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ADVANCED PHOTON SOURCE BOOSTER SYNCHROTRON LOW-EMITTANCE LATTICE COMMISSIONING RESULTS *

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Abstract

Recent efforts at the APS have focused on reducing beam loss during storage ring (SR) injection to minimize radiation damage to the APS undulators. Reducing beam loss at injection is particularly important during top-up operation where injection occurs once every two minutes. One way to potentially improve injection efficiency is to simply reduce the emittance of the beam from the APS booster, thereby allowing the beam to be brought closer to the injection septum. Recently several low-emittance operating modes for the APS booster have been studied. The emittance is lowered from the standard value by increasing the horizontal tune in stages. The vertical tune is simultaneously decreased to minimize the required defocusing sextupole strength for chromaticity correction. Calculations indicate that up to 29% reduction in emittance is possible—a result that has been achieved in studies. A lattice with emittance 17% lower than the standard lattice has been thoroughly commissioned and has been used for routine APS top-up operation since July 2002. Results of beam measurements and comparison to calculations for various low-emittance lattices are reported in this paper.

MOTIVATION

The APS injector machines are presently the focus of studies with the ultimate goals of improving overall injector system availability and reliability for storage ring (SR) top-up operation. Successful studies to lower the emittance of the APS booster synchrotron were completed in December 2002. These studies are part of an ongoing effort to improve injection efficiency into the SR for top-up operation using the SR low-emittance lattice (2.9 nm effective emittance [1]). Improved injection efficiency results in reduced losses and hence less radiation dose to the SR insertion devices. Lower booster emittance combined with ongoing booster-to-storage ring (BTS) transport line matching optimization are helping to improve SR injection efficiency toward the ultimate goal of 100% (present efficiency is 70 to 80%).

BOOSTER STANDARD AND LOW-EMITTANCE LATTICES

The APS booster is designed to linearly ramp the beam (at up to 6 nC) from 0.325 to 7 GeV in 225 ms at a 2-Hz cycle rate for full energy injection into the APS storage ring for top-up. The booster consists of four quadrants with ten FODO cells per quadrant. In each quadrant, one FODO cell is used to suppress the dispersion in the straight sections by removing a single dipole (missing magnet configuration). The booster magnets are arranged in families connected to a single supply in series: 68 dipoles (BM), 40 focusing quadrupoles (QF), 40 defocusing quadrupoles (QD), 32 focusing sextupoles (SF), and 32 defocusing sextupoles (SD). The beam is injected on-axis and extracted while the power supply families are ramping. The rf system consists of four 352-MHz 5-cell cavities located in the dispersion-free straight sections.

The current in the BM, QF, and QD families is linearly ramped from zero starting at the same point in time. This allows the tunes to be set to those required for the nominal 132 nm-radian standard lattice $\nu_x = 11.75$, $\nu_y = 9.80$. For this horizontal tune, the missing magnet in each quadrant results in zero dispersion in the straight sections.

Alternative APS booster lattices were studied using the accelerator design and tracking code **elegant** [2]. This is straightforward with **elegant** because it allows us to optimize the emittance directly. The main constraint on our ability to optimize booster parameters using **elegant** is that each magnet family is wired in series. Therefore, there are exactly four parameters (two quadrupole and two sextupole strengths) that can be varied to set the tunes and correct the chromaticity. In this way, a series of lattices with different quadrupole and sextupole family strengths were obtained with progressively lower emittance. The dynamic aperture was also simulated using **elegant** for the various lattices. Calculations show that dynamic aperture should be more than adequate for lattices with up to 30% lower emittance.

Table 1 shows the three booster lattices commissioned and used for operations. The first lattice listed is the original design lattice (standard lattice) with zero-dispersion straight sections. Increasing the horizontal tune in steps of an integer results in a great reduction in the total emittance. The lowest (92 nm) emittance lattice has a much smaller vertical tune, which has two advantages. First, the required QF focusing strength required to achieve a horizontal tune of 13.75 is minimized. Second, the required sextupole strength to correct chromaticity is also minimized. The booster is presently run with the 92-nm-radian lattice for normal operations. The 92-nm-radian lattice is near the practical lower limit for the booster emittance since for this lattice the QF family is powered nearly at its maximum strength.

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Table 1. Commissioned Lattice Tunes and Emittances

Horizontal Tune ν_x	Vertical Tune ν_y	Emittance (π nm-radians)
11.75	9.8	132
12.75	9.8	109
13.75	5.8	92

BOOSTER LOW-EMITTANCE LATTICE COMMISSIONING

The **elegant** calculations of new booster lattices described in the previous section indicate that there should be no problems in pushing the booster lattice to these lower emittances. Booster lattice commissioning was accomplished by starting with the booster operating in its well-characterized 132-nm-radian standard lattice. Tune measurements (both integer and fractional tunes) were used to determine quadrupole and sextupole family magnet slope parameters. We also made use of new orbit correction software and upgraded beam position monitors (BPMs) [3]. Iterating between orbit correction, tune measurement/correction, and chromaticity correction was necessary to make fine adjustments to the lattices.

Lattice commissioning followed a straightforward process starting with the 132-nm-radian standard lattice. First, the intermediate emittance 109-nm-radian lattice was commissioned by simply increasing the horizontal tune by one full integer while keeping the vertical tune constant. The chromaticity was corrected by simply using the sextupole strength values computed by **elegant**. The orbit was also corrected for the 109-nm-radian lattice and the tunes and chromaticity slightly adjusted as a final step. Next, several intermediate lattices were commissioned—a process that finally resulted in obtaining the 92-nm-radian lattice. Starting with the 109-nm-radian lattice, the horizontal tune was increased 1 full integer while the vertical tune was kept constant. Next, the vertical tune was successively decreased in single integer steps, until the 92-nm-radian lattice tunes were achieved. Finally, the orbit was corrected and the tunes and chromaticity were slightly adjusted for the 92-nm-radian lattice.

In order for the tunes to stay constant up the ramp, the BM, QF, and QD ramps must start at the same zero current point on the time axis [4]. If this is not the case, the tunes will slew with time, possibly resulting in beam loss from the tune crossing a lattice resonance. For a FODO lattice, the tunes are for the most part dependent only on the QF (horizontal tune) and QD (vertical tune) strengths. Therefore, increasing or decreasing the QF (QD) slope changes primarily the horizontal (vertical) tune. In these studies, a small change in the QF or QD slope was made and the corresponding tune change was observed. In this way, an experimental determination was made of the amount of QF or QD slope (dI/dt) change required to increase or decrease the tune by one integer. Typically after the increase or decrease of a given tune was made, small adjustments of the other tune using the complementary quadrupole family were required to precisely set the fractional tunes.

Fractional and Integer Tune Measurements

Measurement of the fractional tune was accomplished using a Hewlett Packard 89440A Vector Signal Analyzer (VSA) in spectrogram mode. Figure 1 shows a typical spectrogram where the horizontal axis is frequency, the vertical axis is time, and color is intensity. In the figure, time increases downward or in other words, the top of the figure represents the injection point. The difference signal obtained from striplines installed in the booster gives the tune signal. The tunes are excited by using the booster extraction kicker to "ping" the beam at a 40-Hz rate. The individual ping excitation of each tune is apparent in Figure 1 as tune lines every 25 ms (1/40 Hz).

The VSA spectrogram is used not only as a tool to set the fractional tune but also to tell on which side of the half integer resonance the tunes are located. One can do this by increasing the QF and QD ramp slope slightly and observing which way the tunes move. In Figure 1, the higher frequency pair of tunes should move higher in frequency if the tunes are above the half integer. The reverse is true of the lower frequency pair of tunes.

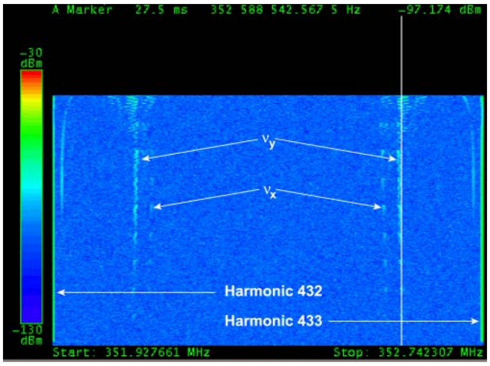

Figure 1: VSA spectrogram of booster tunes from injection to extraction for the 132-nm-radian lattice. The frequency span in the figure equals one revolution frequency (814 kHz) between revolution harmonics 432 and 433. The fractional tunes are set to their nominal ν_x = 0.75 and ν_y = 0.80 and show up as the upper sideband signal pair of harmonic 432 and the lower sideband signal pair of harmonic 433. A synchrotron sideband is also seen next to each revolution harmonic from injection to approximately halfway up the ramp.

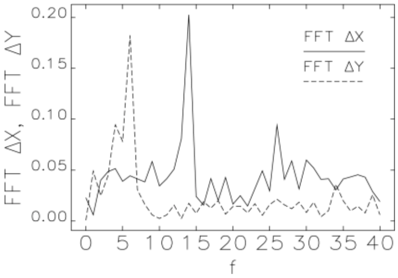

Figure 2: FFT of horizontal and vertical difference orbit showing the integer tunes of 14 (horizontal) and 6 (vertical) for the 92-nm-radian lattice.

The integer part of the tunes can be determined by exciting a difference orbit in each plane using a horizontal and vertical corrector and recording the betatron oscillation for a single turn using the BPMs. The single turn data is processed by normalizing the maximum BPM number index to 1 and taking the FFT. The result is shown in Figure 2. One can clearly see the integer tunes show up as peaks at tunes of 6 and 14, respectively (corresponding to $\nu_x = 13.75$ and $\nu_y = 5.80$ for the 92-nm-radian lattice). The sign of the difference orbit at the position of the exciting corrector can also be used to determine on which side of the half integer the fractional tunes exist.

Orbit Correction

A tool was developed to perform orbit correction in each plane at various points along the ramp. The method uses the standard SVD algorithm applied at selected points anywhere between injection and extraction. The software application allows the user to select BPM and corrector configurations and uses the computed **elegant** inverse response matrix for a given lattice to determine the new vector of corrector current changes from the BPM vector. The application also allows the user to select the number of ramp points to correct the orbit, feedback gain, and BPM averaging, and provides plotting diagnostics to analyze the orbit correction process. This tool was used after setting the fractional and integer tunes for a new lattice.

Chromaticity and Dispersion Measurements

Chromaticity and dispersion measurements were performed on each lattice listed in Table 1 for verification purposes. A convenient software tool was developed to measure both parameters simultaneously while varying the rf frequency. Each measurement can be performed at any given point between injection and extraction. The chromaticity measurement was performed using the VSA to measure the tunes as a function of rf frequency. The dispersion measurement was performed by varying the rf frequency and collecting both horizontal and vertical BPM readings.

The results are shown in Figures 3 and 4 for the 92-nm-radian lattice. Figure 3 shows good agreement between the dispersion measurement compared with the **elegant** calculation for the 92-nm-radian lattice. The chromaticity is shown as a function of time up the ramp. The sextupole settings used were slightly adjusted to zero the chromaticity. Figure 4 shows the chromaticity is slightly negative at parts of the ramp. This does not present a problem from head-tail instability for the 92-nm-radian lattice at up to 4 nC of charge per pulse.

CONCLUSION

Successful commissioning of booster low-emittance lattices is part of the ultimate goal of improving APS injector reliability and availability for SR top-up injection. The APS booster 92-nm-radian lattice has been used since January 2003 for routine SR top-up operation. This lattice used in combination with ongoing matching studies of the BTS transport line have as the ultimate goal improving SR top-up injection efficiency to 100%.

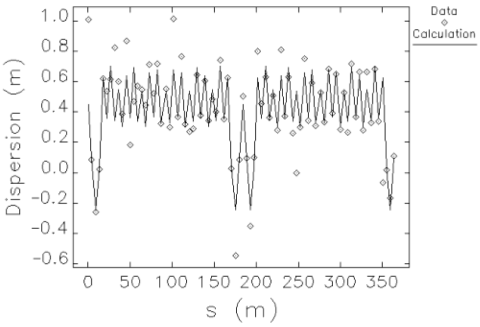

Figure 3: Measured horizontal dispersion at extraction compared to **elegant** calculation for the 92-nm-radian lattice. Agreement is generally good with differences attributable to BPM gain differences.

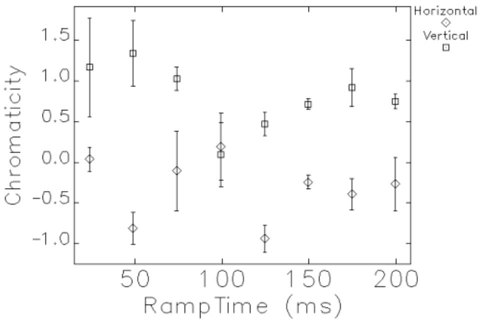

Figure 4: Measured chromaticity for the 92-nm-radian lattice where injection is at 0 ms and extraction is at 225 ms. Vertical data are seen to be biased slightly positive and horizontal slightly negative. The negative horizontal chromaticity at 125 ms may be the reason some loss is is observed at roughly this point above 4 nC/pulse.

ACKNOWLEDGEMENTS

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