SuperKEKB
Status and Future Plan

Workshop on FCC-ee and Lepton Colliders

22nd January 2025

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(on behalf of SuperKEKB)

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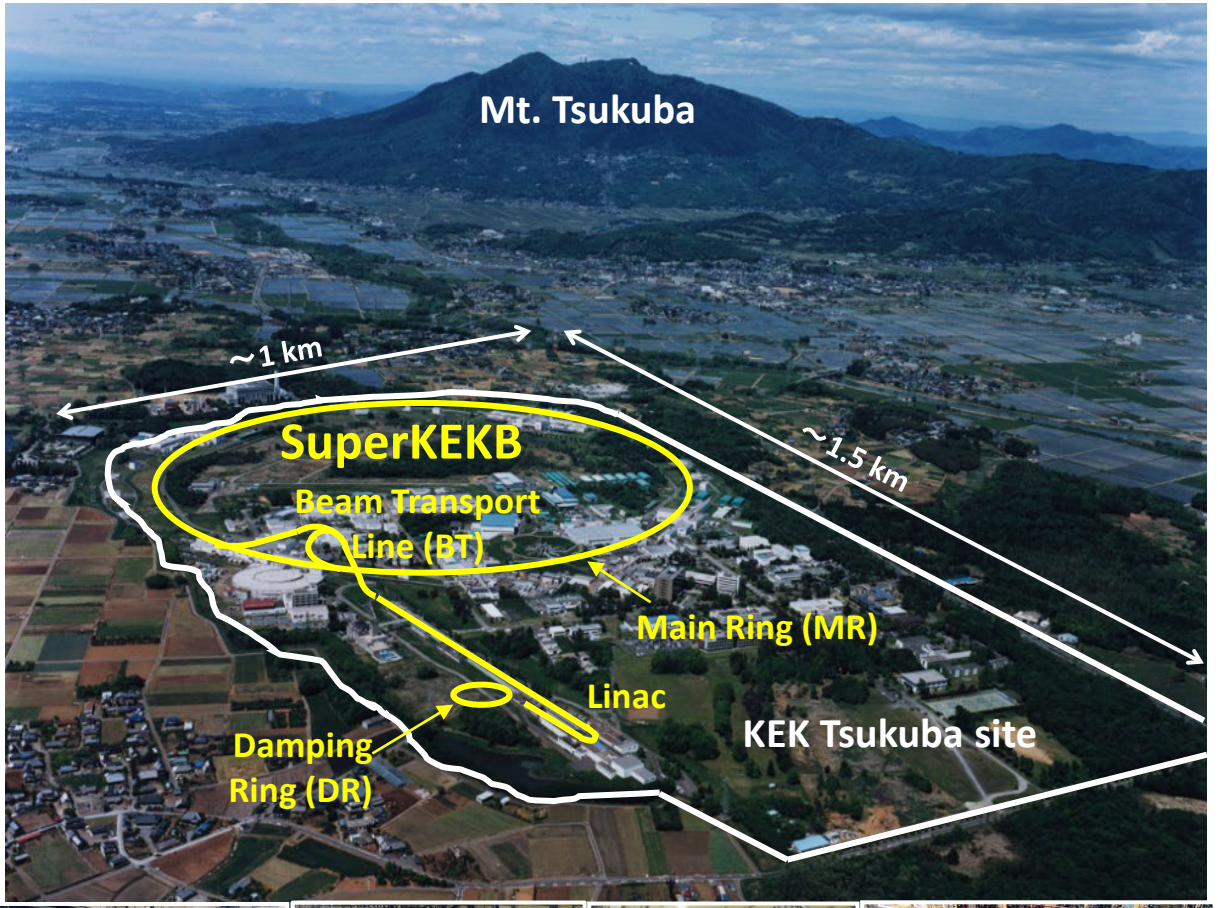
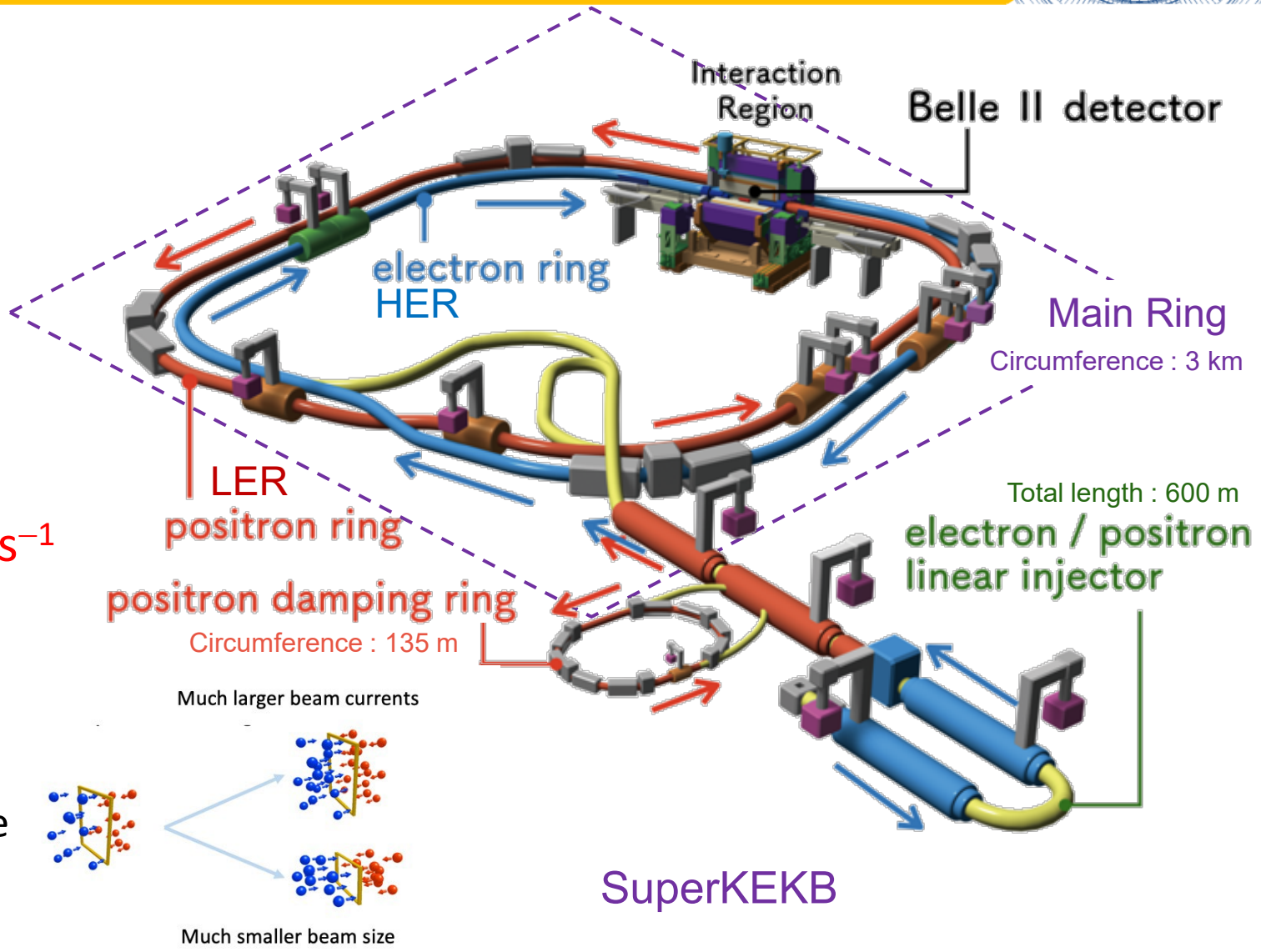
SuperKEKB

- 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"



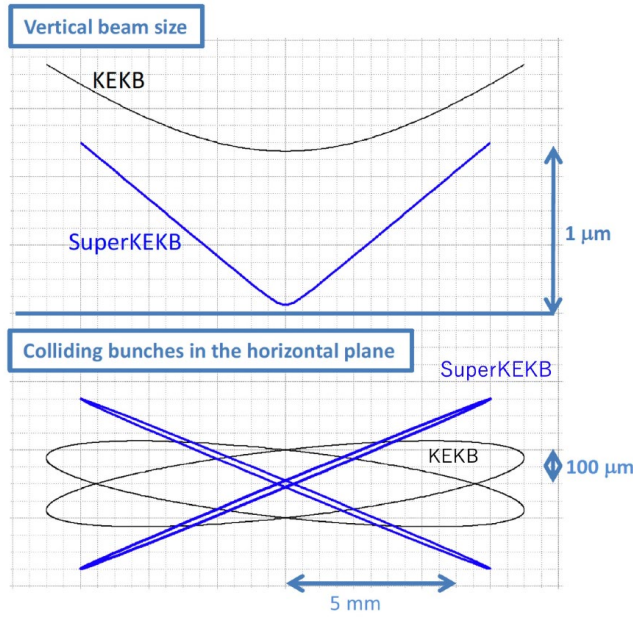
SuperKEKB

- 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}·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

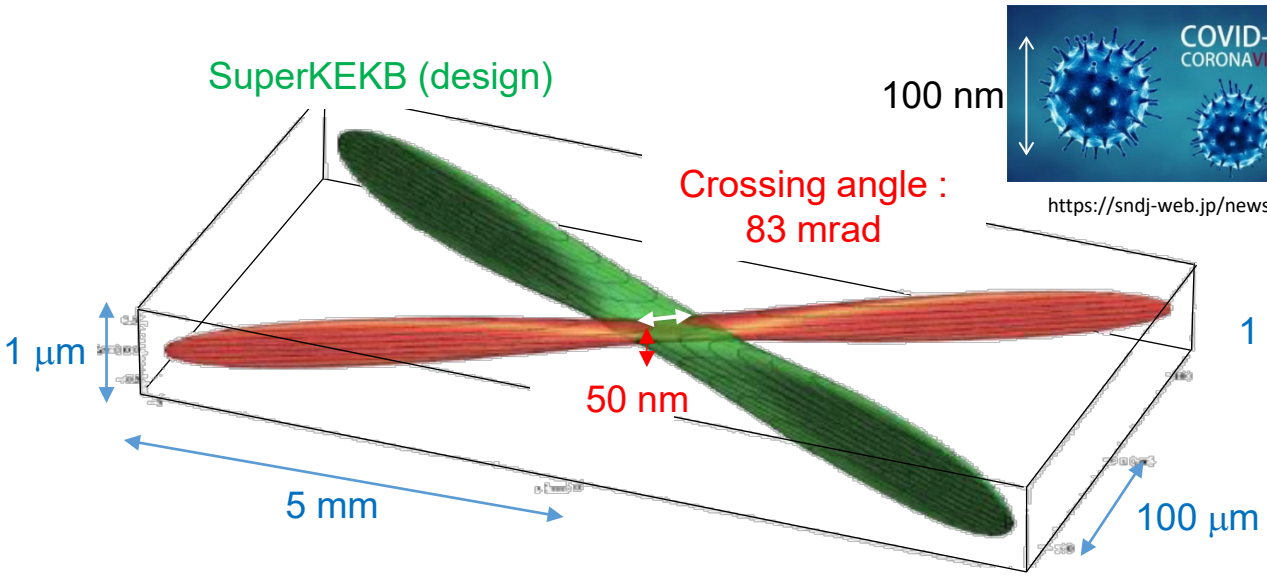


Nano-beam collision scheme

- 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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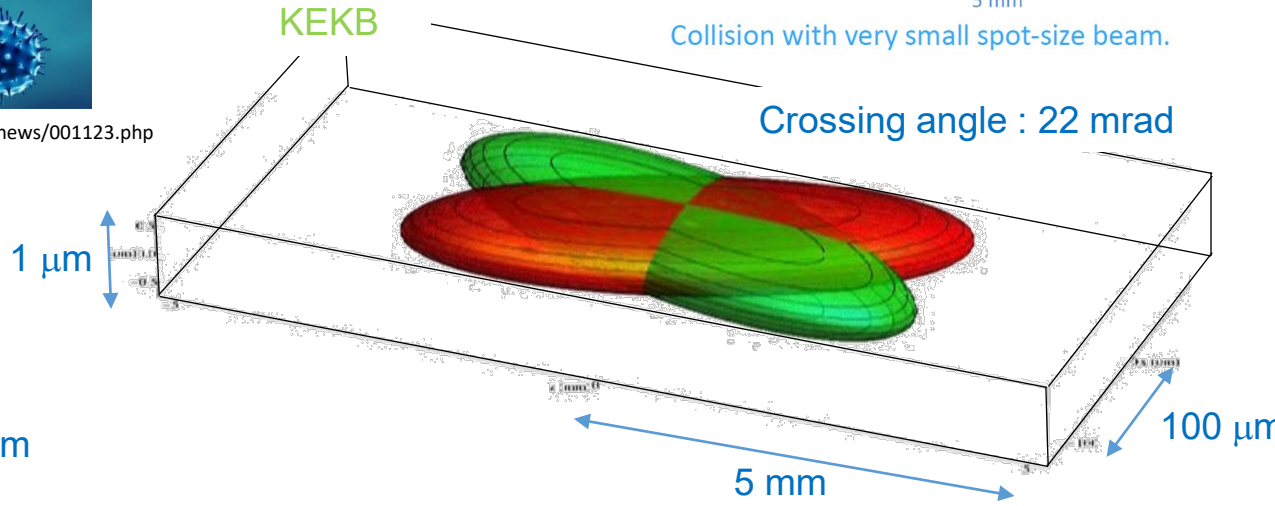
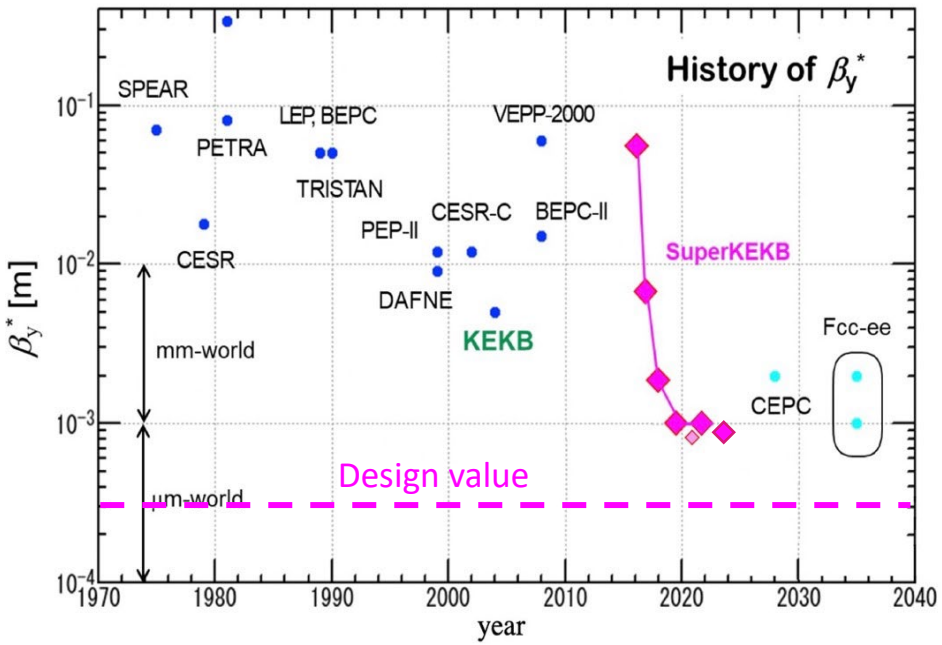


Machine parameters

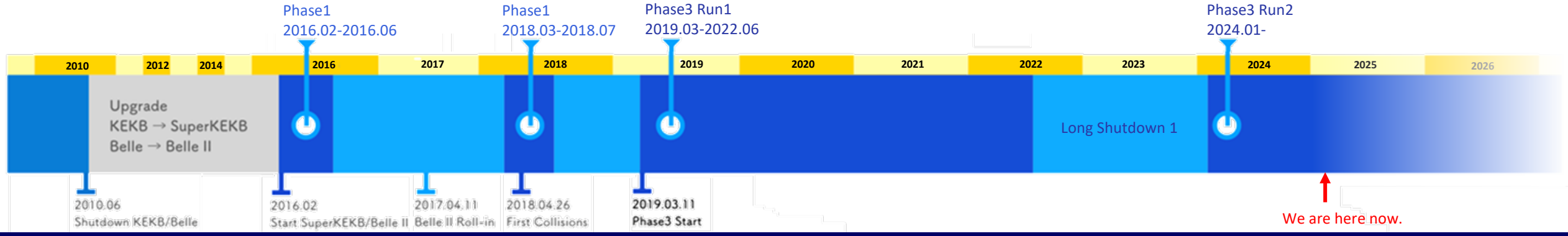
	KEKB (LER/HER)		SuperKEKB (LER/HER) 2024/12/27		SuperKEKB (LER/HER) Design	
Beam Energy [GeV]	3.5/8.0		4.0/7.0		4.0/7.0	
Beam current [A]	1.64/1.19		1.63/1.26		3.6/2.6	
# of bunches	1584		2346		2500	
β_x^*/β_y^* [mm]	1200/5.9	1200/5.9	60/1.0	60/1.0	32/0.27	25/0.3
σ_x^*/σ_y^* [μm]	147/0.94	170/0.94	15.5/0.26	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	



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.

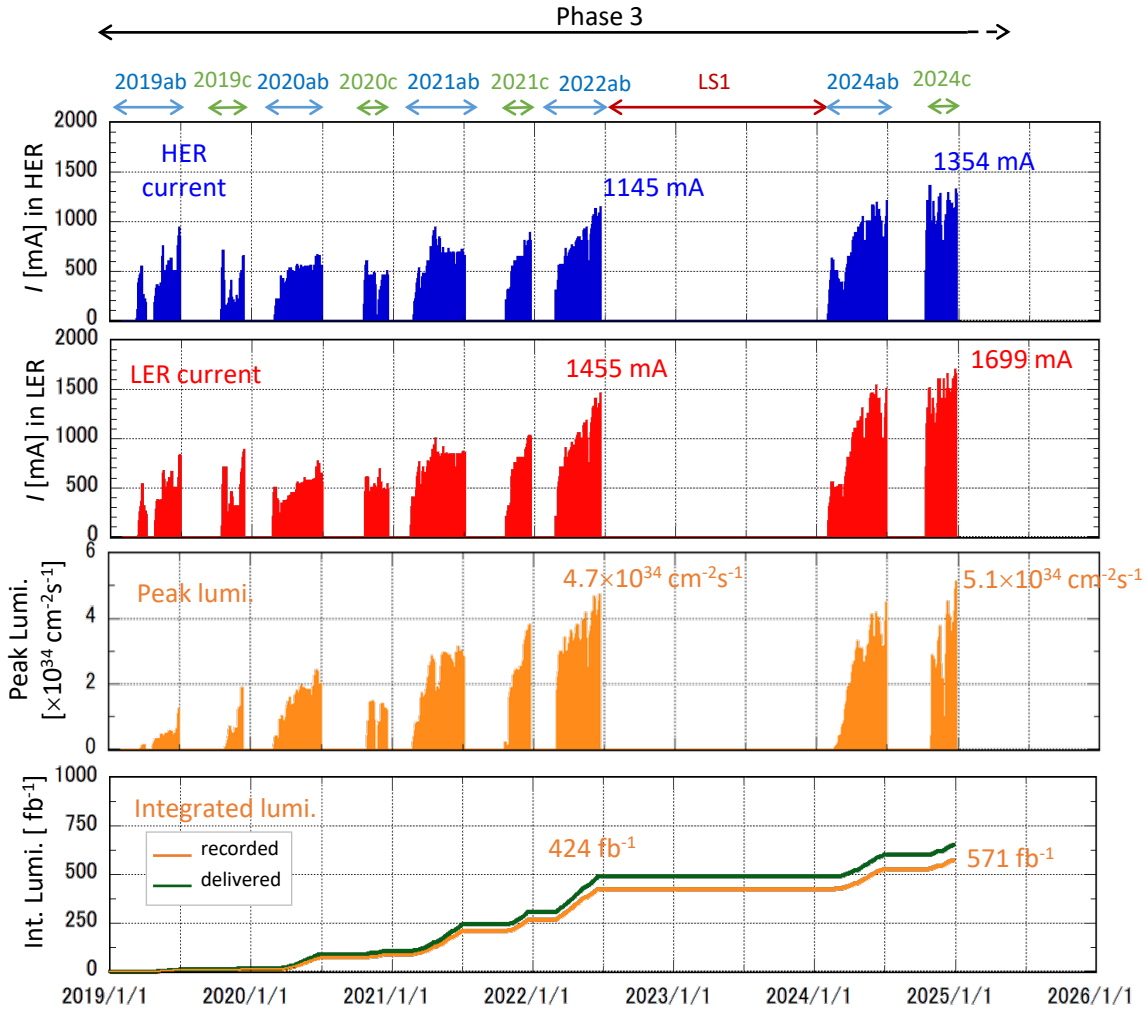
- Phase3 operation (2019.March~);
  - Physics run with fully instrumented detector.
  - Phase3 Run1 : 2019.10~2022.7
  - Long shutdown 1 : 2022.7~2024.01
  - Phase3 Run2 : 2024.01~



Phase 3 commissioning history

- Phase3 operation (2019.March~);
  - Physics run with fully instrumented detector
  - Naming rule of Phase3 operation

    March is end of Japanese fiscal year.
    - "YYYYxx run"
      - Calendar 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)



2024 run overview

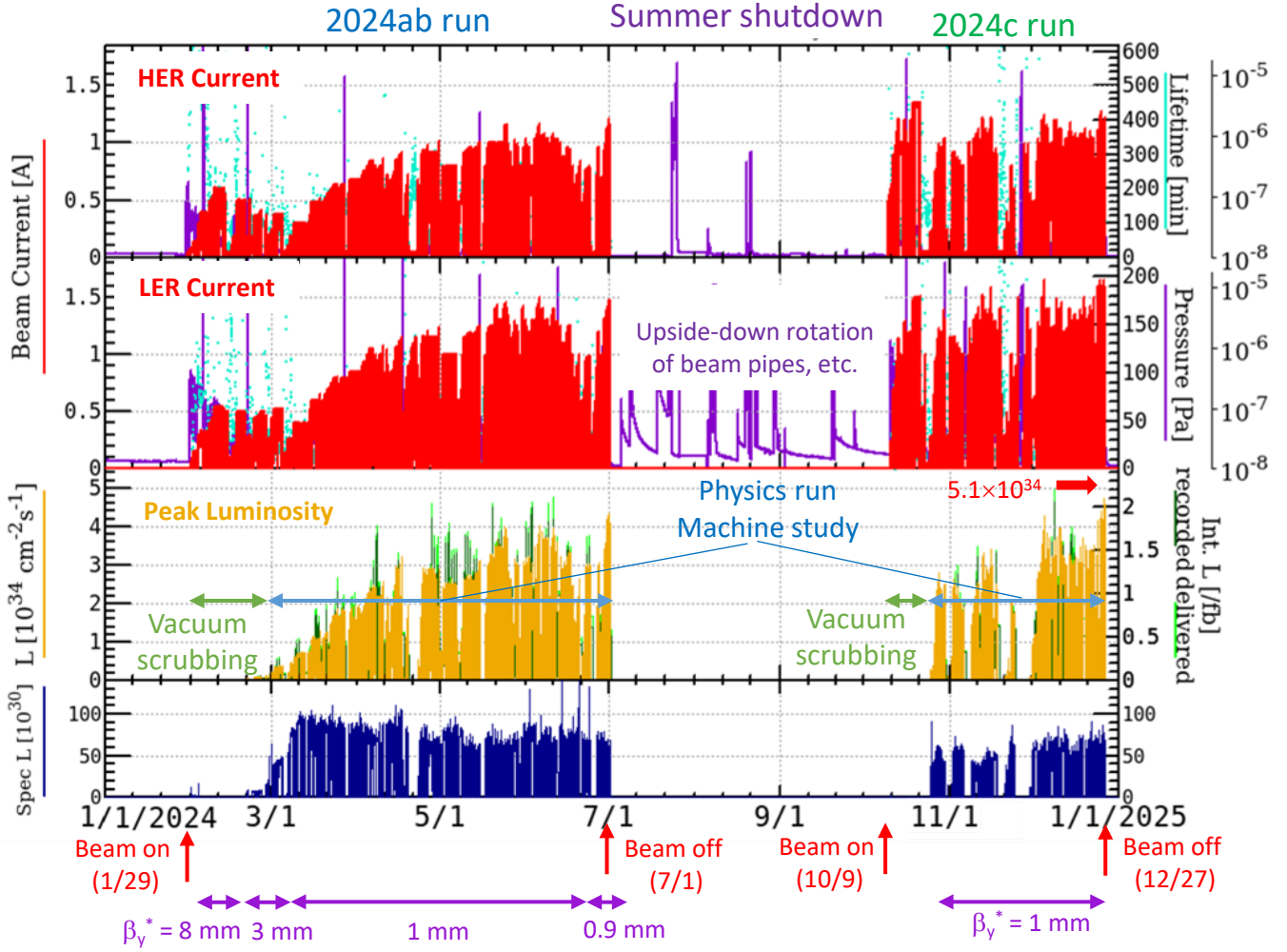
- 2024ab run : 2024/Jan./29 – July/1, 155 days
  - Start-up after a long shutdown
  - First demonstration of the effectiveness of the NLC* system
  - Peak luminosity : 4.47×10^{34} $cm^{-2}s^{-1}$
    - Maximum beam current : HER/LER = 1210/1539 mA
    - βy*-squeezing (Vertical β-function at IP) : ~0.9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

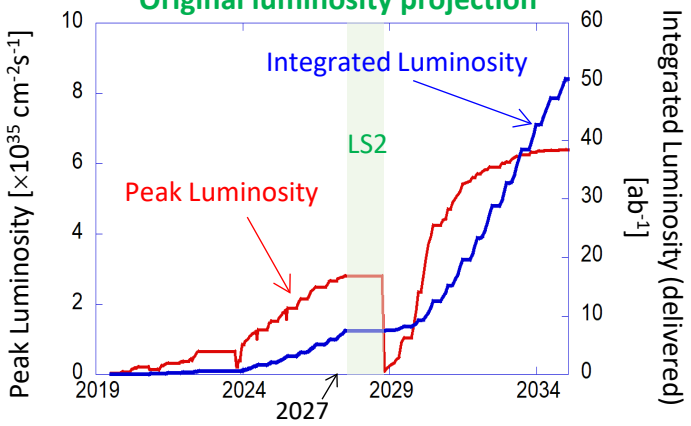
- 2024c run : 2024/Oct./9 – Dec. /27, 79 days
  - More time was spent on machine studies than on physics run.
    - Verification of SBL measures during summer shutdown
    - Machine studies to increase beam currents
    - Machine studies to investigate HER vertical beam blowup
  - Still struggled with 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!!



Long-term plan

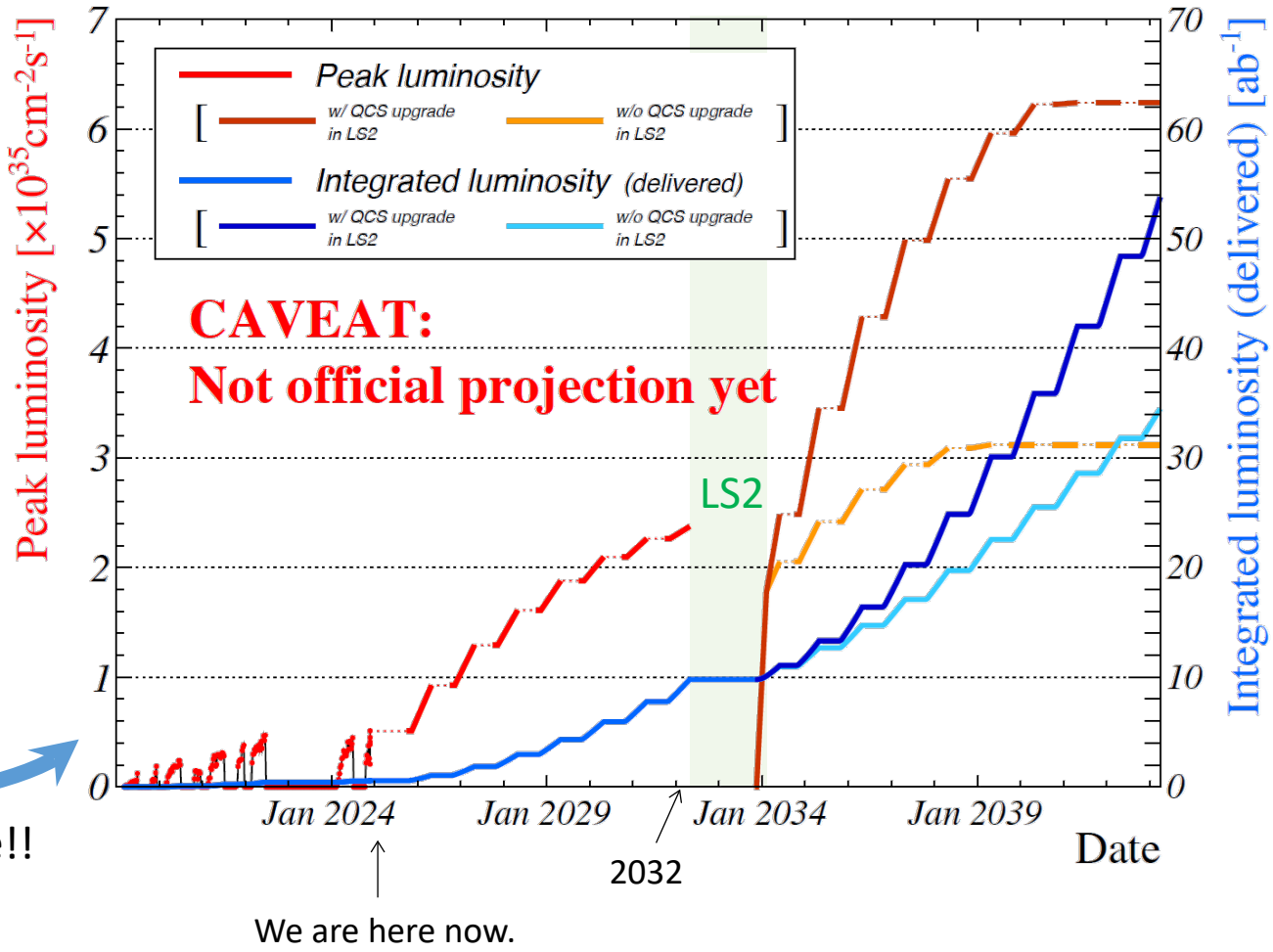
- New long-term plan is currently being created.
  - The proposed luminosity projection is under review.
  - New plan is expected to be finalized in near future.
- Major changes from original plan:
  - Long Shutdown 2 (LS2) is moved from 2027 to around 2032.
  - After LS2, luminosity projection shows two lines.
    - luminosity improvement of x 1.3 is expected due to the beam current increase mainly by the RF reinforcement (beam current increasement).
    - IR upgrade is assumed to be able to increase the luminosity much more.
    - Technical feasibility of the IR upgrade and the exact luminosity gain remain uncertain.
  - Operation needs to be continued by 2042 to deliver 50 ab^{-1} with IR upgrade.

Original luminosity projection



Update!!

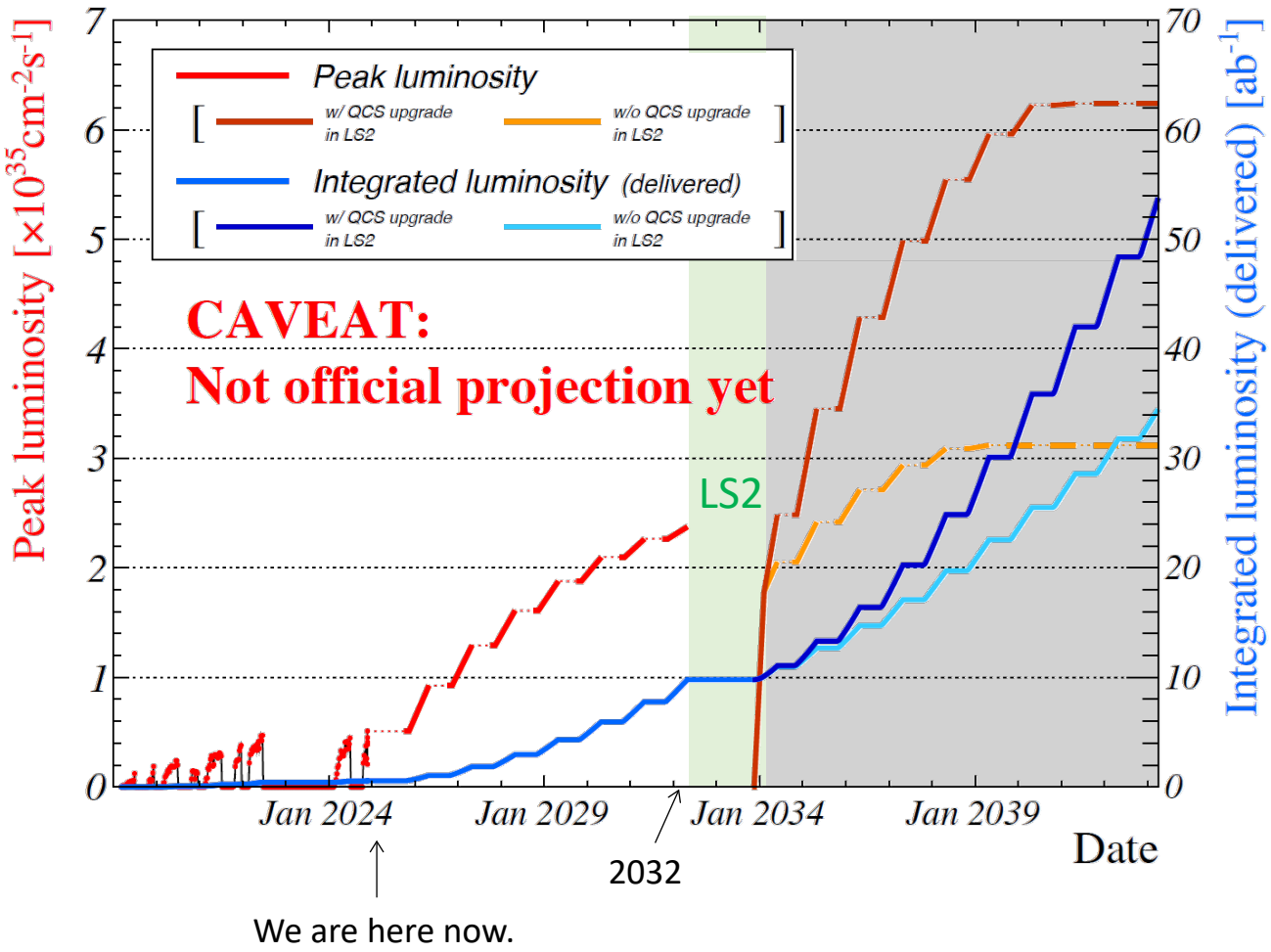
New luminosity projection (under consideration)



Important milestones before LS2

- Integrated luminosity target;
  - 0.58 ab^{-1} in JFY2024 (current value)
  - 1 ab^{-1} in JFY2025
  - 2 ab^{-1} in JFY2026
  - 5 ab^{-1} by around 2028-2029
    - LHC Run3 results will appear around 2028-2029
- Peak luminosity target;
  - 0.51×10^{35} $cm^{-2}s^{-1}$ by the end of JFY2024 (current value)
  - 1.0×10^{35} $cm^{-2}s^{-1}$
  - 2.4×10^{35} $cm^{-2}s^{-1}$ before LS2

New luminosity projection (under consideration)

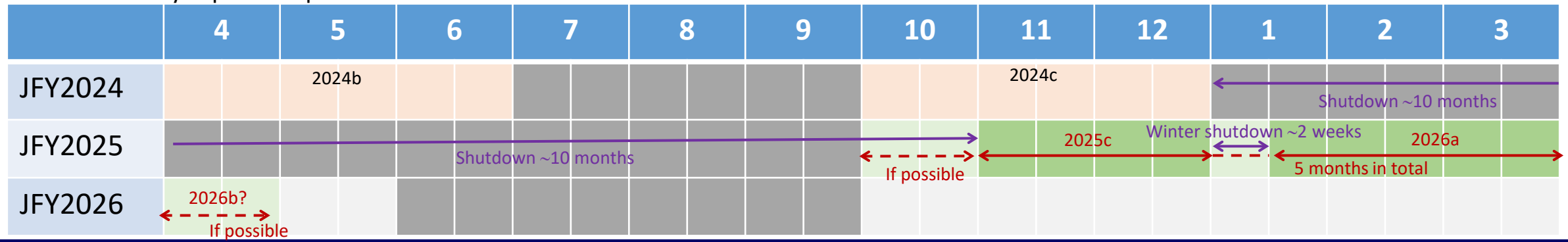


2025 run plan

- By the end of JFY2024
  - Operation is impossible by the end of February due to updating of power receiving equipment.
- From the perspective of operation efficiency
  - The run period should be as long as possible to make the operation efficient.
    - It should be at least 3 months.
  - Operation should be avoided in June as it is too hot and will reduce efficiency.
- From the perspective of budget
  - KEK requested budget for 7 months operation to MEXT.
  - MEXT is very supportive for SuperKEKB/Belle II and is asking MOF for increase of the budget.
    - However, we cannot expect a significant budget increase under Japanese budget system.
    - Assuming a realistic slight budget increase, the expected operation time in JFY2025 would be 3.5 months.
    - Supplementary budget for 1.5 months operation for JFY2024 can be carried over to JFY2025.
  - Realistically expected operation time in JFY2025 would be 5 months.

MEXT : Ministry of Education, Culture, Sports, Science and Technology
MOF : Ministry of Finance

- Our decision;
  - 2025ab run will be skipped.
  - 2025c run and 2026a run will be conducted.
    - 2025c run will start in November.
    - Winter shutdown will be shortened as much as possible. (~2 weeks)
    - 2026a run will be continued by the end of JFY2026.
  - With more supplementary budget, 2025c or 2026b will be extended.
- We are in 10-month shutdown now.
  - Prioritizing works to increase both peak luminosity and integrated luminosity in the next run.
    - Human resources and budget are limited.
  - Begin developing a commissioning plan of 2025c&2026a run



Strategy toward 1.0×10^{35} $cm^{-2}s^{-1}$

- Strategy toward 1.0×10^{35} $cm^{-1}s^{-1}$: Route (B)
  - Increase beam current with β_y^* = 0.9 mm
  - Target current : 2.58 A/ 1.83 A
    - Improve injection under influence of Beam-Beam interactions
    - Reduce injection errors with modified injection scheme
  - Required specific luminosity : $L_{sp} = 5\times10^{31}$ $cm^{-1}s^{-1}$ mA^{-2}

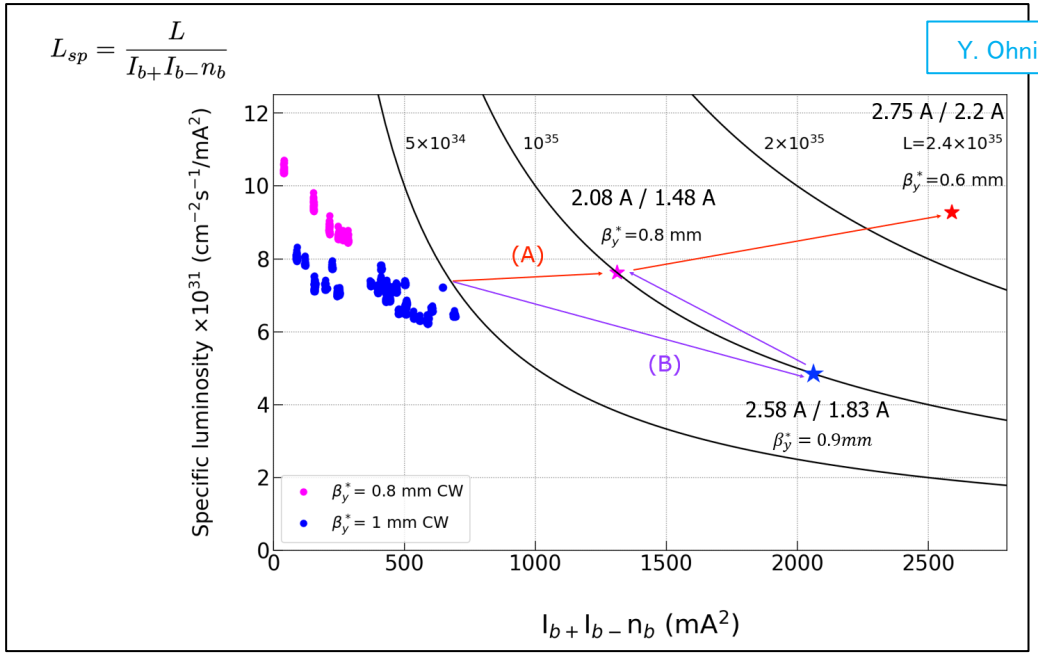
- 2024ab results and outlook
  - With 393 bunches (Result of high bunch current study)
    - L(393 bunches) = 1.38×10^{34} $cm^{-2}s^{-1}$
    - L_{sp}(393 bunches) = $\sim4\times10^{31}$ $cm^{-1}s^{-1}$ mA^{-2}
      - Degradation due to beam blowup at high bunch current
  - With 2346 bunches (outlook)
    - L(393 bunches) = 1.38×10^{34} $cm^{-2}s^{-1}$

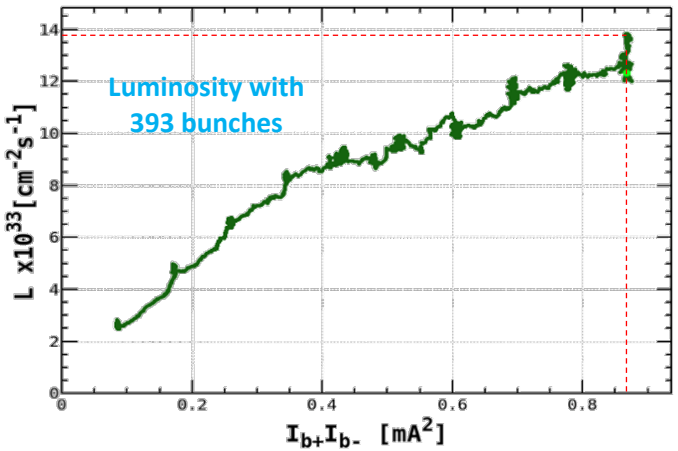
$\downarrow \times 2346/393$ (increase bunches)

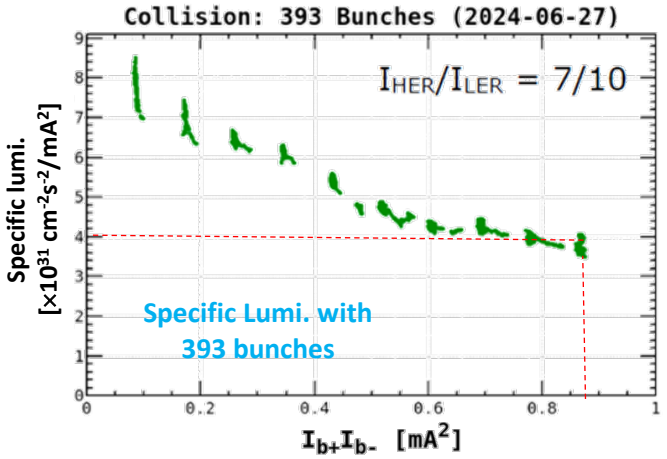
8.27×10^{34} $cm^{-2}s^{-1}$

$\downarrow \times 5/4$ (L_{sp} improvement)

1.0×10^{35} $cm^{-2}s^{-1}$



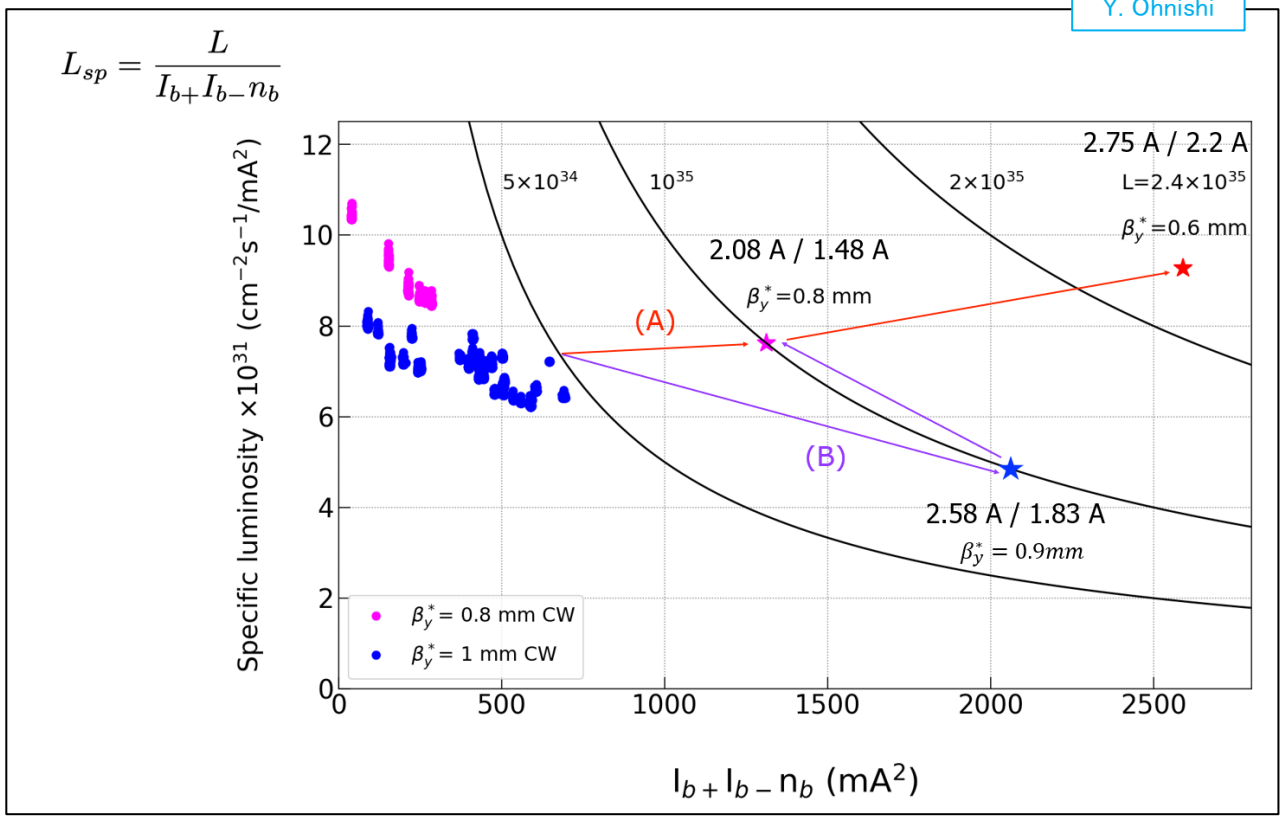




Strategy toward 2.4×10^{35} $cm^{-2}s^{-1}$

- 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

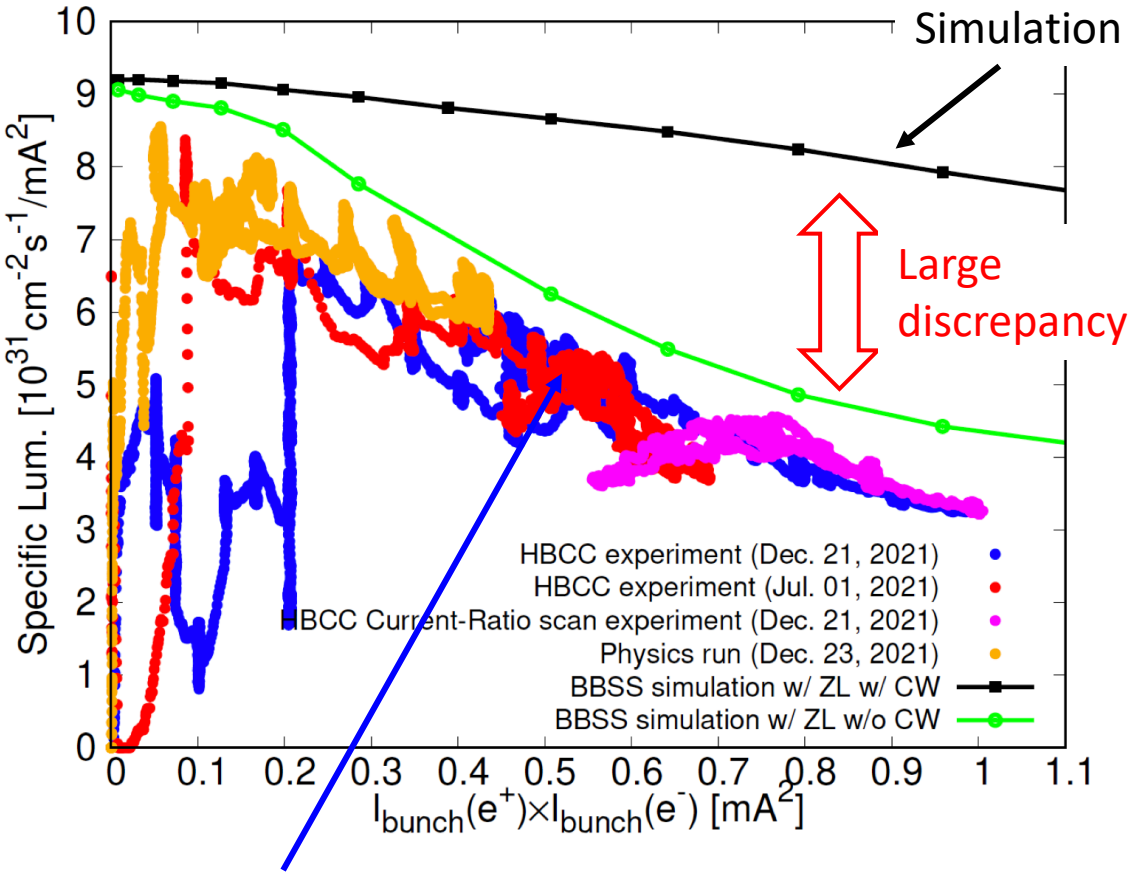
Y. Ohnishi



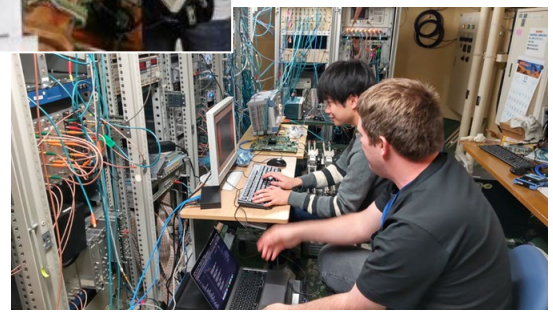
Strategy toward 2.4×10^{35} cm^{-2}s^{-1}

- 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 (under consideration)
    - Professor S. Asai, Director General of KEK, have asked several accelerator laboratories, such as CERN, DESY, IHEP, to support SuperKEKB accelerator.
- 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.

Summary

- SuperKEKB
  - Only operating machine with nano-beam collision scheme.
  - Future Higgs factory colliders will follow a lattice design with nano-beam collision scheme.
- Long-term plan
  - New long-term plan is currently being created.
    - LS 2 is moved from 2027 to around 2032
    - Operation needs to be continued by 2042 to deliver 50 ab^{-1} with IR upgrade.
- 2025 run plan
  - 2025ab run will be skipped.
  - 2025c run and 2026a run will be conducted.
    - Winter shutdown will be shortened as much as possible.
    - With more supplementary budget, 2025c or 2026b will be extended.
  - We are just beginning a 10-month shutdown and developing a commissioning plan of 2025c&2026a runs.
    - Luminosity target : 1×10^{35} $cm^{-2}s^{-1}$ (peak) / 1 ab^{-1} (total integrated)
- Collaboration
  - We surely welcome international collaboration to improve 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.

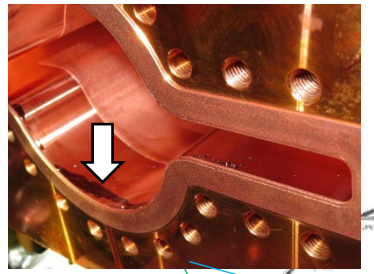
Fin.

Thank you for your attention.

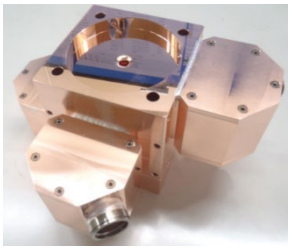
Back up

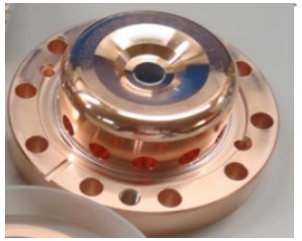
Works during this shutdown 1

- 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



Bending magnet replacement (BTp)





NEW RF-Gun cathode cell

Works during this shutdown 2

- Other work items (under consideration)
  - LER D06V2 collimator relocation to D03 Arc section
    - To protect Belle II and D02V1 collimator from uncontrollable beams
    - The best location is currently being determined.
  - Countermeasure against HER SBL
    - we need to do something, but we don't have any concrete plans yet.
  - And so on.

- Begin developing a commissioning plan of 2025c&2026a run
  - The specific plan is yet to be created.
  - Luminosity target;
    - Peak luminosity : 1×10^{35} $cm^{-2}s^{-1}$
    - Integrated luminosity : 1 ab^{-1}