The Twenty-Fourth KEKB Accelerator Review Committee Report

20 July, 2020

Introduction

The Twenty-Fourth KEKB Accelerator Review Committee (ARC) meeting was held remotely, via Zoom, on July 15, 2020. Appendix A shows the present membership of the Committee. All committee members attended the 24th meeting online. Due to the Covid-19 pandemic, the meeting followed an exceptional format, with a reduced number of presentations. All talks had been pre-recorded and had been made available from midnight of July 12. July 15 was devoted to questions and comments regarding these presentations. This was followed by discussions between the Committee members, which continued on July 16 and July 17. A close-out took place on July 20.

The Agenda for the meeting is shown in Appendix B. The slides of the presentations are available at http://www-kekb.kek.jp/MAC/2020/. Appendix C compares the required and achieved SuperKEKB beam parameters with those of KEKB. Appendix D summarizes parameters of the injector complex. Appendix E presents a few snapshots from the close-out.

Since the 23rd review, SuperKEKB has further carried out the Phase 3 running, with nearly the full Belle II detector installed. The Committee examined the progress of the project and the present challenges.

As always, the high standard of the presentations, in particular the remarkable quality of the pre-recorded 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 with SuperKEKB accelerator experts and various Belle II members both during and after the review.

As highlighted in a previous report, the next generation of new staff is important for the success of SuperKEKB operation over the coming decades. The ARC is concerned that the total number of KEKB accelerator staff continues to decrease. For example, succession planning may be needed for the interaction region, the superconducting final quadrupoles, beam diagnostics, dynamic aperture and beam lifetime simulations. International collaboration could be expanded, e.g. with CERN, IHEP and BNL/JLab (EIC) in the USA, which may provide additional expertise and resources.

The ARC also suggests organizing dedicated small reviews on specific topics more frequently between the main ARC meetings, if necessary or helpful. These can be domestic or international, depending on the issue and situation. For example, mini-review of the SuperKEKB upgrade plan or of the crab-waist optics for low β_y^* could be considered.

The most important recommendations of the Committee were presented to the KEKB staff members on July 20. The Committee wrote a draft report during the meeting that was then improved and finalized by e-mail among the Committee members. The report is available at **http://www-kekb.kek.jp/MAC/** .

Contents

A) Executive Summary

SuperKEKB has carried out beam operation in autumn 2019 (run 2019c), and from February to July 2020 (runs 2020a and 2020b). During these running periods the vertical beta functions of both beams were squeezed in steps, down to 1.0 and even 0.8 mm, a crab waist optics was successfully established for both beams, and with this optics a world record peak luminosity of 2.4x10^{34} $cm^{-2}s^{-1}$ was reached at 1 mm β_y^*. The β_y^* of 0.8 mm also sets a new world record for colliders. The LER optics has been modified to increase the positron-beam horizontal emittance and to improve Touschek lifetime. Even with Belle-II missing most of layer 2 of the PXD, the Belle II physics performance is fine. Detector upgrades (PXD and MCP-PMT) are planned for 2022. An integrated luminosity of about 67 fb^{-1} was delivered to Belle II in run 2020b, i.e. during about three months since April 2020.

At present, the most important challenges are:

1) detector background, beam lifetime and injector/injection performance;
2) electron beam emittance growth in the beam transfer line 2, possibly due to an obstacle;
3) strategy for further squeezing β_y^* in the fall of 2020 and in 2021, and strategy for raising the beam current;
4) long-term plan including possible upgrade paths.

The ARC has formulated recommendations on how to address the above issues; it supports an ambitious luminosity goal and allocation of sufficient operation time for the coming year.

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.

1. We strongly recommend extending the fall/spring Belle II/SuperKEKB run in 2020/2021 by about 45 days to allow Belle II to reach an integrated luminosity of about 240 fb^{-1} by March 2021, which should enable some initial world-leading physics results on B physics and the dark matter sector. This extension will allow many of the SuperKEKB state-of-the-art accelerator improvements expected in the fall 2020 run to be applied to luminosity running (R7.1).

2. During the summer shutdown, make a focused effort to improve the reproducibility of the ring magnets to shorten the recovery time after each maintenance or major intervention (R1.1).
3. Pursue the IR optics development for crab waist collision schemes at smaller β_y^* in order to find a set up without a serious reduction of the dynamic aperture (R6.4).
4. Pursue aggressive linac/injector improvements including the pulsed magnet upgrades, new flux concentrator and emittance reduction to reduce anticipated future IR backgrounds and improve beam delivery (R7.4).
5. Allocate about one hour for systematic background data taking after every major change in beam optics, in addition to a few comprehensive 8 hour background studies per running period (R4.1).
6. Over the next year or so, perform beam measurements to determine if the proposed QCS upgrades with larger apertures are absolutely required to get to the design luminosity or to half the design luminosity (R7.2).
7. Determine which technical studies (essential beam studies and QCS coil parameter studies) need to be carried out now, before a decision can be made, within about 2 years, on starting construction of new QCS quadrupoles (R7.6).
8. Evaluate a backup plan to simply increase the luminosity with the existing hardware to about 2-3 $\times 10^{35}$ $cm^{-2}s^{-1}$ (with small upgrades but without major upgrades and the associated long installation downtimes and serious recommissioning) and then integrate luminosity for about 10-12 years at 7-8 months per year to obtain an integrated luminosity of 50 ab^{-1} by 2032-2034 (R7.8).

C) Findings and Comments

1. Overview of 2020a and b Run

Findings and Comments:

As commissioning and operations proceeded in parallel in the spring of 2020, SuperKEKB reached a new world luminosity record of 2.4×10^{34} $cm^{-2}s^{-1}$, a record previously held by KEKB. This excellent achievement enabled a record integrated daily luminosity of 1.5 fb^{-1}, which is the most important parameter for the experimenters. The Committee would like to congratulate everyone involved in reaching these impressive milestones.

Achieving these milestones validated the design choices made in SuperKEKB, many of which had not been used previously in a collider. The nanobeam scheme (originally proposed by Pantaleo Raimondi for the SuperB project) proved effective, and was completed by an elegant implementation of the crab-waist collision scheme, realized only with the existing interaction-region sextupoles (as first proposed and developed by Katsunobu Oide for the FCC-ee), with a quick recabling and addition of new power supplies for them in the winter shutdown. These techniques resulted in the lowest β_y^* ever achieved in a collider (0.8 mm) as well as in the smallest vertical beam size at the interaction point (224 nm).

As was to be expected, these achievements did not come easily. Several new optics problems were discovered and partially resolved. The rotatable sextupoles installed in the LER were activated to reduce the chromatic *x*-*y* coupling at the collision point. The horizontal emittance of the LER beam was increased by a factor of 2.5 to reduce beam loss due to the Touschek effect. A rather large horizontal angle (0.59 mrad) at the collision point was introduced to minimize the HER synchrotron radiation background during injection. This bump might be required due to the unexpectedly large emittance of the injected e^- beam; it might also perhaps be compensating for a misalignment of the HER quadrupoles (QCS) on the incoming side.

The beam quality from the RF gun has been improved week by week, and the concurrent laser cleaning tried at the end of June looks quite encouraging. The pulse-to-pulse beam flavor/energy/orbit control through the linac including the e^+ damping ring has been properly working, with a fix on the pulsed magnet control software. The injection quality was improved by installing a permanent magnet skew quadrupole between the kickers to cancel the coupling effect induced by the electron-clearing permanent magnets installed around the vacuum chamber. This coupling compensation will be further optimized with a rotatable, electromagnetic skew quadrupole. Details were presented by M. Satoh.

The beam background due to the injection continues to be a major problem as it is one of the main limitations of the beam currents. For the LER, beam-gas scattering still is the dominant background source. Background control demands tight collimator settings, which in turn limit the beam lifetime and increase the required injection current to replace the lost beam. In fact, even with the tight settings, with single beams, both the HER and LER injection efficiencies are very high. However, beam-beam effects rapidly reduce the injection efficiencies to 10-20% at the highest beam currents. So beam-beam effects are the dominant source of low-injection efficiency. This is further supported by the observation that changing the crab-waist strength has a large effect on injection efficiency at high current, i.e. introducing the crab waist clearly improved the injection efficiency. The background situation was surveyed in a dedicated talk by H. Nakayama.

The injected beam current and beam quality are not yet optimized. The positron yield is significantly lower than the design, partly due to a much-reduced current of the flux concentrator. Two-bunch positron operation has not yet been successfully established. The electron emittance is higher than design in the linac and it increases dramatically in the BT2 area of the electron line. Dipole magnets were moved in the ECS to reduce the residual dispersion and 11 of 16 permanent magnet skew quadrupoles were installed to reduce the coupling. The summer shutdown should be used to complete this work, and also to look for other anomalies in both BT2 beamlines, reported by N. Iida.

The RF system is working well and provides stable operation with the LER maximum current of 770 mA and 660 mA in the HER. Since the RF systems are largely unchanged since KEKB operation, it is expected that the RF systems will operate well at even higher currents – although they are aging and will need attention.

The operation statistics showed that BELLE II was receiving physics events for about 60% of the time. This is lower than for KEKB and should be nearer 80%. The hardware downtime was being logged in detail, but was only responsible for about 5% of the lost time, with the magnets, especially magnet power supplies, causing roughly a third of this time and water problems another 13% of the 5%.

More troubling is the recovery time following the bi-weekly maintenance day and other long interruptions. A typical recovery takes 27 hours, following an 8-hour maintenance period. This time is logged as "Tuning" and accounts for 27.5% of the total beam time. This is due to non-reproducibility of the machine optics such that injection has to be tuned up with a 3 mm β_y^*, which is then reduced in steps to reach the operating value. The reproducibility of the magnet fields is the primary suspect, even though the magnets are taken through a hysteresis cycle. The hysteresis cycle is the same as used for KEKB, where non-reproducibility of the orbits and optics were also observed. However, the tolerances for SuperKEKB are much tighter and the hysteresis cycle may need to be optimized.

The summer downtime would be an excellent occasion to use a Hall probe in the magnets to evaluate whether the fields could be made more reproducible by tuning the power supplies to reduce overshoot, slowing down the hysteresis cycle, or increasing the number of cycles. In addition, doing a harmonic analysis of the differences between the orbit before and after a maintenance day could help identify the major sources of non-reproducibility.

It would be worth evaluating whether the magnets and vacuum chamber can be heated with warm water when the beam is off to keep the temperature more stable.

Recommendations:

R1.1 During the summer shutdown, make a focused effort to improve the reproducibility of the ring magnets, to shorten the recovery time after each maintenance or major intervention.

R1.2 During the summer shutdown, carry out an assessment, and where needed, preventive maintenance of systems with increased failure rate, such as the magnets and power supplies.

2. Injector Linac Status

Findings and Comments:

The two gun injector has proven to be a very wise approach to provide independent electron beams to support all five SuperKEKB rings, with very reliable e-beam delivery from a thermionic gun used to feed the photon factories at 0.3 nC and for positron production at ~10 nC bunch charge, while the rf-gun provides beam that meets the more demanding emittance requirements of the HER, presently 1 nC.

Past technical challenges related to the drive laser for the rf-gun appear to be solved, with reliable two-bunch operation demonstrated, and reliable laser operation without interruption for long durations. Electron beam delivery to the HER at 1 nC now employs charge feedback, and improved emittance/beam quality was obtained using laser-table optics that provides a uniform spatial distribution.

Presently, beam generation is limited to 25 Hz operation because of inductive heating at the pulsed dipole, where the beams from the thermionic gun and the rf gun are steered onto a common path, but new vertical pulsed dipoles and vacuum chamber will reduce inductive heating and permit 50 Hz operation.

Photocathode QE was sufficient to support 1 nC beam delivery per the scheduled run plan, but QE was observed to decay more quickly than desired. Laser heating with a focused laser beam, and using one of the two available drive laser beams, was demonstrated to restore photocathode QE. When performed invasively, the process requires about one hour but the method was also implemented non-invasively, with the second focused drive laser beam applied to the photocathode when RF to the gun was turned OFF (making no beam). In this manner photocathode QE was restored while beam was delivered to the HER, and incurring no downtime, which is a very significant and impressive achievement.

For the electron beam delivered to the HER, emittance meets specifications at the rf gun and through linac sector C, but degrades through linac sections 3 to 5, and then “explodes” in the beam transport section BT2. The electron emittance at HER injection appears to be a few 100% above the desired target both horizontally and vertically! For positron beams sent to the LER, emittance meets specifications through the injector linac, but degrades later in the beam transport arcs, and at the end of BT2 is about 25% above the final target value in both directions.

There are not enough diagnostics (BPMs) and steering magnets in the regions between sector C and sector 3 to diagnose and correct the significant emittance blow up in the linac (factor 3-5).

The committee fully supports additional BPM's and dc dipole steering magnets installed in the blind region between sector C and sector 5. We recommend bi-planar BPM coverage/placement at locations of maximum betatron oscillation in either plane. There should be a sufficient number of dipole correctors to control offset and angle at critical locations, e.g. ideally at every quadrupole.

The positron source operating with flux concentrator FC5 functioned very well throughout the recent runs, and caused little downtime. However, the FC operated with a pulse current of 2.5 kA and a yield of 0.23 (simulation predicted 0.33), compared with a target pulse current of 12 kA and simulated yield close to 0.6. With 11 nC e^- beam on target, 2 nC positron bunches are produced and provide 1.2 nC bunches at the end of the linac. A new flux concentrator (FC8) with an improved, optimized shape to support higher e+ bunch charge is being tested off line.

Two bunch injection for positrons has not been made operational yet, due to drifting orbit differences between the two bunches right after the damping ring.

Pulsed-magnet misfires in sectors 3 – 5 sent electron beams for the HER to the wrong place and triggered many beam aborts. These problems were resolved thanks to a big effort of the linac control group, after an event receiver was replaced, but they re-appeared, now with positrons for the LER, toward the end of the run. Network communication problems might be the cause of recent misfires. Beam aborts were also caused by a failing klystron which resulted in low positron injection energy. A new collimator (beam blocker) will be installed to prevent low energy beam injection and the beam aborts that occur as a result.

The implementation of a phase-shifting mechanism for bucket selection is a good investment, which should help in the future with injection efficiency through more efficient and shorter intervals between injection pulses.

The positron injection rate could be increased by an overall factor of up to about 5, with a factor 2 from higher flux concentrator yield (with a new flux concentrator operating at higher field, etc.), pushing the primary electron charge from the thermionic gun by about 35%, and operating with two bunches per pulse.

The electron injection rate could be increased by a similar overall factor of 4-5, with a factor 2 from the RF gun, perhaps another factor 1.2 by improving the intensity of the 2nd bunch, and another factor of 2 from solving the electron emittance explosion in BT2, which should improve the injection efficiency.

Recommendations:

R2.1: KEK should present details of the planned upgrade of the "blind" sections of the linac, showing the locations of new BPMs and steering magnets relative to the beam phase advance.

R2.2: Continue R&D to develop photocathodes with reliably higher QE in order to achieve the ultimate 4 nC bunches at HER. Studying similar efforts in the XFEL community may be useful.

R2.3: Try to understand the difference between measured and simulated yield from the flux concentrator, possibly by measuring the dc field of the FC; explore, through simulations, possible mechanical vibrations during pulsing, which could contribute to the measured large fluctuations in e^+ yield.

R2.4: Identify and fix the source of the drifting orbit difference between the first and second bunches after the damping ring.

R2.5: Try to raise the injector linac currents for e^+ and e^- up by a factor 4 and 2 respectively, with the new FC, two-bunch e^+ operation, and higher e^- charge from the RF gun.

3. Emittance Growth in Beam Transport (BT) and Injection

Findings and Comments:

A beam of lower emittance and higher charge is critical to high luminosity. The luminosity is proportional to the injector currents of e^+ and e^-, and the product of the injection efficiencies of two beams as $L \propto I_{+inj} I_{-inj} \tau_+ \tau_-$ (formula from K. Oide). Therefore, already modest improvements of the injection efficiency enhance the achievable luminosity. The emittance preservation task force group made great efforts on checking and improving the injection rates from the BT lines and the injection process itself, through a lot of detailed measurements of emittance, twiss functions along BT lines, etc. The committee endorses the efforts made by the group, and encourages more studies to resolve the problems found in BT lines, which will be increasingly important as the machine is further developed.

The different orbits for two positron bunches after extraction from the damping ring suggests there is a hardware malfunction, or non-uniformity, of the pulsed magnets or problems with synchronization of the pulsed magnets relative to the master clock.

Effort should be spent on resolving the difference in emittance measurement between collimator scan and wire scan. If taken at the same (or similar) location (similar beta function) both should yield the same or a similar beam size. Could assumptions on fitted beam shapes and cuts explain the discrepancy?

A movable beam loss detector could help resolve beam loss along the line with high precision. Such systems have been deployed in various accelerators. They could be useful for finding loss locations and for steering the beam so as to minimize loss.

Given the amount of beam that has gone through the line, a detailed radiation survey of the residual activation of the vacuum chamber might be enough to find a problem, i.e. the location of a suspected obstacle.

Recommendations:

R3.1: Examine if regular radiation surveys indicate possible hot spot(s) in BT2 line. The committee endorses the plan to fiberscope the BT2 line as well as to replace the screens with OTR ones.

R3.2: Check fields of suspicious dipole or quadrupole magnets in BT2 with a Hall probe. Check the BT2 screen diagnostics mechanical extraction.

R3.3: Track the optics backward from the end of BT2 using the theoretical optics, to reveal a possible error existing at the place where the forward and backward trajectories diverge.

4. Beam Background / MDI Report

Findings and Comments:

The agreement of simulated background and data has greatly improved since last year. For example, the discrepancies in the HER backgrounds were reduced from a factor 1000 down to a factor 2-3. The biggest improvements came from implementing a more realistic shape of collimators in SAD, and including further details plus improving the model of IR structures and beampipe in GEANT4. The treatment of new collimator configurations has been sped up by an order of magnitude too.

A large part of the HER background is attributed to the injected beams, which is due to the "explosion" of the emittance during injection transport. Partly as a result of the poor quality of the injected beam, tight collimator settings are required, which, along with the implied poor injection efficiency, might have resulted in the short lifetime for $\beta_y^* \leq 1$ mm.

The recent finding that many of the vertical collimators in the HER may not have sufficient horizontal coverage to block all high sigma beam particles is a major step forward in getting a closer agreement between background simulation and measured background rates. Although the implementation of the crab waist has not shown any direct improvement in detector backgrounds, this is perhaps not unexpected as the background rates in the detector are, at this time, dominated by beam-gas in the LER and Touschek in the HER and until these backgrounds improve direct beam-beam detector backgrounds will remain a smaller issue. The fact that the detector can now take data at near the record luminosity running conditions indicates that the backgrounds are improving and should continue to improve as the machine continues to run.

Before any new optics are tried out, the corresponding SAD files could be provided to the background team. Preliminary optics files for the proposed future IR upgrade(s) would also be of interest for early background assessments.

Only three background studies were performed during the past run. So the available background data do not suffice to quantify the effect of the various large changes in optics. A so-called "comprehensive bkg study" varying currents, number of bunches etc., takes about one shift (8 hours). One possibility for tracking background changes more closely is adding a large number of short "optimized" ~1-hour bkg studies, one after every major change in optics, to complement the few longer comprehensive background studies.

The beam abort time has been significantly shortened since the last review, and efforts are being made to look for ways to further improve the abort system. The Committee supports the plans for making the beam abort system more robust, as proposed.

In collision, the injection background lasts longer than for single beams. Not only the injected bunch, but also stored bunches behind the injected bunches experience losses and contribute to the background. This coupling between bunches could be due to long-range wake fields.

Longitudinal injection is an option considered to reduce the injection related detector background.

There is evidence that collimator wakes from D06V2 have an effect on injection background. This was found by opening D06V2. Both linear and nonlinear terms of the collimator wake fields could be important, e.g. https://accelconf.web.cern.ch/e06/PAPERS/THPCH061.PDF, and references therein.

Beam-beam effects – e.g. through the nonlinear force, or dynamic beta, dynamic emittance, collision-driven beam tails etc. – should affect the detector background for a stored beam. They will be even more important for the injection-related background. The injected off-axis beam, possibly with a large emittance, will be greatly perturbed by nonlinear beam-beam encounters. The beam-beam collision also limits the dynamic aperture and reduces injection efficiency. Efficiencies and background observed at different beam currents could be benchmarked against simulations.

In addition, beam-beam forces could also influence the physics results of Belle II. For example, FCC-ee MDI studies revealed the importance of the electromagnetic fields of the colliding beams on the trajectories of scattered particles and on the effective detector acceptance. Inspired by this finding, physics results from LEP had to be revised almost 20 years after the stop of LEP, by taking into account the beam-beam forces ("Beam-beam effects on the luminosity measurement at LEP and the number of light neutrino species", https://arxiv.org/abs/1908.01704, 2019).

Recommendations:

R4.1: Allocate about one hour for systematic background data taking after every major change in beam optics, in addition to a few comprehensive 8 hour background studies per running period.

R4.2: Perform a (re-)simulation of the expected pressure evolution in, and around, the two rings as an input to more realistic background predictions.

R4.3: Perform simulations of detector background which include the beam-beam effect. Also examine possible beam-beam effects on the physics results.

R4.4: Further study and pursue the possibility of longitudinal injection.

R4.5: Estimate the effect of the linear and nonlinear collimator wakes on the generation of beam tails, possibly leading to increased backgrounds.

R4.6: Continue the effort to study the vertical collimators as built and as modeled in the background simulator. If insufficient horizontal coverage is confirmed, can one or two critical collimators be modified or replaced this summer?

R4.7: The proposed carbon collimator should be described in more detail. Carbon is also used in LHC collimators but special fibre-reinforced carbon to optimise electrical conductivity. The LHC bakeout is performed at 2000 degree to minimize vacuum outgassing. The placement of the carbon collimator should be analysed for vacuum and impedance impact. Impedance contribution scales strongly with beta function. HOM and heat load should be estimated.

5. Crab-waist performance (TBT Meas.)

Findings and Comments:

For colliders operated with a large crossing angle, at a large Piwinski angle, the Crab Waist collision scheme is expected to improve the dynamics of particles at large horizontal amplitudes. One of the most important expected consequences is the enhancement of the single-bunch beam-beam limit. Beam-beam simulations with and without errors predict a more pronounced beneficial effect, the higher the bunch intensity.

Although the first experimental test of Crab Waist at SuperKEKB demonstrated only a modest gain in the reachable specific luminosity, its value is so far higher than what had been achieved by all other previously attempted tunings. Adjustment of higher-order optics and the development of higher-resolution beam-based techniques are under way. The reported turn-by-turn measurements have already validated the desired optics. Among all higher-order effects, in particular a good control of the local chromatic coupling is desired.

However, the degradation of the dynamic aperture (and the beam lifetime) will not allow taking the full advantage of the Crab Waist operation unless (or until) a Crab Waist IR setting is found with sufficiently long beam lifetime.

The chromatic *x-y* coupling and higher-order vertical dispersion at the IP have been investigated as candidate suspects for causing the observed beam-beam emittance blow-up. However, the resolution of the measurement using turn by turn BPMs near the IP is poor. Also the magnitude of the chromatic coupling required to explain the observed blowup is both much higher than expected and too large to correct.

The measured large local coupling does not seem to play a role in the luminosity degradation when introduced in simulations. However coupling errors at the IR sextupoles (possibly compounded by beta-beating) could generate large sextupolar aberrations including the aforementioned chromatic coupling. An effort to improve the IR optics modeling and correction might be required.

Recommendations:

R5.1: Consider other factors which may degrade the beam-beam performance such as:

- bunch lengthening as well as amplitude dependent synchrotron tune shift
- transverse short range wake, which has already been noticed as a large tune shift
- space charge effect
- emittance increase due to synchro-betatron resonances excited by the lattice with and without beam-beam.

R5.2: Develop true chromatic coupling and nonlinear dispersion knobs at the IP, which keep the linear optics unaffected and do not interfere with each other, to scan and compensate these aberrations empirically during the physics run.

R5.3: Explore in simulation the effect of the crab waist on injection and on the beam loss at injection, as a function of stored and injected bunch intensities.

6. Optics & Beam-Beam Issues

Findings and Comments:

Optics control in modern colliders is a key issue in order to achieve optimal performances. It is even more important for the SuperKEKB machine, which has recently established new world records in terms of peak luminosity and minimum vertical beta value at the interaction point, and is now preparing to face a new challenging phase, stepping into a previously unexplored parameter domain.

The collider activities restarted in fall 2019 with an optics having lower β^* at IP: $\beta^*_{x,y}$= 80,1 mm in LER, and $\beta^*_{x,y}$= 60,1 mm in HER. In this configuration the machine achieved a peak luminosity of the order of 1.14x10^{34} cm^{-2}s^{-1} and efficiently delivered data to the detector. This was a very positive progress with respect to the summer of 2019 run when, using a 2 mm β^*_y optics, it had not been possible to achieve proper running conditions for the detector. The 1 mm β^*_y optics also provided some improvement in terms of beam-beam parameter, 0.0281 in LER, and 0.0193 in HER. However, these results were still rather far from the design values. Beam-beam interaction was still dominated by blowup of the vertical emittance, mainly for the positron beam, even at a very low bunch current, and by a progressive degradation of the specific luminosity as the bunch currents increased.

In this context, the SuperKEKB Team, following also the previous ARC recommendations, decided to implement a crab-waist optics. The crab-waist optics has been implemented by adjusting the optics and detuning the local chromaticity correction sextupoles, SLY, as first proposed and developed for the FCC-ee design by K. Oide (Phys. Rev. Accel. Beams 19, 111005, 2016, https://journals.aps.org/prab/pdf/10.1103/PhysRevAccelBeams.19.111005**)**. This "virtual" crab waist optics was achieved with an almost perfect phase relation between crab-sextupoles and the IP in the vertical plane, but a slightly non-optimal phase advance in the horizontal plane. The imperfect phase advance in the crab-waist transformation introduces some spurious aberrations, which have been evaluated and have been considered negligible. The strength of the crab-waist transformation applied was: 80% in LER, and 40% in HER. In parallel, the emittance of the positron beam has been increased from 2 nm to 4 nm in order to improve the LER Touschek lifetime and to store higher current. A rather large horizontal angle (0.59 mrad) was introduced to minimize the synchrotron radiation background from the HER, primarily coming from the (large) injected beam. This new configuration, together with collimator optimization and linac plus transfer-line tuning yielded remarkable result in terms of:

- L_{peak} = 2.4x10^{34} $cm^{-2}s^{-1}$
- L_{sp} = 5.43x10^{31} $cm^{-2}s^{-1}mA^{-2}$
- ξ_y =0.0389 in LER, ξ_y = 0.0261 in HER
- Higher stored current in collision at the same $\beta^*_{x,y}$: 712 mA in LER, 607 mA in HER
- Background reduction

The peak luminosity measured at SuperKEKB with the crab-waist optics is larger than any value ever measured at KEKB, and represents the new world record. Such relevant results have been achieved despite the limited time available for machine optimization in terms of linear and non-linear optics. Still, specific luminosity appears to exhibit a significant reduction at very low current, but it then stays constant above 0.03 mA^2. Such drop in specific luminosity at low current had also been seen in beam-beam simulations during the SuperKEKB design phase, when additional effects were added. A similar trend has been observed at the DAFNE collider too (see https://accelconf.web.cern.ch/PAC2009/papers/mo4rai01.pdf); it can be due to many different causes, e.g., to a variety of beam dynamics effects. For the SuperKEKB collider this degradation of the specific luminosity has been studied by comprehensive beam-beam simulations, including third order aberrations and chromatic *x-y* coupling terms which, in the presence of certain errors, seems to reproduce reasonably well the specific-luminosity trend observed. Beam-beam simulations suggest that if the underlying cause is identified, corrected or mitigated, the specific luminosity could be further increased by almost a factor of two.

At the LHC the IR coupling sources have been identified and corrected by introducing large waist shifts (see CERN-ACC-NOTE-2020-0013, https://cds.cern.ch/record/2710101) A similar approach with varying momentum offsets could be applied at SuperKEKB to better characterize and control the chromatic coupling at the IP.

Still persisting is a non-negligible orbit fluctuation in the IR. If generated inside the IR, this orbit variation, due to the associated orbit change at the IR sextupoles, could cause fluctuations of the waist position and of the R1 coupling term at the IP.

The *x-y* coupling in the LER injection region, which induced vertical oscillation and background, has been cured by installing temporary permanent magnet skew quadrupoles.

The injected electron beam emittance experiences an anomalous emittance growth in the beam transfer line BT2. This aspect has been extensively investigated during optics studies optimizing: twiss functions, orbit, dispersion, applying localized bumps and by measuring the electron beam profile by wire scanner diagnostics, without obtaining any conclusive results. It seems possible that the effect is caused by an obstruction in the beam pipe. Alternatively it could also be due to a faulty magnet, e.g. a shorted coil in the quadrupole QD4E, or due to a beam-pipe section with unusually poor vacuum conditions.

The ARC is pleased to see that turn-by-turn monitors are now part of the standard optics commissioning tools and they have been used to study *x-y* coupling. However, reliably determining some *x-y* and *x-y* chromatic coupling terms is still difficult. This is the case for the R1 and R2 chromatic coupling terms which eventually have been probed by beam-beam scans. Optimizing coupling measurements is a rather important aspect since there is evidence for non-negligible coupling in the IR also at the location of the IR sextupoles.

In the last weeks of the 2020b run a crab-waist optics with a β_y^* of the order of 0.8 mm has been applied and tested. Due to the lack of time for optimization, no improvement has been observed in terms of peak luminosity and beam-beam parameters. However a very promising specific luminosity increase has been measured. In this configuration a large single bunch vertical tune shift as a function of the beam current has been detected. It could indicate some impedance-related effect becoming more evident due to the higher β_{y} values in the IR. A possible candidate source are the rather tightly closed vertical collimators. Measurements should be compared with the expected tune shift caused by these collimators at their actual settings and for the actual optics.

Bunch lengthening due to the longitudinal impedance can also affect the specific luminosity and the beam-beam dynamics. Bunch length as a function of bunch current could be measured with collimators open and closed, with and without collision etc. Such longitudinal measurements do not require a small β^*. Diagnostics tools could be the existing streak camera, which, however, suffers from a deformation of the synchrotron-radiation extraction mirror, requiring significant set up time. effort, and expertise.

A potential long-term alternative that the KEK team might perhaps like to consider could be electro-optical sampling as isused at some synchrotron light storage rings (e.g. PRAB 22, 022801, 2019, https://journals.aps.org/prab/pdf/10.1103/PhysRevAccelBeams.22.022801), and which will be further developed by KIT and CERN within the EC funded FCCIS project for the FCC-ee.

Recommendations:

R6.1: Improve the agreement between measured ring optics and ring model, by including various machine errors, including known or measured misalignments. The improved model may also help further reduce the vertical emittance.

R6.2: In particular, improve the IR linear optics modeling and correction. Consider, e.g., – first in simulations – the introduction of a large waist shift to better control the coupling and chromatic coupling in the IR, and correct error sources. Study whether misalignments of the final focus QCS can have an impact on IP optics aberrations, in particular the known and measured misalignments.

R6.3: Optimize linear and non-linear crab-waist optics for β_y^* of 0.8 mm, including empirical fine tuning of all sextupoles and octupoles. This may help fully achieve the expected improvements in terms of peak luminosity, beam-beam parameter and lifetime, and also to understand limitations and guide strategies towards a future optics with β_y^* lower than 0.8 mm.

R6.4: Pursue the IR optics development for crab waist collision schemes at smaller β_y^* in order to find a set up without a serious reduction of the dynamic aperture.

R6.5: Try to improve the phase advance between IP and IR sextupoles in the horizontal plane; additional quadrupoles might help keep beta functions equal on both sides of the IP.

R6.6: Try to define a robust approach and efficient tools to deal with global and local chromaticity and nonlinear dispersion correction.

R6.7: Allocate proper manpower to study the possibility of using crab-waist scheme for optics with β_y^* lower than 0.8 mm.

R6.8: Perform a harmonic analysis of the orbit fluctuation in the IR in order to identify its origin; plan to sample the fluctuation at higher frequency during the next run. Consider a dedicated fast orbit feedback for the IR region to maintain the beam orbit at the IR sextupoles.

R6.9: Model collimator wake fields without and with the new carbon head. Infer the effective collimator wake field from tune shift measurements versus beam current with different collimator gap settings. Consider additional measurements of tune shift with varying collimator gap size. Study the bunch lengthening with current for different collimator gaps, and with or without collision. Use existing, possibly improved, or additional, beam diagnostics to measure the bunch lengths under various conditions, e.g. as a function of collimator gaps, with and without collision, etc. Establish a transverse and longitudinal impedance model including collimators at actual settings.

7. Near- and Long-term operation plans

Findings and Comments:

The Near-Term (1 year) and Long-Term (~10 years) plans were presented for the operation of SuperKEKB and the linac injector and for the technical upgrades of the accelerators. These plans match closely what was presented to the ARC in previous meetings but now with more specificity and realism. These plans include new running and technical knowledge obtained from operating SuperKEKB for the past several years.

The present luminosity performance is still improving thanks to the excellent work and dedication of the SuperKEKB accelerator team. More improvements will certainly come. It would be useful to see the detailed explanation of the limits of the presented luminosity folding in near term minor upgrades.

Near Term Plans: The near term plans cover the next year include doing small upgrades over the next few summer months including a few new collimators, replaced flux concentrator, improved tuning tools, preparation for synchrotron injection, and improved collision feedback. The operation of SuperKEKB calls for a Fall 2020 run of 60 days and a Spring 2021 run of about 120 days. By March 2021 a new peak luminosity of 4.5-6.5x10^{34} $cm^{-2}s^{-1}$ is anticipated with about 1174 bunches, beam currents of 900 mA, and with an IP β_y^* of 0.6 mm. The corresponding integrated luminosity of 140 fb^{-1} is expected. The Belle-II collaboration has asked if the overall physics run can be extended by about 1.5 months to increase the integrated luminosity to about 240 fb^{-1} by March 2021.

The anticipated ultimate peak luminosity with the existing QCS IR quadrupoles and RF systems is likely limited to about 2-3x10^{35} $cm^{-2}s^{-1}$, although the limit may be lower if new beam dynamics effects or other issues are discovered.

The present RF system (which was already partially upgraded from KEKB) can support 70% of the design beam currents of SuperKEKB, namely about 2.5 A in LER and 1.8 A in HER. In this operation, at 70% of the design beam currents with the present RF system, the electric power consumption will be increased by about 40% compared with the current mode of operation around 500 mA. In the original plan, to achieve the design beam currents (3.6 A in LER and 2.6 A in HER), it was foreseen to add 4 klystrons, but no cavities. This RF upgrade would have been accompanied by converting 4 RF stations from 1:2 configuration (1 klystron drives 2 ARES cavities) to 1:1 scheme, so that beam power could be increased for the same number of cavities. In this final system configuration at the design beam currents, the electricity power consumption would be increased by about 10-15% compared to the maximum current operation with the current RF system (2.5 A in LER and 1.8 A in HER as described above), which means an increase of about 50-60% (1.4x1.15 = 1.6) compared with the current operation around 500 mA. A partial RF system upgrade plan, recently proposed (only 2 klystrons added), would correspond to an intermediate situation somewhere between these two, e.g. with currents of around 3 A in the LER and 2 A in the HER.

Near Term Recommendations:

R7.1: We strongly recommend extending the fall/spring Belle II/SuperKEKB run in 2020/2021 by about 45 days to allow Belle II to reach an integrated luminosity of about 240 fb^{-1} by March 2021, which should enable some initial world-leading physics results on B physics and the dark matter sector. This extension will allow many of the SuperKEKB state-of-the-art accelerator improvements expected in the fall 2020 run to be applied to luminosity running.

R7.2: Over the next year or so, perform beam measurements to determine if the proposed QCS upgrades with larger apertures are absolutely required to get to the design luminosity or, e.g., to half the design luminosity.

R7.3: Address the reliability of the conventional infrastructure of SuperKEKB and the Linac to address the approximate 15% lost operating beam time (from e.g. cooling, power supplies, water leaks), leading to increased integrated luminosity.

R7.4: Pursue aggressive linac/injector improvements including the pulsed magnet upgrades, new flux concentrator and emittance reduction to reduce anticipated future IR backgrounds and improve beam delivery.

R7.5: Develop a luminosity performance model for the SuperKEKB collider based on empirical data, observations, and parameters, including major imperfections, driving settings, and machine hardware availability. Use the model to predict the needed future improvements. Predict the performance limitations and carry out beam studies to benchmark and confirm the performance model.

Long Term Plans: The long term plans covering ten years have been presented to MEXT as a “Roadmap 2020” proposal with the major goal of delivering 50 ab^{-1} in ten years. These luminosity projections are based on the good progress and physics data that has now been collected. Long-term plans cover several interesting options.

This plan calls for primarily IR and RF upgrades to increase the peak luminosity from an assumed value of about $3x10^{35}$ $cm^{-2}s^{-1}$, without upgrade, to a value of $6.5x10^{35}$ $cm^{-2}s^{-1}$ to be executed starting in about two years and completed in about 2027. With these upgrades, the ultimate goal is to achieve an integrated luminosity of 50 ab^{-1} in about 2031.

The luminosity upgrades required to reach the original goal of $8x10^{35}$ $cm^{-2}s^{-1}$, or the proposed new goal of $6.5x10^{35}$ $cm^{-2}s^{-1}$, include substantial construction projects: up to 4 additional RF stations and running with overall 60% more power consumption than now, new interaction superconducting QCS magnets with increased physical apertures, additional background reductions, shielding enhancements, and injector improvements. Belle II also needs upgrades.

A partial RF upgrade may make sense with or without the QCS upgrade to ensure that RF system reliability and total available power do not limit the luminosity. The RF upgrades can be done gradually in shorter shutdowns. If it is decided that the design maximum current will not be needed it may be worth looking at the cavity coupling factor to see if it can be re-tuned for better efficiency at a new maximum. This may be achievable by adjusting RF matching elements outside of the vacuum. Meanwhile the SuperKEKB team should continue to monitor RF system margin and reliability, as the current is increased.

The expected luminosity ramp-up, after the proposed upgrades are installed, aims towards obtaining an integrated luminosity of 50 ab^{-1} during calendar year 2031 but this could well be optimistic given the required intensive recommissioning period.

Detailed long term upgrade plans should be finally decided once full performance with those upgrades is predicted within a quantitative performance model. This makes sure that the long term quadrupole aperture is chosen wide enough, background sources and paths are understood, lower beam lifetime can be handled, impedance stays under control, and the collimator system is adequate.

The question of the final goal for integrated luminosity of SuperKEKB should be discussed within KEK and Belle-II. If the final goal is 50 ab^{-1}, then the upgrade decisions may be different than if the ultimate desired goal is higher, say, 100 ab^{-1}.

An intermediate mini-review might help evaluate a mature SuperKEKB upgrade plan before the final Snowmass workshop in summer 2021. Such an evaluation might also be needed for planning hardware upgrades (QCS, Belle II vertex detectors etc...).

Long term recommendations:

R7.6: Determine which technical studies (essential beam studies and QCS coil parameter studies) need to be carried out now, before a decision can be made, within about 2 years, on starting construction of new QCS quadrupoles.

R7.7: Determine the technical staffing and accelerator experts needed to construct the required hardware upgrades and examine if new technical staff will need to be trained or hired to design and execute these upgrades.

R7.8: Evaluate a backup plan to simply increase the luminosity with the existing hardware to about 2-3x10^{35} $cm^{-2}s^{-1}$ (with small upgrades but without major upgrades and the associated long installation downtimes and serious recommissioning) and then integrate luminosity for about 10-12 years at 7-8 months per year to obtain an integrated luminosity of 50 ab^{-1} by 2032-2034.

R7.9: Present a detailed SuperKEKB upgrade plan with underlying reasoning and data at the next ARC meeting.

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
Catia Milardi	INFN-LNF
Katsunobu Oide	CERN and KEK (ret.)
Evgeny Perevedentsev	BINP
Matt Poelker	JLab
Qing Qin	IHEP
Bob Rimmer	JLab
John Seeman	SLAC
Michael Sullivan	SLAC
Tom Taylor	CERN (ret.)
Rogelio Tomas	CERN
Seiya Yamaguchi	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

Appendix B

Agenda of the 24th KEKB Accelerator Review Committee

July 15 (Wednesday)		
19:50 - 20:00	Committee Executive Session (Zoom)	
20:00 - 20:05	Welcome	M. Yamauchi
20:05 - 20:30	Overview of 2020a and b Run	Y. Ohnishi
20:30 - 20:55	Injector Linac status	M. Satoh
20:55 - 21:15	Emittance growth in beam transport, and Injection	N. Iida
21:30 - 21:50	Belle 2II background / MDI	H. Nakayama
21:50 - 22:10	Crab Waist Performance (TBT Meas.)	K. Ohmi
22:10 - 22:30	Optics & Beam-Beam Issues	A. Morita
22:30 - 22:50	Near- and Long-term operation plans	U. Suetsugu
22:50 - 23:00	Committee Zoom Meeting	
July 20 (Monday)		
20:00 - 21:00	Close-out	

Appendix C

Required and achieved SuperKEKB parameters and comparison with KEKB

parameter	KEKB w Belle		SKB 2020 w Belle II				SKB Design	
			β_y^* = 1.0 mm CW		β_y^* = 0.8 mm CW			
	LER	HER	LER	HER	LER	HER	LER	HER
E [GeV]	3.5	8	4	7	4	7	4	7
β_x^* (mm)	1200	1200	80	60	60	60	32	25
β_y^* (mm)	5.9	5.9	**1.0**	**1.0**	**0.8**	**0.8**	0.27	0.30
ε_x (nm)	18	24	**4.0**	**4.6**	**4.0**	**4.6**	3.2	4.6
ε_y (pm)	150	150	**80**	**80**	**63** (20 w/o coll.)	**63** (20 w/o coll.)	8.6	12.9
I (mA)	1640	1190	**712**	**607**	**536**	**530**	3600	2600
n_b	1584		978		978		2500	
I_b (mA)	1.04	0.75	0.728	0.621	0.548	0.542	1.44	1.04
ξ_y *	0.098	0.059	**0.0389**	**0.0261**	**0.0345**	**0.0199**	0.069	0.060
L_{sp} ($10^{30}cm^{-2}s^{-1}$ mA^{-2})	17.1		**54.3**		**69.0**		214	
L ($10^{34}cm^{-2}s^{-1}$)	2.11		2.40		2.00		80	

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

Appendix D

Required and achieved parameters (2019 and 2020) in the injector complex

Stage	KEKB Achievement		Phase-2 Achievement		Phase-3 summer'19 Achievement		Phase-3 summer'20 Achievement*		Phase-3 Final Requirement	
Beam	e+	e–	e+	e–	e+	e–	e+	e–	e+	e–
Energy (GeV)	3.5	8.	4.	7.	4.	7.	4	7	4	7
Stored current (A)	1.6	1.1	1	1	0.83	0.94	0.77	0.66	3.6	2.6
Life time (min.)	150	200	50	100	20 (typ)	70 (typ)	10	20	6	6
Bunch charge (nC)	1	1	1.6	3.6	1.35	3.5	1.6 (0.5-1.5 BT2)	3 (0.5-1.5 BT2)	4	4
Norm. Emittance (γβε) (μm)	1400	310	200/5	200/40	120/6	54/67	100/2 BT1, 200/25 BT2	41/45 BT1, 400/300 BT2	100/15 (H/V)	40/20 (H/V)
Energy spread	0.13%	0.13%	n/a	n/a	n/a	n/a	0.16%	0.1%	0.16%	0.07%
Bunch / Pulse	2	2	2	2	1	1	1	1	2	2
Repetition rate (Hz)	50		25		50 (LER+PF+PF-AR < 25 Hz)		50 (LER+PF+PF-AR < 25 Hz)		50	
Simultaneous top-up injection (PPM)	3 rings (LER, HER, PF)		No Top-up		4+1 rings rings (LER, HER, DR, PF, PF-AR)		4+1 rings (LER, HER, DR, PF, PF-AR)		4+1 rings (LER, HER, DR, PF, PF-AR)	

* The e- bunch charge of 3 nC was measured at the first BPM from the RF gun. The e+ bunch charge of 1.6 nC was measured at linac end.

Final Linac Beam Parameters for KEKB and Design Parameters for SuperKEKB

(from the presentation of M. Satoh)

Linac Beam Parameters for KEKB/SuperKEKB

Stage	KEKB (final)		Phase-I		Phase-II		Phase-III (interim)		Phase-III (final)	
Beam	e+	e–	e+	e–	e+	e–	e+	e–	e+	e–
Energy	3.5 GeV	8.0 GeV	4.0 GeV	7.0 GeV	4.0 GeV	7.0 GeV	4.0 GeV	7.0 GeV	4.0 GeV	7.0 GeV
Stored current	1.6 A	1.1 A	1.0 A	1.0 A	–	–	1.8 A	1.3 A	3.6 A	2.6 A
Life time (min.)	150	200	100	100	–	–	–	–	6	6
Bunch charge (nC)	primary e- 10 → 1	1	primary e- 8 → 0.4	1	0.5	1	2	2	primary e- 10 → **4**	**4**
Norm. Emittance (γβε) (μmrad)	1400	310	1000	130	200/40 (Hor./Ver.)	150	150/30 (Hor./Ver.)	100/40 (Hor./Ver.)	**100/15** (Hor./Ver.)	**40/20** (Hor./Ver.)
Energy spread	0.13%	0.13%	0.50%	0.50%	0.16%	0.10%	0.16%	0.10%	0.16%	0.07%
Bunch / Pulse	2	2	2	2	2	2	2	2	2	2
Repetition rate	50 Hz		25 Hz		25 Hz		50 Hz		50 Hz	
Simultaneous top-up injection (PPM)	3 rings (LER, HER, PF)		No top-up		Partially		4+1 rings (LER, HER, DR, PF, PF-AR)		4+1 rings (LER, HER, DR, PF, PF-AR)	

Appendix E

A few snapshots from the close-out of the virtual 24th ARC meeting.