AUTOMATED TUNING OF THE ADVANCED PHOTON SOURCE BOOSTER SYNCHROTRON

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Abstract

The acceleration cycle of the Advanced Photon Source (APS) booster synchrotron is completed within 223 ms and is repeated at 2 Hz. Unless properly corrected, transverse and longitudinal injection errors can lead to inefficient booster performance. In order to simplify daily operation, automated tuning methods have been developed. Through the use of beam position monitor (BPM) readings, transfer line corrector magnets, magnet ramp timing, and empirically determined response functions, the injection process is optimized by correcting the first turn trajectory to the measured closed orbit. These tuning algorithms and their implementation are described here along with an evaluation of their performance.

1 INTRODUCTION

The Advanced Photon Source (APS), located at Argonne National Laboratory, is a third-generation synchrotron light source facility which consists of a main storage ring with attached beamlines and a powerful, high efficiency injector system. The injector system is comprised of a 400-MeV, 60-Hz positron linac, a positron accumulator ring (PAR), and a 7-GeV, 2- Hz booster synchrotron (booster).

The booster synchrotron accelerates a 400-MeV bunch of positrons to 7 GeV in 223 ms. This bunch is then extracted from the booster and is directed toward the storage ring with the entire process being repeated at a 2-Hz rate. The booster lattice is quite simple and is comprised of forty FODO cells laid out over a circumference of 368 m.

Reliable, efficient operation is of key importance at a synchrotron light facility such as the APS. Diagnosing operational problems and treating them effectively must occur to insure that the users obtain maximum beam time. Automation of processes such as injection tune-up and maintenance insures consistent beam quality and allows operators to quickly set up beam and deliver it to the storage ring for use by the experimenters. This paper will focus on the operation and automated injection tuning methods of the booster.

2 BOOSTER SYNCHROTRON INJECTION TRAJECTORY CONTROL

2.1 General

In an ideal machine under ideal conditions, the closed orbit would be immediately revealed on the first turn; however, due to errors in the injection trajectory, energy, and phase, this is not the case. In the case of trajectory errors, if the measured closed orbits and the first turn trajectories are known, then the correction of first turn trajectory to the closed orbit can be automated. If the beam position trajectory history is known at a region of high dispersion, then a similar process can be applied to the longitudinal plane.

2.2 Transverse and Longitudinal Planes

Through the use of pulsed septum and kicker magnets, the beam arrives in the booster from the transfer line during a single turn on axis injection process. Transverse injection errors result when the voltage-controlled PAR extraction and booster injection pulsed magnets drift slightly over time. This causes the injection trajectory to wander. For reasons of simplicity and accuracy, the PAR-to-booster (PTB) transfer line corrector magnets are used to touch up the incoming injection trajectory with an automated tune-up procedure, rather than attempting to accurately control these pulsed magnets.

Eighty beam position monitors exist around the booster synchrotron, each capable of single-pass measurements in both the vertical and horizontal planes, and each attached to a 64k beam history module. After waiting 1 ms and then averaging 1000 or more turns, the measured closed orbits are revealed. The timing of the BPM system is then adjusted so that the BPMs measure the first turn trajectory. This is then compared to the closed orbit, yielding the error signal for the feedback algorithm.

Due to zero dispersion, the injection trajectory feedback in the vertical plane is inherently much less complex than that of the horizontal and will be discussed first. Using timing changes and the BPM system, two vectors are constructed—one for the closed orbit and one for the first turn. Both assume the form of

$$\mathbf{u}_m = (u_1 , u_2 , ..., u_m). \qquad (1)$$

Four horizontal and vertical corrector magnets in the PTB line can be adjusted relative to the behavior of the existing trajectory such that the incoming trajectory will be corrected to the measured closed orbit. To inject automatically onto the closed orbit, two correctors are chosen such that they are separated by approximately 90 degrees phase advance. For each corrector, a beam response is determined at every beam position monitor throughout the booster. These two data sets are then combined into one, giving the desired response matrix. The kick provided to the beam via a corrector k can be represented by θ_k, giving the following matrix equation

$$\Delta \mathbf{u}_m = \Re \, \Delta\theta_n , \qquad (2)$$

where $\Re$ is the response matrix found by the method given above and $\Delta\theta_n$ is the vector giving the size of variation of the correctors used. The objective is to reduce $\Delta\mathbf{u}_m$, the error trajectory used for the feedback loop, to zero, describing the situation in which the first turn trajectory matches the measured closed orbit. Singular value decomposition is used to invert the matrix $\Re$ [1]. After inversion,

$$\Delta\theta_n = \Re^{-1}\,\Delta\,\mathbf{u}_m\,, \tag{3}$$

which reveals the amount the correctors must be adjusted [2]. The calculated currents are then multiplied by a gain factor, and the corrector setpoints are updated by this amount. This process is repeated in a feedback loop until the rms of $\Delta\,\mathbf{u}_m$ is sufficiently small. A gain of 0.5 was empirically determined to maximize the system performance while avoiding instability.

Because longitudinal and horizontal beam motions both appear as positional variations at BPMs located in the non-zero dispersion regions, the longitudinal errors must be corrected before simple correction of the horizontal can begin. The longitudinal injection errors result from slight drifts of the booster dipole magnet ramp or the relative rf phase between the PAR and booster. Phase and energy errors appear 90 degrees out of phase. Upon injection, an energy error, as measured on a turn-to-turn basis at a high dispersion point, assumes a cosine-like form, while a phase error has a sine-like signature. Energy errors are corrected through the adjustment of the start ramp time of the magnet ramping system. Phase errors are corrected by changing the relative phase between the PAR and the booster.

In the longitudinal plane, only one reliable beam position monitor in a high dispersion region need be used. The beam position is recorded over a series of 256 turns and is stored in a beam history module. This number of turns was chosen such that a sufficient number of synchrotron oscillations could be viewed ($Q_s = 4\times10^{-2}$). It is through this data that the energy and phase errors are revealed.

The longitudinal corrections can be approached in a fashion similar to that used for the vertical plane. The required feedback parameters are again empirically determined. The start ramp time and relative phase are adjusted manually to eliminate errors such that only noise remained. Then, the start ramp time is adjusted in a series of five steps relative to the original setpoint, and the slope is determined. Also, the relative phase is adjusted in a series of five steps relative to the original setpoint, and the slope is again determined. Figure 1 exemplifies the results of manual longitudinal tuning in the following order: energy and phase errors eliminated, phase error only (36 degrees), and energy error only (1.25 MeV). Some signal processing is first applied in order to extract only the desired longitudinal motion from the accumulated beam position history. An example of the processed phase error is found overlaid in Figure 2.

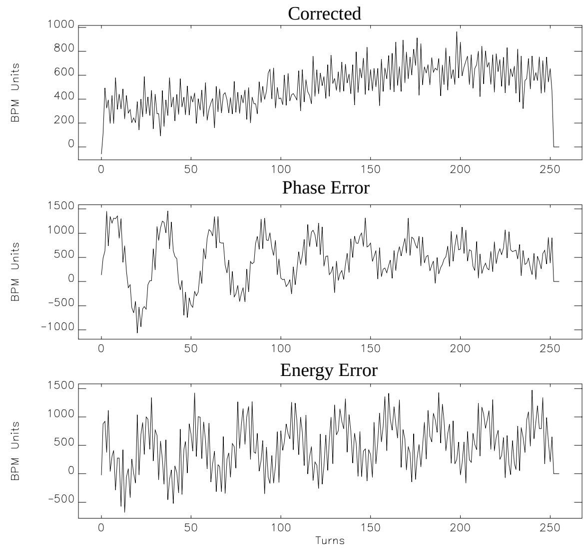

Figure 1: Manual tuning results.

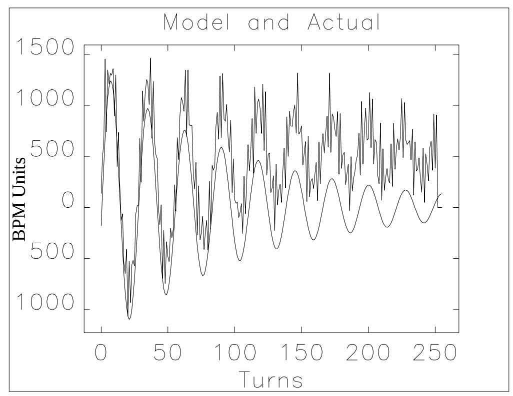

Figure 2: Model and actual phase error.

Regarding correction of the longitudinal errors, a simple method is employed. First, the cosine-like component of the motion is determined. A change in the start ramp time is then made to zero this energy error. The data is then processed on the remaining sine-like component, and a PAR rf system phase change is made to zero the phase error.

With the longitudinal corrected, it is now simple to perform the horizontal correction. This method is quite similar to that used in the vertical plane; however, the dispersion in the horizontal plane adds a small complexity. The revolution freuqency of the booster is adjusted to accommodate the storage ring. This forces the booster to run slightly off-energy and creates a constant off-energy orbit displacement, which must be accounted for and subtracted off the closed orbit measurement to reveal only the betatron closed orbit. This is measured by calculating the average offset of the closed orbit in the horizontal plane and by dividing it by the average dispersion in the booster, i.e.,

$$((dp)/p) = \langle x_E\rangle/\langle\eta\rangle\,. \tag{4}$$

The energy of the incoming trajectory position offset is then determined at each BPM. This result is subtracted from the measured horizontal betatron closed orbit motion, and the same correction algorithm used in the vertical case is employed.

3 RESULTS

3.1 Vertical Tune-up

Automation in the vertical plane has proved quite effective. Figure 3 shows the rms difference of the closed orbit and the first turn trajectory with the feedback loop off and then switched on. Here, the gain was set to 0.5 which was found to be adequate in that it kept the system from becoming unstable yet still rapidly corrected the vertical trajectory. The vertical feedback system can run indefinitely without becoming unstable.

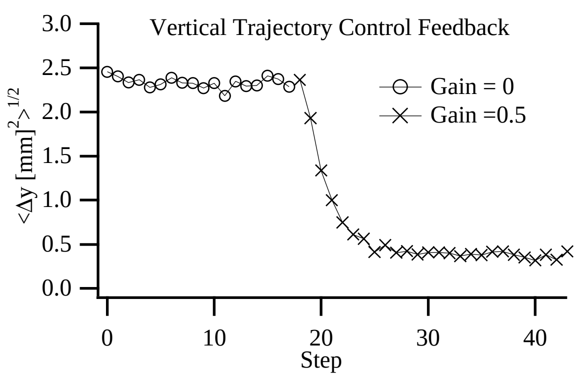

Figure 3: Vertical feedback response.

3.2 Longitudinal Tune-up

Using unity gain in the feedback loop designed for correcting the longitudinal errors proved successful. Both the phase and energy errors were corrected within one iteration. This feedback loop may also be run indefinitely; however, reduction in the gain proves to be slightly less noisy.

3.3 Horizontal Tune-up

The horizontal plane corrected successfully after the longitudinal errors were eliminated; however, if the longitudinal errors are not corrected, the horizontal feedback loop becomes unstable in less than twenty iterations. This is due to the energy and phase offsets of the first turn corrupting the horizontal signal. Figure 4 shows the rms difference of the closed orbit and the first turn trajectory with the feedback loop off, then switched on. As with the vertical, an assigned gain of 0.5 proved successful in that it prevented the system from becoming unstable; however, correction in the horizontal plane it is still not as successful as the results given in the vertical.

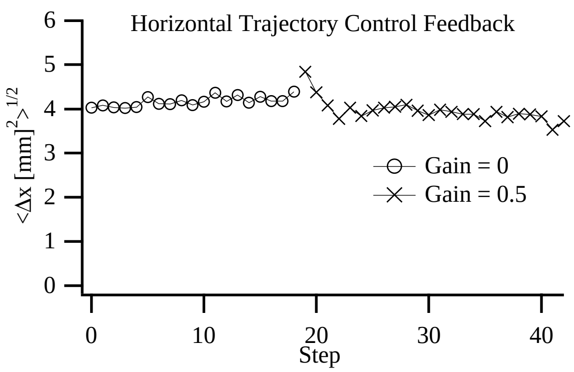

Figure 4: Horizontal feedback response.

4 CONCLUSION

Although this injection tune-up system is in actual fact automated, a graphical user interface, which is currently under development, will provide an easy-to-use system. The automation, however, has proved itself useful by correcting the first turn trajectory in the booster with minimal effort. The vertical was the simplest plane to correct in, thus allowing tests on the automation software to take place, and the automation of the horizontal and longitudinal corrections was built on this knowledge.

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6 BIBLIOGRAPHY

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