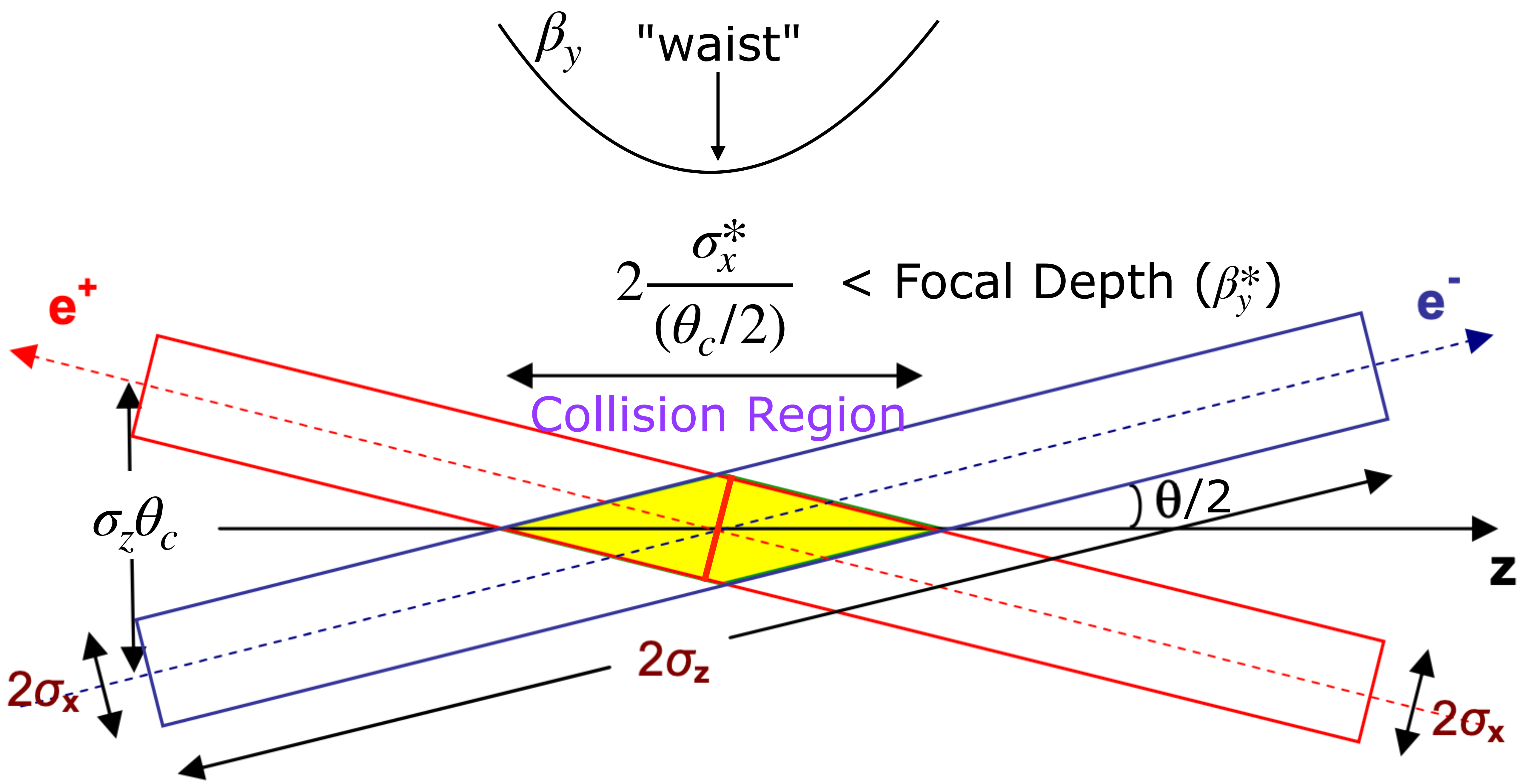
Beam-Beam Blowup

Betatron Resonance → **Crab Waist Scheme can mitigate.**
Combined Effect of Lattice Nonlinear, Beam-Beam, and Wakefield

Two New Technologies

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

1. Nano-Beam Scheme



Effectively Very Short Bunch → "Hourglass"

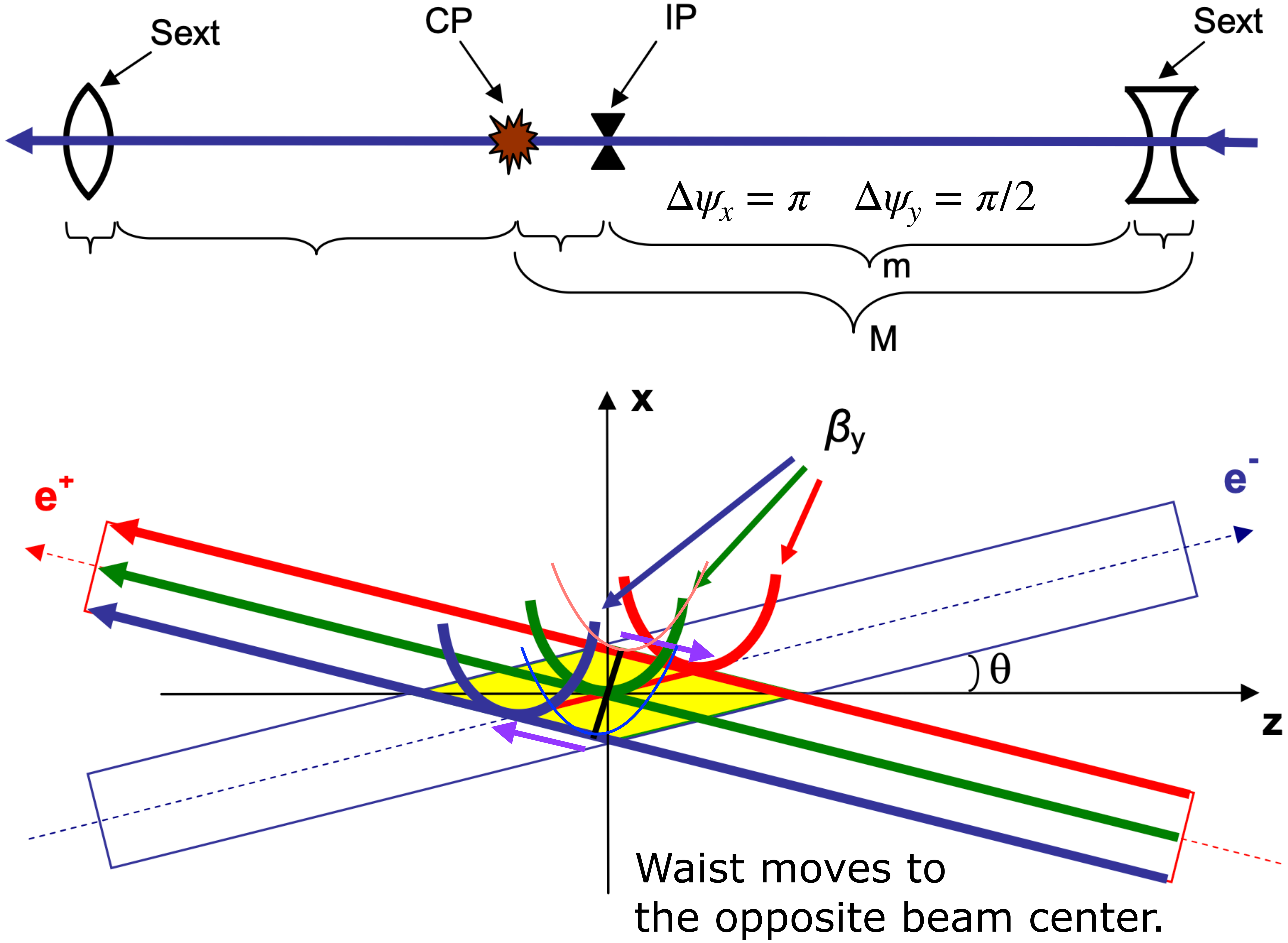
"Head-On Collision"

$$\tilde{\sigma_z} = \frac{\sigma_z}{\Phi} = \frac{\sigma_x^*}{(\theta_c/2)} \quad < 1\ mm \quad \longleftrightarrow \quad \sigma_z = 6\text{ mm}$$

SuperKEKB

Key: Large Crossing Angle with Low ε_x

2. Crab-Waist Scheme



Suppression of Betatron Resonance

Related to Beam-Beam Interaction

Key: Strong Sextupoles with Specific Optics

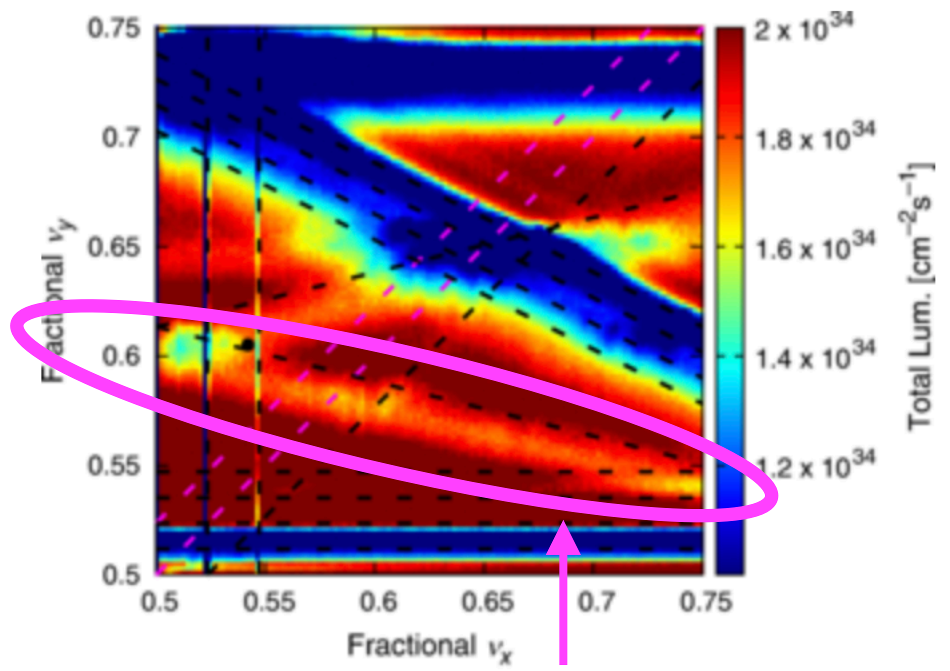
Crab Waist ON and OFF

Experiment on March 12 and March 21-22 2024

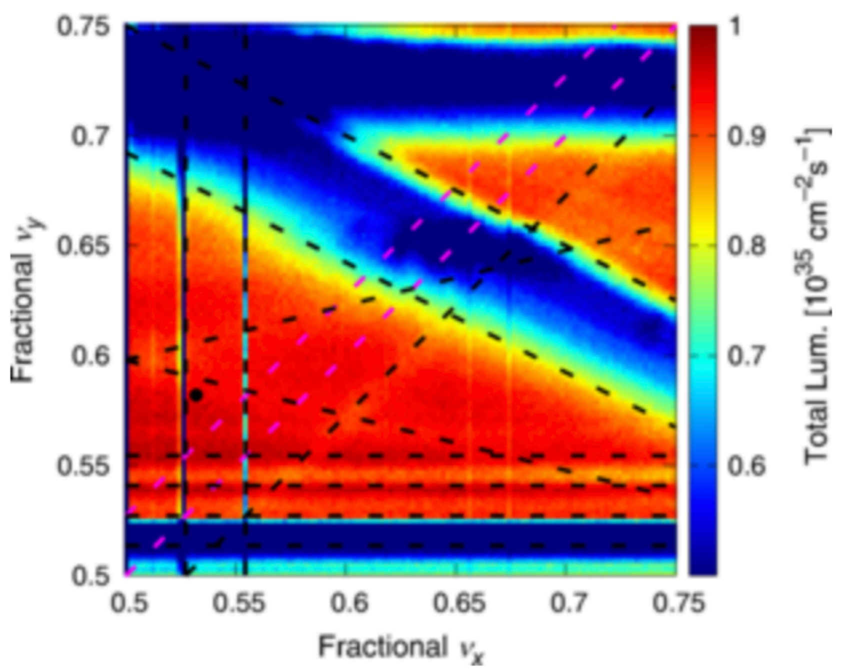
393 Bunches

SuperKEKB Machine Study in 2024

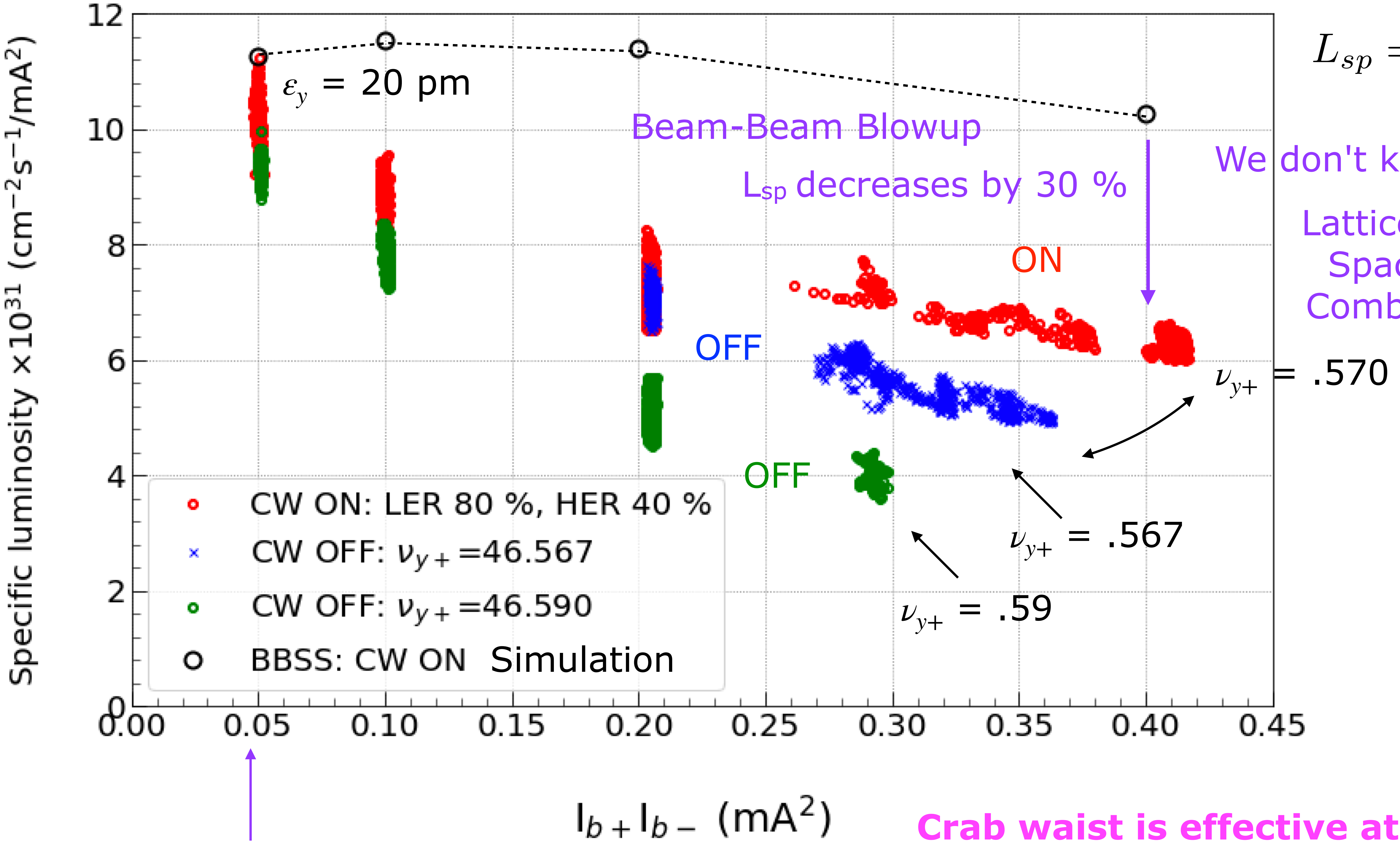
CW OFF



CW ON



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



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

We don't know the reason.

Lattice Nonlinear ?
Space Charge ?
Combined Effect ?

Luminosity is OK for small $I_{b+}I_{b-}$.

Crab waist is effective at high intensity.

Crab waist changes betatron resonance structure.

DAΦNE Performance Summary

Crab Waist Sextupole

P. Raimondi et al.
The first crab sextupole in the world (DAΦNE).
Successfully tested in 2008 - 2009

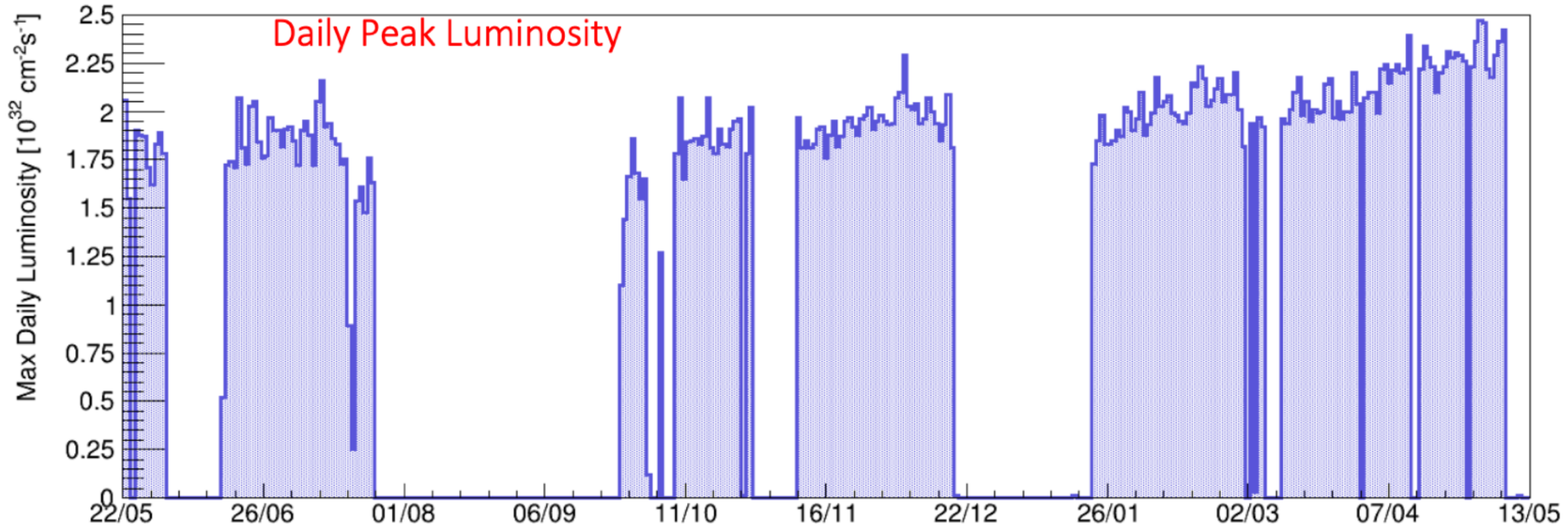
Physics events evaluated on the base of preliminary conservative considerations exhibit a signal to noise ratio 3 time higher with respect to the one measured in 2009.

SHIDDHARTA-2 **2.4×10^{32} cm^{-2}s^{-1}**

Simple IR   Physics for IR

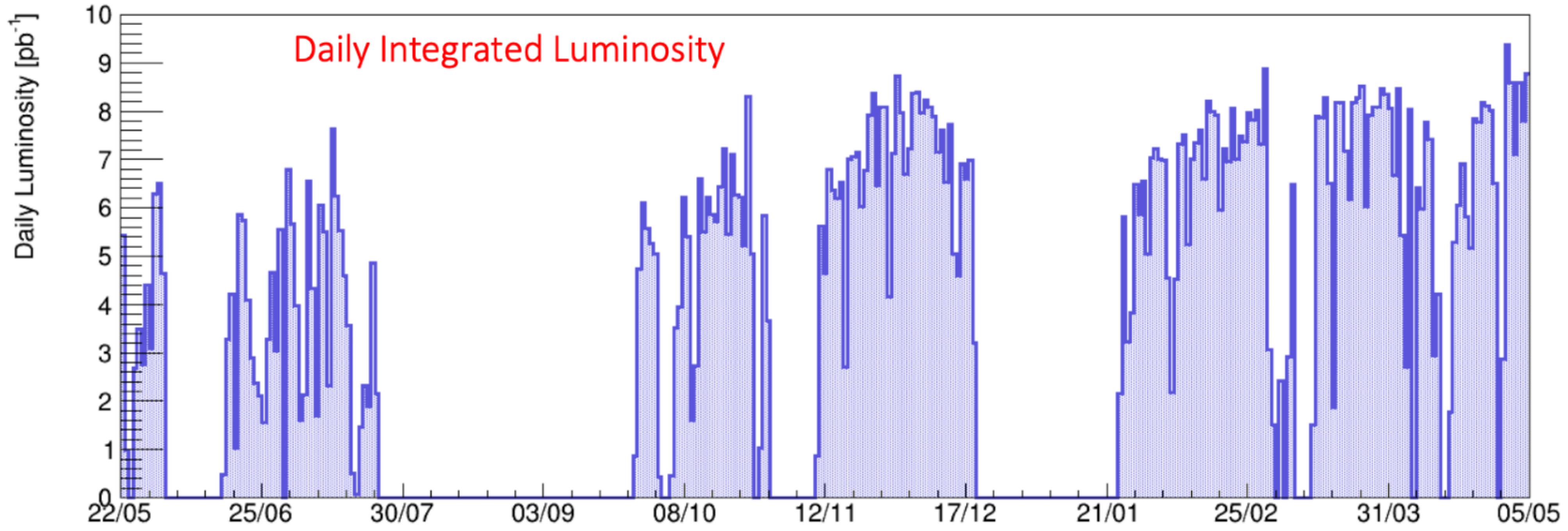
	DAΦNE KLOE (2005)	DAΦNE CW upgrade tested with SIDDHARTA (2009)	DAΦNE (CW) KLOE-2 (2014)	DAΦNE (CW) SIDDHARTA-2 (2024)
L_{peak} [cm^{-2}s^{-1}]	$1.50 \cdot 10^{32}$	$4.53 \cdot 10^{32}$	$2.38 \cdot 10^{32}$	$2.4 \cdot 10^{32}$
I^- [A]	1.4	1.52	1.18	1.29
I^+ [A]	1.2	1.0	0.87	0.887
ε_x [mm mrad]	0.34	0.28	0.28	0.28
$N_{bunches}$	111	105	106	110
$\int_{1h} L$ [pb^{-1}]	0.4	0.79	0.67	0.41
$\int_{day} L$ [pb^{-1}]	9.8 (seldom)	14.98	14.3	9.37
$\int_{1h} L$ [fb^{-1}]	3.0		6.8	1.24
ξ_y	0.0245	0.0443 (0.09 w.s.)	--	--
L_{sp} [cm^{-2}s^{-1}/mA^2]	0.99×10^{28}	3.13×10^{28}	2.46×10^{28}	2.31×10^{28}

Peak Luminosity



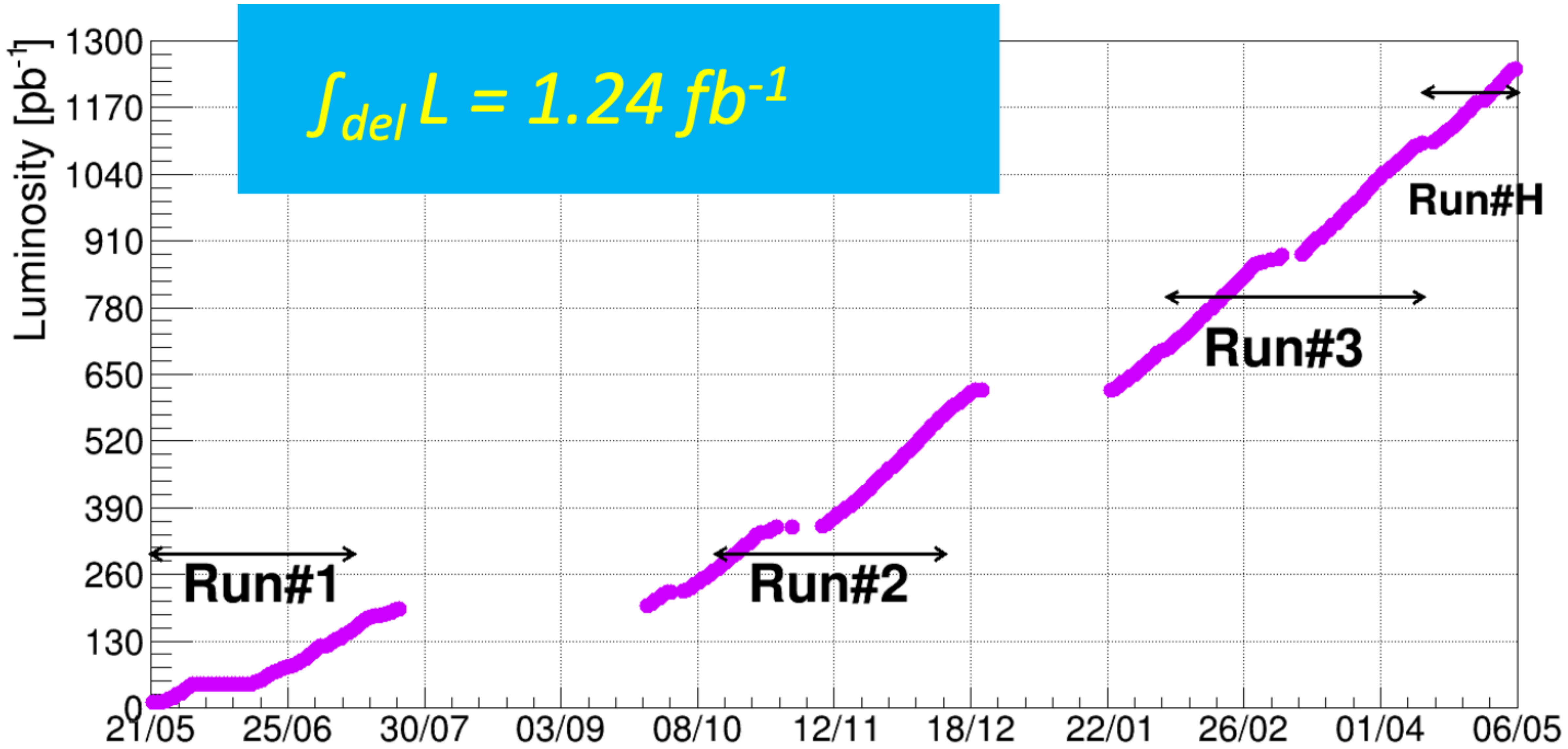
2023   2024

Daily Int. L



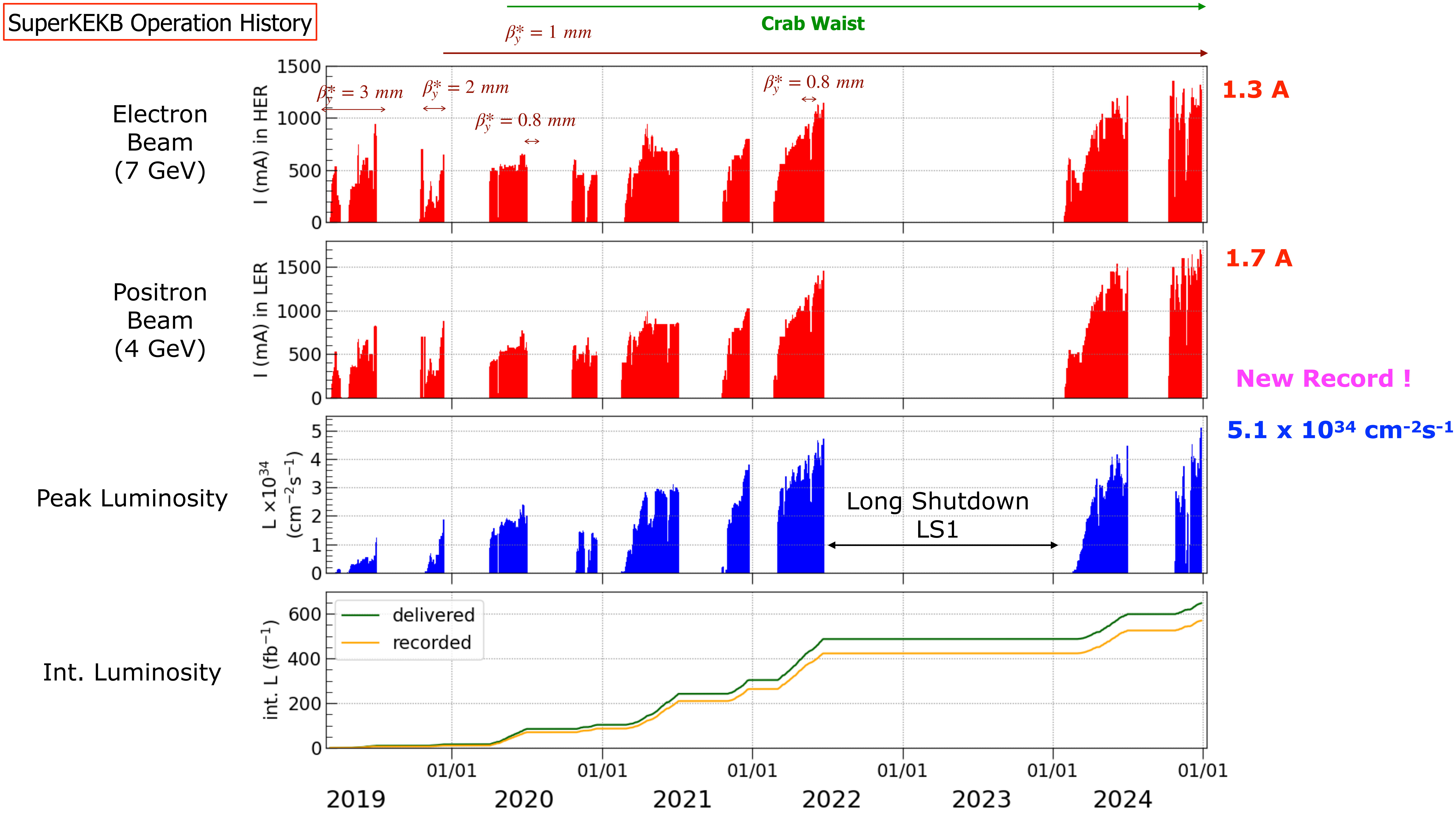
High Intensity
Axial Field in IR

Integrated Luminosity



2023   2024

C. Milardi, eeFACT2025



SuperKEKB Operation History
Crab Waist
$\beta_y^* = 1\ mm$
$\beta_y^* = 3\ mm$
$\beta_y^* = 2\ mm$
$\beta_y^* = 0.8\ mm$
$\beta_y^* = 0.8\ mm$
Electron Beam (7 GeV)
I (mA) in HER
1.3 A
Positron Beam (4 GeV)
I (mA) in LER
1.7 A
New Record !
Peak Luminosity
L ×10^{34} ($cm^{-2}s^{-1}$)
5.1 x 10^{34} $cm^{-2}s^{-1}$
Long Shutdown LS1
Int. Luminosity
int. L (fb^{-1})
delivered
recorded
01/01
2019
2020
2021
2022
2023
2024

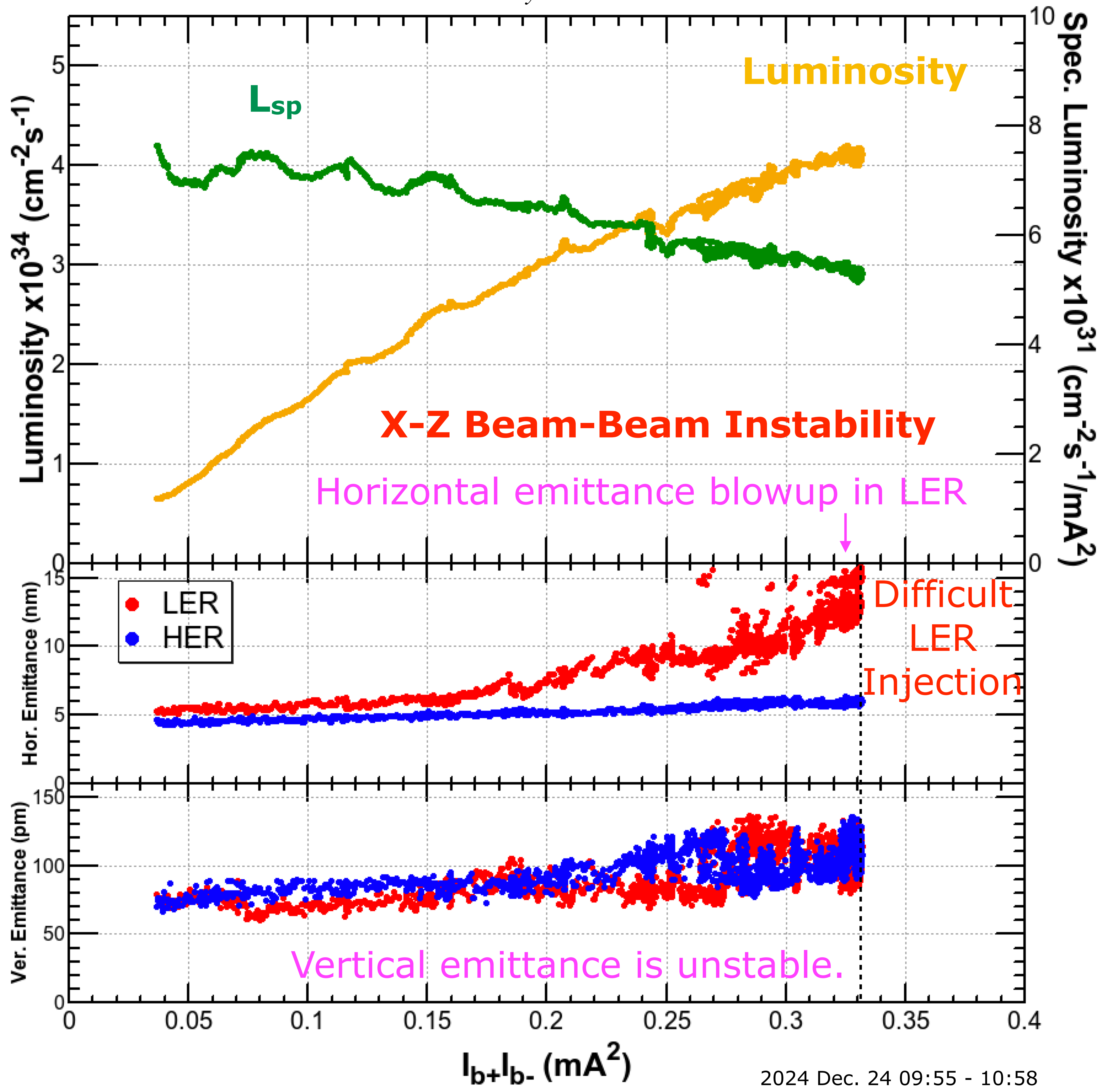
Beam-Beam Issue

Large Crossing-Angle Collision $\theta_c = 83\ mrad$

$\beta_x^* = 60\ mm\ /\ \beta_y^* = 1\ mm\ (HER)$

$\beta_x^* = 80\ mm\ /\ \beta_y^* = 1\ mm\ (LER)$

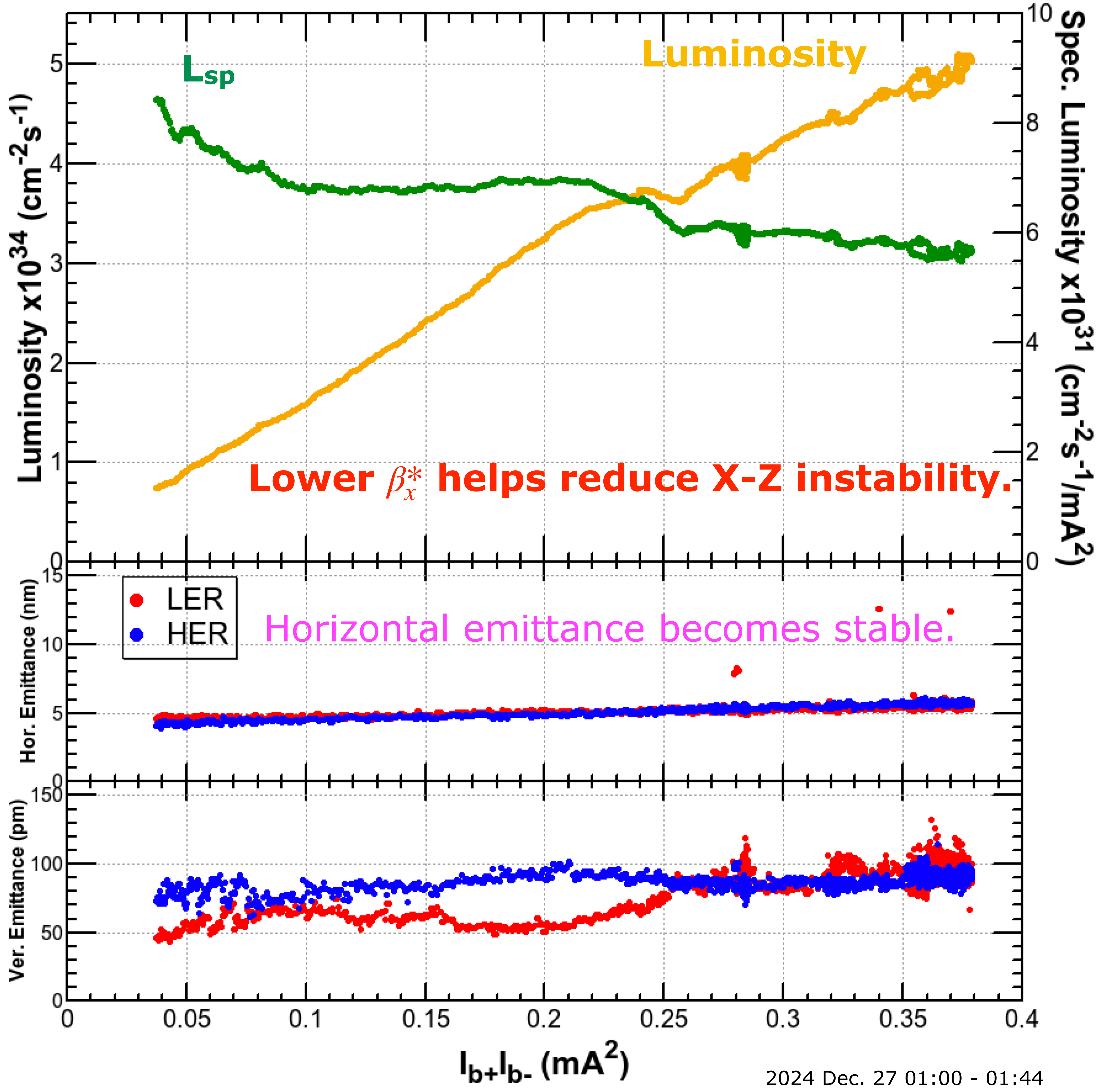
n_b = 2346



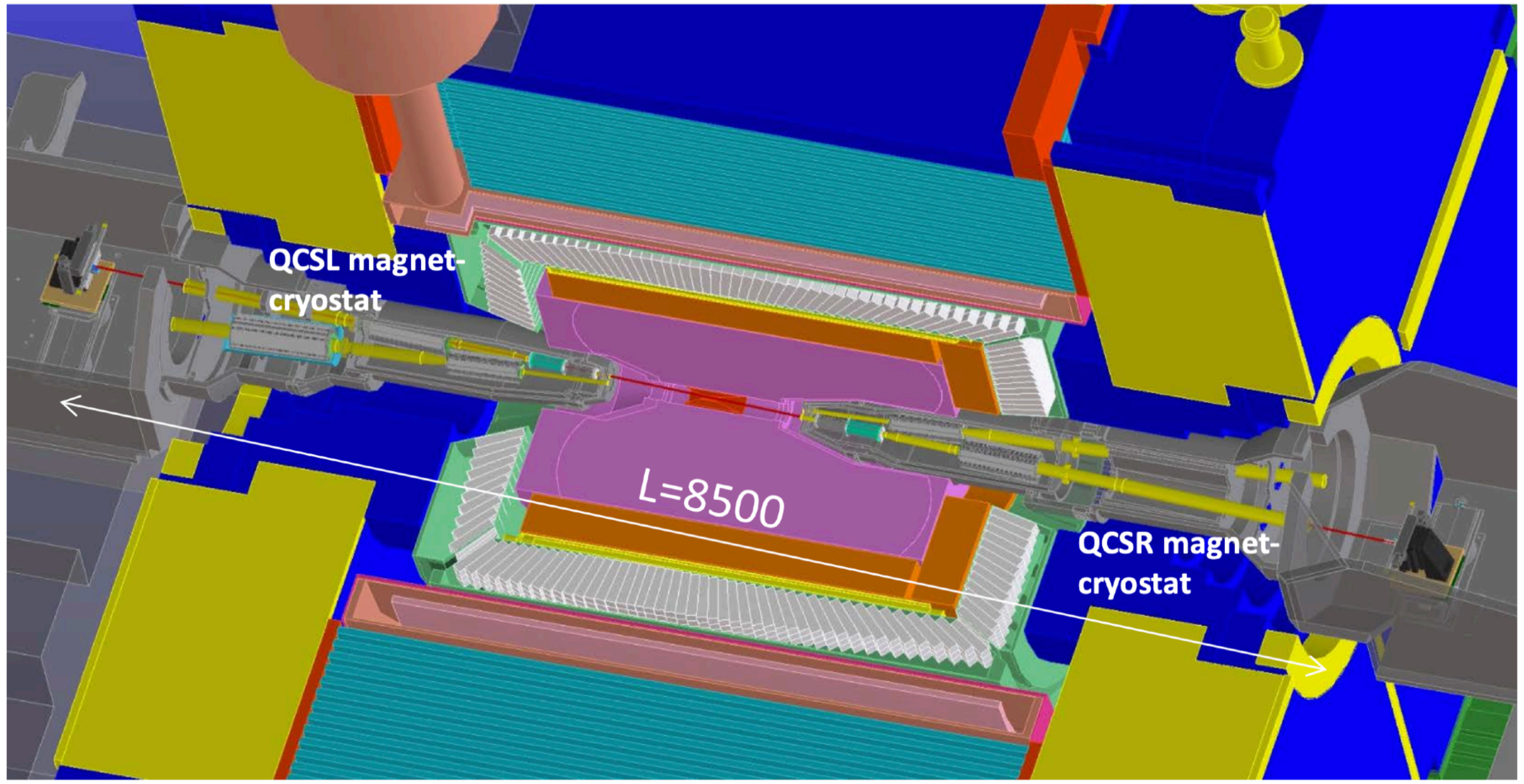
After Squeezing β_x^* in LER

$\beta^* = 60\ mm\ /\ \beta^* = 1\ mm\ (Both)$

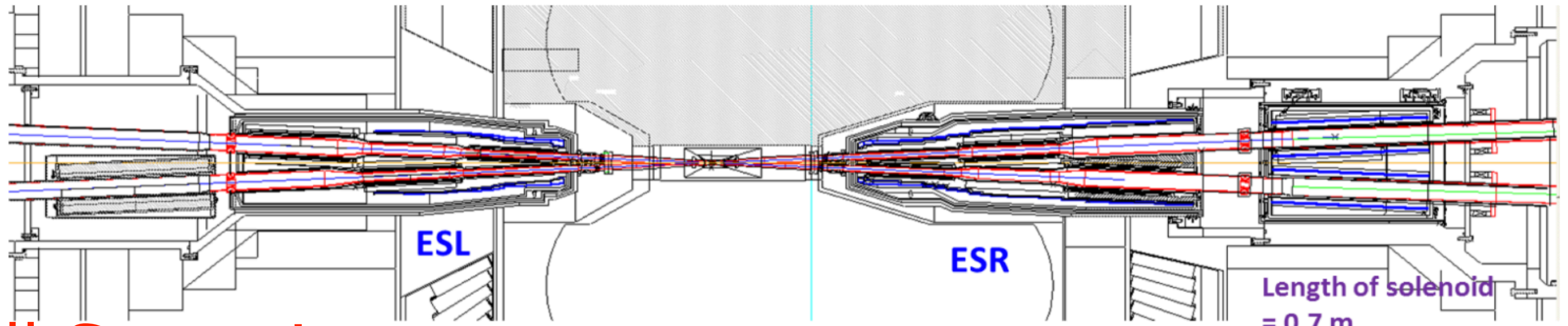
5.1 x 10^{34}



Interaction Region at SuperKEKB

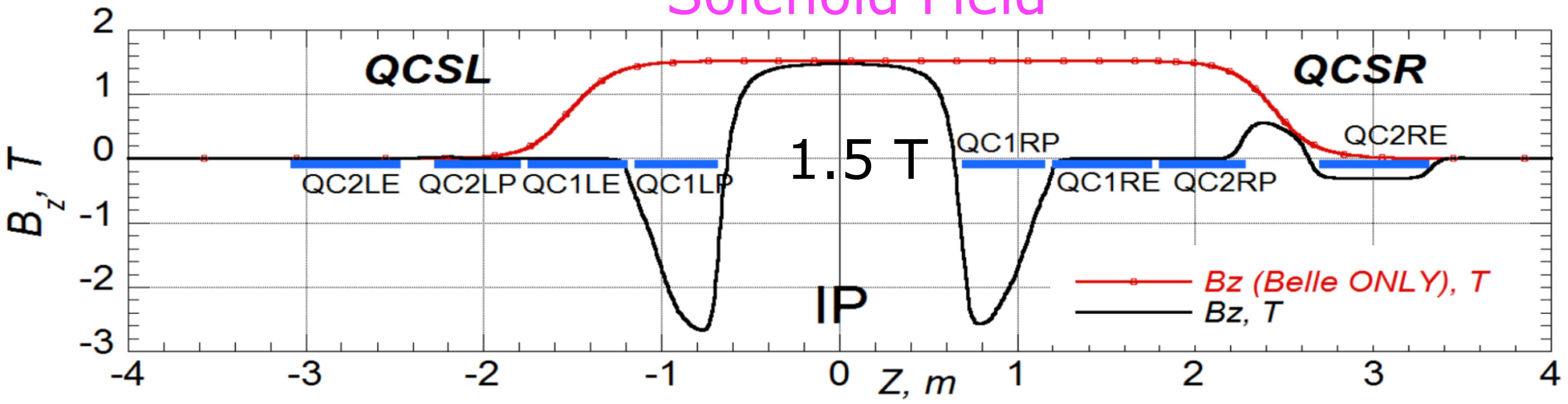


Alignment of the components affects performance. (Larger Impact)

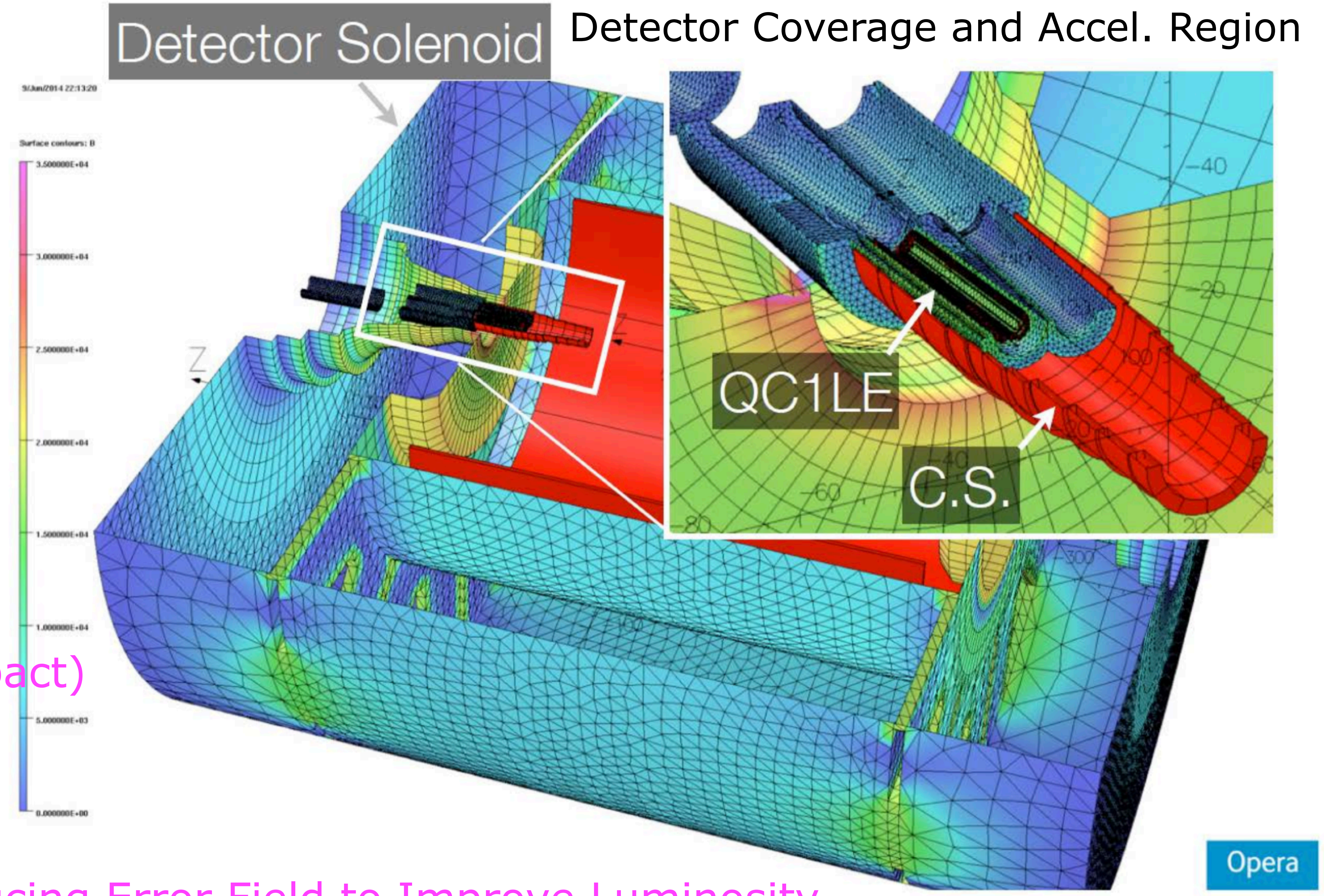


Small Space !

Solenoid Field

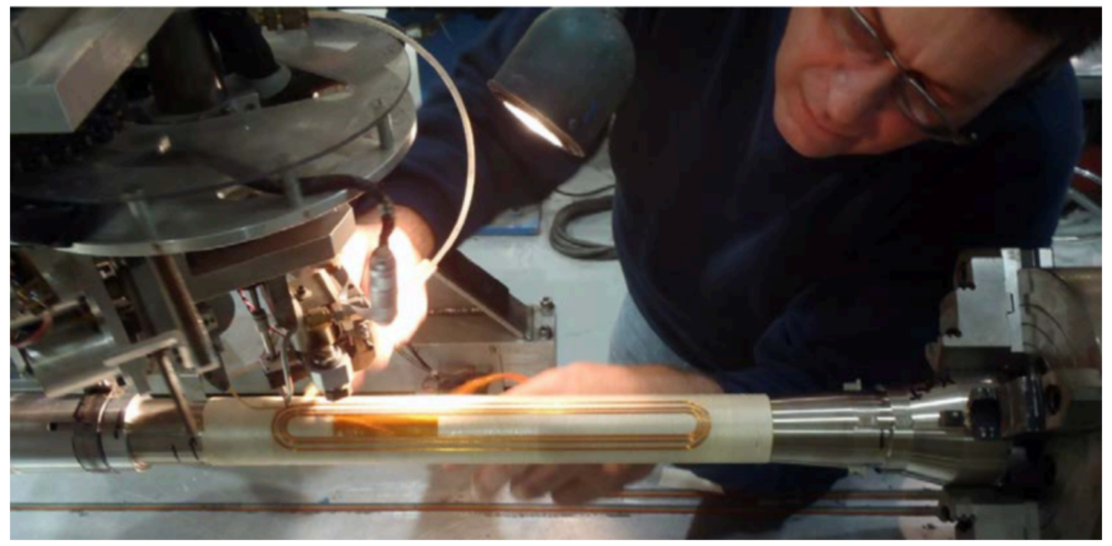


Detector Coverage and Accel. Region



Reducing Error Field to Improve Luminosity.

Direct Winding of SC Corrector Coil (BNL)



Using Many Corrector Coils to Correct Error Field

Obstacles to Increase Beam Current

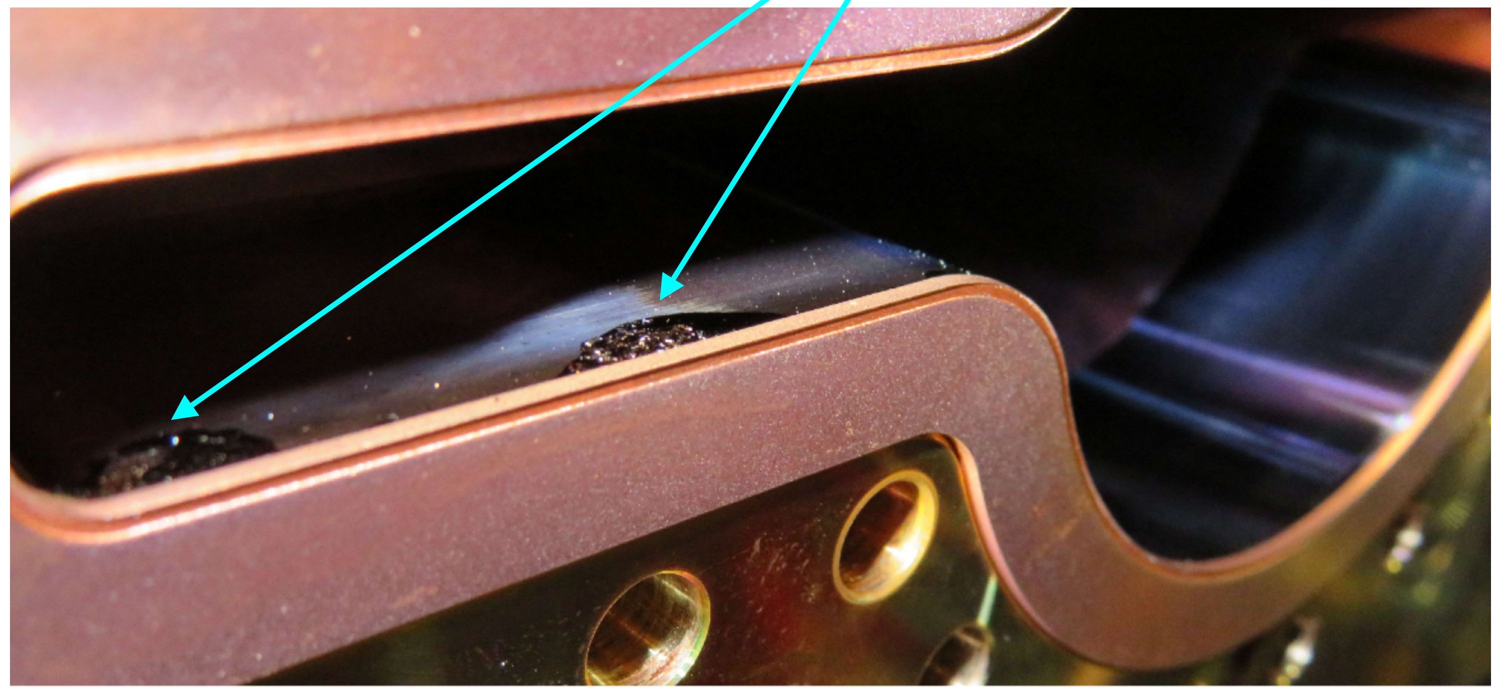
Sudden Beam Loss → Quench of SC Final Focus Magnet, Collimator Damage, Detector Damage

Large beam loss (~40 %) within a few turns
Quit different from known beam instabilities

"VACSEAL" (Vacuum Sealant)

Changes Black Stain
Baked by SR → Amorphous Graphite

MO-Type Flange

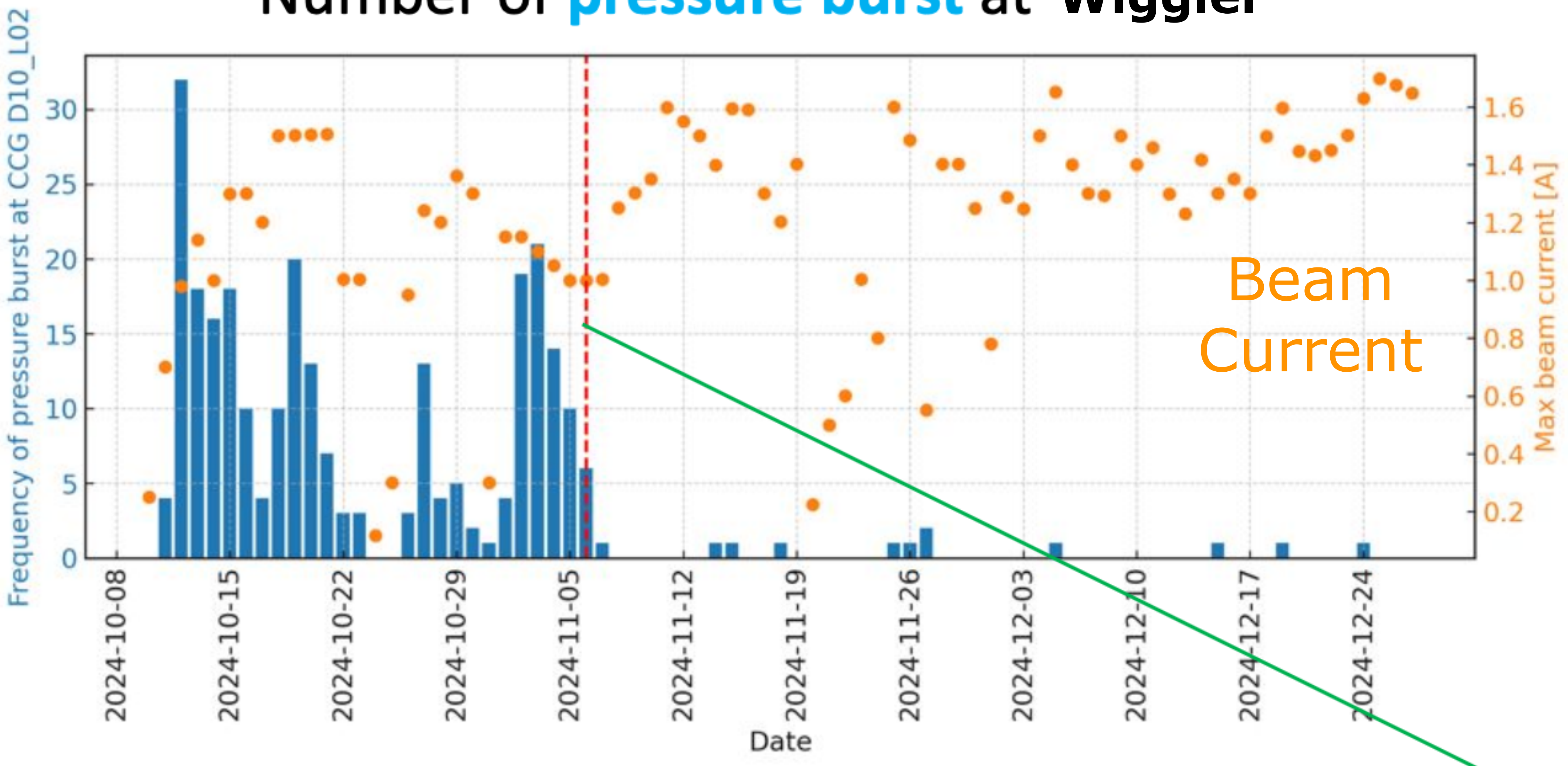


Specific to Wiggler and IR because **VACSEAL** was used there.

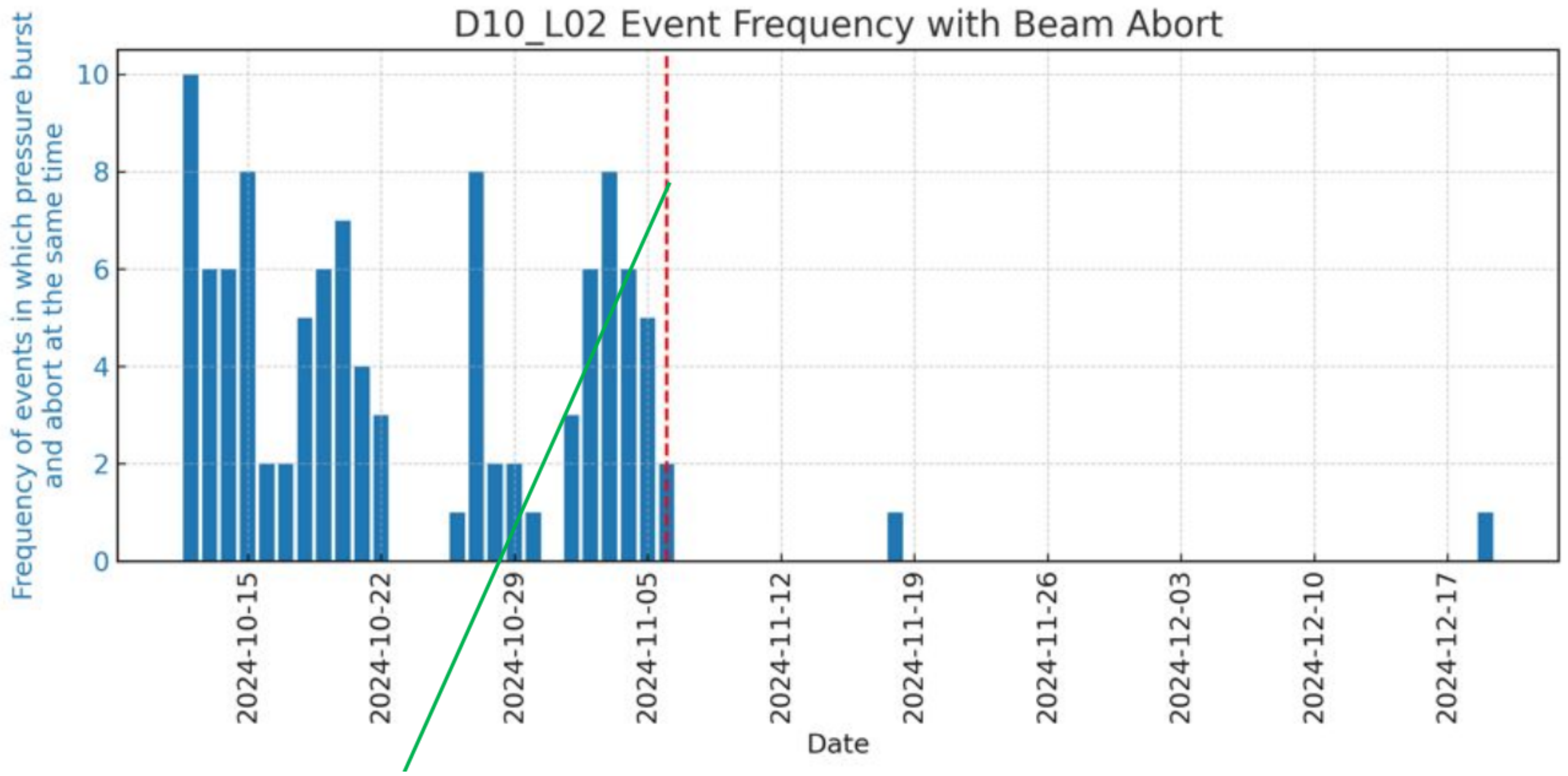
Beam-Dust interaction is a candidate of SBL events.

Cleaning Work → SBL events are significantly reduced.

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



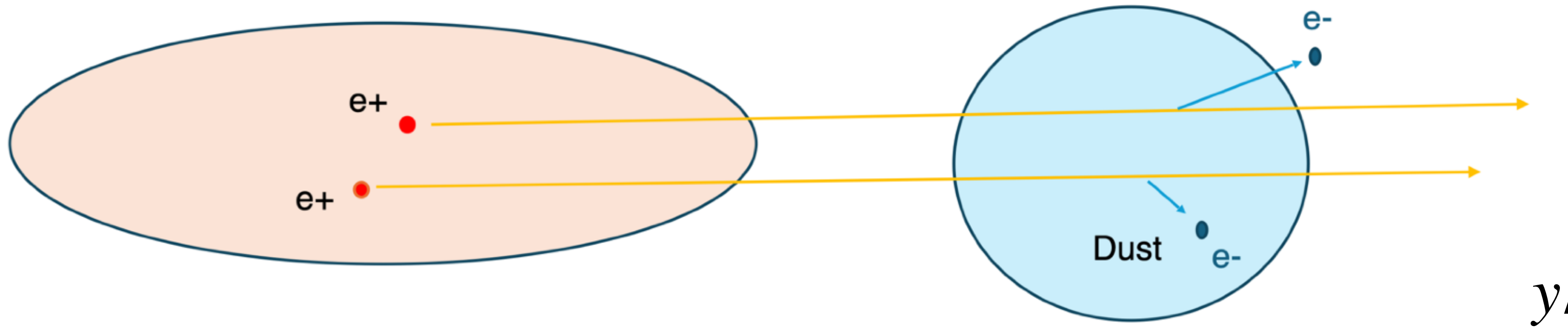
Number of **beam abort accompanied by pressure burst** at **Wiggler**



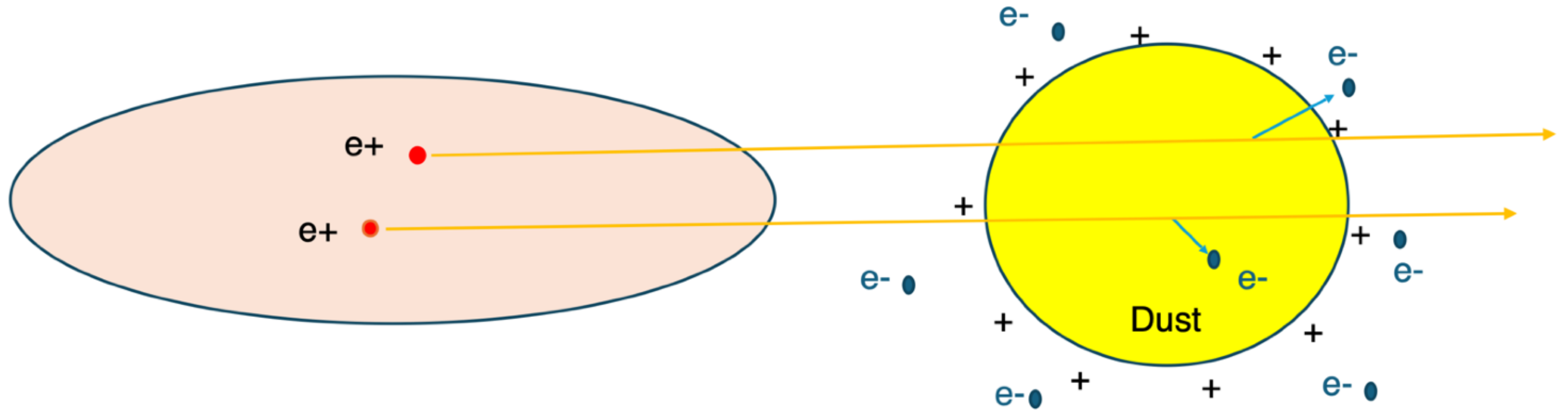
Cleaning Work at Wiggler Flange on November 6

Beam-Dust, Ion, Electron Cloud Interaction

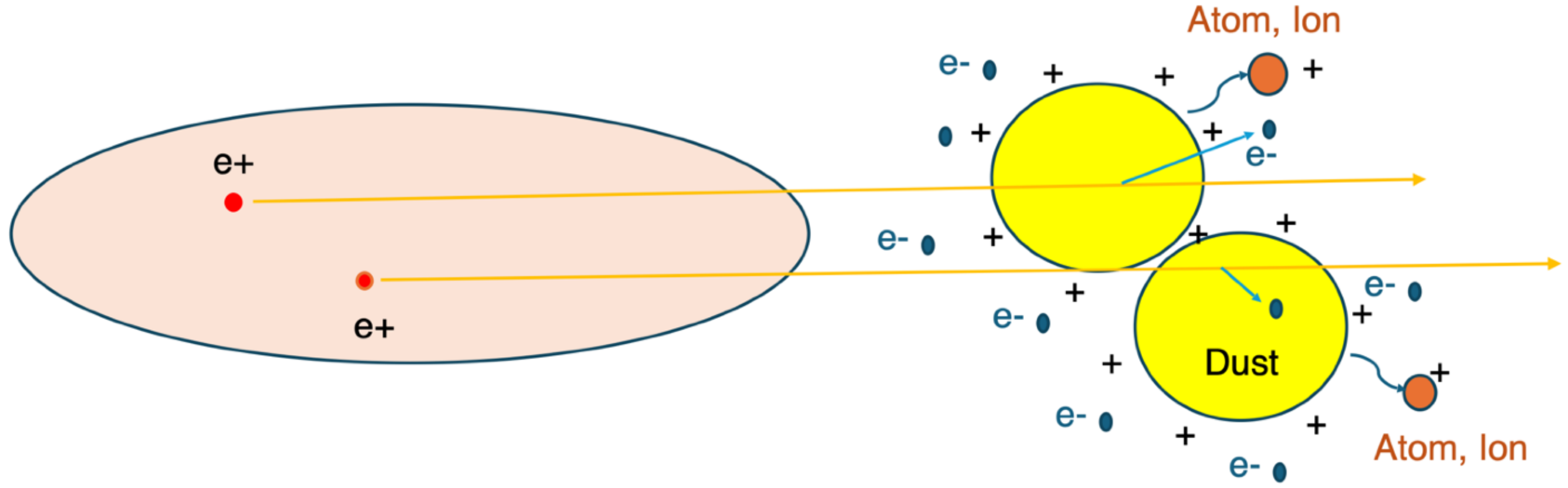
Ionization



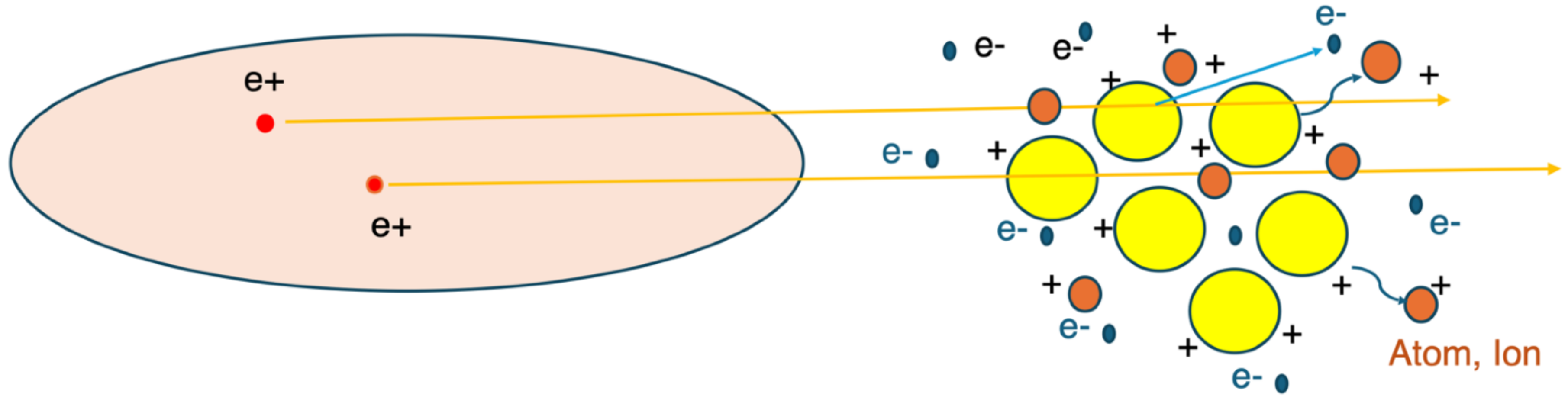
Heating



Fission and Evaporation

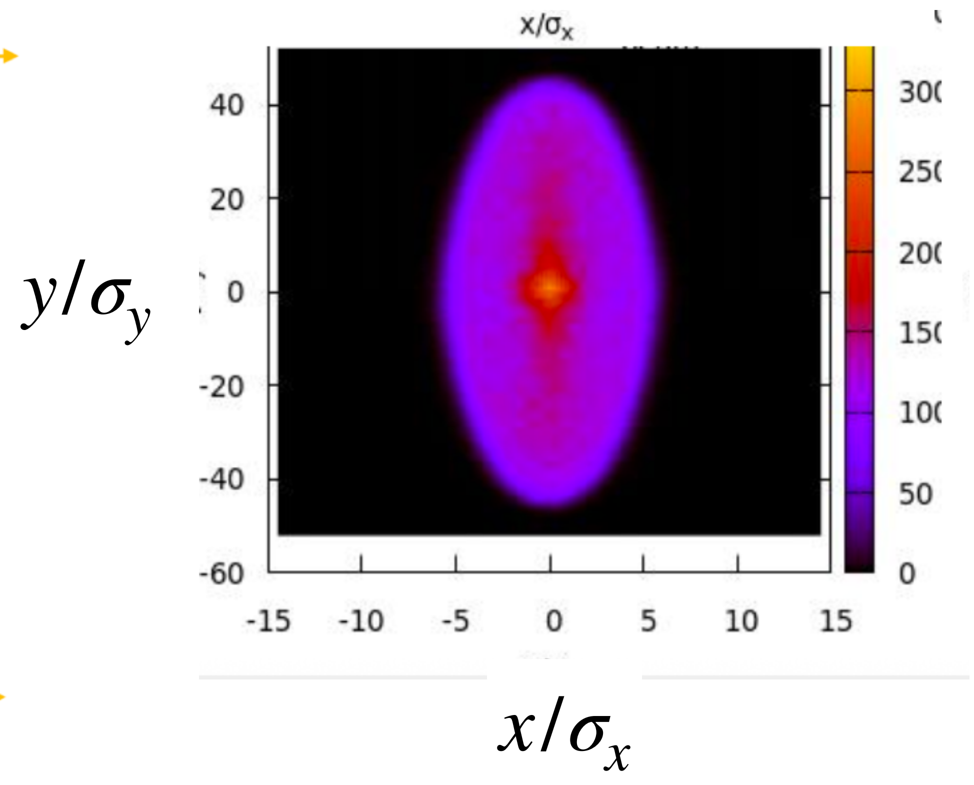


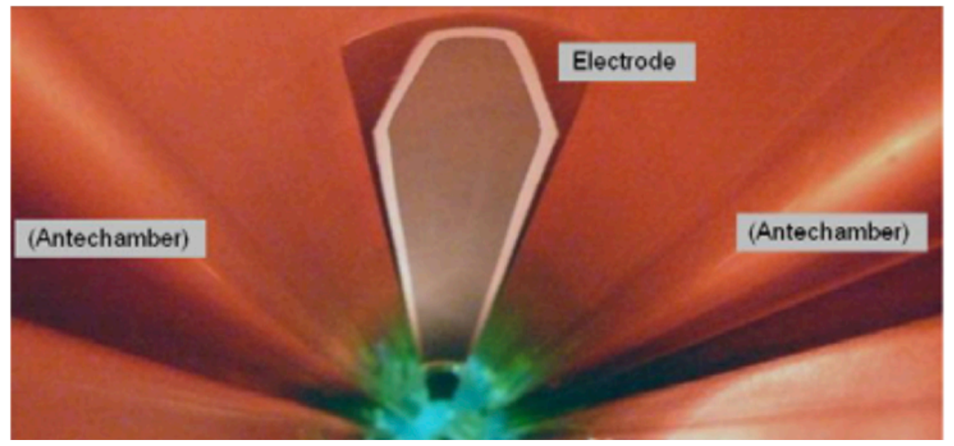
Charged Dust, Ion and Electron Clouds



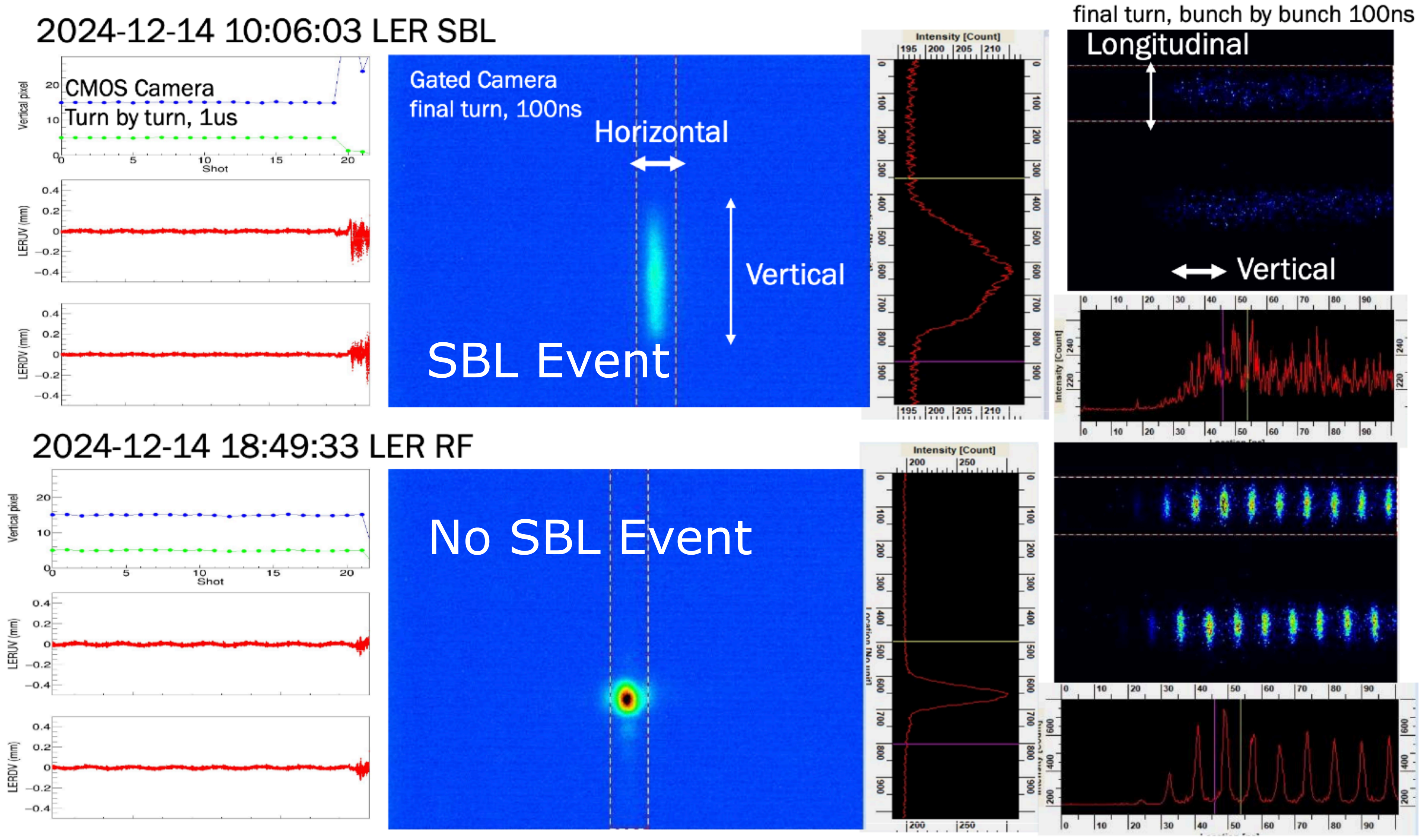
Simulation

4th turn: e⁺ beam



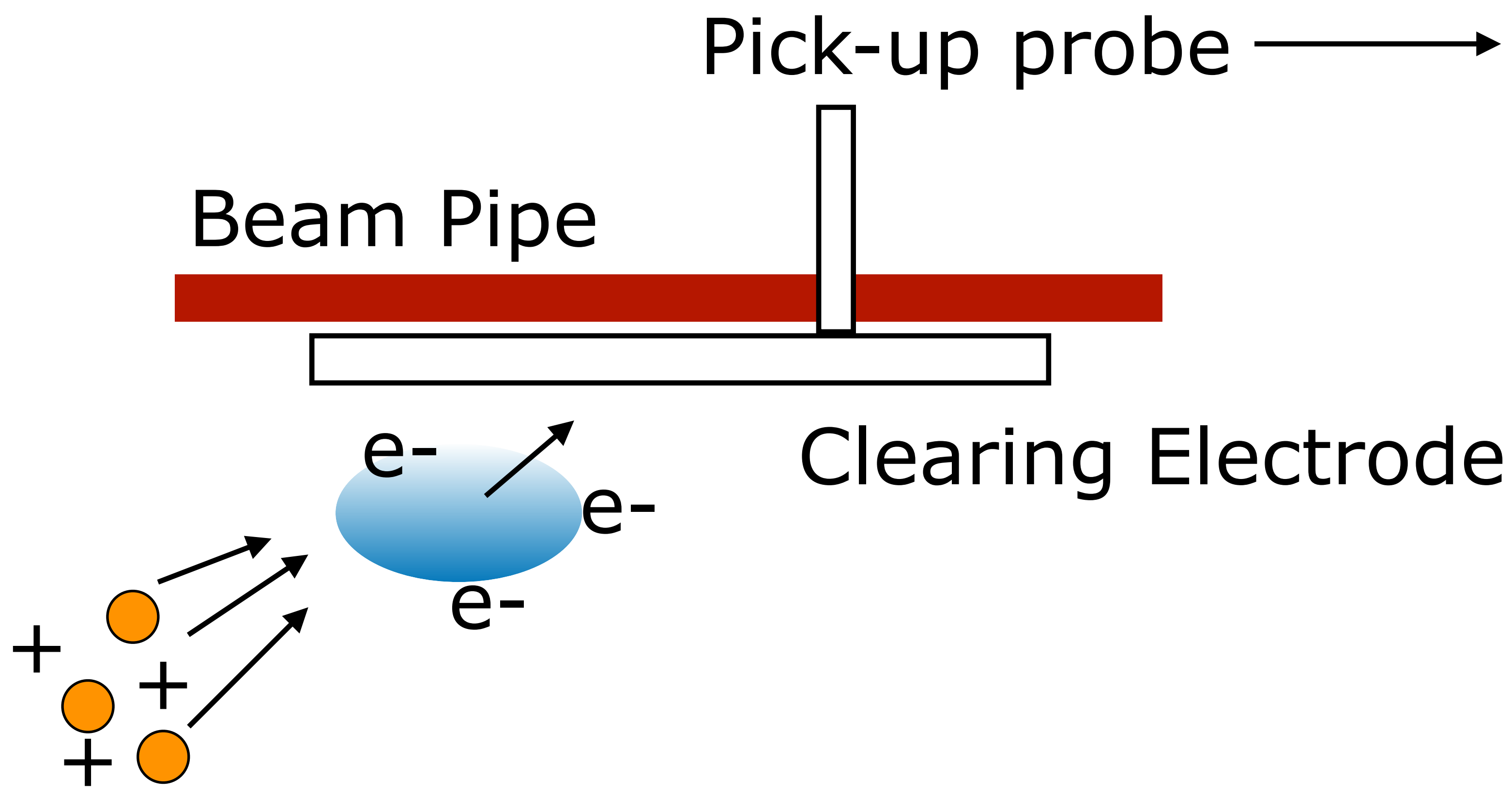


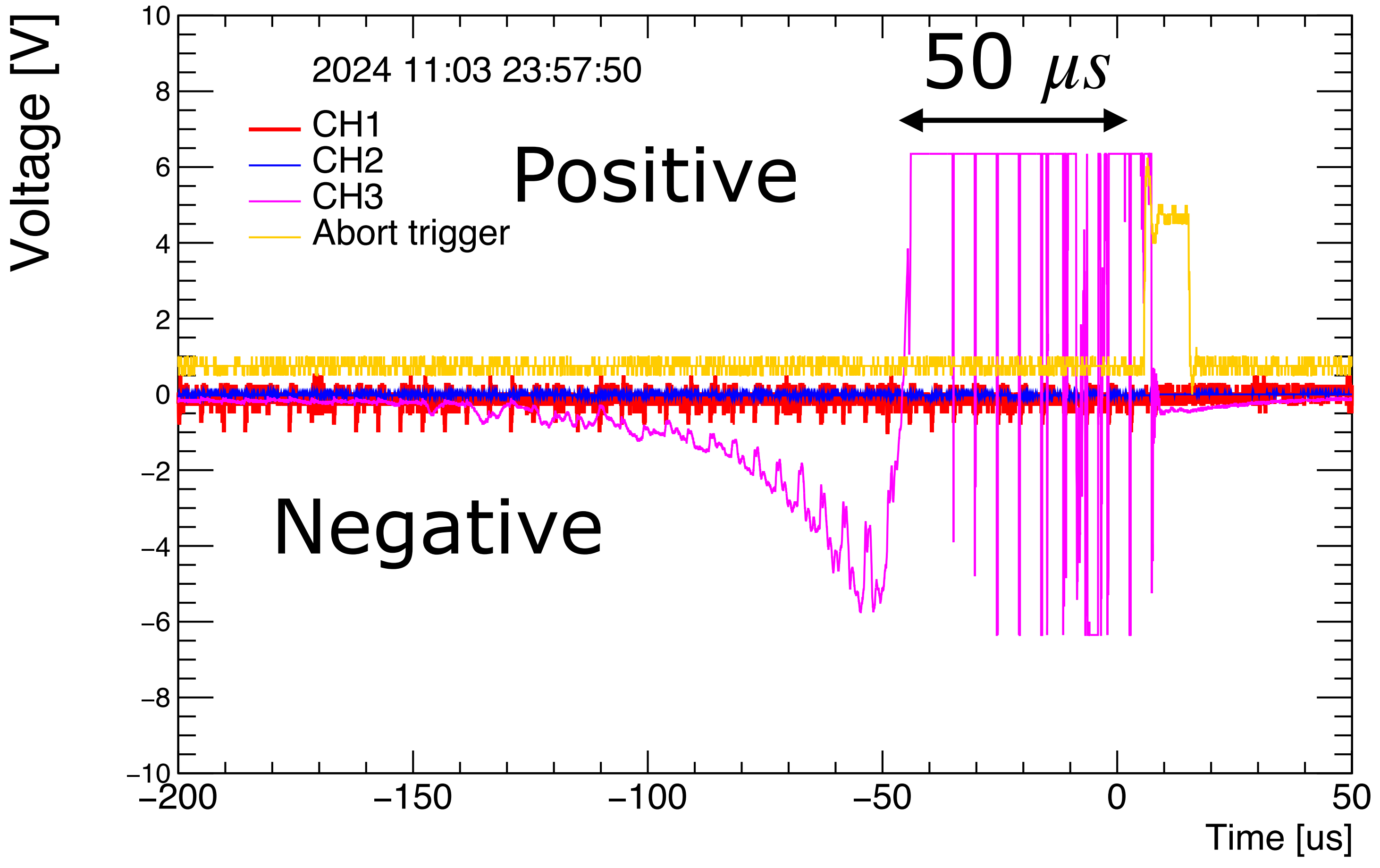
Observation by Streak Camera



Vertical Beam Size Enlargement in SBL Event

Shape of Charged Dust = Flat Beam

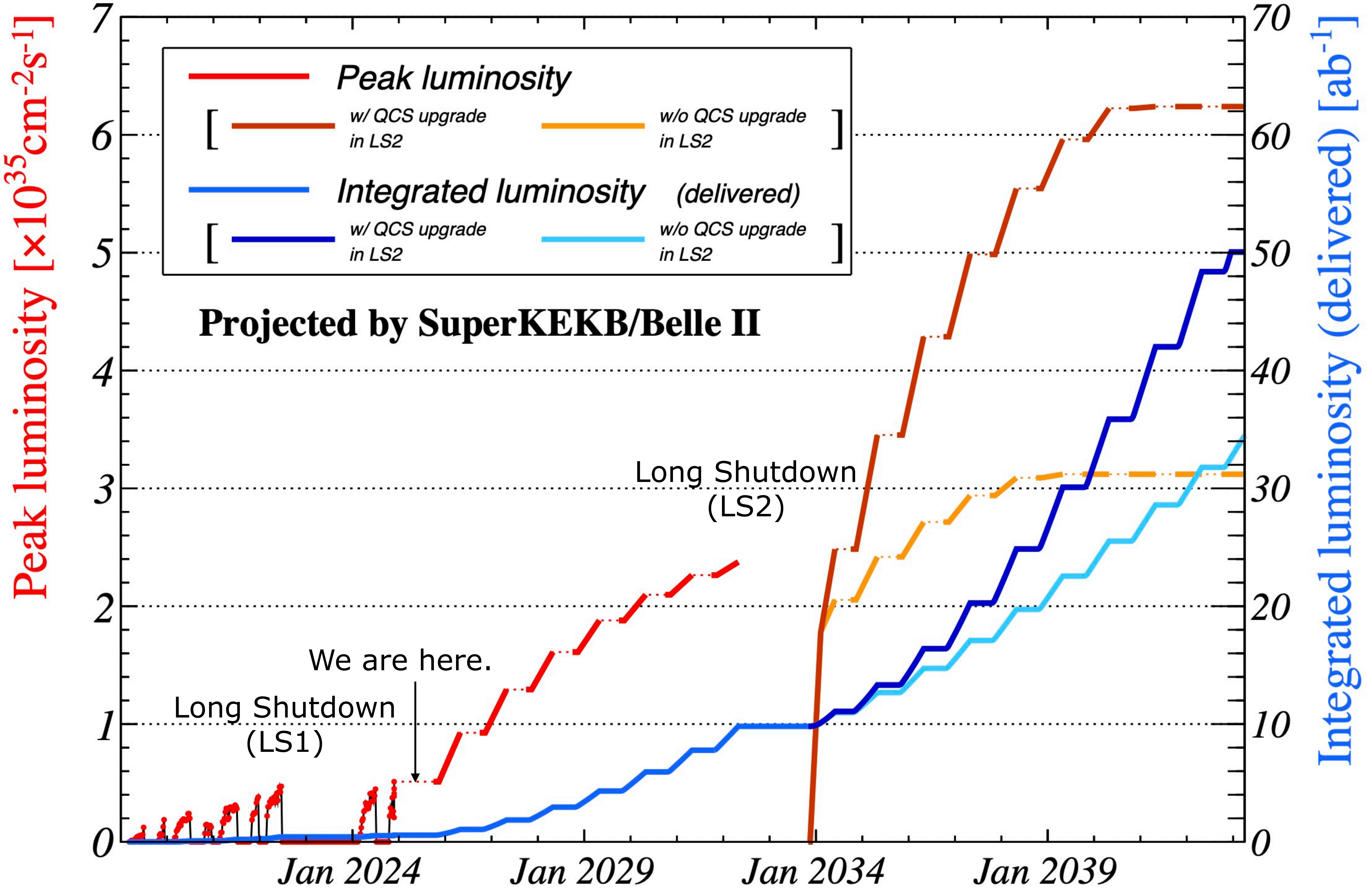




Simulations of Beam-Dust interaction is on-going.

KEKB < FCC-ee < SuperKEKB

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



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
Long Shutdown (LS2)
We are here.
Long Shutdown (LS1)
Peak luminosity [×10^35 cm^-2 s^-1]
Integrated luminosity (delivered) [ab^-1]
0
1
2
3
4
5
6
7
0
10
20
30
40
50
60
70
Jan 2024
Jan 2029
Jan 2034
Jan 2039

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}		$cm^{-2}s^{-1}$

* Bunch lengthening is considered by using streak camera measurements.

	Stand-By	On-Going	Future Collider Projects	
e^+ / e^-	DAΦNE Crab Waist (2024)	SuperKEKB (2024)	FCC-ee (ZH)	CEPC (ZH)
Energy E (GeV)	0.51	4 / 7	120	120
Emittance ε_x (nm)	280	4.0 / 4.6	0.66	0.64
σ_y^* (nm)	**3100 (low current)**	**265**	**32**	**36**
β_x^* (mm)	230	60	240	300
β_y^* (mm)	**8**	**1**	**1**	**1**
Bunch Length σ_z (mm)	15	4.6 (6.0) / 5.1 (6.1)	3.3 (5.6)	2.3 (4.1)
Piwinski Angle Φ	**1.7**	**12.3 (16) / 12.7 (15)**	**3.8 (6.5)**	**2.8 (4.9)**
Bunch Population N ($\times 10^{10}$)	1.63 / 2.37	4.37 / 3.37	12.7	13
Number of Bunches n_b	110	2346	440	268
L ($cm^{-2}s^{-1}$) / IP	2.4×10^{32}	5.1×10^{34}	7.5×10^{34}	5.0×10^{34}
	eeFACT 2025	eeFACT 2025	FCC Integrated Program Stage 1: The FCC-ee	CEPC TDR

Salient Points

- High Intensity Machine → Very Interesting and Big Challenge
- Reducing Impedance
  - Nonlinear collimator helps reduce the impedance with background mitigation. (Full-Swing in the Next Run)
- Design of the IR should be simple as much as possible.
- Lattice nonlinear in the IR reduces dynamic aperture (Touschek lifetime) and can also affect Beam-Beam performance.
  - Try to correct imperfections. SuperKEKB has sextupole, skew sextupole, octupole correctors in the final focus.
- Beam-Beam Blowup
  - Combined effect of Beam-Beam, lattice nonlinear, and wakefield can affect luminosity.
- Squeezing β^* and increasing beam currents form the basis toward higher luminosity.
  - Lower β^* with small emittance reduces dynamic aperture. Chromaticity correction is big challenge.

DAΦNE Team

C. Milardi, D. Alesini, S. Bilanishvili, S. Bini, M. Boscolo, B. Buonomo, S. Cantarella, A. Ciarma, A. Drago, A. De Santis, E. Di Pasquale, D. Di Giovenale, C. Di Giulio, G. Di Pirro, L. Foggetta, G. Franzini, A. Gallo, R. Gargana, S. Incremona, A. Liedl, A. Michelotti, L. Pellegrino, L. Piersanti, R. Ricci, U. Rotundo, S. Spampinati, A. Stella, A. Vannozzi, M. Zobov, LNF-INFN Frascati

Contributions from:
P. Raimondi, Fermilab
J. Chavanne, G. Le Bec, ESRF
O. R. Blanco-Garcia, ALBA
O. Etisken, Kirikalle University

SuperKEKB Team

T. Abe, Y. Arimoto, H. Ikeda, T. Ishibashi, F. Ito, S. Iwabuchi, R. Ueki, S. Enomoto, X. Wang, T. Oki, Y. Ohnishi, T. Okada, S. Ogasawara, H. Kaji, T. Kawamoto, H. Koiso, T. Kobayashi, K. Shibata, H. Sugimura, H. Sugimoto, M. Tawada, M. Tobiyama, S. Nakamura, M. Nishiwaki, Y. Funakoshi, M. Masuzawa, G. Mitsuka, T. Mimashi, A. Morita, S. Yoshimoto, T. Yamaguchi, Y. Yamamoto, K. Watanabe, Y. Mu-Lee, O. E. Driss, M. Kurata, N. Iida, T. Kamitani, Y. Seimiya, K. Furukawa, T. Yoshimoto, F. Miyahara, K. Matsuoka, K. Ohmi, D. Zhou, H. Nakayama, S. Tanaka, I. Nakamura, T. Koga, K. Uno, S. Uno, KEK

Contributions from:
G. Broggi, J. Keintzel, M. L. Garrec, M. Ady, J. Salvesen, K. Oide, R. Soos, F. Zimmermann, R. Tomas, CERN
B. Dalena, Q. Buruant, CEA/Saclay
M. Li, IHEP/IJCLab; S. Wallon, IJCLab
I. Agapov, DESY
M. Migliorati, Sapienza University of Rome
L. Ruckman, SLAC

Conclusion

- Sudden Beam Loss in SuperKEKB
  - Beam-Dust interactions; Amorphous Graphite: VACSEAL Baked by Intense SR in the Flange Connection
  - Cleaning work is on-going. → Expected to Be Solved.
  - Comparison between experiments and simulations is also on-going.
  - Don't use VACSEAL for MO-type flange. (Not found inside HELICOFLEX-type flange)
- Beam-Beam Issues
  - X-Z instability can be understood. Reason for the Beam-Beam blowup is still unclear.
  - Beam-Beam simulations on GPU machines (Weak-Strong and Strong-Strong include lattice, machine imperfections, and wakefield) are on-going.
- Very Short Lifetime in Nono-Beam Scheme with Crab Waist Scheme → Injection Performance
  - Small dynamic aperture and Beam-Beam may require longitudinal phase-space injection.
- International collaboration with CERN, IJCLab, DESY, IHEP, Frascati, SLAC, BNL, and Fermilab works to overcome these challenges.