ARC Intermediate ITF Review

March 7, 2022; revised March 19, 2022

On 25 February 2022, the 5th meeting of the International Task Force (ITF) for SuperKEKB was combined with an intermediate ITF review by the ARC. The ARC participants at this review were R. Assmann, J. Fox, A. Hutton, C. Milardi, K. Oide, E. Perevedentsev, Q. Qin, R. Rimmer, J. Seeman, M. Sullivan, T. Taylor, R. Tomas, and F. Zimmermann (Chair). P. Chiggiato and M. Poelker had sent excuses.

The review featured reports from the ITF working groups, by A. Morita, T. Ishibashi, D. Zhou, and M. Satoh. In a closed ARC session on 28 February, an additional presentation was delivered by M. Masuzawa, which summarized highlights and lessons from the fall 2021 run.

General Remarks

1. Future ITF subgroup meetings could be announced to all KEK accelerator divisions to strengthen the cooperation and to better include the other divisions in the ITF activities.
2. It is important to assign sufficient time to machine studies together with extra manpower (from inside and outside KEK) in order to unravel the limitations in optics, impedance and beam-beam.

Optics

The optics sub-group has organized 3 meetings where the following topics were presented:

- 1st sub-group meeting @ 2021/09/22: https://kds.kek.jp/event/39396/
  - – Jacqueline Keintzel, “Turn-by-turn optics measurements in SuperKEKB”
  - – Leon Van Riesen-Haupt, “Experience in porting SKEKB lattice to MADX”
  - – Hiroshi SUGIMOTO, “Optics Correction at SuperKEKB - Overview and Issues -”
- 2nd sub-group meeting @ 2021/10/13: https://kds.kek.jp/event/39767/
  - – Pantaleo Raimondi, “SuperB Final Focus chromatic correction section with the IP-phase sextupoles”
- 3rd sub-group meeting @ 2021/11/17: https://kds.kek.jp/event/40129/
  - – Yunhai Cai, “SuperKEKB LER Dynamic Aperture analyzed by using LEGO”

The turn-by-turn optics measurements presented by Jacqueline showed compatible results with the usual COD technique used in SuperKEKB for the linear optics parameters, however with apparently lower resolution. Further developments of the technique could improve the performance but due to lack of time no further measurements were taken.

In the non-linear optics regime Jacqueline uncovered some discrepancies between model predictions and beam measurements, e.g. in the amplitude detuning and the non-linear chromaticity. The source of these discrepancies should be examined further.

Leon showed important progress with the modeling of FCC-ee and SuperKEKB in MADX; however, a final lattice reproducing the SuperKEKB optics in MADX was not reported yet.

Sugimoto-san presented an extensive view of the optics related limitations that may affect the SuperKEKB performance. Long and non-reproducible optics tuning was reported as one of the largest concerns. For example, it was observed that the quadrupole strength of the final doublet changed with time after a quench.

Pantaleo proposed to insert a new weak sextupole (SLW) around the βy waist between QC2P and SLY. First attempts of using such a sextupole did not improve lifetime in a simplified model of the machine. Results should be discussed with Pantaleo.

Yunhai Cai proposed a new arc sextupole arrangement with a larger momentum acceptance (increasing from 0.9% to 1.4%) for LER, and first measurements with these sextupole settings were performed in the real machine. Disappointingly, the measured Touchek lifetime of this lattice is lower than for the operational SuperKEKB lattice. Extensive tuning of the machine with the new configuration might be needed before a real conclusion can be drawn. This fact that the Touschek lifetime decreased, instead of greatly increased, implies that existing machine models are incomplete and that unknown machine errors play a critical role in the machine performance.

For comparing different sets of DA, plots showing the DA in a 2-D plane such as Z-X, produced from a common code, are necessary. Just a single number such as "momentum acceptance" is not enough to fully characterize the situation.

The beam-beam sub-group reported that reliable measurements of chromatic coupling at the IP are not available. In addition, the SuperKEKB IR modeling is difficult, which prevents assessing their codes and slows down developments. They would benefit from more complete models of the machine based on both ideal descriptions and measurements. They also reported that reducing the vertical IP beta functions will decrease the vertical beam-beam tune shift and hopefully improve performance. A larger optics change is requested to increase the LER momentum compaction factor by 36%. This lattice has not yet been developed.

Recommendations:

1. Increase effort on **non-linear modeling of SuperKEKB** rings to improve model predictability. This comprises **off-momentum optics and physical aperture including collimators**. Beam measurements, e.g. off-energy optics measurements, might be key to improving the model. **K-modulation** could help understand **final doublet misalignments** and the applied orbit corrector strengths.

2. Improve interaction and **communication with collaborators** for the preparation and **follow-up of specific studies** (e.g. the studies for Yunhai's and Pantaleo's optics).

TMCI

The vertical blowup of the single LER beam above about 0.8 mA / bunch, related to the -1 head-tail mode, is a major concern, and this phenomenon also seems to affect the beam-beam performance. The exact mechanism causing the vertical blow up has not been identified.

Much effort has gone into improving the impedance model of the machine and the codes have been modified to allow the transverse impedance to be split into separate regions and scaled with the local beta functions. This effort has revealed two main regions of concern, the IR and the collimators. It is still not clear which of these is dominant. The QCS is split into two sections; however, the beta function is still varying strongly inside these two regions. It might be appropriate to subdivide those regions further to increase accuracy. Bunch lengthening and tune shift measurements closely agree with the simple formulae. However, these data do not explain the mode -1 instability. Both beam-beam collisions and feedback can suppress the blow up, to some extent. Repeating the tune shift measurements with collimators retracted (carefully after injection) may help determine whether collimators or IR are the dominant source of impedance. One could also open or close individual collimator gaps.

Comments:

- Congratulations on the excellent progress and systematic studies.

Recommendations:

1. Complete the **revision of the impedance budget** mainly for the terms coming from the IR. A detailed understanding of the different impedance contribution will be crucial in view of the IR upgrade. Perform impedance calculations by combining both sides of the IP.
2. Establish the **frequency-dependent transverse impedance** and simulate the single-bunch dynamics with the corresponding **realistic short-range wakefield.**
3. Develop a **theoretical framework** beyond a usual wake(?) for a **region with a large variation of beta function**, like the IR.
4. Future beam studies aimed at investigating impedance coming from IR and at evaluating -1 mode instability threshold could be done, if possible, by **opening collimators** in order to sort out different contributions.
5. Perform **tune spread measurements along the LER bunch train**, in single beam operation mode, in order to further investigate the source of the beam blow up.

6. Further investigate the instability threshold dependence on the t**ransverse feedback configuration.**
7. Study whether **operation with negative chromaticity (plus feedback)** can suppress the vertical blow up.
8. Examine the **RF voltage needs for planned large-momentum-compaction optics.**
9. Measure and quantify the magnitude of any **longitudinal bunch oscillations.**

Beam-beam

Findings

- Simulations show that specific luminosity can be reduced by slow vertical emittance blowup for the HER beam and by bunch lengthening due to longitudinal wakefields
- Is the crab waist scheme as effective as predicted (could observations be explained by not applying 100% crab waist strength)?
- Vertical emittance blowup: beam-beam instability (insufficient. crab waist strength, imperfect crab waist?) —> crab waist strength is shown in simulation to work with 80% (LER), while 40% strength (HER) is not good enough, but limits arise from dynamic aperture.
- Extra decay in specific luminosity is suspected to be possibly due to higher-than-expected longitudinal impedance and extra bunch lengthening (confirmed by streak camera?) or due to microwave instability driven by longitudinal Impedance
- Vertical emittance blowup could be caused by chromatic coupling, by transverse beam coupling, or by noise. A correction of the chromatic R1 parameter was successfully demonstrated in the LER by tuning rotatable sextupoles; a correction of the LER chromatic R2 will be attempted in Run 2022a; the correction of the chromatic coupling in the HER using skew-sextupoles has not been tried yet.
- The horizontal emittance blowup is significant in the LER. This was improved through horizontal tune adjustments.
- Strong-strong BB simulations face CPU time issues (2 months for plot presented) and some physics issues (non-Gaussian beams, beam coupling impedances, full lattice, chromatic coupling at IP, realistic IR model including realistic crab waist). Probably still to be done is a full optimisation of crab waist strength & betatron tunes for realistic machine conditions.
- Mitigations considered:
    - Increase strength of HER crab waist
    - Refine chromatic coupling
    - Extended tune scans
    - Reduce impedance (open Coll)
    - Increase momentum compaction
    - Squeeze beta y functions at IP

Comments:

- Congratulations for the very thorough and detailed work. This is impressive.

Recommendations:

- The **high momentum compaction optics** (when/once available) should be tried in operation before the shutdown.
- Clarify the **performance reach of the crab waist scheme**, its operational range in usable strength and its impact on reachable specific luminosity and on dynamic aperture.
- Consider using **supercomputer facilities** or an upgrade of CPU power for the important and very insightful **strong-strong beam-beam simulations.**
- Complete the inclusion of both **longitudinal and transverse beam coupling impedance** model in the beam-beam simulation tools
- Study the effect of measured magnitude of **longitudinal bunch oscillations** (if any) on the simulated beam-beam performance.
- **Simulate the specific luminosity** versus bunch-current product including the **space charge.** Carry out simulations for **different crab waist strengths**, other than the actual settings (80%/40%).
- From an operations point of view, **refine chromatic coupling optimization** which could give a rather easy gain in terms of vertical blowup control.

Injection

The linac subgroup has been quite active, but only with participation from within KEK. Outreach to international partners should be strongly encouraged, e.g. CSR modeling is an active topic in the light source community.

The straight injection line using the PF-AR injection tunnel has a great potential to improve the injection efficiency drastically, by reducing the regular synchrotron radiation and the R56 coefficient by an order of magnitude. The beam line itself is a conventional transport line and not difficult compared to other fancy devices for the linac. A design study must be started immediately.

Simultaneous top up injection into 4 rings has been operating smoothly. Various linac upgrades including replacing old linac structures have been carried out. The RF gun is operating stably after recommissioning following the arcing event. The diffractive optical element is in routine use and provides a more uniform beam profile. Emittance of the second bunch in 2-bunch injection is still a problem. Degradation of the laser window was noted and will be replaced. New pulsed quads will be installed before/after the J-ARC section for optics matching of each beam mode. This may help to decrease beam loss at J-ARC. The new flux concentrator for positrons is working well. 3 nC charge has been achieved. Emittance growth after BT1 is still a problem. A new transport line with much less bending may be helpful.

Findings:

- 2nC, 20um must be extended to 4nC with 40/20 um (H/V)
- Gradual decrease of bunch charge during run - The reason was traced to laser window deterioration. Excellent that this was identified. Any other possible effects like this?
- Operation of structures at 20 MV/m instead of 8 MV/m. Problems with high field emission and discharges - 4 year plan for new acc. structures, 4 installed and 12 to go.

Recommendations.

- **Identify ways to** reduce the **50% loss of positron intensity in linac**. Full support for **large aperture pulsed quad** for up to 10 nC. Will it also reduce the fractional loss and increase transmission rate? What is the expectation?
- Do we have **CSR calculations**? What are the predictions now and for the new bend chamber?
- Look into the **design of a straighter injection line** and examine its performance.
- **Try to involve additional collaborators and experts from both inside and outside KEK.**