OPERATION OF A FAST DIGITAL TRANSVERSE FEEDBACK SYSTEM IN CESR*

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Abstract

We have developed a time domain transverse feedback system with the high bandwidth needed to control transverse instabilities when the CESR e^+e^- collider is filled with trains of closely spaced bunches. This system is based on parallel digital processors and a stripline driver. It is capable of acting on arbitrary patterns of bunches having a minimum spacing of 14 ns. Several simplifying features have been introduced. A single shorted stripline kicker driven by one power amplifier is used to control both counter-rotating beams. The desired feedback phase is achieved by sampling the bunch position at a single location on two independently selectable beam revolutions. The system adapts to changes in the betatron tune, bunch pattern, or desired damping rate through the loading of new parameters into the digital processors via the CESR control system. The feedback system also functions as a fast gated bunch current monitor. Both vertical and horizontal loops are now used in CESR operation. The measured betatron damping rates with the transverse feedback system in operation are in agreement with the analytical prediction and a computer simulation developed in connection with this work.

I. INTRODUCTION

The Cornell Electron Storage Ring (CESR) is being upgraded to allow collisions of short trains of electron and positron bunches [1]. CESR is now operating with nine trains of two bunches each. We plan to operate with nine trains of as many as five bunches in the near future. A transverse coupled bunch instability [2] in CESR requires the use of active feedback. Before the present work, a time-domain horizontal feedback system based on a coaxial cable delay line and ferrite kicker magnet was used to stabilize the beam [3]. The use of bunch trains requires a redesigned transverse feedback system with higher bandwidth.

We chose to build a time domain feedback system because of the large number of coupled bunch modes that need to be damped. The minimum bunch spacing compatible with efficient injection fixes its sampling rate at 71.4 MHz. We further required that the feedback system accomodate a dynamic beam motion of ± 3 mm and arbitrary changes in tune, produce an error signal normalized to beam current, and provide a damping rate of 1000 s^{-1}.

Transverse feedback damping operates by sensing the beam position and applying a deflection to the beam proportional to its sensed position after its betatron phase has advanced by $\pi/2 + n\pi$. Because of signal processing delays the deflection cannot be applied to the beam on the same turn as the position is sensed. The error signal must be delayed by at least one turn. The 2.56 μs revolution period of CESR implies a delay-bandwidth product of approximately 500 for the error signal. It is difficult to achieve this product by purely analog means, so we chose to delay the error signal digitally, and to implement the current normalization and other signal processing functions digitally as well.

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II. SIGNAL PROCESSING

Figure 1 shows a block diagram of one digital feedback loop. The beam position signal is derived from the button electrodes used by the CESR orbit measurement system. The signals from opposite pairs of electrodes are summed in hybrid combiners. The remainder of the signal processing is done outside the CESR tunnel for access to the electronics during storage ring operation.

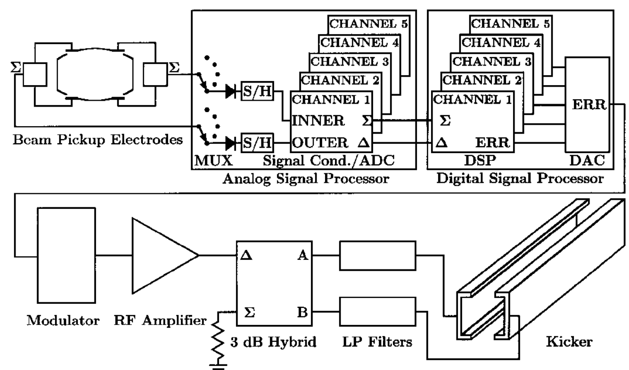

Figure 1. Block diagram of one digital feedback loop.

The receiver for the beam signal consists of a GaAs SPDT switch that serves as a fast gate, a diode rectifier which traps the signal as a charge on a capacitor, and an FET switch which discharges the capacitor before the next time the GaAs switch closes. Five parallel channels are are needed (a sixth is left unused) because of the limited sampling rate of a commercially available 10 bit ADC.

The remainder of the signal processing occurs in five parallel channels. The sum and difference of the receiver signals from opposite pairs of electrodes are formed by a pair of operational amplifiers. These contain information about the bunch current and the product of the bunch current and beam displacement, respectively. These sum and difference signals are then digitized by a pair of 10 bit ADCs.

The position of the beam is reconstructed from the digitized sum and difference signals. The eight most significant bits of the sum word and the 10 bits of the difference word form an 18 bit address for a lookup table that stores a 12 bit beam position word. The contents of the lookup table can be tailored to produce a damping rate that is any desired function of bunch current. It can also be used to compensate the position nonlinearity of the button electrodes, although we have not made use of this feature.

We delay the position word by an integer number of turns in FIFO memory and subtract it from the current position. The resulting number is the 10 bit error word, which is insensitive to static displacements and has a partially suppressed response to low frequency motions such as synchrotron oscillations. Another FIFO memory is used to delay the error word by an integer number of turns before it is used to deflect the beam, with the number of turns chosen to provide the correct $\pi/2 + n\pi$ betatron phase advance. Both of these delays are established in software and can be easily modified to accomodate changes in the storage ring optics, tunes, or feedback hardware location. A 10 bit DAC common to all five channels converts the error word to a voltage.

The digital signal processor is constructed of cards which plug into a VME backplane. Four feedback loops are needed for the horizontal and vertical stabilization of the electron and positron beams. For each of these loops a motherboard is used to provide the internal timing signals and data paths. Each motherboard holds five daughterboards, each of which performs the signal processing functions described above. Each daughterboard in turn holds a board which contains the analog sum and difference circuits and the associated pair of ADCs. Figure 2 shows a photograph of the feedback motherboard assembly containing the five daughterboards and ADC boards. A microprocessor in the VME crate runs the program which is used to enable or disable channels, load the lookup tables, and initialize the system so that it starts in a well-defined state. This program also calculates the current in each bunch by scaling and averaging the data from the 10 bit sum word. This current measurement is used in the CESR control room display and the automated injection procedure. An Xbus to VME interface is used for communication between the control system and the feedback microprocessor. External signals from the CESR ultrafast timing system are used by the feedback processor to generate its own internal timing.

III. RF ELECTRONICS

To drive the stripline kicker, we require a wideband RF amplifier with a flat phase response, the ability to drive a shorted line stably, and tolerance for some beam induced power reaching its output. After a survey of commercially available amplifiers, we chose a 200 W amplifier with a 0.25 to 150 MHz band[1]. Because the lowest transverse mode frequencies fall below this amplifier's range, we upconvert the DAC output in a modulator. A trigger supplied by the digital feedback motherboard generates a 14 ns long bipolar pulse within the modulator. This bipolar pulse is then multiplied by the DAC output in a double balanced mixer. The modulator output is used to drive the power amplifier. There is some ringing in the mixer, so an improved modulator based on a fast four quadrant multiplier has been designed. A prototype of this modulator does not display this ringing and has improved frequency response.

A $180°$ 3 dB hybrid[2] located at the stripline kicker splits the amplifier output into a differential drive for the kicker. The hybrid is protected from the beam induced power from the stripline by matched low-pass filters. To avoid high frequency resonances in the striplines, the filters need to be purely resistive. They are implemented as water-cooled ferrite-loaded coaxial lines.

[1] Model 3200L, ENI, Rochester, NY

[2] Model H3099, Werlatone, Inc., Brewster, NY

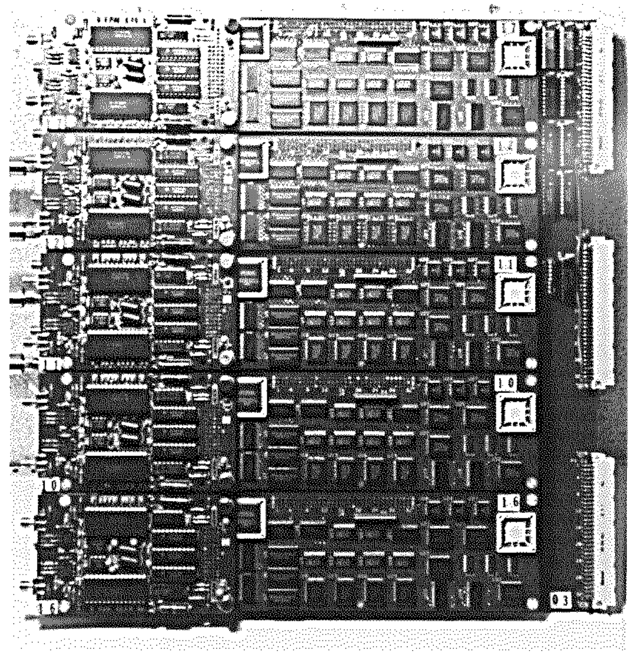

Figure 2. Feedback motherboard with five digital processor daughterboards. Each daughterboard holds an ADC board at its left.

IV. STRIPLINE KICKERS

We use stripline kickers because of their high bandwidth. Each kicker contains two electrodes which act as 50 Ω transmission lines. Each electrode is shorted at one end, which spoils the directionality of the kicker, and allows the use of a single kicker driven by a single RF amplifier for both e^+ and e^- beams. The transverse deflection, voltage induced by the beam at the kicker terminals, and the beam impedance of the shorted kicker are the same as those of a kicker with striplines terminated in their own characteristic impedance [4].

The stripline electrodes are formed from OFHC copper sheet, and have a lip on each side to improve field uniformity and mechanical rigidity. Two flat copper ground electrodes are placed in the midplane between the stripline electrodes. These have the effect of conducting a substantial fraction of the beam image current, which reduces the longitudinal coupling of the kickers to the beam, and hence their beam impedance, while leaving the intended transverse coupling unaffected. The stripline and ground plane electrodes are cooled by water flowing in 5/16 in. O.D. copper tubing welded along their length.

The stripline electrodes and ground plane electrodes are assembled on one of the endplates of the kicker vacuum chamber. This endplate also contains the cooling water tubes and one type HN RF vacuum feedthrough for each stripline electrode. Ceramic spacers maintain a vacuum gap between the end of the stripline electrode and an extension of the beam pipe into the kicker chamber. This gap is designed to produce a 10 pF shunt capacitance to prevent arcing in the RF feedthroughs and external RF components when CESR is operated with high bunch currents. This shunt capacitance is the limitation on the bandwidth of the kicker.

At the other end of the kicker the stripline and ground plane electrodes are welded into a square frame which is surrounded by beryllium copper spring finger contacts. During assembly this frame slides into a square ground contact on the other chamber end flange. The assembly process is shown in Fig. 3.

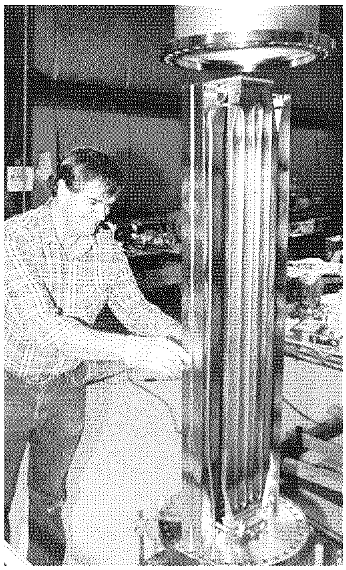

Figure 3. Stripline kicker during assembly. The RF feedthroughs are on the lower endplate in this photograph.

The aperture between the electrodes is larger than the the wide axis of CESR beampipe so that synchrotron radiation does not intercept the electrodes. Stainless steel transitions from the square opening of the kicker chamber to the approximately elliptical beampipe are provided with water-cooled copper absorbers to intercept the synchrotron radiation at a grazing angle. The stainless steel vacuum chamber has its own ion pump.

V. OPERATION

All four loops (e^+ and e^-, vertical and horizontal) of the digital transverse feedback system have been in operation since November, 1994. It is routinely used to stabilize bunch trains in high energy physics operation. Both the digital current normalization and digital phase adjustment have proven successful. In open-loop tests the shorted stripline kickers produced the calculated deflection for both e^+ and e^- beams, and the measured damping rate agrees with the calculated rate. Figure 4 shows a control room display of the amplitude of the $f_0 - f_h$ (182 kHz) horizontal coupled bunch mode as a function of time. The horizontal feedback has been momentarily gated off, then on again, restoring rapid damping of the instability.

Table 1 summarizes the digital feedback parameters.

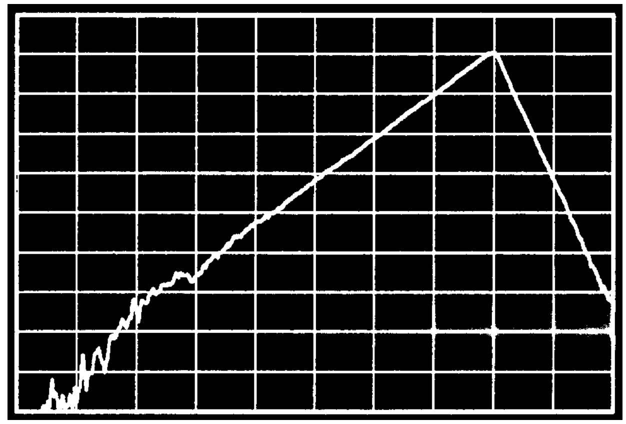

Figure 4. Amplitude of horizontal betatron motion vs. time. The feedback has been gated off during the first 8 divisions, then on again. The vertical scale is 5 dB/div. and the horizontal scale is 2.56 ms/div.

Table 1: Feedback parameters in current operation

L	Stripline electrode length	116 cm
w	Stripline electrode width	17.5 cm
b	Stripline electrode gap	12.0 cm
Z_C	Stripline impedance	50 Ω
k	Stripline HOM loss factor	0.018 V/pC
V_{peak}	Max. amplifier voltage	143 V
p	Beam momentum	5.3 GeV/c
β_x,β_y	Beta function at kicker	25.6,18.2 m
x_{max},y_{max}	Dyn. range ref. to pickup	5, 5 mm
α_x,α_y	Measured damping rate	2.4, 0.58 ms^{-1}

VI. ACKNOWLEDGMENTS

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References

[1] D. Rice, *Proc. 1993 Particle Accelerator Conf.*, 1978 (1993).

[2] L.E. Sakazaki, *et al.*, *IEEE Trans. Nucl. Sci.* **32** 2353 (1985).

[3] R. Littauer, Cornell LNS note CON 87-19 (1987).

[4] J.T. Rogers, Cornell LNS note CBN 95-4 (1995).