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COMMISSIONING SIMULATION STUDY FOR THE ACCUMULATOR RING OF THE ADVANCED LIGHT SOURCE UPGRADE*

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Abstract

The Advanced Light Source Upgrade (ALS-U) to a diffraction-limited soft x-rays light source requires the construction of an Accumulator Ring (AR) to enable swap-out, on-axis injection. The AR lattice is a Triple-Bend-Achromat lattice similar to that of the current ALS but to minimize the magnet sizes the vacuum chamber will be significantly narrower hence requiring a careful evaluation of the magnets' field quality. This work presents the results of a detailed error tolerance study including a complete simulation of the commissioning process.

INTRODUCTION

The proposed lattice for the Advanced Light Source upgrade (ALS-U) [1] into a diffraction-limited soft x-rays light source is a 9-Bend Achromat reproducing the 12-fold symmetric footprint of the existing ALS [2]. The required small emittance is achieved by much stronger focusing than in the present ALS. Stronger focusing leads to larger natural chromaticities and smaller dispersion. Thus a large increase in sextupole strength is needed, resulting in small dynamic aperture on the order of 1 mm^2 even for the ideal lattice.

Due to the small dynamic aperture, traditional accumulation injection is not feasible. Therefore, the ALS-U Storage Ring requires on-axis swap-out injection, which exchanges a stored bunch train with a replenished bunch train simultaneously. For this purpose a 2 GeV Accumulator Ring (AR) [3] will be housed in the storage ring tunnel. It will act as a damping ring for the bunches generated by the booster and to store the beam for top-off in between swap-outs. Figure 1 shows a schematic drawing of the ALS-U facility.

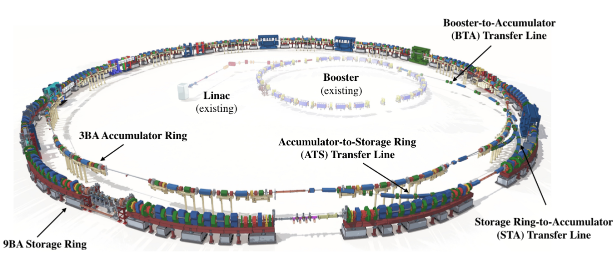

Figure 1: Schematic drawing of the Advanced Light Source upgrade. Up to four bunches are accelerated every 1.4 s in the existing linac and booster and then injected into the new AR. Every 30 s the bunch train in the AR replaces one bunch train in the SR utilizing a swap-out, on-axis injection.

In order to minimize dark time of the accelerator, the installation of the ALS-U AR is scheduled during regular ALS maintenance and two annual shutdown periods lasting several months. Beam based commissioning of the AR will take place during regular user operation of the ALS which limits the available number of beam injections into the AR significantly [4]. To address the challenges posed by rapid commissioning and in general to understand how realistic errors will affect the machine operation and to better define an error tolerance budget we have carried out complete simulation of machine commissioning. The studies are performed using the Accelerator Toolbox (`AT`) [5] based *Toolkit for Simulated Commissioning* (`SC`) [6].

SIMULATION SETUP AND ERRORS

The ALS-U AR lattice is similar to the current ALS lattice, but adjusted to account for the slightly smaller circumference of about 182 m and further optimized considering the smaller physical aperture.

The lattice, providing an emittance of 2 nm rad consists of 12 identical arcs, each equipped with 6 BPMs. Horizontal and vertical corrector magnets (CM) suitable for slow trajectory correction are installed in six sextupole magnets and a set of skew-quadrupole corrector coils is added to one sextupole magnet per sector. A schematic drawing of the lattice properties including the position of the CMs and BPMs is shown in Figure 2.

A variety of errors are considered such as static and shot-to-shot injection errors, calibration errors, offsets and rolls of all magnets and their corresponding girders, diagnostic errors such as BPM offsets and noise, rf frequency, voltage and phase errors and a circumference error. The baseline values can be found in Tables 1 and 2. Furthermore, detailed systematic and random multipole-error tables are included for all magnets and corrector coils. The limits for the CMs and skew quadrupoles are 200 µrad and an integrated K value of 0.1, respectively.

COMMISSIONING SIMULATION

We have studied different correction strategies and analyzed them statistically with respect to the corrected machine properties and success rate of the algorithm. The following sequence for the simulated commissioning procedure was found to be the best performing one for a variety of different error assumptions and was therefore used to define an error budget and set diagnostic requirements. The implemented correction chain can be reviewed in the `SC` applications folder [7].

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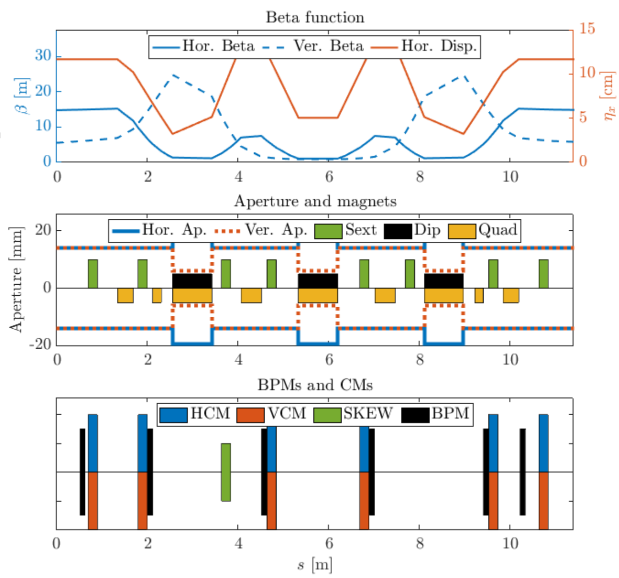

Figure 2: Lattice, magnet distribution and apertures of the first sector of the ALS-U AR.

Initially, the sextupole magnets and the rf cavity are switched off. For early commissioning a single dipole kicker is used for on-axis injection [8]. Without any correction the beam gets lost within the first turn in 80 % of the cases.

For the initial trajectory correction we use an iterative feedback-like approach [9] to bring the machine from its uncorrected state to a state of full one-turn transmission. Subsequently, full two-turn transmission is achieved by 'stitching' the 2nd turn BPM readings to the readings of the first turn which finally corrects the machine to a state with a period-one orbit, from which full transmission through a large number of turns can be expected.

The natural chromaticity of the AR is about -30 and -40 for the horizontal and vertical plane, respectively. Chromatic decoherence of individual particle trajectories quickly compromises the BPM readings within a couple of turns. This makes turn-by-turn evaluation of the betatron oscillation over many turns, as needed for the subsequent commissioning of the rf cavities, difficult. Hence, switching on the sextupole magnets is required at this point in the commissioning process. Ramping up the sextupoles in steps of $1/10$ of their nominal strength while applying the previously described trajectory feedback after each step is found to be successful in 100 % of the cases.

The next step is to correct the rf frequency and phase such that the injected beam is longitudinally launched on the closed orbit. The implemented correction routines make use of the fact that a turn-by-turn (TBT) energy variation will result in a TBT horizontal BPM variation due to dispersion. Thus, the average horizontal BPM difference between two turns is a measure of the energy gain or loss of the bunch.

At first, the rf phase of the cavity is changed in steps within $\pm\pi$ and for each step the BPM readings are evaluated over 25 turns. Since the synchrotron period is 185 turns, the evaluated period covers only small fraction of a revolution, hence representing a good approximation of the 'local' longitudinal phase-space motion at injection. The average horizontal TBT BPM variation is evaluated as a function of the rf phase, a sinusoidal function is fitted and the zero crossing is identified as the synchronous phase. See Figure 3 for an example.

Considering a well corrected rf phase, the rf frequency is corrected similarly by evaluating the mean TBT horizontal BPM variation over 130 turns as a function of a frequency change within ±1 kHz. A straight line is fitted and the zero crossing is identified as the synchronous frequency.

The accuracy of both phase and frequency correction is limited if the corresponding counterpart is not sufficiently well corrected. In order to catch rare cases of e.g. an unfortunate combination of a large circumference and frequency error, both corrections are performed in a loop with three iterations. The corrected phase and relative energy error between the injected beam and the closed orbit is 1.2° and 2×10^{-5}, respectively. This is a satisfactory result considering the longitudinal beam size as shown in Table 2.

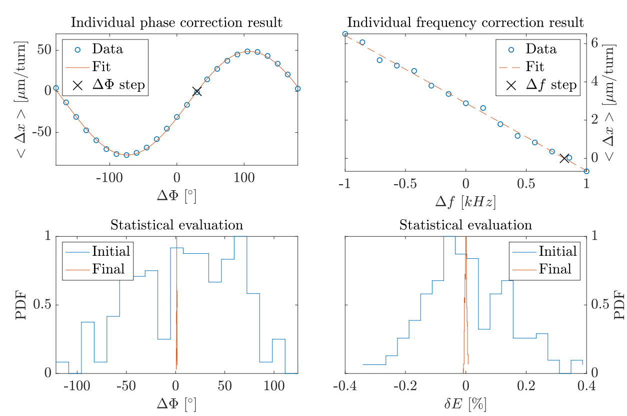

Figure 3: Results of the rf phase (left) and frequency (right) correction. Shown are the mean horizontal TBT BPM variation and the corresponding fit functions (top) and a statistical evaluation of the final results (bottom) over many seeds.

At this point the beam survives 20000 turns, thus more than two damping times in 98 % of the cases while always achieving 2000 turns for the baseline error assumption. Nevertheless, in order to make the scheme robust to more generous error assumptions, linear optics correction is performed.

We studied different trajectory-based linear optics correction strategies and it turned out that the most efficient way at this point is a simple but robust tune scan, while postponing an accurate optics correction scheme until the beam is fully captured. For the tune scan the quadrupole families QF and QD are exercised coherently on a grid of K_F/K_D-values on a spiral like patterns until the beam transmission after 500 turns is above 80 %. A low number of turns with a high transmission was found to be a good approximation of beam capture while minimizing the computational costs of the evaluation. The final transmission at 20000 turns is

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above 75 % in all cases and beam capture can be considered achieved.

Successful routine operation at the ALS [10] indicates that performing beam based alignment (BBA) at the ALS-U AR after achieving beam capture will be straight forward. Therefore, the BBA routine is not explicitly implemented in the commissioning simulation. Based on measurements at ALS we conservatively assume a reduction of BPM offset uncertainty to 50 µm rms.

After reducing the BPM offset uncertainty a more ambitious closed orbit correction can be applied in order to reduce feed down optics perturbations from sextupole magnets and other higher order multipoles. At first, the actual response matrix is measured as well as the dispersion by changing the rf frequency. The previously described orbit feedback is applied including dispersion, thus with the rf frequency as an adjustable parameter. The correction is performed in a loop with a subsequently decreased regularization parameter α for the calculation of the pseudo-inverse matrix [9]. The correction is stopped if a decreased α did not result in a decreased rms BPM reading, e.g. because the calculated CM setpoints are beyond their limits. The final closed orbit deviation is about 100 µm rms.

The LOCO method is implemented in MATLAB® and reliably used for storage rings [11, 12]. For linear optics correction, we use an interface between LOCO and the SC toolkit [6]. The developed correction sequence for the ALS-U AR consists of different steps. The first step includes a coarse correction using all QF and QD quadrupole magnets while at first ignoring coupling (off-diagonal response matrix blocks) and diagnostic errors. In the second iteration, calibration factors of the BPMs and CMs are fitted as well. Thereafter LOCO is applied in a loop with a chromaticity correction. All QF, QD quadrupoles are used as well as all available skew quadrupole correctors. Coupling and diagnostic errors are included in the fit. A beam based chromaticity correction is not yet implemented, instead we use a simple matching scheme which is motivated based on experience at the ALS assuming that the chromaticity can be measured and corrected without problems.

Results shown in Fig. 4 indicate that all requirement have been met. E.g., the horizontal emittance is below 2 nm with less than 1 % coupling and the corrector limits are not exceeded. The larger excursion of QD values is due to the fact that its K value is about 10 times smaller than for the QF magnets.

SUMMARY

We have presented an application of the AT based *Toolkit for Simulated Commissioning* (SC) on the ALS-U Accumulator Ring. A robust correction chain was developed and successfully used to define an error tolerance budget and to define diagnostic requirements. The number of required beam injections lies within 180 and 210 for the analyzed error realizations.

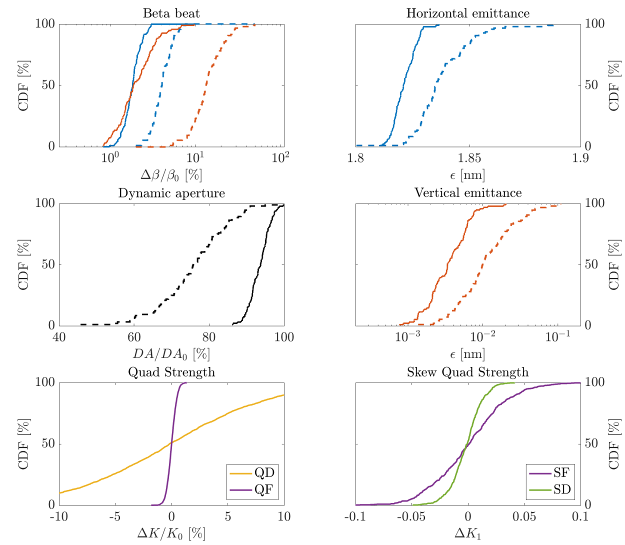

Figure 4: Visualization of LOCO results. Shown are the cumulative distribution functions (CDF) of the beta beat, dynamic aperture and emittance before (dashed) and after (solid) LOCO in the upper four plots. The lower plots show the final relative quadrupole setpoint deviation from the design value (left) and the required skew quadrupole strength (right).

Table 1: Errors Assumed in the Commissioning Simulations

Type	Rms	Type	Rms
Section Offset	100 µm	BPM Offset	500 µm
Girder Offset	50 µm	BPM Roll	4 mrad
Magnet Offset	50 µm	BPM Noise (TbT)	10 µm
Magnet Rolls	200 µrad	BPM Noise (CO)	1 µm
Girder Rolls	100 µrad	BPM Calibration	5 %
CM calibration	5 %	rf Voltage	0.5 %
Magnet calibration	0.1 %	rf Phase	90°
Circumference	0.2 mm	rf Frequency	0.1 kHz

Table 2: Injected-Beam RMS Systematic and Jitter Errors, and RMS Sizes as Assumed in the Commissioning Simulation

	Systematic	Jitter		Beam size
Δx	600 µm	50 µm	σ_x	2.1 mm
$\Delta x'$	150 µrad	5 µrad	$\sigma_{x'}$	150 µrad
Δy	500 µm	5 µm	σ_y	380 µm
$\Delta y'$	100 µrad	2 µrad	$\sigma_{y'}$	80 µrad
$\Delta E/E$	1×10^{-3}	1×10^{-4}	σ_δ	1×10^{-3}
$\Delta\phi$	0	0.1°	σ_ϕ	15°

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