The Twenty-Seventh KEKB Accelerator Review Committee Report

April 28, 2024

Introduction

The Twenty-Seventh KEKB Accelerator Review Committee (ARC) meeting was held on 25-27 March 2024. Appendix A shows the present membership of the Committee. 12 committee members attended the 27th meeting in person, and 2 others on zoom. The meeting was held in hybrid mode and featured two days of oral presentations by KEKB staff members, plus discussions between the Committee members, and a final half a day for another executive session, report drafting, and close-out.

The Committee welcomes the incoming Heads of Accelerator Divisions III and IV, Dr. Kyo Shibata and Dr. Makoto Tobiyama.

The agenda for the meeting is shown in Appendix B. The slides of the presentations are available at https://www-kekb.kek.jp/MAC/2024/ .

During its 27th meeting, the Committee has examined the progress of the project with works during Long Shutdown 1 (LS1) and restart of the collider since end of January 2024, the present challenges, and long-term upgrade plans. As always, the high standard of the presentations impressed the Committee.

Already highlighted in a previous report, the next generation is important for the success of SuperKEKB operation over the coming decades. Although during the past year a total of 6 SuperKEKB staff members retired (5 academic and 1 technical staff), a total of 7 (namely 4+3) new people could be recruited, reversing a negative downward trend of overall staff. The ARC is also pleased that by now 3 PhD students are involved with the SuperKEKB accelerator.

The most important recommendations of the Committee were presented to the SuperKEKB 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/2024/** .

Contents

A) Executive Summary

SuperKEKB has successfully restarted operation after an 18-month long shutdown. The ARC congratulates the SuperKEKB team on the smooth recommissioning, including the new nonlinear collimation section, and achieving vertical single-beam emittances in the storage ring which are lower than in 2022. The vacuum system conditions smoothly and both beam currents are increased stepwise as planned. A vertical beta function of 1 mm has already been established, and the specific luminosity at present bunch currents of ~0.3 mA is comparable to the one of 2022, but lower than the one obtained in some beam-beam simulations. Sudden beam loss events still occur, but additional diagnostics already provide new information that should help track down their origin.

Electricity price and power consumption determine the cost of SuperKEKB operation and limit its running periods. The biggest energy consumer of SuperKEKB is the collider RF system. One or two modifications to the klystron controls might lead to noticeable energy savings.

The ARC would like to emphasize that the SuperKEKB accelerator is a frontier machine and is a world leader in Accelerator Technology with ambitious goals for high peak and integrated luminosity. This accelerator is led by a highly dedicated group of experts who have encountered and overcome technical obstacles, and who will find new issues as they approach the ultimate accelerator design goals. The achievements accomplished by this team and the KEK laboratory are already being incorporated into future collider designs and the worldwide accelerator community is carefully watching the impressive progress of this very exciting enterprise.

The ARC has formulated recommendations on how to address the above issues, as well as various others, and supports the ambitious luminosity goals for the year 2024 and beyond.

B) Key Recommendations

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

1. Try to establish a long, uninterrupted beam run for autumn 2024, in order to fully qualify the benefits, and gains from the LS1 works through a step-wise approach. (R1.1)
2. Schedule a dedicated injector study period, when Photon Factory (PF), PF-Accumulator Ring (AR) and SuperKEKB are not operating, and without access to the Fuji area of the SuperKEKB tunnel; this could be two weeks before the summer shutdown. (R1.2)
3. Study, and reduce, the vertical emittance growth after the electron Beam Transport line (BT1e). (R9.4).
4. Include the error of the QCS “cancel coils” in the base lattice of the High Energy Ring (HER) used for the regular operation and investigate how to mitigate its impact in simulations and experimentally. (R9.5 and R10.3)
5. Further investigate the optimum setting of the Non Linear Collimator (NLC) parameters, such as betas, apertures, sextupole strength, betatron phases from the

injection point to the NLC, considering the collimation performance, injection efficiency, Transverse Mode Coupling Instability (TMCI) threshold, etc. (R11.2)

6. Further improve the Sudden Beam Loss (SBL) diagnostics such as by additional beam oscillation monitors, bunch-by-bunch beam-size monitors, and even more beam-loss monitors around the ring. (R12.1)
7. Re-visit the “usual” effects that could explain the SBL - for instance, coupled-bunch TMCI, electron cloud, arcing or trapped electrons in ion pumps, dust in the beam pipe, Non Evaporable Getter (NEG) pumps heated by Higher Order Modes (HOMs), power supply regulation errors, feedback-related perturbations, beam-induced collimator motion or jaw deformation, … , and motivate their rejection by experimental observations. (R12.2)
8. Based on the PEP-II experience at SLAC with NEG pump heating from HOM power, monitor a few NEG strips feedthroughs with thermocouples for temperature increases with stored currents. Select NEG pumps that are near collimators or other HOM generating structures. (R21.1)
9. Develop a contingency plan as to how one could act should the 35-year-old cryogenics equipment fail. (R22.2)
10. Determine which SuperKEKB accelerator studies need to be done during the next few years, and when, to allow technical decisions related to the future upgrades to be made at an appropriate time. (R26.1)

C) Findings, Comments, Recommendations

Welcome

Findings & comments:

During the past year a total of 7 (namely 4+3) new people were recruited, reversing a negative downward trend of overall staff, as only six persons retired during the same period. The SAC is also pleased that 3 PhD students are now involved with the SuperKEKB accelerator.

We commend the SuperKEKB and KEK laboratory for their outreach to young scientists and the effort to bring Ph.D students, undergraduate and master students to KEK. The commissioning of SuperKEKB is a unique opportunity to train the next generation of accelerator scientists and engineers. The field critically needs this new cadre to advance the future machines, and SuperKEKB can only benefit from the energy and contributions of early career scientists. We suggest expanding the program with EAJADE, including US universities and labs, possibly through the US Particle Accelerator School, and also strengthening ties with the CERN Accelerator School.

1. 2024 Schedule and Summary of Upgrade Work (LS1)

Findings & comments:

The present 2024 SuperKEKB operations schedule is quite limited after summer, due to an extremely tight budget. With the initial budget allocated by MEXT, SuperKEKB may only operate for three months until July (due to huge electricity costs). An additional operating budget by KEK would allow operation for another 1.5 months after the summer. A further, supplementary budget from MEXT, could finally also allow operation in March 2025 (and probably in December 2024). Operation in January and February 2025 is in any case not possible due to scheduled work on a 150 MW power substation.

In JFY2024 the SuperKEKB management will change. Prof, Makoto Tobiyama, presently Head of Accelerator Division III, will become the head of the Accelerator Division IV. Prof. Kyo Shibata will take the reign of the Accelerator Division III. Prof. Hiroyasu Ego will remain the leader of the Accelerator Division V.
The age profile of the SuperKEKB staff still looks precarious, especially for the technical staff. External partners are involved in the frameworks of MNPP-01, the US-Japan collaboration, and the EU EAJADE project.

Vacuum and other work during LS1 included the Interaction Region (IR) chamber work, IR radiation shield modifications (e.g. new shield on IR bellows), replacement of damaged collimator heads in both rings, collimator relocations, repair of an IR QCSR cryostat vacuum leak, aperture enlargements of the injection channel, installation of a non-linear collimator in the LER OHO straight section, installation of beam loss monitors / acoustic sensors and bunch oscillation recorders to monitor the sudden beam losses. For the QCSR re-installation, the remote vacuum connection (RVC) worked very smoothly – no vacuum leak was found. Many collimators were either replaced or upgraded (with copper coating). The majority of the collimators are of the old KEK type, based on a movable vacuum chamber.

In the injector linac, 16 old linac accelerating structures have been replaced with new ones (with larger energy gain, and without water leaks). The fabrication has started for 12 additional structures. A new fast kicker has been installed, which can deflect the first and second bunch independently. Several larger-aperture pulsed quadrupoles have been installed. A successful beam tuning using Bayesian optimization has been implemented, greatly increasing the positron transmission. The source of BT beam emittance blowup is still not understood, but Coherent Synchrotron Radiation (CSR) could be proven innocent, for the positron beam. A new BT energy compressor (Bte-ECS) is planned for 2024-25.

Recommendations:

R1.1: Try to establish a long, uninterrupted beam run for autumn 2024, in order to fully qualify the benefits and gains from the LS1 works through a step-wise approach.

R1.2: Schedule a dedicated injector study period, when PF, PF-AR and SuperKEKB are not operating, and without access to the Fuji area of the SuperKEKB tunnel; this could be two weeks before the summer shutdown.

R1.3: Prepare a performance-ranked list of the anti-ageing measures that had to be delayed and establish a plan for implementing them over the next couple of years.

2. 2024a Run

Findings & comments:

The LS1 shutdown started in June 2022 and was completed in January 2024. Many upgrades and maintenance activities were completed during LS1. These upgrades affected almost every accelerator system such as the IR cryostat, RF systems, vacuum, magnets, controls, magnets, and cryogenics. The 2024a beam run for SuperKEKB started in February 2024. By March 25, 2024, at the time of this review, the peak luminosity had reached 1.9 x 10^{34} $cm^{-2}s^{-1}$, and an integrated luminosity of about 8.4 fb^{-1} was delivered to Belle II in Run 2024a.

The ARC congratulates the SuperKEKB team for successfully completing LS1, and resuming beam operation. The ARC supports the planned priority for raising peak luminosity towards 1 x 10^{35} $cm^{-2}s^{-1}$ and beyond, e.g. by gradually increasing beam currents, ~~and~~ by further squeezing the vertical beta* to 0.8 mm, and correcting the IR optics errors, as fast as possible. This might imply accepting large injection background or turning off the detector.

Beam scrubbing has proceeded without complications.

Early during the turn-on SuperKEKB the vertical beta function at the IR, betay*, was set to 8 mm to help ease IR issues. Over a period of a month the betay* was reduced to 1 mm in steps. One of the goals of this run is to try again a betay* of 0.8 mm to see if work during LS1 helped with former issues here and to see what items need to be worked on in the upcoming summer-fall shutdown. A further goal beyond 2024 is reaching a betay* of 0.6 mm.

The number of bunches in use now is 2346 which is very close to the design number. The beam currents have reached 800 mA in the LER, and 640 mA in the HER. These are about a half of the goal for beam currents for this run.

The LER vertical emittance has been tuned to 10 to 20 pm down from 25-35 pm from the last run, which is an excellent result.

The crab waist has already been switched on, helping increase the luminosity. The theoretically optimum crab waist value in use is 80% in LER and 40% in HER, which are the same values as during the last run.

The vertical fractional tune was changed from about 0.59 to about 0.56, which increased the vertical tune shift from about 0.26 to 0.31. This is a very promising improvement.

After work done on the injection system in LS1, the LER injection efficiency presently reaches values of up to 90%, at intermediate beam currents. However, the HER injection efficiency is still poor at about 20%. The HER injection efficiency is under careful study. The stored beam lifetime is about 7 to 10 minutes.

The vertical emittance improved in this run thanks to the new IR Be beam pipe that allows for flexibility in the orbit control and possibly the improved Beam Based Alignment (BBA) at strong sextupoles. However, it seems that the beam-beam effect blows up the emittances to the same level as in the previous run. The specific luminosity has improved with the new lower vertical fractional tune. The use of crab waist clearly improves the specific luminosity.

The Dynamic Aperture (DA) measurements have not yet been fully analyzed as, e.g., the location of losses could not yet be identified. Similar measurements with open collimators and low beam current could help distinguish between the physical and dynamic apertures.

The measured DA is smaller than in simulations. The DA simulations need further work.

The crab waist sextupoles clearly affect the measured DA. This implies an existence of aberrations from the crab sextupoles.

The Non-Linear Collimator (NLC) system is still under commissioning. So far, the NLC helps the backgrounds from the stored beam, but hurts the background of the injection beam.

There are three proposed "Plans" for reaching the luminosity goal in the 2024a-b run.

Plan A: Positron (LER) current = 2.08 A, electron (HER) current = 1.48 A, betay* = 1.0 mm, luminosity = 8 x 10^{34} $cm^{-2}s^{-1}$.

Plan B: Positron current = 2.26 A, electron current = 1.61 A, betay* = 1.0 mm, luminosity = 9.4 x 10^{34} $cm^{-2}s^{-1}$.

Plan C: Positron current = 2.08 A, electron current = 1.48 A, betay* = 0.8 mm, luminosity = 1.0 x 10^{35} $cm^{-2}s^{-1}$.

Recommendations

R2.1: Push peak luminosity (using a combination of Plans A, B, and C) towards 10^{35} $cm^{-2}s^{-1}$ and beyond, e.g. by gradually increasing beam currents and/or by further squeezing the vertical beta* to 0.8 mm and correcting the IR optics errors, as fast as possible. This might imply accepting a large injection background or turning off the detector for the initial tuning period.

R2.2: Consider operating (perhaps briefly) early in the 2024a run at a betay* of 0.8 mm to observe what are the next technical steps needed to be done during the 2024 summer shutdown to run stably at this value in the fall.

R2.3: As progress allows (just before or after summer), perform accelerator studies related to potential LS2 projects that need early lead-time decisions, e.g. by pushing betay* down to 0.6 mm or to the nominal value, at low current.

3. Belle II status

Findings & comments:

The Belle II detector has improved nearly all detector subsystems in anticipation of accumulating more data and reaching a higher peak luminosity. The pixel detector (PXD) has been fully installed onto a new central beam pipe that has been improved to minimize backgrounds from scattered synchrotron radiation. The Central Drift Chamber (CDC) gas system has been significantly upgraded and monitoring of the gas quality has been greatly improved. The performance of the CDC has improved and now appears to be in very good shape throughout the CDC volume. Most of the conventional Photo-Multiplier Tubes (PMTs) used in the TOP detector have been replaced with extended-life PMTs. The background level in these PMTs has, in the past, been a limiting factor for beam operation. The new PMTs are more robust, but they need to survive as the beam currents and luminosity increase. The gas monitoring system in the KLM has improved to avoid the same mishap in the gas flow system as happened during Run 1. After a careful study of the detector backgrounds, the nose cones of the cryostats have been modified; the tungsten W shielding pieces have been replaced with stainless-steel pieces as these should reduce the shower debris generated by the W pieces. The data acquisition DAQ system has been improved and made more robust and this should improve uptime for the detector. Machine learning is being used to assist the detector team in correlating backgrounds with machine configurations.

Recommendations:

R3.1: Encourage continued collaboration with the linac and accelerator groups to understand backgrounds as they arise and as beam currents and luminosity increase.

4. Injector Overview

Findings & comments:

From 2020 to 2021, the failure rates on the gun increased, while the radiofrequency (RF) systems remained pretty unchanged. In 2022, they reduced the repetition rate from 50 to 25 Hz, the failure rate on RF systems remained unchanged, while on the RF gun it increased as in recent years. In 2022, they also had a problem with the controller of a pulsed magnet that was the cause of about 40% of the downtime. Countermeasures on RF systems are to replace the most critical accelerating structures with new ones and to reinstall a new RF gun. However, in 2022, the beam loss time ratio was less than 1% indicating a reliable injector. The ARC is happy to know that the world's first Diffractive Optical Element (DOE) was installed and put in operation at the $1^{st}/2^{nd}$ line laser, and the DOEs were also updated to the high bunch charge operation. The ARC is also glad to know both the thermionic DC gun and the photocathode RF gun work well. The thermionic DC gun needs to inject a beam to PF, PF-AR, and the linac of SuperKEKB for different beam requests. The goal of e+ bunch charge, 4nC, is nearly obtained with 3.5nC at linac end and BT1. With the help of machine learning, the e+ bunch charge could reach ~5.5 nC at the end of Sector 2. 65% of e+ production efficiency, even higher than the simulation value, was achieved.

In BT2, an important emittance growth was observed for both the positron and electron bunch. Excluding CSR for the positron bunch, it is thought that this may be caused by field errors in the magnets, due to changes made for 4 GeV operation. This will be investigated and mitigated. The electron bunch #2 has a problem with the trajectory stability: an injection test of bunch #2 into the MR will be carried out soon.

To better control the optics in sectors 1 and 2 and J-ARC, additional pulsed quads and associated power supplies were installed.

To mitigate the instability of the trajectory of the second electron bunch, fast kickers were installed at the end of the linac and in BT to correct the orbit. There remains an issue to deal with fast kickers, because they remove the offset but increase the jitter of the trajectory.

A point to clarify is what is the source of the amplification of trajectory jitter? Is it due to long-range wakefield? The amplification of jitter should be investigated considering the transverse wake of the RF structures. Long-range wakefields in current accelerating structures should be calculated.

As a general comment, it seems that the injector is reliable but several open issues need to be addressed in order to provide the nominal charge for both species to be injected into the MR. In the discussions on the injector, the question of stability, in particular of electron bunches, and the emittance growth in BT for both species continually arises.

Emittance values should be consistent between the different presentations. Sometimes it is difficult to identify the absolute values of the normalized emittances and their evolution along the injector and beam transport line. In general the emittances of both beams are (too) large as is illustrated in the following table. For the electron beam, both emittances are much higher than the target emittances at 4 nC (40/20 H/V mm mrad). For the positron beam, the emittances have small values although still high compared to the target emittances at 4 nC (100/15 H/V mm mrad). Optimization of the injector for the electron beam should have a higher priority than that of positrons.

Norm. emittances (micron)	2022 BT2	2024 BT2
e- x (R56=0) at 2.2 nC	~250 (~50 in BT1)	~200 (~100 in BT1)
e- y (R56=0) at 2.2 nC	~120 (~60 in BT1)	**~350** (~100 in BT1)
e+ x	N/A (~125 in BT1)	~175 (~150 in BT1)
e+ y	N/A (~10 in BT1)	~24 (~10 in BT1)

Recommendations:

See R1.2 above.

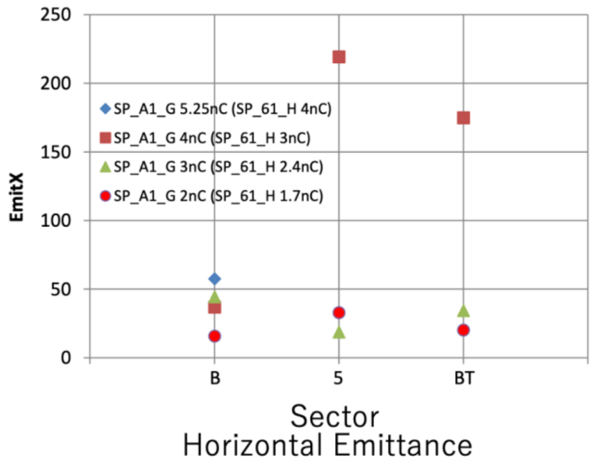
R4.1: Priority should be given to optimize the injector and injection for electron bunches.

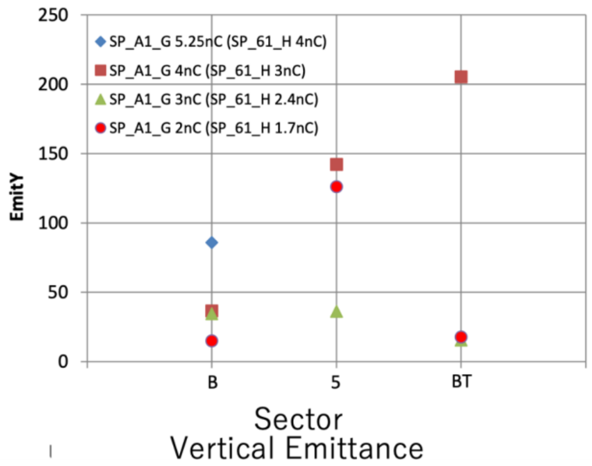
5. RF Gun and electron-beam

Findings & comments:

The RF gun has been operated successfully during the last run. Up to 6 nC have been produced, and charge feedback has been implemented to stabilize the long term current. The in-house produced Ir7Ce2 cathode material has proven to be very robust with a very long lifetime. The DOE optics is working effectively. Temporal shaping is being considered as well. Laser positioning feedback has been implemented to improve pointing stability. Some degradation of the laser windows was observed, apparently due to carbon contamination. The source of the carbon is unclear. Improved pumping close to the window did not completely solve the problem. A new, improved design has been developed and will be installed to eliminate this problem as well as a larger DOE to cover the whole cathode. The RF gun has increased the number of breakdowns in the region behind the cathode, where the choke is located. To solve this problem for the operations, it is planned to install a new rf gun in the next summer with some modifications in the cathode region to address an issue with excessive breakdown rate in the choke. Essentially, the cell geometry of the RF gun will be the same and the emittance should be the same as for the current RF gun. Beam dynamics simulations predict an emittance of 7 mm mrad, which is much lower than the emittance measured from the present rf gun in sector B. The electron source should provide a certain value of normalized emittance, which can then only increase along the linac. This point should be investigated because the RF gun with its small (8 mm) aperture could be the cause of the large emittance value measured in sector B and also generate trajectory jitter due to the transverse wakes. In order to estimate the wake effects in the RF gun, it is necessary to consider the beam size and the laser pointing jitter.

Electron beam emittance along the injector for different bunch charges. BT is at the end of the beam transport line (BT2). In the legend, the charge values refer to charge in BT2. Normalized emittance in sector B at 5.2 nC from the RF gun (4 nC in BT): ε_x = 57.5 mm mrad, ε_y = 86 mm mrad (blue diamonds). Goal values for the normalized emittances at 4 nC are: 40/20 (H/V) mm mrad.





The ARC commends the production of a functional and state-of-the-art injector laser complex for the production of high-charge bunches. However, the cause of the large emittance should be further investigated by comparing the results of the simulations with the measurements performed in linac sector B.

The impact of the laser power variation and RF phase drift on the injected charge has been seen in the operational history. The group has a PID based feedback for this and is developing new instrumentation. The control development for this system may be a good opportunity for a new staff or Ph.D researcher who is interested in state space or modern control.

Recommendations:

R5.1: Install the new RF gun to restore reliable operation.

R5.2: Perform beam dynamics simulations and compare the results with measurements in sector B.

R5.3: Install the energy compression at the linac end. There are several advantages.

6. Accelerating Structure

Findings & comments:

The linac has performed in the main reliably during the last run, however many of the structures are original 40-year old PF type sections. Three S-band structures developed water leaks in the last year. Inspection of the extracted structures showed significant breakdown damage in the input coupler and the beam irises. 21 out of 142 structures are thought to have this problem. A new design has been developed with rounded corners at the input and lower peak field on the irises. 4 prototypes and 12 new production sections have been made and installed. Another batch of 12 will be ordered (subject to available budget). No spare SLED systems are available and they are very expensive to manufacture. A new less expensive spherical SLED cavity has been developed, which costs about half as much, and this was tested successfully up to 80 MW peak power. Several dummy loads have experienced breakdowns and damage, as well as some waveguide flanges. New loads will be ordered in the coming year.

The new structures were designed with a linear detuning of the dipolar mode in order to strongly suppress instabilities due to long range wakes.

Recommendations:

R6.1: Proceed with 12 new linac structures and new dummy loads to replace aging structures (or structures in sector B) to increase the beam stability.

R6.2: Dedicate machine shifts to verify the electron beam stability in the new accelerating structures.

7. Pulsed Magnets / Power Supplies

Findings & comments:

During the shutdown several Linac areas were upgraded and changed from DC quadrupole magnets to pulsed quadrupole or bending magnets with new power supplies. There were 4 major areas covered in the presentation:

- Pulsed quads at the J-ARC matching section

The motivation for this change is to allow interleaving of beams for multiple facilities on a cycle-by-cycle basis. The arc quad system has been demonstrated to work, though there are issues with overheating of the air-cooled design. Better temperature control is in progress.

- Pulsed quads in the Linac e+/e- compatible optics section

The motivation for this new set of pulsed quads is to allow better optimization of the lattice for both e- and e+ (at rather different beam energies), to suppress emittance growth and the improve e+ transmission through the path.

- A ceramic Linac fast kicker for bunch orbit tuning

The motivation for this new fast kicker is to allow independent control on the 2 e+ bunch injection with 96 ns separation between the bunches. There are small differences in bunch orbit that if corrected improve and equalize the charge transfer of both bunches. A ceramic vacuum pipe is required for this fast kicker, as is a new design of fast pulsed power supply. Tests show the kicker has adequate bandwidth to kick a single bunch, but there is an impact on orbit jitter that is still being investigated.

- A pulsed beam line for beam diagnostics (planned for summer 2024 installation)

This new pulsed beam line for dedicated diagnostics will allow parasitic extraction of beam for studies in the diagnostic beamline. Emittance tuning for SuperKEKB is time consuming and the interleaving of diagnostic beams with production beams can be helpful for operating efficiency. This beamline with 2 pulsed bending magnets will be installed in the summer of 2024.

The use of the new machine learning tuning method is an excellent application of new ideas and the committee is excited to see the contributions of the students and new staff. These methods are being applied in both the J-arc and the e-/e+ linac sections.

Discussion:

The arc quads are implemented to allow cycle-by-cycle changes in the optics to deliver various beams to different end facilities. This dynamic configuration change means the magnets must not retain hysteretic memory effects from previous cycles – the magnets seem to be near saturation from the data? How significant will these effects be for realistic beam patterns?

The DC quads had current regulated power supplies. The new pulsed magnets are driven "feed-forward" from a dedicated IGBT switch arrangement. The drive current is controlled by the time duration of a gate signal. It was not clear if there was a current transductor or flux measurement that is used to control the pulse width based on past cycles. The data show there are effects from rep rate (1 Hz vs 50 Hz) as well as temperature. What is the plan for control and monitoring?

The J-ARC pulsed quadrupoles allow different settings for the six different beam configurations. The present pulser circuit must provide the full current for each setting, which makes the needed pulser quite strong. Perhaps, depending on the shared base current in the quadrupole settings, the power supply could be hybrid where most of the current is DC and only a small part (say, 10 to 20%) is an added pulsed current. This hybrid mode would make the pulser power supplies simpler and less costly, and the quadrupole eddy current heating problem far less.

Recommendations:

R7.1: Ensure that the pulse width modulation power supplies for the quads have adequate current monitoring and consider implementing feedback to better control the field seen by the beam.

8. Linac Control Monitors

Findings & comments:

After the increase of the positron yield it became important to install diagnostics for optimizing positron versus electron settings and intensities. Beam diagnostics installation is challenging due to the high radiation environment, the very limited space and the difficulty to simultaneously and separately detect both secondary e- and e+ bunches within a very short time distance. As a solution, Wideband Beam Monitors (WBMs) were installed in the e+ source. The WBMs were successfully commissioned, and they help observing and optimizing the positron Intensities. The motivations for the development of this device were also comprehensively described. The bandwidth of the entire system is the key parameter and it depends on the cutoff frequency of the vacuum chamber where the pickups are allocated, as the propagation of the wake field generated upstream perturbs the measurement itself. In this specific case, the vacuum chamber diameter is 38 mm and corresponds to a cutoff frequency of approximately 5 GHz. However, for qualitative measurements, such as RF phase tuning, it can become an essential device. On the other hand, for absolute charge and bunch length measurements, the device should be equipped with wake field mitigators to overcome the wake effects in the measurements. Furthermore, the RF-phase scan pointed out the possibility of increasing the charge of the positron bunch. This point should be investigated, while also keeping in mind the final positron yield in the damping ring. This is because a larger positron charge per bunch could be produced, but with a larger energy spread, leading to greater losses on the way to and into the damping ring. In general, the ARC is pleased to see the progress with the linac control monitors and looks forward to learning more about its use and benefits in operation.

Recommendations:

R8.1: Use this device (WBM) during machine tuning and eventually design the wake dampers.

9. Injection

This talk presented a comprehensive and detailed analysis of the Injector complex status after the commissioning that followed the LS1 shutdown. During LS1, several modifications have been implemented and many measurements have been prepared in order to meet the injector design parameters, as requested, in order to achieve higher luminosity and to guarantee operational stability and optimized background during the Belle II detector data taking.
The ARC is impressed by the quantity of measurements that were made, and by the accurate, and exhaustive analysis presented. This led to a very clear description of the injector status, and allowed understanding of several key points concerning emittance degradation, and beam transport line setup.
In this initial stage, after the implementation of the ring optics with betay* = 1 mm the effective injection efficiency still needs to be optimized.
Injection into the HER is performed at the rate of 25 Hz, only one bunch is injected, effective injection efficiency is of the order of 20%, and a large injection background is observed.

Injection in the LER is performed at the rate of 23 Hz, only one bunch is injected, effective injection efficiency is in the range 10% to 90%, shorter lifetime and injection saturation are observed at high current, and a large injection background is measured.
Background is evaluated using diamond detectors installed at the QCS and central beam pipe in each ring.
Injection stability is low in both rings.

Concerning Beam Transport sections BT the situation was summarized as follows:
Primary sources of horizontal emittance blowup in BTe1 are Incoherent Synchrotron Radiation ISR (~ + 30 um), and Coherent Synchrotron Radiation (CSR) (~ + 60 um at 2 nC), as already outlined in the previous ARC meeting.
Vertical emittance blow-up still remains unidentified.
Emittance blow-up sources in LER-BT are not fully understood, but now at least partly attributed to local nonlinear magnet fields and coupling sources.
Recent measurements show large bunch-charge dependent emittance growth, which might be related to longitudinal spiky bunch profile causing unexpected CSR effects.
In order to confirm unexpected CSR contributions most of the dipole sections in ARC1 were displaced in the vertical plane, this in turn introduced vertical dispersion, and large resistive wall impedance. To cope with these side effects a proper value for the vertical displacement was identified, 13 mm vertical offset, to maintain emittance growth under control, and optics featuring vertical dispersion suppression has been computed and applied in the ARC1. Then emittance dependence on vertical bump amplitude applied at selected position was studied:
No symptom of CSR or Resistive Wall (RW) wake have been detected in BTp–- ARC1, and in BTp – ARC2,3, on the contrary multipole field errors, and X-Y coupling were observed in BTp – ARC2,3, and at ARC3 entrance respectively.

Relying on experimental results a realistic model of beam transport lines has been developed in the optical lattice simulation code SAD including multipoles in bending, lattice errors, and the permanent skew quadrupoles embedded in the dipole magnets for dispersion correction. Simulations with the upgraded optics model showed that multipoles of bending magnets, and sextupole components inferred from the measured XY coupling can reproduce measured X/Y emittances in BT2p.

About e+ beam emittance at 1.1 GeV in RTL, no relevant emittance blowup, and bunch charge dependence of beam emittances are detected after the Damping Ring (DR). Optical Transition Radiation (OTR) based quadrupole scans returned horizontal normalized emittance $\gamma\varepsilon_x$ comparable with the nominal one, and less than half the nominal value for $\gamma\varepsilon_y$. 7-GeV Electron Beam Transport channel beyond the well-known $\gamma\varepsilon_x$ blow-up induced by ISR and CSR, shows an increased harmful $\gamma\varepsilon_x$ blow-up which has been partially cured by varying R_{56} factor (J-ARC) from 0 to 0.3.

Simulation of the injected beam in HER showed that QCS cancel-coil errors reduced the on-momentum dynamic aperture by ~25%.

-- The dependence of the energy spread, and emittances on the RF phase, measured at the BT line, seems interesting and puzzling. There may be some contribution from a possible vertical dispersion at BT location MSP15, but not all the observations could be explained. A measurement after the correction of the vertical dispersion at this point will be valuable.

The ARC supports the decision of the SuperKEKB team to eliminate the vertical emittance blowup before starting high intensity electron current operations.

Recommendations:

R9.1: Study an implementation of dispersion-free steering and of BNS damping, which simultaneously minimizes energy spread at the end of the linac, and wake-field induced transverse emittance growth along the linac.

R9.2: Attempt to measure the longitudinal bunch profile at some selected points along LER-BT channel.

R9.3: Clarify if the resolution of the OTR diagnostics used for the quadrupole scan is compatible with the measured beam dimensions.

R9.4: Study, and reduce, the vertical emittance growth after BT1e .

R9.5: Investigate if it is possible to mitigate the impact of QCS cancel-coil errors on HER beam dynamics, and include this effect in the ring optics model.

R9.6: Evaluate again the dynamical aperture for HER after including the QCS cancel-coil errors in the optics if this had not been already done.

R9.7: Consider refining terminology of “raw” and “effective” injection efficiencies to be more intuitively understandable.

10. Optics Tuning in 2024a

Findings & comments:

Extra effort was put into orbit tuning, obtaining a smoother HER orbit in 2024. The orbit control at sextupoles has also been improved with automatic tools. Vertical emittance is improved by about a factor 2 in both rings, probably due to the improved orbit, but this is not confirmed. Vertical emittance does not depend on betay*, yet maintaining the low vertical emittance is harder at the lower betay*.

The non-linear collimation system based on strong skew sextupoles is being commissioned. Beta-beating and vertical emittance strongly depend on the orbit deviations at these sextupoles. Commissioning has started with lower beta functions in this region. For increasing sextupole strength larger apparent vertical beta-beating is observed in this region, up to 180%.. This is an artifact coming from the strong deformation of the phase-space due to the skew sextupoles (the orbit response becomes parabolic). This is reproduced in simulations. The linear components can be extracted from a fit; however, this is time consuming. An analytical formula could be used with partial success. Measured beta function would still have a 10% uncertainty.

Amplitude detuning has been measured in the HER via turn-by-turn data of vertically kicked data. Without crab waist, the vertical detuning versus vertical action is measured to be positive, while it is negative in the simulation. One source missing in the simulations is the manufacturing errors in the cancel coils that cause skew sextupole and skew octupole multipoles. After including this source in the model the agreement with measurement significantly improves. The exact mechanism is not yet identified; it could e.g. be via a beam offset at the skew octupole. Horizontal data exists but it is not yet analyzed. Data were taken also with crab waist on. A vertical kicker is only available in the HER and not in the LER yet.

Vertical dispersion, beta-beating and coupling (rms) in 2024 were measured to be similar to 2022. Second order dispersion was not yet measured.

The value of information sharing and coordination within the collaboration cannot be overemphasized.

Recommendations:

R10.1: Investigate and correct the IR optics aberrations (QCS correction coils, crab sextupoles, etc.) with the help of optics measurements in different configurations.

R10.2: Attempt to carry out optics measurements at low current with all collimators open (if possible and safe).

R10.3: Include the error of the QCS correction coils in the base lattice of the HER used for the regular operation.

R10.4: Perform a center-of-mass energy scan.**R10.5:** Install a vertical kicker for beam dynamics studies in the LER.

11. Nonlinear Collimator

Findings & comments:

The study on the Non-Linear Collimator (NLC) is ongoing and not yet finished. It was installed in the OHO straight section. The skew sextupole magnets,“"SNAP.”" and“"SNAP.2”" are already there. Without the NLC the detector background rises quickly with the LER beam current, imposing a limit at about 1.6 A. Also, the LER vertical beam size blow-up with intensity increase, with a bunch-current limit at 1.25 mA. The expectation is that the use of the NLC reduces the impedance and will help overcome some of the current limitations. For example, the TMCI threshold should be raised to 2.1 mA. During the first beam tests the D05V1 device (this is the NLC). a larger gap was used to replace the D06V1 device (standard collimator). The following observations were made:

1) The beam lifetime is the same in two cases.

2) There is a better background reduction from ring losses with the NLC.

3) The injection background is worse with the NLC, as expected.

4) No beam size blowup was seen in the LER up to 1.4 mA and with the NLC.

5) The current dependent tune shift is 40% smaller with the NLC.

Overall, the initial beam observations are very encouraging, demonstrating several benefits of the NLC. The reduced cleaning of the injection background is a limitation, however.

The committee congratulates the team for the excellent work done and the successful installation and first commissioning of the NLC. The NLC seems to be a highly promising device and sufficient beam time should be invested to fully optimize its settings and to exploit its potential for improved performance.

Recommendations:

R11.1: Consider some combination of D05V1 (NLC) closed and D06V1 at a somewhat opened (but not fully open) gap to see if an optimal compromise can be found, reducing impedance while also providing acceptable injection background conditions.

R11.2: Further investigate the optimum setting of the NLC parameters, such as betas, apertures, sextupole strength, betatron phases from the injection point to the NLC, considering the collimation performance, injection efficiency, TMCI threshold, etc. **R11.3:** Calculate the expected reduction in tune shift with the NLC and compare with the observed value.

12. Sudden Beam Loss

Findings & comments:

Since RUN1, the team is performing specific studies and has upgraded the machine during LS1 to better understand the origin of Sudden Beam Loss (SBL) events. Despite all these efforts, the origin of the SBL is not understood yet. An SBL is defined by a significant particle loss occurring within a turn (10 microsecond) in a duration less than the abort trigger time (20 microseconds). SBL were observed during RUN1 in both LER and HER. SBL triggered quenches of QCS, beam dumps etc. Multiple SBL events may strongly deteriorate the beam operation via background to Belle II detector or beam dumps, and severe SBL may ultimately result in the damage of components such as QCS, collimators etc. The observed loss at collimators seems to be insensitive to the location of the loss inducing mechanism. Before an SBL, beam oscillations within 0.1 mm are sometimes observed but not systematically. Pressure bursts are also observed but most probably consequently to the SBL.

Following previous studies, damage of vacuum equipment such as broken RF fingers, dust and electron cloud were ruled out as possible reasons for SBL. Instead, another mechanism is proposed, which involves an interaction with the electromagnetic field of the beam, leading to excessive heating of some metallic debris such as tungsten or tantalum originating from previously damaged collimator heads. In the so-called “fireball” hypothesis, a Cu^{+} based plasma is created within 0.1 microsecond (following the sublimation of the Cu vacuum chamber by the hot metallic debris) leading to large transverse kicks (a few 10 microrad) of the beam bunches.

During LS1, the damaged collimators during RUN1 were replaced and some Ti, Ta, C collimators heads were Cu-coated (hoping) to mitigate the SBL effect. Permanent magnets to suppress any electron cloud build up were also installed at all horizontal collimators. In addition, several instruments were installed: new Beam Oscillation Recorders (BOR), loss monitors (PMT, EMT) for timing resolution, and acoustic sensors at some collimators and at the QCS to assess the “fireball” hypothesis. Existing BORs were also upgraded.

The ARC appreciates the strong effort made during LS1 on installing additional diagnostics to identify the origin of the sudden loss events.

Since the restart of the machine, checks, calibration, and adjustments took place. A first SBL-like event was observed on the 8^{th} of March and others later, but the analysis performed so far could not confirm the “fireball” hypothesis. Focus is presently on defining and establishing a systematic analysis method using beam oscillation, beam loss and acoustic data.

The ARC is very pleased to see the efforts and careful analyses made on this important topic that is limiting the performance of the collider.

Recommendations:

R12.1: Given the promising results from the new monitors, further improve the SBL diagnostics such as by additional beam oscillation monitors, bunch-by-bunch beam-size monitors, and even more beam-loss monitors around the ring.

R12.2: Revisit “usual” effects that could explain the SBL - for instance, coupled-bunch TMCI, electron cloud, arcing or trapped electrons in ion pumps, NEG pumps heated by HOMs, power supply regulation errors, feedback-related perturbations, beam-induced collimator motion or jaw deformation, …- and motivate their rejection by experimental observations.

R12.3: Continue the further development of the “fireball” model using realistic inputs and based on experimental data acquired with SuperKEKB and other experimental systems, and a parallel simulation effort.

R12.4: Continue the development for the acquisition of a set of experimental data with systematic analysis and categorize the different beam loss observations.

R12.5: Identify potential weak areas around the machine and define a set of measures to protect them, while maintaining the integrated and peak luminosity objectives.

R12.6: Try to establish a statistics of the number of SBLs versus time and beam current, in order to see if there is any kind of cleaning effect visible or a dependence on intensity.

R12.7: Study the correlation, if any, between SBL and uneven bunch current filling along the batch.

13. Monitors

Findings & comments:

The ARC is very much impressed that various kinds of monitors, including BPMs (T-B-T and narrowband), bunch oscillation recorders, beam profile monitors, displacement meters, feedback system, beam loss monitors, and ML-assisted beam tuning methods, are maintained or newly installed in LS1, and some are updated. Among these different monitors, the beam profile monitors and feedback systems work well.

The BPM at the HER injection region was improved for better performance. The visible-light beam profile monitors perform well on different beam profile measurements in LER.

Gated T-B-T monitors and beam loss monitors need further maintenance, and a machine learning assisted beam tuning tool is being developed to optimize the beam injection efficiency and lifetime, etc. The system shall come into operation by 2024.

Recommendations:

R13.1: Continue the effort of adjusting the threshold of the beam loss monitors to avoid unnecessary beam abortion due to small beam losses.

R13.2: Start maximization of injection efficiency with machine-learning (ML) from a random or a lower value than the human-optimized one, to develop the tool of ML.

14. Damping Ring

Findings & comments:

The Damping Ring (DR) of the SuperKEKB positron injection system has been working in a smooth and reliable way since it started operating in February 2018.

The DR is used to store a positron beam at 1.1 GeV for 40 msec. The DR must feature a large acceptance in order to accommodate the high-emittance and high-energy-spread beam coming from the Linac. The nominal beam consists of 2 pulses each including 2 bunches. The ring, 135.5 m long, is based on a reverse-bend FODO cell. This lattice allows short damping time, of the order of 12 msec, while using low magnetic field strength dipoles, which are the most suitable for a beam pipe having 34 mm diameter.
In recent years, unexpected emittance growth after DR and the small dynamic aperture in the LER, suggested to reduce the beam emittance in the DR by about 20%.
Moreover, beam orbit drifts and fluctuation made optics modification difficult.
Lastly, an extracted beam orbit drift had been observed, stemming from the temperature dependence of output current of extraction kickers.

Several attempts to reduce DR emittance resulted in large optics distortion, beta beating and horizontal and vertical dispersion that could not be recovered by tuning quadrupoles which, in the present DR configuration, are grouped in six families independently powered.
In this context, during LS1 several studies have been done to better understand the DR optics and to fix orbit drifts.
It was found that the excitation curve of arc quadrupoles had not been properly evaluated. The corrected values are consistent with the optimization factors identified during optics corrections. However, this improvement did not yet result in a reliable lower emittance optics.
Magnetic field measurements have been done on spare dipoles and quadrupoles by using a rotating stretched-wire coil instead of the harmonic coil used in the past. New measurements revealed significant correction factors of the order of few % and 5 -10 % for dipole and quadrupole magnets respectively. The DR team has planned further magnetic field measurements on the remaining different kinds of spare magnets.
Beam orbit fluctuations and drifts were studied, while storing the beam in the DR. It was observed that fluctuations depend on the temperature of the vacuum chamber, which is cooled by a water chiller unit. Reducing the temperature range of the cooling water slightly improved slow orbit drifts, but did not eliminate the effect.
Dispersion measurements taken by varying the RF cavity frequency also unveiled a relevant dependence of orbit on stored beam current.
Extracted beam orbits measured at the LINAC BPM uncovered a slow drift varying with the extraction repetition rate, drift that is more evident for the 2nd extracted bunch. This drift was induced by temperature dependence of the extraction kicker.
Successful tests demonstrated that the kicker deflection dependence on temperature could be reduced to about 1/3 by adopting different technical precautions:

- using mica capacitors instead of ceramic capacitors,
- switching from natural oil cooling to forced oil cooling, which was successfully operated for over 100 hours, at a rated voltage with the mica capacitors.

Unfortunately, these very promising tests could not be completed in time to be implemented on the DR kicker system before the beam startup.
The vacuum level of the RF cavity has been significantly improved by replacing an O-ring.

For the nominal optics, the emittances from the damping ring were determined by quadrupole scans. According to these, the horizontal emittance is consistent with expectation, while the vertical emittance is significantly (about 3 times) smaller than the design value. The synchrotron light monitor in the DR seems to give a far too large value for the vertical emittance.

The ARC endorses the decision to complete magnetic field measurements on the remaining kinds of spare magnets, with a special attention to sextupole magnets.

Recommendations:

R14.1: Use turn-by-turn BPM data to study DR optics errors, esp. for the lower emittance optics.

R14.2: In the case optics studies will not return improvements, try to obtain an optimized lower emittance optics by introducing more independent quadrupole families.

R14.3: To establish priorities for DR studies, developing an optimized optics with lower emittance may be more important than understanding orbit & optics dependence on the beam current.

R14.4: Implement all the technical solutions successfully tested for reducing the extraction kicker deflection dependence on temperature, which is harmful for the second bunch.

15. MDI

Findings & comments:

The MDI team continues to impress this committee with its multi-pronged effort to further understand and improve the machine related backgrounds. There have been impressive improvements in background simulation in tracking down local neutron sources, and in adding shielding to mitigate the neutron backgrounds. In addition, working together with the accelerator team, a very strong effort has been presented to attempt to track down the source of the Sudden Beam Loss (SBL) events. Many more detectors of various types have been installed around both rings which should help in tracing the start of the SBL event. The damaged collimator heads in the LER have all been replaced with new heads, and most of the HER collimators with damaged heads have also been replaced. Efforts are ongoing to further shorten the time between detecting an unstable beam and aborting the beam. Acoustic sensors have been installed around some of the collimators, and have been tested with beam. More Beam Oscillation Recorders (BOR) have been installed including a new recorder using RFSoC (Radio Frequency System on Chip) technology. More beam loss sensors have been installed, and work is ongoing to link these detectors directly to the beam abort system, thereby further shortening the time required to abort the beam. Injection backgrounds are also being analyzed, and related information and signals can be used by the linac team to improve injection backgrounds and injection efficiency.

Recommendations:

R15.1: Continue to attempt to shorten the time between detecting an unstable beam and aborting the beam.

R15.2: Make a controlled test of the BOR modules by applying a known kick to the beam.

R15.3: Synchronize and build a general display package for all of the loss monitors to make it easier to identify possible locations of SBL sources.

16. BT

Findings & comments:

Several crucial aspects concerning the Beam Transport system have been addressed, and many solutions were tested, and in large part implemented during LS1. Upgrades and preparation work were intended to improve injection efficiency in the main rings, to keep under control emittance growth along the BT, to eliminate spontaneous firing of the ring injection kickers, and to stabilize machine operations.
A sizable multipole component on the HER septum plate SE1 generated by a fringe field was eliminated by shimming. This multipole component was already identified during the 2022 run. Its mitigation enlarged the septum magnet stay clear aperture, and improved the septum field uniformity by 54%. Regardless of such positive results, septum field uniformity is still

considerably lower than expected from simulations, indicating that the origin of the nonlinearity was not completely identified.
QI4E next to SE1 was equipped with a new beam pipe providing a 0.8 mm wider clearance for the injected beam.
BPMs in the final part of the BTp have been equipped with I-tech Libera-SPE, which are presently under test. The new hardware will provide the possibility to independently measure the trajectory of two consecutive trains of two bunches separated by 96 nsec.
A new vertical kicker featuring polarity inversion was installed in the HER Fuji-straight section. A similar device is in production for the LER. These devices are intended for dedicated dynamic aperture studies.
17 dipole sections located in the ARC1 have been vertically misaligned, in order to mitigate CSR induced emittance growth in the BTp. It turned out that emittance growth of the e+ beam was not due to CSR, which has given more weight to the hypothesis that the emittance growth is due to high order components in the magnetic fields in ARC3.
A diagnostic for CSR direct measurement has been installed in ARC1 and preliminarily tested. Several OTR monitors with 60 μm resolution have been added in the BT for emittance measurements. However, as the rms beam sizes are comparable with the OTR resolution, these diagnostics need to be upgraded.
A leakage in the LER injection orbit bump, stemming from differences in the injection kicker ceramic duct shape, was cured by a new K2-type ceramic duct and replacing the old device.
Several accidental spontaneous firing events, ASF, affected the LER injection kicker operation during the initial phase of the 2024 run. This type of failure can be mitigated by directly triggering all the other paired kickers when an accidental spontaneous firing is detected.

Recommendations:

R16.1: Render the OTR and CSR diagnostics fully operational, and complete the implementation of the new BPM acquisition; all the tools should be ready before the summer shutdown, in time to be used during machine study periods dedicated to injector optimization.

R16.2: Plan a systematic study to unequivocally identify and mitigate the source of the large emittance growth in the BT, for both beams.

R16.3: Implement mitigation techniques tested in the laboratory to avoid injection kickers ASF.

17. Control

Findings & comments:

The control system for the SuperKEKB facility is literally the “backbone” on which every other system depends. This is a legacy system with many layers of hardware and software, and upgrades that are integrated in the existing system over time. The Controls group can be very proud of their contributions to the success of the SuperKEKB program.

The presentation highlighted the multiple IOC subsystems which are implemented using 6 different IOC platforms. These become obsolete over time. The group has identified a path for the obsolescent PLC modules and is evaluating what to do about the MVME5500 VME controller. The MicroTCA platform is being considered for future implementation.

The EPICS software platform is used widely. This is an excellent choice and allows the group to share software for various functions with other labs.

The new bunch current equalization system was presented, the bucket selection software and hardware for 2 bunch injection is ready. The event trigger and monitor functions have been upgraded and can support turn by turn BPM triggers and synchronization functions such as loss monitors with BPM signals. The general purpose nature of these functions can be useful for Belle II, too.

There has been a development effort on a White Rabbit based event recorder/timestamp system for abort monitoring. The hardware effort is largely complete but the software effort is ongoing. This system will improve the time resolution of the abort monitors to 8 - 100 ns.

The computing systems are being maintained and expanded, as are the backbone networking switches and infrastructure. This is a pragmatic task to preserve the functionality as old computing architectures become obsolete and newer platforms are brought into use. The Controls group deserves our praise for this balancing act.

Several very modern web-based software tools are being implemented for staff communications, software development, code version management, etc. An exciting idea is to develop an automated shift log system and to modernize the existing powerpoint based shift report system.

Recommendations:

R17.1: Be careful with developing new functions to ensure compatibility with legacy functions that may still need to operate. An example is the integration and operation of the new and original abort monitor systems.

R17.2: Many of the new interesting web based tools may have very short commercial lifetimes, probably much shorter than the operating life of SuperKEKB. When developing tools on these web platforms, try to ensure the codes, databases and records they create can be accessed with general purpose software, as in the future someone may want to look at historic shift reports and be able to seamlessly use the legacy and new functions.

18. MR Magnets

Findings & comments:

New skew sextupole magnets, built from new laminated yokes and recuperated coils, for non-linear collimation, were installed within schedule. They are powered in series with an acceptable difference in transfer function. These magnets have skew quadrupole trim coils. A new configuration of power supplies is needed for the new optics, and to power the skew sextupoles and the trim coils. Currently, operation is effected with spare power supplies while awaiting delivery of the new power supplies.

The IR was refurbished. The initial collision beam offset was about 100 μm which could be corrected swiftly.

It was reported that a problem with the power supply QFROE_4 (quadrupole in the OHO straight section) is not yet fixed and needs further investigation.

Recommendations:

R18.1: Fix the power converter for QFROE_4.

19. QCS

Findings & comments:

The main work during LS1 on the IR superconducting magnets QCS concerned 1) modifications of the head of QCS cryostat to reduce background and 2) the repair of the vacuum leak at the QCSR service cryostat. Both activities were completed successfully. The leakage rate of the QCSR cryostat was high before the repair work. A cooling test in December 2023 confirmed that after the repair the same vacuum pressure could be reached as at the QCSL, both at room temperature and at low temperature. The very good operational status of the cooling and of the magnet power supply was presented. Two possible plans for anti-ageing measures on the old system were discussed and compared, namely 1) overhaul of the electric motor for the helium compressor and 2) system renewal of the refrigeration control system. It was decided to overhaul the electric motors for helium compressors annually. The renewal of the refrigeration control system is under consideration, as well as additional heat exchangers to reduce usage of liquid nitrogen and to improve the cooling margin of the refrigerator.

The team is congratulated for the stable operation of the QCS magnet power supply and cooling system from the start of the 2024 run. The ARC supports the plans presented.

Recommendations:

R19.1: Add a heat exchanger to reduce liquid nitrogen consumption as proposed.

20. Safety

Findings & comments:

Radiation levels in the Beam Transport (BT) line, in the Fuji and Tsukuba experimental hall and in the Oho experimental hall can exceed the limit of <0.2 μSv/h for general areas (averaged over 1 hour). The radiation level in front of the most upstream BT escape exit was 0.8 μSv/h in 25 Hz 2- bunch operation before tuning, mainly due to electron beam losses. The injection tuning reduced this to an acceptable level of 0.13 μSv/h. The beam losses along the BT line are monitored using an optical fiber. When a screen monitor is inserted the radiation level strongly increases, and the repetition rate must be reduced to 1 Hz. Additional radiation shields are considered for some of the escape exits. The Fuji and Tsukuba experimental halls become radiation monitoring areas during beam operation. In the Oho experimental hall radiation level increased due to the installation of the NLC. As a mitigation, new concrete shielding towards the hall was added during LS1. The beam pipe of the collimator was surrounded by a 5 cm thick lead shield over a length of 5 m. Simulations of the radiation level in the experimental hall as a function of length of the lead shield motivate a plan to increase the length of the shielding to 11-13 m, and to not only use lead, but a combination of lead and stainless steel or polyethylene (for neutrons). The additional neutron shielding is motivated by measured neutron radiation levels caused by NLC beam losses from injection. Indeed, the radiation to be shielded is caused in roughly equal parts by gammas and neutrons.

The planned installation of a bunch energy-spread compression system (ECS) in the BT line should not compromise the BT tunnel safety.

In 2023, at J-PARC, two fires were caused by power supplies. One fire (25 April 2023) occurred in a newly developed power supply for the MR, due to incompatible parts (transformer) in the startup circuit (initial charge). The second fire (22 June 2023) suddenly occurred in an old power supply, manufactured in 1985, where parts in the polarity changer deteriorated due to long-term use. Countermeasures for both types of events were taken KEK wide. In the near future, power supply equipment related to accelerator operation shall be regularly maintained and inspected by the manufacturer. Power supply units that are older than ~40 years, especially those with polarity changers, should be updated or replaced.

The Personnel Protection System was modified so that even if there are people in the Tsukuba Area (Belle II), a beam can be transferred all the way to BT End; that Injection beam tuning is possible even during long-term shutdown of Belle II (LS1); and that even if there is tunnel access for Belle II work or work on Tsukuba accelerator hardware, the injection beam can be tuned during the day. This change allows for more flexible operation.

Additional radiation shielding will be needed as the beam currents are increased. The scope of added shielding is smaller and less expensive if it is added as close to the radiation source as is possible, for example, around the beam pipe. Accessibility for maintenance must be taken into account.

Recommendations:

R20.1: Continue monitoring and mitigating radiation levels in the BT line, in the experimental halls, and in the collider tunnel. Always put safety first.

R20.2: Periodically check that the safety inspections of the KEK and J-PARC power supplies are done on the agreed-on schedule.

21. Vacuum

Findings & comments:

During LS1, an impressive amount of work was successfully completed by the Vacuum team. Besides the IR work, the collimator repair, upgrade and relocation, each known issue was systematically tackled and solved. Since the machine restart, the vacuum scrubbing has been carefully monitored for both MR rings and the DR. After a beam dose of 310-360 Ahr accumulated at the date of 2024/03/31, the vacuum system of the MR is ready to accept 1.1 A and 1.5 A for the HER and LER, respectively. R&D is ongoing to improve the BPM supporting system, the collimator robustness, and the pressure monitoring.

Recommendations:

R21.1: Based on the PEP-II experience with NEG pump heating from HOM power, monitor a few NEG strips feedthroughs with thermocouples for temperature increases with stored currents. Select NEG pumps that are near collimators or other HOM generating structures.

R21.2: In view of maintaining the robustness and availability of the vacuum system, promote the early implementation for the detection of pressure anomaly in the daily pressure follow-up and set-up a consolidation program of the vacuum system when required.

R21.3: In connection with the sudden beam loss investigation, look for the eventual presence of debris inside the vacuum components dismounted during LS1 (or later), and routinely inspect the vacuum chambers for particulates.

22. Cryogenics

Findings & comments:

We were presented with the long history of the cryogenic system used to cool the superconducting cavities. It was explained that while it still works satisfactorily, spare parts, notably the turbines, are not readily available, as the manufacturer no longer produces this equipment. In addition, the last update of the control system was in 2012. Ideally this should now be updated, but the group hesitates due to the cost. The group plans to continue to use the present turbines with care, and notes that there is some redundancy in that with two of the three turbines working there would still be sufficient cooling capacity. The cryo-plant has 8 kW capacity, upgraded from the original 4 kW. This is more than what is needed for the present SRF configuration. The plant power consumption is ~2.2 MW. A more modern control system configuration and bypassing some of the elements could reduce the total power consumption.

The ARC underlines the importance of a working cryogenics system.

Recommendations:

R22.1: Apply for funding to upgrade the control system.

R22.2: Develop a contingency plan as to how one could act should the 35-year-old cryogenics equipment fail.

R22.3: Consider possible energy savings by improving controls or reconfiguring the plant.

23. RF (ARES + SC)

Findings & comments :

The RF system of SuperKEKB uses superconducting cavity stations as well as the normal-conducting energy storage (ARES) stations. Since the last review there have been incremental improvements in the silicon carbide HOM loads used in the superconducting systems, as well as improvements in the water cooling systems in anticipation of higher HER currents. As configured now, the systems are adequate for 2A HER current.

During LS1 the damping ring RF cavities received new metal vacuum gaskets which show improved vacuum in operation. However, a periodic vacuum bursting was observed during operation that is well below the trip threshold, but which should be monitored. The gas seems to be mainly hydrogen, but the source is not understood. The ARES C-cavity systems have improved water cooling systems which should support 3.6 A LER current. 4 cavities received new power couplers and have been commissioned at full power.

One ARES cavity (DO5-A) has historically exhibited breakdown. Explorations in LS1 showed arcing damage at an internal braze. This cavity has been replaced with a spare unit. In the reassembly, a sealing area between the SC and CC cavities required a metal gasket but a 0.7 mm gap between the copper cavity flanges was left, as the metal weld bellows was not available after two previous reconfigurations. The assembled cavity system has been power tested at full power.

Power testing of the silicon carbide HOM loads was cut short due to problems with a klystron power supply. As a result, the LER power limits “are guaranteed at 2 A and maybe OK for 2.5 -2.6 A”. This is consistent with estimates from observed heating prior to the shutdown.

Recommendations:

R23.1: Instrument and carefully watch the temperature of the flange in DO5-A which may have anomalous heating from both accelerating RF currents as well as beam induced HOM power.

R23.2: Repair the klystron test stand to allow resumption of off-line testing.

24. High Power RF

Findings & comments :

The two-ring RF systems have been mostly reliable and supported beam operations during the last run. One of the oldest original Tristan klystrons suffered end of life failure after 130,000 hours due to increasingly frequent internal breakdowns and was replaced with a spare one. There are several other old tubes, raising concerns about their life span. However, only one other tube has failed over the last 3 years. There are six spare klystrons, three of original type and three of upgraded type. Rebuilding of existing tubes is no longer economical. New klystrons can still be purchased but delivery is ~2 years. Anti-ageing maintenance has been continued to keep the RF stations operating reliably.

One Klystron Power Supply (KPS) failed at the rectifier cable connection on restarting after LS1. The cause is under investigation. There are 21 KPSs, 19 of which were built in the 1980’s, but they have had continuous updates and maintenance. There is an ongoing plan to replace obsolete components.

High Power RF (HPRF) cooling systems have suffered from severe corrosion, but have been stabilized with external bracing. This situation should be monitored closely because cooling system failure could be serious.

As beam currents progressively rise, the stress on the RF systems will increase. Systems should be carefully monitored and anti-ageing updates should continue.

RF systems are a major consumer of electricity. The klystrons have modulation anodes to allow active control of output power; however, the old analog controls are not automated. A new control system is proposed that will allow automatic adjustment to maintain best efficiency. A possible savings of 1.5 MW over all systems is estimated. The HVPS also have a remote control of the klystron voltage. If maximum power demand is below specification due to reduced current operation perhaps this can be adjusted to keep the klystrons just below saturation for maximum efficiency while maintaining headroom for feedback.

Recommendations:

R24.1: Test at least one of the spare klystrons to make sure there is always a ready replacement in case of failure during the run**.**

R24.2: Closely monitor the klystron inventory for any further signs of aging.

R24.3: Continue anti-aging maintenance and updates of RF stations to preserve reliability.

R24.4: Continue to seek energy savings such as modulation anode automated control, and remote adjustment of klystron voltages. Study which amounts of energy could be saved, and estimate the effort and time scale to implement the more sophisticated control.

25. Overview of Collective Effects

Findings & comments :

The SuperKEKB beam operation has made several breakthroughs: (1) the injection background effect on the luminosity measurement was removed; (2) the single-beam vertical emittances are <20 pm; (3) the FB noises were significantly suppressed; (4) the LER impedance was reduced by the NLC; (5) the orbit around the CW sextupoles is better controlled; and (6) both LER and HER can operate around their design working point in the tune diagram (.53, .57).

At present, the vertical beam-beam tune shift is about 0.017 in the HER and 0.025 in the LER. These values are lower than previously reached, and a factor 3.5 or 2.5, respectively, below design.

The luminosity of SuperKEKB is determined by an interplay of different effects.

The combined effect of all known impedance sources yields a CSR-driven MWI threshold at an LER bunch current around 1.2 mA, which is less than the design value of 1.44 mA.

A “-1 mode” instability is caused by the interplay of vertical impedance and resistive bunch-by-bunch feedback with a threshold around 0.5 mA. This instability can be cured by fine-tuning the feedback (introducing a reactive component), as had been done in the 2022 run.

Measured coupled-bunch instability rise times are 2-3 times longer than expected from theory.

No significant electron-cloud effects are seen in the LER, since installation of solenoids in drift spaces in 2017.

A larger number of tune scans were carried out both with single beams, and in collisions with and without crab waist.

Recommendations:

R25.1: Explore the limit of the beam-beam tune shift at higher intensity in operation with a few bunches.

R25.2: Optimize the crab waist strengths for actual operating conditions.

R25.3: Apply ML/AI techniques to IP optics correction and luminosity optimization.

26. LS2

Findings & comments :

The planning has started for long range upgrades for SuperKEKB to be done during a future shutdown, labeled LS2. This future shutdown will likely be needed to increase the luminosity from about 2 x 10^{35} $cm^{-2}s^{-1}$ (possible after LS1) to the ultimate level of 6 x 10^{35} $cm^{-2}s^{-1}$. Exactly what future work needs to be done has not yet been decided, as operational results from the presently upgraded SuperKEKB and injector linac have to come to fruition as well as detailed calculations, simulations, and advanced engineering are needed before these decisions can be made. There are three possible upgrade work scopes: 1) Moderate upgrades (relatively short down), 2) Large scale upgrades (medium length down, e.g. new IP magnets, and cryostats to shorten distance between IP and the first low-β quadrupole L* from 935 mm to 835 mm) or 3) Very large scale (very long down with significant preparation time, under investigation). Which option is chosen will likely change when the upgrades in LS2 are decided, scheduled, and pre-shutdown preparation can be specified. A study group involving magnet, vacuum, diagnostics, Belle II, and industrial teams has been formed to study the proposed changes and upgrades to the IR. The LS2 project team will give an interim report to MEXT in roughly JFY2026.

We were shown a plan to use a newly developed Nb3Sn superconductor with 5 micron filaments, in new stronger quadrupoles with larger apertures to replace the existing first units in the QCS, to allow a reduction in beta* following a proposed new long shutdown, LS2. A trial winding was circulated. We encourage this development.

Recommendations:

R26.1: Determine which SuperKEKB accelerator studies need to be done during the next few years, and when, to allow technical decisions related to the future upgrades to be made at an appropriate time.

R26.2: Encourage laboratory tests of crucial technologies (e.g. thin Nb3Sn coils) to be done over the next few years.

R26.3: Periodically monitor the composition of the upgrade study group to make sure all the relevant skills sets are included.

R26.4: Continue the development work on the new Nb3Sn quadrupoles.

27. ITF

Findings & comments :

The two primary goals of the international task force are to define a realistic path to 10^{35} $cm^{-2}s^{-1}$ and to develop ideas for reaching 6×10^{35} $cm^{-2}s^{-1}$.

75 researchers have joined with about 52% from abroad. The key points to address are sudden beam loss, impedance, beam tuning (time fluctuation and current dependance), beam blow-up and injection issues. For the long-term strategy a large modification of the IR might be needed but this is a difficult topic.

Many activities are on-going with successful results: Mitigation of CSR (FERMI, Italy), machine learning to improve injection performance, sudden beam loss understanding, plan of simulating beam-collimator interaction (under consideration at CERN), new methods to correct local coupling at IP (CERN, applied at LHC), TBT BPMs for optics measurements (CERN), stability of cooling water system, strong-strong beam-beam simulations with full lattice (KEK, IHEP, and CERN), and "PyHEADTAIL" estimates for transverse-mode-coupling instability (TMCI threshold is ~1.8 mA/bunch and introducing a non-linear collimator system will raise the threshold to ~2.1 mA/bunch.)

Support from EAJADE for trips has allowed numerous visits from collaborators.

There is a tentative proposal to reorganize ITF into a Working Group with chairpersons being the three KEK Division Heads, aiming at organizing one workshop per year with summary reports addressed to the ARC. The next step is still to be defined.

A framework for joint hardware development is more complicated but should be explored. The next onsite workshop could profit from the occasion of the collider conference eeFACT 2025 in Tsukuba.

Recommendations:

R27.1: Define and implement the next steps for the ITF-IWG transition soon, perhaps in consultation with the ITF WGs.

R27.2: Further increase engagement from the international community in all aspects of the SuperKEKB effort.

28. Luminosity expectations

With current operational conditions (Plan A) it is not possible to reach 10^{35} $cm^{-2}s^{-1}$. Reaching 10^{35} $cm^{-2}s^{-1}$ at betay*=1mm would require 2.26 A in LER and 1.61 A in HER (Plan B). The Plan C is to squeeze betay* to 0.8 mm. The challenges at injection would be the 2-bunch scheme, and the high repetition rate of 23-25 Hz.

The requirement from the Belle II detector of 150 fb^{-1} per month was established assuming 100% efficiency and they would be happy with 200 fb^{-1} by summer. Highest priority is running stably at 10^{35} $cm^{-2}s^{-1}$ to justify future runs.

Appendix A: KEKB Accelerator Review Committee Members

Frank Zimmermann, Chair	CERN
Ralph Assmann	DESY
Vincent Baglin	CERN
Paolo Craievich	PSI
John Fox	Stanford University
Andrew Hutton	JLab (excused)
In Soo Ko	POSTECH (excused & now retired from committee)
Catia Milardi	INFN-LNF
Evgeny Perevedentsev	BINP
Katsunobu Oide	UNIGE/CERN and KEK (ret.)
Qing Qin	ESRF
Bob Rimmer	JLab
John Seeman	SLAC
Michael Sullivan	SLAC
Tom Taylor	CERN (ret.)
Rogelio Tomas	CERN
Tadashi Koseki	KEK, Director of Acc. Lab., Ex Officio Member
Makoto Tobiyama	KEK, Head of Acc. Division III, Ex Officio Member
Mika Masuzawa	KEK, Head of Acc. Division IV, Ex Officio Member
Hiroyasu Ego	KEK, Head of Acc. Division V, Ex Officio Member

Appendix B: Agenda of the 27th KEKB Accelerator Review Committee meeting

March 25 (Monday)		
08:30 - 09:00	Executive Session	
09:00 - 09:10	Welcome	
09:10 - 09:40	Summary of Upgrade Work (LS1)	M. Tobiyama
09:40 - 10:10	2024a Run	Y. Ohnishi
10:10 - 10:40	Belle II Status	K. Trabelsi
10:50 - 11:20	Injector Overview	M. Satoh
11:20 - 11:50	RF Gun	M. Yoshida
13:10 - 13:40	Accelerating Structure	H. Ego
13:40 - 14:10	Pulsed Magnets / Power Supplies	T. Kamitani
14:10 - 14:40	Linac Control Monitors	T. Suwada
14:40 - 15:10	Injection	T. Yoshimoto
15:20 - 15:50	Optics	H. Sugimoto
15:50 - 16:05	Nonlinear Collimator	S. Terui
16:05 - 16:35	Sudden Beam Loss (SBL)	H. Ikeda
16.35 - 17:05	Monitors	G. Mitsuka
17:05 - 17:35	Damping Ring	M. Tawada
18:00 - 20:00	Executive Session	
March 26 (Tuesday)		
08:30 - 09:00	Executive Session	
09:00 - 09:30	MDI	H. Nakayama
09:30 - 10:00	BT	T. Mori
10:00- 10:20	Control	H. Sugimura
10:30 - 11:00	Magnet	S. Nakamura
11:00 - 11:30	QCS	T. Oki
11:30 - 12:00	Safety	T. Mimashi
13:00 - 13:30	Vacuum	K. Shibata
13:30 - 14:00	Cryogenics	K. Nakanishi
14:00 - 14:30	RF (ARES + SC)	T. Abe
14:30 - 15:00	High Power RF	K. Watanabe
15:10 - 15:40	Overview of Collective Effects	D. Zhou
15:40 - 16:10	LS2	M. Masuzawa
16:10 - 16:40	ITF	Y. Ohnishi
16:40 - 18:00	Report writing	
19:00 - 21:00	Executive Session	
March 27 (Wednesday)		
08:30 - 11:00	Executive Session	
11:00 - 12:00	Close-out	

Appendix C: Targeted & achieved Super-KEKB (SKB) parameters, comparison with KEKB

Parameter	KEKB w/ Belle		SKB 2022b		SKB 1 April 2024		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	80	80	80	60	32	25
β_y^* [mm]	5.9	5.9	**1.0**	**1.0**	**1.0**	**1.0**	0.27	0.30
ε_x^* [nm]	18	24	**4.0**	**4.6**	**7.0**	**4.9**	3.2	4.6
ε_y^* [pm]	150	150	**~50**	**~50**	**~38**	**~31**	8.6	12.9
I [mA]	1640	1190	**1321**	**1099**	**845**	**680**	3600	2600
n_b	1584		2249		2345 + 1		2500	
I_b [mA]	1.04	0.75	0.587	0.489	0.36	0.29	1.44	1.04
ξ_y	0.098	0.059	**0.0407**	**0.0279**	**0.0277**	**0.0197**	0.069	0.060
L_{sp} [10^{30}cm^{-2}s^{-1}mA^{-2}]	17.1		**71.2**		**82.9**		214	
L [10^{34} cm^{-2}s^{-1}]	2.11		4.65		2.03		80	

The beam-beam parameter is computed without the hourglass factor or geometric factor for the luminosity.

Appendix D: Glossary of acronyms

ARES	Accelerator Resonantly coupled with an Energy Storage (warm RF cavity system at KEKB and SuperKEKB)
ASF	Accidental Spontaneous Firing
BPM	Beam Position Monitor
BOR	Beam Oscillation Recorder
BT line	Beam Transport line (between linac and collider rings)
BTe	Beam Transport for electrons
BTp	Beam Transport for positrons
CSR	Coherent Synchrotron Radiation
DOE	Diffractive Optical Element
DR	Damping Ring
ECS	Energy Compressor System
HER	High Energy (electron) Ring of SuperKEKB
HOM	Higher Order Mode
IP	Interaction Point
IR	Interaction Region
ISR	Incoherent Synchrotron Radiation
ITF	International Task Force (set up to boost SuperKEKB performance)
KEKB	Former B factory at KEK, predecessor of SuperKEKB
LER	Low Energy (positron) Ring of SuperKEKB
LS1	Long Shutdown 1 (from summer 2022 to end January 2024)
LS2	Long Shutdown 2 (expected towards the end of this decade)
MDI	Machine Detector interface
MR	Main Ring (at J-PARC)
MWI	Micro-Wave Instability
NEG	Non-Evaporable Getter
NLC	Non-Linear Collimator
OTR	Optical Transition Radiation
PEP-II	Former B factory at SLAC/Stanford in the United States
PF	Photon Factory
PF-AR	Photon Factory Accumulator Ring
QCS	Final focusing superconducting quadrupole magnet system
RF	Radio Frequency
RFSoC	Radio Frequency System on a Chip
SBL	Sudden Beam Loss (not fully understood beam loss events at SuperKEKB)
SC	Super Conducting
SRF	Superconducting RF
TBT	Turn-By-Turn
TMCI	Transverse Mode Coupling Instability