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SIMULATION OF TRAJECTORY CORRECTION IN EARLY COMMISSIONING OF THE ADVANCED LIGHT SOURCE UPGRADE*

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Abstract

The ALS upgrade into a diffraction-limited soft X-rays light source requires a small emittance, which is achieved by much stronger focusing than in the present ALS. Very strong focusing elements and a relatively small vacuum chamber make the required rapid commissioning a significant challenge. This paper will describe the progress towards a start-to-end simulation of the machine commissioning and present first simulation results.

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. For example, maximum quadrupole strengths are larger by almost a factor five. These are typical for the new generation of light sources and e.g. comparable to those required in the APS-U [3]. Stronger focusing leads to larger natural chromaticities and smaller dispersion. Thus a large increase in sextupole strength is needed, resulting in relatively small dynamic aperture (requiring on-axis injection) and short lifetime even for the ideal lattice. Misalignments of the strong quadrupoles generate large orbit/trajectory errors and, again because of the very strong sextupoles, large linear focusing and coupling errors, reducing the dynamic and momentum aperture. While fine tuning of the orbit and linear-optics should in the end restore the desired particle-dynamics stability, this requires a circulating beam with sufficient current which, of course, has first to be established. Commissioning is therefore expected to be a significant challenge also in consideration of a demanding schedule to keep the dark time as short as possible [4].

To address the challenges posed by rapid commissioning and more in general to understand how realistic errors will affect the machine operation and to better define an error tolerance budget we have started to develop start-to-end simulations of machine commissioning. The ultimate goal is to be able to simulate the various steps followed in the actual commissioning process with as much realism as possible, including all major error sources, diagnostics, and correction procedures. This work reports progress toward this goal and first simulation results.

COMMISSIONING PROCEDURE

The simulated commissioning procedure includes the following steps:

- Apply machine and injected-beam errors according to Tables 1 and 2
- Perform local trajectory correction until beam reaches one turn
- Perform global trajectory correction until sufficient multi-turn transmission is achieved
- Perform global trajectory correction including RF cavities until closed orbit is found

The following will describe each step in detail.

Simulation setup: The ALS-U lattice consists of 12 identical arcs, each equipped with 20 BPMs. Horizontal and vertical corrector coils suitable for slow trajectory correction are installed in the sextupole magnets (8 per arc) and in all but one quadrupole magnet families (12 per arc). A schematic drawing of the lattice properties including the position of the Corrector Magnets (CMs) and BPMs is shown in Figure 1.

All simulations were done using the matlab [5] based Accelerator Toolbox (AT) [6]. Magnet misalignment and strengh errors is modeled by adding or changing the relevant entries in the *PolynomA* and *PolynomB* arrays [7]. Higher order multipole errors and longitudinal misalignments are currently not included. A simplified and somewhat conservative model for the vacuum chamber is assumed, consisting of a circular aperture pipe with 2/3/13 mm radius corresponding to the narrowest aperture (thin septa adjacent to the fast kicker) in the injection straight section, the narrowest aperture in the ID straight sections, and the aperture in the arcs respectively.

Synchrotron radiation is generally included while in the calculations for the early-stage commissioning the RF cavities are switched off. The energy loss per turn is about

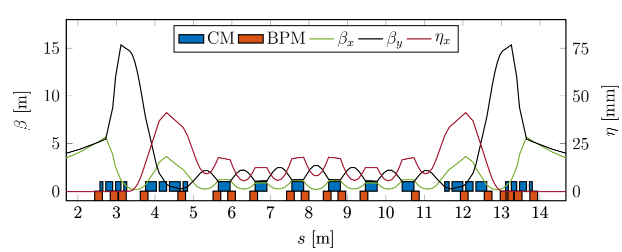

Figure 1: Schematic drawing of the arc section of the ALS-U, including the position of 20 BPMs (red) and 20 CMs (blue). Also plotted are the horizontal (green) and vertical (black) β-functions and the horizontal dispersion (red).

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220 keV. In the ideal lattice with radiation effects included and RF cavities turned-off the beam survives for about 350 turns before it hits the aperture. During early-stage commissioning, however, the sextupole magnets are turned off. Simulations show that the beam survives for about 100 turns before the tune shift due to the large natural chromaticity of about 100 results in a beam loss.

In the simulations we attribute about 2.8 µm single-turn resolution to the BPMs, corresponding to the resolution of the ALS BPMs observed for 0.5 nC bunch charge (about half the ALS-U single-bunch design charge). Initial BPM offset is expected to be 500 µm rms.

Rms machine-error and injected beam trajectory error realizations are assigned according to the values reported in Tables 1 and 2, with each error source having a Gaussian distribution truncated at 2σ. Most of the statistics is done over a population of 20 error realizations. The injected bunch is represented by a 6D distribution of 100 macro particles with rms sizes also reported in Table 2. A beam is considered lost if it loses 60 % of the particles.

Initial transmission: Figure 2 shows a histogram of the beam-loss locations when the beam is injected without any trajectory correction. On average the beam gets lost in the insertion device between sector two and three and passes through the first arc in 98 % of the cases. In the remaining 2 % of the cases the beam gets lost right in the injection straight section; this loss should be easy to circumvent by gentle steering of the upcoming beam in the transfer line. The first sector includes 20 BPMs and 20 CMs, sufficient to start trajectory correction.

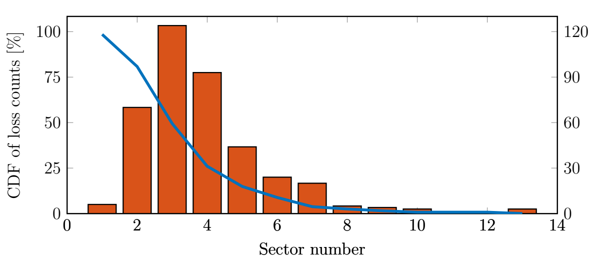

Figure 2: Histogram of the beam loss position (red) without trajectory correction and the corresponding cumulative distribution function (CDF, blue). The beam passes the first arc in 98 % of the cases.

First-turn transmission: In order to achieve the first turn, an SVD based correction algorithm using the ideal trajectory response matrix is applied. The figure of merit to be minimized is the rms BPM reading. The algorithm consists of three nested loops. The outer loop increases the number of used BPM, the mid loop increases the number of upstream CMs, and the inner loop increases the number of Singular Values (SV). The corrector settings are updated each time the beam gets lost at some point further down the ring than the previous loss point. At first, only the signal of the two last BPMs preceding the loss-point is retained and only the first two CM upstream of that BPM is exercised using one SV. The algorithm then progresses by adding more SVs, and engaging more adjacent CMs and BPMs upstream the loss-point through the nested loops until the beam reaches further downstream.

To keep the correctors' strength under control the CM limit is initially set to half its 0.2 mrad maximum and increased gradually if the procedure does not reach the full turn. This procedure achieves first-turn transmission in 100 % of the cases.

Trajectory correction: The next step is to achieve sufficient multi-turn transmission to set the stage for commissioning the RF cavities. At this point it is assumed that a beam-based alignment procedure has been carried out and credited for a significant reduction of the offsets assigned to the BPMs. In the future, we will use simulations of beam-based alignment to estimate the magnitude of this reduction. For now we tentatively assume a reduction by a factor of ten, to 50 µm rms offset errors.

Again, an SVD based global trajectory correction algorithm is applied but now using the ideal trajectory response matrix over two turns. The figure of merit is the overall rms trajectory offset. The algorithm consists of the following three nested loops: the outer loop increases the number of used CMs per sector; the mid loop selects different subsamples of CMs; and the inner loop increases the number of SVs. Initially one SV and one CM every two sectors is exercised, while all other CMs are set as determined in the previous step. The CMs are chosen according to their position, e.g. every 40th or 20th CM in the lattice.

Tracking is performed to calculate the number of turns survived by the beam. The algorithm starts over from the inner loop when both the rms trajectory offset is found to be less then 98 % of the previous value and the location where the beam is lost is not worse than in the previous step.

The correction is terminated if the rms trajectory offset reaches below the 300 µm target and the beam survives more than 60 turns. Finally, the CM setting with the best trajectory offset is chosen for the next step. This routine was able to achieve a transmission of at least 5 turns in 100 % of the cases (73 turns on average).

At this point it is assumed that the RF cavities can be switched on and the closed orbit is searched using the AT function *findorbit6*. If no closed orbit exists, trajectory correction with a target of 200 µm rms as described above is repeated. This routine converged to a closed orbit in 100 % of the 20 error realizations analyzed.

Orbit, lattice functions analysis: The algorithm as described above including multi-macroparticle tracking is computationally expensive and not ideal for extensive statistical analysis over a large population of error realizations. A reasonable simplification can be made by using only one macro particle and capturing the effect of chromatic decoherence of particle trajectories on the diagnostics as an effective

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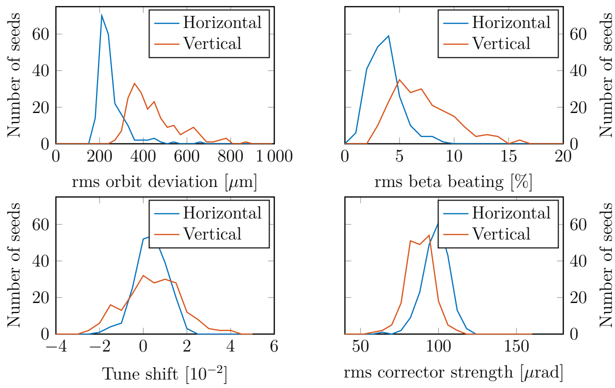

Figure 3: Distribution of selected quantities over 150 machine random-error realizations. The plots show the horizontal (blue) and vertical (red) rms orbit variation (upper left), rms beta beating (upper right), tune shift (lower left) and required rms corrector strength (lower right).

degradation of the BPM resolution in the form of an offset error.

To estimate the effective BPM noise resulting from chromatic decoherence we considered 20 error seeds after successful multi-particle trajectory correction. For each lattice the BPM reading for an ideal macro particle is calculated and compared to the corresponding reading of the signal from 100 separate bunches each containing 100 particles. The rms difference for the trajectory within the first two turns was found to be well described by a linear increase from 2 μm to 6 μm for the horizontal plane and from 2 μm to 20 μm in the vertical plane.

SIMULATION RESULTS

We then repeated our trajectory correction study described above with this augmented noise in the BPMs but by representing a bunch with only one macroparticle thus enabling a statistical analysis over a larger population of error sets in a reasonable time.

The trajectory correction results and properties of the disturbed lattice are statistically analyzed for 200 error seeds. For each lattice realization we calculated the rms relative beta-function beating, the tune error, the corrected-orbit rms deviation and the CM rms strength.

Results are shown in Figure 3. The required corrector strength is well within the 0.2 mrad limit set at the start. Orbit deviation and lattice functions as shown here may be sufficient to start linear optics correction and commissioning of the sextupole magnets.

SUMMARY AND CONCLUSION

Progress towards a start-to-end simulation of the machine commissioning of the Advanced Light Source upgrade was presented, including the development of a reliable trajectory correction algorithm. It converged to a closed orbit in 100% of the analyzed cases and should be sufficient to start linear optics correction and commissioning of the sextupole magnets.

APPENDIX

Tables of lattice errors (Tab. 1) and injected-beam rms systematic and jitter errors, and rms sizes (Tab. 2) as assumed in the commissioning simulation.

Table 1: Initial machine (rms) errors assumed in the commissioning simulations

Magnet fractional strength	0.1 %
Magnet roll	0.4 mrad
Magnet offset	30 μm
Girder offset	100 μm
BPM offset	500 μm
BPM noise	3 μm
BPM calibration	5 %
BPM roll	0.4 mrad
CM calibration	5 %
CM roll	0.4 mrad

Table 2: Injected-beam rms systematic and jitter errors, and rms sizes as assumed in the commissioning simulation.

	Systematic	Jitter		Beam size
Δx	250 μm	10 μm	σ_x	64 μm
$\Delta x'$	150 μrad	6 μrad	$\sigma_{x'}$	31 μrad
Δy	500 μm	1 μm	σ_y	7.8 μm
$\Delta y'$	150 μrad	0.5 μrad	$\sigma_{y'}$	2.6 μrad
$\Delta E/E$	5×10^{-3}	1×10^{-4}	σ_δ	1×10^{-3}

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