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Architecture and technology of 500 Msample/s feedback systems for control of coupled-bunch instabilities. *

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Abstract

Feedback control of coupled-bunch instabilities presents many challenges. Control bandwidths up to 250 MHz are required to damp all of the unstable coupled-bunch modes in recent accelerators. A digital parallel-processing array with 80 DSPs has been developed to control longitudinal instabilities in PEP-II/ALS/DAΦNE machines. Here we present a description of the architecture as well as the technologies used to implement 500 Msample/s real-time control system with 2000 FIR filtering channels. Algorithms for feedback control, data acquisition, and analysis are described and measurements from ALS are presented.

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Abstract

Feedback control of coupled-bunch instabilities presents many challenges. Control bandwidths up to 250 MHz are required to damp all of the unstable coupled-bunch modes in recent accelerators. A digital parallel-processing array with 80 DSPs has been developed to control longitudinal instabilities in PEP-II/ALS/DAΦNE machines. Here we present a description of the architecture as well as the technologies used to implement 500 Msample/s real-time control system with 2000 FIR filtering channels. Algorithms for feedback control, data acquisition, and analysis are described and measurements from ALS are presented.

1 INTRODUCTION

The operation of particle accelerators relies on complex accelerator control systems. Often these systems incorporate feedback loops to regulate operating parameters or compensate for time-varying perturbations to the accelerator systems [1]. The control algorithm might be adaptive or based on a model, but in general the closed-loop bandwidth of the controlled system is in hertz or tens of hertz. In contrast, this paper describes a different type of accelerator feedback control problem, where the system must control up to 2000 channels of dynamic motion requiring sampling rates and output correction rates of 500 MHz.

An important mechanism limiting operating current in modern high-current accelerators and light sources is coupled-bunch instabilities, in which the bunched charged particles in the accelerator exchange energy with parasitic resonators in the RF cavities and vacuum structures. Several new high-current colliders [2, 3] and light sources [4] use special feedback control systems to counteract coupled-bunch instabilities.

These systems can be understood using using a mix of time-domain and frequency domain signal processing concepts - often the control systems are thought of as bunch-by-bunch controllers, where each bunch in the accelerator has an independent control algorithm stabilizing it. In this picture, the systems are comprised of several thousand individual feedback control loops. Of course, the input data is a stream of bunches arriving every 2 ns, and the individual correction signals must be sequentially applied to the proper bunch at the same 2 ns rate. This high sampling and correction processing rate makes the implementation of these control systems technically challenging.

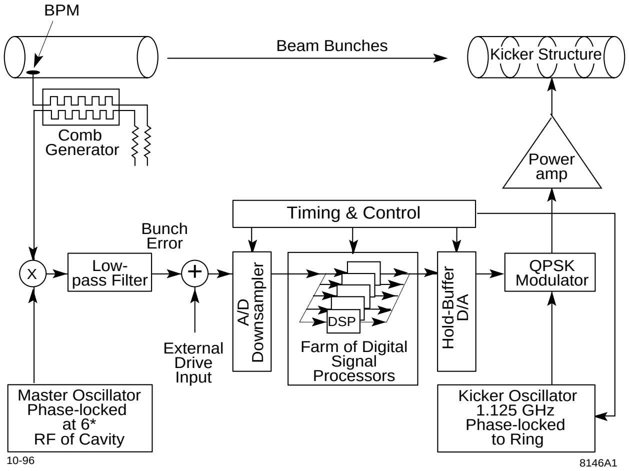

Figure 1: Block diagram of the longitudinal feedback system. The array of digital signal processors operate in parallel to compute correction signals on a bunch by bunch basis.

A general-purpose longitudinal system was developed to control instabilities in the ALS/PEP-II/DAΦNE colliders - it has since been installed and operated at SPEAR, BESSY-II and the PLS [5, 6]. As shown in Fig. 1 the system is configured in a mix of VXI and VME modules, and is based around an array processor of up to 80 individual digital signal processors. The aggregate instruction rate in this array processor is $3.2 * 10^9$ multiply-accumulate operations/sec.

The signal processing uses a phase-detection technique at 3 GHz (6*RF) to generate a baseband analog error signal from each bunch. A programmable downsampler digitizes this baseband stream at the RF frequency (up to 500 MHz) and assembles messages (containing bunch data and configuration information) for 4 consecutive bunches at a time. These messages are distributed using 1.3 Gb/sec links to one of 4 VME backplanes - in each backplane a master decodes the link messages, and performs read-modify-write cycles to the DSP board which has the past data from that particular group. The computed results are then transferred in the 1.3 GB/sec serial format back to the VXI hold buffer, which re-assembles the multiple data streams into a continuous baseband correction signal at the 500 MHz bunch rate. The baseband signal is then encoded onto a 9/4*RF QPSK carrier, amplified, and impressed on the beam in the vacuum kicker antenna structure.

The system developers have tried to make as much use of commercial standards and functions as possible. The choice of standard VME and VXI packaging, the use of off the shelf VXI and VME interface computers running VxWorks, and the selection of EPICS was a deliberate choice to make the operator interface and control functions readily

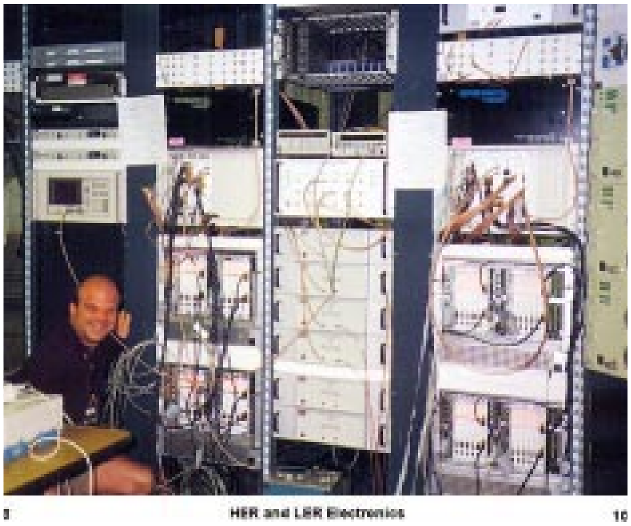

Figure 2: PEP-II LER and HER longitudinal systems. Each system uses a VXI crate and two VME crates for the core signal processing functions, with some RF and microwave functions in chassis form. A portion of the high-power (3 kW) broadband 1 - 2 GHz output microwave amplifiers are visible on the right.

transferable to several installations. Fig. 2 is a photograph of the systems installed at the PEP-II B-Factory.

The use of the programmable downsampler/holdbuffer and programmable DSP elements in the processing makes this a general-purpose signal processing system, rather than a hardwired special-purpose system configured to execute a dedicated algorithm. As such, the hardware modules running at the different labs are all the same, and the accelerator specifics of each installation (RF frequencies, harmonic number, synchrotron tunes, HOM patterns, etc.) are configured from a high-level software process which downloads the programmable elements. DSP codes have been written to implement a family of FIR and IIR control filters, plus additional system and diagnostic utility functions [7]. The programmability also allows the system to continuously grow with new measurement needs and opportunities - new DSP codes can implement entirely unforeseen control and measurement algorithms as accelerator conditions change [8].

2 ALGORITHMS FOR FEEDBACK CONTROL AND DIAGNOSTICS

The control of an unstable beam is very comparable to controlling an unstable configuration of coupled harmonic oscillators [9]. The equation of motion for a single simple harmonic oscillator $\ddot{x} + \gamma\dot{x} + \omega_0^2 x = U_{ext}$, (where the U_{ext} is a driving term) is directly applicable to a single particle bunch in the accelerator, where the natural frequency (ω_0) is the corresponding betatron or synchrotron frequency. The purpose of external feedback in such a system is to insure the γ damping term is positive, so that perturbations decay rather than grow exponentially. Systems to control instabilities increase the damping in this oscillatory system, adding to whatever natural damping may be present from radiation damping or other real impedances.

In a physical system with N coupled bunches, there are N eigenmodes of oscillation. In the frequency domain picture, for each mode there is some damping or anti-damping term from the external impedances, found from summing up the external impedances seen by the beam [10]. External impedances may be present with both damping and anti-damping effective sign - it is the anti-damping terms which drive instabilities. Equivalently, in the time-domain picture each bunch has some complicated driving term and some effective damping term.

In either formalism, the external feedback system adds back a derivative term to insure the stability of the system. The digital control system implements an FIR or IIR filter to compute the correction signal (the FIR is particularly simple in form) -

$$u_i(n) = \sum_{k=1}^{N} h(k)\phi_i(n-k). \qquad (1)$$

where $\phi_i(k)$ etc. is the history of the last k samples of bunch motion, and $h(k)$ a set of N filter coefficients. The coefficients $h(k)$ specify the impulse response of the filter - they are selected to give damping to the system, consistent with constraints on gain and phase margin to insure stability of the feedback controlled oscillator. There are additional practical constraints, such as noise-induced saturation, and control of DC offsets in the processing channel (or synchronous phase variations) considered in specifying the filter coefficients.

Because the filter is a software process, many interesting beam and system diagnostics exploit the flexibility of the processing. One technique very useful in understanding the dynamics of the system is to make the filter coefficients time-varying - for example, stabilizing the system, then for a short several millisecond interval lowering the gain, which allows instabilities to grow. The filter coefficients are then switched back to the stabilizing configuration. If the DSP programs record the beam motion during this transient, the data records can be analyzed to reveal a wealth of information about the beam and surrounding impedances. An example is shown in Figs. 3 and 4, which is such a grow-damp sequence from the ALS. The figures show the growth of unstable motion when the feedback is switched off - in the time domain the bunch envelopes show general increases in amplitude, while in the modal domain the data reveals the exponential growth of modes 204 and 233, followed by damping from the feedback system. Such measurements can also be performed below threshold on an otherwise stable system by exciting the beam with a short interval of positive feedback, then watching the natural damping in the system. Analysis programs have been developed to measure noise on the beams, quantify growth and damping rates, measure the current in individual bunches, measure the synchronous phase transients resulting from irregular fills or gap transients, and

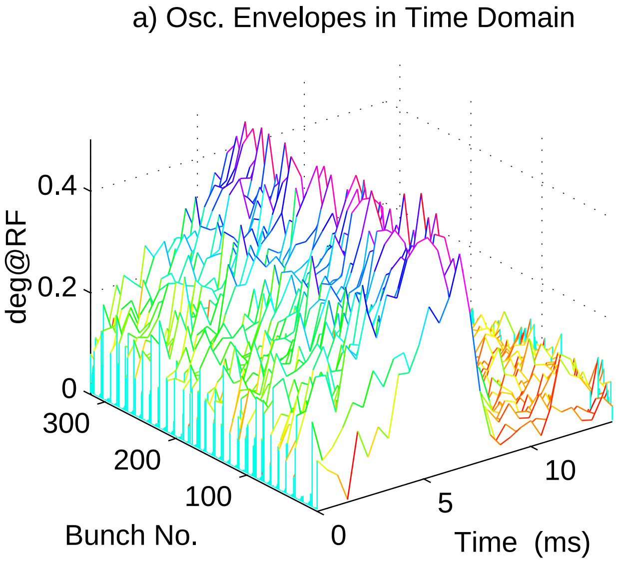

Figure 3: Envelopes of bunch oscillation show growing motion followed by damping

from these measurements compute the effective impedance seen by the beam [11, 12].

3 SUMMARY

The original PEP-II/ALS/DAΦNE longitudinal systems have been commissioned and the systems at SPEAR, PLS and BESSY are in commissioning. We continue to develop operating codes and accelerator diagnostics for longitudinal and transverse motion. The programmable architecture and flexible structure of the longitudinal processing system, especially the design features allowing transient-domain recording, have turned out to be useful for beam diagnostics in a degree the original designers never imagined. The information contained in the time-domain data, in conjunction with the development of new diagnostic codes, continues to surprise us with the variety and subtlety of the behavior of the beams.

4 ACKNOWLEDGMENTS

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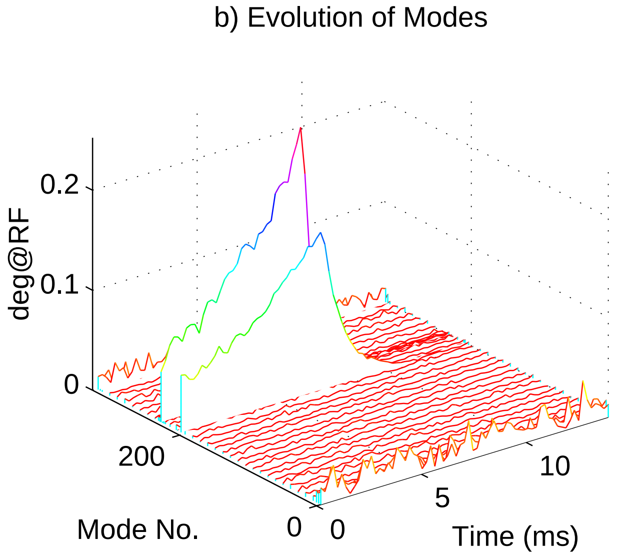

Figure 4: Bunch oscillation data transformed to modal domain shows modes 204 and 233

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