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Beam Diagnostics Based on Time-Domain Bunch-by-Bunch Data*

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Abstract. A bunch-by-bunch longitudinal feedback system has been used to control coupled-bunch longitudinal motion and study the behavior of the beam at ALS, SPEAR, PEP-II, and DAΦNE. Each of these machines presents unique challenges to feedback control of unstable motion and data analysis. Here we present techniques developed to adapt the feedback system to operating conditions at these accelerators. A diverse array of techniques has been developed to extract information on different aspects of beam behavior from the time-domain data captured by the feedback system. These include measurements of growth and damping rates of coupled-bunch modes, bunch-by-bunch current monitoring, measurements of bunch-by-bunch synchronous phases and longitudinal tunes, beam noise spectra. A technique is presented which uses the longitudinal feedback system to measure transverse growth and damping rates. Techniques are illustrated with data acquired at all of the four abovementioned machines.

INTRODUCTION

A bunch-by-bunch feedback system has been developed by a multi-laboratory collaboration for control of coupled-bunch longitudinal motion at ALS, PEP-II and DAΦNE. The architecture of the system has been described in detail in earlier publications (1), (2), (3). DSP-based design allows synchronized real-time data acquisition in conjunction with feedback processing.

Table 1 summarizes the parameters of different machines on which the feedback system has been used. The feedback system is configured in each case to maintain constant ratio between the bunch sampling frequency and the synchrotron frequency. Downsampling matches the feedback processing rate to the longitudinal oscillation frequency and results in a significant reduction in the computational load on the DSP array as compared to the non-downsampling approach. Table-driven programmable downsampler module allows operation on the machines with widely different numbers of bunches and downsampling factors.

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TABLE 1. Machine parameters.

	ALS	DAΦNE	PEP-II	SPEAR
Number of bunches	328	120	1746	280
Bunch crossing rate, MHz	500 MHz	368 MHz	238 MHz	359 MHz
Revolution frequency	1.5 MHz	3 MHz	136 kHz	1.28 MHz
Synchrotron frequency	11 kHz	36 kHz	6 kHz	28 kHz
Growth time	2 ms	90 us	5 ms	16 ms
Downsampling factor	22	14	6	14
Bunch sampling rate	68 kHz	214 kHz	22 kHz	91 kHz
Growth time, samples	130	20	110	1500
Processors	40	60	80	40
Bunches/processor	9	2	22	7
Samples/bunch in a transient record	1008	4032	661	2016

DIAGNOSTIC TECHNIQUES

A large number of diagnostic techniques based on the time-domain transient and steady-state data have been developed. Transient data is used for measurements of growth and damping rates and injection transients. From steady-state data one can extract information on the system noise floor, and a set of bunch-by-bunch parameters such as currents, synchronous phases and synchrotron frequencies.

Different accelerators listed in Table 1 vary significantly in the growth times of the unstable modes. For example, at SPEAR growth time is comparable to the number of samples stored by the DSP. Techniques have been developed to facilitate growth and damping rate measurement in such cases. For weakly unstable modes positive feedback is used to speed up the growth. In cases when damping rates of naturally stable modes are to be determined, external excitation method is used (4).

Records of steady-state bunch motion provide a wealth of information about the beam and the performance of the feedback and RF systems. By capturing bunch motion while in negative feedback mode one can quantify the residual noise level due to quantization as well as determine frequencies and amplitudes of driven motion. Such measurements of driven motion were used during PEP-II HER commissioning to characterize performance of the RF system (5).

From steady-state records one can also extract information about bunch currents and synchronous phases. To measure bunch currents we detect the level of low-frequency driven motion, e.g. line frequency harmonics, in the signal of each bunch. Bunch-by-bunch synchronous phase information can be extracted from the DC levels of different bunches. Bunch currents and synchronous phases can be used to measure machine impedance at the revolution harmonics (6).

EXPERIMENTAL RESULTS

From steady-state measurements synchronous phase and synchrotron frequency per bunch can be extracted. In PEP-II bunches are driven by baseband RF noise. Within the bandwidth of the synchrotron resonance this noise has relatively flat spectrum. Consequently baseband driven motion of the bunches has spectral characteristics of a damped oscillator excited by white noise. To obtain bunch-by-bunch synchrotron frequency, second order oscillator response is fitted to power spectrum of the time-domain motion of each bunch. In the PEP-II, due to the low

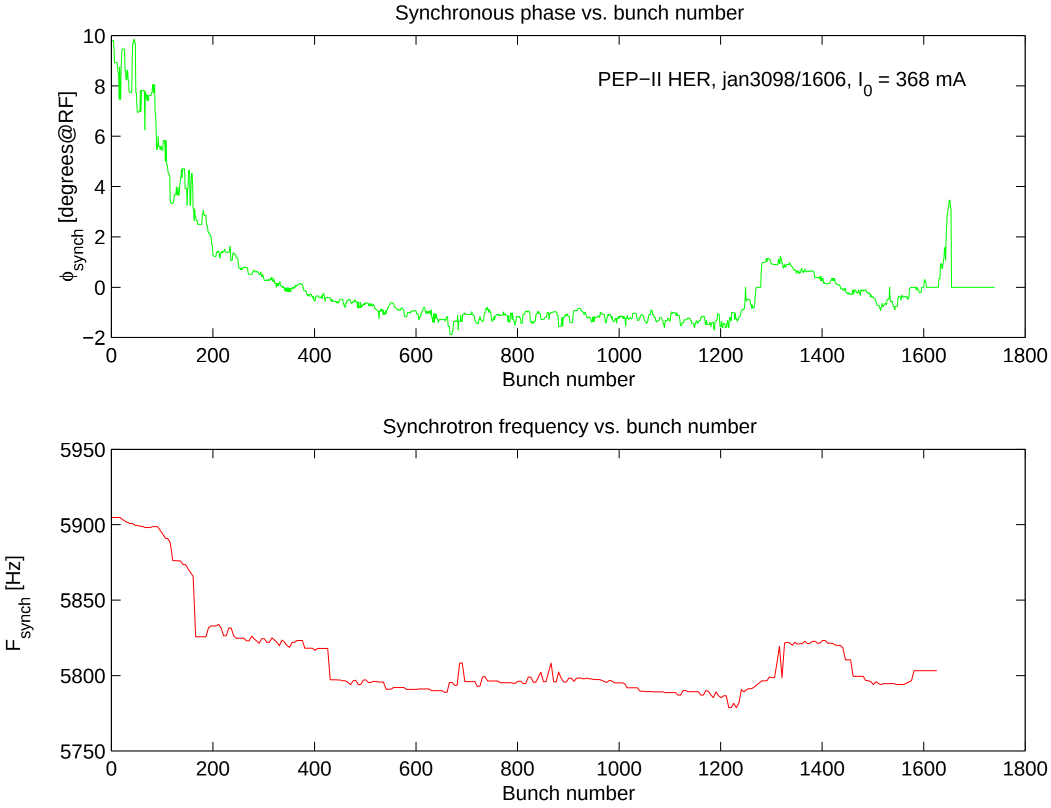


FIGURE 1. Synchronous phase (upper graph) and synchrotron frequency (lower graph) transient in PEP-II HER. Tune shift between the bunches in the head and the middle of the train is more than 100 Hz.

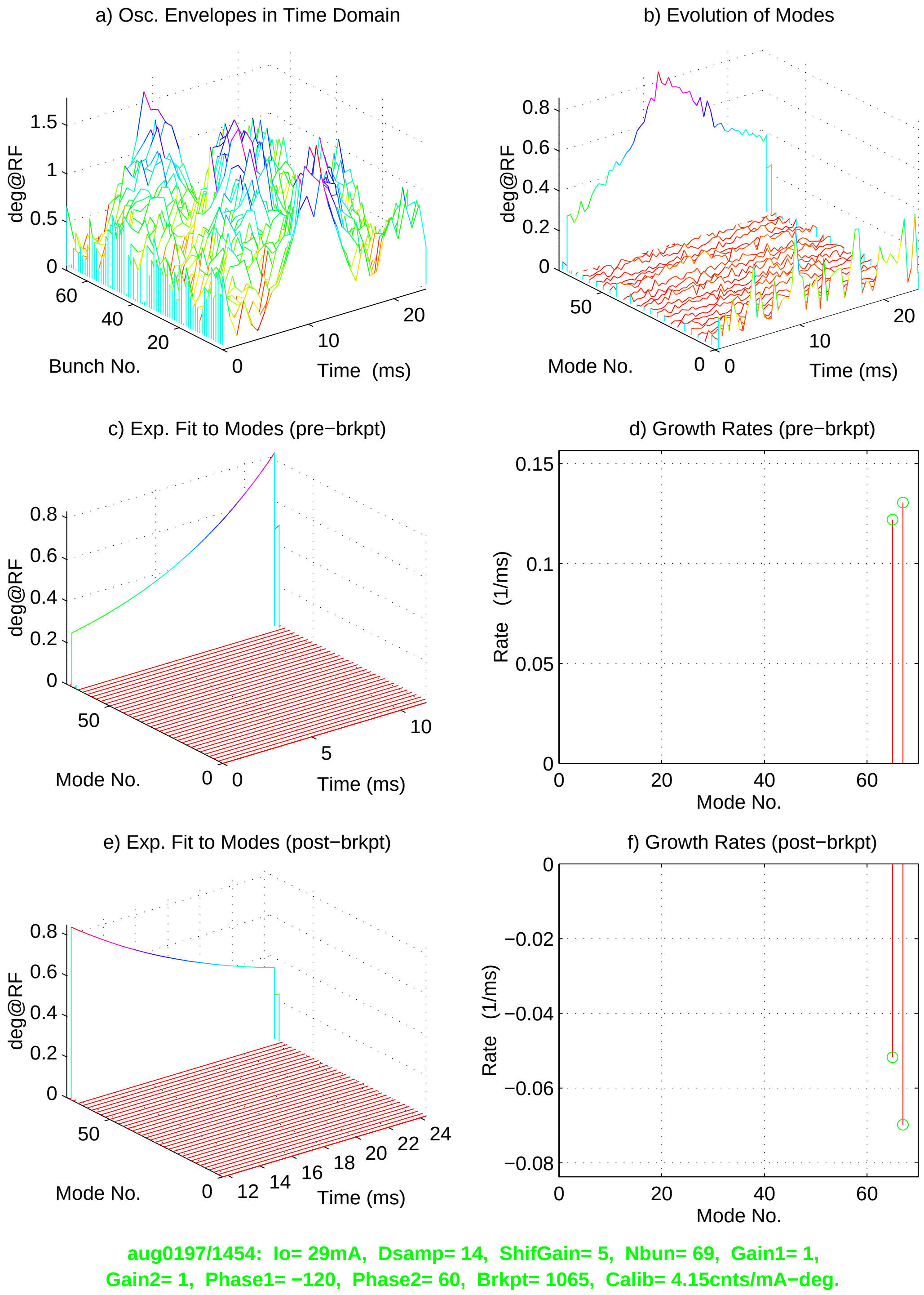


FIGURE 2. Grow/damp transient from SPEAR. System starts in the negative feedback mode controlling unstable motion. On software trigger the sign of the feedback is reversed (positive feedback) and after predetermined hold-off period, recording starts. At t=12 ms system returns to negative feedback and the damping transient is recorded.

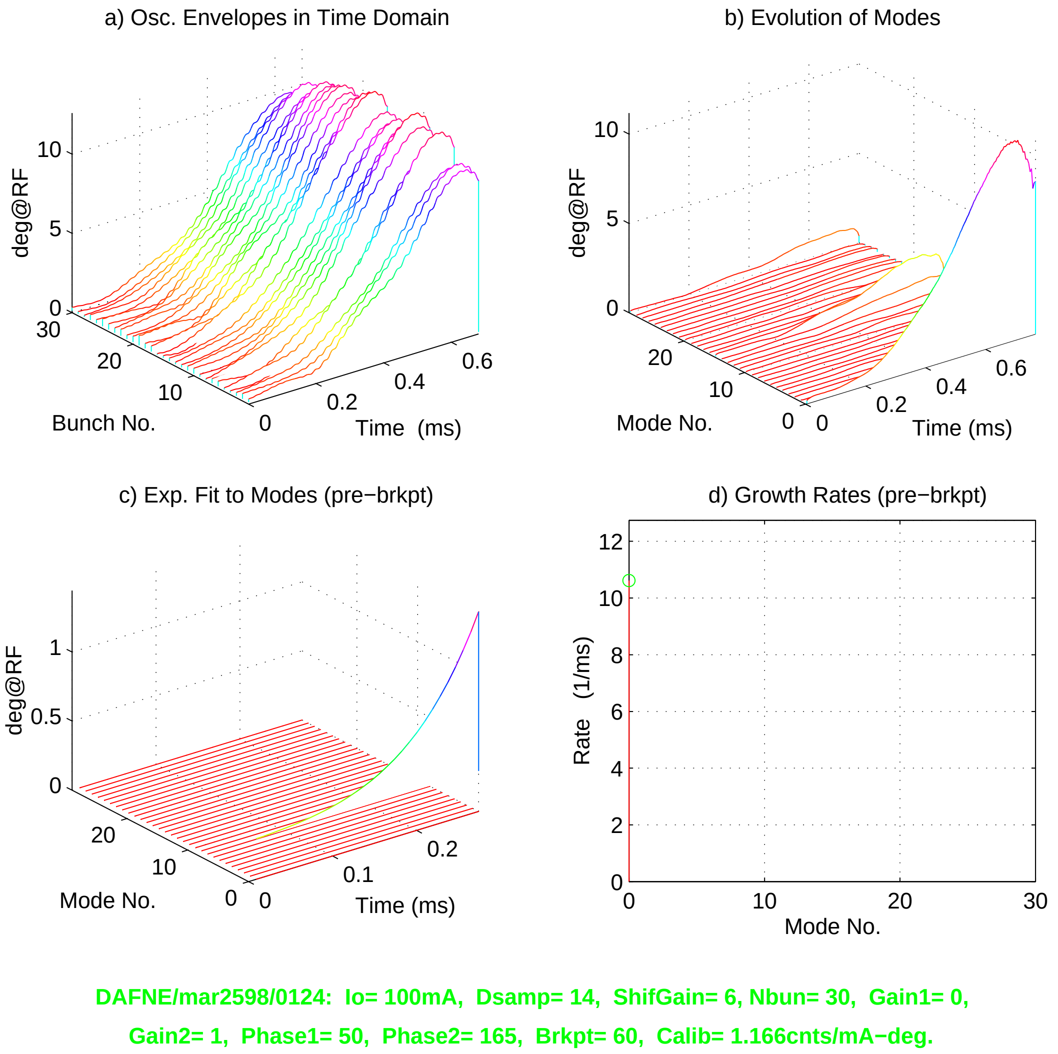
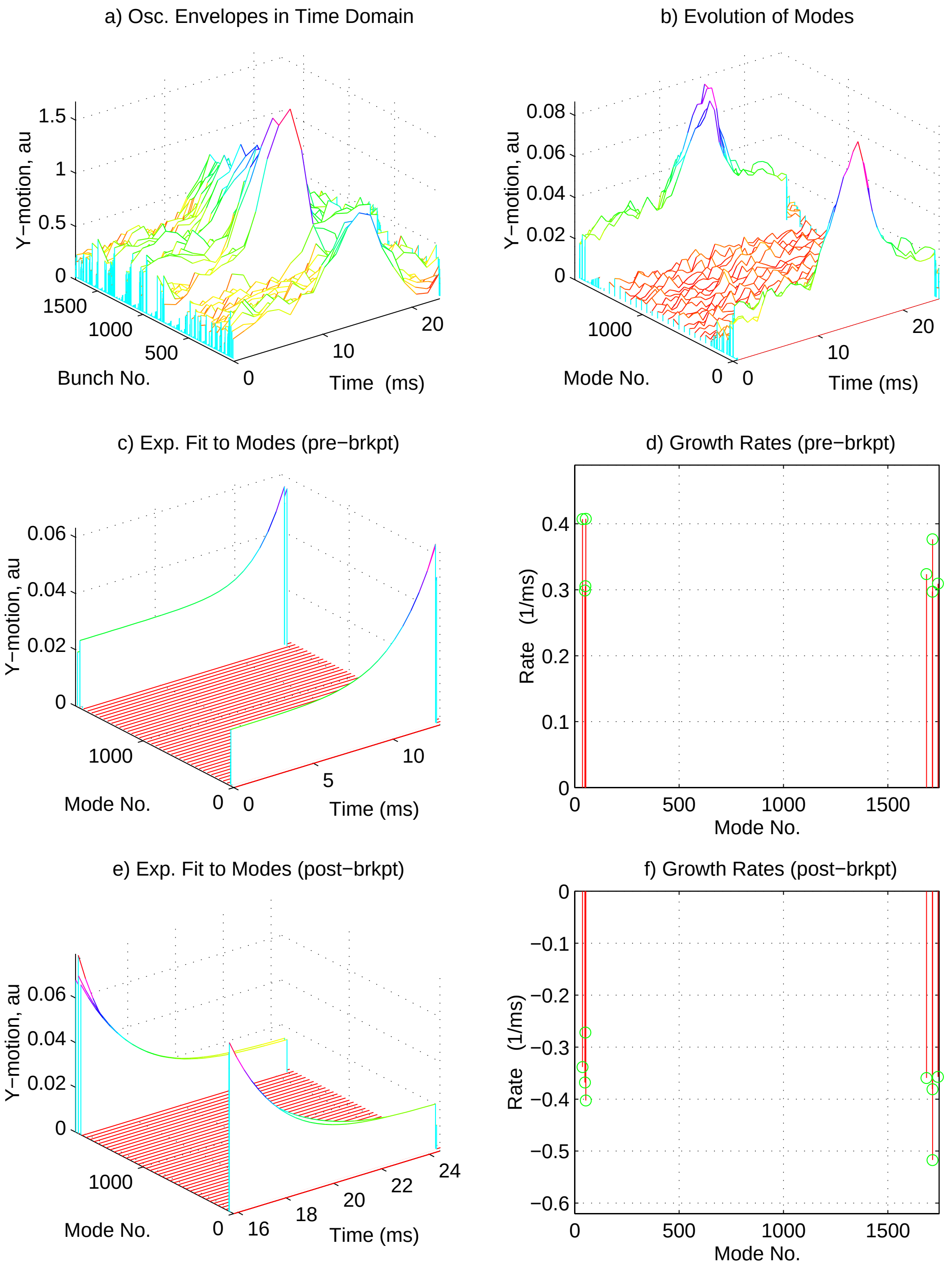


FIGURE 3. Grow/damp transient from DAΦNE. At t=0 feedback is turned off and oscillations of the bunches are recorded. In this transient the growth rate is 10.8 ms^{-1} and motion reaches the full-scale of the phase detector (15 degrees at RF) in 500 μs.

revolution frequency, there is a significant gap transient. This transient is characterized by the synchronous phase and synchrotron frequency variation as illustrated in Figure 1. Significant tune shift of the first group of bunches after the gap provides a possible explanation of the phenomenon observed in PEP-II HER using synchroscan streak camera (7) in which the head of the bunch train does not participate in unstable motion. Due to the tune shift bunches in the head of the train are effectively decoupled from the rest of the bunches.

As discussed earlier, the time scale of transient events differs significantly between different machines. Figure 2 shows a grow/damp transient from SPEAR. At this beam current the growth rate of the unstable modes is very low and positive feedback is used to speed up the growth. Two modes are excited in this transient


a) Osc. Envelopes in Time Domain

b) Evolution of Modes

c) Exp. Fit to Modes (pre−brkpt)

d) Growth Rates (pre−brkpt)

e) Exp. Fit to Modes (post−brkpt)

f) Growth Rates (post−brkpt)

PEP−II LER/jan2998/1558: Io= 195mA, Dsamp= 7, ShifGain= 0, Nbun= 1740, Gain1= 0.9, Gain2= 1, Phase1= 30, Phase2= −140, Brkpt= 302, Calib= 17.34cnts/mA−deg.

FIGURE 4. Transverse grow/damp transient from PEP-II. Two groups of modes participate in unstable motion. Exponential fits to the growth and damping portions allow to measure growth and damping rates for a large number of modes in a single transient.

and their growth and damping rates are measured. In case of DAΦNE the growth rates are an order of magnitude higher. A growth transient from the positron ring is shown in Figure 3.

Using the feedback system as triggered recorder it is possible to capture transverse grow/damp transients. Downsampling aliases betatron tunes to lower frequencies. However in this process phase information is retained, so the coupled bunch mode amplitudes can be reconstructed. Since the envelope of motion is of interest here, downsampling does not affect the measurement of growth and damping rates. Figure 4 shows such a measurement from PEP-II. In this case A/D was connected to the baseband vertical monitor output of the transverse feedback system to obtain bunch-by-bunch vertical positions. A mixer was used to open and close the vertical feedback loop under control of an external trigger. The same signal was utilized to trigger recording in the longitudinal system. In this measurement vertical feedback is turned off at t=7 ms. Bunch oscillations grow until t=11 ms at which point the feedback is turned on. In the modal domain we observe motion at the upper sidebands in two regions: low and high-numbered modes in the spectrum. This corresponds to upper and lower sidebands of the low revolution harmonics which are driven by the resistive wall impedance.

SUMMARY

Transient and steady state diagnostics based on the bunch-by-bunch time-domain data provide a versatile tool for study of longitudinal and transverse beam dynamics. DSP-based architecture and tight synchronization of the longitudinal feedback system support transient measurements in a wide range of beam conditions. Open software architecture allows to quickly develop and integrate new diagnostics.

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