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Downsampled Bunch-by-Bunch Feedback for PEP II*

H. A. Hindi, D. Briggs, J. Fox, W. Hosseini, A. Hutton

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

I. INTRODUCTION

The PEP II B Factory requires a feedback system to damp out longitudinal synchrotron oscillations. A time-domain bunch-by-bunch feedback system has been proposed in which each bunch is treated as an oscillator being driven by disturbances from the other bunches. This is shown in Figure 1.

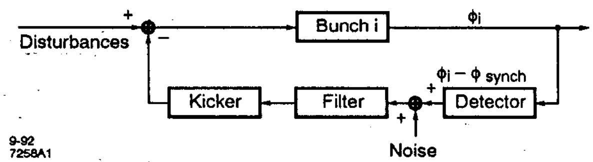

Figure 1: Conceptual diagram of bunch-by-bunch feedback. The phase of each bunch is detected and a feedback signal particular to that bunch is produced by the filter and is applied via the kicker.

The phase is detected, filtered, and the feedback correction signal is applied by the kicker. Since we are damping energy oscillations using measurements of phase, the required feedback signal must be proportional to the amplitude of the phase oscillations but phase shifted by 90 degrees. This signal must be calculated for each of the 1658 bunches, in parallel. In the original proposal, it was estimated that a farm of approximately 480 digital signal processors (DSPs) would be required to implement the feedback system. However, using the technique of downsampling, this number can be reduced to about 50 DSPs. In what follows, we will briefly explain the basic idea of downsampling and its implementation.

2. DIGITAL FILTERS

The filtering of the detected phase signals is done in the DSPs. These compute the correction signal using a finite impulse response (FIR) digital-filter algorithm. If the input to the digital filter is a sequence of samples of the phase oscillations of a bunch $\phi(t_n)$ then the output of the digital filter $y(t_n)$ is given by a discrete-time convolution

$$y(t_n) = \sum_{k=0}^{N-1} h(k)\phi(t_{n-k}). \quad (1)$$

where $h(k)$, $k = 0 \ldots N-1$, are the coefficients of the digital filter. So basically, the present output is given by the weighted sum of past inputs. An important thing to note about the equation is that the summation requires N multiplications and N additions or N MACs. Figure 2 shows an N-tap FIR digital filter implemented as a tapped-delay line.

The approach of using digital filters to compute a feedback signal which is simply 90 degrees out of phase with its input may seem like a very complicated solution to a very simple problem. For example, one could argue that a simple cable-delay line would achieve the same thing. However, in PEP II each bunch will be riding on its own synchronous phase (with respect to the RF), especially if they are close to the gap and hence a different DC offset must be subtracted from the phase of each bunch. The digital filters proposed in [1] and [3] are very simple yet they provide DC rejection and the proper phase shift. Also, their coefficients, $h(k)$, are programmable, which makes the system versatile and easy to adjust to different operating conditions and even to different machines. The reader is referred to [3] for more details on the digital filters to be used in PEP II, and to [6] for basics of digital filters.

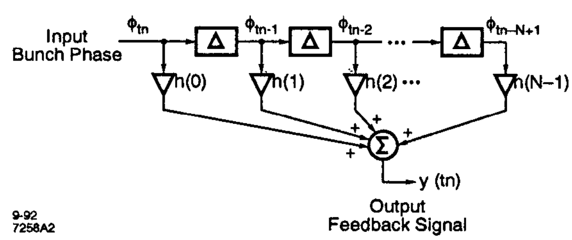

Figure 2: an N-tap FIR digital filter. Delta indicates a unit time delay.

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3. Idea Behind Downsampling

In PEP II, each bunch crosses the detector about 20 times per synchrotron oscillation period. In the original system design it was suggested that the 20 past-phase measurements should be used in equation (1) to compute the feedback correction signal. However, the Nyquist Sampling Theorem states that it is possible to completely recover a signal from its samples provided that the signal is band-limited and that the samples are taken at least at twice the highest frequency present in the signal (Nyquist frequency). In particular, if the signal is a pure sinusoid, then it is possible to detect its amplitude and phase using as little as two samples per period. In practice, however, sampling rates of twice the Nyquist frequency are used (using two samples per period is not reliable since sampling exactly at the zero crossings of the sinusoid could give no signal). Twice the Nyquist frequency corresponds to four samples per period, so 20 is clearly redundant.

Simulations on PEP II show that the least number of samples per period that could be used is five (the oscillations were not pure sinusoids). This corresponds to using five coefficients in equation 1, i.e., a five-tap FIR filter. Therefore only every fourth measurement of phase (out of the 20 measurements of phase per period) is used and the three in between are simply rejected. This is called downsampling by a factor of $n = 4$.

4. Implementation of Downsampling

Downsampling is incorporated into the original feedback system by modifying the loop in Figure 1 with two new components: the down sampler and hold buffer, see Figure 3 (the ADC and DAC are also shown).

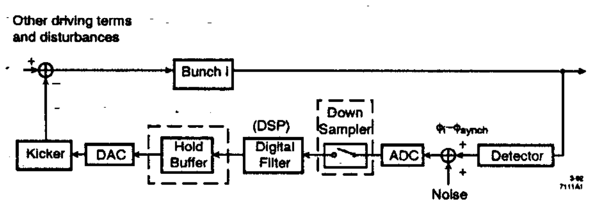

Figure 3: The down sampler allows the DSP to operate at a much lower rate and the hold buffer repeats the most recent kick until the next one is computed.

The down sampler passes only every nth measurement to the digital filter. The filter will compute a new feedback signal every nth turn. In the meantime the hold buffer repeats the last correction signal for $n - 1$ turns until the next filter update. In this way the filter processes only $1/n$ times the amount of data and has n times longer to compute the feedback signal. So the overall reduction in the number of MACs is $1/n^2$.

5. Effects of Downsampling on Beam Dynamics*

In this section, the performance of a non-downsampled feedback system is compared to n=2 and n=4 downsampled systems.

Computer simulations were performed on an accelerator model with ten bunches in which all bunches but the fifth start at equilibrium [3]. The fifth bunch is perturbed by 100 mrad to simulate injection. The whole system is then observed until all bunches are damped to steady state. The simulations included 5% of full-scale white noise in the phase measurements and a single higher-order mode in the cavity. Table 1 shows the feedback system parameters which were kept constant for all three cases.

Table 1: Simulation system parameters

Linear midband filter gain	100 V/mrad
Input quantization size	1.3 mrad
Output quantization size	50 V
Input noise amplitude (rms)	8.3 mrad
Kicker saturation voltage	4 kV

The effects of downsampling on the beam dynamics were compared quantitatively using figures of merit. These are shown in Figure 4. The slope in the saturated feedback region is a measure of the the efficiency of the feedback during the period when the phase deviation is so large as to saturate the feedback system. The slope upper bound is determined by the kicker power while an incorrect phase shift in the filters can reduce it. An exponential fit to the region where the feedback system is operating linearly gives an exponential damping time constant. This is determined by the overall gain of the system at the synchrotron frequency. The steady state behavior is quantified by the rms of the phase deviations from the equilibrium phase.

Table 2 shows the figures of merit for the transient behavior. These figures remain essentially constant as the downsampling factor is increased. We conclude that n=2 and n=4 downsampling has no significant effect on the transient damping dynamics of the beam.

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* These results were also presented in [1].

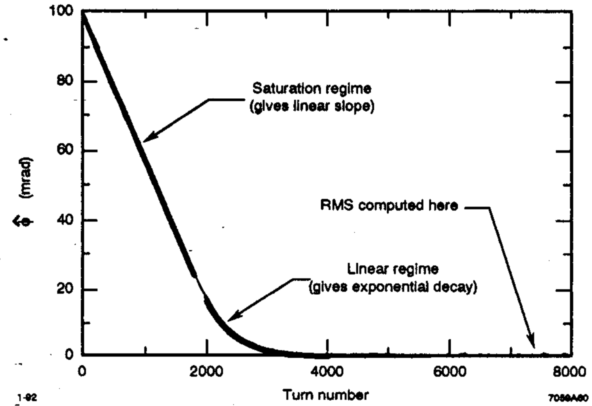

Figure 4. Plot of the phase-space error amplitude for an injected bunch, indicating the operating regimes used to compare filters.

Table 2: Simulation saturation slopes and exponential decay time-constants

	20-tap (n = 1)	10-tap (n = 2)	5-tap (n = 4)
Saturation slope (mrad/turn)	–41	–41	–38
Exponential time-constant (turns)	1098	1102	1111

Figure 5 shows the rms phase error in steady state versus downsampling factor for four bunches roughly equally spaced through the bunch train of the ten bunches. The rise in rms phase error with downsampling factor is mainly the result of the downsampled filters being more broad band than the non-downsampled one (see Figure3). An equivalent time domain argument is that for higher n, we have fewer coefficients, and are therefore sampling fewer data points and thus less able to average out the uncorrelated noise (see Equation1). However, although the rms phase error for each bunch rises with downsampling, they are all kept to within 0.65 mrad, one-half of the quantizing resolution of the input. Thus we conclude that for n = 2 and n = 4 the downsampling has no significant effect on the steady state characteristics of the beam.

The effect of the hold buffer on the final feedback signal in the time domain is shown in Figure 6 (a). The repetition introduces some coarseness into the signal. The fourier transform of these signals, shown in Figure 6 (b), shows the same effect in the frequency domain.

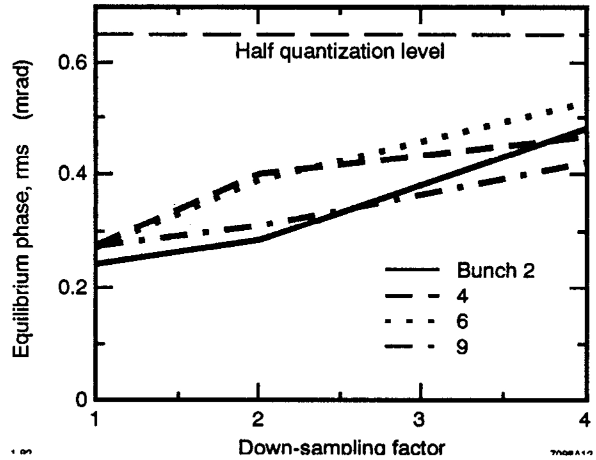

Figure 5. Performance comparison, for several bunches, of the three filters (n=1,2,4) in terms of equilibrium rms phase noise.

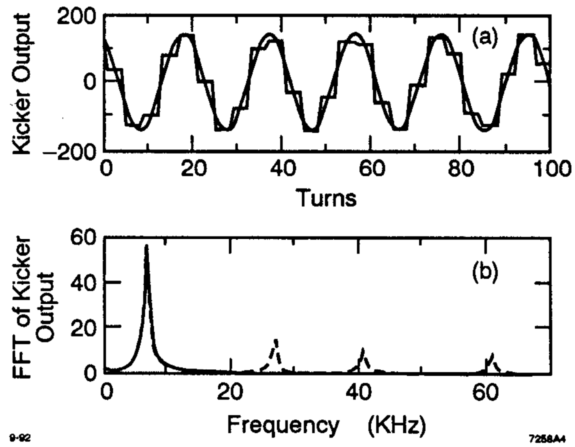

Figure 6. (a) nondownsampled and downsampled kicker outputs for a particular bunch- time domain; (b) non-downsampled and downsampled kicker outputs - frequency domain.

This shows that there are new harmonics present in the feedback signal, but the important thing to note is that the fundamental at the synchrotron frequency of 7 KHz is almost unaffected so the bulk of the power of the feedback signal is still at the fundamental, as it should be. Also, since the beam has such a narrow band response, it will couple very poorly to these new harmonics and hence their effect on the beam dynamics is minimal.

6. CONCLUSION

We have discussed briefly some of the basic principles behind down sampling and its implementation in the bunch-by-bunch feedback system for PEP II.

Figures of merit defined on the transient and steady state dynamics of the beam have allowed a quantitative evaluation of the performance of the feedback system with various down sampling factors. These results show that for n = 2 and n = 4 down sampling has virtually no adverse effects on the beam transients or the steady state behavior. These results, together with the large savings in technical complexity of the hardware due to the reduced computational load on the DSP processors, suggest that down sampled processing is an important development for the practical implementation of the digital feedback system.

ACKNOWLEDGMENTS

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