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Multi-Bunch Longitudinal Dynamics and Diagnostics via a Digital Feedback System at PEP-II, DAΦNE, ALS and SPEAR*

J. Fox, H. Hindi, R. Larsen, S. Prabhakar, D. Teytelman, A. Young
Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

A. Drago, M. Serio
INFN Laboratori Nazionali di Frascati, 00044 Frascati (Roma), Italy

G. Stover
LBL, 1 Cyclotron Road, Berkeley, CA 94563

Abstract

A bunch-by-bunch longitudinal feedback system based on a programmable DSP architecture is used to study coupled-bunch motion and its sources. Experimental results are presented from PEP-II, DAΦNE, ALS and SPEAR to highlight the operational experience from 4 installations, plus show novel accelerator diagnostics possible with the digital processing system. Modal growth and damping rates are measured via short (20 ms) transient recordings for unstable and stable coupled-bunch modes. Data from steady-state measurements are used to identify unstable modes and noise-driven beam motion. A novel impedance measurement technique is presented which reveals the longitudinal impedance as a function of frequency. This technique uses the measured synchronous phase and charge of every bucket to calculate the impedance seen by the beam at revolution harmonics.

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System Description

Several of the new generation B factories, Φ factories and light sources require active feedback to control multi-bunch instabilities. A SLAC-LBL-INFN Frascati collaboration has developed a longitudinal damping system which uses a common processing architecture that is software configured for the individual conditions at each facility[1]. The ALS installation has been in operation since September 1995, while the PEP-II HER and DAΦNE systems have been commisioned in the last year[2, 3, 4]. One of the Frascati systems was operated at the SPEAR facility in the summer of 1997, and additional systems are in constrution for use at SPEAR, the Korean PLS and German BESSY light sources. Table #1 highlights the configurations used at the 4 installations. A comparison of the PEP-II and DAΦNE installations shows the use of downsampled processing to match the sampling rates to the synchrotron frequencies - the 120 bunch ring with the 36 kHz synchrotron frequency requires roughly 3/4 of the DSP processing of the 1748 bunch ring with the 6 kHz oscillation frequency.

Table 1: Longitudinal feedback operating configurations for four installations

parameter	**ALS**	**DAΦNE**	**PEP-II**	**SPEAR**
Number of bunches	328	120	1746	280
Sampling freq. (MHz)	500	368	238	359
Revolution freq. (MHz)	1.5	3	.136	1.28
Synchrotron freq. (kHz)	11	36	6	28
Min. instability growth time	2 ms	90 μs	5 ms	16 ms
Downsampling factor	22	14	6	14
Bunch sampling rate (kHz)	68	214	22	91
e-folding time (samples)	130	20	110	1500
DSP processors	40	60	80	40
Bunches /processor	9	2	22	7
Transient samples/bunch	1008	4032	661	2016

Transient-domain diagnostics

The programmable DSP system has the capability to record bunch motion as the feedback system operates. The raw oscillation co-ordinates of the bunches are a rich source of information about the operating conditions of the accelerator. We have developed Fourier transform techniques to compute frequency domain information from the time-domain data sets. The most direct analysis computes the power spectra of individual bunches, which shows the tune as well as any noise-driven bunch motion. The frequency resolution available with these techniques is 20 - 60 Hz with analysis spans of 1/2 the sampling frequency[5].

Another class of observations determines the unstable modes and growth/damping rates of the controlled system. Figure #1 is a grow-damp example from the ALS.

In this experiment the beam is initially stable under the action of the feedback system. Under software control the feedback gain is set to zero, and then restored to the operating gain after a 6 ms interval. The oscillation information can be visualised in a 2-D map of modal amplitude vs. time - from this processed data the exponential growth and damping rates can be measured. Figure #2 shows a very rapid growth of low-mode instabilities from DAΦNE commissioning - in this case the feedback OFF interval and the rapid growth rate allows such large amplitude motion that the feedback system cannot recapture the motion.

Figure #3 shows a related measurement from SPEAR, in which a naturally stable system is excited by positive feedback for the transient interval, then damped by negative feedback. This technique is useful at low (stable) currents to quantify the damping rates, and predict behavior at higher (unstable) currents. A variant of this transient technique to measure naturally stable modes involves using the feedback system to drive a narrowband excitation of a selected mode through the feedback processing and observing the free decay and fed-back decay rates of the selected mode in the 2-D transient plot.

These examples show systems where a relatively small number of coupled-bunch modes are unstable at an instant, or cases where a small number of modes have growth rates so much faster than other unstable modes that only a few modes dominate in the transient. The PEP-II HER ring has RF cavities with external damping, which significantly broaden the HOM resonances so that they fall across many revolution harmonics. PEP-II instabilities occur in broad bands of individual coupled-bunch modes, all with roughly equal growth rates. This behavior is shown in the beam pseudospectra[5] of figure #4. The data are taken at 331 mA (below the 550 mA threshold of instability), so the positive feedback technique is used to excite the modes closest to instability. Also shown in the figure is the measured strongest cavity HOM impedance[6] aliased into the 119 MHz baseband - there is excellent agreement predicting the band of 60 modes centered around the 770th revolution harmonic.

Synchronous Phases and Machine Impedance

The examples so far examine the oscillatory information present in the samples, but there is additional information in the DC component of the position of each bunch. If there is structure in the bunch filling pattern, or variation in current per bunch, the circulating bunch current driving the machine impedance generates a wakefield voltage which puts each bunch at a unique synchronous phase. Using the DC coupled feedback phase detector it is possible to recover the shift in each bunches' synchronous phase due to the wakefield - additionally the data can be manipulated to identify the current per bunch. This information can be used to calculate the net machine impedance seen by the beam at each revolution harmonic[7]. This technique provides information about impedance vs. frequency, as opposed to a technique which measures the integral of impedance vs. frequency, such as a measurement of single bunch phase vs. bunch current.

Figure #5 shows such a measurement taken during commissioning of the PEP-II HER. The figure shows the bunch current distribution of the fill, which is largely uniform with a step current discontinuity. The resulting transient in bunch synchronous phase is excited by the step current discontinuity and is seen to decay away after roughly three oscillatory cycles per revolution. The machine impedance calculated from these data is figure #6, with an 8 Mohm impedance around the third revolution harmonic. This impedance was discovered to be due to an incorrectly parked unpowered RF cavity, and was driving a strong instability at mode +3 at higher currents. Proper tuning of the parked cavies eliminated the instability (as well as reduce the measured impedance at the third revolution harmonic).

Summary

The time-domain data taken by the digital damping system provides several unique diagnostic measurements of longitudinal motion. The design purpose of the digital feedback system was to control longitudinal instabilities, and the system does exactly that in the four installations. The transient-domain grow-damp diagnostic techniques developed were central to understanding the performance of the feedback systems and estabishing the most useful operating configurations. With the commissioning experience gained from the 4 installations, we have developed new measurement techniques which can reveal additional information about the machine impedance and suggest sources and cures of unstable beam motion. The programmable and flexible structure of the DSP system has been central in adapting and developing new measurements.

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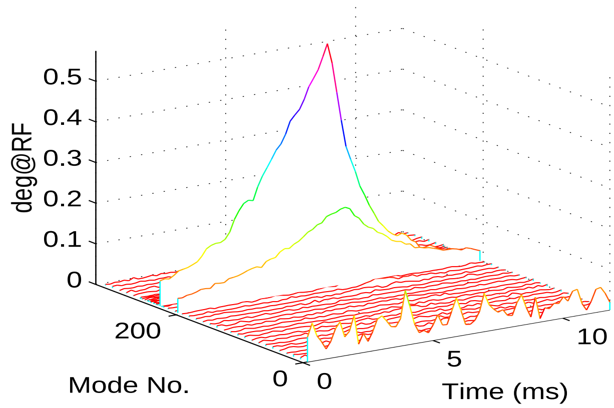

Figure 1: Grow-Damp modal transient from the ALS at 109 mA. The feedback is off for the growing portion of the transient, revealing naturally unstable motion at modes 204 and 233

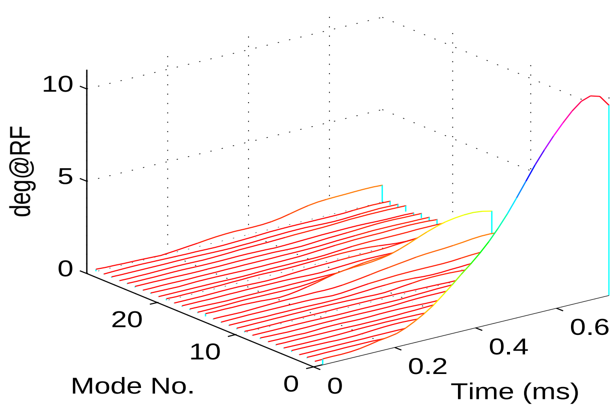

Figure 2: Modal grow-damp transient from DAΦNE. The feedback is turned off and mode 0 in the machine is unstable with a rapid growth rate of 11 ms^{-1}

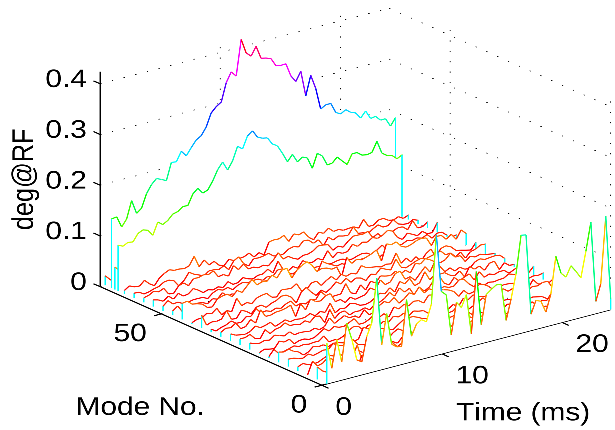

Figure 3: Grow-damp transient from SPEAR. The data is taken at 29 mA, for which the machine is below threshold. Positive feedback is used to excite the growing portion of the transient, revealing modes 65 and 67 as the two modes closest to instability.

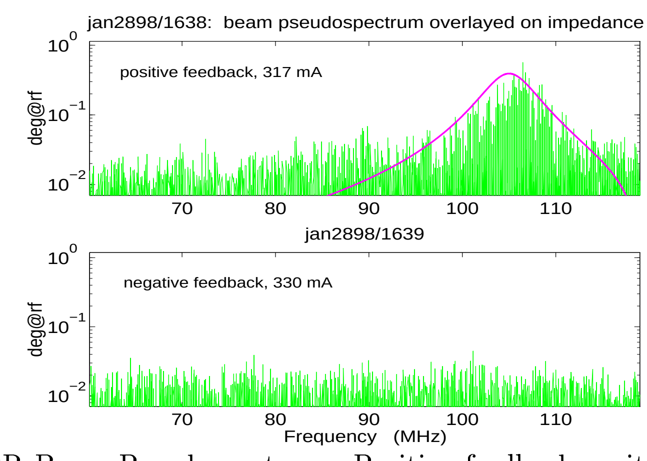

Figure 4: PEP-II HER Beam Pseudospectrum. Positive feedback excites a band of 60 coupled-bunch modes around the 770th revolution harmonic. The strongest cavity HOM impedance, aliased into the DC-119 MHz band, is overlaid, illustrating how the damped HOM is spread in frequency.

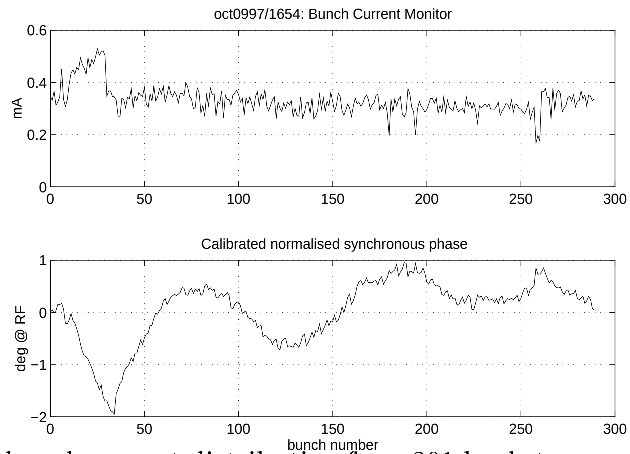

Figure 5: PEP-II HER bunch current distribution for a 291 bucket symmetric fill and the resulting variation in bunch synchronous phase. The step current distribution excites a wake transient which oscillates roughly three cycles in a turn.

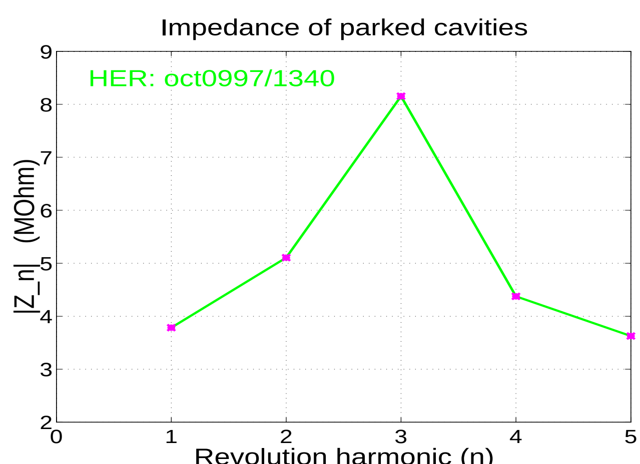

Figure 6: Computed machine impedance vs. revolution harmonic, from the data in Figure #5.