PAUL SCHERRER INSTITUT PSI	Projekt / *Project* **SLS 2.0**
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Autor(en) / Author(s) Masamitsu Aiba	Datum / *Datee* 01. 04. 2022

History

Version 2:

The initial version, 006-1, was in a form of slides (power point file) and is reformatted to be this version. It is planned to add more descriptions in the next versions, for instance, a time estimation of each commissioning steps.

Introduction

The time window allocated for the commissioning is six months: three months dedicated to the accelerator and another three months in parallel to the beamline commissioning. To meet the schedule, the commissioning work should be well organized and prepared in terms of both hardware and software. The preparation of hardware includes dry runs, magnet polarity checks in the tunnel, pre-conditionings of rf cavities and vacuum chambers, etc.

The commissioning is divided into seven phases:
Phase 1 – Linac, booster and transfer line commissioning
Phase 2 – First turn in storage ring
Phase 3 – Second turn and multi turn
Phase 4 – Accumulation, basic feedbacks and linear optics
Phase 5 – Nominal beam current with advanced settings and feedbacks
Phase 6 – Insertion device and collimator setup, making first photon beams
Phase 7 – Finalization

Phase 1 – Linac, Booster and transfer line commissioning

A restart of the linac, which is in a separate tunnel, is foreseen before the main tunnel is closed. Hence it is not included in the time estimation of the beam commissioning.

The SLS booster is currently providing the storage ring with 2.4 GeV beams. The beam energy will be increased to 2.7 GeV for SLS2.0. The transfer line from the booster to the storage ring will be newly constructed with more quadrupole magnets and beam diagnostic capability.

The emittance exchange in the booster [1] needs to be re-implemented during the booster commissioning. Characterization of the booster optics using the refurbished BPM diagnostics, orbit correction and optimization of the ramp is prerequisite of this procedure. It is also tested to vary the extraction timing and/or the maximum magnetic field at the flat top such that the extracted beam energy can be adjusted in Phase 1.

When the booster commissioning is completed, the transfer line optics needs to be properly set up such that the position and angle of the beam at the storage ring injection septum are under control for the injection tuning later. The new transfer line is designed to have a non-dispersive section to ease characterization of the extracted beam. The vertical collimator in the transfer line will be set up once the optics is established. This together with the storage ring collimators will prevent an uncontrolled injection beam from damaging the storage ring magnets and insertion devices.

The goal of Phase 1 is establishing stable beams with design parameters at the storage ring injection septum.

Phase 2 – First turn

As soon as the injector chain and the transfer line are ready, we move on to the storage ring commissioning. The goal of Phase 2 is establishing a full control of the first-turn beam trajectory. The BPMs in turn-by-turn mode are essential beam diagnostics, and they are tested with beam first.

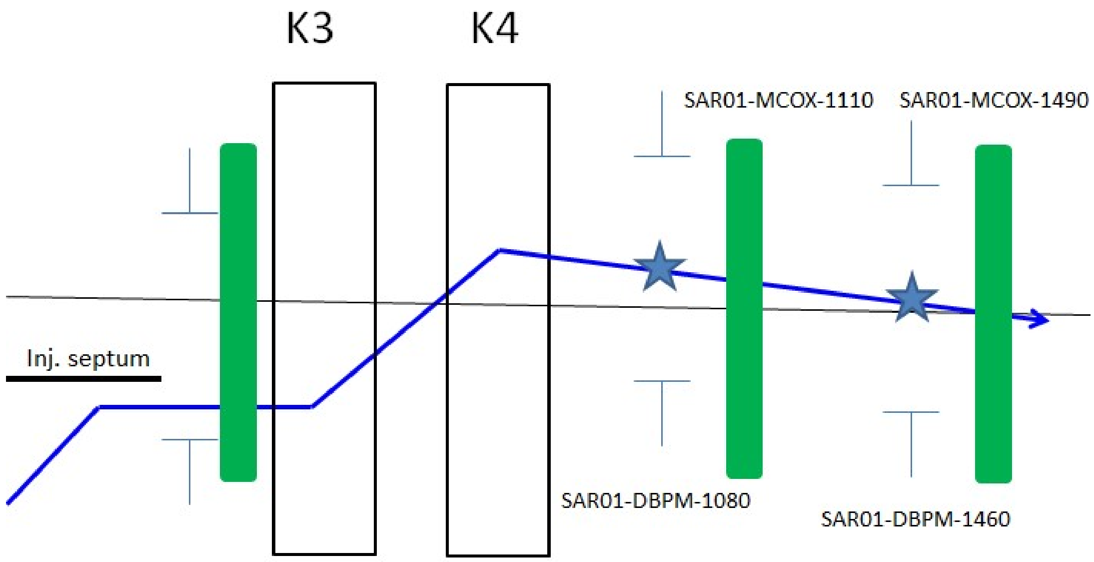
Table 1. Machine imperfections assumed and corrector strength.

Misalignment	
Girder absolute	60 mm rms
Girder-to-girder	20 mm rms
Individual component	30 mm rms
Component roll error	300 mrad rms
BPM	
Electronic offset	300 mm rms
Electronic roll error	10 mrad
Resolution in turn-by-turn mode	50 mm rms
Resolution in orbit mode	50 nm rms
Magnetic field error	0.2% rms
Corrector strength	
Horizontal plane	600 mrad*
Vertical plane	400 mrad

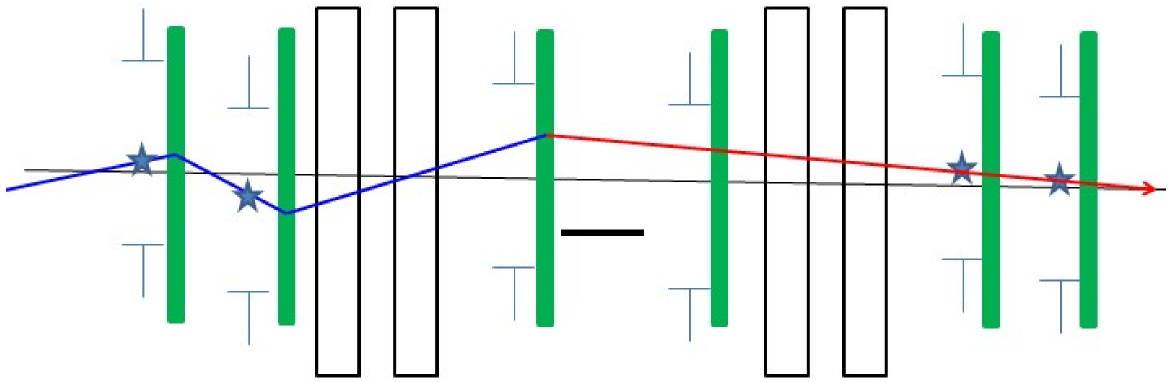
* The horizontal corrector is equipped with an additional winding to increase the maximum strength from 400 μrad to 600 μrad. It can be disconnected when the machine is properly set up and strength of 600 μrad is no longer necessary.

Table 1 summarizes the assumed machine imperfections together with the maximum corrector strength. The imperfection of the storage ring is dominated by BPM electronic offsets arising from non-identical electronics each connected to four button channels and physical offsets with respect to the adjacent magnets. The latter can be significantly large since we cannot align BPMs precisely, which are incorporated to the vacuum chamber, but is subtracted based on alignment survey data before beam commissioning.

Due to the former offset, it may be impossible with the given corrector strengths and actually not desirable to fully correct the first-turn trajectory with respect to the BPM center determined by the up-to-this-point unknown offset. Therefore, the trajectory is first corrected with only effective correctors, i.e., a pseudo inverse matrix with a moderate eigenvalue cut is used when the corrector strength are computed. This "soft correction" will bring the injected beam to the end of first turn as far as the injection beam is properly guided into the storage ring. The kicker bump is used for this such that BPM readings are zeroed at the first two BPMs after the injection kicker in the horizontal plane (see Fig. 1a). If the soft correction does not work well, it is an indication of polarity error(s) of quadrupole, BPM or corrector. Any wrong polarity will be corrected here if it still exists.



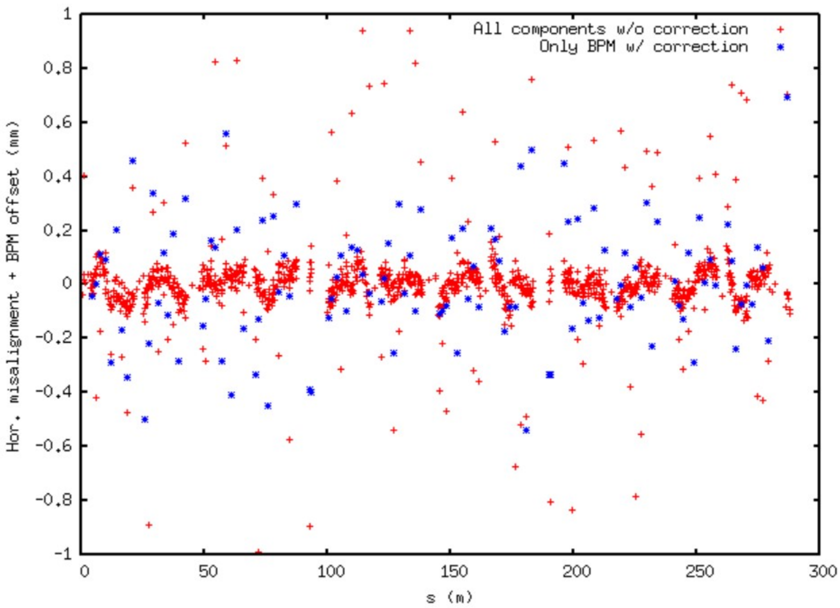
(a) Injected beam (blue line) guided by the kicker K3 and K4. The injected beam is centered at two BPMs after the injection kicker (blue stars). The correctors (green boxes) are turned off. The magnets of the lattice are omitted in the figure.



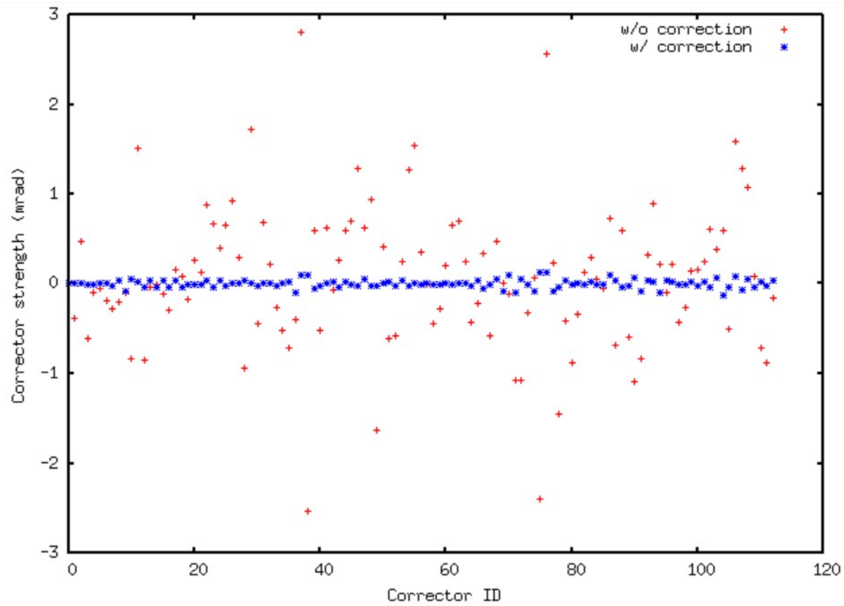
(b) The second turn trajectory (red line) is guided by the second and third correctors of the figure so as to be centered at the BPMs after the injection kicker (the second turn trajectory goes through the blue stars). These correctors do not change the first turn trajectory, and a closed orbit will be established. The BPMs before and after the injection septum are ignored. The injection kicker is turned off in this equalizing procedure (see text Phase 3).

Figure 1: First turn (a) and second turn (b) trajectories around the injection straight, describing how to establish a closed orbit.

Afterward, we apply a special technique to reduce the BPM offsets: we regard the BPM offsets as "another set of correctors" and infer the BPM offsets using again a pseudo inverse matrix with an eigenvalue cut. The rms BPM offset can be reduced by applying a proper cut. After correcting the BPM offsets, it becomes possible to apply a "hard correction", i.e., a simple matrix inversion (no eigenvalue cut), see Fig. 2. Moreover, the injection beam energy can be also evaluated: the average over the BPM offsets found with this technique is proportional to the injection beam energy deviation if the BPM offset distribution is centered to zero. It is noted that sextupoles and octupoles are turned off during Phase 1 (and 2) since they modify significantly the trajectory response to the correctors.



(a) Horizontal misalignments of all components and BPM offsets before correction (red plots), and BPM offsets after correction (blue plots). The large offsets of red plots (500 um rms, exaggerated) are for the BPMs whereas the misalignments of the other components are confined. The blue plots are BPM offsets with correction. The last BPM is not included in the correction. It is not used for establishing a closed orbit (Figure 1b), and its offset will be adjusted later according to the closed orbit.



(b) Horizontal corrector strength to bring the first turn trajectory to the BPM centers, without (red) and with (blue) correction. It is noted that the maximum corrector strength is 600 μrad.

Figure 2: Simulated BPM offset correction and the corresponding corrector strength.

A full control of the first-turn trajectory is established through these procedures, i.e., the offset corrected BPM readings for the first-turn trajectory can be all zeroed with the given corrector strength.

To maximize the efficiency of the work, the final commissioning of the RF system (500 MHz), for example, can be performed in parallel (or perhaps even earlier during the booster commissioning) since the acceleration of beam is negligible for the first-turn trajectory. Other transparent activities such as the commissioning of beam loss monitor can be started already at Phase 1. The entire work should be parallelized as much as possible to shorten the commissioning time.

Phase 3 – Second turn and multi turn

The second and multi turns, the goal of Phase 3, will be achieved by equalizing the first and second turn trajectories (see Figure 1b). The kicker bump is now turned off not to deflect the injected beam at the end/beginning of first/second-turn. Otherwise, the equalizing process is disturbed by the kicker bump. Instead, downstream correctors in the sectors 1 and 2 are used to put the first-turn beam on-axis (zero BPM readings). Once the equalizing is achieved, the above correctors are set back, and the kicker bump is turned on again. A multi turn may be achieved as soon as the kicker bump is on. Alternatively, the fast injection kicker may be used to launch the first turn beam. However, the static elements (correctors) would be easier to handle at this early stage of commissioning.

Phase 4 – Accumulation, basic feedbacks and linear optics

The sextupole and octupole magnets are now set to the nominal value, and the rf system is turned on. Once the injected beam is captured by the rf bucket, we try accumulation. The beam loss monitor may be useful at this time. The BPMs are switched to orbit mode and become most important diagnostics in the following steps.

Before or during the accumulation, a first orbit correction using the circulating beam is applied. Due to the approach used to establish the closed orbit (the BPM offset correction and equalizing), the deflection angle of the corrector SAR01-MCOX-1100 tends to be too high. It can be relaxed by adjusting the offset of its pair BPM ARS01-DBPM-1080. We can look into the corrector pattern, which indicates if the adjustment is necessary, before applying to the machine.

The commissioning of the passive third harmonic cavity system can start once sufficient beam current is stored. With a stored beam, we establish a procedure of closed orbit correction. The commissioning of various diagnostics such as current transformers and beam size monitors starts also in parallel. The vacuum scrubbing starts by itself as soon as there is a stored beam. We keep checking the vacuum pressure along the ring, and we start recording the integrated beam current (the beam current should be recorded in the archiver). At this time temperature sensors installed on the vacuum chamber provide a simple protection of the vacuum system. An orbit interlock provides additional safety.

Commissioning simulation showed that the dynamic aperture is most likely large enough for accumulation after Phase 3 (Fig. 3). For some bad random seeds in simulation, however, it is indicated that we may have to use the kicker bump and the fast kicker simultaneously to bring the injection beam within the deteriorated dynamic aperture.

At the SLS, we have two modes of beam dump, i.e., the normal dump and the emergency dump. In the former, the insertion device gaps are opened before beam dump while the beam is immediately dumped in the latter. These two modes will be also implemented here. As soon as we have a stored beam, these beam dump procedures have to be established. For the normal beam dump, there are several possible approaches. One of them is to generate an orbit bump at the beam dump (1L) and dump the beam by using one of four injection kickers. Otherwise the fast injection kicker can offer a safer procedure, where only selected bunches are dumped at each firing. For the emergency beam dump, a dedicated beam dump kicker is used, and the horizontal collimators have to be roughly positioned.

Afterward, slow orbit feedback and rf frequency feedback can be established. The filling pattern feedback is also prepared to be ready for the next phase. Precise BPM beam-based alignments, and linear optics measurements and corrections follow. Simulation study showed that LOCO style optics correction [2] can correct beta-beats to 1% rms level. Coupling correction with skew quadrupoles can be applied as well using the orbit response data of LOCO. The dynamic aperture after the optics correction and coupling correction is larger than the aperture determined by the injection septum (5.5 mm) as shown in Fig. 4. Tune feedback is set up when the linear optics is well corrected.

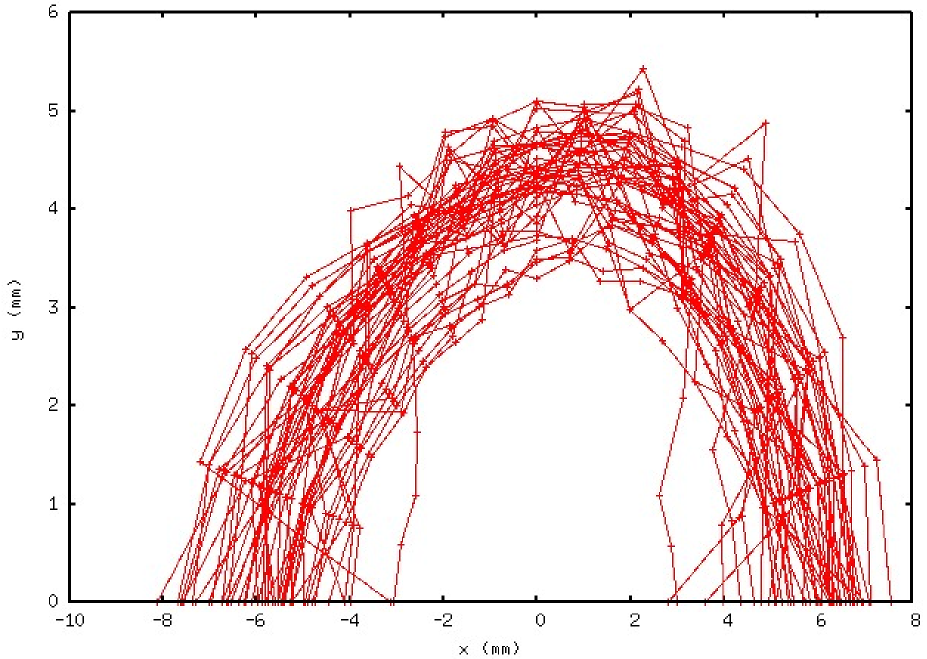


Figure 3: Simulated dynamic aperture at the location of the thin septum before linear optics is corrected (and coupling correction).

Phase 5 – Nominal beam current with advanced settings and feedbacks

Towards an accumulation of the nominal beam current, we need to go through a few steps. First, skew quadrupoles have to be adjusted to control the vertical emittance. Vertical remote girder realignment at this stage will allow reaching small coupling and spurious vertical dispersion. Coupling correction may be repeated prior to the vertical emittance manipulation. Using many skew quadrupoles distributed over the ring, it is possible to suppress the vertical dispersion and the linear coupling along all straights section. Figure 5 shows the “vertical dispersion bumps”, which induce a vertical emittance of 10 pm. The skew quadrupole setting will be confirmed by measuring the orbit response matrix and the vertical dispersion while a direct confirmation by the beam size monitor, which takes a long time to commission, may not be available at this point.

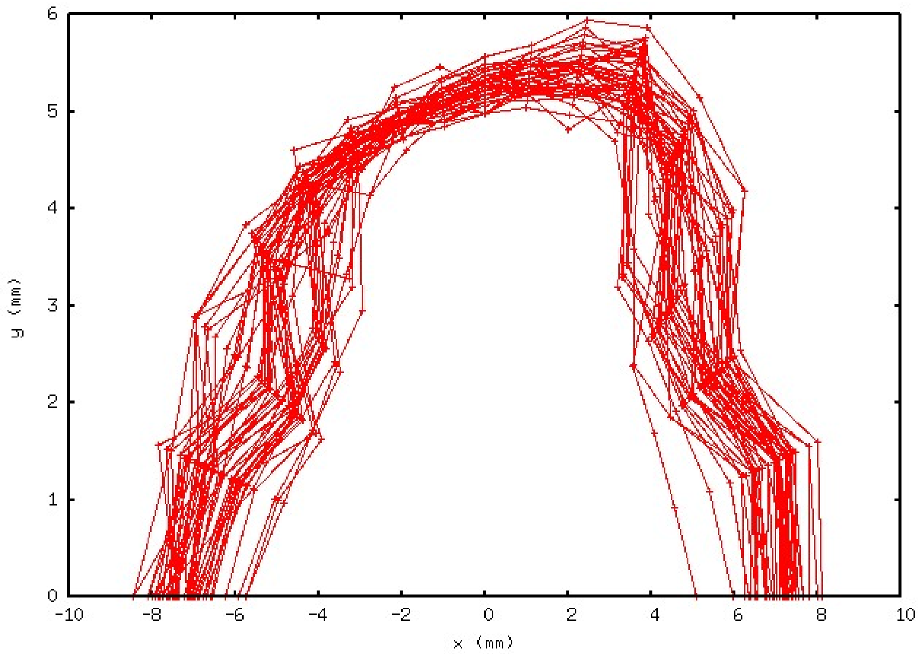


Figure 4: Simulated dynamic aperture at the location of the thin septum after LOCO style optics correction.

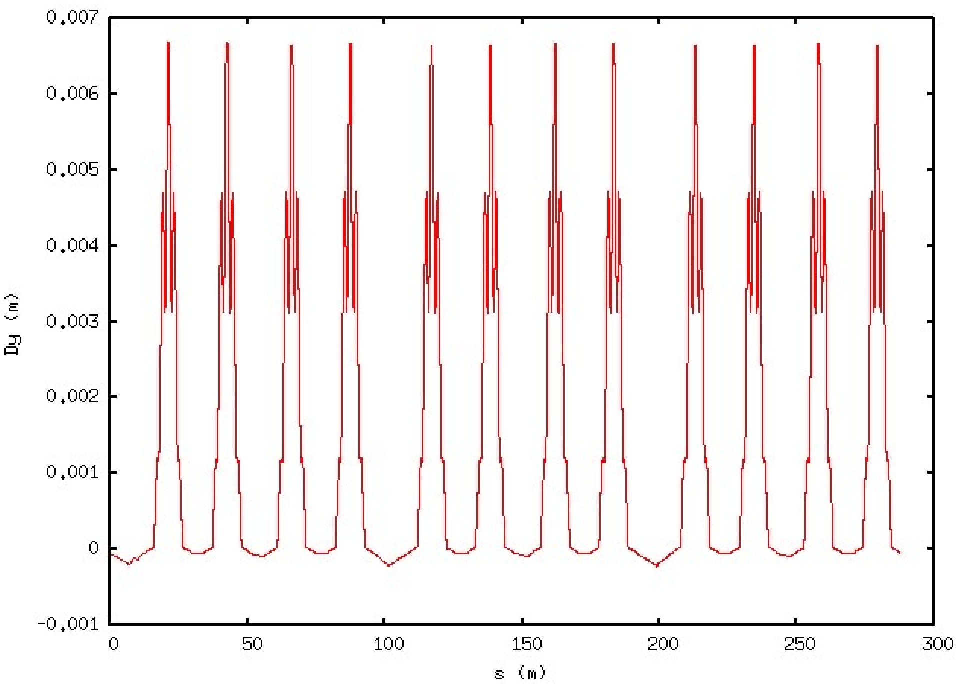


Figure 5. Vertical dispersion bumps to control vertical emittance.

In addition, a re-alignment of combined function magnets in the tunnel might be necessary in order to lower the horizontal corrector strength. We will also consider horizontal girder realignment at locations where it is needed. When the maximum corrector strength is well below 400 μrad the additional windings of horizontal correctors can be disconnected, maximizing the fast orbit feedback performance.

Second, we perform chromaticity measurement and correction. Measurement will be repeated by changing sextupole power supply current family by family, checking if the changes in chromaticity are consistent to the optics model. Positive chromaticity above or equal to 1 is essential to suppress instabilities at the nominal beam current.

Finally, collimators have to be set approximately to protect permanent magnets using the beam loss monitor together with the beam lifetime measurement. The setting will be refined in the next phase.

In addition, we may need to get the bunch-by-bunch feedback working if it is essential to stabilize coupled bunch instabilities at the nominal current or during the accumulation. Also certain time will be required for the conditioning of the rf cavity coupler with beam and for the commissioning of the LLRF-feedbacks with beam. Important parameters, like synchrotron tune and Robinson stability are to be examined.

Once we are ready, an accumulation of the nominal current is tested, and full commissioning of the harmonic cavity is performed. With high current beam, the linear optics correction and BPM beam-based alignment may be repeated and elaborated. Nonlinear optics correction is also foreseen to prolong the beam lifetime as much as possible. First commissioning of the fast orbit feedback is carried out in order to prepare for the characterization and operation of insertion devices. It is most important that the emergency beam dump procedure is fully established during the nominal current accumulation test.

Phase 6 – Insertion devices and collimators, making first photon beams

The insertion devices will be tested one by one, and storage ring collimators will be more precisely set to protect not only storage ring permanent magnets but also the insertion devices. The beam loss monitor would be important diagnostics here and should be functioning well. Simple feedforward, i.e., a look-up table of orbit corrector settings as a function of insertion device gaps, are implemented during these first insertion device tests.

The beam dump procedure needs to be extended, involving insertion devices: no significant beam loss should appear at the insertion device locations. Afterward, the stored beam is fully under control, and finally, we will make “first photon beams”.

The nominal current beam is not essential during Phase 6. Therefore, if the vacuum scrubbing was not enough at the end of Phase 5 and thus the beam lifetime was too short, we proceed to Phase 6 with a lower current beam.

Phase 7 – Finalization

In the last phase, the goal is to make the machine ready for the photon beamline commissioning. We extend the feedforward table to include photon BPMs and storage ring linear coupling. If the multi-bunch feedback was not essential in Phase 5, it will be studied here. The commissioning of the beam size monitor will be continued here. As far as time permits, the previous commissioning steps will be refined. Further refinements will follow during the beamline commissioning.

Remarks

The vacuum scrubbing requires an integrated beam current of 100 A-hours and should ideally be finished after three months, i.e., at the end of dedicated accelerator commissioning. Phase 1 for the injector and the transfer line may take 2 weeks or so (excluding linac commissioning). Therefore we have approximately two and half months left. This imposes a condition that the average beam current should be about 55 mA or higher. This condition seems achievable but indicates that the activities to increase the beam current are priority. Therefore, we have to follow the above commission steps with no shortcut to the first photon beam.

The commissioning will be interrupted with important radiation measurements, and the machine at the end of commissioning has to meet the radiation safety regulations. For instance, the beam lifetime should be long enough. Our target is an operation condition similar to the SLS, where the bam lifetime is typically more than 8 hours.

References

[1] J. Kallestrup and M. Aiba, “Emittance exchange in electron booster synchrotron by coupling resonance crossing”, Phys. Rev. Accel. Beams 23, 020701 (2020)

[R2] M. Böge, “Orbit and optics corrections”, Presentation at machine advisory committee (2020)

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