The Twenty-Fifth KEKB Accelerator Review Committee Report

12 September 2021
revised 10 October 2021

Introduction

The Twenty-Fifth KEKB Accelerator Review Committee (ARC) meeting was held remotely, via Zoom, on 1-2 September 2021. Appendix A shows the present membership of the Committee. All but two committee members attended the 25th meeting online. As in the previous year, due to the Covid-19 pandemic, the meeting followed an exceptional online format. All talks had been made available several days before the meeting. A close-out took place on Monday 6 September.

The Agenda for the meeting is shown in Appendix B. The slides of the presentations are available at http://www-kekb.kek.jp/MAC/2021/. Appendix C compares the required and achieved SuperKEKB beam parameters with those of KEKB. Appendix D shows a few examples of sudden large LER beam losses, which led to beam aborts in spring 2021. Appendix E presents a few snapshots from the close-out.

Since the 24th review, SuperKEKB has further carried out Phase 3 running. The Committee examined the progress of the project, the present challenges, and the proposed medium and long-term plans.

As always, the high standard of the work, in particular the remarkable quality of the presentations, impressed the Committee. The Committee acknowledges the great effort by the SuperKEKB team and by Belle II experts in preparing for this review. The Committee has also appreciated many illuminating discussions, and email exchanges, with SuperKEKB accelerator experts and various Belle II members both during and after the review.

A few weeks prior to this review, a new International Task Force for SuperKEKB was set up by KEK. A significant number of experienced and enthusiastic world experts are already contributing to this effort, in the form of three topical working groups, with noticeable results, in spite of extremely short time available so far. The Committee commends and supports this international effort.

The Committee members wrote a draft report during the meeting that was then improved and finalized by e-mail among the Committee members. The finalized report is available at **http://www-kekb.kek.jp/MAC/**.

Contents

A) Executive Summary

SuperKEKB carried out beam operation in autumn 2020 (run 2020c), and from February to July 2021 (runs 2021a and 2021b). During these running periods the vertical beta functions of both beams were kept at 1.0 mm, and the crab waist optics was implemented at 80% in the LER and 40% in the HER. A new world record peak luminosity of 3.12×10^{34} $cm^{-2}s^{-1}$ was reached in June 2021. Challenging key accelerator components, like the superconducting final focus magnet system, the collider radiofrequency system, the vacuum system, and the warm collider magnets, are all operating reliably with excellent performance. The optics is well controlled. In the injector, the positron bunch charge at the end of the linac was increased, by a factor 2.5, from 1.3 nC in summer 2020 to 3 nC in summer 2021. It is now only a factor 1.3 below the design. So far, a total integrated luminosity of 213.5 fb^{-1} has been recorded by Belle II, more than half of which was obtained in the first half of 2021. Remarkably, this progress was achieved with a limited, and shrinking, number of staff members, and during the covid-19 pandemic.

The important advances accomplished, the remaining large challenges and the noticeable task-force support from the international accelerator community underline that SuperKEKB is a highly innovative facility, of critical importance for particle physics and for the world-wide progress in colliders. We support the KEK management in making every possible effort to ensure the highest priority for SuperKEKB and to maximise available staff support, such that the required substantial workload (see specific recommendations) can be accomplished.

At present, the most important challenges are:

- Top-up injection efficiency and injection stability, including HER beam blow up in the transfer line, mitigating the consequences of accidental kicker-pulser misfiring, problematic HER two-bunch injection, septum drifts, etc.;
- Collimation and machine protection strategy, including overcoming the present bunch intensity limitations due to TMCI; developing a strategy for safe beam current increase; and understanding and avoiding the as yet unexplained sudden large beam losses in the LER;

- Medium and long-term planning including possible upgrade paths; with an overall plan of increasing the beam currents, increasing the number of bunches, and lowering β_y^* to maximize the luminosity.

The ARC has formulated recommendations on how to address the above issues.

B) Recommendations: The Committee has made recommendations throughout the different sections below. The most significant of these recommendations and a few more general recommendations are summarized here.

R1.2: Sufficient beam time should be allocated for beam studies (other than routine tuning) to better understand and characterize the machines and their limitations, and to develop solutions or mitigation measures. More beam diagnostics would be helpful. Planned, dedicated machine study periods would also enable remote participation by Task Force members and other foreign experts.

R2.1: Check the RF gun timing and perform careful RF conditioning of the QTW RF gun to recover the RF pulse width and, possibly, to improve the 2^{nd} bunch emittance.

R3.3: Develop refined procedures including triggers so that Belle II can operate closer to the background limits of its sub-detectors.

R4.2: The six LER kickers should be rewired to use a common power supply, or three power supplies each of which feeds a pair of upstream and downstream magnets, to avoid problems related to thyratron misfiring and injection impact on circulating bunches.

R4.5: Localize, identify and eliminate the source of vertical coupling in the HER injection line.

R7.6: Develop a safe plan for increasing beam intensity in documented phases/machine states, that are each formally verified for optimized performance, background and adequate machine protection.

R12.1: Establish a realistic model of the transverse impedance including accurate collimator wake fields and correct weighting with local beta functions; assess TMCI threshold for this model.

R7.2: Measure the single-bunch tune shift created by each collimator as a function of its gap, compare with theoretical expectation and verify that collimator contributions to the impedance are correctly understood.

R7.4: Further develop and study the non-linear collimation scheme (including the removal of some wiggler sections) and quantify its implications on beam optics and beam dynamics.

R8.3: Carry out more comprehensive beam-beam simulations, incl. crab waist, impedance, lattice errors, etc., to guide the upgrade path.

R9.3: Consider increasing the number of focused task-force groups to other key areas such as linac, injection, collimation and machine protection.

R9.4: Invite external international task-force members to share organization efforts for the ITF sub-task groups.

1. Overview of 2020c, 2021a and b Run

Findings and Comments:

In June 2021, SuperKEKB achieved a new world record luminosity of $3.12 \times 10^{34} cm^{-2}s^{-1}$. So far, a total integrated luminosity of 213.5 fb^{-1} has been recorded by Belle II, more than half of which was obtained in the first half of 2021.

SuperKEKB is routinely operating with the Crab-Waist collision scheme. The Crab-Waist collision enables a considerably higher bunch current product to be obtained. The Crab-Waist sextupoles are currently set at 80% and 40% of the nominal value in the LER and HER, respectively. The present settings could be further optimized with respect to luminosity and beam lifetime. The optimal Crab-Waist transformation strength should be obtained by simulations and validated by machine studies, to find the optimal balance between the maximum achievable instantaneous luminosity value, an efficient control of the beam-tail growth, and the largest possible dynamic aperture. In addition, optimization of the beam-tail growth would have a strong impact on background control during collision and injection.

The LER Touschek beam lifetime of about 8 min is consistent with expectation for the actual physical and dynamic apertures. In collision the vertical emittance blows up by about a factor of 3, from 22-25 pm to ~60 pm at fixed collimator settings, without any improvement in beam lifetime (as would be expected if the cause was the Touschek lifetime). It is possible that the collisions generate beam tails, which contribute to limiting the beam lifetime, or that the collisions further reduce the dynamic aperture. A “coronagraph” beam halo monitor is being prepared (initially for the HER); which could provide insight into the formation of beam tails.

A Transverse Mode Coupling Instability (TMCI) is limiting the single-bunch current in the LER with non-colliding beams. It is not entirely clear if the TMCI is suppressed by the collision; see later sections on beam-beam and TMCI.

Then radiation dose at the collimators is a serious issue, and is likely to get much worse in the future, at higher beam currents and shorter beam lifetime. Installation of additional shielding and the possibility of remote handling should be considered.

There were several cases where long-term solutions are being proposed before exhausting all of the simpler solutions. There are five suggested areas for improvements.

a) The RF gun was reconfigured recently, and since then the second HER bunch injection has been problematic. It is suggested that the gun be returned to the state it was in a few years ago, when 2-bunch HER injection into KEKB was excellent. The experts should try to understand the difference.

b) The coupling source in the HER injection line, which leads to a blow up of the vertical HER emittance, should be identified and removed.

c) The six LER injection kickers are powered independently and have different waveforms. This results in leakage orbit on the circulating bunches, and also means that a thyratron mis-fire kicks the whole bunch train, not just one bunch. The six kickers should be rewired to use a common power supply in order to avoid these problems. At the same time a solid-state alternative to thyratrons could be considered.

d) For the catastrophic event of 2021/06/02, it was reported that the transverse position of the beam centroid did not change at the Libera BPM, which is in a dispersive region. This means that the LER beam loss is caused by diffusion. One possible source of the catastrophic events is the noise on the RF reference line, which might have affected not only the HER, but also the LER through a beam-beam related effect, and which was cured on 29 June 2021.The events could also have been caused solely by a beam-beam flip-flop mechanism at the IP, or by either noise on the HER beam or poor injections inducing such a flip-flop behavior. A study of the past events may be able to differentiate between these sources by investigating the LER loss pattern for all the events and the relative timing of the abort triggers, previous injections and the locations of the injected bunches, as well as the beam sizes of the HER. Looking at the beam loss along the two bunch trains, there are slow and deep modulations at periods ranging from about 1 to 10 microseconds. This could provide a clue as to the mechanism.

e) The committee recommends that KEK purchase additional turn-by-turn bunch position measurement modules to be distributed around the rings, so that the origin of any future events can be more easily identified.

Recommendations:

R1.1 A strategy, with specific current steps, conditions, and checkpoints, should be worked out for increasing the number of bunches and the beam currents in a safe manner.

R1.2 Sufficient beam time should be allocated for beam studies (other than routine tuning) to better understand and characterize the machines and their limitations, and to develop solutions or mitigation measures. More beam diagnostics would be helpful, such as fast beam loss monitors and turn-by-turn beam-position monitors distributed around the ring, halo monitors, bunch-by-bunch beam size measurements, etc. Planned, dedicated machine study periods would also enable remote participation by Task Force members and other foreign experts.

2. Injector (Linac) status (e-/e+ sources)

Findings and Comments:

The injector complex is very sophisticated, serving four different rings each with different energy and charge requirements. Successful top-off injection to all rings was provided in the last year. Improvements and hardening for increased reliability have been performed and are ongoing, including more corrector magnets, replacement of aging structures, controls updates, etc. Most major systems have performed well, with a few challenges that have impacted injection efficiency.

a) The thermal e-gun provides beams with bunch charges of around 0.3 nC for the light sources and 10 nC for positron production. It has worked well through the runs 2020c to 20201b without any significant troubles.
b) The e+ generation and capture system has performed well too. The new Flux Concentrator (FC), made of improved copper alloy, replaced the one damaged by a discharge and has worked very well. Since run 2020c, the new FC has been operated successfully without any significant problems, apart from occasional thyratron noise. The latter was also reduced by some modifications.
c) The nominal e+ bunch charge has been improved from 1 nC to 2.5 nC at the end of the linac. The e+ bunch charge after the target already reached 5 nC, and the best positron production efficiency was 0.59 which is already beyond the design value of 0.58. A best yield of 3 nC at the end of the linac was obtained in studies (goal is 4 nC). The remaining challenge is to reduce beam loss between the e+ capture section and the Damping Ring (DR). Installation of additional pulsed steering magnets is planned to address this issue. The best e+ emittance at 2.3 nC already satisfies the design

specification, however, the horizontal emittance is slightly worse than expected. In the fall 2021 autumn run, the low emittance DR optics will be tested to address this issue.

d) The photocathode RF e- gun is utilized for generating the low emittance e- beam for the HER. The system consists of a quasi travelling wave (QTW) type cavity, Ir7Ce2 photocathode, and 2 laser systems. The 2nd laser is a backup, but is also used for cathode cleaning. A Diffractive Optical Element (DOE) has been installed in the first laser line after run 2020b to reshape the transverse laser profile (flat-top distribution) and has produced a more uniform beam with reduced jitter. Unfortunately at the end of March, during an investigation of the amplifier module, a large discharge occurred in the RF gun cavity. After this event, the cavity power had to be decreased and the RF pulse width was shortened from 1000 ns to 850 ns to prevent further discharges. This impacted the emittance of the second bunch, leading to greatly reduced injection efficiency. RF conditioning is planned in the startup stage of autumn operation in an attempt to recover nominal operation of the RF gun.

e) Some major upgrades have been considered for the mid-term or long-term, including structure movers and an energy compressor for the electrons. However, their specific merits for the beam performance have not been shown to, nor reviewed by the ARC, or any external experts.

Recommendations:

R2.1: Check RF gun timing and perform careful RF conditioning of the QTW RF gun to recover the RF pulse width and, possibly, to improve the 2nd bunch emittance.

R2.2: Find and eliminate the source of emittance blow up in the beam transport to improve injection efficiency and minimize radiation damage to the collimators and detector.

R2.3: Sufficient beam time should be allocated for linac beam studies to achieve and maintain optimum injection performance

R2.4: Commission the additional orbit feedback using new pulsed steering magnets to increase e+ yield at the end of the linac

R2.5: Continue the program of reliability hardening by replacement of damaged accelerator structures, magnet power supplies, controllers, etc.

R2.6: The mid-term and long-term upgrade plans must be reviewed by the ARC, ITF, and/or external experts.

3. Belle II status

Findings and Comments:

Belle II has, to date, recorded 213.5 fb^{-1} on or near the Y4S resonance with an 89.5% efficiency. This is a great start. They are starting to publish world competitive particle physics results. Most of the SuperKEKB 2021a-b beam runs were used for data delivery to Belle II. Over the past year the Belle II collaboration has shown flexibility by using many remotely located people to help run operation shifts to minimize person-to-person contacts. Over the past year, the collaboration has improved event triggering, data collection, and the recovery procedures after beam aborts. A plan is in place to take data above the Y4S for 15 to 20 days of the 2021c run.

The detector issues during the recent beam runs concern large backgrounds, high trigger rates, and radiation damage to sub-detectors. These effects are related to the SuperKEKB beam size enlargement with the beam-beam effect and also due to beam particle losses from

Touchek, beam-beam, and top-up injection effects related to the tight settings of collimator jaws for background protection, and larger-than-design emittance of the injected beams. Belle II is working with the accelerator team to make the collimation more robust and the injection more efficient, and to optimize the early bake-out running.

Since the luminosity in SuperKEKB will need to increase in the future, to achieve the integrated luminosity that Belle II requests (by increasing the number of bunches and beam currents, and lowering betay*), Belle II may need to make upgrades to handle potentially higher backgrounds and more lost particles. As an example, a recent large beam loss in May (still under review) partially damaged the Belle II PXD. A new PXD will be installed in LS1. Future studies will explore if an improved QCS aperture and location can help with aperture restrictions. Belle II needs to investigate the possibility of improving the other sub-detectors to operate at high backgrounds if needed be looking at improving other sub-detectors to operate at high backgrounds if needed , e.g. the Time-of-Propagation detector (TOP).

Recommendations:

R3.1 Determine if studies to improve injection can be done during the bake-out beam time early in each running cycle.

R3.2 Continue QCS improvement studies which may help with aperture restrictions and/or background.

R3.3 Develop refined procedures including triggers so that Belle II can operate closer to the background limits of its sub-detectors.

R3.4 Evaluate if specific future Belle II hardware upgrades could help tolerate higher beam related backgrounds.

R3.5 Develop detailed criteria for the injected beam using detector backgrounds, beam lifetimes, and injection efficiency to indicate when a pause in data taking should be taken so that better injection can be restored.

4. Beam injection

Findings and Comments:

Good efficiencies of single bunch injection for both LER and HER were achieved in the 2020c, 2021a and 2021b runs. The injection systems supported the achievement of a total 213.5 fb^{-1} integrated luminosity in 2021 so far. The efforts by the SuperKEKB team are impressive. However, injection remains one of the critical issues for collider operation with the following unsolved problems:

The six LER injection kickers are powered independently and have different waveforms. This results in leakage orbit change for the circulating bunches, and it also means that a thyratron mis-fire kicks the whole bunch train, and not just one or two bunches, with disastrous consequences.

In the last ARC meeting, the committee was shown the optics measurements in the HER injection line. Things start to go wrong at around 240m, near QD4E. The plot presented reveals a coupling from the horizontal to the vertical plane starting at QD4E. The error could be caused, e.g., by a shorted coil in QD4E or even by a piece of steel trapped inside the magnet. This could be checked in the tunnel, but the element causing the problem can be found offline by initiating x, x’, y and y’ kicks at the beginning of the beamline, and tracking the orbit differences both forwards and backwards from each end, looking for a discontinuity. The fit should be good in the front and back of the line, but there will be a discontinuity near QD4E. This technique is much better suited for error identification than complex orbit-fitting with multiple parameters. Improving the injected emittance will help the injection efficiency.

Another issue for the injection efficiency is the much lower efficiency of the second bunch injection compared with the first bunch. The 2nd bunch injection efficiency in HER is extremely low, but it had been successfully operated for 6 days in July 2019. It appears that the emittance of the second electron bunch is larger than for the 1st bunch, which affects the injection efficiency of the 2nd bunch in the HER. At the LER, the injection efficiency of the 2nd bunch is also much worse than for the 1st bunch. This situation is not consistent with simulations. Unstable injection is observed in the HER, with a lot of tuning required every day and every shift, and even resulting in beam aborts.

The positron damping ring mitigates the beam emittance blow-up for the beam injected into the LER. In addition, it reduces the backgrounds coming from the linac and from the transport line upstream of the collider, and it stabilizes the positron beam injection. For the electron beam, no such stabilizing mechanism exists at present.

When some collimators were opened, the LER injection efficiency increased, while the HER efficiency did not change.

The LER beam background at Belle II is larger than the HER background. For the HER beam, the background at the VXD is low, in spite of its low “raw” injection efficiency.

All known problems related to injection efficiency have been listed and are well analysed.

The proposed new straight transport lines using the AR-BT tunnel can be a possible solution to solve the horizontal emittance growth problem. It will at least reduce the R56 and coherent/incoherent synchrotron radiation drastically.

Recommendations:

R4.1: Check the injection hardware for both LER and HER, ensuring that the equipment works with the design parameters under the correct circumstances. In particular, the conformity of the waveform of the kicker power supplies needs to be checked.

R4.2: The six LER kickers should be rewired to use a common power supply, or three power supplies each of which feeds a pair of upstream and downstream magnets, to avoid problems related to thyratron misfiring and injection impact on circulating bunches. At the same time a solid-state alternative to thyratrons could be considered.

R4.3: Try to monitor the pulsed power supplies during injection as soon as possible.

R4.4: Machine studies on injection are strongly encouraged, with appropriate priority. The orbit and dispersion leakages out of the injection orbit bump need to be measured and mitigated.

R4.5: Localize, identify and eliminate the source of vertical coupling between BT1 and BT2 in the HER injection line.

R4.6: Pursue the design of the straight transport line and examine its performance.

5. Beam Background and MDI

Findings and Comments:

The combined background team of Belle II and the accelerator group have collected an impressive amount of information regarding the various background sources of SuperKEKB.

They have obtained information about beam-gas backgrounds and backgrounds related to Touschek scattering, the two principal steady-state non-luminosity related backgrounds for the detector. Based on current measurements and extrapolations these backgrounds are at acceptable levels and are not limiting the beam currents at present. This partially came about by relaxing some detector limits, notably the TOP detector. This has allowed for a more relaxed collimator setting configuration, which improved the injection efficiency and beam lifetime.

In addition, a great deal of effort has gone into improving the GEANT4 model of the detector and the accelerator beamlines up to +/-30 m from the IP. This has led to a ratio of the data to Monte Carlo (MC) simulation of order 1 for the majority of the sub-detectors in Belle II - a very impressive achievement. This detailed modeling has also led to a better understanding of the observed neutron background levels around and inside the detector. The local sources are now being more carefully shielded and the MC can now be used to optimize further shielding efforts. Efforts are ongoing to further improve the MC detailed geometry in order to obtain more precise information from the local neutron sources.

The two teams have also greatly improved the simulation of the collimators around each ring. The background team has developed sophisticated algorithms for obtaining optimal collimator setting configurations that have been verified with machine data. This understanding has been used to obtain hints about the location of the start of the catastrophic beam loss events.

The catastrophic beam loss events are presently the most problematic backgrounds for the detector. These events occur very rapidly (in a few turns) making it very difficult to abort the stored beam in time to prevent damage to the detector and to machine equipment such as collimators. Some of these events also quench the final focus doublets.

Beam loss detection benefited from the introduction of the new CLAWS diagnostic, which is 4.4 microsec faster, on average, in issuing abort kickers than the diamond sensors. The CLAWS background detector response time can be further improved.

The recently created database containing all the aggregate data concerning the beam abort events has proved to be a powerful working tool in order to perform not only a later analysis of the beam disruptions, but also to investigate the need for new diagnostics and their sensitivity.

There are also backgrounds from poorly injected bunches and it is even possible that some poor injection pulses might cause the start of a catastrophic event at a later time, indirectly through a slow beam-beam mechanism, by blowing up some electron or positron bunches along the train

Recommendations:

R5.1 Continue the excellent effort that has been started in studying the catastrophic beam loss events and in trying to locate the source of these events.

R5.2 Continue to improve background simulation tools in order to understand and eliminate the remaining 20-25% discrepancy between luminosity background predictions and measurements for all the different detector components.

R5.3 The committee agrees with the background team's analysis that faster diagnostics should be placed at various locations around both rings in an attempt to localize the source of fast-loss events. These could be turn-by-turn beam-position monitors, dedicated background detectors (like CLAWS), as well as more temperature sensors at locations where radiation levels are high (i.e. at collimators, photon stops, etc.)

R5.4 Support for the injector upgrade and improvement in injector diagnostics is also a high priority.

R5.5 Beam aborts during injection might be considerably reduced by revising the injection kicker pulser configuration (see section 4).

6. Bunch feedback system and luminosity

Findings and Comments:

The SuperKEKB bunch-by-bunch feedback systems are iterative enhancements of the systems originally developed for KEKB, other colliders and light sources. They have been routinely used at SuperKEKB and have demonstrated their effectiveness at controlling instabilities and also for beam diagnostics. Information from the transverse systems has been used to reveal the most unstable mode (-1) as well as to show the growth and damping rates achieved by the systems. The presentations in this MAC highlight some studies of "noise" in the transverse feedback, and the impacts it had on luminosity and operating current starting in April 2021. As documented in the presentation, the origin of these difficulties was traced to an oscillating power supply in the RF timing and signal distribution system. This problem was not from "noise" in a technical sense; it was from a coherent signal on the RF reference signal.

Once this broken hardware was found on June 29 and replaced, the transverse feedback, and machine luminosity, resumed the historical good behavior.

The impact of "noise" in the feedback processing was studied in KEKB with an earlier version of the feedback, and in 2011 studies showed that coherent signals in the feedback signal on one beam could excite motion of the opposing colliding beam, impacting the luminosity. This effect was seen at high system gains with amplified receiver noise. Future SuperKEKB machine configurations, or higher currents, may well require higher loop gains to fight instabilities. To prevent this noise mechanism from having significant future impact, the transverse signal receivers are being evaluated. They could be reconfigured with different gain partitioning, and/or a different technology of bandpass filter, and achieve a lower system noise floor. If higher system gains are necessary in the future, this modification would have a lower noise floor on the controlled damped beam.

A narrow-band dedicated system to suppress the resistive-wall instabilities could be helpful, if the performance of the present bunch by bunch system is largely consumed by that mode. This approach may require an additional low mode kicker and amplifier system. While it could provide higher gain at the low modes, the added kicker also adds extra impedance to the machine which may be detrimental. However, a hybrid system using the existing kicker could conceivably relax the burden on the bunch-by-bunch system.

Recommendations:

R6.1 Use the "Lessons Learned" from the April RF signal distribution problem to make a system checklist of critical signals required by, and generated by, the feedback system. Identify aging system components for refurbishment or replacement. Confirm the spares inventory of critical operational modules (are they in good working order?).

R6.2 Evaluate the noise floor in a reconfigured receiver front end, and measure such a system in the lab. The quantified improvement, and potential improvement in the residual noise on the beam, can be explored in simulations as well as in machine physics experiments. A decision can then be made if the system should be upgraded.

R6.3 As the total world community of feedback experts is small, the committee encourages the collaboration of the KEK feedback experts with other laboratories working on colliders and high current facilities that require beam instability feedback. Everyone would benefit from this exchange of skills, technology and operational experience.

R6.4 Using the available data, estimate the resistive wall instability growth rate at the design current and verify that the present system has adequate margins up to the design current.

7. Beam collimators (TMCI, damage, plan)

Findings and Comments:

The areas of collimation, collimator-induced impedance, the associated TMCI threshold, detector background and protection against irregular beam loss and associated machine damage remain critical. They continue to limit the progress of the SuperKEKB physics run and its performance. The observation of machine and detector damage is worrisome. The SuperKEKB team has spent an impressive amount of work and effort in extending the collimation system, optimizing its performance reach and reducing background and damage risk. The work addresses the right questions, identifies important issues and develops interesting aspects for a mitigation strategy. Given the unprecedented requirements in SuperKEKB, the remaining challenges are difficult and require careful attention.

Recommendations:

R7.1: Develop a dust-beam interaction model to study whether (any of) the large beam losses and aborts could be attributed to such dust events.

R7.2: Measure the single-bunch tune shift created by each collimator as a function of its gap, compare with theoretical expectation, and verify that collimator contributions to the impedance are correctly understood.

R7.3: Assemble an impedance model of the full SuperKEKB machine, allowing an overview of contributions and an impact estimate for any machine change.

R7.4: Further develop and study the non-linear collimation scheme (including the removal of some wiggler sections) and quantify its implications on beam optics and beam dynamics.

R7.5: Assemble an aperture model of SuperKEKB that includes the phase space cuts for each existing or planned collimator and specifies the aperture to be protected for each phase (e.g. IR doublet aperture versus IP beta with allowances for orbit imperfections etc.). Include the non-linear collimator into this model.

R7.6: Develop a safe plan for increasing beam intensity in documented phases/machine states, that are each formally verified for optimized performance, background and adequate machine protection.

8. Discussions on the long-term operation plan in the last year

Findings and Comments:

The operations plan for the past year for SuperKEKB was discussed. Very solid advances were achieved in the accelerator parameters. The operations plan for the next year to July 2022 was given but with only high-level details. The committee recommends making more detailed plans for the next year so that all accelerator groups will know precisely what is expected from them and Belle II can plan accordingly.

The list of potential upgrades for SuperKEKB is extensive and has been worked on for a while. The SuperKEKB team is analyzing which upgrades would be the most beneficial. It would help the project (and the review committee) if the required manufacturing preparation time and needed down time for installation would be listed for each potential upgrade.

Recommendations:

R8.1: Make a more detailed operations plan for the next year, giving, as precisely as possible, goals for each group.

R8.2 List the preparation time and required downtime needed for implementation for each of the potential accelerator upgrades.

R8.3 Carry out more comprehensive beam-beam simulations, incl. crab waist, impedance, lattice errors, etc., to guide the upgrade path.

R8.4 Analyse the impact of alternative upgrade paths on the integrated luminosity.

9. Kickoff of International Task Force for SuperKEKB upgrade

Findings and Comments:

KEK has assembled a powerful International Task Force (ITF) to address the challenges of the SuperKEKB upgrade. The ITF consists of a large number of experts, and is therefore divided into technical groups to tackle the various issues. The ITF is under the coordination of a highly respected KEK scientist.

Recommendations:

R9.1: Working with the technical task force groups, define study goals and expectations so that each will work toward defined end points.

R9.2: The present work on performance optimization should be complemented with a machine protection sub-group that ensures a safety and risk responsible planning. Additional experts from machine protection (e.g. at CERN/LHC) might provide useful input.

R9.3: Consider increasing the number of focused task-force groups to other key areas such as linac, injection, collimation and machine protection.

R9.4: Invite external international task-force members to share organization efforts for the ITF sub-task groups.

10. International Task Force Joint Meeting: Discussion on Beam-Beam

Findings and Comments:

This activity had an excellent start. Ideal weak-strong beam-beam simulations including the lattice (without errors) and, sometimes, including the space-charge effects, indicate a maximum achievable luminosity of no more than ~$3x10^{35}$ cm-^{2}s^{-1}, which is a factor two below the present revised target. This suggests that reaching the post-LS2 target of $6x10^{35}$ cm-^{2}s^{-1} is extremely challenging. Achieving it might require significant new ingredients or concepts (similar, in scope, to the addition of the crab waist scheme and rebuilding the IR as was done at DAFNE) and with beam parameters rather different from the design.

The vertical beam-beam parameter at present is ~0.037, more than a factor 2 lower than at KEKB. Collision offset noise was found to be important, both in the real machine and in simulation. The offset fluctuations are large, comparable to the beam size. This noise significantly reduces the average specific luminosity and blows up the vertical emittance.

The interplay of beam-beam effects with impedance, electron cloud, offsets, etc. needs to be considered.

Recommendations:

R10.1: Once a realistic impedance model is established (see Section 12), carry out simulations of the combined effect of beam-beam and impedance.

R10.2: Measure and quantify the beam-beam noise and the resulting offset fluctuations (magnitude and frequency spectrum), which are also seen in the luminosity; track down and further eliminate, or suppress by feedback, the remaining noise sources.

R10.3: Perform beam studies to explore the presence, or not, of the coherent x-z beam-beam instability.

11. International Task Force Joint Meeting: Discussion on Accelerator Optics

Findings and Comments:

A large number of activities are on-going in various laboratories (KEK, SLAC, CERN, INFN, ESRF). Translating the SuperKEKB lattices from SAD to MAD-X and LEGO are the first tasks being addressed by collaborators.

A new optics with equal synchrotron tunes has been requested by the beam-beam sub-group.

The optics sub-group will present their proposal of adding sextupoles at the image points of the IPs to improve momentum acceptance.

A new, more refined, optics model based on magnetic measurements is under construction.

Investigation of nonlinear collimator optics has started.

An ARC committee member presented recent results from the "compromised optics match" which could be a good option to avoid installing new magnets (exact matching needed 16 new magnets in the previous proposal).

Communication issues have been identified, but should not pose a problem once the sub-group starts regular meetings.

Recommendations:

R11.1: Increase communication and have regular meetings. The first meeting should be held as soon as possible.

R11.2: The optics tasks should be prioritized, with time estimates, so as to optimize efforts along with identifying the optics tasks where collaborators can be efficient.

R11.3: Lattices for the new optics model based on magnetic measurements and for the IR upgrade foreseen in 2031 to relocate quadrupoles towards the IP could start to be shared.

R11.4: Linear and non-linear optics measurements with comparisons to the model should be considered as part of the sub-group's activity in order to prepare for the reduction of betay* towards nominal design, where these effects could limit performance.

12. International Task Force Joint Meeting: Discussion on TMCI and Impedance Matters

Findings and Comments:

This activity has started recently, and significant progress has been made in a short time. Both tracking codes, like PyHEADTAIL, and various Vlasov solvers are available to compute the TMCI thresholds. The longitudinal wakefield dynamics, i.e., bunch lengthening and microwave threshold, was successfully benchmarked between two different codes. Small discrepancies are attributed to a different treatment of coherent synchrotron radiation.

At present, no complete transverse impedance model for SuperKEKB exists which includes the collimators, that are likely to be the dominant contribution. A first assessment of the effect of the longitudinal impedance, with a much simplified transverse impedance model, did not reveal a large effect on the TMCI threshold. This is quite different from the case of FCC-ee, where including the longitudinal impedance reduced the TMCI threshold by almost a factor of two.

A first attempt was made to explore the effect of a localized impedance. For a specific, resonant choice of betatron and synchrotron tunes, the TMCI threshold itself was almost unaffected, but the vertical beam size started to increase significantly, well below the TMCI threshold.

Collimators normally feature both geometric and resistive wake fields, and these two are not entirely independent. Codes like GDFIDL can, in principle, compute the total wakefield formulae (as was done for the LHC collimators, e.g.). However, the curves presented in some of the presentations assume a perfect conductor and only consider the geometric wakefield. The importance of the resistive collimator wake field was illustrated by the low TMCI threshold when the carbon collimator was installed. It would be helpful to compute and compare wake fields (impedances, kick factors) for a carbon collimator, a tantalum collimator, and the newly developed hybrid collimator (copper plating on tantalum layer on top of carbon).

A clear distinction of dipolar and quadrupolar impedance is important for the evaluation of the TMCI threshold.

Many of the task force studies and efforts to date have been simulations. These are insightful and allow exploration of many possible ideas without requiring dedicated machine time. There may be great value in doing parasitic and dedicated machine measures with existing diagnostics to see how well the models are replicating the machine conditions. A classical impedance study measuring bunch length vs bunch current is an example. The synchrotron light diagnostics and streak camera could be used parasitically, and also in a dedicated study to look at how well the impedance models match the physical machine. Studies of tune shifts vs collimator positions are another class of experiments that can help calibrate the models.

Recommendations:

R12.1: Establish a realistic model of the transverse impedance including accurate collimator wake fields and correct weighting with local beta functions; assess the TMCI threshold for this model.

R12.2: Perform a systematic study of the TMCI threshold as a function of vertical tune.

R12.3: Measure the magnitude of individual collimator wake fields in beam studies (e.g. single-bunch tune shift versus collimator gap) and compare with expectations.

R12.4: Explore in simulations, and/or beam experiments the possibility to suppress the TMCI instability with a larger positive chromaticity or with a negative chromaticity used with a transverse feedback.

R12.5: Examine the possibility to increase the synchrotron tune through a higher momentum compaction factor in the LER.

R12.6: Use the existing streak camera to directly observe and measure, turn-by-turn, the onset of a beam instability, in order to gain important insight into the nature of the limiting instabilities, like TMCI, and validate the model of bunch lengthening.

R12.7: Continue to study the collimator design and material choices to balance resistive and geometric wakes, and the robustness against catastrophic beam loss.

Appendix A

KEKB Accelerator Review Committee Members

Frank Zimmermann, Chair	CERN
Ralph Assmann	DESY
Paolo Chiggiato	CERN
John Fox	Stanford University
Andrew Hutton	JLab
In Soo Ko	POSTECH (excused)
Catia Milardi	INFN-LNF
Katsunobu Oide	CERN and KEK (ret.)
Evgeny Perevedentsev	BINP
Matt Poelker	JLab (excused)
Qing Qin	ESRF
Bob Rimmer	JLab
John Seeman	SLAC
Michael Sullivan	SLAC
Tom Taylor	CERN (ret.)
Rogelio Tomas	CERN
Tadashi Koseki	KEK, Director of Acc. Laboratory, Ex Officio Member
Yusuke Suetsugu	KEK, Head of Acc. Division III, Ex Officio Member
Makoto Tobiyama	KEK, Head of Acc. Division IV, Ex Officio Member
Kazuro Furukawa	KEK, Head of Acc. Division V, Ex Officio Member
Mika Masuzawa	SuperKEKB International Task Force Coordinator

Appendix B

Agenda of the 25th KEKB Accelerator Review Committee

September 1 (Wednesday)		
19:50 - 20:00	Committee Executive Session (Zoom)	
20:00 - 20:07	Welcome address	M. Yamauchi
20:07 - 20:10	Welcome address	T. Koseki
20:10 - 20:40	Overview of 2020c, 2021a and b run	Y. Ohnishi
20:40 - 21:00	Injector (Linac) status (e-/e+ sources)	M. Satoh
21:00 - 21:20	Belle II status	K. Matsuoka
21:20 - 21:30	Break	
21:30 - 21:50	Beam Injection	N. Iida
21:50 - 22:10	Beam background and MDI	H. Nakayama
22:10 - 22:30	Bunch feedback system and luminosity	A. Morita
22:30 - 22:50	Beam collimators (TMCI, damage, plan)	T. Ishibashi
22:50 - 24:00	Committee Zoom Meeting	
September 2 (Thursday)		
19:50 - 20:00	Close-out	
20:00 - 20:20	Discussions on the long-term operation plan in the last year	Y. Suetsugu
20:20-20:30	Kickoff of International Task Force for SuperKEKB upgrade	M. Masuzawa
20:30 - 21:20	International Task Force Joint Meeting :Discussion on beam-beam	D. Zhou
21:20-21:30	Beak	
21:30-22:10	International Task Force Joint Meeting :Discussion on optics	A. Morita
22:10 - 22:50	International Task Force Joint Meeting :Discussion on TMCI and impedance matters	M. Migliorati
22:50 - 24:00	Committee Zoom Meeting	
September 6 (Monday)		
19:00 - 20:00	Committee zoom meetings (Closed session)	
20:00 - 21:00	Review close-out, comments and suggestions	ARC members

Appendix C

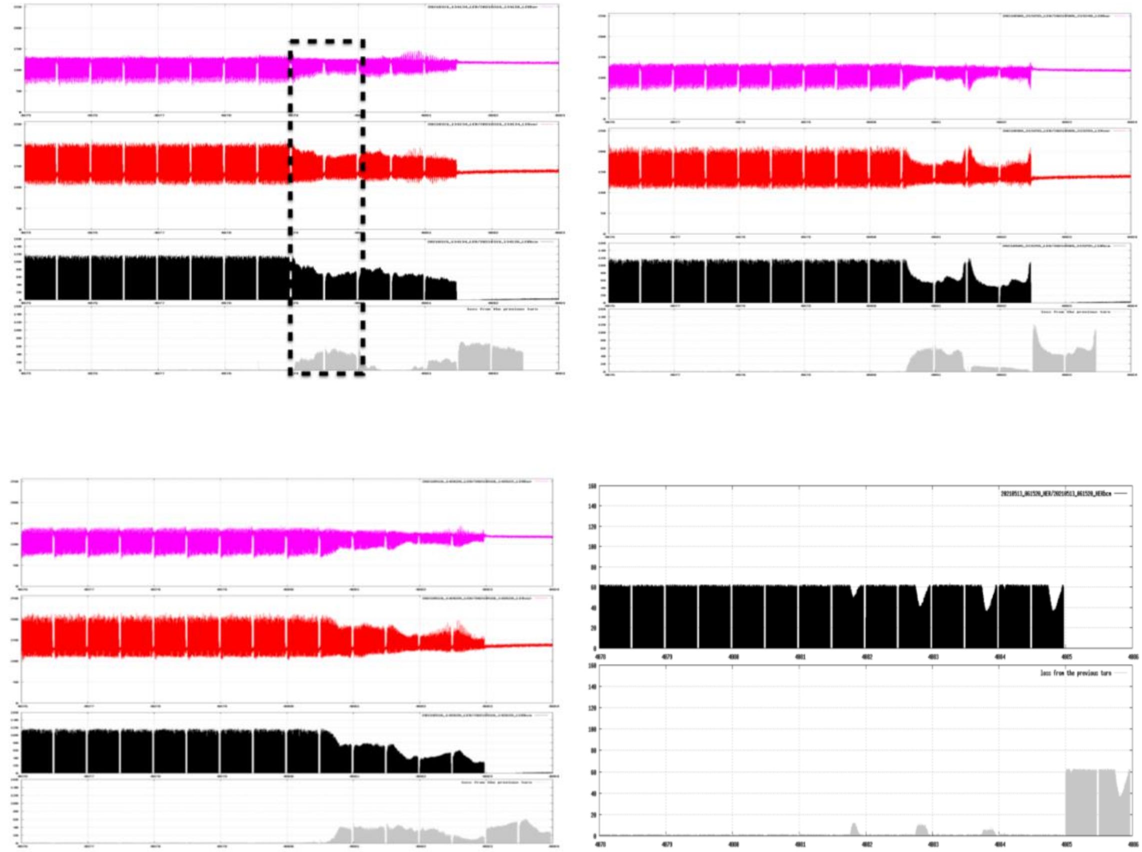
Required and achieved SuperKEKB parameters and comparison with KEKB

parameter	KEKB w Belle		SKB 2021 w Belle II β_y^* = 1.0 mm CW		SKB Design	
	LER	HER	LER	HER	LER	HER
E [GeV]	3.5	8	4	7	4	7
β_x^* (mm)	1200	1200	80	60	32	25
β_y^* (mm)	5.9	5.9	**1.0**	**1.0**	0.27	0.30
ε_x (nm)	18	24	**4.0**	**4.6**	3.2	4.6
ε_y (pm)	150	150	**80**	**80**	8.6	12.9
I (mA)	1640	1190	**790**	**687**	3600	2600
n_b	1584		1174		2500	
I_b (mA)	1.04	0.75	0.673	0.585	1.44	1.04
ξ_y *	0.098	0.059	**0.046**	**0.030**	0.069	0.060
L_{sp} ($10^{30}cm^{-2}s^{-1}$ mA^{-2})	17.1		**67.6**		214	
L ($10^{34}cm^{-2}s^{-1}$)	2.11		3.12		80	

*The beam-beam parameter is computed without hourglass factor or any geometric factors.

Appendix D

A few examples of fast large losses from spring 2021 (D. Zhou, MDI Task Force meeting, 27 May 2021)



Appendix E

A few snapshots from the close-out of the virtual 25th ARC meeting.