

Special Review Meeting of KEK B-factory Project Joint Committee of Accelerator and Experiment

10 February 2026, Hybrid (KEK and Remote) meeting

P. Craievich (PSI), M. Demarteau (ORNL),
R. Forty (CERN), T. Taylor (CERN), R. Tomás (CERN),
N. Neufeld (CERN), M. Sullivan (SLAC),
and chaired by T. Nakada (EPFL)

18 March 2026

1 Introduction

Since the start of full physics running in 2019, the Belle II detector has collected approximately 0.5 ab^{-1} of data by the end of 2025 for physics analyses. According to the current plan, Belle II data taking will continue until the end of the Japanese Fiscal Year (JFY) 2031, i.e. March 2032. By the end of the run, an integrated luminosity of about 10 ab^{-1} is expected to be accumulated with SuperKEKB reaching a peak luminosity exceeding $2 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$. This can be compared with the $\sim 1 \text{ ab}^{-1}$ of data collected by the Belle experiment over 11 years of operation.

In order to further advance flavour physics, a plan is being developed to upgrade both the SuperKEKB accelerator complex and the Belle II detector during the long shutdown period starting in 2032 (LS2), which is foreseen to last two years. The goal of this upgrade is to achieve a peak luminosity of $6 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ and to accumulate an integrated luminosity of 50 ab^{-1} by the end of JFY2043.

A review of this LS2 upgrade plan for the SuperKEKB accelerator complex and the Belle II detector was requested by the Director of the KEK Institute for Particle and Nuclear Physics Studies (IPNS) and the Director of the KEK Accelerator Laboratory (AR). The following charges were given to the committee:

1. *Overall upgrade objectives in the light of the physics goals.*
2. *Coherency and consistency of the plans among LINAC, MR, and Belle II.*
3. *Selection criteria for upgrade options and suitability of the selected ones.*
4. *Feasibility of the plans in terms of schedule, resources, and technical aspects.*
5. *Organisation and management of the overall upgrade project.*

The committee consists of eight members with expertise in accelerator and experimental physics.

During the review meeting, an overview of the upgrade programme was presented, including the proposed organisation and timeline. Three principal accelerator upgrade items were discussed: replacement of the linac Radio Frequency (RF) power units, an increase of the RF power for the SuperKEKB High Energy Ring (HER), and modification of the interaction region (IR) through the installation of new superconducting final focusing quadrupole magnets (QCSs). In addition, the Belle II detector upgrade plan was presented, with particular emphasis on the tracking system, which must be upgraded to ensure sustainable operation in the high-luminosity environment expected after LS2.

2 General Assessment

The committee endorses the overall scope and strategic direction of the LS2 upgrade programme. The replacement of the linac RF power units, already budgeted for JFY2026, is essential to ensure stable long-term operation by consolidating ageing infrastructure that is critical for both current performance and future luminosity goals. Increasing the HER RF power is necessary to reach the high beam currents required to achieve the design luminosities after LS2. Upgrading the interaction region will alleviate current aperture limitations and is therefore crucial for reaching the targeted luminosities after LS2.

The proposed scope and time scale for the upgrade are ambitious, particularly with regard to the production and installation of the new QCS magnets and the implementation of the Belle II tracking upgrade, as the two subsystems must be coherently integrated into the interaction-region design and are therefore strongly interdependent in their planning and execution. Clear prioritisation may be required to ensure timely execution of the whole projects and mitigate schedule risks.

In this context, the committee would welcome a more comprehensive and integrated analysis of the performance of the entire accelerator complex, together with a realistic timeline for the upgrade. Such an analysis should clarify the overall strategy and priorities for the upgrade, taking into account operational experience, present performance limitations, and the interplay between injector systems and storage rings. In close coordination with the Belle II collaboration, this would enable formulation of an optimised upgrade plan that balances performance goals with realistic constraints on time and resources.

This is particularly important for the linac RF power replacement programme starting in JFY2026. Addressing the current challenges in increasing beam currents, while maintaining machine backgrounds at a level tolerable for the experiment, requires sustained technical effort and adequate resource allocation. Resolving these issues is a necessary step toward the successful implementation of the LS2 upgrade. The committee therefore recommends that sufficient flexibility in resource allocation be made to respond effectively to the needs as they arise.

The proposed organisational structure appears appropriate. Given that multiple accelerator groups are contributing to the project, it is essential to establish a management structure capable of ensuring coherent and coordinated efforts across all subsystems, in

close collaboration with the Belle II team. The overall management should be empowered to define priorities and to agree upon resource allocations consistent with the strategic objectives of the upgrade.

In the following sections, the committee presents specific observations and recommendations regarding the three principal accelerator upgrade items and the Belle II detector upgrade. It is noted that the Belle II upgrade plan is also being reviewed in detail by the B-factory Programme Advisory Committee.

3 Specific Issues

3.1 Linac RF power upgrade

As a general comment, the committee would like to emphasize that the development of high-efficiency S-band klystrons is extremely important for the entire accelerator community. This effort directly addresses the sustainability requirements of modern accelerators, and many laboratories worldwide have expressed strong interest in such a project.

In this context, the proposed linac upgrade represents an important step to maintain the long-term reliability of the injector complex, even if it is not strictly driven by new physics goals. Ensuring stable and efficient injector performance is an essential prerequisite for achieving the full physics potential of the collider, and improvements in RF stability could ultimately translate into higher injection efficiency and luminosity.

The new klystrons are expected to deliver a peak power of 80 MW, compared with the 50 MW provided by the klystrons currently in operation. This increase could raise the accelerating gradient by approximately 25 %, from the present value of 21 MV/m to about 26 MV/m. While this performance enhancement is very attractive, the possible impact on the breakdown rate (BDR) of the accelerating structures must be carefully evaluated, as higher gradients may adversely affect structure reliability and lifetime. A more quantitative assessment of the expected operating gradient and its implications would therefore strengthen the upgrade case.

For the new Low Level RF (LLRF) system, a solution already deployed in other laboratories will be adopted, which should ensure reliable performance and reduce development risks. With the introduction of the new modulators, improvements in RF phase and amplitude stability are anticipated. However, the specific phase and amplitude stability (jitter) requirements, as well as the expected level of improvement with respect to the present system, were not discussed in sufficient detail. A clearer definition of these specifications would help to quantify the potential gain in injection efficiency and its possible impact on collider luminosity.

Solid-state high-voltage modulators represent an excellent alternative to Pulse Forming Network modulators, especially as thyatron costs are becoming unsustainable and tube availability may become a short-term issue. The transition to solid-state technology is well aligned with long-term reliability and maintainability goals. Although improved stability is claimed for the new modulators, this aspect should be described more quantitatively in future presentations, including measurable performance indicators and comparisons with the existing system.

The overall upgrade strategy appears technically sound and well motivated from the perspectives of reliability and sustainability. The development of a high-efficiency klystron is a key factor in reducing the energy consumption of the linac, which is an important consideration for future accelerator facilities.

The feasibility of the upgrade, however, must be verified in light of fabrication and delivery times of critical components. Since the plan foresees the replacement of up to 60 RF units, a detailed installation scenario, including manpower estimates and compatibility with ongoing operations, will be essential. Although part of the installation of the new modulators and klystrons can be carried out during operation, the installation of new RF structures and waveguide networks will require careful coordination with shutdown periods.

At present, no detailed timeline has been provided. The results of the tests on the klystron prototype and the new HV modulator, planned for 2027 with beam, will constitute an extremely important milestone for the linac upgrade and should serve as a decision point for the full implementation. More information on the overall organization and management structure of the project would also be beneficial to assess its robustness.

In order to consolidate the upgrade plans, the committee suggests that the following points be addressed:

- HV klystron modulator
 - Evaluate whether the increased compactness of solid-state HV modulators has any impact on maintenance procedures and on the replacement of switching units.
 - Clarify whether the long-term availability of insulated-gate bipolar transistors as spare parts has been investigated and secured.
 - Specify the expected annual production rate of klystrons once the design is finalized.
- Accelerating gradient and RF structures
 - Provide more detailed information on the BDR as a function of accelerating gradient expected in the accelerating structures when powered by the new Multi-beam klystron.
 - Assess whether the power density to be dissipated in the accelerating structures will increase and whether additional cooling improvements are required.
 - Specify how many RF structures are planned to be replaced within the scope of the upgrade.
 - Clarify whether a new RF pulse compressor is being designed (as suggested in the presentation) and confirm whether it will be included in the RF unit test foreseen for 2027.
- LLRF system
 - Define the RF phase and amplitude stability (jitter) specifications.
 - Indicate whether suppliers have been identified and when the first LLRF system is expected to be tested.

- Cost estimate: Clarify what is included in the stated cost estimate for the injector and whether it covers all relevant subsystems.

In addition, the committee makes the following recommendations for revising the upgrade plans:

1. Present a detailed timeline including how many RF stations are expected to be installed during each shutdown period. The schedule should explicitly cover all individual subsystems: LLRF, klystron, HV modulator, accelerating RF structures, and waveguide system.
2. Provide a more detailed breakdown of the cost estimate, indicating the costs of the individual subsystems of a single RF unit (HV modulator, klystron, LLRF, waveguide components), as well as any required improvements to the cooling system and associated infrastructure.

3.2 HER RF power upgrade

The current status of the Low Energy Ring (LER) and HER RF systems was presented. The LER has 22 normal conducting (ARES) cavities with 16 klystrons supplying RF power to the beam. An analysis based on experience indicates that the current LER RF system should be able to deliver enough power to store the design current of 3.6 A. However, a similar study of the HER RF system indicates that the present system has only enough RF power to store 2.2 A which is short of the design current of 2.6 A.

The present HER RF system consists of eight superconducting cavities (SCC) and eight ARES cavities. The eight SCC cavities each have a klystron while the eight ARES cavities have six klystrons with four cavities sharing two klystrons. The upgrade plan is to add two more klystrons giving a total of eight ARES cavities with eight klystrons. An analysis of this upgrade indicates that with the additional two klystrons, the HER RF system is able to store the design beam current of 2.6 A.

In order to have the space to install the two extra klystrons, the upgrade includes the improvement of the LLRF system from analogue to digital for the remaining RF stations in the D4 area. Three of the klystrons in this area already have digital LLRF systems.

The other part of the upgrade to the HER RF system is the insertion of more RF Higher Order Mode (HOM) dampers in the SCC system. Presently, the cooling for the two installed HOM dampers limits the HER beam current to ≈ 2 A. The upgrade calls for installing six more HOM dampers so that each cavity has a HOM damper. In addition, the present chiller system for each cavity needs to be upgraded to a higher capacity chiller.

The committee has the following suggestions:

- The designed power and cavity numbers are based on the KEKB experience. With that performance, the RF system should be able to support a 2.6 A beam current for HER. Presently, the ratio of LER over HER currents is about 1.2 where the design ratio is 1.38. If the current ratio needs to be maintained for achieving the peak luminosity goal, it will imply a need for a higher than design HER beam current as the LER beam current increases. The committee suggests looking into

ways of supporting a HER beam current that is higher than the design value of 2.6 A and also what implications this might have for the HER hardware beyond the RF power system.

- Much of the RF system for both rings is from the KEKB accelerator and some of the LLRF hardware dates back to TRISTAN times. As the analogue LLRF is replaced with digital units, some of the replaced analogue hardware now becomes spares. We encourage the team to draw up a plan to replace all analogue hardware as resources and time allow.
- The extra impedance of the added HOM dampers will lengthen the beam bunch and may require higher cavity voltages to compensate for this effect. The committee suggests that this effect be checked with the beam dynamics team to ensure that this is not an issue.

3.3 QCS and IR upgrade

Beam dynamics wise, the QCS upgrade path is supported in well known principles: Making a more local solenoid compensation to reduce chromatic coupling aberrations and moving the first QCS coil closer to the IP (shortening the distance to the IP by 0.1 m) to reduce its beta functions and chromaticity, and to increase the aperture available for the beam. The presenters supported these arguments with Dynamic Aperture (DA) simulations and chromatic aberrations estimates.

Performance wise, the situation is less clear as the exact trade-offs are not presented. Changes in the IP design lead to the reduction of the detector acceptance. It should be clarified what drives the loss of the detector acceptance in a quantitative way between the addition of the solenoid in front of the QCS and the re-positioning of the first QCS coil. Furthermore, the performance improvements from a larger DA should be estimated addressing the following points:

- Will the increase in DA improve injection efficiency and allow for a reduction in β^* ?
- Is the current discrepancy between simulated and measured DA understood? Would this discrepancy remain after the QCS upgrade?
- Is the current QCS alignment well understood? Will the new QCS incorporate improvements in alignment or instrumentation, as e.g. new beam position monitors?

Technology wise, it is important to make the choice between the two superconducting materials and the number of layers. Three options are presented: Two layers with NbTi and one or two layers with Nb₃Sn. Nb₃Sn coils provide higher temperature margin in the operation but require more R&D effort. Given the timescale and resource availability for the upgrade, progress in the development work must be carefully monitored. It should also be examined whether the operation margin provided by the NbTi solution would be sufficient.

3.4 Belle II upgrade

The upgrade baseline configuration is planned to be finalized in July 2026 and to be documented in a Technical Design Report (TDR) by 2027. The goals of the detector upgrade are to enhance beam background tolerance, improve the vertex resolution and efficiency for low-momentum tracks. Belle II's strengths for photon, electron, π^0 and missing energy measurement should be enhanced, and new unique windows of discovery will be opened in electroweak precision physics with the polarized electron beam (Chiral Belle). The latter is mainly an issue for integrating the necessary machine elements without significantly disturbing the main focus on integrating luminosity; a test of the Touschek-polarization lifetime with polarized beam, taking of order a week, is foreseen in the next year but not yet scheduled; it will be a key step towards validating the feasibility of the polarized setup.

The committee is impressed by the substantial progress made on the vertex detector system (VTX), particularly regarding technology choices and design studies. Reaching a well-defined baseline by July 2026 appears realistic. The committee also welcomes the decision to construct a new central drift chamber for the upgrade.

It is noted that the collaboration is considering the introduction of an intermediate tracking and timing system (ITT) between the VTX and the drift chamber ($17 < R < 34$ cm). Based on experience with the current CDC, the committee considers the ITT to be mandatory in order to ensure sustainable operation of the drift chamber in the radiation environment expected after LS2. The collaboration is encouraged to optimise the ITT design promptly for the baseline decision, taking into account particle identification capabilities via time-of-flight for low transverse momentum tracks. Detailed simulation studies will be needed to decide on the optimal configuration of possible timing (LGAD-based) or silicon strip (CMOS-based) layers. It is a well-defined and innovative project that should help attract new resources to the collaboration. The fallback option of an inner section of drift chamber (iDC) may be worth investigating for its feasibility, but a strong focus is encouraged on making the ITT a success as baseline.

Concerning the other detectors, electronics upgrades are foreseen for the TOP, ECL and KLM. The TOP front-end electronics upgrades for low-gain operation would lead to better survivability of the PMTs; for the KLM it is proposed to operate the Barrel RPCs in proportional mode to provide improved resilience at high rates; for the ECL, new front-end electronics with faster shaping would reduce pileup noise.

Completion of the TDR by 2027 represents a tight schedule and carries schedule risk. For the definition of the new tracking system, careful consideration of space constraints in the interaction region is required. The design of the interaction region is crucial for SuperKEKB performance, and a comprehensive evaluation, including the design of new final focusing quadrupole magnets (QCS), should be performed, to define the interface between machine and detector elements in a timely manner. The committee is pleased to see that an Upgrade Project Office has been established. A strong management structure covering both the accelerator complex and the Belle II detector should oversee overall optimisation and priority setting of the upgrade project.