Commissioning Experience from PEP-II HER Longitudinal Feedback[1]

S. Prabhakar, D. Teytelman, J. Fox, A. Young, P. Corredoura, R. Tighe

Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309, USA

Abstract. The DSP-based bunch-by-bunch feedback system installed in the PEP-II HER has been used to damp HOM-induced instabilities at beam currents up to 605 mA during commissioning. Beam pseudospectra calculated from feedback system data indicate the presence of coupled bunch modes that coincide with the 0-M-2 cavity HOM. Bunch current and synchronous phase measurements are also extracted from the data. These measurements reveal the impedance seen by the beam at revolution harmonics. The impedance peak at 3*frev indicates incorrect parking of the idle cavities, and explains the observed instability of mode 3. Bunch synchrotron tunes are calculated from lorentzian fits to the data. Bunch-to-bunch tune variation due to the cavity transient is shown to be large enough to result in Landau damping of coupled bunch modes.

INTRODUCTION

The PEP-II High Energy Ring (HER) electron beam has a design current of 1A. Beam currents up to 750 mA have been achieved so far. During commissioning, a variety of longitudinal and transverse beam dynamics experiments have been performed [1–3] with the help of the PEP-II longitudinal feedback (LFB) system [4]. The most useful diagnostic characteristic of this system is its ability to record the oscillations of each bunch over a 27 ms time window. The recorded data can then be archived and analysed offline to extract detailed information about beam dynamics and beam conditions.

The two main sources of longitudinal motion identified in PEP-II are cavity impedance-induced coupled bunch instabilities and noise from the klystron. Coupled bunch instabilities are usually caused by unwanted Higher-Order Modes (HOMs) in the RF cavities, or by impedance sources elsewhere in the beam surroundings. At PEP-II however, the large beam current and small revolution frequency combine to produce low-mode instabilities within the bandwidth of the detuned RF cavity fundamental mode [3]. The HOM-induced instabilities have been

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successfully damped by the above-mentioned longitudinal feedback system. Low-mode motion is damped by a combination of RF feedback loops acting through the klystron.

In this paper we demonstrate the ability of the broadband LFB system to drive coupled bunch motion with positive feedback, and damp it with negative feedback. We also present a novel beam-based method for measuring the longitudinal impedance spectrum [2]. The method involves calculation of the transfer function from fill shape (bunch current versus bunch number) to synchronous phase of a multibunch beam, which is shown to yield the longitudinal impedance seen by the beam at revolution harmonics. The technique has been used to measure the impedance of parked cavities at PEP-II, and explain the occasional instability of low order coupled bunch modes at unexpectedly low total currents. Multibunch synchronous phases and bunch currents are extracted from data stored by the LFB system.

In addition to providing impedance information, multibunch synchronous phase measurements are useful in themselves, since HER and LER phase transients need to be matched to achieve high luminosity. The synchronous phase transients are also an indicator of the amount of landau damping afforded by bunch to bunch tune shifts.

Lorentzian fits to bunch motion spectra yield a bunch tune versus bunch number graph that correlate well with the synchronous phase transients. We examine the interesting features of one such graph in the final section, and demonstrate the decoupling of bunch oscillations at the ends of the bunch tune range.

BEAM PSEUDOSPECTRA

Coupled bunch motion can be studied in the frequency domain by constructing beam pseudospectra from feedback system data [5]. A typical piece of HER data includes the sampled oscillation signals of each of the stored bunches over a 27 ms time window. These signals are interleaved and strung out into a single vector of successive samples detected by a stationary observer at the BPM location. The FFT of the resulting vector is nothing but the beam spectrum, with revolution harmonics suppressed. The pseudospectrum resulting from a single 27 ms transient covers the entire 119 MHz frequency range (DC to half the bunch crossing frequency) with a resolution of 37 Hz.

In the absence of feedback, HOM-induced coupled bunch instabilities have been observed at beam currents above 550 mA in the HER. These instabilities are damped when negative feedback is switched on.

Figure 1 compares HER pseudospectra with positive and negative feedback, at beam currents of 317 and 330 mA respectively. It must be noted here that each of the lines in these spectra is a synchrotron sideband, since the revolution harmonics are suppressed. The beam is longitudinally stable in both cases, but positive feedback drives up the amplitudes of synchrotron sidebands in the 100-110 MHz frequency range. This frequency range coincides with the aliased impedance of the 0-M-2 mode, which is the largest measured cavity HOM [6].

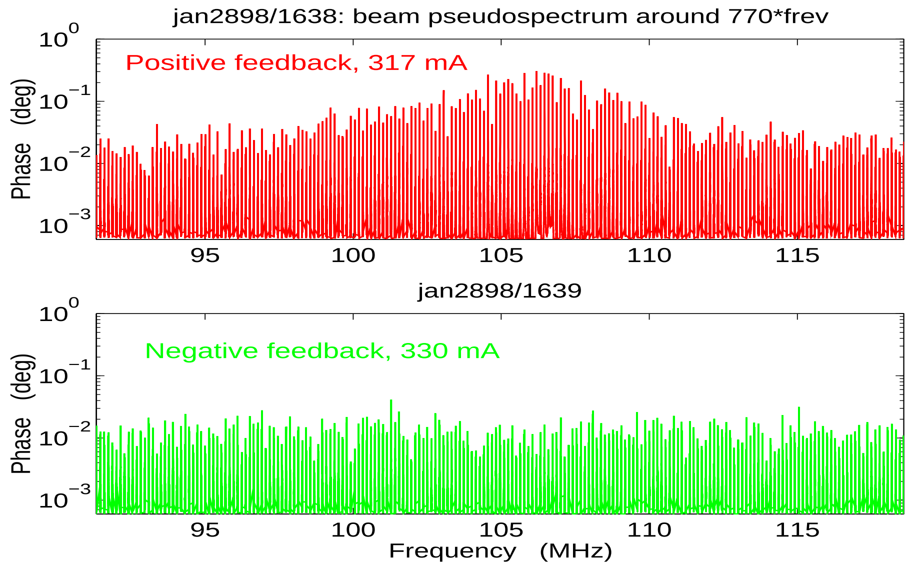

FIGURE 1. Beam pseudospectra with positive and negative feedback. Sidebands are driven up by positive feedback in the 100-110 MHz frequency range, which coincides with the aliased impedance of the 0-M-2 cavity HOM.

BUNCH CURRENTS AND SYNCHRONOUS PHASES

Line harmonics from the klystron impose the same low frequency motion on all bunches. During commissioning 360 Hz and 720 Hz lines from the klystron were large enough to be detected in the bunch data. These spectral lines afford a crude current monitor, since the bunch signals are proportional to charge times longitudinal phase. Bunch currents are estimated by projecting individual bunch signals onto a line harmonic spectrum calculated by averaging over all the bunch signals.

Formal bunch current monitoring using the feedback system has been demonstrated at the ALS [7], and will be used at PEP-II during the next commissioning run.

Since the LFB system detects the product of charge and phase, multibunch synchronous phases are calculated by averaging the digitized signals for each bunch and dividing the averages by the corresponding bunch currents.

Figure 2 shows the averaged low frequency bunch signal spectrum for a 291-bunch 96 mA fill. In this case we calculate bunch currents by projecting individual bunch signals onto the 720 Hz line in the averaged spectrum and then scaling the result so that the calculated total beam current agrees with that measured by the DCCT (DC Current Transformer).

The calculated bunch currents i_k are shown in Figure 3. There is an impulsive discontinuity near the beginning of the bunch train. The resultant synchronous phase ringing is shown in the same figure. We can see from the figure that the "impulse response" goes through about three oscillations and dies out in one revolution period. This indicates that the longitudinal impedance $Z(j\omega)$ has a strong resonance three revolution harmonics away from some multiple of the bunch frequency, which is a twelfth of the RF frequency in this case.

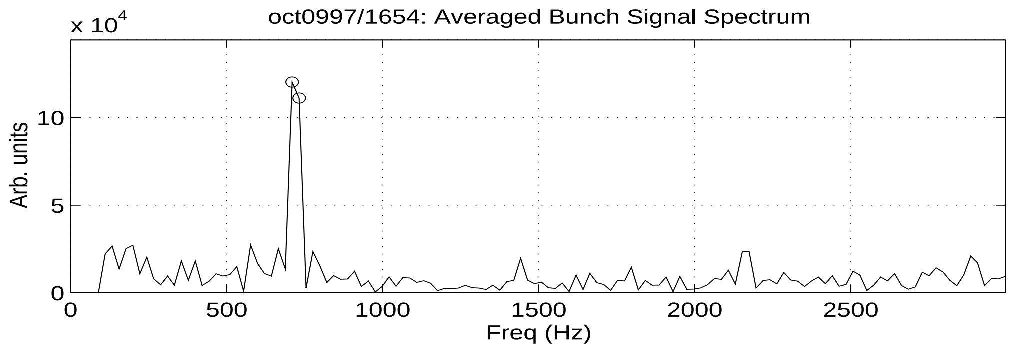

FIGURE 2. Low frequency bunch signal spectrum: 720 Hz line from klystron is demodulated to extract bunch currents from LFB system data.

EXTRACTION OF IMPEDANCE

If we increase the charge in a single bunch, its synchronous phase will ride up the RF voltage waveform to keep up with the increasing loss of energy to wakefields. If we know the slope of the RF voltage, we can easily calculate the energy lost to wakefields per unit current from the synchronous phase increase. This gives us a measure of the integrated beam impedance. In itself the integral reveals nothing about the shape of the impedance. However, some information about the frequency spectrum of the impedance can be gleaned from repeating this measurement at various bunch lengths.

In this note we demonstrate a new method of measuring the longitudinal impedance spectrum using synchronous phase data from multibunch fills. It can be shown that the discrete-time transfer function from bunch currents to synchronous phases is proportional to the aliased longitudinal impedance at revolution harmonics up to the bunch frequency [2].

Figure 4 shows a typical low-frequency impedance spectrum calculated from HER commissioning data using the method described above. We see a resonant impedance of $8M\Omega$ at 3*frev, calculated from the currents and phases shown in the previous figure. This indicates that the 12 parked cavities, which were supposed to be tuned 2.5 revolution harmonics away from the RF frequency, were actually parked much closer to the third revolution harmonic. If they were all parked exactly

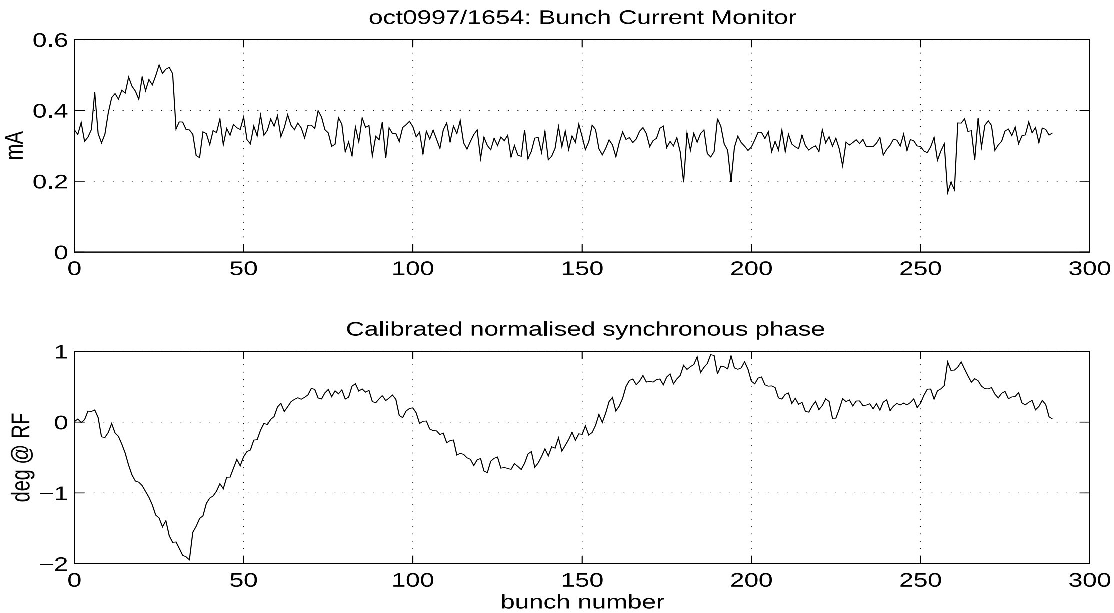

FIGURE 3. The upper figure shows the current variation in a 96 mA 291-bunch HER beam. We see a short impulsive discontinuity in the fill shape. This discontinuity produces a damped oscillation in the synchronous phase transient (lower figure). The transient completes 3 oscillations within the length of the bunch sequence.

3 revolution harmonics away from f_{rf}, their impedances would add up to $9.2M\Omega$ at the third revolution harmonic.

Coupled bunch instability

Inaccurate parking of idle cavities is quite likely to have been the cause of low-mode coupled bunch instabilities seen occasionally at currents below 100 mA during commissioning. Figure 5 shows the low-mode beam pseudospectrum for a 291-bunch 84 mA fill, taken a few days before the data displayed in the previous figure. Each pair of lines in the figure is a pair of synchrotron sidebands. The pseudospectrum shows that mode 3 is unstable, with an average amplitude of 2° at the RF frequency. Shifting of the idle cavity tuners has been seen to attenuate this instablity [8].

BUNCH TUNE VARIATION

The PEP-II beams are expected to have a 5% gap, to forestall conventional ion instabilities. This gap produces a transient in the RF cavity which results in synchronous phase variation across the bunch train. The beam loading transient also causes the bunch tunes to vary across the train.

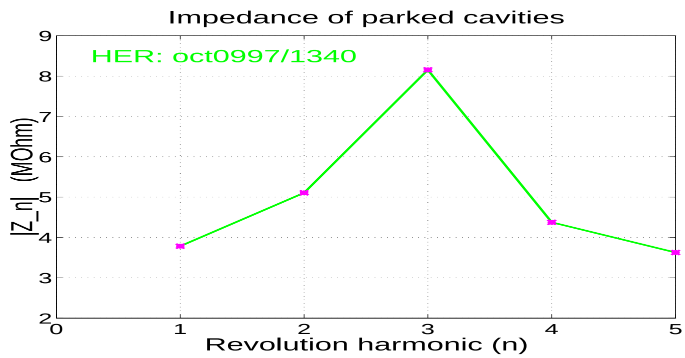

FIGURE 4. Impedance at first few revolution harmonics, extracted from bunch currents and synchronous phases. Large value at n = 3 is due to the fundamental resonances of parked cavities.

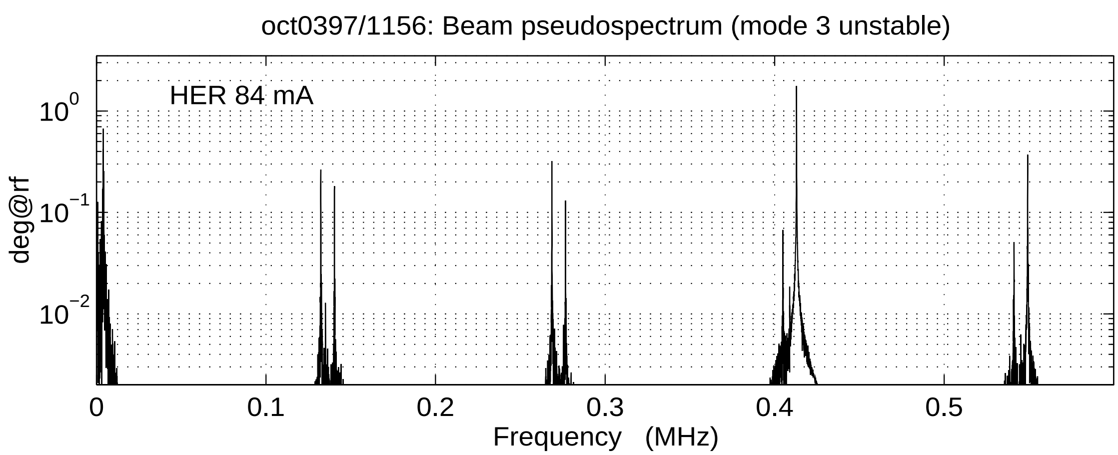

FIGURE 5. Beam pseudospectrum of 84 mA 291-bunch beam, showing an unstable upper sideband at the third revolution harmonic (0.41 MHz).

The upper graph in Figure 6 illustrates synchronous phase variation in a 368 mA HER beam with a 5% gap. The variation is fast in the initial portion of the bunch train, where the phase changes by 10 deg within the first 300 bunches. The corresponding variation in bunch tune is measured simultaneously using lorentzian fits to bunch signal spectra (lower graph). As the bunch train loads the cavity fundamental, the bunch tune decreases from an initial value of 5900 Hz to a mid-train value of around 5800 Hz. Longitudinal oscillations at the beginning of the bunch train are decoupled from oscillations further down, i.e., we have some Landau damping of coupled bunch instabilities. This contributes to the elevation of the instability threshold from the calculated value of 350 mA with no feedback to the measured value of 550 mA.

Although the bunch tune transient broadly matches the synchronous phase transient, we can clearly see local regions of flatness, within which all bunches seem

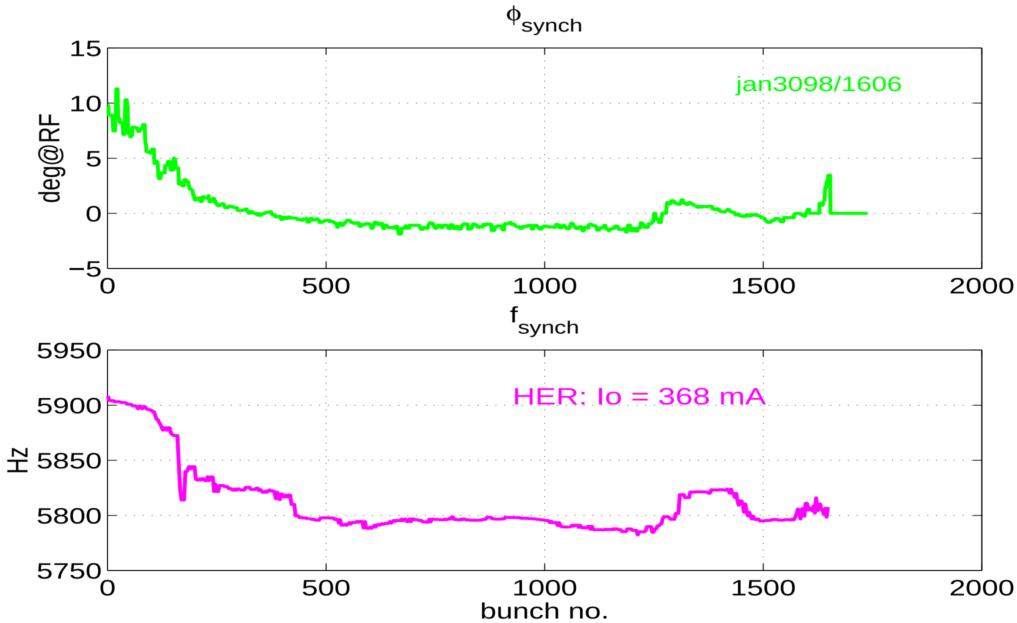

FIGURE 6. Upper figure: Synchronous phase variation across a 368 mA 1658-bunch HER beam due to a 5% gap in the bunch train. Lower figure: Corresponding bunch tune measurement.

to be oscillating at the same frequency. This is due to communication between bunches through wakefields. Bunches with approximately the same tune couple to each other and oscillate in the coherent mode most favored by the beam impedance. Each flat level in the tune transient thus represents at least one distinct coupled bunch eigenmode.

The decoupling of bunch oscillations due tune variation across a bunch train is illustrated by Figure 7. This figure shows lorentzian fits to the oscillation spectra of two bunches at the two extremes of the tune spread. We can see that the spectra show almost no overlap.

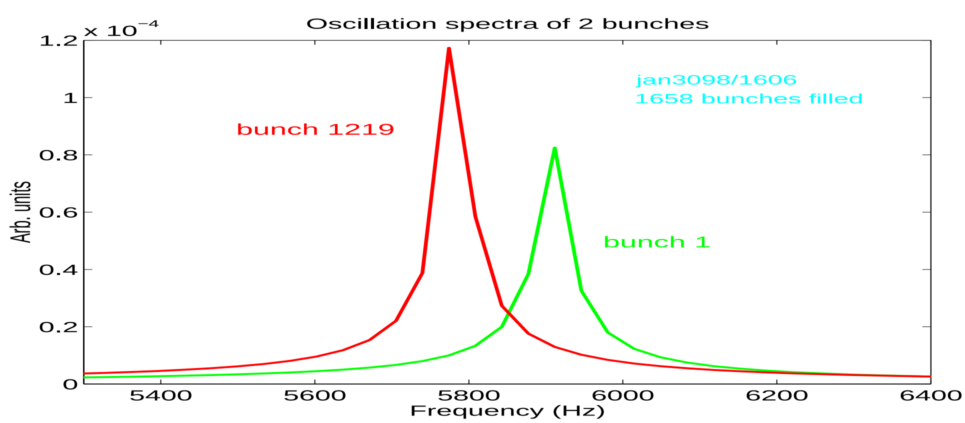

FIGURE 7. Decoupling of bunch spectra due to tune spread.

SUMMARY

Coupled bunch HOM-driven instabilities have been detected in the PEP-II HER at frequencies consistent with the largest measured cavity HOM. The modes are stable under the action of broadband longitudinal feedback.

A novel beam based technique has been used to measure the longitudinal impedance spectrum. The technique involves calculation of the transfer function from fill shape to multibunch synchronous phase. Bunch currents and synchronous phases have been extracted from feedback system data by demodulating the line harmonics that are common to the signals of all filled bunches. The transfer function method has been used to identify inaccurately parked idle cavities as the cause of the mode 3 instability observed during commissioning. Multibunch synchronous phase measurements take on added importance at PEP-II because of the need to match gap transients in the two rings.

Bunch tune variation due to gap transients has been shown to be large enough to decouple the oscillations of bunches in the beginning and middle of a train with a 5% gap at total currents below 400 mA. This contributes to the elevation of the coupled bunch instability threshold from the calculated value of 350 mA to the measured value of 550 mA (in the absence of longitudinal feedback).

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