MULTIBUNCH FEEDBACK—STRATEGY, TECHNOLOGY AND IMPLEMENTATION OPTIONS[*]

J. D. Fox, N. Eisen, H. Hindi, G. Oxoby, and L. Sapozhnikov
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94309
I. Linscott
Stanford University, Stanford, California 94309
M. Serio
INFN Laboratori Nazionali, Frascati,

ABSTRACT

The proposed next generation accelerator and synchrotron light facilities will require active feedback systems to control multi-bunch instabilities. These feedback systems must operate in machines with thousands of circulating bunches and with short (2–4 ns) interbunch intervals. The functional requirements for transverse (betatron) and longitudinal (synchrotron) feedback systems are presented. Several possible implementation options are discussed and system requirements developed. Results are presented from a digital signal processing based synchrotron oscillation damper operating at the SSRL/SLAC SPEAR storage ring.

INTRODUCTION

The proposed next generation of high luminosity B factories, ϕ factories and synchrotron light facilities achieve their operating goals by populating many bunches at high currents[1,2,3]. This choice requires care in suppressing the growth of multi-bunch instabilities. Such instabilities are created by ring impedances which act to couple oscillations from a bunch to neighboring bunches and excite coherent large amplitude motion.[4] Each bunch can be thought of as a harmonic oscillator obeying the equation of motion

$$\ddot{x} + \gamma\dot{x} + \omega_0{}^2 x = f(t)$$

where ω_0 is the bunch synchrotron (longitudinal) or betatron (transverse) frequency, $f(t)$ is an external driving term and γ is a damping term. It is the purpose of an external feedback system acting on the beam to contribute to this damping term sufficiently so that external disturbances $f(t)$ driving the beam are controlled. The external feedback must sense the oscillation coordinate x, compute a derivative (or implement a $\pi/2$ phase shift at ω_0), and apply a correction signal back on the beam to create the γ damping term.

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Figure 1 presents the general form of a feedback controller applied to a dynamic system. This model shows a summing node, from which an error signal is generated, a feedback amplifier with complex gain $A(\omega)$, a second summing node which adds an external driving term $F(\omega)$, and a beam dynamics block with complex transfer function $H(\omega)$. The beam response acts back on the input summing node, closing the feedback loop.

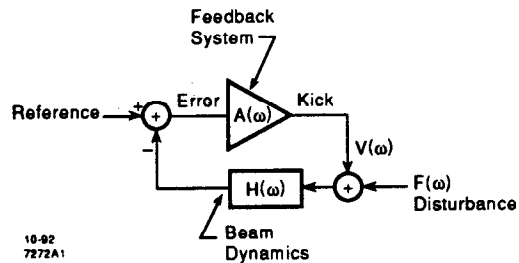Fig. 1. Conceptual diagram of a feedback system $A(\omega)$ acting to stabilize a system $H(\omega)$.

A disturbance $F(\omega)$ applied to the system is reduced by the feedback amplifier by the amount

$$\frac{H(\omega)}{1 + A(\omega)H(\omega)}$$

so that it is desirable to have a large loop gain $A(\omega)H(\omega)$. However, the gain cannot be arbitrarily large or the loop will oscillate at a frequency where the net phase shift around the feedback loop is $2n\pi$ and the magnitude of the loop gain $A(\omega)H(\omega)$ is equal to unity.

This picture can be applied to an accelerator feedback system, in which case the external driving terms reflect excitations from outside disturbances, such as injection transients, other bunches' coupling through ring impedances, or system noise. As the dynamics of the beam $H(\omega)$ is determined by accelerator design, the challenge to the feedback designer is to specify $A(\omega)$ so that the loop is stable, and the response to disturbances $V(\omega)$ is bounded and the transients well damped. The specification of $A(\omega)$, and the implementation of the feedback system has great importance for the ultimate equilibrium behavior of the closed loop system, and of the residual noise in the system.

For systems with N coupled oscillators, the combined behavior of the coupled oscillators can be expressed as a superposition of the N normal modes of oscillation, each with its own natural frequency ω_n. It is still possible to damp the motion of the oscillators by acting on each bunch as if it were a single oscillator.[5,6] In this case the coupling to other bunches is represented by the driving term $f(t)$ of the driven harmonic oscillator.

This model, which treats each bunch as an independent oscillator coupled to its neighbors through an external driving term, is the heart of a bunch by bunch feedback system. This system implements a logically separate feedback system for each bunch in a multibunch accelerator.[7--12] For accelerators with thousands of bunches, this approach requires that the implementation be compact, either by sharing some of the components between bunches (e.g., fast systems that are

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effectively time multiplexed between bunches) or by implementing parallel functions in a very efficient way (e.g., through electronic VLSI techniques).

Both longitudinal and transverse feedback systems can be described by Fig. 1. For the transverse case, the input set point is the desired orbit mean coordinate, and the output signal is applied via a transverse electrode assembly which acts with a transverse kick on the beam. For the longitudinal case, the set point refers to the desired stable bunch phase or energy, and the correction signal is applied back on the beam to change the bunch energy. While longitudinal and transverse systems share a simple conceptual framework, the technical design and implementation of these systems can be quite different, reflecting the actual dynamics of the beam and the signal processing techniques chosen.

One fundamental difference between longitudinal and transverse accelerator feedback systems is the ratio of the oscillation frequency ω_0 to a sampling frequency. If the beam is sensed at a single point in the orbit, any motion is sampled at the revolution frequency ω_{rev}. If $\omega_{rev} \geq 2\omega_0$, the Nyquist sampling limit is not exceeded and spectral information is not lost. As synchrotron frequencies are typically lower than revolution frequencies the sampling process does not alias the longitudinal oscillation frequency. However, in the transverse case betatron frequencies are greater than revolution frequencies, and the sampling process aliases the oscillation to a different (aliased) frequency. Thus, the transverse signal processing must operate at an aliased frequency, and be capable of operating over a range of aliased frequencies representing the machine betatron tune operating range.

SIGNAL PROCESSING OPTIONS

One of the most interesting design options for these systems are the technical choices involved in the error signal processing. This block has several essential functions:

Detect the bunch oscillation

Provide a $\pi/2$ phase shift at the oscillation frequency

Suppress DC components in the error signal

Provide feedback loop gain at ω_0

Implement saturated limiting onlarge oscillations.

Provide processing gain, e.g., as the input signal may be noisy, apply processing techniques to reduce the noise ultimately put back onto the beam.

These requirements describe a bandpass filter, centered at the oscillation frequency ω_0, with some specified gain and a $\pi/2$ phase shift at ω_0. DC rejection of the filter is necessary to keep the feedback system from attempting to restore a static equilibrium position to an artificial set-point. For example, a transverse static orbit offset from a pickup or from a true orbit offset should not result in the feedback system coherently kicking the beam in an attempt to force a new mean orbit. Similarly, if a ring has a ion clearing gap in a filling pattern, there will be an RF transient which places the first bunches after the gap onto

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unique synchronous phases. In this case the longitudinal feedback system must restore oscillating bunches back to their own synchronous phases as opposed to a single common set point. This DC rejection constraint means that a simple time delay is not suitable for a feedback filter. The filter should also reject signals above the oscillation frequency to prevent noise or other high frequency signals from being mixed down into the filter passband and impressed unto the beam. The limiting function allows a bunch to have a large oscillation, larger than the available kicker power can restore with linear operation, but still be kicked with the maximum kicker field with the correct algebraic sign. This limited processing allows injection (and large amplitude excitation of the injected bunch) while still damping neighboring bunches in a linear regime. The saturated processing has been shown to suppress the growth of coherent instabilities from injection-like initial conditions.[1,13]
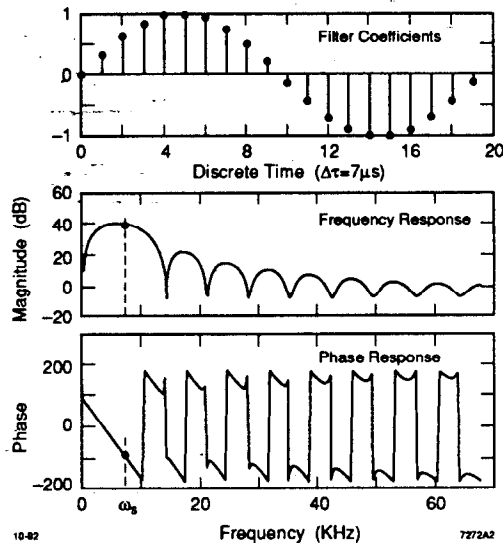

Fig. 2. Impulse response (a) and frequency response (b) of a 20 tap FIR filter.
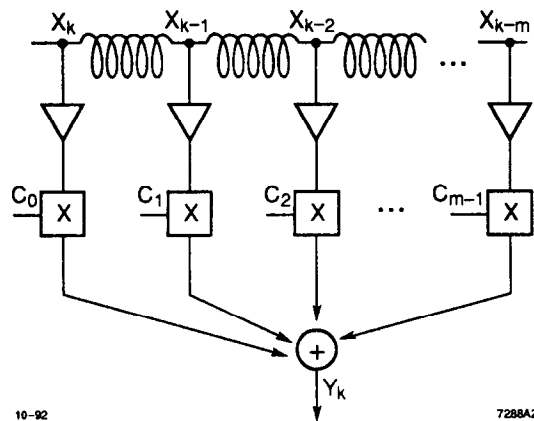
Fig. 3. Signal flow in an m stage analog FIR filter.

For systems with only a few bunches to control one could implement the feedback filters as individual analog bandpass filters.[14] However, for systems with thousands of bunches a more efficient approach is to take advantage of the inherent sampling at ω_{rev} and implement the filter as a convolution filter of either finite impulse response (FIR) or infinite impulse response (IIR) forms. An FIR filter is a convolution in the time domain

$$Y_k = \sum_{n=0}^{m-1} C_n X_{k-n}$$

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where Y_k is the filter output on sample k, X_k is the filter input on sample k, and m is the length of the filter (or number of past input samples used to generate an output). The coefficients C_i describe the impulse response of the filter in the time domain. Figure 2 shows the impulse response and frequency response of a 20 tap FIR filter optimized for a 136 kHz sampling frequency and a 7 KHz oscillation frequency.

These filters can be realized by several approaches. An all-analog approach is possible, in which one might implement the required feedback filter as a transversal filter. As sketched in Fig. 3, the convolution is implemented with several stages of tapped delay lines. At each tap a propagating signal X_{k-n} is multiplied by a coefficient C_n. A parallel summing stage then implements the sum over n and produces an output Y_k. Such an approach looks desirable in that a single device could process all bunches, but dispersion and losses in the delay line must be matched to the filter properties. As an example, a longitudinal filter for a PEP II-like facility (136 kHz ω_{rev}, 7 kHz ω_s) with 4 ns spacing between the bunches would require a total delay time of roughly 140 μs with a signal bandwidth of greater than 120 MHz to provide isolation between the bunches. This delay bandwidth product τB of $1.7 * 10^4$ is impossible to achieve with surface acoustic wave (SAW) filters ($\tau_{max} B = 1 * 10^3$) or even superconducting delay lines. Another approach might use a charge coupled device (CCD) technology to implement the tapped delay line of a transversal filter, with analog multiplexing to select a particular bunch on selected turns, several analog multiplying stages and an analog summing stage to implement the filter. It is also difficult with CCD technology to implement a system with the required delay-bandwidth product in a compact and power efficient manner. An electro-optical approach, in which an optical fiber delay line with low dispersion and large bandwidth ($\tau_{max} B \geq 10^6$) is used to implement the time delay is feasible. Such an scheme requires a modulator to put the signal on the optical carrier, passive or active taps to implement the convolution filter, and at least one (more likely m) demodulators and the summing stage.

One disadvantage with all these approaches is the need to implement programmable bipolar tap coefficients, as any change in operating parameters that change the oscillation frequency (machine tune, RF voltage, lattice parameters, etc.) require new filter coefficients. Additionally, all of the analog based approaches do not simply implement the desired limiting function. A true limiter, with zero AM to PM conversion, is a specialized circuit at these frequencies, and would not offer a simple means to change the limiting value, or system gain, without much adjustment of circuit components.

In contrast, digital signal processing techniques look very attractive as the means to implement the feedback filter. A digital feedback filter architecture is sketched in Fig. 4. In this scheme a digital memory, organized as a circular buffer of length m, implements the time delay, while a second circular buffer holds a

coefficient array C_n. The figure shows how a single multiply-accumulate stage can calculate the output signal Y_k by summing over a sequence index m. Additionally, as the feedback process only uses information from a particular bunch to compute the feedback signal for that bunch, a parallel signal processing is feasible. In this approach many processors operate in parallel, each tracking and processing a fraction of the total bunch population.

This approach is particularly well matched to the commercial activity in digital signal processing microprocessors. The synchrotron frequencies are audio frequencies, so that processing blocks optimized
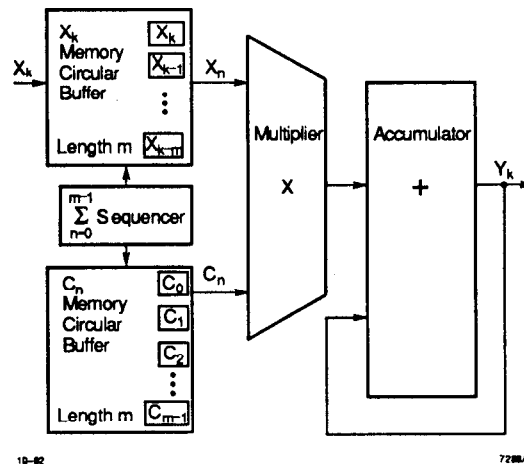

Fig. 4. Signal flow in a digital FIR filter with a single multiply-accumulate stage.

for audio and speech applications serve very well as processing elements. These programmable components offer the possibility of a general purpose feedback architecture which is configured via software to match the particular operating characteristics of an accelerator. A programmable and modular system also allows a single design to be utilized by several facilities, and development costs to be amortized over multiple feedback installations.

FUNCTIONAL REQUIREMENTS

A bunch by bunch time domain system with digital signal processing can be partitioned into major functional components comprising:

Beam pickup—to transform motion of the beam into electrical signals.

Oscillation Detector—to process the pickup signals into an error signal.

Fast Error Digitizer—to convert each bunch's error signal to a digital quantity.

Error Signal processing—required to compute a correction signal to be applied to a bunch from the error signal. It may be useful to use information from several turns of a bunch's error signal in each calculation.

Fast D/A and Kicker Modulator—to convert the computed error signals to an analog signal appropriate for the kicker stage.

Power Amplifier—to generate the high power signal to be applied to the beam.

Beam Kicker Structure—to apply a correction signal to the beam.

These functions must be performed in synchronism with the machine revolution frequency and bunch crossing frequency. For proposed bunch intervals of 2-4 ns, these functions must be implemented with electronic systems with adequate bandwidth to avoid creating multi-bunch coupling in the feedback system itself. We can estimate the required bandwidth of the total system by budgeting an allowable amount of interbunch coupling in the feedback system, and estimating the frequency response required. As an example, for the PEP II, 4.2 ns bunch interval, and an allowable 5% (−26 dB) coupling, a first order system would require a time constant

$$\tau = \frac{-4.2 * 10^{-9}}{\ln 0.05}$$

or a total system 3 dB bandwidth of 120 MHz. As the overall response is the product of all the individual responses, achieving these wideband functions requires care in design.

It is the large processing bandwidth required to separate signals from bunches only a few ns apart, and the need to provide up to several thousand processing channels that drive the technology required to practically implement multi-bunch feedback systems. To illustrate several technical options the PEP II longitudinal-feedback system design will be presented, and the technology of several key constituents detailed.

PEP II LONGITUDINAL FEEDBACK SYSTEM DESIGN

Figure 5 shows the essential components of the proposed PEP II longitudinal feedback systems. This system uses a pickup and comb generator structure to generate a short (eight cycle) tone burst at the sixth harmonic of the ring RF frequency. This burst is multiplied (mixed) with the 6xRF reference, and the phase error signal digitized at the 238 MHz bunch crossing rate. A digital signal processing block is used to process the error signals, and a fast D/A is used to convert previously calculated feedback correction signals and apply them to the bunches via a power amplifier and longitudinal kicker. A group at Lawrence Berkeley Laboratory has been developing the wideband longitudinal kicker.[15] It is a wideband drift tube structure that operates at 1.071 GHz. Table 1 summarizes technical specifications for the longitudinal system, while more detailed system and component descriptions are found in Ref. 1.

The proposed longitudinal system performance has been studied using a machine simulation model/feedback system model code.[13,16] This numeric simulation models the bunch to bunch coupling of higher order modes of the RF cavities and includes engineering level descriptions of the feedback components. With this model it is possible to explore operation of the ring in various

Table 1: Longitudinal Specifications Summary

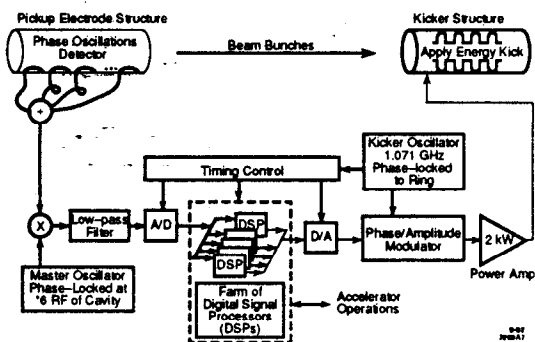|	
RF frequency [MHz]	476
Bunch interval [ns]	4.2
Beam pickup central frequency [MHz]	2856
Phase detector dynamic range (at 476Hz)	$\pm 15°$
Phase detector resolution (at 476Hz)	$0.5°$
Bunch-to-bunch signal isolation [dB]	> 30
Kicker structure operating frequency [GHz]	1.071
Output power [kW]	2.0
FIR tap length, m	5
Down-sampling factor, n	4

Fig. 5. Block diagram of the PEP II longitudinal feedback system.

conditions (injection, steady state, unequal bunch currents, etc.) and understand the impact of various electronic parameters (such as input noise, bunch to bunch coupling in the kicker or pickup, quantizing effects in the A/D and D/A stages, FIR filter coefficients, etc). This simulation model has been applied to produce system designs for the PEP II B factory, the LBL Advanced Light Source, and the Frascati ϕ factory DAϕNE.[17,18]

This system uses a phase detector based front end which directly measures the time (phase) of arrival of a bunch. An alternative approach would measure the transverse displacement of a bunch in a dispersive region. However, the dispersive displacement technique does not reduce the bandwidth requirements in any way, and adds to the filter requirements the need to reject any betatron oscillations present in the detector. The approach selected utilizes a periodic coupler microwave circuit to generate a short (several nanosecond) tone burst from the beam. This burst can be generated from a circuit of the type shown in Fig. 6. Note that this structure is not a resonant circuit with a finite Q, but a coupler structure with a length shorter than the inter-bunch period. The operating frequency of this comb generator is a tradeoff between the increased resolution available at higher frequencies balanced against the concomitant reduction in unambiguous operating range resulting from operation at a large multiple of the ring RF. The PEP II designers have selected the sixth harmonic of the ring RF

(2856 MHz or 6x 476 MHz) which allows a 30 degree operating range at the 476 MHz fundamental. Figure 7 shows the measured response of an eight cycle comb developed as part of the PEP II effort.
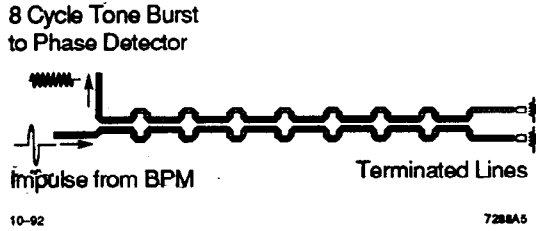

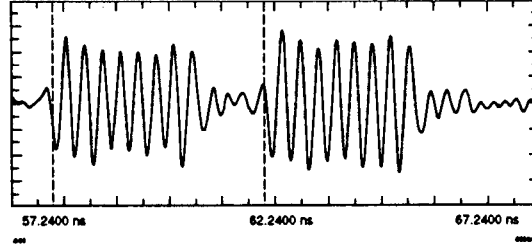Fig. 6. Eight-Tap Stripline Comb Generator Circuit.

Fig. 7. Measured time response of the comb generator for two simulated beam signals with 4 ns spacing.

This tone burst is phase detected against a 2856 MHz reference and the mixing product digitized at the 238 MHz bunch crossing rate. The digitizer selected must have an input analog bandwidth sufficient to maintain the bunch to bunch isolation, and a digitization time consistent with the interval between the bunches. The PEP II designers have specified the eight bit resolution TKADC series components from Tektronix, which are available with 1200 MHz input bandwidth and 2 or 4 ns pipelined conversion cycle times.[19] The back end digital to analog function is just as important, and the PEP II system is based on the TQ6122AM D/A from Triquint Semiconductor. This eight bit resolution part has a 2ns settling time to .4% and is well matched to the system requirements.[20]

Table 2 presents measured resolution, noise and isolation results for the PEP II prototype system front end (driven with simulated beam pulses from step recovery diodes at the 238 MHz bunch rate). The table shows results for two designs of comb generator circuits.

Table 2: Isolation, Resolution, and Noise Measurements

Comb Generator	Configuration	Isolation
Coaxial	A to B	25.9 dB
Coaxial	B to A	28.5 dB
Microstrip	A to B	26.7 dB
Microstrip	B to A	29.4 dB
Phase Detector Range		$\pm 15°$ at 476 MHz
Phase Detector Resolution		1.3 mRad at 476 MHz
	or	0.08° at 476 MHz
Phase Detector Noise		1.55 mRad rms at 476 MHz
	or	0.09° rms at 476 MHz

Table 3: DSP Farm Scale for Three Accelerators

Parameter	PEP II	ALS	DAϕNE
Number of bunches	1746	328	120
Number of filter taps	5	5	5
τ_r Revolution period [sec-1]	7.3E-6	6.6E-7	326E-9
τ_r Synchrotron period [sec-1]	1.4E-4	7.9E-5	26E-6
τ_s/τ_r	19.2	121	79.8
Down-sampling factor	4	24	16
Filter MACS/sec	3E8	1E8	1.2E8
Overhead cycles/filter	11	11	11
Overall processor cycles/sec	1E9	3.3E8	3.7E8
Processor cycle time	50 ns	50 ns	50 ns
Number of DSPs	50	18	20
Number of Boards	14	5	5

The PEP II longitudinal digital processing system takes advantage of the fact that the revolution frequency (sampling frequency) is greater than the synchrotron frequency. This inherent oversampling allows the use of downsampled processing, in which information about a bunch's oscillation coordinate is only used every n crossings, and a new correction signal is updated only every n crossings.[21,22] This approach allows the processing system to operate closer to the Nyquist limit and reduces the number of multiply-accumulate operations in the feedback filter by a factor of $1/n^2$. The PEP II longitudinal system has been specified for a downsampling factor of 4, while smaller rings (such as the ALS or the Frascati ϕ factory DAϕNE) would operate with downsampling factors of 24 or 16, respectively. The downsampled processing technique allows the use of arrays or "farms" of commercial single chip DSP microprocessors to very compactly implement feedback systems for thousands of bunches.

We can estimate the scale of this processing farm knowing the number of processing cycles required to compute a correction signal for a bunch, considering the cycles of processing "overhead" required per bunch (to maintain data lists, etc.) and knowing the synchrotron frequencies and number of bunches of a proposed accelerator. Table 3 estimates the scale of a DSP farm required for longitudinal feedback for the PEP II, ALS and DAϕNE accelerators. These farms might be packaged as boards, each with 4 DSP processors, organized into crates of roughly 16 boards. As shown in Table 3, a B factory processing system fits into two VME crates.

Figure 8 sketches the organization of such a processing farm based around a processing module containing four DSP processors. Only the fast front end, downsampler, hold buffer, and output stages must run at the fast beam crossing rate. The DSP processors run in parallel at a lower rate determined by the synchrotron frequency and the downsampling factor n. Note that this approach still kicks every bunch on every turn, and uses the kicker power efficiently.
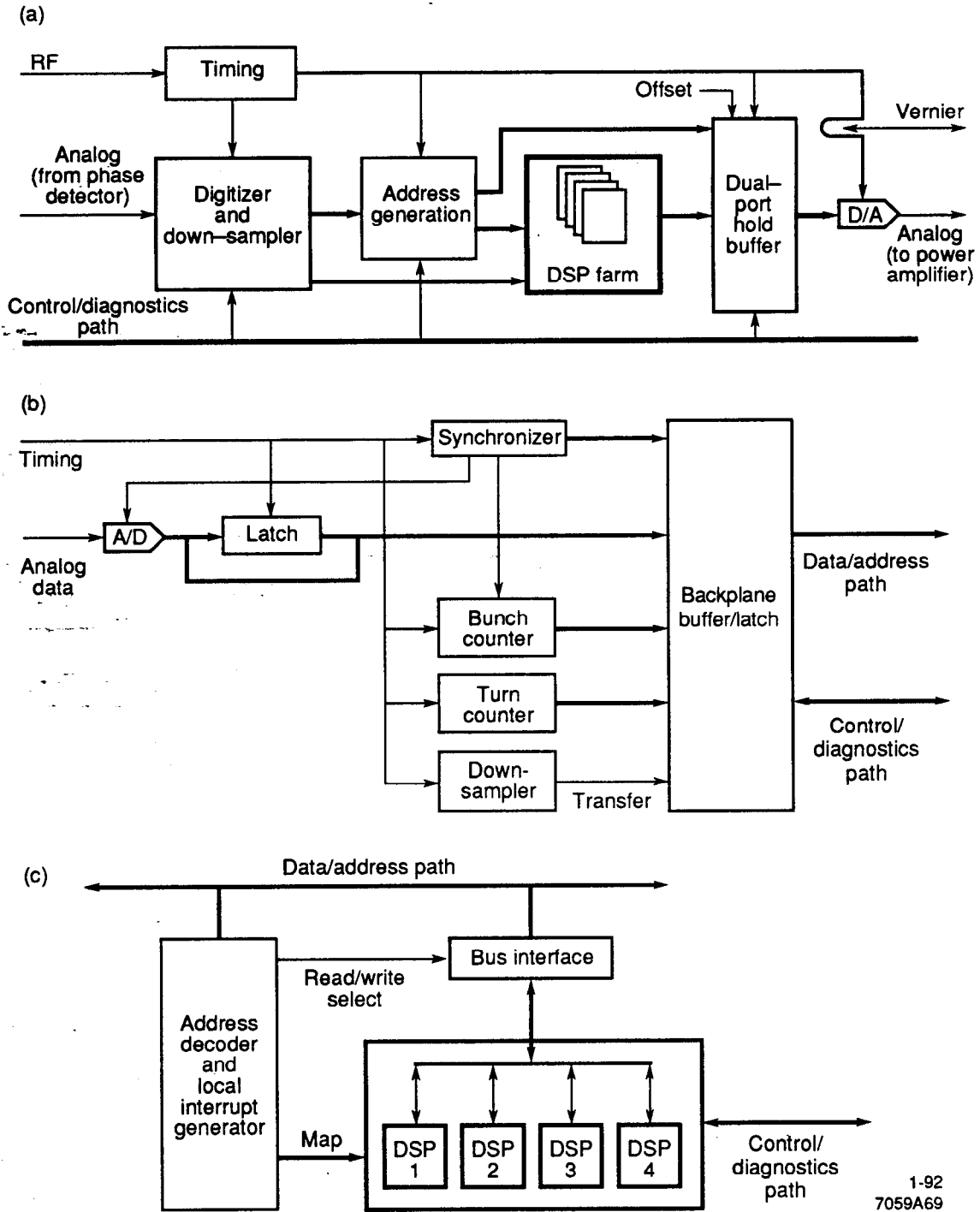
(a)

(b)

(c)

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Fig. 8. Block diagram of (a) the digital signal processing in the longitudinal system, (b) the down sampling block, and (c) the four processor DSP module.

OPERATION OF A DSP FEEDBACK SYSTEM AT SPEAR

A laboratory prototype longitudinal feedback system has been developed at the Stanford Linear Accelerator Center.[23] This lab model implements a full speed (500 MHz) front end phase detector with digital signal processing for a limited number of bunches. This prototype system has been demonstrated on the SSRL/SLAC storage ring SPEAR. As the SPEAR storage ring does not have a wideband kicker, it is not possible in this configuration to control multiple bunches, though it is possible to measure multi-bunch effects using the fast front end.

It is possible to operate this feedback system around a single stored bunch by using the main RF cavity as a beam kicker, and demonstrating the behavior of a single bunch acted upon by a digital feedback system. This approach follows naturally from the logical model of the bunch by bunch system. The behavior of various filter parameters (tap length, downsampling factor, etc.) can be studied with a real beam, and the performance of the front end comb generators, digitizers, etc. measured using realistic conditions. For this experiment the beam was sensed via a button-type BPM electrode and processed by the prototype B factory front end. The phase detector and phase-locked master oscillator was operated at 8X the SPEAR main RF frequency (2864 MHz or 8x 358 MHz) using the comb generator circuits developed for the PEP II prototype. The front end digitizer was run at the nominal 4 ns digitizing cycle, and downsampling circuits were provided to implement a programmable downsampler and hold buffer for a single bunch system. A single AT+T 1610 DSP processor was used to compute the feedback filter.[24] The feedback signal was then put back unto the beam via a phase shifter acting on the RF cavity phase.

A few examples from these measurements help illustrate some of the basic principles of longitudinal feedback systems. For these examples a 5 tap FIR filter, operating with a downsampling factor of 8, was used as the feedback filter. The SPEAR ring was operated with a nominal synchrotron frequency of 32 KHz, and the revolution frequency in SPEAR is 1.28 MHz. Thus, a downsample by 8 filter only updates a new result every 8 turns, while the ring itself requires roughly 40 orbit revolutions to complete a synchrotron oscillation.

Frequency domain measurements of this system can be made by driving the beam via the RF cavity while observing the response of the beam as a function of frequency. Figures 9a and 9b shows the magnitude and phase responses of the beam transfer function for an open loop configuration, and for closed loop gains of 18 and 28 dB. In this figure the open loop response shows a weakly damped harmonic oscillator as described by Equation 1, with a Q of roughly 200. The natural damping present in this case is due to Robinson damping as well as radiation damping. We see in the figure the action of the feedback system to increase the damping term in Equation 1, and lower the Q of the harmonic oscillator. The configuration with 28 dB of loop gain barely displays any resonant behavior ($Q = 5$), and suggests that the transient response of the combined system will damp in a few cycles.
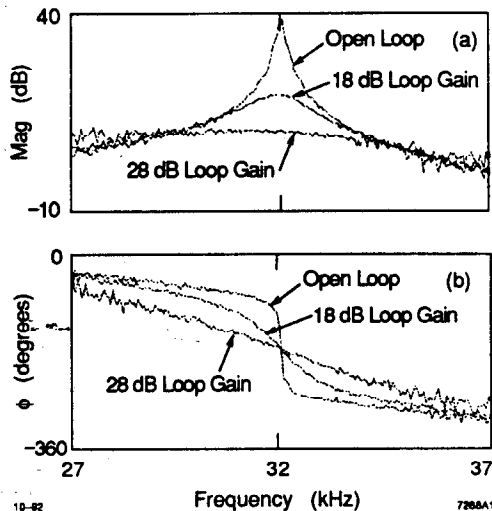
Fig. 9. Magnitude (a) and Phase (b) response for a single bunch for open loop and closed loop gains of 18 and 28 dB. The associated Q factors are 200 (open loop), 20 (18 bD) and 5 (28 db).
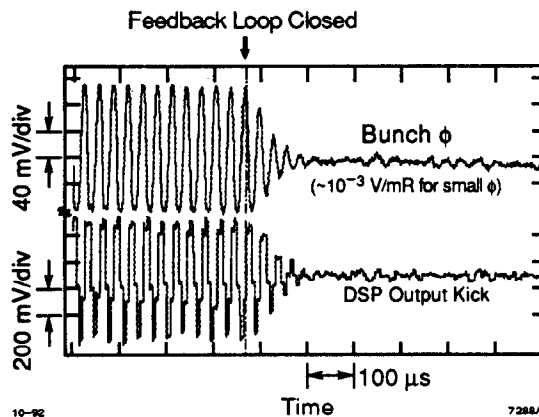
Fig. 10. Time response of an excited bunch and the DSP filter output. The feedback loop is closed at the time of the dotted line in the figure.

The time response of the system can be observed in Fig. 10. In this experiment the feedback loop is opened, and a gated burst at the synchrotron frequency is applied via the RF cavity. This excitation burst drives a growing synchrotron oscillation of the beam. The excitation is then turned off and the feedback system loop closed. The damping transients of the beam can then be studied for various designs of feedback filter and overall loop gain. The figure shows the damping transient of such a gated burst for a 33 dB loop gain configuration, which provides damped transients of only a few cycles. An alternative method of studying the transient response is to operate the feedback system with overall positive feedback for a short interval, which causes any noise present at the synchrotron frequency to produce growing oscillations. After an interval with positive feedback, the overall gain can be made negative, which then damps the oscillations. This process can be made periodic, and the growth/damping rates studied for various configurations of filter gains, such as phase shifts and electronic imperfections.

SUMMARY AND DIRECTIONS FOR THE FUTURE

A working collaboration has been formed between workers at SLAC, LBL, INFN Frascati and the Stanford Electrical Engineering department to jointly design and develop these next generation feedback systems. This group is continuing the development of the longitudinal system prototype, based on the PEP II design, and is collaborating on the design of a transverse prototype. The

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goal of this group is to produce functional modules that may be used by several laboratories, and to develop modular and scaleable feedback system designs which use common hardware configured via software to specify the operating parameters of a system. Results from longitudinal system tests at the LBL ALS facility are expected in the summer of 1993.

ACKNOWLEDGEMENTS

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