IMPROVEMENTS TO THE APS BOOSTER INJECTION CONTROLLAW PROCESS*

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Abstract

The APS booster is a 7-GeV electron synchrotron with a 0.5-second cycle time. The booster runs a set of injection control programs that corrects the injection beam trajectory based on the beam history of two BPMs, one for horizontal and longitudinal planes, and the other for vertical plane. A process in the IOC calculates the I and Q components of beam oscillation from turn-by turn beam position samples over the first 64 turns. The booster injection control programs apply phase, energy, and transverse trajectory corrections based on the result of the processed data. The initial system was installed in 2007; since then the system has mostly worked during user operations. However, occasionally the system has yielded inconsistent results. Recently we reviewed the signals and processes involved in this system and made necessary upgrades and changes to some components, including selection of a new set of BPMs, optimization of FFT parameters, and addition of an injection tune control program. These upgrades have significantly improved the effectiveness and consistency of the system. We report the findings, analysis, and result in this paper.

INTRODUCTION

The booster injection control process [1] is a set of processes that include longitudinal, horizontal, and vertical injection trajectory control. These processes monitor real and imaginary parts of the FFT of turn-by-turn beam history data of a single BPM and adjust relevant actuator process variables to minimize momentum, phase, and trajectory errors of injected beam. These variables include startRamp, which changes the booster injection energy; PAR harmonic phase setpoint, which shifts injection beam arrival time; booster injection kicker and septum amplitudes; and PTB vertical corrector setpoints. The purpose is to minimize beam oscillation at the injection and improve injection efficiency. In the past we mostly ran the longitudinal control process. The performance of horizontal and vertical control processes were inconsistent, and therefore, they were used less. In order to improve the consistency of the transverse injection control processes we upgraded and optimized the system configuration based on analysis of the FFT processes, the PTB lattice, and logged data. After the upgrade, all three control processes are operational. Additionally we also installed an injection-tune control process to stabilize booster tunes at injection. As a result the system now performs well and is routinely used by the operators. Manual tuning of the booster is rarely needed.

*Work supported by the U.S. Department of Energy, Office of Science, under contract No. DE-ACO2-O6CH11357.
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BPMS AND TIMING CONTROL CONFIGURATION

Fig. 1 shows a screen shot of the FFT process control with the raw and detected tune waveforms for horizontal and longitudinal planes.

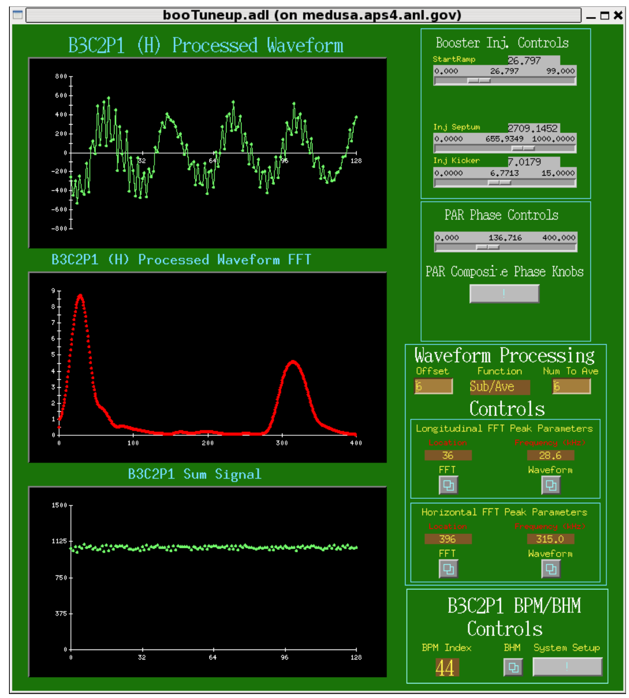

Figure 1: Raw (top) and FFT processed horizontal and vertical tune waveform (middle), and sum signal of B3C2P1 BPM (bottom).

The longitudinal and horizontal controllaw processes share the same BPM with frequency-division. Originally BPM B2C8P2 was selected for horizontal and longitudinal detection, and B2C8P1 was selected for vertical detection. The decision was made based on the availability of a workable beam history module at the time. For the 132-nm booster operational lattice, both β_x and η_x are low at B2C8P2 and β_y is also low at BPM B2C8P1. This essentially reduces the sensitivity of beam position detection. After reviewing several alternatives and the performance of beam history modules of all BPMs, we selected BPM B3C2P1 for horizontal and longitudinal detection and BPM B3C2P2 for vertical detection. The β_x and η_x values are at or close to maximum at B3C2P1, while β_y value is at maximum at B3C2P2. The new choices produce about twice the original sensitivity.

We also re-organized the timing configuration so the two BPMs for injection controllaw share a dedicated

ISBN 978-3-95450-115-1

timing module, and all the remaining 78 BPMs are available for orbit correction and other applications.

The vertical injection control process originally used all four PAR to booster (PTB) transport beamline correctors. An analysis of the PTB lattice found that the vertical betatron phase differences between three of these correctors are close to multiples of 180°. We selected V1 and V3, which have a phase difference of 22°, as the actuators. A test showed the new configuration produces good convergence against perturbations.

OPTIMIZING FFT PROCESSING PARAMETERS

The FFT process uses several adjustable parameters: an offset, a function code, and an average number for box-car averaging. The application of offset and function code is described with the following expression:

$$y(n)=x(n)+x(n\pm k_{offset}) \quad ,$$

where K_{offset} is the offset value and the +/- sign represents the function code. Box-car averaging is performed after this calculation. Varying these parameters is equivalent to applying different digital filters to the input signal sequence, and therefore, the effects represent an amplitude and phase response change. Because of the tune dependency of the beam motion, optimizing these parameters for given lattice tunes allows us to achieve better performance.

For the monopulse-receiver BPM [2] in the booster we must use sub/ave with an even offset number. This suppresses the artificial 0.5 revolution-frequency component due to 0°/180° phase toggling of the receiver circuit.

The effect of K_{offset} and box-car-average number ($N_{average}$) can be calculated by DSP analysis of an FIR filter. Figure 2 shows a direct-form diagram of the filter for the offset part. The box-car-average part can also be shown similarly.

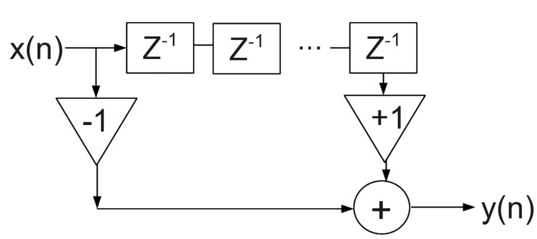

Figure 2: Diagram of the front-filter.

Fig. 3 shows the amplitude response versus tunes for different offsets and box-car-average numbers. Figure 6 shows amplitude responses for the 132-nm lattice, and Table 1 lists the optimized parameters. Due to high tune sensitivity with high offset and box-car-average-turns, we limit both parameters to less than 8.

Phase response depends strongly on the tunes and the FFT parameters, which dictates that in order to be effective, response matrices must measured with the same FFT parameter set and the lattice as that used in real operation.

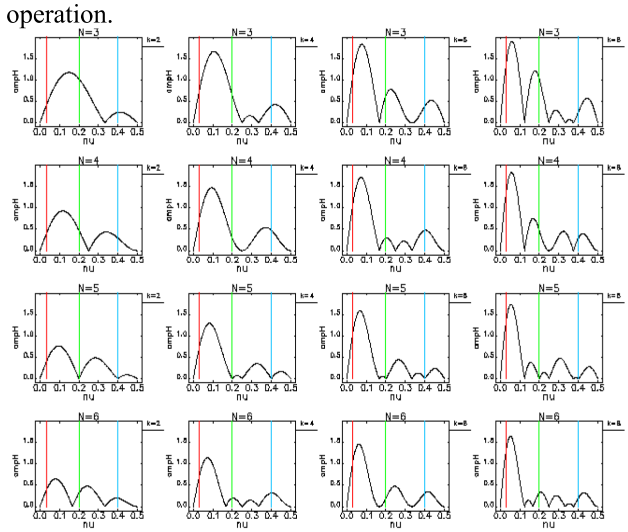

Figure 3: Amplitude response of FFT front-end digital filter for different combination of offset and box-car average number.

Table 1: Gains of the Booster 132-nm Lattice for the Optimized Parameters K_{offset}=6 and $N_{average}$=6

Plane	tunes	Gain
Longitudinal	0.032	1.07
Horizontal	0.4	0.32
Vertical	0.2	0.20

RESPONSE MATRICES

The injection control processes are all implemented as generic `controllaw` processes [3]. Corrections are calculated with inverse response matrices, which can be derived either from model or from direct measurement. In this case we run `quickResponseMmeasurement`, a SDDS-based utility program [3], to acquire and invert the matrices.

PROGRAM STRUCTURE AND HIGH-LEVEL INTERFACE

Fig. 4 shows a block diagram of the program setup. A common graphical user interface (GUI) runs on any workstation to control the processes. `Runcontrol` [3] processes are installed for session control and monitoring. The injection control processes control actuators via EPICS channel-access. Fig. 5 shows a screen shot of the application GUI.

INJECTION-TUNE CONTROLLAW

Since tunes play an important role in injection error detection, a response matrix only works for a given range of tunes. The measured rms tune errors of the booster at injection are around 0.03 in both the x- and y-planes. The tune shift range would make the injection control processes ineffective. In order to stabilize the transverse tunes, we developed an injection-tune control process that uses the FFT detected x- and y-tunes at injection time as monitored variables and uses zero-crossing references of QD and QF magnet current waveforms as control variables. The magnet currents are regulated with a workstation-based `bcontrol` program [3] that runs with an interval of 3 seconds. The injection-tune control process must wait for `bcontrol` to converge. It is configured to run with an interval of 25 seconds.

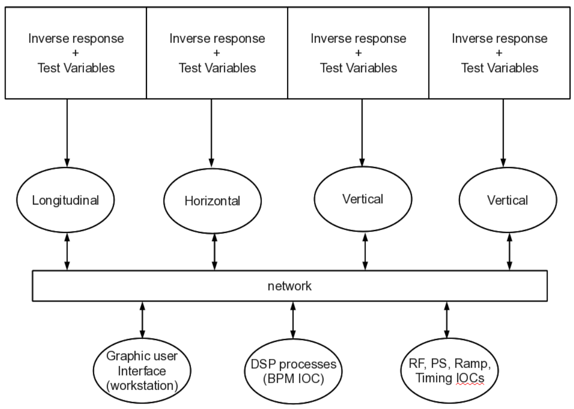

Figure 4: Block diagram of the booster injection control processes.

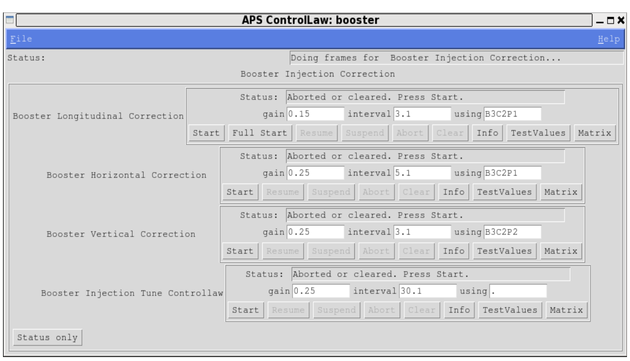

Figure 5: The control screen for the booster injection control processes.

The response matrix of injection tune control is measured with `quickResponseMmeasurement` tool. Table 2 shows one measured response matrix. It is clear that for the 132-nm booster lattice, the x-tune responds mainly to QF zero reference change while the y-tune responds mainly to QD zero reference change.

LOGGED DATA AS DIAGNOSTIC TOOL

Fig. 6 shows the logged history of the real and imaginary parts of longitudinal, horizontal, vertical FFT, and tunes data for one day in February. These data provide useful diagnostic information about the booster. For example, the longitudinal plot in the top-left shows most of the variations are a momentum mismatch of the booster energy and injection beam. The noise fluctuation in the vertical tune frequency in the bottom-right plot may indicate instability of the QD magnet current.

Table 2: Measured Inverse Response Matrix of Injection-Tune Controllaw for the 132-nm Lattice

Actuators	x-tune	y-tune
QFZero	9.928e-04	1.202e-04
QDZero	1.632e-04	1.029e-03

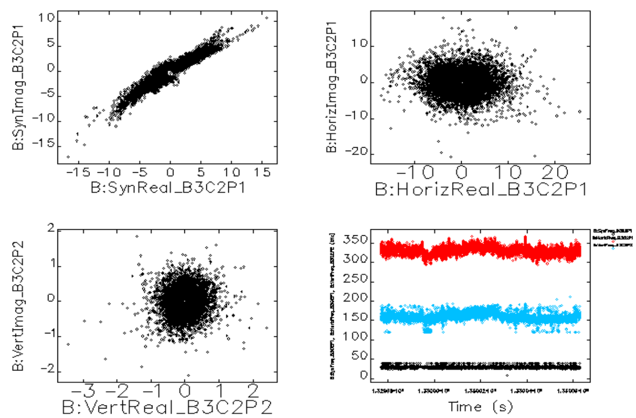

Figure 6: Logged history of real and imaginary parts of longitudinal (top left), horizontal (top right) and vertical (bottom left) FFT data in arbitrary units, and detected frequencies. Red: horizontal, black: longitudinal, blue: vertical, in kHz.

CONCLUSION

Booster injection controllaw has proved effective in maintaining consistent booster beam performance. Recent upgrading and optimization, and the addition of an injection-tune control process, have greatly improved the performance of horizontal and vertical injection controllaw processes.

ACKNOWLEDGEMENTS

We thank Nick Sereno, Lester Erwin, Bob Keane, and Bob Laird for their support and discussions. We also thank the MCR operators for their efforts to evaluate and operate the system.

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ISBN 978-3-95450-115-1