SuperKEKB Accelerator Status

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(on behalf of SuperKEKB Accelerator Team)

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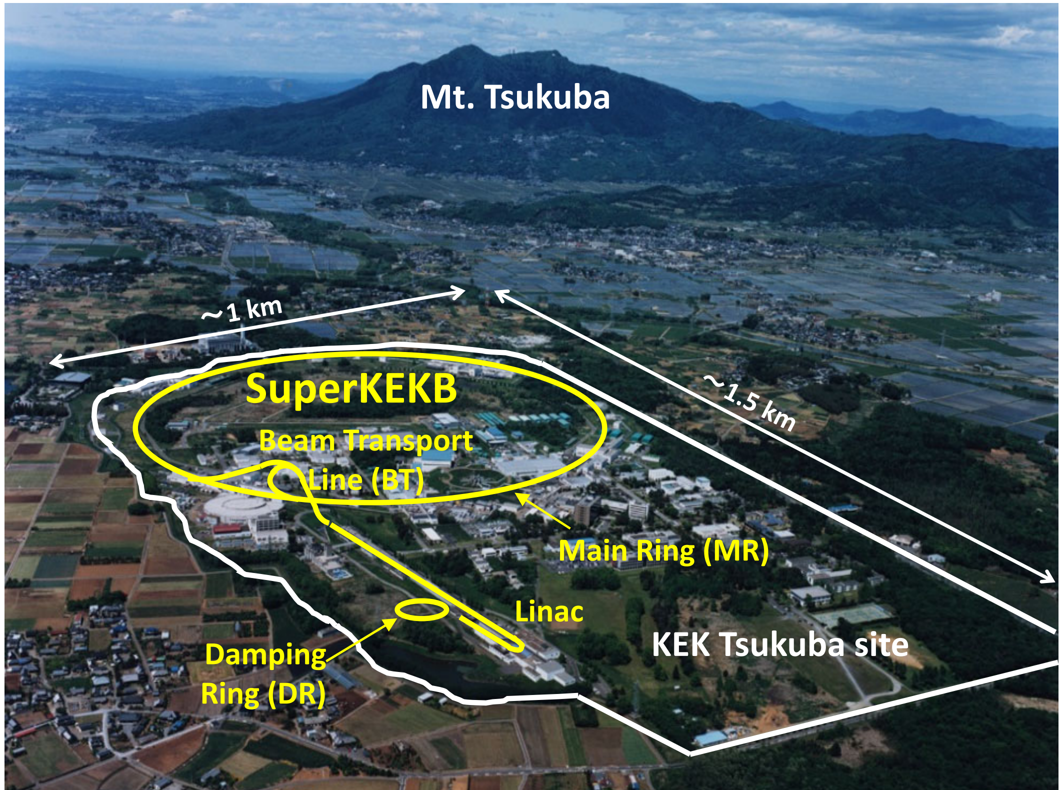
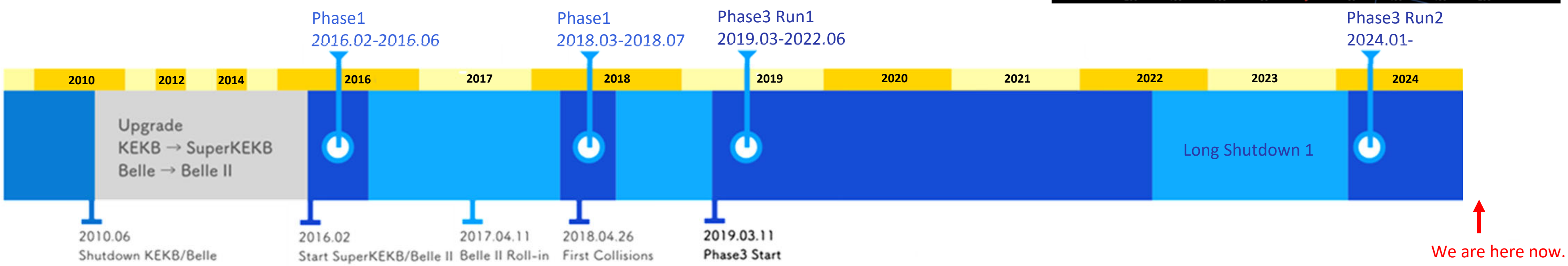
SuperKEKB

- SuperKEKB;
  - Asymmetric-energy electron-positron collider operating at KEK Tsukuba site
    - An upgrade of KEKB B-factory (KEKB)
    - High-luminosity machine in search of new physics in the B-meson regime.
  - Accelerator complex consisting of;
    - Injector (Linac)
    - Positron Damping Ring (DR)
    - Beam Transport Lines (BT)
    - Main Ring (MR) with Belle II Detector
  - The world's first practical application of the "nano-beam scheme"



SuperKEKB project history

- Phase1 operation (2016.Feb. ~ June);
  - Vacuum scrubbing, low emittance beam tuning, and background study for Belle II detector installation
  - w/o final focusing system (QCS) and Belle II detector
- Phase2 operation (2018.Mar. ~ July);
  - Pilot run of SuperKEKB and Belle II w/o pixel vertex detector (PXD)
  - Demonstration of nano-beam collision scheme
  - Study on background larger than at KEKB due to much lower beta functions at IP.
- Phase3 operation (2019.March~);
  - Physics run with fully instrumented detector.
  - Phase3 Run1 : 2019.10~2022.7
  - Long shutdown 1 : 2022.7~2024.01
  - Phase3 Run2 : 2024.01~



2024 run overview

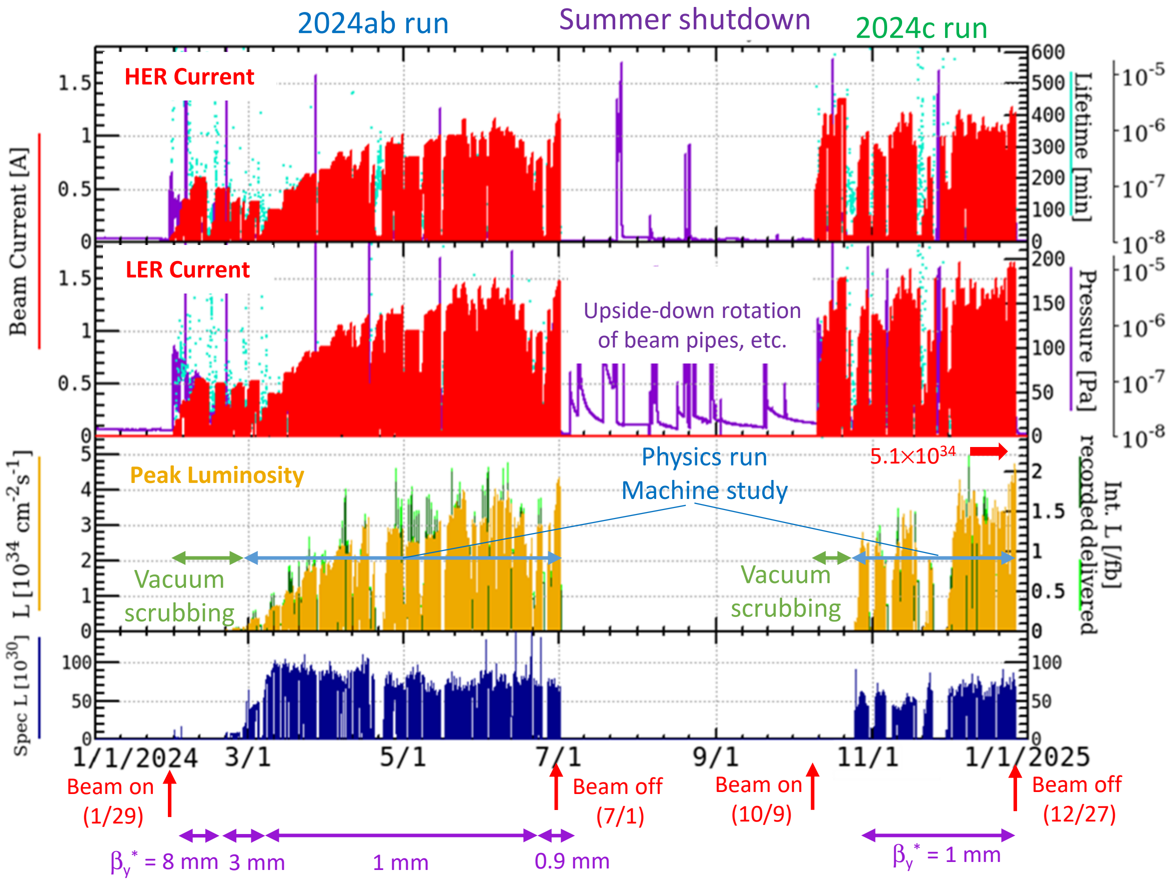
- 2024ab run : 2024/Jan./29 – July/1, 155 days
  - Start-up after a long shutdown
  - First demonstration of the effectiveness of the NLC* system
  - Peak luminosity : 4.47×10^{34} $cm^{-2}s^{-1}$
    - Maximum beam current : HER/LER = 1210/1539 mA
    - β_y^*-squeezing (Vertical β-function at IP) : ~0.9 mm (Mostly operated with β_y^* = 1.0 mm)
  - Struggled with Sudden Beam Loss (SBL), poor injection efficiency, low machine stability

* : Non-linear collimation

- Summer shutdown
  - Upside-down rotation of beam chambers with electron clearing electrodes at Oho wiggler section (SBL countermeasure**), etc.

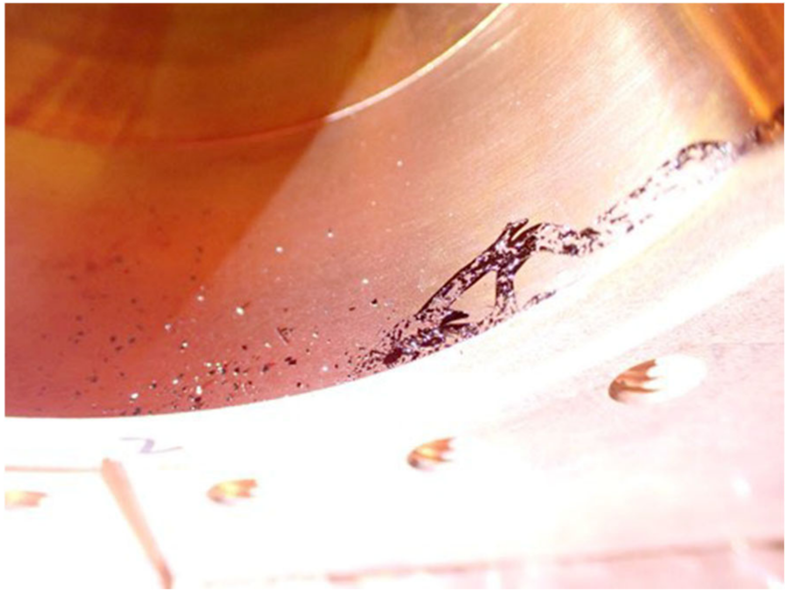
** : To prevent dust from falling on the beam.

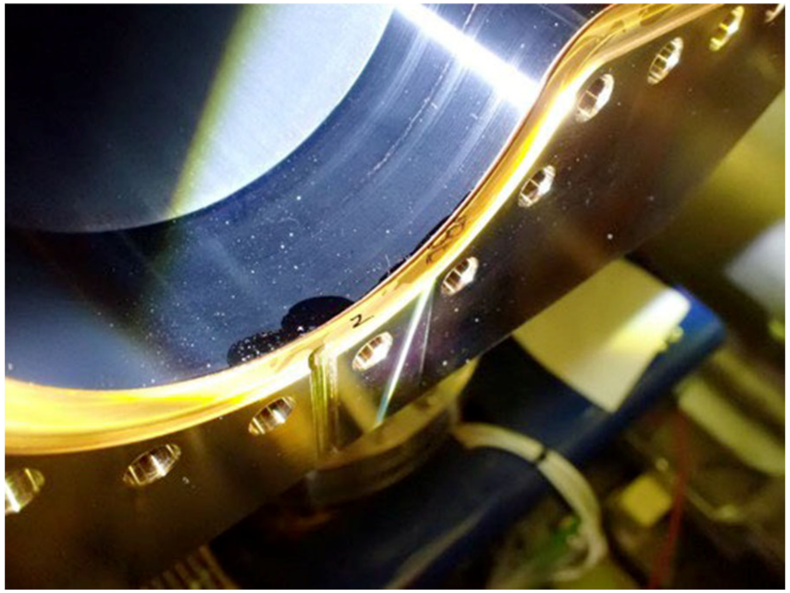
- 2024c run : 2024/Oct./9 – Dec. /27, 79 days
  - More time was spent on machine studies than on physics run.
    - Verification of SBL measures during summer shutdown
    - Machine studies to increase beam currents
    - Machine studies to investigate HER vertical beam blowup
  - Still struggled with SBL and difficulty of current increasing, etc.
    - It was newly found out that the vacuum sealant leaking into the beam pipe is a most likely cause of SBL. (Upside-down rotation of beam chambers doesn't reduce SBL)
    - Methods for injection tuning and increasing currents are being established.
  - Peak luminosity : 5.1×10^{34} $cm^{-2}s^{-1}$ (w/o Belle II operation)
    - We updated our record!!
    - β_y^*-squeezing : 1.0 mm
  - Maximum beam current : HER/LER = 1354/1699 mA
    - We updated our record!!



SBL source →Beam pipe cleaning

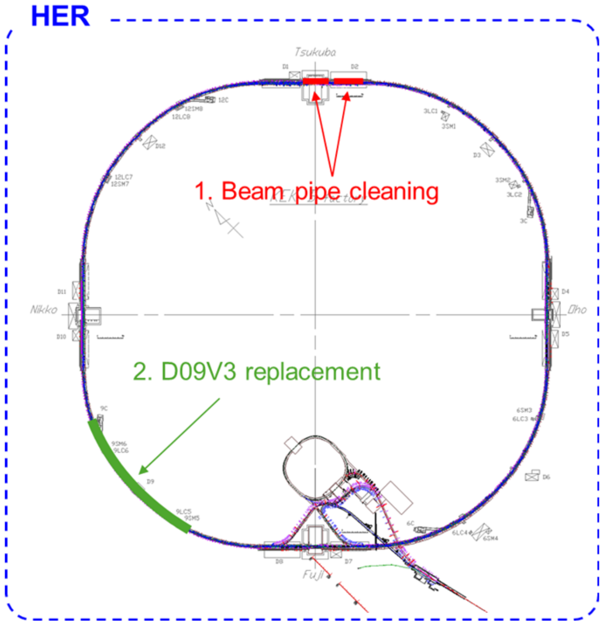
- Internal inspections have been completed, where
  - All MO-type flange connections where VACSEAL was likely used.
  - IR (HER, LER), LER wiggler sections (D04, D10, D11), others
    - Black stains were found on many flange connections and removed.

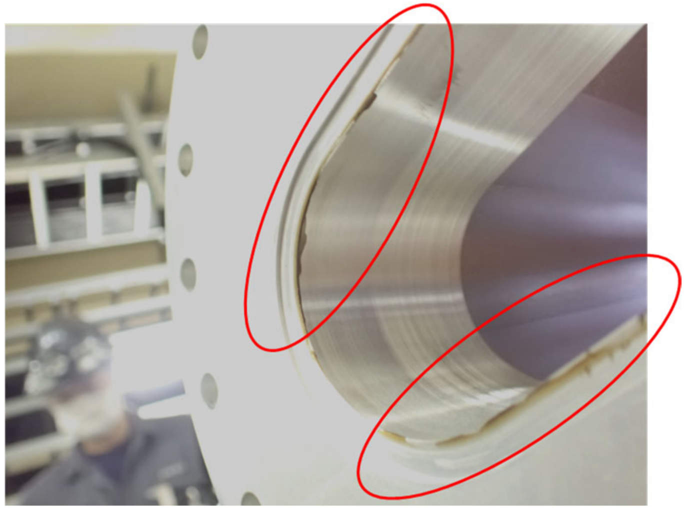




SBL Source → Beam pipe cleaning

- During D9V3 collimator replacement work
  - Black stains were found on HELICOFLEX flange connections.
    - VACSEAL had been used.
    - This is the first time such stains have been found on HELICOFLEX flange.
- Three HELICOFLEX flange connections will be inspected before operation.





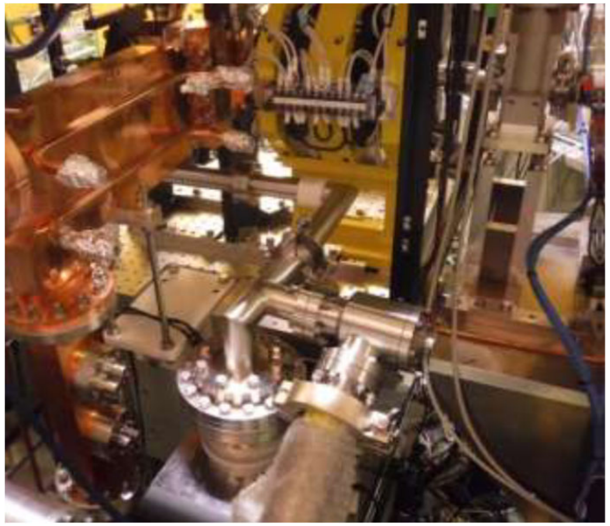
HELICOFLEX flange connection

Installation of the new RF gun (Linac)

New RF gun was installed in the beam line.

- Connection of RF waveguide and vacuum system
- Reconstruction of laser system
- Leak check of vacuum and cooling water

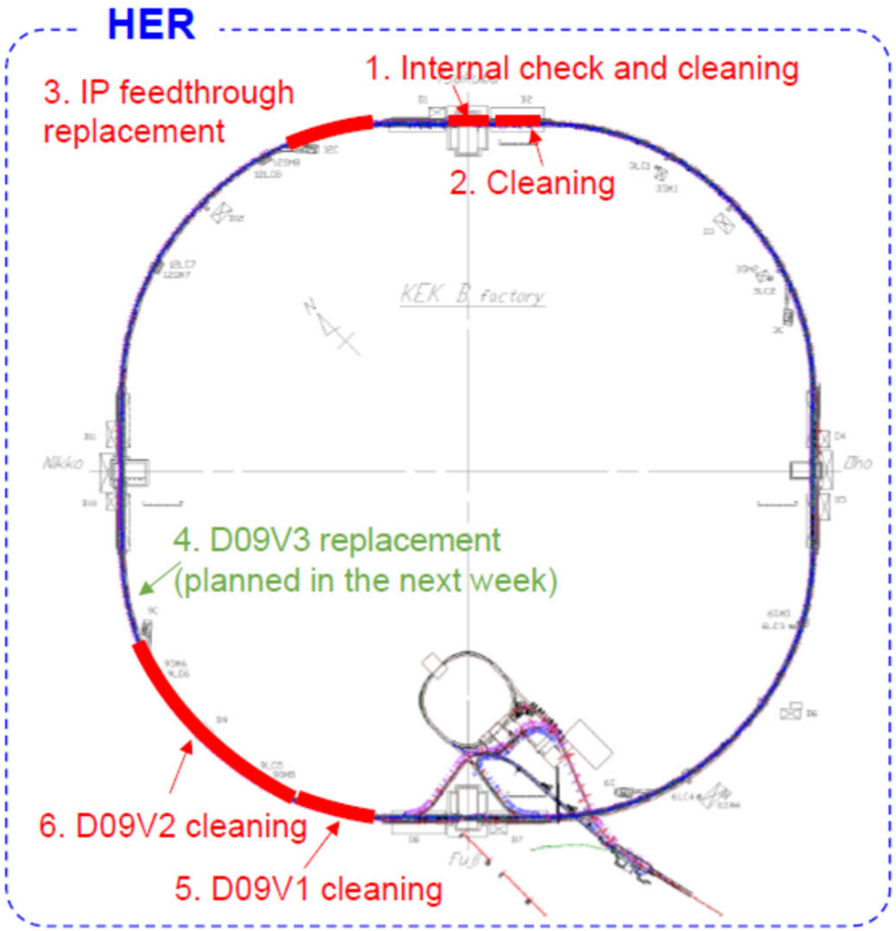
Connection of RF waveguide



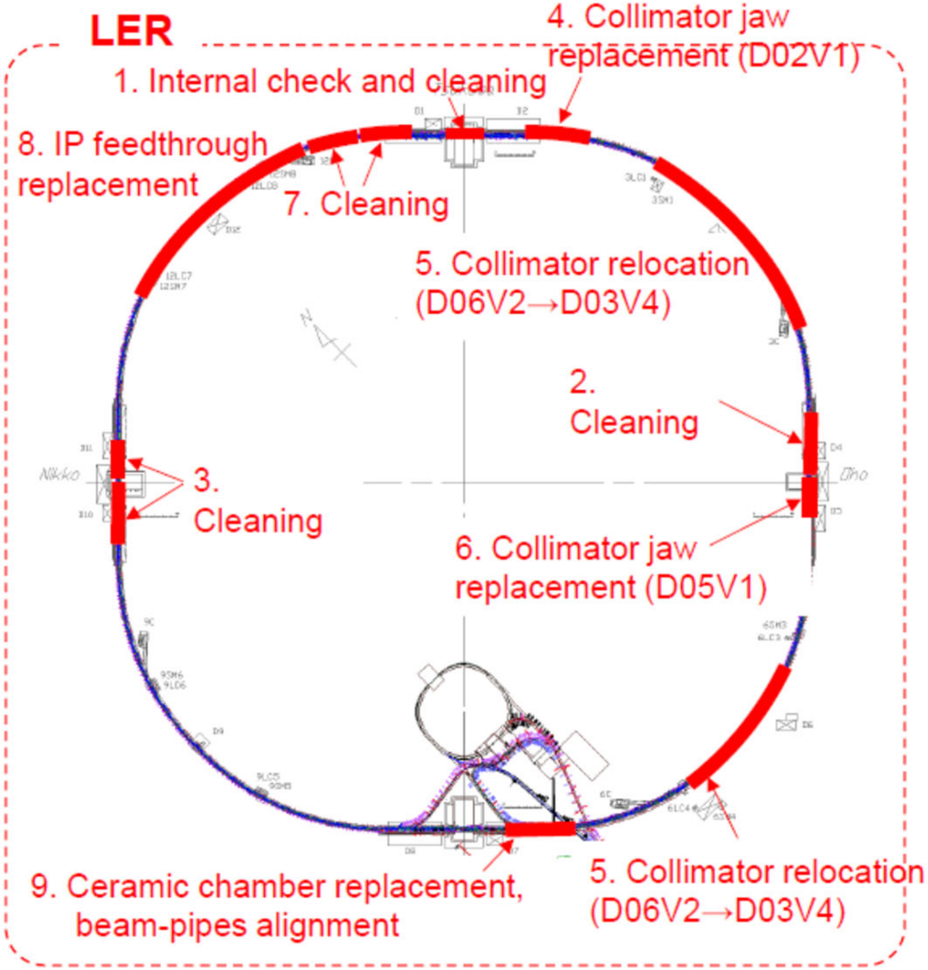
Connection of vacuum system

Reconstruction of laser system

Vacuum works – LER and HER



Required vacuum scrubbing ~50 Ah



Required vacuum scrubbing ~100 Ah

Operation Plan for 2025c/2026ab

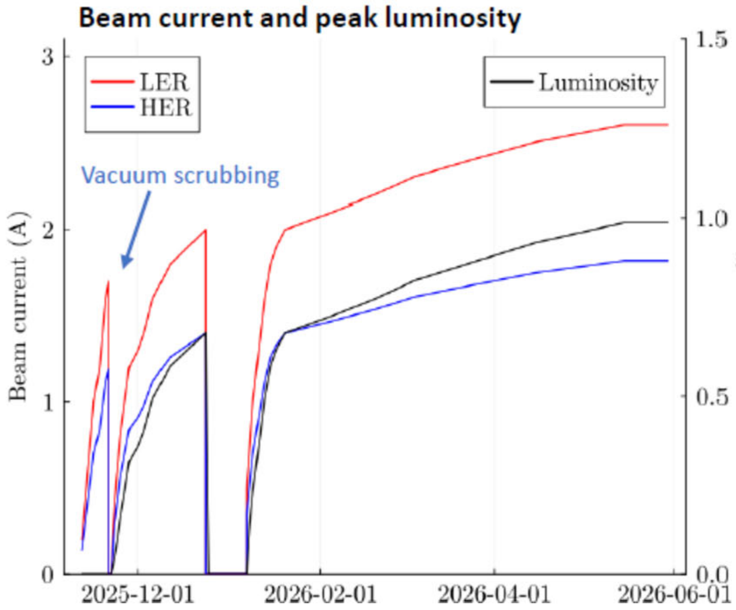
- **Highest priority in 2025c -2026b is integrated luminosity (recorded) > 425 fb -1.**
- 2025c–2026b run: 5 Nov. 2025 – 1 Jun. 2026 Vacuum scrubbing: 5 Nov. 2025 – 17 Nov. 2025 = 13 days
  - Collision run in 2025c: 19 Nov. 2025 – 24 Dec. 2025 = 36 days
  - (Winter shutdown: 24 Dec. 2025 – 7 Jan. 2026 = 15 days)
  - Collision run in 2026a/b: 9 Jan. 2026 – 1 Jun. 2026 = 144 days
  - **Collision run total: 36 days + 144 days = 180 days**
- Physics runs account for 80% of the full collision operation, ~150 days.
  - 4 days per 3-week cycle are allocated to machine tuning, study, maintenance, etc.

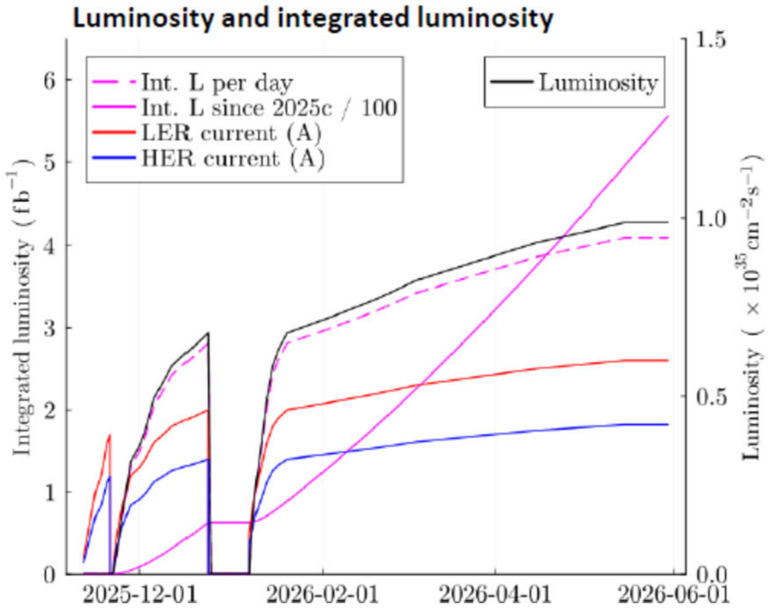
Plan A:basic plan

Target
Peak luminosity = 1 × 10^{35} $cm^{-2}s^{-1}$
Integrated luminosity > 425 fb^{-1}

Key parameters
Specific luminosity = 5.0 × 10^{31} $cm^{-2}s^{-1}mA^{-2}$ at 0.86 mA^2
Accelerator efficiency > 60% (N.B., ~67% at 1.7 A & 1.3A in 2024c)

Requirements
2-bunch injection in HER and LER, β_y^* squeezing to 0.9 mm (plus, possibly β_x^* squeezing)
Mitigation of beam-beam effects





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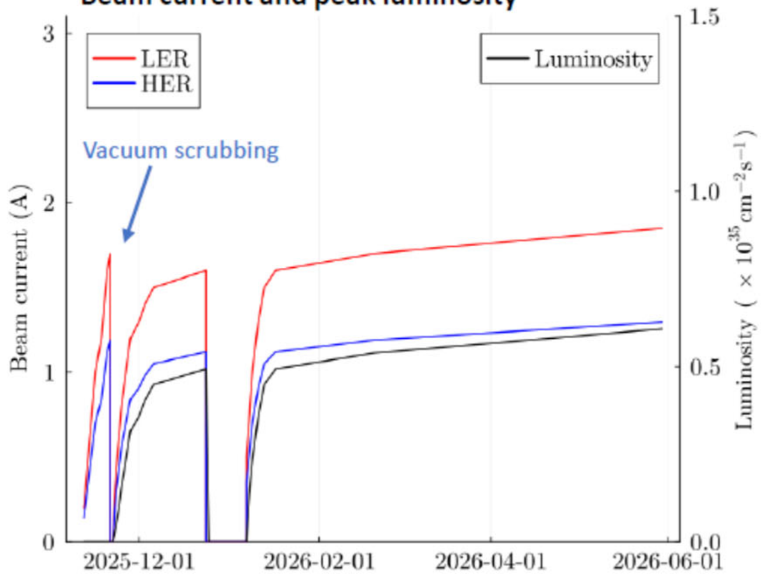
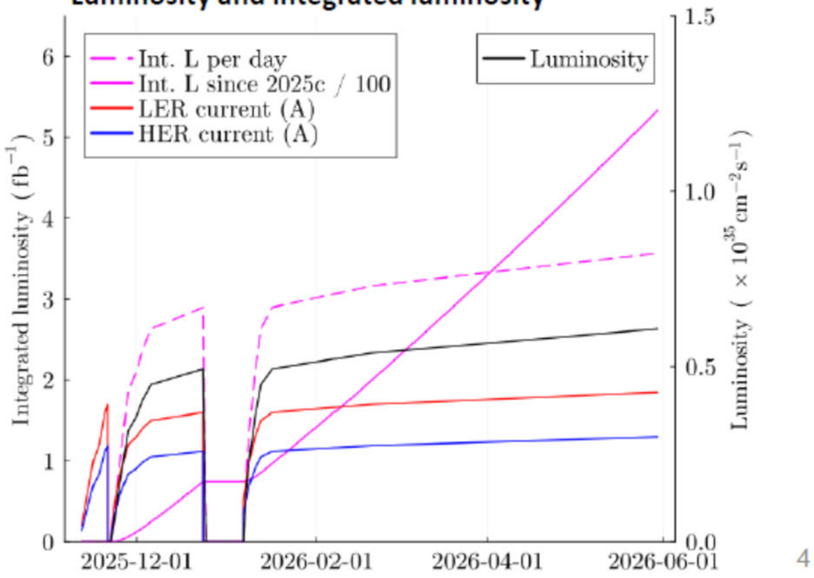
Plan B: optinal

Target
Peak luminosity = 6 × 10^{34} $cm^{-2}s^{-1}$
Integrated luminosity > 425 fb^{-1}

Key parameters
Specific luminosity = 5.9 × 10^{31} $cm^{-2}s^{-1}mA^{-2}$ at 0.44 mA^2
Accelerator efficiency > 85% (N.B., highest record~88% in 2022c)

Requirements
Stable operation (less SBL, less QCS quench, less machine/detector trouble)
2-bunch injection in LER, Relaxing beam-beam effects



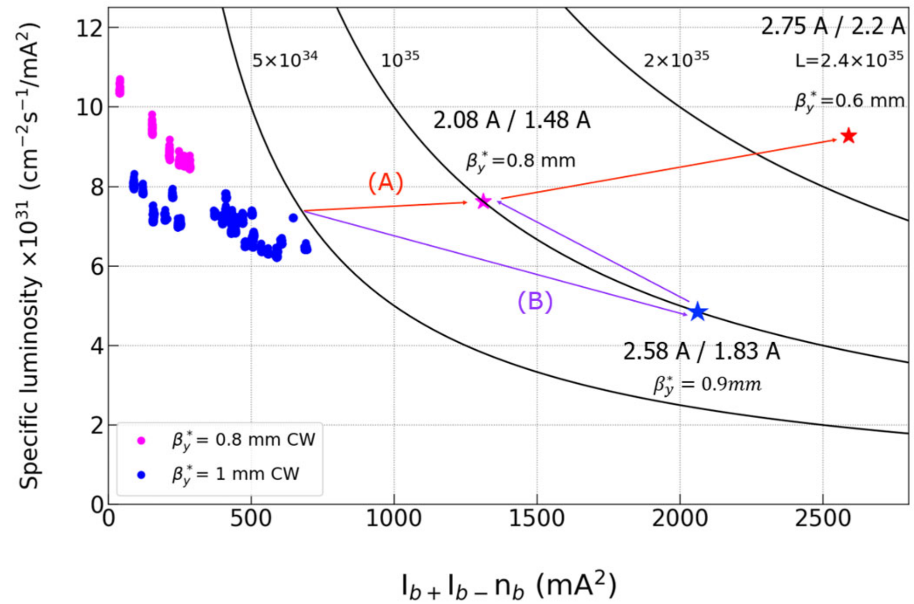


Strategy toward 2.4×10^{35} cm^{-2}s^{-1}

- Strategy toward 2.4×10^{35} cm^{-1}s^{-1} : Route (A)
  - β_y^* squeezing down to 0.6 mm :
    - Down to 0.6 mm from 0.9 mm (3 steps)
    - Dynamic aperture improvement :
      - Sextupole optimization
      - Off-momentum optics tuning
      - Comparison between simulations and measurement
  - Increase beam current : 2.75 A/ 2.2 A
  - Increase specific luminosity (Beam-beam parameter)
    - Up to $L_{sp}\sim 9\times10^{31}$ cm^{-1}s^{-1} mA^{-2}
    - Improve prediction accuracy of Beam-Beam simulation

Y. Ohnishi

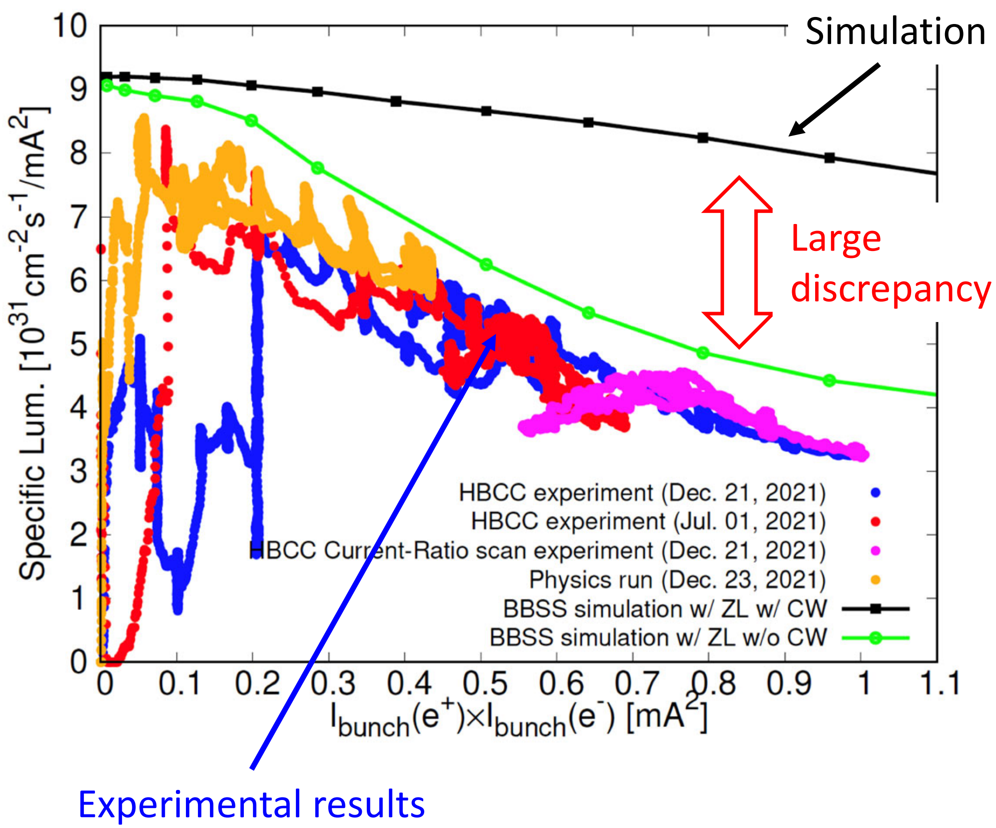
$$L_{sp} = \frac{L}{I_{b+}I_{b-}n_b}$$



Strategy toward 2.4×10^{35} $cm^{-2}s^{-1}$

- Beam-Beam simulation shows much higher specific luminosity
  - It is still unclear why experimental results are much smaller than the simulation.
    - Can simulation miss some important factors?
  - There should be hints to increase luminosity of SuperKEKB.
    - If we identify the cause of the reduction in the luminosity, measures can be taken to improve luminosity.
- Important issue not just for SuperKEKB, but for future colliders with nano-beam collision scheme.
- Currently working on establishing new framework for international collaboration with CERN, IHEP, etc. especially on Beam-Beam simulations.
  - Several researchers will join SuperKEKB beam-beam team for 1-2 years to solve the mystery of SuperKEKB.

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



International collaboration

- International collaboration framework (existing)
  - Multi-National Partnership Project (KEK MNPP)
    - R&D for high luminosity colliders (MNPP-01)
    - Partnership between KEK and INFN, CERN, CNRS/IN2P3, SLAC, IHEP-Beijing
    - Visa support, daily life support, etc.
  - Europe-America-Japan Accelerator Development Exchange Program (EAJADE)
    - Exchanging accelerator scientists and experts between Europe, America (Canada and USA), and Japan
    - Exchange of ideas on R&D and implementation of future accelerators for particle physics
  - US-Japan collaboration on High Energy Physics
    - R&D for SuperKEKB and the next generation high luminosity colliders
    - Development of the SuperKEKB Interaction Region Nb_3Sn Quadrupole Magnet
    - Development of superconducting magnets and the quadrupole field vibration measurement system for SuperKEKB upgrade
  - And more
    - Professor S. Asai, Director General of KEK, have asked several accelerator laboratories, such as CERN, DESY, IHEP, to support SuperKEKB accelerator.
    - Dr. Chuntao Lin had stayed KEK to collaborate beam-beam simulation.

- We surely welcome international collaboration to improve performance of the SuperKEKB accelerators.
  - We would be very grateful if you or your colleague could visit KEK and help us.
  - We would appreciate your consideration of the following points.
    - We are facing an extreme shortage of human resources.
    - During operation period, commissioning staff are often pressed for time and it can be difficult to respond adequately. Therefore, we may have to decline visits for “educational purposes”.

Application form items

1. Name (Family name, First name, Middle name)
2. Institute:
3. Overview of your research
4. Research plan
5. Research period (YYYY/MM/DD – YYYY/MM/DD)
6. Name of Fund; EAJADE, MNPP-01, US-Japan Co-operative Project, etc.
7. Contact person/supervisor at your institute.
8. Contact person/supervisor at KEK, if any.

Remarks:

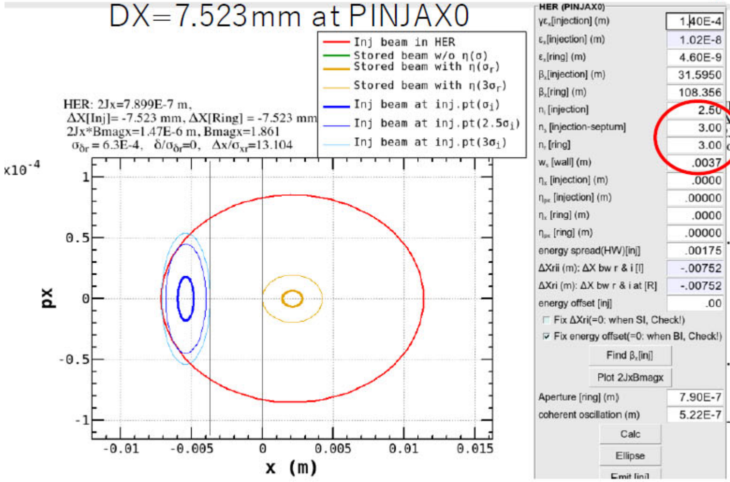
This application form is sent to the international collaboration board for the SuperKEKB project. There, the proposed research is discussed, and a decision is made as to whether the proposal is accepted.

If you are planning to visit, please consult with the host in charge in advance and submit the required application form.

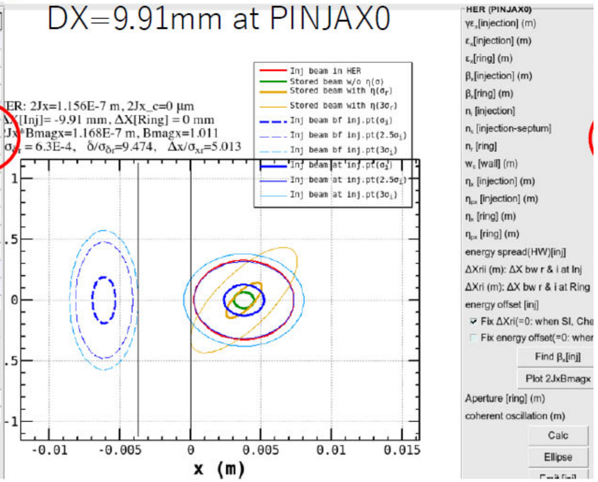
HER: synchrotron injection

N. Iida,

BI w/o cancel coil
DX=7.523mm at PINJAX0

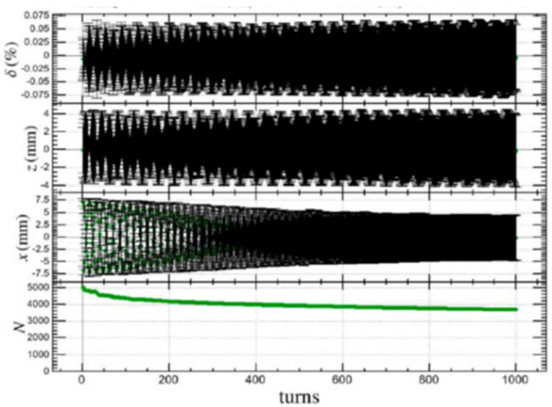


SI βy*=0.9mm, CW60% w/o cancel coil
DX=9.91mm at PINJAX0

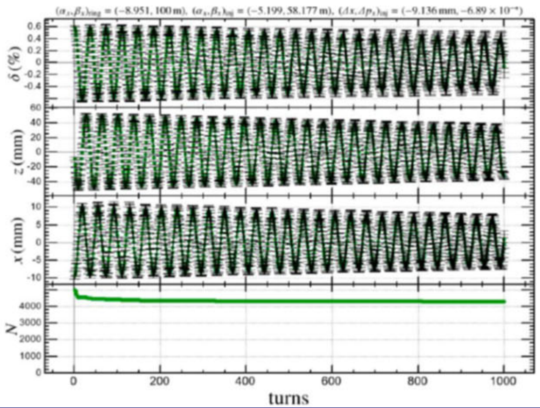


Betatron injection (BI):
conventional method at SuperKEKB, horizontal distance at the injection region (ΔX) goes to betatron (horizontal) oscillation

Synchrotron injection (SI):
proposed method at SuperKEKB, horizontal distance at the injection region (ΔX) goes to synchrotron oscillation



~75%



~85%

In synchrotron injection, beam-beam effects can be reduced, then the beam injection efficiency will come improved.

Summary

- SuperKEKB
  - Only operating machine with nano-beam collision scheme.
  - Future Higgs factory colliders will follow a lattice design with nano-beam collision scheme.
- 2025c run has started on 5/Nov/2025
- Collaboration
  - We surely welcome international collaboration to improve the performance of the SuperKEKB.
  - Some international collaboration frameworks are available.
    - KEK MNPP-01, EAJADE, US-Japan collaboration, etc.
    - If you are planning to visit the SuperKEKB, please consult with the host in charge in advance and submit the required application form.

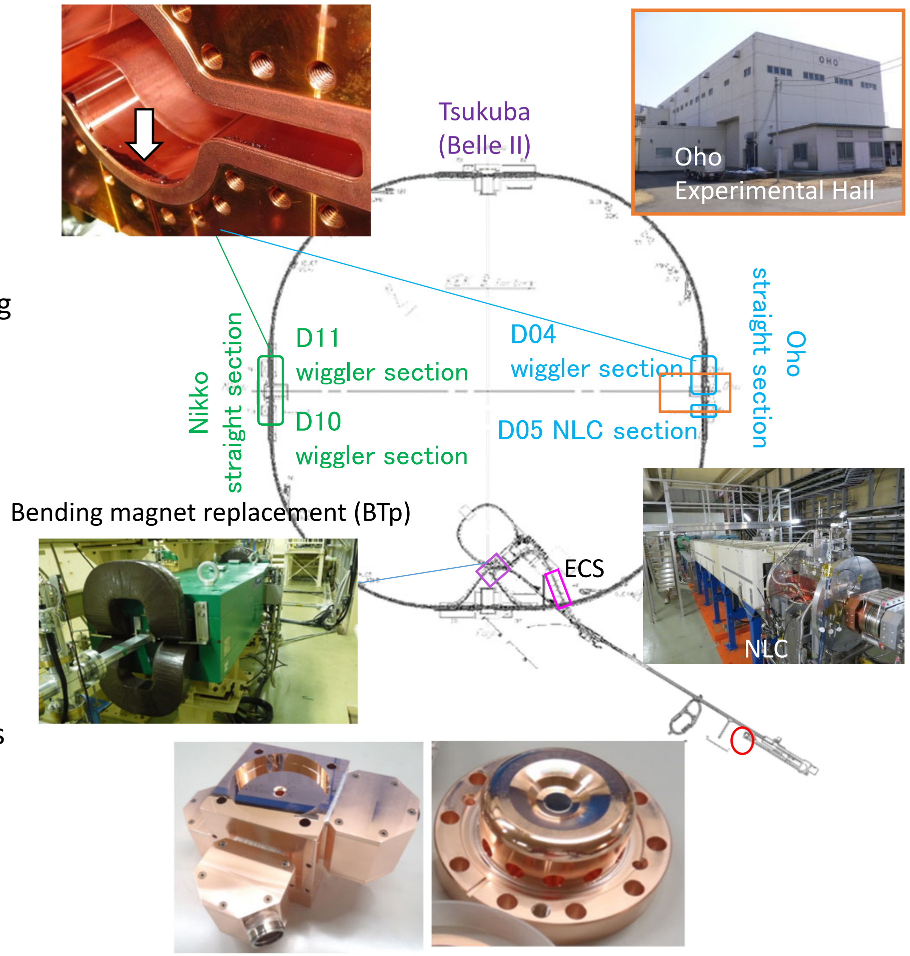
Fin.

Thank you for your attention.

Back up

Works during this shutdown 1

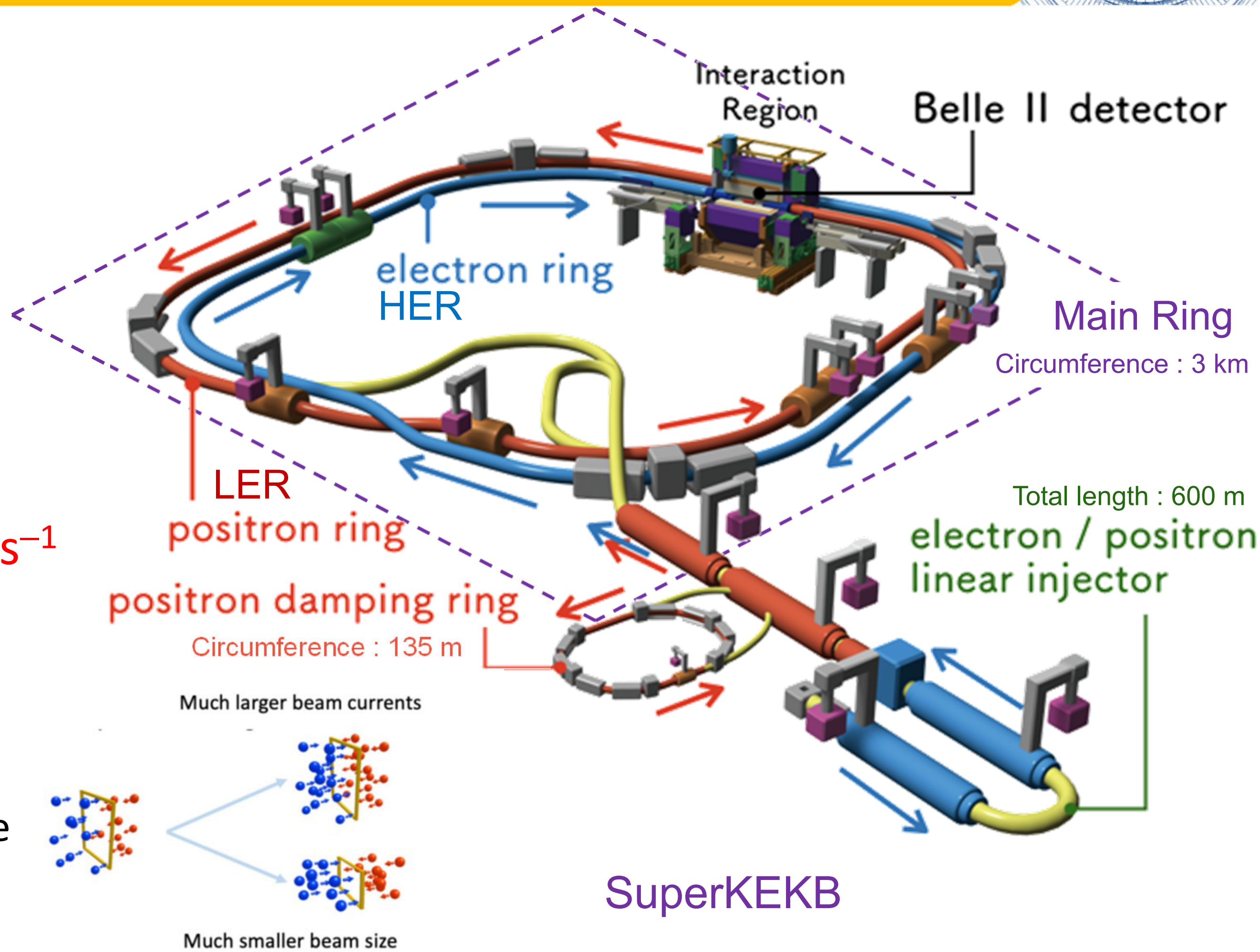
- Major work items (decided)
  - Radiation shielding reinforcement and expanding radiation control area near Oho exp. Hall.
    - Required for achieving higher LER beam current using NLC at OHO.
  - Linac RF gun replacement
    - New RF-gun cathode will be delivered by the end of March and be installed during next summer.
  - ECS installation at BTe
    - Accelerating structure will be installed at BTe by the end of March and new ECS will be available from 2025c run.
  - Bending magnet replacement at BTp
    - A few old bending magnets will be replaced during next summer.
  - Inner cleaning of beam chambers at LER wiggler sections
    - Countermeasure against LER SBL
    - Upside-down rotation of beam pipes with electrodes at Nikko wiggler section was canceled.
  - Various works carried out by the Plant and Facilities Department
    - Roof renovation work in Tsukuba Hall
    - Replacement of 6 kV HV power cables



NEW RF-Gun cathode cell

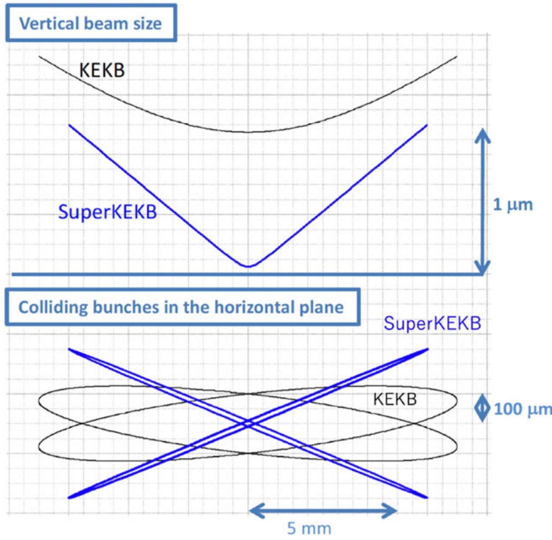
SuperKEKB

- Main ring (MR) is composed of
  - High Energy Ring (HER)
    - 7.0 GeV electron
    - Design beam current : 2.6 A
  - Low Energy Ring (LER)
    - 4.0 GeV Positron
    - Design beam current : 3.6 A
  - Target Luminosity : $\sim 6\times10^{35}$ $cm^{-2}\cdot s^{-1}$
    - ~30 times maximum luminosity of KEKB
    - Higher beam current than those of KEKB (×2)
    - β_y^* squeezing and smaller emittance for nano-beam collision scheme

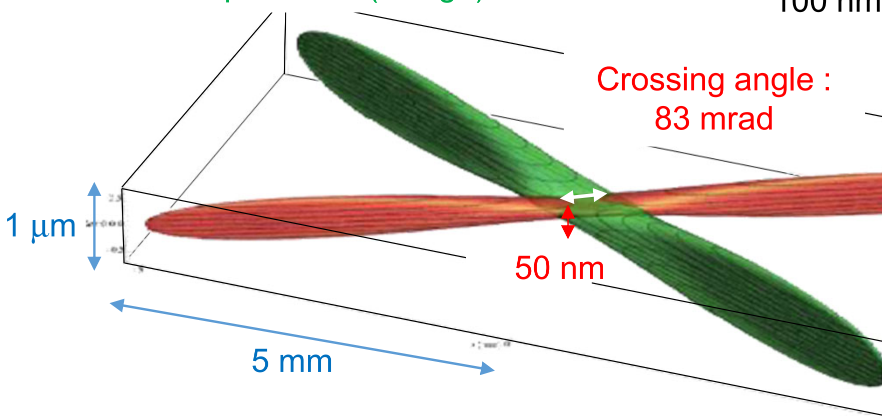


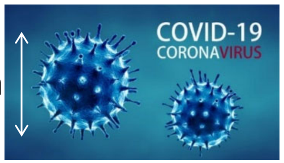
Nano-beam collision scheme

- Proposed by P. Raimondi at INFN-LNF for the Italian SuperB project around 2006 and tested successfully at DAΦNE.
- Extremely vertically squeezed bunches collide with sufficiently small σ_x^* at a large horizontal crossing angle to avoid the Hourglass effect.
  - Luminosity increases in proportion to $1/\beta_y^*$.
- Implemented at SuperKEKB, for the first time, with low-emittance beams on a high-energy collider.
  - SuperKEKB is the only operating machine with the nano-beam collision scheme.
  - Future Higgs factory colliders will follow a lattice design with nano-beam collision scheme.



Collision with very small spot-size beam.





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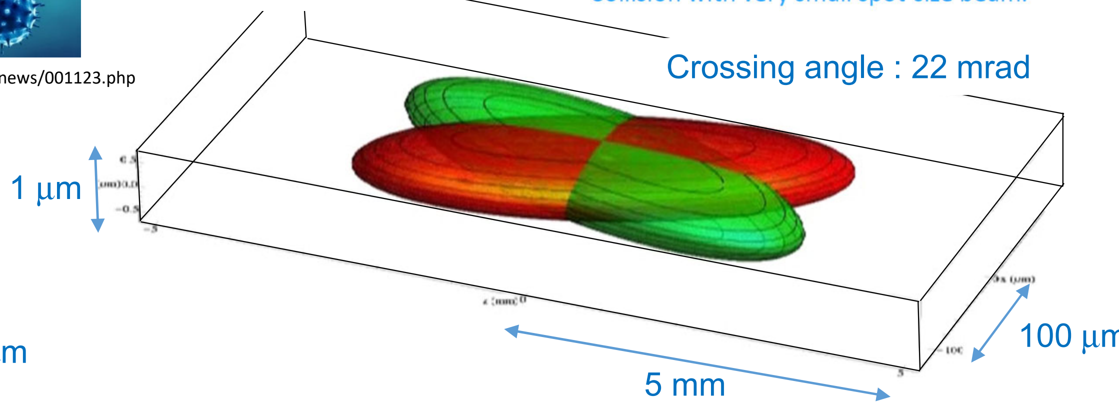
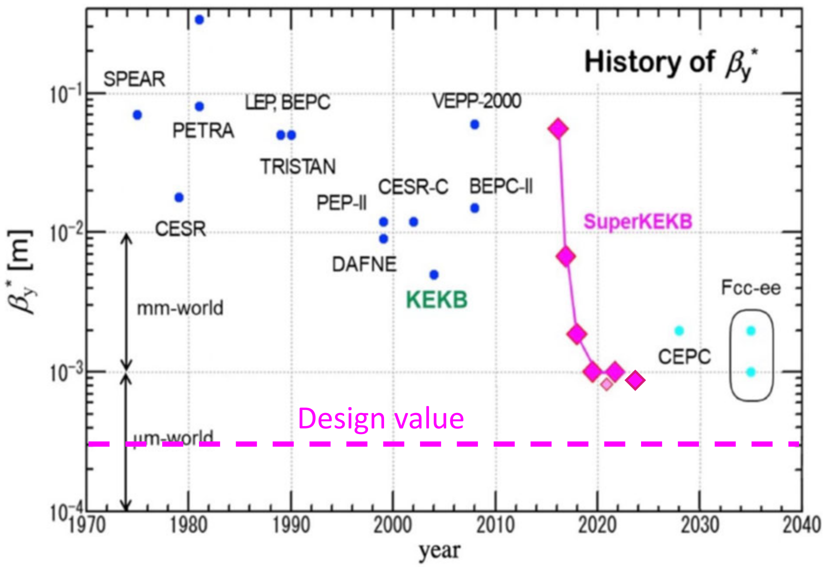


Machine parameters

	KEKB (LER/HER)		SuperKEKB (LER/HER) 2024/12/27		SuperKEKB (LER/HER) Design	
Beam Energy [GeV]	3.5/8.0		4.0/7.0		4.0/7.0	
Beam current [A]	1.64/1.19		1.63/1.26		3.6/2.6	
# of bunches	1584		2346		2500	
β_x^*/β_y^* [mm]	1200/5.9	1200/5.9	60/1.0	60/1.0	32/0.27	25/0.3
σ_x^*/σ_y^* [μm]	147/0.94	170/0.94	15.5/0.26	16.6/0.26	10.1/0.048	10.7/0.062
Half crossing angle θ [mrad]	11		41.5		41.5	
Piwinski angle [rad]	0 with crab crossing		~12		~20	
Luminosity [$\times 10^{34}$ cm^{-2}s^{-1}]	2.1		5.1 New record !! (w/o Belle II operation)		60	



Phase 3 commissioning history

- Phase3 operation (2019.March~);
  - Physics run with fully instrumented detector
  - Naming rule of Phase3 operation
    - "YYYYxx run"
      - Calendar year (YYYY)
      - March is end of Japanese fiscal year.
      - a : End of winter shutdown - March
      - b : April – Start of summer shutdown
      - ab : End of winter shutdown – Start of summer shutdown
      - c : End of Summer shutdown – Start of winter shutdown
  - 2019/March-2022/Jun : Run1
    - 2019c, 2020ab, 2020c, 2021ab, 2021c, 2022ab
    - Luminosity (peak/integrated) : 4.7×10^{34} $cm^{-2}s^{-1}$/424 fb^{-1}
    - β_y^* squeezing : ~0.8 mm (1 mm for most of the time)
    - Maximum beam current : HER/LER = 1145/1455
    - Facing various challenges for luminosity improvement
      - Severe beam-beam effect, Shorter beam lifetime, Lower bunch current limit, Low machine stability, Low injection efficiency, Sudden beam loss, Aging of hardware and facilities.
  - 2022-2024 : Long shutdown 1 (LS1)
    - Accelerator upgrades to address the challenges.
    - Belle II reinforcement and maintenance
  - 2024/Jan.- : Run2
    - 2024ab, 2024c, ···
    - Luminosity (peak/integrated) : 5.1×10^{34} $cm^{-2}s^{-1}$/571 fb^{-1}(total)
    - β_y^* squeezing : ~0.9 mm (1 mm for most of the time)
    - Maximum beam current : HER/LER = 1354/1699
  - 2032? : Long shutdown 2 (LS2)