BEAM POSITION MONITOR UPGRADE FOR THE LOS ALAMOS PROTON STORAGE RING

R. E. Shafer, G. Swain, H. A. Thiessen, and R. Macek
Los Alamos National Laboratory

G. Mackenzie and W. Rawnsley
TRIUMF

INTRODUCTION

The beam diagnostics for the Los Alamos Proton Storage Ring (PSR) are being upgraded in several areas, including the closed-orbit beam position system, the high-frequency longitudinal and transverse beam diagnostics, and the extraction-line beam-position monitoring system. This paper describes the basic design of these new systems.

The PSR is a separated-function proton storage ring[1] designed to accumulate up to 2800 turns of injected 800-MeV protons from LAMPF, producing an average circulating current exceeding 20 A. This stored beam, up to 5×10^{13} protons, is then extracted in a single turn for pulsed neutron research. The PSR revolution frequency, 2.795 MHz, is the 72nd subharmonic of the LAMPF beam-bunching frequency, 201.25 MHz.

The PSR rf system is a single cavity operating at the revolution frequency. The injected beam is chopped so that there are about 18 empty 201-MHz rf buckets out of 72, leaving a gap of about 90 nsec in the circulating beam. The rf system serves the purpose of maintaining this gap so that beam losses can be minimized during the single-turn extraction.

Since the longitudinal emittance ellipse of the injected beam is not matched to the rf bucket, the injected beam undergoes a bunch rotation during the storage cycle (synchrotron period about 1200 µsec). This causes a coherent head-to-tail variation in the beam momentum, which in turn becomes a head-to-tail displacement in the high dispersion areas (about 2.4 cm per % $\Delta p/p$). This head-to-tail displacement is estimated to be about ± 0.3 cm, to be compared to the total measured dynamic aperture of ± 4 cm.

The present closed-orbit beam-position measuring system[2] is based on detecting the 201-MHz modulation on the injected beam, which disappears in about 10 µsec, due primarily to the momentum spread of the beam (about ± 0.1%), and the consequent spread in the revolution frequencies. Thus, although the first few turns of injected beam is monitored with the present system, the main body of the stored beam, which has lost its 201-MHz component, is not. In order to monitor the position of the stored beam, the ring beam-position system is being re-designed to operate at the revolution frequency, 2.8 MHz.

Like the PSR, the extraction line beam diagnostics also are based on detecting the 201-MHz component. Since the bunch shape is only roughly controlled by the PSR rf system, there is no well-defined 201-MHz structure present. The new design for the extracted beam-line diagnostics incorporates ballistic integration of the beam-bunch current signals *prior* to signal processing, leading to a position centroid which is a current-weighted average rather than being a time-averaged position.

THE CLOSED ORBIT SYSTEM

The 20 beam position monitors in the PSR ring [2] are four-electrode 50-ohm striplines, each 34 cm long and 40^0 wide. The sensitivity of the pickup to beam displacement is about 0.66 dB per mm of beam displacement from the center. The downstream ends are back-terminated, and the signals taken off the upstream end. The beam signals are proportional to the derivative of the circulating beam current. Use of impedance-matched striplines is necessary to assure allowable longitudinal and transverse coupling impedances at all frequencies likely to lead to beam instabilities. The large stored-beam currents, up to 60 A peak, produce substantial beam signals in the stripline electrodes at all harmonics of the revolution frequency.

Circuits using two signal processing techniques were constructed and tested on the PSR. Synchronous detection of the signals from the electrodes requires mixing each electrode signal with a local oscillator, which is phase-locked to the rf buncher cavity. The two detected signals are then low-pass filtered, followed by difference-over-sum processing to produce an analog signal representing the beam position.

Amplitude-to-phase modulation conversion (AM/PM), based on a system designed at Fermilab[3], was also evaluated. In this method, the amplitude ratio is converted to a phase difference at 2.8 MHz, and the phase difference is measured. In this technique, no local-oscillator signal is required.

The AM/PM circuit tested used bandpass diplexer filters to remove all but the 2.8-MHz fundamental harmonic, as shown in Figure 1. A 90-degree phase shift is created by a bridged "T" all-pass filter. The signals were then split and recombined in quadrature to convert the input-signal amplitude ratio to a phase difference with a conversion gain of about 6.6 degrees per dB of input amplitude difference. Specifically, the phase variation $\Delta\theta$ at the output is related to the input amplitudes V_+ and V_- by the relation

$$\Delta\theta = 2 \tan^{-1} (V+/V-) - \pi/2.$$

The limiter circuit design used in the tests on the PSR consisted of three stages of emitter-coupled-logic differential amplifiers with a gain of about 400. The limiter outputs were processed with a double-balanced-mixer linear phase detector, followed by a 400-KHz low-pass filter. Since the final limiter design must have a higher gain, the limiter design will probably be based on available fast high-speed amplitude comparators such as the Plessey SP9685.

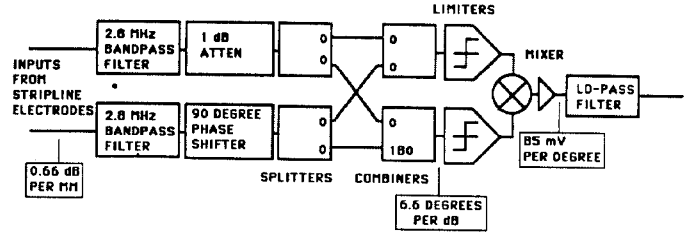

FIGURE 1. Block diagram of the amplitude-to-phase conversion circuit being considered for the new ring closed-orbit system.

In both the difference-over-sum and AM/PM signal processing techniques, the head-to-tail radial beam displacement mentioned above creates some signal phase shifts which need to be considered. Specifically, since the beam intensity signal and the head-to-tail signal are both at 2.8 Mhz and in quadrature, there is a small offset in the processed position signal.

Both circuits were built and tested on the PSR using either stripline or capacitive type pickups. The analog position signals were filtered to remove the 5.6-MHz signal (AM/PM circuit) or the 2.8-MHz (synchronous detector circuit) signal. Both circuits yielded the same absolute position to about ±0.5 mm.

CH2669-0/89/0000-1562$01.00©1989 IEEE

Some motion in the horizontal position (less than 1 mm) was observed during the storage cycle. This may have been due to electronic processing errors, synchrotron oscillations, or dE/dx losses in the stripper foil.

OTHER RING DIAGNOSTICS

Other beam-position pickups in the ring diagnostics upgrade include a four-electrode, wide-band stripline pickup with a 0- to 800-MHz response, and two dual-axis capacitive-type pickup electrode structures separated by about 90 degrees of betatron phase advance. The stripline pickup, which produces a highly differentiated signal, will be used for investigation of high frequency effects, such as longitudinal and transverse beam microwave instabilities. The four capacitive pickups, which are diagonally-cut cylinders to provide a signal highly linear in beam displacement from the centerline, are shunted with sufficient capacitance to provide signals that are representative of the circulating current. They will be used for measuring injection steering and direction errors by observation of betatron oscillations, energy- and phase-injection errors by observation of synchrotron oscillations, turn-by-turn position measurements, evolution of transverse-phase-space ellipses, fractional-tune measurement using fast Fourier transforms, and other low-frequency measurements.

The capacitive pickup electrodes, with shunt capacitance in the range of 2 nF in parallel with a 1 Megohm resistor, need to be impedance-matched to a 50-ohm transmission line by a rad-hard active amplifier circuit within about 30 cm of the pickup electrodes. The present plan is to use an Amperex 7788 tetrode, which has a transconductance in the range of 50,000 μmhos, as a cathode follower. The cathode-follower frequency response is expected to be flat up to about 100 MHz. The stripline electrodes drive 50-ohm cables directly.

In order to minimize electron-trapping and possible secondary-electron emission by trapped electrons hitting the beam pipe wall during the gap in the beam, the present closed-orbit stripline electrodes will be modified so they can be biased with a clearing field voltage up to about 1 kV, and maintain the 50-ohm back termination. At present, there is no clearing electrode system installed in the ring. In addition, since the present aperture limitation seems to be in the electrodes themselves, the plan is to increase the pickup aperture.

The wide-band signal processing system used with these pickups is shown in Figure 2. High-frequency bands are down-converted to a 0- to 75-MHz baseband with a local oscillator phase-locked to the 201-MHz injection modulation. A comb filter, with 30 to 40 dB deep notches at every harmonic of 2.795 MHz, attenuates the revolution harmonics to allow better measurement of the betatron sideband structure. These signals are digitized in a 10-bit, 200-MHz-sample-rate transient waveform digitizer with a 64k buffer memory [4]. An 8-pole 75-MHz low-pass filter is included to prevent signal aliasing. The large buffer memory allows digitizing up to 320 μsec of beam storage time in the PSR. After the data are digitized and stored, they are transferred to a Micro VAX computer for FFT analysis.

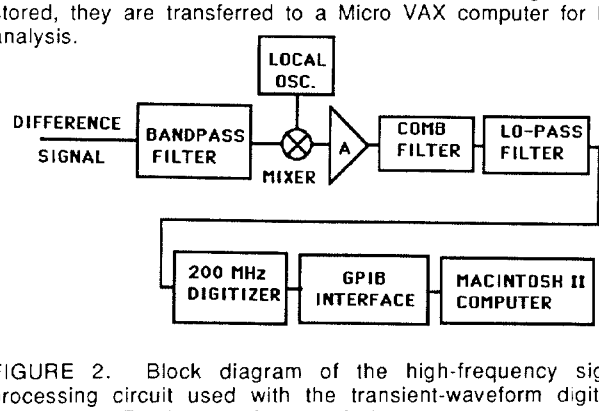

FIGURE 2. Block diagram of the high-frequency signal processing circuit used with the transient-waveform digitizer and the fast-Fourier transform analysis.

EXTRACTION LINE

The extracted-beam pulse is a single 270-nsec-long beam bunch containing up tp 5 x 10^{13} protons with no well-defined microstructure. The present beam position system, based on detecting the 201-MHz component, will be replaced with a new system that uses ballistic integration to derive signals proportional to the total charge in the beam bunch. The ballistic integration is followed by log-ratio processing to provide a signal nearly linear in beam displacement from the center. A block diagram is shown in Figure 3.

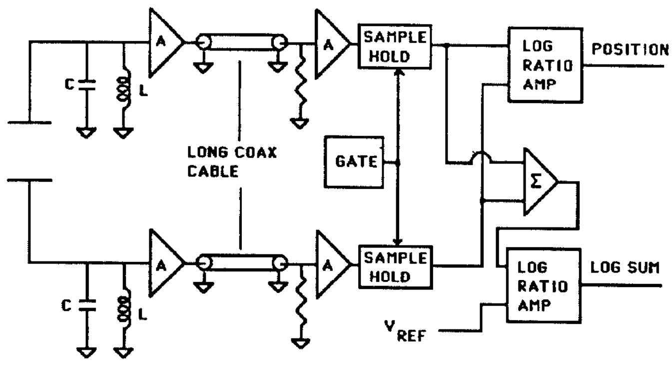

FIGURE 3. Block diagram of the ballistic integrator, log-ratio beam position circuit being designed for the extraction line.

Ballistic integration is basically shock-excitation of a passive, low-frequency, high-Q resonant circuit. If the period of the resonant circuit is of the order of 50 times the duration of the excitation signal (here about 270 nsec), the maximum voltage developed across the circuit is independent of the detailed temporal waveshape of the instantaneous current, and dependent only on the total charge. For the above case, with a beam bunch about 270 nsec long, an LC circuit with C = 2 nF, L = 1.26 mH, and Q =35 provides a damped resonant signal with a period T = 10 μsec. A quarter of a period after passage of the beam pulse, the voltage on the capacitor is

$$V_c(x) = \frac{const}{TC}\int I(x, t)dt$$

where x is the beam displacement from the center, the constant is a parameter depending on the electrode geometry and the beam velocity, and $I(x,t)=I(o,t)^*(1 \pm kx)$ is the excitation current. The integrated individual electrode signals are then held in a sample-and-hold circuit and processed by two log-ratio circuits with large amplitude dynamic ranges.

One of the features of the ballistic integration of the individual electrode signals prior to the log-ratio processing is that the resultant position signal is a current-weighted value rather than the normal time-average value. Specifically, the position signal is approximately of the form

$$\langle x \rangle = \frac{\int x(t) I(o, t)dt}{\int I(o,t)dt}$$

In accelerators where beam currents are very high and minimization of beam losses are important, current-weighted position averages are important considerations.

Commercial single-chip log-ratio circuits with three-decade, 0.5% linearity and with bandwidths in the 100's of KHz are available commercially. Four-decade dynamic range can be obtained using discrete matched-transistor pairs in feedback loops of precision operational amplifiers, followed by a difference-amplifier circuit with the proper temperature-dependent gain to cancel the temperature dependence of the log transistors.

The advantage of the log-ratio circuit in the position channel is that it provides a signal proportional to the ratio of the two signals, and therefore independent of the extracted beam charge. In addition, it is nearly linear in the displacement of the beam from the centerline. To linearize the displacement, a computer-based lookup table will be used. The log-sum circuit for the beam intensity signal is basically a dynamic range compressor, which can compress a three-decade dynamic range of beam intensity into a voltage range that can be digitized by a 10- or 12-bit ADC.

REFERENCES

1. G. P. Lawrence et. al., "Los Alamos High-Current Proton Storage Ring," IEEE Trans. Nucl. Sci. Vol. NS-32, No. 5, page 2662 (1985).

2. E. F. Higgins and F. D. Wells, "A Beam Position Monitor System for the Proton Storage Ring at LAMPF," IEEE Trans. Nucl. Sci. Vol. 28, No. 3, Page 2308 (1981).

3. S. P. Jachim, R. C. Webber, and R. E. Shafer, "An RF Beam Position Measurement Module for the Fermilab Energy Doubler," IEEE Trans. Nucl. Sci. Vol NS-28, No. 3, page 2323 (1981).

4. The waveform digitizer is a Tektronix RTD 710.