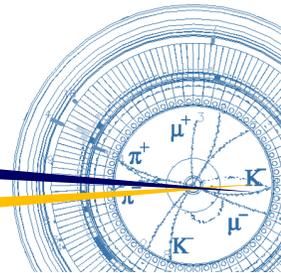


SuperKEKB

Challenges and Countermeasures



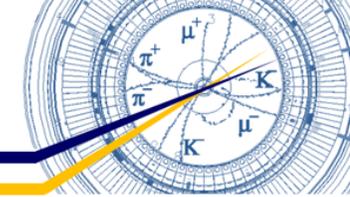
2025.12.18

Kyo Shibata

(on behalf of SuperKEKB)



Challenges limiting the performance



• Major Challenge

1. Low machine stability

- Sudden Beam Loss (SBL) , etc.

2. Low bunch current limit

- Transverse Mode Coupling Instability (TMCI)

3. Low injection efficiency

- Low stability of injected beam, Large emittance injected beam, Small aperture at injection point

4. Short beam lifetime

- Strong beam-beam effect, narrow dynamic aperture

5. Severe beam-beam effect

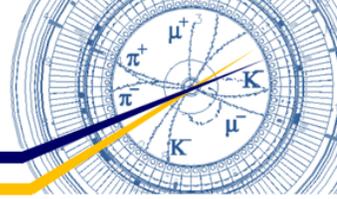
- Large simulation-measurement discrepancy

6. Aging of hardware and facilities

- Mitigation efforts for some of them have already been carried out during the long shutdown 1 (LS1) and the previous shutdown.



Low machine stability



- Sudden Beam Loss (SBL)

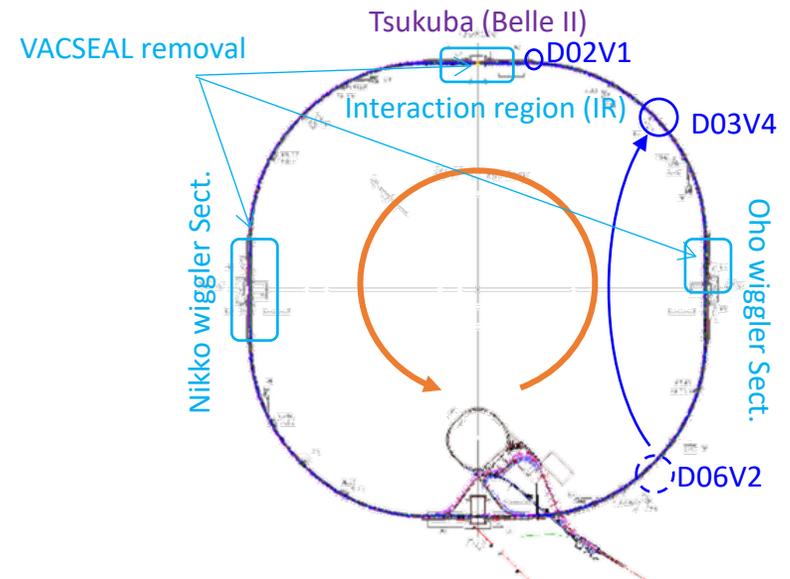
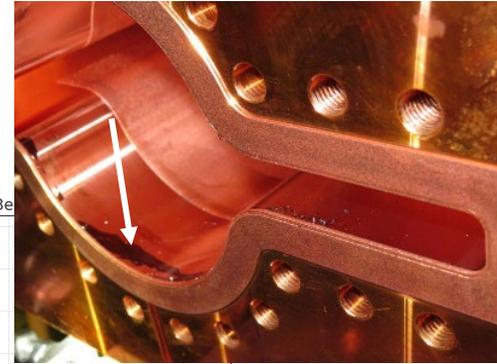
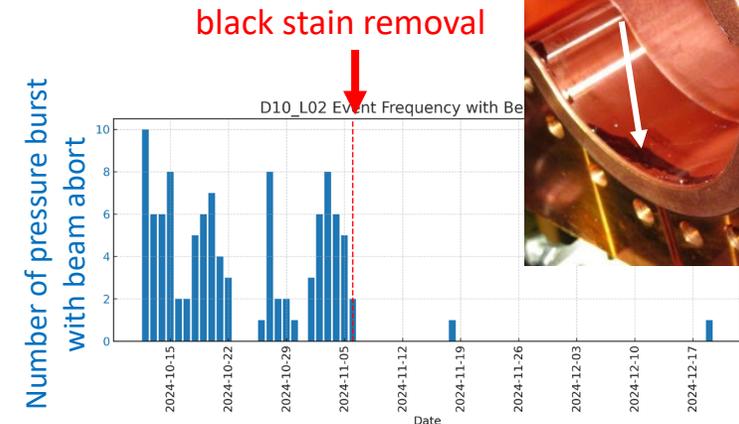
- SBL is the most critical obstacle to achieving stable operation.
 - Part of the beam is suddenly lost within a few turns.
 - It is difficult to prevent uncontrollable beam from damaging Belle II and collimators.
- Countermeasures
 - **Removal of VASCEAL contamination** ← Last shutdown
 - All MO-type flange connections likely used VACSEAL were checked and fully cleaned during the previous shutdown.
 - SBL mitigation effect of VACSEAL removal was confirmed during 2024c run.

➡ Significant reduction in SBL events

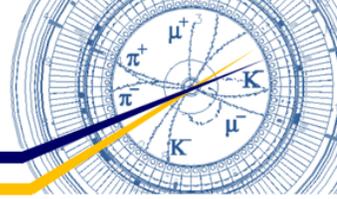
- Additional countermeasures

- Collimator relocation ← Last shutdown
 - D06V2 -> D03V4 (to protect IR (Belle II, QCS, D02V1 collimator) from uncontrollable beam)
- Additional beam loss monitors and acoustic sensors
- Faster beam abort system

T. Ishibashi



Low machine stability



• Others

• Injection kicker accidental firing

- Carbon collimator (D06H3) to stop accidentally kicked beam

← LS1

➡ No damage from accidental firing so far

- Optimization of thyatron parameters

← Last shutdown

➡ No accidental kicker firing in 2025c so far

• Collimator damage

- Development of new robust jaws (Ti, Hybrid(Cu+Ta))

➡ Damage mitigation (No damage to Hybrid jaw so far, Not all collimators can be replaced with Ti or Hybrid types)

- Development of revolver-jaw type collimator (Significant reduction in down time for replacing work)

← Ongoing

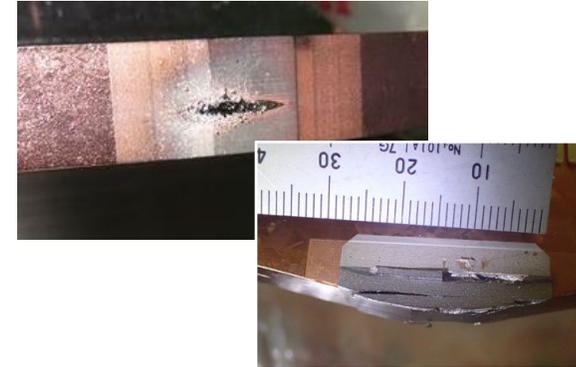
• Thermal deformation of the beam pipe due to SR irradiation (Shift in Q-magnet and BPM)

- Isolation of the BPM block from the Q-magnet

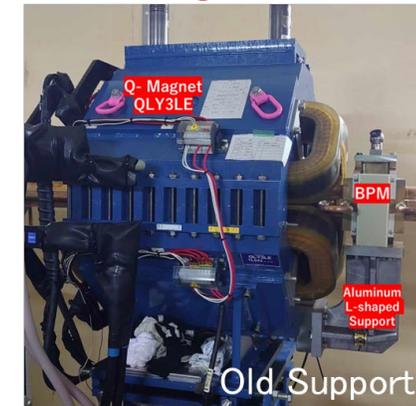
← During 202ab run + Last shutdown

➡ Beam stability improvement

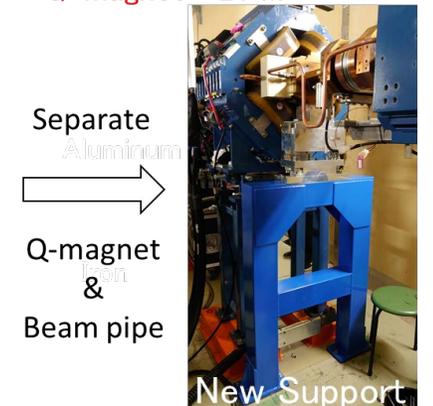
Damaged collimator jaws



Revolver-type collimator jaws



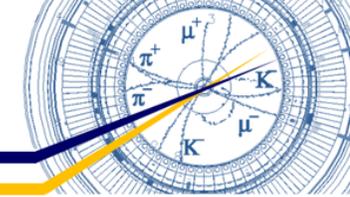
Old Support



New Support

➡ Separate Aluminum Q-magnet & Beam pipe

Low bunch current limit



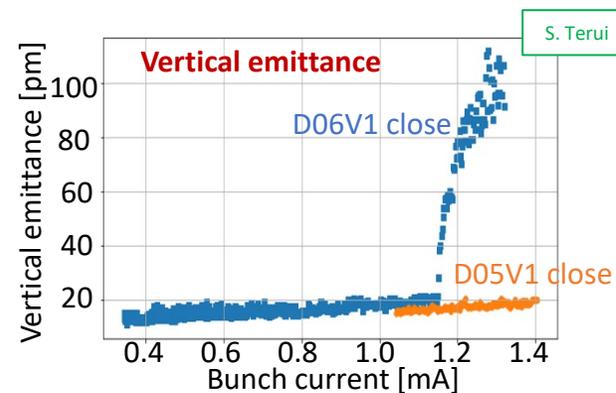
- Transverse Mode Coupling Instability (TMCI) could limit bunch current.

- Before LS1

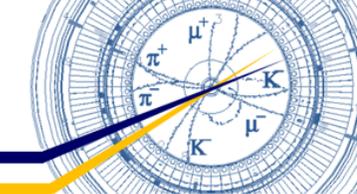
- To reduce Belle II BG noise, LER collimators had to be closed more than expected.
- High impedance due to narrow collimator setting resulted in a lower TMCI threshold.
- To ensure stable operation at high bunch current without inducing TMCI, a world-first nonlinear collimator system was installed in the Oho Straight section during LS1.

- 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 previous shutdown.
- Full usage of the NLC has started from this run.



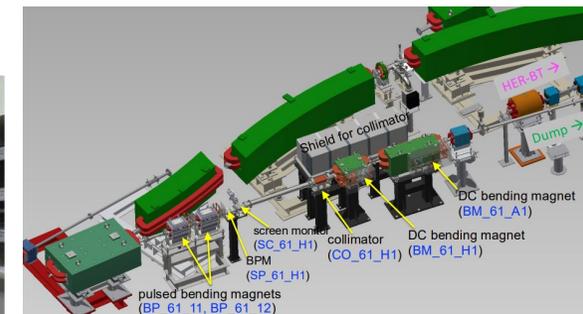
Low injection efficiency



- Hardware Improvements to improve the injection efficiency.

- Linac

- Installation of fast kickers for independent 1st/2nd bunch control
- Implementation of a dedicated e⁻ beam diagnostic line ← Last shutdown
- Installation of pulsed magnets for independent e⁻/e⁺ beam control

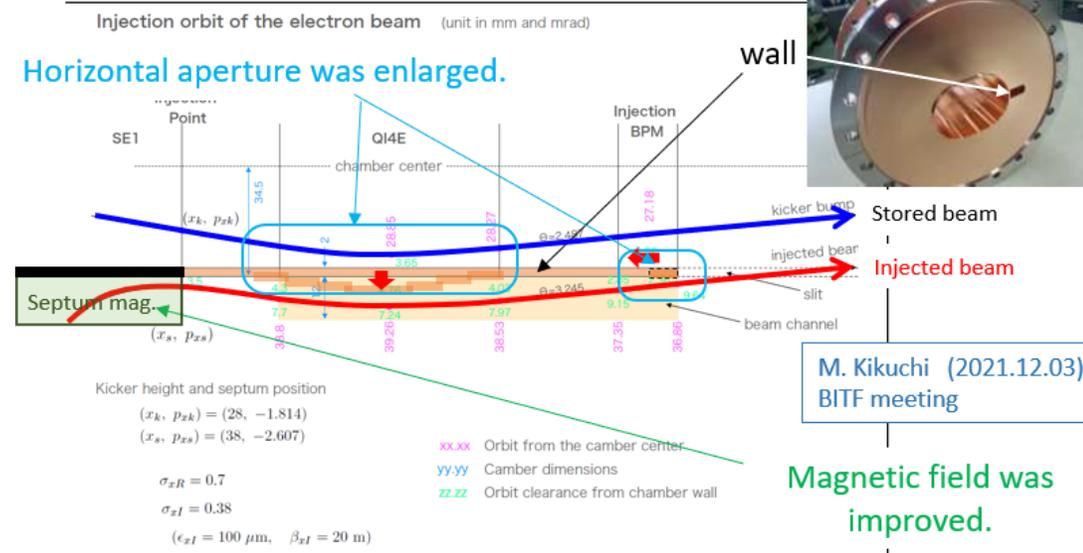


- Beam Transport Line (BT)

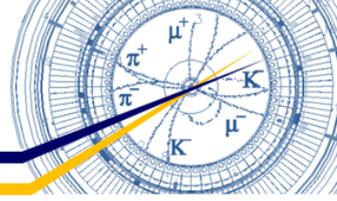
- Investigation of emittance growth (cause still understudy)
- Replacement of ARC03 bending magnet poles (BTp) ← Last shutdown
- Installation of an Energy Compression System (ECS) (greater effect at higher bunch charge expected.)
- Improved magnet alignment ← LS1

- Main ring (MR)

- Installation of vertical kicker
 - Precise aperture survey enabled
- Aperture enlargement in the HER injection point ← LS1
- Realignment of the LER injection point. ← Last shutdown



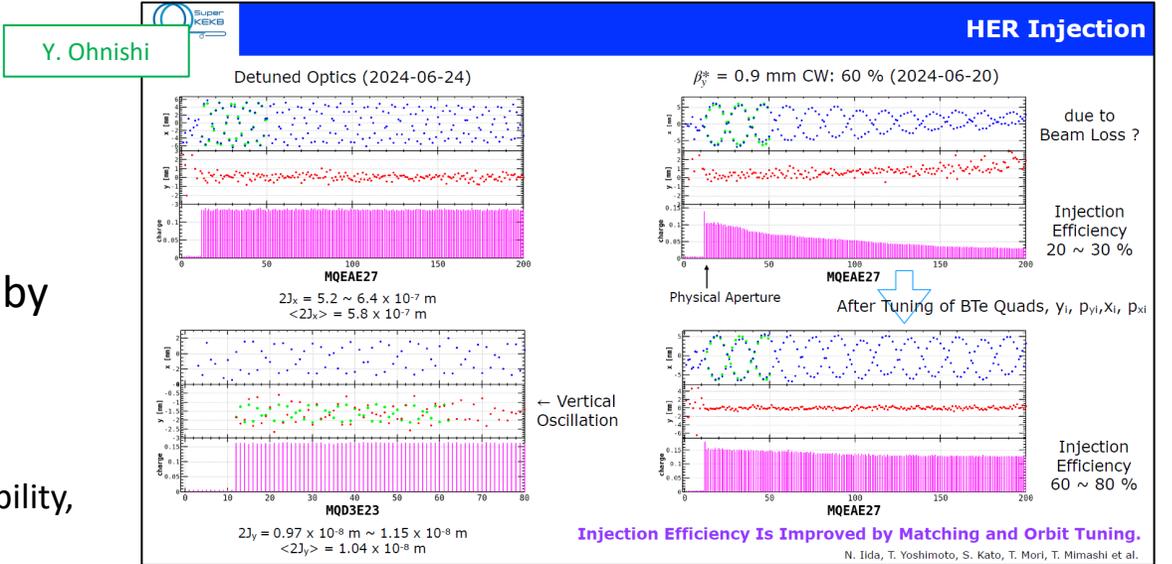
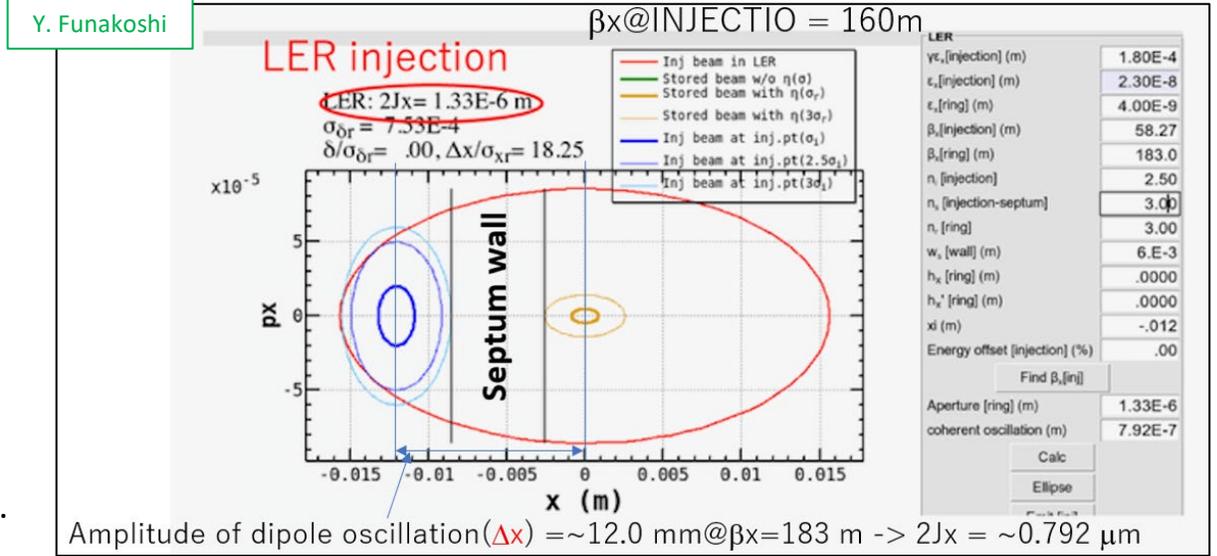
Low injection efficiency



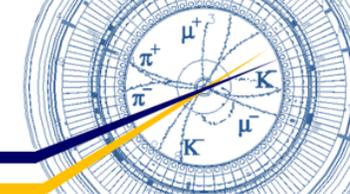
- Beam commissioning measures
 - Establishment of an injection tuning procedure
 - Optics matching between BT and MR
 - 3D phase-space aperture survey in MR
 - Injected beam oscillation measurements using TbT BPMs
 - Optics modification at the Injection point
 - Increasing the beta function at the injection point to suppress betatron oscillation.
 - Optics modification at the IP
 - Decreasing the beta function at IP to suppress beam-beam effect.
 - Operation tune survey



- Injection efficiency has been steadily improving, and LER/HER maximum beam currents have reached 1699/1354 mA
 - At high beam currents, injection efficiency is degraded by the beam-beam effect.
 - The following issues of the injected beam also requires further improvement
 - Energy jitter, Orbit drift, Emittance growth at BT, Poor reproducibility, etc.

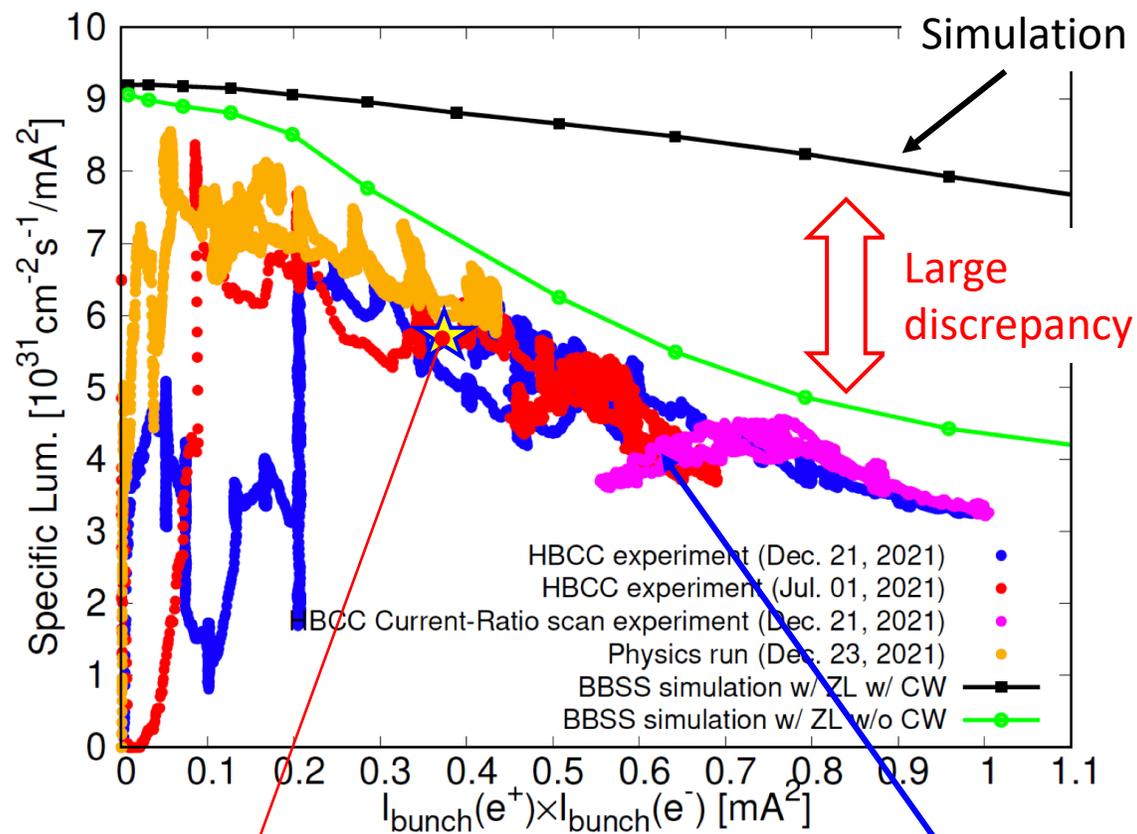


Severe beam-beam effect



- Low specific luminosity at high bunch current product
 - The cause of the L_{sp} drop is still unknown.
 - There remains a significant discrepancy between simulation and measurement.
- Low injection efficiency due to beam-beam effect
 - Injection efficiency appears to be limited by the beam-beam effect.
 - Maximum achievable beam current is limited by the beam-beam effect.
 - The dynamic aperture needs to be enlarged.
- Countermeasures
 - An improvement was achieved after introducing the crab-waist collision scheme.
 - An international collaboration on beam-beam simulation studies has now been launched.

Strong-Strong Beam-Beam simulation (D. Zhou)

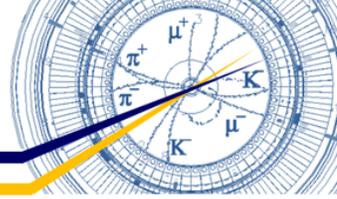


2024c run

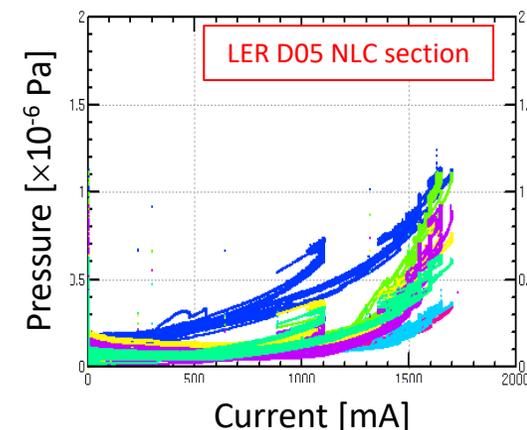
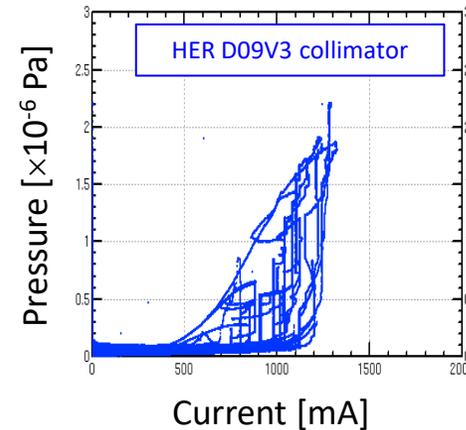
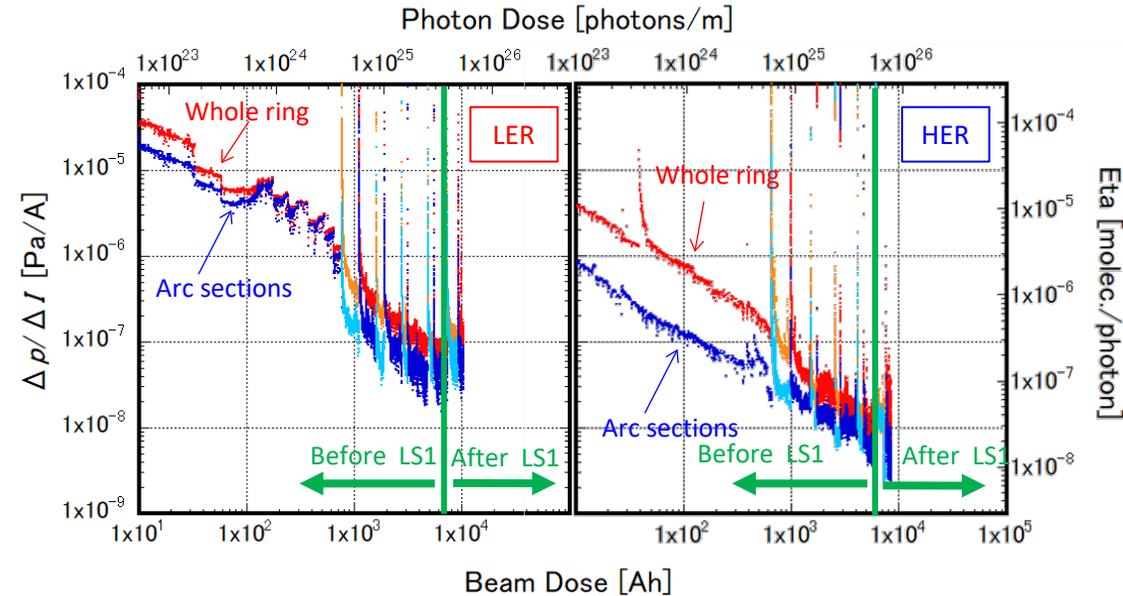
Experimental results

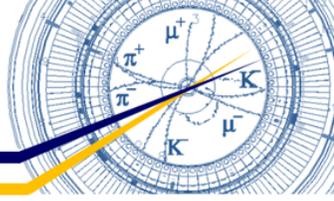


Short beam lifetime



- Dynamic aperture is smaller than expectation.
 - Further optimization of the sextupoles may allow for an increase in the dynamic aperture.
- The vacuum pressure may become the dominant factor limiting the maximum beam current.
 - At high beam current, the lifetime determined by vacuum pressure is comparable to the Touschek lifetime in the LER.
 - The LER shows a large pressure rise per unit beam current (dp/dI) than the HER, and vacuum scrubbing requires a longer time.
 - Abnormal pressure increases are a concern for further current increase.
 - Nonlinear pressure increases have been observed in the LER NLC section, HER D09 collimator section, etc.
 - They may limit maximum beam currents.
 - Countermeasures
 - Installation of RF-shielding gaskets on ion pumps
 - D09V3 collimator was replaced with new water-cooled one. ← Last shutdown
 - Ongoing and Future work
 - Investigation will continue in parallel with physics run.
 - Residual gas analysis and further studies are ongoing.





- RF electron gun discharge
 - 2-bunch injection became unavailable during 2024c due to discharge in RF cavity.
 - The RF gun was replaced with a new RF electron gun. ← Last shutdown
 - ➔ 2-bunch injection tuning is planned.
- HER vertical emittance growth
 - The cause remains unknown.
 - The impact may remain acceptable because the beam size becomes large as the bunch current product increases.
 - ➔ Investigation will continue in parallel with physics run.
- Abort procedure in case of abort-kicker failure
 - The issue become apparent in 2025c run.
 - ➔ Development of an alternative abort procedure has been initiated.

Summary

- **Low machine stability**

- SBL events significantly reduced by VACSEAL removal
 - SBL still occurs and additional countermeasures are required.
- Mitigation measures for other instability sources are also proving effective.
 - Further improvements in machine stability are expected through the development of new collimators.

- **Low bunch current limit**

- The NLC has been functioning well so far.
 - The effectiveness of the enhanced radiation shielding will be evaluated.

- **Low injection efficiency**

- Beam currents have been gradually increasing as a result of implemented countermeasures.
 - The effectiveness of the countermeasures introduced during the last shutdown will be evaluated during 2025c-2026ab.
- At higher currents, the beam-beam effect becomes the limiting factor for further current increase.
- The following issues of the injected beam require further improvement
 - Energy jitter, Orbit drift, Emittance growth at BT, Poor reproducibility, etc.

- **Severe beam-beam effect**

- Both specific luminosity and efficiency are limited by the beam-beam effect.

- **Short beam lifetime**

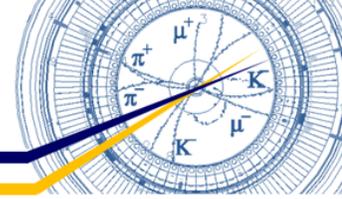
- Further optimization of the sextupoles is required to enlarge the dynamic aperture.
- Abnormal pressure increases are a concern for further current increase.

- **Aging of hardware and facilities**

- Continuous mitigation efforts will be required.

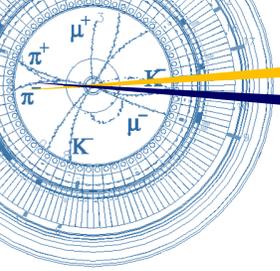


Summary

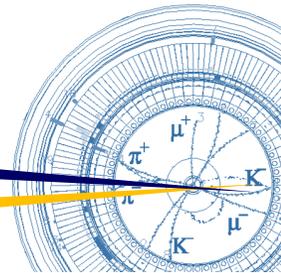


Challenge	Countermeasure implemented	Remaining issues
Low machine stability	<ul style="list-style-type: none">VACSEAL removal, Collimator relocation, Additional loss monitor & acoustic sensorsRobust collimator jawsKicker PS optimizationIsolation of BPM block from Q-mag.	<ul style="list-style-type: none">Investigation of remaining SBL causesFurther robust jawsRevolver-type collimator
Low bunch current limit	<ul style="list-style-type: none">Installation of Nonlinear collimatorReinforced radiation shielding	<ul style="list-style-type: none">Further reinforcement of radiation shielding
Low injection efficiency	<ul style="list-style-type: none">Hardware upgrades (Linac, BT, MR)Injection tuning procedure establishedOptics matching and aperture survey	<ul style="list-style-type: none">Severe beam-beam effectEnergy jitter, orbit drift, poor reproducibility
Severe beam-beam effect	<ul style="list-style-type: none">Introduction of crab-waist collision schemeLaunch of international simulation collaboration	<ul style="list-style-type: none">Large simulation-measurement discrepancy
Short beam lifetime	<ul style="list-style-type: none">Sextupole optimization studiesWater-cooled collimator (D09V3)	<ul style="list-style-type: none">Still small dynamic apertureAbnormal pressure rises



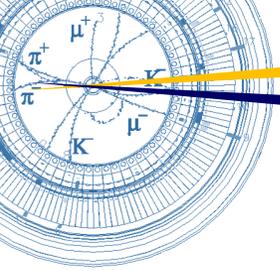


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Thank you for your attention.





Back up

