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COMMISSIONING SIMULATIONS FOR THE APS UPGRADE LATTICE*

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Abstract

A hybrid seven-bend-achromat lattice that features very strong focusing elements and a relatively small vacuum chamber has been proposed for the APS upgrade. Achieving design lattice parameters during commissioning will need to be accomplished quickly in order to minimize dark time for APS users. The paper will describe start-to-end simulation of the machine commissioning beginning from first-turn trajectory correction, progressing to orbit and lattice correction, and culminating in evaluation of the nonlinear performance of the corrected lattice.

INTRODUCTION

Several existing synchrotron light source facilities are considering replacing operating storage rings in order to increase the brightness of delivered photon beams. These light sources have large user communities who insist that facility "dark time" is minimized. APS, for example, is targeting 12 months for removal, installation, and commissioning. Of this 12 month period, only three months are set aside for commissioning of the new multi-bend achromat ring.

The proposed lattice [1] has natural emittance that is 40 times smaller than the present APS ring, which is achieved by much stronger focusing than in the present ring. For example, maximum quadrupole strengths increase nearly five-fold in the new lattice. Stronger focusing inevitably leads to larger natural chromaticity and thus a nearly seven-fold increase in sextupole strength is needed, resulting in rather small dynamic aperture and short lifetime even for the ideal lattice. Misalignments of the strong quadrupoles generate large orbit errors, which in the presence of very strong sextupoles leads to huge lattice and coupling errors. Add to this smaller vacuum chamber gaps that are required to achieve high gradients in the magnets, and the required rapid commissioning seems doubtful. In this paper, we address this issue using a highly realistic simulation of the commissioning.

SIMULATION PROCEDURE

While the effect of individual lattice imperfections on accelerator performance can be estimated or calculated analytically, including all errors together is beyond the realm of analytical estimations. To understand how various errors combine together and impact commissioning, a start-to-end simulation of machine commissioning was performed taking into account as many errors as possible. All simulations were done using `elegant` [2]. Table 1 gives the list of errors included in the simulations (official specification for girder alignment is 100 μm which was found to be equally workable in earlier runs).

Table 1: Rms Values for Various Errors Used for Start-to-end Commissioning Simulation

Girder misalignment	50 μm
Elements within girder	30 μm
Dipole fractional strength error	$1 \cdot 10^{-3}$
Quadrupole fractional strength error	$1 \cdot 10^{-3}$
Dipole tilt	0.4 mrad
Quadrupole tilt	0.4 mrad
Sextupole tilt	0.4 mrad
Initial BPM offset error	500 μm
BPM gain error	5%
BPM orbit measurement noise	1 μm
Corrector calibration error	5%

The simulation procedure closely follows the steps that will be performed during commissioning. We assume that before setting up the lattice, the betatron tunes are adjusted away from integer and coupling resonances (the design fractional tunes are 0.12 in both planes, they are adjusted to 0.18 and 0.24). The procedure consists of the following major steps: (1) Generate errors for all elements according to Table 1 using Gaussian distributions with 2σ cut off. (2) Correct trajectory until closed orbit is found. If needed, optimize tunes and low-order beta function harmonics. (3) Correct closed orbit down to acceptable level. (4) Correct optics and coupling.

The entire simulation procedure was automated, allowing commissioning to be simulated for 200 different error sets. The procedure was able to correct orbit and optics in 98% of all cases. The correction results were statistically analyzed for residual orbit and lattice perturbations, correctors strengths, emittances, etc. For each error set, various performance measures (e.g., rms horizontal beta error) are computed. These are then histogrammed over all error sets. Before presenting such results, we first discuss the detailed commissioning procedure.

Trajectory Correction

Simple estimations show that in order to expect a reasonable probability of the closed orbit not exceeding the vacuum chamber dimensions, magnet alignment tolerances must be three times tighter than in Table 1. Since this is considered prohibitively expensive, trajectory correction will need to be performed first in order to find a closed orbit.

Trajectory correction consists of two steps. First, `elegant`'s one-to-best method is applied, wherein steering is performed by pairing one corrector with the BPM that has the best response to this corrector. Only four correctors

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per sector per plane are used in this step. This method is used to make the beam complete the first full turn. We have found that this method of trajectory correction tends to drive several correctors quickly to the limit. To reduce corrector strengths, correction is first done with the corrector limits reduced to one quarter of the actual strength. If first-turn transmission cannot be achieved with these limits, then the correction is repeated with increased limits.

After first-turn transmission is achieved, global trajectory correction is performed using the ideal response matrix. At this step, six correctors per sector are used, with the goal of finding a closed orbit. The correction is first performed with a response matrix inverted using a small number of singular values (SV), then the SV number is slowly increased. If the closed orbit exists at any step, it is recorded. When the singular value number scan is complete, the case with the best closed orbit is chosen. Also, if any corrector reaches a limit at any step, it is reduced by a certain fraction.

We found that this procedure finds a closed orbit in 100% of cases. However, having a closed orbit does not guarantee that the lifetime is long enough to allow for orbit correction. In real life, this would correspond to a situation when the beam completes only a few hundred turns. Assuming that no reasonable measurements are possible at this point, a simplex optimization is performed that varies the betatron tunes and the lowest beta function correction harmonics using predefined quadrupole knobs. In real life, this optimization will try to maximize the number of turns that the beam is able to survive; in our simulation procedure, we maximize the transmission of a bunch consisting of five particles with 0, ±0.5%, and ±1% momentum errors.

Figure 1 shows the final results of this step. Lifetime is calculated based on Local Momentum Aperture for a 1-mA bunch. With 90% certainty, the lifetime is longer than one minute, while the median lifetime is 5 minutes. The lifetime is rather short due to large lattice errors (see Fig. 1), but should be adequate to start orbit correction.

Orbit Correction

As was previously mentioned, one of the goals of the procedure is to keep corrector strengths low. To accomplish that, the orbit correction consists of two loops. The correction starts with a small number of SVs and correctors. The inner loop increases the number of SVs. At every iteration of this loop, the orbit correction is calculated. If a corrector reaches a certain fraction of its limit, this corrector is reduced by a certain fraction, and orbit correction is repeated until all correctors are safely away from their limits. After that, the tunes are adjusted to keep them away from integer resonances. The inner loop is interrupted when the orbit errors are reduced below the target for this iteration or when the SV number reaches the limit.

The outer loop increases the number of correctors per sector that are used for correction. The correction starts with two correctors per sector per plane, and increases this number to ten correctors in five steps. After the first two iterations of the outer loop, it is assumed that the BPM offset

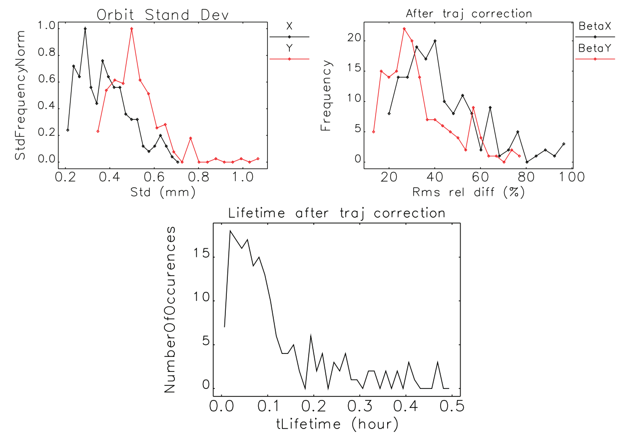

Figure 1: Top left: Distribution of standard deviation of orbit after trajectory correction calculated over 200 random error seeds. Top right: Distribution of rms relative beta function errors after trajectory correction. Bottom: Lifetime after trajectory correction for 1-mA bunch.

measurement is performed. The measurement is assumed to be simple enough, and therefore it is not simulated in this procedure. Instead, BPM offsets are simply reduced by a factor of ten from 500 μm to 50 μm. A future refinement will verify that the beam lifetime is sufficient to perform the BPM offset measurements.

If at any time during iterations the orbit correction starts diverging, a coarse optics correction is performed that is based on fast kick and analysis of the turn-by-turn motion. This measurement is considered fast enough and is possible to do even when the beam lifetime is only a few minutes. A 0.1 mrad kick in horizontal plane is used. The coupling at this stage is so strong that the motion immediately couples into the vertical plane. The measurement uses the simple fact that the maximum oscillation amplitude on a BPM is proportional to the square root of the beta function at that BPM. This approach is complicated by BPM gain errors, and normally the turn-by-turn based optics correction also requires the measurement of the oscillation phases on every BPM to obtain gain-independent measurements. In our case, we expect BPM gain errors to be less than 10% while the optics errors could be hundreds of percents. Therefore, we can simply ignore the BPM gain errors. Since we are only interested in the modulation of the maximum oscillation amplitude, only a few tens of turns are required, and therefore the decoherence of the oscillations should not be a problem. Another unknown factor in the fast kick-based measurement is the average beta function on all BPMs. Since the betatron tunes of the lattice are close to the ideal tunes, it is assumed that the average inverse beta functions are equal to those of the ideal lattice. For simplicity, only one BPM and quadrupole per sector were used, and that was enough to reduce beta function beating.

The goal of the orbit correction was to bring the maximum orbit errors below 0.5 mm. This goal was achieved in

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98% of cases. Final rms orbit errors are shown in Figure 2, top left; the correction achieves about 100 μm rms orbit error. Beta function errors are shown in Figure 2, top right. They are smaller than those shown in Figure 1 but still large. The last plot in Figure 2 shows the lifetime: with 90% certainty the lifetime is above 8 minutes, and median lifetime is 15 minutes.

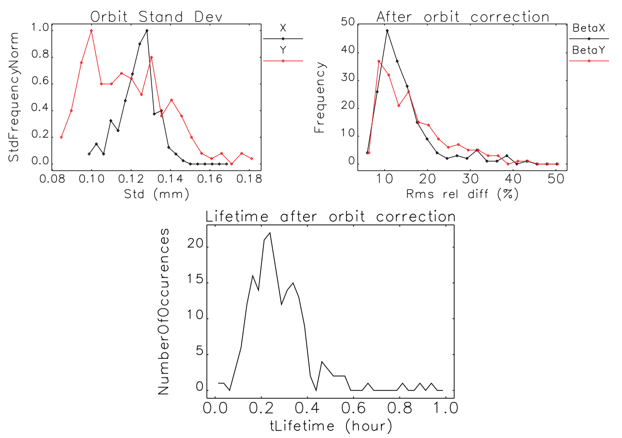

Figure 2: Top left: Distribution of standard deviation of orbit after correction calculated over 200 random error seeds. Top right: Distribution of rms relative beta function errors after orbit correction. Bottom: Lifetime after orbit correction for 1-mA bunch.

Lattice Correction

After the orbit correction is complete, the lifetime is considered to be long enough to start optics correction. A standard correction procedure that was developed for the present APS is used. First, a response matrix measurement is simulated. BPM noise, BPM gain, and corrector calibration errors are added to the simulated response matrix. For measurement and calculation speed, only eight correctors per plane are used. Based on the present experience, the measurement should not exceed five minutes. After the response matrix is generated, the response matrix fit is run to derive focusing and coupling errors.

Beta function and horizontal dispersion correction is calculated using ideal beta function response matrix (rather then using direct inverse quadrupole errors from the response matrix fit), as this allows for simple correction strength and fraction control using different numbers of singular values. Coupling is corrected by minimizing the cross-plane orbit response matrix together with vertical dispersion. All quadrupoles are used for beta function correction, and four skew quadrupoles per sector are used for coupling minimization. Lattice and coupling correction is performed in several iterations while increasing number of SVs. After every iteration, orbit correction is also performed.

After the lattice and coupling correction is complete, the coupling is adjusted to achieve a target emittance ratio of $\kappa = 10\%$ by exciting the nearest difference resonance using skew quadrupoles. At this point, if necessary, $\kappa = 100\%$ can be achieved by just moving the tunes to the coupling resonance.

Results of the lattice correction are shown in Figure 3. The beta functions are corrected below 1% relative rms difference. Dispersion is also corrected very well, with horizontal dispersion showing better correction due to larger number of quadrupoles compared to skew quadrupoles. Figure 4 shows emittances before and after optics correction. One can see that the design horizontal emittance of 66 pm is achievable after lattice correction.

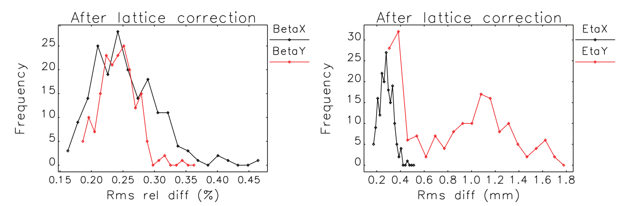

Figure 3: Left: Distribution of rms relative beta function errors after lattice correction. Right: Rms errors of the dispersion after lattice correction.

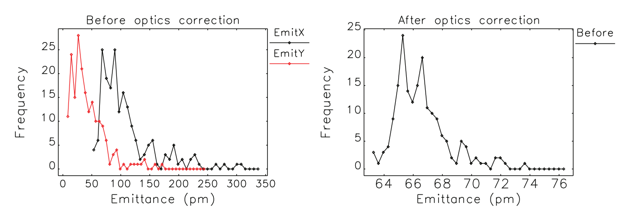

Figure 4: Left: Distribution of horizontal and vertical emittances after orbit correction (before lattice correction). Right: Horizontal emittance after lattice correction.

CONCLUSIONS

An automated commissioning procedure was written, and commissioning was simulated for many random error seeds. The automated commissioning was successful in 98% of the cases. The lattice after correction was nearly perfect. The commissioned lattices can be used for evaluation of nonlinear properties of the lattice, as presented in [1]. The results of these simulations were also used to determine maximum required strengths of correctors and skew quadrupoles.

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[2] M. Borland. ANL/APS LS-287, Advanced Photon Source (2000).