OPTIMIZATION OF THE LOW-EMITTANCE LATTICE OF THE APS BOOSTER SYNCHROTRON*

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Abstract

The APS booster is a 7-GeV electron synchrotron. Three lattices have been originally designed with a nominal beam emittance of 132, 109, and 92 nm, respectively. In the past we have mostly operated the booster with the 132-nm lattice because of its better stability. The lower-emittance lattices are not utilized. In early 2010 we upgraded the booster ramp correction and reduced the 360-Hz current ripples of the ramp supplies. Current ramp errors have been significantly reduced. These improvements prompted our interest in running with the low-emittance lattice to improve APS storage ring injection efficiency and reduce radiation losses; both are important to APS upgrade project. This report presents the optimization methods and measurement results of booster beam performance of the booster 92-nm lattice.

Table 1: Main Parameters of The Booster Low-Emittance Lattice

Beam energy (GeV)	0.325 to 7.0
Circumference (m)	368
Revolution period (μs)	1.227
Tunes (x,y)	13.75, 5.80
Nat. Chrom. (x,y)	-12.94, -20.19
Max. beta (x, y)(m)	16.89,22.20
Ave. beta (x, y)(m)	7.87,12.57
Bunch length (ps)	65.3
Damp. time at ext. (x,y,E) (ms)	2.69,2.69,1.35

INTRODUCTION

The APS booster is a 7-GeV electron synchrotron. Three lattices have been designed with three nominal beam emittances of 132, 109, and 92 nm [1]. In the past we have mostly operated the booster with the original 132-nm lattice. The lower-emittance lattices were only operated briefly due to their inconsistent injection efficiency. In early 2010 we upgraded the booster ramp correction process and reduced the 360-Hz current ripples of the ramp supplies [2]. Current ramp errors have been significantly reduced. This has helped our tuning and optimization of the low-emittance lattice. This report presents the methods of optimzation and measurement results of the booster 92-nm lattice.

Table 1 shows the lattice parameters. It has an x-tune of 13.75 and y-tune of 5.80, and a nominal emittance of 92 nm. Due to the focusing sextupole field produced by the eddy current in the vacuum chamber in the dipole magnet the natural chromaticity in the y-plane is much higher than that of the x-plane for the low-emittance lattice. And our sextupole current is limited to a maximum of 150 A, which is insufficient for the required chromatic correction at the end of ramp. Chromatic correction presents a challenge.

Several processes were involved in tuning the low-emittance lattice:

(1) Re-configuration of the ramp timing so more sextupole strength can be produced at injection time,
(2) Establishment of initial beam with tunes close to the model lattice,
(3) Optimization of beam orbit to maximize aperture during a ramp cycle.
(4) Optimization of chromaticity to stabilize beam at higher single-bunch charge,
(5) Optimization of the matching and trajectory of PTB (PAR to booster transport) and BTS (booster to storage ring transport) beamlines.

After this optimization we achieved stable beam with a 3-nC single-bunch charge and close to 100% PTB to BTS efficiency. Preliminary tests show an on-axis storage ring injection efficiency of 90%. Further beam studies will be performed to evaluate the benefit of or any issues with running the low-emittance booster for storage ring operations.

RE-CONFIGURING MAGNET RAMP TIMING FOR BETTER CHROMATIC CORRECTION

The booster main magnet supplies are voltage-regulated. We achieve current regulation via workstation-based ramp correction programs. The program employs a linear-current-ramp scheme, in which the current ramps are corrected to close to a linear curve. With this approach tuning the lattice is mainly performed by adjusting the slopes (slopeRef) and zero-crossings (zeroRef) of current waveforms. To enhance magnet strength at injection we lower zeroRef. Similarly, to enhance strength at extraction we increase slopeRef. Sometimes we perform both adjustments in order to achieve the best result. This applies to both tuning k1 values of quads and k2 values of sextupoles.

Our studies have shown that most of the beam losses happen around injection time when the beam is less

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stable, and they are related to insufficient chromatic correction in defocusing sextupoles (SD). To provide more chromatic correction we must move the timing of SD magnets earlier. In order to provide a sufficient tuning range in timing we re-configured the ramp timing so maximum adjustable ranges of zeroRef of all ramp magnets and booster injection timing (startRamp) are increased from the original 9 ms to 16.7 ms.

TUNE ADJUSTMENT AND CONTROL

The originally modeled tunes of the 92-nm low emittance lattice for the booster are 13.75 and 5.80 (x- and y-tune, respectively). The actual tunes with which we can store beam are x-tune=13.85 and y-tune=5.63. We tried to move the tunes closer to model values but the effort always resulted in very poor efficiency.

We also tried to run the machine with the same x-tune but with a different y-tune of 6.2 or 6.8. These were not successful due to the QF current limit.

We found that booster injection efficiency is very sensitive to the tunes at injection time. A change of quad slope by 0.003 (or 0.1%) would reduce the injection efficiency drastically. The ramped supplies, especially the dipole, always have about 0.1% rms drift at injection. To compensate for that we installed an injection-tune controller process [3] that regulates injection-time tunes based on readings of turn-by-turn BPM history. The process helped maintaining injection efficiency. Fig. 1 shows a plot of the final tunes.

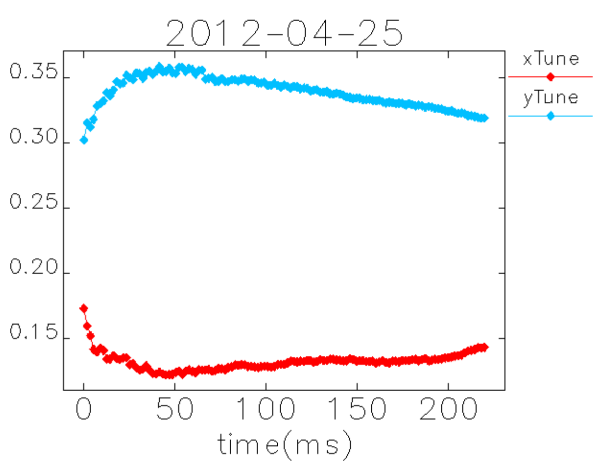

Figure 1: Plots of x- and y-tune of low-emittance lattice after optimization.

MAXIMIZING BOOSTER APERTURE BY CORRECTOR BUMP SCANS

Due to its ramped nature there is always some movement of beam orbit during a ramp cycle. The corrector supplies in the booster are driven by different AFGs (arbitrary function generators) and their waveforms must be pre-loaded. Loading the corrector ramps takes around 20 seconds. During initial tuning beam current fluctuates. This makes BPM readings less useful and impossible to run orbit correction. We decided to use a corrector bump scan to do the initial orbit tuning.

The booster has 80 correctors in each plane. We organized these correctors into forty 4-corrector-2-BPM closed-orbit bumps. Each bump covers a span of two sectors of the booster. We also divided a ramp cycle into four segments: injection, extraction, and two middle ranges. Fig. 2 shows the delta-waveforms of corrector bump B1C2H between 86 ms and 160 ms. By scanning the amplitude of the bumps one at a time in sequence and searching for maximum transmission efficiency at each step, the process slowly maximizes booster aperture and injection efficiency. Fig. 3 shows a typical scan result in the x plane.

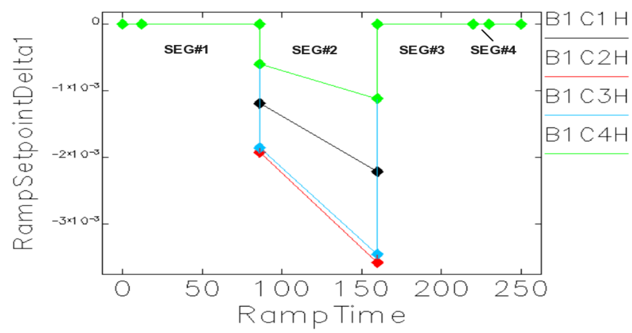

Figure 2: Plot of ramp setpoint changes of the four correctors of the B1C2H bump. The tuning segments are: 12-86 ms, 86-160 ms, 160-220 ms, and 220-230 ms.

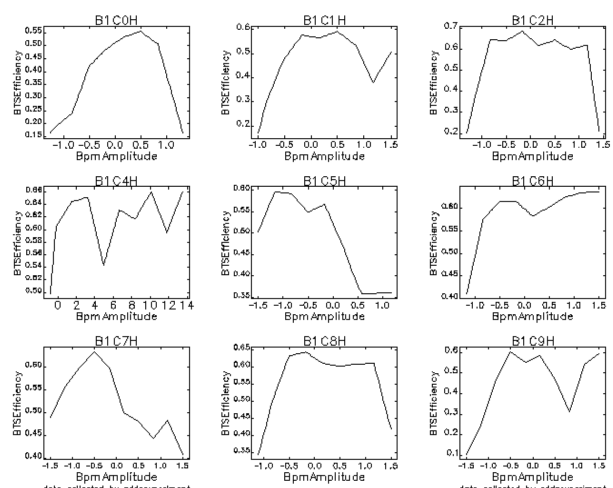

Figure 3: Plot of the bump scan data. The y-axis is PTB-to-BTS efficiency while the x-axis is the the corrector bump amplitude.

OPTIMIZING SEXTUPOLE CORRECTIONS

Comparison and modeling of chromaticity measurement data of the booster 132-nm emittance operational lattice and the low-emittance lattice provided information for the initial sextupole zero- and slope-

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reference setup [4]. After that we optimized sextupole correction with `sddsoptimize` [5]. The tool reads BTS beam current data while varying sextupole zeroRef and slopeRef setpoints. Fig. 4 shows a plot of the optimization process. We observe that beam current waveform is very sensitive to SD zero changes. At some point the waveform starts showing drop downs around 70 ms into a ramp cycle. We think this is the most unstable point when bunch length has damped to its shortest but beam energy is still relatively low (~2.4 GeV). By combining manual adjustments and running the optimizer, we found a range in which a ~3.0-nC charge bunch is stable. Fig. 5 shows the measured chromaticity of the optimized configuration. The y-chromaticity is between 0 and 2.5 during the ramp cycle. The x-chromaticity actually is negative between -2.5 and -4. This result shows that the optimizer actually compensates the insufficient y-chromaticity by moving x-chromaticity negative. We think there is sufficient damping in the x-plane to maintain a stable beam.

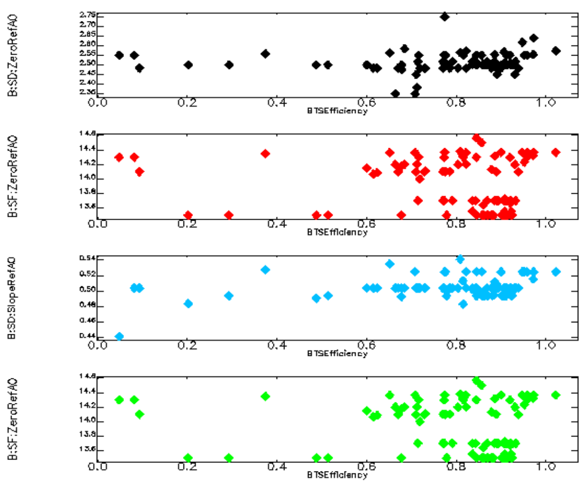

Figure 4: Plot of optimization run data.

BOOSTER UPGRADES FOR LOW-EMITTANCE LATTICE OPERATIONS

During the low emittance lattice study we found some limitations of booster subsystems that must be addressed in order to operate the booster with a low-emittance lattice. These include the following.

The QF magnet supply does not provide enough current to provide the necessary field strength for exploring optional x- and y-tune combinations. The SD magnet strength is also insufficient to provide enough chromatic compensation for high-charge operations. A 20% increase of both is needed. Stability of the main ramped supplies still needs to be improved by a factor of 2.

The timing system needs more range in moving timing of the SD and SF magnet current ramps. Loading time of corrector ramps needs to be reduced substantially so orbit correction can be operated continuously.

BPM system barely works and there is no calibration and orbit offset data. We can only correct orbit in one segment of time at a time. This makes the orbit correction a tuning tool instead of operational system. We also need to develop a practical emittance measurement tool.

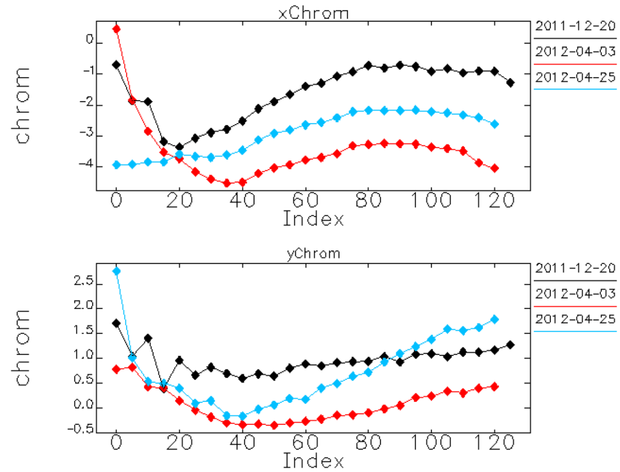

Figure 5: Plot of x- and y-chromaticity of booster low-emittance lattice during tuning processes. The data for optimized result are in blue color.

CONCLUSION

We successfully commissioned a booster low-emittance lattice that can provide stable beam for storage ring injections. Some subsystem deficiencies were identified. In order to make the lattice available for operations, some subsystem upgrades and more optimization are necessary.

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