MEASUREMENT OF COHERENT DAMPING RATE OF THE APS STORAGE RING*

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Abstract

The APS storage ring is a 7-GeV electron storage ring with a single-bunch current of up to 16 mA during normal user operations. To overcome beam instability we employ both chromatic correction and a bunch-by-bunch feedback system. Typically we run a chromaticity of 4 for a 24-single fill pattern and 9 for a hybrids fill pattern in both the x- and y-planes with the feedback system loops closed.

The APS upgrade (APS-U) calls for a beam current of 150 mA and installation of vertical deflecting cavities for short-pulse x-ray (SPX) production. High-Q deflecting cavities produce additional transverse impedance and may cause transverse beam instability. In order to estimate whether the current chromatic correction and bunch-by-bunch feedback system are adequate for the upgrade, we performed coherent damping rate measurements with two methods: a pinging method, in which the beam is kicked with a kicker pulse, and a excitation-with-feedback method, in which the beam is excited with the bunch-by-bunch feedback system. We measured damping rate in two operation modes: (1) feedback loops are open and beam is stabilized by chromaticity correction alone; (2) feedback loops are closed. Several fitting algorithms were employed to process damping rate from measured data. This report presents the measurement data and results of the analysis.

INTRODUCTION

Recently we measured the damping rate in two operation modes: feedback loops off and on. In the loops-off mode we measure damping rate versus horizontal or vertical chromaticity. In the loops-on mode we measure damping rate versus gains of the feedback system. We excite the beam with a kicker or with the bunch-by-bunch feedback system (BBFB) [1], and monitor the beam position with a stripline pickup. Figure 1 shows the test configuration.

In the pinging method one important parameter is kick strength. We applied a 0.5- to 1.5-kV PFN voltage setpoint to IK1 and 0.75 to 1.5 kV for the vertical pinger. The data conversion ADCs are 14 bits. The input gain is adjusted to avoid saturation of the ADC. Because of the beta-function of the S3PU location, y-plane sensitivity is about twice that of the x-plane. The APS event system provides a convenient way of triggering the data acquisition in synch with the pinging.

In the excitation-with-feedback method we adjust the gain and polarity of the BBFB system to establish a steady beam oscillation. The feedback system is then turned off and the beam starts to damp. Turning off the feedback is triggered by a 10-second interval event. Data acquisition is triggered by the same event. Manual adjustment of a delay process variable (PV) is necessary to capture the full waveform of the damping process.

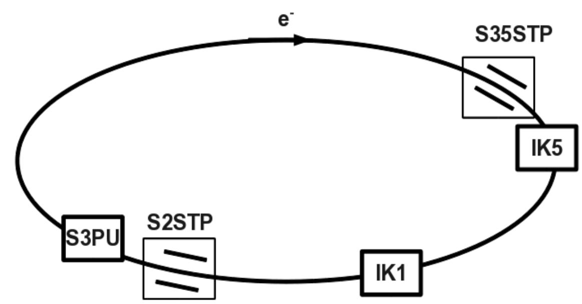

Figure 1: Damping time measurement setup: Two kickers, IK1 (x-plane) and IK5 (y-plane) are used to ping the beam; two drive striplines, S2STP for vertical and S35STP for horizontal excitation; a stripline pickup, S3PU, to monitor beam position.

The feedback system has a maximum drive strength of 0.78 µrad in the x-plane and 0.25 µrad in the y-plane. At chromaticity above 7.0 it can't produce sufficient beam oscillation amplitude. At low chromaticity, if the gain is too high, the beam would develop a saw-tooth mode oscillation. We found that if this happens, the damping rate results are not reliable.

PROCESSING DAMPING RATE

Due to the high chromatic correction beam centroid oscillation damps within a few hundred turns due to de-coherence and amplitude-dependent tune shift. The waveforms can't be simply fit with a simple exponential damped oscillation. Figure 2 shows a plot of typical raw data. Several fitting algorithms were tested.

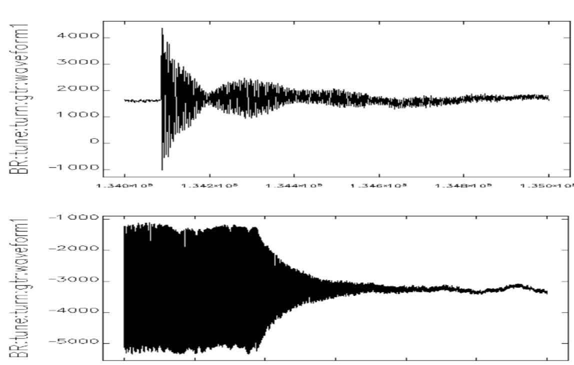

Figure 2: Typical raw data of damping time measurement. Top: horizontal beam motion after a ping. Bottom: vertical beam motion after excited by feedback system. The horizontal axis is in turn units.

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Exponential Fitting on Waveform Spread

We first evaluated the maximum oscillation amplitude, and removed data with amplitude above a threshold (70-80% of maximum amplitude). The remaining data were broken into records with a record length of 5 to 10 data points. We calculated the spread of each record and then fit with an exponential function. The advantage of taking spread data is that any slow baseline beam fluctuation, such as DC offset, slow synchrotron motion, noise from septum magnet pulse, or 60 Hz ripples from grounding, etc., are removed from the data before fitting. One major problem of this method is that total data points are reduced by a factor of 5 or more, which inevitably reduces fitting quality, especially if the damping time is short.

Generic Fitting with De-coherence and Tune-shift Terms

The centroid motion of a kicked bunch can be described with three components: a damped sinusoidal terms that represents a single-particle oscillation, an amplitude-dependent tune spread envelope modulation term, and a chromatic envelope modulation term that has a period of two synchrotron oscillation periods [2, 3]. The following expression summarize all three terms:

$$x(n)=A_0\frac{1}{1+C_\nu^2 n^2}\, e^{-\frac{Z^2}{2}\frac{C_\nu^2 n^2}{1+C_\nu^2 n^2}}\, e^{-2C_\xi^2\sin^2(\pi\nu_s n_0+\phi_s)}\, e^{-r_d n}\times$$
$$\sin\left(2\pi\nu_x n+\phi+\frac{Z^2}{2}\frac{C_\nu n}{1+C_\nu^2 n^2}+2\tan^{-1}(C_\nu n)\right),$$

where A_0 is the initial amplitude; C_ν and C_ξ are amplitude-dependent-tune-shift and energy-spread-tune-shift constants; Z is a variable proportional to the initial kick; r_d represents damping rate; ν_x and ν_s represent transverse and synchrotron tunes, respectively; n_0, φ_s, and φ are fitting variable related to initial phase and turn number; x(n) represents the beam centroid position on the n-th turn.

This equation has 10 variables. By fitting x(n) to measured turn-by-turn beam history data we can in principle obtain the damping rate and other parameters. If this model is correct, the fit result C_ν should increase with sextupole strength, and C_ξ should increase with chromaticity. Z should be proportional to the initial amplitude.

We used `sddsoptimize`, a SDDS-based generic fitting program [4], to fit the waveform data. Initial tunes are calculated with FFT processing.

Figure 3 shows fit results of horizontal data. We found that this method works well at low single-bunch beam current. It does not converge well when the bunch current is high.

Exponential Fitting with NAFF-based Amplitude Processing

The third method is similar to the first method except for the addition of a numerical analysis of fundamental frequency (NAFF)-based [5] amplitude detection. The turn-by-turn beam position history waveform is broken into box-car records of a length determined by the fractional tunes derived from the waveform. NAFF analysis derives the tune frequency of each record, which is then used to calculate oscillation amplitude. Since we ignore the effect of de-coherence and amplitude-dependent tune shift, the first few tens of turns data are removed before processing. Figures 4 to 6 show the fit results of the pinging and exciting-with-feedback methods. The pinging method data were collected with single bunch beam with currents around 1.5 mA, and the exciting-with-feedback data were collected around 2.5 mA in order to avoid instability at low chromaticity.

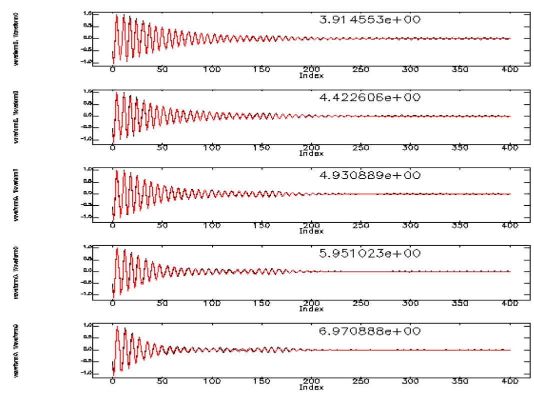

Figure 3: Fit x-plane damping waveforms (Red) and raw waveforms (baseline removed, Black) for different x-chromaticities (indicated by the labels) and a single bunch with a current of ~1.5 mA.

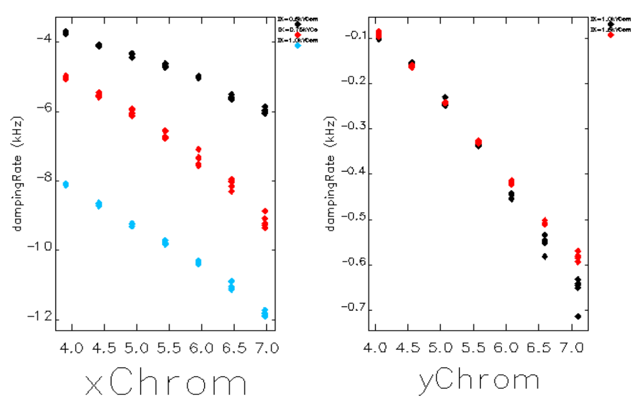

Figure 4: Damping rate versus chromaticity with the pinging method. In the horizontal plane (left), an injection kicker (IK1) is used; the color represents different kicker voltage. In the vertical plane (right) the vertical pinger (IK5) is used; the vertical damping rate is not sensitive to the kicker voltage.

Generally at lower chromaticity, probably due longer de-coherence time, the fit results are more consistent. At chromaticity above 7.0 the results are less reliable with both the pinging and exciting-with-feedback methods. Several factors may contribute to this: fewer useful data points due to shorter de-coherence and damping time;

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reduced relative data conversion resolution due to smaller driven amplitude; lack of centroid motion at high chromaticity, etc. Problems with the horizontal plane may also be due to the lower beta-function at the pick-up stripline, making the acquisition resolution low. Tables 1 to 3 summarize the measurement results.

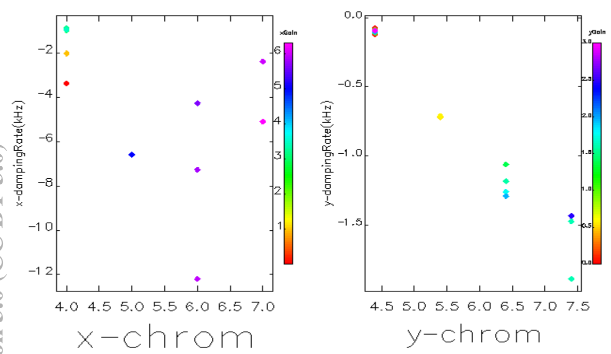

Figure 5: Horizontal (left) and vertical (right) damping rate versus chromaticity using the BBFB drive method. The colors represent different feedback gains applied.

Table 1: Damping Rate with Pinging Method

x-/y-chrom	x-dampingRate (kHz)	y-dampingRate (kHz)
4.0	3.2	0.10
5.0	6.0	0.26
6.0	7.3	0.43
7.0	8.9	0.62

Table 2: Damping Rate with BBFB Loops Closed

x-/y-gains	x-dampingRate (kHz)	y-dampingRate (kHz)
0.0	3.3	0.10
2.0	4.7	0.41
4.0	5.5	0.76
6.0	6.1	1.19
8.0	-	1.50
9.0	6.4	-

Table 3: Damping Rate with BBFB-Excite Method

x-/y-chrom	x-dampingRate (kHz)	y-dampingRate (kHz)
4/4.5	2.0	0.2
5/5.4	6.5	0.7
6/6.4	10.0	1.2
7/7.4	6.0	1.5

We conclude that with chromaticity of 7 in both planes we can produce damping rates of 9 kHz and 0.62 kHz in x- and y-planes, respectively; with BBFB loops closed and a chromaticity of 4 in both planes, we can produce a damping rate of similar range. Results from both the pinging method and the exciting-with-feedback method are in general agreement.

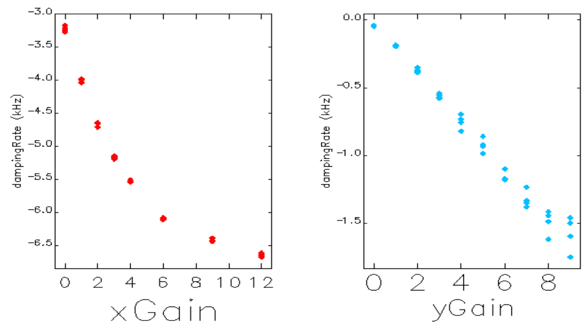

Figure 6: Horizontal (left) and vertical (right) damping rate versus BBFB gain with pinging method.

CONCLUSION

Coherent damping rate measurement is difficult for the APS storage ring at operational single-bunch beam charge due to the de-coherence effect and amplitude-dependent tune shift due to strong chromatic correction. Both the pinging method and the exciting-with-feedback method have produced similar results. Three processing methods were tested to process the damping rate from the measured data. The NAFF-based envelope-detection method with exponential fitting produced more reliable results. The measured damping rate of the APS storage ring for the nominal chromaticity is about 9 kHz and 0.6 kHz in the x- and y-planes, respectively. These results are for low single-bunch current. Further study is needed for the high single-bunch current case. We also found it difficult to process damping rate reliably for high chromaticities.

ACKNOWLEDGEMENTS

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