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EXPERIMENTAL TESTS OF THE AUTOMATED APS-U COMMISSIONING ALGORITHM AT APS*

V. Sajaev†, Argonne National Laboratory, Lemont, IL, USA

Abstract

APS Upgrade (APS-U) will feature hybrid seven-bend achromat lattice [1] with very strong focusing elements, reverse bends [2,3] and relatively small vacuum chamber aperture. Achieving design lattice parameters during commissioning will need to be accomplished quickly in order to minimize dark time for APS users. This paper describes the automated start-to-end lattice commissioning algorithm starting with first-turn trajectory correction and ending with lattice correction. It will then present the results of experimental tests of the commissioning at the existing APS.

INTRODUCTION

The Advanced Photon Source [4] is a 7-GeV, 100-mA, 40-sector third-generation storage ring light source with a 1104-m circumference, providing beams to dozens of insertion device (ID) and bending magnet (BM) beamlines simultaneously. After more than 20 years of operation, a major upgrade of the lattice is in progress. APS has a large user community who insist that facility "dark time" during the upgrade is minimized. APS is targeting 12 months for removal of old magnets, installation of new ones, and commissioning. Of this period, only three months are set aside for commissioning of the new multi-bend achromat ring.

The 41-pm emittance in the new lattice [5] is achieved in part by using much stronger focusing than in the present APS ring. Stronger focusing inevitably leads to larger natural chromaticity and stronger sextupoles, 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. Another difficulty originates in the smaller vacuum chamber apertures that are required to achieve high gradients. In addition, small-gap insertion device chambers will be installed prior to commissioning, in order to facilitate moving directly into operation once commissioning is completed. These many factors suggest that the commissioning will be very challenging. Automation is seen as a key to fast and successful commissioning.

AUTOMATED COMMISSIONING

The automated commissioning procedure was created and used to simulate commissioning [6,7] of 200 machines with errors. The simulations showed that the automated commissioning procedure succeeds in about 95% of cases, with the remaining 5% requiring some human intervention. Before starting the commissioning, the betatron tunes (design values are ν_x=95.10 and ν_y=36.10) are moved away from integer and coupling resonances to ν_x=95.17 and ν_y=36.23. In addition, all sextupoles are set to zero, because the simulations showed that the commissioning would be much harder with the sextupoles turned on. The procedure consists of the following major steps:

- Trajectory correction of the injected beam based on beam trajectory in the first sector.
- Trajectory threading to achieve first-turn transmission. Due to weak correctors in APS-U, multi-corrector threading – when several correctors are used to correct trajectory at one location – is used. When the beam transmission reaches half the ring, the injected energy is measured as average horizontal position on all BPMs and corrected. The incoming beam trajectory correction is performed again and threading is restarted from the beginning.
- The trajectory at the end of the first turn is made equal to the trajectory of the injected beam in an attempt to create closed-orbit conditions, giving ~5 turns.
- Global trajectory correction utilizing the ideal trajectory response matrix, giving ~20 turns.
- Closed orbit correction utilizing the ideal orbit response matrix. The beam is not captured yet at this stage, so there is no real closed orbit. The orbit is obtained by averaging the first 20 turns of the multi-turn trajectory on every BPM. Adjustment of rf parameters is performed every few orbit correction iterations by analyzing turn-by-turn beam energy error, which is calculated as the average horizontal position on all BPMs over one turn. In addition, betatron tunes are derived from the measured trajectory response and adjusted to keep the tunes away from integer resonances.
- Slow sextupole ramp is performed in parallel with the orbit correction. According to simulations, after sextupoles are ramped to their design values, the beam should be captured with reasonable lifetime.
- BPM offset measurement is performed, and orbit is corrected.
- Lattice and coupling are corrected using the response matrix fit [8].

The procedure uses multi-particle tracking in `elegant` [9] to obtain the simulated beam trajectories. An up-to-date, detailed description of the commissioning procedure and results of the commissioning simulations for APS-U can be found in [7].

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† sajaev@anl.gov

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EXPERIMENTAL TESTS

The commissioning procedure described above was applied to APS to test the entire approach. Since the tests are not fully completed, we describe the present status. The initial conditions of the APS are the following: all sextupoles are set to 0, but there are no changes in quadrupoles or rf. Since the lattice distortion at APS is dominated by the orbit inside sextupoles, setting them to zero should introduce enough lattice uncertainty. BPMs for these tests are operated in one-plane mode (horizontal or vertical), BPM offsets in this mode are significantly different from the operational mode and were never measured.

The first step of the test was writing the trajectory measurement program that reports beam trajectory in a fashion similar to `elegant`. APS presently has two types of BPMs: BSP-100 [10] and Bergoz [11]. There are seven BSP-100 BPMs and four Bergoz BPMs per sector with minor exceptions. Only BSP-100 BPMs are capable of providing turn-by-turn information; in addition, they can only provide position in one plane at a time. Every BPM reports turn-by-turn position as an EPICS waveform process variable consisting of 4096 elements. The trajectory measurement program configures the BPMs for horizontal plane acquisition, injects the beam, collects waveforms from all BPMs, and re-arranges them in trajectory form. Then the process is repeated for the vertical plane. The synchronization in handled by groups of four BPMs. Occasionally, the synchronization signal can shift by one turn for a particular BPM unit. Before re-arranging the waveforms into the trajectory form, the program analyzes the BPM waveforms and performs a waveform shift to adjust for timing variation if necessary. In total, the trajectory measurement takes about 15 seconds.

First Turn Threading

Simulations of the APS-U commissioning showed that any "one-to-one" threading method where a single corrector is used to correct trajectory on one BPM fails due to limited corrector strengths. Since real APS-U commissioning will be performed with the vast majority of ID chambers already installed, and since the ID chambers represent the limiting apertures in the ring, the beam will most likely always be lost on an ID chamber (the same holds true for the APS). Hence, the procedure for threading the beam through the first turn attempts to correct the beam trajectory at every ID chamber. A virtual BPM in the middle of the ID vacuum chamber is created that utilizes three real BPMs on each side of the ID chamber to calculate position and angle of the trajectory in the middle of the ID chamber. This calculation assumes ideal transfer matrices between BPMs, and only BPMs with sufficient beam present (i.e., sufficient sum signal) are used in the calculation. To overcome strength limits of individual correctors, all correctors in the sector immediately upstream of the ID chamber are used simultaneously to reduce both the position and angle of the beam at the location of the virtual BPM. The corrector strengths are calculated using singular value decomposition of the ideal trajectory response matrix.

The threading algorithm relies on the BPM sum signal to detect where the beam is lost, therefore it is important to have well calibrated BPM sum signals. APS BPMs were never required to have sum signal calibration and show large BPM-to-BPM variations. As was mentioned earlier, the beam is expected to be lost not inside a sector but in the small-gap ID vacuum chambers, so the transmission is determined on a sector-by-sector basis by averaging the sum signal of all BPMs in each sector. Figure 1 shows the results of this threading procedure applied to APS; the beam transmission shown is the one obtained by averaging over one sector.

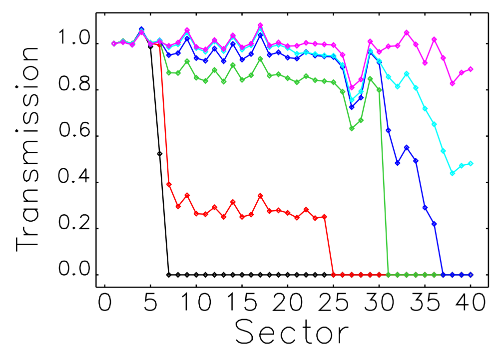

Figure 1: First-turn threading results. Several threading iterations are shown.

After first-turn transmission is achieved, one can imagine that if the beam coordinates at the end of the first turn are made exactly the same as at the entrance into the ring, this would constitute a closed orbit. Equalizing the coordinates at the end of sector 40 to the coordinates of the injected beam allow increasing beam transmission to several turns. The results are shown in Fig. 2. One can see that some fraction of the beam now reaches 8 turns.

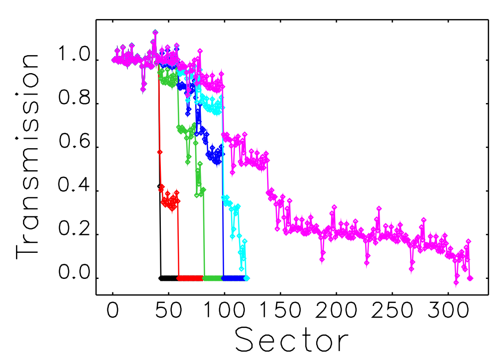

Figure 2: Beam transmission improvement by equalizing the coordinates at the end of sector 40 to the coordinates of the injected beam. Several iterations are shown, one turn equals 40 sectors.

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Tune Determination

In simulations, the tune was determined using numerical analysis of fundamental frequencies (NAFF [12]) applied to the sector-by-sector trajectory response. This method provides reasonable tune determination accuracy when the beam only survives several turns, but didn't work well in APS due to two factors: first, there are fewer turn-by-turn capable BPMs in APS than in ASP-U; second, there are four special sectors in APS that differ significantly from the other 36 sectors, which introduces large sector-by-sector phase advance variation. Instead, measured trajectory correlation with ideal trajectories calculated for different tunes was used and provided adequate accuracy of about 0.05 rms.

RF Setup

RF setup is performed by analyzing the beam energy as a function of turn. The beam energy is obtained as the average of the horizontal position on all BPMs over one turn divided by the average dispersion. In simulations, the injected beam is tracked only for 20 turns to save the execution time, and rf is adjusted to minimize the energy variation during that period. It turned out that this approach was not suitable for RF setup in the experiment. It was noted during rf phase setup that a phase value that resulted in worse beam energy behavior over the first 20 turns actually resulted in better beam transmission. After noticing that, a manual rf frequency scan was performed and immediately increased beam transmission from few dozens of turns to hundreds of turns, see Fig. 3.

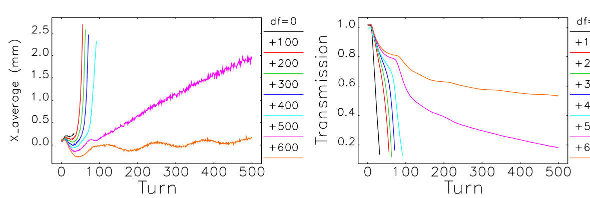

Figure 3: Average horizontal beam position (left) and beam transmission (right) as a function of turns for different rf frequency.

After beam was circulated for several hundreds of turns, synchrotron oscillations of the injected beam were analyzed to determine the booster extraction energy and phase error. At this time an interesting feature was observed: the beam with different injection energy settled on different orbits, as shown in Fig. 4 (left). Obviously, this should not happen as the closed orbit is defined by the storage ring settings, and they were not changed. After looking at the corresponding beam transmission signal, see Fig. 4 (right), it became clear that different apparent closed orbits resulted from the BPM position dependence on beam intensity.

Using an analytic expression to fit the measured trajectory (as is done in simulations) is preferred because it provides rf adjustment without additional trajectory measurements. However, the tests showed that minimization of energy oscillations does not always provide the best beam transmission.

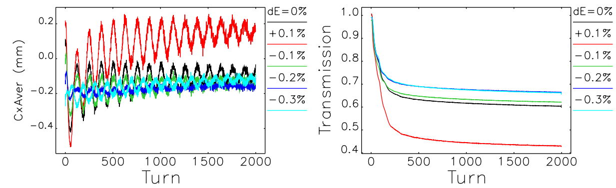

Figure 4: Left: Average horizontal beam position for different booster extraction energy. Right: Beam transmission for different booster extraction energy.

In addition, the BPM intensity dependence complicates the long-term trajectory analysis. Based on this, the rf setup was changed to a simple scan: every few trajectory correction iterations the rf frequency is scanned, and the frequency is set based on the best beam transmission.

Sextupole Ramp

With the tune adjustment and rf adjustment procedures working, the sextupole ramp could be started. The ramp was performed in ten steps, with the rf and betatron tune adjustment being run immediately after every sextupole increase. Four orbit correction iterations are run between the ramp steps. The orbit is maintained approximately at the level of the rms BPM offset errors, which is around 0.7 mm. As was mentioned earlier, the orbit used for calculation here is not the actual closed orbit, since there is not one yet, but the multi-turn average of the beam trajectory.

Unlike APS-U, at APS the injected beam goes off axis through several sextupoles before it is placed on axis. Therefore the kicker configuration for on-axis injection that was determined before the trajectory correction needs to be adjusted after every sextupole ramp step. The first stored beam with the lifetime of several seconds was observed with sextupoles ramped to 40% of their strength. With sextupoles ramped to 60% of their strength, the lifetime increased to 10 minutes. At this point, BPM offset errors can be measured, though this part was not tested yet.

CONCLUSION

An automated procedure was created for APS-U lattice commissioning. Simulations showed that this procedure can successfully store the beam and correct the lattice. Presently, this procedure is being tested experimentally at APS. All major steps of the procedure have been tested, and it was shown that the stored beam can be achieved as expected after the sextupole ramp. One important step still remains to be tested – determination and exclusion of bad BPMs.

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