The Twenty-Third KEKB Accelerator Review Committee Report

10 July, 2019

Introduction

The Twenty-Third KEKB Accelerator Review Committee (ARC) meeting was held on July 8-10, 2019. Appendix A shows the present membership of the Committee. All committee members attended the 23rd meeting. The meeting followed the standard format, with two days of oral presentations by KEKB staff members, followed by discussions between the Committee members.

The Committee welcomes the new Heads of KEK Accelerator Divisions III (Yusuke Suetsugu) and IV (Makoto Tobiyama).

The Agenda for the meeting is shown in Appendix B. The slides of the presentations are available at http://accphys.kek.jp/indico/conferenceDisplay.py?confId=125. Appendix C compares the required and achieved SuperKEKB beam parameters with those of KEKB. Appendix D summarizes parameters of the injector complex.

Since the 22nd review, SuperKEKB has carried out the Phase 2 commissioning from March to July 2018 and an initial Phase 3 running, with nearly the full Belle II detector installed, from March to July 2019. The Committee examined the progress of the project and the present challenges.

As always, the high standard of the presentations impressed the Committee. The Committee was also pleased to see many presentations from newly hired KEKB staff. As highlighted in a previous report, the next generation 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. International collaboration could be expanded, e.g. with CERN and IHEP, 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.

The most important recommendations of the Committee were presented to the KEKB staff members before the close of the meeting. 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/** .

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A) Executive Summary

SuperKEKB has carried out the Phase 2 commissioning from 19 March 2018 to 17 July 2018, and already operated 3-4 months in Phase 3, from 11 March to 1 July 2019. During these two running periods the vertical beta functions of both beams were squeezed in steps, down to 3 mm, and even to 2 mm with detector off, yielding peak luminosities of about 5×10^{33} $cm^{-2}s^{-1}$ and 1.2×10^{34} $cm^{-2}s^{-1}$, respectively. The β_y^* of 2 mm is almost 3 times smaller than at KEKB and sets a new world record for storage-ring colliders. The commissioning time to reach a luminosity of 10^{34} $cm^{-2}s^{-1}$ was 5 times shorter than for the previous KEKB. In Phase 3 the Belle II detector is almost fully installed. An integrated luminosity of about 6/fb was delivered to Belle II during about two months from end of April to June 2019.

At present, the most important challenges are:

1) fast beam losses leading to collimator damage, QCS quenches and beam showers hitting the Belle II pixel detector;
2) high detector background dominated by beam-gas scattering in the LER, which limits the beam current and minimum beta*, and jeopardizes the integrity of the detector; and
3) luminosity tuning with significant vertical emittance blow up and low beam-beam tune shift in collision.

The ARC has formulated recommendations on how to address the above issues; it supports an ambitious luminosity goal 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. Develop priorities for the next year in collaboration with the Belle II detector group in order to achieve an integrated luminosity of about 200/fb by July 2020. (R1.1)

2. The ARC endorses the proposed operational goals for Phase 3.1, toward β_y^* of 0.64 mm, 2 kAh, 200/fb, $3 \times 10^{34}$$cm^{-2}s^{-1}$ by summer 2020. (R2.1)

3. By autumn 2019, evaluate different operating scenarios, select the one with the best risk-reward ratio, and establish a detailed commissioning plan for accelerator and background studies. (R2.2)

4. To avoid detector and QCS damage, separate the functions of machine protection and detector background reduction. The first role can be fulfilled by a robust collimator (lower Z material) placed at an adequate location close to the abort system, far from the experiment. The second one is taken by the existing collimators closer to the detector with a larger normalized gap. This approach implies the installation of additional collimators in the two main rings. (R14.4)

5. Once the main rings are in a safe condition, i.e. after the installation of the additional collimators, increase the beam current in steps and develop optimized beam-scrubbing scenarios to accumulate, before summer 2020, approximately 2000 Ah at the maximum possible beam current in accordance with the planning of the physics runs. (R14.6)

6. Ensure that a power converter trip does not cause the QCS magnets to quench. (R9.1)

7. Perform a bakeout (T>100°C for several days) of vented vacuum sectors; evaluate the impact of the in-situ bakeout on the mechanical integrity of the vacuum system (vacuum chamber expansion, bellow compressions, fixed points). (R14.1)

8. Allocate sufficient machine time for increasing the specific luminosity, including tuning the linear, chromatic, and nonlinear IP aberrations of both beams, and for optimizing their offsets, crossing angles, and betatron tunes, in order to increase the beam-beam tune shift and to reduce the vertical emittance blow up. (R5.6)

9. Develop a Crab-Waist lattice to mitigate the beam-beam blowup, even if it may not work with the final design value of β_y^*. DAFNE experience clearly indicates that the Crab-Waist optics can greatly improve the background, in addition to increasing the maximum beam-beam tune shift. (R2.6 and R5.11)

10. Develop a new nomenclature for the names of beam runs, e.g. “Phase 3.14 etc.” or “Run20S”. (R2.7)

D) Findings and Comments

1. Overview of SuperKEKB Status

The goals defined for Phase-2 commissioning were: 1) to demonstrate positron injection through the damping ring; 2) collision tuning with QCS (the final focusing quadrupoles); 3) to demonstrate “nano-beam” collision scheme; and 4) to confirm that the background is tolerable for the vertex detector (VXD) to be installed in Phase-3. All of these objectives were accomplished in a rather short time given the complexity of the machine (~4 months).

For the first time, simultaneous beam injection into five rings was accomplished (HER, LER, Damping Ring, PF and PF-AR). This means that all of the experimental programs at KEK can be operated at the same time without interference, an achievement that will permit a lot of scheduling flexibility in the years to come.

The damping ring commissioning was exceptionally fast, and the damping ring has been operating satisfactorily ever since. A detailed optimization of the beam emittance and studies of some other beam parameters remain to be done.

Collision tuning with the QCS magnets proceeded squeezing the beam sizes at the interaction point until the first event could be recorded on 26th April 2018. The increase in luminosity inversely proportional to the beta value at the interaction point demonstrated that the "nano-beam scheme" was working correctly. The nanobeam scheme had been proposed by Pantaleo Raimondi at INFN-LNF for the Italian SuperB project around 2006, and tested successfully at DAFNE with two different detectors. At SuperKEKB, it has now been implemented, for the first time, with low-emittance beams on a high-energy collider. This is a major success for the KEK laboratory that will be copied by other colliders in the world.

The QCS magnets worked well, meeting all the required specifications. These are extremely complex superconducting magnets with many correction coils so this is also a major success. There were problems with magnet quenches, mostly triggered by beam loss, possibly induced by beam-dust interaction in the beampipe.

The background was systematically studied and reduced to the point where the go-ahead was given to install the delicate VXD detector, a difficult installation challenge which took eight months.

In Phase 2 a peak luminosity of 5.5×10^{33} $cm^{-2}s^{-1}$ was reached without Belle II pixel detector and without Belle II CDC high voltage.

Phase-3 commissioning started in March 2019 and ended just before this ARC Review. The goals for the Phase-3 were: 1) to start full-scale physics run with the complete VXD in Belle II; and 2) accelerator and collision tunings with lower beta for higher luminosity.

Phase-3 was interrupted for three weeks by a fire in a building adjacent to the Injector Linac, which spread carbon deposits on the Injector power supplies and modulators (see Section 15). After the recovery, the beta value at the interaction point was reduced to 3 mm and continuous injection in both rings was initiated. The luminosity was increased in parallel with a reduction in backgrounds so as to reach a luminosity of 5×10^{33} $cm^{-2}s^{-1}$ with acceptable detector background.

In late June, the vertical beta value was reduced to 2 mm and a luminosity of 1.23×10^{34} $cm^{-2}s^{-1}$ was recorded. However, for this luminosity peak, the Belle II detector was switched off due to high backgrounds.

These results are a significant progress towards the goals of the Phase-3 commissioning program. However, there are significant challenges for further increases in luminosity. The beam-beam effect increases the vertical emittance, reducing the specific luminosity. This effect was not expected and the underlying mechanism is still not clear; the blow up depends on the betatron tunes. The background in the detector (primarily from the LER) is still high and, more importantly, there are background bursts from the stored beam which quench the QCS magnets and have damaged the VXD detector.

At this time, the Committee sees no fundamental reason why the progress achieved so far will not be continued in the next run. However, things will get harder and harder, so it is important to manage expectations.

Recommendation:

R1.1 Develop priorities for the next year in collaboration with the Belle II detector group in order to achieve an integrated luminosity of about 200/fb by July 2020.

R1.2 Strengthen communication and understanding among the accelerator groups including linac, the Belle-II group, and foreign collaborators on commissioning procedures and strategy.

2. Present performance and plans

The run from March to July in 2019 was mostly dedicated to the goal of accumulating integrated luminosity of 6 fb^{-1}, as requested by Belle II. Despite the reduction of the run time due to a fire in the modulator of a nearby X-band test facility (nextef), this goal was successfully achieved. On the other hand, due to the short running time, the development of the machine performance was not fully carried out. The achieved peak luminosity, 1.23×10^{34} $cm^{-2}s^{-1}$, was the goal of "Phase II". On a positive note, the running time required to reach a luminosity of 10^{34} $cm^{-2}s^{-1}$ was 200 days, which is 1/5 of the time taken by the previous KEKB collider.

During this run $\beta^*_{x,y}$ was set at (200/100, 3) mm for most of the time (LER/HER), and squeezed to (80, 2) mm at the end of run. The luminosity performance at 2 mm looked acceptable, but a good running condition for the detector has not been established yet.

The beam-beam parameter reached 0.036/0.020 (LER/HER) in the 2 mm optics. These values are still much lower than the goal (~0.07). Several issues are observed in the beam-beam phenomena:
a) Blowup of the vertical emittance of the LER, even at a very low bunch current.
b) Slow degradation of specific luminosity with an increase of bunch currents.

Several causes are suspected for the blowup including higher order parameters such as chromatic coupling, but not yet identified. Most first-order knobs have been scanned except the vertical crossing angle, which has been left untouched until the last week of the run. A scan of the vertical angle was indeed effective and improved the luminosity by 20%. Thus all other knobs must be rescanned again, and then again, to find the optimum.

For most of the time, the bunch current of positrons and electrons did not satisfy the energy transparent condition, i.e., inverse of the beam energy ratio. Unlike for the previous KEKB, there should not exist any a-priori constraints on the beam parameters, such as due to electron cloud, so that the basic collision tuning should be performed starting from the energy transparency condition.

The observed bunch lengthening in both rings introduces a significant drop of the specific luminosity, by about 20% for the typical bunch intensity of the last running period. Thus, this effect should be taken into account in the luminosity analysis.

A future plan has been proposed as an example including β_y^* squeeze, beam scrubbing dose, peak and integrated luminosities. This plan shown in the second day of the review squeezes the betay* down to 0.64 mm, adds 2 kAh of beam scrubbing dose, and accumulates an integrated luminosity of 200/fb by the summer ; thus, it is more or less consistent with Belle-II's plan for the next year. We may define this accelerator commissioning phase as "Phase 3.1".

The collimation issue will be the most annoying issue for the beta squeeze. Currently the IP upstream collimator of the LER (D02V1) has been set at about 60 σy, including the beam-beam blowup. It is a little bit smaller than the physical aperture of QC1 quadrupole (70 σ_y). Since the optics between the collimator and the IP is fixed through the beta squeeze, the beam size at the collimator increases as β_y^* is reduced. For the design β_y^*, the collimator aperture becomes 22 σ_y, assuming the same level of the blowup as today.

The designation of Phase 1, 2 and 3 for accelerator and detector commissioning worked well over the past several years separating the various work packages that needed to be done. However, labeling the next 10 years of accelerator operation as part of Phase 3 will not be descriptive enough to allow staff to efficiently plan for future work. Making a new nomenclature would be good with a new set of names for future beam runs. As an example, each run could be called by the calendar year and whether it will happen in the fall or spring (e.g. Run 20F or Run 21S).

Recommendations:

R2.1: The ARC endorses the proposed operational goals for Phase 3.1, toward β_y* of 0.64 mm, 2 kAh, 200/fb, $3x10^{34}cm^{-2}s^{-1}$ by summer 2020.

R2.2: By autumn 2019, evaluate different operating scenarios, select the one with the best risk-reward ratio, and establish a detailed commissioning plan for accelerator and background studies.

R2.3: Do basic collision tuning around the energy-transparent condition. Confirm that each scan covers a sufficient range for every parameter. Repeat each set of scans many times until the luminosity saturates. Mitigate the limitations of knobs due to heating or capacity of power supplies, if necessary.

R2.4: Develop a collimation scenario down to the design β_y^*. Try to close the D02V1 collimator down to $22\sigma_y$ with the current β_y^*, to check the operability of such a narrow collimation. If it is not operable, for instance due to tip-scattering, the project may need to prepare special collimation sections in other places of the ring. Such additional collimators, separated from the IP, would also improve machine protection.

R2.5: The origin of the much larger than expected increase of bunch length with current should be investigated. Measure bunch length versus current with collimators open and closed, and also with and without collisions. Attempt to measure or indirectly infer the energy spread and look for signs of microwave instability. The bunch lengthening must be taken into account in luminosity estimations.

R2.6: Develop a Crab-Waist lattice to mitigate the beam-beam blowup, even if it may not work with the final design value of β_y^*.

R2.7: Develop a new nomenclature for the names of beam runs, e.g. “Phase 3.14 etc.” or “Run20S”.

3. Belle II status

The Belle II detector collaboration has worked very hard to get the detector ready for data taking. Over the last summer and fall the temporary detectors (Beast 2) have been removed from the central region. The SVD and part of the PXD have been installed and are now working. Only one of two layers of the PXD was ready at this time. Several problems in various subsystems were uncovered during the Phase 2 running and these have been addressed with a much more robust and improved efficiency for the overall performance. There is still much to do and more data will help to shake down the detector into a high performance mode.

The backgrounds in the detector are still higher than expected and at the highest currents and highest luminosity the backgrounds were too high by about a factor of 3 for the detector to take data. It should be noted that the high luminosity reached near the end of the run was with a collimator-setting configuration not optimized for minimizing the backgrounds.

In addition, part of the PXD has been damaged by a very short, sharp radiation burst which also quenched the QCS magnets. These events are so fast that the current abort system is unable to dump the beam in time to prevent either QCS quenches or high radiation bursts going into the detector. The high background levels and the possibility of these intense radiation bursts have made it more difficult to make progress toward improving the accelerator performance.

Frequent injection background bursts, that are not catastrophic, but trip the CDC and make large backgrounds in the outer detector (TOP, ECL), seem to be due to "rogue pulses" in the linac/BT. These injection background bursts are limiting the present Belle II operation to a greater extent than the steady state (DC) backgrounds, which are mostly from LER beam gas scattering.

Recommendations:

R3.1: Continue to maintain close relations with the accelerator team. We strongly encourage the continuation of a background liaison shifter in the control room.

R3.2: Assist the accelerator team in looking for ways of either creating an earlier signal to abort the beam and in coming up with a collimator configuration that can protect the detector and QCS magnets.

R3.3: The accelerator team should closely cooperate with Belle II to develop countermeasures against injection background bursts (e.g. additional BT collimators, injection phase control, energy feedback, optics and orbit stabilization, etc.).

4. Beam-beam issues

At the end of June 2019, the SuperKEKB collider has reached a luminosity of 1.23×10^{34} $cm^{-2}s^{-1}$ with 1576 bunches and e^+ and e^- beam currents of 830 mA and 820 mA, respectively, with a large Piwinski angle of greater than 10. This luminosity was achieved during machine studies without the Belle II detector taking data. In Phase 3, when Belle II was taking data, the peak luminosity achieved was 5.5×10^{33} $cm^{-2}s^{-1}$ with 1576 bunches and e^+ (LER) and e^- (HER) beam currents of 617 mA and 644 mA, respectively. In Phases 2 and 3 the β_y* was lowered from 8 mm to 3mm in several steps, and finally to 2 mm near the end of June 2019 during dedicated machine studies. During Phase 3 data taking, the β_x^* was 100 mm in the HER and 200 mm in the LER, but both horizontal beta functions were reduced to 80 mm at the end of June 2019. The highest vertical beam-beam parameters for e^+ and e^- were 0.030 and 0.021, respectively, a very good start. The e^- beam-beam parameter was limited by positron beam-beam vertical blow-up at higher currents. With future careful tuning the vertical beam-beam parameters will increase towards the design value, which is about two or three times higher, for the LER and HER, respectively.

Many of the accelerator tuning tools for increasing the luminosity have been developed and tested. Optics terms have been optimized including R1 through R4, IP dispersion, and centering of the horizontal and vertical beam centroids. Feedbacks keep the colliding beams centered. A factor of two in specific luminosity was achieved by x-y coupling correction (R2) allowing the vertical IP spot sizes to be lowered from 1.25 micrometer to 0.33 micrometer. The specific luminosity agrees with the geometrical calculated value at low currents. The R3 correction deals with the skew term in QC1 and needs to be corrected near the QC1 location. The linear coupling parameters were well controlled. Vertical scans with dispersion corrections were done at the end of June. The correction of the vertical crossing angle increased the luminosity by 20%. The measurement accuracy of the vertical angle is about 0.1 mrad and this angle presently needs to be set to about 0.5 mrad for optimal luminosity improvement.

The specific luminosity falls faster with the product of the bunch charges than the ideal beam-beam simulations suggest. Most (x2) of the drop in specific luminosity comes when the beam bunch current product I^+I^- changes from 0 to 0.05 mA^2 , while the desired final value will be about 1.5 mA^2. In detail, for the LER there are two blow-up regions 1) at bunch currents below 0.1 mA and 2) above 0.5 mA, while for the HER only a gradual blow up is seen over the same range. The beam-beam simulations can match the observed specific luminosity fall-off if skew sextupole and chromatic Twiss optics error terms are added. These terms will need to be corrected to increase the luminosity and illuminate the next layer of beam-beam issues.

The multi-bunch beam-beam effect was observed to be small.

If head-tail effects are observed in the future, then crab-waist controls may need to be added.

The study of the beam-beam effects in SuperKEKB has made a lot of progress but it is still early days for many overall studies. Centering the colliding beams, IP angle corrections, and IR dispersion have been initially corrected. The β_y^* has been lowered systematically over Phase 2 and 3 to increase the specific luminosity. The specific luminosity goes down by about a factor of 2 with only small bunch charges. In the longer term, the β_y^* needs to be lowered by another order of magnitude (from 2-3 mm to 0.27 mm) which will require the beam-beam correction algorithms to work better and the IP beam measurements to be more precise. At a given value of β_y^*, the specific luminosity needs to be increased by about a factor of two. These efforts will likely couple directly to increased backgrounds in the detector.

There was some heating observed in the HER during the vertical angle beam scan. The mechanism behind this heating should be discovered and mitigated.

Recommendations:

R4.1: Finish optimizing the luminosity at a β_y^* of 2.0 mm, concentrating on the skew sextupole components and chromatic Twiss corrections.

R4.2: Make a detailed commissioning plan for the accelerator and backgrounds studies during the next run needed for lowering the β_y^* from 2 mm to 1 mm and, shortly after, by summer 2020, to 0.64 mm.

R4.3: Identify the most efficient knobs for increasing luminosity, as for example found with the vertical IP angle.

R4.4: Establish a hierarchy of the expected most efficient knobs to be tried in operation for luminosity optimization, including the betatron tunes.

R4.5: Establish and implement a clear strategy how to always re-optimize the full performance after changes in a tuning knob (e.g. after the vertical IP angle is changed).

R4.6: Analyze the frequency content in the spiking luminosity jumps seen in the fast Belle-2 luminosity monitor. This could provide insight into the beam-beam processes and provide further ideas on improving luminosity, avoiding emittance blow-up, and reducing background.

R4.7: Mitigate the beam heating observed during HER vertical angle scans.

R4.8: Include the bunch lengthening with beam current and, possibly, a model of the single-bunch transverse wake fields, in the beam-beam simulations.

R4.9: Study the possible impact of 22 Hz vertical IP orbit oscillations with 40 nm amplitude in beam-beam simulations.

5. Optics analysis and issues

Optics control in modern colliders is fundamental to ensure machine safety and to maximize peak luminosity.

Phase 3 optics global commissioning was very satisfactory with the excellent achievement of reducing β_y^* to 2 mm, a new world record for circular-collider IP beta functions.

Optics parameters at the IP are difficult to measure directly, and they are mainly optimized with luminosity measurements. This approach shows some limitations such as a weak response over the available tuning range of some corrector magnets. Stronger tuning magnets might be needed, as it is being investigated.

Beam based alignment was not performed for Run 3. The vertical crossing angle, identified and corrected during the run, could presumably have been detected at the start of the run using beam-based alignment techniques.

Global optics deviations such as beta-beating, spurious dispersion and orbit distortion were satisfactory, but slightly worse than in previous runs. For example, during the initial Phase 3 run, the vertical beta-beating was 7% in the LER and the horizontal rms dispersion error 20 mm in the HER, while in previous runs the largest beta-beating was 4% and largest horizontal rms dispersion error 11 mm. The vertical rms orbit distortion has been steadily increasing since Phase 1. Similarly, xy coupling has also slightly degraded. The permanent magnets used for e-cloud mitigation do not seem to be the cause, as concluded from the tests performed by changing configuration of permanent magnets.

HER vertical X-ray beam size monitor system has some smearing effects which limit the resolution at about 7 μm. The measured beam size was found to be independent of the beta function at the source point for beta values in the range between 7 m and 28 m.

Chromatic and non-linear optics have not been corrected yet, and the first measurement indicates a significant chromatic coupling.

Turn-by-turn beam position monitor data is not yet part of standard optics commissioning and it is used only in dedicated measurements.

Allocated time and human resources seemed to be not sufficient to address all linear and non-linear optics commissioning.

Recommendations:

R5.1: Continue with the reduction of β_y^*.

R5.2: Next commissioning should start with applying beam-based alignment techniques especially in the IR.

R5.3: Special attention should be paid to global optics deviations in order to reach a similar optics performance as in Phase 2.

R5.4: Investigate possible new techniques that could help in the measurement of IP optics parameters. Three examples are: (i) Measuring amplitude detuning, (ii) Measuring tuneshift versus closed orbit bumps in the IR and (iii) Measuring resonance driving terms from turn-by-turn BPM data around the ring.

R5.5: First steps towards chromatic and non-linear optics commissioning should be taken in the fall 2019 run.

R5.6: Allocate sufficient machine time for increasing the specific luminosity, including tuning the linear, chromatic, and nonlinear IP aberrations of both beams, and for optimizing their offsets, crossing angles, and betatron tunes, in order to increase the beam-beam tune shift and to reduce the vertical emittance blow up.

R5.7: Exploit turn-by-turn BPM capabilities for optics and resonance driving terms measurements.

R5.8: Measurements or estimates of momentum compaction factor and second order dispersion might be useful to understand some issues of the machine, such as the anomalous bunch length. Momentum compaction factor can be estimated from dispersion or from synchrotron tune versus RF voltage.

R5.9: Could vertical beta at HER X-ray source be increased beyond 28 m? At least for a test.

R5.10: If a crab-waist optics is considered for the future, first optics tests should be performed to assess its difficulty, possibly after the installation of additional quadrupoles and BPMs.

R5.11: DAFNE experience clearly indicates that the crab-waist optics can greatly improve the background, in addition to increasing the maximum beam-beam tune shift.

R5.12: Explore collaborations with external laboratories to support the tasks mentioned in these recommendations.

6. Beam background (Belle II)

The background team of Belle II has been very active in using machine time to separate out the various background sources. They have been working together with the accelerator team to better understand the various sources and to concentrate on mitigation of the backgrounds. The team studied the large Touschek backgrounds seen in Phase 2 and came up with a collimator configuration (that includes a new collimator installed last summer) that was completely effective in suppressing the Touschek background for Belle II. This is a very impressive achievement. This accomplishment indicates that an effective simulator for the background is now in hand and this should help in giving the team confidence when they study the next level of background suppression. The background team has concluded that the LER beam-gas events are presently the dominant term in the Belle II backgrounds. They are now studying this background source to see how either a new collimator or collimators, or a different collimator configuration with the present collimators can improve this background for Belle II.

The discovery of very fast beam loss events in which the QCS magnets quench, detector collimator jaws are damaged and very high radiation levels hit the PXD detector has become a major concern. Effort has been initiated to speed up the beam abort signal that comes from the diamonds located around the central beam pipe and just under the PXD detector. There is also a concerted effort in conjunction with the accelerator team to see if there are other locations around each ring in which sensors can be placed that can detect a very early signal that the beam has become unstable, and allow, thereby, to abort the beam before it can damage any machine or detector component.

Recommendations:

R6.1: Establish scrubbing time to improve the vacuum in the LER. This should improve the current primary beam-gas background. This means initially limited time for physics running in the fall. However, the combination of more β_y^* squeezing and scrubbing should improve further physics running.

R6.2: Care needs to be taken to try to minimize the number of QCS magnet quenches and damage to collimators until an improved abort and/or protection system is in place (either more collimators or collimator position changes and/or improved sensor positioning to detect a bad beam in order to induce an abort sooner). The possibility of a non-synchronized abort should be studied.

R6.3: The background team will need to continue to study the background levels of various background sources as the machine continues to improve and as lattice parameters change. An old background may resurface or a new background source may appear. As the luminosity improves, the background team will need to keep on the alert for the expected luminosity induced backgrounds.

7. Beam background (Inj. Tuning)

Continuous horizontal injection was successfully set up for both beams. The stability of the injected beam parameters (orbit, energy, energy spread, emittance, etc.) compared with Phase 2 was, and is being, improved by a variety of measures and tools, such as energy feedbacks for the J-ARC, DR and BT (beam transport). The actual injection efficiency is not known due to large calibration errors of the beam current signals.

An injection tuning procedure was established which minimizes the detector background caused by the injected beam. The optimum injection phase suggests the presence of a long longitudinal tail. Betatron tunes were optimized for minimum background during injection. It is not obvious that these tunes are also the optimum tunes for beam-beam performance. Injection into LER is extremely stable and does not cause any background concern. Background from horizontal injection into the HER is also not expected to present any showstopper for future operation at higher beam current or higher luminosity. However, at present, in the horizontal plane synchrotron-radiation photons may hit the detector after a single reflection.

Beam aborts during injection are seen roughly once per day. 10% of these aborts are caused by sudden energy and orbit changes in the linac. For both LER and HER, new collimators will be installed in the BT to intercept a low-energy beam. This should avoid beam aborts in case of a linac klystron failure. The causes for the other 90% of injection beam aborts are still unknown.

Recommendations:

R7.1: Continue the efforts to optimize and stabilize the beam injection.

R7.2: Improve the calibration of the beam current signals used for monitoring the injection efficiency.

R7.3: Allocate more machine time for beam background studies, to maintain low beam background conditions due to HER injection over longer periods of time.

R7.4: Compare injection efficiency and background with or without the other beam present.

R7.5: Simulate the beam background taking into account the experience from Phase 2 & early Phase 3 operation, and try to predict the beam background for the future running with higher beam currents and lower beta function at IP

8. Beam aborts status

The SuperKEKB beam-abort system is presently designed to dump the beams within 37-48 micro-seconds from the interlock event to full extraction of all stored bunches. The exact duration depends on the relative timing with respect to the beam abort gap and on the number of bunches stored in the beam. The total dump execution time includes 2 micro-seconds for the device request, 19 micro-seconds for the interlock processing time, 6-17 micro-seconds wait time for the abort gap and up to 10 micro-seconds until all bunches are extracted. In SuperKEKB there are 12 local instrumentation rooms that collect dump requests around the ring. For each abort from an interlock a detailed abort analysis is performed.

In Phase 3 operation there have been 5 QCS quench aborts, triggered twice by power supply trips and three times by beam loss events. The beam loss dump threshold had been lowered on June 5th. Beam losses during some of those QCS quench aborts were severe and have caused damage not only to some collimators, but also to the vertex detector of Belle II. A careful analysis of the sequence of events, signals recorded and damage induced was presented. About 100 signals are connected to the beam abort system.

The team has worked out a list of measures that would reduce the time required for beam abort to 23-28 micro-seconds, 40% faster than presently. The proposed measures include a speed-up of the quench detection, lower loss thresholds, shorter sampling times for the interlock from the Belle II diamond loss detectors, optimized cable paths with shorter lengths and the introduction of a second abort gap.

The experience with beam aborts illustrates the great importance of a well designed and complete machine protection and beam abort system. The team has performed a careful analysis of what happened and presented quite complete logging files of signals and events. Several useful measures for system improvements have been worked out.

Recommendations:

R8.1: It is recommended that failure modes in the accelerator systems of SuperKEKB should be reviewed for completeness and cases like an asynchronous beam dump, fast magnet failures, ... should be added.

R8.2: It is recommended to install additional “protection” collimators away from the IR, potentially close to the dump kickers, for defining the closest aperture, for intercepting beam losses at an uncritical location as early as possible, for avoiding the generation of beam background close to the IR and for fastest possible beam dump (see recommendations for vacuum/collimators for more details).

R8.3: It is strongly supported that the Belle II detector establishes an independent interlock with fast connection to the abort system for an additional layer of detector protection.

R8.4: It is recommended to continue the measures for improving the coverage and reaction time of the machine protection and beam abort system. An international review might provide useful input from other colliders with high stored beam energy.

9. QCS status and plans

The committee continues to be impressed by the compact design of the QCS superconducting low-beta magnet system, and the fact that it is performing optically as expected. While the magnet system itself is reliable, its operation has been marred by numerous beam-induced, and some power converter-induced, quenches, compounded by the long time required to re-cool the system due to limitation of the power of the refrigerator. Some of these problems are being addressed in collaboration with other sections of the SuperKEKB team. In particular the beam-induced quenches are part of a global problem of beam-gas (or -dust) interaction and inadequate collimation that also leads to background problems. Some progress has been made in going from Phase 2 to Phase 3, but as discussed elsewhere in the report there is still room for improvement – by introducing aperture limiting collimators, for example. Hardware upgrades, such as installing tungsten radiation shields close to the QCS vacuum chamber, were suggested and should be considered to reduce the beam background. Could this be done during the shutdown in 2020? Appropriate circuitry should be included to preclude quenching due to power converter faults. Although the magnets have been designed such as to withstand quenching, care should be taken to avoid damaging the compact (and complex) magnet system.

An associated problem is the time it takes to re-cool the QCS after a quench. This has become worse, particularly on the right side, presumably due to degraded insulation vacuum – which, it is assumed, will be repaired during the summer shutdown. However, the installed cooling power is barely sufficient, and it is proposed to improve the margin by replacing some of the present current leads with High Temperature Superconductor (HTS) lower sections cooled by liquid nitrogen at the warm end. This could be effective, the implication on the rest of the system (and the total cost) should first be fully evaluated, and compared with other ways of increasing the cooling power (e.g. boosting by introducing LN_2 cooling in the refrigerator cooling cycle, to be used during the cooldown process).

Given the problem with the bellows connecting the QCS system to the central vacuum tube consider improving the connection process. This should be done with special care to avoid applying excessive force to the RF fingers. It would be advisable to set up a quality procedure, or have a check-list, associated with this process.

KEK proposes to study the possibility of replacing some sextupoles and correctors (presently warm magnets) with stand-alone superconducting units cooled with cryo-coolers, using A15 (Nb_3Sn, Nb_3Al), or HTS, superconductors to take advantage of their higher critical temperature. This would enable running at about 10 K at which temperature the cryocooler is 4 times more efficient than at the 5 K required for standard Nb-Ti superconductor. These materials are however brittle and it is recommended that full account be taken of their strain dependence, and the available strand sizes, before embarking on tests of samples that should imperatively precede the manufacture of models. Present conductors also feature filament diameters of at least 50 microns, which has an impact on stability when the conductors are used at the relatively low current density being considered for this application. It is noted that presently KEK possesses neither expertise nor specialized tooling for the application of A15 materials, but it has built a sextupole using HTS.

Recommendations:

R9.1: Ensure that a power converter trip does not cause the QCS magnets to quench.

R9.2: Investigate the possibility of boosting the cooling power of the cryogenic system.

R9.3: As part of the long term strategy, explore the possibility of increasing the aperture of QCS to mitigate the beam loss and quench issues in the quest for achieving smaller β_y^*. This should be done without diverting significant resources from the present program.

R9.4: Determine with the help of energy-deposition simulations (FLUKA, Geant,...) the amount of local beam loss which quenches the QCS.

R9.5: Any future QCS upgrade should take full account of experience gained in using the present QCS, and the system optimization (performance, cost, risk) should be done in close collaboration with the optics team.

10. Collision tuning (feedback, dithering)

This year the committee heard a report on the collision tuning dithering system, which will be required to keep the small beams in accurate alignment at the IP to maximize the luminosity. The talk lists 17 contributors Who actually knows how this system works and how it is set-up? What do the phase shifters etc. chassis do? The work is based on the system developed and operated in PEP-II. It has numerous hardware elements and uses a commercial lock-in amplifier as the heart of the detection of a luminosity signal. As presented, excitation coils are used to modulate the horizontal position of the LER beam in collision across the HER beam, which results in a small modulation of the luminosity. A synchronous detection method is used to provide an error signal for a feedback servo which adjusts the HER beam position to maximize the luminosity. If the beams move at the IP this system acts to remove the disturbance and keeps the beams at the IP aligned.

The general principle is clearly shown on slide 3, which highlights the use of a multiplier in the lock-in detection to process the luminosity signal, but does not show the entire signal processing, especially the low pass filter required to separate the luminosity error signal from the higher frequency components.. The slide shows the rationale for the small modulation of the LER beam. This small modulation acts to generate a detection signal that is the derivative of the luminosity with respect to offset. The dither excitation excites the beam at a frequency omega (79 Hz), but as seen in slide 3 and as explained on slide 16 the lock-in has to detect at 2*omega, so the reference signal used in the demodulator must be at 2*omega to detect the modulation in luminosity at 2*omega.

This small modulation provides an error signal with the sign of error changing at the luminosity maximum. The sign is critical for the position feedback as it provides a single-valued signal which determines the direction to move the corrector. The derivative signal has a zero at the maximum luminosity, and error switches sign on either side. The PI loop should take this error signal and try to keep it at a reference level of zero.

If the modulation signal is so large as to move the beams completely out of collision, the error signal is no longer the derivative. Instead, it will have the form of the luminosity vs. offset, so the errors at offsets on either side have the same sign. In this case, the feedback position servo does not know which direction to move, and the error signal is not single valued with offset.

A single overview system block diagram was not provided, and it would be helpful in understanding the results. The reviewers were trying to understand the origins of the modulating signal, how the 2*omega term is generated (in the lock-in reference channel?). There are numerous frequency dependent aspects, for example, the bandwidth and noise of the luminosity monitor must be considered, the modulating frequency has to be slow compared to the bandwidth and response of the luminosity monitor. The bandwidth of the lock-in detection has to be appropriately selected to reduce the noise in the luminosity signal. Similarly, the bandwidth of the PI servo loop has to be consistent with the bandwidth of the lock-in filter but fast enough to follow the beam motion and keep the luminosity at the maximum. How noisy is the luminosity monitor at low currents or low luminosity? Do the various parameters change at low vs. high luminosity? None of these details were presented to the reviewers.

The results presented looked at horizontal scans as well as at the impact of coupling between horizontal dither and vertical offset. Slides 6 and 8 do not show the derivative shape of the detected error signal. Instead, the magnitude shows a minimum at the luminosity peak, suggesting that something is not right in the signal processing. One explanation is that the excitation was so large it moved the beams completely out of collision, another is that the detection was done at omega and not at 2*omega.

A PI loop to position beam is mentioned, but what is the error signal to this loop? The detected magnitude? The detected phase? And the timescales and time responses look so slow as to be of little use. The results show that the position does not settle in 10 minutes, which seems a strange choice. The system seems to lose lock and the talk comments "The cause is not yet understood, we are checking the algorithm".

In summary, the system status is not yet operational, but it will be needed in the future.

We are confident this system will be in operation later during Phase 3 commissioning, and hope these comments are helpful in moving towards the next tests.

Recommendations:

R10.1: A block diagram showing the functions and the nominal signal levels for operation would be very helpful in checking and operating the system. It should show the major signal paths and have clear details of the signals from each of the various functions and chassis.

R10.2: A simple operating guide with set-up instructions and enough detail to allow operations without a special expert is needed. A small group should be defined who can operate and configure the system, and this group should do the next beam tests.

R10.3: There are several nested feedback loops and signal processing functions which must have consistent bandwidths and the excitation of the beam via the dither coils has to be appropriate for the beam size. It is necessary to have a table with important design choices or operational specifications for commissioning as well as for future operations.

R10.4: The next system tests should be carefully structured to verify the proper small modulation of the beam position, and to verify the expected derivative form of the detected signal before trying to close the PI loop. This requires care in setting up the system, as the excitation level has to be carefully selected to match the beam cross section and kicker strength. You need a small modulation, not a displacement so large that the beams go out of collision.

11. MR Magnet System

The mission of the magnet group includes not only normal-conducting magnets but also magnet power supplies including for QCS, and survey and alignment work for the entire magnet system. It is recalled that a large portion of magnets of the Main Rings (MR) have been reused, and most of magnet power supplies are recycled units after refurbishment. Despite such difficulties, the magnet group has managed to maintain the performance of their systems in a responsible manner. However, the occurrence of repeated problems with QC2LE is a serious concern calling for a radical solution.

As was to be expected, decayed components of reused magnets such as flow sensors and switches have shown failures and led to interruption of beam operation. While the flow switches for HER dipole magnets were all replaced entirely, there are still many quadrupoles and sextupoles equipped with old switches and sensors and it will take time and resources to replace them entirely. Adequate planning may be needed to schedule this work so as to minimize the risk of trouble. A similar effort applies to the entire complement of rubber hoses.

We appreciate the clever way of adding coils for skew fields to enable a wider range in the IR coupling knob scan, as well as the group's effort to maintain their systems. Also with regard to the nonlinear optics, it should be possible to correct the chromatic x-y coupling at the IP in the LER using the rotation feature of the sextupoles to create skew components, but this has not yet been tested. We expect this to be carried out in the near future.

Recommendations:

R11.1: Prepare adequate planning and resources for replacing old related components such as switches, sensors, and rubber hoses not yet replaced.

R11.2: Carry out the test of correcting chromatic x-y coupling at the IP in the LER.

R11.3: QC2LE may need a radical approach to solve repeated problems.

12. Beam instrumentation at SuperKEKB

Several relevant R&D activities on beam diagnostics have been carried out during Phase 3 operation in order to maintain and improve the performance of existing tools, as well as to develop new devices, aimed at optimizing beam parameters and collision setup, which are expected to be necessary to achieve design luminosity.

Concerning the BPMs of the main rings, during the QCS cryostat insertion one out of the four signal cables of the MQC1LE/LP beam position monitors in the final vertical focusing quadrupole magnets got damaged. However, beam orbit measurements were still possible, although with reduced accuracy, by exploiting the other three electrode signals. Since these BPMs are important for beam position and optics measurement, it has been correctly decided to restore their full functionality during the summer shutdown 2019. This operation is not simple and not without risk, since it requires to disassembly the QCS cryostat located inside the Belle II detector.

The performance of the gated turn-by-turn beam-position monitor has been presented. This module is based on FPGA, log-amps ADC and a fast gate switch. It has been mainly developed for beam optics studies and used, so far, for beta and phase advance measurements. The new board being integrated in the EPICS control system can profit from the Analysis Server providing efficient FFTW and NAFF algorithms for data analysis. Experimental measurements have shown that phase advance and beta function can be determined with an accuracy of 0.07 x(2 Pi) and 17% respectively, when exciting the beam by using the injection kicker.

Several beam size diagnostics tools serve the damping ring and the main rings.

Horizontal beam size in the damping ring is efficiently measured by a gated camera; fit of the data as a function of the time returns a horizontal damping time consistent with the design value.

The true resolution of the X-ray monitor was not measured in Phase 3, because the beta function at the source point could not be sufficiently reduced. However, in Phase 2, a smearing function on the order of 7 μm was measured, which is smaller than any beam expected to be seen at SuperKEKB.

A new kind of X-ray monitor based on Si-pixel sensor capable to return bunch-by-bunch beam size has been presented. The monitor architecture integrates a spectrometer chip developed at SLAC and is equipped with high speed readout electronics. The detector has been preliminarily tested on the HER and it will be permanently installed during the next summer shutdown.

Several presentations have shown how the beam trajectory optimization in the Transport Lines (TLs) is crucial for minimizing emittance growth in the TLs and injection background in the collision rings. The BPMs installed along the TL are equipped with a rather old-fashioned acquisition system based on obsolete components and working asynchronously. A detailed plan has been presented to equip at least a subset of such BPMs with Libera acquisition modules and to replace the acquisition of the remaining ones with a new generation Tektronix 12-bit ADC scope, which will deal with a stream of data merging input from different BPMs.

Large parts of the WS and LM transport line sections have been equipped with optical fiber beam loss monitors. Such diagnostics tool has been successfully tested and used to verify the impact of beam trajectory correction on the beam transport efficiency.

The longitudinal bunch-by-bunch feedback is operating stably with a damping time of less than 2 ms at a beam current of 500 mA in the LER. Studies in May 2019 showed the machine had no unstable modes driven by HOMs, but motion at low modes from the fundamental cavity impedances could be excited. The LLRF system has dedicated mode -1, -2 and -3 loops which can be commissioned at higher currents.

The fast vertical IP orbit feedback is being tuned and commissioned. At present, it can suppress oscillations below 30 Hz, but induces a large oscillation around 230 Hz.

Recommendations:

R12.1: Develop a comprehensive plan for the intervention aimed at restoring the damaged cable of the MQC1LE/LP BPM in order to avoid other possible inconveniences and to restore the proper alignment conditions of the components which must be removed.

R12.2: Consider a further development of the gated turn by turn monitor board in order to use it for accurate single pass beam orbit measurements in the collider rings.

R12.3: Try to improve the X-ray monitor resolution by revising the optical setup and the kind of mask used by the detector.

R12.4: Test the long-term radiation resistance of the silicon-pixel detector of the new X-ray monitor before installing it on the machine.

R12.5: Provide synchronization for the BPMs in the transfer lines, at least for the ones which will run under the Libera module control.

R12.6: Investigate the origin of, and try to mitigate, the 230 Hz peak excited by the fast orbit feedback.

R12.7 Explore the effect of the fast orbit feedback on beam-beam blow-up and luminosity performance.

R12.8 Try to extract information of intrabeam scattering from the damping of horizontal and longitudinal emittance of DR. This will provide additional information on vertical emittance, etc.

13. RF system status

The main ring RF systems are operating very well with very few trips and low down time. There were a few trips of the ARES systems due to breakdown events in the coupling cavity. These should be monitored in case they are a sign of aging, or become more frequent as the beam current is increased. Two high power water load windows failed, leaking water into the waveguide. These windows had operated reliably for many years. Failures are thought to be a result of unusual “water hammer” events. Water leak detectors have been installed to give early warning of future failures. A secondary gas barrier could be considered to separate the load window from the rest of the waveguide, with the water leak detector in front of the window. A modulation anode controller failed on one station, it was replaced with a fixed voltage divider. This does not allow optimization of efficiency but otherwise did not prevent running. A new controller should be installed when convenient and other systems monitored in case of similar failure.

The SRF systems are operating well with no reported degradation over time. The new beamline HOM absorbers are effective and no signs of HOM-driven coupled bunch instabilities have yet been detected by the transverse or longitudinal feedback systems. Low-mode oscillations have been observed and can be controlled by the dedicated feedback systems. These oscillations swill become more challenging as currents increase and the feedback controls must be flexible to accommodate parked cavities and other changes in the RF system.

Failures of the piezo stacks reported at the last review have been traced to water absorption. Drying with silica gel can stabilize the piezos in the tunnel. However running only mechanical tuners without piezos was stable, it should be investigated whether piezos are really necessary.

Nine RF stations are running the new digital LLRF system with no issues. The remaining stations are operating reliably on the old analog system. Plans should be made to phase out the old systems and to replace them with new ones, as they become unsupportable.

The number of installed klystrons was adequate for Phase 2 and the beginning of Phase 3 but the system has not been fully converted to the final configuration. Additional new klystrons will need to be installed to reach the final 1-to-1 configuration. Given the high cost and long lead time of the high power klystrons it would be prudent to buy ahead to support the planned current increases.

No issues with the RF system beam loading transients were reported (R21.6 from the 2018 ARC report: Continue to study and understand the gap induced transients in the RF systems and the effect on luminosity). RF overhead and control margin were adequate in the last run but as currents increase this will become more difficult. For the next review it would be good to have a presentation on the transient matching scheme and performance to date.

Recommendations:

R13.1: Monitor water load windows for signs of aging. Consider gas barriers to separate the waveguide from the water windows.

R13.2: Given the high cost and long lead time of the high power klystrons plan ahead to support the planned current increases.

R13.3: Plan for the eventual phase out the old analog RF systems and replacement with new ones as they become unsupportable.

R13.4: Implement drying and protection of the piezos and investigate whether these piezos are really necessary.

R13.5: For the next review prepare a presentation on the transient matching scheme and performance to date.

14. Vacuum system status (collimators)

In this initial part of Phase 3, the SuperKEKB vacuum team has obtained three crucial results. First of all, the dynamic pressure rise due to the circulating beam is decreasing as expected for the LER and it is much lower in the HER, thanks to the accumulated photon dose in the KEKB era. Then, the electron cloud effects are not present anymore after the installation of permanent magnets in most of the drift vacuum chambers. Finally, the vacuum system of the damping ring perfectly fulfils the requirements.

Despite these important achievements, the pressure around the interaction region (IR) is too high to ensure a safe running of the detector. The high background, most probably generated by beam-gas scattering, prevents the detector from achieving its ideal running performance and spoils its discovery capability.

An attempt to understand the correlation between gas density in different locations and detector background has been made by heating the NEG pumps: hydrogen released from the NEG material increases the pressure locally and a simultaneous growth of the detector background is recorded. This elegant measurements should be coupled with beam-gas simulations to better understand the detector behaviour.

The pressure profile around the IR indicates that the highest pressures are in the LER at the location of the collimators that were changed after Phase 2 2, i.e. D02V1 and D02H1. Even if all precautions were taken to preserve the surface conditioning, the installation of unscrubbed components resulted in inevitable pressure bumps at the position of the new equipment. In the future, the effect of the installation of new components could be mitigated by ex-situ pre-baking. After baking, the components should be kept under vacuum and installed in the rings in a flow of dry nitrogen.

To attain safe conditions for the detector at nominal beam parameters, the dynamic pressure around the IR should be 10 times lower than the present one. This objective can be tackled in two different ways. Firstly by baking as much as possible of the two sectors where the recently installed collimator are located. If the heating is carried out at a temperature higher than 100°C for several days, an average pressure decrease by at least a factor of three seems to be achievable. However, the local bakeout cannot fully avoid additional beam scrubbing and, possibly, a dedicated beam run. At the present trend, additional 2000 Ah seem to be necessary, obtainable, e.g., by about 2 to 3 months of running at the present maximum beam current in the LER. More time will be needed if the selected current is lower or if the scrubbing is performed parasitically during physics runs and low-beta tests.

Another important component that can affect the gas density and the vacuum system integrity is a bellows of the interaction-point vacuum chamber (HER side). It has been found that the external wall temperature rises up to 60°C at the present highest current; a much higher temperature is expected in the RF shield. These problems have been attributed to a lack of electrical contact in one of the fingers. The plan is to change the affected bellows. This will provoke a loss of the beam pipe conditioning that could be recovered during a dedicated beam-scrubbing run.

The most worrying event that affected the collimators system is the beam impact on the jaws of three collimators, two in Phase 2 (D02V1 and D01V1) and another one in Phase 3 (D02V1), and the subsequent quenching of the QCS magnet and a pressure bump in the position of the damaged collimator. The beam instabilities developed extremely fast, only in a few turns. After Phase 2, the scratched jaws were replaced; those damaged in Phase 3 will be replaced in this year’s summer or winter.

A possible cause of the beam instability is a falling dust particle, most probably made of aluminium. The detailed mechanism leading to fast instability after collision with dust is not known at present. It deserves more attention in view of the large impact it could have on the future runs at higher beam current.

The consequences of such disrupting instabilities on the machine and detector safety triggered a discussion about the need for additional collimators, the change of their configurations and the need for a faster beam abort system.

The first action should be to separate, in the collimation system, the role of machine protection and detector background reduction. In detail, this suggests to add a robust collimator as a first line of defence, designed for intercepting the beam in dangerous situations, and equipped with a robust jaw material of lower Z. This first-line collimator has to be placed at $N\pi$ phase advance from the triplet magnets to protect them; possibly two phases for better phase space coverage: $N\pi$, $(N+0.5)\pi$, ideally close to beam dump kicker for fast beam extraction. The protection collimators has to be put deepest in beam sigma, e.g. 15σ, and be equipped with fast-reacting beam loss monitors that trigger beam dump in case of excessive losses. The collimators close to the IP will be kept at a wider setting, e.g. larger than 20σ, to ensure the protection of the detector. The setting strategy has to be studied in detail and adapted to the squeeze.

Recommendations:

R14.1: Perform a bakeout (T>100°C for several days) of vented vacuum sectors; evaluate the impact of the in-situ bakeout on the mechanical integrity of the vacuum system (vacuum chamber expansion, bellow compressions, fixed points).

R14.2: To avoid excessive dynamic pressure rise, carry out ex-situ bakeout of new components to be installed in the rings and store them under vacuum or dry nitrogen.

R14.3: Investigate a possible change in the design of the RF shields in the IP, so that impedance-related heating is avoided. For example, analyse the design of the new RF shield proposed for the HL-LHC project in the triplet magnets area. Check for HOM heating.

R14.4: To avoid detector and QCS damage, separate the functions of machine protection and detector background reduction. The first role can be fulfilled by a robust collimator (lower Z material) placed at an adequate location close to the abort system, far from the experiment. The second one is taken by the existing collimators closer to the detector with a larger normalized gap. This approach implies the installation of additional collimators in the two main rings.

R14.5: Remeasure the collimator impedance with the beam, and estimate the total impedance with the additional collimators.

R14.6: Once the main rings are in a safe condition, i.e. after the installation of the additional collimators, increase the beam current in steps and develop optimized beam-scrubbing scenarios to accumulate, before summer 2020, approximately 2000 Ah at the maximum possible beam current in accordance with the planning of the physics runs .

R14.7: If necessary, repeat the dust removal operation to reduce beam-dust interactions and the the associated risk of damage for the collimator jaws.

R14.8: Determine with the help of energy-deposition simulations (FLUKA, Geant,...) the amount of local beam loss which may damage the various collimators.

R14.9: Critically revise the mechanical design of the collimators in order to exclude possible sources of significant HOM heating or discharge events.

15. Fire at Nextef

Around 10:00pm in the evening of 3 April 2019, there was a serious fire at the Nextef facility, which is adjacent to (but separate from) the Injector Linac. Nextef is dedicated to testing high-power RF structures and has two RF modulators. It has been in operation for over ten years and there is only a local operator during the day shift. This meant that the fire, which was preceded by two, rather common faults, was already out of control by the time the fire alarm was triggered. The cause was identified to be a capacitor encased in a plastic case which punctured. This capacitor ignited its nearby neighbor capacitors to make the fire larger. This fire caused soot to be deposited over a large area of the linac. This kind of capacitor has since been improved by the manufacturer and the new version was installed at the ATF. This kind of capacitor is not used in the B-Factory Injector.

Nextef has initiated a series of corrective actions to prevent a reccurrence. These include: replacing the plastic-cased capacitors with ceramic cased capacitors (the kind installed in the SuperKEKB linac modulators), reducing the voltage gradient in the capacitors, performing routine checks of the capacitors, installing remote visual monitoring via TV cameras, and putting the fire detectors and fire suppression equipment inside the modulators.

The first equipment to be re-installed will be the S-band test stand that is required for the replacement of accelerating modules in the SuperKEKB injector.

Recommendations:

R15.1: Implement the proposed fire suppression improvements.

R15.2: Prepare the S-band test station as soon as possible.

16. Recovery of injector linac

The impact of the Nextef fire on the SuperKEKB commissioning program was considerable. While there were no injuries or direct damage to the injector equipment, carbon soot infiltrated the injector equipment room, covering everything. The soot is liable to cause discharge of the high-power pulsed modulators and could short-circuit the instrumentation. It was decided to clean all of the components as quickly as possible, but some equipment was left un-energized until the summer shutdown in order to speed up the recovery.

The clean-up was extremely well organized and proceeded rapidly with first beam out of the injector after only three weeks. The linac energy was lowered from 1.5 GeV to 1.35 GeV, but this did not have much impact on the injection at this stage of the commissioning.

The state of the injector equipment protection was re-evaluated after the fire. Many of the factors that affected Nextef are not present in the SuperKEKB injector. However, additional TV cameras will be installed.

Recommendations:

R16.1: Move the fire detection and suppression equipment inside the modulators.

R16.2: High voltage cables outside the cabinet are also flammable and should be protected.

R16.3: Consider providing isolation barriers between sections of the equipment gallery to limit the damage in case of a fire.

17. Injector beam operation

The injector can perform the stable simultaneous top-up injection to HER, LER, PF, and PF-AR with the thermionic gun, RF gun, pulsed magnets and moveable girder in Phase 3, which increased the integrated luminosity by 237% compared with the normal injection. The HER injection with RF gun worked well enough for the whole run without any significant problem. The committee congratulates the SuperKEKB team for these great accomplishments. The stability of the stored beam current during simultaneous top-up injection is better than 0.5% in all the rings, and even as small as 0.02% in the PF ring. Energy feedback, beam orbit feedback, dispersion measurement and correction, and emittance measurement are all contributing to the good performance of the injector, with an energy jitter at the BT smaller than 0.025% and a correction of the ~1 mm orbit drift down to ~0.1 mm.

The vertical emittance of the positron beam increases by a factor of 3 after the damping ring , which could be caused by insufficiently optimized DR extraction.

Recommendation:

R17.1: Try to understand the dilution of vertical emittance of the positron beam after the DR, by optimizing the beam transport and optics parameters, during and after extraction.

R17.2: Develop a detailed plan for realizing the final goal of the injector performance. The heating issue is the first priority for increasing the repetition rate of the thermionic gun. More detailed studies are necessary.

18. Injector RF and LLRF

The injector and linac RF systems are operating well, supporting simultaneous injection into four machines plus the damping ring, and fast top-up of LER and HER. The phase control between the main ring and the linac was improved and many sources of RF drift and jitter were identified and corrected including intermittent cable connections and pulsed magnet jitter. Some slow drifts remain, leading to emittance increase over time and injection losses. Further improvements in timing stabilization are planned for the summer, including the sub-harmonic buncher.

The damping ring RF operated reliably with two cavities installed. No issues were reported. Damping ring synchronization and bunch selection timing are working as planned. The beam gate rate was increased without issues allowing more frequent top-up.

Some linac RF equipment was affected by smoke and soot from the nearby fire at Nextef and was off-line for 3 weeks for clean up. Thanks to a great effort by many people the linac operation was restored and ran reliably for the rest of the run. The energy of the first part of the linac was reduced as a precaution and some diagnostics were not available, but overall injector performance was good.

Normal top-up injection does not seem to produce unacceptable backgrounds however off-normal pulses can cause spikes in losses. Energy collimation in the transfer line may help. The team should investigate whether fast enough detection is possible to inhibit injection of off-normal pulses. Hunting significant sources of jitter in the injector and linac should continue.

New RF monitoring systems are installed on all RF sources and can capture waveforms on a pulse by pulse basis and save the last pulse after an interlock. This will be very useful in diagnosing problems and sources of jitter.

Detection of off-normal pulses may be automated to collect statistics or flag systems for expert intervention. The team should consider developing a machine learning algorithm to filter this large data set as is being considered in other places.

Recommendations:

R18.1: Investigate whether fast enough detection is possible to inhibit injection of off-normal pulses.

R18.2: Continue hunting sources of jitter in the injector and linac.

R18.3: Consider developing a machine learning algorithm to process captured RF waveforms and other profiles.

19. Injector Beam Monitors

An upgraded injector Beam Position Monitor (BPM) readout system provides position resolution below the 10 μm requirement of SuperKEKB. The system is gated and synchronized to distinguish the position of the four (or five) independent beams, which of course is exceptionally useful.

Each BPM can be calibrated without beam, and using this feature, it was found that approximately 30% of the BPMs exhibit instability (at a small level). This issue will be further investigated.

The beam size at dispersive regions is related to the beam energy spread. A clever KEK-era technique based on an 8-channel BPM was re-applied using the new BPM readout system to monitor the quadrupole moment of the beam, which is related to beam size, and provides a non-invasive measurement of the relative energy spread of the beam. The technique cannot distinguish beam size from beam distribution, but nonetheless provides a valuable relative measurement of energy spread. The method was validated using a nearby view screen.

YAG view screens and improved optical imaging provide higher resolution for beam profile monitoring compared to older Chromox view screens.

Recommendation:

R19.1: Investigate if sufficient synchrotron light is available at the end of the J-ARC to provide real-time non-invasive monitoring of the beam energy spread.

20. RF Gun, Laser and Electron Beam Commissioning

To meet SuperKEKB luminosity goals, the biggest challenges imposed on the RF gun were succinctly stated: the photogun must provide 4 nC bunches with 10 μm beam emittance and it must operate reliably. These are very demanding requirements.

It seems the three gun approach is a good design, with the highly reliable thermionic gun providing beams for the photon factories and the LER, the Quasi-Travelling Wave RF gun providing beam to the HER, and the third gun (the Cut Disc Structure RF gun) serving as a spare. Both the RF and thermionic guns are operating reliably, but have not yet been required to operate continuously at full bunch charge. The back-up RF gun is available in case of problems with the primary gun.

There remain many choices for RF gun designs, drive lasers and photocathodes, but the primary QTW RF gun with Ir_7Ce_2 photocathode, driven with the “simple” Nd/Yb hybrid laser system proved to be very reliable and fulfilled all the demands of the recent run periods, exhibiting over four months of continuous operation – a remarkable achievement.

Noteworthy accomplishments that served to improve reliability included the implementation of switchable master oscillator oscillators, higher dopant Nd:YAG amplifier crystals to reduce pump diode currents, and a 3x improvement in QE from the Ir_7Ce_2 photocathode using a novel heating plug.

A two-laser beam approach could be implemented to provide some temporal control of the laser pulses (and thereby explore space charge effects) but most operation to date was performed with one laser beam.

It seems that adequate diagnostic systems and controls were implemented.

Beam emittance at ~1 nC operating condition was sufficiently good.

The group remains very ambitious and enthusiastic about implementing improvements, with no shortage of ideas.

Recommendation:

R20.1: Proceed as planned, preparing for operation at higher bunch charge.

R20.2: Fully test the Cut Disc Structure RF gun located at the 90degree position at A1 before replacing it with another RF gun design.

21. Positron source

The flux concentrator (FC) presently installed at the positron source was successfully bench tested at the design current of 12 kA but has only been operated at 3.5 kA during Phases 2 and 3. This was sufficient for recent runs but higher current operation will be required once Belle II background rates are reduced. There is still concern of high voltage discharge at the flux concentrator. So far this has not limited injection or top-up. The snubber circuit is effective in reducing the peak voltage. The new flux concentrator was made from non-work hardened copper. New stronger alloys are under consideration. A detailed mechanical analysis is in progress and should be completed. The fatigue limit of the materials should be compared, not just the initial yield strength.

A number of steps are being taken to ensure rugged and reliable operation of the FC at 12 kA: uniform gap between coil windings, gap optimization, snubber circuit to reduce the voltage during the current pulse. A new FC made of copper alloy will arrive in October.

Additional steering magnets in the area of the solenoids should help address orbit issues.

The steps being taken seem reasonable; however, this work lacks manpower.

Recommendation:

R21.1: Complete the mechanical analysis of the flux concentrator and the evaluation of alternative materials, including fatigue limit. Continue to study the solid insulation in the gap and a reliable work-hardening technique.

22. Status of beam transport line (BT)

In preparation for Phase 3, some important modifications were done in the Beam Transport Lines (BTL):

1) To prevent septum field leakage in the MR ducts, the beam pipe was replaced by a whole carbon-steel section; as a result the measured leakage was suppressed by a factor of more than 20, both its dipole and quadrupole components. This has been confirmed by measuring the longitudinal field distribution and by a horizontal scan. The leakage field acting on the circulating beam was reduced to BL_max=1.35 e-5 Tm/fringe , B'L_max = 6e-4 T/fringe. It is worth noticing that the same conclusions could have been obtained, with much less effort, by measuring the variation of the beam parameters when switching the septum on and off.
2) Wire scanners were improved: a 3 times thinner wire is used, and a 45 degree rotation is applied.

3) Optical fibers were installed in the BT tunnels for both wire scanners and loss monitors. They are ready for 2-bunch, 25 Hz, 2 nC/bunch injection.

Beam status is presently marked by a beam loss in the final section of BTL, to be cured through careful orbit steering. In Phase 3 operation a few problems were found:

1) The DR extraction septum suffered a malfunction of its main capacitor voltage control unit, to be followed up during the summer maintenance.
2) The BPM system does not meet the measurement accuracy goals; electronics and software need upgrade.

A collimator will be relocated to intercept energy-modulated beams caused by linac single pulse faults.

There are future plans for modification of the radiation safety system and the construction of a beam diagnostics beamline within the BT.

Recommendations:

R22.1: Continue to go forward toward zero beam loss in the BT lines.

R22.2: Refine the design of the diagnostics line.

23. Emittance Preservation

For the NanoBeam collision concept, the quality of the injected beam is a critical issue. So far, the SuperKEKB injection team is working on meeting the injection requirements.

The beam emittance growth is a key concern here. Closely following the recommendations of the previous Review, a serious work is carried out to identify the emittance growth sources, to analyse the possible cures, and to implement needed improvements.

The target emittances are (horizontal/vertical) 100/15 μm LER, 40/20 μm HER, with the energy spread of 0.16% and 0.07%, respectively.

Five potential sources of emittance growth in Linac and BTL were under study:

a) Residual dispersion that transforms energy spread into beam size. Indeed, its correction in the J-Arc resulted in 187-47=140 μm, or almost −50 μm emittance reduction. The KEK team believes that in addition to bends, strong quadrupoles and sextupoles give a serious contribution to residual dispersion, and conclude that orbit feedback is necessary to preserve emittance values at the linac end. Its operation is successfully tested. In BT the dispersion correction is not yet done, insufficient BPM resolution is one of the problems. An upgrade of relevant BPMs is planned.

b) Beam phase space jitter contributes a lot to the linac emittance; dispersion and beta-function mismatch need to be corrected. A few hardware-malfunction sources of jitter ("binarization" of a pulse magnet, RF phase jitter caused by bad cable connections) have been found and eliminated.

c) Wakefield in accelerating structure is a reason for bunch-tail oscillations that blow-up the projection emittance. The effect will be especially serious with 2x2 nC bunches from Thermoionic Gun in the future. Wake-free steering, to avoid beam orbit offset in the accelerating structures, will be needed in the next run.

d) Dispersion in accelerating cavities converts energy offset into betatron emittance. Experimental evidence from ECS on/off is given where horizontal positron emittance showed a 5-fold blowup when the ECS was on. This effect is attributed to residual dispersion at the ECS RF cavity plus jitter effect.

e) Emittance excitation by quantum fluctuations in BT bends is also addressed; the estimated effect is reported not to be serious.

First results of emittance measurement showed serious degradation at the end of June 2019, when the linac recovery after the fire accident was presumably not yet complete. In the end of the BT the measured electron beam emittance is 400/150 μm with a 1 nC bunch; quantitative understanding of these numbers is still underway. Another planned improvement is realigning the bending magnets and installing quadrupole magnets in the ECS to cancel the quadrupolar component of the bending magnets, and. thereby, to correct the residual dispersion at the ECS accelerating cavities.

The Committee is impressed by the considerable effort paid to understanding the emittance growth problem and encourages further studies, as were outlined in the recommendations from the previous ARC review.

Recommendations:

R23.1: Pursue the work on analyzing and understanding the results of emittance measurements.

R23.2: Compare the normalized jitter amplitude and its evolution to the beam loss locations and an aperture model.

R23.3: Determine the frequency contents of the beam position jitter. In case that dominant frequencies in the position jitter are found, correlate them to possible technical sources.

R23.4: Perform a careful and rigorous study on the timing jitter of the RF trigger and the gun trigger, which might explain the observed energy jitter.

R23.5: Develop robust convergent algorithms for monitoring and/or minimizing the emittance growth in the linac and BT lines, suitable for everyday operation.

24. Control system (timing system)

The committee was very impressed by the presentation which highlighted the major progress in the control and timing system for SuperKEKB. This is a major and critical technical function which is integral with operation of the Linac, the damping ring, the HER and LER rings as well as operation of the Photon factory. Some of the technical functions are also integral to the ATF facility. The basic control system provides control/monitoring of over 10,000 discrete components through more than 150 IOC devices, while the flexible timing system coordinates every timed function and synchronizes thousands of pulsed devices.

The successful results in Phase 1, Phase 2 and Phase 3 show the strength of the timing and control functions implemented. This is a challenging job, which requires integration of numerous legacy modules and operating modes with the necessary functions for the new machines. The reviewers greatly respect the skill and care the team has brought to the tasks. They can be proud that every success in the commissioning rests on the core control and timing functions they have developed.

This review highlighted recent progress in the web-based monitoring systems, the implementation of a site-wide synchronized timestamp function, and the development of synchronizing beam gate and permission functions to control timed elements.

The rapid commissioning of the top-up injection was possible only because the timing and control functions were there and ready. Similarly, the expanded software and hardware functionality allows more complex damping ring operations and synchronization of the linac, damping ring and HER/LER rings for future high current operations. The efficiency of the top-up injection is seen to be an important result of the timing system flexibility.

Several new archiver software functions have been developed which are shown to be faster and more efficient than the existing CSS system. These important software functions will be necessary in fault file and system diagnostics for the operating machine.

The design team has made excellent use of modular hardware and software functions that are shared with other labs and projects. This is an excellent way to leverage the unique skills at KEK and take advantage of the investments made by the larger community. The use of EPICS and the modular EVG and EVR hardware functions allow the team to keep the complex system operational and allow flexible upgrading without lots of interventions and re-engineering.

Recommendations:

R24.1: Continue to develop the synchronization and timing functions to support flexible operations in SuperKEKB.

R24.2: Consider developing a machine learning algorithm or other automated processing to process captured RF waveforms and other fault file profiles.

R24.3: Continue to collaborate with partner labs and coordinate on shared software and hardware projects.

R24.4: The presentation highlighted 11 publications in progress, and this contribution to the field and literature is to be praised and encouraged going forward.

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
Evgeny Perevedentsev	BINP
Matt Poelker	JLab
Katsunobu Oide	CERN and KEK (ret.)
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 23rd KEKB Accelerator Review Committee

July 8 (Monday)		
08:30 - 09:00	Executive Session	
09:00 - 09:05	Welcome	M. Yamauchi
09:05 - 09:20	Overview of SuperKEKB Status	Y. Suetsugu
09:20 - 09:50	Present Performance and Plans	Y. Ohnishi
09:50 - 10:20	Belle II Status	T. Iijima
10:40 - 11:10	Beam-Beam Issues	K. Ohmi
11:10 - 11:30	Optics Analysis and Issues	H. Sugimoto
11:30 - 11:50	Beam Background (Belle II)	H. Nakayama
11:50 - 12:10	Beam Background (Inj. Tuning)	N. Iida
13:30 - 13:50	Beam Aborts Status	H. Ikeda
13:50 - 14:20	QCS Status and Plans	N. Ohuchi
14:20 - 14:40	Collision Tuning (Feedback, Dithering)	R. Ueki
14:40 - 15:00	MR Magnet System	M. Masuzawa
16:10 - 16:25	Beam monitors (XRM, SRM, Loss mon., FB)	G. Mitsuka
16:30 - 16:49	RF System Status	T. Kobayashi
16:55 - 17:17	Vacuum System Status (collimators)	T. Ishibashi
July 9 (Tuesday)		
08:30 - 09:00	Executive Session	
09:00 - 09:22	Fire at Nextef	T. Abe
09:30 - 09:52	Recovery of Injector Linac	K. Furukawa
10:20 - 11:20	Injector Beam Operation	M. Satoh
11:35 - 11:57	Injector RF and LLRF	T. Miura
13:30 - 13:42	Injector Beam Monitors	F. Miyahara
13:45 - 13:57	RF Gun	R. Zhang
14:00 - 14:22	Positron Source	Y. Enomoto
14:30 - 14:45	DR Injection and Extraction Beam Line	T. Mori
14:50 - 15:20	Emittance Preservation	Y. Seimiya (presented by N. Iida)
15:30 - 15:40	Control System (Timing System)	H. Kaji
15:40 - 20:00	Report writing / Executive Session	
July 10 (Wednesday)		
08:30 - 11:00	Executive Session / Report Writing	
11:00 - 12:00	Close-out	

Appendix C

Required and achieved SuperKEKB parameters and comparison with KEKB

parameter	KEKB w Belle		SKB Phase 3 w Belle II		SKB Phase 3 w/o Belle II		SKB Design	
	LER	HER	LER	HER	LER	HER	LER	HER
E [GeV]	3.5	8	4	7	4	7	4	7
β_x^* (mm)	1200	1200	200	100	**80**	**80**	32	25
β_y^* (mm)	5.9	5.9	**3**	**3**	**2**	**2**	0.27	0.30
ε_x (nm)	18	24	**2**	**3.8**	**2**	**3.8**	3.2	4.6
ε_y (pm)	150	150	?	?	**88**	**61**	8.6	12.9
I (mA)	1640	1190	**495**	**496**	**800**	**822**	3600	2600
n_b	1584		1576		1576		2500	
I_b (mA)	1.04	0.75	0.314	0.317	0.51	0.52	1.44	1.04
ξ_y *	0.098	0.059	**0.0333**	**0.0189**	**0.0355**	**0.0197**	0.069	0.060
L_{sp} ($10^{30}cm^{-2}s^{-1}mA^{-2}$)	17.1		**30.7**		**29.5**		214	
L ($10^{34}cm^{-2}s^{-1}$)	2.11		0.48		1.23		80	

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

Appendix D

Required and achieved parameters in the injector complex

Stage	**KEKB Achievement**		**Phase-2 Achievement**		**Phase-3 summer'19 Achievement**		**Phase-3 1st Year Plan**		**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	3.6	2.6	3.6	2.6
Life time (min.)	150	200	50	100	20 (typ)	70 (typ)	–	–	6	6
Bunch charge (nC)	e- 10 → 1	1	1.6	3.6	1.35	3.5	e- 10 2-3	2 - 3	e- 10 → 4	4
Norm. Emittance (γβε) (μm)	1400	310	200/ 5	200/ 40	120/6	54/67	100/ 15 (H/V)	40/2 0 (H/)	100/ 15 (H/V)	40/20 (H/V)
Energy spread	0.13 %	0.13%	n/a	n/a	n/a	n/a	0.16 %	0.07 %	0.16 %	0.07%
Bunch / Pulse	2	2	2	2	1	1	2	2	2	2
Repetition rate (Hz)	50		25		50 (LER+PF+PF-AR < 25 Hz)		50		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)	