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PROMPT BUNCH BY BUNCH SYNCHROTRON OSCILLATION DETECTION VIA A FAST PHASE MEASUREMENT*

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ABSTRACT

An electronic system is presented which detects synchrotron oscillations of individual bunches with 4 ns separation. The system design and performance are motivated by the requirements of the proposed B Factory facility at SLAC.

A comb generator is used to produce an eight cycle coherent tone burst at 3 GHz from each bunch. The phase of the coherent burst is compared with a master oscillator in a double balanced mixer. The detected mixer output is digitized at a 250 MHz rate, yielding a unique phase measurement for each bunch.

Laboratory results are presented which show that the prototype is capable of measuring individual bunch phases with better than 0.5 degree resolution at the 476 MHz RF frequency. A system design for damping longitudinal oscillations of 1658 bunches using this detector is also shown.

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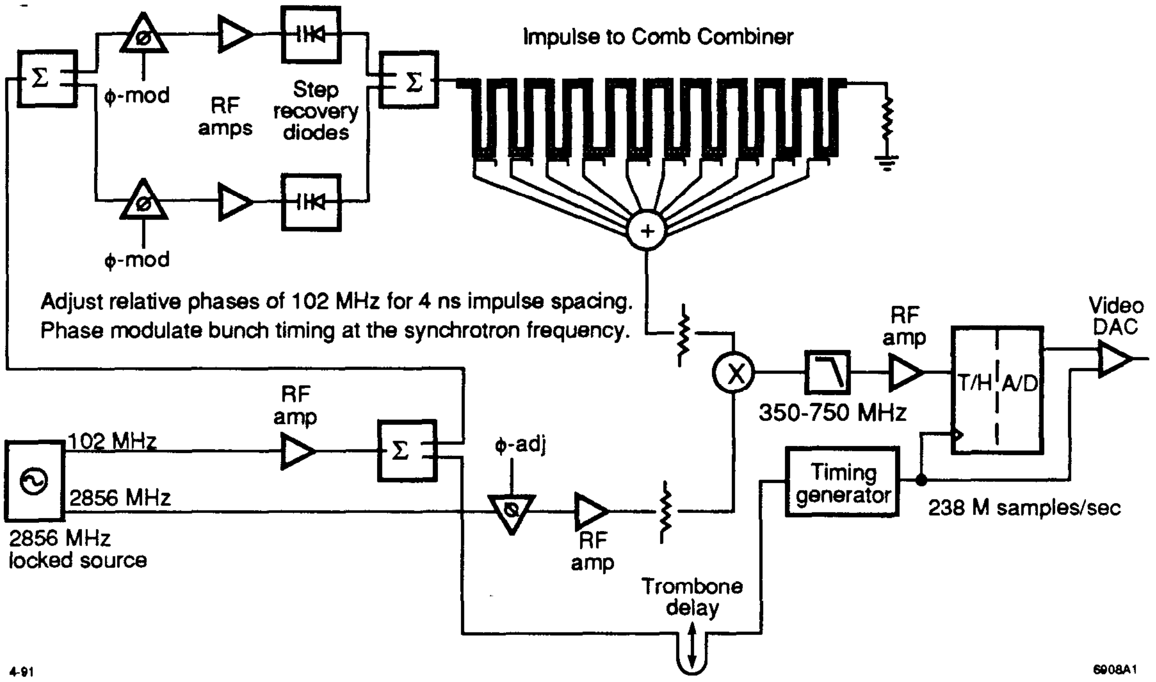

Figure 1. Block diagram of the prototype front end circuitry. This system converts a beam signal impulse into a 2856 MHz 8-cycle tone burst, and compares the phase of the burst against a reference oscillator. A 250 MHz A/D digitizes the phase each bunch crossing. The proposed B Factory design has 1658 bunches with a 4.2 ns bunch interval. The laboratory prototype uses two-step recovery diodes and phase shifters to simulate bunches with independent synchrotron oscillations.

INTRODUCTION

Many accelerator facilities have incorporated feedback systems to suppress the growth of coupled-bunch oscillations (Refs. [1–5]). The proposed SLAC-LBL-LLNL B Factory design presents several challenges in the design of transverse and longitudinal feedback systems. To achieve a design luminosity of 3×10^{33}, the B Factory will contain 1658 bunches per ring (total current 1.5 A for the high energy ring, 2.1 A for the low energy ring), spaced every other RF bucket at the 476 MHz RF frequency. This large number of bunches, plus the short (4.2 ns) inter-bunch period, forces difficult constraints on the detection, processing and energy correction stages of the feedback system. Our proposed feedback design uses a bunch by bunch (time domain) strategy that treats each bunch as an independent oscillator (Refs. [6–10]). This approach has the additional advantage that it damps not only coupled bunch oscillations, but any disturbance, such as injection timing errors, that may induce energy oscillations. In this paper we present laboratory measurements of the front end phase detection components of our proposed design.

PRINCIPLE OF OPERATION

Figure 1 presents a system constructed to test and evaluate various signal detection schemes for the longitudinal feedback system. In this laboratory prototype we have implemented a two bunch system with a time structure similar to the planned accelerator. The master oscillator of this model uses a 102 MHz oscillator that is harmonically multiplied by a factor of 28 to generate a phase synchronous 2856 MHz reference. The 102 MHz oscillator provides the excitation for two step recovery diodes which generate 60 ps FWHM impulses to simulate beam bunches. Two analog phase shifters are used to adjust the spacing of the bunches relative to the 102 MHz master oscillator, and these phase shifters allow simulated synchrotron oscillations to be impressed on the 60 ps impulses. We space the nominal positions of the bunches with a 4.2 ns interval which corresponds to the B Factory ring design, however in our test there is an extra 2 ns gap following the second bunch, after which the sequence repeats. With this system we can simulate independent synchrotron oscillations of the two bunches at frequencies up to 100 kHz, and study the performance of the detection system.

Figure 1 also shows the detection circuitry. A periodic coupler is used to generate a short eight cycle tone burst from each bunch. The phase of each burst is compared against the 2856 MHz reference oscillator in the double balanced mixer. The output of the phase detector is filtered with a 750 MHz low pass filter to remove the second harmonic and to limit the bandwidth for noise reduction. A fast analog to digital converter (with an internal track and hold) digitizes the phase error signal at a 238 MHz rate (Ref. [11]). This process provides a unique error signal for each bunch crossing. In a complete feedback system this digital data stream would undergo further digital processing, but in our laboratory model we reconstruct the digitized values with a fast digital to analog converter which allows us to use traditional lab instruments to study the system performance (Ref. [12]). A digital timing system, constructed with 100 K

ECL logic, is clocked by the 102 MHz master oscillator and provides the timing for the A/D and D/A stages. This timing generator provides triggers for both bunches, or either of the bunches can be selected for isolated study. This system allows us to measure the resolution, noise, and inter-bunch isolation of the bunch phase measurements. Also shown in the figure are various phase shifters, amplifiers, and attenuators required to synchronize the signals and create proper power levels.

RESULTS

The beam pick-up generates a short (less than 4 ns) tone burst at the 2856 MHz frequency. We use a periodic coupler, rather than a tuned resonant structure, to avoid coupling between adjacent bunches. This RF burst can be generated in several ways, using stripline pickups, power dividers and combiners, or delay lines. We have studied two possible configurations. We have constructed a comb generator in a coaxial geometry, using an array of quarter wave couplers aligned 10 cm apart along a coaxial transmission line. All the coupler outputs are then combined coherently in a power combiner as shown in Fig. 2. As an alternative, we have also fabricated and measured a structure constructed of periodically coupled stripline circuits. This latter approach minimizes the number of RF connections, and in the case of a beam coupled structure, would also minimize the number of vacuum feedthroughs.

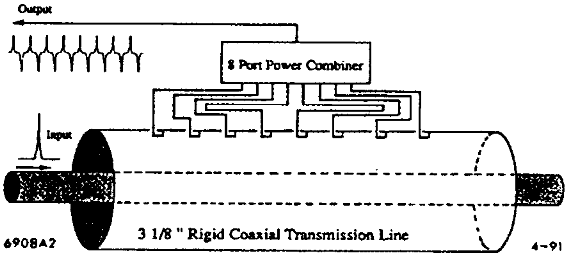

Figure 2. The eight quarter wave couplers are aligned 10 cm apart along the transmission line. Their outputs are connected to the power combiner with semi-rigid cables of equal length.

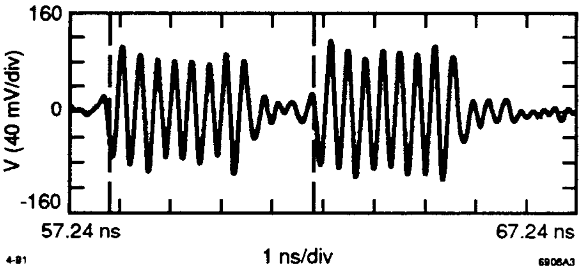

Figure 3. Measured response of the coaxial comb generator for two simulated beam signals with 4 ns bunch spacing.

The measured response of the coaxial generator is shown in Fig. 3. We see the signature of the time of arrival of each bunch as an eight cycle tone burst. There is a small amount of residual ringing ($\approx$ 5–10%) evident in the time domain measurements. In comparison, the stripline fabricated generator produced fewer reflections, but due to its larger design coupling value and skin effect losses displayed less amplitude uniformity during the output burst.

LAB MEASUREMENTS OF COMBINED SYSTEM

This periodic coupler output has been used to study the performance of the electronic system. Fig. 4 presents the analog output signal of the mixer for the two bunch system, for a case where the two bunches are offset nearly 180 degrees apart with respect to the 2856 MHz reference. Also shown in the figure is the reconstructed analog output of the D/A converter. We can see that the bunch spacing atternates between 4 and 6 ns, as produced by our beam simulator. The response shows the bandwidth required for independent measurements on bunches with the 4.2 ns spacing.

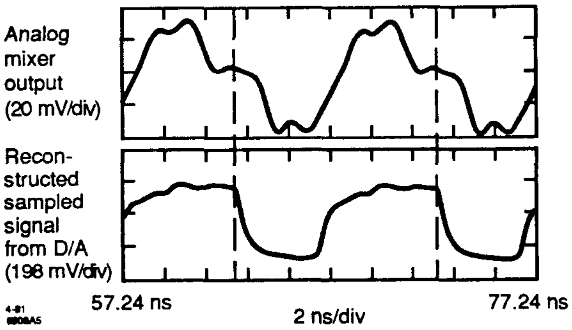

Figure 4. Measured response of the mixer (phase detector) for two bunches nearly 180 degrees apart. Also shown is the digitized phase signal after reconstruction in the D/A.

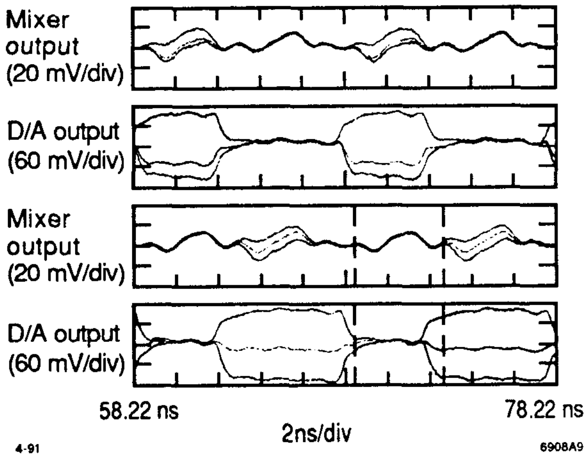

Figure 5. Analog and digital responses of the system for A and B bunch modulation.

Figure 5 shows the system response for six independent DC phase offsets of the bunches. The top traces show the analog mixer response for three distinct DC phases of bunch A, with bunch B left undisturbed. The next trace shows the reconstructed D/A output. Similarly, the lower pair of traces show three DC phases of bunch B, with bunch A left undisturbed. Again, the lowest traces are the reconstructed D/A output showing excellent isolation of the bunches.

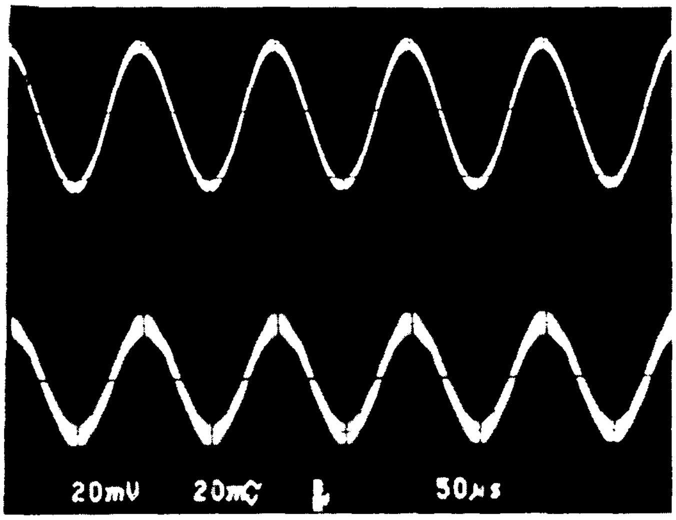

Figure 6. The upper trace shows the signal applied to a step recovery diode phase shifter, and represents a synchrotron oscillation amplitude of 0.7 degrees (±0.006 radians) at the 476 MHz RF frequency. The lower trace shows the output of the reconstruction D/A.

Figure 6 is an oscilloscope photograph which shows the AC response of the system. In these measurements a 10 KHz AC sine wave is impressed on the control signal of the step recovery diode of a selected bunch. The AC modulation exactly simulates a synchrotron oscillation. In the figure bunch A is modulated with an amplitude corresponding to 0.7 degrees p/p (±0.006 radians) at the 476 MHz ring RF frequency. The upper trace shows the signal applied to the diode phase shifter, while the lower trace displays the output of the reconstruction D/A signal for bunch A. We note the prompt in-phase detection of this oscillation, which corresponds to a ±2 ps time displacement of the bunch. The rms noise floor in this measurement is found to be better than 0.1 degrees at the 476 MHz RF frequency within the 10 kHz oscillation bandwidth.

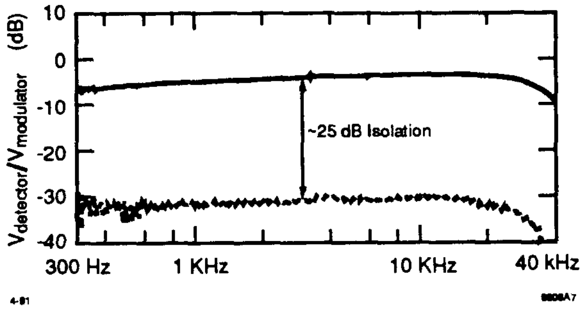

Figure 7. Network Analyzer measurement of coupling between the two bunches. Some fraction of the measured −25 dB is due to residual ringing in the comb generator.

Table 1
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		±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

The bunch to bunch coupling in our system is measured using a variant of the technique used in Fig. 6. By driving bunch A with a large oscillation, and detecting the bunch B output signal at the modulation frequency we can measure the coupling from A to B. Figure 7 presents such a network analyzer measurement for the A driving B case. We see that the isolation, over the range of synchrotron frequencies, is better than 25 dB. Some fraction of this coupling is due to residual ringing in the comb generator, while a smaller fraction is due to the finite bandwidth of the mixer IF port (1 GHz), the low pass bandwidth (750 MHz), and the track and hold bandwidth (1.2 GHz).

Table 1 presents a summary of the measured performance of our various system components for the configuration of Fig. 1. We see that the performance of the two comb generators is similar. We also note that the coupling between the bunches for the A to B and B to A cases is very similar, notwithstanding the extra 2 ns present for the B to A case. The noise performance of the system is consistent with the eight bit quantization of the digitizer, and suggest that a system using this technique could easily achieve measurement resolutions of better than 0.5 degrees at the 476 MHz RF frequency.

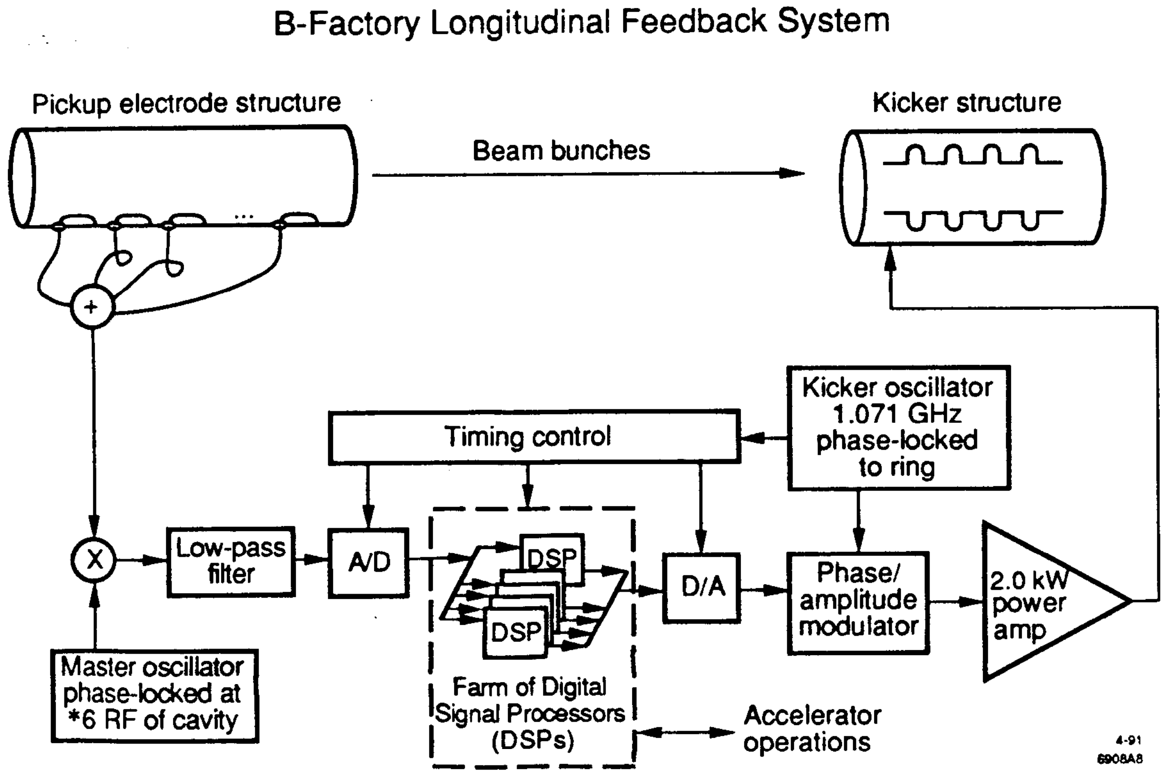

Figure 8. The proposed longitudinal feedback system includes digital processing of the bunch error signals and a 2kW power amplifier to correct the bunch energy via a traveling wave kicker structure.

FUTURE DIRECTIONS

We are continuing the development of this detection technique, as well as the development of the other components required for a complete longitudinal damping system. Figure 8 shows a block diagram of such a feedback system using this front end, digital processing of the phase error signals, and a 1 GHz power amplifier and kicker to control the beam energy. We have been actively designing and simulating this system. (Ref. [13])

SUMMARY AND CONCLUSIONS

We have demonstrated a signal processing system designed to detect longitudinal oscillations of stored bunches in a B Factory like storage ring. Our prototype system has been shown to be capable of measuring the phase of individual bunches separated by 4.2 ns with better than 0.5 degree resolution (at 476 MHZ). We have shown that the periodic coupler is capable of generating isolated tone bursts from the simulated bunches, and that the detection of individual bunch phases for a large number of bunches (1658) with a 4.2 ns interval is feasible.

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