PROCEEDINGS OF SCIENCE

The Belle II upgrade program

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The Belle II detector at the SuperKEKB accelerator complex covers a wide range of exciting physics topics. To achieve the project's research goals, a substantial increase of the data sample to 50 ab^{-1} is needed, and for that, the luminosity must reach the ambitious goal of 6×10^{35} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Progress towards the design luminosity is accompanied by research and development on the accelerator, operation methods, detector components, and their upgrades. In this contribution, the status and plans of the project will be discussed, along with timescales for upgrades, their motivations and opportunities, an overview of upgrade options, and an outlook and summary.

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1. Introduction

The SuperKEKB collider [1] consists of two storage rings. In the high-energy ring, electrons are accelerated to 7.0 GeV, in the low-energy ring positrons are accelerated to 4.0 GeV (Figure 1). The center-of-mass energy of 10.58 GeV corresponds to the peak of the $\Upsilon(4S)$ production cross section. By employing the "nano beam" technique [2] SuperKEKB shrinks the vertical beam size to tens of nanometers at the interaction point (IP). Compared to KEKB, the interaction region

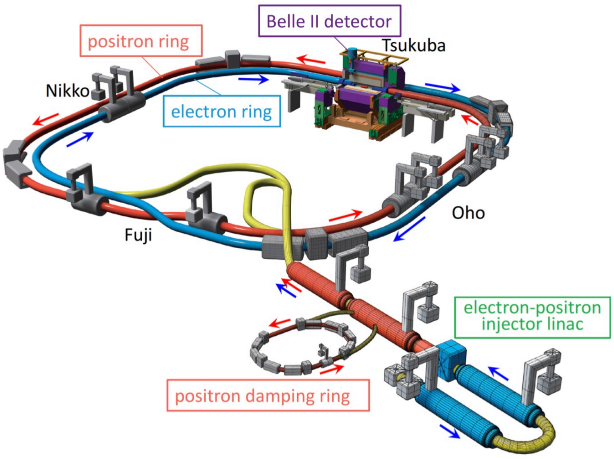

Figure 1: Schematic view of SuperKEKB. The electron and positron rings have four straight sections. The Belle II detector is located at the collision point in the Tsukuba sector.

has been redesigned with superconducting quadrupole magnets (QCS) positioned closer to the interaction region, a new positron production target, an additional damping ring for the positron beam, and several other upgrades. The Belle II detector (Figure 2) retains the same structure as the Belle detector but the pixel and silicon detectors (PXD/SVD) and the particle identification detector in the barrel region (TOP) are completely new. Other detectors, such as the Central Drift Chamber (CDC), Electromagnetic Calorimeter (ECL), particle identification detector in the forward region (ARICH), and the KL and muon detector (KLM), have been substantially improved. In the following the status and plans of the project, upgrade options, their motivations, and timescales will be discussed.

2. SuperKEKB/Belle II status and schedule

The first run period (Run1) started in spring 2019. A maximum instantaneous luminosity of 4.7×10^{34} cm^{-2}s^{-1} was achieved and an integrated luminosity of 0.43 ab^{-1} was collected. Run1 ended in June 2022. During the first long shutdown (LS1), lasting 20 months, both the accelerator and the detector were upgraded. The beam pipe has been redesigned to reduce synchrotron radiation near IP. The beam abort monitoring system was improved with additional diamond sensors. RF cavities and collimator jaws were modified to improve beam lifetime and accelerator stability. The pixel detector was installed in the full version with 8 inner and 12 outer layers. About 50%

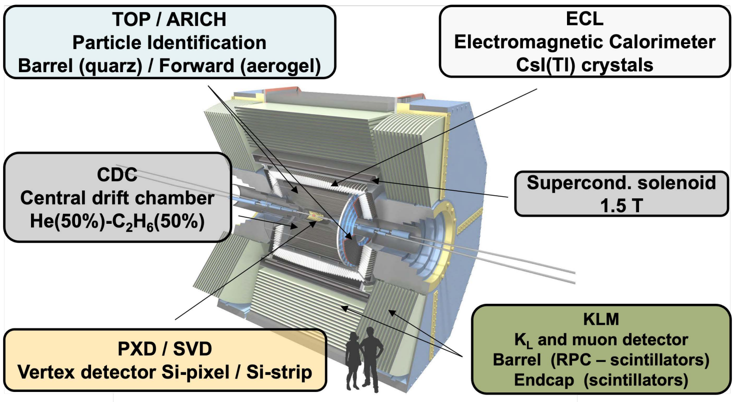

Figure 2: Overview of the Belle II detector.

of the TOP detector's microchannel plate photomultipliers (MCP-PMTs) that had short lifetimes were replaced with long-lifetime MCP-PMTs. Electronics components with dead channels in all sub-detectors were repaired or replaced. The second run period (Run2) started in February 2024. Figure 3 shows the integrated luminosity as function of time from 2019 to 2024. A maximum instantaneous luminosity of 5.1×10^{34} cm^{-2}s^{-1} was achieved, and an integrated luminosity of 0.57 ab^{-1} was collected. A further increase in instantaneous luminosity was limited by higher-

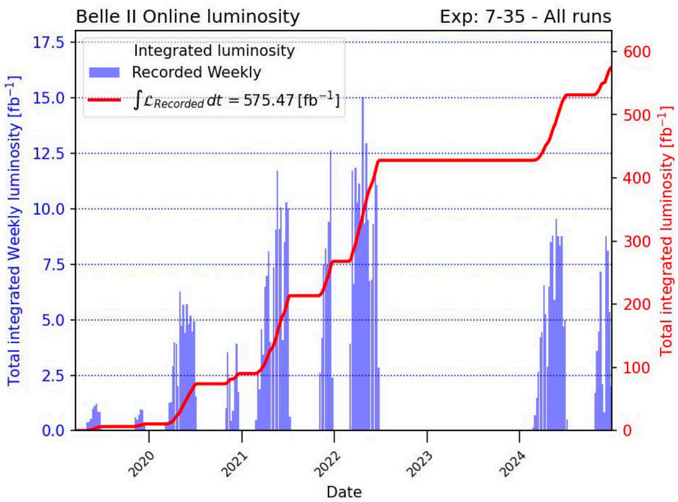

Figure 3: *Recorded weekly and total integrated luminosity as a function of time.*

than-expected beam background and instability observed when increasing beam currents. About one beam abort occurred every 1.5 hours, of which 6% were sudden beam lost (SBL). The PXD detector was switched off to protect it from significant damage. Run stops were mainly due to beam abort (26%) and firmware errors in sub-detectors electronics (TOP 29%, CDC 15%, SVD 7%). A long break from January 2025 to October 2025 was scheduled to further improve accelerator and detector performance. Extensive beam pipe cleaning was undertaken to remove black stains found inside beam pipe flanges, likely caused by vacuum sealant residue. Almost no SBL events occurred in sections that were already cleaned in 2024. Some collimators have been relocated to improve beam stability, and beam abort time was shortened. Firmware and software of CDC, TOP, SVD and DAQ systems were updated to reduce downtime related to single-event upset (SEU). The

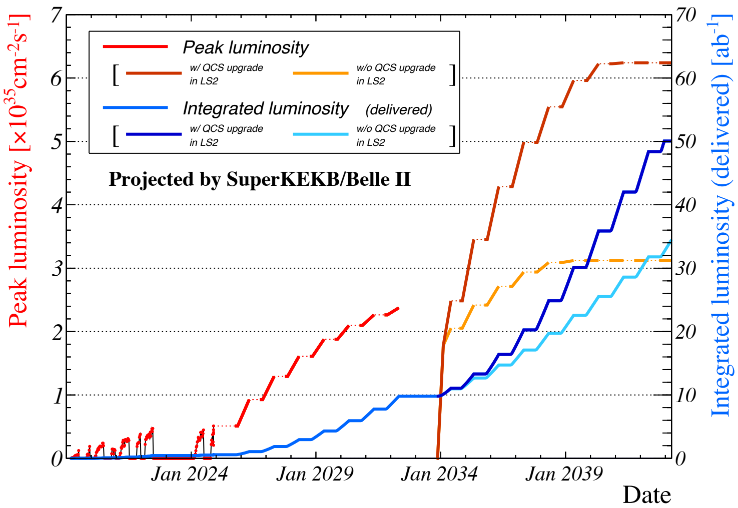

Figure 4: *Instantaneous and integrated luminosity achieved from 2019 to 2024, and their projections from 2025 to 2042. A second long shutdown (LS2) to upgrade the accelerator and the detector is scheduled in 2032 and 2033. Two projections have been considered after LS2, within and without QCS upgrade.*

restart is expected in November 2025. Figure 4 shows the instantaneous and integrated luminosity projections up to the end of the SuperKEKB program.

3. Near-term upgrades

The near-term and and longer-term Belle II and SuperKEKB upgrade programs are detailed in the Conceptual Design Report (CDR) published in June 2024 [3]. Figure 5 shows the specific luminosity depending on the product of the positron beam current (I_{b^+}), electron beam current (I_{b^-}), and the number of bunches (n_b). The work plan scheduled between 2025 and 2032 (before LS2) is to move from the curve corresponding to 5×10^{34} cm^{-2}s^{-1} to the curve corresponding to 2.4×10^{35} cm^{-2}s^{-1} of instantaneous luminosity by increasing the beam current I_{b^+} from 1.63 A to 3 A, I_{b^-} from 1.26 A to 2 A, and reducing β_y^* from 1 mm to 0.6 mm. Possible improvements to the accelerator during these steps include optimising sextupole magnets, tuning off-momentum optics, and improving prediction accuracy of the beam-beam interaction simulation. The TOP sub-detector still has 220 non life-extended MCP-PMTs. They are expected to reach the relative 80% quantum efficiency limit by 2028 or 2029 depending on background conditions after the accelerator restart. New life-extended MCP-PMTs are already available, and their testing is expected to be completed by the end of 2026. Replacement may take place from summer 2027. A new asymmetric high-voltage divider is currently being tested for MPC-PMTs. Its implementation is expected to increase their lifetime.

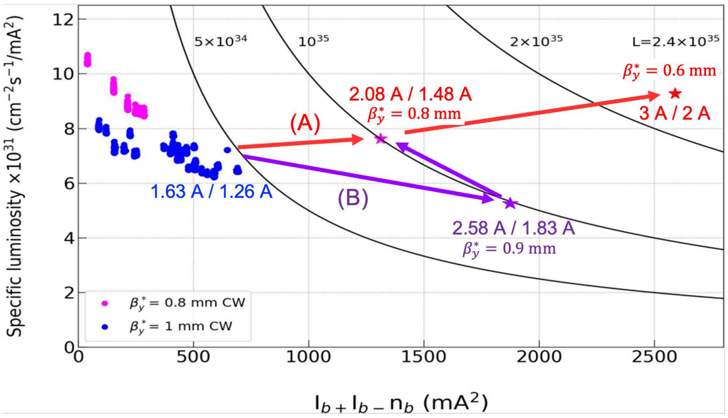

Figure 5: *Specific luminosity as a function of the product* $I_{b+}I_{b-}n_b$. *Three curves are described for the current, intermediate and target instantaneous luminosities. Options (A) and (B) describe how we plan to reach the target instantaneous luminosity of* 2.4×10^{35} cm^{-2}s^{-1} .

4. Longer-term upgrades

The goal of LS2 is to upgrade the accelerator to achieve an instantaneous luminosity of 6.0×10^{35} cm^{-2}s^{-1} with stable beams, and to upgrade the detector to improve its background tolerance and physics performance. By moving the superconductive final-focus quadrupole magnets QC1P 100 mm closer to the IP (from the current 935 mm to 835 mm), the Touschek lifetime increases from 261 seconds to 424 seconds. The lifetime estimation was made using the SAD simulation program at $\beta_y^* = 0.27$ [4]. To avoid mechanical interference between the two beam lines, thinner conductors will be needed, leading to an increase in current density. Replacing the NbTi superconducting cable with the Nb_3Sn high-performance type II superconductor will increase the critical current density J_c, doubling the temperature margin for maintaining superconductivity [5]. Tests to build quadrupole magnets with the new superconductor are ongoing. Figure 6 shows the current and upgraded IP region. With the new geometry a new vertex detector will be required. Background rates for the Belle II sub-detectors have been estimated for post-LS2 operation at an instantaneous luminosity of 6×10^{35} cm^{-2}s^{-1}. Different scenarios have been considered. In the intermediate scenario, Touschek and beam-gas backgrounds are assumed to increase by a factor of 5 after LS2, which could raise the hit rate of the TOP and CDC detectors and the occupancy of the SVD detector, reaching the limits that reduces their efficiencies. New detectors are planned for SVD and CDC, new electronics and photodetector improvement with higher lifetime are planned for TOP. The new Vertex Detector (VTX) replacing SVD and PXD is under development, it will use a monolithic CMOS pixel sensor named OBELIX [6]. The first version of the new sensor OBELIX-1, is currently in its final design, the goal is to produce the prototype within Q2 2026. The expected maximum hit rate for VTX is estimated to increase from 120 MHz/cm^2 to 650 MHz/cm^2.

5. Summary

The SuperKEKB accelerator and the Belle II detector have been upgraded during LS1 and the 2025 break. Additional improvements will enable achievement of an instantaneous luminosity of 2.4×10^{35} cm^{-2}s^{-1} by 2032. A major upgrade will take place during LS2, which will enable achievement of 6.0×10^{35} cm^{-2}s^{-1}. The feature and design of the new CDC are still being finalized. A new vertex detector is under development. Electronic and software upgrades for TOP, ECL and KLM sub-detectors and the trigger system, will improve their performances in high radiation environment.

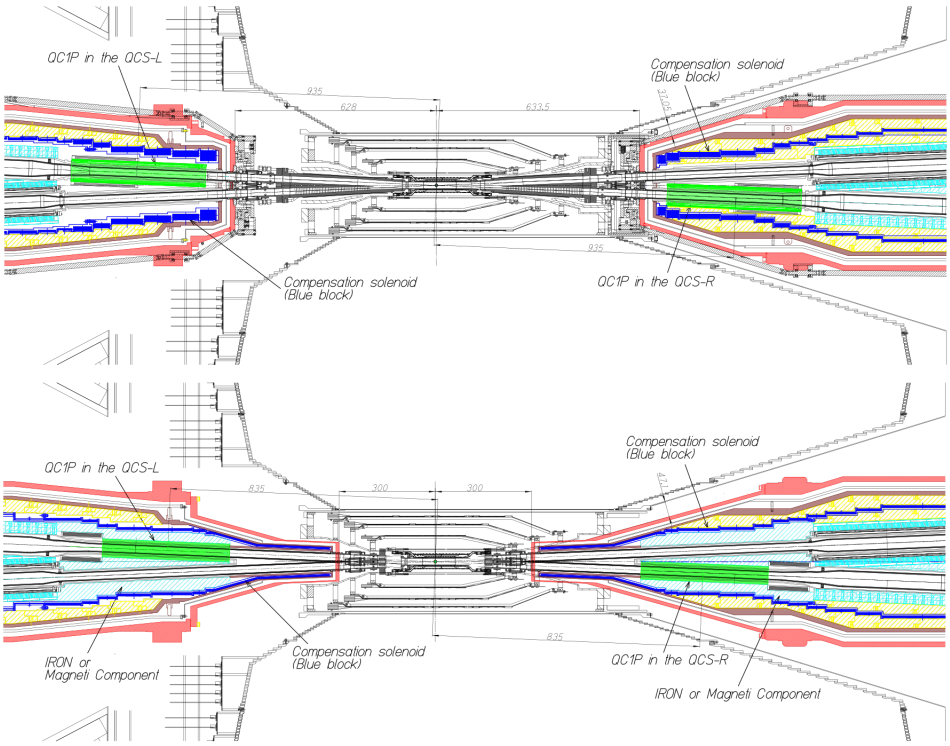

Figure 6: *On the top the current IP region with the vertex detector, on the bottom the upgraded IP region. The QC1P magnets are shown in green, the magnetic yoke/shields in cyan, the anti-solenoid coils in blue, the radiation shields in yellow, the liquid-helium vessel in brown, the cryostat in red.*

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