Longitudinal Multibunch Feedback Experiment with Switched Filter Bank*

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Abstract

Fast bunch to bunch feedback is necessary to control instabilities caused by coupled bunch oscillations in high intensity machines. A time domain active feedback scheme is discussed with focus on effective error detection using simple analog filters. Fast electronic switches direct each beam bunch signal from a beam pickup to a corresponding filter. The filters are excited at steady states. The output of the filters are steady sine waves tracking the phase and amplitude variations of individual bunches, allowing easy phase comparison with a reference rf signal. Amplitude detection of the signals yields valuable information of higher order beam oscillation modes. The beam motion information is processed and multiplexed to a fast phase or amplitude modulator that drives a wideband kicker. The feedback system can also be used to correct individual bunch oscillations caused by injection errors in larger machines filled by a number of booster cycles.

I. INTRODUCTION

Classical global rf beam feedbacks are effective in damping the coherent synchrotron oscillations and are widely used in modern synchrotrons [1]. When the oscillations vary from bunch to bunch, such as in the case of coupled bunch oscillations [2], coherent feedback is no longer effective. The feedback in such a case needs to be bunch specific and can be implemented in either frequency or time domain [3].

In the frequency domain method, sidebands responsible for the oscillations of various modes are identified, processed and fed back to a wideband correction kicker. Elaborate filters, usually realized by digital signal processing technology, are used to provide the necessary transfer function of the feedback loop. The technique can possibly damp very fast instability growths relative to the synchrotron tune. No instantaneous error detectors and modulators are necessary since the feedback works entirely in the frequency domain. The signal processing filters, however, need to know accurate information about the oscillations since prescribed phase and amplitude characteristics must be realized at various sideband frequencies.

The time domain method treats individual beam bunch as a harmonic oscillator coupled to adjacent bunches. The motion of the bunch can be described as that of an undamped simple harmonic oscillator:

$$\ddot{x} + \omega_s^2 x = f(t) \tag{1}$$

where x can be either the phase or energy variations caused by oscillations, ω_s the synchrotron oscillation frequency, and $f(t)$ the driving term. If the driving term $f(t)$ can be made to contain a term that is proportional to the first time derivative of x, damping can be achieved. In practice this is realized by detecting x and phase-shifting it by 90 degrees, resulting in a net differentiated term. The signal is then used to modulate a wideband rf cavity. In this method, exact information of oscillations is not necessary and a properly designed system can cover synchrotron tunes varying with time.

So far as damping is concerned, the two methods are equivalent and output the same correction signals to the wideband kicker [3].

II. IMPLEMENTATION OF TIME DOMAIN FEEDBACK

Our damping experiment uses the time domain method, with focus on effective error detection.

For the dipole mode oscillations, the time domain method must pick up the beam phase or energy error with respect to a reference. Energy errors can be picked up by position detectors in a region of high dispersion. The post-detection signal processing, however, has to be able to subtract the component of betatron oscillations. This adds complexity to the implementation.

The detection of phase errors is thus employed in our experiment. The hardware needs to detect the instantaneous phases of individual beam bunches and have a fast phase shifter that provides different correction phase values for each bunch.

A simple measurement of time difference between rf and a preset level of beam profile cannot produce the precise location of the centroid of the beam bunch due to the short

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time involved and the complexity of beam profile. When a beam is tightly bunched in an rf bucket, such as in many electron rings, the precision of timing measurement can be improved by generating a train of pulses with a suitable bandpass filter (such as a Bessel constant delay type), or a microwave pulse to comb generator [4] [5]. The resulting pulse train is then compared with an rf reference by a phase detector. The timing measurement has very good accuracy due to error averaging over many cycles by phase detection.

In our experiment we pick a specified harmonic component of a beam profile (usually the fundamental revolution frequency) as a reference to the position of a relative wide beam bunch. This is often a reasonable measurement of beam bunch centroids for many types of complex beam profiles with certain symmetry.

Fig. 1 is a block diagram of our experimental scheme. The beam signal is taken from a wall gap monitor. The ring operating rf frequency is divided by the ring harmonic number. A digital counter is used to accomplish the task. The state of the digital counter is decoded to drive the switches connected to filters, so that each switch closes when a corresponding beam bunch arrives. The filter bank consists of *n* filters, corresponding to *n* bunches in the ring. Each filter only sees the beam profile of its corresponding bunch in the period of one particle revolution due to fast switching and tracks the fundamental (or other harmonic) component of a single beam bunch. The filters can either be lowpass or bandpass to obtain the desired harmonic component of the beam bunch.

Since the filters operate in the steady state instead of transient state, the parameters of the filters are quite tolerant. The filter output frequency will be locked to the revolution frequency in our setup. Properly designed filters can cover the frequency swing of machines of relativistic energies. For lower energy machines in which the velocities of particles vary a lot, the filters can be electronically tuned due to their simplicity.

The rf system frequency is divided down to the same frequency as that of filters and distributed to the phase comparators in each channel. Because the synchrotron oscillations are relatively slow, the phase errors vary slowly and can be processed by normal op-amp circuits for 90 degree phase-shifting and offset compensations.

The output of the signal processors is fed into another array of fast electronic switches operating synchronously with the demultiplexing switches. The time-multiplexed signal is then used to modulate a high speed phase modulator that drives a wideband rf kicker. The time delay between the demultiplexing switches and multiplexing switches is set as such that a beam bunch sees the correction signal generated by its error. A delay of some integer numbers of revolution periods is allowed since the synchrotron tune is usually much smaller than unity.

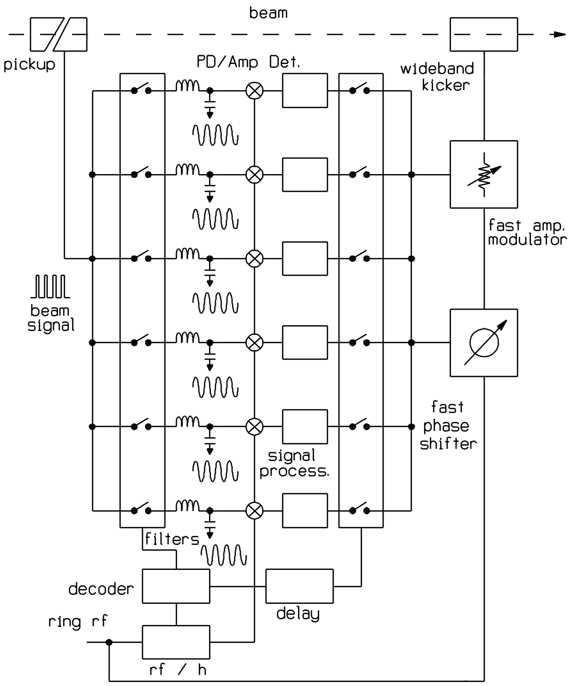

Figure 1. Block diagram of fast bunch to bunch feedback experiment.

The amplitude information of the filter output reflects higher mode bunch oscillations and is very useful, too. As shown in Fig.1, it can be amplitude detected and processed in the same fashion as the phase errors. A multiplexed fast amplitude modulator can then amplitude-modulate the wideband rf kicker to damp the oscillations.

III. HARDWARE CONSIDERATIONS

The success of the approach depends heavily on the quality of high speed electronic switches. Thanks to the state of microwave technologies, switches with excellent on/off characteristics and a couple of nanosecond switching time are readily available commercially.

Fig.2 is a scope picture of a switched beam signal. The top trace is an electron cooled 140 MeV polarized proton beam signal from the IUCF Cooler Ring. The signal is obtained from a wall gap monitor. The lower trace shows that every fourth bunch seen by the wall gap monitor is being switched to a filter. The bunches shown were in fact the same beam bunch passing through the beam monitor at the revolution frequency since the synchrotron was operating at the harmonic *h*=1. The switch was in fact being switched on every four revolution periods. So far as switching is concerned, however, there is no difference between such a setup and true individual bunch switching.

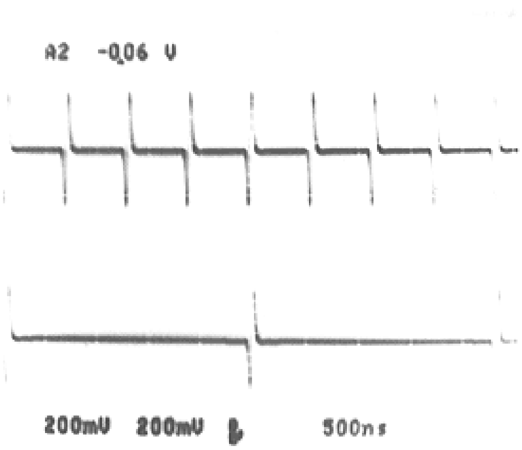

Figure 2. Every fourth bunch of beam in this scope picture is switched into a filter.

The filters are simple LC types. The phase at the output of the filters is delayed by the phase delay of the filters at the operating frequency and shows up as a DC offset at the phase detector output. The group delay of the filters delays the amplitude envelop of the filter output and is usually not a concern since the bunch oscillation periods are relatively long. If the fundamental revolution frequency is chosen from the beam profile, the filters can be lowpass types. Other harmonics usually require bandpass filters at the harmonic frequency. The Q of the bandpass filter must be such that $f/2Q \gg f_s$. In other words, the synchrotron sidebands must be able to pass the filter. The expression of a given harmonic of a phase modulated beam signal is:

$$x(t) = A_h \sum_{n=-\infty}^{\infty} J_n(m) \cos(\omega_h + n\omega_s)\, t \qquad \textbf{(2)}$$

where J_n is the nth Bessel function of the first kind, n the nth harmonic of f_s, m the phase excursion in radian and A_h the amplitude of the hth harmonic. When the phase excursion is large, the filter bandwidth needs to cover all the higher order sidebands with significant amplitudes.

Because real beam with coupled bunch oscillations is not readily available, an electronic signal source is set up to simulate the individual bunch oscillations. Fig.3 is a block diagram of such a simulator source. Two beam bunch signals capable of independent phase modulations are simulated in this setup with a "bunch spacing" of 1/f. An f/2 rf signal is split two ways. One channel is being phase modulated directly while the other channel is delayed by 1/f and then phase modulated. Two one-shot pulse generators are triggered by the phase modulated signals. The output of the pulse generators are added by a combiner, forming the desired simulation signal. N bunches can be simulated in a similar fashion from an f/N rf source that is split N channels and then recombined.

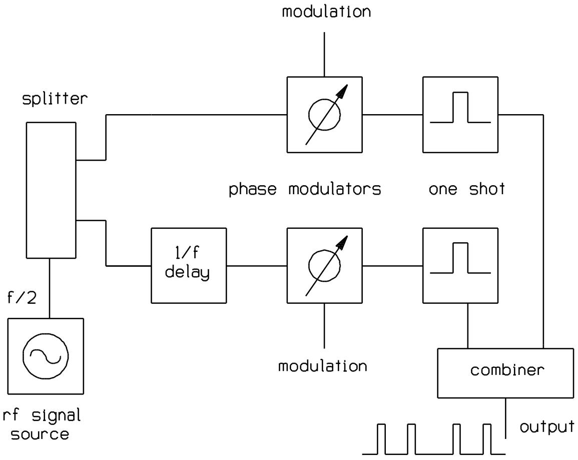

Figure 3. Block diagram of a beam signal simulation source with two independent oscillation modes.

IV. EXPERIMENTAL PLANS

We have been focusing on the error detection of coupled bunch oscillations. A wideband longitudinal kicker is needed to conduct beam experiments. A principle demonstration experiment can be conducted in the IUCF Cooler Ring attempting to damp the non-coherent bunch oscillations induced by an intentional injection phase mismatch. Further experiments can then be conducted in facilities with sufficiently high beam intensities and high impedance elements.

V. REFERENCES

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