SuperKEKB and Lessons for FCC-ee*

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*based on https://arxiv.org/abs/2509.07448v4 plus recent updates

1. disclaimer

This presentation reports the current understanding of the speaker.

Alternative or complementary descriptions and interpretations of the SuperKEKB luminosity performance were presented elsewhere [1,2,3]

[1] D. Zhou, K. Ohmi, Y. Funakoshi, Y. Ohnishi, Y. Zhang, Simulations and Experimental Results of Beam-Beam Effects in SuperKEKB. Phys. Rev. Accel. Beams 26, 071001 (2023). https://doi.org/10.1103/PhysRevAccelBeams.2

[2] D. Zhou, K. Ohmi, Y. Funakoshi, Y. Ohnishi, Luminosity Performance of SuperKEKB. JINST 19(02), T02002 (2024). https://doi.org/10.1088/1748-0221/19/02/T02002 , arXiv:2306.02692 [physics.acc-ph]

[3] J. Gao, Analyses of Super KEK B Luminosities Compared with Theoretical Formulae with DA Limitation Effects, 29 July 2025, unpublished (2025)

1. acknowledgements

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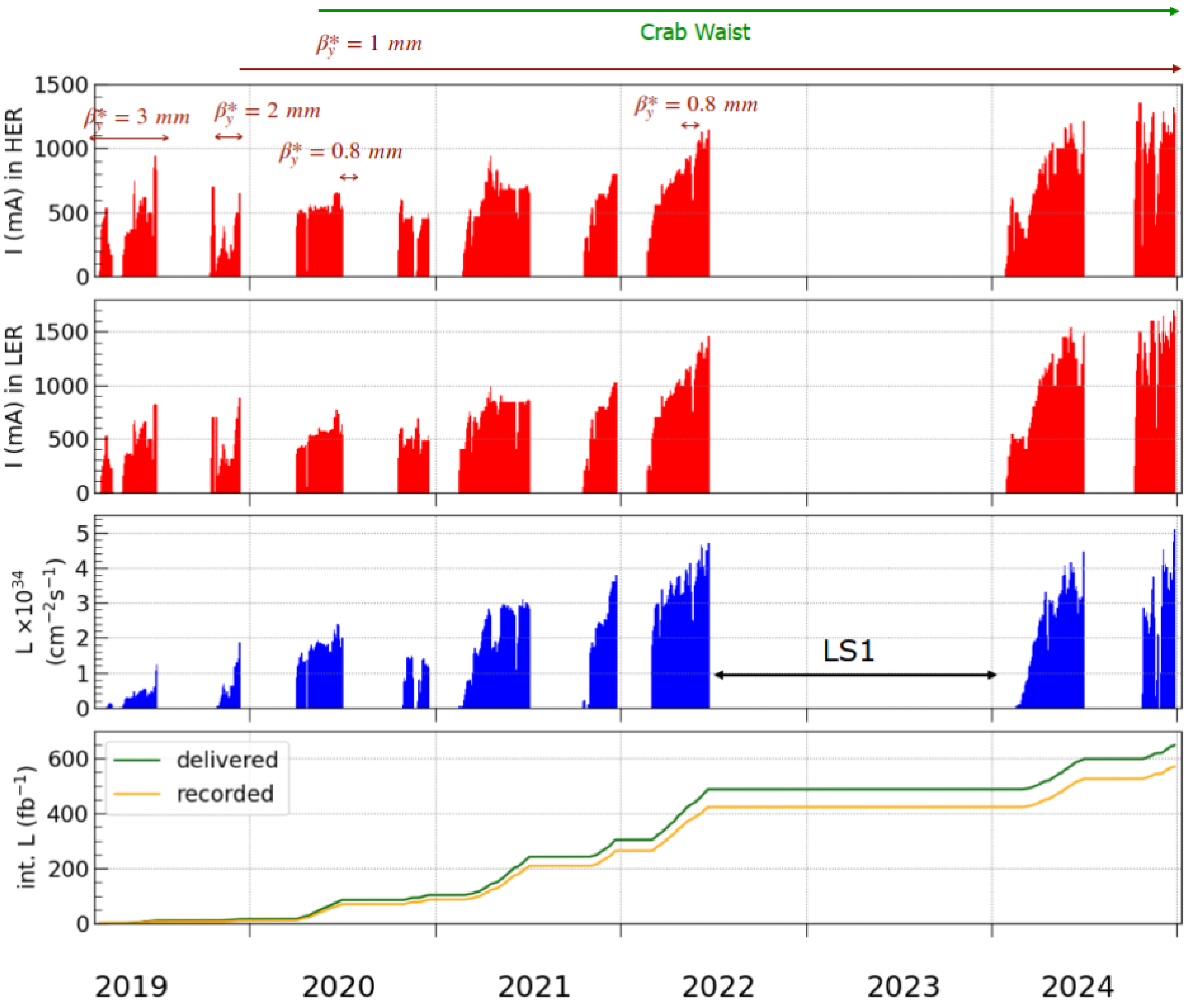
2. achievements: run history

beam currents in HER (e^-) and LER (e^+), along with instantaneous and integrated luminosity as a function of time from 2019 through 2024, as reported by Y. Ohnishi

8 short runs, in 6 out of 8 runs new luminosity (world) records



2. achievements: FCC-ee concept validation

SuperKEKB has successfully demonstrated three (soon four) essential FCC-ee design features:

- an ultralow β_y^*~0.8–1.0 mm†,
- the virtual crab waist collision scheme,
- electron and positron beam currents exceeding 1.3 A

- longitudinal top-up injection (being implemented as we speak)

† with about 100 (10,000)x larger ε_y of stored (injected) beam than FCC-ee, and ~1/2 *l**

2. achievements and goals: parameters

parameter	KEKB w Belle		SKB 2022b		SKB 27 Dec. 2024		SKB design	
	LER	HER	LER	HER	LER	HER	LER	HER
E [GeV]	3.5	8	4	7	4	7	4	7
β_x^* [mm]	1200	1200	80	80	60	60	32	25
β_y^* [mm]	5.9	5.9	1.0	1.0	1.0	1.0	0.27	0.30
ε_x^* [nm]	18	24	4.0	4.6	4.0	4.6	3.2	4.6
ε_y^* [pm]	150	150	$\sim$50	$\sim$50	$\sim$70	$\sim$70	8.6	12.9
I [mA]	1640	1190	1321	1099	1632	1259	3600	2600
n_b	1584		2249		2346		2500	
I_b [mA]	1.04	0.75	0.587	0.489	0.696	0.537	1.44	1.04
ξ_y ‡	0.098	0.059	0.0407	0.0279	0.036	0.027	0.069	0.060
L_{sp} [$\mu b^{-1} s^{-1} mA^{-2}$]	17.1		71.2		58		214	
L [10^{34} $cm^{-2} s^{-1}$]	2.11		4.65		5.1		80	

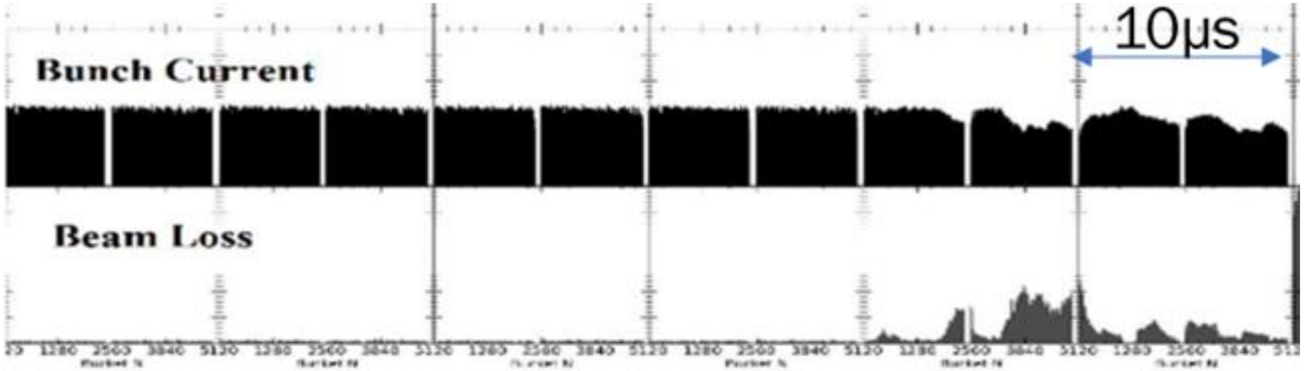
‡The beam-beam parameter is computed without accounting for hourglass effect or geometric factor.

2. challenges encountered

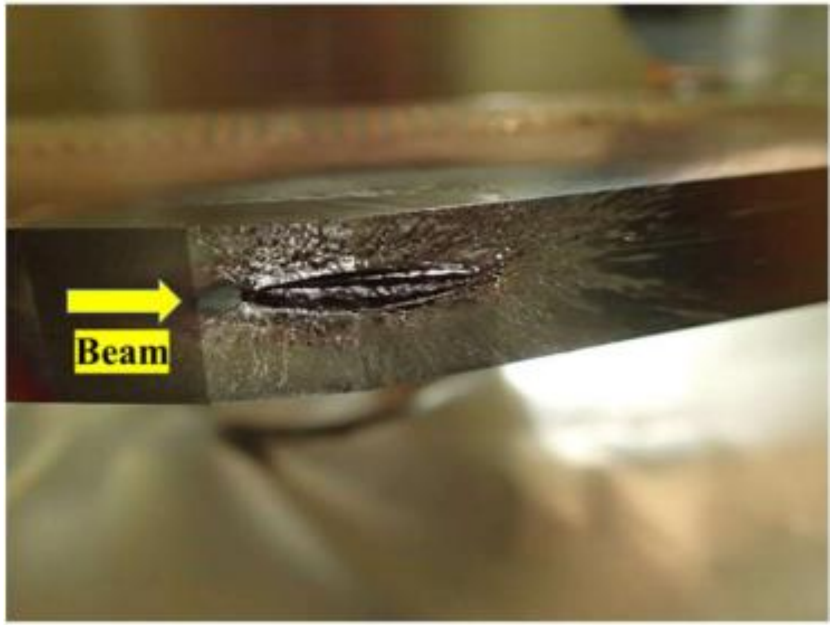
- **sudden beam loss** (being addressed)
- **stored beam vertical emittance** (~10x design)
- **injected vertical beam emittance** (currently ~1000x the design stored beam emittance)
- **injection efficiency** (due to large injected emittance & physical + dynamics aperture; limiting beam current)
- **interaction region** (highly complex source of IP aberrations)
- **IP beta** β_y^* (limited by injected beam emittance, IR aperture, DA)
- **specific luminosity** (**linear & chromatic coupling**, **design lattice,** optics errors, space charge, impedance, **feedback**/noise,…)
- limited number of experts

3. sudden beam losses

Large sudden beam loss (SBL) events occur **within 1 turn (10 μs).**
A significant portion of the beam is lost before the beam abort.
SBLs often lead to **damage of collimators and other accelerator components**, occasionally also to **quenches of the final focusing superconducting magnets (QCS), and to large detector backgrounds** plus potential damage inside the Belle 2 experiment.
SBLs occur for both beams, in collision and without collision, with a squeezed and relaxed optics, but more frequently and more impactfully in the Low Energy positron Ring (LER).
In the LER, about 250 such events were observed in 2024. The rate of SBL events is higher the higher the beam current.



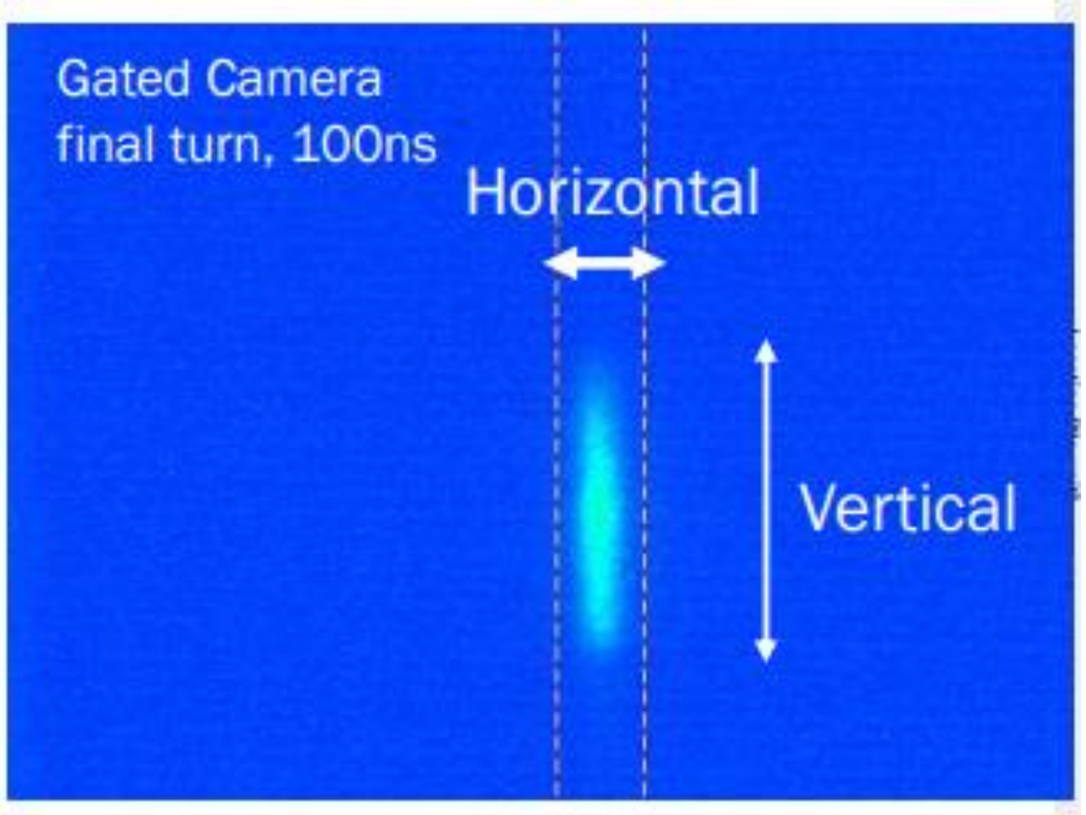
Example SBL event, presented by H. Ikeda

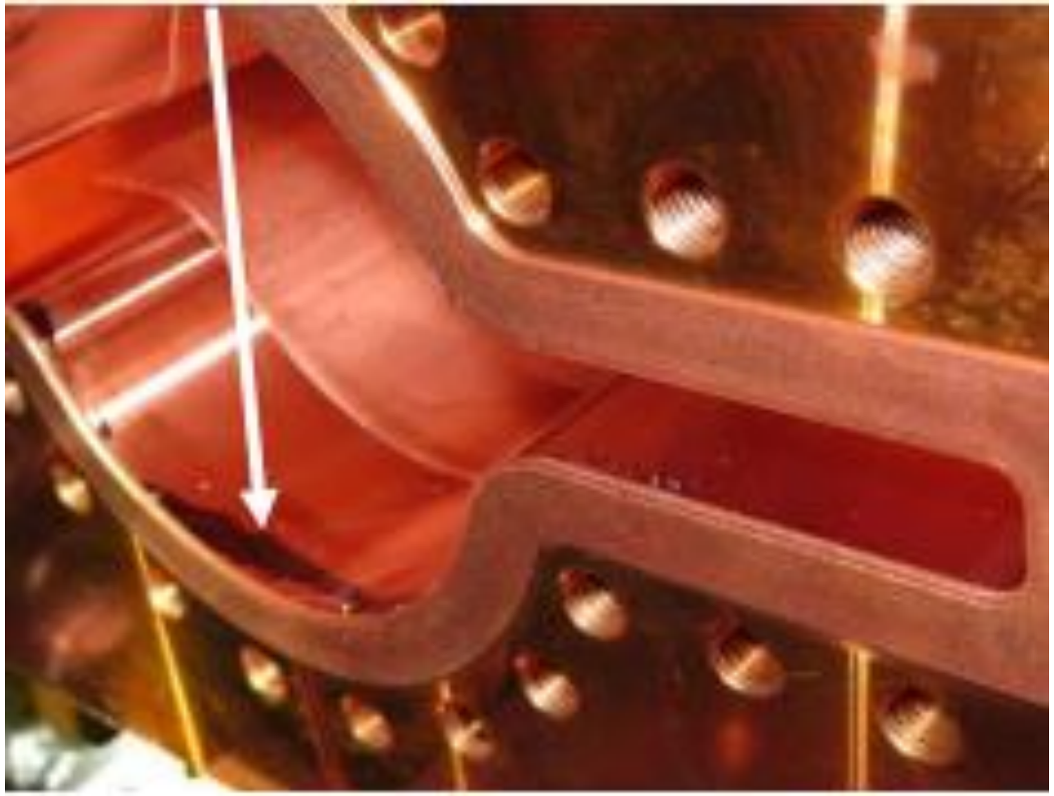


SuperKEKB collimator jaw damaged by an SBL event, from H. Ikeda

3. sudden beam losses cont’d

Several turns before the sudden beam loss happens, the vertical beam size often increases significantly.





Vertical blow during a sudden beam loss event (left), from H. Ikeda, and **black stain next to an “MO’”-type flange** (right), shown by K. Shibata

3. sudden beam losses cont'd

No other accelerator has used MO flanges, and no other collider, including PEP-II, KEKB and DAFNE, nor any low-emittance light sources, such as ESRF-EBS, APS-U, etc., reported SBL events like those seen at SuperKEKB, or any sudden vertical blow up, with or without accompanying beam loss. Modern light sources have much smaller emittances – ESRF-EBS: $\varepsilon_{x,y}$=(110, 5) pm ; SuperKEKB: $\varepsilon_{x,y}$~(4000, 100) pm

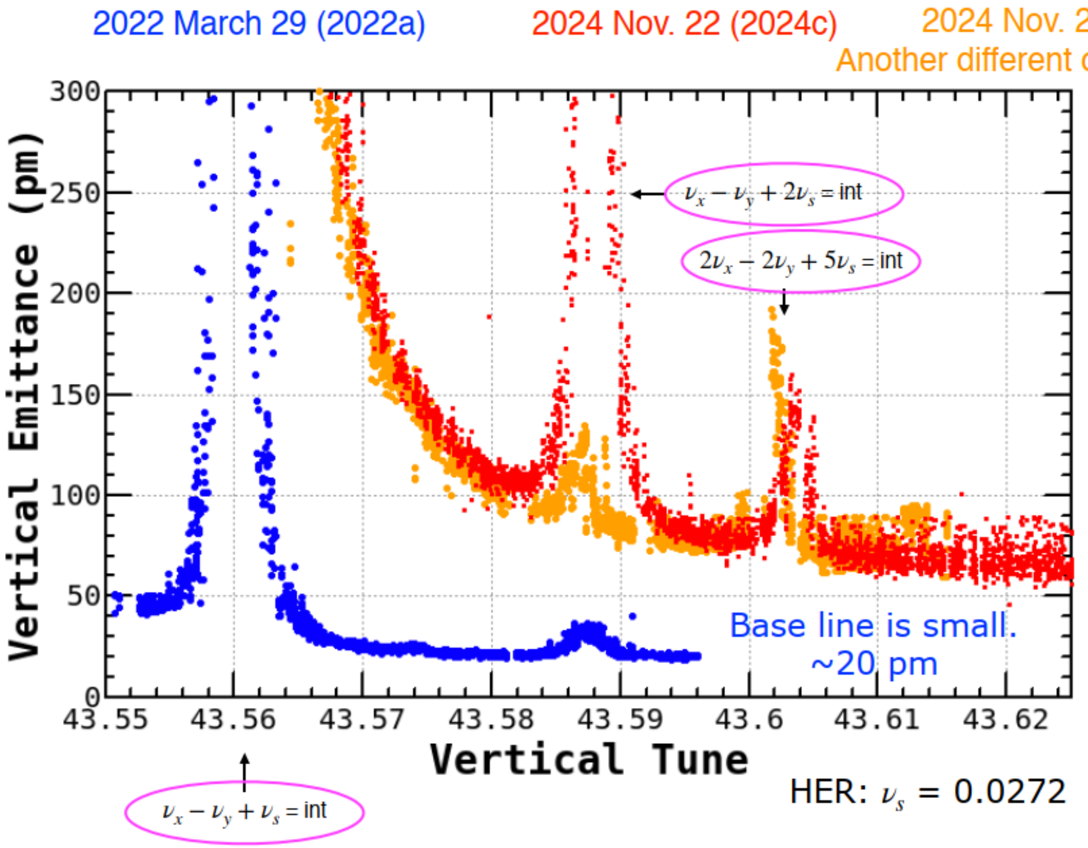
For FCC-ee, neither MO-type vacuum flanges nor VacSeal nor clearing electrodes will be used; and sudden beam losses in the form experienced at SuperKEKB are not expected to occur.

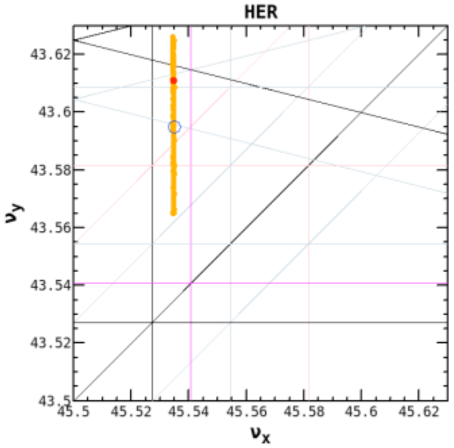
4. stored beam emittance

The design values for the rms vertical emittance are 8.6 pm in the LER and 12.9 pm for the HER.. The low-current emittances sometimes come close to this value, but often are larger.

The **vertical emittance tuning and the achievable vertical emittance are ultimately limited** by the available beam diagnostics (Appendix 1) and by the vertical deformation of the SuperKEKB tunnel floor, which worsens every year (Appendix 2).

During the 2024c run, the minimum vertical emittance in the HER increased from 20 pm to a value above 50 –100 pm, and did not decrease below 45 – 50 pm afterwards, even w/o collision and at low current. Strong high order synchro-betatron resonances were observed in the tune scans without collision. Optics corrections could not recover the small vertical emittance, not even with a “relaxed” optics.

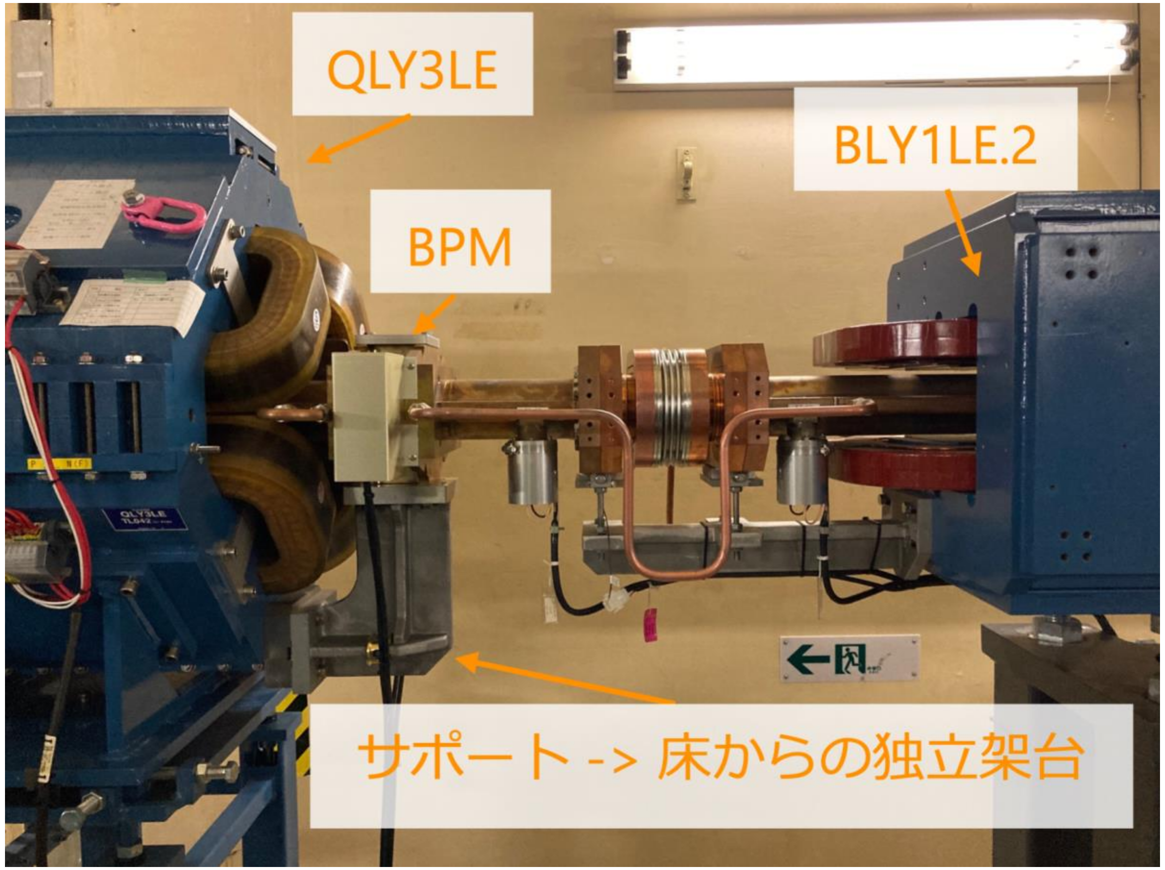


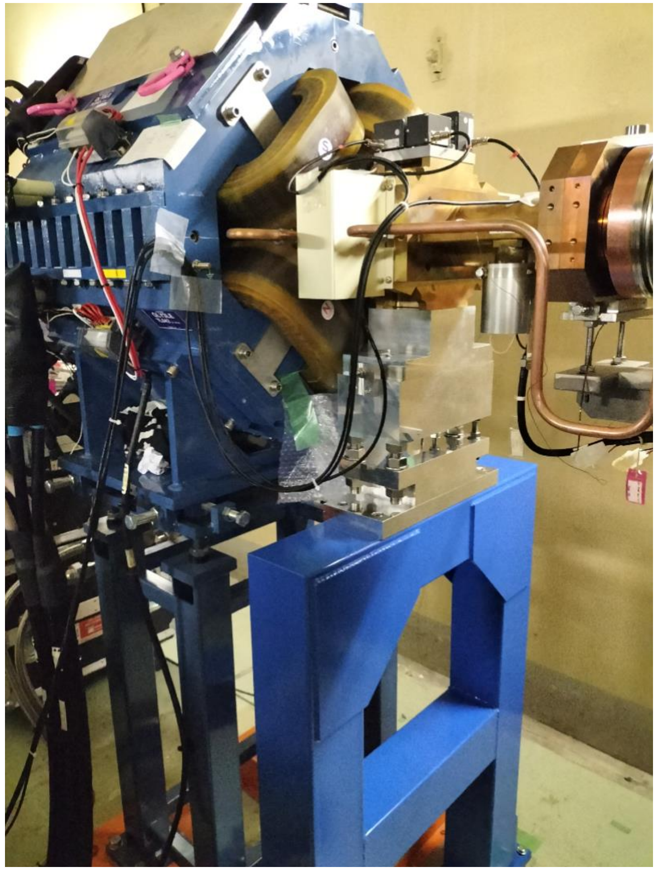


Y. Ohnishi

4. stored beam emittance cont'd

One hypothesis (K. Oide): sudden HER emittance growth could be related to a change of the mechanical support of critical BPMs in the final focus prior to the 2024c run.

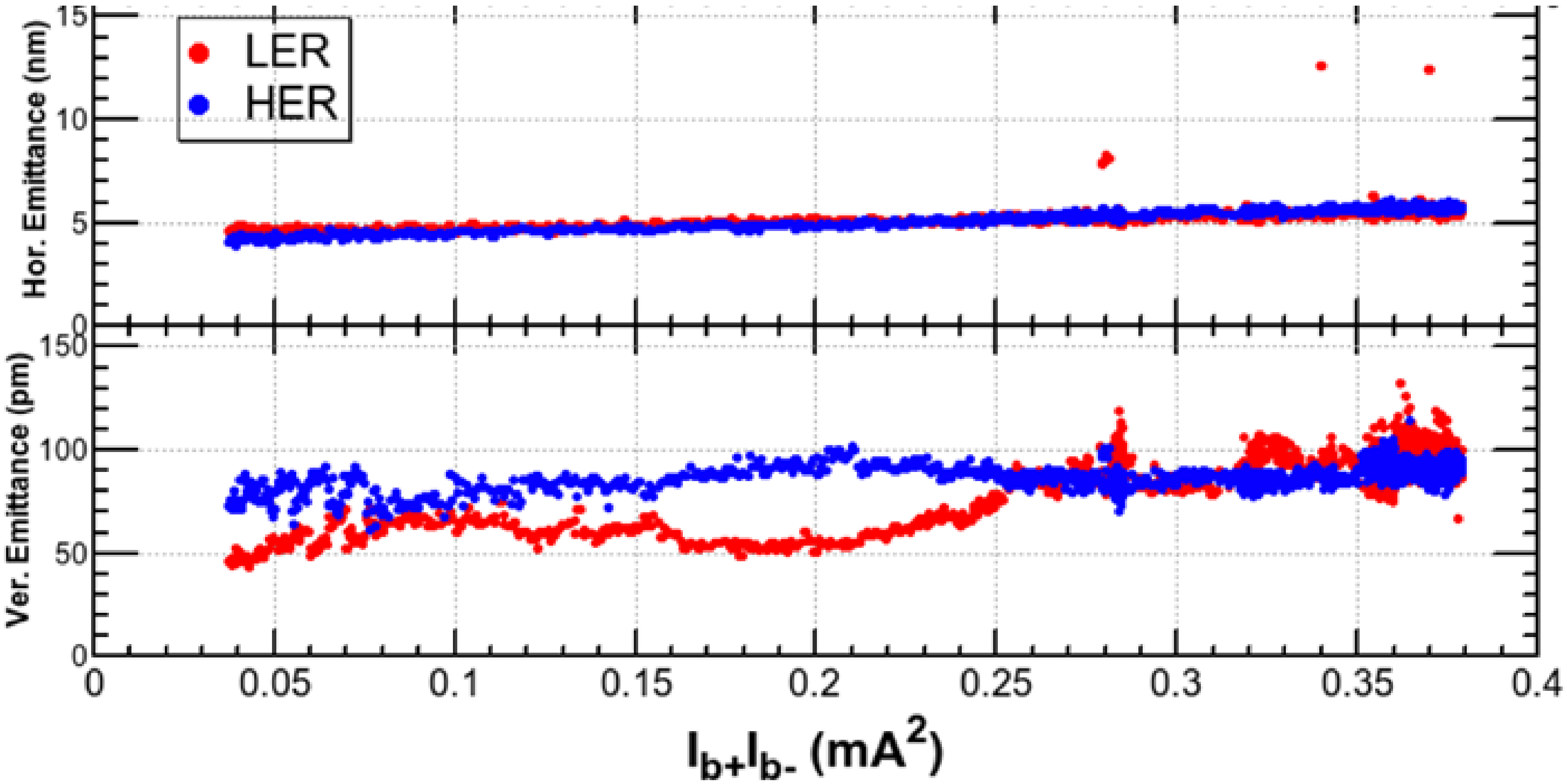




Final focus BPM supported from the nearby quadrupole magnets prior to the 2024c run (left) and the **BPM placed on its own support with vacuum chamber no longer connected to the magnet** (right), as reported by Y. Ohnishi.

4. stored beam emittance cont'd

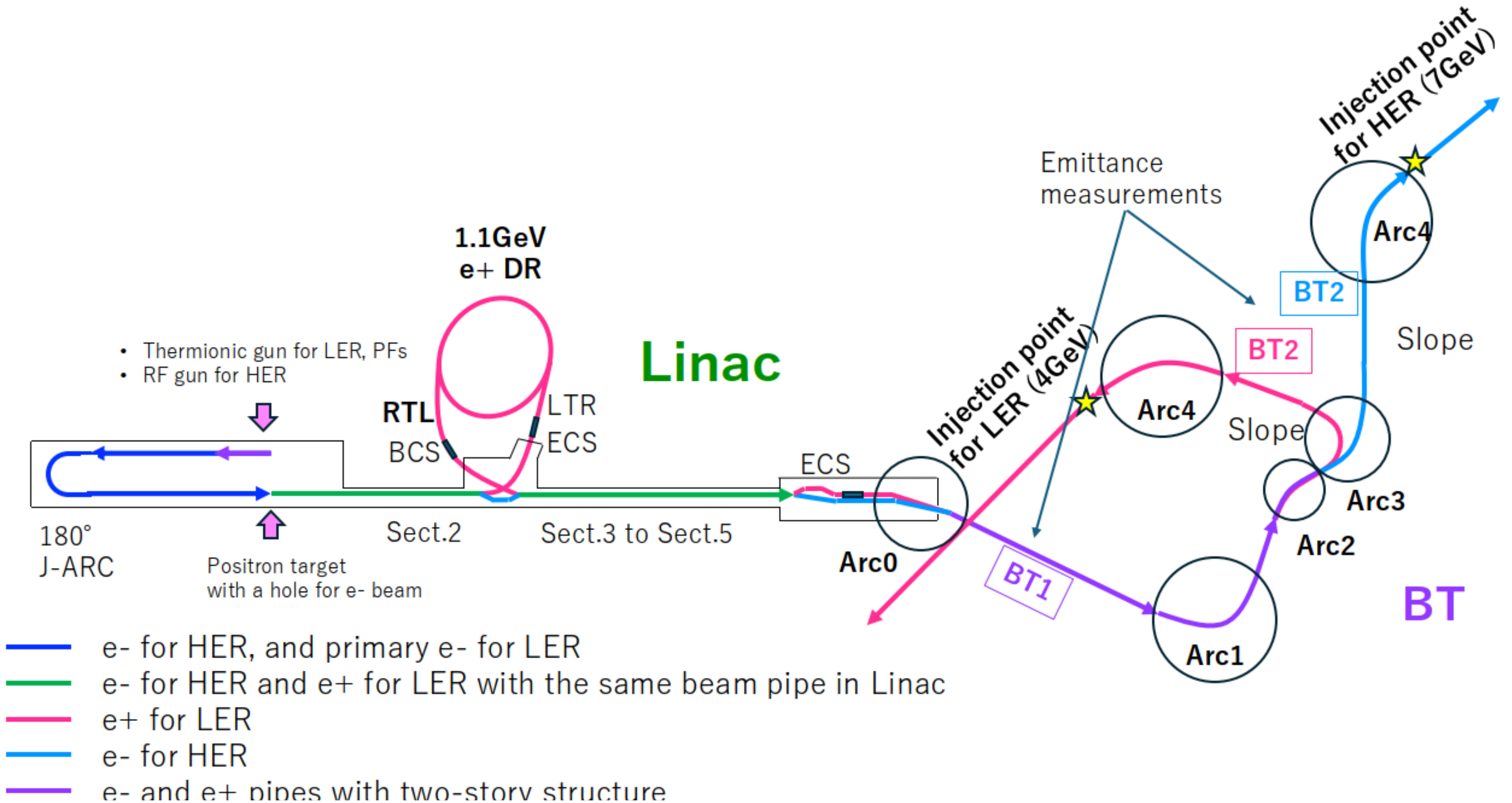
At higher currents and in collision, the measured vertical emittances further increase to about 100 pm, and hence are about 10 times larger than the design.



design bunch current product is ~1.5 mA^2

Horizontal (top) and vertical emittance evolution (bottom) for SuperKEKB HER and LER, observed in collision after reducing β_x^* to 60 mm, as a function of the bunch current product, as reported by Y. Ohnishi

5. injected beam emittance



Layout of the SuperKEKB injector and the beam transport (BT) lines (BTLs),as presented by N. Iida. Each BTL comprises **five arcs**, which can be a source of emittance growth.

e^+	BT1	BT2	e^-	BT1	BT2
$\gamma\varepsilon_x$	$110 \pm 10\ \mu m$	$169 \pm 16\ \mu m$	$\gamma\varepsilon_x$	$39.2 \pm 9.6\ \mu m$	$142 \pm 37\ \mu m$
$\gamma\varepsilon_y$	$10.5 \pm 4.0\ \mu m$	$81 \pm 20\ \mu m$	$\gamma\varepsilon_y$	$42.5 \pm 7.7\ \mu m$	$136 \pm 22\ \mu m$

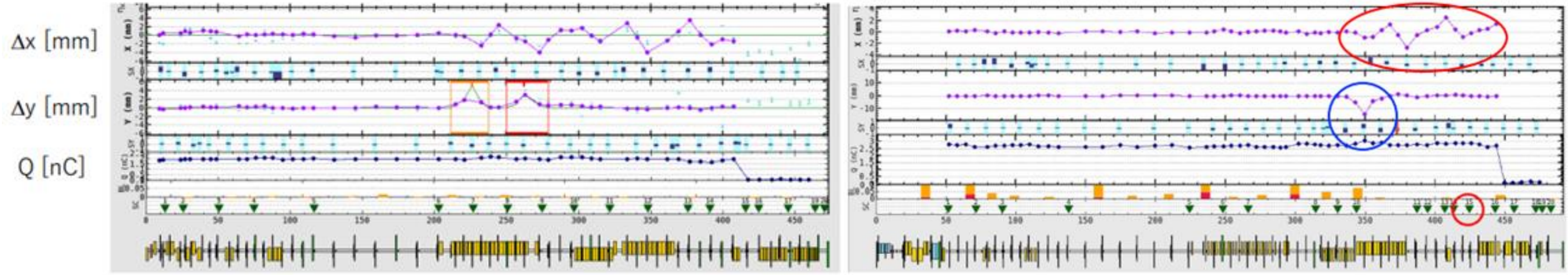
$\gamma\varepsilon$= 100 μm ↔ ε=13 nm

$\gamma\varepsilon$= 100 μm ↔ ε=7 nm

Emittance growth in the beam transport lines of the SuperKEKB injector measured in 2024, as reported by N. Iida.

5. injected beam emittance cont’d

Unexpected nonlinear field errors were found to exist in the BT dipole magnets for either beam. In addition, **strong local sources of horizontal-to-vertical coupling** were detected in both electron and positron transport



A local vertical orbit bump generated a large horizontal orbit oscillation of comparable amplitude, in both SuperKEKB HER BT (left) and LER BT (right), as reported by N. Iida.

In presence of the BTL large blow up, the **vertical emittance of the injected beam is about a factor 1000x than the design emittance of the stored beam.**

The enormous vertical emittances of the injected electron and positrons beams **degrade the injection efficiency and hinder a further squeeze of β_y^*** since in the interaction region (IR) the normalised physical aperture decreases when reducing β_y^*, becoming too small for the large vertical emittance of the injected beam; see Appendix 3.

6. injection efficiency and beam current

The SuperKEKB design beam currents are a factor 2, or more, larger than the maximum beam currents that could be achieved so far. **The beam currents are limited by both injection efficiency and bunch charges available from the linac.**

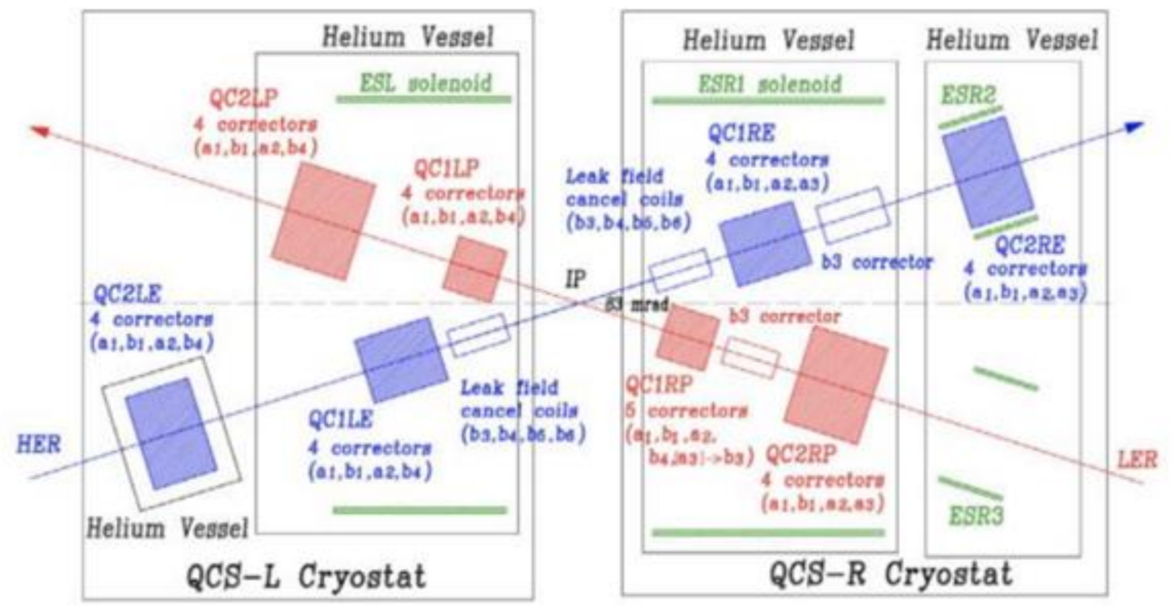
The **injection efficiency measured 100 turns after injection was about 80% for the LER and 60% for the HER**. The interaction-region (IR) aperture bottlenecks and associated collimator settings at $\beta_y^* = 1$ mm amount to a normalised vertical aperture smaller than 3σ, if expressed in terms of the injected beam size (Appendix 3).

With an expected beam lifetime of about 5 (LER) or 17 minutes (HER), respectively, **reaching the intermediate target luminosity of 10^{35} cm^{-2} s^{-1} would require a doubling of the effective injected positron bunch charge** (N. Iida).

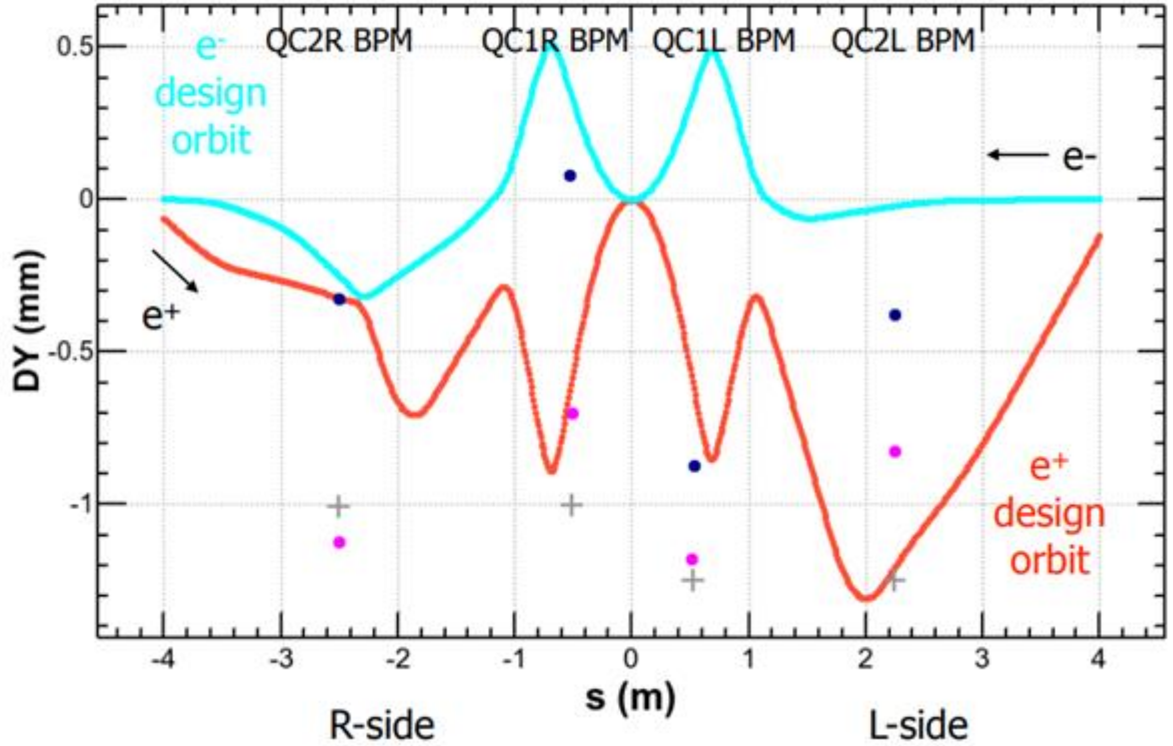
The **SuperKEKB record luminosity at the end of 2024 was achieved in conditions where the injection was approximately saturated and the beam current could not be increased**

7. interaction region

The interaction region (IR) of SuperKEKB is complex. IR aperture bottlenecks are discussed in Appendix 3.

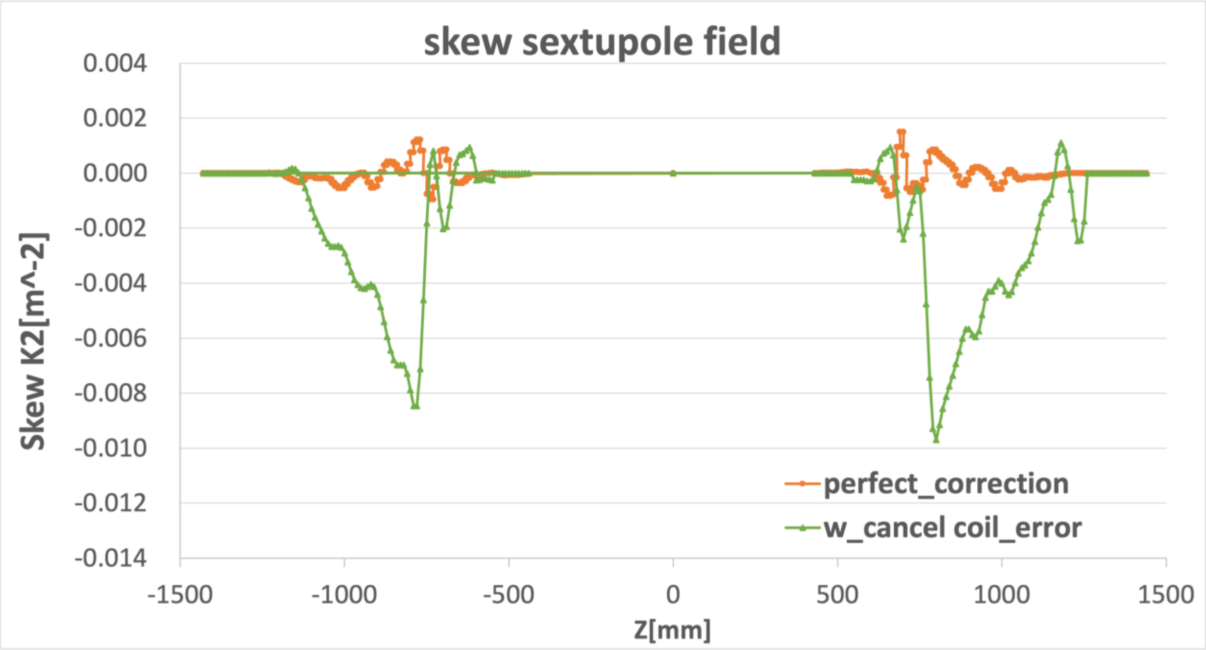


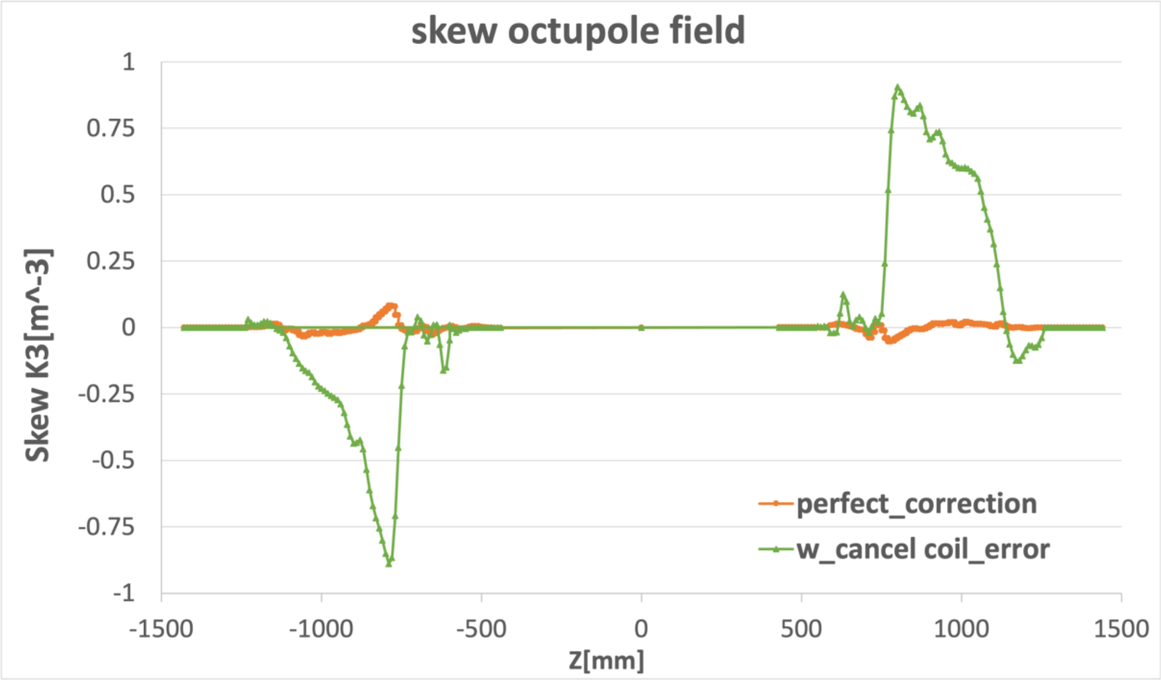
Layout of the **superconducting IR magnet system** of SuperKEKB. The effect of the solenoid field of Belle II is compensated by the **compensation solenoids** ESL, ESR1, ESR2, and ESR3. An **imperfect cancellation would give rise to a residual chromatic skew coupling** at the collision point, which is not easily measured and corrected.



Vertical design orbits of e^- (light blue curve, from right to left) and e^+ beams (red curve, from left to right) around the SuperKEKB IP and measured beam positions (dots), shown by Y. Ohnishi. Dark blue points represent the HER beam orbit measured at the QC1LE and QC2LE BPMs. Pink points correspond to the measured LER orbit. The ``+'' signs indicate the vertical offset from a straight reference orbit of the LER BPMs at QC1LP, QC2LP, QC1RP and QC2RP. The magnets have the same (or a similar) mechanical offset as their associated BPMs. The BPM readings were corrected for mechanical offsets.

7. interaction region cont'd





The design (orange) and **actual (green) leakage skew sextupole and octupole field components**, generated by the LER final quadrupoles, as seen by the HER beam, versus the distance from the collision point, shown by L. Meng based on input from Y. Ohnishi.

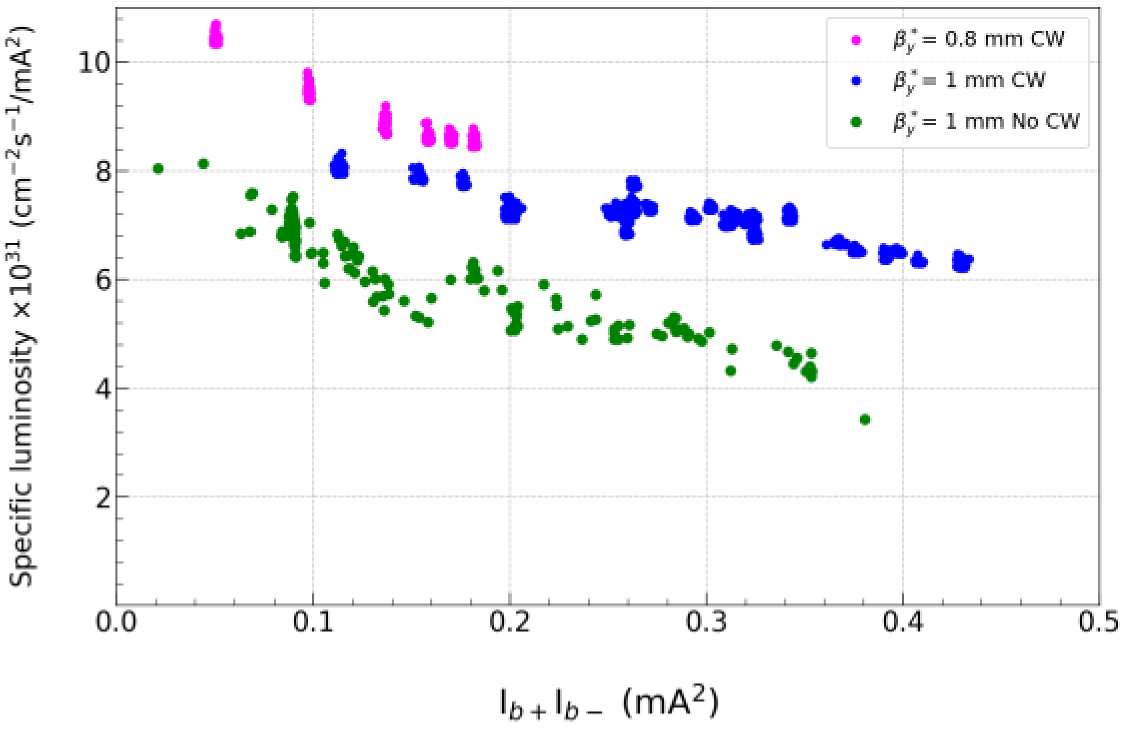
Recent simulations by M. Li reveal that the cancel coil errors degrade the on-momentum dynamic aperture from 80 to 65σ_y , and from 22 to 16 σ_x (with geometric rms emittances of ε_x=4.5 nm and ε_y =25 pm, which is up to four times smaller than the typical vertical emittance in collision), and decrease the injection efficiency by more than 10% (with injected beam emittances of ε_x =25 nm and ε_y =20 nm).

8. beta function at the collision point

In Run 2021c – 2022b, the vertical beta functions were reduced to β_y^* =0.8 mm, leading to a significantly higher specific luminosity at low bunch currents.

The specific luminosity for β_y^* =0.8 mm was about 20% higher than for 1 mm at a bunch-current product of 0.1 mA^2. However, the gain in specific luminosity decreased to ~12% at 0.16 mA^2.
These observations are illustrated on the right.
The design bunch current product is ~1.5 mA^2.

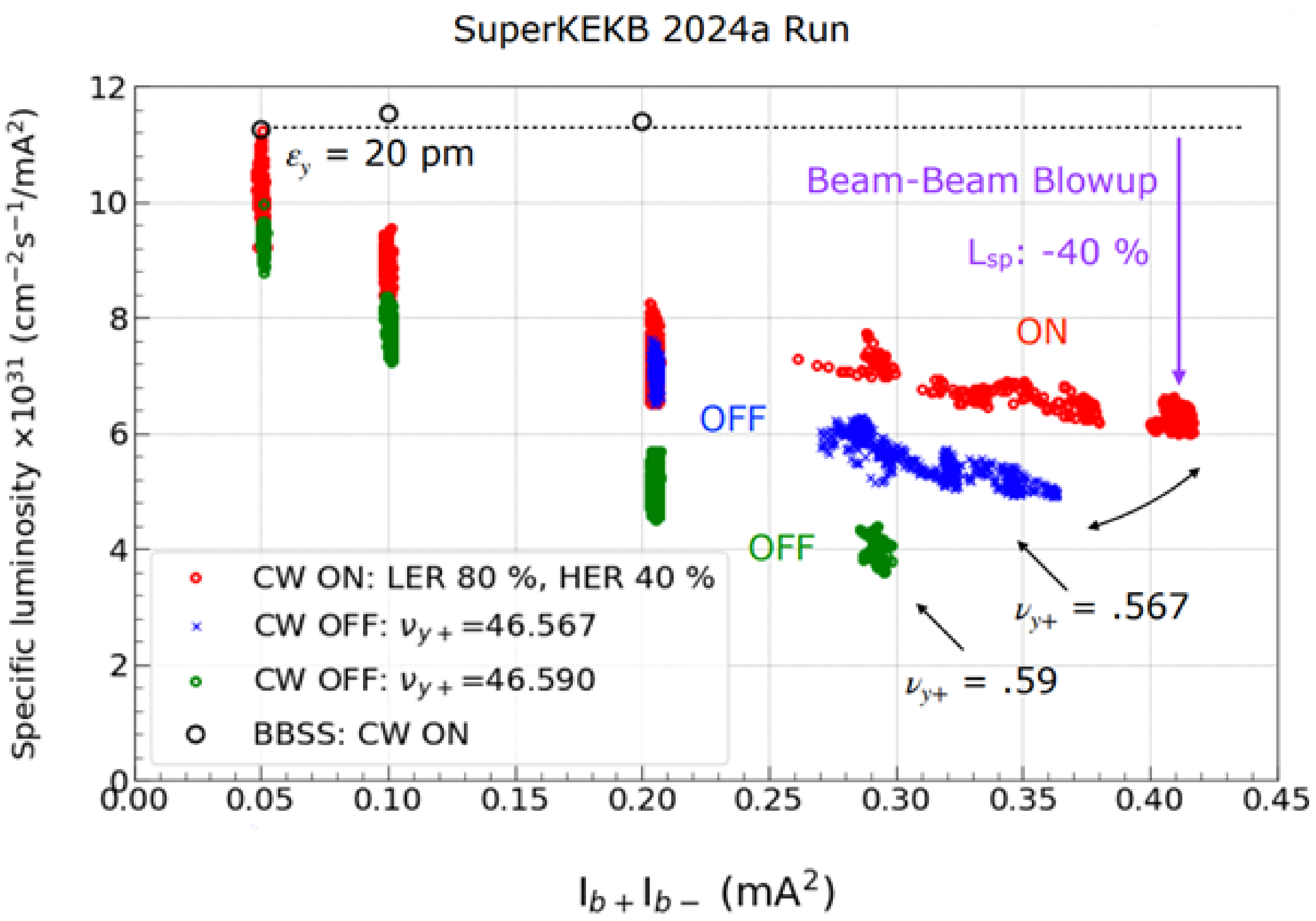
The injection efficiency and the beam lifetime also degrade with smaller β_y^* while the detector background worsens. **In 2024, the vertical beta function was not squeezed below a value of 1 mm**.



Measured specific luminosity as a function of bunch-current product, for β_y^* values of 0.8 and 1.0 mm, including crab waist, and at β_y^* =1.0 mm also without, presented by Y. Ohnishi in 2023

9. specific luminosity: observations

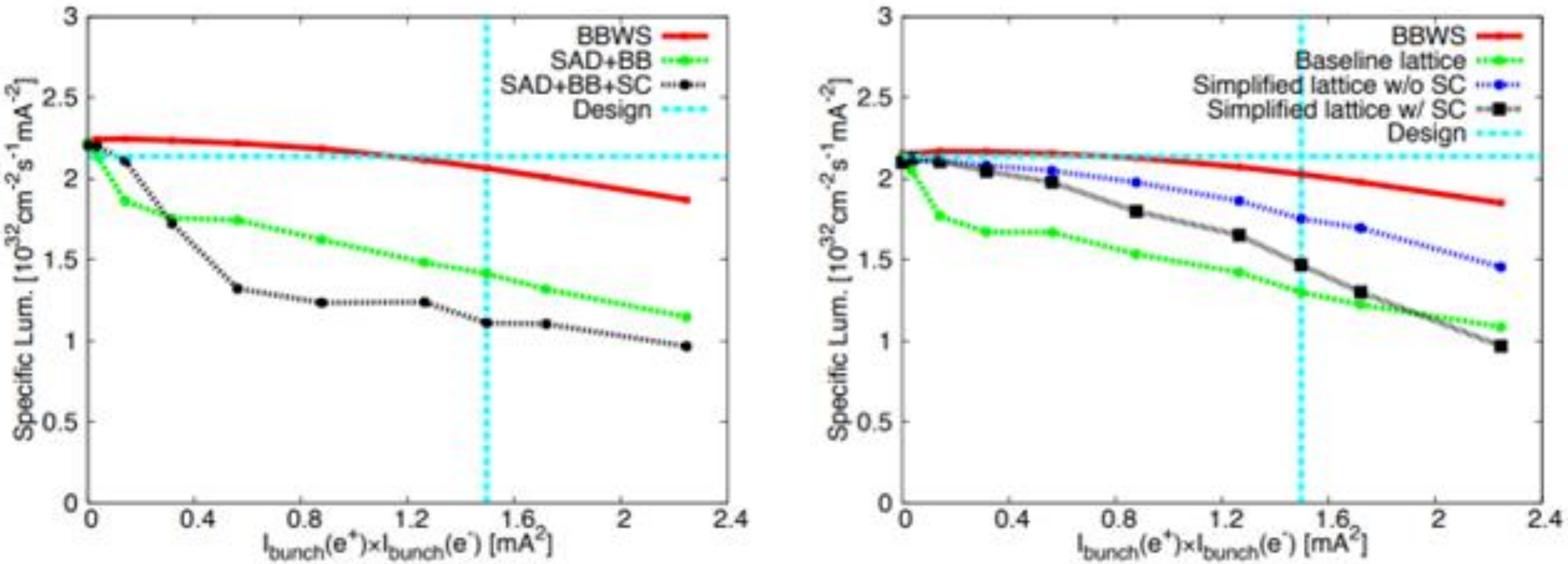
At higher bunch-current products the SuperKEKB specific luminosity decreases. The crab waist collisions scheme improves the situation, but it does not fully restore the value achieved at very low bunch currents.



Measured specific luminosity as a function of bunch-current product without the crab waist at two betatron tunes (green and blue) and with the nominal crab waist (red), presented by Y. Ohnishi

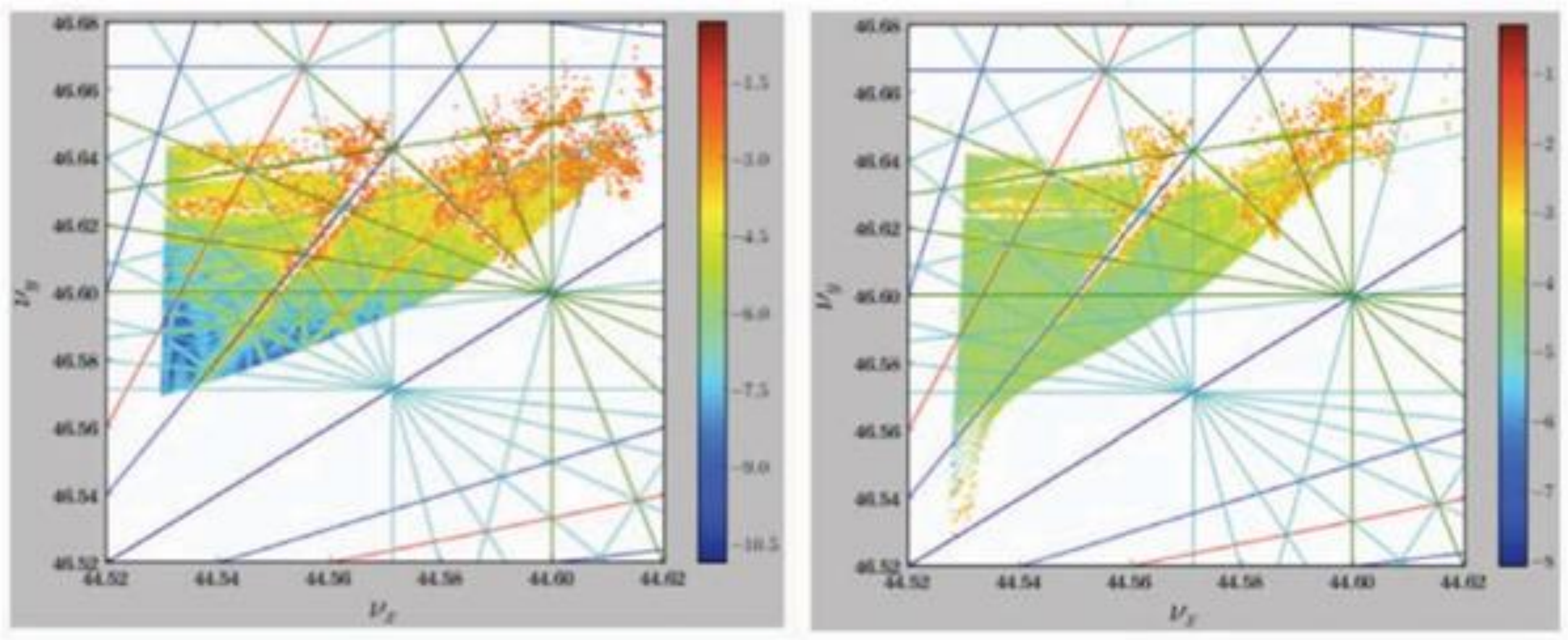
9. specific luminosity cont'd: simulation w lattice and SC

A **significant reduction of the SuperKEKB specific luminosity at higher bunch currents had long been expected from simulations** (Zhou 2015). The importance of adding the nonlinearity had earlier been demonstrated for the former SLAC PEP-II B factory, where beams collided with zero crossing angle (Cai 2005).



Specific luminosity as a function of bunch current product obtained from weak-strong simulations for the LER, considering an ideal situation with a linear machine ("BBWS'", red curve), a realistic baseline lattice with detector solenoid ("SAD'", green curve), the effect of space charge (SC) added to a simplified lattice (black curve, right picture), or the combined effect of the full lattice and space charge (black curve, left picture), presented by D. Zhou in 2015. The black curve with space charge in the right picture can be compared with the blue curve presenting the effect of the simplified lattice only; the latter contains simpler final-focus quadrupoles and no solenoids.

9. specific luminosity cont'd: effect of space charge



SuperKEKB design :

$$\Delta Q_{SC}^{LER} \approx -\xi_y$$

but different dependence on $z \rightarrow$ intriguing & novel beam dynamics

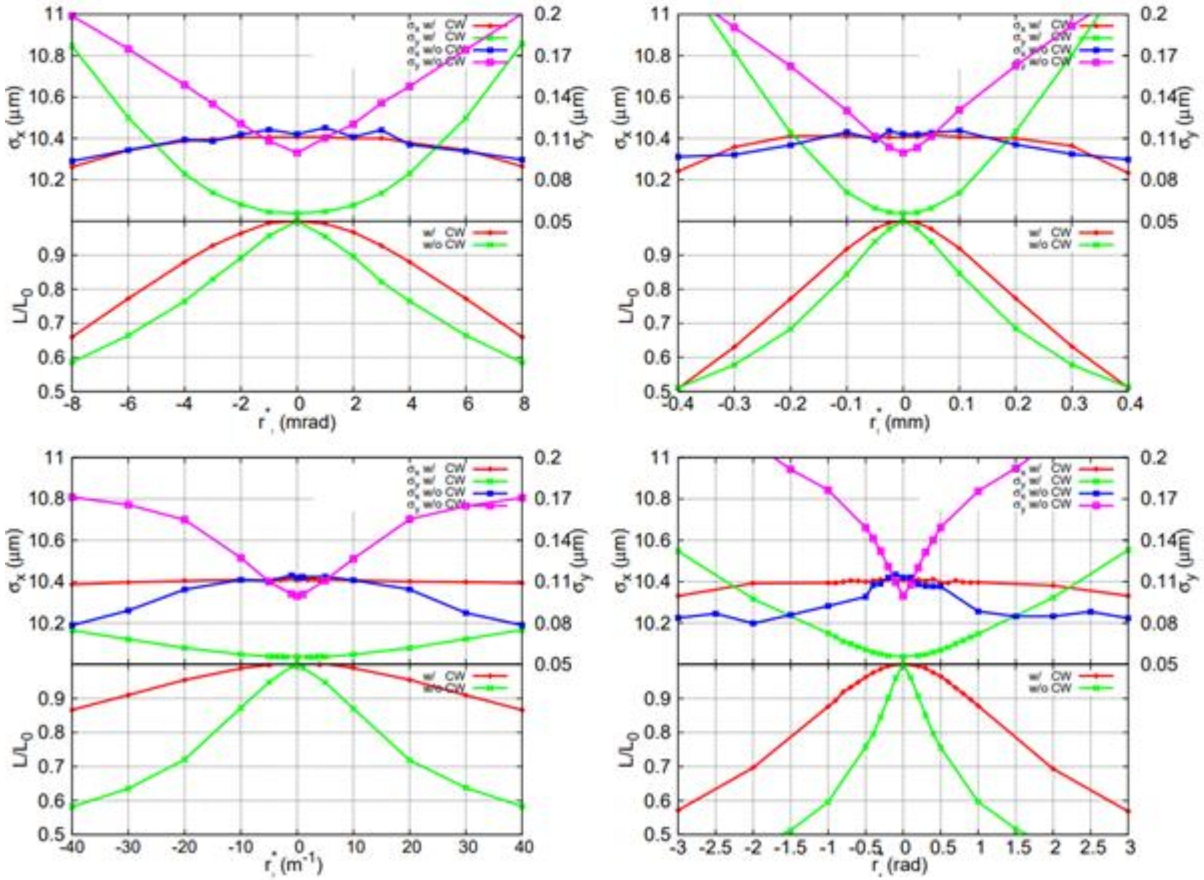
In 2022 and 2024:

$$\Delta Q_{SC}^{LER} \approx -0.02 \sim -\frac{\xi_y}{2}$$

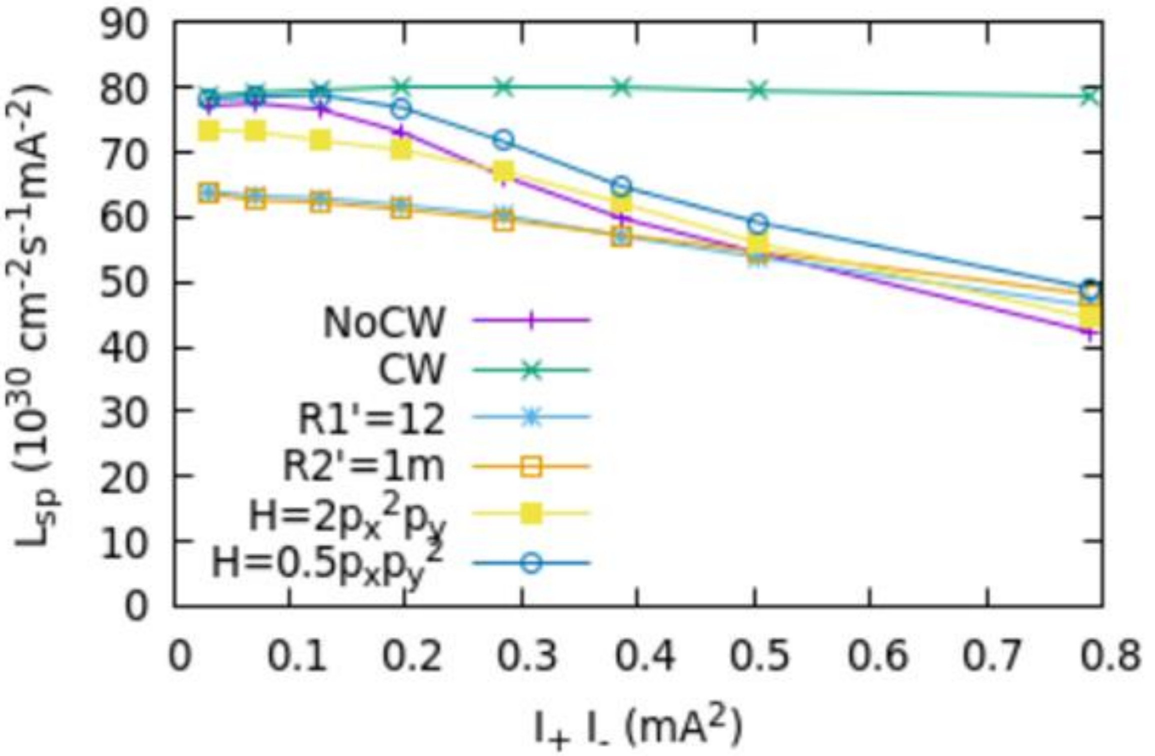
(J. Salvesen w. Xsuite)

Simulated betatron tune footprint for a lattice of the SuperKEKB LER, including the beam-beam collision, without (left) and with (right) space-charge effect, presented by D. Zhou in 2015. Resonance lines up to 7th order are indicated.

9. specific luminosity cont'd: linear & chromatic coupling

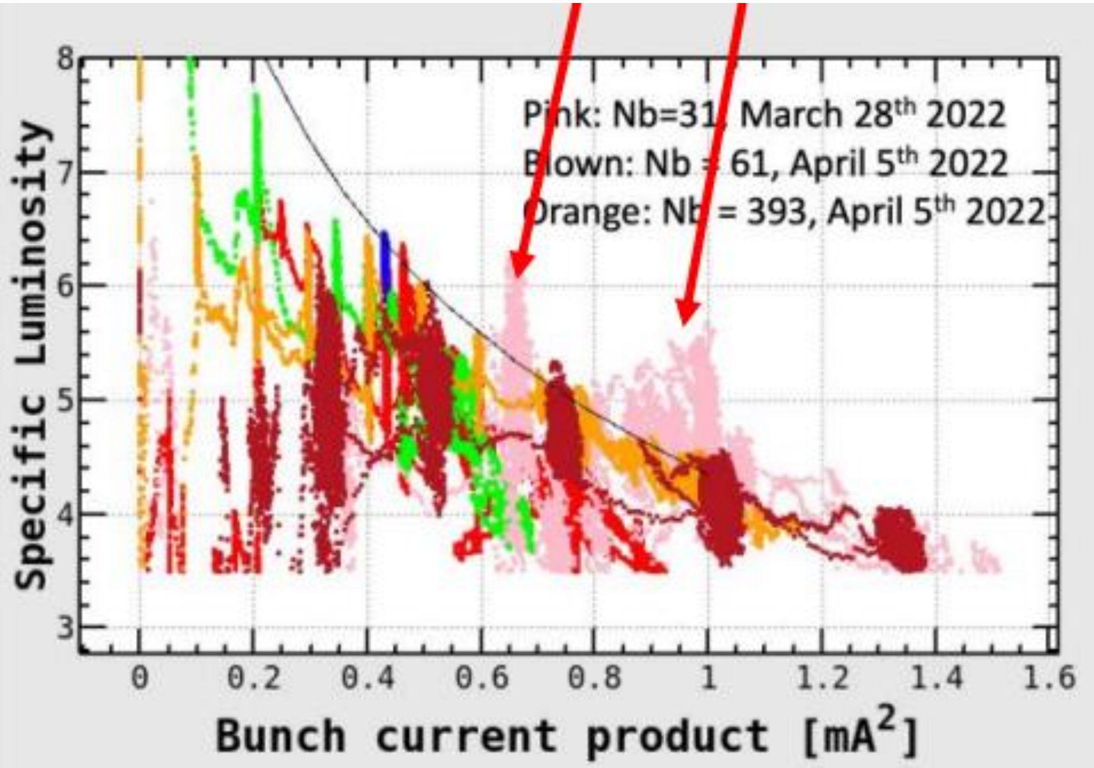


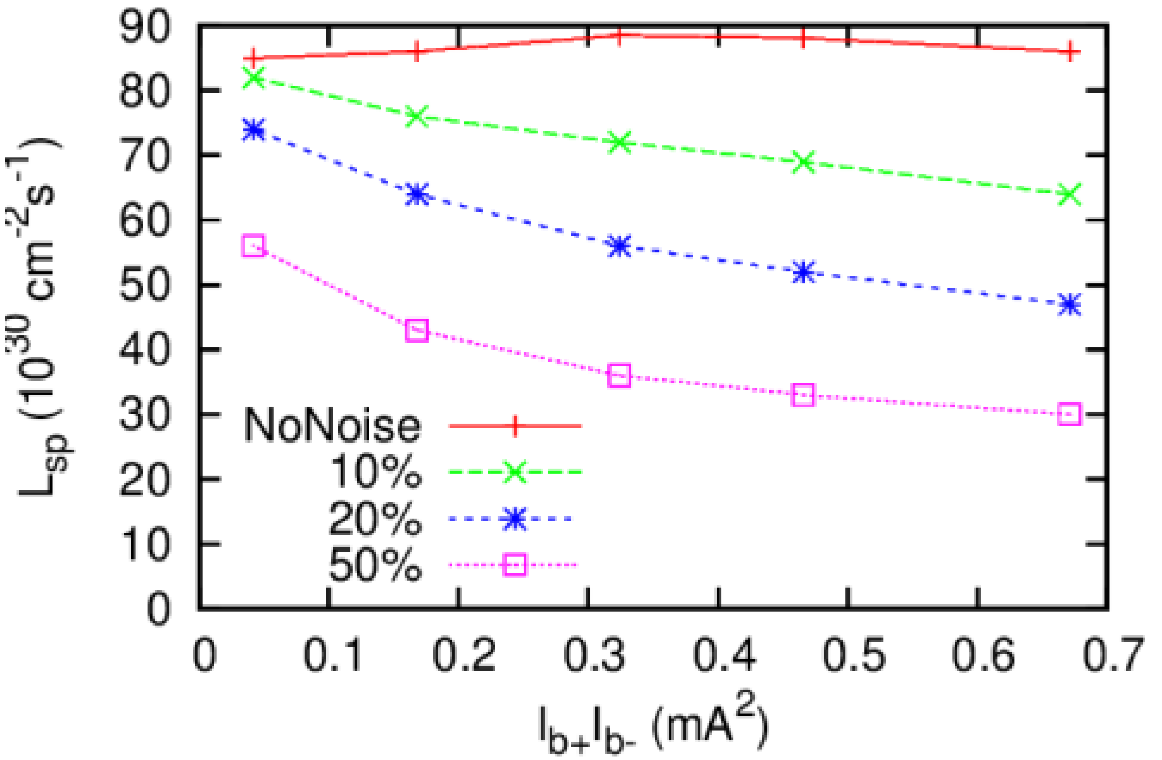
Simulated beam sizes and **relative luminosity as a function of the linear *x-y* coupling parameters at the IP** with and without the crab waist collision scheme, presented by D. Zhou in 2010, where he considered slightly different SuperKEKB design parameters.



Simulated specific luminosity as a function of bunch-current product, for different values of the chromatic coupling $R_1'=dR_1^*/d\delta$, and $R_2'=dR_2^*/d\delta$, presented by K. Ohmi.

9. specific luminosity cont'd: feedback and noise





Measured (left) and simulated specific luminosity (right) as a function of bunch-current product, presented by K. Ohmi. The **pink data on the left were taken with transverse bunch-by-bunch feedback system switched off**, while the feedback was active, with more bunches, for the other colors. Different curves on the right consider various levels of feedback noise, expressed in percent of the rms vertical beam size.

10. summary and conclusions

SuperKEKB experience provides **important lessons and input for the FCC-ee design.**

The **SuperKEKB luminosity performance is still an order of magnitude short of the target value.**

As discussed, **a number of issues** are limiting the present SuperKEKB luminosity performance. All of these appear to be **very specific to SuperKEKB**. They were not observed, in this form, at any previous colliders or at any of the modern light sources. A few additional and complementary issues faced by SuperKEKB are addressed in the Appendices, e.g., effect of longitudinal impedance in Appendix 4.

We see no reason or argument to suggest that any of these problems should be encountered at FCC-ee. Specifically, we highlight the following points (next page).

10. summary and conclusions cont'd: specific points FCC

- FCC-ee, no **MO-type vacuum flanges** and no **VacSeal**.
- FCC-ee: beam injected from a **full-energy booster,** providing vertical beam emittance similar to (or even smaller than) the design emittance of the collider and not several orders of magnitude higher. **Nevertheless, a factor 10 margin for vertical emittance included** in the FCC-ee injection design.
- A y/x emittance ratio without collision of ~0.1-0.2% (FCC-ee) should be achievable, according to **simulations with realistic errors**. Ratios down to 0.01% demonstrated at light sources.
- **FCC-ee interaction region simpler, with at least an order-of-magnitude larger aperture normalised to injected beam size; full local compensation** of coupling & chromatic coupling.
- FCC-ee **beam-position monitors fixed on a common girder** with nearby quadrupole and sextupole magnets; magnet supports more robust.
- Most of available beam diagnostics at SuperKEKB does not have turn-by-turn, bunch-by-bunch detection capability; insufficient for measuring the beam optics in collision or analysing nonlinear terms.
- **FCC-ee will have state-of-the-art optics diagnostics like the BPM system of the LHC**.
- The SuperKEKB tunnel is floating; significant vertical tunnel deformation increases every year, degrading vertical beam emittances. D**eeper FCC-ee tunnel should be stabler (**LEP/LHC example)
- **Space-charge effects at FCC-ee smaller thanks to higher beam energy & longer bunches.** Bunch lengthening w current due to impedance is much weaker since **beamstrahlung dominant**.

10. summary and conclusions cont'd: issues compared

Issues encountered by SuperKEKB together with the estimated resulting luminosity loss factor with respect to the design luminosity at nominal beam current, and the corresponding expectation for FCC-ee.

effect / problem	SuperKEKB	FCC-ee	comment
injected beam vert. emittance & limited IR aperture	**~0.3**	1.0	both β_y^* squeeze and injection efficiency (beam current) affected
stored beam vert. emittance due to tunnel deformation, non-anchored BPMs, etc.	~0.5	~1.0	reduction in spec. luminosity
nonlinear lattice	0.6	1.0	reduction in spec. luminosity
bunch lengthening	0.6	~1.0	reduction in spec. luminosity
residual linear & chromatic coupling at the IP	0.5	1.0	reduction in spec. luminosity
IR coil errors	0.5	1.0	reduction in spec. luminosity
space charge	0.6	~1.0	reduction in spec. luminosity
feedback noise	0.8	~1.0	reduction in spec. luminosity
combined effect of last 7 items	**~0.3** (?)	~1.0	total spec. luminosity reduction
effective total loss factor	**~0.09**	~1.0	

10. summary and conclusions cont'd: SuperKEKB path

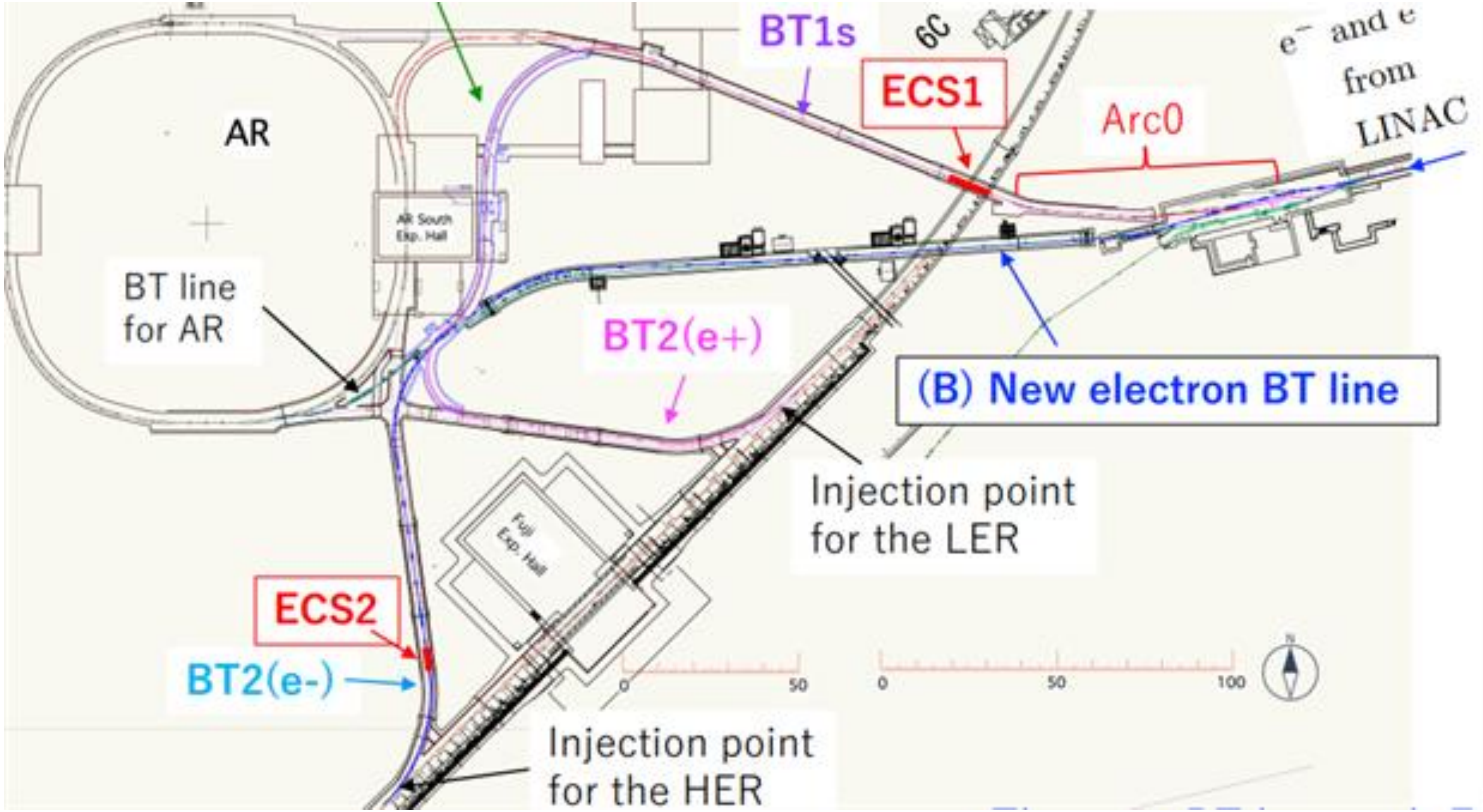
green color: immediate action, blue color: medium term

Recommended path towards the design luminosity:

- **clear the chamber of black stain** (vacuum sealant debris), which is presently underway;
- develop **strategy for fully correcting and controlling linear and chromatic coupling at IP**;
- **eliminate large sources of local betatron coupling and emittance growth in both electron and positron transfer lines between linac and collider rings**, e.g., by installing – in an existing tunnel – **proposed new straight e$^-$ beam transport line** to effectively suppress CSR and ISR effects (next slide)
- further investigate the effect of, plus possibly reducing, **impact of the transverse damper noise**.
- **reconnect the BPMs in the final focus with adjacent magnets** and reinforce magnet supports;
- **study and mitigate the effect of space-charge forces in the LER;**
- **include effects of nonlinear lattice, space charge, and impedance in the beam-beam simulations** in order to explore their combined impact, which has (re-)started;
- implement **improved turn-by-turn BPM diagnostics**, which will assist both in identifying residual optics aberrations at the IP and in understanding the possible degradation of dynamic aperture and momentum acceptance with reduced β_y^*
- **further optimise the collimation system and reducing losses after injection**, e.g., via **the new energy compressor, through a longitudinal or hybrid long.-transv. top-up injection scheme** (next-next slide), or by suitable **pre-collimation** of large-amplitude particles in the transport lines prior to injection into the collider rings.

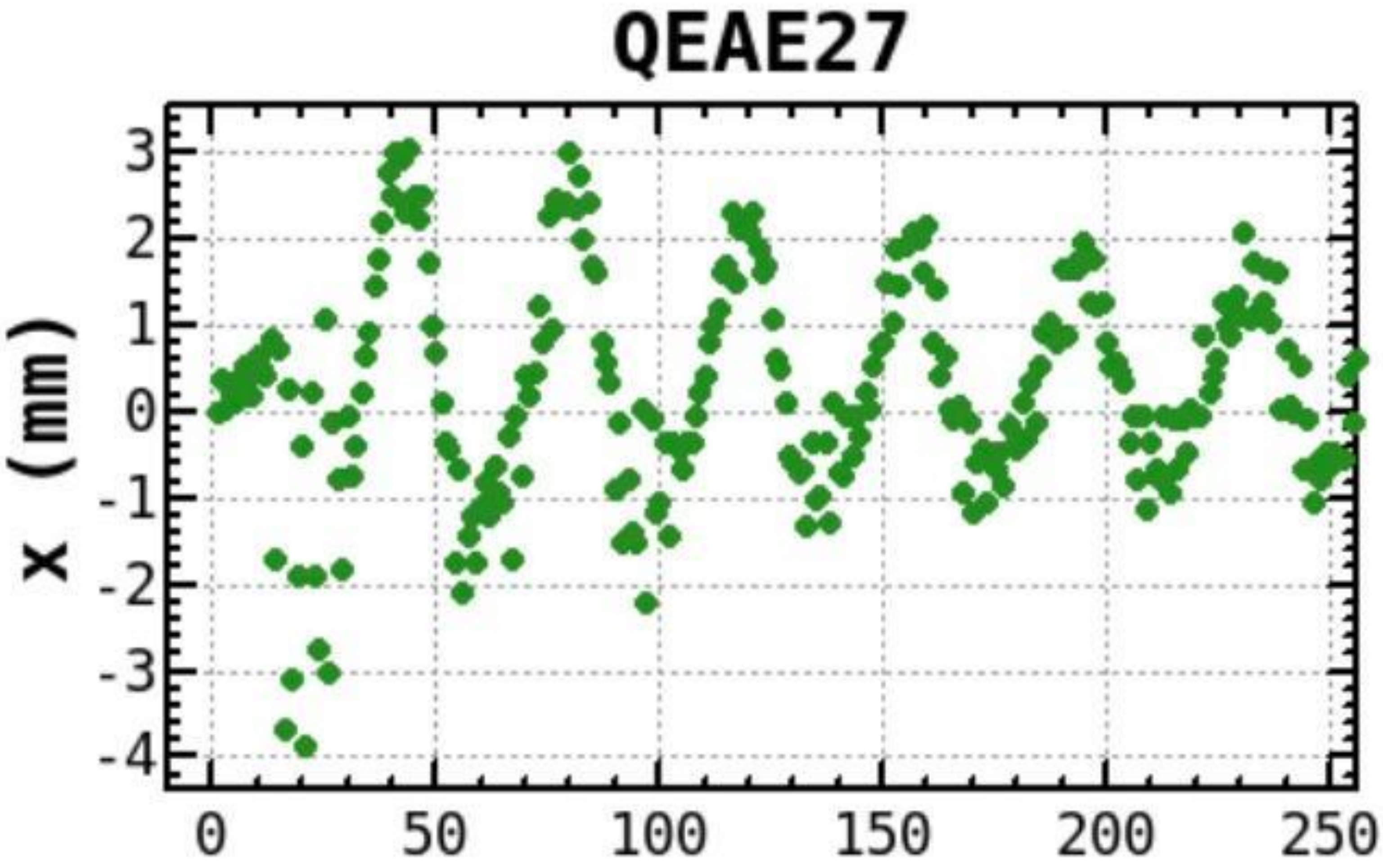
SuperKEKB should be able to reach a luminosity of 10^{35} cm^{-2}s^{-1} & beyond (up to 2-3x10^{35} cm^{-2}s^{-1})

10. summary and conclusions cont'd: new e$^-$ BT line



A new straighter electron beam transport line in an existing tunnel, as proposed by N. Iida

10. summary and conclusions cont'd: longitudinal injection



First longitudinal injection into the SuperKEKB HER incl. ECS,
5 November 2025

The horizontal injection oscillation shows only synchrotron component!

(private communication, K. Oide)

appendix 1: beam diagnostics

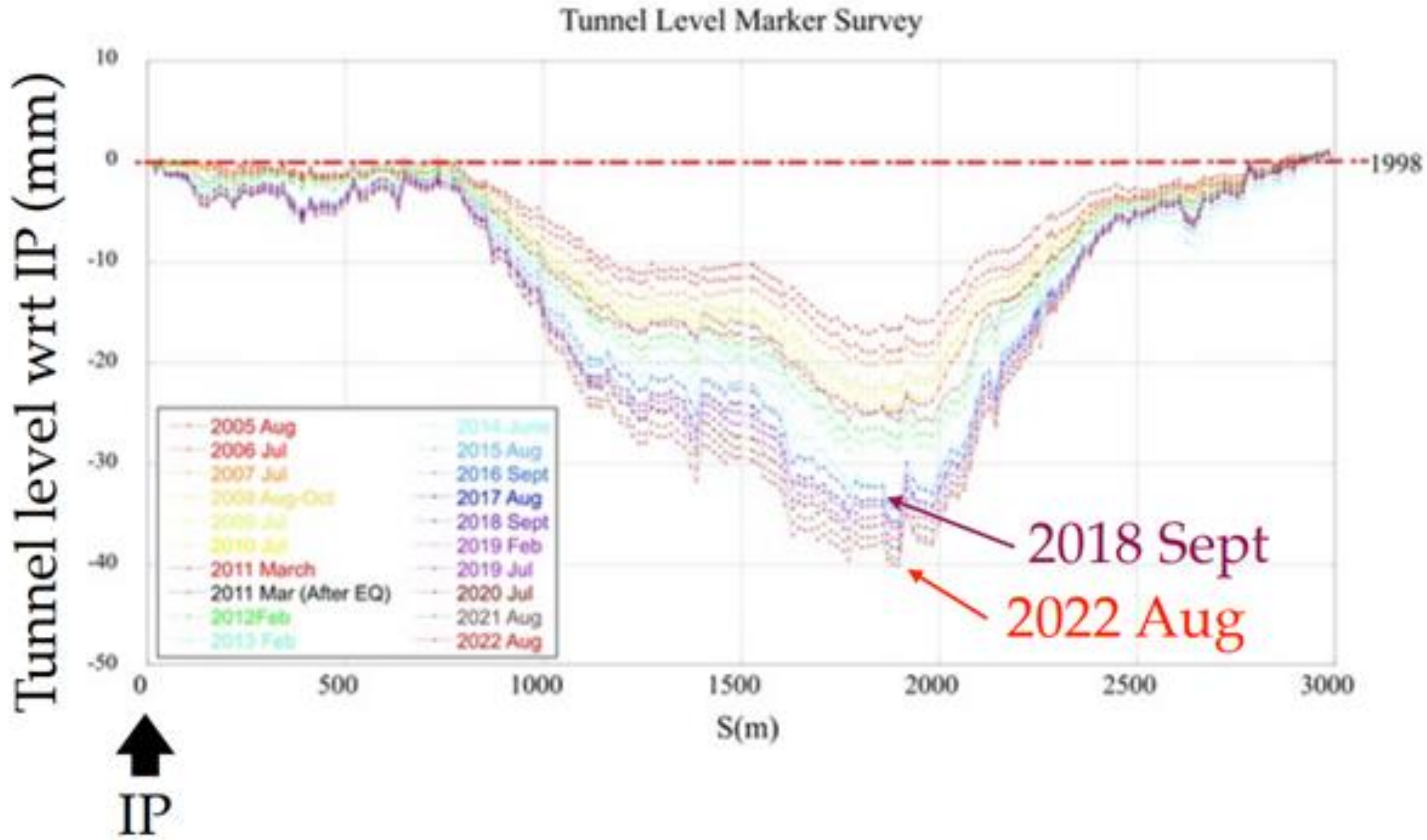
SuperKEKB lacks turn-by-turn, bunch-by-bunch BPMs, except for a few out of 450 BPMs per ring. Some of the SuperKEKB BPMs (about 50 per ring) have a turn-by-turn detection capability (albeit with a rather limited resolution, as shown the table below1), but even these cannot record bunch-by-bunch oscillations. Therefore, it is not possible to diagnose the beam optics with colliding beams by exciting, or kicking, the non-colliding pilot bunches or one of the colliding bunches.

storage ring storage ring	rms TbT prec. [μm]	bunch int. [10^{10}]	no. bunches	rms bunch length [mm]	beam pipe diameter (x,y) [mm]
ESRF	10	0.04	330		79, 33
ALBA	14	0.1	45	6	72, 28
PETRA III	22	23	1–5	13.2	80, 40 and 94,...
LHC	100	1	1	70	49
SuperKEKB LER	200	6	1		94
SuperKEKB HER	125	6	1		104, 50

Rms precision (noise) of turn-by-turn (TbT) BPM measurements at various storage rings along with other relevant parameters (R. Tomas, M. Hofer et al.)

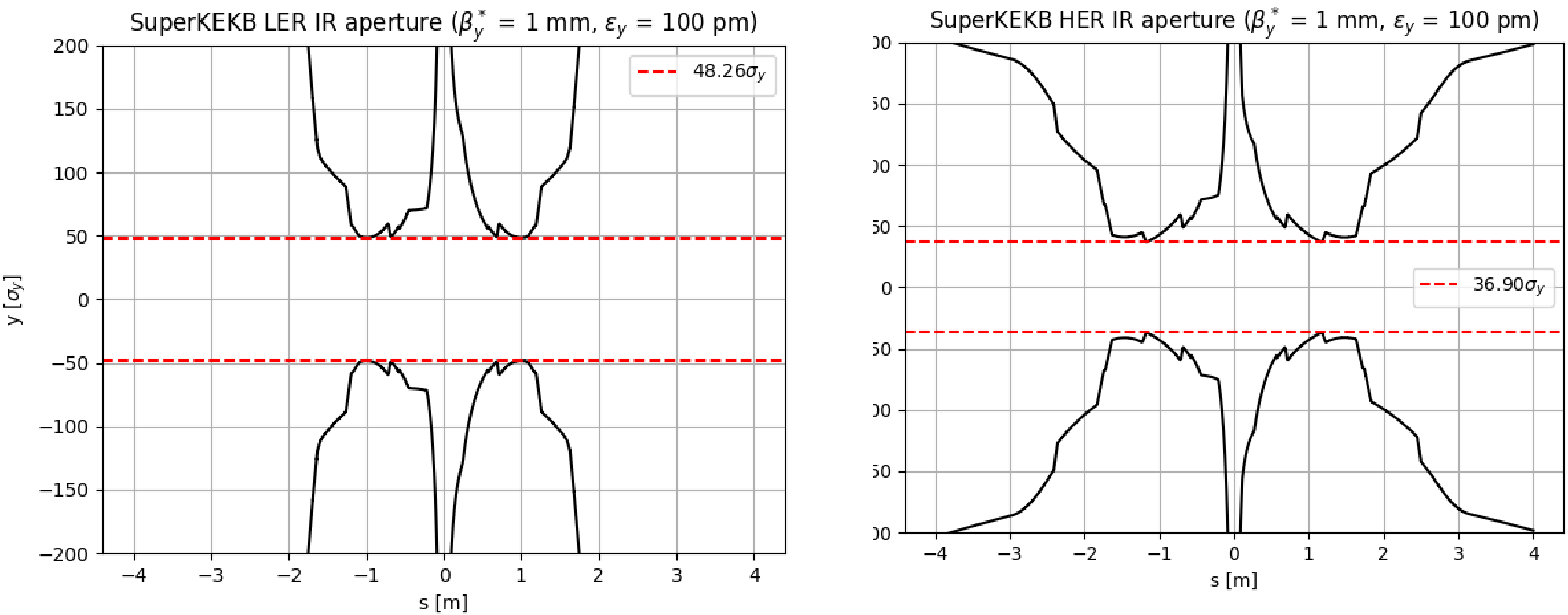
appendix 2: tunnel floor movement

The SuperKEKB tunnel is not supported by stable rock. Instead, it is floating in the soil. A large part of the tunnel is sinking by about 1 mm per year with respect to the interaction point.



Measured year-by-year variation of the (Super)KEKB tunnel level with respect to the interaction point, presented by M. Masuzawa

appendix 3: physical aperture in the IR

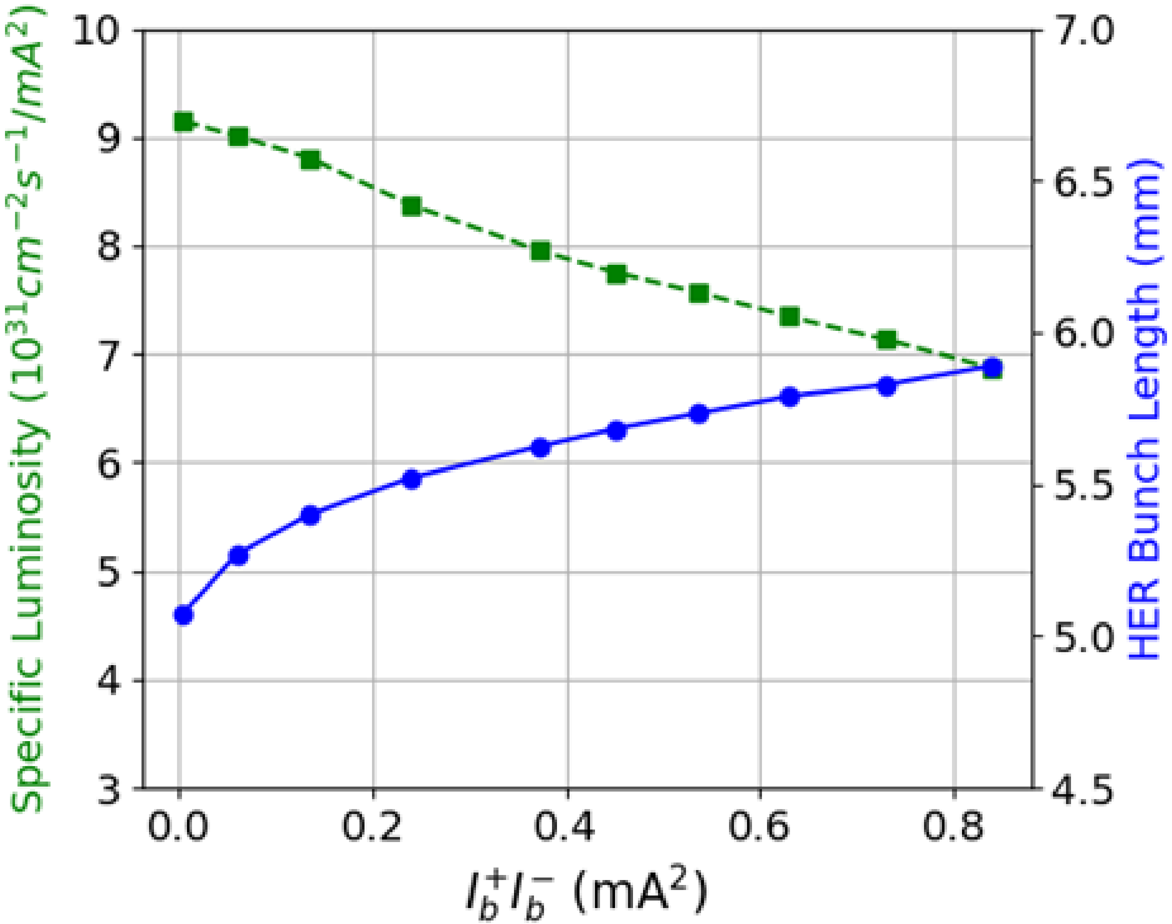


Interaction-region physical aperture at the SuperKEKB LER (left) and HER (right), in units of rms vertical beam size, σ_y, computed for a stored-beam geometric emittance of 100 pm and β_y^* = 1 mm (Courtesy G. Broggi).

With a normalised vertical injected beam emittance of 100 μm for the LER and 150 μm for the HER, at β_y^* =0.3 mm, **the collimators protecting the SuperKEKB IR aperture would sit at only 1.5 σ_y**. The injected beam emittance must be reduced before further squeezing β_y^* below 0.8-1.0 mm.

appendix 4: incomplete beam dynamics

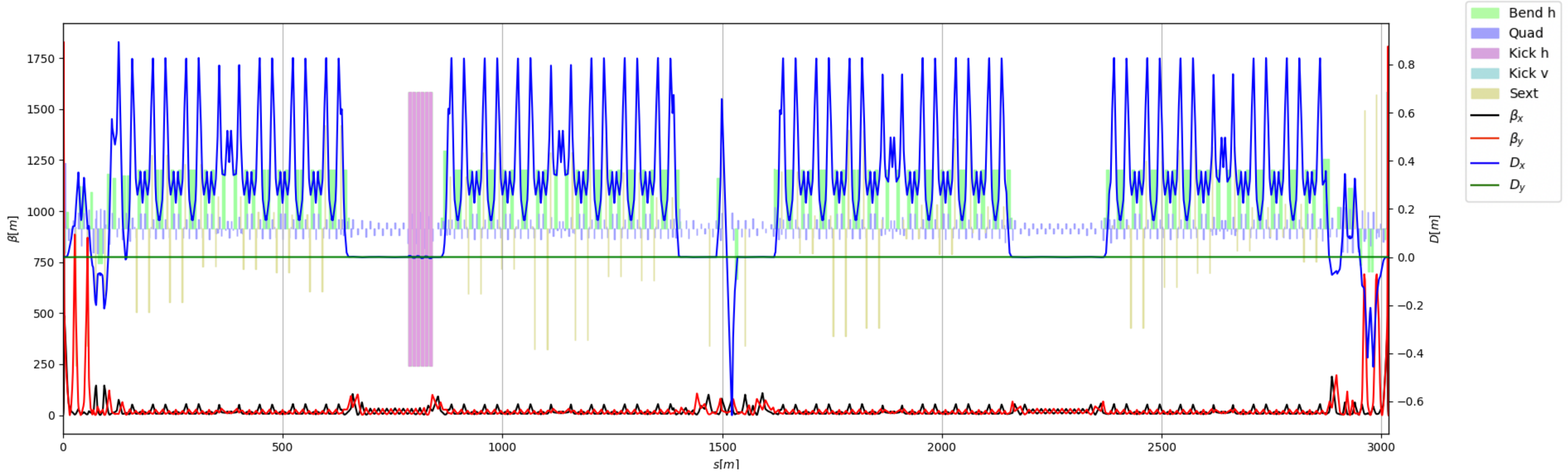
The effects of the nonlinear lattice, space charge, and impedance, were not routinely considered for the SuperKEKB performance estimates. A noticeable impact of the nonlinear lattice and space charge on the specific luminosity was pointed out by D.~Zhou ten years ago, but left unresolved. Bunch lengthening due to the longitudinal impedance will further reduce the specific luminosity (See PhysRevAccelBeams.26.071001).

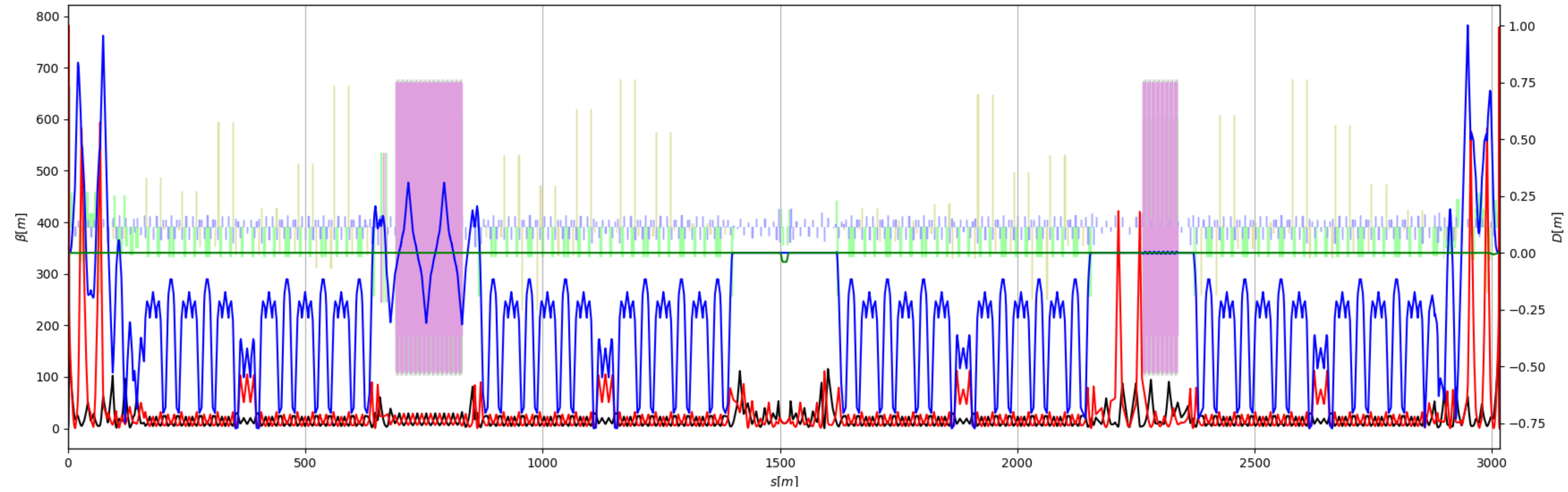


Simulated specific luminosity as a function of bunch-current product (green curve), in APES simulations, including the bunch lengthening predicted from the longitudinal impedance model (blue curve), from C. Lin in 2025, presented by X. BuffaT.

appendix 5: SuperKEKB in Xsuite

- strong collaboration between CERN and KEK
- alternative modelling strategy for IR
- many additional features & improvements to Xsuite have come about as a result of this effort



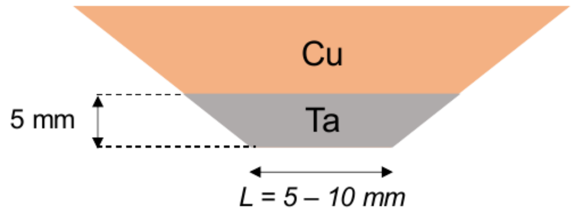


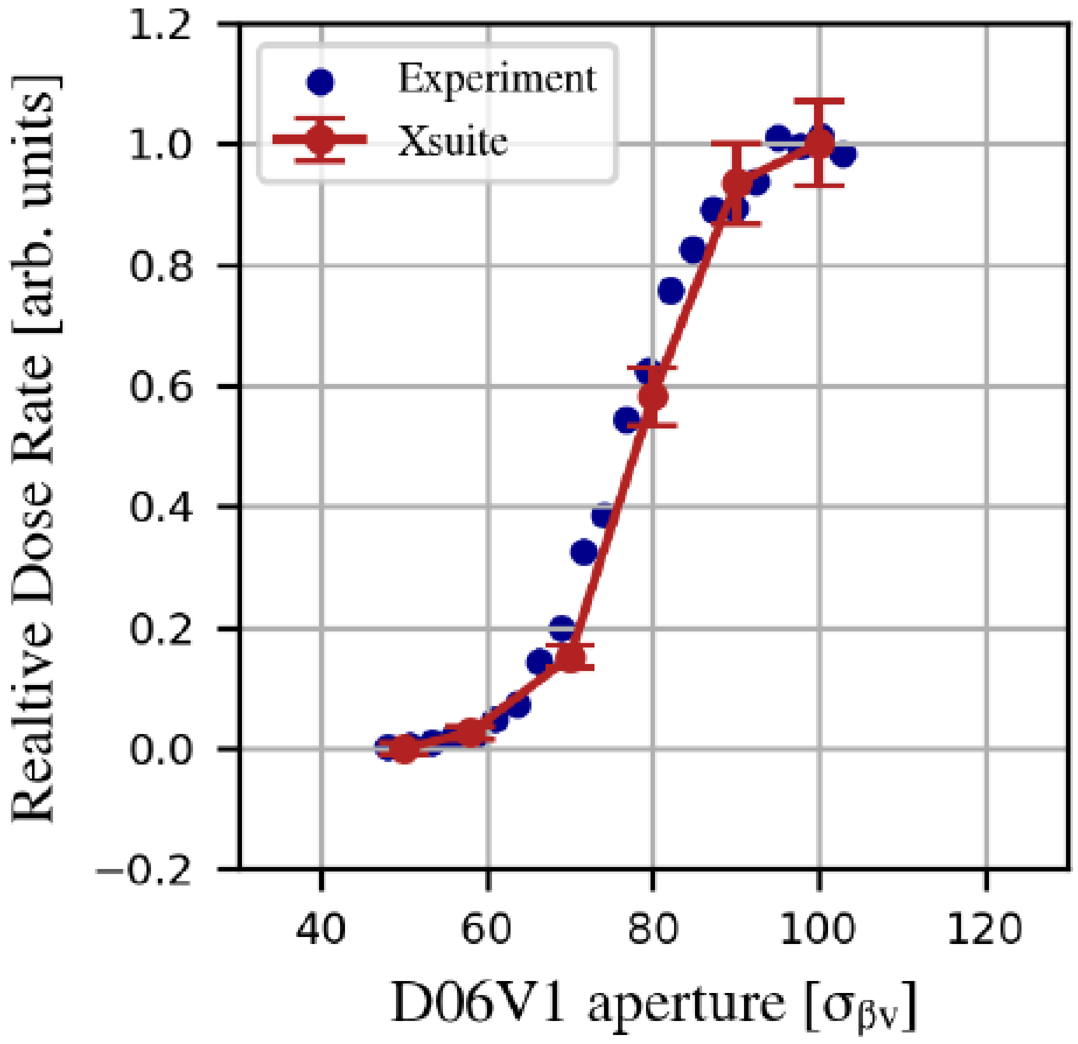
J. Salvesen, G. Iadarola, G. Broggi, H. Sugimoto, K. Oide

appendix 5 cont'd: Xsuite simulations for SuperKEKB

G. Broggi, J. Salvesen, G. Iadarola, H. Sugimoto, K. Oide

Touschek & beam-gas scattering for different collimator settings, including **collimator-matter interaction**





Xsuite-simulated response of Belle-II diamond detector to change in collimator position

demonstrating importance and strength of international collaboration in the accelerator field