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MEASUREMENTS OF TRANSVERSE COUPLED-BUNCH INSTABILITIES IN PEP-II *

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Abstract

At the design currents the PEP-II High and Low Energy Rings operate above the coupled-bunch instability thresholds in horizontal and vertical planes. Both machines have used analog bunch-by-bunch feedback systems to stabilize the beams since commissioning. Here we present a measurement technique that uses the capabilities of the PEP-II programmable digital longitudinal feedback system to provide transient diagnostics in X or Y directions. This technique allows one to measure instability growth or damping rates as well as oscillation frequencies in both open-loop and closed-loop conditions. Based on these measurements the configuration of the relevant transverse feedback channel can be optimized. The technique will be illustrated with instability measurements and feedback optimization examples. Comparisons of the measured modal patterns and growth rates to the theoretical predictions will be presented.

INTRODUCTION

PEP-II is a two ring collider designed to operate above the coupled-bunch instability thresholds in both longitudinal and transverse directions. Bunch-by-bunch feedback systems are used to stabilize the beams in both rings [1, 2]. This approach has been extremely successful as evidenced by the operating currents of the High-Energy Ring (HER) reaching 1550 mA - more than twice the design value of 750 mA. The Low-Energy Ring has also exceeded the design current of 2140 mA and has reached 2450 mA.

These accelerator performance levels require careful attention to the configuration of the feedback systems. Unfortunately for diagnostics, in routine closed-loop operation these systems act to damp bunch centroid oscillations to a relatively constant level. As long as the system has net damping, the final equilibrium motion is largely independent of the feedback settings or the instability growth rates. Consequently, observation of beam motion with the feedback systems in operation provides no information on the instability growth rates and the achieved feedback damping. This information is important both for day-to-day operation and maintenance of the coupled-bunch feedback systems as well as for estimating future performance and necessary upgrades.

In both horizontal and vertical planes the feedback requirements are relaxed in collision due to the beam-beam damping. However it is still desirable to maintain beam stability out of collision, so that a beam abort in one ring would not cause a transverse instability and a consequent beam abort in the other ring.

Transient measurements of instability growth rates and feedback damping rates have been used extensively to quantify the coupled-bunch instabilities and the feedback system performance [3, 4]. However, transient measurement capabilities are natively available in PEP-II only in the longitudinal plane. In this paper we will describe an experimental setup that uses a longitudinal feedback system borrowed from one ring for transient diagnostics in the transverse plane of the second ring.

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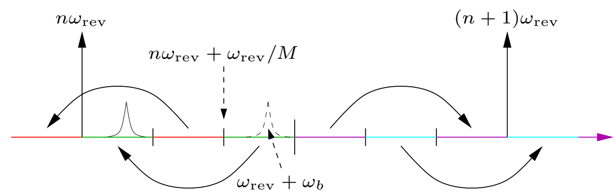

Figure 1: Aliasing of betatron signals illustrated for the downsampling factor $M = 3$.

EXPERIMENTAL SETUP

In order to measure growth and damping rates above the instability threshold two elements are required: a bunch motion recorder and a way to open the feedback loop for a controlled interval. In measuring the transverse instabilities in the PEP-II HER we used the LER longitudinal feedback system (LFB) as a motion recorder.

PEP-II LFB is designed to downsample the beam data to match bunch signal processing rate to the synchrotron oscillation frequency [5]. When used to record transverse motion, downsampling leads to undersampling and aliasing of the betatron oscillations. Naively one would expect aliasing of the beam motion to render the data useless. However in the case of the coupled-bunch instabilities such undersampling is perfectly acceptable as long as the envelope of beam motion is properly acquired. Note that the instability growth rates in the longitudinal and transverse directions are of the same order of magnitude, so the LFB can record the envelope of the transverse transients quite well. Aliasing due to downsampling is illustrated in the frequency domain in Fig. 1. Depending on the integer part of $\nu_b M$ where ν_b is the fractional betatron tune

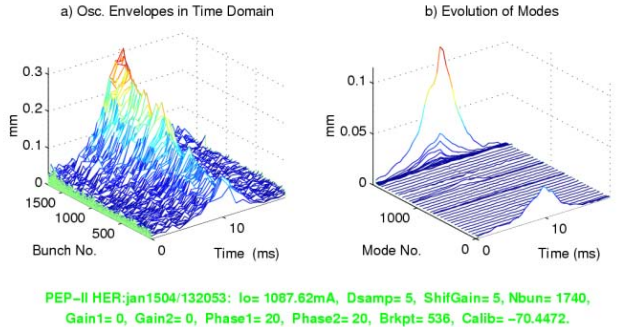

Figure 2: A horizontal grow/damp transient showing a) bunch oscillation amplitudes; b) EFEM amplitudes.

$\omega_b/\omega_{\rm rev}$, the upper sideband can alias to upper (green) or lower (red) sideband in the downsampled signal. As long as the signal does not straddle a multiple of the Nyquist frequency $\omega_{\rm rev}/(2M)$ the original betatron motion can be reconstructed using simple frequency translation.

To perform transient instability measurements in PEP-II transverse planes we installed high-isolation voltage-controlled RF switches in both horizontal and vertical HER feedback processing channels. During the measurements the LFB controls the switch in the appropriate channel using a TTL-level programmable output of a DSP. One can set in firmware breakpoints during the transient measurement and the desired switch state transitions. A typical setup opens the switch at the beginning of the recording and closes it at the midpoint of the data acquisition. As a result, the first part of the data set corresponds to the open-loop growth of transverse instabilities, while the second part provides information on the closed-loop damping.

GROWTH AND DAMPING RATE MEASUREMENTS

To characterize transverse coupled-bunch instabilities in PEP-II HER we performed a series of transient grow/damp measurements at different beam currents in both horizontal and vertical planes. Using the knowledge of the betatron tune we reconstruct the original beam motion. Bunch signals are then transformed into the even-fill eigenmode (EFEM) basis. Using joint estimation of modal eigenvalues we extract modal growth rates and oscillation frequencies from the open and closed-loop sections of the transients [6].

Horizontal plane

A typical grow/damp transient is illustrated in Fig. 2. Horizontal feedback loop is open during the first 10 ms of the transient allowing the unstable betatron motion to grow. All bunches participate in the transient motion with the oscillation amplitudes increasing toward the end of the train. Upon transforming the motion to the EFEM basis we see that one eigenmode dominates the motion - EFEM -1 with other low-frequency eigenmodes growing slower. This frequency signature is characteristic of the transverse instabilities driven by the resistive wall impedance.

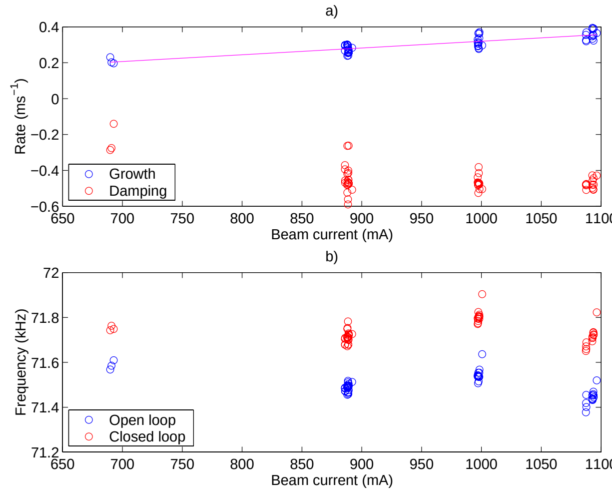

Figure 3: Transient measurements of horizontal EFEM -1 vs. beam current; a) Growth, damping rates, and a linear fit to growth rates; b) Growth (open loop) and damping (closed loop) modal oscillation frequencies

A summary plot of grow/damp measurements in the horizontal plane is presented in Fig. 3. Using a linear fit to the open-loop growth rates we extract the zero-current damping time (radiation damping) $\tau^x_{\rm rad} = 17.5$ ms and the instability threshold current of 151 mA. Horizontal feedback produces damping rates roughly equal to the growth rates indicating a 6 dB gain reduction margin. At the currents above 900 mA damping rates do not increase appreciably, pointing to the feedback channel saturation. At this level of feedback damping one can expect to support HER beam currents in the 2-3 A range. In the tested configuration the horizontal feedback system is not fully resistive and produces a tune shift of 0.0015. The overall eigenvalue shift is $800 + 1256i$ with real part expressed in $\rm s^{-1}$ and the imaginary part - in rad/s.

Vertical plane

In the vertical plane even fill eigenmode -1 was also the fastest growing mode. Fig. 4 plots the open and closed loop eigenvalues of that mode vs. beam current. The vertical growth rates show non-linear scaling with beam current not seen in the horizontal measurements. The growth rates in Y are also 4 to 5 times faster than in X. Comparing the open and closed-loop oscillation frequencies we note that there is barely any difference between the open and closed loop oscillation frequencies. Thus, the vertical feedback has very small reactive component. The large frequency shift with beam current is most likely caused by the tune feedforward system [7].

During the measurements in the vertical plane we observed that with increasing current the bunches in the tail

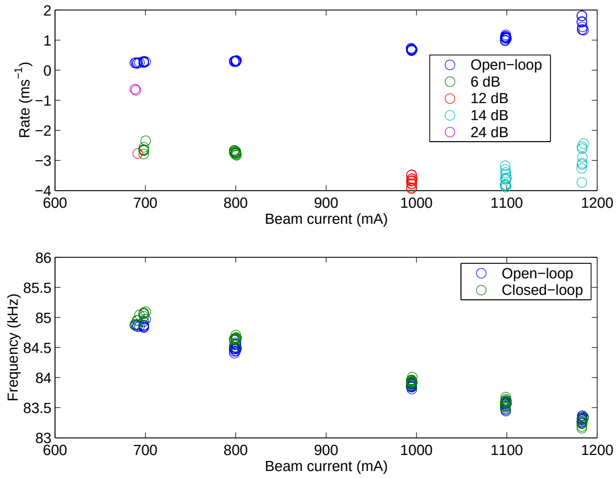

Figure 4: Transient measurements of vertical EFEM -1 vs. beam current; a) Growth and damping rates at different feedback gains (dB reading refer to attenuation, larger setting means lower gain); b) Growth (open loop) and damping (closed loop) modal oscillation frequencies

of the train started breaking out in oscillation. In order to regain stability we lowered the feedback gain using an attenuator in the vertical processing channel. Damping rates shown in Fig. 4 are labeled according to the attenuator setting. Again we see evidence of saturation, especially obvious around 700 mA where attenuation change from 6 dB to 12 dB does not affect the damping rates.

The effect of the tail bunches breaking out in oscillation is nicely illustrated in Fig. 5. This transient measurement is started with the bunches in the tail oscillating at large amplitudes. When the feedback turns off those bunches damp while the rest of the train grows. After the feedback loop is closed at 10 ms the opposite effect is clearly seen. This indicates that the vertical feedback system has excessive gain and is exciting a subset of bunches. If we consider the motion in the EFEM basis we see the resistive wall modes growing and damping as expected. However, there is a band of modes around EFEM 500 that has the opposite

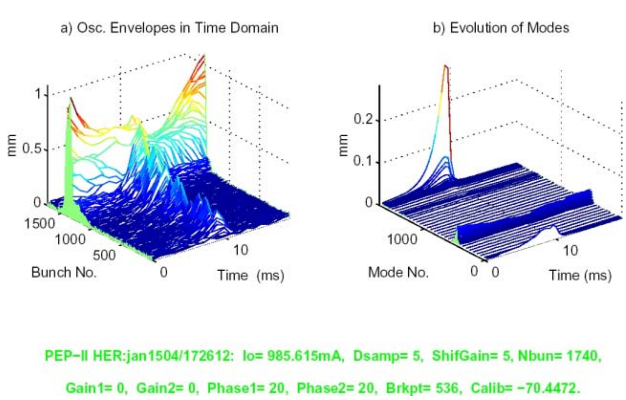

Figure 5: A vertical grow/damp transient showing significant motion of the bunches at the end of the train

behavior. Clearly, the bunches at the tail of the train are oscillating at a higher-order mode frequency driven by the large vertical feedback gain. In process of the vertical instability measurements and feedback optimization the gain had to be lowered by a total of 18 dB.

CONCLUSIONS

Transient diagnostics of coupled-bunch instabilities are a powerful tool for characterizing both the instabilities and the performance of the feedback systems. Using the diagnostic capabilities of the LER longitudinal feedback system we have extensively measured the growth and damping rates in the X and Y planes of PEP-II HER. The fastest growing modes in both planes are those driven by the resistive wall impedance. The horizontal feedback system has been shown to provide adequate damping at the operating beam currents. It does, however introduce a reactive tune shift. The growth rates in the vertical plane are significantly higher and place more stringent requirements on the feedback system. The grow/damp measurements allowed us to determine that the vertical feedback was configured with excessive gain and to optimize the settings. The vertical growth rates also exhibit non-linear scaling with beam current the causes of which are still being investigated.

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