SuperKEKB
Challenges and Countermeasures

2025.12.18

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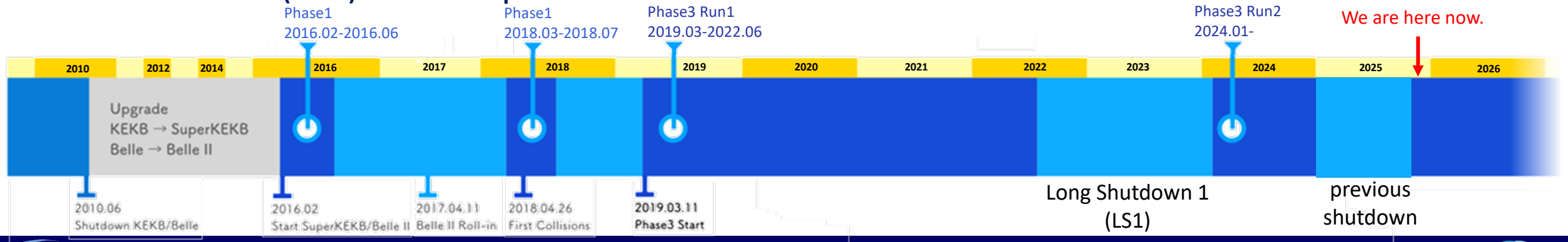
(on behalf of SuperKEKB)

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.



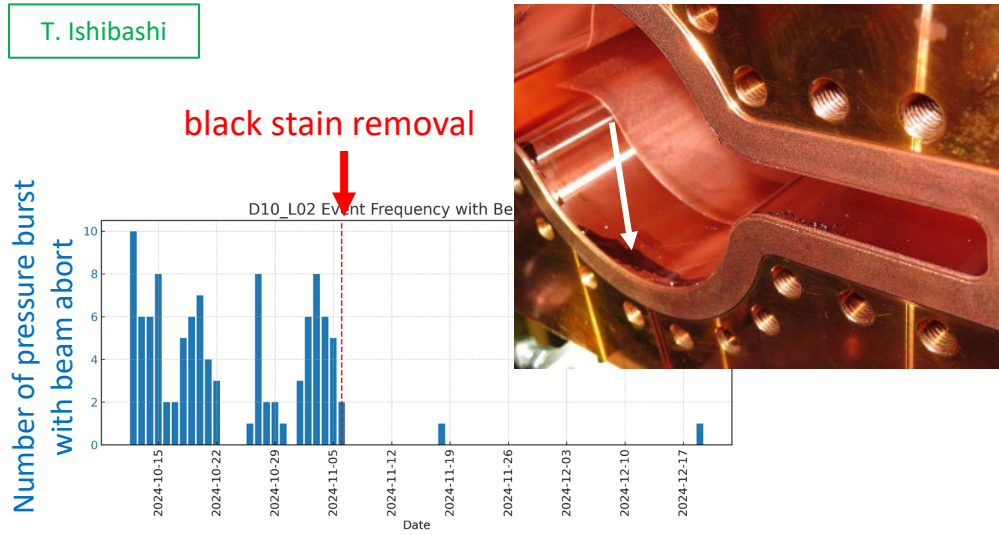
Low machine stability

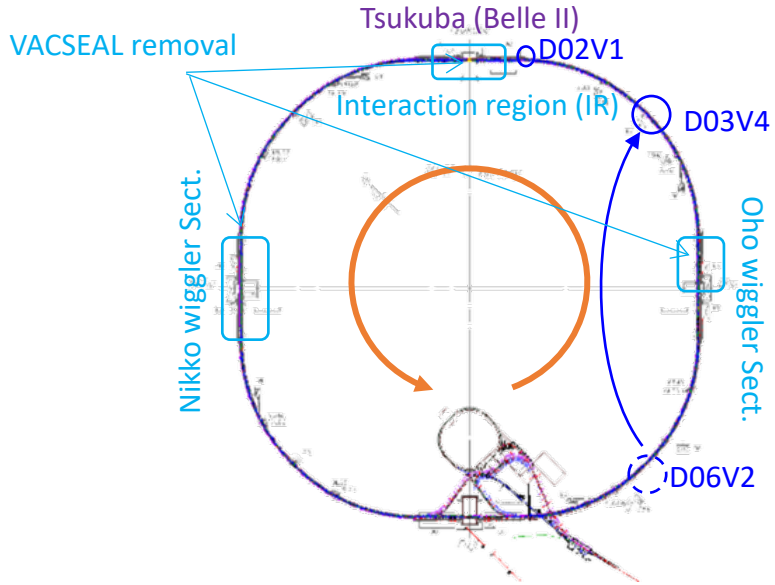
- Sudden Beam Loss (SBL)
  - SBL is the most critical obstacle to achieving stable operation.
    - Part of the beam is suddenly lost within a few turns.
    - It is difficult to prevent uncontrollable beam from damaging Belle II and collimators.
  - Countermeasures
    - **Removal of VASCEAL contamination** ⬅ **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

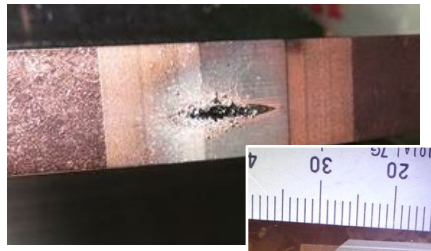


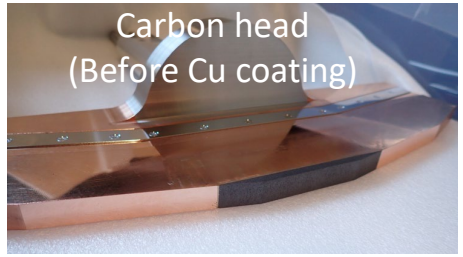


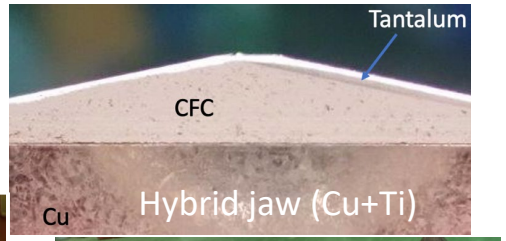
Low machine stability

- Others
  - Injection kicker accidental firing
    - Carbon collimator (D06H3) to stop accidentally kicked beam ← LS1
    - → No damage from accidental firing so far
    - Optimization of thyratron 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

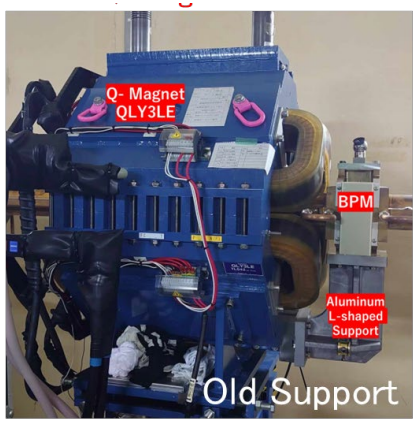
Damaged collimator jaws



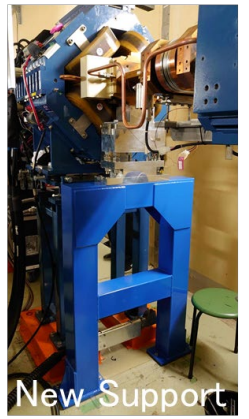




Revolver-type collimator jaws

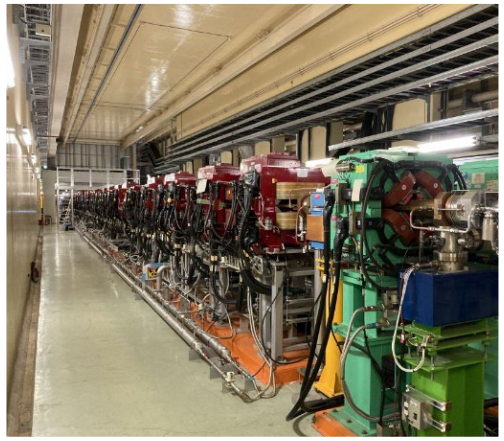


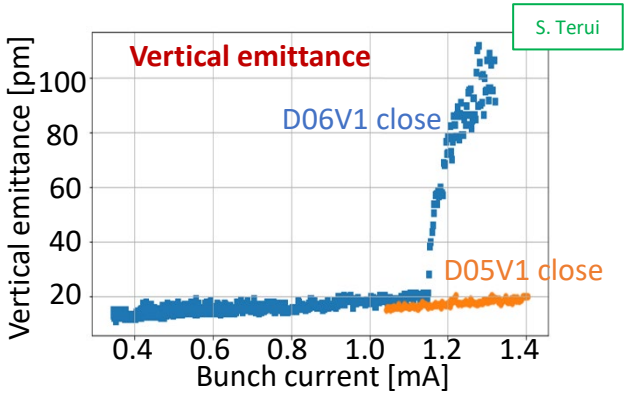
Separate Aluminum Q-magnet & Beam pipe



Low bunch current limit

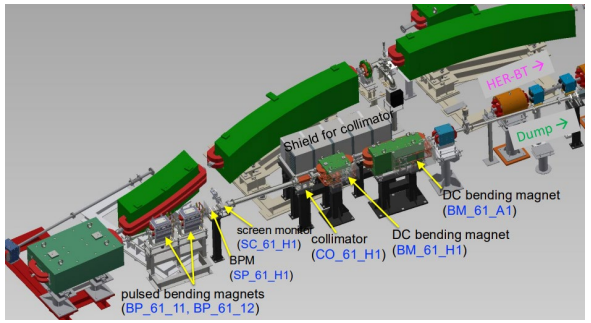
- Transverse Mode Coupling Instability (TMCI) could limit bunch current.
  - Before LS1
    - To reduce Belle II BG noise, LER collimators had to be closed more than expected.
    - High impedance due to narrow collimator setting resulted in a lower TMCI threshold.
    - **To ensure stable operation 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.

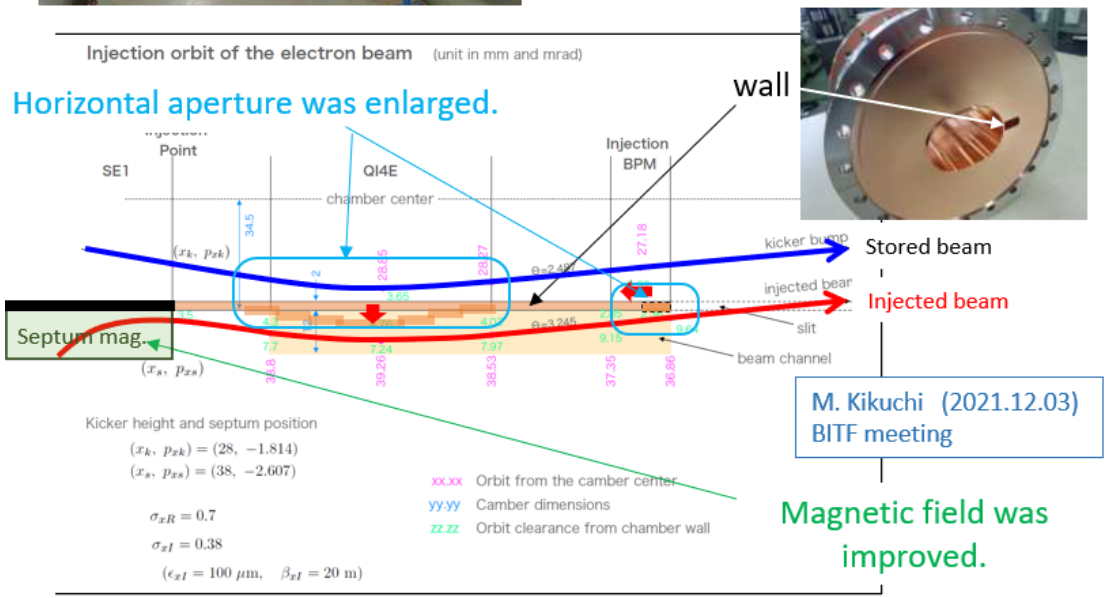




Low injection efficiency

- 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**



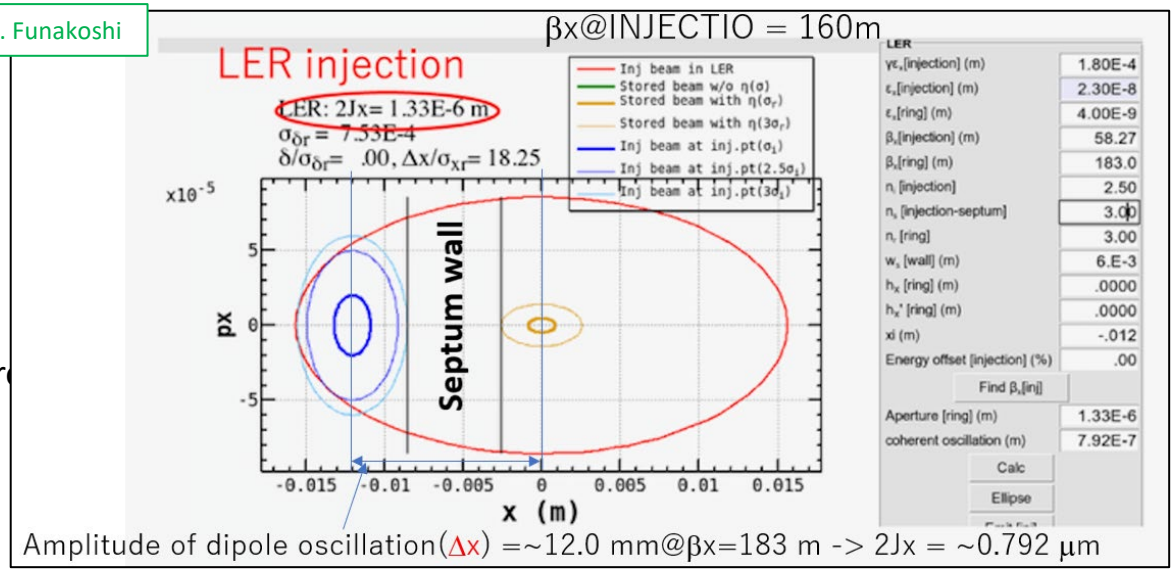


Low injection efficiency

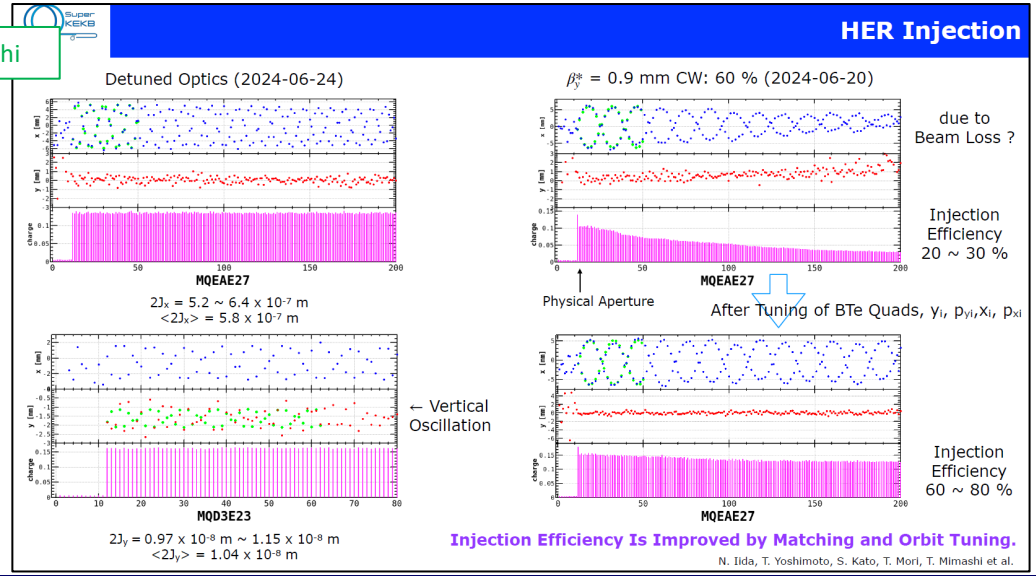
- Beam commissioning measures
  - Establishment of an injection tuning procedure
    - Optics matching between BT and MR
    - 3D phase-space aperture survey in MR
    - Injected beam oscillation measurements using TbT BPMs
  - Optics modification at the Injection point
    - Increasing the beta function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

Y. Funakoshi



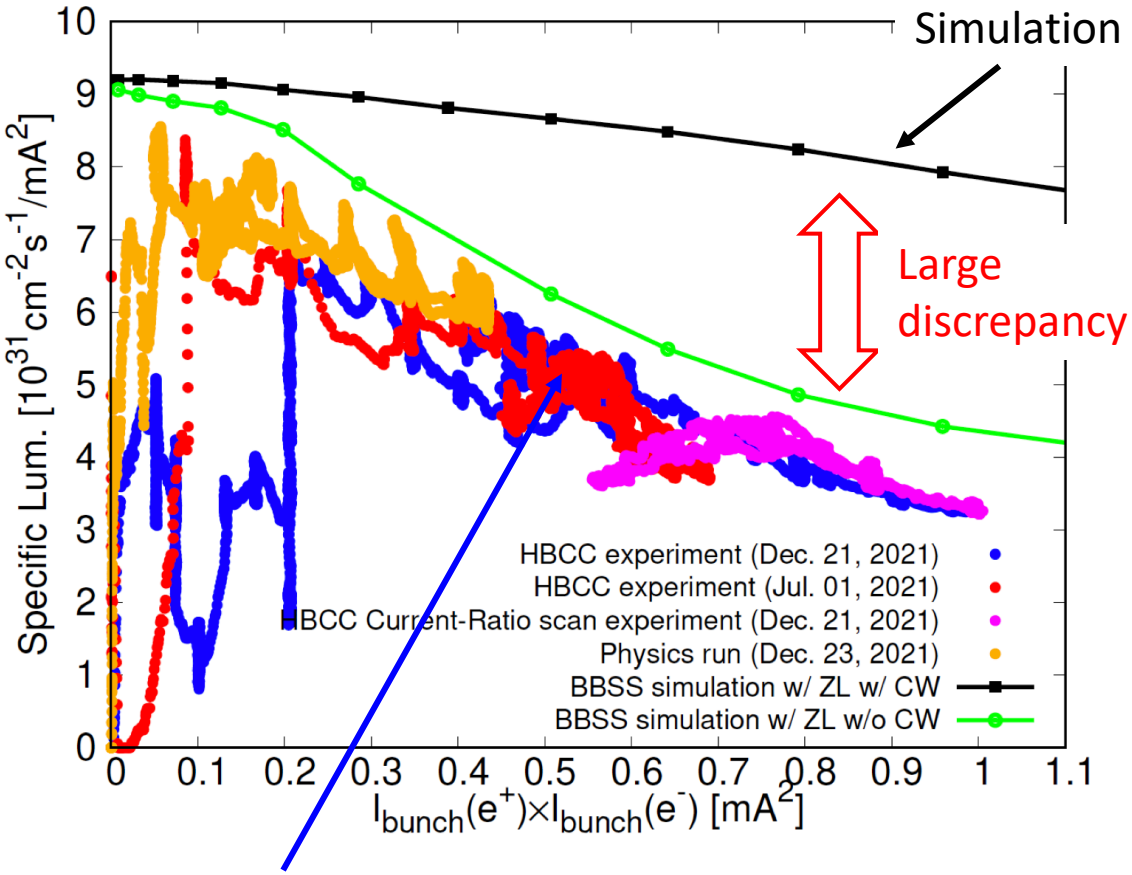
Y. Ohnishi



Severe beam-beam effect

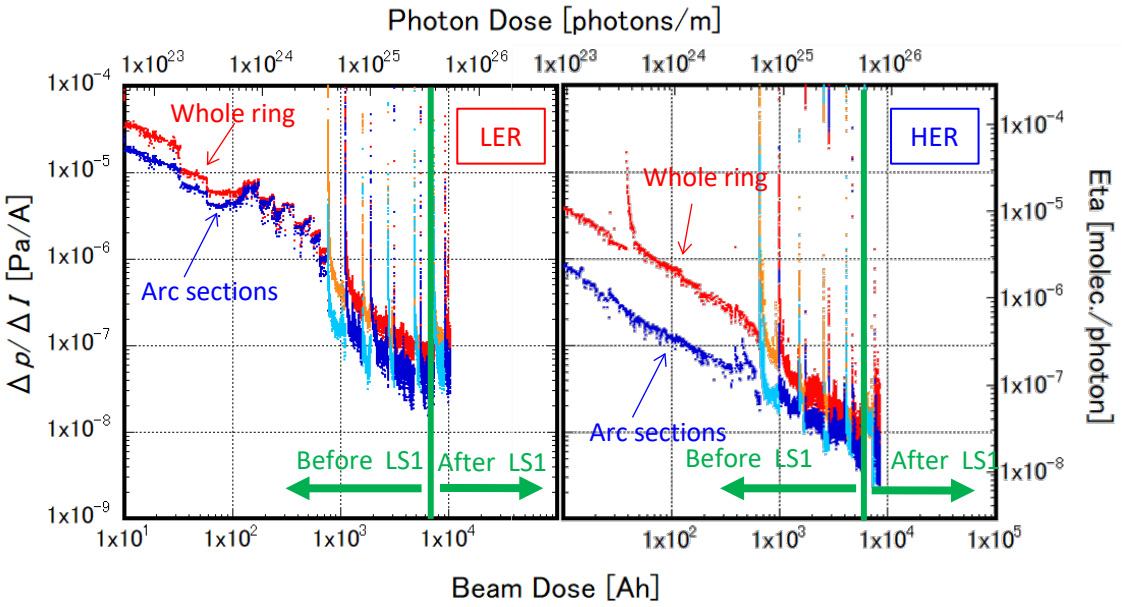
- Low specific luminosity at high bunch current product
  - The cause of the L_{sp} drop is still unknown.
  - There remains a significant discrepancy between simulation and measurement.
- Low injection efficiency due to beam-beam effect
  - Injection efficiency appears to be limited by the beam-beam 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)

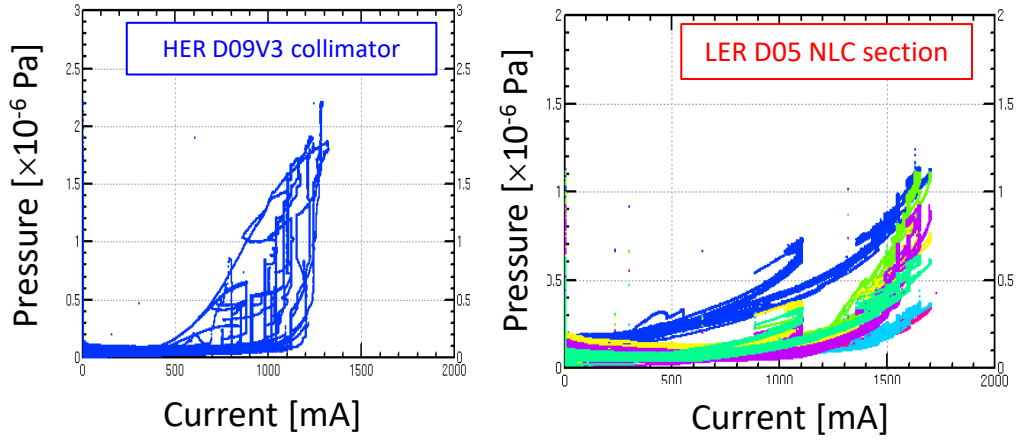


Short beam lifetime

- 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.
    - Ongoing and Future work
      - Investigation will continue in parallel with physics run.
      - Residual gas analysis and further studies are ongoing.



Last shutdown



Others

- 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.

Fin.

Thank you for your attention.

Back up

Aging of hardware and facilities

- 老朽化機器の更新状況の紹介