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CHARACTERIZATION OF LINEAR OPTICS AND BEAM PARAMETERS FOR THE APS BOOSTER WITH TURN-BY-TURN BPM DATA *

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Abstract

We take turn-by-turn (TBT) beam-position monitor (BPM) data on the energy ramp of the APS Booster [1] and analyze the data with independent component analysis. The extraction kicker was used to excite the betatron motion. The linear optics of the machine is characterized with the TBT BPM data. We also analyze the decoherence pattern of the kicked beam, from which we are able to derive beam distribution parameters, such as the momentum spread.

INTRODUCTION

The APS Booster accelerates electron beams from 425 MeV to 7 GeV for the APS storage ring. Its lattice consists of 40 FODO cells over a circumference of 368 m. The machine is equipped with 80 BPMs [2], all capable of taking turn-by-turn data over the entire ramp of 223 ms.

TBT BPM data provide a detailed record of the beam centroid motion, from which we can derive valuable information such as the tunes, linear optics, and coupling. In this study we used TBT BPM data to measure the linear optics functions of the APS Booster. The independent component analysis (ICA) [3] method was used to measure the betatron phase advances, from which the beta functions were determined with the 3-BPM method [4]. We also took advantage of the beam decoherence seen on the TBT data and used it to measure beam distribution parameters, such as the momentum spread.

BOOSTER TBT BPM DATA OVERVIEW

In a normal Booster cycle betatron oscillation is seen only right after injection. Two devices can be used to excite coherent betatron oscillations, which are needed to sample the linear optics. One is the tune driver, the other is the extraction kicker. The tunes on the energy ramp can be measured with the tune driver, for example, as shown in Fig. 1. The extraction kicker can introduce larger oscillation amplitude and is better suited for linear optics measurements. Figure 2 shows the raw data on one BPM with the extraction kicker firing every 25 ms.

Applying singular value decomposition (SVD) to a matrix of TBT BPM data and removing the 16 (out of 160) leading modes, the BPM noise sigmas are estimated to be 0.05 ~ 0.15 mm, with an average around 0.1 mm.

The ICA method was used to separate the synchrotron motion from the betatron oscillations. Figure 3 shows the dispersion functions measured from spatial pattern of the synchrotron mode and the oscillation of momentum deviation. The dispersion error sigma can be estimated with

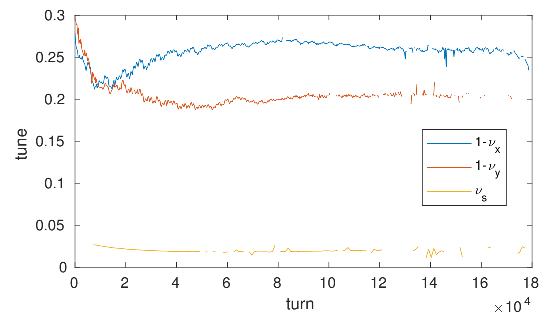

Figure 1: Betatron and synchrotron tunes on the Booster energy ramp measured by TBT BPM.

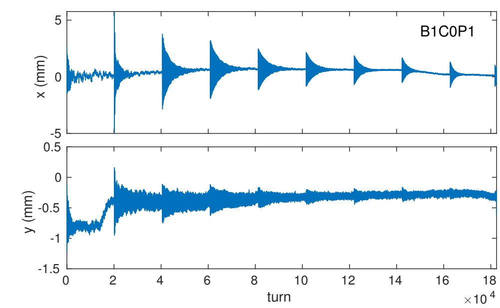

Figure 2: Horizontal (top) and vertical(bottom) BPM data on the ramp of the APS Booster observed at one BPM. Horizontal motion was excited by the extraction kicker.

$\sigma_D = \sqrt{\frac{2}{N}}\frac{\sigma}{A_\delta} \approx 0.02$ m, with N the turns of data, σ BPM noise, and A_δ the amplitude of momentum deviation.

LINEAR OPTICS MEASUREMENT

Beta functions and phase advances can be measured from the spatial pattern of the ICA modes corresponding to the betatron motion. Since the beta functions obtained with the spatial patterns are subject to BPM calibration errors, we used the 3-BPM method [4] and the measured phase advances to derive the measured beta functions.

Figure 4 shows the horizontal and vertical phase advances and the beta beating. Beta beating up to 20% is seen. The phase advance measurement error sigmas are estimated to be around 10 mrad and the corresponding $\frac{\Delta\beta}{\beta}$ error sigma, estimated with error propagation, is between 1.4 ~ 2.4%. The vertical measurement is not as accurate as the horizontal plane as the vertical oscillation amplitude is smaller, especially in the later stage of the ramp.

The horizontal beta beating is dominated by the $2\nu_x$ harmonic (w/ $\nu_x = 11.8$), as is often the case. The beta beating

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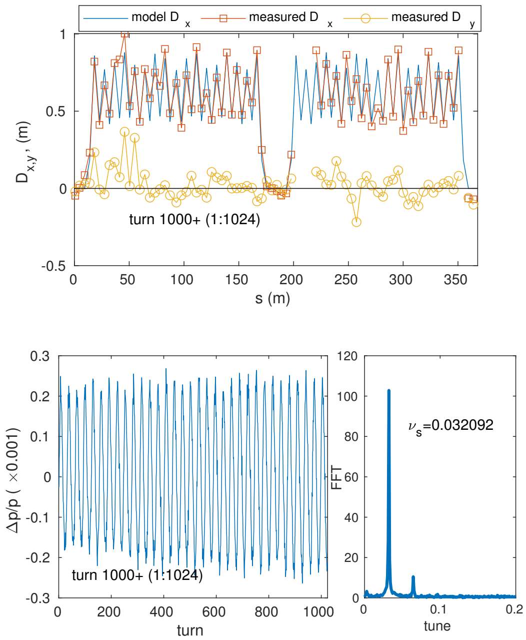

Figure 3: The dispersion functions (top) and the corresponding momentum deviation oscillation (bottom) measured 1000 turns after injection.

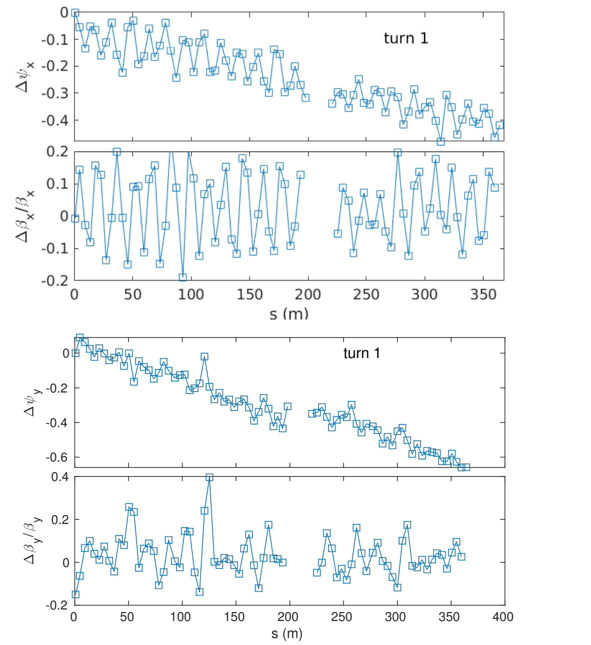

Figure 4: Horizontal (top) and vertical (bottom) phase advance obtained with ICA and the corresponding beta beating derived with the 3-BPM method, at injection.

pattern is persistent during the early stage of the energy ramp. As is shown in Fig. 5, a similar optics distortion pattern is present 60,000 turns after injection. We are able to fit 80 quadrupole gradients in the lattice model with the phase advance data.

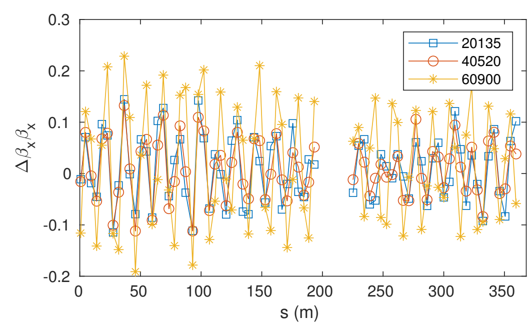

Figure 5: Beta beating at three points on the energy ramp

DECOHERENCE AND BEAM PARAMETERS

Decoherence of a kicked beam due to chromaticity and amplitude-dependent detuning causes the oscillation amplitude of the beam centroid to decrease. These effects have been studied analytically [5,6]. The formulas are found to make accurate predictions of the beam behavior on TBT BPM data in simulations [7], which led us to apply the formula to measured data to determine the related beam parameters [8].

The oscillation envelope of a kicked beam under decoherence due to linear chromaticity is given by [5],

$$\langle x(n)\rangle = x_0 F_\delta \cos(2\pi\nu_\beta n + \phi_\beta), \tag{1}$$

where x_0 is the initial oscillation amplitude, ν_β and ϕ_β are the betatron tune and phase, respectively, and for a Gaussian beam, the form factor is given by

$$F_\delta = \exp(-\frac{\alpha^2}{2}), \quad \alpha = \frac{2\xi\sigma_\delta \sin\pi\nu_s n}{\nu_s}, \tag{2}$$

where σ_δ is the momentum spread, ν_s is the synchrotron tune, and ξ is the chromaticity. Therefore, the envelope oscillates with the synchrotron tune and reaches a minimum $F_\delta = \exp(-\frac{2\xi^2\sigma_\delta^2}{\nu_s^2})$, as illustrated in Fig. 6 for chromaticity values typical of the APS booster [9].

Figure 7 shows the horizontal BPM data from one BPM right after a kick at about 20,000 turns. The oscillation envelope was retrieved with an FIR filter [10]. The envelope oscillation right after the kick is clearly seen. The synchrotron tune can be measured accurately from the oscillation. By fitting the envelope to Eq. (2), we can determine the product of $\xi\sigma_\delta$. As the chromaticity can be measured directly, we can thus determine the momentum spread.

Figure 8 shows the horizontal oscillation envelope at 4 points on the ramp after the kicker is fired, along with fitting curves by Eq. (2). The fitted $\xi\sigma_\delta$ for points along the ramp is shown in Fig. 9, with results from two BPMs compared.

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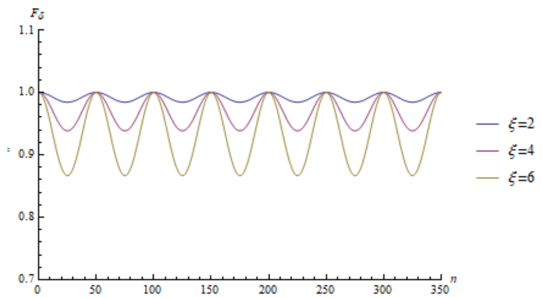

Figure 6: Form factor calculated with Eq. (2), using ν_s = 0.02, σ_δ = 0.0891, and ξ=2, 4, 6.

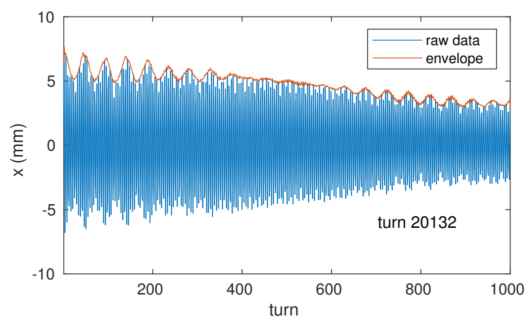

Figure 7: Horizontal BPM data after the kick at turn 20132 observed at one BPM, with oscillation envelope.

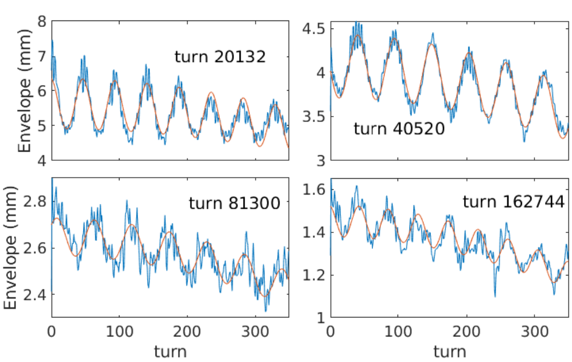

Figure 8: Fitting horizontal oscillation envelope to Eq. (2) for four points on the ramp.

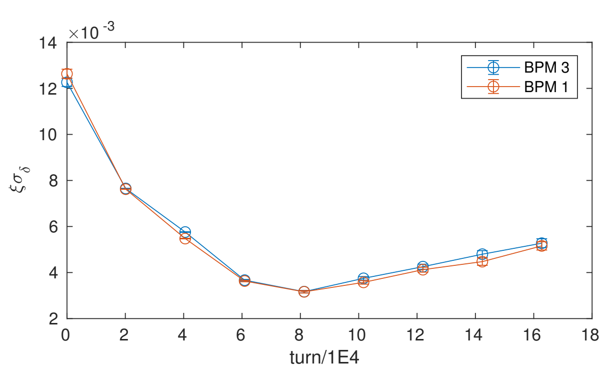

Figure 9: Fitted $\xi\sigma_\delta$ on the ramp with data from two BPMs.

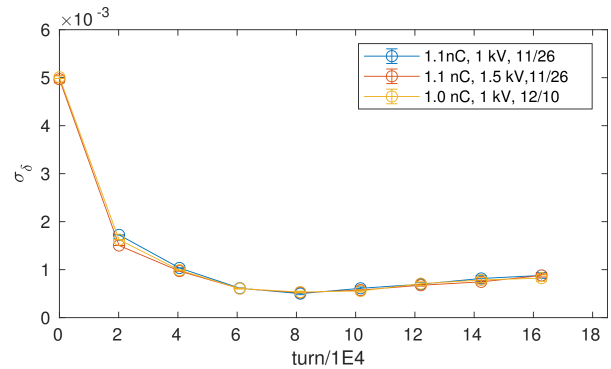

Figure 10: The beam momentum spread on the energy ramp for the APS Booster measured from decoherence for three data sets, with bunch charge and kicker strength indicated in the legend.

With the horizontal chromaticity measured by varying the RF frequency, we derived the momentum spread on the ramp. Figure 10 shows results from three data sets, taken under about the same bunch charge. The momentum spread is large at the bottom of the ramp because of the long bunch length coming from the particle accumulator ring (PAR). It decreases on the ramp due to adiabatic damping until at the later stage quantum excitation by synchrotron radiation becomes the dominant factor. The measurement results are in good agreement with simulation [11] using `elegant` [12].

It is possible to derive other beam parameters such as the horizontal emittance from the decrease of centroid oscillation, although other damping mechanisms (e.g., adiabatic damping, radiation damping, head-tail damping) and decoherence due to nonlinear chromaticity need to be considered.

SUMMARY

We took turn-by-turn (TBT) BPM data on the full energy ramp of the APS Booster, using the extraction kicker to periodically excite horizontal betatron motion. The data are analyzed with independent component analysis [3] to obtain the synchrotron and betatron modes, from the spatial patterns of which the dispersion functions and phase advances are derived. The beta functions are determined with the 3-BPM method from the lattice model and the phase advance measurements [4]. It was found that beta beating is up to 20% in the machine.

Oscillation of the betatron motion envelope is observed in the horizontal TBT BPM data following the excitation kick. This is due to the decoherence of a kicked beam by linear chromaticity [5]. We extracted the betatron motion envelope and fitted it to an analytic function, from which the product of chromaticity and momentum spread is obtained. The momentum spread on the ramp is subsequently determined using the measured chromaticity.

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