Recent Progress and luminosity challenges at the SuperKEKB Collider

Makoto Tobiyama (KEK, Accelerator Laboratory)
on behalf of the SuperKEKB commissioning group

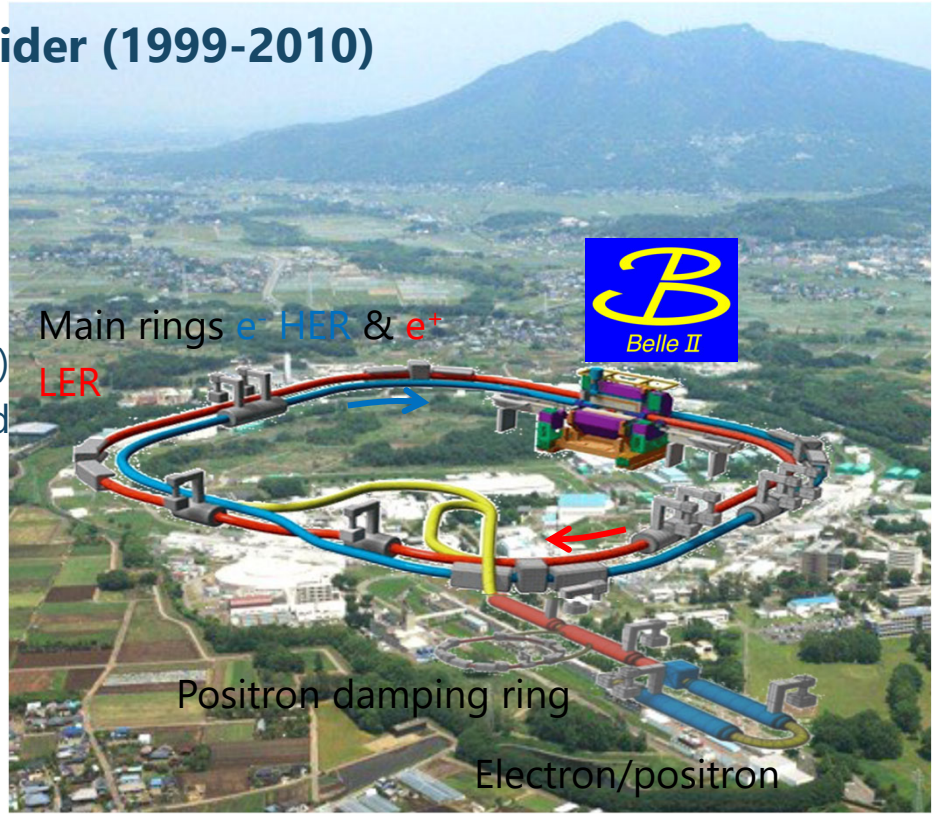




Slides based on ICHEP2026 by Prof. G.Mitsuka

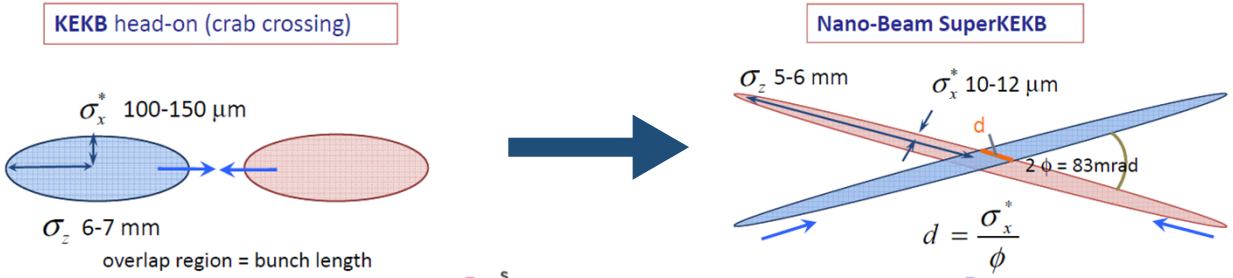
The SuperKEKB e^+e^- collider

- **Major upgrade to the KEKB e^+e^- collider (1999-2010)**
- **Main rings**
  - 7 GeV e^- storage ring (HER)
  - 4 GeV e^+ storage ring (LER)
- **Design parameters**
  - Beam currents: 3.6 A (LER) and 2.6 A (HER)
  - Horizontal crossing angle: 41.5+41.5 mrad
  - $\beta_y^* \sim 0.3$ mm(target), 0.9 mm
  - $\sigma_x^* \sim 10$ μm, $\sigma_y^* \sim 50$ nm, $\sigma_z \sim 6$ mm
- **Injector complex**
  - Electron/positron linac
  - 1.1 GeV positron damping ring (DR)

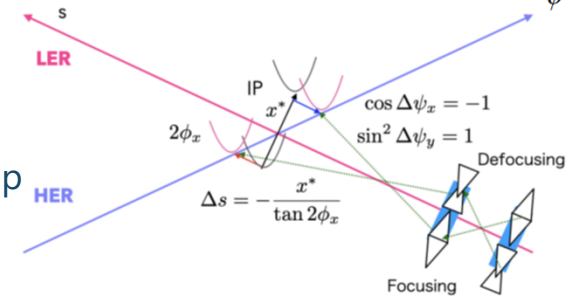


Advanced accelerator technologies

- **Nano-beam scheme**
  - At KEKB, when beams collide head-on, they collide outside the waist as well. Even reducing β_y^* no longer contributes to luminosity (the hourglass effect: $\beta_y^* > \sigma_z$, σ_z~6 mm at KEKB and SuperKEKB).
  - At SuperKEKB, the beams, also horizontally squeezed and colliding at a crossing angle φ, prevent the beams from colliding outside the waist, allowing β_y^* to be squeezed down to the effective bunch length $\sigma_x^*/\sin\varphi$.



- **Crab-waist (since 2020)**
  - Rotate the position of the β_y^* waist to the axis of the opposite beam using the sextupole pair for LCC
  - Suppress beam-beam-induced resonances & σ_y blowup
  - Increased the peak luminosity by about 30% at SuperKEKB
  - However, it reduces the dynamic aperture.



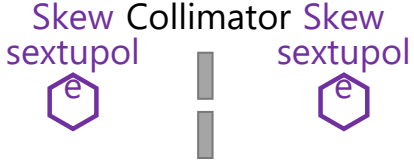
Crab waist sextupoles (-I' transfer)

Advanced accelerator technologies

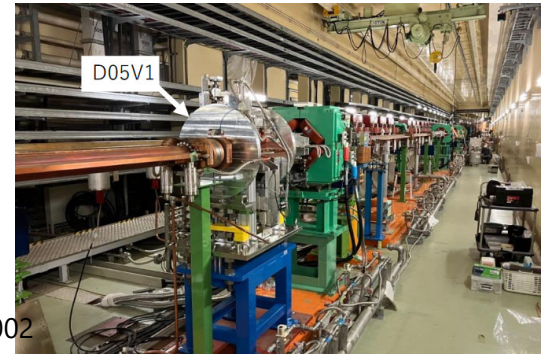
- **Non-linear collimator (since 2024)**
  - Deflect halo particles away from the beam core to remove halo effectively while minimizing impedance effects.

Beam kick by skew sextupole:

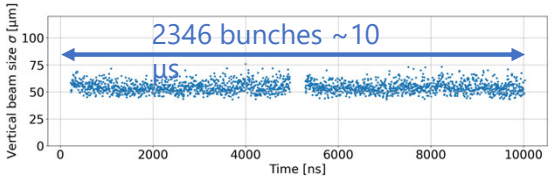
$$\Delta p_y = \frac{SK_2}{2}(y^2 - x^2),\ \ \Delta p_x = SK_2 xy$$



Phys. Rev. Accel. Beams **29**, 041002



- **Bunch-by-bunch beam diagnostics**
  - Beam position monitor, current monitor, size monitor, loss monitor, e



- **Machine learning application to accelerator control**
  - Beam orbit control at the Linac, beam injection tuning, anomaly detection, etc.

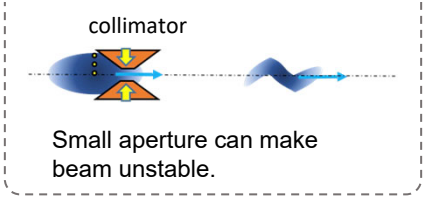
arXiv:2607.08205

The technologies developed at SuperKEKB will be the base of the future Higgs factories.

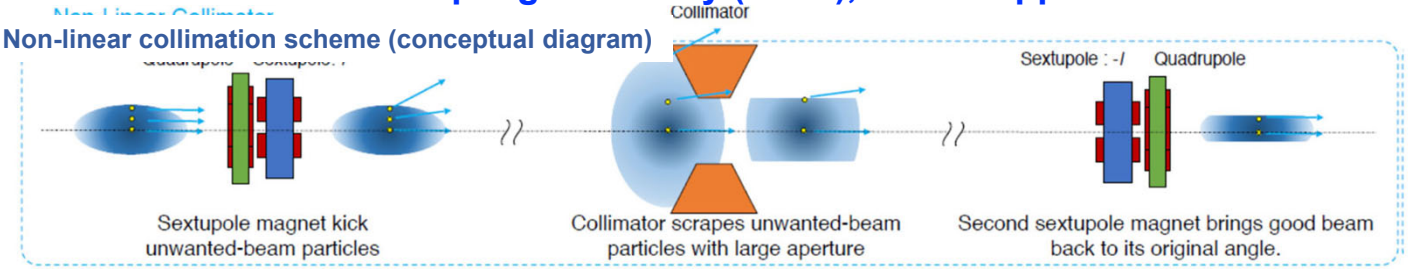
Non-linear collimator

In order to relax the transverse mode coupling instability (TMCI), NLC is applied to LER.

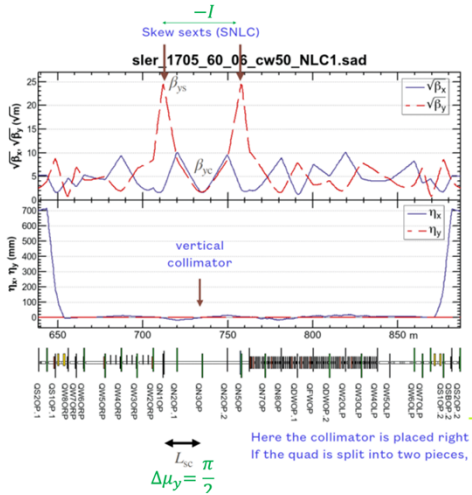
Conventional collimation scheme



Non-linear collimation scheme (conceptual diagram)



■ Enlarge beam size by nonlinear kick of the skew-sextupole



[K. Oide]

Requirements for the NLC optics:

- Large $\beta_y = \beta_{ys}$ at the (skew) sextupole.
- $\beta_y = \beta_{yc}$ at the collimator: $\sqrt{\beta_{yc}\beta_{ys}} \approx 1.7 \times L_{sc}$
- A (skew) sextupole pair connected by a $-I$ transformation.
- No dispersion at the sextupoles and the collimator.
- ≈ 0.25 vertical phase advance between the sexts and the IP.

Five sections of wigglers are removed!

L_{sc} $\Delta\mu_y = \frac{\pi}{2}$

Here the collimator is placed right before the center quad (QN3OP).
If the quad is split into two pieces, the collimator can be placed in the middle of them.

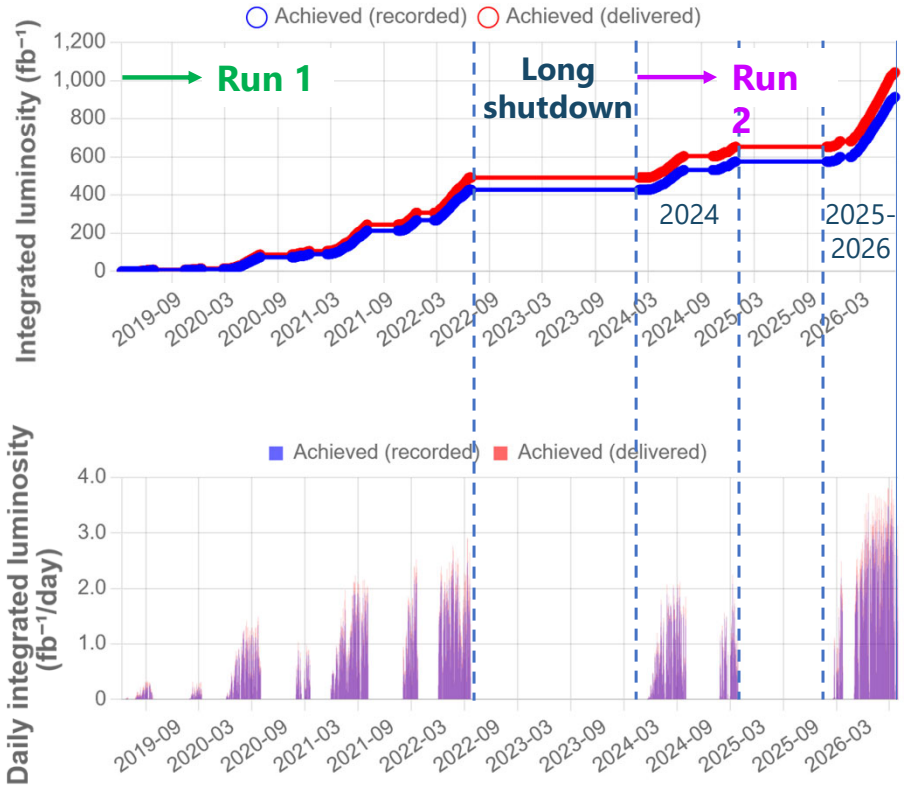
June 17, 2021 K. Oide

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- **NLC system was installed in LER Oho straight section where the optics satisfies the requirements for NLC**
  - Impedance of NLC is much lower than that of conventional collimator due to its large aperture.
  - NLC can relax TMCI bunch current limit.
  - Oho straight section is the location where the optics satisfies the requirements for NLC.
  - A part of wiggler magnets was removed to make space for NLC.
  - New skew sextupole magnets and beam pipes in them were fabricated.
  - New power supplies, cabling works and new radiation shields were also required.

Operation history

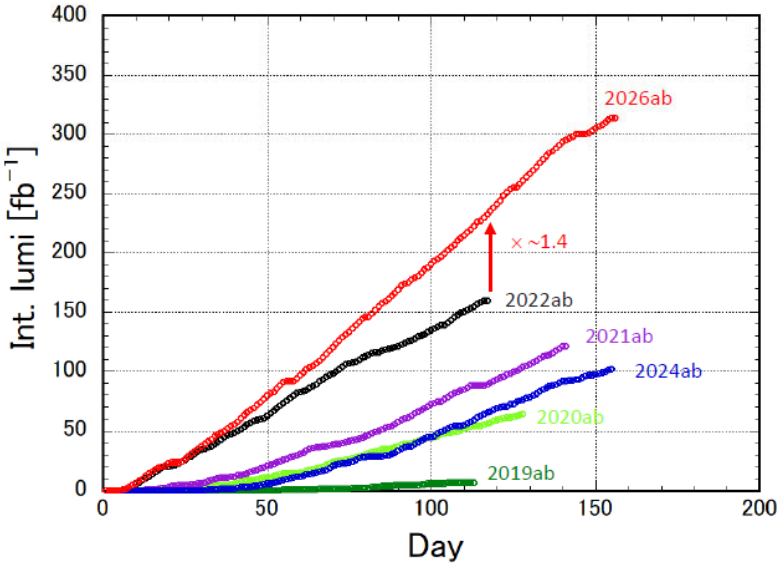
- **Run 1: March 2019 – June 2022**
  - Peak luminosity: $4.7 \times 10^{34} cm^{-2} s^{-1}$
  - Integrated luminosity (recorded): 428 fb^{-1}
  - Various challenges for luminosity improvement
    - Injection efficiency, beam lifetime, machine stability, sudden beam loss, transverse mode coupling instability
- **Long shutdown 1: June 2022 – January 2024**
  - Fast kickers for 2nd bunch operation, HER injection region, LER non-linear collimator, etc.
  - Belle II reinforcement and maintenance
- **Run 2: January 2024 –**
  - Peak luminosity (Belle II OFF): $5.32 \times 10^{34} cm^{-2} s^{-1}$
  - Peak luminosity (Belle II ON): $5.28 \times 10^{34} cm^{-2} s^{-1}$
  - Total integrated luminosity (recorded): 914 fb^{-1}
    - Y(4S) integrated luminosity: 808 fb^{-1}
      → about 100 fb^{-1} more than Belle recorded.



2026ab run overview

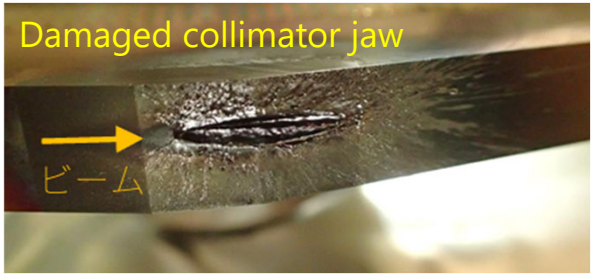
- The rate of integrated luminosity accumulation increased significantly.
  - Higher peak luminosity and more stable operation were achieved during the 2026ab run.
  - 1.4 times the accumulation rate achieved in the 2022ab run.
- Challenges in achieving higher luminosity remained.
  - Degradation of specific luminosity with increasing beam current
  - Decrease in injection efficiency with increasing beam current
    - Short beam lifetime and large beam-beam effect
  - SBLs
    - Beam currents were not aggressively increased because of frequent SBL events accompanied by QCS quenches.
    - SBLs in the HER became more prominent, though the frequency of SBL in the LER decreased.
  - Other concerns about increasing beam currents
    - Vacuum pressure deterioration in ARES cavity, Beam pipe heating in the wiggler sections, etc.
    - Addressing these issues was identified as essential for increasing beam currents and luminosity in the 2027ab run
  - Hardware failures due to aging caused prolonged interruptions to operation
    - Failures of the injection kicker power supply, QCS cryogenic gas line solenoid valve, air conditioner at the control room, etc.
    - Reduced cooling water flow in the BT magnets also caused operation interruption

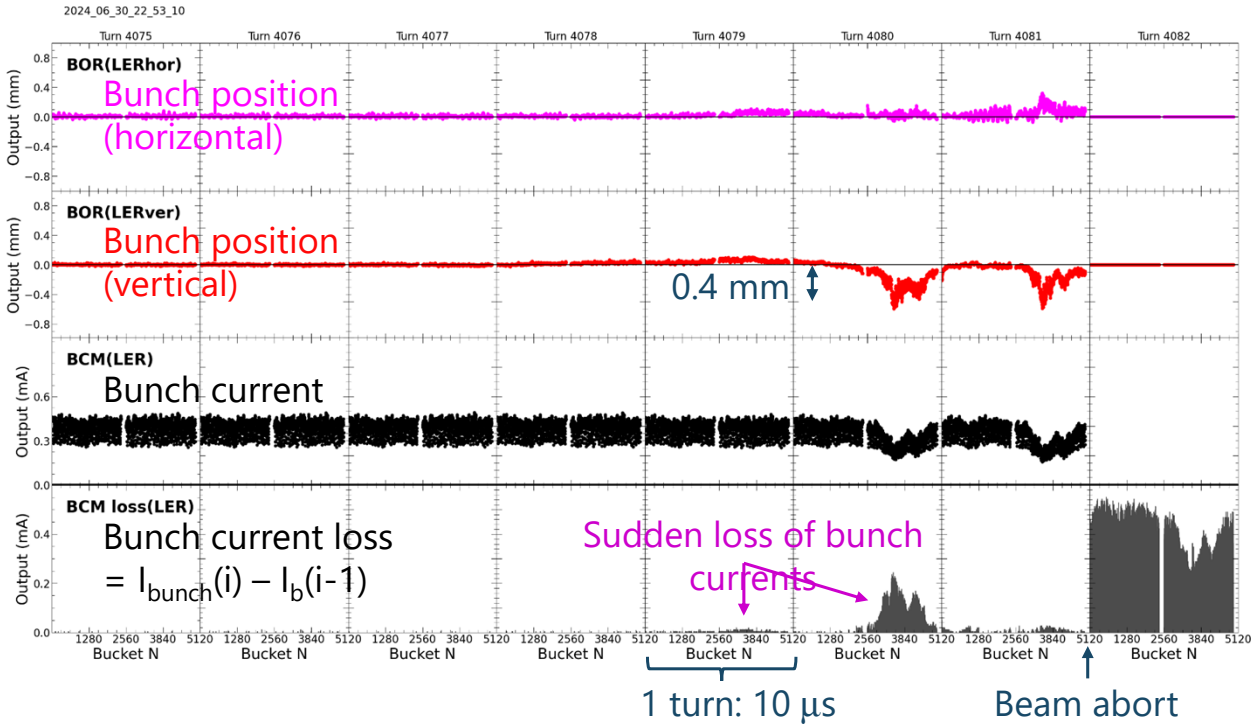
Comparison of integrated luminosity during spring runs (2019ab – 2026ab)



Sudden Beam Loss (SBL) events

- **A peculiar event in which the stored beam suddenly disappears within several turns (20-100 μs)**
  → resulting in a beam abort
- SBL events sometimes cause
  - damage to the collimators and the Belle II detectors
  - quenching of the QCS system (superconducting final focusing)
- **SBL events limit beam current and operation time.**

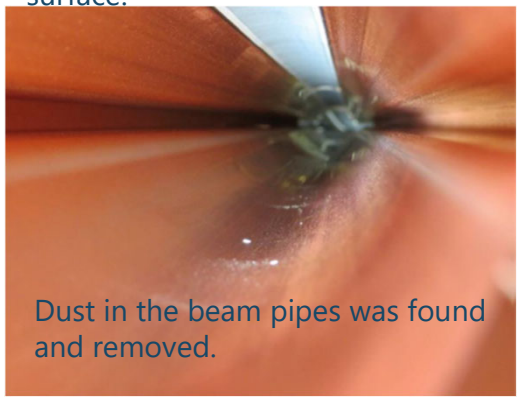




Countermeasure of sudden beam loss events

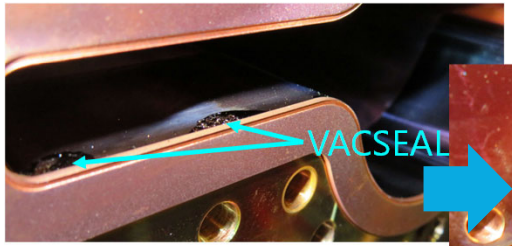
- SBL events are accompanied by pressure bursts, particularly in the wiggler sections.
  - In the LER (e^+) wiggler sections, beam pipes have “electron clearing electrodes” for suppressing electron cloud effects.
  - In the 2024 summer shutdown, the pipes were flipped upside down so that the electrode was positioned at the bottom.

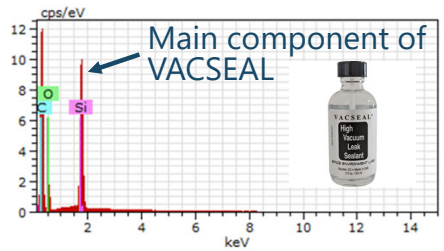
Electrode with 0.1 mm tungsten on 0.2 mm Al_2O_3 ceramic only on the top surface.



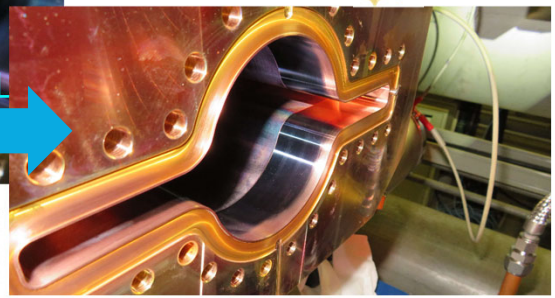
Dust in the beam pipes was found and removed.

- However, SBL occurred at the same rate even after the pipe was inverted.
- It was finally determined that the VACSEAL used to seal the vacuum leak had solidified and turned into dust due to intense synchrotron radiation.
- Before the 2025 operation, we cleaned the flange connections at the IR and LER wiggler sections.

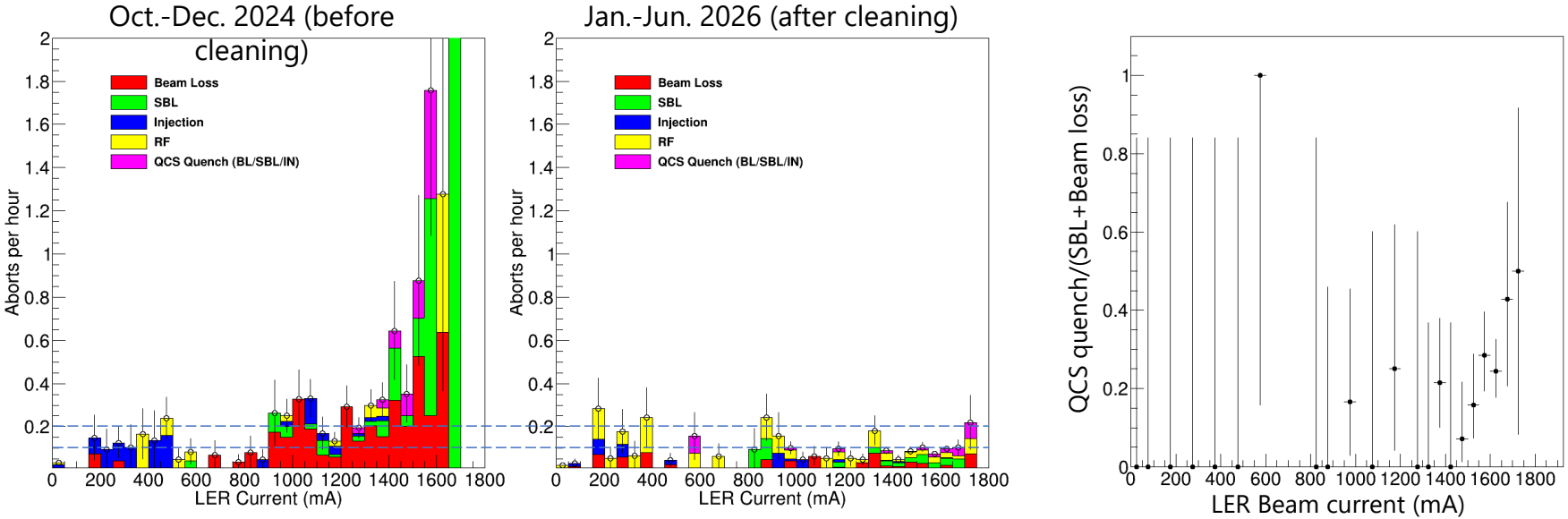




After cleaning



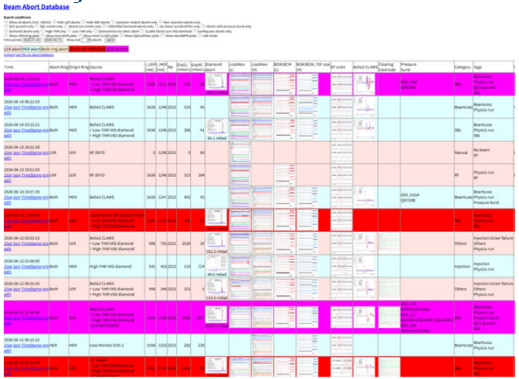
Beam abort frequency in LER



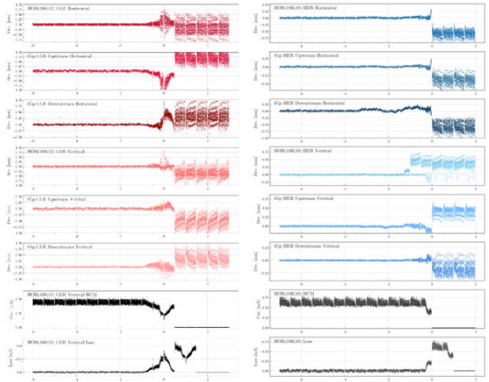
- Chamber cleaning in Dec. 2024 and Jan. 2025 dramatically decreased the abort frequency, < 0.1/hour.
- The proportion of QCS quenches to total beam loss aborts (BL + SBL) becomes higher with the current.
  - QCS: final focusing superconducting magnets
  - A QCS quench requires 1.5-2.0 hours to recover beam operation, i.e., x4 longer than the normal BL abort.
  - Sill searching to see if there are any other sources…

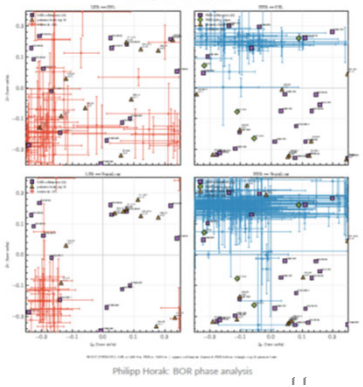
Hunt for the source point(s) of SBL

- Use BRAM of iGp12s (Upstream, Downstream, H and V) for the rings.
  - Same signal as the bunch feedback system (good resolution, good isolation).
  - Around 90-deg betatron phase difference between the upstream and downstream.
  - Post-mortem bunch positions up to 96 turns, automatically transferred to a NAS.
  - Automatic software processing developed by Belle II MDI collaborators.



- Since oscillations are observed at two points with different betatron phases, if the oscillation source is a single point, we can determine the betatron phase difference between the point where the beam was kicked and the position monitor. Under these conditions, there are as many possible locations as the integer part of the betatron tune; however, if we further assume that the horizontal and vertical directions are the same and that the kick occurs simultaneously at that location, the number of candidate locations is narrowed down even further.





Luminosity & Feedback parameters

- By replacing the 2 GHz filter in the feedback detector from a 3-tap stripline-coupled type to a 2-tap cable-delay type, the noise figure improved by approximately 20 dB, and the broadband noise level observed with the iGp12 was significantly reduced (15 counts to 3 counts of ADC RMS level).
- The large LER noise line coming from the reference RF has vanished with the cleaner HER RF line.
- By increasing/decreasing the bunch feedback gain has shown no significant effect on the luminosity.
  - Still tried to operate with minimum transverse feedback gain.

Luminosity vs HER FB room temperature

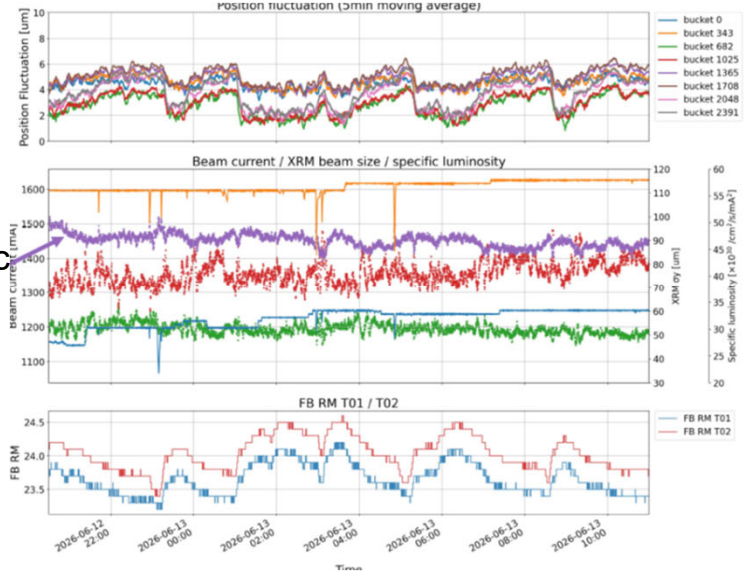
- It was pointed out that there is a correlation between the temperature in the Luminosity and HER Feedback control rooms (Fuji B4).
  - Although the temperature fluctuations themselves were greater in the LER control room (up to 2 degrees), the subtle temperature changes in the HER control room showed a stronger correlation.
  - We took measures to minimize the impact of air conditioning in areas that seemed susceptible to temperature fluctuations, but they weren't very effective.

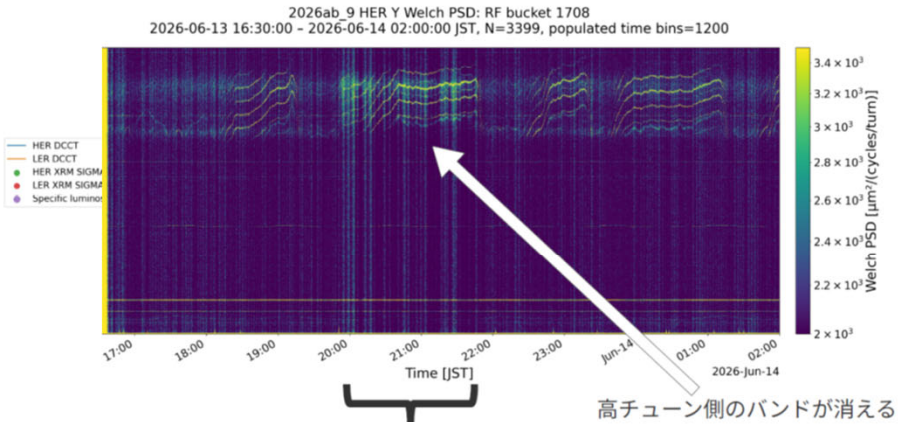
Measurement by RFSoC long-data

By R.Nomaru (Grad. student)

Specific

Room Temp

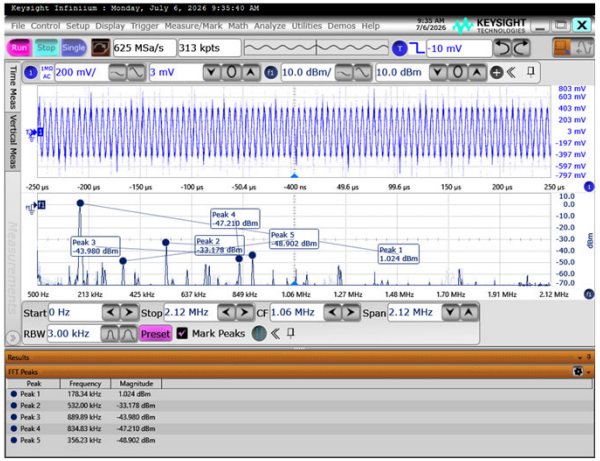


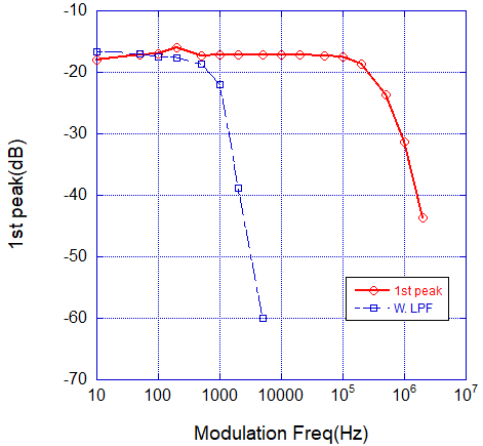


Single beam (HER only)

Identifying Source of variation

- We discovered that the +6V and -6V lines of NIM power supply were oscillating in the buffer amplifier module for the DAC output, which was controlling a 2 GHz phase shifter.



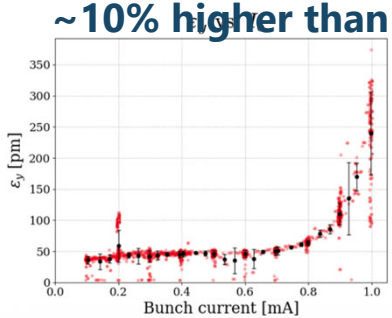


Frequency response of the control line of 2GHz phase shifter. Inserting the 1 kHz low-pass filter should suppress noise injection, even at such a large amplitude.

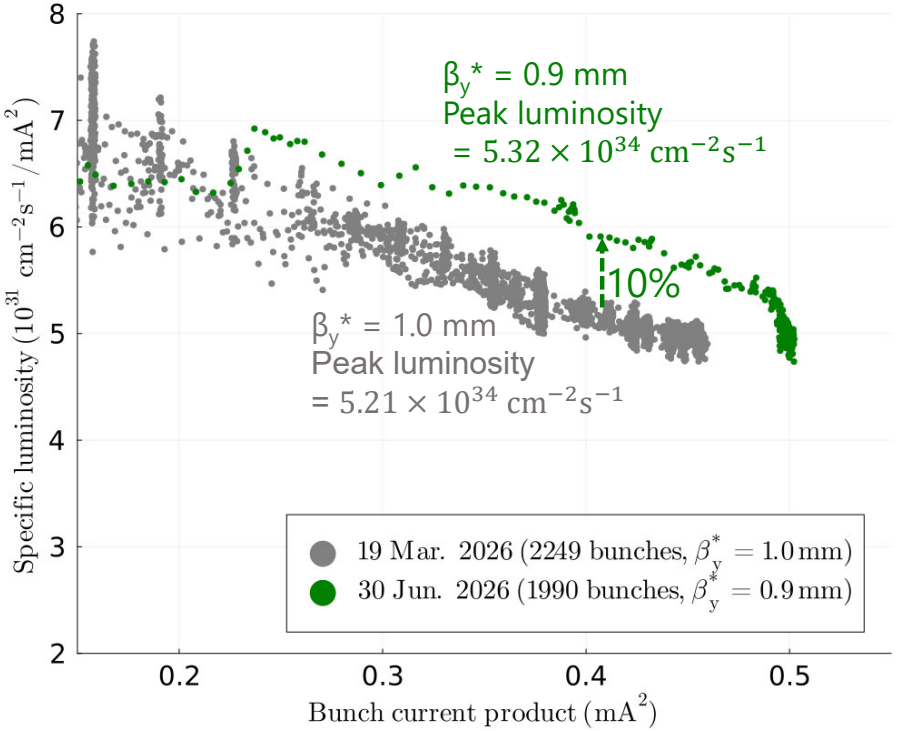
The oscillation frequency strongly depends on the environment temperature.

Increasing peak luminosity with lower β_y^*

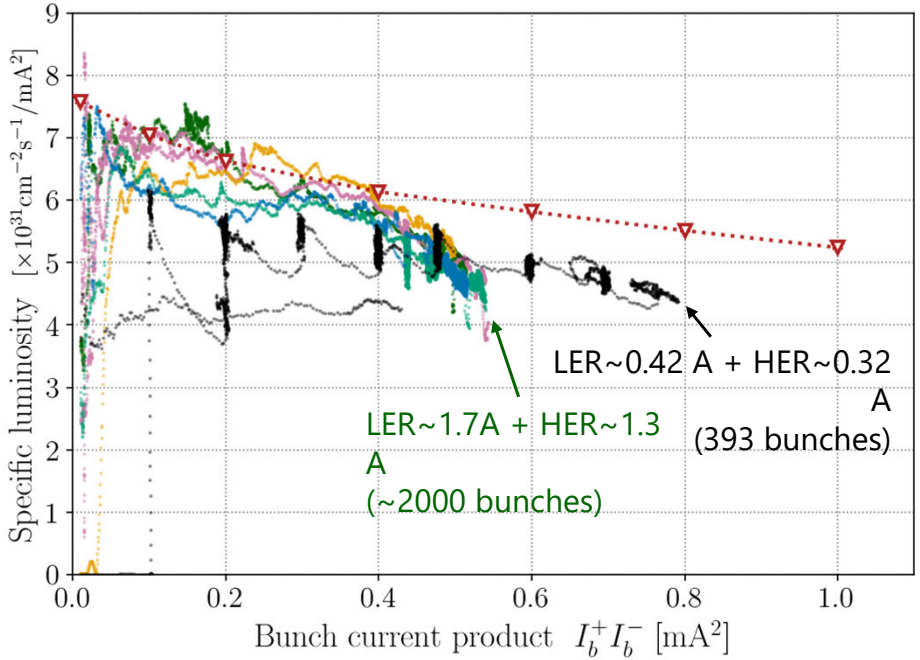
- SuperKEKB has been successfully operated with β_y^* = 0.9 mm since 30 Apr. 2026 (1.0 mm until then).
  - For increasing luminosity and accumulating integrated luminosity
  - Without raising the beam current, which would be accompanied by an increase in the abort rate.
  - A trial aimed at a future peak luminosity of 10^{35}.
  - Could maintain dynamic aperture enough for the beam current >1.7 A (LER) and >1.3 A (HER).
- **Specific luminosity with β_y^* = 0.9 mm is ~10% higher than β_y^* = 1.0 mm.**

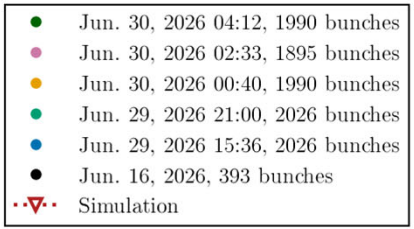


The specific luminosity drop-off around 0.5 mA^2 possibly result from increased impedance and beam size due to damaged collimator(s).



Further increasing luminosity



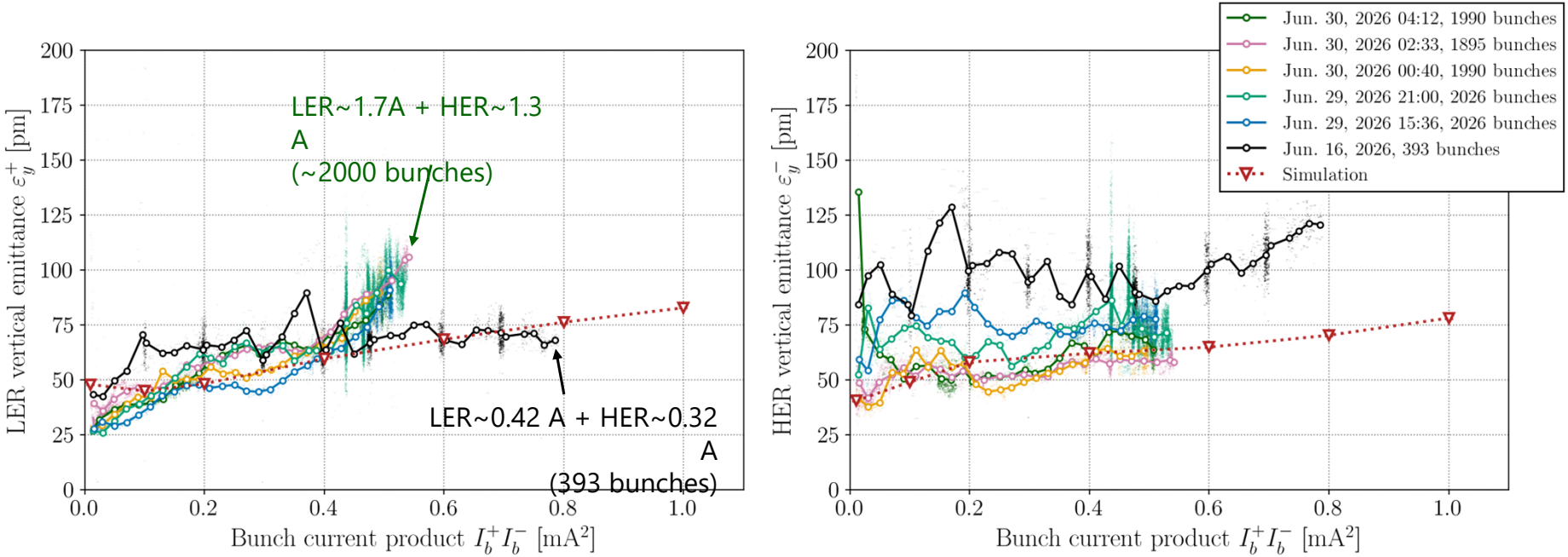


Simulation parameters

Parameters	LER (e^+)	HER (e^-)	Units
I_b	I_b^+ (variable)	$I_b^- = 0.75 \times I_b^+$	mA
ε_x	4.05	4.43	nm
ε_y	40	40	pm
$(\beta_x^*,\ \beta_y^*)$	(55, 0.9)	(55, 0.9)	mm
$(\nu_x,\ \nu_y)$	(44.537, 46.584)	(45.531, 43.607)	
ν_z	0.0237	0.0272	
σ_z	4.6	5.1	mm
(τ_x, τ_y, τ_z)	(53.0, 53.0, 26.5)	(58.0, 58.0, 29.0)	ms
CW ratio	80	60	%

- With a high number of bunches, a drop-off of in the specific luminosity is observed starting around 0.4 mA^2.
- Total current-dependent effects, such as SR-induced beamline deformation or resistive wall, may hinder luminosity performance.
- In the beam-beam simulation, wake fields are included based on measured tune shifts.

Further increasing luminosity



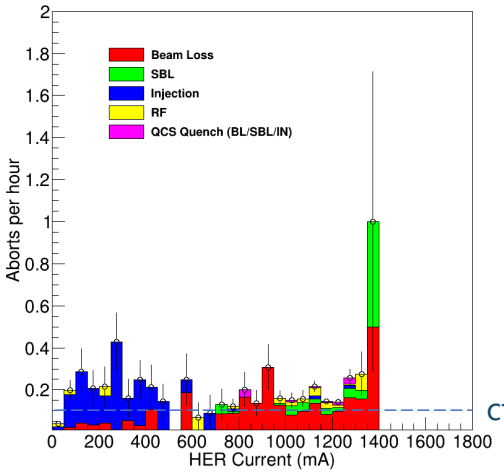
- In the LER, an increase in beam size was observed at >0.4 mA^2 during physics run operations (~2000 bunches).
  - In contrast, no rapid beam size increase occurred during 393-bunch collision operations or in simulations.
- In the HER, no clear beam size increase proportional to the bunch current is observed.

Luminosity challenges in January-June 2027

Estimated machine parameters

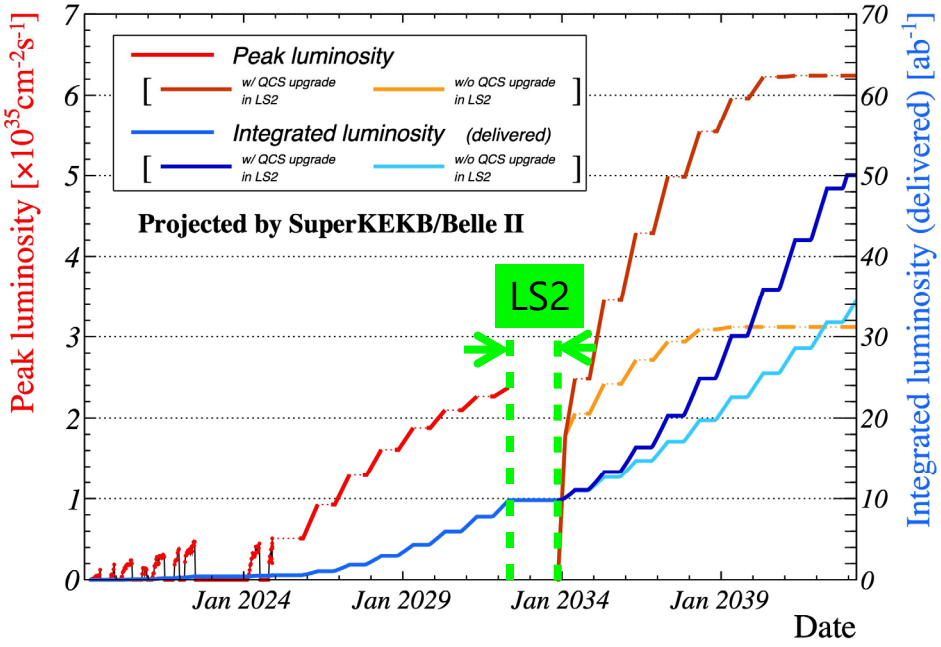
Peak luminosity	5e34	6e34	7e34	8e34	9e34	10e34
Specific luminosity	5.5	5.3	5.1	4.8	4.5	4.4
HER beam (A) / bunch (mA) current	1.31/0.56	1.46/0.62	1.62/0.69	1.77/0.75	1.93/0.82	2.00/0.85
LER beam (A) / bunch (mA) current	1.64/0.70	1.83/0.78	2.02/0.86	2.21/0.94	2.41/1.03	2.60/1.11

- **The LER has a beam lifetime of 6–7 minutes at 1.7 A during both colliding and non-colliding operations.**
  - The lifetime shorter than 5 minutes requires high beam injection capability.
  - Increase injection bunch charge and reduce emittance.
  - Prevent pressure rises near the IR and collimators.
- **The beam abort frequency of the HER is twice that of the LER.** Identifying the cause is essential for increasing integrated luminosity.
- **Injection-induced background needs to be reduced.**



cf. LER rate~0.1/h

Further Future Projection



Major upgrade plans in Long Shutdown 2

- **HER RF System**
  Enhancing ring RF systems to provide massive high power by increasing number of klystrons.

- **Superconducting final focus system (QCS)**
  Redesigning QCS to optimize the beam orbit at the interaction point.

- **Injector linac**
  Modernizing the Linac (particularly RF system) for high bunch charge, highly stable, and high-efficiency top-up continuous sourcing without operational limits.

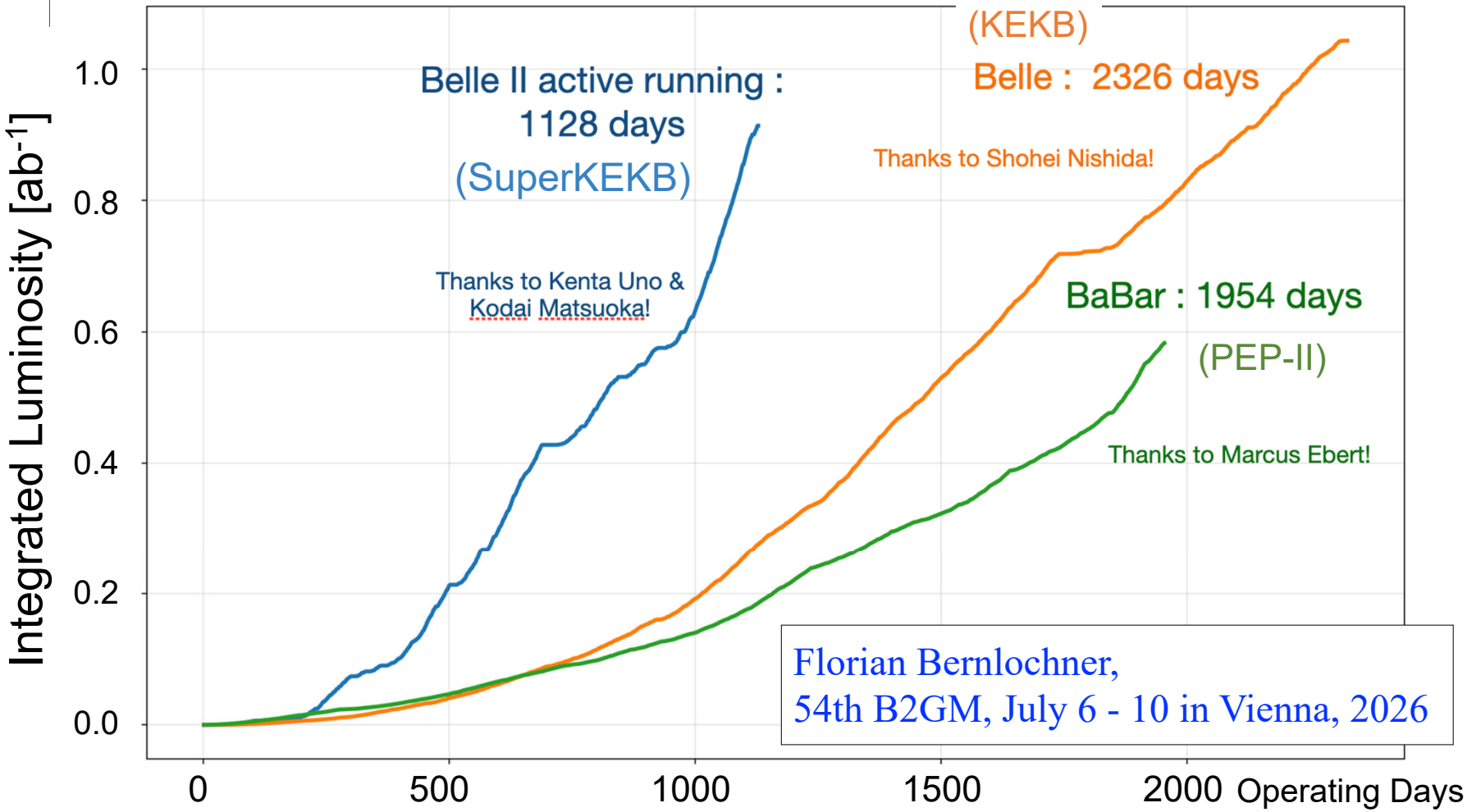
- **Infrastructure maintenance**

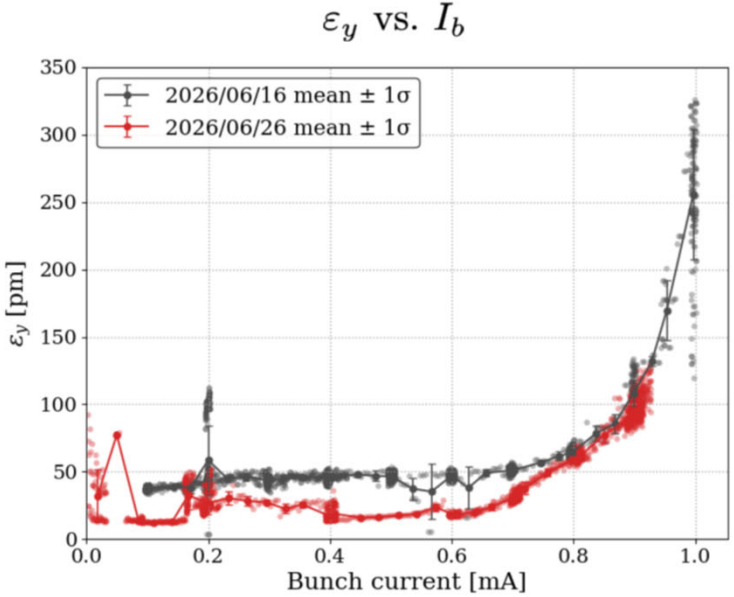
Summary

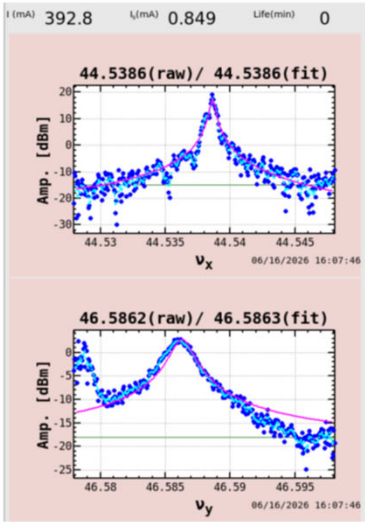
- **Record luminosity**
  Run 2 peak: 5.32×10^{34} $cm^{-2}s^{-1}$, 914 fb^{-1} recorded (808 fb^{-1} at Y(4S)) since 2019
- **SBL mitigated**
  VACSEAL identified as a cause; cleaning cut aborts to <0.1/hour in LER.
- **QCS quenches remain**
  Growing abort rate at high current; 1.5–2 h recovery each.
- **Luminosity drop-off at high current**
  Above ~0.4–0.5 mA^2, from impedance, beam-size growth, and resistive-wall effects.
- **2027 outlook**
  LER lifetime 6–7 min at 1.7 A
  HER abort rate 2× LER
- **Long-term path**
  LS2 (HER RF, QCS redesign, linac upgrade) needed to reach design current & target luminosity.


Thank you for your attention!

Backup


Integrated Luminosity [ab^{-1}]
1.0
0.8
0.6
0.4
0.2
0.0
0
500
1000
1500
2000
Operating Days
Belle II active running :
1128 days
(SuperKEKB)
Thanks to Kenta Uno &
Kodai Matsuoka!
(KEKB)
Belle : 2326 days
Thanks to Shohei Nishida!
BaBar : 1954 days
(PEP-II)
Thanks to Marcus Ebert!
Florian Bernlochner,
54th B2GM, July 6 - 10 in Vienna, 2026

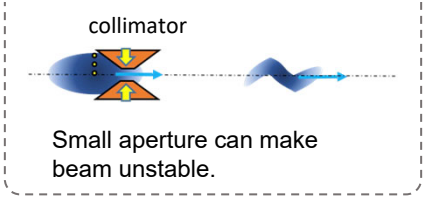

ε_y vs. I_b
2026/06/16 mean ± 1σ
2026/06/26 mean ± 1σ
ε_y [pm]
Bunch current [mA]
0
50
100
150
200
250
300
350
0.0
0.2
0.4
0.6
0.8
1.0


I (mA) 392.8
I_b(mA) 0.849
Life(min) 0
44.5386(raw)/ 44.5386(fit)
Amp. [dBm]
ν_x
06/16/2026 16:07:46
46.5862(raw)/ 46.5863(fit)
Amp. [dBm]
ν_y
06/16/2026 16:07:46

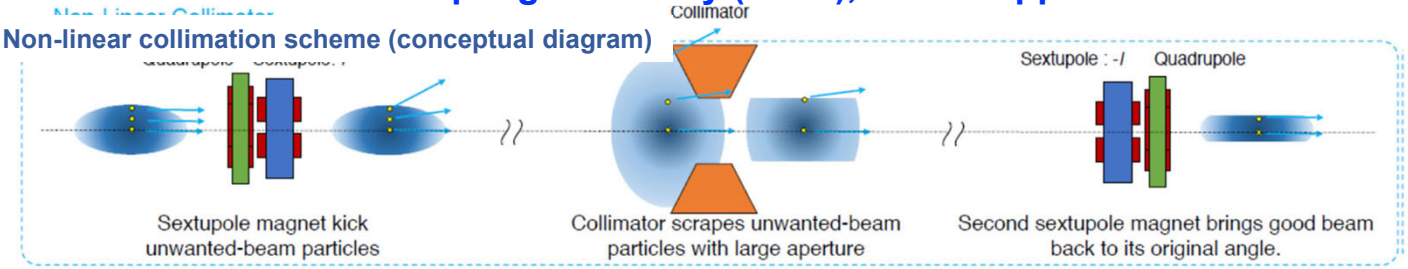
Non-linear collimator

In order to relax the transverse mode coupling instability (TMCI), NLC is applied to LER.

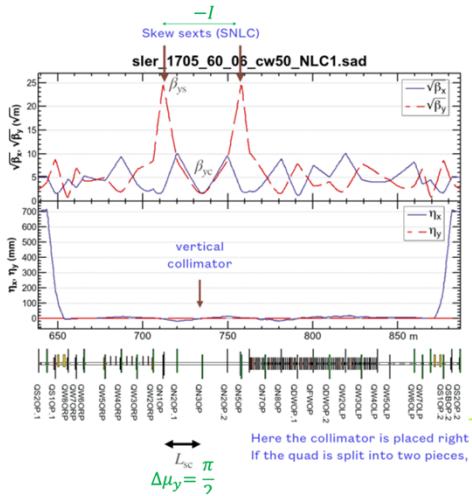
Conventional collimation scheme



Non-linear collimation scheme (conceptual diagram)



■ Enlarge beam size by nonlinear kick of the skew-sextupole



[K. Oide]

Requirements for the NLC optics:

- Large $\beta_y = \beta_{ys}$ at the (skew) sextupole.
- $\beta_y = \beta_{yc}$ at the collimator: $\sqrt{\beta_{yc}\beta_{ys}} \approx 1.7 \times L_{sc}$
- A (skew) sextupole pair connected by a $-I$ transformation.
- No dispersion at the sextupoles and the collimator.
- ≈ 0.25 vertical phase advance between the sexts and the IP.

Five sections of wigglers are removed!

Here the collimator is placed right before the center quad (QN3OP).
If the quad is split into two pieces, the collimator can be placed in the middle of them.

June 17, 2021 K. Oide

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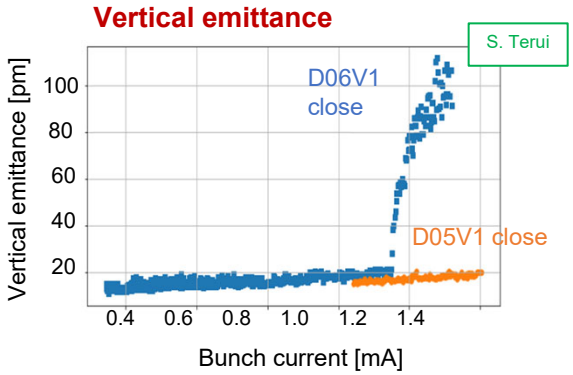
- **NLC system was installed in LER Oho straight section where the optics satisfies the requirements for NLC**
  - Impedance of NLC is much lower than that of conventional collimator due to its large aperture.
  - NLC can relax TMCI bunch current limit.
  - Oho straight section is the location where the optics satisfies the requirements for NLC.
  - A part of wiggler magnets was removed to make space for NLC.
  - New skew sextupole magnets and beam pipes in them were fabricated.
  - New power supplies, cabling works and new radiation shields were also required.

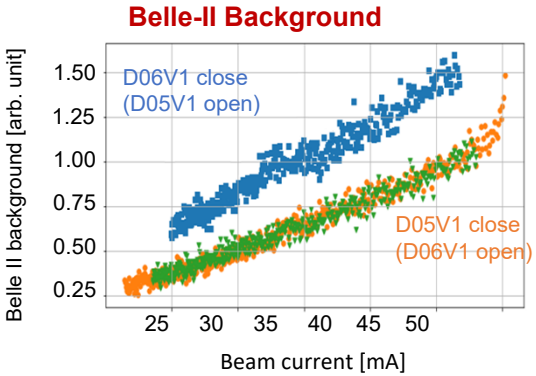
Outline

1. **Background**
   SuperKEKB e+e- collider design & technologies
2. **Operation history**
   Run 1 & Run 2 luminosity milestones
3. **Sudden Beam Loss (SBL)**
   Cause and mitigation
4. **Peak luminosity at lower β_y^***
   β_y^* squeezing and specific luminosity drop-off
5. **Further luminosity gains**
   High-beam current, high-bunch-current effects
6. **2027 run challenges**
   LER lifetime, HER abort frequency
7. **Summary & outlook**
   Path to design current, LS2 upgrades

- Before LS1
  - To reduce Belle II BG noise, LER collimators had to be closed more than expected.
  - High impedance due to narrow collimator setting resulted in a lower TMCI threshold.

- After LS1
  - **The BG and impedance reduction effects of the NLC have been confirmed.**
    - **Radiation level in the OHO experimental hall increased, resulting in restricted NLC usage.**
  - Radiation shielding was reinforced during the shutdown in 2024 for full usage of the NLC.





- 前回の打合せメモ
- - シングルビームかつ多数バンチの条件でblowupが見られていたか、過去のデータを調査する。（杉本）

- について、2026年6月に取得したデータから、HER電流がほぼゼロの条件で、LER垂直エミッタンスのバンチ電流依存性をフィルパターンごとにプロットしました。
- さらに、6月30日のluminosity challengeにおける1990バンチ衝突データを重ねています。
- 今回確認した範囲ではsingle-beam条件において明瞭な閾値的blowupが見られたのは393バンチのみでした。
- また、393バンチ（non-collision）と1990バンチ（collision）では、0.6 mA/bunch以上におけるblowupの電流依存性が似ているように見えます。

- それから、 6/29-30のルミノシティチャレンジの時のLERのRFSoC-BORデータを能丸さんにお願いしたのですが、残念ながらHERの測定しかないということでした。

